

The Environments of Core-Collapse Supernovae

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“ Tick, Tick... Boom! ”

by Jonathan Larson

— a favourite musical of mine

Declaration

I declare that, unless otherwise stated, the work presented in this thesis is my own.

No part of this thesis has been accepted or is currently being submitted for any other qualification at the University of Sheffield or elsewhere.

The following chapters are based wholly or in part on previous publications:

- Chapter 3 (The Environment of iPTF13bvn): Singleton et al. (2025)

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Summary

The relationship between the evolution of massive stars and the resultant supernova classification at the end of their lives is an incomplete picture, mostly relying on high quality pre/post-explosion data for a limited number of nearby supernovae. Direct detections of Type II supernovae progenitors converge on red supergiant stars, but the progenitors and mass-loss mechanisms of stripped-envelope supernovae remain elusive. To remedy this, in this thesis I combine high spatial-resolution photometric data with integral-field unit spectroscopic data to resolve the stars and ionised gas in the environments of core-collapse supernovae. A series of indirect methods are applied and compared, resolving stellar populations and identifying H II regions in the galactic neighbourhoods of core-collapse supernovae. In doing so, essential progenitor properties can be constrained including stellar age, mass, extinction and metallicity. This way, the fortuitous nature of the direct observational approach is avoided. Application of the environmental analysis to a catalogue of local supernovae facilitates an investigation into potential correlations between environmental properties and the supernovae classification groups. This thesis highlights the complex relationship between stars, gas and dust and takes steps towards resolving degeneracies that have plagued previous studies of the environments of supernovae. With the rapidly rising rates of transient discoveries from large time-domain surveys, an environmental analysis can assist in uncovering the ‘progenitor tree’ of core-collapse supernovae.

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Acronyms and Abbreviations

AST artificial star test

BSG blue supergiant

CCSN core-collapse supernova

HST Hubble Space Telescope

LBV Luminous Blue Variable

LoS line of sight

MS main sequence

MUSE Multi Unit Spectroscopic Explorer

RSG red supergiant

SESN stripped-envelope supernova

SN supernova

SNR signal-to-noise ratio

VLT Very Large Telescope

WR Wolf-Rayet

YSG yellow supergiant

Chapter 1

Introduction

1.1 A History of Core-Collapse Supernovae

Over a century ago, Swedish astronomer Knud Lundmark was hesitant in calculating a -16 absolute magnitude for the 1885 ‘Nova S’ object in the Andromeda Nebula (Lundmark, 1925). Far more luminous than classical novae, a cataclysmic nuclear explosion on the surface of a white dwarf, he instead compared it to the famous 1572 Tycho’s Nova (‘Nova B’ Cassiopeiae) and suggested they originate from more energetic events. A decade later, Baade & Zwicky (1934b) popularised the ‘super-novae’ class whilst investigating the potential origins of neutron stars, and hypothesised that these explosions were driven by gravitational collapse. Through this finding, and progression in stellar evolution theory (Hoyle & Fowler, 1960), supernova (SN) were linked to massive stars and the creation of neutron stars (NSs) and black holes (BHs). Following an initial spectroscopically motivated separation into Type I and Type II SNe by Minkowski (1941), a subgroup (later Type Ia) were attributed to a different explosion mechanism: the thermonuclear detonation of a white dwarf (WD) star. Core-collapse supernova (CCSN), the explosive end of a massive star’s life, were deemed responsible for the remaining SNe transients following a theoretical breakthrough in the explosion mechanics by Colgate

& White (1966), built upon the work of Burbidge, Burbidge, Fowler & Hoyle (1957). Pivotal confirmation of a massive star origin for CCSNe came with the detection of SN 1987A in the Small Magellanic Cloud, whose progenitor star was directly confirmed to be a blue supergiant (Gilmozzi et al., 1987; Hillebrandt et al., 1987). Aside from being some of the brightest observable explosions, studying the origin and influence of SNe has transformed our understanding of the Universe. They act as laboratories to test extreme physics and have allowed us to observe how their enrichment of the Universe with heavy elements (Matteucci & Greggio, 1986) ties to our own origins.

1.2 A Modern View of Core-Collapse Supernovae

Advancements in time-domain astronomy instrumentation over the past few decades has resulted in thousands of SNe detections annually, primarily sourced from the Zwicky Transient Facility (ZTF), Dark Energy Survey (DES) and the All-Sky Automated Survey for SuperNovae (ASAS-SN). Coupled with more complex stellar evolution models and computationally expensive simulations, our understanding of how CCSNe explode has come a long way. It is now widely accepted that most massive stars with initial masses $M_{\text{initial}} \gtrsim 8 M_{\odot}$ (Smartt, 2009) will end their lives as CCSNe, leaving behind a NS, or collapse directly to a BH. The $8 M_{\odot}$ threshold distinguishes the remnant compact object (either a WD or a NS), but is not a fixed value when metallicity and other factors are considered (Ibeling & Heger, 2013). When an explosion occurs, the main stages can be summarised as follows (Janka, 2012; Pejcha, 2020):

- After evolving off the main-sequence and undergoing a series of core-contractions (reheating) the post-main-sequence star has developed an ‘onion-shell’ structure, with shell burning occurring at the boundaries of layers (Figure 1.1). Proceeding carbon, neon, oxygen and (lastly) silicon burning, fusion is exhausted in the core of a massive star; earlier stages of massive star evolution are described in greater

detail in Section 1.4.1. The iron or oxygen-neon-magnesium core becomes unstable and rapidly contracts until it reaches nuclear densities (Woosley & Janka, 2005).

- Before the core is stabilised through a combination of neutron degeneracy pressure and the repulsive strong nuclear force, it overshoots this equilibrium. This causes the core to rebound and bounce, sending a shockwave outwards from the newly forming NS.
- Layers above the core have already begun to collapse towards the proto-NS, increasing its mass through accretion. The shockwave travels through these dense layers, stalling as it experiences energy losses.
- This point separates theoretical predictions of successful and failed SNe, with the latter case seeing continued accretion and further collapse of the NS into a BH.
- The formation of degenerate matter through electron capture in the core, as well as pair production in the shockwave, creates vast quantities of neutrinos, accounting for $\sim 99\%$ of the liberated gravitational energy during the collapse of the core.
- Layers above the proto-NS are semi-transparent to neutrinos. Potentially through a combination of neutrino absorption, turbulence and instabilities, the stalling shockwave can be re-energised (revived) and propagate through the remaining stellar layers. Depending on whether the star has retained an extended outer envelope or if it is an exposed compact core, the shockwave can take anywhere from several seconds to days to cross the stellar interior.
- The traversing shockwave heats the stellar interior, triggering further nuclear burning to iron group elements. Shock breakout occurs when the shockwave reaches the surface of the star, allowing the first electromagnetic signatures of the CCSNe to be detected. The outer layers are now unbound from the core, and the hot ejecta continually expands.

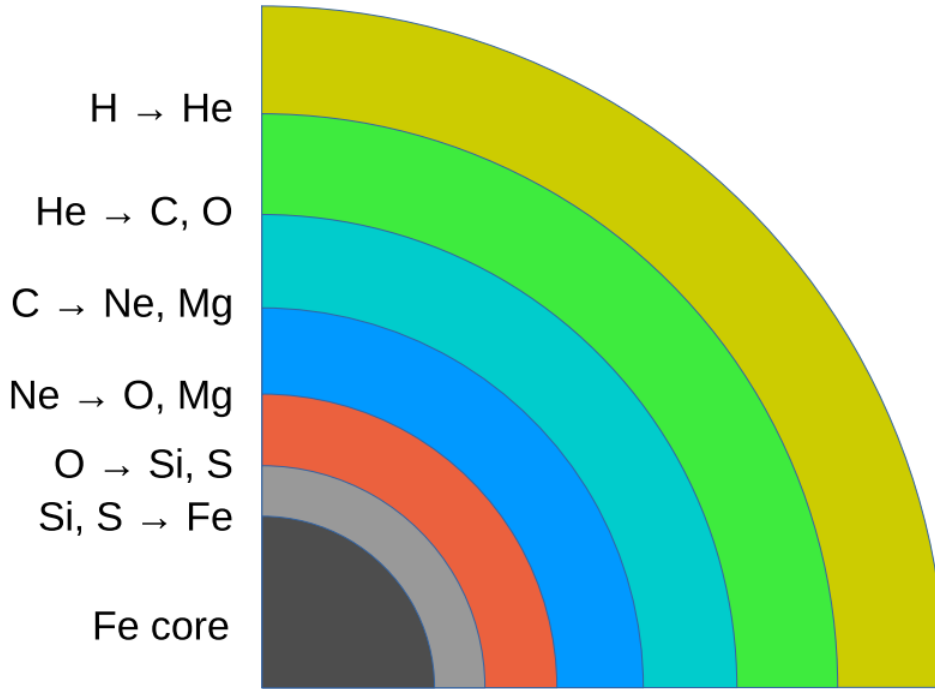


Figure 1.1: The ‘onion-shell’ structure (not to scale) of massive stars, in this case a red supergiant, prior to explosion. Above the iron core there are six distinct layers with hydrogen, helium, carbon, neon, oxygen and silicon burning occurring at the boundaries. Burning processes are listed on the left, not necessarily all active before collapse. This figure was taken from [Jerkstrand et al. \(2026\)](#).

- Non-uniform acceleration and deceleration of the shockwave as it encounters material can produce reverse shocks (travelling backwards towards the explosion origin).
- The characteristic energy budget of an explosion (kinetic + radiation) is of the order $\sim 10^{51}$ erg, and is almost entirely afforded to the kinetic energy of the expanding nebula. A significant portion of the electromagnetic radiation output of CCSNe is powered by the radioactive decay chain of synthesized ^{56}Ni into ^{56}Co and ^{56}Fe .

Many details are missing from this simplified picture, and the specifics of the explosion mechanism are still highly theoretical. Other theoretical explosion mechanisms include the magneto-rotational mechanism ([Bisnovatyi-Kogan, 1971](#)), acoustic wave mechanism ([Burrows et al., 2006](#)), phase-transition mechanism ([Sagert et al., 2009](#)) and the jittering-jets mechanism ([Papish & Soker, 2011](#)). The neutrino-heating mechanism is widely

accepted by the community, however the physical reality could pull from multiple of these theories in tandem.

Outside of the standard iron-core SNe, specific conditions could result in electron-capture, pair-instability or gamma-ray burst SNe. Electron-capture SNe are predicted for a narrow mass range of $8 - 10 M_{\odot}$ progenitors. A high density oxygen-neon-magnesium core can initiate electron-capture onto Ne and Mg nuclei, triggering a SN explosion (Leung & Nomoto, 2019). For very massive progenitors, $> 70 - 100 M_{\odot}$, conditions in their He cores are hot enough and low enough density that radiation can convert into electron-positron pairs ($e^{\pm}$). Reduced radiation pressure in the core makes it unstable, leading to repeated episodic mass loss (pulsation pair-instability) or a single pair-instability supernova explosion (Renzo & Smith, 2026). Some SNe show association to gamma-ray bursts (GRBs) believed to originate from rapidly rotating progenitors and differential rotation in the collapsing iron core (Woosley & Bloom, 2006). The explodability of massive stars as CCSNe is incredibly sensitive to the initial stellar parameters, stages of evolution across their lifetime and final conditions prior to stellar death. Detailed 1D hydrodynamical simulations mapping the myriad of stellar parameters to the likelihood of explosion find ‘islands of explodability’ (Sukhbold et al., 2016; Ertl et al., 2016, 2020). Rather than a monotonic relation between initial mass and explodability, the parameter space contains irregular regions that result in an explosion and others that lead to a direct collapse to a BH; an example of such results is provided in Figure 1.2.

From the onset of shock breakout a CCSNe enters an optically thick period, known as the *photospheric phase* (or ‘diffusion phase’ in lightcurves), where a photosphere emits a thermal, blackbody-like spectrum. Over a period of weeks to months, observables are governed by the diffusion of internal energy through the expanding nebula. During this phase a SN will reach and surpass peak brightness, with characteristic luminosities of $\sim 10^{42} \text{ erg s}^{-1}$. Spectra are dominated by overlapping *P-Cygni* line profiles (Figure

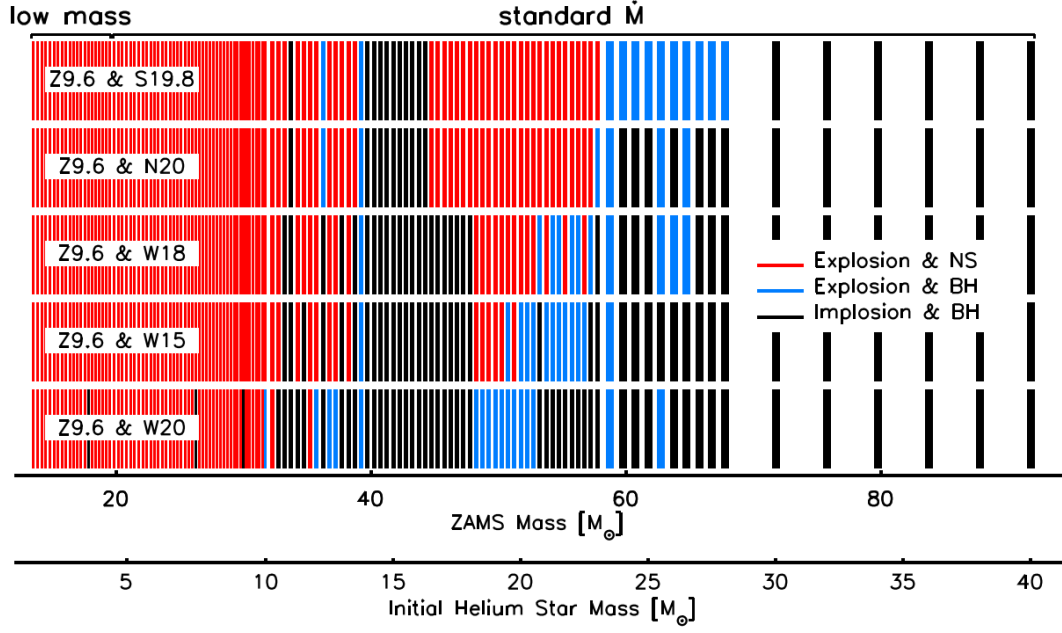


Figure 1.2: Figure 3 from Ertl et al. (2020) testing the ‘islands of explodability’ for helium stars in binaries evolved with mass loss, using the Prometheus-Hot Bubble code. The rows represent different modelled stellar configurations, coloured bars represent the explosion and compact remnant outcome: explosion & NS (red), explosion & BH (blue) representing "fallback supernovae" (massive fallback accretion); implosion & BH (black). The five horizontal sets of results represent varying neutrino engine configurations, with the strongest (largest number of successful explosions) at the top, and weakest at the bottom. An example would be "Z9.6 & W18", a $9.6 M_{\odot}$ SN 1054-Crab-like progenitor (Z9.6) and a $18 M_{\odot}$ blue supergiant star (W18). A $19.8 M_{\odot}$ red supergiant star (S19.8) was also included for its likeness to the progenitor of the well-studied SN 1987A. Simulations were performed in discrete initialisations, such that any white spaces are missed regions of the parameter space.

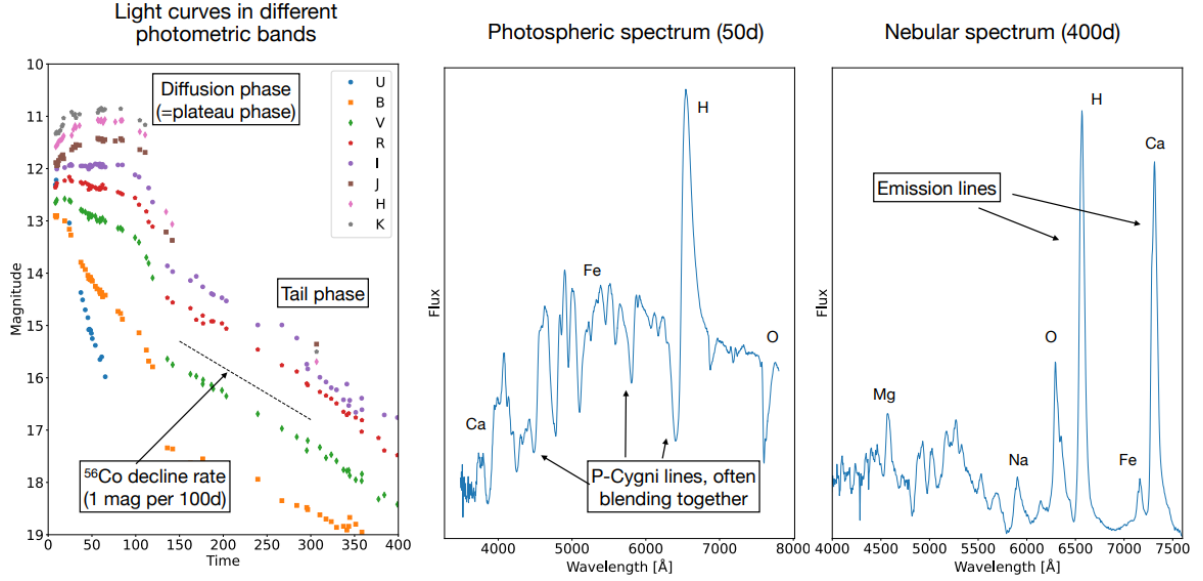


Figure 1.3: Figure 4 from [Jerkstrand et al. \(2026\)](#) with data from [Maguire et al. \(2010\)](#). Example lightcurves of Type II-P and II-L SNe and spectroscopy in the photospheric and nebular phases.

1.3). Initial hard radiation (mostly X-ray) from shock breakout may photoionise any surrounding CSM, which are reprocessed and emitted as recombination lines.

Following the end of the photospheric phase, the ejected material has reached low enough densities to enter an optically thin period known as the *nebular phase* (or ‘tail phase’ in lightcurves). Generated radiation can now escape on short time-scales and is observed as broad emission (recombination) lines in the spectrum (Figure 1.3), reflecting the expansion velocities of different regions of the ejecta. This phase can last months to years, depending on the explosion mechanics, the amount of ejected material and subsequent interactions with CSM.

Proceeding the nebular phase, the explosion is eventually considered to be over and what remains is labelled as a *supernova remnant*. The homologous expansion of the nebula has encountered the surrounding CSM and now reached the interstellar medium (ISM). These interactions can be studied, as well as the production of dust.

1.3 Supernovae Classifications

Supernovae are separated into subgroups by their spectroscopic and photometric features, and how they evolve with time. Spectroscopy allows us to identify the presence of elements and constrain their abundances through emission line strengths and ratios. Emission line widths inform the velocity dispersions of ejected material. Temporally, emission lines can evolve or disappear entirely. Imaging SNe in different passbands allows the brightness and colour evolution to be measured, producing a lightcurve with repeated measurements.

As described in Section 1.1, SNe were initially separated into Type I and Type II based on the absence and presence of hydrogen in their spectra respectively. Today, the classification scheme has expanded to encompass finer details. The Type II class is still identified through the presence of hydrogen, but is divided into two subgroups based on lightcurve features. Type II-P display a ‘plateau’ (P) phase during their lightcurve decay after reaching peak brightness, where the brightness remains roughly constant for timescales of ~ 100 days. This brightness is maintained through H recombination as the hot ejecta ionises circumstellar material (CSM) close to the exploding star. Comparatively, Type II-L shows a linear decay post peak brightness. Both II-P and II-L then demonstrate exponential decay tails from the radioactive decay of ^{56}Ni and ^{56}Co , until they completely fade. Example lightcurves for Type II-P and II-L are provided in Figure 1.3. A lack of hydrogen lines with prominent helium signatures defines the Type Ib classification, and a further lack of He lines defines Type Ic (for example spectra see Filippenko 1997). Bridging the gap between II and Ib, Type IIb SNe initially show signatures of hydrogen that quickly vanish and spectroscopically evolves to resemble Type Ib (Woosley et al., 1994). Separate from the CCSNe mechanism, Type Ia SNe are identified through a lack of hydrogen and strong silicon absorption features in their spectra at maximum light. Since these SNe represent the thermonuclear detonation of WDs, they

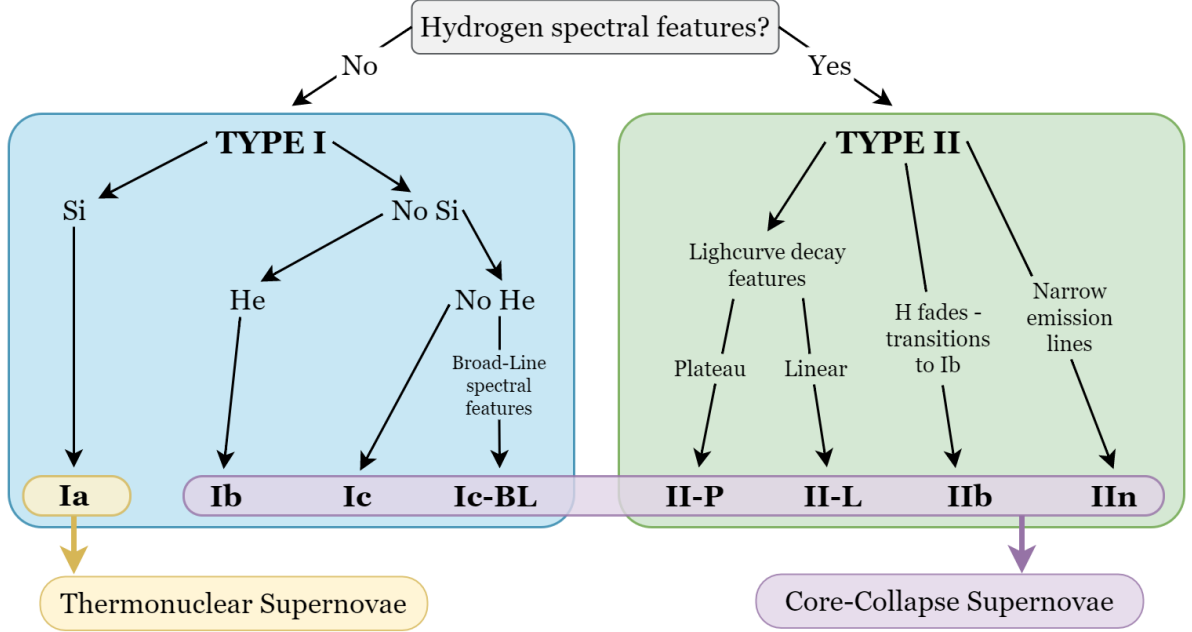


Figure 1.4: Supernova Classification Scheme.

will not be discussed further.

Some CCSNe demonstrate very narrow emission lines in their spectra, owing to a strong interaction between the propagating SN ejecta and surrounding dense CSM. The high CSM density slows the ejecta, dumping kinetic energy and ionising the surrounding material. Instead of the typical broader emission observed because of the ejecta velocity, strong narrow features dominate (Schlegel, 1990). These types of transients can occur in any of the classifications, and are denoted by an ‘n’ (i.e. Type II_n, Ib_n, Ic_n). Oppositely, some Type Ic SNe are found to have broad-lined (BL) emission produced by comparatively high ejecta velocities, thought to be linked to an unusually energetic explosion mechanism (Patat et al., 2001). Any SNe whose lightcurve or spectroscopic features deviate from the subgroup general populace are branded as peculiar (‘-pec’), such as the case of SN 1987A. This modern classification scheme is summarised in Figure 1.4

1.3.1 Other Transients

Other transients form additional classifications, likely produced by the CCSNe mechanism, including superluminous supernovae (SLSNe), hypernovae and fast-rising blue optical transients (FBOTs). SLSNe reach luminosities 10 or more times those of typical SNe, and have been proposed to originate from pair-instability SNe of very massive progenitors (Dessart et al., 2012; Woosley et al., 2007). Further subgroups differentiate those that are radioactively powered (SLSN-R), hydrogen-rich (SLSN-II) and hydrogen-poor (SLSN-I), with the latter corresponding to the most luminous class (Gal-Yam, 2012). Hypernovae have kinetic energies in excess of 10 times those of typical SNe and are associated to Type Ic SNe with long-GRB counterparts (Iwamoto et al., 1998; Mazzali et al., 2003). Their energetic origins have been linked to rapidly-rotating magnetic progenitors that launch highly collimated jets (Burrows et al., 2007). The newest and least understood classification are FBOTs. Their luminosities are comparable to SLSNe, but with a rise time too short to be solely produced by radioactive decay. AT2018cow was the closest FBOT to be detected and closely monitored, but the power mechanism and progenitor of such systems is still unknown. Sun et al. (2022b) studied the luminous late-time (2-3 year) brightness of AT2018cow, concluding that it is not indicative of a companion star, stellar cluster, surviving progenitor, CSM interaction, magnetar or tidal distribution event. Lyutikov & Toonen (2019) have suggested that AT2018cow was an electron-capture explosion produced by colliding white dwarfs. Chrimes et al. (2026), however, find stronger support for a very massive star core-collapse origin. Continued monitoring of AT2018cow and other FBOTs may reveal their origins, but their discovery highlights the importance of high cadence time-domain astronomy and the possibility of other unknown transients.

1.3.2 Rates

There have been many studies (Smartt et al., 2009; Li et al., 2007; van den Bergh et al., 2005; Prieto et al., 2008; Cappellaro et al., 1999) that explore the rates of core-collapse supernovae, each using different observatory samples. Table 1 of Smartt (2009) summarises the results of the above five studies, which mostly find good agreement. Their constraints (errors) of the rates of each SN classification, however, can be poor due to limited sample sizes. Only van den Bergh et al. (2005) achieve a sample size in the triple digits (277) extending to a distance of ~ 140 Mpc with the Lick Observatory SN Search (LOSS) sample. An example of CCSNe rate estimates are presented in Figure 1.5; Smith et al. (2011a) also used the LOSS sample. By calculating these rates we can gain insight into predictions about which evolutionary progenitor channels contribute to a given CCSN group. For instance, the observed rates of stripped-envelope supernovae (SESNe; Types IIb, Ib, Ic) can not be solely produced by single massive stars and simultaneously agree with the initial mass function (Smith et al., 2011a). Instead, as many as half of Type Ib/c and a third of all CCSNe progenitors (Eldridge et al., 2013) must originate from progenitors that are stripped by binary interaction (discussed further in Section 1.4.2). As can be seen above, Type II-P is the most common type of SN observed in the local universe (out to ~ 100 Mpc) and similar estimates of their rates are found unanimously across studies. It is within the less common groups that discrepancies over their rates begin to emerge, in particular Type IIn and IIb. Acquiring larger samples of these underrepresented SN types and catching photometric and spectral information at early-times (to better refine classification) may push their predicted rates into agreement. A recent study by Srivastav et al. (2026) looked at the larger ATLAS-100 sample, containing 1729 supernovae and other explosive transients within ~ 100 Mpc. Removing their sample of Type Ia, 'unclassified' and 'other' objects they find $\sim 74\%$ SNe II (Types II, IIn and II-pec) and $\sim 26\%$ SESNe (Types IIb, Ib and Ic), similar rates to those

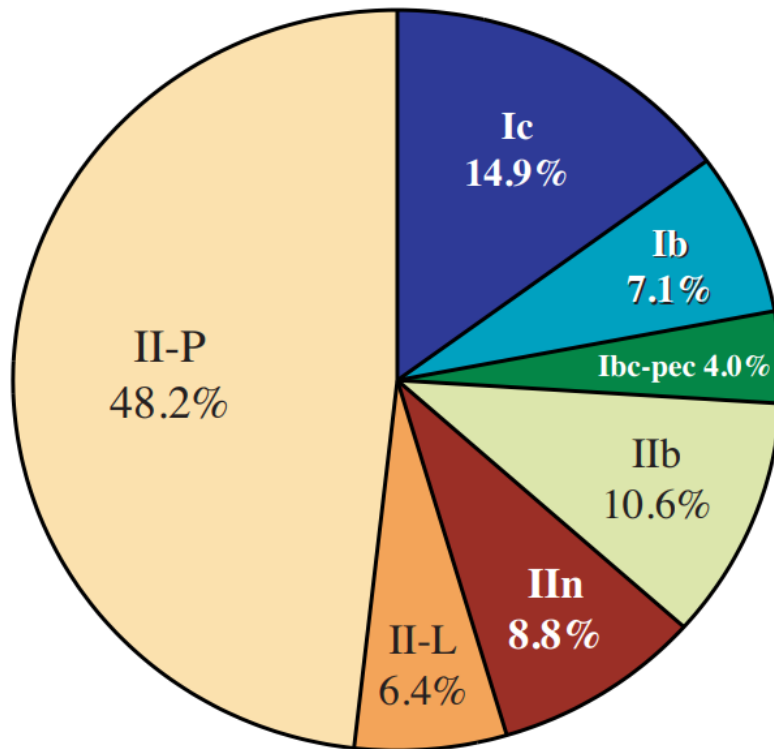


Figure 1.5: Figure 1 in [Smith et al. \(2011a\)](#), showing core-collapse supernova rates from the Lick Observatory SN Search (LOSS) sample.

observed in past work with a slightly enhanced fraction of hydrogen-rich SNe (excluding Type IIb). More work is needed to investigate how these rates change with respect to redshift (distance) and metallicity, but some investigations with larger modern surveys have been executed: [Strolger et al. \(2015\)](#) and [Dahlen et al. \(2012\)](#). This could confirm predictions, like those by [Heger et al. \(2003\)](#), that imply an increase in the rates of SESNe in higher metallicity environments.

1.4 Core-Collapse Supernovae Progenitors

1.4.1 Massive Stars

Massive stars are distinct from low- and intermediate-mass stars as they achieve high enough temperatures in their cores to surpass helium burning and begin advanced nuclear

burning phases (C, Ne, O, Si). As described in Section 1.2, massive stars can be defined as those with initial masses above a threshold of $\sim 8 M_{\odot}$. Massive stars have comparatively short lifetimes, in the range of a few million to tens of millions of years. On galactic and kinematic timescales, this short delay between stellar birth and death means massive stars remain close (typically < 500 pc; Crowther 2013) to their birthsites, making them ideal tracers of star formation (Adamo et al., 2020). In line with the initial mass function, massive stars are rare objects, however their high luminosities, strong UV output and stellar winds greatly impact their galactic neighbourhoods by shaping and ionising the interstellar medium (St-Louis, 1998). Massive stars occupy the upper regions of the Hertzsprung-Russel (HR) diagram, spending most of their lives powered by the CNO cycle. Spectroscopically they are identified as O-Type (surface temperatures $> 30,000$ K; strong He II absorption lines) and B-Type (surface temperatures $10,000 - 30,000$ K; strong He I absorption lines), sometimes grouped as OB-stars (Martins & Palacios, 2017). Depending on the initial mass of the star, post main sequence evolution can take different courses; summaries of the main potential outcomes are described below.

Red Supergiants: When hydrogen shell burning begins, the outer layers of a massive star expand and cool until the structure settles and a red supergiant (RSG) has formed. The formation of a strong convection layer extends to the stellar surface, allowing mixing of heavier nucleosynthesis products through the star. The red supergiant (RSG) phase lasts on the scale of $10^5 - 10^6$ years, during which the star can experience intense dusty mass-loss (van Loon, 2025).

Blue Supergiants: Blue supergiant (BSG) stars are not a homogeneous group, instead representing a short-lived evolutionary phase. A subgroup belongs to stars with high enough mass (temperature) that they directly evolve into BSGs post main sequence, instead of a RSG, owing to their higher surface temperatures. Others are in a transitional stage, either entering or exiting a ‘blue loop’ on the HR diagram (Langer et al., 1989).

Yellow Supergiants: Similar to the arguments made for a BSG, yellow supergiant

(YSG) represent a short-lived evolutionary phase. Potentially a later evolved RSG, they have increased surface temperatures that naturally occur in higher mass stars or are induced from the extreme mass-loss of a RSG (Georgy, 2012).

Helium Stars: A ‘helium star’ is a broad category of stars that display strong helium spectral lines, due to most (or all) of the outer hydrogen envelope being lost. The hydrogen envelope could have been lost to radiatively-driven stellar winds or stripping from a binary companion, however binary interaction may be the more common route (Drout et al., 2023).

Luminous Blue Variables: Luminous Blue Variable (LBV) stars are an incredibly luminous class of BSGs with the highest observationally observed mass-loss rates of any stellar class. They are associated with irregular variability (unlike Cepheid Variables), high mass-loss and instability-driven eruptive mass loss (Smith, 2026). These giant eruptions achieve high enough luminosities that they are a source of ‘supernova impostors’ (Smith et al., 2011b).

Wolf-Rayet Stars: The signature of a Wolf-Rayet (WR) star is spectacularly strong and broad emission lines from their powerful stellar winds. Essentially, they are the exposed core of a massive star that has suffered immense stripping of its outer layers. This can occur in the post-LBV phase of what was once an O-Type main sequence (MS) star, or other types of massive stars can be driven to a WR phase through binary interaction. Spectroscopically, they are classified as either WN, WC or WO depending on whether nitrogen, carbon or oxygen emission dominates respectively. This spectral classification reflects elemental abundances at the stellar surface, governed by the severity of wind-driven mass-loss (WC/WO stages are only reached by the most massive stars). (Crowther, 2007)

1.4.2 Mass Loss

An important factor in the evolution and final fate of a massive star is the mass-loss history across its lifetime. Mass-loss in massive stars typically occurs through two main channels: radiatively-driven winds or stripping of the outer layers by interaction with a binary companion. Radiatively-driven winds are powered by the exchange of photon momentum through metal absorption lines, and are therefore heavily dependent on metallicity (Hainich et al., 2017; Mokiem et al., 2007). Varying power law prescriptions for metallicity - mass loss relations exist for O-, B-Type and supergiant stars (Crowther, 2001). Mass-loss by winds also scales with luminosity and temperature. Winds remain comparatively steady during the MS phase of a massive star, only scaling with the slow rise in luminosity. The effect of wind clumping on observable diagnostics (i.e. $H\alpha$) revealed them to be weaker than previously thought, reducing the severity of wind-driven mass-loss in high mass stars ($\sim 30\%$ less for O-Type stars) (Smith, 2014). As massive stars evolve off the MS and into later evolutionary stages (AGB, LBV and WR stars) wind strengths are enhanced. Steady winds, as well as other mass-loss mechanisms discussed below, can result in the build up of gas reservoirs of varying density profiles around the star, known as circumstellar material (CSM).

High rates of multiplicity in massive stars (Sana & Evans, 2011) leads to mass-loss through close binary interaction, with over 70% of massive stars exchanging mass with a companion in their lifetimes (Sana et al., 2012). This process is highly sensitive to the orbital separation, mass ratio and changes in the evolutionary state of the binary stars. Roche-lobe overflow is triggered when the radius of the donor star exceeds its Roche lobe, resulting in stable or unstable mass transfer. Depending on the configuration of the binary, this can happen at different stages of core burning in the donor star: hydrogen burning ('Case A'), helium burning ('Case B'), or beyond helium burning ('Case C'). Under binary mass transfer the two stars could enter a common-envelope (CE) phase,

where their outer layers and expelled material enshrouds the binary system. Rapid angular momentum losses under the CE phase result in extremely compact binaries (if the envelope is expelled) or a merger (Ivanova et al., 2013).

In recent years, evidence for eruptive mass-loss in the final years to decades of massive stars has grown and is a key missing ingredient from stellar evolution models (Smith, 2014). Violent episodic eruptions were expected and observed in LBV stars, but could also occur in something as humble as the RSG (Cheng et al., 2026). Evidence for eruptive mass-loss has been indirectly observed in CSM structure illuminated by SNe (Gkini et al., 2026; Baer-Way et al., 2025), yet observing them directly has remained challenging and may be better understood with the upcoming surveillance of the Vera C. Rubin Observatory. Examples of well observed eruptive mass-loss episodes include the LBV progenitor of the Type II_n SN 2011ht (Fraser et al., 2013) and carbon-oxygen WR progenitor of the Type Ib-pec SN 2006jc (Pastorello et al., 2007). Any combination of these mass loss channels can impact the progenitors of CCSNe, particularly those that result in the SESN group.

1.4.3 Type II Supernovae Progenitors

The ‘gold standard’ for progenitor detections requires deep pre-explosion archival images, typically sourced from the extensive Hubble Space Telescope (HST) data archive. Later, post-explosion images are required to conclusively claim that the progenitor candidate has disappeared from the SNe site. In the last two decades, the search for the progenitors of Type II SNe has converged on RSG (Smartt et al., 2004; Maund et al., 2004; Smartt et al., 2009; Smartt, 2009), which aligns well with theoretical predictions of stellar evolution (Paczynski, 1970). Using 20 Type II-P SNe from a 10.5 year, volume limited (< 28 Mpc) sample, Smartt et al. (2009) estimates the mass range for Type II-P progenitors to be within $M_{\min} = 8.5_{-1.5}^{+1.0} M_{\odot}$ and $M_{\max} = 16.5 \pm 1.5 M_{\odot}$. When com-

pared to [RSGs](#) in the Local Group, with masses as high as $25 M_{\odot}$, their value for $M_{\max}$ introduces an approximately $17 - 25 M_{\odot}$ mass gap for observed Type II-P SNe. This is referred to as the “*red supergiant problem*” and it is, as of yet, unclear if this missing mass range is due to underestimations of extinction, an unknown type of transient, faint SNe or a direct collapse into a black hole (BH). More recently, [Morozova et al. \(2018\)](#) used a 15 year sample of 20 Type II-P SNe lightcurves and numerical simulations of dense CSM around [RSGs](#) to constrain their progenitor zero-age main sequence (ZAMS) mass, ejected mass and CSM parameters. They highlight the importance of the final stages (years to months) of [RSG](#) star evolution, in which CSM is expected to form close to the [RSG](#) and influence the observed lightcurve upon explosion. From their model they find four II-P SNe with best-estimate ZAMS masses that lie within the “red supergiant problem” mass gap ($> 17 M_{\odot}$), but direct observational evidence is still yet to close this gap and confirm the fate of stars in this mass range.

It is still not well understood what distinguishes the [RSG](#) progenitors of II-P and II-L, except that II-L have less hydrogen in order for their observed lightcurves to have faster declines after peak luminosity. Although it seems logical to expect their progenitors to fill the “red supergiant problem” mass gap, this is not what is observed ([Valenti et al., 2016](#)). [Arcavi et al. \(2012\)](#) find evidence, from a lightcurve analysis, that the progenitors of II-L are distinct from II-P and that the decrease in hydrogen envelope mass going from II-P $\rightarrow$ II-L $\rightarrow$ IIb does not represent a continuum of physical parameters.

Despite being one of the more observationally rare SN classes, many studies ([Gal-Yam et al., 2007](#); [Taddia et al., 2013a](#)) expect [LBVs](#) to be the dominant progenitor for Type IIn SNe. These stars have the necessary mass-outbursts to produce dense, hydrogen rich CSM responsible for the narrow emission features observed in their spectra. This would put their progenitor mass $> 25 M_{\odot}$. [Gal-Yam et al. \(2007\)](#), however, propose that some of the most massive progenitors ($> 80 M_{\odot}$) could explode as [LBVs](#) (without evolving to Wolf-Rayet stars) and produce IIn SNe, as they could still retain some hydrogen.

Alternatively, [Smith et al. \(2009\)](#) argue that extreme [RSGs](#) with large mass-loss rates, like VY Canis Majoris, are potential progenitors for Type IIn SNe.

SN 1993J ([Nomoto et al., 1993](#); [Aldering et al., 1994](#); [Woosley et al., 1994](#)) and SN 2011dh ([Maund et al., 2011](#); [Bersten et al., 2012](#); [Ergon et al., 2015](#)) are examples of well studied Type IIb SNe with direct detections of their progenitors. The first was identified as a non-variable [RSG](#) of $13 - 20 M_{\odot}$ and the second a $13 M_{\odot}$ yellow supergiant, both with binary companions responsible for extensive stripping of their H envelopes prior to explosion. In the case of SN 1993J, [Maund et al. \(2004\)](#) directly detected the binary companion in the fading SN remnant HST images. Binary interaction can therefore be considered a likely mode of mass-loss for producing the progenitors of Type IIb SNe.

1.4.4 Type Ib/c Supernovae Progenitors

Detections of Type Ib/c progenitors have remained the most elusive, with respect to Type II. The first possible progenitor detection of Type Ib came with SN iPTF13bvn ([Cao et al., 2013](#); [Eldridge et al., 2015](#); [Eldridge & Maund, 2016](#); [Folatelli et al., 2016](#)), followed by Type Ic SN 2017ein ([Kilpatrick et al., 2018](#); [Van Dyk et al., 2018](#); [Xiang et al., 2019](#)) and Type Ib SN 2019yvr ([Kilpatrick et al., 2021](#); [Sun et al., 2022a](#)). These studies suggest an assortment of possible progenitors: helium giants, massive binaries ([WR](#) or B stars) or cool and inflated stars in close binaries. Often the best-estimate properties of a progenitor produces a dichotomy in its proposed evolution, as it can not be determined whether the system is singular or binary. Resolution also limits whether a point source can be distinguished from a stellar cluster, but the latter implies a very massive ($> 65 M_{\odot}$) progenitor. Moreover, pre-explosion images reveal eruptive mass-loss episodes in the decades leading up to the explosion, imposing dense, optically-thick CSM around the system. Historically, [WR](#) stars have been proposed as potential progenitors for Type Ib/c SNe ([Gaskell et al., 1986](#)), owing to their extensively stripped

outer layers. Unlike the WR mass loss pathway, binary interaction can generate Type Ibc progenitors from a ZAMS mass $< 25 M_{\odot}$. Therefore, a combination of both forms of mass loss are expected to contribute to Type Ib/c SNe. As outlined by Eldridge et al. (2013), this mixture of progenitor channels can be observationally supported even when a progenitor is not directly observed. They highlight how a fraction of these non-detections could still have progenitors that originate from WR populations, estimating a $\sim 16\%$ probability of chance non-detection. Type Ibc relative rates and ejecta mass estimates, however, must require a mixture of high mass progenitors and stars in binaries with initial masses $< 20 M_{\odot}$, the latter of which has an even higher probability of non-detection. By searching for broad, long-duration lightcurves in the Palomar Transient Factory (PTF) and intermediate-PTF (iPTF) sample, indicative of high ejected mass systems and thus high mass progenitors, Karamehmetoglu et al. (2023) confirm a high mass origin for some stripped SNe. Zapartas et al. (2026) compare the current population of surviving binary companions to binary population-synthesis predictions, finding evidence of high fractions ($> 80\%$) of Type Ibc progenitors exploding with a binary companion, but disfavour efficient accretion. This highlights how even when binary companions are found they can not conclusively be determined as the source of mass loss. By finding similar environmental properties (molecular gas densities) between Type II and Type Ic SNe, Solar et al. (2024) suggest they both originate from progenitors at the lower mass range. This would imply predominant binary stripping for Type Ic progenitors, but also demonstrates the power of indirect approaches to investigating this question. Difficulties arise in trying to predict a mass range for Type Ib/c progenitors due to all of the complications discussed above. What appears clear is the probable diversity in progenitors that produce Type Ibc SNe, which can only be illuminated and constrained with further observations.

1.5 Environmental Studies of Core-Collapse Supernovae

Relying solely on the ‘gold standard’ method of constraining the properties of SNe progenitors yields few direct detections annually. Slowing this more, initially proposed progenitors can be false and later ruled out by late-time imaging (Zhao et al., 2024). An alternative approach to accelerate constraining the progenitors of CCSNe uses the surrounding environment as an indirect probe. The first examples of environmental studies of SNe investigated correlations between the host galaxy morphology and the classifications of observed SNe (then only Type I vs. Type II). This found that CCSNe occur exclusively in late-time, star-forming galaxies (Baade & Zwicky, 1934a; Reaves, 1953; van den Bergh, 1959). With instrumental advancements and the expansion of the SNe classification scheme, later studies could begin to examine the local environments of CCSNe. van Dyk (1992) studied the distances of SNe (now Type Ia, Type Ibc and Type II) explosion sites to the nearest H II region, finding that CCSNe show a strong association with H II regions and therefore suggest high mass progenitors. Further studies (Bartunov et al., 1994; van Dyk et al., 1996) found similar results. In the 21st century, the introduction of larger SN (and extragalactic) catalogues prompted statistical analyses and, as Anderson et al. (2015) outline in a review, there has historically been three branches of analysis:

1. Host galaxy pixel statistics.
2. Radial distributions.
3. H II region metallicities.

A popular approach to pixel statistics is Normalised Cumulative-Rank (NCR) method, used by James & Anderson (2006) and Anderson & James (2008) to investigate the spatial association of SNe types with ongoing star formation (SF), using H α as a proxy, in their host galaxies. These studies probe median physical sizes on the order of 300

pc, meaning individual H II regions become grouped into larger star forming regions. [James & Anderson \(2006\)](#) is also an example of a radial distribution study, investigating where within their host galaxies different SNe explosion sites fall. H II region metallicity studies ([Modjaz et al., 2008](#); [Anderson et al., 2010](#); [Kuncarayakti et al., 2013b,a](#); [Taddia et al., 2013b](#)) generally find that Type Ibc SNe have higher metallicities than Type II (although this difference is small or undetected in some studies). The spectroscopic data in these studies suffers from a biased association to the nearest bright H II region, as emission lines directly from the SNe sites are too weak.

Recent studies ([Maund & Ramirez-Ruiz, 2016](#); [Maund, 2017, 2018](#); [Sun et al., 2021](#); [Ganss et al., 2022](#); [Sun et al., 2023](#)) considered individual stars or ionised gas in the SN environment to constrain the progenitor age, extinction and metallicity. [Maund & Ramirez-Ruiz \(2016\)](#) used a Bayesian approach with Nested Sampling to fit the surrounding stellar populations in the environment of the Type Ic SN 2007gr. Later, [Maund \(2018\)](#) expanded this to a catalogue providing age and extinction estimates of 23 stripped-envelope SNe (Type IIb & Type Ibc). Their characteristic ages support a substantial number of high mass ($M_{\text{initial}} > 30 M_{\odot}$) progenitors for Type Ibc SNe. [Sun et al. \(2021\)](#) expanded upon this analysis by including integral-field-unit (IFU) spectroscopy to model the ionised gas component of two SNe environments (2004dg [II-P] & 2012P [IIb]), revealing a star forming complex that has photo-ionised a giant H II region within NGC 5806. [Sun et al. \(2022a\)](#) repeated a similar analysis for the Type Ib SN 2019yvr.

1.6 Thesis outline

Over the past three and a half years I have been developing and refining an environmental analysis for core-collapse supernovae that takes advantage of the existing archive of high spatial resolution images and the growing archive of integral-field unit spectroscopy data. After exploring the potential of the environmental analysis, I aimed to apply it to a

catalogue of local CCSNe to constrain progenitor properties and test for correlations between environmental parameters and SN classifications. This thesis seeks to answer some open questions in the field:

- To what extent can an environmental analysis assist in constraining the progenitors of core-collapse supernovae?
- Do environmentally measured quantities correlate with supernovae classifications?
- How do different indirect methods compare to one another in estimating environmental parameters?
- What are the limitations of an environmental analysis?

To try and answer these questions and demonstrate the process of investigating the environments of core-collapse supernovae, this thesis is outlined as follows:

- In Chapter 2, I introduce the instruments and data used throughout my work and the employed methodologies that encompass the environment analysis. This includes: reduction of the data; obtaining photometry from images; a Bayesian approach to fitting stellar populations; the creation of my own spectral fitting algorithm.
- In Chapter 3, I develop my environmental analysis with data of the Type Ib SN iPTF13bvn. Photometric and spectroscopic avenues of the environmental analysis are explored independently, as well as an intersectional study connecting both. New estimates of the progenitor constraints are compared to past studies of iPTF13bvn, and interpreted in the context of other Type Ib supernovae.
- In Chapter 4, a catalogue of local core-collapse supernovae is compiled and subjected to a refined environmental analysis. The sample of environmental parameters are presented and different indirect methods are compared. Where available, new

progenitor estimates are interpreted within the context of existing constraints from past studies.

- In Chapter 5, I discuss the success and limitations of the environmental analysis, and address how it helps to answer the above open questions.
- In Chapter 6, I summarise the conclusions of this thesis and the implications for the broader community. I propose potential future work with the advent of new instruments and an ever-growing number of identified transients.

Chapter 2

Methodology

In this Chapter, I will describe the components that construct my own environmental analysis, motivated by those that have come before. Firstly, I will present the instruments providing the imaging and spectroscopic data (Section 2.1), which compliment the goals of my environmental analysis with powerful spatial information. In later sections (2.2, 2.3 and 2.4) I describe my methods for reducing and analysing the data, as well as the models that assist the fitting of environmental parameters. When combined, these methods form the entire environmental analysis.

2.1 Instrument Specifications

Provided below is the historical context, instrument specifications and performance details of all ground and space based telescope instruments from which data was collected and then later sourced for use in this work. This includes high spatial resolution images and integral-field unit (IFU) spectroscopic data, both representing essential components of the environmental analysis.

2.1.1 Hubble Space Telescope

The **Hubble Space Telescope (HST)** has been a pivotal instrument in observational astronomy since its launch in April 1990, and represents the longest-running and most productive active space telescope today. It is the product of a partnership between the National Aeronautics and Space Administration (NASA) and the European Space Agency (ESA). Implemented into its design, the telescope has undergone various servicing missions to repair or replace instruments from 1993 - 2009. Throughout its 36 year lifetime **HST** has provided high resolution imaging spanning the far-ultraviolet, visible and near-infrared wavelengths with numerous imagers: Wide Field and Planetary Camera 1 (WF/PC; 1990-1993), Faint Object Camera (FOC; 1990-2002), Wide Field and Planetary Camera 2 (WFPC2; 1993-2009), Near Infrared Camera and Multi-Object Spectrometer (NICMOS; 1997-present; on-board hibernation), Advanced Camera for Surveys (ACS; 2002-present) and Wide Field Camera 3 (WFC3; 2009-present). Spectroscopic instruments include Goddard High Resolution Spectrograph (GHRS/HRS; 1990-1997), Faint Object Spectrograph (FOS; 1990-1997), NICMOS, Space Telescope Imaging Spectrograph (STIS; 1997-present) and Cosmic Origins Spectrograph (COS; 2009-present). Although many are now legacy instruments, STIS, COS, ACS and WFC3 remain currently active onboard **HST**. Each of these instruments are fed light from a 2.4 m primary mirror. Control over **HST** is handled by the Space Telescope Operations Control Center (STOCC) at NASA's Goddard Space Flight Centre (Greenbelt, Maryland), however management of scientific programmes and observational proposals is carried out by the Space Telescope Science Institute (STScI) in Baltimore, Maryland.

Wide Field Camera 3

The WFC3 instrument offers high-resolution imaging across a broad wavelength range of 200 to 1700 nm, covering near-infrared to far-ultraviolet. Under the ultraviolet and

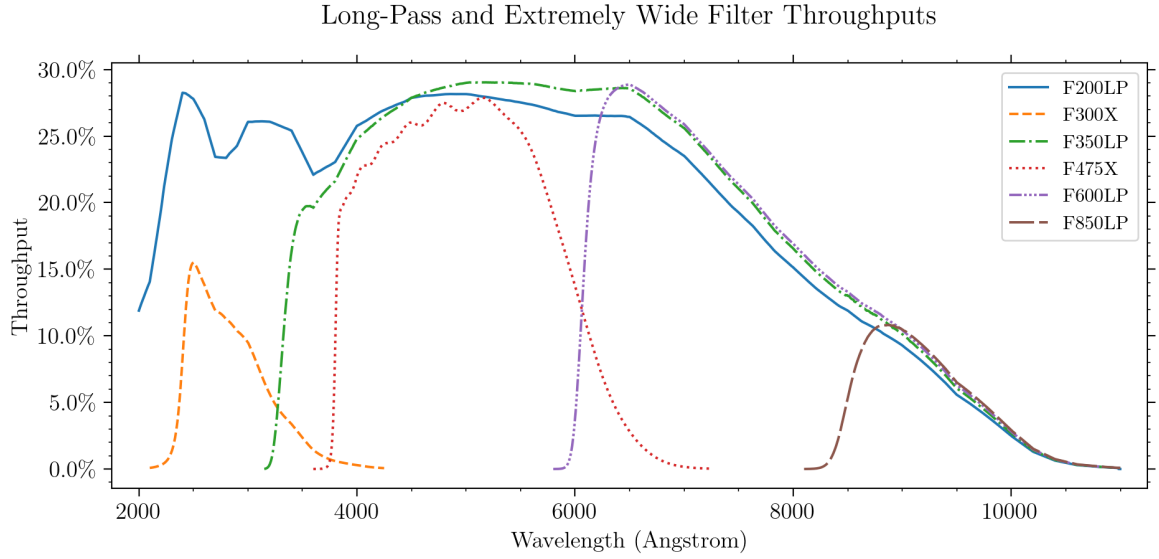


Figure 2.1: HST/WFC3 Long-Pass and Extremely Wide Filter Throughputs. Image sourced from <https://www.stsci.edu/hst/instrumentation/wfc3/performance/throughputs>.

visible (UVIS) channel, photon measurements are detected by two ($2k \times 4k$) CCD chips and are sensitive to an approximately 200 - 1000 nm range. Across a 162×162 arcsec² FoV there is a pixel scale of 0.04 arcsec/pix. Within the UVIS mode, a comprehensive set of wide-, intermediate- and narrow-band filters are available depending on the desired imaging objective. For each filter the start, central and end wavelengths, as well as their performance, can be gauged through the throughput plots in Figure 2.1 and 2.2.

Throughput plots for the medium and narrow filters are not shown here, as they were not utilised in this work. Readout of measurements can be done across the entire CCD array or, alternatively, a selection of smaller subarray readout configurations are available. In combination with a choice of apertures, observing programmes can take advantage of the most sensitive parts of the CCDs. Users can specify which of the two CCD chips to use (UVIS1 or UVIS2) if the full FoV is not required. Various suffixes to the channel name (UVIS, UVIS1, UVIS2), such as ‘-FIX’, ‘-SUB’ and ‘-CTE’, describe the additional choice of aperture and readout array. Definitions of these acronyms and

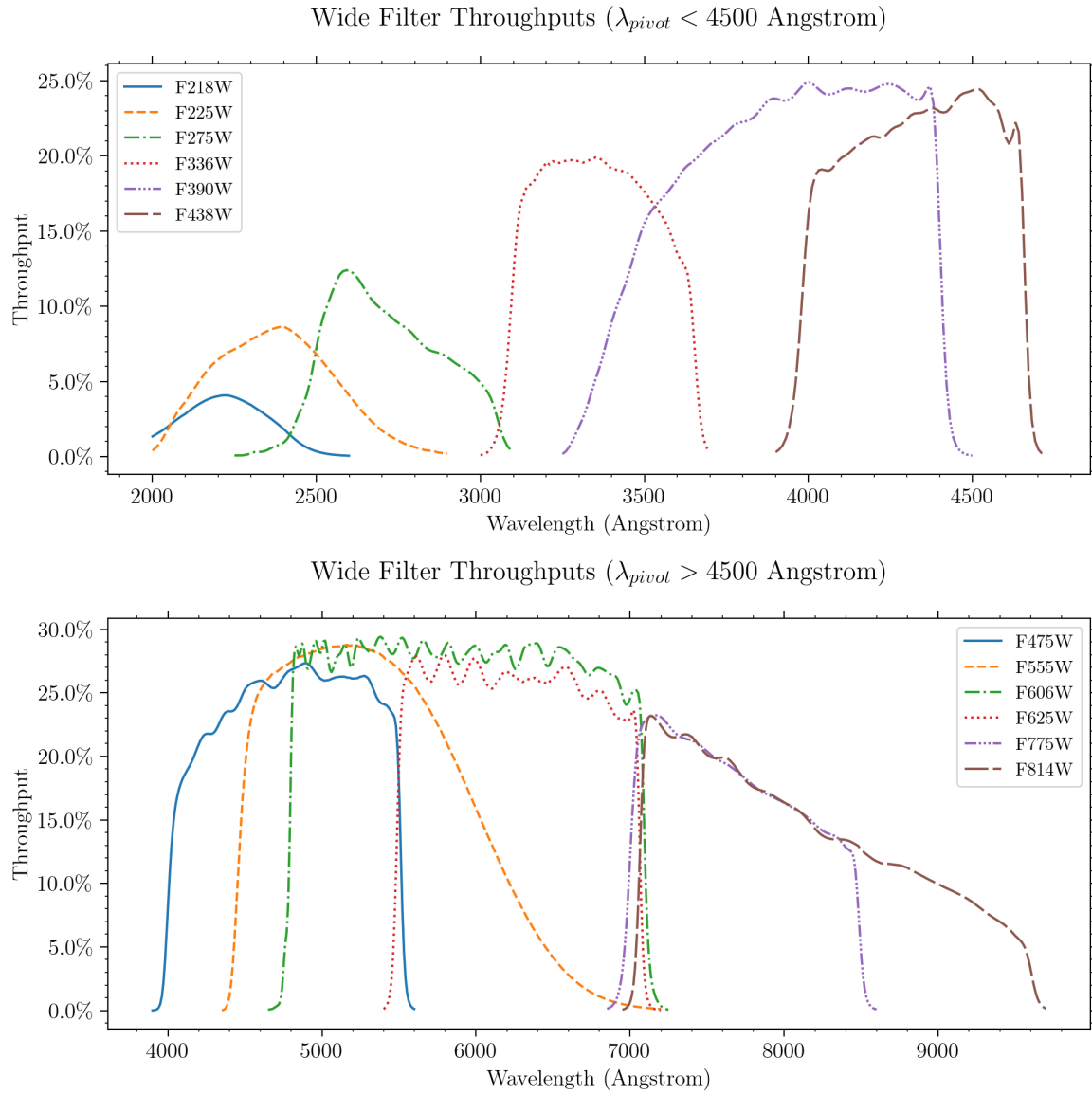


Figure 2.2: HST/WFC3 Wide Filter Throughputs. Image sourced from <https://www.stsci.edu/hst/instrumentation/wfc3/performance/throughputs>.

a full description of the WFC3 instrument can be found at [Marinelli & Green \(2025\)](#).

Raw data received from HST/WFC3 is sent to the STScI Operational Pipeline Unified System (OPUS) to be processed. Their pipeline creates Multi-Extension FITS format science images with unique filenames and a suffix to identify the degree of processing. Single exposures ('_flt.fits') are appropriately calibrated: flagging bad pixels, bias subtraction, dark current subtraction, non-linearity correction, flat-fielding and gain conversions. Additional Charge Transfer Efficiency (CTE) corrections are applied to some single exposures, instead having a '_flc.fits' suffix, to correct for a radiation-induced impact to the readout process over time. Multiple single exposures can be combined into a single image corrected for instrumental geometric distortion and cosmic-ray rejection under the ASTRODRIZZLE pipeline (part of the DRIZZLEPAC package; [Gonzaga et al. 2012](#)). These final scientific products have a suffix of either '_drz.fits' or '_drc.fits', with the latter having undergone the additional CTE-correction at the single exposure stage.

Advanced Camera for Surveys

The ACS instrument also offers deep, wide-field imaging over a slightly narrower wavelength range of visible to near-infrared with the Wide Field Channel (WFC). A range that extends to the near-UV was available with the High Resolution Channel (HRC), but this feature has been out of service since early 2007. Equipped with two 4096×2048 CCDs (WFC1 and WFC2), ACS has an ~ 0.05 arcsec/pixel spatial resolution and a mosaic FoV of 202×202 arcsec². Considerable overlap can be found between the longpass, wide-, medium- and narrow-band filters of ACS and those of WFC3. A throughput plot for the ACS filters used in this work is provided in Figure 2.3. For a complete ACS instrument handbook the reader is directed to [Stark \(2025\)](#). The data processing stages are not reiterated here, as they very closely mimic that of WFC3.

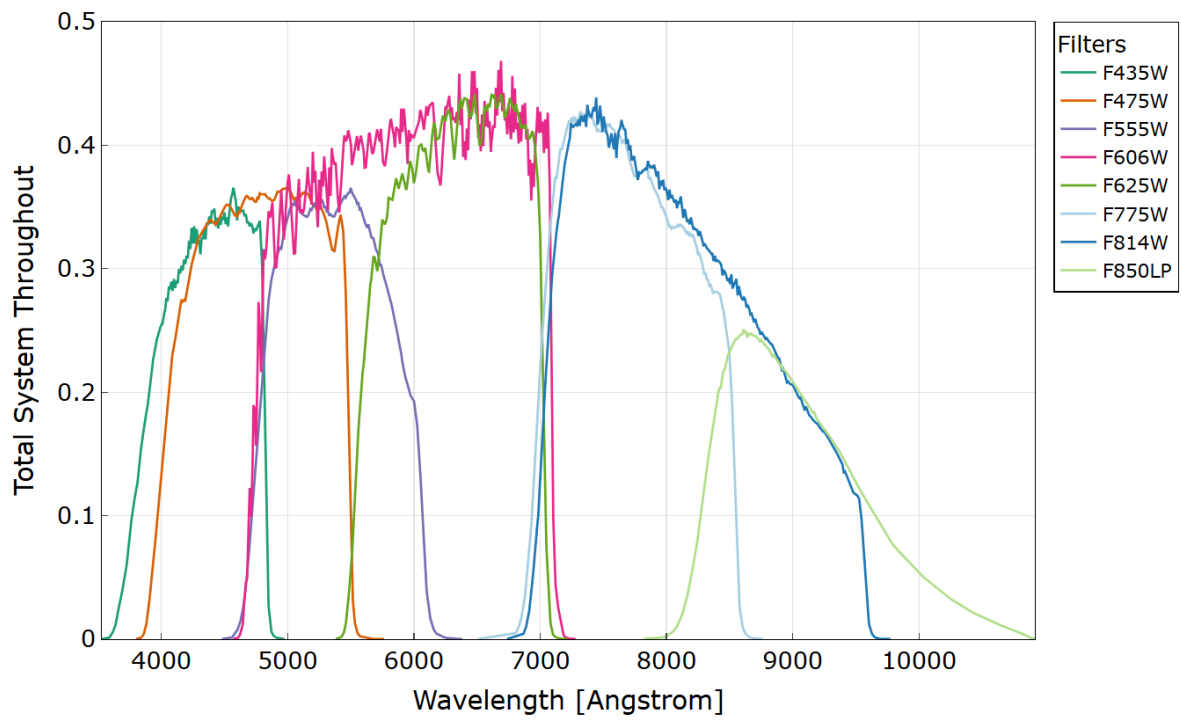


Figure 2.3: HST/ACS Wide and Longpass Filter Throughputs. Image sourced from <https://www.stsci.edu/hst/instrumentation/acs/data-analysis/system-throughputs>.

2.1.2 Multi Unit Spectroscopic Explorer

The [Multi Unit Spectroscopic Explorer \(MUSE\)](#) is a second generation instrument mounted on the [Very Large Telescope \(VLT\)](#) in the Atacama Desert in northern Chile, operated by the European Southern Observatory (ESO). It is an integral-field spectrograph composed of 24 identical integral-field unit (IFU) modules that receive light from the 8.2 m diameter primary mirror of Unit Telescope 4 at the [Very Large Telescope \(VLT\)](#). The spatial resolution of [MUSE](#) takes advantage of the [VLT](#) Adaptive Optics Facility (AOF), using four laser guide stars and a deformable secondary mirror. A narrow- and wide-field mode (WFM) are available, but only the latter is applicable to this work. In the WFM, [MUSE](#) has a nominal spectral wavelength coverage of 4750 - 9350 Å with a spectral sampling of 1.25 Å. This wavelength range can be stretched in an extended mode; values differ for nominal and extended modes depending on whether the AOF is invoked. A mean spectral resolution of 3000 can be broken down into 1770 at the blue (480 nm) and 3590 at the red (930 nm) end. Spatial sampling is constrained to 0.2×0.2 arcsec² pixels with spatial resolution of 0.3 – 0.4 arcsec, forming a full FoV of 1×1 arcmin². The throughput performance across the full wavelength range in the WFM is displayed in Figure [2.4](#).

Raw data is measured across the 4224×4240 pixel CCDs, with readout occurring through four equal sized quadrants, resulting in 24 raw images that are later combined into a single file. Most of the publicly available MUSE data has been ran through the standard processing pipeline described in [Weilbacher et al. \(2020\)](#). In short, two additional extensions are added to the FITS file with the same dimensions as the original image: one for data quality, where integer values > 0 for each pixel correspond to a flagged quality problem (i.e. CCD defects, cosmic rays); another with independent variance estimates for each spectral bin measurement across the full spectrum range of each pixel. Standard corrections are applied to the ‘DATA’ extension: bias subtrac-

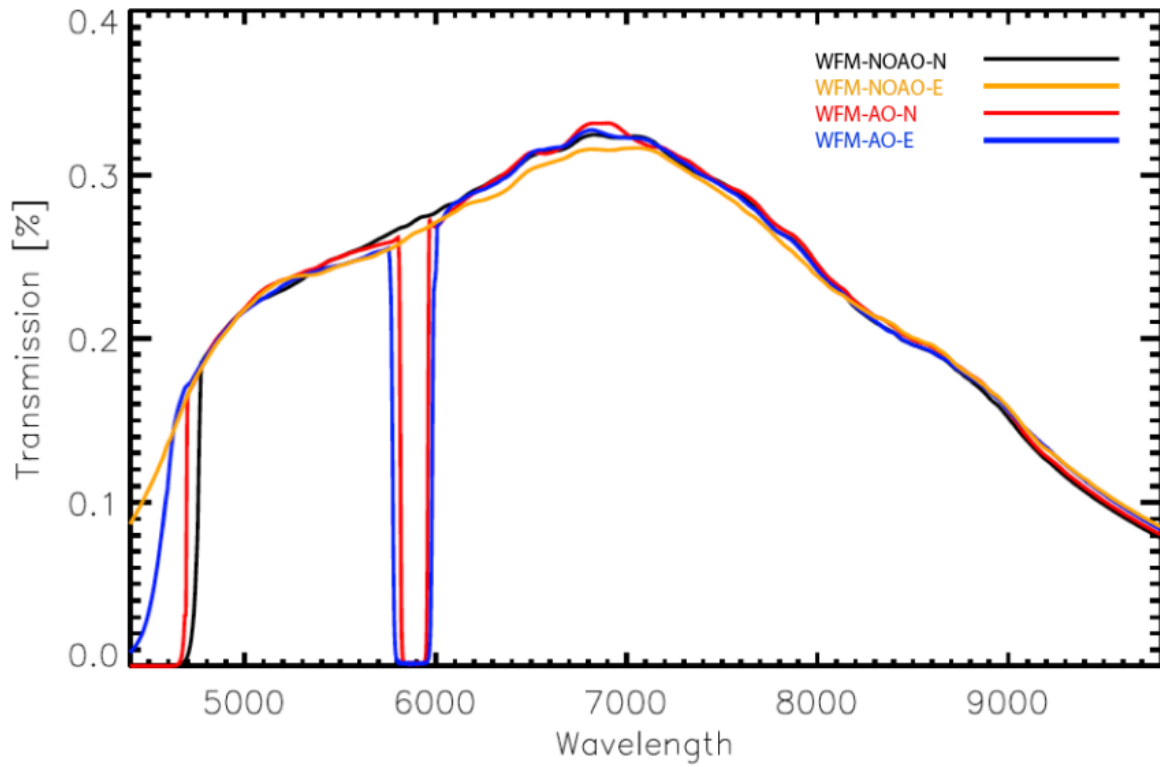


Figure 2.4: VLT/MUSE Wide Field Mode (WFM) throughput performance across end-to-end spectral coverage, derived from spectroscopic standard observations. The legend refers to different observing modes: all WFM; either a nominal (‘-N’) or extended (‘-E’) wavelength range; either with Adaptive Optics (‘-AO’) assistance or without (‘-NOAO’). Image sourced from [Richard & Bacon \(2026\)](#).

tion, conversion to electron counts coupled with the CCD gain, (optional) dark current image subtraction, wavelength zero point corrections (if applicable) using sky emission lines, (optional) relative illumination corrections and interpolated twilight sky corrections. Before producing the final science product, flux measurements are corrected for various atmospheric effects and spatial coordinate corrections account for instrumental motions and projection onto sky coordinates, following a drizzle-like (HST) algorithm. Once all 24 exposures are concatenated, the final product is a $(\lambda \times p \times q)$ dimensional ‘datacube’ (or ‘cube’). Discrete (p, q) values correspond to individual pixel coordinates in the spatial axes, and λ refers to the wavelength coordinate along the spectral axis. A pixel, (p, q) , with an associated spectrum is commonly referred to as a ‘spaxel’. Normally, MUSE cubes are computed such that North is up and East is left.

2.2 Photometry with DOLPHOT

The stellar photometry package DOLPHOT (Dolphin, 2016) is an adaptation of the HSTPHOT package, both developed by Andrew Dolphin. HSTPHOT was specifically created to tackle the undersampled point-spread functions (PSFs) of WFPC2 (HST) images. Later, DOLPHOT was introduced to apply many of the same algorithms from HSTPHOT to images from a broader scope of instruments: ACS, WFPC2, WFC3 and, most recently, JWST instruments (NIRcam, NIRISS and MIRI). The main processes of DOLPHOT are:

1. Image preparation.
2. Image cleaning and combination.
3. Background determination.
4. PSF fitting and star detection.

The first three items are handled with built in functions, i.e. *wfc3mask* (specifically for WFC3 images), *splitgroups* and *calcsky*. Firstly, *wfc3mask* (or *acsmask*) will mask any

pre-flagged bad pixels and any saturated pixels, thereafter excluded from the photometry fitting. This stage rejects any cosmic-rays and multiplies the image by the pixel area map so that units are approximately in electrons. With *splitgroups* the images are split into individual instrument CCD chips, such that the appropriate portion of the image can be processed. Finally, a sky image is created with *calcsky* by calculating a background value at every pixel. Each background value is taken as the mean pixel value of an annulus of pixels centred on the target. Pixels that fall one standard deviation above or below this mean are rejected, repeating until no rejections occur and a final mean can be deduced. This process is then repeated across all pixels until a sky map is produced.

Now that the images have undergone the pre-processing steps, they can be searched for star-like objects with the main *dolphot* algorithm. Stellar PSFs are consistent for all images from a single HST instrument under a fixed filter. This means that a library of PSF initial guesses for the desired filters of an instrument need to be downloaded, and are all available through the DOLPHOT webpage. A sky image is subtracted off the data image and the residuals are searched for peaks in a hierarchical system, looking for the brightest peaks first, then for slightly dimmer sources etc. Initial PSFs are fit to the sources, then a series of adjusted PSFs fittings attempt to optimise the positional localisation of the source, with magnitude measurements taken at each iteration. Once the algorithm converges on a best fitting PSF with a corresponding magnitude measurement, fitting parameters and errors can be determined through comparisons to a collection of ‘next best’ PSF fittings. The reader is guided to [Dolphin \(2000\)](#) for a complete description.

Prior to launching the *dolphot* algorithm, a parameter file must be generated to specify the number of images being combined, define the reference image and (if desired) tailor the algorithm settings. Throughout this work I use the recommended input parameters found in the relevant user manuals¹. Photometric results from DOLPHOT include

¹<http://americano.dolphinsim.com/dolphot/>

quality of fitting parameters, which assist in filtering the product for star-like objects. To that effect, the output parameters utilised in this work are *type*, *flag*, *crowd*, *sharp* and *signal-to-noise ratio (SNR)*. The *type* value represents the quality of fitting as follows:

- 1: good star
- 2: star too faint for PSF determination
- 3: elongated object
- 4: object too sharp
- 5: extended object.

A *flag* value represents a specific encountered error:

- 1: photometry aperture extends off chip
- 2: too many bad or saturated pixels
- 4: saturated at centre of star
- 8: extreme case of one of the above.

The *crowd* parameter is a value in magnitudes representing how much brighter the star would be without simultaneous fitting of nearby stars. A value of zero is reported for a perfectly isolated star. The *sharp* parameter can take a range of values: zero for a perfectly-fit star; positive for an object that is too sharp (i.e. a cosmic ray); negative for a broad object (i.e. a star cluster or galaxy). *SNRs* are generated for each independent magnitude measurement. Apparent magnitudes and errors are reported in the Vega magnitude system.

2.2.1 Artificial Star Tests

Artificial star tests (ASTs) are a built-in function of the DOLPHOT package, allowing the reliability of the photometry to be tested within the context of individual images. As the name suggests, artificial stars can be dropped into an image and the recovery of its brightness and morphology can be tested. With this tool the detection limits of images can be probed by analysing the recovery of artificial stars of decreasing magnitude. Throughout this work I apply the same strategy:

- Create artificial stars with discrete apparent magnitudes that span the range of 20 - 33 mag, in increments of 0.5 mag.
- For each discrete apparent magnitude value, perform 15 independent ASTs.
- Find the recovered fraction within each magnitude bin.
- Fit the recovery curve with the cumulative normal distribution function through non-linear least squares optimisation (*scipy.optimize.curve_fit*).
- Take the ‘50% recovered’ value as the detection limit.

The cumulative normal distribution function ($F(x, \mu, \sigma)$) is taken as the integral over the standard normal distribution ($f(x, \mu, \sigma)$):

$$F(X, \mu, \sigma) = \int_{-\infty}^X f(x, \mu, \sigma) dx \quad (2.1)$$

and

$$f(x, \mu, \sigma) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(x-\mu)^2}{2\sigma^2}}, \quad (2.2)$$

where the mean (μ) and standard deviation (σ) are the optimised parameters. When classifying an artificial star as recovered, the defined (input) and the measured (output) apparent magnitudes (m) have to be compared and a threshold set for the acceptable

difference in these values. The following three thresholds were tested:

$$|m_{\text{input}} - m_{\text{output}}| < \sigma_{\text{mag}}, 3\sigma_{\text{mag}} \text{ or } 0.25 \text{ mag}, \quad (2.3)$$

Where σ_{mag} is the error of the measured (output) apparent magnitude and 0.25 is simply half a bin width. Using results from Chapter 3, all three thresholds were tested and no significant difference was observed between them. For simplicity, I proceeded with a threshold of half a bin width (0.25 mag). As well as being below this threshold, to be considered as recovered an artificial star had to have quality-of-fitting parameters (*type*, *flag*, *crowd*, *sharp* and SNR) that fall within the desired ranges.

2.3 Stellar Population Fitting

2.3.1 Bayesian Framework

In this work, the resolved stars in the environment of a SN are fit to a stellar population under a Bayesian framework. The Bayesian approach for determining the parameters (x) of a stellar environment from a given set of data (D) and stellar evolution model starts with Bayes' theorem,

$$p(x|D) = \frac{p(D|x)p(x)}{p(D)}. \quad (2.4)$$

The posterior probability distribution, $p(x|D)$, is comprised of the likelihood function, $p(D|x)$, prior probability, $p(x)$, and evidence, $p(D)$. Following the methods employed by Jørgensen & Lindegren (2005), Maund & Ramirez-Ruiz (2016) and Sun et al. (2021), I construct a hierarchical Bayesian mixture model for estimating the age (τ or $\log(t/\text{years})$) and extinction (A_V) of N_m stellar populations. For the i^{th} star in a data set, D_i , the

posterior probability distribution can be expressed as

$$p(\tau, A_V | D_i) \propto \iint p(D_i | \tau, A_V, \mu', M_i) p(\tau, A_V, \mu', M_i) d\mu' dM_i \quad (2.5)$$

where the distance modulus, μ' , and stellar mass, M_i , are marginalised over as nuisance parameters. Assuming these parameters are independent, the prior probability for the stellar mass follows a Salpeter (1955) Initial Mass Function (IMF) normalised over the mass range of the stellar evolution model, with an IMF exponent of -2.35. Throughout this work, my choice of stellar evolution model was the PARSEC stellar isochrones (Girardi et al., 2002); details can be found in Section 2.3.5. For each star the likelihood function is a product of normal distributions which directly compare the observed apparent magnitude in the j^{th} filter, m_j , to the predicted absolute magnitude of a star with mass M_i on an isochrone of age τ and extinction A_V , $m_j(\tau, A_V, M_i)$, taking the form:

$$p(D_i | \tau, A_V, \mu', M_i) = \prod_j \frac{1}{\sigma_j \sqrt{2\pi}} \exp \left\{ -\frac{1}{2} \left(\frac{m_j - m_j(\tau, A_V, M_i) - \mu'}{\sigma_j} \right)^2 \right\}. \quad (2.6)$$

The exception to this is a substitution for stars missing photometry in a specific filter. In this case the detection limits (m_j^{lim} , σ_j^{lim}) of the filter are used alongside the error function, giving:

$$p(m_j^{lim}, \sigma_j^{lim} | \tau, A_V, \mu', M_i) = \frac{1}{2} \left\{ 1 + \operatorname{erf} \left(\frac{m_j^{lim} - m_j(\tau, A_V, M_i) - \mu'}{\sqrt{2}\sigma_j^{lim}} \right) \right\}. \quad (2.7)$$

This allows multiple filters to be included in the analysis even when the photometry is partially incomplete. Flat priors are used for both τ and A_V and a normalisation condition is implemented on the likelihood function, such that it integrates to unity over the prior ranges of τ and A_V .

Implementation of the mixture model allows contributions from non-interacting binaries to be simultaneously included, as well as a mixture of N_m populations (temporally

separated epochs of star formation). Probability distributions are treated as the sum of the single and binary case weighted by the binary fraction P_{bin} , where $P_{\text{bin}} = 0.5$ is a fixed value throughout the analysis. With this form,

$$p(\tau, A_V | D_i) = (1 - P_{\text{bin}})p(\tau, A_V | D_{i,\text{single}}) + P_{\text{bin}}p(\tau, A_V | D_{i,\text{binary}}), \quad (2.8)$$

each star is simultaneously treated as single and binary whilst exploring feasible values within the parameter space. Considering that an environment may contain a mixture of stellar populations and the parameters that describe each population may have an intrinsic spread, we can not expect a single, unique solution for each star in the $\tau - A_V$ plane. The same can be said for the degeneracies in the underlying parameters of the isochrone models. A hierarchical approach uses each star separately to probe the distributions within this parameter space, and then uses the collection of stellar properties to fit a distribution to an entire population. A normal distribution is assumed for the age and extinction, $\mathcal{N}(\tau', A'_V, \sigma'_\tau, \sigma'_{A_V})$, when fitting for the collection of stars inside the selected environment. One example of the hierarchical form of a posterior probability distribution,

$$p(\tau', \sigma'_\tau | D_i) \propto \int \int p(D_i | \tau, A_V) p(\tau | \tau', \sigma'_\tau) p(\tau', \sigma'_\tau) p(A_V) d\tau dA_V \quad (2.9)$$

only considers a single extinction value across all populations that are being fit. Finally, parallel to the mixture model implementation for binary contributions, a mixture of distributions to account for multiple age components in the stellar environment are included. The age distributions can be parameterised by $\boldsymbol{\tau}', \boldsymbol{\sigma}', \boldsymbol{\omega}'$, where $\boldsymbol{\omega}$ is a vector of relative weights for each age component and $\sum_k \omega_k = 1$. This gives the final form of the posterior distribution over the complete data set ($\mathbf{D}$), summing over the total

number of stars (N_{star}) and age components (N_m):

$$p(\boldsymbol{\tau}', \boldsymbol{\sigma}' | \boldsymbol{D}) \propto \prod_i^{N_{\text{star}}} \sum_k^{N_m} \omega_k p(D_i | \tau_k, \sigma_k, A_V) p(\tau_k, \sigma_k, A_V) \quad (2.10)$$

This represents a continuation of equation 2.9, however it can be redefined to include unique extinction solutions for each stellar population (when $N_m > 1$).

2.3.2 Likelihood Grids

The likelihoods of each star were calculated using a Python script developed by Dr Ning-Chen Sun, in line with equations 2.5, 2.6, 2.7 and 2.8. In summary, this code converts the isochrone tables to apparent magnitudes, interpolates each isochrone to the desired magnitude resolution, finds the IMF definite integral relative to each isochrone (of varying age), dereddens the observed data (using the input galactic extinction) and calculates the likelihood grid for each individual star. Interpolation of the isochrone tables fills in sparsely sampled regions of the curves, such that there is uniform resolution across the mass-magnitude range. The mass of a star is assigned a prior probability of the form:

$$p(M_i) = \frac{M_i^{-\alpha}}{\int_{M_{\min}}^{M_{\max}} M_i^{-\alpha} dM_i} \quad (2.11)$$

which follows a Salpeter (1955) IMF with $\alpha = 2.35$. To optimise the calculation runtime the isochrones are split into lower and upper branches at a mass that corresponds to the faintest observed detection in a given image (or the detection limit). The IMF is integrated over the mass range of the upper branch when considering single stars, but the lower branch is included when sourcing the secondary star contribution for the binary case. In this regard, $M_{\max}$ and $M_{\min}$ values change depending on whether you are considering single or binary stars, as well as the age of the isochrone table. The final 2D $(\tau - A_V)$ probability distribution functions are a sum of the single and binary searches,

appropriately scaled by their individual mass priors.

2.3.3 Nested Sampling with UltraNest

In order to source the Bayesian evidence (sometimes referred to as the marginal likelihood; $p(D)$ in Equation 2.4; with a symbol of Z it should not be confused with metallicity) and posterior distribution from the precalculated likelihood grids, the Nested Sampling algorithm (Skilling (2004)) is applied through the open-source code ULTRANEST (Buchner (2021)). Where Markov Chain Monte Carlo convergence may get stuck sampling a narrow region of the parameter space and miss entire peaks within the posterior distribution, Nested Sampling distributes live points throughout the parameter space and samples from ellipsoids surrounding each live point. This way it is able to iteratively improve likelihood contours by rejecting the live points with the lowest likelihood, whilst the corresponding removed prior mass informs the Bayesian evidence and posterior distribution. Maund & Ramirez-Ruiz (2016) discuss two important considerations when using Nested Sampling, which are:

- (i) Due to the interchangeable nature of the distribution labels in the model the evidence is overestimated by a factor of $N_m!$, which can easily be corrected for. However, this means the Nested Sampling algorithm is allowed to explore all modes of the mixture model, including mirror modes, requiring the results to then be sorted into N_m components.
- (ii) The Jeffreys' scale (Jeffreys, 1939) is used to inform how Z informs the number of age components that provide the best-fit model to the data. An increase in the corrected evidence ($\ln[Z/N_m!]$) greater than ~ 30 is deemed 'strong evidence' in support of that model (discussed further in Section 2.3.4).

Using ULTRANEST to perform the Nested Sampling algorithm was done under the *ReactiveNestedSampler*. This has the ability to react to the performance of the algorithm

and adjust its exploration strategy. For example, if sampling of a live point becomes inefficient, MCMC-based methods can be invoked to search for a new location within the prior space for it to be moved. There are various inputs for the user to control the strategy, specifically for when to terminate the algorithm. In this work, the utilised termination control is a minimum error threshold ($dlogz$) on the collected evidence ($logz$). Alternatively, the maximum number of iterations that the algorithm is allowed to perform can be fixed. To run the Nested Sampling algorithm, ULTRANEST requires simple function definitions of the *log-likelihood* and the *hyper-priors*. In the *log-likelihood* function, the free parameters are unpacked and defined as sets of multivariate normal random variables independently for each stellar population, weights are assigned to each set of stellar population variables and likelihood grids are scaled to a logarithmic base. On the same logarithmic scale, prior ranges for each free parameter are defined in *hyper-priors*.

2.3.4 Jeffreys' Scale

Jeffreys' scale (Jeffreys, 1939) is a qualitative interpretation of the Bayes factor, classifying subdivisions of values into varying degrees of support for or against a model with respect to another. For data, x , and two independent models, M_1 and M_2 , the posterior odds ratio is:

$$\frac{p(M_1|x)}{p(M_2|x)} = \frac{p(x|M_1) p(M_1)}{p(x|M_2) p(M_2)}, \quad (2.12)$$

where the Bayes factor, comparing model 1 to model 2, is:

$$B_{1,2} = \frac{p(x|M_1)}{p(x|M_2)}. \quad (2.13)$$

In this work, a slightly modified version of the Jeffreys' scale by Lee & Wagenmakers (2014) is used. Their minor modifications include the rounding of some boundary values, and a scaling back in the assigned 'confidence level' of some subdivisions. Mapping of the

Table 2.1: Modified Jeffreys’ scale by Lee & Wagenmakers (2014) comparing ranges of values of the Bayes factor to the respective evidentiary strength in support of model 1 over model 2.

$B_{1,2}$	Evidentiary Strength
1 - 3	anecdotal
3 - 10	moderate
10 - 30	strong
30 - 100	very strong
>100	extreme

Bayes factor numerical ranges to descriptions of the evidentiary strength are presented in Table 2.1 For the comparison of more than two models, the Bayes factor subscript can be switched out and reordered depending on which models are being compared. Throughout this work, it was decided that the ‘very strong’ category ($B_{1,2} > 30$) was required to support one model over another.

2.3.5 Stellar Evolution Models: PARSEC

The PAdova and TRieste Stellar Evolution Code (PARSEC) provides stellar evolution tracks for low-, intermediate- and high-mass stars and isochrone tables for stellar population synthesis. It is a continuous collaborative effort to create publicly available stellar evolution models, with up-to-date physics. Throughout this work PARSEC version 1.2S is adopted, which has iteratively built upon the original Padova stellar evolution code (Bressan et al., 1993; Girardi et al., 2000; Marigo et al., 2001). As implemented by Chen et al. (2015), PARSEC v1.2S covers a wide range of metallicities, $0.0001 \leq Z \leq 0.04$, and initial masses up to $M_{\text{initial}} = 350 M_{\odot}$ from pre-main-sequence to the central carbon ignition. Their additions to the code include an enhanced mass-loss formalism as stars approach the Eddington limit, and updated metallicity-dependent stellar wind models. Other considerations are implemented for the lowest metallicity (Tang et al., 2014) and mass (Chen et al., 2014) stars. The PARSEC interface allows stellar evolution tracks to be converted to a wide scope of photometric systems, including current and legacy

instruments for HST. As of the writing of this work, PARSEC version 2.0 has recently become available which incorporates the rotational effects of stars (Nguyen et al., 2022, 2025), but does not yet cover the full mass range of version 1.2S.

2.4 Spectral Fitting Algorithm

Fitting of the MUSE spectra was handled by my own algorithm, motivated by the aim of retaining the spatial resolution of the data by minimising the number of spaxels that are combined across a datacube. Instead of having a uniform SNR target that results in non-uniform clustering of spaxels (i.e. Voronoi tessellation) my approach retains a uniform spatial resolution, but a varying degree of spectral strength and quality. Since this will sometimes require the fitting of low flux or SNR nebular line features, simple Gaussian functions are optimal. Strong nebular lines within the MUSE data include the Balmer hydrogen recombination lines ($H\alpha$ $\lambda 6563$ and $H\beta$ $\lambda 4861$) and the collisionally-excited [N II] $\lambda\lambda 6548, 6583$ doublet. However, as is intrinsically observed, the $\lambda 6548$ line is much weaker than the $\lambda 6584$ line. Other weak lines that appear include He I $\lambda 5876$, He I $\lambda 6678$, [O III] $\lambda\lambda 4959, 5007$, [O I] $\lambda\lambda 6300, 6363$ and [S II] $\lambda\lambda 6717, 6731$. An existing MUSE spectral fitting package, IFUANAL (Lyman et al., 2018), performs a stellar continuum fitting and subtraction before analysing the nebular lines. This approach is not inherited by my fitting algorithm to avoid underlying assumptions about the stellar population in a given aperture resulting in residual stellar features in the MUSE spectra. Alternatively, I independently fit each spectrum for stellar continuum and absorption features. I acknowledge that this is a simplified approach that does *not* represent the underlying physics, however, since my main goal is to remove any absorption features to better estimate the emission integrated flux, a simple Gaussian is adequate.

Due to the relatively low spectral resolution of the MUSE data, an elementary approach to fitting was favoured. Function fitting to continua or nebular lines was

performed using *scipy.optimize.curve_fit* (non-linear least squares regression) and subsequent reduced-chi-squared (χ_r^2) comparisons. All spectra in a datacube had the continuum fit against a series of increasing order polynomials, across the full 4750-9350 Å wavelength range. From the optimal fitting, a mean value is taken to represent the continuum flux level of each spaxel. Narrow wavelength regions were extracted before fitting emission lines: 6520-6640 Å and 4780-4940 Å for H α and H β respectively. Once the lines were masked, including the [N II] lines either side of H α , the remaining data points were linearly fit and continuum subtracted. The remaining nebular line feature (for H α λ 6563, H β λ 4861, [N II] λ 6548, 6583 and [O III] λ 4959, 5007) was then fit with a series of functions:

- (1) **‘Weak’ Double:** low flux spectra fit with a double Gaussian, accounting for both emission and absorption.
- (2) **‘Strong’ Double:** high flux spectra fit with a double Gaussian, accounting for both emission and absorption.
- (3) **‘Weak’ Single:** low flux spectra fit with a single Gaussian, accounting solely for emission.
- (4) **‘Strong’ Single:** high flux spectra fit with a single Gaussian, accounting solely for emission.
- (5) **Absorption:** single Gaussian fit to pure absorption feature.
- (6) **Continuum:** linear fit to featureless spectra.

Out of these six options, the corresponding minimum χ_r^2 is subjected to a series of comparisons before being selected as the optimum fitting. For example, the difference between the minimum χ_r^2 and the ‘Continuum’ χ_r^2 must surpass 100 to maintain ‘optimum’ status. Other χ_r^2 comparisons between ‘Double’ and ‘Single’ Gaussian fits are

included to avoid overfitting of the lowest flux emission lines. Moreover, $\text{SNR} \geq 15$ is required of any emission line to be considered for a double Gaussian fitting. Spectral features are only considered emission if the peak exceeds 3σ above the mean continuum flux level. The series of χ_r^2 comparison criteria were deduced through trial and error, with the aim of minimising overfitting to spectral noise or remaining artifacts from the MUSE data pipeline. A complete visualisation of the quality-of-fitting comparison is provided in Table 2.2, where the first column represents the initial fitting function (based purely on the minimal χ_r^2) and the top row shows the final choice of fitting function after filtering through all quality conditions. The threshold values for χ_r^2 comparisons (Table 2.2) were tailored by-eye to optimise the fitting of data from Chapter 3. When fitting Gaussians to emission features, the central wavelength value was allowed to vary within the boundary of $\pm 3 \text{ \AA}$ to account for differential velocities from host galaxy rotation across an extracted region of a MUSE datacube.

Post-filtering, the surviving χ_r^2 for fittings (1) through (6) is labelled as the ‘best fitting’ and used to derive physical values: integrated flux, full width at half maximum (FWHM), equivalent width (EW), etc. Emission flux errors were estimated by performing 1000 random draws from a multivariate normal distribution of the optimised Gaussian parameters and corresponding covariance matrix. Each randomly drawn Gaussian is integrated and the standard deviation of the resulting sample is taken as the final flux error. Some examples of applying the fitting algorithm to the $\text{H}\beta$ line are given in Figure 2.5, using data from Chapter 3 and providing insight into when the different fitting functions are applied. Additionally from this dataset, Figure 2.6 shows how the algorithm performs across the range of SNR values on the $\text{H}\alpha$ line. Whilst it performs well, even at the lowest SNR values, there is a tendency for the algorithm to want to choose the fitting functions that incorporate absorption when in the low SNR regime, and just single Gaussians when in the high SNR regime. For low SNR cases where this would be overfitting, this is minimised by the fitting conditions described above.

Nevertheless, it should be acknowledged that this may introduce a minor bias when integrating emission line fluxes from high SNR spectra compared to low SNR. This would be considered minor since the lost integrated flux (by missing weak signatures of absorption) when fitting high SNR lines will have a negligible effect. Whereas a tendency to fit for absorption features on low SNR lines, when the algorithm is confident they exist, incorporates a significant amount of integrated flux that would otherwise be missed by a single Gaussian. Later use of my spectral fitting algorithm, in Chapter 4, required it to be generalised to work for any SN environment rather than the specific environment of SN iPTF13bvn (Chapter 3). This was done by scaling all χ_r^2 values for the fitting functions of a given implementation of the algorithm by the minimum χ_r^2 value of that case. Then the thresholds for χ_r^2 comparisons could be scaled down to fixed values that work for any general environment. In this later version of the spectral fitting algorithm, fitting to any nebular line (additional to H α and H β) follows the same reduction and use of the fitting functions as described above.

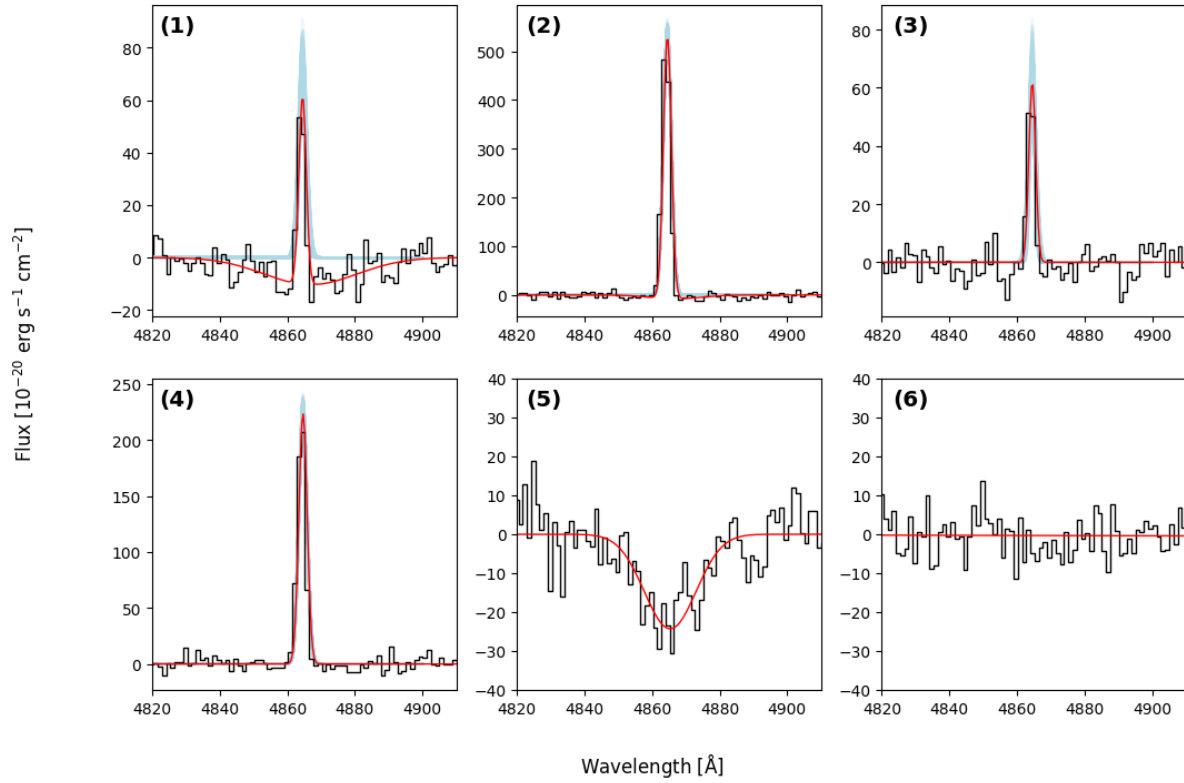


Figure 2.5: Examples of fitting algorithm performance across the $H\beta$ line range, with my (1) $\rightarrow$ (6) fitting functions labelled in the top right of each subplot (Section 2.4). Black lines correspond to the MUSE data, red lines show the overall function fit and shaded blue regions show the error range of the emission line Gaussian for the relevant cases.

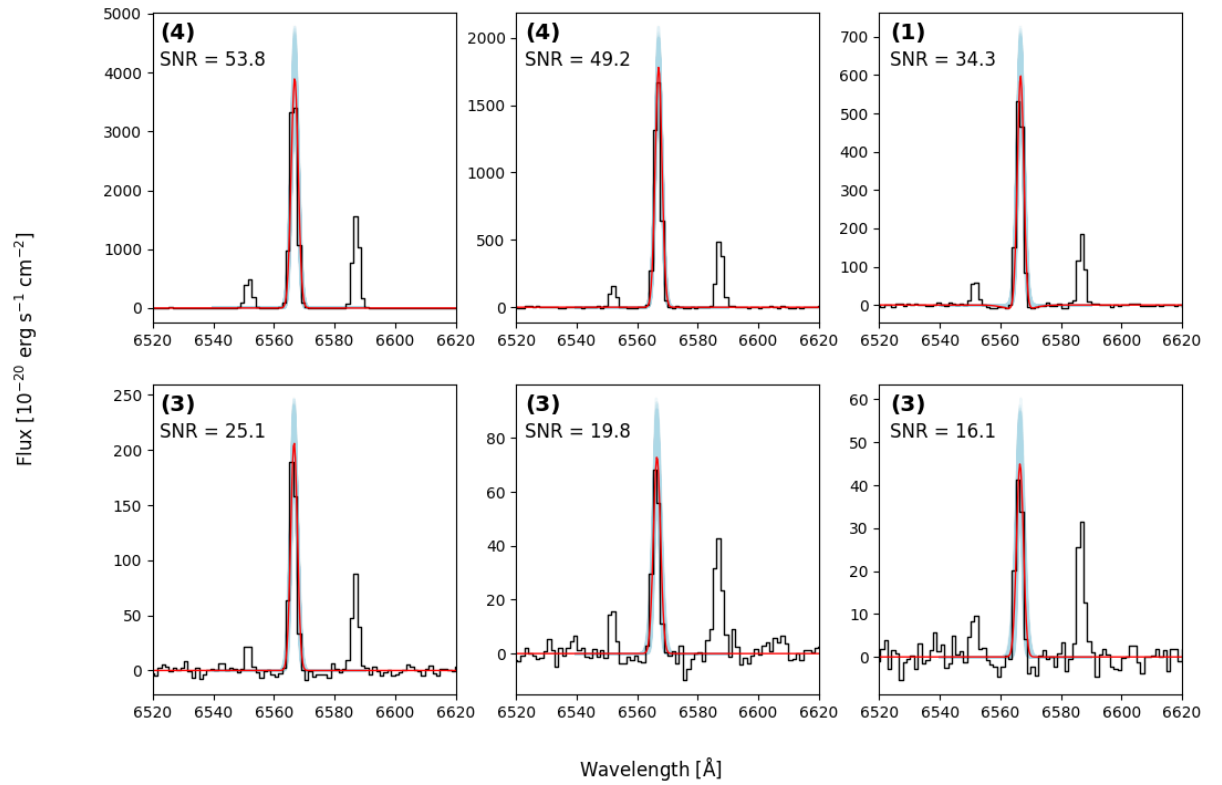


Figure 2.6: Examples of the algorithm performance across the full range of SNR values for the H α line. The optimum fitting function (Section 2.4) and SNR value of each spectrum is presented in the top left corner. Black lines correspond to the MUSE data, red lines show the overall function fit and shaded blue regions show the error range of the emission line Gaussian for the relevant cases.

Table 2.2: Spectral fitting algorithm conditions when choosing the optimum fitting function ($i = (1) \rightarrow (6)$; described above). Variables include: reduced chi-squared ($\chi_{r,i}^2$), signal-to-noise ratio (SNR), flux at the peak of an emission line (peak), standard deviation of continuum flux ($\sigma_{\text{continuum}}$). Initial fitting functions, corresponding to the minimum $\chi_{r,i}^2$ value, are listed in the first column, and the final fitting function corresponds to the top row. Cell colours are assigned to show the order in which functions are considered, in order of first-to-last: yellow, green, blue, red and orange.

Function	1	2	3	4	5	6
1	peak $\geq 3\sigma_{\text{continuum}}$	-	$ \chi_{r,1}^2 - \chi_{r,3}^2 < 60$ AND $ \chi_{r,1}^2 - \chi_{r,5}^2 \geq 40$ AND $ \chi_{r,1}^2 - \chi_{r,6}^2 \geq 100$ AND peak $\geq 3\sigma_{\text{continuum}}$	-	$ \chi_{r,1}^2 - \chi_{r,6}^2 < 40$ AND $ \chi_{r,1}^2 - \chi_{r,6}^2 \geq 100$	$ \chi_{r,1}^2 - \chi_{r,6}^2 < 100$
2	-	peak $\geq 3\sigma_{\text{continuum}}$	$ \chi_{r,2}^2 - \chi_{r,3}^2 < 40$ AND $ \chi_{r,2}^2 - \chi_{r,5}^2 \geq 40$ AND $ \chi_{r,2}^2 - \chi_{r,6}^2 \geq 100$ AND peak $\geq 3\sigma_{\text{continuum}}$	$ \chi_{r,2}^2 - \chi_{r,4}^2 < 20$ AND $ \chi_{r,2}^2 - \chi_{r,5}^2 \geq 40$ AND $ \chi_{r,2}^2 - \chi_{r,6}^2 \geq 100$ AND peak $\geq 3\sigma_{\text{continuum}}$	$ \chi_{r,2}^2 - \chi_{r,6}^2 < 40$ AND $ \chi_{r,2}^2 - \chi_{r,6}^2 \geq 100$	$ \chi_{r,2}^2 - \chi_{r,6}^2 < 100$
3	-	-	peak $\geq 3\sigma_{\text{continuum}}$	-	-	-
4	-	-	-	peak $\geq 3\sigma_{\text{continuum}}$	-	-
5	-	-	-	-	-	$ \chi_{r,5}^2 - \chi_{r,6}^2 < 20$
6	-	-	-	-	-	

2.5 Summary

In this chapter I have provided the specifications of all the telescope instruments that have collected data to be used throughout my exploration of the environments of core-collapse supernovae. This includes important context of the relative performance between HST filters, which will have implications for the results presented in Chapters 3 and 4 and the limitations of my analysis. This chapter outlines the standard pipelines through which all my data will be processed prior to analysis, as well as how I find photometric detection limits. The formulation of the Bayesian framework provides key details of assumptions and the overall methodology to fitting environmental stellar populations from HST photometry with the Nested Sampling algorithm and PARSEC stellar evolution models. The complimentary IFU-spectroscopic analysis is guided by my own spectral fitting algorithm, allowing the surrounding dust and ionised gas to assist the environmental analysis. Full details of how my spectral fitting algorithm was constructed, the motivations and assumptions are provided at the end of this chapter. Together, the independent photometric (resolved stellar populations) and spectroscopic (dust and ionised gas) analyses act as a powerful tool to spatially resolve the environments of core-collapse supernovae and provide constraints over the progenitors that produced them. This was first applied to the strong dataset of NGC 5806, hosting the Type Ib SN iPTF13bvn, and then later refined for a broader catalogue study.

Chapter 3

The Environment of iPTF13bvn

3.1 Introduction

Connecting the properties and evolutionary stages of massive stars to the classification features we observe when they explode as a [CCSN](#) at the end of their lives remains an ongoing area of research between the supernovae and massive star communities. The ‘gold standard’ for progenitor detections requires deep, high-resolution pre-explosion archival images, typically sourced from the extensive [HST](#) data archive. Later, post-explosion images are required to conclusively claim that the progenitor candidate has disappeared from the [SNe](#) site. In the last two decades, direct searches for progenitor stars have converged on [RSGs](#) for Type II ([Smartt et al., 2004](#); [Maund et al., 2004](#); [Smartt et al., 2009](#); [Smartt, 2009](#)), have found some binary systems for Type IIb ([Nomoto et al., 1993](#); [Aldering et al., 1994](#); [Woosley et al., 1994](#); [Maund et al., 2004, 2011](#); [Bersten et al., 2012](#); [Ergon et al., 2015](#)) and have found the progenitors of Type Ibc to be more elusive ([Kilpatrick et al., 2018](#); [Van Dyk et al., 2018](#); [Xiang et al., 2019](#); [Kilpatrick et al., 2021](#); [Sun et al., 2022a](#)). The fortuitous nature of the ‘gold standard’ approach, yielding a handful of progenitor identifications annually at best, means relying on it solely will lead to a slow progression in finding the physical causes of the diverse [CCSNe](#)

classification scheme. Alternatively, indirect methods provide an adjacent approach to building statistically robust constraints over the progenitors and allow for additional environment context to be tested for correlations to the classification.

Environmental studies began by looking at the overall galactic morphology (Baade & Zwicky, 1934a; Reaves, 1953; van den Bergh, 1959), eventually probing locally (van Dyk, 1992; Bartunov et al., 1994; van Dyk et al., 1996). James & Anderson (2006) and Anderson & James (2008) pioneered a pixel statistics approach with the Normalised Cumulative-Rank (NCR) method to investigate the spatial association of SNe types with ongoing star formation (SF), using $H\alpha$ as a proxy, in their host galaxies. These studies probe median physical sizes on the order of 300 pc, meaning individual H II regions become grouped into larger star forming regions. Recent studies (Maund & Ramirez-Ruiz, 2016; Maund, 2017; Sun et al., 2021; Ganss et al., 2022; Sun et al., 2023) considered individual stars or ionised gas in the SN environment to constrain the progenitor age, extinction and metallicity. Maund (2018) used a Bayesian approach with Nested Sampling to fit the surrounding stellar populations, providing age and extinction estimates of 23 stripped-envelope SNe (Type IIb & Type Ibc). Their characteristic ages support a substantial number of high mass ($M_{\text{initial}} > 30 M_{\odot}$) progenitors for Type Ibc SNe. Sun et al. (2021) expanded upon this analysis by including integral-field-unit (IFU) spectroscopy to model the ionised gas component of two SNe environments (2004dg [II-P] & 2012P [IIb]), revealing a star forming complex that has photo-ionised a giant H II region within NGC 5806. Sun et al. (2022a) repeated a similar analysis for the Type Ib SN 2019yvr.

In this chapter I will expand upon this approach to studying the environments of CCSNe, utilising the high spatial information of HST and MUSE data to combat the limitations of past studies. Development of the analysis will focus on a single SN, iPTF13bvn, with high quality long-exposure HST imaging and a complimentary MUSE IFU-spectroscopic datacube. The SN iPTF13bvn was discovered by Cao et al. (2013) and reported by the intermediate Palomar Transient Factory (iPTF) on 2013 June 16.238

UT, in the galaxy NGC 5806. An early-time spectral and photometric series classified iPTF13bvn as a Type Ib SN. [Cao et al. \(2013\)](#) observed iPTF13bvn at radio wavelengths; synchrotron self-absorption modelling produced mass-loss parameters consistent with a Wolf-Rayet progenitor. Conversely, [Bersten et al. \(2014\)](#) were the first to claim an interacting binary progenitor for iPTF13bvn through bolometric lightcurve fitting to hydrodynamic models. Subsequent studies have formed a growing consensus for the binary progenitor ([Eldridge et al., 2015](#); [Kuncarayakti et al., 2015](#); [Eldridge & Maund, 2016](#)). Errors in the initially quoted progenitor photometry for iPTF13bvn were identified and corrected by [Eldridge et al. \(2015\)](#). Their reanalysis agreed with a range of binary models, but ruled out typical Wolf-Rayet models. A late-time study by [Eldridge & Maund \(2016\)](#) confirmed that the identified progenitor had disappeared, as well as providing constraints on the suspected companion.

The chapter is outlined as follows. First, I provide any additional (to Chapter 2) methodology information specific to the case of iPTF13bvn, as well as details of the sourced data, in Section 3.2. The results of all parts of my environmental analysis are then presented separately in Section 3.3. Finally the implications, limitations and context of my results, with respect to past studies of iPTF13bvn, are discussed in Section 3.4, followed by concluding remarks (Section 3.5).

3.2 Observations and Methods

My analysis of the environment around iPTF13bvn consists of two components: 1) a photometric study of resolved stars in the environment that relies on long-exposure, high-spatial-resolution images of the host galaxy; and 2) a comparative study of the gas/dust/stars across a broader environment of iPTF13bvn, using IFU spectroscopic data. Throughout this chapter I use a foreground Galactic extinction in the V -band ([Schlafly & Finkbeiner, 2011](#)), quoted from the NASA/IPAC Extragalactic Database

(NED)¹ towards NGC 5806 of $A_V = 0.139$ mag. I adopt the Tully-Fisher distance to NGC 5806 of 22.5 Mpc (Tully et al., 2009), corresponding to a distance modulus $\mu = 31.76 \pm 0.36$ mag for consistency with Eldridge et al. (2015).

3.2.1 Data Reduction

Photometry with HST/WFC3

HST archival data for NGC 5806 was retrieved from the Mikulski Archive for Space Telescopes², as detailed in Table 3.1. Three long-exposure observations taken with the Wide Field Camera 3 (WFC3) with the Ultraviolet-Visible (UVIS) channel were obtained with the F225W (30 June 2015), F438W and F555W (25 June 2019) wide-band filters. The wavelength coverage spans the visible through UV. WFC3/UVIS has a pixel scale of 0.04 arcsec and a 160×160 arcsec² field of view (FoV). This dataset contains most of NGC 5806 (see Figure 3.1) and no residual light from iPTF13bvn. An additional WFC3/UVIS F555W (2 September 2013) subarray image of the site of iPTF13bvn, centred on the SN, was obtained for localising the SN position. Each download contains the raw files after charge transfer efficiency corrections (`*_flc.fits`) and the combined file corrected for cosmic-rays and distortion (`_drc.fits`) using the ASTRODRIZZLE package. The world coordinate system (WCS) of the three (`_drc.fits`) files were aligned using TWEAKREG and TWEAKBACK from the DRIZZLEPAC package, with the F438W image used as the reference for the WCS.

Point-spread-function (PSF) photometry was then performed using DOLPHOT (Dolphin, 2016) with the recommended input parameters and the F555W image (2019) used as the reference image, since this resulted in the largest number of common objects between all three WFC3 images. Resolved objects were filtered using DOLPHOT PSF output parameters according to the following criteria:

¹<https://ned.ipac.caltech.edu/>

²<https://archive.stsci.edu/missions-and-data/hst>

- (1) type of source, $\text{TYPE} = 1$ (corresponding to ‘star’);
- (2) photometry quality flag, $\text{FLAG} \leq 3$;
- (3) source crowding, $\text{CROWD} \leq 2$;
- (4) source sharpness, $-0.5 \leq \text{SHARP} \leq 0.5$;
- (5) signal-to-noise ratio, $\text{SNR} \geq 5$.

An object was retained in the final photometric catalogue if it met these quality checks in a minimum of one WFC3 image. When an object did not meet the above criteria in all three images, non-detections were substituted with a detection limit and corresponding error. Detection limits were found using [ASTs](#) within DOLPHOT, performed individually on each image. Details of the procedure are outlined in Section 2.2.1. Each ‘50% recovered’ magnitude was taken to be the detection limit and the resulting values are listed in Table 3.1.

A post-explosion [HST](#) image of iPTF13bvn, acquired in 2013 (see Table 3.1), was used to locate the SN on the later [HST](#) images. Photometry of the 2013 [HST](#) WFC3/UVIS F555W image, with DOLPHOT, was used to derive the positions of 25 common stars, that were used to find a coordinate transformation to determine the location of the SN on the 2019 [HST](#) WFC3/UVIS F438W image. The location of iPTF13bvn was transformed with a precision of $(\pm 0.18, \pm 0.26)$ [HST](#)/WFC3 pixels. The stellar environment of iPTF13bvn was defined as a circular region of 300 pc, centred on the SN position. This 300 pc region (corresponding to 68.761 F555W image pixels) is represented by the dotted cyan circle in Figure 3.1, with the environment displayed in each [HST](#)/WFC3 filter long-exposure image on the right panel.

Table 3.1: HST/WFC3 and VLT/MUSE data for the site of iPTF13bvn used in this study.

Program ID	Date (UT)	Instrument	Filter/Mode	Exposure Time (s)	m_j^{lim} (mag)	σ_j^{lim} (mag)
15152 ^a	2019-06-25	HST/WFC3/UVIS	F555W	5437.00	27.96	+0.56
15152 ^a	2019-06-25	HST/WFC3/UVIS	F438W	5408.00	27.78	+0.58
13822 ^b	2015-06-30	HST/WFC3/UVIS	F225W	8865.00	25.95	+0.52
12888 ^a	2013-09-02	HST/WFC3/UVIS	F555W	300.00	-	-
097.B-0165 ^c	2016-04-07	VLT/MUSE/LIFU	WFM	3600.00	-	-

^a PI: S. D. Van Dyk^b PI: G. Folatelli^c PI: D. M. Carollo

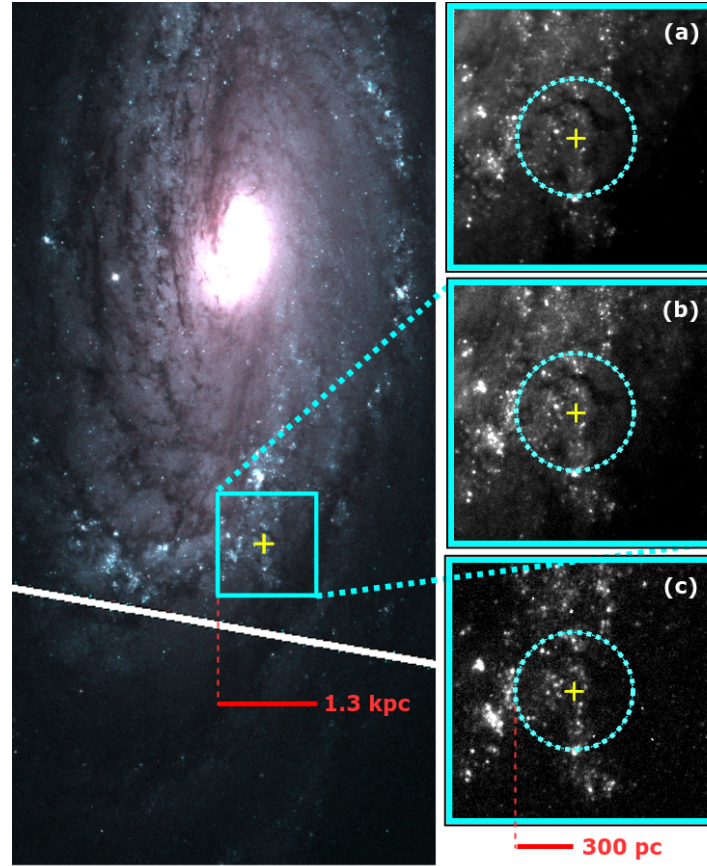


Figure 3.1: Left: A false colour *HST* image of NGC 5806 using the F555W and F438W images. A cyan box highlights the extracted region of the VLT/MUSE IFU datacube, a gold cross marks the location of iPTF13bvn. Right: a close-up of *MUSE* region in all three *HST* filters, (a) F555W (b) F438W (c) F225W. A dotted cyan circle (radius = 300 pc) highlights the environment definition used to resolve stellar populations. The image is orientated such that North is up and East is left.

IFU Spectroscopy with VLT/MUSE

For the second phase of our environmental analysis, spatially-resolved integral-field-unit (IFU) spectroscopic data is required. The [Multi Unit Spectroscopic Explorer \(MUSE\)](#) mounted on the [Very Large Telescope \(VLT\)](#) acquired IFU spectroscopy of NGC 5806 on 7 April 2016 (see [Table 3.1](#)). Operating in the wide-field mode (WFM) provides a $1 \times 1 \text{ arcmin}^2$ FoV with 0.2 arcsec spatial sampling covering a spectral range of 4750–9350 Å with 1.25 Å sampling. Once processed through the standard pipeline, the IFU datacube is publicly available through the European Southern Observatory (ESO) Archive Science Portal³. Manipulation of the datacube was achieved with the MPDAF ([Piqueras et al., 2019](#)) and IFUANAL ([Lyman et al., 2018](#)) packages. Following the alignment procedure presented in [Section 3.2.1](#), 8 common objects between the MUSE datacube and WFC3 images produced transformed coordinates for iPTF13bvn in the MUSE field. To improve the signal-to-noise ratio (SNR) of spectra across the datacube, 2×2 spaxels were resampled into single spaxels and their errors added in quadrature. This approach was chosen over the commonly used Voronoi tessellation approach for resampling IFU data, where spaxels are grouped into tiles of varying shape and size to ensure uniform spectral SNRs. Although spectral SNR is still an important consideration within this work, it was decided that retaining the spatial information within the environment of iPTF13bvn would be more valuable. A 30×30 spaxel (along the spatial axes) cube, centred on transformed coordinates of iPTF13bvn, was extracted and is highlighted by the cyan squares in [Figure 3.1](#). Within this extracted cube the exact position of iPTF13bvn is at the binned spaxel position $(14.17 \pm 0.08, 14.19 \pm 0.11)$. Given that (14, 14) occurs at the centre of the spaxel, we can confidently conclude that iPTF13bvn falls inside this spaxel. Hereafter, references to the MUSE datacube or individual spaxels refer to this new, resampled, 30×30 spaxel datacube. The original, full FoV datacube of NGC 5806 can be found in [Figures 1, 2, 3 and 4 of Sun et al. \(2021\)](#).

³<http://archive.eso.org>

With IFUANAL, the datacube was de-redshifted and dereddened assuming values of $z = 0.00449$ and $E(B - V) = 0.044$ mag (assuming a Galactic [Cardelli et al. 1989](#) reddening law with $R_V = 3.1$). The galactic rotational velocity across this environment was found using a summed spectrum of the entire datacube, and a single Gaussian fitting to the Balmer $H\alpha$ emission line. Subtraction from the rest-frame peak wavelength gave an averaged rotational velocity of $v_{\text{rot}} = 70.6$ km/s. This estimate for our extracted region agrees with the corresponding values in the rotational velocity map of NGC 5806 by [Sun et al. \(2021\)](#). Differential rotation across the extracted MUSE datacube is minimal, with the maximum discrepancy to our average v_{rot} value corresponding to a $\Delta\lambda = 2.5$ Å (i.e. two spectral bins). A description of how I account for these minor central wavelength shifts is provided in Section 2.4, as well as a description of how nebular line features were fit. Example plots of the galactic rotational velocity fitting process are provided in Section 4.3.2.

3.2.2 Balmer Decrement Extinctions

Extinctions found spectroscopically use the Balmer decrement, comparing the observed (obs) flux ratio between the $H\alpha$ and $H\beta$ lines to the intrinsic (int) ratios from [Osterbrock & Ferland \(2006\)](#). Following the standard approach, see [Domínguez et al. \(2013\)](#), the colour excess can be defined as

$$E(B - V) = \frac{E(H\beta - H\alpha)}{k(\lambda_{H\beta}) - k(\lambda_{H\alpha})} = \frac{2.5}{k(\lambda_{H\beta}) - k(\lambda_{H\alpha})} \log \left[\frac{\left(\frac{H\alpha}{H\beta}\right)_{\text{obs}}}{\left(\frac{H\alpha}{H\beta}\right)_{\text{int}}} \right] \quad (3.1)$$

and converted to the V-band using

$$A_\lambda = k(\lambda)E(B - V). \quad (3.2)$$

For this conversion a value of $k(V) = R_V = 3.1$ is applied, corresponding to the Galactic diffuse interstellar medium average. Values of $k(\lambda_{H\alpha})$ and $k(\lambda_{H\beta})$ are the Cardelli, Clayton & Mathis (1989) reddening curves evaluated at $H\alpha$ and $H\beta$ wavelengths. Intrinsic flux ratios from Osterbrock & Ferland (2006) form a grid of values, dependent on four electron temperature values ($T_e = 2500, 5000, 10000, 20000$ K).

3.2.3 Resampling HST-to-MUSE

For an intersectional study between the two datasets, I resample the HST images into maps of surface brightness on the same spatial pixel scale as MUSE. Following the guidelines on (<https://www.stsci.edu/hst/instrumentation/wfc3/data-analysis/photometric-calibration/uvis-encircled-energy>) pixel count rates are converted into Vega magnitudes with

$$m_{\text{Vega}} = \text{zeropoint} - 2.5 \log(\text{counts} - \text{background}) - 2.5 \log(1/\text{EE}). \quad (3.3)$$

Values substituted for zeropoints and encircled energy (EE) corrections are listed in Table 3.2 for the three main HST images. All EE corrections are for an aperture of radius = 0.20 arcseconds, equivalent to a single MUSE spaxel. Also in Table 3.2 are newly found background estimates for our F555W, F438W and F225W images. Processed images from the HST archives are background subtracted with a single value, corresponding to a peak in a histogram of dark pixels. Our new background estimates were found by averaging across dark pixels; their low (10^{-3}) negative values could imply a slight oversubtraction of the background in the HST/WFC3 pipeline.

Table 3.2: Values substituted into Equation 3.3 to convert HST image electron counts into surface brightness magnitudes: backgrounds, zeropoints and Encircled Energy (EE) corrections.

Filter	Background $10^{-3} \text{ (e}^{-}/\text{s)}$	Zeropoint (mag)	EE Corrections [$r = 0.20''$]
F555W	-8.95	25.823	0.85435
F438W	-5.54	24.990	0.85247
F225W	-2.76	22.646	0.78

3.3 Results

3.3.1 Stellar Populations and the Environment of iPTF13bvn as seen through HST/WFC3

As can be seen in Figure 3.1, iPTF13bvn is located in one of the spiral arms of NGC 5806 where massive star formation would be expected. iPTF13bvn appears to be situated on the edge of the spiral arm, such that the West portion of the environment is less populated. In this lower density region, a dark filament feature appears in all three of the WFC3 filters that wraps around the site of iPTF13bvn and could imply a gas/dust structure along the line-of-sight. Performing PSF photometry with DOLPHOT yields 138 ‘good quality’ stars in the environment of iPTF13bvn (cyan dashed circle in Figure 3.1). The majority of magnitude detection limit substitutions occur for the F225W filter (93 substitutions), followed by F438W (54 substitutions) and minimal for F555W (4 substitutions). Given that our definition of the environment ($r = 300 \text{ pc}$) encloses a relatively large volume when considering regions of star formation, 138 resolved stars implies a sparse population of massive stars.

When applying our Bayesian approach the k^{th} stellar population has three free parameters: $\log(\text{age years})$ (τ_k), extinction ($A_{V,k}$) and extinction dispersion ($\delta A_{V,k}$) which relates to the standard deviation of the normal distribution through $\sigma_{A_{V,k}} = 0.05 \times 10^{\delta A_{V,k}}$. Likelihood functions were obtained for each of the 138 stars, following

the formulation described in Section 2.3.2. PARSEC isochrones were downloaded over the logarithmic age range of $6.0 \leq \tau \leq 8.0$ in steps of 0.01 and a fixed metallicity fraction of 0.02 (solar; Section 3.3.2). The photometry used in the likelihood calculations was corrected for foreground galactic extinction with a value of $A_V^{MW} = 0.139$ mag (NED; Schlafly & Finkbeiner 2011) and a standard extinction law with $R_v = 3.1$.

Sourcing the posterior probability distributions of free parameters through ULTRANEST requires simple function definitions for the expected form of our log-likelihoods and priors, alongside the predetermined likelihood distributions for each star, to perform the Nested Sampling algorithm. The log-likelihoods were assumed to follow a multivariate normal distribution, $\mathcal{N}(\tau_k, A_{V,k}, \sigma_{\tau_k}, \sigma_{A_{V,k}})$, for each stellar population. Modelling two or more stellar populations requires the weight (ω_k) of each distribution to be included as free parameters. For N_m populations, only $N_m - 1$ weights that obey a Dirichlet distribution need to be defined in the ULTRANEST log-likelihood functions. This assists in reducing the number of free parameters in the model and speeds up each run. The final weight is simply calculated using the normalisation condition $\sum_k \omega_k = 1$. Flat priors are imposed on τ_k , $A_{V,k}$ and ω_k with the following ranges: $6.00 \leq \tau \leq 8.00$, $0.00 \leq A_V \leq 2.00$, $0.00 < \omega_k < 1.00$. To further reduce the computational expense when trying to fit for a high number of population components (i.e. $N_m = 4$) initial ULTRANEST runs fit for N_m age components, but only a single internal extinction component and fixed age/extinction dispersions: $\sigma_{A_{V,k}}, \sigma_{\tau_k} = 0.05$. With the above implementation, ULTRANEST runs with 400 live points were separately performed on models with 1, 2, 3 and 4 age components. Bayesian evidence was collected and corrected for (as described in Section 2.3.4) following each run, the results of which are presented in Figure 3.2. Also included as a subplot is the evolution of the evidence accumulation with increasing iterations, showing that the evidence converges towards a limit in each case. Following the interpretation by Jeffreys (1939), the largest relative jump in evidence is seen between the $N_m = 1$ and $N_m = 2$ age component models. Therefore, I can conclude

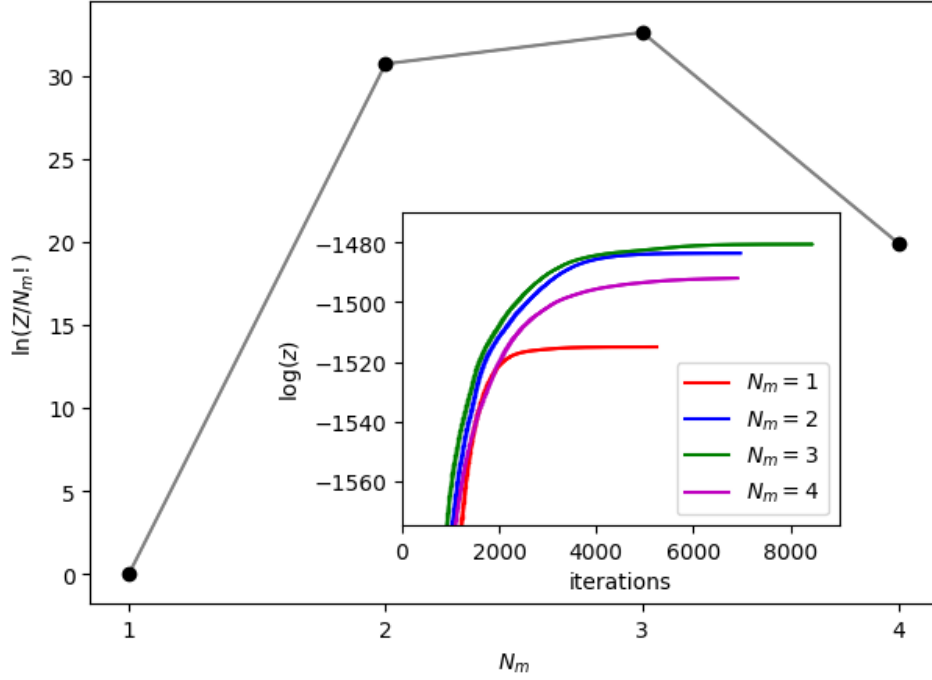


Figure 3.2: Main plot: corrected Bayesian evidence values for 1, 2, 3 and 4 age component ULTRANEST runs. Subplot: evolution of evidence collection during nested sampling algorithm for each ULTRANEST run.

that the photometry from the environment of iPTF13bvn is best-fit by two populations of stars representing distinct epochs of star formation.

Following this, a secondary ULTRANEST run was performed with unique extinction estimations for each population. Log-likelihood and prior functions follow the same initialisation as described above, except I almost double the number of free parameters in this comprehensive model: τ_1 , τ_2 , $A_{V,1}$, $A_{V,2}$, $\sigma_{A_{V,1}}$, $\sigma_{A_{V,2}}$. Prior ranges for each free parameter were informed by the results of the original two age component model: $6.20 \leq \tau_k \leq 7.20$, $0.40 \leq A_{V,k} \leq 1.20$, $0.00 \leq \delta A_{V,k} \leq 1.00$ (corresponding to $0.05 \leq \sigma_{A_{V,k}} \leq 0.50$). The extinction was chosen to have a unconstrained dispersion since this is a physical parameter that could be expected to capture variation between populations, as well as a spread within each population. Conversely, we expect population ages to be tightly constrained; therefore, the age dispersion remains fixed, but is slightly relaxed to a value of $\sigma_{\tau_k} = 0.10$.

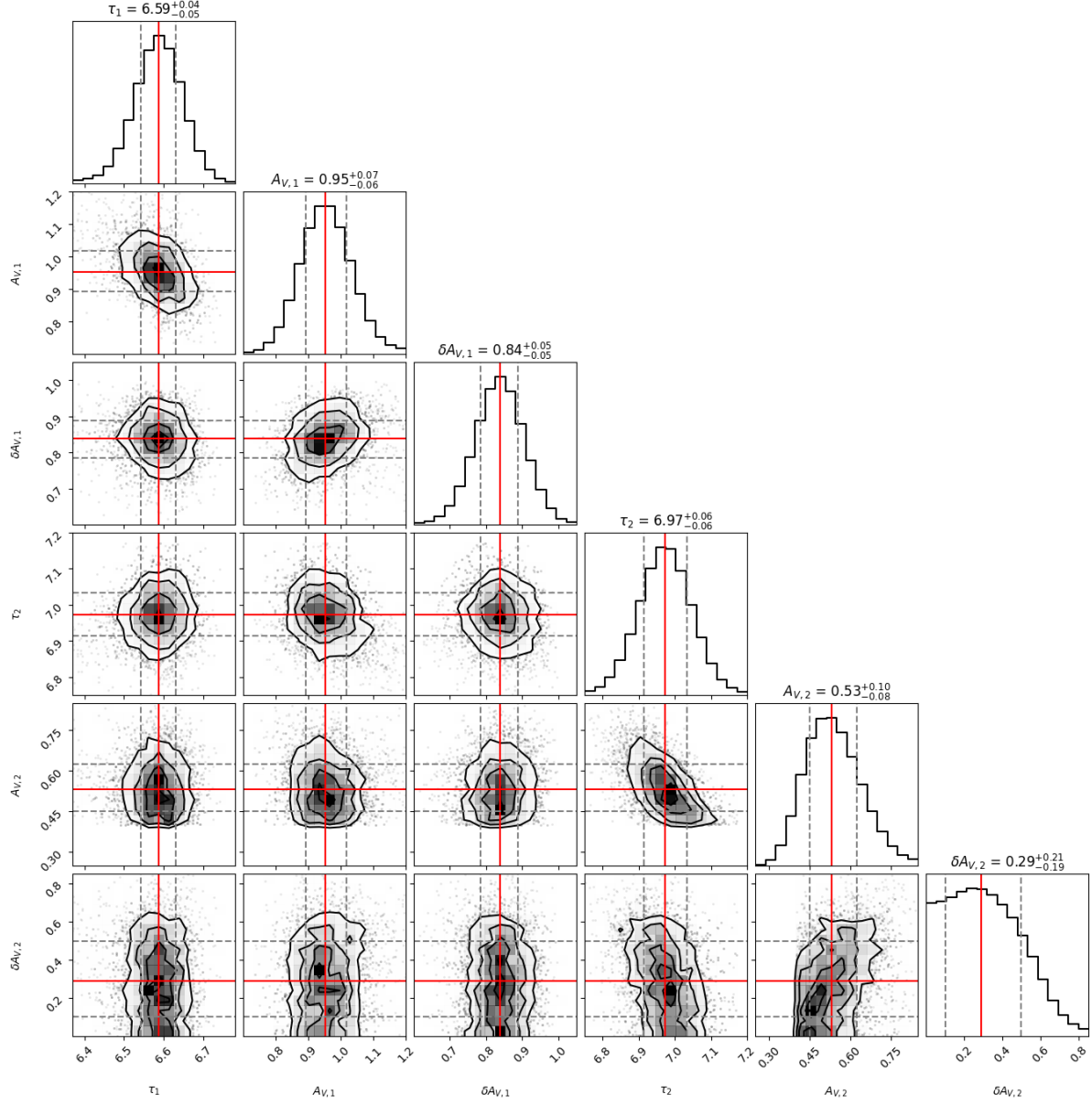


Figure 3.3: ULTRANEST results using two age, $\tau_k = \log(\text{age}_k)$, and extinction, $A_{V,k}$, components, with a fixed age dispersion of $\sigma_{\tau_k} = 0.10$. The extinction dispersion parameter $\delta A_{V,k}$, where $\sigma_{A_{V,k}} = 0.05 \times 10^{\delta A_{V,k}}$, is left as a free parameter to be fit. Posterior distributions are plotted as histograms with the corresponding contour plots. Red lines show the best-fit values and grey dashed lines represent the 16% and 84% quantiles.

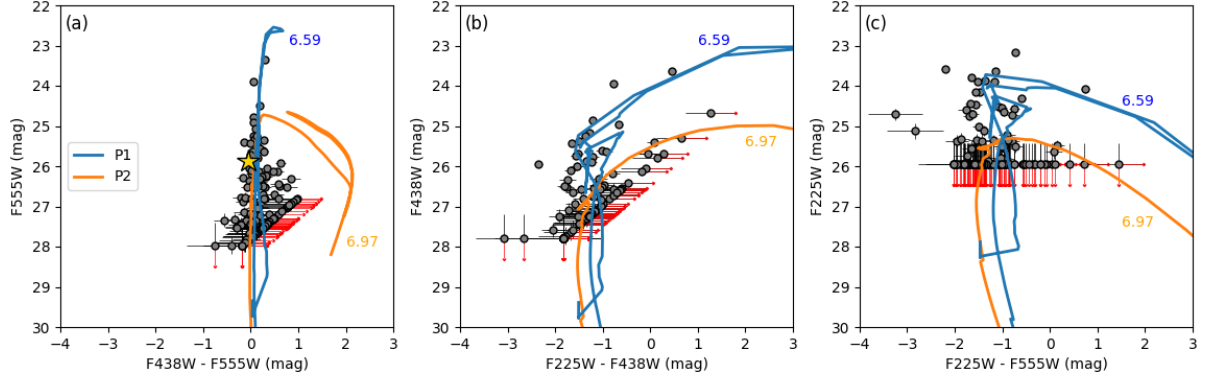


Figure 3.4: Colour magnitude diagrams (CMDs) of the 138 stars (black data points) in the environment of iPTF13bvn, using three colours from the *HST* filters: F555W, F438W, F225W. Best-fit PARSEC isochrones from the results of the two age/extinction component ULTRANEST run are plotted over the data; population 1 (pop1; blue) uses $\tau_1 = 6.59$, $A_{V,1} = 0.95$ mag; population 2 (pop2; orange) uses $\tau_2 = 6.97$, $A_{V,2} = 0.53$ mag. Both isochrones account for foreground galactic extinction; $A_V^{MW} = 0.139$ mag. The gold star in plot (a) shows the apparent magnitudes of the iPTF13bvn progenitor, reported by Eldridge et al. (2015). Grey circles represent measured apparent magnitudes and colours for individual stars in the $r = 300$ pc environment, and red arrows highlight filters where detection limits were substituted.

Figure 3.3 shows the results from this model run, which has successfully resolved two stellar populations with significantly different extinctions. Best-fit values for the age, extinction and corresponding dispersion are $\tau_1 = 6.59^{+0.04}_{-0.05}$, $A_{V,1} = 0.95^{+0.07}_{-0.06}$ mag, $\sigma_{A_{V,1}} = 0.35^{+0.04}_{-0.04}$ and $\tau_2 = 6.97^{+0.06}_{-0.06}$, $A_{V,2} = 0.53^{+0.10}_{-0.08}$ mag, $\sigma_{A_{V,2}} = 0.10^{+0.06}_{-0.03}$ for population 1 (P1) and population 2 (P2), respectively. Doubling the age dispersion resulted in differing peak posterior values for the population ages between our original simplified model and those seen in Figure 3.3. However, the P1 ages agree within 2σ and the P2 ages within 1σ ; given the small errors of our age estimates, such a minimal shift in values implies that relaxing the age dispersion has negligible effect on the final result. Our two population ages correspond to $\sim 3.89^{+0.38}_{-0.42}$ million years for P1 and $\sim 9.33^{+1.38}_{-1.20}$ million years for P2, temporally separating the epochs of star formation by ~ 5.44 million years. The respective PARSEC isochrones for P1 and P2 are displayed in Figure 3.4, overlaid on the photometry of the resolved stars (grey data points) within the $r = 300$ pc environment.

Taking the maximum mass of the corresponding age PARSEC isochrone to be the best estimate of the progenitor mass for single star evolution, the following initial (zero-age main sequence) and final masses were found:

$$M_{\text{initial,P1}} = 65.4 \text{ M}_{\odot}.$$

$$M_{\text{final,P1}} = 20.1 \text{ M}_{\odot}.$$

$$M_{\text{initial,P2}} = 20.0 \text{ M}_{\odot}.$$

$$M_{\text{final,P2}} = 17.8 \text{ M}_{\odot}.$$

PARSEC final masses reflect mass-loss across advanced evolutionary phases, as late as central carbon ignition (Chen et al., 2015). Since this does *not* model rapid mass-loss in the final centuries of massive stars, nor mass-loss through binary interaction, the final masses do *not* represent pre-explosion masses. Designating a population age and mass to the progenitor of iPTF13bvn is subject to interpretation and is discussed further in Section 3.4.1. In short, although I cannot conclusively assign a natal stellar population, the collective environmental information for iPTF13bvn motivates a statistical comparison to other Type Ib CCSNe, as well as other classifications in a future sample study.

3.3.2 The Environment of iPTF13bvn as seen through VLT/MUSE

Running the algorithm described in Section 2.4, fitting the continuum and $\text{H}\alpha/\beta$ Balmer lines of individual spaxels in the 30×30 datacube, produced a myriad of parameter maps displayed in Figure 3.5. From the top row of plots (mean continuum; $\text{H}\alpha$ flux; $\text{H}\beta$ flux) the distribution of white-light sources against numerous bright H II regions can be seen. However, the immediate site of iPTF13bvn is comparatively dark despite being coincident with the spiral arm; instead it is encircled by H II regions. Where I

suspect there is a dust lane arching around the site of iPTF13bvn from a dark feature in Figure 3.1 coincides with a drop in signal in the MUSE data, specifically where we see missing spaxels inside the spiral arm (Figure 3.5[c]). Looking at rows 2 and 3 of the first column of Figure 3.5, my fitting functions (outlined in Section 2.4) show contrasting results for both Balmer lines. Fitting of $H\alpha$ favours the ‘weak’ single Gaussian (3) function, with only the brightest H II regions optimised by the ‘strong’ single Gaussian (4). Comparatively, fitting of $H\beta$ applies the full range of (1) $\rightarrow$ (6) fitting functions, producing identifiable regions and borders within the datacube environment. Mainly, the spiral arm becomes visible and is overwhelmingly fit with either ‘weak’ or ‘strong’ double Gaussian functions (1) and (2), whilst some spaxels on the arm-edge are enforced with ‘weak’ single Gaussian fittings (3) due to decreasing SNR. Whilst the dual absorption-emission features across the spiral arm are correlated with cospatial stars and gas, the ‘pure absorption’ (5) fitting seen in the top left corner indicates dense (likely older) stellar populations external to the spiral arm. The remaining spaxels are mostly fit with a featureless ‘continuum’ (6).

Given the known correlation between $EW(H\alpha)$ and the specific star-formation rate (sSFR) (Mármol-Queraltó et al., 2016), the brightest observed H II regions correspond to the highest sSFR. Overall, we can summarise the environment of iPTF13bvn to be: within a spiral arm of NGC 5806; lacking in ongoing star-formation; comparatively deficient in hard radiation from massive star populations.

Additionally, a gas-phase metallicity estimate for the environment of iPTF13bvn (‘13bvn-outer’ in Figure 3.5) was found using a strong-line diagnostic, specifically the O3N2 calibration of Marino et al. (2013). From the summed spectrum within this aperture, emission line fluxes for the [O III] $\lambda 5007$ and [N II] $\lambda 6584$ lines were estimated from a single Gaussian fit ($H\alpha$ and $H\beta$ fluxes are estimated as standard by the fitting algorithm). Through the [O III] $\lambda 5007/H\beta$ and [N II] $\lambda 6584/H\alpha$ line ratios, I find an abundance estimate of $12 + \log(O/H) = 8.69 \pm 0.18$ dex. This matches the current solar

value (8.69 dex; [Asplund et al. 2009](#)), therefore all prior assumptions of solar metallicity in this analysis are valid.

3.3.3 Extinctions from MUSE Spectral Analysis

Implementation of the Balmer decrement method to acquire extinction estimates across the environment of iPTF13bvn was applied to individual spaxels, as well as the summed spectra of spaxels contained within a defined region. Since the electron density and temperature are not constrained in this study, any single extinction estimate comprises a set of four values to cover the full temperature range (2500 - 20000 K) with independent intrinsic $I[\text{H}\alpha]/I[\text{H}\beta]$ ratios from [Osterbrock & Ferland \(2006\)](#), see full derivation in Section 3.2.2. Figure 3.6 shows the distribution of single spaxel extinctions ($T = 10,000$ K) throughout the datacube, where the majority of spaxels are constrained between $A_V = 0.5$ mag and $A_V = 3.0$ mag. Propagating the flux error estimates produces reasonable extinction errors for most of this distribution, even in the low (< 15) SNR regime. The few exceptions to this, with large errors, highlight the limitations of my fitting algorithm where low $\text{H}\beta$ flux results in poorly constrained Gaussian fits. Further confidence in the performance of my fitting algorithm can be gained by the smoothly varying nature of the spatial map of extinctions in Figure 3.5(j). For the single spaxel containing the position of iPTF13bvn, the extinction estimate (assuming $T = 10000$ K) is shown as a golden datapoint in Figure 3.6 and corresponds to a value of:

$$A_{V,13\text{bvn-single}} = 1.92 \pm 0.13 \text{ mag.}$$

Given the pair of population results from the photometric-isochrone fitting, an equivalent environment definition (circular aperture; $r = 300$ pc; centred on iPTF13bvn) was applied to the MUSE datacube. All spaxels which fall inside this aperture had their spectra summed and the fitting algorithm was applied to the product. The resulting extinction estimate can be interpreted as a single averaged value across the environment

(env):

$$A_{V,13bvn-env} = 1.74 \pm 0.05 \text{ mag.}$$

To complete the available methods for estimating the environmental extinction, I find a weighted mean ($\bar{A}_V$) for the sample within the $r = 300$ pc environment. This allows us to gain a new parameter, the standard error ($\sigma_{\bar{A}_V}$), representing the constraint over this weighted mean. For the photometric-equivalent ($r = 300$ pc) environment, this produces:

$$\bar{A}_{V,13bvn} = 1.463 \text{ mag.}$$

$$\sigma_{\bar{A}_{V,13bvn}} = 0.005 \text{ mag.}$$

The above set of extinctions are significantly different, the only agreement can be found between $A_{V,13bvn-single}$ and $A_{V,13bvn-env}$ to within 2σ . The mean of individual spaxel extinctions ($\bar{A}_{V,13bvn}$) does *not* reproduce the stacked spectrum estimate ($A_{V,13bvn-env}$) across the $r = 300$ pc environment of iPTF13bvn. This prompts an investigation into whether this result is systematically observed across the [MUSE](#) datacube or unique. Although varying the electron temperature shifts these extinctions values (discussed further in Section 3.4.2), the disagreement remains.

3.3.4 Comparison Environments

The ensemble of extinction estimates for the environment of iPTF13bvn requires context within the larger environment around iPTF13bvn. Selected comparison environments are shown in Figure 3.5, where regions A, B and C are the nearest H II regions (A and B are considerably brighter than C) and region D was selected for its likeness to the environment of iPTF13bvn. These regions were selected based on the $H\alpha$ and $H\beta$ flux, centred on the brightest spaxels of the [MUSE](#) data. An additional region within the environment of iPTF13bvn was created, ‘13bvn-inner’, that provides an equivalent aperture to the comparison environments (A, B, C and D). My photometric-equivalent

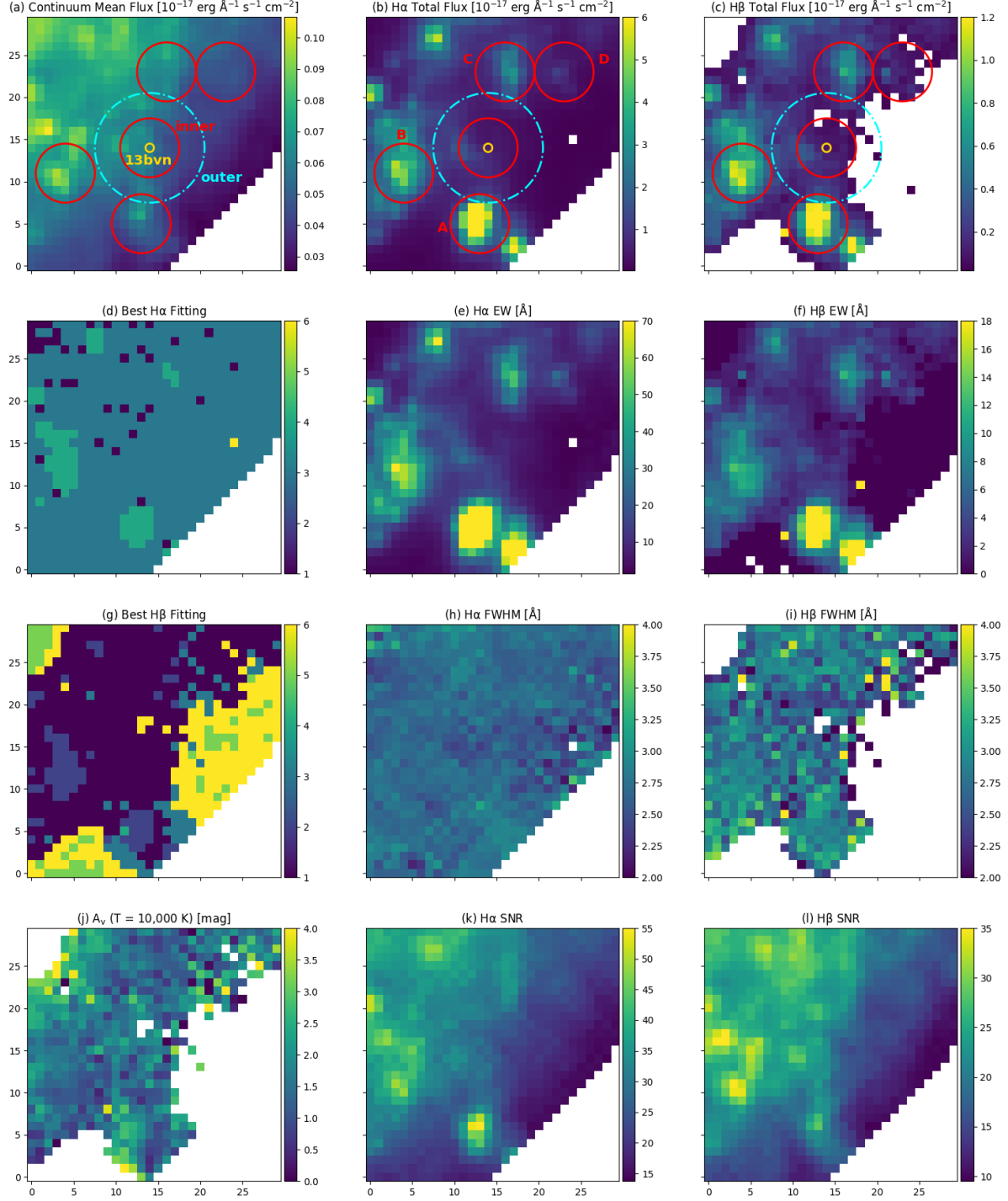


Figure 3.5: Maps of measured spectroscopic observables, described by plot headers and in the main text, for the extracted 30×30 rebinned MUSE datacube. Overlaid are circular apertures for '13bvn_inner' (radius = 3.5 spaxels) and '13bvn_outer' (radius = 6.5 spaxels), as well as comparison environments (A, B, C and D) with radii = 3.5 spaxels (refer to Table 3.3). The site of iPTF13bvn lies at the centre of the image (14,14) and is labelled in gold.

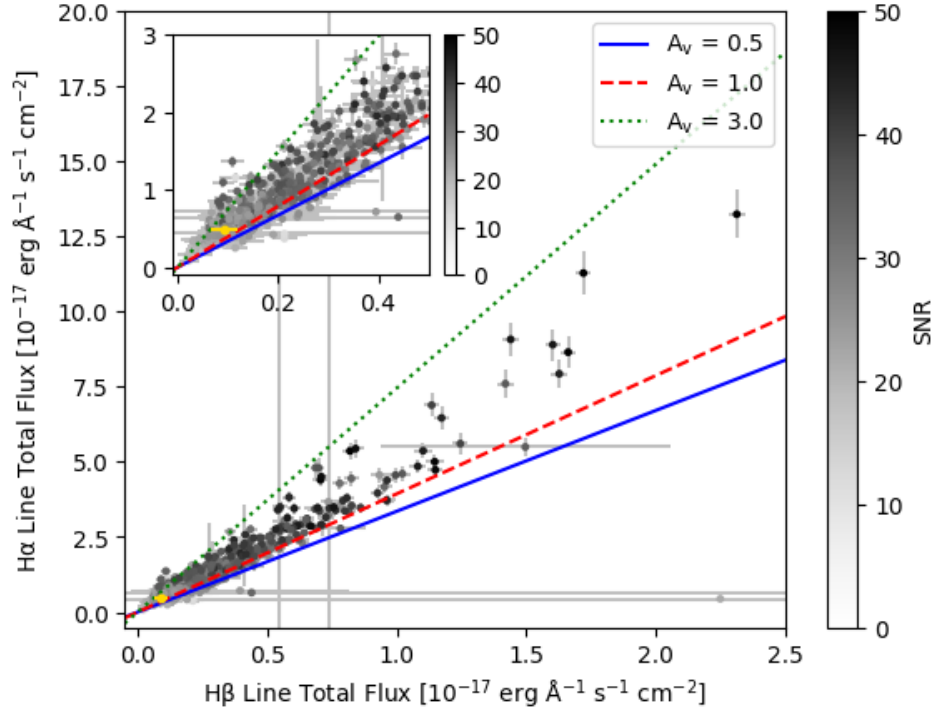


Figure 3.6: Main plot: Balmer line ($H\alpha$ and $H\beta$) emission fluxes of individual rebinned spaxels from our extracted MUSE datacube, and corresponding error estimates. Grey-scale colourbar on datapoints represents the $H\alpha$ line SNR. Spaxel (14,14) in Figures 3.5 and 3.7, containing the location of iPTF13bvn, is highlighted as a golden datapoint. Subplot: zoom-in of bottom left corner of main plot. Linear lines represent constant values of extinction derived from the Balmer decrement: $A_V = 0.5$ mag (blue), $A_V = 1.0$ mag (red; dashed), $A_V = 3.0$ mag (green; dotted).

environment is now labelled as ‘13bvn-outer’. Region D and ‘13bvn-inner’ both lie on the edge of the spiral arm, with relatively low flux levels in continuum and emission. The smaller of the apertures have radii of 3.5 rebinned **MUSE** spaxels (~ 150 pc), whereas the ‘13bvn-outer’ aperture has $r = 6.5$ rebinned **MUSE** spaxels (~ 300 pc).

Values for $A_{V,\text{env}}$, $\bar{A}_V$ and $\sigma_{\bar{A}_V}$ were determined for every defined region in Figure 3.5, the results of which are summarised in Table 3.3. Notably, all regions besides ‘13bvn-outer’ find good agreement, within 1σ , between their environmentally stacked spectrum estimate and the mean of individual spaxels. Following the question raised in Section 3.3.3 this result for ‘13bvn-outer’ is unique to the comparison environments, implying that the larger aperture (increased number of spaxels) of ‘13bvn-outer’ results in the disagreement between A_V and $\bar{A}_V$. The cause of this discrepancy can be attributed to Jensen’s inequality. For a given distribution, Jensen’s inequality states that a non-linear, convex function, $f(x)$, applied to expected value, $E[X]$ (mean), of this distribution is less than or equal to the mean of the function’s values: $f(E[X]) \leq E[f(X)]$ (Mitrinovic & Vasic, 2012). If the function is convex this inequality flips. When finding extinction estimates, Equation 3.1 is **non-linear** and **convex**. Remaining specific to the results of the ‘13bvn-outer’ aperture extinctions, $A_{V,\text{env}}$ had Equation 3.1 applied to a mean spectrum, whereas $\bar{A}_V$ had Equation 3.1 applied first to individual spaxels and the weighted mean calculated thereafter. It then follows that we should expect $A_{V,\text{env}} \geq \bar{A}_V$ in accordance with Jensen’s inequality, as is found observationally. As to why this behaviour is only observed for the ‘13bvn-outer’ aperture, it must relate to the increased number of spaxels. What appears to be found is the crossing of a threshold in the number of spaxels (aperture size) over which the Jensen’s inequality takes on a measurable impact. This stresses the importance of not using physical results from large apertures (radius > 150 pc) to represent the value for a single, localised event or object (e.g. SN or star). Outside of this discussion, the weighted mean standard error, $\sigma_{\bar{A}_V}$, for ‘13bvn-inner’ and region D are twice what is found for the remaining environments, potentially linked to

Table 3.3: Summary of extinction results for all environments (iPTF13bvn and comparisons) defined in Figure 3.5 including: the single extinction estimate of the summed spectrum for each region ($A_{V,\text{env}}$), the weighted-mean of the distribution of single spaxel extinction estimates within each region ($\bar{A}_V$) and the corresponding standard error of each weighted-mean ($\sigma_{\bar{A}_V}$). Projected distances to iPTF13bvn are found from the SN site spaxel (14,14) to the central spaxel of each region, it is worth noting that regions A through D have aperture radii of ~ 152.6 pc (3.5 MUSE spaxels). The final column shows the EW equivalent $\log(\text{age years})$ for STARBURST99 models (instantaneous; $Z = 0.02$); errors are not included as our EW errors are outside the resolution of the models.

Region	Aperture Radius [pc] (spaxels)	$A_{V,\text{env}}$ [mag] ($T=10\text{kK}$)	A_V [mag]	$\sigma_{\bar{A}_V}$ [mag]	Projected Distance to iPTF13bvn [pc]	H α EW [Å]	STARBURST99 $\log(\text{age years})$
iPTF13bvn outer	283 (6.5)	1.738 ± 0.052	1.467	0.005	0.0	13.5 ± 1.5	7.04
iPTF13bvn inner	153 (3.5)	1.479 ± 0.060	1.423	0.011	0.0	12.5 ± 1.5	7.05
A	153 (3.5)	1.832 ± 0.109	1.760	0.005	394.8	78.6 ± 19.0	6.80
B	153 (3.5)	1.399 ± 0.061	1.384	0.004	455.2	41.5 ± 5.9	6.81
C	153 (3.5)	1.361 ± 0.047	1.407	0.006	402.0	23.4 ± 2.4	6.86
D	153 (3.5)	1.770 ± 0.065	1.775	0.016	554.9	11.3 ± 1.4	7.05

increased variability in extinction (Section 3.4.2).

3.3.5 H II Region Ages with STARBURST99

Following the standard practice of estimating the ages of bright H II regions using the equivalent widths (EWs) of their H α profiles, I directly compare my measurements to the STARBURST99 tabular dataset (Leitherer et al., 1999). The STARBURST99 models synthesize instantaneous star formation (i.e. a single stellar population) and implement stellar evolution models by the Geneva group (Maeder, 1990; Schaller et al., 1992; Schaerer et al., 1993b,a; Charbonnel et al., 1993) across a range of discrete metallicities ($Z = 0.040, 0.020, 0.008, 0.004$ and 0.001). The EWs were derived from the summed spectra of the defined apertures in Section 3.3.4, for the three closest bright H II regions to the site of iPTF13bvn: Regions A, B and C. These were compared to the instantaneous SF STARBURST99 model with $Z = 0.02$ (their analogue to $Z_{\odot}$), a Salpeter (1955) IMF with a power law exponent $\alpha = 2.35$ and steps of 100,000 years. My EW values are listed in Table 3.3, along with the STARBURST99 model ages for the closest matching EW. Since they consider $Z_{\odot} = 0.02$, which is higher than current day best-estimates ($Z_{\odot} = 0.0134$; Asplund et al. 2009), we also compare to the $Z = 0.008$ models, but the difference in resulting age estimates is negligible for the purposes of this comparison. The corresponding $\tau_{\text{env}} = \log(\text{age} / \text{years})$ are $\tau_{\text{A}} = 6.80$, $\tau_{\text{B}} = 6.81$ and $\tau_{\text{C}} = 6.86$; here each τ_{env} value represents a unique age estimate from independent H II regions (refer to Figure 3.5). Errors are not stated, as the EW errors are less than the age resolution of the STARBURST99 models. All three ages fall between the photometrically derived stellar population values (τ_{P1} and τ_{P2} ; Section 3.3.1).

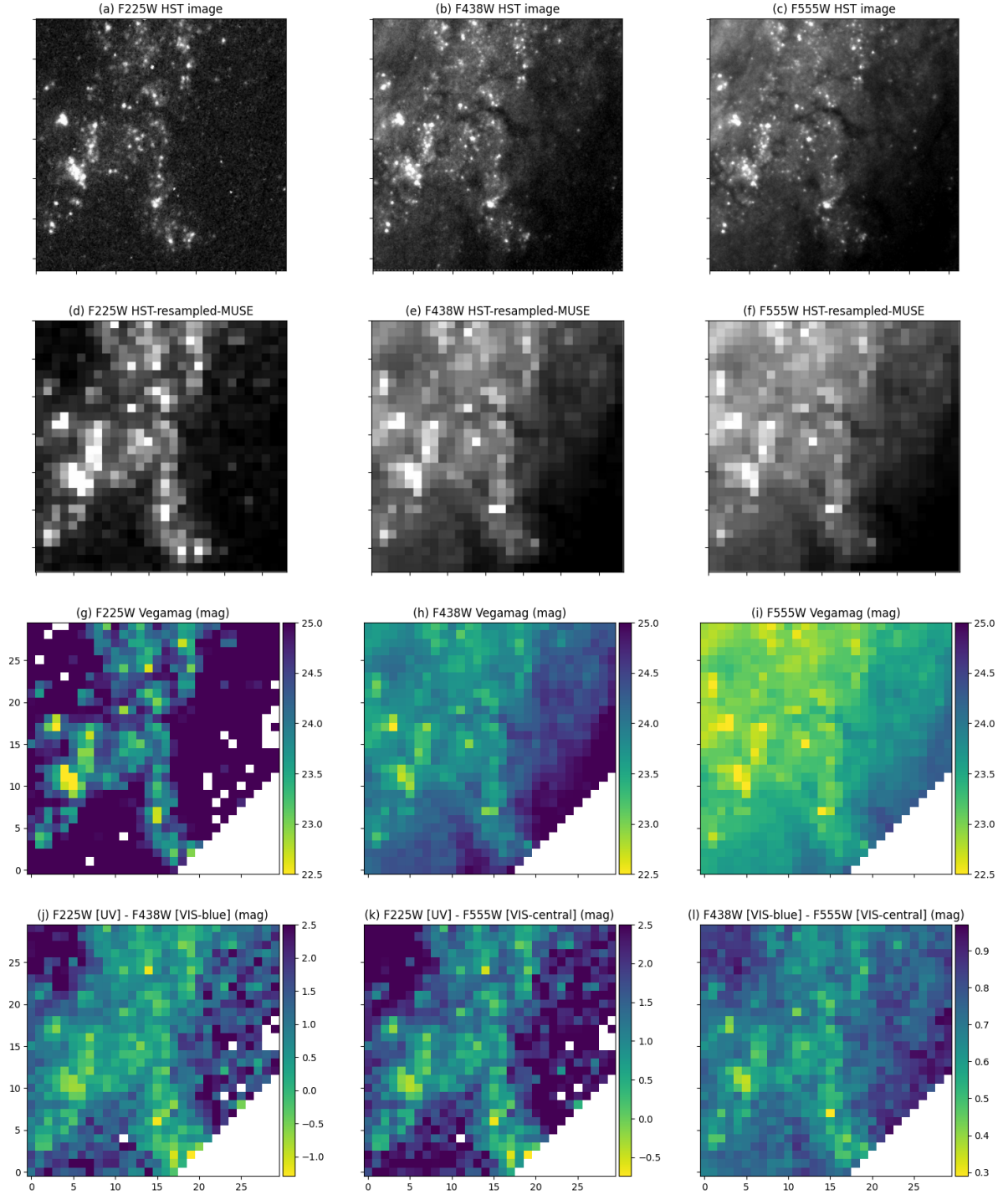


Figure 3.7: Row by row stages of transforming HST images into Vega magnitude and colour-colour maps with the same spatial sampling as our 30×30 rebinned spaxel MUSE datacube. Columns correspond to a given filter: F225W (left), F438W (central) and F555W (right). First row: HST (`_drc.fits`) images. Second row: raw spatially-resampled images. Third row: electron counts have been converted into Vega magnitudes (Section 3.2.3). Fourth row: colour-colour maps.

3.3.6 Additional Information from Resampled HST-to-MUSE Data

Given the advantageous 0.04 arcsec pixel scale of the [HST](#)/WFC3 data, we can see how resolved stars and clusters transform onto the larger (0.2 arcsec) pixel map of the [VLT/MUSE](#) datacube. Conversion of electron counts into surface brightness allows us to visualise these resampled images as magnitude and colour maps, presented in [Figure 3.7](#). The ability of my fitting functions ([Figure 3.5](#); ‘Best $H\beta$ Fitting’) to outline the galactic spiral arm is traced, almost one-to-one, by the brightest UV (F225W) sources. Despite being brightest in pixels cospatial with the brightest $H\alpha$ flux ($H\ II$ regions in [Figure 3.5](#)), the UV flux is observed across the entire spiral arm. This F225W Vega magnitude map also reconfirms the harsh edge in ionising sources close to the site of iPTF13bvn. Most of the ionising sources align centrally with bright $H\ II$ regions in the MUSE data, however some unexpectedly show an offset from the bright spectroscopic emission.

3.4 Discussion

3.4.1 Host Resolved Population (HST)

Identifying the host population of iPTF13bvn from the resolved stellar populations (P1 & P2) remains inconclusive. [Sun et al. \(2023\)](#) used the same approach to population fitting, but in the cases where more than one population was recovered the youngest population was preferentially selected, as these populations represent the greatest contributors to the UV flux at the centre of their study. Since my data extends across a larger wavelength coverage, the same assumption will not be made. The probabilities of each star belonging to either resolved stellar population in the environment of iPTF13bvn were found in an attempt to spatially distinguish the two populations. As was found by [Maund \(2018, ; see their Fig. 10\)](#) for [SN 1993J](#), I find an even blend of stars belonging to both

Table 3.4: Summary of results from past studies of iPTF13bvn.

Reference	Distance (Mpc)	Age (log(t years))	Local Extinction	Progenitor	Methods
Cao et al. (2013)	22.5	-	$E(B - V) = 0.0437$ ($A_V \approx 0.14$ mag †)	Single; Wolf-Rayet	Extinction: EW of Na I D line. Progenitor: pre-explosion detection limits, mass-loss estimate from radio data.
Bersten et al. (2014)	25.54	-	$E(B - V) = 0.17$ ($A_V \approx 0.53$ mag †)	Binary; $\sim 3.5 M_\odot$ pre-explosion low-mass helium star; initial mass $\sim 20 M_\odot$.	Extinction: comparing corrected $E(B - V)$ colours to an intrinsic colour law derived from a sample of SESNe . Progenitor: hydrodynamical modelling of lightcurve.
Eldridge et al. (2015)	22.5	-	$E(B - V) = 0.0437 - 0.17$	Binary; low-mass helium star; initial mass $\sim 10 - 20 M_\odot$.	Extinction: previous studies. Progenitor: revised photometry, SED model fitting.
Kuncarayakti et al. (2015)	-	-	-	Binary; oxygen mass $\leq 0.7 M_\odot$, initial mass $\leq 15 - 17 M_\odot$.	Progenitor: spectroscopic emission line fluxes and ratios.
Eldridge & Maund (2016)	22.5-26.8	-	$E(B - V) = 0.0437 - 0.17$	Binary; initial mass $10 - 12 M_\odot$ helium giant.	Extinction: previous studies. Progenitor: SED fitting to BPASS models.
Folatelli et al. (2016)	25.8	-	$E(B - V) = 0.17$	Binary; non-definitive.	Extinction: previous studies. Progenitor: obtained deep HST photometry in nebular phase, fit SED to models.
Maund (2018)	26.10	$\tau_1 = 6.74 \pm 0.02$ $\tau_2 = 7.38^{+0.01}_{-0.06}$	$A_V = 0.98 \pm 0.02$	Initial mass $10.5^{+1.0}_{-0.7} - 36^{+9}_{-6} M_\odot$	Extinction and Age: hierarchical Bayesian mixture model fitting.
Sun et al. (2023)	27.0	$\tau = 6.71 \pm 0.04$	$A_V = 0.78 \pm 0.13$	Initial mass $39.9^{+6.9}_{-5.2} M_\odot$	Extinction and Age: hierarchical Bayesian mixture model fitting.
This Work	22.5	$\tau_1 = 6.59^{+0.04}_{-0.05}$ $\tau_2 = 6.97^{+0.06}_{-0.06}$	$A_{V,1} = 0.95^{+0.07}_{-0.06}$ $A_{V,2} = 0.53^{+0.10}_{-0.08}$	Initial mass $20.0 - 65.4 M_\odot$	Extinction and Age: hierarchical Bayesian mixture model fitting.

† Conversion from $E(B - V)$ to A_V assumes an $R_V = 3.1$.

populations across the environment of iPTF13bvn, therefore it is *not* viable to spatially separate either population as an approach to identifying a host population. A growing consensus in binary interaction being the predominant mass-loss channel for stripped envelope **SESNe** (Smith, 2014, 2019) may advocate for the older population to be the stronger choice; binary mass exchange allows lower mass (longer lived) progenitors to successfully explode and the IMF favours lower mass progenitors.

In the case of iPTF13bvn, we are afforded the luxury of a reasonably well constrained progenitor from over a decade of studies. The results of which are condensed into Table 3.4 and can assist in constraining a host population. Maund (2018) and Sun et al. (2023) are past results that employed the same Bayesian methodology as in this chapter. A key difference is that Maund (2018) used three **HST**/ACS/WFC1 filter (F435W; F555W; F814W) images, with comparatively short exposure times and a wavelength coverage mostly contained to the visible. Sun et al. (2023) focused their study on the UV data of **SESNe** with two **HST**/WFC3/UVIS filter (F300X and F475X) images for iPTF13bvn. My wavelength range encompasses those of both studies and our images achieve deeper detection limits. Of the two stellar populations recovered by Maund (2018), the youngest most closely resembles my P1 result, particularly their estimate for the extinction ($A_V = 0.98 \pm 0.02$ mag). The single young population found by Sun et al. (2023) agrees with my P1 age estimate (within 3σ). Their extinction ($A_V = 0.78 \pm 0.13$ mag) estimate falls in-between P1 and P2, but their relatively large error means it is within 2σ of both values. This supports the need to apply two distinct stellar populations to the environment of iPTF13bvn in order to produce well constrained extinction estimates.

Excluding Maund (2018) and Sun et al. (2023), the remaining studies rely on two extinction estimates: Cao et al. (2013) $E(B - V) = 0.0437$ ($A_V \approx 0.14$ mag) and Bersten et al. (2014) $E(B - V) = 0.17$ ($A_V \approx 0.53$ mag). Furthermore, the progenitor converges on a binary system with a primary initial mass within the range of $10 - 20 M_\odot$, ending its life as a low-mass helium star. This aligns with our results for P2: $A_{V,P2} = 0.53^{+0.10}_{-0.08}$

mag; $M_{initial,P2} = 20.0 M_{\odot}$ (zero-age main sequence); $M_{final,P2} = 17.8 M_{\odot}$ (post advanced evolutionary stages; Section 3.3.1). Maund (2018) finds an older population with $\tau = 7.38^{+0.01}_{-0.06}$, which does not agree with our P2 result. Although their corresponding progenitor mass estimate ($10^{+1.0}_{-0.7} M_{\odot}$) still falls within the $10 - 20 M_{\odot}$ predicted mass for iPTF13bvn. It is worth noting that the PARSEC stellar evolution tracks are computed for single stars. Although the final mass estimates incorporate mass-loss throughout the main sequence and final evolutionary stages, mass lost to binary interaction is neglected. Including binary stripping of the primary star would result in a much lower final mass, as is concluded by Bersten et al. (2014) through hydrodynamical modeling of the lightcurve of iPTF13bvn (best fit by a $\approx 3.5 M_{\odot}$ helium star). My P2 extinction also agrees with the Bersten et al. (2014) value, which they estimated by comparing their $(B - V)$ colours (corrected for Galactic extinction) to an intrinsic colour law derived from a sample of SESNe observed by the Carnegie Supernova Project. Overall, the results of this chapter are able to reproduce the populations found by Maund (2018) and Sun et al. (2023), as well as a new population that agrees with the progenitor constraints for iPTF13bvn from the remaining studies in Table 3.4. Despite this implying that P2 should be considered the host population for iPTF13bvn, there is still no independent check for future applications to other CCSNe environments.

Plotting a CMD of the objects and isochrones corresponding to the resolved populations in the environment of iPTF13bvn, shown in Figure 3.4, allows us to see which stars contribute to each fitting. This can highlight the strength of each population fitting. For P2 in plots (b) and (c) of Figure 3.4, only a handful of data points with complete photometry (in all filters) constrain this older population in the region where the isochrones part. The majority of sources that assist the fitting here are detection limit substitutions. It makes sense that the older (cooler) stars appearing in the F555W and F438W images are missing from F225W, but it must be acknowledged that they are weaker probes of this portion of the CMD. It also follows that Sun et al. (2023) does not

find an older population when solely using UV images. Besides the differences in our studies discussed above, Maund (2018) also found detection limits for individual stars to account for variations in background and crowding. This difference in method should not massively impact how our older populations are fit, instead the main driving force behind the difference in our age estimates is likely the choice of HST images and distance estimates to the host galaxy NGC 5806. Since these cooler stars always lie close to or below detection limits, the choice of band-width, central wavelength, throughput and image depth (exposure time) all greatly impact how many of these objects are detected. In this sense, our Bayesian approach is more sensitive to fitting younger populations compared to older.

Eldridge et al. (2015) found apparent magnitudes of the detected iPTF13bvn progenitor candidate in HST/ACS/WFC F435W and HST/WFC3 F555W filters (VEGAMAG system; using DOLPHOT): $m_{F435W} = 25.81 \pm 0.06$ mag and $m_{F555W} = 25.86 \pm 0.08$ mag. Considerable overlap between the F435W (WFC) and F438W (WFC3) band-widths and throughputs allow us to substitute the former for the latter; both magnitudes are included in plot (a) of Figure 3.4. Reassuringly, it falls upon the space occupied by the brightest stars within the field, but overlaps with the isochrones of both P1 and P2.

3.4.2 Sources of Variation in Extinction (MUSE)

Systematic Uncertainties

When interpreting the extinctions produced through my analysis of the MUSE IFU spectroscopy data, it is important to consider the sources of uncertainty and any assumptions. Systematic uncertainties include:

1. distance to NGC 5806;
2. inclination;

3. metallicity;
4. spectral resolution;
5. integrated flux of emission lines;
6. temperature dependence of extinction;
7. and choice of R_V .

As introduced in Section 2.4, the ionised gas temperature is not assumed to be a singular value across the spiral arm of NGC 5806. Instead, I consider the full [Osterbrock & Ferland \(2006\)](#) range spanning $T = 2500 - 20000$ K. Different extinctions may be found when studying the stars in the environment compared to the ionised gas, as both can act as probes at varying depths through the galactic plane. In this sense, agreement or disagreement between values found with these independent probes can inform the 3D structure along our [line of sight \(LoS\)](#). Inclination also affects the angle of incidence between our [LoS](#) and the galactic plane, increasing the cylindrical volume of the galaxy that we observe along any [LoS](#) with decreasing inclination. This effect is more dramatic for galaxies approaching edge-on. In the case of NGC 5806, its inclination of $i = 60.4$ deg negates this effect from having a dramatic impact. All quoted distances within NGC 5806 stated in this paper are projected distances, not corrected for inclination. My choice of a 22.5 Mpc distance to NGC 5806 has negligible effect on the spectroscopic analysis, as the induced wavelength shift from varying this distance value is minuscule. Distance estimates to NGC 5806 reported on NED extend to 27.4 Mpc, the effects of which are explored by [Eldridge & Maund \(2016\)](#). To summarise, increasing the distance to NGC 5806 would have the greatest impact on my resolved stellar population analysis in Section 3.3.1. Increasing this distance would increase the absolute magnitudes of individual stars and the progenitor mass estimate (decrease the stellar population age). This increase in progenitor mass would be small, nevertheless it suggests my $20.0 M_{\odot}$ estimate should be

treated as a lower limit. Uncertainty in the integrated flux of emission lines produced by my fitting algorithm are minimised by the various methods described in Section 2.4 to discourage overfitting any spectra. Where it is necessary (mainly in the low SNR regime) I account for stellar absorption in order to better approximate the emission flux. In the rare case that the fitting algorithm catastrophically fails, mainly when attempting to fit the lowest flux emission, I can identify them through their unphysical error estimates and reject the data accordingly. The main limitation of my derived fluxes stems from the resolution of the MUSE spectra.

Temperature Dependence of Extinction Law

Intuitively, we should expect there to be variation in gas temperature when considering the $\sim 1.7 \text{ kpc}^2$ surface area of NGC 5806 in my extracted MUSE datacube (Figure 3.5). The ionised gas electron temperature can be estimated with the $[\text{O I}] (\lambda 6300 + \lambda 6363)/\lambda 5577$ or $[\text{N II}](\lambda 6548 + \lambda 6584)/\lambda 5755$ ratios. Unfortunately, neither the $[\text{O I}] \lambda 5577$ nor the $[\text{N II}] \lambda 5755$ lines are detected in the single spaxel or summed spectra of iPTF13bvn; indicative of low temperatures. My environmental and single-spaxel extinction estimates for iPTF13bvn approach the resolved stellar population values with decreasing gas temperature. Even when a 2500-5000 K temperature range is assumed, these values still significantly differ within their respective errors and the greatest discrepancy corresponds to the single-spaxel of iPTF13bvn. Although there are various interpretations (above) of where this disagreement between estimates for the extinction derived from the ionised gas and resolved stellar populations originates, the factor of ~ 3 jump in A_V between the single-spaxel (IFU; gaseous) and P2 (photometric; stellar) extinctions is significant. Evidence in support of a lower ($< 6000 \text{ K}$) temperature environment includes: the lack of bright H II regions within an $\sim 400 \text{ pc}$ radius of the SN site; limited emission lines in the MUSE spectra (e.g. $[\text{O I}] \lambda 5577$ and $[\text{N II}] \lambda 5755$ are not detected); low flux levels in spectra; relatively low number of bright ionising stars; lack

of large stellar clusters or star forming complexes; and a dark dust lane intersecting the environment. This could direct us away from measured (Peimbert, 1967; Dennefeld & Kunth, 1981; Caswell & Haynes, 1987) or assumed (Galbany et al., 2016) typical values of $T_e \gtrsim 6000$ K for Galactic and extragalactic H II regions. Further complicating this case is a lack of constraint over the electron density (n_e) of the ionised gas. Madsen et al. (2006) and McClymont et al. (2024) find higher T_e with decreasing n_e for diffuse ionised gas in the ISM of spiral galaxies.

Interpreting the 3D Structure and iPTF13bvn’s Extinction

Sun et al. (2021) gave an indepth interpretation of the environments of SNe 2004dg and 2012P, which also show a factor of $\sim 2 - 3$ increase when looking at the ionised gas extinctions compared to the mean stellar population extinctions. Their schematic diagram attributes this to stellar groups with lower (higher) mean population extinctions being situated in the foreground (background) relative to the observer. Moreover, the highest extinctions that are observed in the ionised gas would place these gaseous structures behind any resolved stellar populations. Sun et al. (2021) also acknowledged that this distance interpretation can only be applied to mean population extinctions, but not on the scale of single stars where this interpretation breaks down and local variation is observed in the ISM. When finding the mean population extinctions within my Bayesian approach, I account for this local variation by fitting for the dispersion hyperparameter (δA_V ; see Section 3.3.1). Transforming these back to a linear scale ($\sigma_{A_{V,k}} = 0.05 \times 10^{\delta A_{V,k}}$), we find $\sigma_{A_{V,1}} = 0.35 \pm 0.04$ mag and $\sigma_{A_{V,2}} = 0.10^{+0.06}_{-0.04}$ mag. These results imply increased dispersion about the mean population extinctions for P1 compared to P2, perhaps as a result of seeing P1 through P2.

SNe 2004dg and 2012P (Sun et al., 2021) also occurred in NGC 5806, but in the denser central region of another spiral arm and either within (2012P) or nearby (~ 200 pc; 2004dg) a bright star-forming complex. Within this complex, the ongoing star formation

and young stellar populations clear (in the direction of the observer) a ‘bubble’ in the gas that accumulates in the traversing density wave of the spiral arm. The ionised gas observed in the background is compressed and potentially triggers further star formation.

Within the context of the environment of iPTF13bvn, the same interpretation can be applied. P2 ($A_V = 0.53$ mag) would sit in the foreground (along our LoS), followed by P1 ($A_V = 0.95$ mag) and then a background source of ionised gas. Yet, unlike SNe 2004dg and 2012P, iPTF13bvn is situated on the edge of the spiral arm. Given that region D and “13bvn-inner” share similarly positioned environments, them having $\sigma_{\bar{A}_V}$ values 2 - 4 times that of the remaining comparison environments could suggest increased variations in extinction. This could be increased variation in extinction from local (foreground) sources, background sources or a combination of both; the source of increased variation could originate from a loss of a smoothly-varying ionised gas background, replaced by clumpy gas and dust formations. Given that we see a sharp drop-off due to a dust lane in Figure 3.7 (in particular, the F225W images), the background source of compressed photo-ionised gas proposed by Sun et al. (2021) seems like a less likely scenario on the edge of a spiral arm (iPTF13bvn).

Looking to the single spaxel of iPTF13bvn, regardless of constraints over the gas temperature, we only see disagreement between the MUSE vs. HST derived extinctions. With the arguments laid out above, any contribution from local variations to the single spaxel extinction of iPTF13bvn could imply a significantly higher extinction than the value we previously assigned (P2; $A_V = 0.53$ mag). Although this is not definitive, it does still suggest that smoothed population parameters (such as extinction) are potentially underestimating the true values for individual stars and misrepresent the implied progenitor properties. Furthermore, the comparatively higher levels of dispersion ($\sigma_{\bar{A}_V}$) about the weighted mean extinction (seen for both ‘13bvn_inner’ and Region D) suggests certain environments (i.e. the edges of spiral arms) are poor environments to assume smooth singular values for population parameters.

Association with nearby H II Regions?

As presented by Crowther (2013), Type II SNe are more weakly associated with H II regions than Type Ib/c. This has been interpreted as typical Type Ib/c progenitors being higher in mass than Type II, but there are past examples of both showing no association to any nearby H II regions. For iPTF13bvn, my study finds no strong association between the SN site and nearby H II regions (Table 3.3 and Figure 3.5), which further justifies the choice of P2 being its natal stellar population. Since I still have no diagnostic for choosing a natal population when more than one is resolved in a given SN environment, future studies may want to use H II region association as the indicator (i.e. choosing the oldest population when no association is found). Finally, the lack of association between iPTF13bvn and any bright H II region highlights the danger of the ‘nearest H II region’ approach used in past environmental studies. In this case, using the age estimates of the nearest H II regions would lead to an overestimation of the progenitor mass.

Following the scenarios for SNe association with H II regions by Crowther (2013) (Section 2.3), iPTF13bvn would fall under Class 2 or 3. As required by Class 2, iPTF13bvn is *not* coincident with a detectable star cluster and a H II region is *absent*, favouring an older birth cluster and therefore lower mass progenitor ($< 20 M_{\odot}$). We cannot rule out the scenario of a dynamically ejected progenitor (Class 3), given a minimum distance of ~ 400 pc from the nearest H II region to the site of iPTF13bvn. For a typical ejected velocity of 50 km s^{-1} , the progenitor would require a lifetime $\gtrsim 8$ Myr and corresponding initial mass $\lesssim 23 M_{\odot}$ to traverse this distance. Both ‘cases’ again align with my P2 result for iPTF13bvn. In active SF galaxies like NGC 5806, H α emission and UV trace SF one-to-one (Salim et al., 2007). It then follows that observing bright UV emission across the site of iPTF13bvn (and broader spiral arm; Section 3.3.6), but a lack of H II region association, indicates lower levels of older (< 100 Myr) continuous SF, more aligned with the explosion of a lower mass progenitor.

Probing stellar population ages using the instantaneous starburst model (Section 3.3.5) for the H II regions surrounding iPTF13bvn creates viable estimates for *their* individual stellar populations. By retaining high spatial resolution in the MUSE data, I have shown that iPTF13bvn cannot be conclusively linked to any of these H II regions and presuming association to the nearest bright H II region would miss the two unique stellar populations presented in Section 3.3.1. If the case of the environment of iPTF13bvn were to repeat in the sites of other CCSNe, then studies that apply ‘nearest H II region’ (van Dyk, 1992; Bartunov et al., 1994; van Dyk et al., 1996), Voronoi tessellation (Lyman et al., 2018; Sun et al., 2022a) or NCR pixel statistics (Ransome et al., 2022; Kuncarayakti et al., 2018; Anderson & James, 2008) approaches may swallow-up this spatial information into single pixels or apertures in an attempt to improve the data quality when deriving natal population properties. Although improving the data quality (i.e. spectral SNR) this way is good practice, it can remove finer details that would otherwise reveal a more complex environment at the sites of CCSNe capable of assisting in breaking the degeneracy when high and low mass population progenitors are simultaneously observed.

3.4.3 Context within other Type Ib Supernovae

Well observed and studied Type Ib supernovae are still rare objects, slowing our investigation into the differences between SESNe and Type II SNe. A question at the forefront of SESNe research is the fractional contribution of single star vs. binary system progenitors. An investigation by Yoon et al. (2012) suggests that progenitor bolometric luminosities do not provide enough information to probe the single-binary partition. The limited number of highly studied Type Ib SNe are inclined towards binary interaction as the mass-loss mechanism, compared to the strong-winds single massive star model.

SN 2019yvr (Sun et al., 2022a), SNe 2016bau and 2015ap (Aryan et al., 2021) and SN 2014C (Sun et al., 2020) all have identified or suspected lower mass ($M_{\text{ZAMS}} \lesssim 30 M_{\odot}$)

binary progenitors. An environmental analysis of SN 2019yvr by Sun et al. (2022a) found three separated episodes of star formation within an active star-forming region. As I find for iPTF13bvn, SN 2019yvr is spatially offset from the stellar surface density and gaseous nebular emission. A low ejecta mass suggests SN 2019yvr belongs to their oldest stellar population, corresponding to a progenitor initial mass of $10.4^{+1.5}_{-1.3} M_{\odot}$. Aryan et al. (2021) find that both SN 2016bau and 2015ap are best fit by a $12 M_{\odot}$ model, too low to be explained by single star evolution. Through SED fitting, Sun et al. (2020) find a cluster age of $20.0^{+3.5}_{-2.6}$ Myr for SN 2014C, and binary stellar evolution models estimate a progenitor mass of $\sim 11 M_{\odot}$. SN 2014C was, however, a peculiar case having transitioned from a Type Ib to IIn classification. Alternatively, Schweyer et al. (2025) recently studied the progenitor of SN 2019odp. Pseudo-bolometric light curve modeling found an ejecta mass of $M_{\text{ej}} \sim 4 - 7 M_{\odot}$ and nebular spectroscopy modelling found an oxygen mass $> 0.5 M_{\odot}$, implying a pre-explosion mass $> 18 M_{\odot}$ that best resembles a single massive star, likely a Wolf-Rayet progenitor. My progenitor mass estimate for iPTF13bvn ($M_{\text{initial}, P2} = 20.0 M_{\odot}$) substantiates its binary classification and amplifies the case that the majority of local Type Ib SNe are stripped through binary interaction. Although a $20.0 M_{\odot}$ single star is potentially explodable (Sukhbold & Adams, 2020), it would lack sufficient mass-loss (via strong-winds) across its lifetime to result in a Type Ib SN. Beasor et al. (2021) find that single stars with initial masses $< 30 M_{\odot}$ will *not* explode as H-poor SNe, which validates why iPTF13bvn was not observed as a Type IIn or transitional Ibn SN.

Extinctions for Type Ib SNe progenitors encompass a broad range of values that go beyond our relatively high value ($A_{V, P1} = 0.95^{+0.07}_{-0.06}$ mag) for the youngest stellar population that we resolve in the environment of iPTF13bvn. Aryan et al. (2021) found a relatively high extinction of $E(B - V)_{\text{host}} = 0.566 \pm 0.046$ for SN 2015ap, and similarly Kilpatrick et al. (2021) find $E(B - V) = 0.51^{+0.27}_{-0.16}$ for the site of SN 2019yvr, suggesting my P1 value is *not* extreme for Type Ib SNe.

3.5 Conclusions

In this chapter I have examined the environment of the Type Ib SN iPTF13bvn with archival photometric (HST/WFC3) and IFU spectroscopic (VLT/MUSE) data. Using a Bayesian approach to fitting stellar populations to all detected stars within 300 pc of iPTF13bvn produced updated estimates of the SN progenitor age, mass and extinction. Although two unique stellar populations were found, I find the greatest agreement between past progenitor constraints for iPTF13bvn and the oldest resolved stellar population: age $\sim 9.33^{+1.38}_{-1.20}$ million years, a corresponding initial mass $M_{initial,P2} = 20.0 M_{\odot}$, and extinction $A_{V,P2} = 0.53^{+0.10}_{-0.08}$ mag. Spectroscopically examining the same environment and beyond, a minimum factor of ~ 2.5 increase in extinctions derived from the ionised gas was found, potentially higher depending on the environmental temperature. Various signatures (lack of nebular lines, sparse population of massive stars, no associated bright H II region), however, point towards a lower temperature (≤ 6000 K) ionised environment. Comparing extinction results between individual MUSE-IFU spaxel distributions and the summed spectrum of spaxels within a given aperture, I find evidence for increased variability in extinction in the environment of iPTF13bvn, compared to the central, smoothly-varying regions of the extragalactic spiral arm. The same variability is found in an equivalent comparison environment, with both environments falling on the edge of the spiral arm of the host galaxy NGC 5806. Although this result cannot be definitively interpreted, it suggests that previously used assumptions in the environmental analysis of CCSNe (i.e. Voronoi tessellation in low signal-to-noise environments, using single stellar population properties to constrain progenitors) may fail in environments like iPTF13bvn's and any similar. Future work expanding this investigation to a catalogue of nearby CCSNe with high-quality photometric and IFU spectroscopic data will reveal if these findings for iPTF13bvn are replicated in other SN sites and if they are connected to their environmental properties, SN classification or stand alone. This

motivates the refinement of my environmental analysis to be applied to a catalogue of local CCSNe in Chapter 4.

Chapter 4

A Catalogue of Local Core-Collapse Supernovae Environments

4.1 Introduction

In Chapter 3, I presented my initial investigation into the environment of iPTF13bvn and explored the potential of combining a photometric and IFU spectroscopic analysis of the surrounding stars and ionised gas. I showed that, under a Bayesian framework, resolved local stellar populations are capable of producing updated progenitor mass and extinction estimates that agree with past studies. Additional examination of the ionised gas can provide further environmental context: the presence of H II regions, metallicity estimates, perception of the LoS depth through extinctions, environmental features (gas/dust lanes, DIG, voids). Identifying H II regions can also provide alternative methods for estimating stellar population ages. Streamlining and expanding my environmental analysis to a catalogue of local CCSNe provides the opportunity to probe any correlations between environmental properties and SNe classifications. Past works in this field (Sun et al., 2023; Maund, 2018, 2017) have applied the same approach of photometrically resolving stellar populations for a catalogue of SNe, but the inclusion

of recently discovered transients and an updated [HST](#) data archive expands upon these results.

Progressively more massive progenitors for [SNe](#) classifications, Type II $\rightarrow$ IIb $\rightarrow$ Ib $\rightarrow$ Ic, has been proposed and supported for some time ([Anderson et al., 2012](#); [Kuncarayakti et al., 2018](#); [Maund, 2018](#)). Recent studies ([Sun et al., 2023](#)), however, have challenged this, finding similar progenitor masses for all subtypes besides Type Ic (II=IIb=Ib<Ic). A growing appreciation for the impact of binary progenitor systems ([Solar et al., 2024](#); [Smith, 2014](#)) may explain this diversification in progenitor channels. Alternative indirect methods for investigating [CCSNe](#) progenitors include tracing H α line emission ([Anderson & James, 2008](#)) and association to nearby H II regions ([Kuncarayakti et al., 2018](#); [Mayker Chen et al., 2024](#)). With this in mind, a goal of this chapter is to apply multiple indirect methods of constraining progenitor properties across a substantial local catalogue of [CCSNe](#), as they have yet to be tested and compared under one study.

The outline of this chapter is as follows: I describe the compilation of the catalogue in Section 4.2; details of the data processing and streamlining of the analysis pipeline are provided in Section 4.3; holistic catalogue results are presented and discussed in Sections 4.4, 4.5, 4.7 and 4.8; breakdowns of individual [SNe](#) results comprise Section 4.9. Finally, I provide brief concluding remarks and future directions of studies in Section 4.10.

4.2 Building the Catalogue

The creation of a local catalogue of [CCSNe](#) began with the full Transient Name Server (TNS) database. As of January 2025, a search for classified supernovae with redshifts $z < 0.01$ yields 173 targets. Since the TNS database is partially incomplete, this total was expanded through literature searches containing supernovae catalogues aimed at [HST](#) or [MUSE](#). After cross-matching with the ESO Archive Science Portal (EASP) and the Mikulski Archive for Space Telescopes (MAST), 56 targets survived filtering for both

[HST](#) and [MUSE](#) datasets. Distances (Mpc), distance moduli and Milky Way extinctions (V-band) were compiled from the NASA/IPAC Extragalactic Database (NED). Distance estimates on the NED often comprise a list of studies dating back decades with several methods, and a wide spread of distances can be associated with a single target host galaxy. To combat this, modern estimates were favoured and methods of estimating a distance were prioritised in the following order:

1. Cepheid variable star period-luminosity relation,
2. Tully-Fisher relation,
3. Type II Supernovae optical modelling.

In certain cases, a single method can provide a large range of distance estimates for a given host galaxy. Here, a value that falls in the middle of this range was taken as my chosen value. Specifically the closest match to

$$\frac{D_{\max} + D_{\min}}{2}, \quad (4.1)$$

with a maximum ($D_{\max}$) and minimum ($D_{\min}$) range of available distances. For example, [SN 2009hd](#) in NGC 3627 has a Cepheid distance estimate range of 8.73 - 15.60 Mpc. The most up-to-date (2008) value of 12.60 Mpc was the most favourable choice.

The RA and Dec of each [SN](#) site from TNS were carried forward and compared to values quoted on Hyperleda. If the RA and Dec on Hyperleda provided a higher degree of accuracy, these values replaced the originals from TNS. Advanced localisation of the [SN](#) coordinates with images of residual [SN](#) light and surrounding common stars, as performed on iPTF13bvn, was not applied to the catalogue. High quality images of the [SN](#) detections were not available consistently across the catalogue. Moreover, the improvement found for iPTF13bvn, with this approach, was negligible with respect to the extracted environment sizes (150 pc, 300 pc, 1 kpc). Host galaxy inclinations (i)

were sourced from Hyperleda. Although $i < 60$ degrees is desirable, it was not used as a selection criteria to prevent further shrinking the catalogue and to intentionally compare the effect inclination has on the analysis. An inclination of $i > 60$ degrees introduces a higher chance of observing a mixture of unassociated sources, as the LoS becomes more aligned with the galactic plane as i approaches 90 degrees.

Further removal of targets from the remaining catalogue of 56 were the result of unique circumstances: poor data quality, falling outside the FoV, no available redshift estimates, no available distance estimates. Targets not falling directly on a given dataset is owed to the imperfect overlap between the FoV of the various telescope instruments and the 3 arcminute search radius used on the MAST and EASP. The site of SN 2013ej falls just outside the nearest MUSE datacube. SN 2014cw has no distance estimate to its low-luminosity host galaxy PGC 68414; a redshift of $z = 0.00915$ puts it as far out as 40 Mpc and at the limit of my desired spatial resolution. Similarly, SN 2000P and SN 2006be occurred in NGC 4965 and IC 4582 at distances of 47.8 Mpc and 37.3 Mpc respectively, beyond the desired distance for my analysis. Some SNe without recorded redshifts slipped through the TNS database filtering such as SN 2016bsb, whose host SDSS J113427.87+114153.7 has no reported redshift or distance. The final case of removal for this line of reasoning was ASASSN15bd, with no reported distance estimate to its host galaxy SDSS J155438.39+163637.6. This brings the final catalogue total to 50 SNe sites. The compiled specifications of each object are detailed in Table 4.1, retrieved HST datasets are listed in Table 4.2 and the fractions of SN classifications are displayed in Figure 4.1.

Table 4.1: Specifications of catalogue targets. Subtype classifications and host galaxies are pulled directly from the Transient Name Server. Distance estimates (D), distance moduli (μ), redshifts (z) and Galactic extinctions A_V^{MW} were sourced from the NASA/IPAC Extragalactic Database. Host galaxy inclinations were sourced from the HyperLeda database.

Target	Type	Host	Distance D (Mpc)	μ	Redshift z	Inclination i (deg)	Galactic Extinction A_V^{MW} (mags)
2023abdg	II	NGC 7421	27.8	32.22	0.005979	36.2	0.039
2023ijd	II	NGC 4568	17.3	31.19	0.007446	67.5	0.089
2022wsp	II	NGC 7448	26.1	32.08	0.007318	70.1	0.154
2022acko	II	NGC 1300	14.5	30.81	0.005264	61.8	0.083
2022aau	II	NGC 1672	12.5	30.49	0.00444	28.9	0.064
2020jfo	II	NGC 4303	14.5	30.81	0.005224	18.1	0.061
2018pq	II	IC 3896A	28.4	32.26	0.007111	48.4	0.578
2018ivc	II	NGC 1068	10.1	30.02	0.00379	90.0	0.091
AT2018bbl	II	NGC 7421	27.8	32.22	0.005979	36.2	0.039
2017ivv	II	GALEXASC J202849.46- 042255.	24.09	31.91	0.0056	–	0.155
2017ivu	IIP	NGC 5962	33.3	32.61	0.006531	51.4	0.149
2017bzb	II	NGC 7424	11.5	30.3	0.0031	59.0	0.029
2017aym	IIP	NGC 5690	18.5	31.33	0.005844	75.9	0.106
2016hgm	II	NGC 493	22.8	31.79	0.007815	74.6	0.089
2016cok	IIP	NGC 3627 (M66)	12.6	30.5	0.002408	67.5	0.093
2016bmi	IIP	IC4721	19.9	31.49	0.007455	75.3	0.211
ASASSN-16at	IIP	UGC 8041	15.2	30.91	0.004416	54.0	0.061
2016afa	II	NGC 5962	33.3	32.61	0.006531	51.4	0.149
ASASSN-15oz	II	HIPASS J1919-33	28.83	32.3	0.006931	–	0.253
ASASSN-14ha	II	NGC 1566	17.9	31.27	0.005017	49.1	0.025
2012ec	IIP	NGC 1084	18.7	31.36	0.004707	49.9	0.073
2009hd	II	NGC 3627 (M66)	12.6	30.5	0.002408	67.5	0.093
2009H	II	NGC 1084	18.7	31.36	0.004707	49.9	0.073

Target	Type	Host	Distance D (Mpc)	μ	Redshift z	Inclination i (deg)	Galactic Extinction A_V^{MW} (mags)
2004dg	IIP	NGC 5806	27.4	32.19	0.004493	60.4	0.139
1999br	IIP	NGC 4900	20.8	32.11	0.003212	19.0	0.065
1998dl	II	NGC 1084	18.7	31.36	0.004707	49.9	0.073
1996an	II	NGC 1084	18.7	31.36	0.004707	49.9	0.073
1986l	IIP	NGC 4254 (M99)	14.4	30.82	0.008026	20.1	0.106
1973R	IIP	NGC 3627 (M66)	12.6	30.5	0.002408	67.5	0.09
1967H	II	NGC 4254 (M99)	14.4	30.82	0.008026	20.1	0.106
2020fqv	IIB	NGC 4568	17.3	31.18	0.007446	67.5	0.089
2016gk _g	IIB	NGC 613	26.4	32.11	0.00494	35.7	0.053
2012P	IIB	NGC 5806	27.4	32.19	0.004493	60.4	0.139
2009dq	IIB	IC 2554	28.3	32.26	0.004659	70.8	0.562
2022frl	Ib-pec	MCG -01-39-003	28.4	32.26	0.00643	90.0	0.269
2020hvp	Ib	NGC 6118	20.8	31.59	0.005247	68.7	0.433
2019yvr	Ib	NGC 4666	14.7	30.83	0.005047	69.6	0.068
2019ehk	Ib	NGC 4321 (M100)	17.2	31.18	0.00524	24.0	0.072
2015dj	Ib	NGC 7371	31.2	32.47	0.008966	25.0	0.169
iPTF13bvn	Ib	NGC 5806	27.4	32.19	0.004493	60.4	0.139
2012au	Ib	NGC 4790	23.7	31.87	0.004483	58.8	0.132
2004dk	Ib	NGC 6118	20.8	31.59	0.005247	68.7	0.432
2017gax	Ib/c	NGC 1672	12.5	30.81	0.00444	28.9	0.064
2020oi	Ic	NGC 4321 (M100)	17.2	31.18	0.00524	24.0	0.072
2019yz	Ic	UGC 09977	27.3	32.18	0.006388	90.0	0.312
2016iae	Ic	NGC 1532	17.3	31.19	0.003468	83.0	0.042
2016coi	Ic-BL	UGC 11868	17.2	31.18	0.003646	25.5	0.233

Target	Type	Host	Distance D (Mpc)	μ	Redshift z	Inclination i (deg)	Galactic Extinction A_V^{MW} (mags)
2014L	Ic	NGC 4254 (M99)	14.4	30.82	0.008026	20.1	0.106
2013dk	Ic	NGC 4038	18.1	31.29	0.005417	51.9	0.127
2004cc	Ic?	NGC 4568	17.3	31.19	0.007446	67.5	0.089

Table 4.2: List of Hubble Space Telescope instrument images downloaded for each catalogue object from the Mikulski Archive for Space Telescopes: <https://archive.stsci.edu/missions-and-data/hst>.

Target	Date	Exp Time (s)	Instrument	Filter	Program
2023abdg	2021 Oct 8	780	ACS/WFC	F606W	15446 ¹
2023ijd	2022 Mar 6	710	WFC3/UVIS	F606W	16691 ¹²
	2022 Mar 6	780	WFC3/UVIS	F814W	16691 ¹²
2022acko	2020 Jan 4	2324	WFC3/UVIS	F275W	15654 ²
	2020 Jan 4	2284	WFC3/UVIS	F336W	15654 ²
	2024 Aug 27	1054	WFC3/UVIS	F555W	17506 ³
2022wsp	2023 Oct 9	1650	WFC3/UVIS2	F275W	17179 ⁴
2022frl	2022 Sep 16	1650	WFC3/UVIS2	F275W	16741 ⁴
2022aau	2019 Jun 25	2877	WFC3/UVIS	F275W	15654 ²
	2019 Jun 25	2480	WFC3/UVIS	F336W	15654 ²
	2019 Jun 26	1500	WFC3/UVIS	F555W	15654 ²
2020jfo	2020 Mar 29	1110	WFC3/UVIS	F336W	15654 ²
	2023 Jun 29	2364	WFC3/UVIS	F555W	17165 ⁵
	2023 Apr 19	2356	WFC3/UVIS	F814W	17165 ⁵
2020hvp	2021 May 22	710	WFC3/UVIS	F555W	16179 ⁹
	2021 May 22	780	WFC3/UVIS	F814W	16179 ⁹
2020fqv	2022 Mar 6	710	WFC3/UVIS	F606W	16691 ¹²
	2022 Mar 6	780	WFC3/UVIS	F814W	16691 ¹²
2020oi	2020 Mar 15	1110	WFC3/UVIS	F336W	15654 ²
	2020 Mar 15	1050	WFC3/UVIS	F438W	15654 ²
	2020 Mar 15	836	WFC3/UVIS	F814W	15654 ²
2019yvr	2017 Apr 21	1140	WFC3/UVIS2	F438W	14611 ¹¹
	2017 Apr 21	1200	WFC3/UVIS2	F555W	14611 ¹¹
	2017 Apr 21	1152	WFC3/UVIS2	F814W	14611 ¹¹
2019ehk	2020 May 21	1500	WFC3/UVIS	F555W	16075 ³
	2022 May 5	868	WFC3/UVIS2	F814W	16500 ³
2019yz	2024 Aor 24	1200	WFC3/UVIS2	F275W	16657 ²²
2018ivc	2024 Sep 16	1000	WFC3/UVIS	F336W	17502 ⁶
	2024 Feb 23	2364	WFC3/UVIS	F555W	17165 ⁵
	2024 Feb 17	2356	WFC3/UVIS	F814W	17165 ⁵
AT2018bbl	2021 Oct 8	780	ACS/WFC	F606W	15446 ¹
2018pq	2022 Aug 20	1650	WFC3/UVIS	F275W	16287 ⁷
2017ivv	2021 May 16	1500	WFC3/UVIS	F275W	16287 ⁷
2017ivu	2021 May 30	1500	WFC3/UVIS2	F275W	16287 ⁷

Target	Date	Exp Time (s)	Instrument	Filter	Program
2017gax	2023 Jun 6	4201	WFC3/UVIS2	F336W	17203 ¹⁰
	2020 Nov 22	2614	WFC3/UVIS2	F555W	16165 ¹⁰
	2020 Nov 27	780	WFC3/UVIS	F814W	16179 ⁹
2017bzb	2022 Oct 26	760	WFC3/UVIS	F555W	17070 ⁸
	2022 Oct 26	780	WFC3/UVIS	F814W	17070 ⁸
2017aym	2022 Mar 3	1800	WFC3/UVIS	F275W	16287 ⁷
2016iae	2019 Sep 8	710	WFC3/UVIS	F555W	15166 ⁹
	2019 Sep 8	780	WFC3/UVIS	F814W	15166 ⁹
2016hgm	2020 Oct 5	1500	WFC3/UVIS	F275W	16287 ⁷
2016gkg	2021 May 14	1500	WFC3/UVIS2	F275W	16287 ⁷
	2021 Aug 19	710	WFC3/UVIS	F438W	16179 ⁹
	2021 Aug 19	780	WFC3/UVIS	F606W	16179 ⁹
2016cok	2019 Nov 11	1110	WFC3/UVIS	F336W	15654 ²
	2013 Nov 28	1119	WFC3/UVIS1	F555W	13477 ¹³
	2013 Nov 28	1119	WFC3/UVIS1	F814W	13477 ¹³
2016coi	2023 Jul 28	4047	WFC3/UVIS2	F336W	17203 ¹⁰
	2020 Oct 13	2381	WFC3/UVIS2	F555W	16165 ¹⁰
	2020 Dec 6	780	WFC3/UVIS	F814W	16179 ⁹
2016bmi	2020 Oct 17	1500	WFC3/UVIS	F275W	16287 ⁷
2016afa	2021 May 30	1500	WFC3/UVIS	F275W	16287 ⁷
ASASSN-16at	2021 Apr 6	1800	WFC3/UVIS	F275W	16287 ⁷
2015dj	2019 May 31	710	WFC3/UVIS	F555W	15166 ⁹
	2019 May 31	780	WFC3/UVIS	F814W	15166 ⁹
ASASSN-15oz	2021 May 22	1650	WFC3/UVIS2	F275W	16287 ⁷
ASASSN-14ha	2013 Sep 3	1119	WFC3/UVIS	F336W	13364 ¹⁶
	2024 Aug 12	3928	WFC3/UVIS2	F438W	17429 ¹⁷
	2024 Aug 12	2200	WFC3/UVIS2	F555W	17429 ¹⁷
	2013 Sep 3	989	WFC3/UVIS	F814W	13364 ¹⁶
2014L	2020 Mar 23	2190	WFC3/UVIS	F275W	15654 ²
	2020 Mar 23	1110	WFC3/UVIS	F336W	15654 ²
	2020 Mar 23	1050	WFC3/UVIS	F438W	15654 ²
	2020 Mar 23	830	WFC3/UVIS	F814W	15654 ²
iPTF13bvn	2015 Jun 30	8865	WFC3/UVIS	F225W	13822 ¹⁴
	2019 Jun 25	5408	WFC3/UVIS	F438W	15152 ¹⁵
	2019 Jun 25	5437	WFC3/UVIS	F555W	15152 ¹⁵
2013dk	2017 Jun 27	2610	WFC3/UVIS	F275W	14593 ²⁰
	2010 Jan 27	5534	WFC3/UVIS	F336W	11577 ²¹
	2010 Jan 22	1032	WFC3/UVIS	F555W	11577 ²¹
	2010 Jan 22	1032	WFC3/UVIS	F814W	11577 ²¹

Target	Date	Exp Time (s)	Instrument	Filter	Program
2012ec	2023 Jul 14	1680	WFC3/UVIS	F275W	17179 ⁴
	2016 Jul 30	1560	ACS/WFC1	F475W	14226 ¹⁸
	2016 Jul 30	940	ACS/WFC1	F606W	14226 ¹⁸
	2016 Jul 30	1728	ACS/WFC1	F814W	14226 ¹⁸
2012au	2013 Dec 3	1100	WFC3/UVIS2	F438W	12888 ¹⁵
	2013 Dec 3	1100	WFC3/UVIS2	F606W	12888 ¹⁵
2012P	2015 Jun 30	8865	WFC3/UVIS	F225W	13822 ¹⁴
	2019 Jun 25	5408	WFC3/UVIS	F438W	15152 ¹⁵
	2019 Jun 25	5437	WFC3/UVIS	F555W	15152 ¹⁵
2009hd	2013 Oct 29	2392	WFC3/UVIS2	F336W	12968 ¹⁸
	2013 Oct 29	1632	WFC3/UVIS2	F438W	12968 ¹⁸
	2013 Oct 29	1340	WFC3/UVIS2	F555W	12968 ¹⁸
	2013 Oct 30	1668	WFC3/UVIS2	F814W	12968 ¹⁸
2009dq	2016 Nov 19	1200	WFC3/UVIS2	F300X	14762 ¹⁸
	2016 Nov 20	350	WFC3/UVIS2	F475X	14762 ¹⁸
2009H	2023 Jul 14	1680	WFC3/UVIS	F275W	17179 ⁴
2004dk	2021 May 30	1500	WFC3/UVIS2	F275W	16287 ⁷
2004dg	2024 Feb 2	2328	WFC3/UVIS	F275W	17506 ³
	2019 Jun 25	5408	WFC3/UVIS	F438W	15152 ¹⁵
	2019 Jun 25	5437	WFC3/UVIS	F555W	15152 ¹⁵
2004cc	2022 Mar 6	710	WFC3/UVIS	F606W	16691 ¹²
	2022 Mar 6	780	WFC3/UVIS	F814W	16691 ¹²
1999br	2002 Dec 23	400	ACS/WFC1	F435W	9353 ¹⁹
	2024 Feb 7	760	ACS/WFC	F555W	17070 ⁸
	2024 Feb 7	780	ACS/WFC	F814W	17070 ⁸
1998dl	2023 Jul 14	1680	WFC3/UVIS	F275W	17179 ⁴
	2016 Jul 30	1560	ACS/WFC1	F475W	14226 ¹⁸
1996an	2023 Jul 14	1680	WFC3/UVIS	F275W	17179 ⁴
	2016 Jul 30	1560	ACS/WFC1	F475W	14226 ¹⁸
	2016 Jul 30	940	ACS/WFC1	F606W	14226 ¹⁸
	2016 Jul 30	1728	ACS/WFC1	F814W	14226 ¹⁸
	2016 Jul 30	940	ACS/WFC1	F606W	14226 ¹⁸
1986I	2020 Mar 23	2190	WFC3/UVIS	F275W	15654 ²
	2020 Mar 23	1110	WFC3/UVIS	F336W	15654 ²
	2020 Mar 23	1050	WFC3/UVIS	F438W	15654 ²
	2020 Mar 23	830	WFC3/UVIS	F814W	15654 ²

Target	Date	Exp Time (s)	Instrument	Filter	Program
1973R	2019 Nov 11	2190	WFC3/UVIS	F275W	15654 ²
	2019 Nov 11	1110	WFC3/UVIS	F336W	15654 ²
	2019 Nov 11	1050	WFC3/UVIS	F438W	15654 ²
	2019 Nov 11	830	WFC3/UVIS	F814W	15654 ²
1967H	2020 Mar 21	2250	WFC3/UVIS	F275W	15654 ²
	2020 Mar 21	1950	WFC3/UVIS	F336W	15654 ²
	2020 Mar 21	1062	WFC3/UVIS	F438W	15654 ²
	2020 Mar 21	1055	WFC3/UVIS	F555W	15654 ²

Table 4.3: Principal investigator: ¹J. Dalcanton; ²J. Lee; ³W. Jacobson-Galan; ⁴L. Galbany; ⁵M. Bentz; ⁶D. Thilker; ⁷J. Lyman; ⁸C. Kilpatrick; ⁹A. Filippenko; ¹⁰O. Fox; ¹¹O. Graur; ¹²R. Foley; ¹³C. Kochanek; ¹⁴G. Folatelli; ¹⁵S. Van Dyk; ¹⁶D. Calzetti; ¹⁷M. Tucker; ¹⁸J. Maund; ¹⁹S. Smartt; ²⁰N. Bastian; ²¹B. Whitmore; ²²C. Fremling.

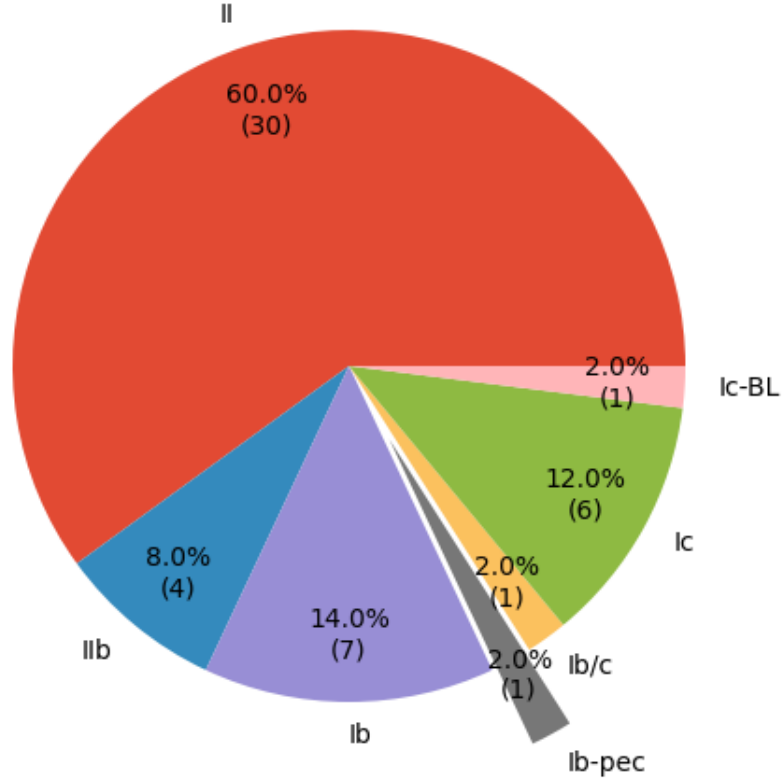


Figure 4.1: Pie chart representation of the SN classification fractions that comprise the full catalogue.

4.3 Data Reduction and Preparation

4.3.1 Photometric Data

Following the reduction process outlined in Section 2.2 each HST WFC3/ACS image listed in Table 4.2 was prepared for extraction of the stellar photometry. Image alignment was performed using the TWEAKREG and TWEAKBACK procedure. A reference image for a given dataset of images was selected on the basis of having a comparatively high exposure time and falling central to the wavelength range covered by the available instrumental filters. Where available, images that have had charge transfer efficiency (CTE) corrections (drc/flc) were preferentially downloaded. As a baseline, however, all downloaded datasets contain an image that has undergone ASTRODRIZZLE processing (drc/drz): geometric distortion corrections, effective pixel area map corrections, matching sky backgrounds, cosmic-ray rejection and the combining of dithered observations. Alignment corrections were found between the reference image and remaining drc/drz images, then applied back through the relevant flc/flt images.

The aligned images were then run through the DOLPHOT preprocessing steps: wfc3mask or acsmask, splitgroups and calcsky. These mask bad pixels, split files into their respective CCD chips and generate a sky map. Finally the photometry was measured using the main DOLPHOT pipeline with the respective PSFs of each instrument (WFC3 or ACS) and their utilised filters. In the required input parameter files for running DOLPHOT the WFC3useCTE and ACSuseCTE parameters were used to specify if a CTE correction is required, depending on whether drc/flc (= 0; no correction) or drz/flt (= 1, apply CTE correction) files were available. DOLPHOT was run multiple times on a given dataset for the purpose of two objectives. Firstly, running DOLPHOT on the dataset as a whole to obtain the PSF fitting photometry. This takes advantage of DOLPHOTs ability to search for common objects across all HST filter images, resulting in a higher number of resolved objects in the final product. Secondly, running DOLPHOT on each set of HST

images individually for a given filter, for the purpose of performing ASTs. Individual DOLPHOT runs for ASTs produce cleaner magnitude detection limit plots. The process for determining detection limits follows that described in Section 2.2.1 and example plots for varying dataset sizes are provided in Figure 4.2.

Filtering of the photometry is informed by the quality parameters generated by DOLPHOT, and follows the standard accepted ranges used throughout this research:

- (1) type of source, TYPE = 1 (corresponding to ‘star’);
- (2) photometry quality flag, FLAG ≤ 3 ;
- (3) source crowding, CROWD ≤ 2 ;
- (4) source sharpness, $-0.5 \leq \text{SHARP} \leq 0.5$;
- (5) signal-to-noise ratio, SNR ≥ 5 .

Resolved objects are required to meet these standards in a minimum of one HST image and where an object is not detected throughout the remaining images in a dataset, AST detection limits are substituted. The surviving objects are then filtered for a 150pc environment centred on the RA and Dec of each supernovae in the catalogue. If there are no resolved stars within 150pc or there are too few for a reliable fitting (<10 stars), the environment aperture was extended to 300pc. Cases where this was necessary are highlighted in Table 4.4 with an asterisk above the number of resolved stars (N_*).

4.3.2 Spectroscopic Data

Reduction of the MUSE datacubes began with deredshifting and dereddening the spectra with the IFUANA package. Dereddening applies a Cardelli, Clayton & Mathis (1989) polynomial with an $E(B - V)$ value pulled from the header information of each file, matching the A_V^{MW} values listed in Table 4.1. Each spectrum in the datacube had its $\text{H}\alpha$

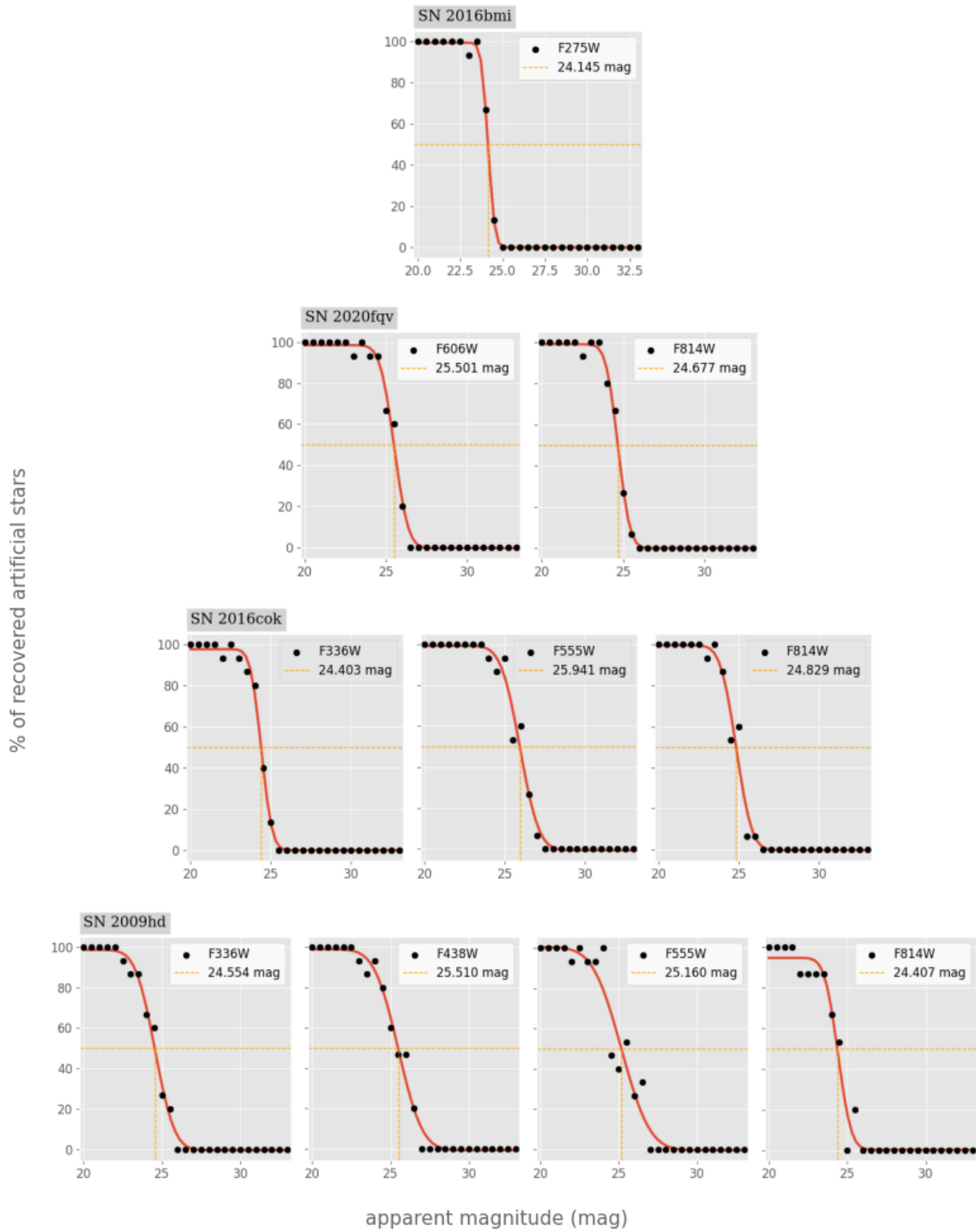


Figure 4.2: Examples of detection limit determination through ASTing with DOLPHOT for four of the catalogue targets. The AST process is described in full in Section 2.2.1. Red lines represent the non-linear least-squares best fit of the cumulative normal distribution function to the data, dashed orange lines highlight the '50% recovered' magnitude (detection limit). In descending order, the example datasets have an increasing number of HST images of various filters, stated in the legend along with the inferred detection limit.

Balmer line fit with a single Gaussian and the central wavelengths were compared to the rest frame value of 6564.6 Å. These wavelength shifts were used to produce rotational velocity maps for a given host galaxy. Spaxels within an aperture centred on the SN coordinates and a radius of 150 pc were extracted. A median H α wavelength shift within this extracted aperture was taken to be the rotational velocity correction for each SN environment, and was applied across the extracted 1×1 kpc cube. Examples of this process for four catalogue SNe are provided in Figure 4.3.

The 1×1 kpc cube, centred on the SN position, was rebinned into a new spaxel size containing 2×2 spaxels, increasing the SNR across each spectrum. Flux errors were added in quadrature. Masked regions across nebular line wavelengths were checked for each MUSE dataset to account for varying degrees of line widths. The data was then properly prepared to have continuum and emission line fittings following the algorithm described in Section 2.4. Initially, this was performed on the 150 pc aperture centred on the SN site, to acquire an estimate of the environmental metallicity. Gas-phase metallicities were estimated using a strong-line diagnostic, the O3N2 calibration by Marino et al. (2013). Line flux ratios for [O III] $\lambda 5007$ /H β and [N II] $\lambda 6584$ /H α were found through the fitting algorithm and substituted into the

$$12 + \log(\text{O}/\text{H}) = 8.533[\pm 0.012] - 0.214[\pm 0.012] \times \text{O3N2} \quad (4.2)$$

calibration. Scaling of measured metallicities to the solar value used a bulk composition of $Z_{\odot} = 0.0142$ and $12 + \log(\text{O}/\text{H}) = 8.69$ (Asplund et al., 2009).

Ionised gas extinctions were estimated using the Balmer decrement method (see Section 3.2.2), and converted to V-band magnitudes (A_V) with the Cardelli, Clayton & Mathis (1989) extinction law and an $R_V = A_V/E(B - V) = 3.1$. Intrinsic flux ratios ($I[\text{H}\alpha]/I[\text{H}\beta] = 3.42, 3.10, 2.86$ and 2.69) from Osterbrock & Ferland (2006) were imposed, with corresponding gas temperatures $T = 2500, 5000, 10000$ and 20000 K re-

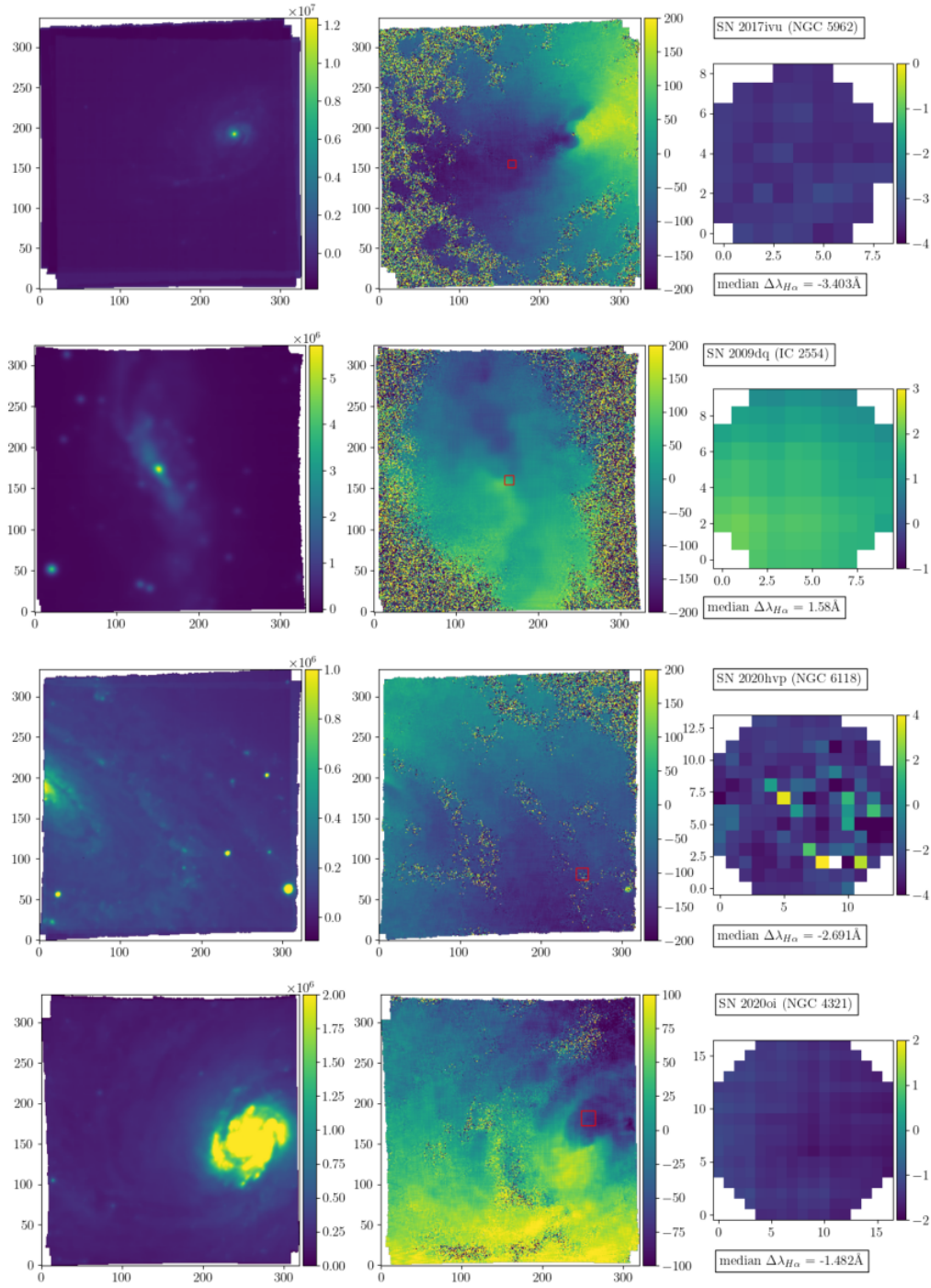


Figure 4.3: Examples of the host galaxy rotation correction for four of the catalogue targets. Left: white light images of the entire MUSE datacube. Centre: $H\alpha$ maps from single Gaussian line profile fittings of all spaxels. Red boxes highlight the extracted regions for the localised 150 pc environments, expanded in the right column. Colourbars represent the respective fluxes (left; $10^{-20}\text{erg } \text{\AA}^{-1}\text{s}^{-1}\text{cm}^{-2}$), velocities (centre; km/s) and wavelength shifts (right; $\text{\AA}$). Displayed on the right are median wavelength deviations of the $H\alpha$ line profile maximum from the rest-frame vacuum value ($\Delta\lambda_{H\alpha}$) across the extracted 150 pc apertures.

spectively. Assigning the appropriate theoretical flux ratio requires an estimate of the gas electron temperature, T_e . These were estimated using the empirical T_e - metallicity calibration by López-Sánchez et al. (2012):

$$T_e[\text{O III}] = 25200 - 1400x - 2000|x - 7.0|^{1.7} \quad (4.3)$$

where $x = 12 + \log(\text{O}/\text{H})$. Although electron temperatures are not uniform throughout H II regions and vary depending on the observed ion, only an approximation is required to match the scope of the Osterbrock & Ferland (2006) temperatures. López-Sánchez et al. (2012) highlight a drop-off in reliability for their T_e - metallicity calibration for metallicities below $\log(\text{O}/\text{H}) \sim 8.0$. This does not concern this analysis, as all measured metallicities exceed this critical value.

4.3.3 Fitting Photometry to Stellar Isochrones

Likelihood grids for individual stars, in $\log(\text{age} / \text{yr})$ and A_V prior space, were calculated using the standard approach established in Section 2.3.2. Inputs include PARSEC stellar evolution isochrone tables, photometry of resolved stars and metallicity estimates within each SN environment. The appropriate isochrone table was selected from a grid of increasing metallicity, $Z/Z_\odot = [0.4, 0.5, 0.6, 0.7, 0.8, 0.9, 1.0, 1.1, 1.2]$, and customised to contain the required photometric system: HST/WFC3 (UVIS+IR) filters or HST/ACS WFC filters. All isochrone tables were downloaded with zero total extinction and a Salpeter (1955) IMF.

In a Bayesian approach to fit the stellar populations in each SN environment, posterior probabilities for free parameters were sourced through the Nested Sampling algorithm with ULTRANEST. Every variation of an ULTRANEST run was performed under the reactive nested sampler. To reduce the expense of fitting for an increasing number of stellar populations ($N_m = 1, 2, 3$ or 4), fitting began with ‘initial’ runs with a minim-

ised number of free parameters. Free parameters for each initial model comprises N_m ages, a single extinction and the respective population weights (Section 2.3.1). The log-likelihoods were assumed to follow a multivariate normal distribution, $\mathcal{N}(\tau_k, A_{V,k}, \sigma_{\tau_k}, \sigma_{A_{V,k}})$, for each k^{th} stellar population. For initial runs σ_{τ_k} and $\sigma_{A_{V,k}}$ were fixed at 0.1.

Following the Jeffreys scale (Section 2.3.4), the optimum initial model was used to inform the number of stellar populations to include in an ‘advanced’ model. Free parameters for each advanced run comprises N_m ages with unique population extinctions, respective population weights, as well as a dispersion parameter for each age and extinction. Advanced runs were only accepted if the corrected Bayesian evidence exceeds that of the comparative initial run by ≥ 10 . For cases where the advanced run is rejected and $N_m > 1$, an ‘intermediate’ model was performed to maintain unique extinctions for each population age. These intermediate models include unique extinctions for each age component, but drop the additional dispersion free parameters.

4.4 Resolved Stellar Populations

4.4.1 Corrected Bayesian Evidence

For a given SN environment, investigating the optimum number of stellar populations was either capped at $N_m = 3$ or $N_m = 4$ depending on the evolution of the corrected Bayesian evidence. If the evidence peaked at $N_m = 2$ then it was deemed unnecessary to test beyond $N_m = 3$, but this degree of testing was performed as a minimum on every dataset. If the photometry contained a high number of resolved stars an $N_m = 4$ model was included as a precaution, as these datasets had a higher chance of resolving more stellar populations. Regardless, the highest number of stellar populations that optimised a given dataset in this catalogue was $N_m = 3$ (Table 4.4), with the majority of environments falling below this value. Some examples of corrected Bayesian evidence

plots are shown in Figure 4.4. SN 1973R, SN 2019yvr and SN 2009hd are examples of environments with $N_m = 1, 2$ and 3 stellar populations respectively. Each of these examples have advanced models that outperform their initial models, highlighted by the additional golden data points. Conversely, SN 2017ivv demonstrates a steady decline in collected evidence proceeding the $N_m = 1$ model and a comparative loss in performance by the advanced model. The convergence of the evidence towards a maximum was checked for each model run, demonstrated by the right column of plots in Figure 4.4.

4.4.2 Posterior Probabilities

Posterior probabilities for all free parameters in a model were sourced through ULTRANEST. Results were ordered and separated out into the relevant number of resolved stellar populations, and displayed in cornerplots. Each cornerplot shows the shape of the posterior probability peak, a red line highlights the peak value within the prior range and surrounding grey dashed lines the 1σ confidence levels. Between posterior probability plots are the sampled regions within the prior space between each free parameter. Grey data points are the results from individual iterations of the Nested Sampling algorithm and overlaid is a greyscale density plot, demonstrating a local maxima within the prior space. Black contours represent the 1σ , 2σ and 3σ confidence levels ordered from the inner to outer-most ring respectively. Strong convergence on a free parameter solution displays a compact and symmetrical set of contours. The exception to this typically occurs at the edge of the prior space, where ULTRANEST struggles to fully explore the surrounding prior space as it includes unphysical values (i.e. negative values when exploring close to zero). Three examples of such cornerplots are provided here. Figure 4.5 are the results for SN 2022acko, for which 1 stellar population was found. Based on the Bayesian evidence, the advanced model was accepted and the reliability of the fitting is reflected in the well defined peaks and contours across all free parameters. This can

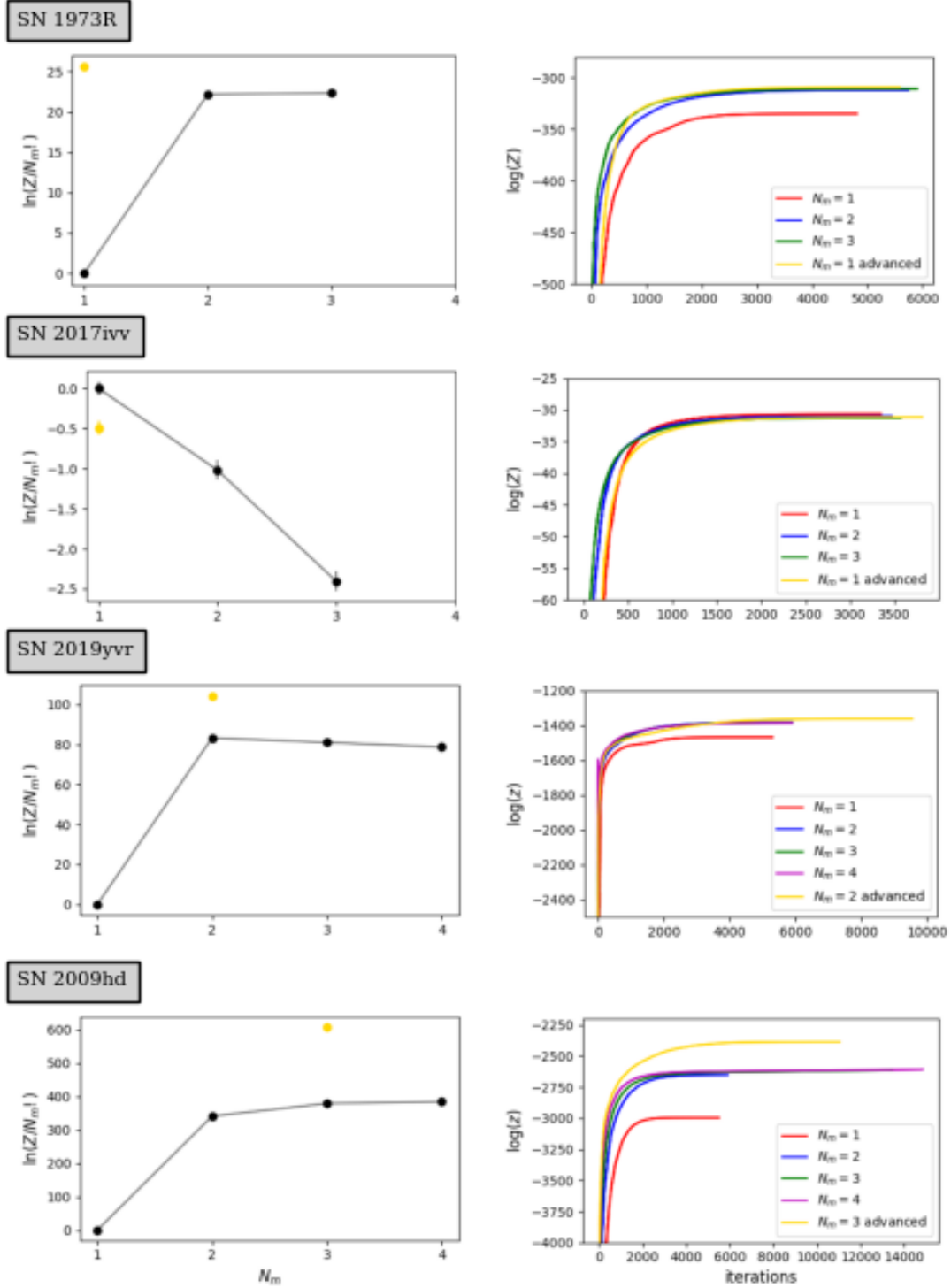


Figure 4.4: Examples of corrected Bayesian evidence evolution and corresponding convergence plots of evidence collection for the respective ULTRANEST runs with N_m stellar populations. Four catalogue targets are presented: SN 1973R, SN 2017ivv, SN 2019yvr and SN 2009hd. On the left, black datapoints correspond to 'initial' ULTRANEST runs and gold datapoints 'advanced'. On the right, ULTRANEST runs are defined in the legend.

not be said for the advanced runs for SN 2017gax and SN 2009hd, whose environments contain 2 and 3 stellar populations respectively. Rejection of poorly sampled posterior probability peaks required the application of the intermediate model in both cases. The results of these intermediate models are presented in Figures 4.6 and 4.7, demonstrating how this provides a cleaner fitting.

4.4.3 Stellar Population Ages

Following the methods outlined thus far, each SN environment has been searched for stellar-like sources and a Bayesian framework for fitting the prime number of stellar populations has been applied. The final catalogue results for stellar populations are reported in Table 4.4. Despite a final catalogue size of 50, SN 2018pq and ASASSN15oz do not appear in Table 4.4 because there were no resolved stars in their environments (even when extended to 300 pc). They remain a part of the catalogue as this lack of stars speaks to their environments, and the remainder of the analysis (IFU spectroscopy) is still applicable. It may be expected that a higher number of resolved stars or a higher number of HST images (broader wavelength coverage) would correlate with an increased number of resolved stellar populations. A higher number of resolved stars could suggest neighbouring or overlapping stellar populations. Having an image dataset that spans from UV to IR is more likely to detect younger (UV) and older (IR) stars. This effect is not observed uniformly across the catalogue results. SN 2009hd supports this effect, having 188 resolved stars in a 150 pc environment, 4 HST images (F336W, F438W, F555W and F814W) and 3 resolved stellar populations ($\tau = 6.51^{+0.03}_{-0.04} - 7.40^{+0.02}_{-0.02}$). Alternatively, SN 2017bzb opposes this with 36 resolved stars in a 150 pc environment, 2 HST images (F555W and F814W) and 2 resolved stellar populations ($\tau = 6.44^{+0.11}_{-0.15} - 7.54^{+0.15}_{-0.12}$).

Resolved stars and population results can be displayed as colour-magnitude diagrams (CMD) if more than one HST image is available. Example CMDs from datasets with 2,

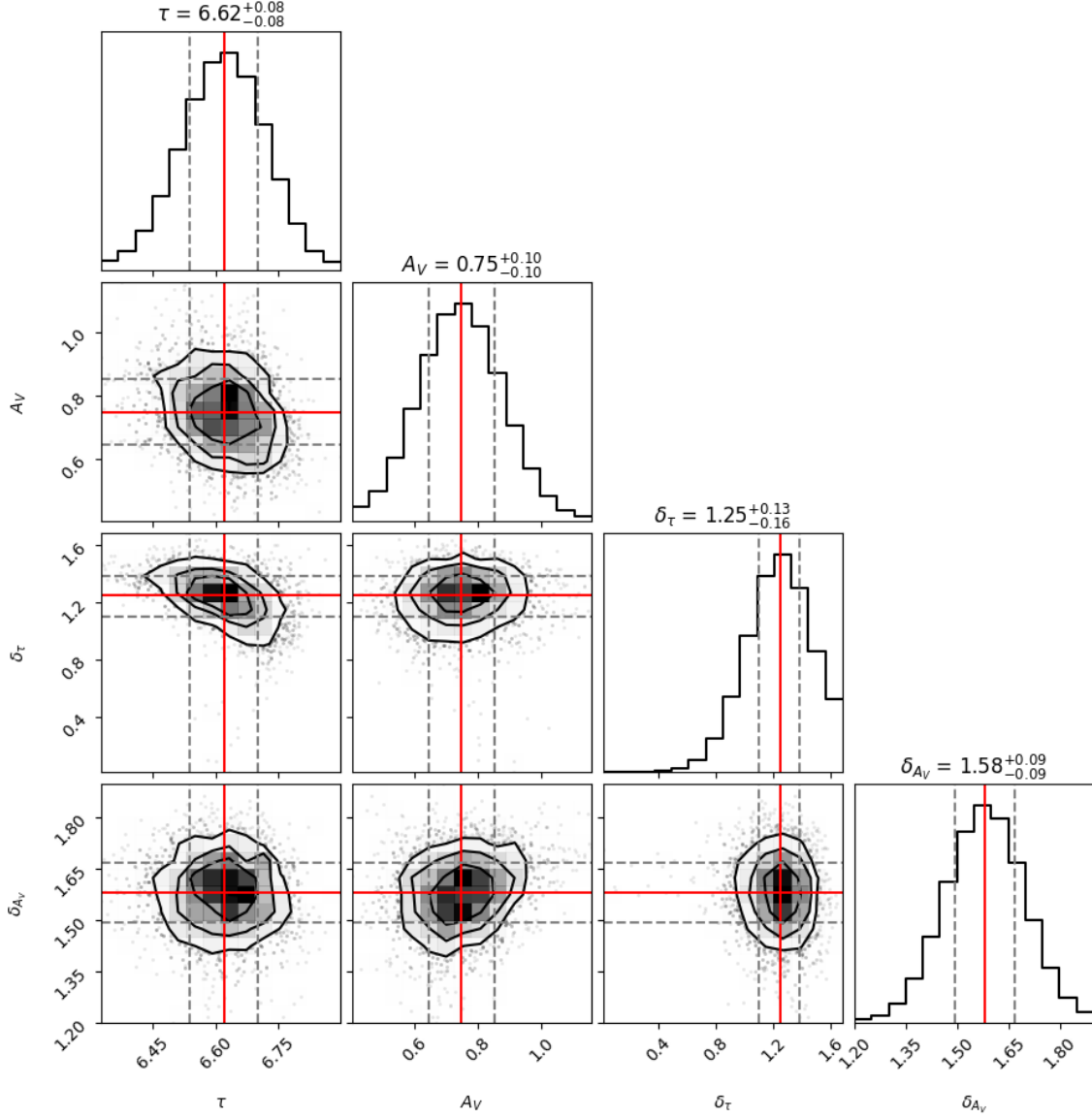


Figure 4.5: SN 2022acko cornerplot of optimised free parameters for a single stellar population, 'advanced' ULTRANEST model. Here $\tau = \log(\text{age}/\text{yrs})$ and the Normal distribution dispersions (σ) are parameterised by $\sigma_\tau = 0.01 \times 10^{\delta_\tau}$ and $\sigma_{A_V} = 0.01 \times 10^{\delta_{A_V}}$ for τ and extinction (A_V) respectively. Localisation of maxima within the prior space is highlighted by 1σ , 2σ and 3σ black contours. Red lines represent the optimal values, with 1σ bounds shown again with dashed grey lines.

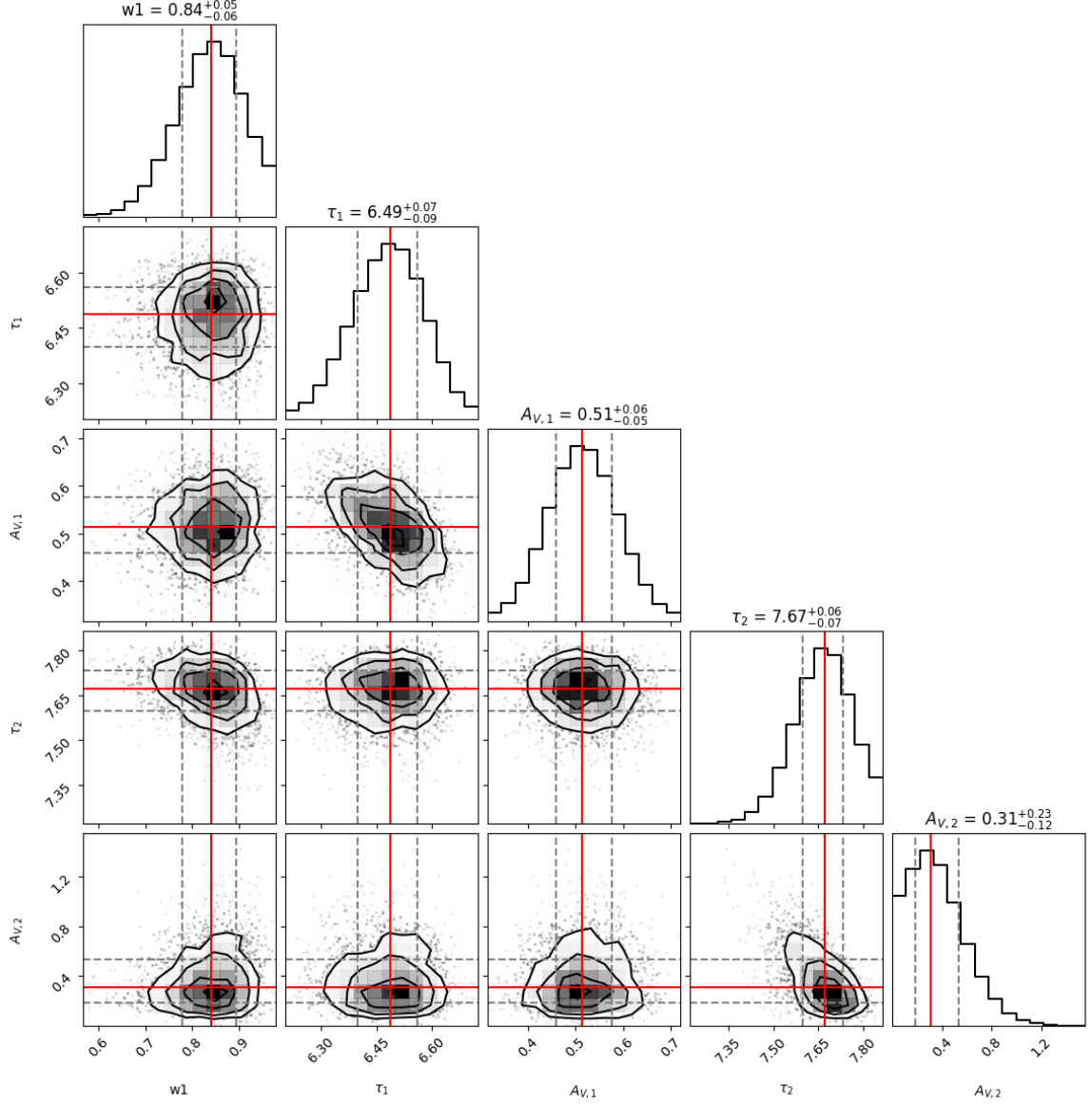


Figure 4.6: SN 2017gax cornerplot of optimised free parameters for a three ($N_m = 2$) stellar populations, 'intermediate' ULTRANEST model. Each population has a $\tau = \log(\text{age}/\text{yrs})$ and extinction (A_V). Localisation of maxima within the prior space is highlighted by 1σ , 2σ and 3σ black contours. There are ($N_m - 1$) weights for the respective populations. Red lines represent the optimal values, with 1σ bounds shown again with dashed grey lines.

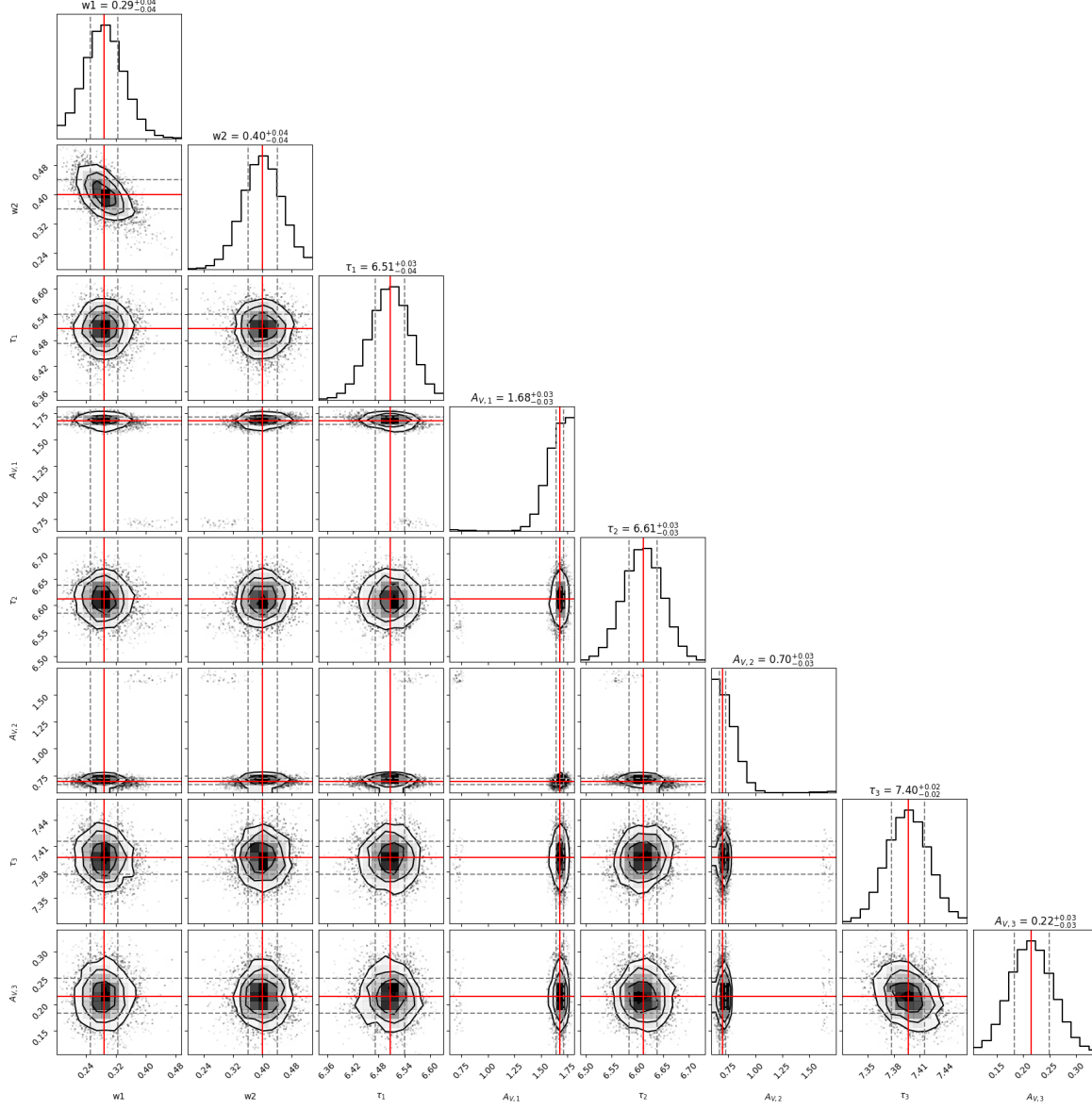


Figure 4.7: SN 2009hd cornerplot of optimised free parameters for a three ($N_m = 3$) stellar populations, 'intermediate' ULTRANEST model. Each population has a $\tau = \log(\text{age}/\text{yrs})$ and extinction (A_V). Localisation of maxima within the prior space is highlighted by 1σ , 2σ and 3σ black contours. There are $(N_m - 1)$ weights for the respective populations. Red lines represent the optimal values, with 1σ bounds shown again with dashed grey lines.

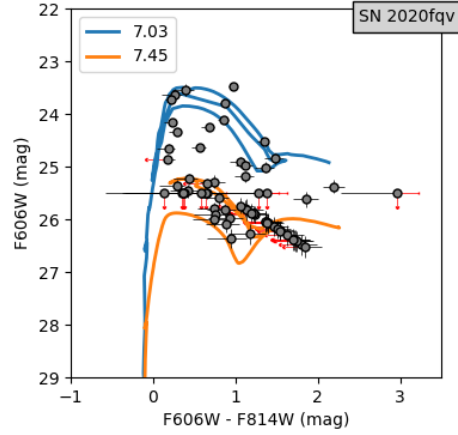


Figure 4.8: A colour-magnitude diagram of the photometric results for SN 2020fgv with two HST images and two resolved stellar populations. Grey datapoints represent the apparent magnitudes and colours of individual resolved stars within the 150 pc environment, red arrow error bars highlight detection limit substitutions. The PARSEC isochrones for the corresponding resolved stellar populations are overlaid, and their $\tau = \log(\text{age}/\text{yr})$ values appear in the legend.

3 and 4 HST images are displayed in Figures 4.8, 4.9 and 4.10 respectively, each found to have 2 resolved stellar populations. The case of SN 2014L (Figure 4.10) demonstrates that compact cluster contaminants in the photometry have no impact over the final population fitting, falling above the youngest isochrone. These contaminants are identified as stellar-like objects post DOLPHOT filtering, but their non-stellar absolute magnitudes result in a likelihood grid with zero probability density across the prior space. This advantageously results in them having no contribution to the population fitting.

4.4.4 Stellar Population Masses

Stellar population ages can be converted to progenitor initial mass estimates using the maximum stellar mass in the respective PARSEC isochrone table. Breakdowns of these results for all resolved stellar populations in each catalogue SN environment are provided in Section 4.9. Looking at the catalogue as a whole, the progenitor initial mass mean, median and standard deviation for the main four SN classifications are provided in Table

Table 4.4: Resolved stellar population results for all catalogue targets. Within the 150 pc environment of each target, N_* stars and N_m stellar populations were resolved. Cases where the environmental aperture had to be extended to a radius of 300 pc have an asterisk above their N_* values. The age ($\tau_k = \log(\text{age}_k/\text{yrs})$), extinction ($A_{v,k}$) and weight (w_k) of the k^{th} stellar population are presented.

Target	N_*	N_m	τ_1	τ_2	τ_3	w_1	w_2	$A_{v,1}$	$A_{v,2}$	$A_{v,3}$
2023abdg	13	1	$6.44^{+0.13}_{-0.16}$	...	...	...	...	$0.25^{+0.15}_{-0.09}$	...	...
2023jld	10	1	$7.54^{+0.04}_{-0.04}$	...	...	...	...	$0.23^{+0.10}_{-0.08}$	...	...
2022acko	30	1	$6.62^{+0.08}_{-0.08}$	...	...	...	...	$0.75^{+0.10}_{-0.10}$	...	...
2022wsp	15	1	$6.49^{+0.08}_{-0.14}$	...	...	...	...	$0.18^{+0.08}_{-0.06}$	...	...
2022ftl	17	1	$6.41^{+0.07}_{-0.10}$	...	...	...	...	$0.17^{+0.06}_{-0.04}$	...	...
2022aau	137	2	$6.58^{+0.01}_{-0.02}$	$7.43^{+0.04}_{-0.04}$	...	0.79	...	$1.23^{+0.06}_{-0.06}$	$0.04^{+0.02}_{-0.01}$	...
2020jfo	141	2	$6.56^{+0.08}_{-0.06}$	$7.58^{+0.05}_{-0.03}$	...	0.34	...	$0.51^{+0.13}_{-0.10}$	$0.32^{+0.14}_{-0.21}$	...
2020hvp	12*	1	$6.91^{+0.16}_{-0.15}$	...	...	...	...	$0.21^{+0.23}_{-0.14}$	...	...
2020fqv	66	2	$7.03^{+0.03}_{-0.04}$	$7.45^{+0.03}_{-0.03}$	...	0.39	...	$0.34^{+0.11}_{-0.10}$	$0.25^{+0.08}_{-0.05}$	...
2020oi	99	1	$6.52^{+0.01}_{-0.01}$	...	...	...	...	$0.97^{+0.06}_{-0.06}$	...	...
2019yvr	125	2	$6.44^{+0.02}_{-0.02}$	$7.47^{+0.01}_{-0.01}$	...	0.51	...	$0.59^{+0.10}_{-0.11}$	$0.28^{+0.04}_{-0.04}$	...
2019ehk	16	1	$7.60^{+0.05}_{-0.05}$	...	...	...	...	$0.28^{+0.17}_{-0.11}$	...	...
2019yz	2	1	$6.38^{+0.10}_{-0.10}$	...	...	...	...	$0.10^{+0.09}_{-0.06}$	...	...
2018ivc	212	2	$6.71^{+0.04}_{-0.04}$	$7.41^{+0.03}_{-0.03}$	...	0.63	...	$1.23^{+0.06}_{-0.06}$	$0.06^{+0.04}_{-0.02}$	...
AT2018bbl	17	1	$6.47^{+0.12}_{-0.15}$	...	...	...	...	$0.23^{+0.11}_{-0.07}$	...	...
2017ivv	3	1	$6.43^{+0.19}_{-0.23}$	...	...	...	...	$0.26^{+0.27}_{-0.15}$	...	...
2017ivu	2*	1	$6.32^{+0.14}_{-0.15}$	...	...	...	...	$0.19^{+0.15}_{-0.11}$	...	...

Target	N_*	N_m	τ_1	τ_2	τ_3	w_1	w_2	$A_{v,1}$	$A_{v,2}$	$A_{v,3}$
2017gax	59	2	$6.49^{+0.07}_{-0.09}$	$7.67^{+0.06}_{-0.07}$	...	0.84	...	$0.51^{+0.06}_{-0.05}$	$0.31^{+0.23}_{-0.12}$	...
2017bzb	36	2	$6.44^{+0.11}_{-0.15}$	$7.54^{+0.15}_{-0.12}$	...	0.79	...	$0.64^{+0.09}_{-0.09}$	$0.73^{+0.20}_{-0.26}$	...
2017aym	13*	1	$6.46^{+0.15}_{-0.17}$	...	...	...	...	$0.19^{+0.08}_{-0.06}$	...	...
2016iae	51	1	$6.51^{+0.05}_{-0.07}$	...	...	...	...	$0.49^{+0.06}_{-0.07}$	...	...
2016hgm	5	1	$6.34^{+0.11}_{-0.11}$	...	...	...	...	$0.15^{+0.11}_{-0.07}$	...	...
2016gkg	4	1	$6.29^{+0.19}_{-0.13}$	...	...	...	...	$0.89^{+0.13}_{-0.14}$	...	...
2016cok	147	2	$6.68^{+0.07}_{-0.07}$	$7.60^{+0.03}_{-0.03}$	...	0.35	...	$0.98^{+0.10}_{-0.10}$	$0.05^{+0.02}_{-0.01}$	...
2016coi	24	1	$6.73^{+0.10}_{-0.10}$	...	...	...	...	$0.34^{+0.09}_{-0.07}$	...	...
2016bmi	2*	1	$6.46^{+0.25}_{-0.25}$	...	...	...	...	$0.28^{+0.37}_{-0.17}$	...	...
2016afa	10*	1	$6.38^{+0.11}_{-0.13}$	...	...	...	...	$0.17^{+0.09}_{-0.06}$	...	...
ASASSN-16at	8*	1	$6.47^{+0.18}_{-0.21}$	...	...	...	...	$0.19^{+0.11}_{-0.07}$	...	...
2015dj	8*	1	$7.01^{+0.06}_{-0.30}$	...	...	...	...	$0.45^{+0.69}_{-0.20}$	...	...
ASASSN-14ha	50	2	$6.75^{+0.04}_{-0.04}$	$7.37^{+0.03}_{-0.03}$	...	0.57	...	$0.71^{+0.06}_{-0.07}$	$0.16^{+0.05}_{-0.04}$	...
2014L	84	2	$6.57^{+0.02}_{-0.02}$	$7.12^{+0.03}_{-0.03}$	...	0.76	...	$0.89^{+0.07}_{-0.07}$	$0.52^{+0.17}_{-0.16}$	...
iPTF13bvn	27	1	$7.13^{+0.12}_{-0.07}$	...	...	...	...	$0.39^{+0.12}_{-0.16}$	...	...
2013dk	74	2	$6.51^{+0.04}_{-0.04}$	$7.16^{+0.03}_{-0.03}$	...	0.59	...	$0.99^{+0.09}_{-0.09}$	$0.72^{+0.12}_{-0.12}$	...
2012ec	85	1	$6.97^{+0.01}_{-0.01}$	...	...	...	...	$1.03^{+0.05}_{-0.05}$	...	...
2012au	31	1	$6.45^{+0.05}_{-0.05}$	...	...	...	...	$0.98^{+0.08}_{-0.09}$	...	...
2012P	27	1	$6.60^{+0.05}_{-0.05}$	...	...	...	...	$0.85^{+0.13}_{-0.16}$	...	...
2009hd	188	3	$6.51^{+0.03}_{-0.04}$	$6.61^{+0.03}_{-0.03}$	$7.40^{+0.02}_{-0.02}$	0.29	0.40	$1.68^{+0.03}_{-0.03}$	$0.70^{+0.03}_{-0.03}$	$0.22^{+0.03}_{-0.03}$

Target	N_*	N_m	τ_1	τ_2	τ_3	w_1	w_2	$A_{v,1}$	$A_{v,2}$	$A_{v,3}$
2009dq	16	1	$6.64^{+0.04}_{-0.04}$	...	...	...	...	$0.17^{+0.06}_{-0.05}$	...	...
2009H	22	1	$6.47^{+0.10}_{-0.15}$	...	...	...	...	$0.18^{+0.05}_{-0.04}$	...	...
2004dk	4	1	$6.36^{+0.13}_{-0.14}$	...	...	...	...	$0.19^{+0.15}_{-0.10}$	...	...
2004dg	17	1	$6.77^{+0.33}_{-0.19}$	...	...	...	...	$0.72^{+0.32}_{-0.19}$	...	...
2004cc	73	1	$7.27^{+0.02}_{-0.02}$	...	...	...	...	$0.20^{+0.03}_{-0.03}$	...	...
1999br	52	1	$7.24^{+0.02}_{-0.02}$	...	...	...	...	$0.06^{+0.03}_{-0.02}$	...	...
1998dl	102	1	$7.29^{+0.02}_{-0.02}$	...	...	...	...	$0.10^{+0.03}_{-0.03}$	...	...
1996am	138	1	$6.95^{+0.01}_{-0.01}$	...	...	...	...	$0.69^{+0.04}_{-0.04}$	...	...
1986l	111	2	$6.52^{+0.03}_{-0.03}$	$7.15^{+0.07}_{-0.04}$	...	0.74	...	$0.76^{+0.06}_{-0.06}$	$0.42^{+0.12}_{-0.15}$	...
1973R	24	1	$7.12^{+0.09}_{-0.08}$	...	...	...	...	$1.01^{+0.15}_{-0.17}$	...	...
1967H	69	2	$6.49^{+0.04}_{-0.04}$	$7.07^{+0.04}_{-0.03}$	...	0.70	...	$0.92^{+0.09}_{-0.08}$	$0.74^{+0.11}_{-0.14}$	...

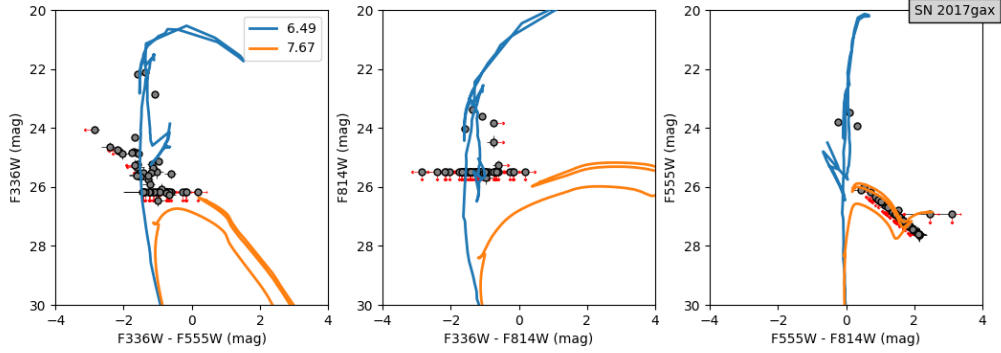


Figure 4.9: A colour-magnitude diagram of the photometric results for SN 2017gax with three *HST* images and two resolved stellar populations. Grey datapoints represent the apparent magnitudes and colours of individual resolved stars within the 150 pc environment, red arrow error bars highlight detection limit substitutions. The PARSEC isochrones for the corresponding resolved stellar populations are overlaid, and their $\tau = \log(\text{age}/\text{yr})$ values appear in the legend.

Table 4.5: Statistics of SN classification progenitor masses.

SN Type	Number	Mean ($M_{\odot}$)	Median ($M_{\odot}$)	Standard Deviation ($M_{\odot}$)
II	20	20.6	14.0	14.7
IIb	4	37.0	36.7	23.4
Ib	6	14.0	12.7	6.2
Ic	6	42.9	28.2	33.1

4.5.

These statistics were drawn from catalogue objects that fall under the ‘gold’ and ‘silver’ ranks, based on the number of available high resolution images (Section 4.9). Of these catalogue subgroups, only reasonable mass estimates were incorporated. Rejected mass estimates include those that were poorly constrained (large errors) or unrealistic progenitors of CCSNe (i.e. $> 100 M_{\odot}$). All ‘bronze’ ranked SNe were excluded, as all of their inferred masses meet the previously stated rejection criteria. If a single SN environment contains two plausible mass estimates, both were included in producing the results in Table 4.5.

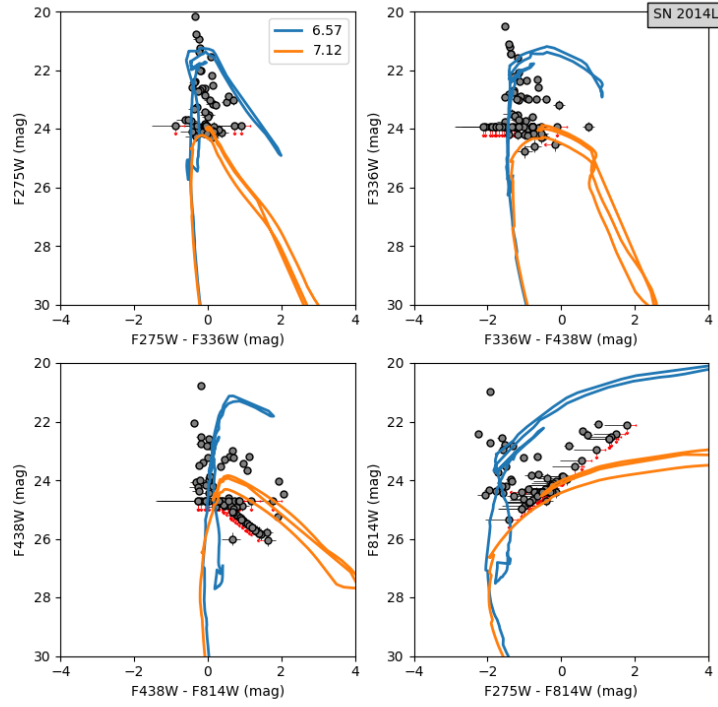


Figure 4.10: A colour-magnitude diagram of the photometric results for SN 2014L with four HST images and two resolved stellar populations. Grey datapoints represent the apparent magnitudes and colours of individual resolved stars within the 150 pc environment, red arrow error bars highlight detection limit substitutions. The PARSEC isochrones for the corresponding resolved stellar populations are overlaid, and their $\tau = \log(\text{age/yr})$ values appear in the legend.

Besides Type Ib, the mean and median masses increase from Type II→IIb→Ic. The lower values found for Type Ib could imply a majority binary channel for producing these stripped progenitors. It can not be overlooked, however, that high mass progenitors have been found in some of these environments by my analysis and subsequently rejected before producing these statistics. Nonetheless, the result is significant given that the same rejection criteria was applied uniformly across all SN types. As a subgroup, Type Ic has the largest standard deviation. A greater spread in masses could suggest a mixture of massive single-stars and binary systems for these highly stripped progenitors. Results for my Type II population align well with lower mass RSG progenitors, as previously found for many directly observed systems. Although they suffer from low sample statistics, statistics for Type IIb could imply these progenitors represent the upper mass limit for RSGs or, instead, transitional YSGs.

4.5 Metallicities

Before finding the likelihood grids for individual stars, environmental metallicity estimates were required. Employing the O3N2 calibration necessitates the fitting of the $H\alpha$, $H\beta$, [O III] $\lambda 5007$ and [N II] $\lambda 6584$ emission lines, which was possible for 38 of the catalogue objects. The remaining catalogue objects were missing one or more of these essential lines, due to them being too weak, too noisy or missing entirely. Most commonly the [O III] $\lambda 5007$ line was missing from the SN site. Catalogue metallicities are represented in cumulative distribution plots, Figures 4.11 and 4.12. From this distribution a median value of $Z = 0.683 \pm 0.016 Z_{\odot}$ was substituted for the 12 catalogue SNe lacking in metallicity estimates.

The total distribution (black line; Figure 4.11) implies the majority of SNe environments are sub-solar, with the solar value falling at $12 + \log((O/H)) = 8.69$. Comparing the distributions between Type II and stripped-envelope SNe suggest no metallicity-

dependent distinction between these groups and their progenitor channels. The only difference in distributions could be identified at the lowest measured metallicities ($12 + \log(\text{O}/\text{H}) < 8.4$) where the greatest separation exists. Splitting the [SESNe](#) distribution into Type Ib and Type Ic suffers from low sample statistics, but emphasises how only these two classifications contribute to the [SESNe](#) distribution for $12 + \log(\text{O}/\text{H}) < 8.4$ (no contribution from Type IIb). It is worth noting that of the four lowest measured metallicities, 3 originate from Type Ib/c [SNe](#) and 1 from Type II. At such low metallicities, binary interaction is the more expected mass-loss channel compared to stellar winds. Particularly for highly stripped progenitors (Type Ic). This could strongly support binary system progenitors for these [SESNe](#): [SN 2016coi](#) (Ic-BL), [SN 2019yz](#) (Ic) and [SN 2022frl](#) (Ib-pec).

Although historically an increasing trend of metallicity from Type IIP→IIb→Ib→Ic was proposed, modern studies find a mixture of results. Some converge on little to no metallicity dependence on the spectrum and lightcurve features (classification) of [CCSNe](#) ([Anderson et al., 2016](#); [Kuncarayakti et al., 2018](#); [Xi et al., 2025](#)). [Kuncarayakti et al. \(2013a\)](#) found that Type Ic [SNe](#) have metallicities, on average, ~ 0.1 dex higher than Type Ib, but later found no statistically significant metallicity difference amongst [SN](#) types ([Kuncarayakti et al., 2018](#)). [Pledger et al. \(2024\)](#) and [Galbany et al. \(2018\)](#) find a narrow distribution for Type Ib with a tendency towards higher metallicities, but no significant difference in the average metallicity for each [SN](#) subtype. [Pledger et al. \(2024\)](#) attribute this narrow distribution to a lower binary contribution to the stripped progenitors of Type Ib [SNe](#). Additionally, [Galbany et al. \(2018\)](#) find that Type Ic [SNe](#) occur in more metal rich H II regions compared to the mean values of their host galaxies, suggesting they originate from more massive progenitors. More recently, [Pessi et al. \(2023\)](#) have found evidence of a metallicity dependence on the occurrence of [CCSNe](#). By splitting their sample at $12 + \log(\text{O}/\text{H}) = 8.6$ dex, they demonstrate that low-metallicity host galaxy [CCSNe](#) trace star formation with no correlation to the local

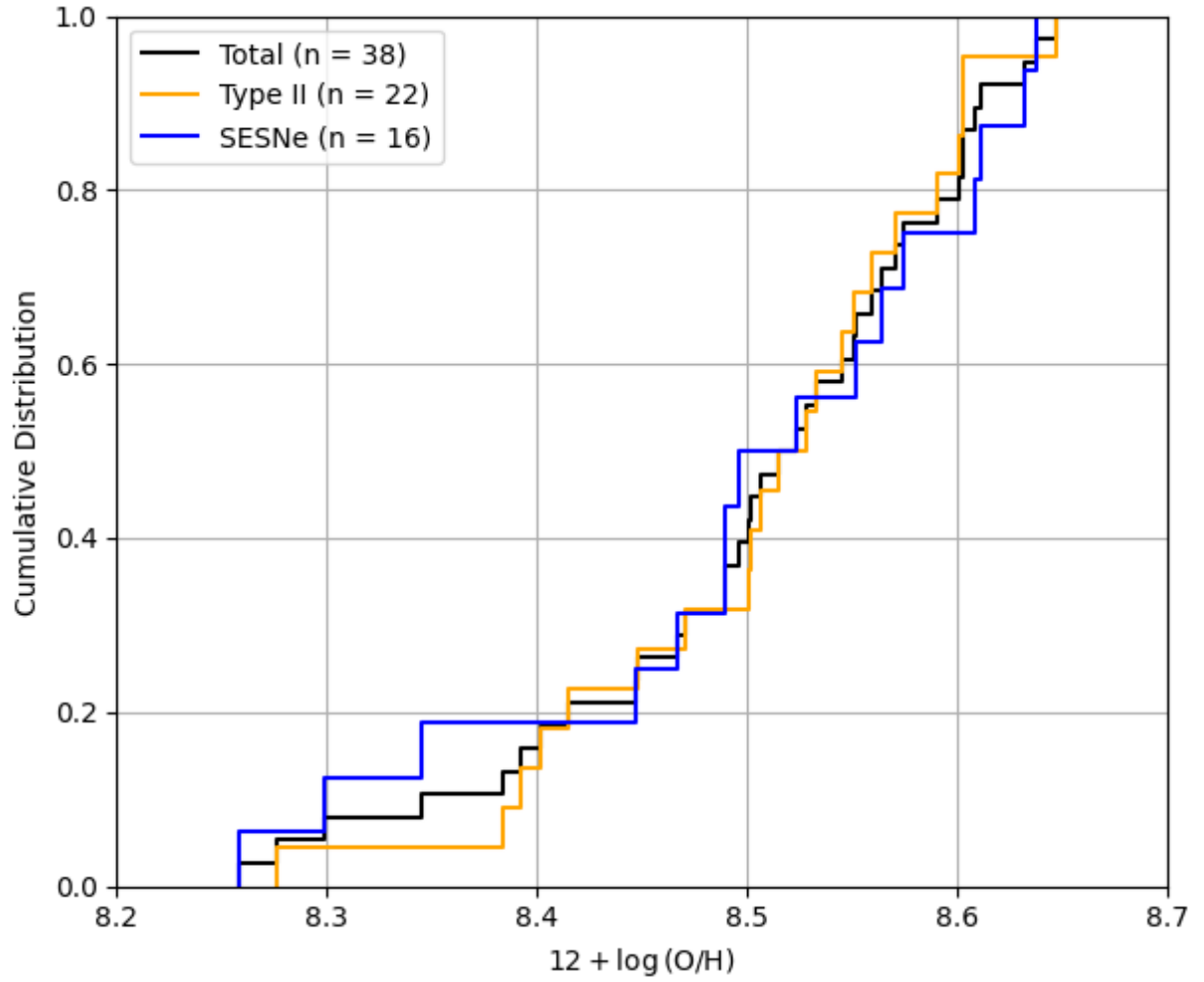


Figure 4.11: Cumulative distribution plots of oxygen abundance values for all 38 catalogue targets for which $12 + \log(\text{O}/\text{H})$ values could be estimated from the [MUSE](#) data. The total distribution is presented (black) and has been sub-divided by [SN](#) classification groups: Type II (gold) and [SESNe](#) (blue).

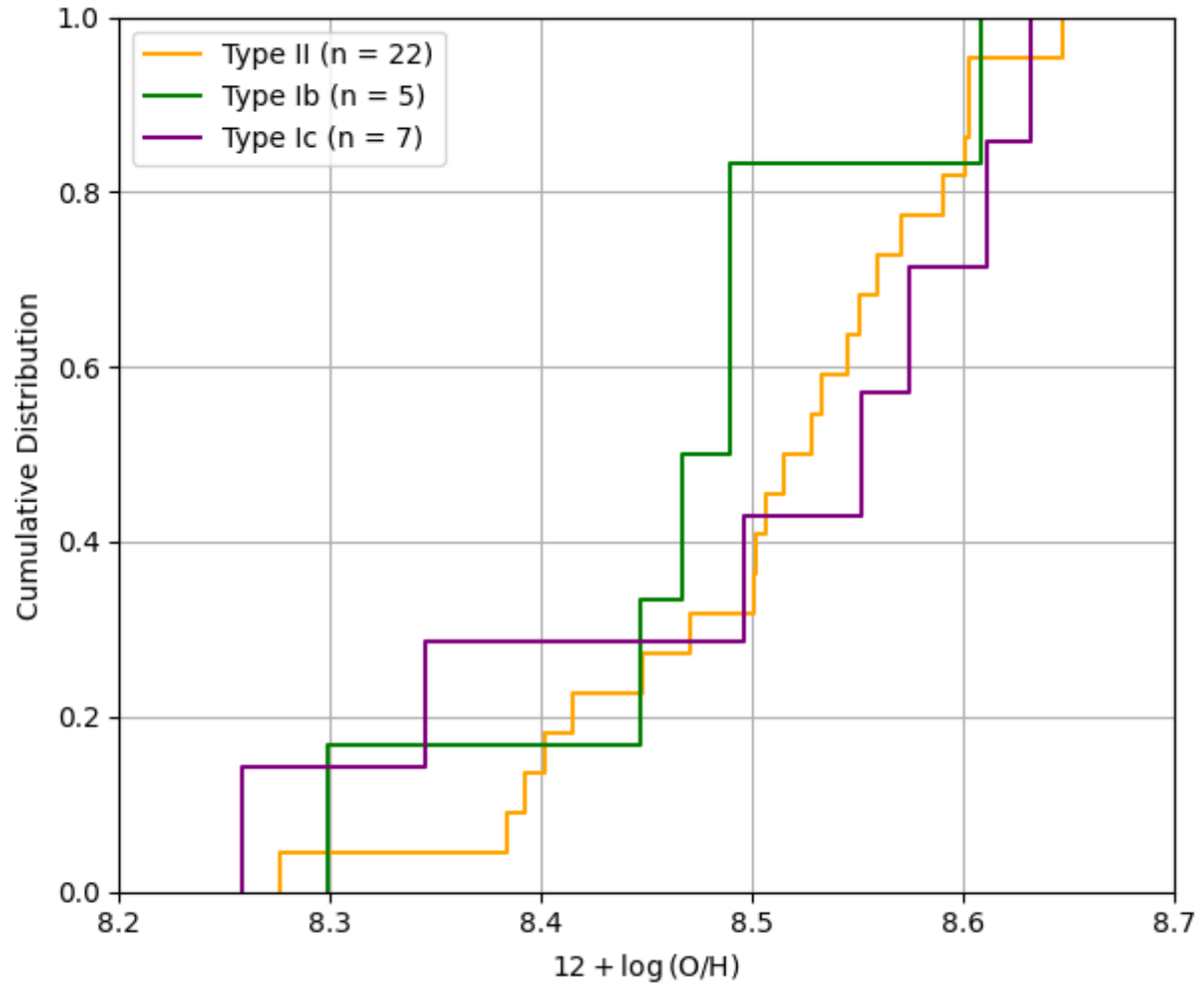


Figure 4.12: Cumulative distribution plots of oxygen abundance values for catalogue targets for which $12 + \log(\text{O}/\text{H})$ values could be estimated from the MUSE data. The results have been separated into SN classifications/: Type II (gold), Type Ib (green) and Type Ic (purple). Of the 38 total in Figure 4.11 only 34 appear here, as 4 Type IIb results are discarded.

metallicity. Whereas in high-metallicity host galaxies, they preferentially occur in star forming regions with lower oxygen abundances. Given that my catalogue is likely biased towards starforming galaxies with, on average, higher metallicities, this could explain the uniformly sub-solar metallicities measured across all SN sites.

4.6 Extinctions

Another environmental parameter measured within the 150 pc aperture centred on each SN was the Balmer decrement extinction (A_V). The Balmer decrement method is most effective when the hydrogen nebular lines are prominent, so that they can be reliably fit and compared. A bright H II region would provide this, however only some of the immediate SN environments are coincident, or contain, one. Therefore, when fixing this analysis to the 150 pc environments, the measured extinctions could be probing H II regions or diffuse ionised gas (DIG) either of which could be co-spatial with the SN stellar population or background sources. With this in mind, the spectroscopically measured extinctions have been directly compared to the average stellar population extinctions from the photometric analysis (Figure 4.13), including results from environments that contain multiple resolved stellar populations. From the full catalogue, within their respective errors, only five stellar populations show reasonable agreement between both measurements. Two of these confidently fall on the dashed line ($y = x$) of Figure 4.13, belonging to the local environments of SN 2012au and SN 2009hd. The remaining three stellar populations have substantially larger errors, one belonging to SN 2004dg and two belonging to the same environment of SN 2017bzb. All 47 other SN sites in the catalogue exhibit an excess, mostly of order 0.3 – 2.5 mag, in their Balmer decrement extinctions with respect to their resolved stellar population extinctions. As was the case for iPTF13bvn (Chapter 3), a depth interpretation places these as background sources relative to the resolved stellar populations. In terms of co-spatiality between the resolved

stellar populations and the ionised gas sources, some degree of difference between their measured extinctions could be expected. If the ionised gas originated from a dense H II region, the spectroscopic measurement could achieve greater depths (higher extinction) compared to the average stellar population value, as resolved stars would quickly become undetectable further along the LoS. Towards the lower end of the discrepancy range observed between A_V s, i.e. a difference of $\approx 0.3 - 0.5$ mag, an association between a H II region and the resolved stellar population could hold. For at least half of the catalogue, however, this is not the case and it highlights the high likelihood of chance alignment between photometrically and spectroscopically identifiable sources along any LoS.

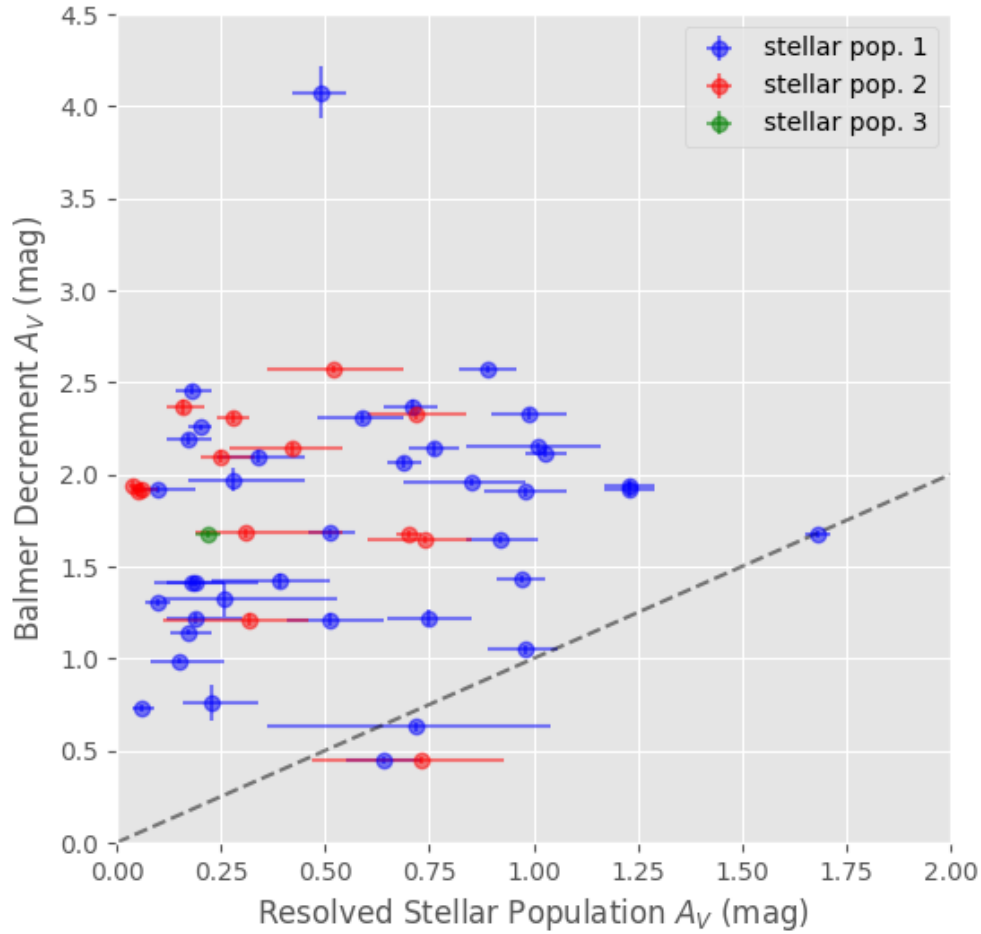


Figure 4.13: A comparison between measured extinctions from the 150 pc environments of the catalogue SN targets. Firstly, from the resolved stellar population fittings of the *HST* photometry; all results were included for environments that contain multiple stellar populations (distinguishable through the legend). Secondly, the measured Balmer decrement extinction from the summed environmental *MUSE* spectra. A dashed grey line is included to highlight the one-to-one ($y = x$) comparison.

4.7 Resolved H II Regions

Within the extracted 1×1 kpc [MUSE](#) environments, H II regions were identified using the image segmentation pipeline that is part of the [PHOTUTILS](#) package. This labels and groups pixels that form a single extended object that exceeds the measured background flux by a 2σ threshold. Tests were performed on a range of values from $1-3\sigma$, and 2σ was chosen as the ideal threshold to balance either rejecting too many identifiable sources or creating over-extended sources. No upper limit was enforced on the number of pixels that could form a single H II region, but a minimum of 4 pixels was required. Furthermore, the source deblending procedure was applied to the map of segmented objects. This identifies sources that are connected by a saddle point and separates them into individual objects. Figure [4.14](#) shows an example of a comparatively complex and crowded environment centred on [SN 2014L](#). Here the segmentation algorithm identifies 5 H II regions, amongst diffuse ionised gas and voids. The top plot displays a background-subtracted $H\alpha$ map, smoothed with a 2D Gaussian kernel with a FWHM of 3 pixels. The bottom plot presents the identified extended objects, with clear examples of the deblending procedure in action. Although by-eye it may seem more reasonable to further divide some of these objects, this highlights the limitations of having a consistent methodology to extracting H II. The complexity of the environment, the amount of diffuse ionised gas and the available spatial resolution (distance dependent) all impact the reliability of the measured background level. In turn, this affects the ability of a 2σ threshold to identify H II regions. Comparatively, Figure [4.15](#) shows an example of a simple environment, with a single central bright H II region containing the site of [SN 2004dk](#).

All identified H II regions were subjected to the same spectral analysis as the summed 150 pc apertures centred on individual [SNe](#) sites: continuum fitting and subtraction; fitting of nebular lines; estimates of metallicity, extinction and electron temperature. Results for every H II region are presented in Table [4.6](#), listed in ascending order of

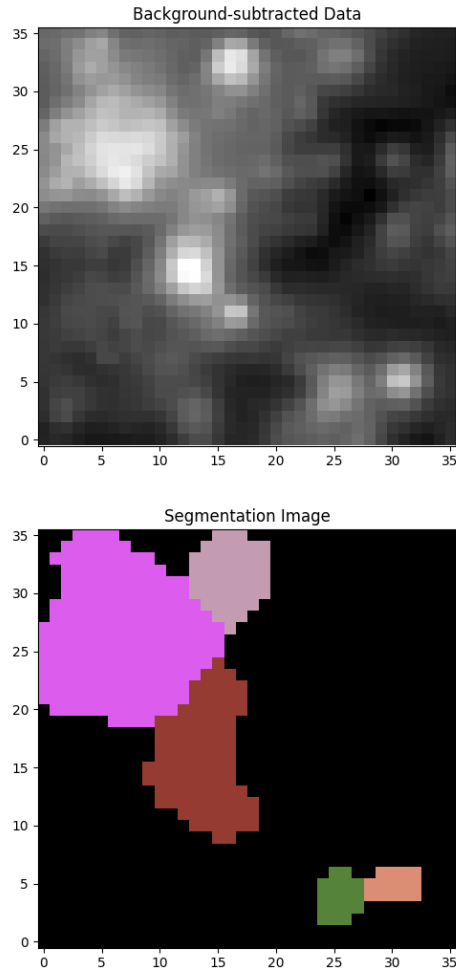


Figure 4.14: Identification of H II regions within the 1×1 kpc environment of SN 2014L; the axis' are pixel coordinates and the SN site falls in the central pixel of both images. The top image shows the background subtracted $H\alpha$ map smoothed with a 2D Gaussian kernel with a FWHM of 3 pixels. The bottom image shows the selected pixels grouped by colours, that represent individual H II regions and their pixel area on the sky. Both procedures follow the standard segmentation pipeline from the PHOTUTILS package.

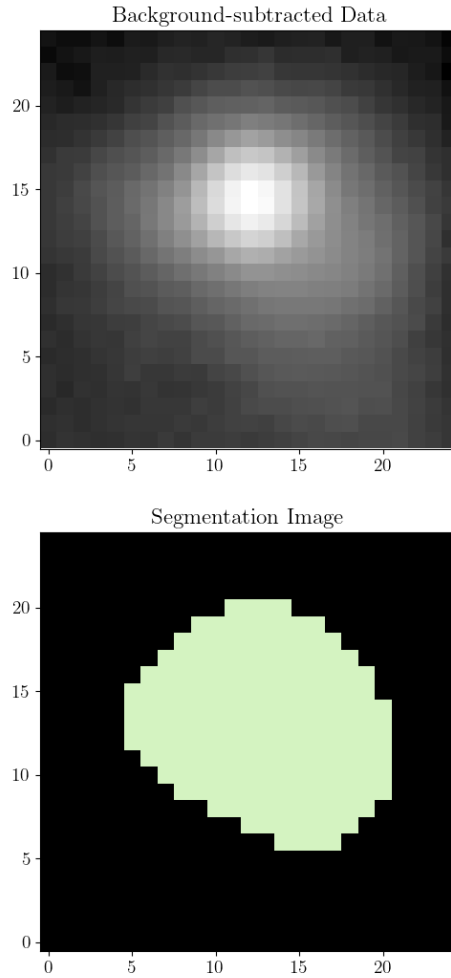


Figure 4.15: Identification of H II regions within the 1×1 kpc environment of SN 2004dk; the axis' are pixel coordinates and the SN site falls in the central pixel of both images. The top image shows the background subtracted $H\alpha$ map smoothed with a 2D Gaussian kernel with a FWHM of 3 pixels. The bottom image shows the selected pixels grouped by colours, that represent individual H II regions and their pixel area on the sky. Both procedures follow the standard segmentation pipeline from the PHOTUTILS package.

Table 4.6: Measured properties for all identified H II regions in the 1×1 kpc environments of all catalogue targets. Distances are measured from the SN coordinated to the nearest edge-pixel of each H II region, coupled with no host galaxy inclination corrections, meaning they represent a minimum distance. Other parameters include H α line equivalent widths ($EW(\text{H}\alpha)$) in Angstroms, $\log(EW(\text{H}\alpha))$, oxygen abundances ($12 + \log(\text{O}/\text{H})$) from the O3N2 strong-line diagnostic (Equation 4.2; Marino et al. (2013)), electron temperatures (T_e) from the empirical calibration by López-Sánchez et al. (2012) (Equation 4.3) and extinctions from the Balmer decrement method.

Target	Distance (pc)	$EW(\text{H}\alpha)$ (Å)	$\log(EW(\text{H}\alpha))$	$12 + \log(\text{O}/\text{H})$	T_e (K)	A_V (mag)
2023abdg	194	$126.4 (\pm 5.4)$	$2.102 (\pm 0.019)$	$8.544 (\pm 0.014)$	9053	$0.857 (\pm 0.020)$
	216	$56.7 (\pm 2.6)$	$1.753 (\pm 0.020)$	$8.607 (\pm 0.030)$	8669	$1.451 (\pm 0.031)$
2023ijd	201	$14.5 (\pm 0.9)$	$1.163 (\pm 0.026)$	$8.535 (\pm 0.017)$	9105	$1.926 (\pm 0.036)$
	271	$20.0 (\pm 1.0)$	$1.302 (\pm 0.021)$	$8.600 (\pm 0.020)$	8716	$1.470 (\pm 0.026)$
	317	$17.3 (\pm 1.0)$	$1.237 (\pm 0.026)$	$8.552 (\pm 0.017)$	9005	$1.568 (\pm 0.031)$
2022acko	0	$11.7 (\pm 0.8)$	$1.069 (\pm 0.028)$	$8.549 (\pm 0.022)$	9023	$1.269 (\pm 0.048)$
	80	$41.3 (\pm 2.1)$	$1.616 (\pm 0.022)$	$8.617 (\pm 0.016)$	8608	$1.127 (\pm 0.023)$
	151	$24.1 (\pm 1.3)$	$1.383 (\pm 0.024)$	$8.581 (\pm 0.031)$	8832	$1.786 (\pm 0.031)$
	169	$10.9 (\pm 0.6)$	$1.038 (\pm 0.025)$	–	–	$1.243 (\pm 0.049)$
	406	$25.3 (\pm 1.6)$	$1.403 (\pm 0.027)$	$8.586 (\pm 0.023)$	8798	$1.332 (\pm 0.034)$
2022wsp	51	$34.6 (\pm 1.9)$	$1.539 (\pm 0.024)$	$8.555 (\pm 0.014)$	8986	$1.620 (\pm 0.025)$
	406	$25.3 (\pm 1.6)$	$1.403 (\pm 0.027)$	$8.586 (\pm 0.023)$	8798	$1.332 (\pm 0.034)$
2022ftl	275	$165.6 (\pm 4.4)$	$2.219 (\pm 0.011)$	$8.168 (\pm 0.026)$	11160	$1.210 (\pm 0.012)$
2022aau	0	$46.6 (\pm 3.0)$	$1.668 (\pm 0.028)$	$8.603 (\pm 0.016)$	8695	$1.722 (\pm 0.029)$
	291	$52.4 (\pm 3.4)$	$1.720 (\pm 0.028)$	$8.632 (\pm 0.017)$	8517	$1.686 (\pm 0.030)$
	412	$9.1 (\pm 0.9)$	$0.957 (\pm 0.041)$	$8.460 (\pm 0.020)$	9549	$2.574 (\pm 0.062)$
2020jfo	0	$29.8 (\pm 1.7)$	$1.474 (\pm 0.024)$	–	–	$1.023 (\pm 0.032)$
	178	$21.1 (\pm 1.2)$	$1.325 (\pm 0.024)$	$8.571 (\pm 0.017)$	8891	$1.366 (\pm 0.028)$
	220	$31.8 (\pm 1.9)$	$1.502 (\pm 0.026)$	$8.479 (\pm 0.015)$	9439	$1.367 (\pm 0.030)$
	277	$82.5 (\pm 4.6)$	$1.917 (\pm 0.024)$	$8.551 (\pm 0.014)$	9012	$1.926 (\pm 0.025)$
	366	$47.0 (\pm 3.0)$	$1.672 (\pm 0.027)$	$8.534 (\pm 0.014)$	9111	$2.129 (\pm 0.029)$
	540	$62.1 (\pm 3.3)$	$1.793 (\pm 0.022)$	$8.415 (\pm 0.015)$	9813	$1.585 (\pm 0.025)$

Target	Distance (pc)	$EW(H\alpha)$ (Å)	$\log(EW(H\alpha))$	$12 + \log(O/H)$	T_e (K)	A_V (mag)
2020hvp	285	25.2 (± 1.4)	1.401 (± 0.024)	–	–	2.447 (± 0.049)
	307	15.7 (± 0.9)	1.196 (± 0.024)	8.544 (± 0.023)	9051	2.671 (± 0.041)
	372	21.3 (± 1.0)	1.328 (± 0.021)	–	–	1.817 (± 1.244)
	486	1.2 (± 0.2)	0.068 (± 0.06)	–	–	–
	513	23.8 (± 1.3)	1.377 (± 0.024)	8.569 (± 0.020)	8905	1.518 (± 0.033)
2020fqv	549	25.7 (± 1.2)	1.409 (± 0.021)	–	–	1.733 (± 0.039)
	304	40.4 (± 1.9)	1.607 (± 0.020)	8.601 (± 0.017)	8709	1.965 (± 0.022)
	450	52.5 (± 2.0)	1.720 (± 0.017)	8.637 (± 0.020)	8486	2.395 (± 0.019)
	451	24.7 (± 0.9)	1.393 (± 0.016)	8.604 (± 0.029)	8688	3.242 (± 0.026)
2020oi	67	62.4 (± 2.1)	1.795 (± 0.015)	8.664 (± 0.022)	8319	1.451 (± 0.015)
	149	72.0 (± 2.8)	1.857 (± 0.017)	8.644 (± 0.019)	8440	1.947 (± 0.018)
	434	9.1 (± 1.4)	0.960 (± 0.065)	–	–	4.449 (± 0.091)
	307	56.0 (± 2.8)	1.748 (± 0.022)	8.463 (± 0.014)	9530	1.909 (± 0.023)
2019yvr	334	9.2 (± 0.5)	0.961 (± 0.025)	8.489 (± 0.020)	9382	2.930 (± 0.042)
	399	17.8 (± 1.0)	1.250 (± 0.025)	8.527 (± 0.016)	9155	2.729 (± 0.029)
	428	60.8 (± 2.8)	1.784 (± 0.020)	8.400 (± 0.015)	9895	1.841 (± 0.021)
	94	10.1 (± 0.5)	1.002 (± 0.021)	8.537 (± 0.022)	9097	1.325 (± 0.034)
2019ehk	329	14.9 (± 0.6)	1.174 (± 0.017)	8.470 (± 0.038)	9493	1.656 (± 0.023)
	0	97.5 (± 2.3)	1.989 (± 0.010)	8.310 (± 0.018)	10403	1.943 (± 0.012)
2019yz	385	88.9 (± 1.7)	1.949 (± 0.008)	8.249 (± 0.020)	10733	1.336 (± 0.011)
	78	55.7 (± 4.4)	1.746 (± 0.035)	8.432 (± 0.016)	9712	2.149 (± 0.035)
2018ivc	158	43.6 (± 3.2)	1.640 (± 0.031)	8.465 (± 0.015)	9522	1.897 (± 0.032)
	193	72.4 (± 4.7)	1.860 (± 0.028)	8.457 (± 0.015)	9569	2.558 (± 0.029)
	386	35.1 (± 2.5)	1.546 (± 0.031)	8.435 (± 0.015)	9695	1.539 (± 0.032)
	447	10.7 (± 2.0)	1.028 (± 0.082)	8.347 (± 0.024)	10195	1.563 (± 0.085)
AT2018bbl	381	13.3 (± 0.9)	1.125 (± 0.028)	8.544 (± 0.023)	9053	1.600 (± 0.048)
2018pq	0	13.0 (± 0.9)	1.113 (± 0.029)	–	–	–
2017ivv	0	29.0 (± 0.3)	1.462 (± 0.004)	8.191 (± 0.450)	11039	0.552 (± 0.031)
2017ivu	–	–	–	–	–	–

Target	Distance (pc)	$EW(H\alpha)$ (Å)	$\log(EW(H\alpha))$	$12 + \log(O/H)$	T_e (K)	A_V (mag)
2017gax	0	66.9 (± 3.8)	1.825 (± 0.024)	8.555 (± 0.014)	8987	1.431 (± 0.025)
	159	50.4 (± 2.6)	1.703 (± 0.023)	8.570 (± 0.014)	8895	1.501 (± 0.024)
	501	33.9 (± 1.9)	1.530 (± 0.024)	8.547 (± 0.015)	9032	1.586 (± 0.027)
2017bzb	0	72.6 (± 1.3)	1.861 (± 0.008)	8.391 (± 0.019)	9950	0.467 (± 0.013)
	150	168.6 (± 2.8)	2.227 (± 0.007)	8.290 (± 0.019)	10513	0.366 (± 0.008)
2017aym	307	26.3 (± 1.8)	1.420 (± 0.029)	8.485 (± 0.017)	9404	3.240 (± 0.039)
2016iae	121	45.6 (± 2.3)	1.659 (± 0.022)	8.541 (± 0.018)	9074	2.467 (± 0.035)
	242	70.0 (± 3.7)	1.845 (± 0.023)	8.532 (± 0.015)	9127	2.507 (± 0.028)
	522	51.7 (± 2.6)	1.713 (± 0.022)	8.510 (± 0.019)	9257	2.493 (± 0.033)
2016hgm	0	82.7 (± 2.4)	1.918 (± 0.013)	8.375 (± 0.016)	10036	0.981 (± 0.014)
	88	112.9 (± 3.6)	2.053 (± 0.014)	8.393 (± 0.015)	9938	0.999 (± 0.014)
2016gkg	0	3.8 (± 0.3)	0.578 (± 0.032)	–	–	–
	307	18.6 (± 1.0)	1.269 (± 0.024)	–	–	1.41 (± 5.686)
	544	26.3 (± 1.4)	1.419 (± 0.022)	–	–	–
2016cok	101	46.9 (± 2.5)	1.671 (± 0.023)	8.558 (± 0.014)	8968	1.784 (± 0.024)
	176	76.6 (± 3.8)	1.884 (± 0.021)	8.617 (± 0.015)	8609	2.332 (± 0.022)
	225	34.3 (± 1.7)	1.535 (± 0.021)	8.548 (± 0.016)	9031	3.011 (± 0.028)
	244	55.4 (± 2.8)	1.744 (± 0.022)	8.556 (± 0.016)	8982	4.021 (± 0.026)
	309	62.7 (± 2.9)	1.797 (± 0.020)	8.627 (± 0.016)	8548	2.427 (± 0.021)
2016coi	106	59.0 (± 1.0)	1.771 (± 0.007)	8.238 (± 0.022)	10790	0.968 (± 0.014)
	243	125.4 (± 2.1)	2.098 (± 0.007)	8.303 (± 0.022)	10440	0.743 (± 0.009)
	300	38.5 (± 1.0)	1.586 (± 0.011)	8.553 (± 0.032)	9001	1.141 (± 0.027)
2016bmi	417	98.4 (± 1.4)	1.993 (± 0.006)	8.218 (± 0.026)	10899	0.527 (± 0.029)
2016afa	–	–	–	–	–	–
ASASSN16at	0	43.9 (± 1.0)	1.642 (± 0.010)	8.311 (± 0.018)	10394	1.021 (± 0.019)
	30	36.5 (± 0.9)	1.562 (± 0.011)	8.294 (± 0.019)	10488	1.104 (± 0.021)
	66	39.6 (± 0.8)	1.597 (± 0.009)	8.343 (± 0.020)	10217	1.431 (± 0.038)
ASASSN15oz	391	44.9 (± 1.3)	1.652 (± 0.012)	–	–	–
2015dj	424	41.0 (± 1.9)	1.612 (± 0.020)	8.505 (± 0.030)	9286	1.480 (± 0.050)

Target	Distance (pc)	$EW(H\alpha)$ (Å)	$\log(EW(H\alpha))$	$12 + \log(O/H)$	T_e (K)	A_V (mag)
ASASSN14ha	78	$40.5 (\pm 2.1)$	$1.608 (\pm 0.023)$	$8.605 (\pm 0.016)$	8685	$1.695 (\pm 0.024)$
2014L	28	$95.4 (\pm 4.4)$	$1.980 (\pm 0.020)$	$8.623 (\pm 0.015)$	8572	$2.215 (\pm 0.021)$
	179	$54.5 (\pm 2.0)$	$1.736 (\pm 0.016)$	$8.617 (\pm 0.018)$	8608	$1.828 (\pm 0.017)$
	281	$42.6 (\pm 2.0)$	$1.630 (\pm 0.020)$	$8.587 (\pm 0.016)$	8795	$1.881 (\pm 0.021)$
	380	$79.4 (\pm 4.1)$	$1.900 (\pm 0.022)$	$8.555 (\pm 0.014)$	8988	$1.754 (\pm 0.023)$
	455	$109.9 (\pm 5.5)$	$2.041 (\pm 0.022)$	$8.617 (\pm 0.015)$	8609	$1.770 (\pm 0.022)$
iPTF13bvn	119	$77.9 (\pm 4.4)$	$1.892 (\pm 0.025)$	$8.602 (\pm 0.015)$	8701	$1.995 (\pm 0.025)$
2013dk	35	$62.9 (\pm 3.7)$	$1.799 (\pm 0.026)$	$8.576 (\pm 0.014)$	8858	$1.751 (\pm 0.026)$
	256	$93.6 (\pm 4.8)$	$1.971 (\pm 0.022)$	$8.633 (\pm 0.015)$	8509	$1.383 (\pm 0.022)$
	267	$48.0 (\pm 2.7)$	$1.681 (\pm 0.024)$	$8.536 (\pm 0.014)$	9100	$1.971 (\pm 0.025)$
	353	$26.0 (\pm 1.7)$	$1.414 (\pm 0.028)$	$8.518 (\pm 0.015)$	9209	$1.420 (\pm 0.030)$
	472	$20.1 (\pm 1.0)$	$1.304 (\pm 0.021)$	$8.447 (\pm 0.015)$	9627	$1.003 (\pm 0.026)$
2012ec	256	$70.9 (\pm 3.4)$	$1.850 (\pm 0.021)$	$8.434 (\pm 0.014)$	9702	$1.603 (\pm 0.022)$
	262	$68.3 (\pm 3.4)$	$1.834 (\pm 0.022)$	$8.585 (\pm 0.014)$	8803	$1.345 (\pm 0.023)$
	283	$74.8 (\pm 3.3)$	$1.874 (\pm 0.019)$	$8.474 (\pm 0.014)$	9467	$1.132 (\pm 0.021)$
2012au	184	$29.4 (\pm 1.4)$	$1.469 (\pm 0.021)$	$8.479 (\pm 0.014)$	9437	$0.948 (\pm 0.022)$
	280	$90.3 (\pm 3.6)$	$1.956 (\pm 0.017)$	$8.395 (\pm 0.015)$	9928	$0.897 (\pm 0.018)$
	291	$69.9 (\pm 2.8)$	$1.845 (\pm 0.017)$	$8.437 (\pm 0.014)$	9686	$1.149 (\pm 0.018)$
	325	$77.4 (\pm 3.0)$	$1.889 (\pm 0.017)$	$8.418 (\pm 0.015)$	9796	$1.274 (\pm 0.018)$
2012P	0	$140.6 (\pm 7.2)$	$2.148 (\pm 0.022)$	$8.633 (\pm 0.015)$	8508	$1.894 (\pm 0.022)$
2009hd	0	$91.9 (\pm 4.4)$	$1.963 (\pm 0.021)$	$8.622 (\pm 0.015)$	8580	$2.358 (\pm 0.022)$
	350	$126.2 (\pm 6.4)$	$2.101 (\pm 0.022)$	$8.612 (\pm 0.014)$	8640	$3.011 (\pm 0.022)$
	437	$59.5 (\pm 3.9)$	$1.775 (\pm 0.028)$	$8.525 (\pm 0.014)$	9164	$1.353 (\pm 0.029)$
2009dq	0	$132.3 (\pm 9.2)$	$2.122 (\pm 0.030)$	$8.595 (\pm 0.015)$	8743	$2.317 (\pm 0.030)$
2009H	243	$80.0 (\pm 3.7)$	$1.903 (\pm 0.020)$	$8.528 (\pm 0.013)$	9152	$2.224 (\pm 0.022)$
	334	$106.4 (\pm 5.0)$	$2.027 (\pm 0.020)$	$8.471 (\pm 0.014)$	9486	$1.624 (\pm 0.021)$
2004dk	0	$98.2 (\pm 4.0)$	$1.992 (\pm 0.018)$	$8.501 (\pm 0.013)$	9311	$1.236 (\pm 0.018)$
2004dg	159	$139.5 (\pm 7.0)$	$2.144 (\pm 0.022)$	$8.630 (\pm 0.015)$	8527	$1.871 (\pm 0.022)$
	387	$124.5 (\pm 6.3)$	$2.095 (\pm 0.022)$	$8.603 (\pm 0.014)$	8696	$0.984 (\pm 0.022)$

Target	Distance (pc)	$EW(H\alpha)$ ($\text{\AA}$)	$\log(EW(H\alpha))$	$12 + \log(O/H)$	T_e (K)	A_V (mag)
2004cc	34	51.4 (± 1.6)	1.711 (± 0.013)	8.546 (± 0.047)	9043	2.347 (± 0.016)
	522	38.2 (± 1.1)	1.582 (± 0.013)	8.645 (± 0.032)	8437	2.490 (± 0.016)
1999br	57	201.4 (± 7.1)	2.304 (± 0.015)	8.352 (± 0.016)	10170	0.658 (± 0.015)
	451	123.9 (± 4.7)	2.093 (± 0.016)	8.410 (± 0.015)	9838	1.000 (± 0.017)
	543	95.0 (± 3.8)	1.978 (± 0.017)	8.456 (± 0.014)	9575	0.995 (± 0.019)
1998dl	154	74.2 (± 3.5)	1.870 (± 0.021)	8.523 (± 0.013)	9180	2.329 (± 0.023)
	290	78.5 (± 3.7)	1.895 (± 0.020)	8.465 (± 0.014)	9520	0.951 (± 0.022)
1996an	73	87.9 (± 4.5)	1.944 (± 0.022)	8.512 (± 0.013)	9243	1.480 (± 0.023)
	364	111.2 (± 5.3)	2.046 (± 0.021)	8.467 (± 0.014)	9512	1.660 (± 0.022)
	437	101.9 (± 4.8)	2.008 (± 0.020)	8.467 (± 0.014)	9510	1.270 (± 0.021)
1986I	125	90.5 (± 3.7)	1.956 (± 0.018)	8.629 (± 0.015)	8537	1.320 (± 0.019)
	250	123.0 (± 5.6)	2.090 (± 0.020)	8.616 (± 0.014)	8615	1.977 (± 0.020)
	391	84.3 (± 3.8)	1.926 (± 0.020)	8.611 (± 0.015)	8648	2.049 (± 0.021)
	451	59.9 (± 2.3)	1.778 (± 0.017)	8.585 (± 0.015)	8805	2.267 (± 0.019)
	594	131.0 (± 5.9)	2.117 (± 0.020)	8.673 (± 0.017)	8263	1.606 (± 0.020)
1973R	0	50.7 (± 2.2)	1.705 (± 0.019)	8.611 (± 0.016)	8646	1.632 (± 0.020)
	202	51.2 (± 2.8)	1.709 (± 0.024)	8.622 (± 0.018)	8579	3.453 (± 0.026)
	209	58.8 (± 2.7)	1.769 (± 0.020)	8.630 (± 0.016)	8527	2.269 (± 0.021)
1967H	0	277.5 (± 14.1)	2.443 (± 0.022)	8.536 (± 0.013)	9101	1.655 (± 0.022)
	140	147.6 (± 7.6)	2.169 (± 0.022)	8.489 (± 0.014)	9378	2.133 (± 0.023)
	373	187.6 (± 9.7)	2.273 (± 0.023)	8.515 (± 0.013)	9229	1.963 (± 0.023)

distance from each SNe site. Distances were measured from the SNe position to the nearest edge of the H II region, and so represent a minimum distance. A quoted distance of zero is the result of the SN coordinates falling inside the defined H II region. When considering the number of SN in my catalogue associated with H II regions, a lower limit can be found from all those directly coincident with their H II regions and an upper limit can be taken as all within distances < 100 pc. This gives a range of 34 - 54% of SNe associated with a H II region. Mayker Chen et al. (2024) performed a study on 32 SN sites, 23 of which are CCSNe, looking for association to H II regions with MUSE. Purely looking for coincidence with H II regions, they find 52% (12/23) alignment. Applying a stricter criteria of coincidence with a $H\alpha + CO$ bright H II region, this fraction drops to 43%. Therefore, we find good agreement between these ranges, and they could be combined to a more simplified statistic of 1/3 to 1/2 of all CCSNe being coincident with a H II region. Mayker Chen et al. (2024) perform further tests on the MUSE $H\alpha$ maps folded with simple stellar population (SSP) models from STARBURST99 to estimate the probability of chance alignment between any randomly placed SN and the density maps of $H\alpha$ emission (across both 500×500 pc and 1×1 kpc regions). They find as many as $\approx 1/3$ of all SN appear associated to a H II region by chance alone. Nevertheless, using this chance statistic, they find an excess of SNe associated with H II regions that increases from all Types $\rightarrow$ Type II $\rightarrow$ SESNe (7.6% $\rightarrow$ 10.5% $\rightarrow$ 38% excess).

An exploration of correlations between measured environmental parameters and SN classifications reveals no strong dependencies. H II region ages and balmer decrement extinctions show random scatter, with some clustering between 6 - 8 million years and 1.5 - 2.5 mag.

4.8 Comparing Stellar Population and H II Region Ages

Under the assumption that identified H II regions represent the ionised birthsites of massive stellar populations, their measured $EW(H\alpha)$ values can be associated with a population age using the STARBURST99 models. This allows for a direct comparison between two methods for age dating SNe. Initial age estimates from STARBURST99 were drawn from the instantaneous star formation models, with a Salpeter (1955) IMF. The closest match in metallicity between measured oxygen abundances (Table 4.6) and the STARBURST99 metallicity grid ($Z/Z_{\odot} = 0.001, 0.004, 0.008, 0.020, 0.040$) were selected for a given H II region. Using the nearest H II region to each SN site, a direct comparison to the resolved stellar population ages are presented in Figures 4.16 and 4.17.

Strong agreement (within $1\sigma_{\text{stellar}}$) between ages from both methods is only observed for three of the SNe in the entire catalogue: SN 2004dg, SN 2015dj and SN 2020hvp. It is worth noting that all of these cases have comparatively large stellar population $\log(\text{age/yr})$ errors, but find direct overlap between their optimum stellar population ages and their nearest H II region ages. Other SNe find weak agreement, within $3\sigma_{\text{stellar}}$ and an associated stellar population $\log(\text{age/yr})$ error $\sigma_{\text{stellar}} \leq 0.07$: SN 2016coi and SN 2016cok. Even when including the latter, weaker cases, this implies only 10% of the catalogue provide evidence of agreement between the two methods of aging stellar populations. This is not to say that either method is wrong, but that perhaps, for many SN environments, association to the nearest H II region is a poor assumption and the true natal stellar population of a SN progenitor is missed through this approach. Of course, the opposite could be said, as the resolved stellar population method has limitations. For example, there is no conclusive test for whether a stellar population is in fact a foreground population obscuring the true natal population of a SN. Nevertheless, given that the resolved stellar population approach draws from detected sources within a 150 pc vicinity to each SN site, it should be considered the more reliable of the two methods.

This raises the question of the distances between each SN and its nearest neighbouring H II region. For the strongest four cases mentioned above, these are 154 pc (SN 1998dl), 159 pc (SN 2004dg), 424 pc (SN 2015dj) and 285 pc (SN 2020hvp). Anything below ~ 200 pc suggests a high likelihood of association to the H II region; exceeding 400 pc does not, except for the rare cases of high velocity ejected systems. The weaker cases of SN 2016coi and SN 2016cok have distances of 106 pc and 101 pc respectively, strengthening the argument that they originate from their closest H II region.

Interestingly, all age estimates from the tables of STARBURST99 models fall within a narrow range of $\log(\text{age/yr}) = 6.71 - 7.17$ corresponding to 5.13 - 14.79 million years (grey shaded regions in Figures 4.16 and 4.17). This is shallow in comparison to the $\log(\text{age/yr}) = 6.29 - 7.67$ range of ages found through resolved stellar populations, corresponding to 1.95 - 46.77 million years. Such a difference in detected ranges implies a sensitivity limit for the $EW(\text{H}\alpha)$ -age diagnostic, imposing a bias towards age estimates within this narrow range. One explanation could be that H II regions younger than ~ 5 million years are still shrouded in dense ISM, however this contradicts the predicted luminosities from STARBURST99. Moreover, the expectation would be that winds from O and B stars, as well as ongoing SNe shockwaves, would drive out much of this material. Only in rare circumstances, with exceptionally dense gas and dust deposits, would we expect this scenario to be plausible. This brings into question if the source of this discrepancy stems from the reliability of the measured $EW(\text{H}\alpha)$ values in this study. Looking to past examples of H II region EW measurements, Kuncarayakti et al. (2013b) and Kuncarayakti et al. (2013a) find an upper-range of values that greatly exceed those found here. Their most extreme EW values are also paired with unreasonably large errors that devalue their reliability. Furthermore, they find a disproportionate number of extreme EWs with respect to their small sample size (19), that correspond to exceptionally rare high-mass progenitors ($> 100 M_{\odot}$). Reassuringly, the single common SN between this work and Kuncarayakti et al. (2013b) (SN 2009hd) shows agreement

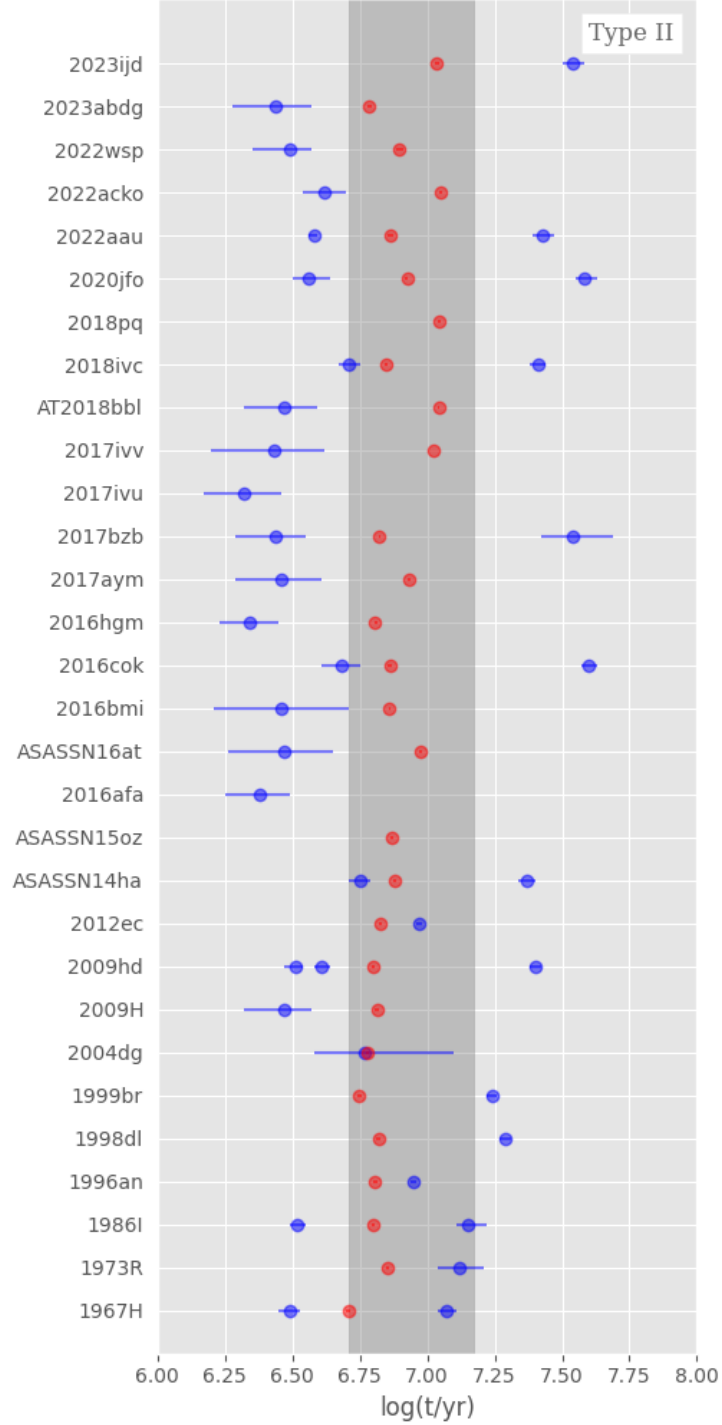


Figure 4.16: Comparison of age estimates from resolved stellar populations (blue datapoints) and the nearest H II region (red datapoints) for all Type II catalogue SNe. All results from environments with multiple resolved stellar populations are included. Stellar population ages are from the best-fit PARSEC isochrone, and H II region ages correspond to a $\log(EW(H\alpha))$ value in the instantaneous star-formation STARBURST99 tables. Errors on the H II ages are too small to be seen. A grey shaded region highlights the narrow range of ages found for all of the nearest H II regions.

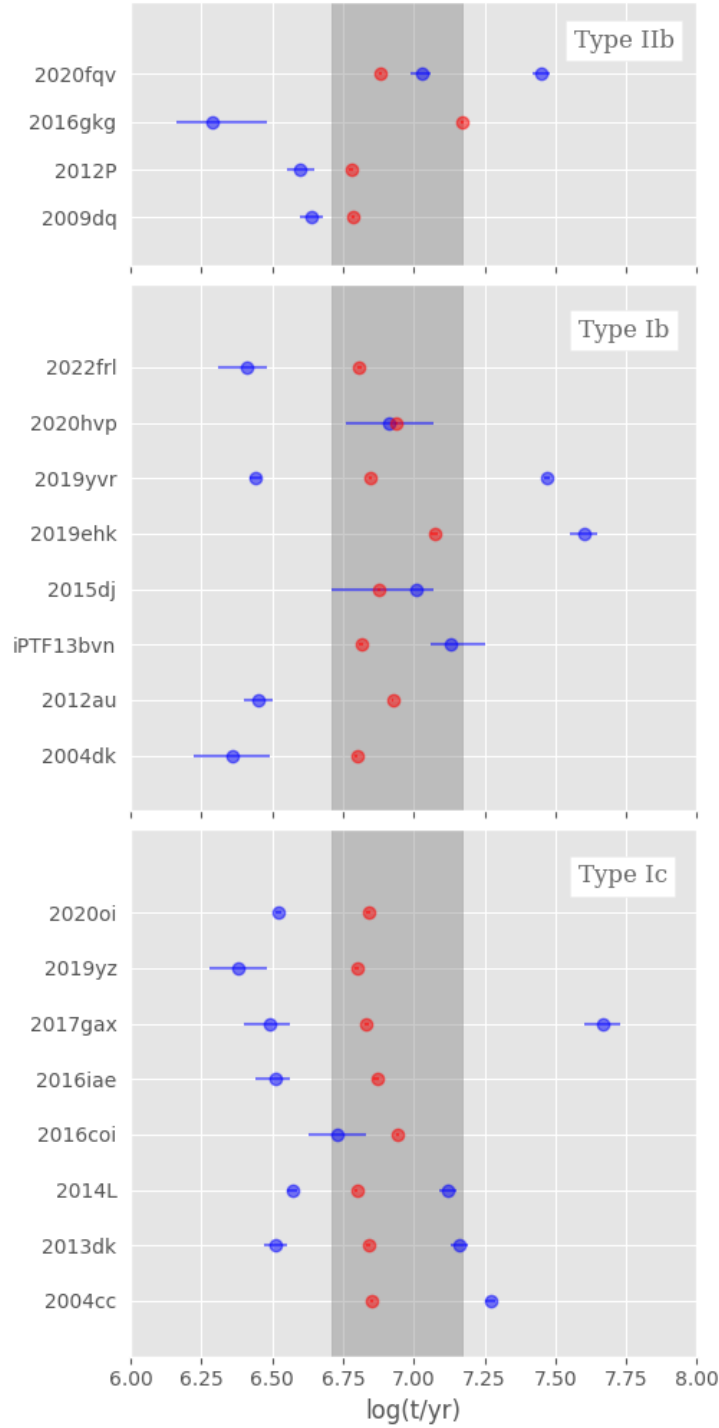


Figure 4.17: Comparison of age estimates from resolved stellar populations (blue datapoints) and the nearest H II region (red datapoints) for all catalogue SESNe (Type IIb, Ib and Ic). All results from environments with multiple resolved stellar populations are included. Stellar population ages are from the best-fit PARSEC isochrone, and H II region ages correspond to a $\log(EW(H\alpha))$ value in the instantaneous star-formation STARBURST99 tables. Errors on the H II ages are too small to be seen. A grey shaded region highlights the narrow range of ages found for all of the nearest H II regions.

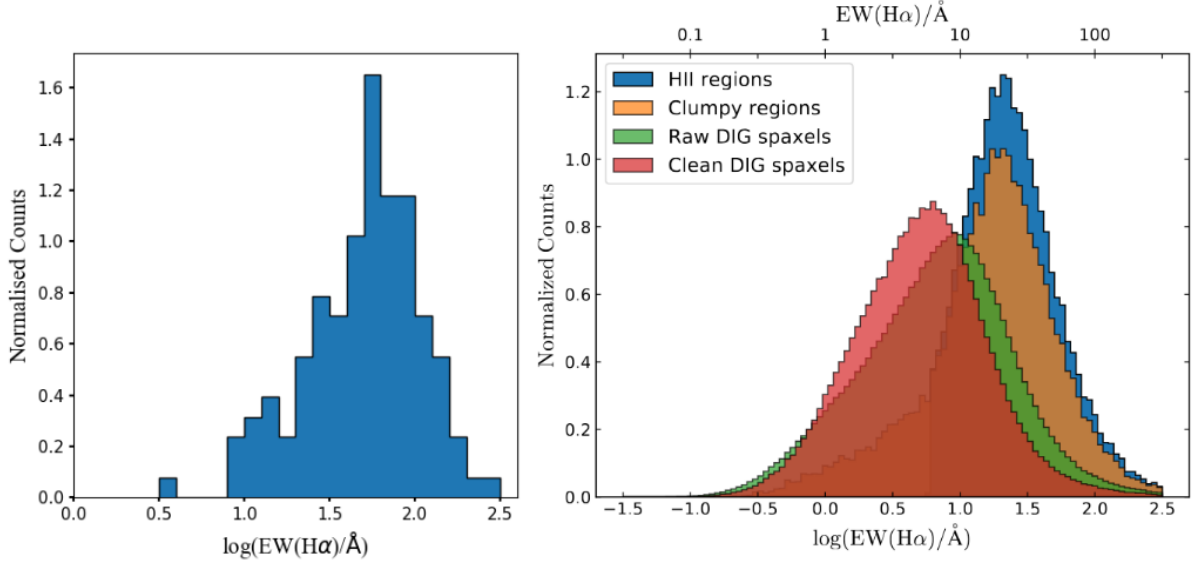


Figure 4.18: Normalised histograms comparing H II region $\log(EW(H\alpha))$ distributions from my own catalogue and those found by [Espinosa-Ponce et al. \(2020\)](#). On the left are my own results from all resolved H II regions in Table 4.6. On the right is a plot pulled directly from [Espinosa-Ponce et al. \(2020\)](#), showing their own results for a sample of nearby galaxies of various morphologies. Their plot contains distributions for four different sub-groups of ionised regions that they define, with the closest comparison to my own results being for 'H II regions'.

between EW values, although this corresponds to the most distant H II region in Table 4.6. [Kuncarayakti et al. \(2013a\)](#) finds a range of EW values that more closely resembles my own distribution, but still includes more extreme values. A more modern study that utilises IFU spectroscopy, [Espinosa-Ponce et al. \(2020\)](#), finds a distribution of H II region $\log(EW(H\alpha))$ from a complete sample of galaxy morphologies. Figure 4.18 shows the similarity in minimum, peak and maximum values between my distribution and [Espinosa-Ponce et al. \(2020\)](#). Overall, my EWs seem to reliably reflect commonly measured values.

Finding H II regions at such a young and luminous stage as $\log(EW(H\alpha)) \gtrsim 2.5$ would result in progenitor mass estimates $\gtrsim 40M_{\odot}$, representing rare high-mass progenitors. Alternatively, the lack of detected H II regions with ages $\lesssim 5$ million years could represent a low probability of finding a high-mass SN progenitor coincident with a very young H

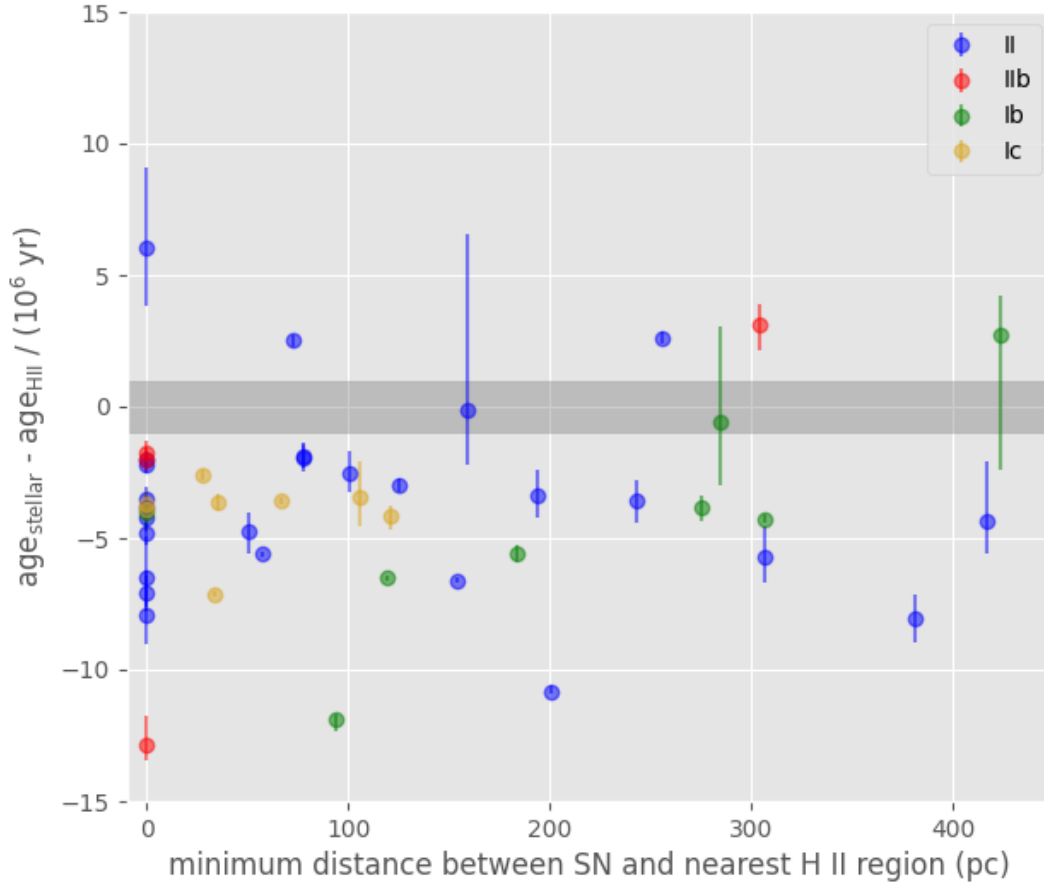


Figure 4.19: Differences in age between resolved stellar populations and the nearest H II region as a function of minimum distance between the SN site and H II region. A grey shaded region shows ± 1 Myr, to emphasize targets with strong agreement between the two dating methods. For catalogue environments with multiple resolved stellar populations, the population age within closest agreement to the nearest H II region age was chosen. The results are colour-coded by SN classification (see legend).

H II region.

Having two approaches for estimating the ages of resolved environmental features (stellar populations and H II regions) motivates a comparison between methods, as well as SN classifications. Figure 4.19 shows the difference in age between the nearest H II region and the resolved stellar population as a function of the distance between them. If

there were multiple stellar populations to choose from, the closest in age to the respective H II region was selected. A grey ± 1 million year shaded region represents a range of good agreement between both methods; the three examples where this was the case can be seen to intersect this region. Colour-coded datapoints represent the four main SN classifications that form the catalogue (Type II, IIb, Ib, Ic). The only classification to show any group behaviour is Type Ic, with a clustering of the golden datapoints. All seven Type Ic SNe are no more than ~ 120 pc from a H II region and their age differences, with the exception of one SN, are < 5 million years. For all Type Ic SNe their nearest H II regions are systematically older than their resolved stellar population, however four of these environments also contain an older resolved stellar population. Considering the more random spread of other SN classifications in Figure 4.19 and the low number (7) of Type Ic, this observed group behaviour seems unlikely to be coincidental. This result aligns with the previously discussed study Mayker Chen et al. (2024) (Section 4.7), who find a greatest excess of association to H II regions for SESNe. My results suggest this excess is strongest for Type Ic, if association is treated as simultaneously minimising the distance and difference in age between both dating methods. For Type Ib, there is a trend of finding closer agreement between the two ages with increasing distance between the SN site and H II region. My small sample (4) of Type IIb shows mixed results, with two demonstrating spatial coincidence and good agreement between ages and the remaining two displaying strong discrepancies in either distance or age.

4.9 Individual Supernovae

When presenting results for individual SNe, my catalogue can be divided into ranks. Since the entire catalogue has MUSE data, these ranks are based on the amount of high spatial resolution HST images available. They are as follows:

1. **Gold:** 3+ images of different filters.

2. **Silver**: 2 images of different filters.

3. **Bronze**: 1 image.

Any progenitor mass estimates quoted from my results correspond to the maximum possible mass in the relevant PARSEC stellar isochrone table for a given age and metallicity.

4.9.1 Gold Targets

SN 2022acko

SN 2022acko was first detected on 6 December 2022 (Lundquist et al., 2022), and quickly classified as Type IIP (Meza et al., 2022). It exploded in the outer spiral arm of its host NGC 1300, a barred spiral galaxy. Bostroem et al. (2023) obtained extensive spectroscopic coverage with HST spanning 5 – 21 days post-explosion. Modelling this data with CMFGEN finds a good match to a pre-explosion progenitor of a low-mass RSG, corresponding to $12 M_{\odot}$ at solar metallicity. Through a combination of JWST and HST imaging, Van Dyk et al. (2023) confirmed the disappearance of a detected progenitor source. This objects SED and overall luminosity is consistent with an initial mass progenitor, for a single-star model, within a range that potentially falls below the canonical $8 M_{\odot}$ theoretical value, but extends as high as $9 M_{\odot}$. Through a combination of HST and Spitzer imaging, spanning UV - IR, Teixeira et al. (2026) find conflicting progenitor mass estimates whilst modelling data with direct and indirect approaches. Through shock cooling modelling of the early-time photometry, they find a $9 - 10 M_{\odot}$ RSG progenitor. Alternatively, the inferred ^{56}Ni mass from the radioactive decay tail suggests a progenitor initial mass in the range $10 - 15 M_{\odot}$. Finally, blackbody fitting to the detected pre-explosion source, similarly to Bostroem et al. (2023), yields a very low-mass estimate of $\sim 7.5 M_{\odot}$.

The larger scale environment of SN 2022acko contains multiple star forming regions, with a H II region coincident with the site and four neighbouring H II regions within close

proximity (most < 200 pc). One of these is a considerably larger star forming complex, whilst the others are more well-defined, smaller H II regions. A single, young stellar population was resolved within 150 pc corresponding to a progenitor mass estimate of $59.6^{+28.9}_{-16.3} M_{\odot}$ and an extinction of $A_V = 0.75^{+0.10}_{-0.10}$. Given the convergence towards a low-mass RSG progenitor from past studies of SN 2022acko, this suggests an older stellar population was missed by the photometric analysis. Alternatively, the age of the local H II region corresponds to a mass estimate of $\sim 17.8 M_{\odot}$. All of the aforementioned studies find evidence of negligible host extinction for the progenitor (upper value of $A_{V,\text{host}} \approx 0.12$ mag; Bostroem et al. 2023), which contradicts my higher value of $A_V = 0.75^{+0.10}_{-0.10}$ mag. Although they acknowledge a potential underestimation of the host extinction, this discrepancy points towards the ‘missing’ older stellar population corresponding to foreground stars.

SN 2022aau

SN 2022aau was first detected on 20 January 2022 (Bostroem et al., 2022) and was classified more broadly as Type II, having a red spectrum that is consistent with significant host-galaxy reddening (Siebert & Foley, 2022). Analysis of this event is complicated by its close proximity to the galactic centre of its host galaxy, NGC 1672. This likely contributes to the lack of detailed progenitor studies within the literature. Nagao et al. (2022) confirmed, with spectropolarimetry data, that SN 2022aau is heavily impacted by dust in its host galaxy.

Most of the large-scale environment of SN 2022aau is devoid of features, besides a large star forming complex that has been divided into three bordering H II regions by my pipeline. Within the local 150 pc environment, two stellar populations were resolved. Firstly, the youngest population corresponding to an initial mass of $71.4^{+7.7}_{-3.4} M_{\odot}$ with a high local extinction of $A_V = 1.23^{+0.06}_{-0.06}$ mag. Secondly, an older population corresponding to an initial mass of $10.2^{+0.5}_{-0.5} M_{\odot}$ with a negligible local extinction of $A_V = 0.04^{+0.02}_{-0.01}$.

mag. A H II region is coincident with the SN 2022aau site, with an age corresponding to a $27.2^{+0.6}_{-1.2} M_{\odot}$ progenitor mass, falling in between the photometrically determined estimates.

SN 2020oi

SN 2020oi was first detected on 7 January 2020 (Forster et al., 2020a) and classified within a few days as a Type Ic (Siebert et al., 2020). Rho et al. (2021) and Gagliano et al. (2022) independently found agreement between their estimates for the progenitor explosion energy, ejecta mass and ^{56}Ni mass. Using the coincident stellar cluster photometry, with extensive archival HST pre-explosion images, Gagliano et al. (2022) find a best-fit BPASS model of a binary system with an initial mass of $9.5 \pm 1.0 M_{\odot}$ and a corresponding age of 27 ± 7 Myr. They use a local extinction of $A_V \approx 0.47$, around half the value found by my fitting ($A_V = 0.97^{+0.06}_{-0.06}$ mag).

A high density of stars (99) in the local 150 pc environment confirms the previously identified dense stellar cluster, with a single resolved stellar population. As well as a larger extinction, I find a much younger stellar population (3.31 ± 0.08 Myr) with a corresponding progenitor mass estimate of $98.6^{+6.4}_{-5.6} M_{\odot}$. Looking at the wider environment, SN 2020oi is surrounded by bright star forming regions, with the nearest H II region at ~ 67 pc. This H II region is dated slightly older (~ 6.90 Myr) and implies a lower mass progenitor of $\sim 28.4 M_{\odot}$. Nevertheless, the case of SN 2020oi highlights the limitations of my fitting, similarly to iPTF13bvn, of not being able to identify binary channels of stellar evolution that often result in very different progenitor masses compared to single-star channels.

SN 2020jfo

SN 2020jfo was first detected on 6 May 2020 (Nordin et al., 2020) in an outer spiral arm of its host galaxy NGC 4303. Initially it was spectroscopically classified as Type

II (Perley et al., 2020) and later refined to Type IIP through its lightcurve. Various studies have constrained the progenitor of SN 2020jfo (Sollerman et al., 2021; Teja et al., 2022; Kilpatrick et al., 2023; Ailawadhi et al., 2023; Utrobin & Chugai, 2024) through spectroscopic, lightcurve or nebular-phase modelling, as well as one direct detection. A fully inclusive range of progenitor mass estimates spans $7.2 - 15 M_{\odot}$, however more often values fall between $8 - 13 M_{\odot}$. All of these studies converge on a lower-mass RSG. The lowest value of $7.2 M_{\odot}$, falling below the accepted theoretical minimum ($\sim 8 M_{\odot}$), is from a direct detection with archival HST imaging by Kilpatrick et al. (2023). They conclude that the discrepancy between this low value and indirect mass estimates likely originates from an underestimated extinction from material close to the progenitor, lowering its observed optical luminosity.

My exploration of SN 2020jfo reveals highly fragmented star forming regions across its larger environment, a coincident H II region and two photometrically resolved stellar populations (within 150 pc). These comprise a younger, $M_1 = 79.5^{+32.9}_{-24.8} M_{\odot}$ $A_{V,1} = 0.51^{+0.13}_{-0.10}$, and older, $M_2 = 8.3^{+0.3}_{-0.5} M_{\odot}$ $A_{V,2} = 0.32^{+0.14}_{-0.21}$, population, the latter of which agrees well with past literature. The H II region coincident with SN 2020jfo produces a progenitor mass estimate of $\sim 22.9 M_{\odot}$, which doesn't support one stellar population over the other.

SN 2019yvr

SN 2019yvr was first detected 29 December 2019 (Tonry et al., 2019) in its host galaxy NGC 4666, and spectroscopically classified as Type Ib (Dimitriadis et al., 2019). Late-time (>150 days) interaction of the SN ejecta with a hydrogen rich, dense CSM is indicative of eruptive mass-loss or common envelope evolution scenarios (Ferrari et al., 2024; Kilpatrick et al., 2021). Direct analysis of the progenitor, with HST imaging, by Kilpatrick et al. (2021) finds a best-fit binary model with initial masses of approximately $19 M_{\odot}$. They acknowledge, however, that this model retains a low-mass hydrogen

envelope on the progenitor, inconsistent with the observed evolution of SN 2019yvr. Moreover, this reflects the models inability to incorporate rapid mass-loss (eruptive) in the final decades of the progenitors life. Indirect estimates agree with the low-mass binary interpretation. Ferrari et al. (2024) obtained a He-core mass from nebular spectrum modelling, which implies an initial mass of $13 - 15 M_{\odot}$. A similar environmental analysis to my own, by Sun et al. (2022a), finds three episodes of star formation and a well constrained progenitor mass estimate of $10.4^{+1.5}_{-1.3} M_{\odot}$. Deconstruction of the SED reveals a hot and compact SN progenitor, plus a cool and inflated yellow hypergiant (YHG) companion that dominates the brightness.

Looking at the larger-scale environment of SN 2019yvr unveils a mostly inactive immediate environment surrounded by more active regions, with all identified H II regions at distances greater than 300 pc of the SN site (similar to iPTF13bvn). Two stellar populations were found in the central 150 pc environment: $M_1 = 176.6^{+37.7}_{-27.8} M_{\odot}$ and $A_{V,1} = 0.59^{+0.10}_{-0.11}$ mag; $M_2 = 9.5^{+0.1}_{-0.1} M_{\odot}$ and $A_{V,2} = 0.28^{+0.04}_{-0.04}$ mag. As found by Sun et al. (2022a), the oldest resolved stellar population finds closest agreement to a low-mass binary system.

SN 2018ivc

SN 2018ivc was first detected on 24 November 2018 (Valenti et al., 2018) in the inner spiral arm of its host galaxy NGC 1068, and spectroscopically classified as Type II Yamanaka (2018). Further exploration of lightcurve and spectroscopic data suggest SN 2018ivc could exhibit features of a bridge between Type IIL and IIb SNe (Reguitti et al., 2024; Maeda et al., 2023), also displaying CSM interaction. Bostroem et al. (2020) find progenitor constraints through $EW(H\alpha)$ measurements of the parental H II region, as well as pre-explosion HST photometry, finding two initial mass estimates. They find evidence it could be as large as $52 M_{\odot}$, but is more likely $< 12 M_{\odot}$. Studies of the mass-loss history and subsequent CSM interaction (Maeda et al., 2023) points towards an

extreme version of binary interaction, causing the unusual slope changes in the lightcurve of SN 2018ivc (Bostroem et al., 2020).

Through my own investigation, the site of SN 2018ivc falls nearby a narrow chain of interconnected bright H II regions or a potential larger starforming complex. A 150 pc aperture, centred on SN 2018ivc, coincides with the highest density of resolved stars found within my catalogue (212), separated into two stellar populations. The youngest corresponds to an initial mass of $42.6^{+6.6}_{-5.3} M_{\odot}$ and $A_V = 1.23^{+0.06}_{-0.06}$ mag extinction; the oldest instead finding $10.2^{+0.4}_{-0.4} M_{\odot}$ and $A_V = 0.06^{+0.04}_{-0.02}$ mag. Both of these values align with those found by Bostroem et al. (2020), although I do not find strong evidence of a single parental H II region. Instead the nearest H II region to SN 2018ivc, at a distance of 78 pc, has an estimated age that corresponds to a $\sim 28 M_{\odot}$ progenitor.

SN 2017gax

SN 2017gax was first observed on 14 August 2017 (Valenti et al., 2017) in the inner spiral arm of its host galaxy NGC 1672, and classified as Type Ib/c (Jha et al., 2017). Progenitor constraints do not exist in the literature for SN 2017gax.

The environment contains a large, bright H II region coincident with SN 2017gax. An age estimate, from the $EW(H\alpha)$ measurement, corresponds to a $\sim 29.1 M_{\odot}$ progenitor. Alternatively, the resolved stellar populations provide a further two possible progenitors. A young population corresponds to a very high-mass, poorly constrained, progenitor of $120.0^{+188.9}_{-40.3} M_{\odot}$ and a $A_V = 0.51^{+0.06}_{-0.05}$ mag extinction. From the older population, a more realistic progenitor of $7.4^{+0.7}_{-0.5} M_{\odot}$ and $A_V = 0.31^{+0.23}_{-0.12}$ mag extinction is found. Although all masses are viable, prior SESNe in this work have found closest agreement between the oldest resolved stellar population and prior progenitor constraints. The low-mass estimate from this older population would imply a binary system, in order to achieve a highly stripped star.

SN 2016gkg

SN 2016gkg was first detected on 21 September 2016 (Otero & Buso, 2016) in the outer spiral arm of its host galaxy NGC 613, and a series of spectra later classified it as Type IIb (Van Dyk et al., 2016). The first analysis of a directly detected progenitor source, Tartaglia et al. (2017), in archival HST imaging yields a mass range of $15 - 20 M_{\odot}$, dependent on the assumed distance modulus. A second direct analysis (Kilpatrick et al., 2017), assisted by Keck-II adaptive optics imaging, finds best agreement between the photometry and a binary model. This binary model consists of a yellow supergiant primary star with $M_{\text{ZAMS}} = 15 M_{\odot}$ and a secondary with $M_{\text{ZAMS}} = 15 M_{\odot}$. Late-time imaging has since confirmed the disappearance of the suspected progenitor candidate (Kilpatrick et al., 2022).

My photometric analysis of SN 2016gkg is highly limited by the low number (4) of resolved stars across the range of filters in a 150 pc aperture. Extending to a 300 pc aperture negligibly increased this number, and so these additional sources were not included to avoid skewing the results. A single, very young stellar population was found, implying a progenitor mass of $\sim 350 M_{\odot}$ with a moderately high extinction of $A_V = 0.89^{+0.13}_{-0.14}$ mag. Not only is this at the theoretical limit of physically possible stars, but it can be presumed to not result in a CCSN. Instead, it is more likely that the resolved objects are dense stellar clusters and all single stars are photometrically missed. Alternatively, a bright H II region was resolved coincident with the site of SN 2016gkg. No extinction was obtained for this H II region owing to a lack of $H\beta$ emission, indicative of a potentially very high local extinction. This could explain the lack of detected stars that may be intensely reddened. An $EW(H\alpha)$ age estimate of the H II region corresponds to a progenitor mass of $\sim 14.4 M_{\odot}$, which agrees strongly with past studies.

SN 2016cok

SN 2016cok was first detected on 28 May 2016 (Bock & Dong, 2016) in the spiral arm of its host galaxy NGC 3627, and spectroscopically classified as Type IIP (Zhang et al., 2016a). Kochanek et al. (2017) searched for a progenitor in archival HST data, however the source was a blend of several stars. Nevertheless, under their assumptions they infer a mass $\lesssim 17 M_{\odot}$, most likely within the range $8 - 12 M_{\odot}$.

The larger environment of SN 2016cok is rich in diffuse ionised gas and bright star forming regions, with five H II regions within 300 pc of the SN site. The central 150 pc environment is dense in resolved stars (147), best-fit by 2 unique populations. A younger population produces a progenitor estimate with $46.6_{-9.9}^{+15.9} M_{\odot}$ mass and $A_V = 0.98_{-0.10}^{+0.10}$ mag extinction, and an older population with $8.1_{-0.3}^{+0.3} M_{\odot}$ and $A_V = 0.05_{-0.01}^{+0.02}$ mag. For a typical Type IIP SN, a lower mass RSG is more plausible and would more closely agree with Kochanek et al. (2017).

SN 2016coi

SN 2016coi was first detected on 27 May 2016 (Stanek, 2016) in the outer region of its host galaxy UGC 11868, and spectroscopically classified as Type Ic-BL (Elias-rosa, 2016). Spectra and lightcurve modelling by Prentice et al. (2018) produces a progenitor mass range of $M_{ZAMS} = 23 - 28 M_{\odot}$, but they highlight the uncertainty in distance and $E(B-V)_{\text{host}}$ values. This initial progenitor was then stripped down, almost entirely, to a C/O core. Features of the late-time optical spectra are indicative of a large progenitor core mass at the time of collapse (Terreran et al., 2019). Both studies converge on a massive single-star progenitor, but binary scenarios can not be ruled out.

Through the lens of MUSE the immediate environment of SN 2016coi is mostly devoid of H α emission and star forming regions, also noted by Prentice et al. (2018). At larger scales, there were three identified H II regions at distances > 100 pc. A single

stellar population was photometrically resolved, corresponding to a progenitor mass of $40.2^{+17.9}_{-10.4} M_{\odot}$ and $A_V = 0.34^{+0.09}_{-0.07}$ mag extinction. Although poorly constrained, this supports the massive single-star progenitor.

ASASSN-14ha

ASASSN-14ha was first observed on 11 September 2014 (Brown, 2014) very close to the nucleus of its host galaxy NGC 1566. Initial spectroscopic classifications labelled it as Type II (Arcavi et al., 2014), but subsequent lightcurve data upgraded this to Type IIP. Progenitor constraints do not currently exist in the literature.

My analysis found the environment of ASASSN-14ha to contain two resolved stellar populations with unique ages. The youngest population corresponds to a progenitor mass of $36.7^{+5.2}_{-4.1} M_{\odot}$ and extinction of $A_V = 0.71^{+0.06}_{-0.07}$ mag. Alternatively, the older population matches a $10.8^{+0.5}_{-0.4} M_{\odot}$ mass and $A_V = 0.16^{+0.05}_{-0.04}$ mag extinction. The larger environment is almost entirely devoid of $H\alpha$, besides an extended H II region close to the site of ASASSN-14ha (~ 78 pc). Both stellar population mass estimates are plausible, but the lower of the two is more typical of commonly observed Type IIP SNe progenitors.

SN 2014L

SN 2014L was first observed on 26 January 2014 (Zhang et al., 2014) in the inner spiral arm of its host galaxy NGC 4254, and spectroscopically classified as Type Ic (Yamaoka et al., 2014). Zhang et al. (2018) have constrained the synthesized ^{56}Ni mass, explosion energetics and ejecta mass; no constraints of the progenitor and its initial mass exist in the literature.

The broader environment of SN 2014L is rich in diffuse ionised gas and bright star forming regions. Five H II regions were resolved in total, with one in close proximity to the SN site (~ 28 pc). Analysing the local 150 pc environment finds two photometrically resolved stellar populations. These produce unique progenitor constraints: (younger)

$M_1 = 75.4^{+8.4}_{-7.1} M_\odot$ and $A_{V,1} = 0.89^{+0.07}_{-0.07}$ mag; (older) $M_2 = 16.1^{+0.9}_{-0.8}$ and $A_{V,2} = 0.52^{+0.16}_{-0.17}$ mag. Within the argument of explodability, the lower mass is more likely to result in a CCSN.

SN 2013dk

SN 2013dk was first detected on 22 June 2013 in the central region of its host galaxy NGC 4038 (one of the Antennae Galaxies), and spectroscopically classified as Type Ic (Carrasco et al., 2013). An attempt to directly observe the progenitor of SN 2013dk, by Elias-Rosa et al. (2013), resulted in a non-detection. They did identify a nearby bright extended source thought to be a compact star cluster that could be associated with the SN, though this is not conclusive. Reasonable fitting of the cluster SED dates it at 15 – 22 Myrs, implying a progenitor mass in the range of 10 – 15 $M_\odot$.

My own look at the environment of SN 2013dk reveals scattered regions of star formation, none directly coincident with the SN site. Local to SN 2013dk (150 pc), the oldest resolved stellar population corresponds to a progenitor mass of $15.0^{+0.8}_{-0.7} M_\odot$ and an extinction of $A_V = 0.72^{+0.12}_{-0.12}$ mag, in agreement with the range proposed by Elias-Rosa et al. (2013). There was, however, a secondary younger population found which implies a higher mass of $105.6^{+23.4}_{-21.8} M_\odot$ and extinction $A_V = 0.99^{+0.09}_{-0.09}$ mag. Similar explodability arguments made for SN 2014L still apply, favouring the smaller of the two progenitor mass estimates.

iPTF13bvn

The case of iPTF13bvn has been extensively covered in Chapter 3, along with progenitor constraints from past studies. Nevertheless, the environment was reanalysed in accordance with the streamlined catalogue pipeline. Compared to the previously applied 300 pc aperture, these secondary results were obtained for 150 pc. This stringent selection of resolved stars resulted in a single, older stellar population of $\tau = 7.13^{+0.12}_{-0.07}$ compared

to my previous results ($\tau_1 = 6.59_{-0.05}^{+0.04}$; $\tau_2 = 6.97_{-0.06}^{+0.06}$) and a slightly more relaxed extinction of $A_V = 0.39_{-0.16}^{+0.12}$ mag compared to the favoured original value of $A_{V,2} = 0.53_{-0.08}^{+0.10}$ mag (still overlapping within 1σ). This new age more closely resembles the oldest stellar population resolved in Maund (2018) of $\tau = 7.38_{-0.06}^{+0.01}$. Conversion of my own new age estimate into a progenitor mass gives $15.8_{-2.8}^{+2.2} M_\odot$, still comfortably within the $10-20 M_\odot$ range from past studies of alternative methods and no longer contested by a secondary stellar population.

SN 2012ec

SN 2012ec was first detected on 11 August 2012 in its host galaxy NGC 1084, and spectroscopically classified as Type IIP (Monard et al., 2012). Maund et al. (2013) directly detected a progenitor source in archival HST images and subsequent SED modelling produced a potential progenitor mass range of $14-22 M_\odot$. This mass range is further supported by parameters derived from a photometric and spectroscopic monitoring campaign (Barbarino et al., 2015). The suspected progenitor was later confirmed to have faded from late-time HST imaging (Zhao et al., 2025). Nebular line modelling is consistent with a $13-15 M_\odot$ (Jerkstrand et al., 2015).

From the H α map of SN 2012ec, the immediate environment is of lower surface brightness compared to the bright star forming regions that encircle it. All identified H II regions are found at distances > 250 pc. A single stellar population was photometrically resolved, corresponding to a progenitor mass of $21.1_{-0.5}^{+0.4}$ and a relatively high extinction of $A_V = 1.03_{-0.05}^{+0.05}$ mag. This falls at the upper end of the range suggested by Maund et al. (2013) and would imply a very massive RSG progenitor.

SN 2012P

SN 2012P was first observed on 22 January 2012 (Dimai et al., 2012) in the outer spiral arm (neighbouring SN 2004dg) of its host galaxy NGC 5806, and classified as

Type IIb from a spectral sequence (Fremling et al., 2016). Careful studying of late-time spectroscopy by Fremling et al. (2016) suggests a progenitor $M_{\text{ZAMS}} \approx 15 M_{\odot}$. From a similar analysis to my own, (Sun et al., 2021) resolve a stellar population for SN 2012P with a mass estimate of $15.2^{+2.0}_{-1.0} M_{\odot}$.

The environment of SN 2012P is dominated by a single, giant H II region coincident with the SN site. This H II region has an age that corresponds to a $\sim 26.9 M_{\odot}$ progenitor mass. Alternatively, a single resolved stellar population implies a very high mass estimate of $64.9^{+18.5}_{-12.6} M_{\odot}$. Neither of these estimates agree with previous constraints. For the case of SN 2012P, it is worth mentioning that the evolution of the corrected Bayesian evidence for fitting stellar population models includes a ~ 20 jump in $\ln(Z/N_m!)$ going from $N_m = 1 \rightarrow N_m = 2$ models. Although this does not meet my requirement of a > 30 jump in $\ln(Z/N_m!)$ to be considered a superior model, it still suggests a significant improvement. If the $N_m = 2$ model for SN 2012P were to be accepted, it would introduce an older secondary stellar population with an age of $\tau_2 = 7.32^{+0.06}_{-0.06}$ and corresponding mass of $11.8^{+1.2}_{-0.9} M_{\odot}$. Although only a handful of catalogue targets exhibit this behaviour in Bayesian evidence between models, it highlights the impact of how it is interpreted and the effect of having a fixed rule (> 30 jump in $\ln(Z/N_m!)$) on the final results.

SN 2009hd

SN 2009hd was first detected on 2 July 2009 (Monard, 2009) in the spiral arm of its host galaxy NGC 3627 and spectroscopically classified as Type II (Kasliwal et al., 2009), possibly Type IIL Elias-Rosa et al. (2011). Constraints from an identification of the progenitor directly from a single archival HST image (F814W) provides a conservative upper mass limit of $\lesssim 20 M_{\odot}$ Elias-Rosa et al. (2011). Within this upper limit, Davies & Beasor (2018) find an initial mass of $18.3^{+1.6}_{-1.5} M_{\odot}$ by imposing updated bolometric corrections.

The broad environment of SN 2009hd contains large voids, as well as collimated

diffuse ionised gas containing bright $H\alpha$ spots converging on a large star forming complex that is in close proximity to the SN site. Analysis of the central 150 pc aperture reveals a high stellar density (188 resolved stars), that were best divided into three unique stellar populations. Their respective progenitor properties are as follows: $M_1 = 105.6^{+23.4}_{-17.1} M_\odot$ and $A_{V,1} = 1.68^{+0.03}_{-0.03}$ mag; $M_2 = 62.3^{+9.4}_{-7.6} M_\odot$ and $A_{V,2} = 0.70^{+0.03}_{-0.03}$ mag; $M_3 = 10.5^{+0.3}_{-0.3} M_\odot$ and $A_{V,3} = 0.22^{+0.03}_{-0.03}$ mag. As previously discussed, a progenitor mass as high as $\sim 100 M_\odot$ is unlikely to result in a CCSN. Although the progenitors of Type IIL SN are not as well refined as the more frequent Type IIP (RSG), my lowest mass estimate seems the most probable. A mass estimate from the coincident H II region, $\sim 31.6 M_\odot$, does not align with any of the resolved stellar populations.

SN 2004dg

SN 2004dg was first discovered on 19 July 2004 (Vagnozzi et al., 2004) in the outer spiral arm of its host galaxy NGC 5806, and spectroscopically classified as Type II (Elias de la Rosa et al., 2004). Subsequent lightcurve data evolved this to a II-P classification. Initial investigations into the progenitor, from a non-detection in pre-explosion HST images, found an upper mass limit of $12 M_\odot$ (Smartt et al., 2009). With a new bolometric correction, Davies & Beasor (2018) refined this to $< 9.5^{+0.7} M_\odot$. A similar environmental analysis to my own by Sun et al. (2021) constrains the progenitor to a $10^{+0.3}_{-0.2} M_\odot$ RSG, aligned with the previously determined upper limits.

Although the corrected Bayesian evidence suggests an improvement with an ‘advanced’ ULTRANEST fitting of the resolved stars in the environment of SN 2004dg, the posterior probability distributions for the model parameters are poorly constrained. Inferring the progenitor properties from these results yields a $34.5^{+37.2}_{-17.8} M_\odot$ initial mass, much higher than prior estimates. The age of this population, however, agrees with the nearest H II region to SN 2004dg, at a distance of ~ 160 pc. Such young stars may dominate the environment, but not represent the natal population. Similar arguments

to those made for SN 2012P, looking at the $N_m = 2$ model results would introduce an secondary older population with a progenitor mass estimate of $\sim 13.6 M_\odot$, much closer to the consensus of past studies. Only a jump in $\ln(Z/N_m!)$ of ~ 12 , however, going from $N_m = 1 \rightarrow N_m = 2$ was found.

SN 1999br

SN 1999br was first detected on 12 April 1999 (King, 1999) as a low luminosity Type II SN (Garnavich et al., 1999; Hamuy, 2003) in the outer regions of its host galaxy NGC 4900. A series of photometric and spectroscopic measurements later upgraded this classification to II-P (Hamuy, 2003; Pastorello et al., 2004). Van Dyk et al. (2003) were the first to find consistency between the absolute magnitude of the directly detected progenitor in archival HST imaging and a typical RSG star. Zampieri et al. (2003) suggested, however, that a high ejecta mass with such low ^{56}Ni yields could imply a more massive progenitor. An upper limit of $< 14.1^{+1.8} M_\odot$ from Davies & Beasor (2018), which agrees with those by Maund & Smartt (2005) ($\leq 12 M_\odot$). The current consensus is that low-luminosity Type II SNe originate from low-mass RSG progenitors Lisakov et al. (2018).

This aligns well with the single resolved stellar population found through my photometric analysis, corresponding to a progenitor initial mass of $13.0_{-0.4}^{+0.4} M_\odot$. A nearby (~ 57 pc) H II region was found to have a much younger age, and is in fact a large star forming complex that extends to much greater distances from the position of SN 1999br. Association, in this case, between the SN progenitor and this complex is unlikely. The immediate environment of SN 1999br is comparatively low in H α emission from diffuse ionised gas with a relatively low metallicity of $\sim 0.5 Z_\odot$.

SN 1998dl

SN 1998dl was first discovered on 20 August 1998 (King et al., 1998) in its host galaxy NGC 1084, and spectroscopically classified as Type II (Filippenko & De Breuck, 1998). No prior constraints to the progenitor of the SN could be found in a search of the literature. A high density of stars (102) in the 150 pc environment was best fit by a single stellar population. From this we can infer a typical Type II progenitor of a RSG with a $12.0^{+0.4}_{-0.3} M_{\odot}$ initial mass. Only part of the 1×1 kpc environment was captured in the MUSE datacube for SN 1998dl. Nevertheless, the immediate environment does not contain a bright H II region, with the nearest being resolved at distances > 150 pc.

SN 1996an

SN 1996an was first detected on 27 July 1996 (Nakano et al., 1996), also in the host galaxy NGC 1084. Compiled lightcurve and spectroscopic data allocates a Type II-P classification (Tsvetkov et al., 2001). No prior constraints to the progenitor of the SN could be found in a search of the literature. A high density of stars (138) in the 150 pc environment was best fit by a single stellar population with a corresponding progenitor mass estimate of $22.0^{+0.5}_{-0.5} M_{\odot}$. A H II region in close proximity (~ 73 pc) to SN 1996 was found to have a similar age to the resolved stellar population within the immediate environment. This age gives a larger initial mass estimate of $\sim 31 M_{\odot}$, but could reasonably be the progenitor birth site.

SN 1986I

SN 1986I was first detected on 17 May 1986 (Pennypacker et al., 1986) in a spiral arm of its host galaxy NGC 4254 (M99). Spectroscopic and photometric follow up revealed it to be a typical Type II-P SN (Filippenko et al., 1986; Tsvetkov, 1988). No prior constraints to the progenitor of the SN could be found in a search of the literature. The

broader environment of SN 1986I contains regions of star formation, identified through bright H α emission, which surround the SN site itself at distances exceeding 125 pc. The SN site itself is devoid of any bright emission, but the 150 pc environment is dense in stars (111). These were found to contain two independent stellar populations: one very young population corresponding to an progenitor initial mass estimate of $99.6^{+20.4}_{-15.5} M_{\odot}$; another older population analogous to a $14.9^{+1.1}_{-1.6} M_{\odot}$. Although the younger population slightly dominates the number of stars ($w_1 = 0.74$), the older population has a lower extinction ($A_V = 0.42^{+0.12}_{-0.15}$) and is therefore, on average, more in the foreground. Given the convergence on RSG progenitors for standard Type II-P SNe, my lower mass estimate likely reflects the best estimate for SN 1986I.

SN 1973R

SN 1973R was first detected on 19 December 1973 in the spiral arm of its host galaxy NGC 3627 (M66), and classified as a Type II event (Ciatti & Rosino, 1977). No prior constraints to the progenitor of the SN could be found in a search of the literature. Part of the broader 1×1 kpc environment is incomplete, owing to the SN site falling on the edge of two MUSE datacubes. From what can be observed, an extended source of bright ionised gas stretches across the SN site, with two compact H II regions at either end. Using the coincident H α emission, the inferred star formation history suggests a progenitor mass of $\sim 27.8 M_{\odot}$. A high Balmer decrement extinction of $A_V = 1.63 \pm 0.02$ mag, however, could place this as a background source of chance alignment. Alternatively, a single stellar population was resolved within the local 150 pc environment corresponding to an initial mass estimate of $16.1^{+2.6}_{-2.3} M_{\odot}$. This is much more aligned with the general population of RSG stars found for other Type II events.

SN 1967H

SN 1967H was first detected on 2 July 1967 in the inner spiral arm of its host galaxy NGC 4254 (M99), and spectroscopically classified as Type II (Fairall, 1967). No prior constraints to the progenitor of the SN could be found in a search of the literature. Looking at the wider 1×1 kpc environment of SN 1967H it is mostly devoid of features and emission, with the exception of a single, very bright H II region. The boundary of this H II region extends to the SN position, but it should be noted that the bright centroid is offset by a distance > 200 pc. Both the H II region and the youngest resolved stellar population (within 150 pc) give unrealistically high progenitor mass estimates of $\sim 41.9 M_{\odot}$ and $120.0^{+18.7}_{-26.0} M_{\odot}$ respectively. Using the older resolved stellar population a more sensible initial mass estimate of $17.2^{+0.9}_{-1.2} M_{\odot}$ was found, aligned with a RSG progenitor.

4.9.2 Silver Targets

SN 2023ijd

SN 2023ijd was discovered on 14 May 2023 (Stanek, 2023) in the outer region of its host galaxy NGC 4568, and spectroscopically classified as Type II (Perley, 2023). As of yet, there are no existing progenitor constraints within the literature. Examining the 1×1 kpc environment, there are no large H II regions or star forming complexes. Instead a small number (3) of compact H II regions can be found at distances > 200 pc from the site of SN 2023ijd. The immediate environment is mostly empty, with traces of diffuse ionised gas appearing in the H α map and only 10 stars photometrically resolved in a 150 pc aperture. These stars were fit to a single stellar population with low extinction ($A_V = 0.23^{+0.10}_{-0.08}$ mag) and an age that implies a $8.7^{+0.4}_{-0.4} M_{\odot}$ initial mass star. As was found for many other Type II SNe in this study, this upholds the trend of a RSG progenitor.

SN 2020hvp

SN 2020hvp was first detected on 21 April 2020 (Tonry et al., 2020; Fulton et al., 2020) in its host galaxy NGC 6118, and spectroscopically classified as Type Ib (Burke et al., 2020). As of yet, there are no existing progenitor constraints within the literature. The wider 1×1 environment is littered with compact H II regions encircling the site of SN 2020hvp, which mostly resembles an emissionless void. A low stellar density (12 stars) in an extended 300 pc aperture resulted in a single resolved stellar population from the HST images. Converting the population age to an initial mass estimate gives a $23.9_{-6.7}^{+11.7} M_{\odot}$ progenitor, indicative of a high-mass RSG star. SN 2020hvp is one of the few catalogue targets that finds agreement between its stellar population age and the nearest H II region age. At a distance of ~ 285 pc, the H II region suggests a progenitor mass of $\sim 22.4 M_{\odot}$. Although it is possible that this H II region was the original birth site of the progenitor, it could instead suggest a single last epoch of star formation across the broader environment. At such intermediate mass estimates, the mass-loss channel that produced the Type Ib SN can not be constrained; stellar winds from a single star or stripping from a binary system are both plausible.

SN 2020fqv

SN 2020fqv was first detected on 31 March 2020 (Forster et al., 2020b) in the spiral arm of its host galaxy NGC 4568. Rapid spectroscopic follow-up of the SN evolution identified it as Type IIb (Zhang et al., 2020; Dimitriadis et al., 2020). Probing of the mass-loss history through the dense CSM and modelling of the lightcurve and nebular spectroscopy by Tinyanont et al. (2022) produced a progenitor mass constraint of $M_{\text{ZAMS}} \approx 13.5 - 15 M_{\odot}$. Their study highlights the dramatic mass-loss that can occur in the final years of a RSG star's life.

My own investigation into SN 2020fqv reveals poorly defined H II regions, but an

abundance of extended sources of bright ionised gas across the 1×1 kpc environment. Immediately surrounding SN 2020fqv two stellar populations were resolved, both with older ages compared to the general catalogue results. These produce progenitor initial mass estimates of $18.5^{+1.5}_{-1.0} M_{\odot}$ and $9.7^{+0.4}_{-0.4} M_{\odot}$, straddling the range found by Tinyanont et al. (2022). Unless induced by binary interaction, my lower mass estimate would unlikely result in a significantly stripped outer hydrogen envelope. This could indicate the higher mass estimate is the stronger candidate, but neither can be fully ruled out. Regardless, both suggest a RSG progenitor for SN 2020fqv.

SN 2019ehk

SN 2019ehk was first detected on 29 April 2019 (Grzegorzek, 2019) in the inner region of its host galaxy NGC 4321 (M100). It represents a peculiar and rare Ca-rich transient with a double-peaked lightcurve, consistent with CSM interaction (Jacobson-Galán et al., 2020). Its classification remains controversial, with some proposing it has a CCSNe (Type Ib/IIb) origin (De et al., 2021; Nakaoka et al., 2021) and others unable to rule out a double-degenerate binary system (Jacobson-Galán et al., 2020). To add to the uncertainty of the progenitor, SN 2019ehk had co-temporal X-ray detections (a first among Ca-rich transients) and is not associated with a star-forming environment (Nakaoka et al., 2021). If of CCSNe origin, De et al. (2021) find consistency with a stripped low-mass progenitor of $9 - 9.5 M_{\odot}$. From deep HST pre-explosion imaging, Jacobson-Galán et al. (2020) find a progenitor consistent with their lowest mass bin of $\sim 10 M_{\odot}$.

My own investigation into SN 2019ehk finds a mostly featureless 1×1 kpc environment, with a nearby (~ 94 pc) source of weak H α emission and a much brighter star forming region at a greater distance of ~ 329 pc. A low density of stars (19) resolved a single stellar population, corresponding to an progenitor initial mass estimate of $8.1^{+0.5}_{-0.5} M_{\odot}$. This agrees with the low-mass constraints from past studies, and definitively

implies a binary companion is responsible for primary stripping and dense CSM.

SN 2017bzb

SN 2017bzb was first detected on 7 March 2017 (Parker, 2017) in the outer spiral arm of its host galaxy NGC 7424, and spectroscopically classified as Type II (Morrell, 2017). No prior constraints to the progenitor of the SN could be found in a search of the literature. A 1×1 kpc map of H α emission identifies two cleanly resolved H II regions, one of which is coincident with the site of SN 2017bzb. Age dating the $\log(EW(H\alpha))$ measurement reveals it to be a young H II region, indicative of a $\sim 30.3 M_{\odot}$ progenitor, and a relatively low metallicity $\sim 0.5 Z_{\odot}$. Fitting the photometry in a 150 pc aperture finds two resolved stellar populations of opposing ages. The youngest indicates a very high mass progenitor of $178.7^{+171.3}_{-93.3} M_{\odot}$, but the older population gives a more reasonable estimate of $8.7^{+1.4}_{-1.0} M_{\odot}$ of a more typical RSG origin.

SN 2016iae

SN 2016iae was discovered on 7 November 2016 (Tonry et al., 2016) in the central region of its host galaxy NGC 1532, and spectroscopically classified as Type Ic (Zhang et al., 2016b). No prior constraints to the progenitor of the SN could be found in a search of the literature. A single, very young stellar population was resolved in the central 150 pc environment and suggests a high-mass progenitor of $106.8^{+69.8}_{-26.5} M_{\odot}$. Unfortunately the host galaxy is highly inclined at 83.0 degrees, likely limiting the analysis by creating a bias detection of the brightest sources along our LoS. These stars may not share an association and could skew the population fitting towards younger ages. Looking at the IFU spectroscopic view, the nearest (~ 121 pc) resolved H II region gives a more reasonable progenitor mass estimate of $\sim 26.3 M_{\odot}$, but could still suffer from the same limitations.

SN 2015dj

SN 2015dj was first detected on 10 July 2015 (Itagaki, 2020) in the spiral arm of its host galaxy NGC 7371, and was spectroscopically classified as Type Ib (Benetti, 2020). Modelling of the lightcurve and nebular phase spectral lines by Singh et al. (2021) found a progenitor mass range of $13 - 20 M_{\odot}$, which they attribute to a binary scenario.

My environmental analysis of SN 2015dj suffered from a low number of stars, with only 8 resolved in an extended aperture of 300 pc. Nevertheless, a single stellar population gives my own initial mass estimate of $19.3^{+22.6}_{-2.1} M_{\odot}$, which aligns with results by Singh et al. (2021). A poorly constrained upper limit is likely the result of minimal detections contributing to the overall population fitting. SN 2015dj is a second example of a catalogue target that finds reasonable agreement between the stellar population and H II region ages. This time, however, it is at an even greater distance of ~ 424 pc from the SN site. Features in the 1×1 H α map appear difficult to resolve, likely due to the large distance to the host galaxy of 31.2 Mpc. Potential lower luminosity H II regions closer to SN 2015dj may exist, but were missed by my algorithm. The distant H II region corresponds to a progenitor mass of $\sim 25.7 M_{\odot}$.

SN 2012au

SN 2012au was discovered on 14 March 2012 close to the nucleus of its host galaxy NGC 4790, and spectroscopically classified as Type Ib (Howerton et al., 2012). Given its high peak luminosity ($\sim 7 \times 10^{42}$ erg s $^{-1}$; Takaki et al. 2013) and explosion energy ($\sim 10^{52}$ erg), SN 2012au is seen as a ‘golden link’ between stripped CCSNe and super-luminous SNe (Milisavljevic et al., 2013). Nicholl et al. (2016) find evidence of high ejecta mass ($M_{ej} = 7 - 30 M_{\odot}$) from lightcurve and spectroscopic modelling, suggesting a very massive progenitor. Others constrain this ejecta mass to the lower range of $M_{ej} \sim 4 - 8 M_{\odot}$ (Takaki et al., 2013; Pandey et al., 2021). A Wolf-Rayet star of initial

mass $\sim 17 - 25 M_{\odot}$ was proposed as the progenitor by Pandey et al. (2021) from late nebular phase spectroscopy.

My own exploration of SN 2012au finds little evidence of ionised gas in the immediate environment, but H II regions that surround at distances in excess of 180 pc from the SN site. A single stellar population was photometrically resolved with a comparatively high extinction $A_V = 0.98^{+0.08}_{-0.09}$ mag and young age. Maund (2018) find a similarly young population, as well as an older population of age $\tau = 7.22^{+0.03}_{-0.13}$ that is missed by my analysis. My single resolved population corresponds to a high progenitor initial mass estimate $161.9^{+118.4}_{-48.2} M_{\odot}$, which is poorly constrained. This certainly points towards a high-mass progenitor, but a more reasonable mass estimate likely originates from the missed stellar population.

SN 2009dq

SN 2009dq was first detected on 24 April 2009 (Pignata et al., 2009) in its irregular host galaxy IC 2554, which suffers from close proximity to the galactic plane (high galactic extinction of $A_V^{MW} = 0.562$ mag). Spectroscopic follow-up classified SN 2009dq as a Type IIb event (Anderson et al., 2009). No prior constraints to the progenitor of the SN could be found in a search of the literature. Within the broader 1×1 kpc environment of SN 2009dq, a single giant H II region dominates. Converting its age to an progenitor initial mass estimate yields a value of $\sim 23.0 M_{\odot}$. Inside the local (150 pc) environment, a low density of 16 stars were resolved that were best fit by a single stellar population. The age of this population corresponds to a mass estimate of $54.8^{+10.7}_{-8.2} M_{\odot}$, considerably higher than the H II region estimate. My stellar analysis may perform poorly under these conditions, due to a high galactic extinction along our LoS.

SN 2004cc

SN 2004cc was discovered on 10 June 2004 (Monard & Li, 2004) in the inner region of its host galaxy NGC 4568, and spectroscopically classified as Type Ic (Foley et al., 2004). Constraints of the mass-loss history of the progenitor of SN 2004cc were conducted by Wellons et al. (2012), but no estimation of the progenitor initial mass could be found within the literature. From a 1×1 kpc H α map, the wider environment of SN 2004cc is rich in ionised gas and H II regions. One of the brightest H II regions is within very close proximity (~ 34 pc), giving an initial mass estimate of $\sim 27.6 M_{\odot}$. Alternatively, the single resolved stellar population within the immediate (150 pc) environment suggests a much lower initial mass of $12.4^{+0.4}_{-0.4} M_{\odot}$ from a fitting to 73 resolved stars. Such a low mass progenitor would imply a binary system origin, with extreme mass transfer, to produce a highly stripped star prior to explosion.

4.9.3 Bronze Targets

All 16 bronze ranked catalogue targets suffer from systematically young resolved stellar populations in their immediate environments, resulting in very high mass progenitor mass estimates. There could be unique reasoning behind why this occurs in each dataset, but it is more likely their commonalities that is the cause. These factors include:

- Being limited to a single image.
- The majority of these images come from the F275W HST/WFC3 filter, which suffers from a poor throughput. A minority of these targets utilise the F606W filter instead.
- Looking mostly in the UV increases the likelihood of resolving young stellar populations.

Table 4.7: Summary of progenitor mass estimates for bronze ranked catalogue targets. One estimate from the photometrically resolved stellar population, and another from the nearest H II region.

Target	Type	Stellar population mass estimate ($M_{\odot}$)	H II region mass estimate ($M_{\odot}$)
2023abdg	II	$141.9^{+208.1}_{-66.2}$	32.6
2022wsp	II	$120.0^{+230.0}_{-44.3}$	25.1
2022frl	Ib-pec	$236.0^{+114.0}_{-103.9}$	31.5
2019yz	Ic	$344.4^{+5.6}_{-213.2}$	32.4
2018pq	II	—	17.8
AT2018bbl	II	$132.6^{+217.4}_{-64.0}$	18.1
2017ivv	II	$145.1^{+204.9}_{-85.4}$	19.0
2017aym	IIP	$148.8^{+201.2}_{-86.0}$	22.5
2016hgm	II	~ 350	31.2
2016bmi	IIP	$135.6^{+214.4}_{-93.7}$	27.6
ASASSN-16at	IIP	$141.8^{+208.2}_{-88.2}$	21.4
2016afa	II	~ 350	—
ASASSN-15oz	II	—	26.3
2009H	II	$139.7^{+210.3}_{-63.5}$	30.8
2004dk	Ib	~ 350	31.9

- A significant number of environments with a low number of resolved stars, even when extended from a 150 pc to a 300 pc aperture.

Since the photometric analysis performs poorly, the spectroscopic search for the nearest H II region provides my best mass constraint for these catalogue targets. A comparison between values found from both approaches is provided in Table 4.7. Targets coincident with these H II regions include: SN 2019yz, 2018pq, 2017ivv, 2016hgm, ASASSN-16at and 2004dk. The site of SN 2022wsp is only ~ 51 pc from its H II region. All remaining targets have distances between 200–420 pc. Of the Type II targets within this coincident subset, SN 2018pq, 2017ivv and ASASSN-16at find reasonable RSG progenitor mass estimates. The same can be said for AT2018bbl and SN 2017aym, yet their H II regions fall at distances of ~ 381 pc and ~ 307 pc respectively. Of the SESNe targets within the coincident subset, SN 2019yz (Ic) and SN 2004dk (Ib) find high mass ($\sim 32 M_{\odot}$)

progenitors.

The environments of both SN 2018pq and ASASSN-15oz contained no resolved stars out to 300 pc. For SN 2018pq, extinction estimates were not possible for the immediate 150 pc environment or the coincident H II region, owing to a lack of $H\beta$ emission. Given the strong $H\alpha$ emission, this suggests a very high extinction is responsible for the lack of photometrically detected stars. For ASASSN-15oz, the lack of stars is instead the result of poor quality data.

4.10 Conclusions

In this chapter I have applied a streamlined environmental analysis, built on a prior in-depth investigation of the environment of iPTF13bvn (Chapter 3), to a catalogue of local CCSNe with archival HST images and MUSE IFU spectroscopy. By resolving the stellar populations and H II regions in the local and wider environments, I have provided a series of environmental properties for 50 CCSNe. Whilst constraining the progenitor masses of these systems, I have compared two commonly employed techniques: stellar isochrone fitting to resolved stars and star formation models of H II region $\log(EW(H\alpha))$ values. Agreement between both approaches was rare, but no justification to use one over the other could be found. The results from all aspects of the analysis can be summarised as follows:

- SN classification based statistics of the estimated progenitor masses finds an increasing average mass for Type II→IIb→Ic, with the exception of Type Ib. An interpretation could be that Type II mostly originate from the lower-mass range ($\sim 8 - 35 M_{\odot}$); Type IIb typically straddle the upper mass range of Type II and more highly stripped progenitors ($\sim 35 - 40 M_{\odot}$); Type Ib originate mostly from binary systems with lower-mass progenitors; Type Ic contain a greater mixture of lower-mass binary and high-mass progenitors.

- Metallicities of the SNe sites show no statistically significant dependence on the SN classification, potentially suggesting it plays a minimal role in determining SNe features. A bias towards sub-solar metallicities may exist in my catalogue, however, due to a high number of star-forming host galaxies.
- Extinctions show no correlation to the SN classification, but are systematically higher when measured through ionised gas along the LoS.
- For SNe coincident with H II regions, natal association between them may be as low as 50%, with the remaining 50% being chance alignment.
- Age estimates of coincident or surrounding H II regions mostly disagree with those found from resolved stellar populations. On a classification basis, when arguing if they represent the birthsites of SNe, only Type Ic show a group behaviour of minimal spatial separation and difference in age. This could suggest a high fraction of Type Ic SN are genuinely associated with H II regions.

Overall, I have demonstrated the potential of using indirect methods to constrain the progenitor properties of local CCSNe through an exploration of their environments. Moreover, it offers an alternative approach to gain insightful information about the origins of their classifications whilst direct observations of their progenitors or shock-breakout remain difficult and rare.

Chapter 5

Discussion

5.1 Performance of Stellar Population Fitting

The use of a Bayesian mixture model to resolve stellar populations from the stellar photometry of HST images is advantageous for including effects from binaries, and resolving multiple populations under a single model. It does, however, sometimes require assumptions about the underlying models, particularly when distinguishing between my ‘initial’, ‘intermediate’ and ‘advanced’ models in Chapter 4. Ideally, the data would always be strong enough to impose the ‘advanced’ model, allowing for the inclusion of free dispersion parameters (σ_τ and σ_{A_V}) for the distributions of $\tau = \log(\text{age} / \text{years})$ and A_V . Under the ‘initial’ and ‘intermediate’ models, these dispersions were fixed at values of 0.1. As seen in Chapter 3, changing the fixed values of dispersion from 0.05 to 0.1 had minimal impact on the resulting population age and extinction values. With an expanded dataset in Chapter 4, I am able to test the validity of these assumptions, as presented in Figures 5.1 and 5.2. Of the 50 catalogue targets, 38% (19) were successful in running the ‘advanced’ model; having an increase in corrected Bayesian evidence from ‘initial’ to ‘advanced’ >10 . These targets include: SN 1973R, 1986I, 1996an, 1998dl, 2004dg, 2009hd, 2012ec, 2012P, 2013dk, 2014L, 2016coi, 2016cok, 2018ivc, 2019yvr, 2020hvp,

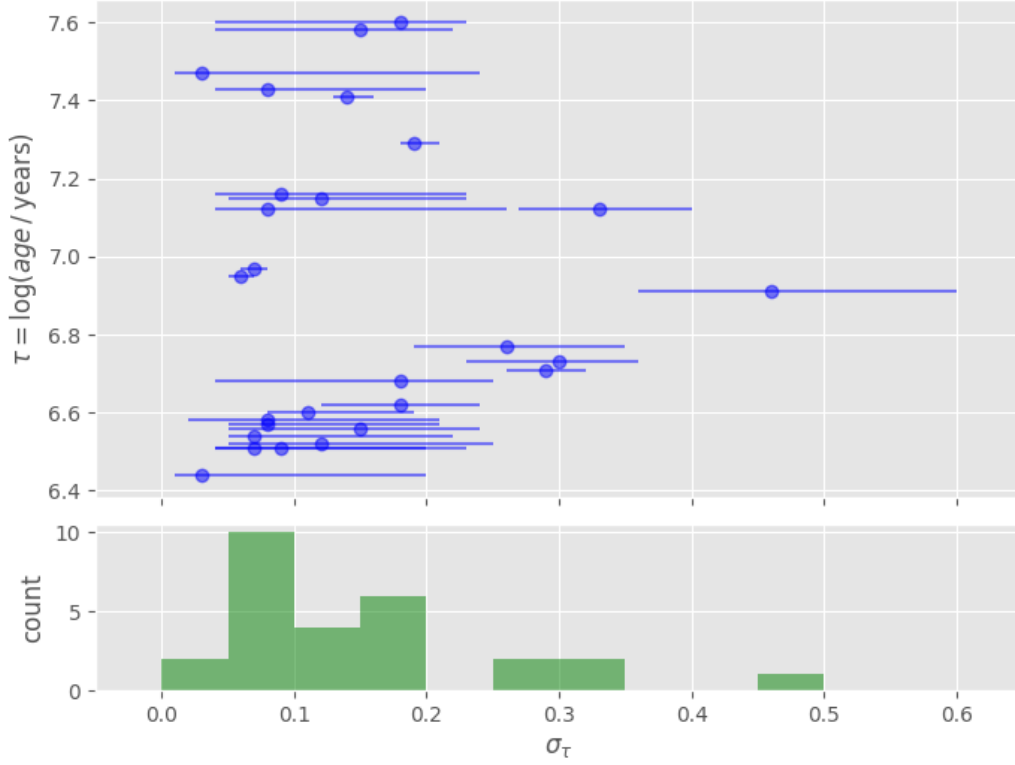


Figure 5.1: Distribution of $\tau = \log(\text{age} / \text{years})$ dispersions (σ_τ) for 19 of the catalogue targets under the ‘advanced’ model. Dispersions represent the standard deviation of the assumed underlying normal distribution of stellar population ages. Values of σ_τ have been converted from the model parameter δ_τ , under the parameterisation $\sigma_\tau = 0.01 \times 10^{\delta_\tau}$.

2020jfo, 2020oi, 2022aau and 2022acko.

From these we can see a mixture of poorly and well constrained dispersions. From Figure 5.1, there is significant clustering of σ_τ around 0.1. This validates the choice of my fixed dispersion value for the alternative models, and suggests that the overall approach works well when assuming tightly constrained epochs of star formation in the environments of CCSNe. Comparatively, the extinction dispersions (Figure 5.2) find a much greater spread, suggesting the fixed dispersion value of 0.1 for stellar population extinctions is a poorer assumption. Since the spread in extinction of any given stellar

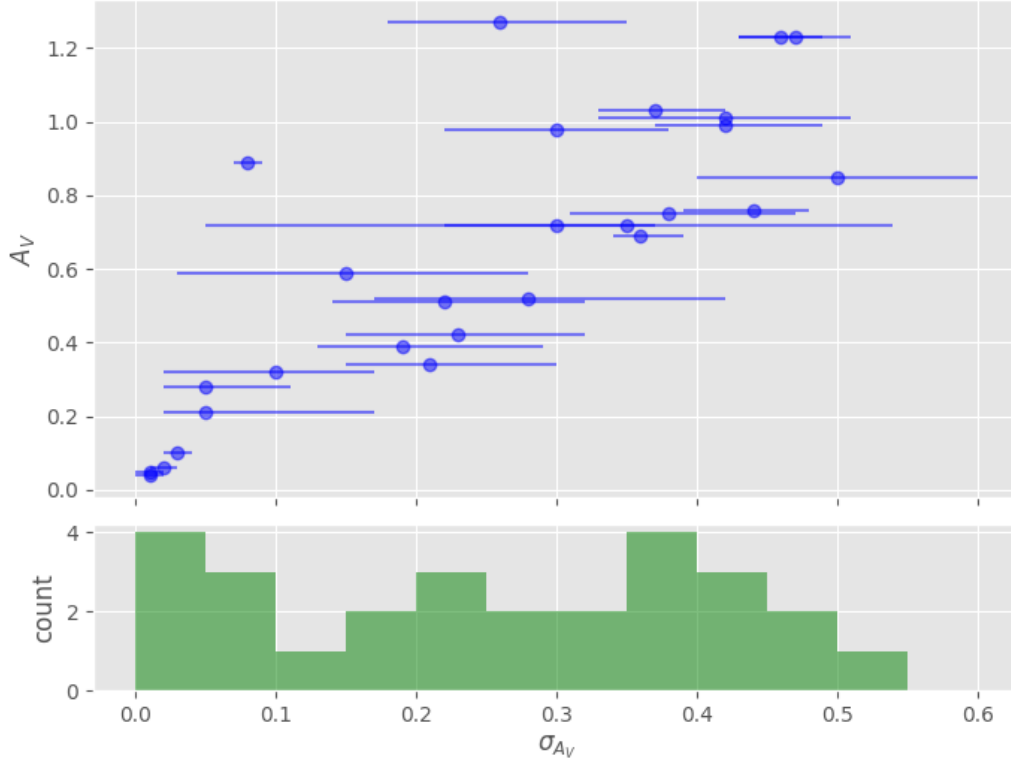


Figure 5.2: Distribution of A_V dispersions (σ_{A_V}) for 19 of the catalogue targets under the ‘advanced’ model. Dispersions represent the standard deviation of the assumed underlying normal distribution of stellar population extinctions. Values of σ_{A_V} have been converted from the model parameters δ_{A_V} , under the parameterisation $\sigma_{A_V} = 0.01 \times 10^{\delta_{A_V}}$.

population cannot be predicted beforehand, a relaxed dispersion value more central to the distribution I have found (i.e. $\sigma_{A_V} = 0.25$) would be more appropriate going forward. The distribution of age dispersions shows no correlation with the best-fit age value itself. For extinction, however, there appears to be a positive trend between the best-fit extinction value and the extinction dispersion. This suggests that a mean stellar population extinction is a weaker assumption for high extinction environments.

Another impact to the performance of fitting stellar populations is the choice of requiring ‘strong evidence’ (>30 jump in corrected Bayesian evidence) when comparing

models and determining the best number of stellar populations that represent a SN environment. As seen for SN 2012P and SN 2004dg, relaxing this requirement would result in a higher number of resolved stellar populations. This effect is harder to reconcile, given that it is purely a choice of the analyst. In future applications of the environmental analysis a ‘staggered confidence’ approach could be taken where more relaxed Bayesian evidence comparisons are allowed, but reflect the confidence in the inferred stellar population results.

5.2 Data Limitations

After discussing the performance of the stellar population analysis, it is also important to consider limitations that originate from the data itself. This has been partially covered in Section 3.4.2. Although the uncertainties of host galaxy distances are not incorporated into the stellar population analysis, many targets in my catalogue have poorly constrained distances. For most, the range of distance estimates would only marginally shift the inferred photometry and, in turn, the predicted population parameters. Yet, in order to achieve the best constraints over the progenitors of CCSNe from the perspective of an environmental analysis, or any type of analysis for that matter, better constraints over the distances to local galaxies is an essential factor. Additionally, the fitting of isochrones to stellar population photometry is most sensitive to the most massive stars, which are best constrained over UV wavelengths. High spatial-resolution imaging with HST offers an invaluable range of passband filters, however it performs sub-optimally in most of its UV filters (F225W and F275W). This is reflected in the progenitor constraints of catalogue objects with a single UV image available. Moreover, despite the extensive archive of HST data, some local galaxies have minimal images often bound to a narrow region of the potential wavelength coverage.

As mentioned in Section 3.4.2, regarding the MUSE data we are mostly limited by

the spectral resolution. The ability to recover spatial information with IFU-spectroscopy makes it perfect for an environmental analysis. This comes with the reality of achieving comparatively low spectral resolution, which limits the amount of spectral lines that can be recovered. An increase in spectroscopic information and quality could enrich the capabilities of the environmental analysis, and (equally to the HST) a larger data archive would boost the number of targets that could contribute to the catalogue.

Proposed in Section 4.2, the effect of including catalogue targets with high host galaxy inclinations on the performance of my environmental analysis was to be tested. Those with high inclination ($i > 70$ degrees) include: SN 2022wsp, 2017aym, 2016iae, 2016hgm, 2016bmi and 2009dq. Additionally, SN 2022frl, 2019yz and 2018ivc have very high ($i > 80$ degrees) host galaxy inclinations. The majority of these examples suffer from unrealistically high progenitor mass estimates from the resolved stellar population analysis. This reinforces the breakdown of the assumption that we are detecting stars that are co-spatial with the missing SN progenitor star. They do, however, mostly fall into the 'bronze' rank, only having a single available image filter in the UV. The limitations of these filter throughputs have already been discussed above. Interestingly, SN 2018ivc has one of the highest host galaxy inclinations, but finds progenitor mass estimates that agree well with past studies. SN 2016iae and SN 2009dq find reasonable progenitor mass estimates from the H II region analysis. Perhaps the H II region approach is more reliable in these high inclination systems, as it requires lower levels of spatial resolution.

5.3 Answering Open Questions

In Section 1.6 I outlined the open questions that this thesis aimed to answer, and will now discuss the degree to which this has been possible:

- **To what extent can an environmental analysis assist in constraining the**

progenitors of core-collapse supernovae?

For this to be assessed, we must look to the catalogue results with previously well constrained progenitors that can be compared to my own results. This is exclusively sourced from the ‘gold’ and ‘silver’ ranked targets with well constrained progenitor masses: Sections 4.9.1 and 4.9.2. I found 11 catalogue targets that meet this standard: SN 2020jfo, 2019yvr, 2019ehk, 2018ivc, 2016gkg, 2016cok, 2015dj, 2013dk, iPTF13bvn, 2012ec and 1999br. These almost exclusively stem from the photometric analysis, with the exception of SN 2016gkg which found the best agreement with its H II region mass estimate. This instills reasonable confidence in the ability of an environmental analysis to constrain the progenitors of CCSNe, but its reliability could be enhanced. Improved data quality and coverage is the most likely path to boosting reliability, rather than the method itself. Insight into the potential mass-loss channel that results in the stripped progenitors of SESNe is within the capabilities of the environmental analysis. Although it can not be definitively claimed, I find strong evidence for low initial mass progenitors in support of the binary interaction mechanism for Type Ibc SNe: SN 2019yvr, 2019ehk, 2017gax, 2013dk, iPTF13bvn and 2004cc. Personally, I think the capability for an environmental analysis to greatly assist direct methods in understanding the ‘progenitor tree’ for CCSNe is strong. It is clear that a collaborative effort, from multiple direct and indirect approaches, to better understand the variety of progenitors and the role of stellar multiplicity will better inform the stellar evolution and population models, iteratively improving the capabilities of the environmental analysis.

- **Do environmentally measured quantities correlate with supernovae classifications?**

No strong dependencies between the environmental parameters and the main SN classification groups were found. The strongest environmental correlation that was observed

relates to Type Ic SNe and their tendency to be nearby to and have similar ages to H II regions.

- **How do different indirect methods compare to one another in estimating environmental parameters?**

Of the two methods for estimating progenitor mass employed in this work, fitting stellar photometry and comparing the spectroscopically observed $\text{EW}(\text{H}\alpha)$ to stellar evolution models, agreement was rarely found between both. The photometric analysis had better success at finding progenitor parameters that agree with past studies, and is (almost) always capable of probing the direct sites of CCSNe. Alternatively, finding progenitor estimates from coincident or nearby H II regions yields a comparatively narrow range of ages. It is worth noting that where the photometric analysis was least successful, where only a single HST image was available (‘bronze’ targets; Section 4.9.3), the H II region approach produces many reasonable progenitor mass estimates.

- **What are the limitations of an environmental analysis?**

This has been covered in Sections 3.4.2, 5.1 and 5.2. In short, the main limitations are poorly constrained distances to host galaxies, limited high-quality UV images (weak throughputs of HST wide-band filters) and the spectral resolution of the IFU data.

Chapter 6

Conclusions and Future Work

In this thesis, I have demonstrated the ability of indirect methods to constrain the progenitor properties of core-collapse supernovae through their environments. I have described the development of a Bayesian approach for fitting stellar population models to resolved stars in the local environment, attempting to identify natal populations. This method allows multiple stellar populations to be identified from HST photometry with independent ages and extinctions, from which progenitor masses can be estimated. Moreover, I have cultivated a spectral fitting algorithm to be applied to integral-field-unit spectroscopy data from MUSE, to gain additional constraints from nebular line information. The choice of these datasets was motivated by the high spatial-resolution available, allowing the local environments to be explored in fine detail, as well as in the context of the broader galactic environment. Identification of H II regions across these environments encouraged a comparison between methods for constraining the progenitor mass. Ultimately, the main aims of this thesis were to explore the potential avenues for an environmental analysis, provide additional or first-time estimates of progenitor star properties (age; mass; extinction; metallicity), compare methods of constraining these properties and search for indicators of stellar evolution channels (single stars vs. binaries). In Chapter 2, I described the various methods I have used and the motiva-

tions behind their development, particularly for the construction of the spectral fitting algorithm. In Chapter 3, I first applied my environmental analysis to the strong dataset of the Type Ib SN iPTF13bvn. Here, I found my first progenitor estimates and explore the different ways both types of data (images and IFU-spectroscopy) can be utilised in tandem to gain additional information. With a better understanding of the strengths of the environmental analysis, in Chapter 4 I applied it to a local catalogue of 50 CCSNe with both HST images and MUSE datacubes. This allowed for a comparison between indirect methods, as well as testing for correlations between environmental parameters and SN classification groups (Type II vs. SESNe). Finally, in Chapter 5 I briefly discussed the successes and limitations of my analysis, and answer the open questions I outlined at the beginning of this thesis. In the next sections, I will provide summaries of the main conclusion from the main science chapters, and then provide suggestions of future work that could further this project.

6.1 The Environment of iPTF13bvn

In the environment of iPTF13bvn I resolved two unique stellar populations the oldest of which agrees with estimates of the progenitor from past studies, corresponding to an age of $\sim 9.33_{-1.20}^{+1.38}$ million years, an initial mass $M_{initial,P2} = 20.0 M_{\odot}$ and extinction $A_{V,P2} = 0.53_{-0.08}^{+0.10}$ mag. Spectroscopy revealed systematically higher extinctions measured from the coincident ionised gas compared to mean extinctions from stellar populations, allowing the 3D structure along our LoS to be interpreted. Without constraints over the electron temperature, a low temperature environment was inferred from a lack of nebular lines, a sparse population of massive stars and no association to a bright H II region. Comparing mean extinctions to the distribution of values from individual spaxels revealed evidence of increased extinction variability in environments like that of iPTF13bvn close to the edge of the galactic spiral arm. These results were only pos-

sible through the retention of the high spatial resolution otherwise missed by alternative approaches, such as Voronoi tessellation, that seek to maximise the data quality.

6.2 A Catalogue of Local Core-Collapse Supernovae Environments

Application of my environmental analysis to a catalogue of 50 local CCSNe finds mean progenitor mass values for the main SN classification groups that reconfirms an increasing average mass for Type II $\rightarrow$ IIb $\rightarrow$ Ic, with the exception of Type Ib. This could suggest a high fraction of Type Ib SNe with mass-loss origins from binary interaction. Minimal correlations between environmental properties were found, with the exception of Type Ic SNe. They appear nearby or coincident with H II regions, and have minimal differences between their stellar population and H II region ages. For SNe coincident with H II regions, natal association between them may be as low as 50%, with the remaining 50% being chance alignment. When comparing approaches to estimating the progenitor mass, H II region estimates appear to be sensitive to a narrow range of ages compared to the resolved stellar population approach. This could speak to a comparatively lower reliability for the ‘association to H II region’ approach, or a systematic failure in the underlying assumptions of models, such as STARBURST99 models.

6.3 Discussion

Overall, the environmental analysis shows promise in assisting direct progenitor detections in unveiling the ‘progenitor tree’ for CCSNe. In its current state, it is limited by its fitting sensitivity to UV bright objects (most massive stars) coupled with the reduced quality of HST images in its UV filters, as well as poorly constrained host galaxy distances and the low spectral resolution of MUSE data. Some catalogue objects provide

strong evidence of binary interaction as a dominant mass-loss channel for SESNe.

6.4 Future Work

The work undertaken in this thesis opens a range of unexplored avenues, and some that can be continued. I summarise my main suggestions below:

- In Chapter 3 I performed an intersectional study that resampled the HST data onto the pixel scale of MUSE datacubes. This allowed the stellar sources to be spatially associated with ionised sources detected in the MUSE data. Although the majority show stellar clusters at the centre of these ionised sources, others show an offset between the brightest stars and the brightest ionised gas. Standard models of the formation of H II regions would not predict this, prompting an investigation into whether this is observed across my catalogue of CCSNe environments.
- For the sake of computational expense, streamlining of the environmental analysis for application to my catalogue missed some tests performed on iPTF13bvn. This includes the identification of increased extinction variability in environments that fall on the edge of spiral arms compared to those observed more centrally. This also prompts an investigation into whether this behaviour is observed universally, or shows any correlation to the type of SN.
- IFU-spectroscopy datacubes from MUSE are limited by its mostly southern hemisphere sky coverage. Adapting my environmental analysis to work on alternative IFU-data, such as the newly operational William Herschel Telescope Enhanced Area Velocity Explorer (WEAVE; Jin et al. 2024), would expand the catalogue size by including more northern hemisphere targets. This would help to improve sample statistics, and extend the applicability of my analysis.

- The sophistication of the stellar population fitting could be improved by using more complex stellar evolution models, such as incorporating the Binary Population and Spectral Synthesis (BPASS; [Eldridge et al. 2017](#)) models. This would introduce a vastly larger grid of models with a more varied inclusion of binary systems in the synthesised stellar populations, but would greatly increase the computational expense of running my analysis on a catalogue of CCSNe. The effects of upgrading to PARSEC version 2.0 could also be tested.

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Appendix A

Appendix

A.1 Colour-Magnitude Diagrams

From Chapter 4, targets with more than one image could have their stellar population fitting results displayed as colour-magnitude diagrams (CMDs). Where possible, I present those results here:

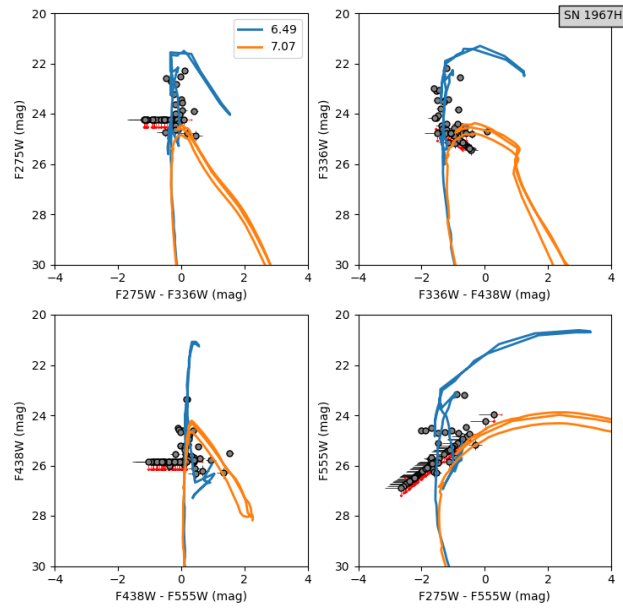


Figure A.1: SN 1967H CMD: data points correspond to the resolved stellar photometry and the best-fit PARSEC stellar isochrones are overlaid for the corresponding number of resolved populations.

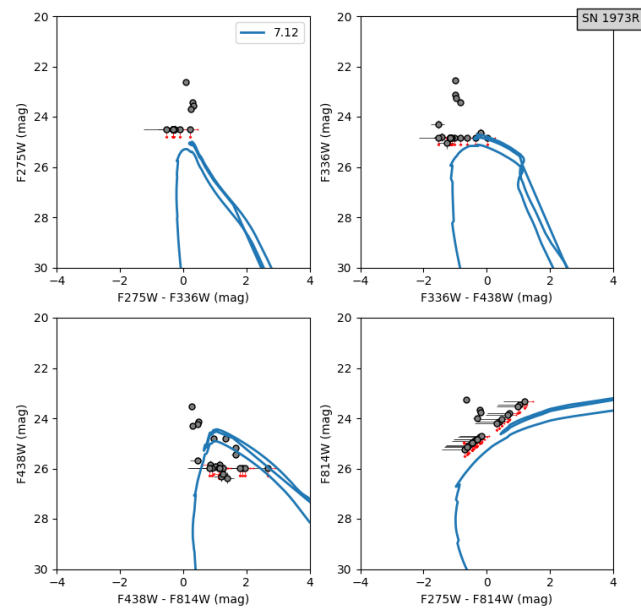


Figure A.2: SN 1973R CMD: data points correspond to the resolved stellar photometry and the best-fit PARSEC stellar isochrones are overlaid for the corresponding number of resolved populations.

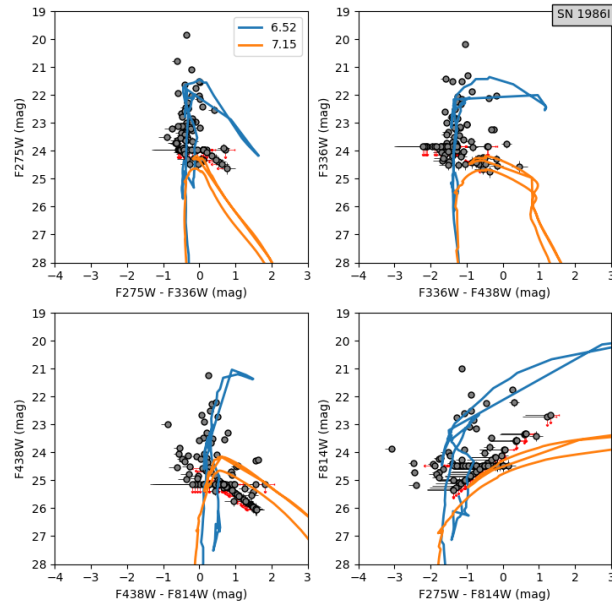


Figure A.3: SN 1986I CMD: data points correspond to the resolved stellar photometry and the best-fit PARSEC stellar isochrones are overlaid for the corresponding number of resolved populations.

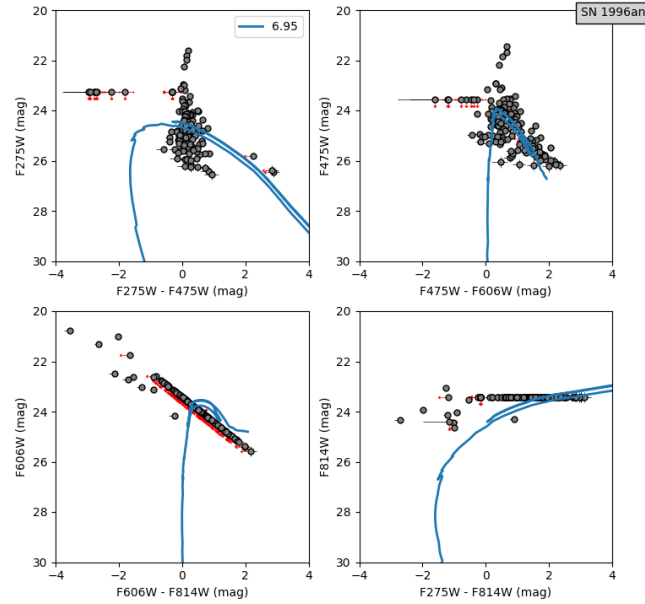


Figure A.4: SN 1996an CMD: data points correspond to the resolved stellar photometry and the best-fit PARSEC stellar isochrones are overlaid for the corresponding number of resolved populations.

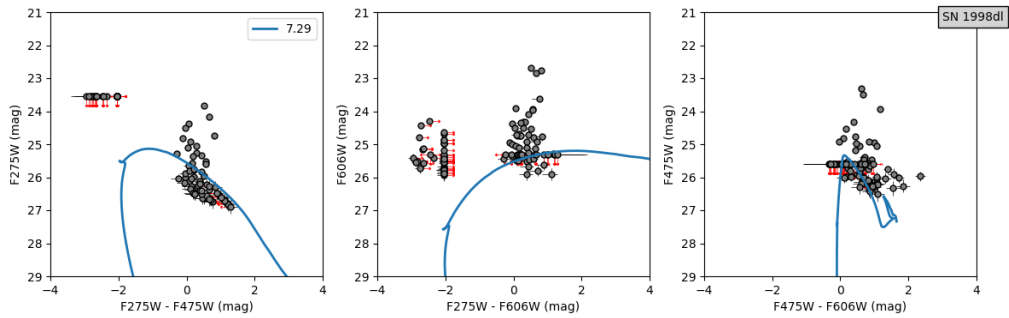


Figure A.5: SN 1998dl CMD: data points correspond to the resolved stellar photometry and the best-fit PARSEC stellar isochrones are overlaid for the corresponding number of resolved populations.

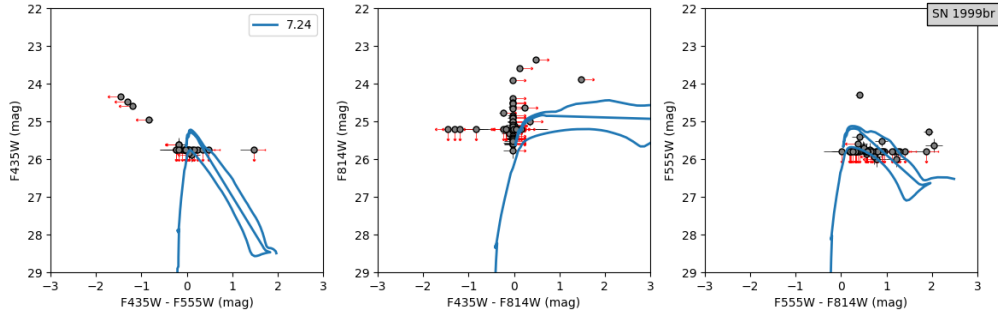


Figure A.6: SN 1999br CMD: data points correspond to the resolved stellar photometry and the best-fit PARSEC stellar isochrones are overlaid for the corresponding number of resolved populations.

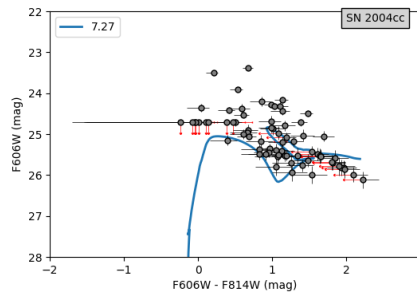


Figure A.7: SN 2004cc CMD: data points correspond to the resolved stellar photometry and the best-fit PARSEC stellar isochrones are overlaid for the corresponding number of resolved populations.

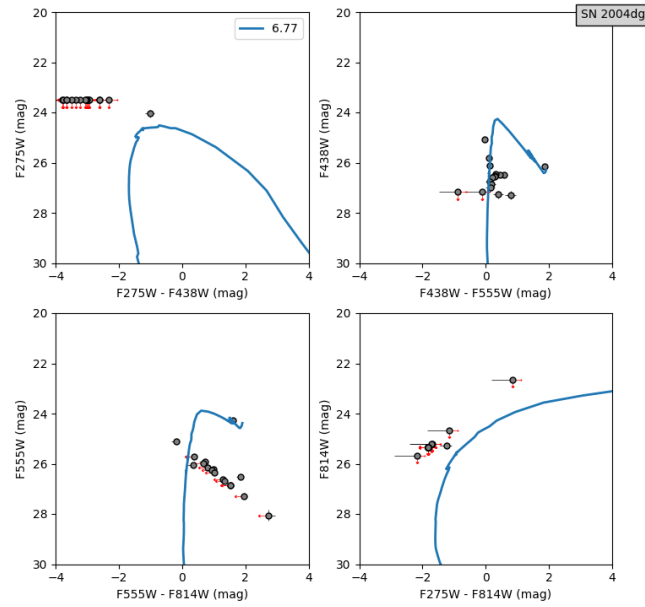


Figure A.8: SN 2004dg CMD: data points correspond to the resolved stellar photometry and the best-fit PARSEC stellar isochrones are overlaid for the corresponding number of resolved populations.

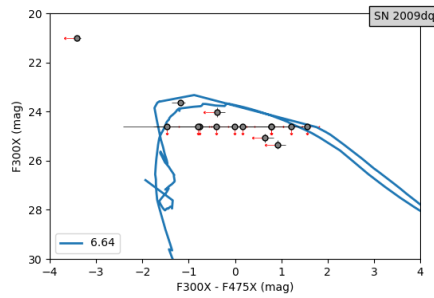


Figure A.9: SN 2009dq CMD: data points correspond to the resolved stellar photometry and the best-fit PARSEC stellar isochrones are overlaid for the corresponding number of resolved populations.

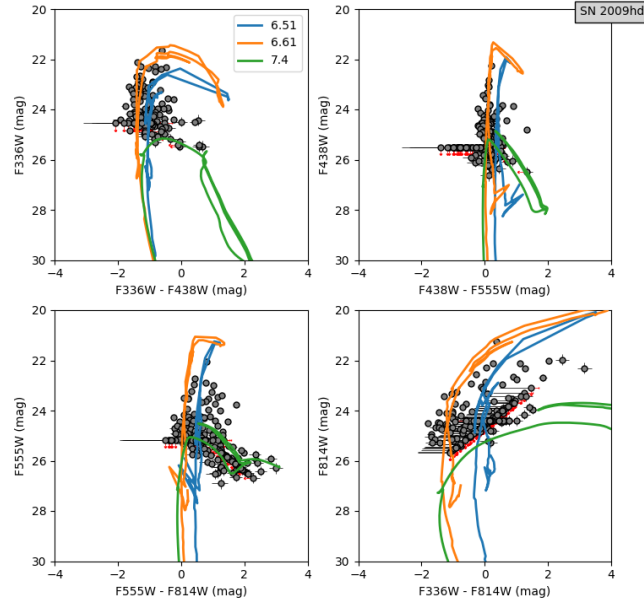


Figure A.10: SN 2009hd CMD: data points correspond to the resolved stellar photometry and the best-fit PARSEC stellar isochrones are overlaid for the corresponding number of resolved populations.

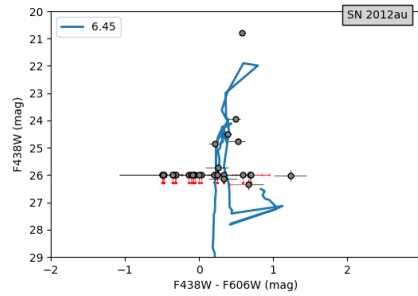


Figure A.11: SN 2012au CMD: data points correspond to the resolved stellar photometry and the best-fit PARSEC stellar isochrones are overlaid for the corresponding number of resolved populations.

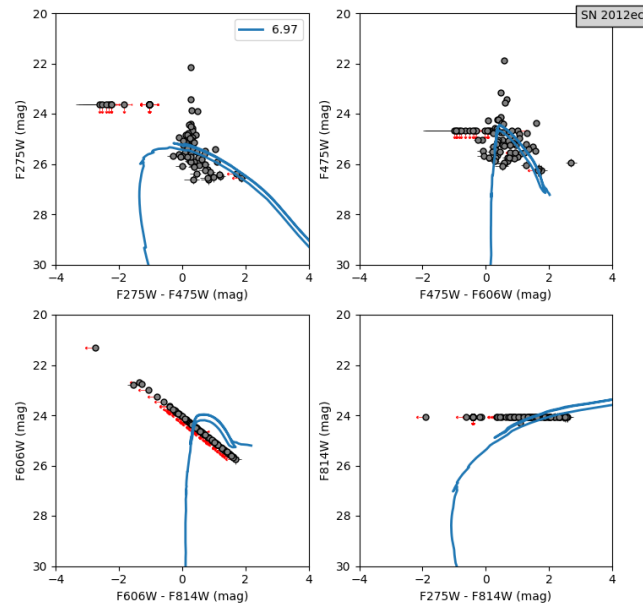


Figure A.12: SN 2012ec CMD: data points correspond to the resolved stellar photometry and the best-fit PARSEC stellar isochrones are overlaid for the corresponding number of resolved populations.

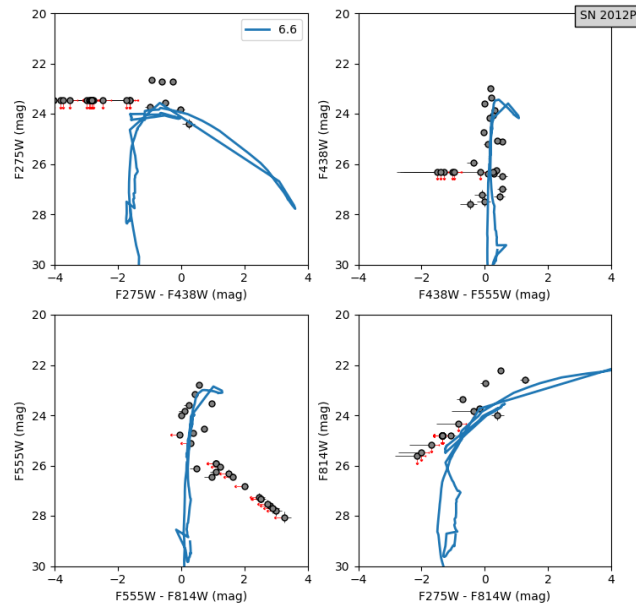


Figure A.13: SN 2012P CMD: data points correspond to the resolved stellar photometry and the best-fit PARSEC stellar isochrones are overlaid for the corresponding number of resolved populations.

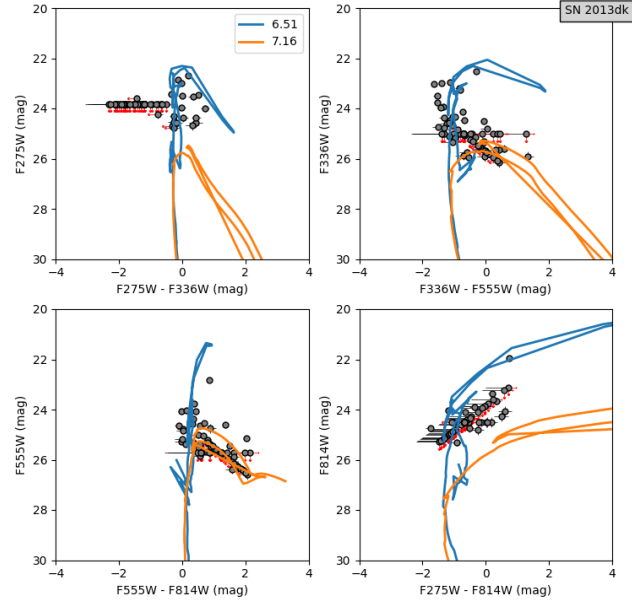


Figure A.14: SN 2013dk CMD: data points correspond to the resolved stellar photometry and the best-fit PARSEC stellar isochrones are overlaid for the corresponding number of resolved populations.

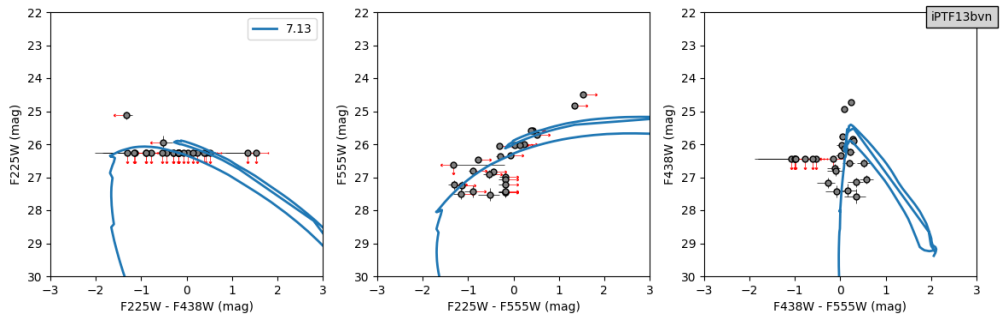


Figure A.15: SN iPTF13bvn CMD: data points correspond to the resolved stellar photometry and the best-fit PARSEC stellar isochrones are overlaid for the corresponding number of resolved populations.

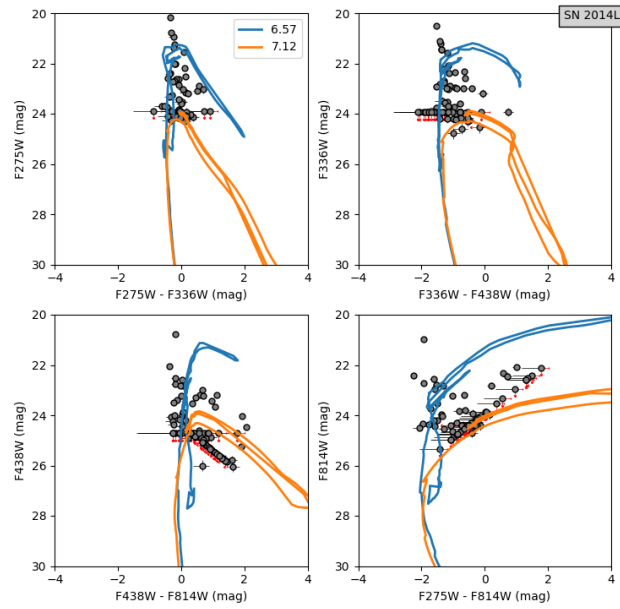


Figure A.16: SN 2014L CMD: data points correspond to the resolved stellar photometry and the best-fit PARSEC stellar isochrones are overlaid for the corresponding number of resolved populations.

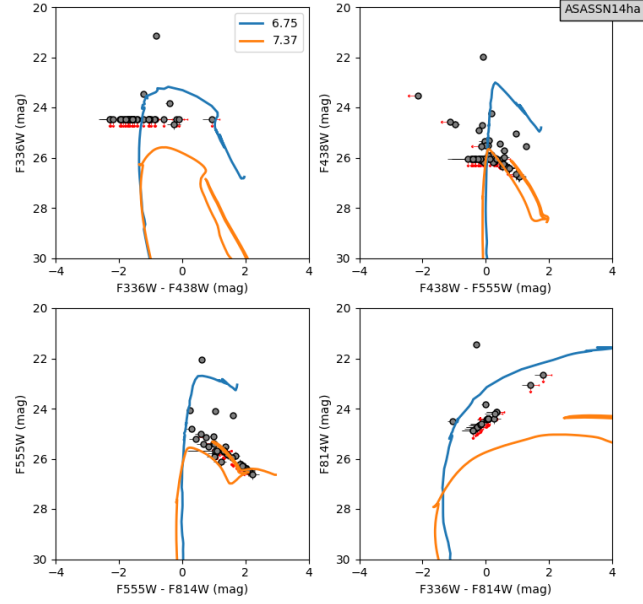


Figure A.17: ASASSN-14ha CMD: data points correspond to the resolved stellar photometry and the best-fit PARSEC stellar isochrones are overlaid for the corresponding number of resolved populations.

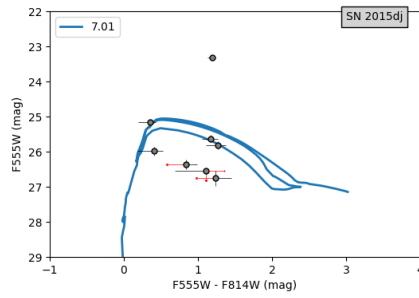


Figure A.18: SN 2015dj CMD: data points correspond to the resolved stellar photometry and the best-fit PARSEC stellar isochrones are overlaid for the corresponding number of resolved populations.

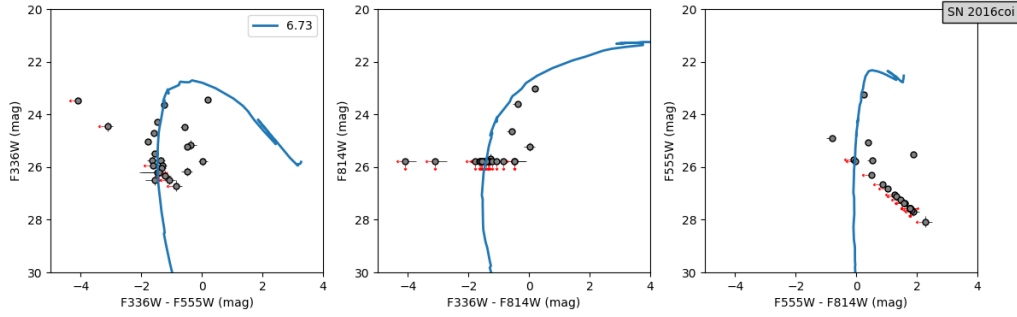


Figure A.19: SN 2016coi CMD: data points correspond to the resolved stellar photometry and the best-fit PARSEC stellar isochrones are overlaid for the corresponding number of resolved populations.

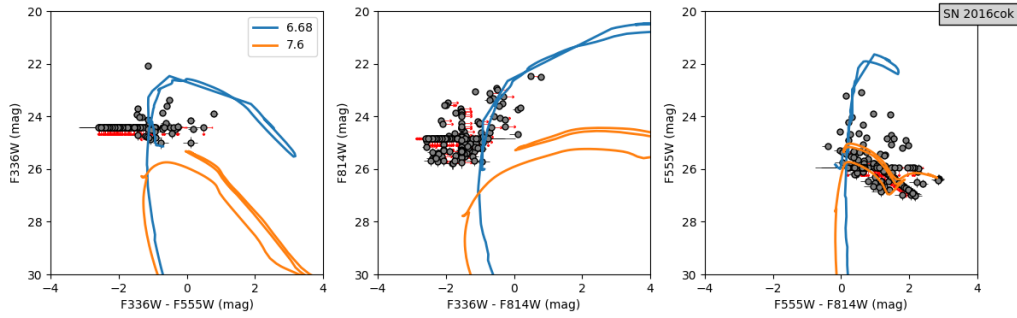


Figure A.20: SN 2016cok CMD: data points correspond to the resolved stellar photometry and the best-fit PARSEC stellar isochrones are overlaid for the corresponding number of resolved populations.

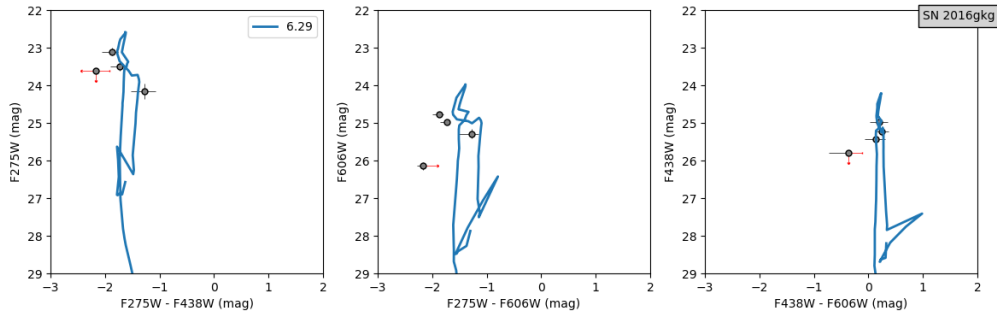


Figure A.21: SN 2016gkg CMD: data points correspond to the resolved stellar photometry and the best-fit PARSEC stellar isochrones are overlaid for the corresponding number of resolved populations.

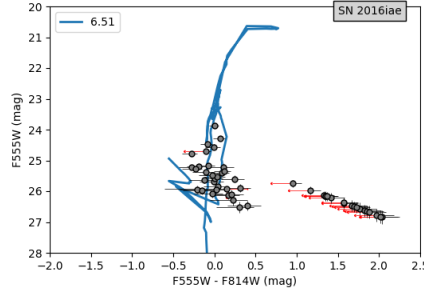


Figure A.22: SN 2016iae CMD: data points correspond to the resolved stellar photometry and the best-fit PARSEC stellar isochrones are overlaid for the corresponding number of resolved populations.

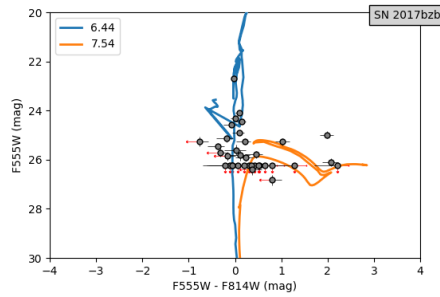


Figure A.23: SN 2017bzb CMD: data points correspond to the resolved stellar photometry and the best-fit PARSEC stellar isochrones are overlaid for the corresponding number of resolved populations.

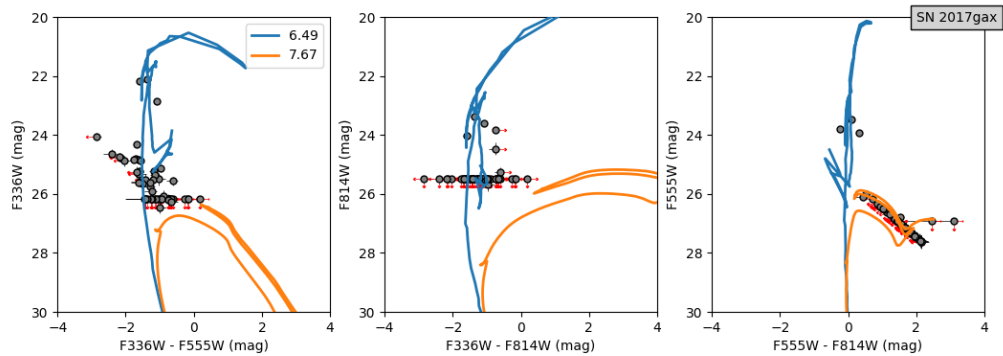


Figure A.24: SN 2017gax CMD: data points correspond to the resolved stellar photometry and the best-fit PARSEC stellar isochrones are overlaid for the corresponding number of resolved populations.

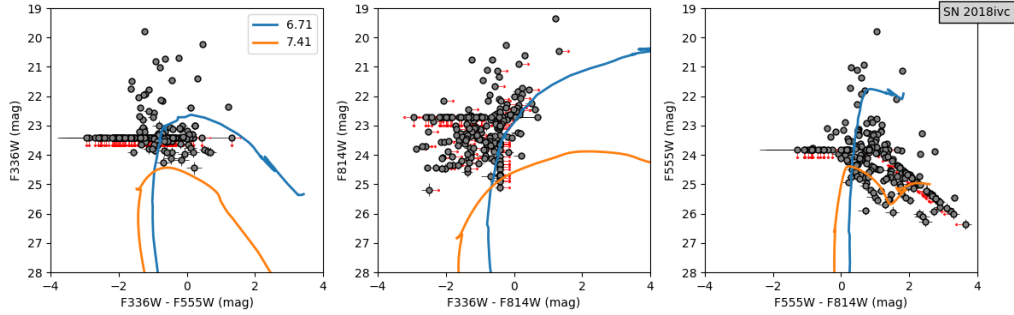


Figure A.25: SN 2018ivc CMD: data points correspond to the resolved stellar photometry and the best-fit PARSEC stellar isochrones are overlaid for the corresponding number of resolved populations.

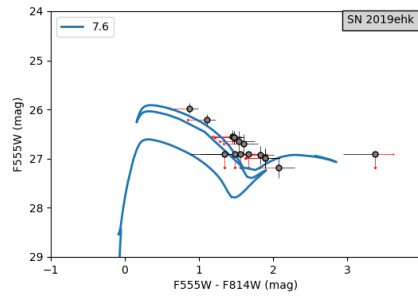


Figure A.26: SN 2019ehk CMD: data points correspond to the resolved stellar photometry and the best-fit PARSEC stellar isochrones are overlaid for the corresponding number of resolved populations.

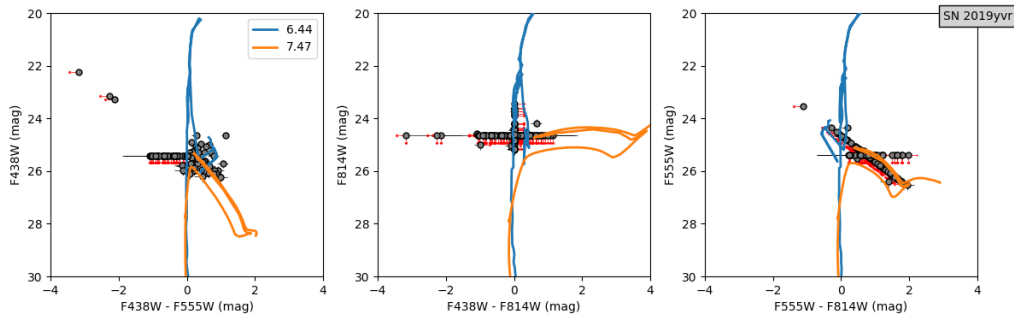


Figure A.27: SN 2019yvr CMD: data points correspond to the resolved stellar photometry and the best-fit PARSEC stellar isochrones are overlaid for the corresponding number of resolved populations.

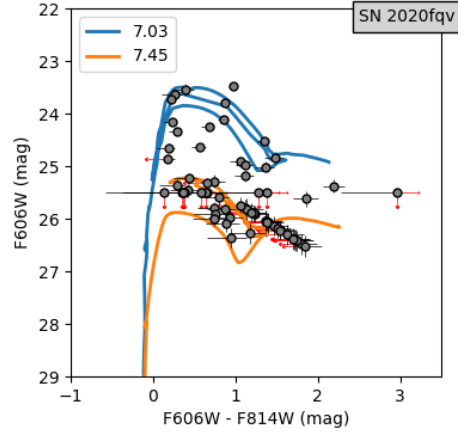


Figure A.28: SN 2020fqv CMD: data points correspond to the resolved stellar photometry and the best-fit PARSEC stellar isochrones are overlaid for the corresponding number of resolved populations.

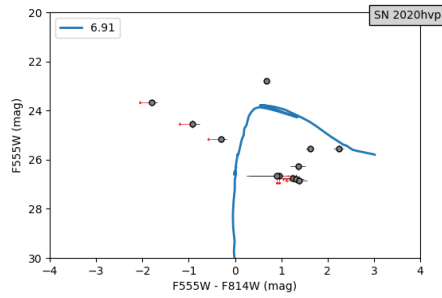


Figure A.29: SN 2020hvp CMD: data points correspond to the resolved stellar photometry and the best-fit PARSEC stellar isochrones are overlaid for the corresponding number of resolved populations.

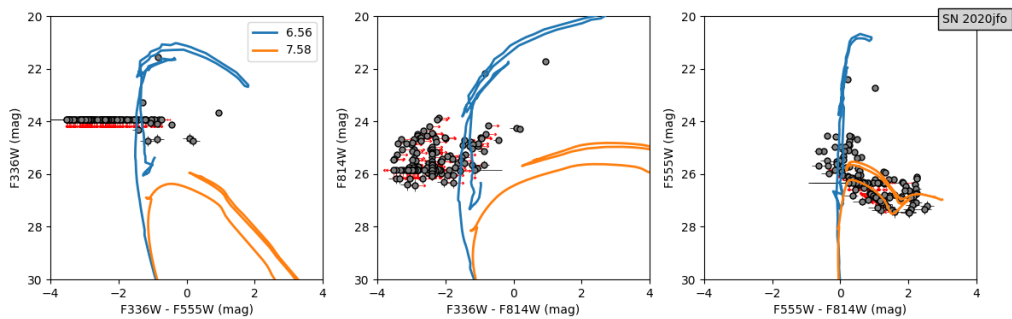


Figure A.30: SN 2020jfo CMD: data points correspond to the resolved stellar photometry and the best-fit PARSEC stellar isochrones are overlaid for the corresponding number of resolved populations.

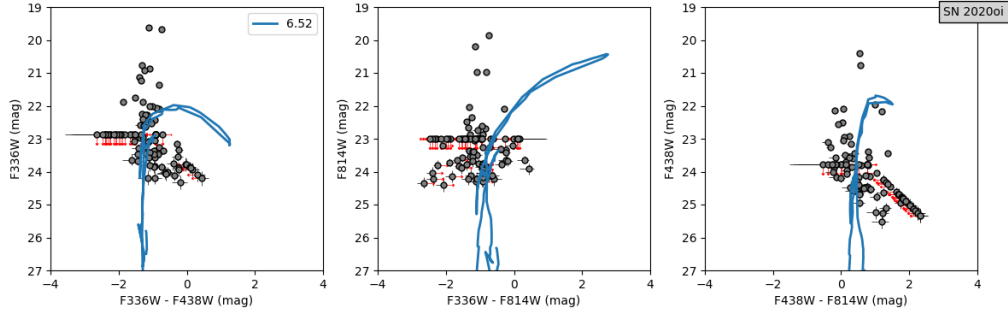


Figure A.31: SN 2020oi CMD: data points correspond to the resolved stellar photometry and the best-fit PARSEC stellar isochrones are overlaid for the corresponding number of resolved populations.

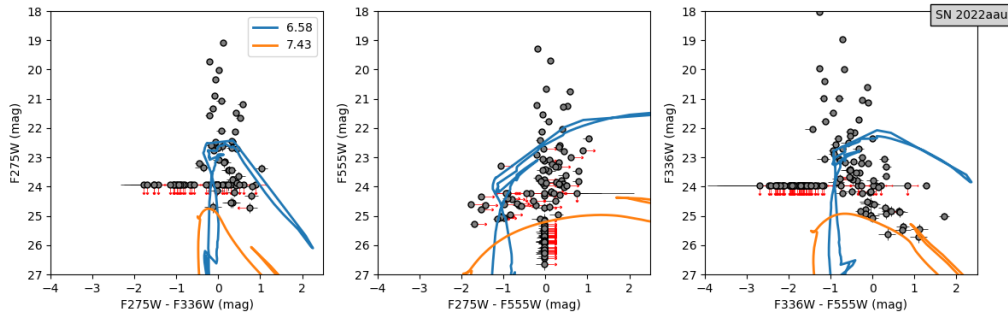


Figure A.32: SN 2022aau CMD: data points correspond to the resolved stellar photometry and the best-fit PARSEC stellar isochrones are overlaid for the corresponding number of resolved populations.

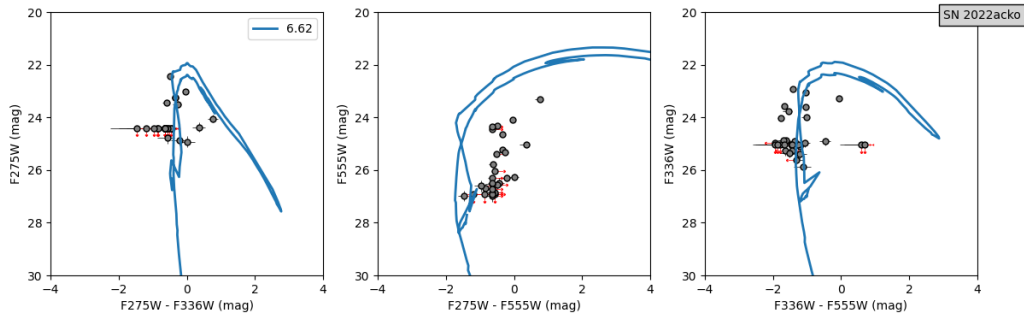


Figure A.33: SN 2022acko CMD: data points correspond to the resolved stellar photometry and the best-fit PARSEC stellar isochrones are overlaid for the corresponding number of resolved populations.

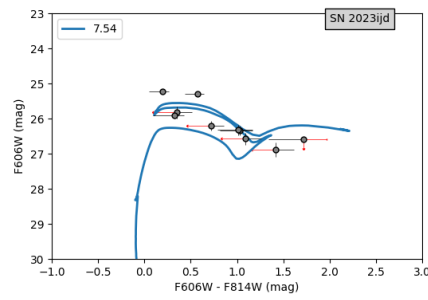


Figure A.34: SN 2023ijd CMD: data points correspond to the resolved stellar photometry and the best-fit PARSEC stellar isochrones are overlaid for the corresponding number of resolved populations.

