Detection strategies for the first supernovae with JWST

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ABSTRACT

Pair-instability supernovae (PISNe) are very luminous explosions of massive, low metallicity stars. They can potentially be observed out to high redshifts due to their high explosion energies, thus providing a probe of the Universe prior to reionization. The near-infrared camera, NIRCam, on board the James Webb Space Telescope is ideally suited for detecting their redshifted ultraviolet emission. We calculate the photometric signature of high-redshift PISNe and derive the optimal detection strategy for identifying their prompt emission and possible afterglow. We differentiate between PISNe and other sources that could have a similar photometric signature, such as active galactic nuclei or high-redshift galaxies. We demonstrate that the optimal strategy, which maximizes the visibility time of the PISN lightcurve per invested exposure time, consists of the two wide-band filters F200W and F356W with an exposure time of 600 s. For such exposures, we expect one PISN at $z \lesssim 7.5$ per at least 50,000 different field of view, which can be accomplished with parallel observations and an extensive archival search. The PISN afterglow, caused by nebular emission and reverberation, is very faint and requires unfeasibly long exposure times to be uniquely identified. However, this afterglow would be visible for several hundred years, about two orders of magnitude longer than the prompt emission, rendering PISNe promising targets for future, even more powerful telescopes.

Key words: early Universe – cosmology: dark ages, reionization, first stars – stars: Pop III – supernovae: general

1 INTRODUCTION

The frontiers of astronomy are approaching the epoch when the first generation of stars and galaxies were born. These first, so-called Population III (Pop III), stars are the key for understanding the formation of all subsequent structures in the Universe: they lit up the Universe when its age was less than 5% of its current age, they might have provided the seeds for supermassive black holes, and their creation of heavy elements had set the scene for the emergence of the first galaxies. Pop III stars are believed to have formed at redshifts $z = 10 – 25$ and to have had a higher characteristic mass than present-day stars, due to the lack of metals as efficient coolants at high redshift (Bromm et al. 1999; Abel et al. 2002; Yoshida et al. 2003). Their exact mass range and distribution is needed for accurately determining the ensuing radiative and chemical feedback, but it is still debated (Stacy et al. 2010; Clark et al. 2011; Hosokawa et al. 2011; Susa et al. 2014; Hirano et al. 2014; Hartwig et al. 2015; Stacy et al. 2016; de Bennassuti et al. 2017; Hirano & Bromm 2017). In addition to existing numerical simulations, it is important to obtain observational evidence to constrain the initial mass function (IMF) of the first stars.

Low-metallicity stars in the mass range $140 – 260 M_\odot$ are expected to go through a pair-instability supernova (PISN) at the end of their stellar lifetime. These very luminous explosions with energies of $10^{51–53}$ erg are triggered by electron-positron pair production in the hot core of massive stars. The resulting reduction in radiation support causes the core to collapse, thus igniting explosive oxygen and silicon burning which completely disrupts the star, leaving no compact remnant behind (Rakavy & Shaviv 1967; Barkat et al. 1967; Fraley 1968; Bond et al. 1984; Fryer et al. 2001). PISNe are powered by the diffusion of the shock energy, the interaction of the ejecta with the surrounding medium, and by a major contribution from radioactive decay of nickel

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over a time of about one year (Kasen et al. 2011). At slightly lower masses, metal-free stars can also encounter pulsational PISNe, where the pair production does not completely disrupt the star, but initiates a pulsational sequence of several core contractions, which are individually not powerful enough to unbind the star (Whalen et al. 2013; Spera & Mapelli 2017; Woosley 2017; Tolstov et al. 2017). With stellar rotation, PISNe can occur down to stellar masses of $\sim 80$ M$_\odot$, avoiding the pulsational phase (Chatzopoulos & Wheeler 2012; Yoon et al. 2012; Smidt et al. 2015). Other types of superluminous supernovae (SLSNe) were proposed in the literature as well (Umeda & Nomoto 2003; Tomimaga 2009; Moriya et al. 2010; Gal-Yam 2012; Nicholl et al. 2013; Yoshida et al. 2014; Abbott et al. 2017; Moriya et al. 2018). Cooke et al. (2012) reported the detection of two SLSNe at $z = 2$ and $z = 4$ with slowly evolving lightcurves. They predicted that the rate of SLSNe at higher redshift is one order of magnitude higher than in the local Universe. None of the detected SLSNe (Pan et al. 2017; Chen et al. 2017; Bose et al. 2018) sits comfortable within the model predictions for PISNe, and alternative mechanisms for these classes of SLSNe are advocated and debated (Dessart et al. 2012; Nicholl et al. 2013; Yusof et al. 2013; Lunnan et al. 2017; De Cia et al. 2017).

The possibility of detecting PISNe at high redshift and thereby constraining the properties of their stellar progenitors has been previously discussed (Mackey et al. 2003; Scannapieco et al. 2005; Whalen et al. 2013; Pan & Loeb 2013; de Souza et al. 2014; Wang et al. 2017). Those predictions are based on theoretical models of PISN lightcurves with multidimensional radiative transfer codes (Scannapieco et al. 2005; Woosley et al. 2007; Kasen et al. 2011; Pan et al. 2012; Chen et al. 2014; Jerkstrand et al. 2016; Kozyrev et al. 2017; Gilmer et al. 2017). Cosmological simulations and semi-analytical models of structure formation predict the PISN rate as a function of redshift (Miralda-Escudé & Rees 1997; Wise & Abel 2005; Hummel et al. 2012; Pan et al. 2012; Johnson et al. 2013; Takami et al. 2013; Magg et al. 2016), concluding that PISNe are rare events that require an optimised survey strategy and a large field of view to detect them. A PISN has not yet been observed, but a direct detection would be extremely valuable for our understanding of Pop III star formation, because this mass range has not been probed by stellar archaeology (but see Aoki et al. 2014).

The main focus of this paper is to find efficient detection strategies to detect PISNe at high redshift with the James Webb Space Telescope (NASA) as well as other next-generation facilities. Based on realistic lightcurves, we determine their photometric signature and derive the optimal detection strategy by maximizing the visibility time of a PISN event for a given exposure time. We present the optimal 2-filter combination and exposure time for the prompt emission. We also discuss the possibility to detect the PISN afterglow, caused by nebular emission and reverberation in the surrounding gas. We thus introduce a novel probe of the pre-galactic medium, whose utility, however, has to await the advent of even more powerful telescopes in the future.

2 METHODOLOGY

The first stars are expected to form as small multiples in metal-free gas, with a distribution that extends to high masses (Stacey et al. 2010; Clark et al. 2011; Greif et al. 2011). As a result, they produce a strong UV flux, which partially or completely ionizes the surrounding interstellar medium (ISM). If at least one star is in the mass range $140 - 260$ M$_\odot$, a PISN will be triggered. In this section, we describe how we model the ISM, the underlying stellar population, the radiative feedback on the ISM, and the interaction of the PISN with the gas. We also consider other astrophysical sources that exhibit a similar spectral energy distribution (SED), thus possibly mimicking a PISN signature.

2.1 Single Stellar Population

We assume that the PISN progenitor stars are embedded in a metal-free stellar cluster or group. Consequently, we also account for the radiative feedback from the underlying stellar population, resulting in the build-up of a HII region. To generate synthetic spectra of these primordial clusters, we consider single stellar population (SSP) models by Schaerer (2002), where Pop III stars radiate close to a blackbody (Bromm et al. 2001). We have verified that our modeling agrees with the Pop III SEDs by Zackrisson et al. (2011).

As a fiducial model, we use a logarithmically-flat IMF in the range $M_{\text{min}} = 3$ M$_\odot$ to $M_{\text{min}} = 300$ M$_\odot$, motivated by simulations (Clark et al. 2011; Greif et al. 2011; Dopcke et al. 2013) and empirical hints (Aoki et al. 2014). Given that metal-free stars with masses of $140 - 260$ M$_\odot$ are predicted to explode as PISNe (Heger & Woosley 2002), we expect on average one PISN event per 500 M$_\odot$ in Pop III stars. We further assume that all Pop III stars form in one initial burst with a duration of $\Delta t_{\text{sb}} = 10^5$ yr, which corresponds to the free-fall time at typical densities in the pre-stellar core (Stacey et al. 2010; Clark et al. 2011). This is short compared to typical stellar lifetimes of over several million years.

The rest-frame time interval over which the prompt PISN emission is bright extends for $\sim 1$ yr, whereas the time over which stars explode as PISN, averaged over their different progenitor masses, is $\Delta t_{\text{PISN}} \approx 10^7$ yr. Together with $\Delta t_{\text{sb}}$, this yields an interval of $\sim 2 \times 10^5$ yr over which PISNe are possible for a given primordial galaxy. Consequently, one has to be lucky to observe such a galaxy at the right moment to detect a PISN signature. Even for a galaxy with a total mass of $10^5$ M$_\odot$ in Pop III stars, and hence $\sim 200$ expected PISN explosions, the probability to observe two PISNe at the same time is negligibly small. We hence focus on the case in which one single PISN explodes at a time.

2.2 PISN spectra

We use the tabulated PISN spectra by Kasen et al. (2011) in the form of the SED of PISNe for different times after the explosion. Specifically, we employ the model of red supergiants, since Pop III stars in the PISN mass range are expected to have convective envelopes, which can mix the central metals with the outer hydrogen layers. The prompt emission of each PISN is brighter than the underlying stellar
population for only about 1 yr in the source frame, and previous studies have focused on the detection of this prompt emission (Weinmann & Lilly 2005; Frost et al. 2009; Hummel et al. 2012; Whalen et al. 2013; de Souza et al. 2013, 2014). Even if this time interval gets extended due to cosmological expansion by a factor of ∼10, it is still very unlikely to detect this prompt emission in high-redshift surveys and we have to determine the optimal diagnostic. We consider two additional effects in our modeling, which stretch the time of possible observation to several hundreds of years in the source rest-frame: nebular emission from the ionized gas and the geometrical echo effect of the ambient medium.

2.3 Nebular Emission

To model the observed SED of the superposed Pop III stellar population and a possible PISN contribution, we use the photoionization code CLOUDY (Ferland et al. 2013), with gas of primordial composition and no dust. For the geometry and density of the ambient gas we assume three different models: a constant gas density of $n_H = 1$ cm$^{-3}$ or $n_H = 100$ cm$^{-3}$ or $n_H = 100$ cm$^{-3}$ out to a radius of 100 pc, falling off as $r^{-2}$ beyond (Wang et al. 2012), or the idealized case of very low ambient gas density, for simplicity represented as $n_H = 0$. The first two models correspond to the typical conditions in a minihalo ($M_{\text{vir}} = 10^6 M_{\odot}$) and an atomic cooling halo ($T_{\text{vir}} \gtrsim 10^4$ K), respectively. The last model, lacking any reprocessing of the emitted radiation, corresponds to a negligibly low nebular density, caused by strong stellar feedback, or the clumpiness of the gas into a few high-density regions with a small covering fraction (Santos et al. 2002). The assumed density is in agreement with observations of the circumburst medium of the gamma-ray burst GRB09090423 at $z = 8.2$ (Chandra et al. 2010). For the inner radius of the spherical gas distribution we assume 1 pc, which corresponds to the size of the Pop III star-forming region. We have verified that the exact choice of this value has no significant influence on the final results.

The Strömgren radius, within which gas is completely ionized, is given by

$$R_S = \left( \frac{3Q_H}{4\pi \alpha n_H} \right)^{1/3} \approx 66 \text{ pc} \left( \frac{M_*}{10^5 M_{\odot}} \right)^{1/3} \left( \frac{n_H}{100 \text{ cm}^{-3}} \right)^{-2/3}$$

(1)

with an ionizing photon flux of $Q_H$, a recombination coefficient of $\alpha = 5 \times 10^{-13}$ cm$^3$ s$^{-1}$, and a total mass in Pop III stars of $M_*$. To relate the flux of ionizing photons to the stellar mass, we use tabulated stellar evolution models (Schaerer 2002), averaged over the IMF, whereas the exact upper limit of the IMF for this average has only a minor influence (Bromm et al. 2001). We note that the Strömgren radius is smaller than the constant density core for a gas density of $n_H = 100$ cm$^{-3}$, but larger for a gas density of $n_H = 1$ cm$^{-3}$. This indicates that the gas is already completely ionized when a PISN explodes in a minihalo, and we do not expect a significant additional contribution from nebular emission in this case (Zackrisson et al. 2011).

The SED of a single stellar population (SSP) with and without the contribution of different PISNe can be seen in Fig. 1. The prompt PISN emission is about two orders of magnitude brighter than the underlying Pop III stellar population.

Figure 1. SEDs of a SSP of $10^5 M_{\odot}$, with and without PISN contribution, and an ambient gas density of $n_H = 100$ cm$^{-3}$. The PISN SEDs are averaged over the time of explosion, weighted by their bolometric luminosity. Photons bluewards of 912 Å are absorbed by the neutral surrounding medium, and re-emitted in the IR.

2.3.1 Recombination

The nebular emission caused by the PISN decays over the recombination time scale of $t_{\text{rec}} \sim 400$ yr at $n_H = 10^2$ cm$^{-3}$. This time scale is between the characteristic time scale of the PISN light curve ($\lesssim 1$ yr) and the typical stellar lifetimes of several Myr. We can consequently assume that the energy input from the PISN is almost instantaneous and that the SED of the underlying stellar population does not significantly change over $t_{\text{rec}}$. We model the nebular emission with CLOUDY, assuming a time-dependent incident radiation field. The resulting time evolution of the SED can be seen in Fig. 2. Already 3 yr after the explosion, the prompt emission decayed and only a few recombination lines render the PISN afterglow brighter than the underlying stellar population. The additional nebular emission from the PISN derives almost exclusively from recombination lines, with only a small contribution of free-free emission to the continuum.

2.3.2 Geometrical echo effect

The light-crossing time for a spherical gas cloud with radius $R = 100$ pc is $\sim 650$ yr, which is comparable to the recombination time. Consequently, we also have to take into account geometrical effects of the ambient gas and the reverberation that is created by photons that are absorbed and re-emitted by gas off the line of sight. We assume a central energy source that emits isotropically in all directions, embedded in a spherical ambient medium and an observer at infinity. Photons get absorbed and might be re-emitted into the direction of the observer, but they will arrive later at the observer than photons that are directly emitted into the observer’s direction. The locus for which photons have
channel, which together cover the range of $0.5 - 5 \mu m$. This makes NIRCam the perfect instrument to probe high-redshift galaxies, whose strong rest-frame UV emission gets shifted into the NIR in the observer frame. For the calculation of the luminosity distance, we assume a flat Universe with cosmological parameters determined by the Planck satellite [Planck Collaboration et al. 2016].

3 PHOTOOMETRIC SIGNATURES

3.1 SEDs of high-redshift sources

We first present the resulting SEDs of the PISNe, their time evolution, and the effects of nebular emission and reverberation. In addition, we construct the SEDs of other sources at high redshift, which could have the same photometric signature as PISNe and hence confuse their detection.

3.1.1 PISNe

For the low density case, and that without any ambient medium, there is no additional afterglow or echo effect because the underlying SSP already keeps all the gas ionized [Zackrisson et al. 2011]. We only expect to see the prompt emission in these cases over a typical time scale of one year.

In Fig. 3, we compare the bolometric light curves after SN explosion with and without the echo effect. The reprocessing of the prompt emission stretches the lightcurve from $\sim 1$ yr to $\gtrsim 10$ yr and hence increases the time interval of possible detection. However, the recombination line emission decays exponentially towards the contribution from the nebular emission powered by the underlying stellar population. This yields luminosities of the reprocessed radiation that are brighter by only a factor of a few than the stellar population for $\gtrsim 1$ yr after the PISN explosion. The echo effect smooths the lightcurve over the light crossing time of the ISM. Although this increases the time interval in which we can detect PISNe by more than two orders of magnitude, the luminosity of the PISN lightcurve is reduced by about two orders of magnitude due to conservation of the explosion energy (Section 3.3).

3.1.2 AGN

The typical PISN (averaged over progenitor masses and time after explosion) has a luminosity of $\sim 10^{43}$ erg s$^{-1}$ and peaks at $\sim 200$ nm. An AGN with a BH mass of $\sim 10^7 M_\odot$ peaks in the same wavelength range and has the same luminosity as a typical PISN for an Eddington rate of 1% [Volonteri et al. 2017]. We model the emission from a typical broad line region (BLR) illuminated by such an AGN with CLOUDY, assuming a density of $n_H = 10^{10}$ cm$^{-3}$ and solar metallicity for the BLR.

Direct collapse black holes (DCBHs) are an advocated sub-type of high-redshift quasars that form due to the isothermal collapse of a pristine protogalaxy under the influence of a nearby photodissociating source [Bromm & Loeb 2003]. The isothermal collapse of pristine protogalaxies can yield seed BHs with masses of up to $\sim 10^5 M_\odot$, which can then further accrete gas to become more massive. These accreting DCBHs might also be detectable with
We also verify that our proposed photometric diagnostic is suited to distinguish a PISN from a typical high-redshift galaxy. We use the SEDs by Barrow et al. (2017), who present synthetic observations of $z \geq 6$ galaxies, based on the Renaissance simulation. They demonstrate that there is no “typical” high-redshift galaxy, but their spectra vary with stellar mass, metallicity, gas mass fraction, formation history, and viewing angle. To account for these effects, we use averaged spectra over all galaxies with a stellar mass in the range $5.5 < \log(M_*/M_\odot) < 6.5$ and assume an average bolometric luminosity of $5 \times 10^{41}$ erg s$^{-1}$. This mass range is the best trade-off between the abundance and luminosity of high-redshift galaxies: low-mass galaxies are more abundant and hence more typical at high redshift. However, the faintest galaxies are below the sensitivity threshold of JWST and despite their abundance they will not be the most frequently observed sources with JWST. Galaxies with $M_* \approx 10^6 M_\odot$ have a comoving number density of

$$\frac{dn}{d \log M_*} \approx 10^{-3} \text{cMpc}^{-3}$$

at redshift $z = 6$ (Barrow et al. 2017). The SED of a typical, metal-enriched high-redshift galaxy is close to the SED of our Pop III SSP with roughly the same luminosity. Due to the averaging over several galactic SEDs, their emissions lines are not as prominent as for the Pop III SSP or the PISNe with nebular emission. Once we find a diagnostic to photometrically distinguish PISNe and the underlying Pop III SSP, we expect metal enriched galaxies not to compromise this diagnostic. We will discuss this distinction and the corresponding constraints more quantitatively in the next sections. For a more general discussion on the JWST signatures of high-redshift galaxies, see Zackrisson et al. (2017).

### 3.2 Detection strategy for prompt emission

Many previous studies focused on the modeling and observational signatures of the prompt PISN emission (Scannapieco et al. 2005; Weinmann & Lilly 2005; Frost et al. 2009; Kasen et al. 2011; Pan et al. 2012; Hummel et al. 2012; Whalen et al. 2013; de Souza et al. 2013, 2014). In this section, we present the photometric signature of PISNe and for the first time derive the optimal filter combination to detect their prompt emission and determine the most efficient exposure time and detection strategy.

The basic idea and strategy to detect PISNe at high redshift is as follows: PISNe are very bright over a period of roughly one year in the source rest frame. This time interval stretches to about one decade in the observer frame due to the cosmic expansion. If we could identify a PISN candidate in one observation, we can observe the same source a few months later to verify if it is a transient source, which would confirm the detection of a PISN. The crucial point is to maximize the fraction of the lightcurve that we can observe, because the probability to find a PISN in the first place is directly proportional to the visibility time, $t_{vis}$, over which we can detect it.

In this section, we only focus on the prompt emission and do not account for the nebular emission or echo effect. We cut the SED below $\lambda < 912$ Å to mimic the neutral IGM at high redshift, but this has only a minor influence on the calculated photometric fluxes. Due to the very faint fluxes, the wide band filters of JWST are the best choice for the photometric detection of PISNe. The expected light curves in the observer frame can be seen in Fig. 4. The flux increases with progenitor mass and with decreasing redshift. The time evolution of the flux is not monotonous with time and differs from filter to filter. The flux is very faint in the 070W and 090W filter, because we only have the direct prompt emission and no reprocessed recombination lines in this wavelength range. The filters with the highest expected signal-to-noise ratio (SNR) to detect PISNe are: F150W, F200W, F277W, F356W, F444W. The typical high-$z$ galaxy...
Figure 4. Lightcurves of the prompt PISN emission for three different progenitor masses (top: $150 \, M_\odot$, middle: $200 \, M_\odot$, bottom: $250 \, M_\odot$) at three different redshifts (left: $z = 6$, middle: $z = 9$, right: $z = 12$) in the JWST wide-band filters as a function of time in the observer-frame. The left vertical axis indicate the flux in nJy and the right axis yields the corresponding monochromatic AB-magnitude. The different filters are illustrated by the different colors and the corresponding sensitivity limit for a 600 s exposure are indicated by the horizontal dotted lines in each panel. The grey area indicates the expected flux from an AGN, powered by a $10^7 \, M_\odot$ BH. For simplicity we only plot the AGN flux in the 444W filter, which is the highest flux and hence represents a conservative upper limit.

and AGN yield fainter fluxes, although an AGN at $z \approx 6$ has the same flux in certain filters as a PISN at $z \approx 12$.

We are interested in a reliable diagnostic to find PISN candidates that can then be further analysed for their transient nature. We want to maximize the observer frame time over which a PISN is detectable for a given diagnostic, because the probability to find a PISN is linearly proportional to this visibility time and since PISNe are very rare events (see Section 4.1), we need to identify an efficient filter combination. In the following sections, we derive the optimal detection strategy by maximizing the visibility time of the PISN lightcurve per exposure time invested. This visibility time depends on the selected filter, progenitor mass, redshift, and the desired signal-to-noise threshold. To calculate the visibility time, we define our standard sample of 5 PISNe ($150, 175, 200, 225, 250 \, M_\odot$) at 3 different redshifts ($z = 6, 9, 12$). We then identify the observer frame visibility of this ensemble of 15 PISNe as the cumulative time over which a PISN is detectable for a given diagnostic, be it the lightcurve that is observable. In the optimal case, we can observe 100% of the lightcurve, but as we will see below, this requires unnecessary long exposure times. This fraction of the lightcurve depends on our definition of the duration of the prompt emission. To simplify the comparison, we use the $250 \, M_\odot$ as standard scenario, which has a maximum visibility time of $\sim 340 \, d$ in the source rest frame. All following fractional visibility times of the lightcurve are for a $250 \, M_\odot$ PISN, normalized to this value.

NIRCam on board JWST has a beam splitter that allows simultaneous observation of a source in one short wavelength and one long wavelength channel. In the following sections, we make use of this feature by combining two corresponding filters. The tabulated sensitivity $f_{\text{lim}}$ of NIRCam is given at a SNR of $S/N = 10$ and for an exposure time of $t_{\text{exp}} = 10 \, ks$. These values are for point sources and the actual signal-to-noise depends on the galactic foregrounds and therefore on the source position. Our derived exposure times at $S/N = 10$ should hence be treated as an optimistic lower limit. To convert the tabulated to an arbitrary exposure time, we assume the proportionality $f_{\lim} \propto t_{\text{exp}}^{1/2}$ and a linear response of the detector over its dynamical range.

3.2.1 2-filter diagnostic

The most efficient diagnostic is based on two filters that can be exposed simultaneously. In Fig. 5 we show one possible 2-filter diagnostic (which we demonstrate later to be...
the optimal filter combination) to illustrate the effect of a varying exposure time. As expected, the PISN visibility time increases with the exposure time. Already in a 450 s exposure we can identify the most luminous 225 M\(_{\odot}\) and 250 M\(_{\odot}\) PISN at \(z = 6\) with \(S/N > 10\). With a longer exposure time of \(\gtrsim 10\) ks we can even detect the 200 M\(_{\odot}\) PISN at \(z = 6\) and the 225 M\(_{\odot}\) out to \(z = 12\). Also the observational uncertainty decreases with the exposure time. In order to not only maximize the PISN visibility, but to optimise the effort, we maximize the ratio of the visibility time to the exposure time to obtain the highest probability of finding PISNe per invested exposure time. PISNe with \(M < 200 M_{\odot}\) are not detectable with \(S/N > 10\) for \(t_{\exp} \lesssim 10\) ks, but this does not affect the performance of the diagnostic. PISNe at higher redshift are favorable because their lightcurve gets stretched by a larger factor, which increases their observer frame visibility, but they are also significantly fainter.

We compare our photometric diagnostic to other SN types. For this comparison we select a Type Ia SN based on the theoretical model by Blondin et al. (2013), Type II based on the observation of the SLSN 2008an (Chatzopoulos et al. 2011), and the Type IIP SN 1999em (Leonard et al. 2002) at their peak luminosity and illustrate them with the dash-dotted, dotted, and dashed lines in Fig. 3 respectively. The first criterion to differentiate SNe is their absolute flux in the individual filters. For our optimal diagnostic with the most promising 250 M\(_{\odot}\) PISN at \(z = 6\) we expect fluxes of 46 – 70 mJy in the F200W filter and of 55 – 119 mJy in the F356W filter. None of the other three SN types fulfills both flux criteria simultaneously at any redshift. For example, the Type IIn SN has a flux in this range in the F200W filter at a redshift of \(z = 2.3 – 3.1\) and the corresponding flux in the F356W filter at redshifts of \(z = 0.8 – 1.6\). To illustrate the flux ratio, we therefore choose the intermediate redshift of \(z = 2\). Our PISNe appear redder than other SNe at lower redshift. Although PISNe can be photometrically distinguished from these selected SNe at peak brightness we note that this does not cover all classes and variations of SNe and we further discuss this challenge in section 3.3.

For different filter combinations and various exposure times we provide the cumulative observer frame visibility of the PISNe in Table 1. The visibility time for \(t_{\exp} \lesssim 10\) ks is dominated by the 225 M\(_{\odot}\) and 250 M\(_{\odot}\) PISNe at \(z = 6\). We assume that all PISNe have the same probability to occur and that the rate of PISNe is constant in the redshift range \(z = 6 – 9\), which agrees with Magg et al. (2016); however, see Hummel et al. (2012), Johnson et al. (2013). For a different IMF or PISN rate, one could weight the contributions to the red frame visibility accordingly. Moreover, we do not explicitly take other sources into consideration, such as metal enriched galaxies or an AGN, because they are fainter than the prompt PISN emission and vary on much longer timescales than the PISN. The visibility fraction is an additional illustration to demonstrate the effect of a varying exposure time. It saturates for exposure times \(\gtrsim 10\) ks and doubling the exposure time does not yield much more information.

We further quantify the ratio of the visibility to the exposure time in Fig. 4. We find a peak of the efficiency for the filter combination 200W–356W at an exposure time of 600 s. With this optimal combination of filters and exposure time we can detect roughly two days of the PISN lightcurves in the observer frame per one second of exposure time. The 200W–277W color has a comparable but slightly weaker performance, and for other filter combinations the most economic exposure time is \(\gtrsim 1000\) s, but their overall performance is significantly smaller.

The filters 200W and 356W are in the short and long wavelength channel of NIRcam and can hence be used simultaneously. Our results imply that ten individual observations of different fields of view (FoV) with 600 s exposure time each are more promising than one with an exposure time of 6000 s.

### 3.2.2 4-filter diagnostic

The identification of PISNe as transient sources poses two challenges: first, we have to identify them as promising candidates and second, we have to verify their transient nature and their unique colors in a follow-up observation. Although the PISN SED changes with time, some colors are constant over \(\gtrsim 4\) yr (see Fig. 5), which makes it difficult to identify their transient nature with a two filter diagnostic. Moreover, we cannot account for all astrophysical sources that could have a similar photometric flux, and possibly even time evolution, as the PISN. Therefore, we also provide a color-color diagnostic based on 4 filters, which, shows a more reliable time evolution of the colors and helps to better distinguish the PISN from other sources.

Since we require that the PISN has to be detected in 4 filters simultaneously at \(S/N > 10\), the visibility time is shorter than in the 2-filter diagnostic. By maximizing the ratio of visibility time to exposure time we determine the optimal filter combination and corresponding exposure time (see Fig. 7). We find a peak of the efficiency for the two color combination 150W–277W vs. 200W–356W at an exposure.

| \(t_{\exp}\) [ks] | 150W | 150W | 150W | 200W | 200W | 200W |
|-------------------|------|------|------|------|------|------|
| 0.45              | 0    | 0    | 0    | 532  | 672  | 0    |
|                  | (0%) | (0%) | (0%) | (22%)| (24%)| (0%) |
| 0.54              | 0    | 0    | 0    | 700  | 1078 | 14   |
|                  | (0%) | (0%) | (0%) | (26%)| (28%)| (1%) |
| 0.6               | 0    | 0    | 0    | 994  | 1288 | 56   |
|                  | (0%) | (0%) | (0%) | (29%)| (32%)| (1%) |
| 0.72              | 0    | 0    | 0    | 1498 | 1526 | 32   |
|                  | (0%) | (0%) | (0%) | (33%)| (34%)| (14%)|
| 1.2               | 0    | 0    | 0    | 2268 | 2184 | 840  |
|                  | (0%) | (0%) | (0%) | (44%)| (44%)| (34%)|
| 3.6               | 1788 | 1540 | 826  | 3746 | 3458 | 2562 |
|                  | (16%)| (12%)| (4%)  | (77%)| (74%)| (57%)|
| 5.4               | 2274 | 2070 | 1358 | 4276 | 3992 | 2940 |
|                  | (31%)| (29%)| (16%)| (83%)| (81%)| (63%)|
| 10                | 3216 | 2848 | 2156 | 6784 | 6434 | 4786 |
|                  | (45%)| (45%)| (37%)| (94%)| (94%)| (86%)|
| 100               | 7138 | 7188 | 5928 | 14608| 14732| 13326|
|                  | (73%)| (73%)| (72%)| (100%)| (100%)| (100%)|
time of 3 ks. With this optimal combination of filters and exposure time we can detect \( \sim 11 \text{ h} \) of the PISN lightcurves in the observer frame per one second of exposure time. Note that the stated exposure times are for one filter only. If the short and long wavelength channel are used at the same time, the stated exposure times have to be multiplied by two for the overall exposure time for this 4-filter diagnostic.

### 3.2.3 Only \( z \geq 9 \) PISNe

Our previous estimates depend on the assumptions that the probability of a PISN explosion is independent of the redshift in the range \( 6 \leq z \leq 12 \). Whereas Magg et al. (2016) find an almost constant rate of PISNe between \( z = 20 \) and \( z = 6 \), Hummel et al. (2012) and Johnson et al. (2013) report a steep decrease in the PISN rate after \( z \approx 10 \) with almost no PISN at \( z = 6 \). The rate of PISNe is to first order proportional to the star formation rate of Pop III stars and both are strongly suppressed at lower redshift by radiative and chemical feedback. Under the assumptions that no PISNe explode at \( z < 9 \), we derive the optimal diagnostic to identify PISN at \( z \geq 9 \). We use the same standard set of PISN with 5 different progenitor masses as before, but now consider only the redshifts \( z = 9 \) and \( z = 12 \).
This restriction to PISN at higher redshift increases the required exposure times to > 6 ks. The 250 M\textsubscript{\odot} PISN is faint between 2 and 4 yr in the observer frame, which renders the 225 M\textsubscript{\odot} PISN at z = 9 the dominant contribution for the optimal exposure time of 3 ks. The steady change of the 200W/277W color with time after explosion makes it easy to detect these PISN as transient sources.

Even for very long exposure times the visible fraction of the lightcurve of z > 9 PISNe remains below ~ 60%. In Fig. 8 we show the efficiency of these filter diagnostics and derive the optimal exposure time. The combination of the 200W and 277W filters is the best choice to detect PISNe at z > 9 with an optimal exposure time of 12 ks.

### 3.3 Detecting the afterglow

We show the most promising 4-filter combinations to detect the PISN afterglow for an ISM density of n\textsubscript{H} = 100 cm\textsuperscript{-3} in Fig. 9. Evidently, the unique identification of a PISN afterglow is beyond the capabilities of JWST, because it is too faint to be distinguished from the underlying stellar population. We still wish to outline a possible strategy for detection, with even more powerful telescopes in the future.

The most promising diagnostic is \( F_{115W} - F_{444W} \), because it offers the largest range in which we only expect PISNe (green area). For the \( F_{115W} - F_{277W} \) color, e.g., the z = 12 AGN is unfavourably close to the PISN signature, which would require an even higher sensitivity to distinguish them. The \( F_{980W} - F_{2377W} \) color on the horizontal axis cannot be used to discriminate the PISNe from other sources, because the evolution of the squares with redshift has to be seen as a continuous time sequence (gray dotted line). However, this color could be used as an additional constraint.

For the \( F_{115W} - F_{444W} \) combination, we need a sensitivity of at least 0.2 nJy in both filters to discriminate the 250 M\textsubscript{\odot} PISN 300-600 yr after its explosion from the underlying stellar population. This requires an exposure time of ~ 5 yr, far beyond the capabilities of JWST. Taking into account the observational uncertainty and the consequently required high signal-to-noise ratio requires even longer exposure times, which makes the identification of a PISN afterglow more challenging.

The remarkably long visibility time of ~ 300 yr in the source rest frame would be stretched by the cosmic expansion to over 2000 yr. However, this yields an efficiency of only 7 min of visibility per 1 s invested exposure time and is hence significantly less economical than the detection of the direct PISN emission. Moreover, not every Pop III host halo is expected to exhibit high enough densities to maintain neutral gas and create this afterglow.

This derivation is not intended to guide blind deep field surveys to detect and identify the PISN afterglow. We rather want to illustrate the typical color evolution of such a PISN afterglow, discuss the typical timescales, and highlight which other sources could mimic such a photometric signature. The unique identification of the PISN afterglow is beyond the capabilities of JWST, but these results are relevant for possible future observations: after the detection of prompt PISN emission, our model predicts the expected afterglow signature, depending on the ISM properties. Hence, the PISN afterglow can be used to probe the ISM at high redshift.
4 DETECTION STRATEGIES

4.1 Detection Rates

With our optimised 2-filter detection strategy (200W–356W, 600 s exposure) JWST can detect PISNe of progenitor masses 225\,M\odot and 250\,M\odot out to redshift \( z \sim 7.5 \). For a 250\,M\odot PISN we can see 32\% of the lightcurve (S/N\( > 10 \) in both filters), which directly translates into the probability of observing the PISN at the right moment. For a 225\,M\odot PISN we can detect 22\% of the lightcurve. Assuming a logarithmically flat IMF in the PISN mass range (140–260 M\odot), the 225\,M\odot and 250\,M\odot PISNe probe together 33\% of the PISN mass range. In Table 2 we list different PISN rates from the literature. Whereas the different models yield PISN rates, which differ by almost 2 orders of magnitude at \( z = 6 \), they all agree on the expected rates for PISNe from \( z \approx 9 \). If we assume the optimistic rate for \( z < 7.5 \) by Magg et al. (2016), and multiply it with the fraction of the PISN progenitor mass range that is observable and with the probability that we see the PISN lightcurve at the right time, the detection rate for PISNe with JWST is

\[
R_{\text{JWST}} = 2 \times 10^{-5} \text{yr}^{-1} \text{FoV}^{-1}.
\]  

With an optimized survey strategy, JWST will be able to detect one PISN per year per 50,000 different exposures of 600 s each. In the more conservative case, with no PISNe at \( z \leq 7.5 \), the detection rate will be \((2.7 \pm 0.4) \times 10^{-5} \text{yr}^{-1} \text{FoV}^{-1} \), but for a longer exposure time of 12 ks for each individual FoV. This detection rate is in agreement with the mean and variance of the models by Hummel et al. (2012), Johnson et al. (2013), Magg et al. (2016).

The detection rates are proportional to the star formation efficiency of Pop III stars, and are directly linked to the range and shape of their IMF. Any JWST constraints will therefore help to reveal the nature of the first stars, and even their non-detection can be used to elucidate the Pop III IMF by providing an upper limit on the occurrence of Pop III PISNe (Yoshida et al. 2004).

4.2 Optimal Detection Strategies

PISNe are rare events and a total exposure time of at least \( 3 \times 10^7 \) s, distributed over 50,000 FoVs, is required to detect at least one event. It is evident that a blind survey, only dedicated to find such PISNe from the first stars, is not feasible. We therefore present other strategies and approaches to detect the first SNe with JWST.

Archival data helps to select promising targets for follow-up observations. The most unique feature of PISNe is not their extreme luminosity or specific color, but rather their transient nature and shape of their lightcurve. A lower threshold than S/N\( = 10 \) yields shorter optimal exposure times and hence a higher probability of identifying PISNe. Especially for searching the archival data for PISN candidates, the desired signal-to-noise ratio can be lowered to identify more interesting candidates for follow-up observations. Also strong gravitational lensing by massive galaxies and galaxy clusters at lower redshift could boost the flux from the first SNe and therefore increase their detection rates (Ryderberg et al. 2013; Whalen et al. 2013). The afterglow of a PISN is fainter than the prompt emission and distinguishing it from other sources requires sub-nJy sensitivities, which will not be feasible with JWST.

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The more reliable and realistic confirmation of the afterglow is its transient nature on timescales of several hundred years. We can create catalogs of PISNe and their candidates and monitor them over the next decades and even centuries, similar to follow-up studies of historical SN events (Somers et al. 1997; Shara et al. 2012; Miszalski et al. 2016; Shara et al. 2017). As is the case for GRBs (Gehrels et al. 2009), this opens a novel and unique technique to study the host environments of the first stars.

4.3 Caveats

Our model is based on several assumptions and approximations that we want to critically discuss.
The PISN lightcurves employed here are based on the model by Kasen et al. (2011), although there are other models, which yield different predictions for the spectral time evolution (Scannapieco et al. 2005; Woosley et al. 2007; Pan et al. 2012; Chen et al. 2014; Jerkstrand et al. 2016; Kozyreva et al. 2017; Gilmer et al. 2017). A quantitative comparison of the different models is beyond the scope of this paper, and our photometric signatures may be affected by our specific choice (Kozyreva et al. 2017). Our optimal survey strategy targets the remnants of Pop III stars with masses above 200 M_☉. Their existence is not yet confirmed and simulations of primordial star formation tend to predict lower typical masses for the first stars (Stacy et al. 2010; Hirano & Bromm 2017). However, the possible non-detection of PISNe over the next decade would not exclude their existence, because Pop III stars below 200 M_☉ could also yield PISNe, but they might be below our detection limits.

We have included several high-redshift sources that could mimic a PISN, but we cannot exclude all possible objects. Especially tidal disruption events of stars in the strong tidal field near a supermassive black hole have a similar signature and transient nature as a SLSN (Leloudas et al. 2016; Holoien et al. 2016), and it is difficult to distinguish them photometrically. We compare the photometric signature of PISN with our optimized exposure time to other Types of SNe and find that PISN at z > 6 are redder than the considered types of SNe. The unique signature of PISN is their long lightcurves powered by significant amounts of 56Ni. Especially the most massive PISNe are clearly distinguishable from other SN types by their long rise to maximum luminosity (Kozyreva et al. 2014). Moreover, the lack of metal lines at early times could provide a unique spectroscopic signature for PISNe (Hummel et al. 2012). In addition, M-dwarfs have a similar red spectrum and their proper motion mimics an intrinsic variability if they disappear at their location in a follow-up survey. A comprehensive analysis of possible local, photometrically similar, sources needs to be carried out in future work.

Although the a-posteriori treatment of the resonant Lyα scattering does not change the photometric signature of the afterglow, it affects its time evolution: the path of Lyα photons is longer due to multiple scatterings, and our predicted time over which we smooth the emission gets also stretched. A self-consistent radiative transfer calculation is better suited to correctly predict the photometric time evolution of the afterglow signature. Also the ISM substructure and SNe that explode off the halo center will alter the reprocessing of the radiation. Although these effects are crucial for a proper characterization of the afterglow, the reprocessed radiation is below the detection limit of JWST, and only prompt emission will be observable, if at all.

5 SUMMARY AND CONCLUSIONS

We determined the photometric signature of PISNe and derive the optimal filter combination and detection strategy for their detection with JWST: two wide-band filters F200W and F356W, together with an exposure time of texp = 600 s, maximize the visibility time per invested exposure time. The goal is to analyze > 50,000 different FoVs to select promising PISN candidates at z ≤ 7.5 that can be further analyzed with follow-up observations for their transient nature. Consequently, we have to maximize the fraction of the sky covered by JWST with NIRCam. To achieve this, we have to make use of the parallel observation mode of JWST for which our modest requirements are a strong advantage. Every primary exposure with texp ≥ 600 s that does not use co-ordinated parallels and allows for parallel observation with NIRCam is suitable for our purpose. NIRCam can be used as second parallel instrument together with MIRI imaging, NIRISS WFSS, or NIRSPEC MOS as primary instrument.

Moreover, archival searches will be of great benefit to identify PISN candidates. The results from the guaranteed time observations can be searched for unique signatures of PISNe and then targeted for follow-up observations.

In parallel to high-redshift gamma-ray bursts (Ciardi & Loeb 2000; Gehrels et al. 2009), PISNe will also help us to probe their host environment and the pre-reionization intergalactic medium (IGM) via their afterglow emission. The time evolution of the afterglow is sensitive to the density and radius of the ISM, with the change in magnitude revealing the ionization state of the gas and hence the emissivity of ionizing photons of the underlying stellar population, and the absorption spectroscopy probing properties of the IGM.

The planned launch of JWST in 2019, together with complementary facilities such as WFIRST or the LSST, will enable the detection of the first SNe, thus ushering in the epoch of direct detections of the first stars. Our novel approach to determine the optimal filter combination and exposure time can also be applied to other surveys to maximize their success. The transient Universe at high redshifts is about to provide an exciting new window into the end of the cosmic dark ages.

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