**Euclid: Searching for pair-instability supernovae with the Deep Survey**

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ABSTRACT

Pair-instability supernovae are theorized supernovae that have not yet been observationally confirmed. They are predicted to exist in low-metallicity environments. Because overall metallicity becomes lower at higher redshifts, deep near-infrared transient surveys probing high-redshift supernovae are suitable to discover pair-instability supernovae. The *Euclid* satellite, which is planned launch in 2023, has a near-infrared wide-field instrument that is suitable for a high-redshift supernova survey. The *Euclid* Deep Survey is planned to make regular observations of three *Euclid* Deep Fields (40 deg$^2$ in total) spanning the *Euclid*’s six-year primary mission period. While the observations of the *Euclid* Deep Fields are not frequent, we show that the predicted long duration of pair-instability supernovae would allow us to search for high-redshift pair-instability supernovae with the *Euclid* Deep Survey. Based on the current observational plan of the *Euclid* mission, we conclude that the *Euclid* Deep Survey can be discovered within $z \lesssim 3.5$ can be discovered within the *Euclid* Deep Survey. We also show that pair-instability supernova candidates can be efficiently identified by their duration and color, which can be determined with the current *Euclid* Deep Survey plan. We conclude that the *Euclid* mission can lead to the first confirmation of pair-instability supernovae if their event rates are as high as those predicted by recent theoretical studies. We also update the expected numbers of superluminous supernova discoveries in the *Euclid* Deep Survey based on the latest observational plan.

Key words. stars: massive – supernovae: general – surveys

1. Introduction

Optical transient surveys have revealed the existence of huge diversity in supernovae (SNe), and many new kinds of SNe that were not recognized before have been discovered (Inserra 2019). For example, SNe that are often more than ten times more luminous than other SNe, known as superluminous SNe (SLSNe; see Gal-Yam 2019 for a recent review), were discovered through unbiased optical transient surveys (Quimby et al. 2011). Just after the existence of SLSNe was recognized, they were often theoretically linked to pair-instability SNe (PISNe; e.g., Smith et al. 2007; Gal-Yam et al. 2009). PISNe are theorized thermonuclear explosions of very massive stars (Barkat et al. 1967; Rakavy & Shaviv 1967) with a helium core mass between $65 M_\odot$ and $135 M_\odot$ (e.g., Heger & Woosley 2002). Some PISNe are predicted to produce a large amount of radioactive $^{56}$Ni, up to $60 M_\odot$, which heats SN ejecta, and they can be as bright as SLSNe (Kasen et al. 2011; Dessart et al. 2013; Gilmer et al. 2017). However, the light-curve and spectral properties of SLSNe are now found to be different from those predicted for PISNe (e.g., Dessart et al. 2012; Nicholl et al. 2013; Jerkstrand et al. 2016; Inserra et al. 2017; Mazzali et al. 2019). Therefore, it is generally believed that most SLSNe are not PISNe and that they are powered by a different mechanism (see Moriya et al. 2018 for a review on SLSN powering mechanisms). No SNe have been confirmed to be PISNe to date, although there are several possible PISN candidates (e.g., Lunnan et al. 2016; Terreran et al. 2017) and some possible indirect signatures of PISNe (e.g., Aoki et al. 2014; Isobe et al. 2022). Confirming the existence of PISNe is a critical test of the...
stellar evolution theory (Langer 2012). PISNe can play an important role in chemical evolution (e.g., Nomoto et al. 2013). PISNe are also essential components for the proper understanding of black hole mass distributions observed by gravitational waves (e.g., Marchant et al. 2016; Farmer et al. 2019).

Pair-instability SNe are believed to appear in low-metallicity environments below $Z_\odot/3$ (Langer et al. 2007, but see also Georgy et al. 2017). Thus, they may preferentially appear at high redshifts where metallicity is low (e.g., Chru{\l}inska & Nelemans 2019). However, it is difficult to discover high-redshift PISNe with optical transient surveys as they become faint in the optical wavelength range because of redshift. For example, a deep optical transient survey with Subaru/Hyper Suprime-Cam (HSC) carried out a search for high-redshift PISN candidates, but no candidates have been found so far (Moriya et al. 2021). The future Vera C. Rubin Observatory/Legacy Survey of Space and Time (LSST) may be able to discover PISNe depending on its survey strategy that has not yet been determined (e.g., du Buisson et al. 2020). A deep transient survey in the near-infrared (NIR) is observationally better suited to discover PISNe appearing at high redshifts (Scannapieco et al. 2005; Pan et al. 2012; Whalen et al. 2013; Moriya et al. 2019, 2022; Wong et al. 2019; Regős et al. 2020).

There are several wide-field NIR instruments planned for the 2020s such as the Wide Field Instrument on Nancy Grace Roman Space Telescope from 2026 (Spiegel et al. 2015) and the ULT-MATE Wide Field Instrument on Subaru from 2027. Among them, Euclid is planned to be launched in 2023 (Laureijs et al. 2011). It has wide-field (0.53 deg$^2$) imagers, one in the visual range (with a passband that we denote $I_{\text{E}}$) and the other in the NIR range with three filters ($Y_{\text{E}}$, $J_{\text{E}}$, and $H_{\text{E}}$). The Euclid mission plans wide (15 000 deg$^2$) and deep (40 deg$^2$) surveys in the four filters (Euclid Collaboration 2022a). As introduced below, the Euclid Deep Survey (EDS) covering 40 deg$^2$ in total is planned to visit the survey fields regularly during the six-year primary survey period of the Euclid mission (Laureijs et al. 2011; Euclid Collaboration 2022a). Although the current EDS plan is not suitable for searching for short-duration Type Ia SNe (SNe Ia, Astier et al. 2014), Inserra et al. (2018a) previously showed that the regular observations planned in EDS allow us to search for high-redshift SLSNe up to $z \simeq 3.5$.

High-redshift PISNe are expected to be bright in the NIR and have long durations (Sect. 2.1). Therefore, it is possible that high-redshift PISNe can be identified even with the long cadence observations planned in EDS (Sect. 3.1). In this work, we performed transient survey simulations in order to quantify the expected numbers of PISN discoveries in EDS. We also investigated the expected numbers of SLSN discoveries in EDS, because the EDS observational plan has been updated since the publication of Inserra et al. (2018a).

The rest of this paper is organized as follows. We first introduce the light-curve templates of PISNe and SLSNe we used in our survey simulations in Sect. 2. We then introduce the assumptions in our survey simulations in Sect. 3. The survey simulation results are presented in Sect. 4. We discuss how to identify high-redshift PISN and SLSN candidates efficiently with photometry in Sect. 5. Section 6 concludes this paper. All magnitudes presented in this paper are in the AB system. We adopt the $\Lambda$CDM cosmology with $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_\Lambda = 0.7$, and $\Omega_m = 0.3$.

### 2. SN templates

SN templates are required to estimate the observational properties at high redshifts. The SN templates we used in this study are introduced in this section. They are summarized in Table 1.

#### 2.1. PISNe

We used the synthetic spectral evolution of PISNe obtained by Kasen et al. (2011), who took the PISN explosion models from Heger & Woosley (2002) and calculated their spectral evolution by performing radiative transfer calculations. Kasen et al. (2011) calculated PISN properties for red supergiant (RSG), blue supergiant (BSG), and Wolf-Rayet (WR) progenitors. The RSG and BSG PISN progenitors have hydrogen-rich envelopes, while WR PISN progenitors are hydrogen-free. The BSG PISN progenitors are expected to exist mainly at zero metallicity (Heger & Woosley 2002). The highest redshift PISNe that can be discovered by the Euclid survey, which is determined by the maximum expected luminosity of PISNe, is $z = 3.5$ as we show later and most of them are not likely to have zero metallicity. Thus, a significant fraction of PISNe discovered by Euclid would be from RSG and WR progenitors, and we adopted RSG and WR PISN models in this study. The RSG PISN models have a metallicity of $10^{-4} Z_\odot$. Although the metallicity of the host galaxies in the redshift range we can probe with EDS is higher than $10^{-4} Z_\odot$ (e.g., Steidel et al. 2014; Chruslinska & Nelemans 2019), their light-curve properties are not significantly different from those with high metallicity (e.g., Kozyreva et al. 2014). We also take PISNe with WR progenitors into account in this study. The WR PISN models in Kasen et al. (2011) were calculated with the zero-metallicity condition (Heger & Woosley 2002), but WR PISNe can appear with finite metallicity (e.g., du Buisson et al. 2020). The light-curve properties of zero-metallicity WR PISN models are not significantly different from those of higher metallicity WR PISNe up to the proposed PISN metallicity threshold of around $Z_\odot/3$ (Moriya et al., in prep.). Thus, we adopted the WR PISN properties from the zero metallicity progenitors in this study. We note that the adopted progenitor models do not take stellar rotation into account (e.g., Chatzopoulos & Wheeler 2012). In addition, only the wind mass loss is considered.

Kasen et al. (2011) provide the RSG PISN explosion models for 250 $M_\odot$ (R250), 225 $M_\odot$ (R225), 200 $M_\odot$ (R200), 175 $M_\odot$ (R175), and 150 $M_\odot$ (R150) stars at the zero-age main sequence, and we investigated them all. We adopted the WR PISN models whose progenitor evolution is calculated from the helium

### Table 1. List of SN templates used in this study.

| Name | Explosion | Progenitor | Mass |
|------|-----------|------------|------|
| R250 (a) | PISN | RSG | 250 $M_\odot$ |
| R225 (a) | PISN | RSG | 225 $M_\odot$ |
| R200 (a) | PISN | RSG | 200 $M_\odot$ |
| R175 (a) | PISN | RSG | 175 $M_\odot$ |
| R150 (a) | PISN | RSG | 150 $M_\odot$ |
| He130 (a) | PISN | WR | 130 $M_\odot$ |
| He120 (a) | PISN | WR | 120 $M_\odot$ |
| He110 (a) | PISN | WR | 110 $M_\odot$ |
| He100 (a) | PISN | WR | 100 $M_\odot$ |
| He090 (a) | PISN | WR | 90 $M_\odot$ |
| SLSN (b) | SLSN | – | – |

Notes. (a) Kasen et al. (2011), (b) Moriya et al. (2022).
We did not consider \textit{Ly}_{\alpha} absorption by the intergalactic medium (IGM) and circumgalactic medium (CGM) in this study. The IGM and CGM absorption affect the brightness in the $I_E$ band for SNe mainly at $z \geq 3$. PISNe at $z \geq 3$ are fainter than the $I_E$-band detection limit (25.5 mag) except for the R250 PISN model (Fig. 4). In addition, the maximum redshift up to which we can discover R250 PISNe with the assumed cadence is estimated to be $z \approx 2.5$, as shown in the following sections. Thus, the \textit{Ly}_{\alpha} absorption does not affect our conclusions in this study.

2.2. SLSNe

In this study, we only considered hydrogen-poor (Type I) SLSNe as in our previous study (Inserra et al. 2018a), and we refer to hydrogen-poor SLSNe simply as SLSNe. This is because the observational properties of nearby hydrogen-poor SLSNe have been thoroughly investigated and we can reliably estimate their high-redshift properties. Contrarily, hydrogen-rich (Type II) SLSNe are known to exist (e.g., Smith et al. 2007; Inserra et al. 2018b), but their rest-frame ultraviolet properties have not been studied well enough to estimate their high-redshift properties.

We used the SLSN template presented in Moriya et al. (2022). The SLSN spectral template was constructed by assuming a broken blackbody function as originally introduced by Prajs et al. (2017). The template spectra above 300 nm follow the blackbody function as observed in SLSNe (e.g., Quimby et al. 2018). Below 300 nm, the blackbody function is truncated to match the spectral shape of the well-observed SLSN iPTF13ajg (Vreeswijk et al. 2014). iPTF13ajg has the typical shape of SLSN ultraviolet spectra at around peak luminosity, although some SLSNe are known to be brighter in the ultraviolet (Nicholl et al. 2017). We only take the spectral shape of iPTF13ajg, and the template peak luminosity is adjusted to match an average value. The template has a peak $u$-band absolute magnitude of $-21.1$ mag, which is an average SLSN peak brightness estimated by Lunnan et al. (2018). The $u$-band light-curve rise time of the template is 30 days.

The rise time and peak absolute magnitude of the SLSN template in the rest frame are compared to those of the PISN models in Fig. 2. The peak observer-frame magnitudes of the SLSN
template at $0.5 < z < 4$ obtained by convolving the *Euclid* filters are presented in Fig. 5. In the following survey simulations, the peak SLSN magnitudes are assumed to randomly scatter from the average value by a standard deviation of $0.7$ mag with a Gaussian probability distribution in order to account for the SLSN luminosity diversity (Lunnan et al. 2018). While the actual luminosity function of SLSNe may not have a Gaussian distribution function (e.g., De Cia et al. 2018; Perley et al. 2020), a Gaussian distribution with $0.7$ mag standard deviation covers the wide peak luminosity range observed in SLSNe. Similarly, the rise times are independently set to have a standard deviation of ten days with a Gaussian probability distribution, but the rise times are not allowed to be shorter than ten days. As mentioned in Sect. 2.1, no Ly$\alpha$ absorption in the IGM and CGM is taken into account because no SLSNe at $z \gtrsim 3$ are brighter than the detection limit.

3. Survey simulation setups

In this section, we summarize the assumptions in our survey simulations.

3.1. Euclid Deep Fields, cadence, and sensitivity

The EDS will cover three Euclid Deep Fields (EDFs)\(^2\). Two fields are planned at the north and south ecliptic poles (EDF and EDFS, respectively). The third field is in the *Chandra* Deep Field South located in Fornax (EDFF). We introduce the current

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\(^2\) [https://sci.esa.int/web/euclid/-/61407-the-euclid-wide-and-deep-surveys](https://sci.esa.int/web/euclid/-/61407-the-euclid-wide-and-deep-surveys)
The observational plan at each field in this section, and this is also available in Euclid Collaboration (2022a).

EDFN will cover 10 deg$^2$ and will be visited ten times at the beginning of the Euclid mission for calibration purposes. Then, it will be observed regularly roughly every six months during the six-year primary mission period. EDFS will cover 20 deg$^2$ and the whole field will be visited 45 times. The first ten visits will be done at the beginning of the mission, and then the subsequent 35 visits will span five years. Finally, the 10 deg$^2$ area in EDFF will be observed 56 times in total over six years.

Figure 6 summarizes the current observational plan for the EDFs. The observations at each EDF will be conducted at the epochs indicated by squares. The numbers above the squares show the number of visits within each epoch. For example, five visits are planned for EDFF with the above 5 deg$^2$ area in every epoch shown with the squares. The visits within one epoch are made within 15 days. We assume that the images taken in the first 1.25 yr of the mission are used to construct the reference images and the SN search starts after 1.25 yr.

3.2. Event rates

Event rates are an essential assumption in the transient survey simulations. Because no confident PISNe have been discovered so far, the PISN event rate is unknown. Observationally, the PISN event rate is constrained to be less than the SLSN event rate (e.g., Nicholl et al. 2013; Moriya et al. 2021). The SLSN event rate and its redshift evolution have been constrained by optical transient surveys (Quimby et al. 2013; Prajs et al. 2017; Frohmaier et al. 2021). The SLSN event rate at $z \approx 0.2$ is estimated to be 30 Gpc$^{-3}$ yr$^{-1}$ (Quimby et al. 2013). The SLSN event rate up to $z \approx 1$ is estimated to be consistent with that obtained by extrapolating the $z \approx 0.2$ rate following the cosmic star-formation rate (SFR) density of Madau & Dickinson (2014, Fig. 7). We currently have a few possible PISN candidates, as discussed in Sect. 1. The total number of SLSN discoveries is currently around 100–200 (e.g., Nicholl 2021; Chen et al. 2022a,b). Although it is likely inappropriate to compare the numbers of the PISN candidates and the SLSN discoveries because their different properties especially in spectral energy distributions (Sect. 2), the current fraction of PISN candidates to SLSNe should be around a few per cent.

Theoretical predictions for the PISN rates are also very different (see Langer et al. 2007; Magg et al. 2016; Takahashi 2018; Farmer et al. 2019; du Buisson et al. 2020; Tanikawa et al. 2022). If we simply assume a Salpeter initial mass function and a SFR mass range of 150–300 $M_\odot$ (Heger & Woosley 2002), 1% of core-collapse SNe ($8–25 M_\odot$) would be PISNe. Given core-collapse SN rates of $10^3–10^6$ Gpc$^{-3}$ yr$^{-1}$ at $z \approx 0–2.5$ (Ströger et al. 2015), the corresponding PISN rate is $10^3–10^6$ Gpc$^{-3}$ yr$^{-1}$, which is much higher than the aforementioned SLSN rate. Recently, Briel et al. (2022) provided theoretical predictions for the PISN rates. By using several cosmic SFR densities from both observations and cosmological simulations, they predicted PISN rates based on stellar evolution models from Binary Population and Spectral Synthesis (BPASS, Eldridge et al. 2017; Stanway & Eldridge 2018). The PISN rate predictions at $z \approx 3.5$ are shown to be 10–100% of the SLSN rate (Fig. 7).
Event rates used in survey simulations. The SLSN event rate is estimated by setting the SLSN event rate at $z = 0.2$ to be $30 \, \text{Gpc}^{-3} \, \text{yr}^{-1}$ (Quimby et al. 2013; Frohmaier et al. 2021) and extrapolating it following the cosmic SFR density of Madau & Dickinson (2014). For reference, the SLSN rates constrained by observations at $z \sim 0.2$ (Frohmaier et al. 2021) and $z \sim 1.1$ (Prajs et al. 2017) are shown. We also used the 10% and 1% SLSN rates for PISNe. Four theoretical PISN rate estimates by Briel et al. (2022, dotted lines) are shown for comparison. The four models have different assumptions on the cosmic SFR history.

Although the PISN event rate is unknown, we need to assume some PISN event rates for our survey simulations. We think it is reasonable to assume PISN rates that are scaled with the SLSN event rate for our purpose. The SLSN event rate is constrained observationally, and we do not need to rely on uncertain theoretical predictions in this way. A fraction of SLSNe may be PISNe, even though we do not have a conclusive case. In addition, the latest theoretical study by Briel et al. (2022) predicts that the PISN rate at $z \lesssim 3.5$ is $10$–$100\%$ of the SLSN rate (Fig. 7). In light of the above and given the large uncertainties involved in this type of estimate, we make three assumptions for the PISN event rate: (i) the same as the SLSN event rate, (ii) 10% of the SLSN event rate, and (iii) 1% of the event rate.

NIR and radio surveys for core-collapse SNe in the local Universe have shown that a significant fraction of the events are lost from current optical surveys as they explode in very dusty environments (e.g., Mannucci et al. 2007; Pérez-Torres et al. 2009; Mattila et al. 2012; Kool et al. 2018; Jencson et al. 2019; Kankare et al. 2021; Fox et al. 2021). In particular, the fraction of star-formation activity that takes place in luminous star-bursting and dusty galaxies increases sharply with redshift and becomes the dominant component of star formation at $z \approx 1$. Consequently, an increasing fraction of SNe are expected to be lost from high-redshift optical searches. Up to 60% of core-collapse SNe are likely to be lost at $z \approx 2$ (Mannucci et al. 2007). Since the SLSN rates discussed in this section are based on optical surveys, the rates extrapolated to $z \approx 4$ should be taken with some caution. They can probably be considered as lower limits to the actual event rate.

**3.3. Discovery criteria**

PISNe and SLSNe are assumed to appear randomly following the assumed event rates in the survey simulations. Once a PISN or SLSN appears, the expected magnitudes in each epoch are estimated for the event. If it satisfies the discovery criteria presented below, the event is regarded as a discovery.

High-redshift PISNe remain bright for a year or more (Fig. 3), while other common high-redshift SNe such as SNe Ia do not remain bright for a long time (Hounsell et al. 2018), as can be seen in Fig. 2. Thus, the transient duration is important information to identify rare high-redshift PISNe among many other kinds of high-redshift SNe. We therefore count the numbers of PISNe that become brighter than the limiting magnitude for two epochs or more in any band in our survey simulations. We also investigate the PISN candidate selection through their color in Sect. 5. Even if we have a detection only in a single band, non-detection in the other bands can constrain the color of SN candidates.

High-redshift SLSNe usually have shorter durations than those of PISNe (Figs. 2 and 3) and it is difficult to distinguish them from other high-redshift SNe by duration with the current EDS plan having a cadence of about a half year (Fig. 6). However, high-redshift SLSNe can be identified among other short-duration SNe by their color even with a single epoch when they are brighter than 24 mag in the NIR bands (Sect. 5). We count the number of SLSNe that become brighter than the detection limit at the first visit of each epoch in any band, although many other short-duration SNe will be detected with this criterion (Sect. 5). For comparison, we also show the number of SLSNe that exceed the detection limits for two epochs.

**4. Simulation results**

Survey simulations with one set of assumptions are performed $10^3$ times, and we obtain the average numbers of discoveries. The survey simulations are performed in the three EDFs independently, with their areas and cadences as discussed in Sect. 3.1. However, there are no significant differences in the redshift distributions of the discovered PISNe and SLSNe among the three EDFs. Therefore, we show and discuss the combined numbers of PISN and SLSN discoveries in the three fields. The total numbers of PISN and SLSN discoveries in the three EDFs are summarized in Table 2.

Figure 8 shows the cumulative redshift distributions of PISNe discovered in our survey simulations. We show the distributions for the three different assumptions for the event rates of the PISN models (100%, 10%, and 1% of the SLSN rate), and the expected discovery numbers are roughly proportional to the assumed rate. The brightest PISN models such as R250 and He130 can be discovered with EDS if their rates are more than about 1% of the SLSN rate. Meanwhile, the faintest PISN models in our survey simulations such as R150 and He090 can only be discovered if their event rates are as high as those of SLSN. Figure 9 shows the redshift distributions of the discovered PISNe for the same event rates as the SLSN event rate. The shapes of the redshift distributions do not depend on the assumed rate. The brightest PISN model He130 can be discovered up to $z \approx 3.5$. The brightest RSG PISN models (R250 and R225) can be discovered up to $z \approx 2.5$. The faintest PISN models (R150 and He090) can be discovered only up to $z \approx 0.6$–0.8 and, therefore, their expected discovery numbers are relatively small.

The expected cumulative number distributions for SLSNe are presented in Fig. 10 and their number density distributions are shown in Fig. 9. As discussed previously, the durations of high-redshift SLSNe are much shorter than those of PISNe. Figure 11 shows the distribution of the number of detection epochs in our survey simulations. Only about 20% of high-redshift SLSNe can be identified if we require them to...
Table 2. Expected numbers of PISN and SLSN discoveries with EDS.

| Model Rate | Detection | Total | Redshift range |
|------------|-----------|-------|----------------|
|            | (epochs)  |       | 0–0.5 | 0.5–1.0 | 1.0–1.5 | 1.5–2.0 | 2.0–2.5 | 2.5–3.0 | 3.0–3.5 | 3.5–4.0 |
| R250 1     | 2         | 145   | 4.5    | 25      | 47      | 49      | 19      | 0.030   | 0      | 0      |
| R250 0.1   | 2         | 14    | 0.46   | 2.5     | 4.7     | 4.9     | 1.9     | 0.0030  | 0      | 0      |
| R250 0.01  | 2         | 1.5   | 0.045  | 0.27    | 0.52    | 0.49    | 0.19    | 0.0010  | 0      | 0      |
| R225 1     | 2         | 158   | 4.4    | 25      | 47      | 53      | 28      | 0      | 0      |
| R225 0.1   | 2         | 16    | 0.46   | 2.6     | 4.8     | 5.2     | 2.7     | 0      | 0      |
| R225 0.01  | 2         | 1.6   | 0.036  | 0.25    | 0.43    | 0.54    | 0.29    | 0      | 0      |
| R200 1     | 2         | 49    | 4.4    | 23      | 21      | 0       | 0      | 0      |
| R200 0.1   | 2         | 4.9   | 0.47   | 2.4     | 21      | 0       | 0      | 0      |
| R200 0.01  | 2         | 0.52  | 0.056  | 0.24    | 0.23    | 0       | 0      |
| R175 1     | 2         | 7.5   | 2.9    | 4.6     | 0       | 0       | 0      |
| R175 0.1   | 2         | 0.79  | 0.29   | 0.49    | 0       | 0       | 0      |
| R175 0.01  | 2         | 0.081 | 0.038  | 0.044   | 0       | 0       | 0      |
| R150 1     | 2         | 3.2   | 1.5    | 1.7     | 0       | 0       | 0      |
| R150 0.1   | 2         | 0.32  | 0.13   | 0.19    | 0       | 0       | 0      |
| R150 0.01  | 2         | 0.033 | 0.018  | 0.015   | 0       | 0       | 0      |
| He130 1    | 2         | 210   | 4.2    | 24      | 47      | 53      | 43      | 28      | 12      | 0.0060 |
| He130 0.1  | 2         | 21    | 0.41   | 2.3     | 4.7     | 5.3     | 4.3     | 2.7     | 1.2     | 0      |
| He130 0.01 | 2         | 2.1   | 0.040  | 0.26    | 0.46    | 0.51    | 0.45    | 0.26    | 0.12    | 0.0005 |
| He120 1    | 2         | 164   | 4.3    | 21      | 47      | 51      | 36      | 3.8     | 0      |
| He120 0.1  | 2         | 16    | 0.46   | 2.1     | 4.6     | 5.1     | 3.6     | 0.37    |
| He120 0.01 | 2         | 1.6   | 0.048  | 0.20    | 0.43    | 0.47    | 0.38    | 0.037   |
| He110 1    | 2         | 103   | 4.3    | 20      | 45      | 32      | 2.2     | 0       |
| He110 0.1  | 2         | 10    | 0.43   | 2.1     | 4.5     | 3.2     | 0.24    |
| He110 0.01 | 2         | 1.1   | 0.051  | 0.20    | 0.47    | 0.32    | 0.027   |
| He100 1    | 2         | 25    | 4.1    | 16      | 4.7     | 0       | 0       | 0       |
| He100 0.1  | 2         | 2.4   | 0.40   | 1.6     | 0.45    | 0       | 0       | 0       |
| He100 0.01 | 2         | 0.24  | 0.049  | 0.16    | 0.038   | 0       | 0       | 0       |
| He090 1    | 2         | 2.0   | 1.9    | 0.16    | 0       | 0       | 0       |
| He090 0.1  | 2         | 0.20  | 0.18   | 0.024   | 0       | 0       | 0       |
| He090 0.01 | 2         | 0.027 | 0.027  | 0       | 0       | 0       | 0       |
| SLSN 1     | 2         | 28    | 2.6    | 8.5     | 8.9     | 5.1     | 2.1     | 0.75    | 0.25    | 0.096  |
| SLSN 1     | 1         | 121   | 4.9    | 23      | 37      | 31      | 16      | 6.4     | 2.1     | 0.42   |

Notes. The total discovery numbers in the three EDFs are shown. (a) The event rate relative to the SLSN rate presented in Fig. 7. (b) The minimum number of detected epochs required to be regarded as a discovery.

be detected at multiple epochs. 28 SLSNe are expected to be detected at two epochs, while 121 SLSNe are discovered if SLSNe with only a single epoch detection are included. High-redshift SLSNe could be distinguished from high-redshift SNe Ia and II through color, as we discuss in Sect. 5. In addition, we have multiple visits at each epoch, and the luminosity evolution in individual visits can also be used to distinguish high-redshift SLSNe from high-redshift SNe Ia and II.

Although we lose a large fraction of high-redshift SLSNe if we take only those detected at multiple epochs, we still have 28 SLSNe with multiple epoch detection. Because of the unknown PISN rates, these SLSNe could be contaminants. The color of PISNe and SLSNe can be similar, and it is difficult to distinguish high-redshift PISNe and SLSNe by color alone (Sect. 5). Because almost no high-redshift SLSNe are expected to be detected at three epochs and many high-redshift PISNe can be brighter than the detection limits for three epochs, transients with three-epoch detection are likely to be genuine high-redshift PISN candidates.

Finally, no extinction is assumed in our survey simulations. The EDFs have little Galactic extinction, but the SNe could suffer from severe host galaxy extinction. However, PISNe and SLSNe preferentially appear in low-metallicity environments where little extinction is expected (Garn & Best 2010). Thus, overall, the effect of extinction may not be significant.

5. PISN and SLSN candidate identification with photometry

The efficient identification of rare PISN and SLSN candidates among many other abundant SNe such as SNe Ia is critical for triggering spectroscopic follow-up observations to confirm their discovery. The transient duration is an essential piece of information for identifying PISN candidates especially, as discussed in the previous section. Figure 11 clearly shows that most luminous PISNe are detected at more than two epochs, while other SNe are usually expected to be bright for one epoch with the half-year cadence observations. Still, it is important to have as much information as possible to screen the best PISN and SLSN candidates to make the best use of follow-up resources.

In this section, we discuss the color of PISNe and SLSNe, which can be used to distinguish them from other common SNe.
Fig. 8. Cumulative redshift distributions of PISNe discovered in survey simulations. The total discovery numbers in the three EDFs are presented. The top, middle, and bottom panels show the results for the event rates of 100%, 10%, and 1% of the SLSNe rate for each PISN model.

Figure 12 shows the color-magnitude diagrams in the $I_E$ and $H_E$ bands for RSG PISNe at $z > 0.5$ (top), WR PISNe at $z > 0.5$ (middle), and SLSNe at $z > 0.5$ (bottom). Each point shows color and magnitude for a certain epoch, and all epochs in the models are presented in the figure. We also present the expected color and magnitude regions for SNe Ia and SNe II at $z > 0.5$, assuming that those at $z < 0.5$ can be discovered by optical transient surveys with, for example, Subaru/HSC, Blanco/Dark Energy Camera, or the future Vera C. Rubin Observatory/LSST. A few SNe per square degree at $z < 0.5$ are likely to appear at each epoch (Yasuda et al. 2019). The expected SN Ia brightness is obtained by using the Hsiao template (Hsiao et al. 2007) with a peak $B$-band absolute magnitude of $-19.26$ mag (Richardson et al. 2014), which is an average absolute magnitude at peak. The SNe II includes SNe IIP, SNe IIL, and SNe IIn from the Nugent template. The peak absolute magnitudes for SNe II are set as $-18$ mag in the $V$ band in all the subtypes. The assumed SN II peak absolute magnitude is brighter than the average (Richardson et al. 2014), but the bright SNe II are preferentially discovered at high redshifts.

Figure 12 shows that high-redshift SNe Ia and SNe II can be as bright as high-redshift PISNe and SLSNe in the $I_E$ band, but high-redshift SNe Ia and SNe II do not become as bright as high-redshift PISNe and SLSNe in the $H_E$ band. Thus, the color between the $I_E$ and $H_E$ bands allows us to efficiently distinguish high-redshift PISNe and SLSNe from other SNe. While we do not assume any extinction in Fig. 12, the fact that SNe Ia and II are detected in the $I_E$ band but not in the $H_E$ band indicate their detections.

Host galaxy information of transients is also an important clue to identifying their redshift information. The reference

[^3]: [https://c3.lbl.gov/nugent/nugent_templates.html](https://c3.lbl.gov/nugent/nugent_templates.html)
images taken at the beginning of EDS as well as deep optical images available in the EDFs would allow us to estimate host-galaxy photometric redshifts if the host galaxies are bright enough. Some host-galaxy spectra needed to determine their redshifts could be simultaneously obtained by the grisms on Euclid. The limiting magnitude of the reference images in the $I_E$ band are around 26 mag or deeper. Therefore, host galaxies with absolute magnitudes brighter than around $-19$ mag in the rest-frame ultraviolet can be identified in the reference images. Many galaxies are fainter than $-19$ mag in the ultraviolet (e.g., Bouwens et al. 2021), and a large fraction of PISNe could be observed as hostless. Even if we have the host galaxy photometry, the photometric redshift estimates at high redshifts are challenging (e.g., Euclid Collaboration 2020). Despite the difficulties, host galaxy information provides additional clues that help identify the nature of transients. The NIR reference images will be shallower than that of $I_E$, but they can trace fainter stellar masses, and some host galaxies could only appear inside them.

Active galactic nuclei (AGNs) can be variable over long timescales and such a long-term AGN variability can contaminate our sample of high-redshift PISNe and SLSN candidates. The variable component of unobscured AGN spectra at ultraviolet to optical wavelengths is estimated to be proportional to $\nu^{1/3}$, where $\nu$ denotes the frequency (e.g., Kokubo et al. 2014). Thus,
the color of the AGN variability does not significantly change, and it remains at $I_e - H_e \approx -0.34$ mag. Because the color of PISNe and SLSNe changes much more with time (Fig. 13), the color evolution is an essential piece of information to exclude AGN variability. In order to exclude AGNs with short-timescale variability, simultaneous short-cadence optical transit surveys are helpful. The location of transients in their host galaxies is also important to exclude AGNs, and the high spatial resolution of Euclid can help to constrain the nuclear versus nonnuclear location in host galaxies. Ultimately, spectroscopic confirmation of the transient would be required to confirm the classification as PISNe or SLSNe. It is possible that a part of the spectroscopic follow-up observations will be realized by the grisms on Euclid. The James Webb Space Telescope will also be powerful with regard to the spectroscopic follow-up observations. Photometric observations in narrower optical bands than $I_e$ may also be useful to distinguish PISNe and SLSNe because of the different rest-frame ultraviolet properties expected in them (e.g., Dessart et al. 2012).

6. Conclusions
We estimated the expected number of PISN and SLSN discoveries in EDS, in which three EDFs (40 deg$^2$ in total) are planned to be observed regularly for six years during the Euclid mission. Although the EDF observations are not frequent (Fig. 6), the intrinsically long duration of PISNe and SLSNe allows us to discover them in the high-redshift Universe with the current survey plan. With the currently planned limiting magnitudes, it is possible to detect PISNe and SLSNe up to $z \approx 3.5$ (Fig. 4).

We find that we can discover up to several hundred PISNe with the current survey plan. With the currently planned limiting magnitudes, it is possible to detect PISNe and SLSNe up to $z \approx 3.5$ (Fig. 4). Therefore, our study indicates that the Euclid mission will allow us to directly confirm the existence of such objects that have never been identified with certainty before. The PISN properties can be compared with the theoretical predictions aimed at testing the theory of the evolution of massive stars in low-metallicity environments. They can also constrain massive star formation in the early Universe by providing the formation rate of the massive stars in the PISN mass range. The PISN discovery by the Euclid mission will be an important base to discover and characterize PISNe at higher redshifts ($z \gtrsim 3.5$), which can be reached by future missions such as the Nancy Grace Roman Space Telescope (e.g., Moriya et al. 2022; Lazar & Bromm 2022). Even if we do not discover any PISNe, we will be in a position to obtain a strong constraint on the PISN event rate at $z \lesssim 3.5$ that will challenge the current understanding of stellar evolution theory.

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Fig. 13. Color evolution of the PISN models and SLSN template presented in Fig. 3.

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