Detectability of High-Redshift Superluminous Supernovae with Upcoming Optical and Near-Infrared Surveys - II. Beyond z=6

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ABSTRACT
Observational identification of the first stars is one of the great challenges in the modern astronomy. Although a single first star is too faint to be detected, supernova explosions of the first stars can be bright enough. An important question is whether such supernovae can be detected in the limited observational area with realistic observational resources. We perform detailed simulations to study the detectability of superluminous supernovae (SLSNe) at high redshifts, using the observationally-calibrated star formation rate density and supernova occurrence rate. We show that a 100 deg2 survey with the limiting magnitude of 26 mag in near-infrared wavelengths will be able to discover about 10 SLSNe at z > 10. If the survey is extended to 200 deg2 with 27 mag depth, about 10 SLSNe can be discovered at z > 15. We emphasize that the observations at ≥ 3 µm are crucial to detect and select SLSNe at z > 10. Our simulations are also applied to the planned survey with Euclid, WFIRST, and WISH. These surveys will be able to detect about 1000, 400, and 3000 SLSNe up to z ∼ 5, 7, and 12, respectively. We conclude that detection of SLSNe at z > 10 is in fact achievable in the near future.

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

1 INTRODUCTION
The first stars, or Population III stars, are predicted to be formed at redshift \( z > 15 \) in the standard cold dark-matter scenario (e.g., Bromm, Coppi & Larson 1999; Abel, Bryan & Norman 2000; Yoshida et al. 2003; O'Shea & Norman 2007; Turk, Abel & O'Shea 2009; Stacy, Greif & Bromm 2010; Bromm et al. 2011; Greif et al. 2011; Clark et al. 2011). Observational identification of the first stars is one of the great challenges in the modern astronomy. In fact, a cluster of first stars can be detected in the future with the next-generation telescopes, such as James Webb Space Telescope (JWST, see e.g., Bromm, Kudritzki & Loeb 2001; Gardner et al. 2006). However, an isolated, single first star is too faint to be observed (Gardner et al. 2006; Rydberg et al. 2013).

Detection of supernova (SN) explosions of the first stars is an interesting possibility worth pursuing. A single SN explosion can give rise to a luminosity of \( L \gtrsim 10^8 L_\odot \), powered by the radioactive energy or the kinetic energy of the explosion. Note that the luminosity of SNe is comparable to high-redshift galaxies recently discovered with Hubble Space Telescope (HST, e.g., Bouwens et al. 2011a). This is more than a few orders of magnitude higher than the luminosity of a single very massive star (\( L \sim 10^7 L_\odot \) for a 500 M_\odot star, Bromm, Kudritzki & Loeb 2001).

Because of this advantage, detectability of SNe at high redshift have been studied in the past literature (e.g., Miralda-Escude & Rees 1997; Mesinger, Johnson & Haiman 2006; Whalen et al. 2013c). These studies revealed, however, that normal core-collapse SNe are too faint to be detected at \( z > 6 \). Detection of...
normal SNe at $z > 6$ requires observations deeper than 30 AB mag in near-infrared (NIR) wavelengths, which can be reached only with a long exposure of JWST ($\sim 2 \times 10^4$ seconds for 5 $\sigma$ significance).

In this circumstance, several literatures (Scannapieco et al. 2005; Pan, Loeb & Kasen 2012; Whalen et al. 2012; de Souza et al. 2013; Hummel et al. 2012; Pan, Kasen & Loeb 2012; de Souza et al. 2013; Dessart et al. 2013) have examined the detectability of pair-instability SNe (PISNe, see e.g., Heger & Woosley 2002; Kasen, Woosley & Heger 2011; Dessart et al. 2013). PISNe give rise to an extremely high luminosity ($L \sim 10^{50} L_\odot$) powered by $> 1-10 M_\odot$ of $^{56}$Ni, and, they can be as bright as $26 - 27$ AB mag in NIR at $z \gtrsim 10$ (Whalen et al. 2012, 2013b). These works in part were motivated by the discovery of a PISN candidate SN 2007bi (Gal-Yam et al. 2008; Young et al. 2010). It is noted that there is ongoing debate on typical masses of Population III stars. Theoretically, both very massive stars ($\gtrsim 100 M_\odot$, as massive as progenitor of PISNe, e.g., Bromm, Coppi & Larson 1999; Abel, Bryan & Norman 2000) and ordinary massive stars ($\lesssim 50 M_\odot$, e.g., Yoshida, Omukai & Hernquist 2005; Hosokawa et al. 2011) might have existed in the early universe. Observationally, the existence of ordinary massive stars are corroborated by chemical abundances of metal poor stars (e.g., Frebel, Johnson & Bromm 2009, see Ren, Christlieb & Zhao 2012 for ongoing search of PISN signature).

The recent discovery of superluminous supernovae (SLSNe) (see Quimby et al. 2011; Gal-Yam 2012; and references therein) opens a new window to observe SN explosions of the first stars. SLSNe are thought to be powered by a huge amount of $^{56}$Ni (Umeda & Nomoto 2008; Young et al. 2010; Moriya et al. 2010) and/or strong interaction with the circumstellar material (CSM). The latter is supported by characteristic Type IIn spectra, e.g., narrow hydrogen emission lines, in some SLSNe-II (SLSN with hydrogen, according to the classification by Gal-Yam 2012), such as SNe 2006gy (Ofek et al. 2007; Smith et al. 2008; A&A 2009; Kawabata et al. 2009) and 2008fz (Drake et al. 2010). Numerical simulations of radiation hydrodynamics of SN explosion with dense CSM have been performed by Moriya et al. (2013; hereafter M13), who found that their models can reproduce the light curve of SN 2009gy. Thanks to the high luminosity, SLSNe are ideal targets at high redshift Universe. In fact, a few SLSNe and luminous Type IIn SNe have been detected at $z \sim 2 - 4$ (Cooke et al. 2009, 2012).

It has been argued by Cooke (2008; Quimby et al. (2011); M13; Whalen et al. (2012a)) that SLSNe and luminous Type IIn SNe are bright enough to be detected at $z > 4$. However, SLSNe are known to be extremely rare ($\sim 10^{-3}$ of core-collapse SNe, Quimby et al. 2011; Gal-Yam 2012; Quimby et al. 2013). Thus, an important question still remains; is there enough number of high-redshift SNe in the limited observational area that can be observed with realistic observational resources?

Earlier in our paper (Tanaka et al. 2012, hereafter Paper I), we studied the detectability of high-redshift SLSNe in the limited observational area for the first time. We showed about 100 SLSNe up to $z \sim 4$ can be detected with upcoming Subaru/Hyper Suprime-Cam (HSC) Deep survey, which reaches 24.5 mag depth in $z$-band. By using Ultra Deep survey for 3.5 deg$^2$ (25.6 mag in $z$-band), the maximum redshift can be as high as $z \sim 5$. We also showed that deep NIR survey can detect SLSNe even at $z \sim 6$.

In the present paper, we extend the study of Paper I to redshifts beyond $z = 6$, which is near the end of reionization of the Universe, with a special emphasis on $z > 10$, the era of the first star formation. We first describe our models for SLSNe in Section 2. The method and setup for mock observations are described in Section 3. Results of simulations are presented in Section 4. Based on the results, the optimized

![Figure 1](http://example.com/f1.png)
survey strategy is proposed in Section 5. We discuss selection methods to pick up high-redshift SLSNe in Section 6. Then, we apply our simulations to planned NIR surveys in Section 7. Finally, we give conclusions in Section 8.

Throughout the paper, we assume the $\Omega_M = 0.3$, $\Omega_{\Lambda} = 0.7$ and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$ cosmology. The magnitudes are given in the AB magnitude unless otherwise specified.

2 MODELS OF SUPERLUMINOUS SUPERNOVAE

To study the detectability of SLSNe at high redshifts, we use two models for spectral evolution of SLSNe. One is a theoretical model of interacting SNe and the other is actual observational results. For a large part of the simulations shown in this paper, we use the latter, observationally-calibrated model.

For the theoretical model, we adopt the result of radiation hydrodynamic simulations by M13. We use their "Model F1". In this model, the SN ejecta has mass of $M = 20 M_\odot$ and kinetic energy of $E = 1 \times 10^{52}$ erg. This SN ejecta collides with the dense CSM with $M = 15 M_\odot$. The density distribution of the CSM is assumed to be flat ($\rho(r) = $ constant), and the inner and outer radius of the CSM is set to be $5 \times 10^{15}$ cm and $11 \times 10^{15}$ cm, respectively. Details are found in M13.

This model nicely reproduces the light curve of SN 2006gy (Ofek et al. 2007; Smith et al. 2008; Agnoletto et al. 2009; Kawabata et al. 2009). The peak absolute magnitude is about $-21.5$ mag in the optical wavelengths, and the duration around the peak is about 100 days. The color temperature reaches $T \sim 15,000$ K near the peak. The behavior of the light curves depends on the distribution and the mass of the dense CSM. Note that although the formation scenario of the dense CSM might depend on the metallicity of the progenitor, we keep using the same model over the wide range of redshifts.

For this model, we construct apparent-magnitude light curves for various redshifts. By taking $L_\nu$ spectra from the simulations, we numerically compute K-correction by using Equation 8 of Hogg et al. (2002). For the bandpass filters, we adopt the broad-band filter of JWST/NIRCAM [1]. In Figure 1, which shows a clear contrast to Model F1, the wavelengths longer than $3 \mu$m progressively become more important at higher redshifts.

3 METHOD AND SETUP FOR MOCK OBSERVATIONS

3.1 Method of Simulations

We generate SNe for given survey parameters and perform mock observations of generated SNe. The method of the simulation is similar to that in Paper I. We briefly describe the method here.

We first setup the redshift grids at $z = 0 - 20$, with the interval of $dz = 0.01$. In each redshift bin, the number of SNe is computed according to the adopted SN rate (see Section 3.2).

The multi-band light curves of the SLSN models (see Section 2) in the observer’s frame are computed in each redshift bin. To account for the observed dispersion in the peak luminosity of SLSNe (see Gal-Yam 2012), we introduce a dispersion of $\sigma = 0.3$ mag. We adopt this relatively small value so that the bright end of the luminosity function does not affect the detectability at high redshifts.

The effect of extinction is crudely included when we use Model 08es because the extinction in the host galaxy is not corrected in the model by Miller et al. (2009). Note that the host galaxies of SLSNe are underluminous (Quimby et al. 2007; Neill et al. 2011), and the typical host extinction seems to be small. At higher redshifts, the intergalactic absorption by neutral hydrogen is not negligible. To take this absorption into account, we set the model flux below Lyman limit to be zero.

The generated model SNe are observed with a certain observational strategy. We set (1) the duration of a survey, (2) the number of visits at the same field (or cadence), (3)
the survey area, and (4) the detection limit per visit. Note that the detection limit per visit does not necessarily match the limiting magnitude of each observation. The limiting magnitude can also be that of the stacked images for a period within the cadence. Considering the light curves in Figure 1, the limiting magnitude of each observation. The limiting that the detection limit per visit does not necessarily match the survey area, and (4) the detection limit per visit. Note both to the limiting magnitudes.

We impose stringent detection criteria as in Paper I. Our definition of detection is fulfilling both of the following two criteria; (1) brighter than the detection limit in more than 2 bands at least at one epoch, and (2) brighter than the limiting magnitude at more than 3 epochs at least in one band.

3.2 Rate of Superluminous Supernovae

A key ingredient of our simulations is cosmic occurrence rate of SLSNe at high redshifts. It is reasonable to assume that the occurrence rate is proportional to the cosmic star formation rate (SFR) density \( \rho_* \). We adopt the SFR density derived from existing observations. Figure 3 shows various measurements of SFR density using galaxies (Bouwens et al. 2011, Zheng et al. 2012, Bouwens et al. 2012, Coe et al. 2013, Ellis et al. 2013) and gamma-ray bursts (GRBs, Ishida, de Souza & Ferrara 2011, Robertson & Ellis 2012). To cover the possible range of the SFR density, we adopt two cases; (A) SFR density model by Robertson & Ellis (2012), which is consistent with the lower bound of the SFR density derived from GRBs. Case B is a simple extrapolation of the formula by Hopkins & Beacom (2006), which is consistent with the galaxy measurements.

\[
R_{\text{SLSN}}(z) = f_{\text{SLSN}} \rho_*(z) \int_{M_{\text{min}} \text{ SLSN}}^{M_{\text{max}} \text{ SLSN}} \psi(M) dM \int_{M_{\text{min}}}^{M_{\text{max}}} M \psi(M) dM ,
\]

where \( \psi(M) \) is the stellar initial mass function (IMF), \( \psi(M) \propto M^{-(\Gamma+1)} \). We adopt a modified Salpeter A IMF of Baldry & Glazebrook (2003) with the slope \( \Gamma = 0.5 \) for \( 0.1M_\odot (= M_{\text{min}}) < M < 0.5M_\odot \) and \( \Gamma = 1.35 \) for \( 0.5M_\odot < M < 100M_\odot (= M_{\text{max}}) \).
As in Paper I, we assume that (1) from the wide mass range of stars, only massive stars with the mass of $M_{\text{max,SLSN}} = 50M_\odot - M_{\text{max,SLSN}} = 100M_\odot$ can be a potential progenitor of SLSNe, and (2) a fraction $f_{\text{SLSN}}$ of such massive stars actually explode as SLSNe. The fraction $f_{\text{SLSN}}$ can be calibrated by the observational constraints of the SLSN rate. Quimby et al. (2013) estimated the rate of SLSNe to be $2 \times 10^{-3} \text{ Mpc}^{-3} \text{ yr}^{-1}$ at $z \sim 0.2$. Adopting the SFR density from Hopkins & Beacom (2006), this rate is obtained if $f_{\text{SLSN}}$ is set to be $2 \times 10^{-2}$ for $M_{\text{max,SLSN}} = 50M_\odot$. This fraction corresponds to $10^{-2}$ of total core-collapse SNe (with the progenitor mass range of $M = 8 - 100M_\odot$). Hereafter we use this value of $f_{\text{SLSN}}$ for both Cases A and B SFR density. Since redshift evolution of this fraction is poorly understood both observationally and theoretically, $f_{\text{SLSN}}$ is assumed to be constant over redshifts. Possible impact of different IMFs is briefly discussed in Section 4 (see also Paper I). Note that Paper I adopted $f_{\text{SLSN}} = 2 	imes 10^{-3} - 2 \times 10^{-2}$, which gave conservative estimates.

The left panel of Figure 4 shows the SN rate per unit comoving volume as a function of redshift. The solid and dashed lines represent the SN rate with Cases A and B SFR density, respectively. The SN rate with Case B SFR density is consistent with the observed rate of SLSNe (blue point, Quimby et al. 2013). The adopted SN rates are also roughly consistent with the rate $\sim 4 \times 10^{-7} \text{ Mpc}^{-3} \text{ yr}^{-1}$ derived using a single detection at $z \sim 2$ and 4 by Cooke et al. (2012) although this rate may not represent the total SLSN rate. The right panel of Figure 4 shows the SN rate per unit area of the sky per redshift and per unit time in the observer’s frame. The expected number of SNe is an order of 0.01 deg$^{-2}$ yr$^{-1}$ redshift$^{-1}$ at $z > 10$.

Since at least one progenitor of Type IIn SN is known to be as massive as $M_{\text{ZAMS}} > 50 - 80M_\odot$ (Gal-Yam et al. 2007, Gal-Yam & Leonard 2009), we set the minimum mass of SLSNe to be $M_{\text{max,SLSN}} = 50M_\odot$.

Although Quimby et al. (2013) derived the rates of SLSN-I (SLSN without hydrogen, $3 \times 10^{-8} \text{ Mpc}^{-3} \text{ yr}^{-1}$) and SLSN-II (SLSN with hydrogen, $1.5 \times 10^{-7} \text{ Mpc}^{-3} \text{ yr}^{-1}$) separately, we simply use the total rate.

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**Figure 4.** (Left) The cosmic occurrence rate of SLSNe per unit volume. The solid and dashed lines represent Cases A and B SFR density models. Blue point is the observed total SLSN rate by Quimby et al. (2013). (Right) SLSN rate per unit area and per unit time in the observer’s frame.

**Figure 5.** Expected number of SN detection per $dz = 0.5$ bin as a function of redshift with the survey area of 100 deg$^2$ and the limiting magnitude of 26 mag in 1-5 $\mu$m. The solid and dashed lines show the dependence on the adopted SFR density (Cases A and B, respectively). The blue and red lines represent Model F1 and Model 08es, respectively.

### 4 RESULTS

We first show the results of our fiducial survey; observations with the survey area of 100 deg$^2$, and the limiting magnitude of 26 mag. The survey duration and cadence are set to be 3 years and 3 months, respectively. Figure 5 shows the expected number of SNe per $dz = 0.5$ bin as a function of redshift. The expected number of SNe at $z > 10$ is an order of 1-10 with Model 08es (red lines in Figure 5).

The solid and dashed lines show the dependence on the adopted SFR density (Cases A and B, respectively). The expected number with the Case A SFR density is higher than that with Case B by a factor of about 3 at $z > 6$, as expected from Figures 3 and 4.

Figure 5 shows the dependence on the limiting magnitudes. The observations deeper than 27 mag at $> 3\mu$m are deep enough not to miss SLSNe at $z \sim 15$ (see also Figure 3). With 100 deg$^2$ area, SLSNe beyond $z = 15$ can be detected.
survey depth. For the case of transient survey, (3) cadence is another important factor. However, SLSNe at high redshifts have a long timescale (Figure 1), and thus, the requirement for the cadence is not strong (we fix the cadence to be 3 months in all the simulations presented so far). Thus, optimization of the survey strategy means finding the best combination of the survey area and depth to maximize the number of SLSNe.

Figure 8 shows the expected total number of SLSNe at $z > 6$ (upper), 10 (lower left) and 15 (lower right) in the two-dimensional plane of the survey area and depth (see Appendix for similar simulations for optical surveys). The contours show the survey area and depth giving 1, 10, and 100 SLSNe (from left bottom to right top). Figure 8 includes the survey area up to the whole sky. Note that, in actual survey, the visibility of the sky that can be visited multiple times during the survey period is limited. When observations with a NIR satellite are considered, a typical maximum area with nearly permanent visibility is about 1000 deg$^2$ around the ecliptic poles.

The contours are nearly vertical around 25 mag ($z > 6$), 26 mag ($z > 10$), and 27 mag ($z > 15$). This clearly indicates that, irrespective of the survey area, observations at least deeper than 25 mag, 26 mag and 27 mag are required to detect SLSNe at $z > 6$, 10, and 15, respectively (see also Figure 7). On the other hand, the contour becomes horizontal at limiting magnitudes deeper than 28 mag. This indicates that, for a given survey area, observations deeper than 28 mag do not increase the number of SNe.

The gray dashed lines in Figure 8 represent the combination of the survey area and depth for a given survey power (i.e., $A_t \Omega t$, a product of certain set of photon-correction power $A$, field of view $\Omega$, and observational time $t$). From the comparison with simulations, we conclude that the optimized survey strategy to detect more than 10 SLSNe at $z > 10$ would be 100 deg$^2$ survey with the limiting magnitude of 26 mag.

In order to detect more than 10 SLSNe at $z > 15$, wider and deeper survey should be performed. The optimized strategy would be 200 deg$^2$ survey with the limiting magnitude of 27 mag. Compared with the survey to detect 10 SLSNe at $z > 10$, the survey power $A_t \Omega t$ should be increased by a factor of $\sim 13$.

Our results can also be applied for PISNe. The existence or occurrence rate of PISNe are not established well, and the predicted rates have a wide range: $10^{-2} - 10^{-7}$ deg$^{-2}$ yr$^{-1}$ redshift$^{-1}$ (Wise & Abel 2007; Weinmann & Lillie 2003; Johnson, Dalla & Khochfar 2013). Note that these rates may increase by the effect of rotation of progenitor stars (Chatzopoulos & Wheeler 2012). When the prediction by Johnson, Dalla & Khochfar (2013) is adopted, the rate is $10^{-2} - 10^{-6}$ deg$^{-2}$ yr$^{-1}$ redshift$^{-1}$, which is similar to the expected SLSN rate (Figure 3). According to the calculations by Whalen et al. (2012, 2013), the peak brightness of some PISN models is as bright as 26 mag at $z = 10$ and 27 mag at $z = 15$ in the NIR wavelengths, which are also similar to those of SLSNe (Figures 1 and 2). In this case, the same observing strategy with SLSNe will be able to discover a similar number of PISNe: a 100 deg$^2$ survey with the limiting magnitude of 26 mag will discover about 10 PISNe at $z > 10$, and a 200 deg$^2$ survey with the limiting magnitude of 27 mag will discover about 100 PISNe at $z > 6$. This clearly suggests that in order to discover high-redshift SLSNe efficiently, observational resources should be devoted to enlarge the survey area, instead of making the observation deeper than 28 mag. The optimized survey strategy is discussed in the next section.

5 OPTIMIZED SURVEY STRATEGY

Since observational resources are limited, it is important to find an optimized survey strategy. In general, survey observations can be characterized by (1) survey area and (2) limiting magnitude of 27 mag (solid line) and 28 mag (dashed line) in 1-5 µm. Case A SFR density is adopted. The blue and red lines represent Model F1 and Model 08es, respectively.

Figure 7. Expected total number of SLSNe beyond $z = 6$ (black), 10 (blue), and 15 (red) as a function of limiting magnitude. Case A SFR density and Model 08es are adopted.

Figure 6. Expected number of SN detection per $dz = 0.5$ bin as a function of redshift with the survey area of 100 deg$^2$ and the limiting magnitude of 27 mag (solid line) and 28 mag (dashed line) in 1-5 µm. Case A SFR density is adopted. The blue and red lines represent Model F1 and Model 08es, respectively.
Figure 8. Expected total number of SLSNe at $z > 6$ (upper), 10 (lower left) and 15 (lower right) as a function of survey area and limiting magnitude. The contours show the combination of the survey area and limiting magnitude giving 1, 10, and 100 SLSNe (from left bottom to right top). White squares show the survey area and limiting magnitude for planned surveys (Table 1). The contours are nearly vertical at the limiting magnitudes of 25 mag ($z > 6$), 26 mag ($z > 10$), and 27 mag ($z > 15$). This indicates that the observations deeper than at least 25, 26 and 27 mag are required to detect SLSNe at $z > 6$, 10 and 15, respectively. On the other hand, the contours are horizontal at the limiting magnitude deeper than 28 mag do not increase the number of SLSNe dramatically. The gray dashed lines represent the combination of the survey area and depth for a given survey power (i.e., $A \Omega t$). Case A SFR density and Model 08es are adopted.

6 SELECTION OF HIGH-REDSHIFT SLSNE

We discuss selection methods for SLSNe at high redshifts. Since SLSNe are rare objects, it is naturally expected that more Type Ia SNe and normal core-collapse SNe at lower redshifts will be discovered with the NIR surveys presented...
in the previous sections. Thus, we must efficiently pick up candidates of high-redshift SLSNe.

A clear difference is its timescale of the variability. Because of the intrinsically long timescale and time dilation by high redshifts, the expected timescale of the variation of SLSNe is longer than 100 days (Figure 9). This is much longer than that of Type Ia SNe at lower redshifts (z ≤ 2).

However, Type IIP SNe may have a similar timescale at the plateau phase. For the further selection, observations more than 2 bands are helpful. Figure 9 shows the spectral energy distribution (SED) of high-redshift SLSNe, compared with those of low-redshift Type Ia SNe (black) and Type IIP SNe (gray) with similar observed magnitudes. For the SEDs of Type Ia and IIP SNe, we use spectral templates by Nugent, Kim & Perlmutter (2002). In the NIR wavelengths, SLSNe at high redshifts are observed around the peak of the SED or at the bluer side of the peak. In contrast, Type Ia and IIP SNe are always observed at the redder side of the peak. As a result, SLSNe at high redshifts are redder than Type Ia and IIP SNe with similar observed magnitudes.

The red color of high-redshift SLSNe is more clearly seen in a color–color diagram (Figure 10). In this figure, we use bandpass filter of JWST ([2.0], [2.8], and [3.6] are magnitudes in F200W, F277W, and F356W filters, respectively). SLSNe at high redshifts tend to have a redder color in [2.0]−[2.8] and [2.8]−[3.6], compared with Type Ia and IIP SNe with similar observed magnitudes. We note, however, that only with 2-band observations, confusion with Type Ia SNe are not fully solved. We emphasize that observations at ≥ 3 μm is useful not only for detection at higher redshifts, but also for the target selection. Objects having both [2.0]−[2.8] > 0 and [2.8]−[3.6] > 0 colors (dashed lines in Figure 10) are likely to be high-redshift SLSNe.

### 7 APPLICATION TO FUTURE SURVEYS

Based on the results shown in the previous sections, we apply our simulations to several planned surveys in the near future. We consider NIR survey with Euclid and the Wide-Field Infrared Survey Telescope (WFIRST). Euclid plans to perform a wide (15000-20000 deg$^2$) and deep (40 deg$^2$) survey (Laureijs et al. 2011). A part of deep survey may have multiple visits for Type Ia SNe, although the exact cadence is not yet fixed. The wavelength coverage is up to 2 μm (H band). The survey depth per visit is 24.5 mag in the visual band and 24.0 mag in the NIR bands. We hypothetically assume 10-day cadence and 3-year survey period. We perform mock observations with these parameters.
Throughout this section, we adopt Case A SFR density and Model 08es. For the adopted survey parameters, see Table 1. WFIRST (black and blue lines) covers the wavelength range up to K-band (2.4 μm). If a 3 μm-band is hypothetically added, the highest redshift will exceed z = 10 (pink line). Since WISH plans to cover up to 4μm, SNe at higher redshifts can be detected. All the simulations have been performed for Case A SFR density and Model 08es.

Next, we consider surveys with WFIRST. WFIRST plans to perform dedicated SN survey in a part of the observational time (Green et al. 2012). The planned survey area is 6.5 deg² (wide) and 1.8 deg² (deep). Since a large survey area is critical for the detection of SLSNe (Figure 5), we adopt 6.5 deg². The wavelength coverage is up to 2.4 μm (K-band) and the survey depth per visit is 26.0 mag. Cadence and survey period are 5 days and 1.8 years, respectively, which are optimized for Type Ia SNe. The result of mock observation with these parameters (WFIRST, Table 1) is shown in black line in Figure 11. Thanks to the deep observations at 2.4 μm, WFIRST will be able to discover ∼ 400 SLSNe up to z ∼ 7.

It is also shown, however, that the survey area of 6.5 deg² is not enough to fully utilize its observational depth. To see this effect, we hypothetically perform the simulations with the survey area of 100 deg² with all the other parameters kept the same (WFIRST-extended, Table 1). Such a survey dramatically increases the number of SLSNe (see Figure 9): ∼ 6000 SLSNe up to z ∼ 9 will be detected (blue line in Figure 11).

Even with the extended survey area, there is a clear cutoff in the expected number of SLSNe below z ∼ 10. This is because the expected brightness of SLSNe in the K-band (1.8-2.4 μm) becomes dramatically fainter at the redshifts higher than z ∼ 5 (Figure 8). To see the advantage to have 3μm band, we perform a simulation by hypothetically adding 3μm band to the WFIRST-extended survey (pink line in Figure 11). If WFIRST possibly covers 3μm, it will be able to carry out the nearly ideal survey, detecting SLSNe at z > 10. We emphasize the importance of observations at ≥ 3 μm.

WFIRST plans to focus on the deep survey with ∼ 100 deg² (Yamada et al. 2012). The wavelength range is 1.0-4.5 μm and the survey depth per visit is about 26.0 mag. Cadence and survey period are not yet fixed, and thus, we hypothetically assume 10-day cadence and 1-year survey period (see WISH in Table 1). The brown line in Figure 11 shows the expected number of SLSNe with WISH survey. WISH will be able to detect about 3000 SLSNe in total. Thanks to the wavelength coverage up to 4.5 μm, the maximum redshift is higher than those of Euclid and WFIRST. It may be able to discover SLSNe up to z ∼ 12. This is, in fact, quite similar to the optimized survey strategy to detect SLSNe at z > 10 suggested in Section 6.

WFISH and extended WFIRST surveys will be able to detect more than 100 SLSNe at z > 6 (see also Figure 9). Such high-redshift SLSNe can be spectroscopically observed with JWST and also ground-based 30m-class telescopes, such as Thirty Meter Telescope (TMT, see e.g., Wright et al.).
We emphasize that the proposed optimized survey strategy to detect SLSNe at $z > 10$ is not far from reality. In fact, we show that the planned NIR surveys partly achieve the required specification, and that a slight modification of the planned surveys makes the surveys closer to the ideal survey to detect SLSNe at $z > 10$. We will be able to reach a single star at $z > 10$, possibly out of the first stars, with such NIR surveys in the near future. Such surveys will provide a unique way to unveil the properties of the first stars and IMF in the early Universe.

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expected (Paper I). Thus, it is natural to adopt a shorter duration of the survey and a higher cadence than those of NIR surveys. Here we simply adopt (1) 0.5-year survey and (2) 10-day cadence. For simplicity, simultaneous observations in the optical $ugrizy$ bands with the same limiting magnitudes are assumed. Figure A1 shows the expected total number of SLSNe at $z > 2$ (left) and 4 (right) as a function of survey area and limiting magnitude per single visit. All the simulations have been performed for Case B SFR density (better calibrated at $z < 6$ than Case A SFR density) and Model 08es.

Our simulations are also applied for planned survey with Large Synoptic Survey Telescope (LSST, Ivezić et al. 2008, LSST Science Collaborations et al. 2009). LSST will perform 20000 deg$^2$ survey in the optical $ugrizy$ bands. Each visit consists of a short exposure (15 seconds), giving following limiting magnitudes; 23.9 ($u$), 25.0 ($g$), 24.7 ($r$), 24.0 ($i$), 23.3 ($z$), and 22.1 ($y$). Each patch of the sky is visited about 100-200 times for 10 years. Thus, the parameters of the survey using the single visit can be roughly approximated as (1) 3-month survey for each year (repeating for 10 years) and (2) 10-day cadence (see Table A1). The black line in Figure A2 shows the expected number of SLSNe using the single visits of LSST. LSST will be able to discover about $10^6$ of SLSNe up to $z \sim 3 - 4$. In this overwhelming sample, some SLSNe ($\gtrsim 10 - 100$) may be discovered as extremely luminous sources because of the magnification by gravitational lensing (Oguri & Marshall 2010, see also Takahashi et al. 2011).

By appropriately stacking the data, giving a deeper limiting magnitude, the maximum redshift will be higher. One promising strategy is using “deep drilling” fields of LSST. About 10 % of the observing time will be devoted to observe several deep fields. Even with 10 % of the observing time, if we limit the survey area to 100 deg$^2$ and the survey duration to 0.5 year, deep observations (with about 100 images stacked) can be performed with 10-day cadence. Such a deep image will give limiting magnitudes of about 26 mag (Table A1, LSST deep drilling). Simulations with these parameters show that LSST deep drilling observations will be able to detect about $10^3$ SLSNe up to $z \sim 5 - 6$ (pink line in Figure A2).

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**Table A1. Parameters for upcoming optical surveys**

| Survey                  | Area (deg$^2$) | Depth (mag) | Cadence | Duration  |
|-------------------------|----------------|-------------|---------|-----------|
| HSC Deep *              | 30             | 25.0        | 10 days | 0.5 years |
| HSC UltraDeep *         | 3.5            | 26.0        | 10 days | 0.5 years |
| LSST                    | 20000          | **          | 10 days | 0.25 years x 10 |
| LSST deep drilling      | 100            | 26.0        | 10 days | 0.5 years |

* For simplicity, a constant limiting magnitude is assumed. See Paper I for more realistic simulations.

** Limiting magnitude per single visit for LSST: 23.9 ($u$), 25.0 ($g$), 24.7 ($r$), 24.0 ($i$), 23.3 ($z$), and 22.1 ($y$).