Are Stripped Envelope Supernovae Really Deficient in $^{56}\text{Ni}$?

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Abstract

Recent works have indicated that the $^{56}\text{Ni}$ masses estimated for stripped envelope supernovae (SESNe) are systematically higher than those estimated for SNe II. Although this may suggest a distinct progenitor structure between these types of SNe, the possibility remains that this may be caused by observational bias. One important possible bias is that SESNe with low $^{56}\text{Ni}$ mass are dim, and therefore more likely to escape detection. By investigating the distributions of $^{56}\text{Ni}$ mass and distance of samples collected from the literature, we find that the current literature SESN sample indeed suffers from a significant observational bias, i.e., objects with low $^{56}\text{Ni}$ mass—if they exist—will be missed, especially at larger distances. Note, however, that those distant objects in our sample are mostly SNe Ic-Bl. We also conducted mock observations assuming that the $^{56}\text{Ni}$ mass distribution for SESNe is intrinsically the same as that of SNe II. We find that the $^{56}\text{Ni}$ mass distribution of the detected SESN samples moves toward higher mass than the assumed intrinsic distribution because of the difficulty in detecting the low-$^{56}\text{Ni}$ mass SESNe. These results could explain the general trend of the higher $^{56}\text{Ni}$ mass distribution (than SNe II) of SESNe found thus far in the literature. However, further finding clear examples of low-$^{56}\text{Ni}$ mass SESNe ($\lesssim 0.01 M_\odot$) is required to strengthen this hypothesis. Also, objects with high $^{56}\text{Ni}$ mass ($\gtrsim 0.2 M_\odot$) are not explained by our model, which may require an additional explanation.

Unified Astronomy Thesaurus concepts: Supernovae (1668); Massive stars (732)

1. Introduction

Core collapse supernovae (SNe) are the explosions of massive stars, marking the termination of their lives. A small fraction of the gravitational energy of the collapsing iron core is converted into the kinetic and thermal energy of the ejected matter (Woosley et al. 2002). Core collapse SNe are classified into several categories, based on their spectra and light curves. SNe with hydrogen lines in their spectra are classified as Type II SNe (SNe II), while those lacking hydrogen lines are classified as Type I SNe (SNe I). Among SNe I, those having He lines are classified as Type Ib SNe (SNe Ib) and those lacking He lines classified as SNe Ic. Type IIb supernovae (SNe IIb) are characterized by hydrogen lines in their early phase spectra, which gradually disappear, and by the He lines that become increasingly strong at later phases (Filippenko 1997). SNe IIb, Ib, and Ic are considered to originate from massive stars that have lost a significant fraction of the envelope during their evolution, and thus they are collectively called stripped envelope SNe (SESNe; Smartt et al. 2009).

It has been established that SNe IIP are the explosions of red supergiants based on light-curve models (Falk & Arnett 1977; Elmhamdi et al. 2003; Bersten et al. 2011) and also from the direct detection of the progenitors on pre-SN images (Smartt 2009, 2015). On the contrary, the progenitors of SESNe are more uncertain. For SNe IIb, Ib, and Ic, two possible progenitor channels have been proposed. One is a massive Wolf-Rayet star (with the main-sequence mass $M_{\text{ms}} \gtrsim 25 M_\odot$) that has blown off the H-rich envelope by its own stellar wind (Begelman & Sarazin 1986; Georgy 2012; Gräfener & Vink 2016). The other is a relatively low mass star that loses its envelope by mass transfer to a binary companion (Podsiadlowski et al. 1992; Stancliffe & Eldridge 2009). Recent observational evidence favors the latter scenario.

Light-curve modeling and direct progenitor detection indicate that the progenitors are relatively low mass stars ($M_{\text{ns}} \lesssim 18 M_\odot$), being consistent with the binary scenario (Maund et al. 2011; Bersten et al. 2014; Van Dyk et al. 2014; Folatelli et al. 2015). Also, for some SESNe, companion star candidates have been detected, which indicate a binary origin (Maund et al. 2004; Folatelli et al. 2014).

One of the most important power sources of SNe is newly synthesized $^{56}\text{Ni}$. $^{56}\text{Ni}$ decays into $^{56}\text{Co}$, and then into $^{56}\text{Fe}$. This nuclear decay chain powers the tail phase of SNe II and most of the light curve of SESNe. $^{56}\text{Ni}$ masses of SNe have been estimated using several methods (Anderson 2019). For SNe II, the tail luminosity has mostly been used to estimate the $^{56}\text{Ni}$ mass, assuming the complete trapping of $\gamma$-rays produced from the nuclear decay. For SESNe, on the contrary, the tail luminosity cannot be easily used due to the incomplete trapping of the $\gamma$-ray photons, and the $\textit{Arnett rule}$ has often been used instead (Arnett 1982; Wheeler et al. 2015). This rule dictates that the peak luminosity of SESNe should be equal to the instantaneous energy deposition rate by the nuclear decay. For both types of SNe, the mass of synthesized $^{56}\text{Ni}$ has also been estimated from light-curve modeling (e.g., Utrobin & Chugai 2011; Bersten et al. 2014).

Interestingly, mounting evidence has shown that the masses of synthesized $^{56}\text{Ni}$ of the observed SESNe are systematically higher than those of SNe II. This result was first formally outlined by Kushnir (2015). Later, Anderson (2019) collected the $^{56}\text{Ni}$ masses for 258 SNe from the published literature and compared the $^{56}\text{Ni}$ mass distributions for various types of SNe. Anderson (2019) found that the $^{56}\text{Ni}$ masses estimated for SNe II are systematically lower than SESNe; the median of the $^{56}\text{Ni}$ masses is 0.032 $M_\odot$ for SNe II, 0.102 $M_\odot$ for SNe IIb, 0.163 $M_\odot$ for SNe Ib, 0.155 $M_\odot$ for SNe Ic, and 0.369 $M_\odot$ for SNe Ic broad line (SNe Ic-Bl).
This result has important implications. The production of $^{56}\text{Ni}$ is sensitive to the explosion mechanism (Maeda & Tominaga 2009; Suwa & Tominaga 2015; Sawada & Maeda 2019) and the progenitor mass (Suwa et al. 2019). Thus, $^{56}\text{Ni}$ is considered an important diagnostic indicator for understanding the details of the explosion mechanism of core collapse SNe (Sawada & Suwa 2021). Indeed, this may be qualitatively consistent with some indications that the progenitors of SESNe may be more massive than SNe II either as an entire class or for the particular SN Ic class (e.g., Anderson et al. 2012; Valenti et al. 2012; Fang et al. 2019). The possible difference in the nature of the progenitors between SNe II and SESNe may introduce some uncertainty to the popular suggestion for a binary origin for SESN progenitors, since the core structure should be similar between SESNe and SNe II; the binarity mainly affects the outer envelope but not the core structure (Yoon et al. 2010, 2017; Ouchi & Maeda 2017). However, this picture may also be an oversimplification since there are several factors that can affect the nature of the progenitor even in the binary scenario. For example, massive stars are claimed to be preferentially formed in close binary systems (Moe & Di Stefano 2017). The angular momentum transfer may also have effects on the core structure and boost the synthesized $^{56}\text{Ni}$ mass (Schneider et al. 2021). In any case, understanding the origin of different $^{56}\text{Ni}$ masses between SESNe and SNe II should help clarify the progenitors of SESNe.

Before concluding that the systematically different $^{56}\text{Ni}$ mass between SESNe and SNe II may be caused by a different structure in the progenitor cores, systematic errors in calculating the $^{56}\text{Ni}$ masses should be addressed (Anderson 2019). Indeed, the Arnett rule, which has been widely used for SESNe, has been claimed to overestimate the $^{56}\text{Ni}$ mass (Dessart et al. 2015, 2016; Khatami & Kasen 2019). However, several works have concluded that even by taking into account the different methods to derive the $^{56}\text{Ni}$ mass and various observational errors, a difference in $^{56}\text{Ni}$ masses between SNe II and SESNe remains (Afsariardchi et al. 2021; Meza & Anderson 2020; Sharon & Kushnir 2020). Meza & Anderson (2020) further noted the possibility that SESNe with a small amount of $^{56}\text{Ni}$ might have been missed by existing surveys. Since the luminosity of SESNe is mostly powered by the radioactive decay of $^{56}\text{Ni}$, SESNe with the lowest $^{56}\text{Ni}$ masses are the faintest (Lyman et al. 2016). Thus, they can possibly escape detection, depending on the survey depth. On the contrary, SNe II with a small amount of $^{56}\text{Ni}$ can still power themselves by diffusion of the thermal energy coming from the explosion energy. Thus, SNe II can more easily be detected than SESNe, even if the $^{56}\text{Ni}$ mass is small. Indeed, several Ni-poor SESNe ($M_{\text{Ni}} \lesssim 0.02 M_\odot$) have been detected (Kasliwal et al. 2010; Shivvers et al. 2016; Nakaoka et al. 2019). However, it should also be noted that none of these examples are just a low-luminosity version of canonical SESNe as they all show unusual properties.

The aim of this paper is to investigate how much observational bias may lie in the $^{56}\text{Ni}$ mass distribution of the samples collected from the published literature. In Section 2, we define the samples that are used throughout the paper. Section 3 describes some equations that are used in this paper. In Section 4, we investigate whether there is an observational bias in the $^{56}\text{Ni}$ mass distribution of our data samples by examining the relation between distance, luminosity, and $^{56}\text{Ni}$ mass. In Sections 5 and 6, we conduct mock observations of SESNe and theoretically investigate the effect of observational bias on the observed $^{56}\text{Ni}$ mass distribution. We discuss the results in Section 7 and finally conclude the paper in Section 8.

2. Data Sample

In this section, we describe the observational samples used in this paper. Throughout the paper, we use the samples of $^{56}\text{Ni}$ estimates collected from the published literature both for SESNe and SNe II. Anderson (2019) recently compiled such samples, including 143 SESNe and 115 SNe II. Specifically, Anderson (2019) used the SAO/NASA ADS astronomy query form, searching for articles with “supernova” and “type II” that were published through 2018 August, then “supernova” and “type Ib” and so forth in manuscript abstracts. Then, Anderson (2019) identified those publications with published $^{56}\text{Ni}$ mass estimates. In addition to this sample, we add newly published objects between 2018 August and 2020 November. The newly added reference list can be found at the end of this manuscript. Note that we do not include $^{56}\text{Ni}$ estimates that are derived from combined models, such as the “magnetar + $^{56}\text{Ni}$ model” or the “circular interaction + $^{56}\text{Ni}$ model” (e.g., Gangopadhyay et al. 2020). We refer to these final samples as “LS-SESNe (large sample SESNe)” and “LS-SNe II (large sample SNe II),” respectively. The sample sizes are 187 and 115 for LS-SESNe and LS-SNe II, respectively.

Several different methods have been used to derive the $^{56}\text{Ni}$ masses in the literature. For SNe II, the tail luminosity is commonly used to measure $^{56}\text{Ni}$ mass. For SESNe, on the contrary, $^{56}\text{Ni}$ mass is often derived by feeding a peak luminosity into the Arnett relation. It is true that tail luminosity has also been used for SESNe to constrain their $^{56}\text{Ni}$ masses. However, since the assumption of complete $\gamma$-ray trapping is usually not valid for SESNe, the tail luminosity underestimates $^{56}\text{Ni}$ mass (unless additional modeling is employed; see, e.g., Sharon & Kushnir 2020).

In addition to LS-SESNe, we also use a different sample of SESNe, which we refer to as “Meza-SESNe;” this is the same sample as that used by Meza & Anderson (2020). Those authors defined an SESN sample with well-sampled photometry at optical and near-IR wavelengths. This led to a sample of 37 events. To obtain peak luminosities, they applied a local polynomial regression with a Gaussian kernel, using the public modules from PyQt-fit in Python-4. Note that the integration was done in the wavelength range from the B band to H band without extrapolation outside. Therefore, their resulting light curves should be considered to be pseudo-bolometric, and are a lower limit to the true bolometric luminosity at all times. However, the wavelength coverage is reasonably large, and therefore the error here is probably less significant than that coming from the different methods to derive the $^{56}\text{Ni}$ mass. In the paper, they tested three different methods to derive the $^{56}\text{Ni}$ mass. In the first method, they used the Arnett rule. In the second method, they used a tail luminosity. The third method employed, which was recently proposed by Khatami & Kasen (2019), overcomes several limitations of Arnett-like models.

4 https://ui.adsabs.harvard.edu/classic-form

5 The size of LS-SNe II is the same as the sample of Anderson (2019). This occurred because this time we excluded objects with only upper or lower limits for the $^{56}\text{Ni}$ mass. The number of thus removed events was by chance equal to that of the newly added events.
Meza & Anderson (2020) showed that using the different methods does not change the overall trends in the derived $^{56}\text{Ni}$ masses and their conclusions. In the present work, we mostly use the Arnett rule in our analysis (Section 3), but we show that our results are not affected by this choice in Appendix B.

In Section 4.2, in order to compare the luminosity function between SESNe and SNe II, we use the sample of 57 SNe II taken from Hamuy (2003), Pejcha & Prieto (2015), and Müller et al. (2017). These events have published values of mid-plateau phase luminosity. These papers are included in the reference list of Anderson (2019), and thus, this is a subsample of LS-SNe II. We refer to this small sample as “SS-SNe II (small sample SNe II).”

Finally, in Section 7, we will compare our results to a sample of candidate ultra-stripped envelope SNe (USSNe). The data for the USSN candidates are also collected from the literature published before 2020 November by searching for “ultra-stripped” and “supernova” in the ADS abstract form. The references for them are listed at the end of the manuscript.

For all these objects, we adopt the distance to the host galaxy from the redshift independent measurement in NED. In case there is no redshift independent measurement of the distance to the host, we adopt the Hubble distance on NED, which contains the correction of Virgo, GA, and Shapley. For the cosmological parameters, $H_0 = 67.8\,\text{km\,s}^{-1}\,\text{Mpc}^{-1}$, $\Omega_{\text{matter}} = 0.308$, and $\Omega_{\text{vacuum}} = 0.692$ have been used. If the host was anonymous or the distance was not found in NED, we took the distance from individual published literature.

### 3. The Relations Used in This Paper

#### 3.1. The Relations for the Peak Luminosity and the Timescale of SESNe

Two important quantities that characterize the light curves of SESNe are the peak luminosity ($L_p$) and the time it takes from the explosion to the peak ($t_p$). In the following analyses, we require the relations that connect these values to the $^{56}\text{Ni}$ mass.

For a given $^{56}\text{Ni}$ mass, the peak luminosity is estimated from the formula shown in Stritzinger & Leibundgut (2005), which is based on the Arnett rule. This rule assumes that the peak luminosity ($L_p$) of an SN powered by the decay of $^{56}\text{Ni}$ is equal to the instantaneous energy deposition rate by radioactive decay at that time:

$$L_p = 10^{43} \times \left(M_{\text{Ni}}/M_\odot\right) \times (6.45 \times e^{-t_p/8.8} + 1.45 \times e^{-t_p/111.3}) [\text{erg \,s}^{-1}].$$  \hspace{1cm} (1)

The timescale, $t_p$, is not necessarily determined by a $^{56}\text{Ni}$ mass. However, in this paper, we take a phenomenological approach using the observational data, and express $t_p$ as a function of the $^{56}\text{Ni}$ mass. For that purpose, we derive a fitting formula for $t_p$ as a function of $^{56}\text{Ni}$ mass using the well-observed sample of Meza-SESNe taken from Meza & Anderson (2020). Since this sample is composed of nearby objects (the median distance of their SESNe sample, excluding Ic-Bl, is 46.7 Mpc), the objects are considered to be less affected by a possible observational bias than the other SESN samples (and note that the observational bias we will discuss later would not affect this relation much). Furthermore, the objects in their sample are chosen under the condition that they contain the data around the peak. Thus, $L_p$ and $t_p$ in their sample are considered to be relatively accurate.

As shown in the left panel of Figure 1, $t_p$ and log $M_{\text{Ni}}$ broadly follow a linear correlation. Thus, we conducted a linear regression to the data, using the least squares method. We did not use SNe Ic-Bl samples for the fit since they may indeed involve a different explosion mechanism from canonical SNe II and SESNe, and also they are taken at relatively distant locations. The derived formula becomes

$$t_p = (9.41 \pm 2.98) \times \log_{10}(M_{\text{Ni}}/M_\odot) + (29.74 \pm 3.42)[\text{day}].$$  \hspace{1cm} (2)

Using this equation, together with Equation (1), we can estimate $t_p$ for a given $^{56}\text{Ni}$ mass. In the right panel of Figure 1, the peak luminosity calculated for a given $^{56}\text{Ni}$ mass using Equations (1) and (2) are compared to the data points of Meza-SESNe. It is seen that the data points for the peak luminosity are well reproduced by our fitting formula.
circles are for SNe Ic-BL among LS-SESNe. For reference, the limiting magnitude of the distance. It can be seen that there is a strong trend that the distance we can detect it assuming a fixed limiting magnitude. For this purpose, we use the relation in Hamuy (2003):

$$\log D_{\text{lim}}[\text{cm}] = \frac{1}{5} \times (2.5 \log L[\text{erg s}^{-1}] + V_{\text{lim}} - A_V + BC + 8.14).$$

Here, $V_{\text{lim}}$ is the limiting magnitude in the $V$ band, $D_{\text{lim}}$ is the limiting distance, $A_V$ is the total extinction and $BC$ is the bolometric correction. For simplicity, we assume zero both for $A_V$ and $BC$. Using this relation, we can calculate the observable distance for a given luminosity, assuming a fixed limiting magnitude.

4. Investigating Observational Bias in the Data Sample

In this section, we investigate whether there is an observational bias in the $^{56}\text{Ni}$ mass distribution of our data samples by examining the relation between distance, luminosity, and $^{56}\text{Ni}$ mass.

4.1. $^{56}\text{Ni}$ Mass and Distance

In order to clarify how the observational biases may affect the $^{56}\text{Ni}$ mass distribution in our samples, we look at the $^{56}\text{Ni}$ mass of our samples plotted as a function of the distance. Figure 2 shows the $^{56}\text{Ni}$ mass distribution of our samples plotted as a function of the distance. It can be seen that there is a strong trend that the $^{56}\text{Ni}$ mass decreases as the distance decreases for SESNe. This suggests that the objects with low $^{56}\text{Ni}$ masses (i.e., dim objects) and large distance, if they exist, may be missed. It is, however, important to emphasize that we are still lacking the SESNe with low $^{56}\text{Ni}$ mass ($M_{\text{Ni}} \lesssim 0.02 M_\odot$) even at small distance (log distance (Mpc) $\lesssim 1$). For SNe II, even though the $^{56}\text{Ni}$ mass slightly decreases as the distance decreases, the effect is much less significant than for SESNe.

These trends can be confirmed by looking at Figures 3 and 4. Figure 3 shows how the $^{56}\text{Ni}$ mass distribution changes when we take different sizes of volume-limited samples. It is expected that the $^{56}\text{Ni}$ mass distribution approaches to the intrinsic distribution as we take the volume-limited sample at a closer location. It is seen that the $^{56}\text{Ni}$ mass distribution of SESNe significantly shifts to the lower mass when we take the smaller volume-limited sample. On the contrary, the $^{56}\text{Ni}$ mass distribution of SNe II does not change notably for the different sizes of volume-limited sample. From this, we can infer that the LS-SESNe may not trace the intrinsic $^{56}\text{Ni}$ mass distribution, while LS-SNe II nearly do. Figure 4 shows the average $^{56}\text{Ni}$ mass in the volume-limited samples plotted as a function of the threshold distance. This figure, again, shows that LS-SESNe suffer from a significant observational bias and the discrepancy between SESNe and SNe II becomes smaller as we take the smaller volume-limited sample, and finally becomes within a factor of 3.

Note, however, that if we remove SNe Ic-BL from LS-SESNe, then, the trend that $^{56}\text{Ni}$ mass decreases with distance is greatly weakened. This may indicate that SNe Ic-BL, whose distances are larger than the other types of SNe, are heavily affected by an observational bias, while other types of SESNe (e.g., SNe IIb, Ib, and Ic) are less affected by it.

Figure 5 compares the distance distribution between LS-SESNe and LS-SNe II. We can see that the distance distribution is closer for SNe II than for SESNe. Meza & Anderson (2020) showed that their sample of 35 SESNe, excluding two Ic-GRB objects, have a mean distance (46.7 Mpc) similar to that of their SNe II sample (42.7 Mpc). However, our significantly larger sample of LS-SESNe has the larger mean distance of 226.6 Mpc, while LS-SNe II has the mean distance of 41.5 Mpc. Even if we remove Ic-GRB from the SESNe sample, the mean distance is 99.8 Mpc, which is more than twice the value of LS-SNe II. This indicates that the SESN samples are collected at more distant locations than SNe II, where the objects suffer from more significant observational bias, supporting the results derived above.

4.2. Luminosity Distribution

In this section, we investigate the luminosity distribution of our samples. We emphasize that the analysis in this section is not affected by the assumption about the relation between the $^{56}\text{Ni}$ mass and the peak luminosity of SESNe. As noted in Section 2, here, we only use the sample of 57 SNe II taken from Hamuy (2003), Pejcha & Prieto (2015), and Müller et al. (2017), which we refer to as SS-SNe II. Note that Hamuy (2003) only published the $V$-band magnitude, so, we convert it to the bolometric luminosity assuming the bolometric correction to be zero, following Goldberg et al. (2019). For SESNe, we use the sample of 37 from Meza-SESNe.

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8 Note, however, that the distributions for the lowest 20% of the $^{56}\text{Ni}$ masses are nearly the same for these different sizes of volume-limited samples. This may indicate that the lack of canonical SESNe with relatively low $^{56}\text{Ni}$ mass ($\lesssim 0.02 M_\odot$) is real.

9 Although the samples in Meza & Anderson (2020) were taken at small distances ($\approx 40$–$50$ Mpc), the SESNe with low $^{56}\text{Ni}$ mass ($\lesssim 0.02 M_\odot$) were still lacking. We will further discuss this issue in Section 7.2.
The left panel of Figure 6 shows the luminosity distribution as a function of distance for these samples. For SESNe we show the peak luminosity, while we show the mid-plateau luminosity for SNe II. There is a positive correlation between the luminosity and distance both for SESNe and SNe II. Also, the minimum luminosity for a fixed distance is similar between SNe II and SESNe. This indicates that the luminosity distributions seen in both of our samples (SESNe and SNe II) may be suffering from the same observational selection effect. The right panel of Figure 6 compares the luminosity functions of SESNe and SNe II. We note that there is a luminosity cutoff for both types at around log $L$ [erg s$^{-1}$] $\sim$ 41.7. The SNe II plateau phase and the SESN peak phase are powered by different physical mechanisms, with the former powered by the explosion energy and the latter powered by the radioactive decay of $^{56}$Ni. It is true the plateau luminosity and the $^{56}$Ni mass of SNe II are known to be positively correlated, but it is unlikely that the lower luminosity cutoff is the same between the two groups of SNe just in terms of physics. Thus, we speculate that this simultaneous cutoff of the luminosity functions for both types of SNe is caused by an observational selection effect. This selection effect will introduce a bias in the $^{56}$Ni mass distribution for SESNe, as the $^{56}$Ni mass is closely connected to their peak luminosities.

In summary, the results derived in Section 4 all point to the following interpretation: The $^{56}$Ni masses of SESNe collected from the published literature suffer from notable observational bias, i.e., the distant objects with relatively low $^{56}$Ni mass are missed, meaning that the samples are biased toward the luminous objects. On the contrary, the $^{56}$Ni masses of SNe II samples suffer much less from such bias. We, again, emphasize that the analyses in this section are not affected by the assumption about the relation between the $^{56}$Ni mass and the peak luminosity of SESNe.$^{10}$

5. Method of Mock Observations

In the following sections, we conduct mock observations of SESNe and investigate the effect of observational bias on the $^{56}$Ni mass distribution of detected SESNe. In the previous sections, we found that the $^{56}$Ni mass distribution in our SNe II

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$^{10}$ We note, however, that Meza & Anderson (2020) have shown that the statistical difference of $^{56}$Ni mass between SESNe and SNe II remains even if they take relatively close samples ($\approx 40$–$50$ Mpc), which is also confirmed by our analyses (Figures 3 and 4). Thus, the observational bias alone may not be sufficient to explain all of the statistical difference in the $^{56}$Ni mass (Section 7).
sample is not notably suffering from the observational bias. Therefore, below, we start additional analysis based on the following two working hypotheses: (1) The $^{56}\text{Ni}$ mass distribution in our SNe II sample (LS-SNe II) represents the intrinsic $^{56}\text{Ni}$ mass distribution of SNe II, and (2) SESNe have the same intrinsic $^{56}\text{Ni}$ mass distribution as that of SNe II. The second assumption is based on the hypothesis that assuming a binary origin for SESNe, progenitors of SESNe and SNe II are expected to share a similar range in the initial mass (see Section 1). Based on these hypotheses, we conduct mock observations of SESNe. In the rest of this section, we describe the procedure of the mock observation in more detail.

### 5.1. $^{56}\text{Ni}$ Mass Distribution

As noted above, here we assume that the intrinsic $^{56}\text{Ni}$ mass distribution of SESNe is the same as the $^{56}\text{Ni}$ mass distribution of LS-SNe II. To simplify the numerical analyses, we fit the cumulative histogram of $^{56}\text{Ni}$ mass (denoted here as $f(x)$) by the function of $f(x) = \tanh (a_0 \times x)$, using nonlinear least squares fit. We obtained $a_0 = 14.60$ as the best-fit parameter. The comparison of our fitted curve with our sample is shown in Figure 7. Below, we use the function of $f(x) = \tanh (14.60 \times x)$ to represent the assumed intrinsic $^{56}\text{Ni}$ mass distribution of SESNe.

### 5.2. Simulating the Observations

We simulate one SESN by selecting the $^{56}\text{Ni}$ mass and distance from the given probability distributions. We select a value of $^{56}\text{Ni}$ mass from the distribution derived in Section 5.1. Then, for each $^{56}\text{Ni}$ mass thus derived, the distance is randomly chosen following the probability function of $p \propto \text{distance}^3$, i.e., the volume size. The range of distance is set from zero up to the limiting distance corresponding to the peak luminosity of SESNe with a $^{56}\text{Ni}$ mass of 1.0 $M_\odot$, unless otherwise noted.

For each object with a given $^{56}\text{Ni}$ mass and distance, we decide whether to add it to the detected sample or not based on the following procedure. First, from the given $^{56}\text{Ni}$ mass, we randomly pick a value of $t_p$ based on the distribution, taking into account the dispersion, derived from the fit in Section 3. Combining this value of $t_p$ with the chosen value of $^{56}\text{Ni}$ mass, we can estimate a peak luminosity of SESNe (see Equation (1)). Next, we estimate the limiting distance using Equation (3) for the peak luminosity derived above. If the selected distance is within the observable distance corresponding to its peak luminosity, we consider it to be detected and add it to the detected sample. Otherwise, we consider that the object escapes detection and do not add it to the detected sample. Once the number of detections reaches a specified number, we stop one iteration of the mock observation. Below, the number of detections is set to be 100, unless otherwise noted. The number of 100 is chosen to be consistent with the order of magnitude of our LS-SESN sample size. We iterate the

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Note, however, that there are indications that the progenitors of SESNe may be more massive than SNe II either as an entire class or for the particular SN Ic class (e.g., Anderson et al. 2012; Valenti et al. 2012; Fang et al. 2019).
6. Results of Mock Observation

6.1. Luminosity Function

Here, we show the results of the mock observation described in Section 5. We assume a fixed limiting magnitude of 19 mag in this section. Figure 8 compares the luminosity functions derived from the mock observations to the luminosity function of Meza-SESNe. Here, in order to make the direct comparison to Meza-SESNe, we stop one iteration of mock observation when the number of detected objects reaches 37 (i.e., the Meza-SESNe sample size), not 100. Then, we repeat this $10^3$ times to clarify the possible range of the distributions.

Interestingly, we can see that the luminosity function in the detected samples is shifted to high luminosity compared to the model intrinsic luminosity function. As can be seen from Figure 1, the objects with higher $^{56}$Ni mass, in general, have higher peak luminosity. Thus, they have the larger observable volume and dominate the detected sample. It is also worthwhile to note that the luminosity function of our detected samples in the mock observation roughly explains the observed luminosity function of Meza-SESNe. Especially, the lower cutoff at around $\log L \sim 41.7$ is naturally obtained.

6.2. $^{56}$Ni Mass Distribution

Figure 9 compares the cumulative $^{56}$Ni mass distribution in the detected samples to different data samples. Note that, below, we stop one iteration of mock observation when the number of detect objects reaches 100, unless otherwise noted. The $^{56}$Ni mass distribution in the detected sample of our mock observation is skewed to higher mass compared to the assumed intrinsic distribution. This is due to the observational bias, being consistent with the shift of the luminosity function discussed in the previous section.

To make quantitative comparisons of the different $^{56}$Ni mass distributions, we conducted a Kolmogorov–Smirnov (K-S) statistical test as shown in Table 1. We used the library, *scipy.stats.kstest*, for conducting the K-S statistical test. When we compared the result of the mock observation to a data sample, we set the number of detections for one iteration to be the same as the number of samples being compared to. Then, we took the mean of the $D$ parameter and the $p$ value for $10^3$ iterations. The $p$ value between the result of our mock observation and Meza-SESNe (Arnett) is quite high, being 0.60. This indicates that the $^{56}$Ni mass distribution in Meza-SESNe may be explained by taking into account an observational bias on the intrinsic distribution similar to that of LS-SNe II. Also, this result is consistent with the reasonable match of the $^{56}$Ni mass distribution and luminosity function of our mock observation to Meza-SESNe (Figures 8 and 10).

However, the assumption that the $^{56}$Ni mass distributions from the mock observations and LS-SESNe originate from the same distribution is rejected, with a quite low $p$ value of $5.6 \times 10^{-13}$. Even if we exclude SNe Ic-BL from the sample, the $p$ value is still low, being $5.9 \times 10^{-7}$. One of the possible reasons for this is that our assumption for the intrinsic $^{56}$Ni distribution (Section 5.1) may have been too simplistic. Indeed, from the intrinsic $^{56}$Ni mass distribution we assumed, a high value of $^{56}$Ni mass (≥ 0.2 $M_\odot$) is rarely produced, while such high values are found in LS-SESNe (Figure 9). Another possible reason is that while our mock observation is based on the Arnett rule (Section 3.1), which is the same method used in Meza-SESNe (Arnett), the LS-SESNe consists of the $^{56}$Ni masses estimated by various kinds of methods. Thus, direct comparison of our mock observation to LS-SESNe may not be appropriate.

In short, the $^{56}$Ni mass distribution taking into account an observational bias is consistent with the well-observed sample of Meza-SESNe. However, further explanation is needed for the discrepancy between our mock observation and a larger sample of LS-SESNe. Indeed, the difference between the two samples, Meza-SESNe and LS-SESNe, is intriguing. It suggests that the $^{56}$Ni mass distribution of SESNe is dependent on how the sample is constructed; the different samples may thus be contaminated by different degrees of possible observational biases.

6.3. Effect of Different Limiting Magnitudes

In the previous section, we assumed a limiting magnitude of $V_{\text{lim}} = 19$ mag. Next, we will see how the different values of the limiting magnitudes affect our results. In the left panel of Figure 10, we show the $^{56}$Ni mass distribution of the detected samples in the mock observation for the different limiting magnitudes. We can see that the $^{56}$Ni mass distribution is quite insensitive to the different values of the limiting magnitudes. This can be explained as follows. The $^{56}$Ni mass distribution in the observed sample can be derived by multiplying the assumed intrinsic distribution of $^{56}$Ni mass by the observable volume, i.e., $D_{\text{lim}}(M_{\text{Ni}})^3$. Here, $D_{\text{lim}}(M_{\text{Ni}})$ is the limiting distance calculated using Equation (3). It can be seen that the term of $V_{\text{lim}}$ only changes the scale of the $^{56}$Ni mass distribution, but does not affect the normalized distribution. Note that this apparently counterintuitive result is obtained because we consider a magnitude-limited sample here. For comparison, in the right panel of Figure 10, we show the results of mock observations, assuming the outer boundary of all the events is 80 Mpc. This constructs the volume-limited samples. In this case, the cumulative distribution of $^{56}$Ni mass...
Figure 9. Left: the $^{56}$Ni mass distribution in the detected sample of our mock observation (green) is compared to the different samples, excluding SNe Ic-BL. The green-solid line represents the mean distribution of the mock observation with the $10^3$ iterations (and 100 detected objects in one interaction), assuming the limiting magnitude of 19 mag. The shaded region represents the standard deviation obtained with $10^3$ iterations. Blue- and cyan-dotted lines denote the Arnett mass and tail mass in Meza-SESNe, while the red-dotted line denotes the LS-SESNe. Right: the $^{56}$Ni mass distribution, excluding SNe Ic-BL (dotted) and including SNe Ic-BL (solid) are compared for the different samples.

Table 1

| SN Distributions (Number of Samples) | $D$  | $p$  |
|--------------------------------------|------|------|
| LS-SNe II (115), LS-SESNe (187)      | 0.690| $3.4 \times 10^{-34}$ |
| LS-SESNe (187), Meza-SESNe (37)      | 0.453| $2.6 \times 10^{-6}$  |
| LS-SNe II (115), mock                | 0.472| $1.5 \times 10^{-9}$  |
| LS-SESNe (187), mock                 | 0.433| $5.6 \times 10^{-11}$ |
| LS-SESNe (w/o Ic-BL; 131), mock      | 0.317| $5.9 \times 10^{-5}$  |
| Meza (Arnett, 37), mock              | 0.182| 0.60 |
| Meza (Arnett, w/o Ic-BL; 33), mock   | 0.220| 0.46 |
| Meza (tail; 20), mock                | 0.462| $6.7 \times 10^{-2}$  |
| Meza (tail, w/o Ic-BL; 18), mock     | 0.523| $3.9 \times 10^{-2}$  |

Note. In the first column, the two distributions being compared are listed together with the number of samples in brackets. In the second column, the $D$ parameter is given, while in the last column the $p$ value is presented. *Mock* means the result of the mock observation assuming a limiting magnitude of $V_{\text{lim}} = 19$ mag. Here, the number of the simulated objects in one iteration is set to be the same as the size of the sample with which the mock observation is compared. The $D$ and $p$ for mock are the mean values computed with the $10^3$ iterations.

In order to compare our results to Figure 4, i.e., the average $^{56}$Ni mass for the volume-limited samples of different sizes, we conduct an additional analysis as follows. We set the number of detections to be $10^3$ (not 100) and repeat the mock observation conducted above. For this larger sample, we investigate how the cumulative $^{56}$Ni mass distribution changes for the different values of distance cuts. In Figure 13, we show the results of such an analysis. The right panel of Figure 13 shows that the average $^{56}$Ni mass decreases as the distance cut is decreased, just like as shown in Figure 4. This behavior can be understood as follows. As seen in Figures 8 and 10, the average peak luminosity of the detected samples in a magnitude-limiting sample is a few $10^{47}$ erg s$^{-1}$ (i.e., $M_{^{56}Ni} \sim 0.1 M_e$), irrespective of the values of limiting magnitude. However, those dominant objects are detected at different distances depending on the limiting magnitudes. Actually, Figure 11 shows that such dominant objects are found at $\sim 30$–$40$ Mpc for $V_{\text{lim}} = 17$ mag, while they are found at $\sim 100$ Mpc for $V_{\text{lim}} = 19$ mag. Thus, if we consider a sufficiently large volume-limited sample, then, the average $^{56}$Ni mass becomes $\sim 0.1 M_e$. However, if we consider a distance cut smaller than a value (e.g., $\sim 100$ Mpc for $V_{\text{lim}} = 19$ mag), then, part of the dominant objects in a magnitude-limited sample would be missed and the average $^{56}$Ni mass starts to decrease.

Here, it is crucial to mention that the right panel of Figure 13 does not perfectly match Figure 4. It is true that the decrease of average $^{56}$Ni mass for SESNe at $\sim 100$ Mpc can be seen in Figure 4, just as in Figure 13. However, Figure 13 implies that the average $^{56}$Ni mass should decrease down to $\sim 0.05 M_e$ at sufficiently small distance ($\lesssim 100$ Mpc), which is not the case in Figure 4. These results imply either that an observational bias alone may not be sufficient to explain the different $^{56}$Ni mass between SESNe and SNe II or that the objects with low $^{56}$Ni mass may escape detection due to other reasons (see Section 7.2). Still, our result here suggests that an observational bias is likely to be present at least for high $^{56}$Ni masses, and one needs to consider this when discussing the $^{56}$Ni mass distribution of SESNe.

6.4. Effects of Different Observational Cadences

So far, we implicitly assumed an infinitely small observational cadence in the mock observation. This means that an

approaches to the intrinsic one as the limiting magnitude is set larger, which is consistent with our intuition.

In Figure 11, we show the distance distribution of the detected samples in the mock observation for the different limiting magnitudes. We can see that the distance distribution is sensitive to the different values of the limiting magnitude. The higher the limiting magnitude is, the larger the observable volume becomes. Thus, the more distant objects dominate the observed sample.

In the right panel of Figure 12, the $^{56}$Ni masses and distances of the detected samples for the different limiting magnitudes are overplotted onto Figure 2. As discussed above, the objects with low $^{56}$Ni mass are lacking compared to the assumed intrinsic distribution, which is consistent with the data samples. However, our predictions from the mock observations fail to explain the high $^{56}$Ni masses of $\geq 0.2 M_e$ (mostly SNe Ic-BL) that exist in the data samples collected from the published literature, as already noted in Section 6.2. We will discuss this issue in Section 7.3.
The 56Ni mass distribution of LS-SNe II is shown with a gray line. Right: the same lines refer to the limiting magnitude of 17, 19, and 21 mag, respectively. Each line is the mean of the distributions derived with $10^3$ iterations. For reference, the observational timescale is set larger. This happens because some objects may be missed due to infrequent observations, even if the peak luminosity exceeds the observational limiting magnitudes. Therefore, here we attempt to take this into account. Following this, we investigate how the different observational cadences affect our results. We fix the limiting magnitude as 19.0 mag in this section for simplicity.

To proceed with this investigation, we take a simplified approach. We assume that the peak luminosity is maintained for the duration of $t_p$ calculated using Equation (2). In the mock observation, we add a procedure as follows, in order to decide whether an object is detected or not: if the duration of the event is less than the observational cadence, we add it to the observed sample with the probability of $p = t_p / t_{\text{cadence}}$. If the duration of the event is longer than the observational cadence, we consider the object is detected and add it to the observed sample.

Figure 14 compares the 56Ni mass distribution of the detected samples for the different observational cadences. It is seen that the cumulative distribution shifts to higher mass, as the observational cadence is set larger. This happens because an object with relatively low 56Ni mass tends to escape the detection for a large observational cadence, due to its short timescale. However, the difference seen in the 56Ni mass distributions is almost negligible. Thus, we conclude that our results are robust to the different assumptions about the observational cadences.

Note, however, that our assumption that a peak luminosity maintains for $t_p$ is quite simplistic. Thus, although our discussion clarifies the qualitative effect of observational cadence, we do not consider that it has a quantitative predictive power. Also, this investigation is based on the linear fitting (Equation (2)). This fitting is done using the samples with 56Ni masses above 0.03 $M_\odot$, and the validity of the linear extrapolation to the lower 56Ni masses is not trivial (see Section 7).

7. Discussion

In this section, we first discuss some caveats about our analyses presented above. Next, we discuss the lack of low 56Ni mass objects ($\lesssim 0.02 M_\odot$) in the literature. Then, we discuss the high 56Ni mass ($\gtrsim 0.2 M_\odot$) objects that are not explained by our model.

7.1. Caveats

In Section 4, we found that the 56Ni masses of SESN samples collected from the published literature suffer from notable observational bias, while those of SNe II samples suffer from much less bias. This may be because (1) SNe II samples are collected at closer distances compared to SESN samples (Figure 5), meaning that the former suffers less bias; or (2) the luminosity of SESNe have higher dependence on the 56Ni mass than SNe II. Indeed, the peak luminosity of SESNe is theoretically expected to follow $L_{\text{peak}} \propto M_{\text{Ni}}$ (Arnett 1982), while the mid-plateau luminosity of SNe II is phenomenologically known to follow $L_{\text{plateau}} \propto M_{\text{Ni,65}}$ (Pejcha & Prieto 2015). Moreover, at the early phase, SNe II generally have higher luminosity than the mid-plateau phase. Thus, the detectability of SNe II is much less affected by the 56Ni mass than SESNe.

We have assumed that SESNe share the same 56Ni mass distribution as SNe II. However, as noted in Section 1, there are several indications that at least a fraction of SESN progenitors may be more massive than those of SNe II (e.g., Anderson et al. 2012; Maund 2018; Fang et al. 2019). This allows the...
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The possibility that SESNe indeed have higher $^{56}\text{Ni}$ mass than SNe II in general. If this is the case, then the $^{56}\text{Ni}$ mass distribution from the mock observation would shift to even higher mass with the observational bias effect found in this paper. It may then match with the LS-SESN samples better.

The results derived in Section 6 are based on the fitting relation for $t_p$, as a function of $^{56}\text{Ni}$ mass (Equation (2)). These $^{56}\text{Ni}$ masses have been derived using the Arnett rule, which has been claimed to overestimate the value by a factor of a few (Dessart et al. 2016; Khatami & Kasen 2019). In Appendix B, we have shown that even if the $^{56}\text{Ni}$ mass derived from tail luminosity for deriving the $t_p-M_{\text{Ni}}$ relation, our main results do not change notably. Thus, our results in Section 6 are not affected by the methods for deriving the $^{56}\text{Ni}$ mass.

For the mock observation, we assumed zero both for $A_r$ and $B_C$. In reality, nonzero values of $A_r$ and $B_C$ would shift the observable distance for a given limiting magnitude. While the effect of the $B_C$ is probably not large given that their colors are similar around the peak, the extinction may be systematically different between SNe II and SESNe; the latter are typically associated with a more active star-forming region (Anderson et al. 2012). If we would assume a larger value for $A_r$, for SESNe, the limiting distance for SESNe will be decreased and the effect of the observational bias investigated in this paper will become even more substantial.

Throughout the paper, we have contrasted the SNe II to SESNe in general. Anderson (2019) has suggested that there may be difference in the $^{56}\text{Ni}$ mass distribution even among the different types of SESNe. Especially, SNe Iib seem to have smaller $^{56}\text{Ni}$ masses than SNe Ib/Ic. One possible observational bias that might explain this behavior is that SNe Iib can be detected more easily than SNe Ib/Ic due to their cooling emission. However, quantitatively investigating this possibility is beyond the scope of this paper.

7.2. Low $^{56}\text{Ni}$ Mass Objects

We have conducted mock observations and shown that if we assume that the intrinsic $^{56}\text{Ni}$ mass distribution of SESNe is the same as that of LS-SNe II, the $^{56}\text{Ni}$ mass distribution of SESNe in the detected samples becomes more massive compared to the assumed intrinsic distribution; the resulting distribution is found to be very close to the distribution of Meza-SESNe. This indicates that even if a significant number of SESNe with low $^{56}\text{Ni}$ masses (i.e., similar to those found in the SNe II samples) existed, we would find difficulty in detecting them and thus they would be significantly underrepresented in the current literature samples.

However, some problems still remain to be solved. It is true that our mock observations predict that the detection of SESNe is dominated by relatively luminous objects. This would predict that there should be at least a few SESNe with a low $^{56}\text{Ni}$ mass, $M_{\text{Ni}} \lesssim 0.02 M_\odot$, especially at small distances, considering that many SNe II with such low $^{56}\text{Ni}$ masses have been detected and that the observed fraction of SESNe to that of SNe II is 0.52 (Li et al. 2011). However, in our samples, very few SESNe have been found with such a low $^{56}\text{Ni}$ mass. Of course, it may indicate that SESNe with such low $^{56}\text{Ni}$ masses actually do not exist and the statistical difference in $^{56}\text{Ni}$ mass between SESNe and SNe II is real. However, it is also possible that the SESNe with low $^{56}\text{Ni}$ masses would not appear as canonical SESNe but instead appear as peculiar objects, and therefore they may not be labeled as SESNe and thus missing in the present SESN samples.

First, such low- $^{56}\text{Ni}$ mass SESNe may be related to the so-called rapidly evolving transients. As shown in Figure 15, there

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13 The colors of SNe II in the plateau (e.g., de Jaeger et al. 2019) are similar to those of SESNe around the peak (e.g., Drout et al. 2011), and $B_C$ is nearly the same for a given color between SNe II and SESNe (Lyman et al. 2016).

Figure 12. Left: the $^{56}\text{Ni}$ mass and distance of the detected samples in one iteration (i.e., 100 detections) for the limiting magnitudes of 19 mag. Gray points are all the events that were randomly picked until the number of detections reached 100. For reference, the limiting distance for a given $^{56}\text{Ni}$ mass estimated as in Section 3 is also shown assuming the limiting magnitudes of 19 (green) and 25 (red) mag. The latter represents the limiting magnitude for the single-visit depth in LSST (Ivezić et al. 2019). Right: the $^{56}\text{Ni}$ mass and distance of the detected samples in one iteration for the different limiting magnitudes. Blue, green, and orange points refer to the case of limiting magnitude of 17, 19, and 21 mag, respectively. We add the USSN candidates with magenta-star symbols (see Section 7 for a discussion of these events). The references for USSNe are listed at the end of the manuscript. The limiting distance for a given $^{56}\text{Ni}$ mass estimated as in Section 3 is also shown assuming the different limiting magnitudes.
is a hint that the $^{56}$Ni mass and the timescale of SESNe are positively correlated. Thus, SESNe with lower $^{56}$Ni mass are expected to have shorter timescales. Also shown in Figure 15 are USSN candidates. Taking these objects into account, the timescale of SESNe may decrease more rapidly than our prediction (Figure 15). Thus, our linear fit (Section 3.1) may not be valid at small $^{56}$Ni masses, and it is possible that SESNe with a low $^{56}$Ni mass ($\lesssim 0.02 M_\odot$) are observed as rapidly evolving transients with timescales shorter than 10 days.\footnote{Note, that some of the rapidly evolving transient are known to be difficult to explain by only considering the radioactive decay model (e.g., Drout et al. 2014). However, the properties of the rapidly evolving transients are diverse (Pursiainen et al. 2018) and there are many that are compatible with the radioactive decay scenario. Indeed, a recent compilation of the rapid transients found by the ZTF shows that this population is indeed largely contaminated by rapidly evolving SESNe (Ho et al. 2021).}

Actually, SN 2017czd in our sample is an SN IIb with very small $^{56}$Ni mass of 0.003 $M_\odot$. This object was classified as a rapidly evolving transient (Nakaoka et al. 2019). Drout et al. (2014) estimated that the rate of rapidly evolving transients is 4\%–7\% of the core collapse SN rate. Since the fraction of SESNe in the core collapse SNe is 36.6\% (Smith et al. 2011), the rapidly evolving transients occupy 11\%–19\% of SESNe. This number is comparable to the fraction of SESNe with $M_{\text{Ni}} \lesssim 0.01 M_\odot$, assuming the same $^{56}$Ni mass distribution as LS-SNe II. Since the events with short timescales ($\lesssim 10$ days) can be easily missed, this hypothesis may be consistent with the lack of SESNe with low $^{56}$Ni masses ($\lesssim 0.02 M_\odot$).\footnote{Note, that most of the rapidly evolving transient discovered so far have $^{56}$Ni mass of $\lesssim 0.03 M_\odot$ (Drout et al. 2014; Pursiainen et al. 2018; Tampo et al. 2020). However, considering that the number of samples detected so far is limited (\approx 100) (Pursiainen et al. 2018), it is natural that they are dominated by the relatively luminous objects as we have shown in Section 6.}

The SESNe with low $^{56}$Ni mass may also originate from the so-called USSNe. Actually, the ejecta mass and $^{56}$Ni mass of SESNe are known to be positively correlated (Lyman et al. 2016). Thus, the ejecta mass of the SESNe with low $^{56}$Ni mass are expected to be small. In Figure 12, the USSN candidates are also shown. They have $^{56}$Ni masses lower than most of our SESN sample. Theoretical calculations also indicate that USSNe should synthesize a quite low $^{56}$Ni of $\sim 0.01 M_\odot$ (Suwa et al. 2015; Moriya et al. 2017). Specifically, SN2019dge, an USSN candidate, has an estimated $^{56}$Ni mass of 0.017 $M_\odot$ (Yao et al. 2020), which is quite low. The rate of such events is estimated as 2\%–12\% of core collapse supernova, i.e., 5.6\%–
33.3% of SESNe (Smith et al. 2011). This number is consistent with the fraction of SESNe with $M_{56Ni} \lesssim 0.02$ $M_\odot$ under the distribution we assumed. Furthermore, the timescale of USSN candidates is known to be short (<10 days), which is much less than our prediction (Figure 15). Such short-timescale objects may be systematically non-detected in the existing surveys as noted in the previous paragraph. Note, however, that the $^{56}$Ni masses of USSN candidates discovered so far are in general not too low, i.e., many SNe II have been detected with $^{56}$Ni mass lower than these objects. Therefore, these objects alone may not be sufficient to explain the deficit of SESNe with low $^{56}$Ni mass.

The SESNe with low $^{56}$Ni masses may also have a possible link to SNe Ibn, which are not included in our samples. SNe Ibn are characterized by He emission lines that are considered to originate from the interaction with the He-rich circumstellar material. These objects are shown to eject less $^{56}$Ni than the bulk of other SESNe (Moriya & Maeda 2016). Further, Ho et al. (2021) recently showed that SNe Ibn with short timescale do contaminate the Zwicky Transient Facility (ZTF) rapid transient sample substantially, together with the rapid (non-interacting) SESNe.

When deep surveys like Legacy Survey of Space and Time (LSST) are deployed in the future, we can test our hypotheses. In the left panel of Figure 12, we show the detection limit for a limiting magnitude of 25 mag, representing the single-visit depth in LSST (Ivezić et al. 2019). We can see that basically all the SESNe with low $^{56}$Ni masses ($\lesssim 0.02$ $M_\odot$) are detected if they occur closer than $\approx 100$ Mpc. Thus, we will be able to construct a complete sample of SESNe in the local universe. With such a sample, we can test whether the lack of SESNe with $\lesssim 0.02$ $M_\odot$ is real or not.

### 7.3. High $^{56}$Ni Mass Objects

As previously noted (Figures 9 and 12), our predictions from the mock observations fail to explain the objects with high $^{56}$Ni masses ($\gtrsim 0.2$ $M_\odot$). One of the possible reasons for this is that such objects may indeed represent a different population from other SESNe that does not have a counterpart in SNe II. Indeed, most of those objects are SNe Ic-BL, for which the nature of the progenitor and the explosion has been proposed to be different from canonical SESNe. Actually, in Dessart (2020), they have investigated the individual bright SNe Ib/c objects that have log $L_p > 42.6$ erg s$^{-1}$ and concluded that they are either peculiar events, like SNe Ib/c or GRB/SNe, or were given an overestimated reddening. Thus, our analyses may not be applicable to these objects. Note, however, that Sollerman et al. (2021) have recently shown that normal SESNe do sometimes reach log $L_p > 42.6$ erg s$^{-1}$ by collecting a sample of normal SNe Ib/c from Zwicky Transient Survey (ZTF) with the strict selection criteria. Another possible reason is that our assumption about the intrinsic $^{56}$Ni mass distribution (Section 5.1) may be too simplistic. Indeed, the intrinsic $^{56}$Ni mass distribution we assumed rarely produces such a high value of $^{56}$Ni mass ($\gtrsim 0.2$ $M_\odot$). Yet another possibility is that the different amounts of the hydrogen-rich envelope may indeed affect the $^{56}$Ni production, even though the core structure would be similar between SNe II and SESNe: SNe II have the thick hydrogen envelope outside the He core, and the shock is decelerated while it is propagating through the envelope. Thus, it is expected that SNe II suffer from a fallback of the inner material, including $^{56}$Ni, more substantially than SESNe. In this case, the $^{56}$Ni mass distribution of SNe II we used may provide a lower limit for SESNe (S. Sawada et al., in preparation).

### 8. Conclusions

The nuclear decay of $^{56}$Ni is one of the most important power sources of SNe. Recent works have indicated that the $^{56}$Ni masses estimated for SESNe are systematically higher than those estimated for SNe II. Although this may indicate a distinct progenitor structure or explosion mechanism between these types of SNe, the possibility remains that this may be caused by observational biases.

By investigating the distributions of $^{56}$Ni mass and distance for the data samples collected from the literature, we found that SESN samples suffer from significant observational bias; objects with low $^{56}$Ni masses may be systematically missed, especially at larger distances. Thus, this work has elucidated that observational bias must be taken into account in discussing the different $^{56}$Ni masses between SNe II and SESNe.

We also conducted mock observations assuming that the intrinsic $^{56}$Ni mass distribution of SESNe is the same as the $^{56}$Ni mass distribution of SNe II collected from the literature. We have found that the $^{56}$Ni distribution for the detected samples of SESNe becomes more massive compared to the assumed intrinsic distribution due to the observational bias. This result may, at least partially, explain the lack of low $^{56}$Ni mass objects in the data sample of SESNe collected from the literature. Although this result relies on the assumption noted above, this supports that at least a part of the systematically different $^{56}$Ni masses between these types of SNe are due to observational bias.

We emphasize, however, that the SESNe with low $^{56}$Ni mass ($\lesssim 0.02$ $M_\odot$) are still lacking even at small distances ($\lesssim 30$ Mpc). This may indicate that observational bias alone may not be sufficient to explain all of the statistical difference between SESNe and SNe II. Another possibility is that SESNe with low $^{56}$Ni mass appear as either rapidly evolving transients or USNNe, which are difficult to detect due to their short timescales.

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### Appendix A

#### Newly Added Reference List for $^{56}$Ni Masses

Below, the newly added references to the reference list in Anderson (2019) are listed. SNe II: Utrobin & Chugai (2011), Bose et al. (2018), Lisakov (2018), Singh et al. (2018), Singh

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15 Although there are many objects with $M_{56Ni} \lesssim 10^{-3}$ $M_\odot$, as shown in the left panel of Figure 12, they are considered to be an artifact caused by an analytical fitting to the distribution, considering that there are no such objects in LS-SNe II (Section 7).

16 Among those objects with high $^{56}$Ni masses ($\gtrsim 0.2$ $M_\odot$), there are several objects that are not SNe Ic-BL (Figure 12). A possible reason why they are not classified as SNe Ic-BL is that they are highly off-axis, considering that SNe Ic-BL often have a jet-like structure (Valenti et al. 2008).
Appendix B

The Case When Using Tail Luminosity to Derive $^{56}$Ni Masses

The results derived in Section 6 are based on the fitting relation for $t_p$ as a function of $^{56}$Ni mass (Equation (2)). The $^{56}$Ni mass used for the fit has been derived using the Arnett rule, which has been claimed to have an uncertainty of a factor of a few. An alternative method to derive a $^{56}$Ni mass is to use a tail luminosity, as shown in the right panel of Figure 16. Then, from this relation thus derived, we use Equation (1) and calculate the peak luminosity as a function of $^{56}$Ni mass, propagating the errors. Since the tail mass gives the lower limit to the actual value, the peak luminosity calculated from it should be lower than the observed value. This is indeed the case, as shown in the right panel of Figure 16.

In Figure 17, we compare the luminosity function and $^{56}$Ni mass distribution for the cases of using the tail mass and the Arnett mass. The $^{56}$Ni masses for the tail mass case are slightly higher than those in the case of the Arnett mass. However, it can be seen that the difference in the luminosity function and the $^{56}$Ni mass distribution between these two cases is nearly indistinguishable.

From these analyses, we conclude that our results in Section 6 are robust to the different methods of deriving $^{56}$Ni mass. It is true that several works model the incomplete $\gamma$-ray trapping when using the tail luminosity of SESNe (Afsariardchi et al. 2021; Sharon & Kushnir 2020). Since the $^{56}$Ni masses derived from such methods typically lie between tail mass and Arnett mass (Sharon & Kushnir 2020), the effect of using such methods on the mock observation is covered by our discussion of the two cases above (i.e., Arnett mass and tail mass).

Figure 16. The same figure as Figure 1, except that we use the tail mass for the fit and plots.
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