Supernova follow-up strategy for IceCube neutrino events

Masaomi Tanaka (Tohoku University) on behalf of Subaru/HSC transient WG

Yasuda, MT, Tominaga+19, arXiv:1904.09697
Why supernovae (SNe)?  See talks by Xiang-Yu Wang and Zhuo Li

Blazars’ contribution to the diffuse neutrino flux

**Figure 4.**

- **2LAC Blazar Upper Limit**
  - $\Gamma_{SI} = -2.5, E_\nu > 10$ TeV
  - $\Gamma_{SI} = -2.2, E_\nu > 10$ TeV

**Table 3**

<table>
<thead>
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<th>Blazar Class</th>
<th>LSP-BL Lacs</th>
<th>ISPs</th>
<th>FSRQs</th>
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Supernova with chocked jet?

=> Observed as low-luminosity gamma-ray bursts (GRBs)?
=> Special type of supernovae?

See talks by Xiang-Yu Wang and Zhuo Li

Murase & Ioka 2013
\textbf{“Broad-line” supernovae}

\begin{itemize}
  \item GRB 980425/SN 1998bw
  \item Si II
  \item O I Ca II
  \item SN 1994I
  \item \(~20,000 \text{ km/s}\)
  \item \(~7,000 \text{ km/s}\)
\end{itemize}

\begin{itemize}
  \item Ic-BL
  \item Ic
  \item Ib
  \item IIb
  \item II-87A
  \item \(\text{II}\)
\end{itemize}

\textbf{Shivvers et al. 2017}

\textbf{\~1}\% of core-collapse SNe

\textbf{c.f. Long GRBs (\~0.1 \% of core-collapse SNe)}
Can we conclude that such SNe are the origin of IceCube neutrinos?

We need to
- identify certain types of SNe in the localization area
- exclude a chance coincidence
Electromagnetic emission from supernovae

UV-optical-infrared

Broad-line SN

$10^{43}$ erg s$^{-1}$

$10^{42}$ erg s$^{-1}$

$10^{41}$ erg s$^{-1}$

Days after the explosion

Absolute magnitude
Magnitude

\[ m = -2.5 \log_{10}(F_\nu) - 48.6 \]

\[ = -2.5 \log_{10}\left( \frac{F_\nu}{3631 \times 10^{-23} \text{ erg s}^{-1} \text{ Hz}^{-1} \text{ cm}^{-2}} \right) \]

*Absolute magnitude: magnitude at 10 pc distance

Required size (diameter) of telescopes

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<td>1m</td>
<td>2m</td>
<td>8m</td>
<td>30m</td>
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Spectroscopy

| 1m | 2m | 8m | 30m |

TXS 0506+056

TXS 0506+056

TXS 0506+056
Challenges in identifying SNe as neutrino sources

- Limits on short transients.
- Limits on longer lasting transients.

Fig. 7: Flux upper limits from the multiwavelength observations. The confidence level varies between the different observations as indicated in the legend and some limits depend on the assumed source spectrum (Swift XRT and BAT = 2 and Fermi LAT = 2.1; see Sect. 4). For the optical telescopes, the limit corresponding to the deepest observation is shown, while for the other instruments, all analyzed data were combined. The limit for the Swift BAT is purely based on the observation taken 100 s after the detection of the first neutrino (compare Sect. 4.2.1) and hence applies to prompt gamma-ray emission. Follow-up observations were triggered 22 h after the detection of the neutrino triplet.

We simulate a population of transient neutrino sources that accounts for the complete astrophysical neutrino flux. The cosmic star-formation rate approximately describes the redshift distributions of several potential neutrino sources, like CC-SNe (Cappellaro et al. 2015) and GRBs (Wanderman & Piran 2010; Salvaterra et al. 2012; Krühler et al. 2015) which however tend to be located at slightly larger redshifts. We simulated a source population using the star-formation rate of Madau & Dickinson (2014) and calculated for each source the probability of detecting it with a certain number of neutrinos after applying the event selection of the follow-up program. We find that a source detected with a single neutrino is located at a median redshift of \( z = 1.1 \), as shown in Fig. 8.

To calculate the distance to a source detected with multiple neutrinos, we have to simulate how bright the individual sources are. We assume a population with a local source rate of \( 10^{6} \) Mpc \(^{-3} \) yr\(^{-1} \), which corresponds to \( \sim 1\% \) of the CCSN rate (see e.g., Strolger et al. 2015). If this population accounts for the astrophysical neutrino flux, we expect the detection of one neutrino triplet (or higher multiplet) per year. The rate of multiplet alerts, however, strongly depends on the spectral shape and considered energy range of the neutrino flux. We further assumed that the luminosity fluctuations between the neutrino sources follow a log-normal distribution with a width of one astronomical magnitude, which is comparable to the luminosity spread of CC-SNe in optical light at optical wavelengths.

Figure 8 shows that the source of a neutrino doublet has a median redshift of \( z = 0.06 \) and the median redshift of a triplet source is \( z = 0.02 \). We note that these results strongly depend on the spectral shape of the astrophysical neutrino flux. Considering only neutrino events with an energy above 10 TeV, the source rate that yields one triplet per year is \( \sim 3 \times 10^{8} \) Mpc \(^{-3} \) yr\(^{-1} \).
Strategy for multiplet event is straightforward

IceCube-160217 (triplet, $z \sim< 0.05$)

*32% probability of a chance alignment of background

Number of unrelated SNe in 1 degree at 100 Mpc $\sim 0.05$
Strategy for singlet event

~ 26 mag if SN is the counterpart => need 8m class telescope
104 CCDs
\sim 900 \text{ Mpix}

2 \text{ GB/image}
\sim 300 \text{ GB/night}

Subaru/Hyper Suprime-Cam
Subaru HSC transient surveys (~26 mag sensitivity)

Fig. 14. Images of SN candidates at various redshifts. Redshifts are spec-z, except for HSC17aydg (HSC photo-z) and HSC16adga (COSMOS photo-z). Three panels are shown for an SN: reference (left), new image (middle), and subtracted image (right). Three filter-bands (r2-, i2-, and z-bands) make up this color composite.

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nearby and distant SNe, up to redshift 1. Available ultraviolet (UV) spectra from the International Ultraviolet Explorer (IUE) are also included. The model is valid in the spectral range of 2,500−8,000 Å. The public version of the SALT2 package provides light curve fitting algorithms based on this model. Light curve fitters can estimate $T_{\text{max}}$ (time of peak brightness in the $B$-band), redshift, $c$ (the SN color parameter of the model), $x_0$ (the flux scale or luminosity distance), and $x_1$ (the light curve shape parameter of the model) to fit the observed multi-band photometric data by minimizing $\chi^2$.

A commonly used fitting tool, `snfit`, fixes the redshift to a given value, allowing the other four parameters to be determined. Another fitter, `snphotoz`, fits all parameters. At the first stage of `snphotoz`, both $c$ and $x_1$ are fixed to 0 (mean values of SN Ia), and then the redshift is scanned to find the minimum $\chi^2$ value. This redshift is then used as an initial value for a full parameter fit. One may question the validity of using the SALT2 model at a redshift beyond 1. Balland et al. (2018) found no evidence of redshift evolution from Very Large Telescope (VLT) spectra of SNe Ia below a redshift of 1.0. There has been no observational study clearly showing the evolution of SN Ia beyond redshift 1, mainly because the observations are limited by the faintness of the objects. In this paper, we simply assume that the SALT2 model is valid beyond redshift 1.

For all SNe, we ran `snfit` by constraining the redshift to the best available redshift. For SNe that do not associate with a clear host galaxy (hostless), or which have only photometric redshifts from HSC broad-band photometry, we also ran `snphotoz` to estimate both the redshift and light curve parameters. For both `snfit` and `snphotoz`, we added a option "-w2500 8000" to use a wider wavelength range. When the reduced $\chi^2$ of `snphotoz` was less than 70% of the reduced $\chi^2$ of `snfit`, we adopted the result of `snphotoz`. Note that the $y$-band images suffer from scattered light, and some of the objects are affected by imperfect correction (Aihara et al. 2018b).
~1800 SNe in 0.5 yr (~6 deg$^2$)

Fig. 1. Pointing layout on the sky (Ultra-Deep : blue (solid), Deep : blue (dashed), Original COSMOS (Scoville et al. 2007) coverage : green (dash dot)) overlaid on SFD (Schlegel et al. 1998) reddening map. Positions of detected SN candidates are indicated by red points. Since we are dithering around fiducial pointings, actual coverage is a bit wider than dashed blue line and some SN candidates are detected in those areas.

The difference imaging has been done for each warped images and warped difference images are coadded to make deep difference images for each filter and epoch. With this method we can avoid bad subtraction caused by discrete PSF change at CCD gaps in coadded images. Once difference coadded images are created, we have detected and measured sources on difference coadded images. Based on these sources, transient sources are identified (see section 2.4 for details) and forced photometry have been done at the location of transients for images of all filters and epochs. The location of transients has been defined as a direct mean position of detected images.

2.3 Limiting magnitude/Detection efficiency

To estimate the limiting magnitude of each epoch images, we have injected artificial stars with magnitudes between 24 and 28 mag in processed CCD images (CORR file in the HSC pipeline world). The 5

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~50 SNe / deg$^2$ / 1 visit

(c.f. ~500,000 objects / deg$^2$)
In this section, we examine the properties of objects classified as SN. Figure 12 shows the distribution of observed $i$-band magnitudes at the peak. Here “peak” refers to the brightest magnitude within the observation and not the result of light curve fitting. For the “SNe Ia” sample described below, the difference between this “peak” magnitude and the peak magnitude obtained from the light curve fit shows a 0.08–0.15-mag offset (the “peak” magnitude is fainter) and a 0.08–0.15-mag scatter. A majority of our samples exhibit 24.0–25.5 mag at the peak, with a tail to 26.0–27.0 mag. Thus, the HSC-SSP transient survey is among the deepest transient surveys (see also Figure 1), detecting a larger number of SNe than SN surveys with the HST (Dawson et al. 2009; Rodney et al. 2014; Graur et al. 2014).

With deep depth, these transients are located at high redshifts. By virtue of the rich dataset in the COSMOS field, 207 and 371 SN candidates have spectroscopic redshifts (hereafter, spec-z) and COSMOS2015 photometric redshifts (COSMOS photo-z), respectively, by identifying potential host galaxies of the SN candidates. Figure 13 shows the redshift distribution of these 578 objects. The distribution has a median of $z=0.85$; 187 objects (32%) are located at $z>1$. Image sources for examples in each redshift range are displayed in Figure 14. For 141 of the SN candidates, we were unable to identify a clear host galaxy. A detailed analysis of hostless samples will be described in a separate paper.

For classification of SNe Ia and other types of SNe, we applied the SALT2 light curve fitter (Guy et al. 2007) to our SN sample. SALT2 is an empirical model of SN Ia’s spectro-photometric evolution over time. The model is constructed using a large data set that includes light curves and spectra of both Typical redshift range of singlet event

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How many supernovae in 1 visit (26 mag)?

\[ N \sim RV \Delta t f_\Omega \sim 10 \left( \frac{R}{10^5 \text{ Gpc}^{-3} \text{ yr}^{-1}} \right) \left( \frac{V}{100 \text{ Gpc}^3} \right) \left( \frac{\Delta t}{20 \text{ days}} \right) \left( \frac{\Omega}{1 \text{ deg}^2} \right) \]

<table>
<thead>
<tr>
<th>Type</th>
<th>( M_{\text{abs}} ) (mag)</th>
<th>( z_{\text{max}} )</th>
<th>( \Delta t ) (days)</th>
<th>Local rate (Gpc(^{-3}) yr(^{-1}))</th>
<th>( N ) (deg(^{-2}))</th>
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<td>Ia</td>
<td>-19</td>
<td>1.3</td>
<td>20</td>
<td>0.3 \times 10^5</td>
<td>10 - 30</td>
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<td>II (H-rich)</td>
<td>-17</td>
<td>0.7</td>
<td>50</td>
<td>0.7 \times 10^5</td>
<td>10 - 30</td>
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<td>IIln (CSM)</td>
<td>-18</td>
<td>1.0</td>
<td>50</td>
<td>0.1 \times 10^5</td>
<td>4 - 12</td>
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<td>Ibc (H-free)</td>
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<td>20</td>
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<tr>
<td>Broad line (hypernova)</td>
<td>-18</td>
<td>1.0</td>
<td>20</td>
<td>0.01 \times 10^5</td>
<td>0.2 - 0.6</td>
</tr>
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For IceCube-170922A
0.15 deg\(^2\) (50 %) and 0.97 deg\(^2\) (90%)

Local rate \( \times 3 \)
How to identify broad-line SNe at z ~ 1?
(among >10 of Type Ia/II SNe)

(1) Photometric classification
Need good time sampling
cadence of 2-3 days
continuous monitoring for ~50 days

Need color information
>= 3 filters
(no redshift information in advance)

(2) Spectroscopic confirmation
Need realtime spectroscopy
Multi-object spectroscopy? (Subaru/PFS)
30m-class telescope (late 2020?)
How to estimate the explosion date?

~5 days uncertainty should remain for objects at z ~ 1

Number of unrelated broad-line SNe in a window of Δt ~ 5 day ~ 0.05-0.15 / deg²

* Contamination becomes higher if neutrino emission lasts longer (dense material around Type IIIn or IIP SNe, see Zhuo Li’s talk)
Summary: strategy to identify SNe as neutrino sources

- **Multiplet events (z < 0.1)**
  - Follow-up with 1-2m telescopes => spectroscopy
  - Low contamination

- **Singlet events (z ~ 1)**
  - Deep observations (~26 mag w/ Subaru/HSC and LSST)
    - High probability, but high contamination
  - Moderate observations (22-24 mag w/ 2-4m class telescopes)
    - Low probability, but low contamination

- **IceCube-Gen2**
  - Better sensitivity => more multiplet
  - Better localization => lower contamination (needs ~0.1 deg)