

Constraining High-Energy Neutrino Emission from Supernovae with IceCube

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ABSTRACT

Core-collapse supernovae are a promising potential high-energy neutrino source class. We test for correlation between seven years of IceCube neutrino data and a catalog containing more than 1000 core-collapse supernovae of types II_n and IIP and a sample of stripped-envelope supernovae. We search both for neutrino emission from individual supernovae, and for combined emission from the whole supernova sample through a stacking analysis.

No significant spatial or temporal correlation of neutrinos with the cataloged supernovae was found. The overall deviation of all tested scenarios from the background expectation yields a p-value of 93% which is fully compatible with background. The derived upper limits on the total energy emitted in neutrinos are 1.7×10^{48} erg for stripped-envelope supernovae, 2.8×10^{48} erg for type IIP, and 1.3×10^{49} erg for type II_n SNe, the latter disfavouring models with optimistic assumptions for neutrino production in interacting supernovae.

We conclude that stripped-envelope supernovae and supernovae of type II_n do not contribute more than 14.6% and 33.9% respectively to the diffuse neutrino flux in the energy range of about $10^3 - 10^5$ GeV, assuming that the neutrino energy spectrum follows a power-law with an index of -2.5 . Under the same assumption, we can only constrain the contribution of type IIP SNe to no more than 59.9%. Thus core-collapse supernovae of types II_n and stripped-envelope supernovae can both be ruled out as the dominant source of the diffuse neutrino flux under the given assumptions.

Keywords: neutrino astronomy, IceCube, core-collapse supernovae

1. INTRODUCTION

IceCube has detected a diffuse flux of high-energy astrophysical neutrinos (Aartsen et al. 2015, 2013). The majority of the high-energy neutrinos follows an isotropic distribution which suggests an extra-galactic origin. The active galaxy NGC 1068 was recently re-

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ported to be the first extra-galactic point-source of high-energy neutrinos beyond the 4σ level (IceCube Collaboration et al. 2022). While there is evidence that gamma-ray blazars and tidal disruption events (TDEs) produce high-energy neutrinos (Aartsen et al. 2018a,b; Stein et al. 2021; Reusch et al. 2022), the rate of observed coincidences constrain the overall diffuse flux contribution of resolved gamma-ray blazars and tidal disruption events to no more than 30% (Aartsen et al. 2017a) and 26% (Stein 2019) respectively, leaving the majority of the diffuse flux unexplained.

In general, high-energy neutrinos are created through interactions of high-energy protons with ambient matter or photon fields. Charged and neutral pions produced in those interactions decay to neutrinos and gamma rays, respectively. While gamma rays can also be produced in leptonic processes such as Inverse Compton scattering, neutrinos are considered to be the clear signature for hadronic interactions, and thus also cosmic-ray acceleration.

Several source classes have been proposed as candidate neutrino (and cosmic-ray) sources. Among the most promising are Active Galactic Nuclei (AGN), Gamma-Ray Bursts (GRBs) and Supernovae (SNe) – see Kura-hashi et al. (2022) for a recent review. While gamma-bright GRBs are strongly disfavored as the main contributor to the measured diffuse neutrino flux (Aartsen et al. 2017b), a large population of nearby low-luminosity bursts could still contribute significantly. The discovery of a connection between GRBs and type Ic-BL SNe implies that (mildly) relativistic jets should also exist in a fraction of core-collapse SNe (Senno et al. 2016; Ando & Beacom 2005; Razzaque et al. 2004; Denton & Tamborra 2018), where such jets might be choked inside the envelope of the star. In this scenario, the gamma rays would be absorbed but the neutrinos could still escape. A short neutrino burst (~ 100 s) would be expected, in coincidence with the explosion time of the SNe (Senno et al. 2016).

Another possibility for producing high-energy neutrinos in core-collapse supernovae (CCSN) is through interactions of the SN ejecta with a dense circumstellar medium (CSM). Strong stellar winds in the star’s late evolution stages or pre-outburst could produce a sufficiently-dense CSM (Ofek et al. 2013; Strotjohann et al. 2021). When the supernova shock front reaches this dense medium, efficient acceleration of charged particles on timescales ranging from a few tens of seconds to ~ 1000 days may occur (Murase et al. 2011; Zirakashvili & Ptuskin 2016; Sarmah et al. 2022). CSM interactions can be revealed through the detection of a combination of narrow and broad emission lines (as observed in type II_n SNe). The narrow component of the spectral lines is produced by circumstellar gas, which is ionised as the shock breaks out of the star. The intermediate and broad components are produced by shocked, high-velocity SN ejecta, arising as a result of the collision of

the ejecta with circumstellar gas. Another indication might be a long plateau in the SN light curve (as seen in Type IIP SNe), which could be partly powered by SN shock breakout interaction with dense CSM (Moriya et al. 2011, 2012). Some IIP SNe show direct observational evidence for interactions (Mauerhan et al. 2013; Faran et al. 2014; Yaron et al. 2017; Nakaoka et al. 2018). Pitik et al. (2022) found the high-energy neutrino IC200530A in spatial coincidence with the optical transient AT2019fdr, which they interpret as a Type II_n superluminous supernova.

Optical follow-up campaigns of IceCube high-energy neutrino alerts (Stein et al. 2022b; Necker et al. 2022) are close to constraining the brightest observed superluminous supernovae.

Here, for the first time, we probe different SN classes as potential neutrino sources and calculate their possible contribution to the observed diffuse neutrino flux. To search for cross-correlation between neutrinos and optically observed SNe, we utilize data recorded by the IceCube Neutrino Observatory.

This paper is organized as follows: Section 2 describes the relevant data sets, followed by a discussion of the analysis methods in Section 3 and the presentation of the results in Section 4. Section 5 presents the constraints on the contribution of CCSNe to the diffuse neutrino flux. Section 6 summarizes the paper. Upper limits on the total energy released in neutrinos from individual SNe can be found in the Appendix C.

2. THE DATA

IceCube is a cubic-kilometer-sized neutrino detector, located in the transparent ice of the 2.8 km-thick glacier covering the bedrock at the geographical South Pole (Aartsen et al. 2017a). Neutrino-nucleon interactions in the ice are detected indirectly, via Cherenkov light emission from secondary particles, by 5160 photomultiplier tubes. While charged-current interactions of muon neutrinos produce track-like signatures with sub-degree angular resolution, both charged-current interactions of electron and tau neutrinos, and neutral-current interactions, have angular resolutions of several degrees. This analysis utilizes a selection of seven years of IceCube muon-track data that was optimised for point-source searches (Aartsen et al. 2017b), with roughly 700,000 events from years 2008 to 2014.

The CCSN catalog for this analysis was compiled using publicly available records of optical detections of SNe. The primary sources were the WiseREP SN catalog (Yaron & Gal-Yam 2012) and the OpenSupernova-Catalog (Guillochon et al. 2017). In total, the compiled source sample contains 339 SN type II_n, 198 SN type IIP, 503 type Ib/c and type IIb SNe. The latter are referred to as stripped-envelope supernovae. Both type II_n and type IIP SN are candidates for CSM interaction, while stripped-envelope supernovae might host choked jets. In Figure 1 the distance distribution of the two

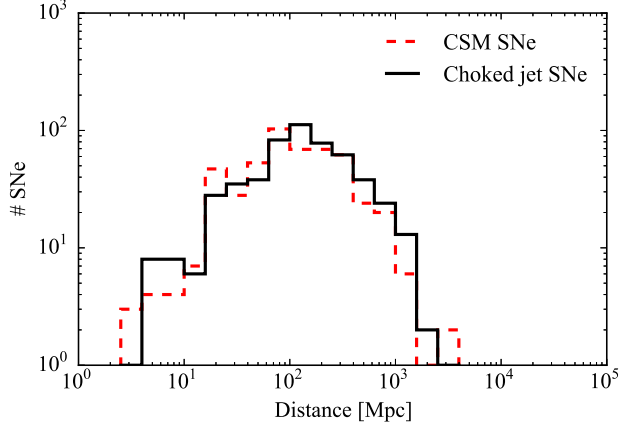


Figure 1. Distance distribution of CSM SN sample and the stripped-envelope SN sample. The decrease at large distance is a result of limited detection sensitivity and a selection bias towards brighter objects, which are easier to classify spectroscopically.

sub-samples is shown. Note that while we did include many supernovae in the analysis, we list only those of a smaller subsample in Tables 2, 3 and 1 as explained below.

The distance was taken from the previously-cited catalogs. For cases in which entries were missing in the catalogs, the distances were estimated using redshift measurements. The Λ CDM model, with cosmological parameters measured by Planck (Ade et al. 2016), were used to convert from redshift to luminosity distance. We have assumed a peculiar motion of 300 km s^{-1} , which also provides a lower distance limit for SNe with very small redshifts. SNe with neither distance nor redshift measurements were excluded from the catalog. The distance distribution peaks at about 100 Mpc, as can be seen in Fig. 1.

3. ANALYSIS METHOD

To find an excess of neutrinos from the given SN positions and times, a time dependent point source likelihood method (Braun et al. 2010) is used. The likelihood function is given by

$$\mathcal{L} = \prod_{i=1}^N \left(\frac{n_s}{N} \mathcal{S}(\nu_i) + \left(1 - \frac{n_s}{N}\right) \mathcal{B}(\nu_i) \right) \quad (1)$$

where N is the number of neutrino events, ν_i the i th neutrino and n_s is the number of signal events. $\mathcal{S}$ and $\mathcal{B}$ are signal and background probability distribution functions (PDFs). Each PDF is a product of a spatial term $\mathcal{N}$, an energy term $\mathcal{E}$ and a time term $\mathcal{T}$, which gives for the signal PDF:

$$\mathcal{S} = \mathcal{N}_S \times \mathcal{E}_S(\gamma) \times \mathcal{T}_S \quad (2)$$

and similarly for the background PDF $\mathcal{B}$ (Braun et al. 2010). The signal time PDF $\mathcal{T}_S$ corresponds to the expected neutrino flux as a function of time (light curve) and the background time PDF $\mathcal{T}_B$ assumes a constant background rate.

The energy term $\mathcal{E}$ describes the expected neutrino energy spectrum. As the dataset is highly background-dominated¹, we can safely assume that the signal contribution is negligible. The background energy proxy distribution is thus assumed to follow the distribution observed in the data. The signal neutrino energy distribution is described as a power-law function, $E^{-\gamma}$, where γ is the spectral index. For similar reasons, the background spatial PDF as a function of declination is chosen to match the distribution of declinations found in data. We assume that the background spatial PDF is uniform in right ascension, leading to $\mathcal{N}_B(\delta, \phi) = \frac{1}{2\pi} \times \mathcal{N}_{B,\text{dec}}(\delta)$ for source declination δ and right ascension ϕ . The signal spatial PDF, $\mathcal{N}_S$, is assumed to follow a 2D-Gaussian distribution.

The likelihood function is maximized with respect to n_s and γ . The best fitted value n_s gives an estimate of the number of signal-like events, i.e., those that are likely to originate from a given SN.

In addition to probing the neutrino fluxes from single SNe, we combine the signal of a sample of SNe with a stacking analysis. Such a source stacking is implemented through a weighted sum of the signal PDFs $\mathcal{S}_j$ of individual SNe j :

$$\mathcal{S} = \sum_j w_j \mathcal{S}_j \quad (3)$$

where the weights w_j represent the expected signal strength of the sources. In this analysis, the weights are assumed to be proportional to:

$$w_j \propto \underbrace{\frac{\Phi_0}{D_p^2}}_{\text{Source Properties}} \times \underbrace{\int_{t_{\text{start}}}^{t_{\text{end}}} \int_{E_{\text{min}}}^{E_{\text{max}}} L_j^\nu E^{-\gamma} A_{\text{eff}} dt dE}_{\text{Time Dependence}} \quad (4)$$

with Φ_0 as the intrinsic neutrino power of the sources, D_p as the proper distance (Hogg 1999) of the SN, $L_j^\nu(t)$ the estimated neutrino light curve, $E^{-\gamma}$ the neutrino energy spectrum and $A_{\text{eff}}(t, \delta_j, E)$ the effective area, the energy E and the declination of the source δ . The effective area is time-dependent, because the dataset covers several distinct phases of detector construction. The weighting scheme assumes a standard candle ansatz, since we assume the same Φ_0 for each source. It is very

¹ For an astrophysical signal component in the dataset with a spectral index of $\gamma = 2.5$, we expect $\mathcal{O}(10^3)$ signal events and $\mathcal{O}(10^5)$ atmospheric background events, amounting to a signal contribution of $< 1\%$

sensitive to the estimated source distances, which can have large uncertainties.

A more detailed investigation of the Supernova light curves could mitigate these uncertainties but the optical lightcurves of the supernovae in our catalogue are typically sparse and make detailed modeling complicated. Wrongly estimated weights will impact the sensitivity of the analysis so for the first time in an IceCube analysis we use a novel method of directly fitting the weights w_j . Adding the flux per source as an additional free parameter to the maximum likelihood removes the standard candle assumption and also the dependence on the SN distance estimate, but requires a more advanced numerical procedure to maximize the likelihood function. To test the power of this method, we simulated five sources with random positions on the sky and respective weights. We then perturbed the weights according to a log-normal distribution and used them to compute the sensitivity of the standard, fixed-weights likelihood. Comparing to this, we find an improvement of up to 40% when using the fitting-weights likelihood. We applied this method in addition to the traditional standard-candle one, yielding two separate results.

We define the test statistic (TS) by

$$\lambda = 2 \times \log \left(\frac{\mathcal{L}(\hat{n}_s, \hat{\gamma})}{\mathcal{L}(0)} \right) \quad (5)$$

where $\mathcal{L}(\hat{n}_s, \hat{\gamma})$ corresponds to the maximum of the likelihood function and $\mathcal{L}(0)$ to the null hypothesis, i.e., the case of neither spatial nor temporal correlation of neutrinos and SNe (Braun et al. 2008; Braun et al. 2010). The TS distribution is estimated by generating background-only datasets and maximizing the likelihood function with respect to n_s and γ . Repeating this procedure many times gives a numerical estimate of the TS distribution. Given an experimental outcome λ_{exp} and the TS distribution $P(\lambda)$, the p-value is computed as $p = \int_{\lambda_{\text{exp}}}^{\infty} P(\lambda) d\lambda$.

4. CONSTRAINTS ON SUPERNOVA SUBCLASSES

In the following we present results for selected individual CCSNe, as well as for different subclasses of CCSNe.

Stripped-envelope SNe, which might have choked jets, are expected to emit a short burst of neutrinos in coincidence with the SN explosion time (Senno et al. 2016). Motivated by theoretical uncertainties in the duration of the expected neutrino emission, and even larger uncertainties in the SNe explosion time due to sparse optical light curve data, we used a box function starting at 20 days before and extending up to the first available optical data. This ensures the inclusion of the explosion time for a typical SN even if the first detection happened at peak time.

All SN types were tested with box function PDFs of length 100, 300 and 1000 days, starting at the first available optical data, since longer neutrino emission would

be expected under the scenario of CSM interaction. In addition, for SNe IIn and IIP light curves were tested of the form:

$$\mathcal{T}(t) \propto (1 + t/t_{\text{pp}})^{-1} \quad (6)$$

where values of 0.02, 0.2 and 2 years were used for the characteristic time scale constant t_{pp} , as proposed by Zirakashvili & Ptuskin (2016).

We first applied the maximum likelihood method described above to a selection of individual SNe, which were identified based on their expected relative signal strength w_j as promising. We did not find a statistically significant excess for any of the selected sources.

The resulting upper limits on the total energy emitted in neutrinos between 10^2 GeV and 10^7 GeV, assuming an E^{-2} power-law spectrum, are presented in Appendix C. In the conversion from the number of neutrino events to flux, the systemic uncertainty is estimated to be about 11%, mainly arising from uncertainties in the optical properties of the ice and detector effects (Coenders 2016).

The individual upper limits range from 10^{49} to 6.5×10^{50} erg², which corresponds to 1-65% of the typical bolometric electromagnetic energy released in SNe. As the individual stripped-envelope and IIP SNe are typically closer than the IIn, we generally obtain more stringent limits for these objects.

In order to improve our sensitivity we performed a stacking analysis, looking for a combined excess from a catalogue instead of individual sources. As explained above we separate supernovae into types IIn, IIP and stripped-envelope SNe. Note that we decided to treat the types IIn and IIP separately because the presence of CSM interaction in IIP is less certain.

Each of the three sub-catalogs was split into two samples, a bright sample of nearby sources, containing about 70% of the expected signal, and a larger sample, containing the remaining dimmer sources. The bright samples include about 10 SN each, depending on the SN class and the model. The catalogues of the bright samples are listed in Tables 2, 3 and 1. Testing both independent samples allowed us to benefit from the better optical observations of the nearby sources in the small sample, but also utilize the larger statistics in the large sample. Because each source adds a free parameter in the likelihood maximisation when fitting the weights, this was only feasible for the smaller bright sample. This sample contains $\mathcal{O}(10)$ sources which is a manageable amount of fit parameters. For the large sample the standard candle *ansatz* was applied instead.

The p-values are given in Appendix B. The most significant pre-trial p-value is 0.62%, and is found in the search for neutrinos from the large sample of type IIP

² Calculated by integrating over time.

SNe in a 1000-day-long box-shaped light curve. This however corresponds to a post-trial p-value of 19.5%, after accounting for the multiple tested scenarios through simulated pseudo-experiments of the ensemble of p-values, and is thus consistent with background expectations. If this excess were due to astrophysical neutrinos, one would expect a corresponding excess in the sample of nearby type IIP SNe, where we do not find such an excess. The second smallest p-value of 6.3% is found for the nearby type IIn SNe in case of the fitted weights for the box-shaped lightcurve model. The overall deviation of all tested scenarios from the background expectation using a Kolmogorov-Smirnov-test leads to a p-value of 29%.

To be conservative we use the result from the fitting weights analysis in the rest of the paper as it resulted in weaker upper limits on the total emitted neutrino energy. Including systematic uncertainties, those are shown in Fig. 2 for both models of the neutrino light curve. These limits assume that SNe within each category behave as neutrino standard candles.

The stacking result provides us with stronger limits than individual source limits. We find that SNe type IIn emit less than 1.3×10^{49} erg and type IIP less than 2.4×10^{48} erg, while the strongest limits for stripped-envelope SNe of 4.5×10^{48} erg are obtained from the choked-jet scenario. If the longer box models that are associated with CSM interaction are assumed, then the strongest limit becomes 2.7×10^{48} erg. In general, the box time window provides tighter constraints for CSM interacting SNe compared to the specific light curve model by [Zirakashvili & Ptuskin \(2016\)](#).

5. DIFFUSE NEUTRINO FLUX

Using the limits on neutrino energy obtained in the stacking analysis (shown in Fig. 2) we can estimate the maximal contribution from the entire cosmological population of SNe to the measured diffuse neutrino flux ([Aartsen et al. 2015](#)). Using the CCSNe rate by [Strolger et al. \(2015\)](#), $\rho(z)$, the diffuse flux is computed following the procedure in [Ahlers & Halzen \(2014\)](#) assuming a 1:1:1 ($\nu_e : \nu_\mu : \nu_\tau$) neutrino flavour ratio at Earth. Note that we assume that the rate for the individual subclasses scales according to the corresponding percentage in the local universe ([Li et al. 2011](#)). The diffuse flux is given by

$$\phi(E) = \int_0^\infty \frac{\rho(z)}{1+z} \frac{dN}{dE} \frac{c}{H(z)} dz, \quad (7)$$

where dN/dE is the time integrated flux upper limit for each SN subclass, assuming that the subclass behaves as a neutrino standard candle class with an $E^{-2.5}$ energy spectrum as motivated by the central value of the global fit diffuse neutrino flux ([Aartsen et al. 2015](#)) and that the power law holds over our sensitive energy range. This energy range is calculated by finding the energy bound

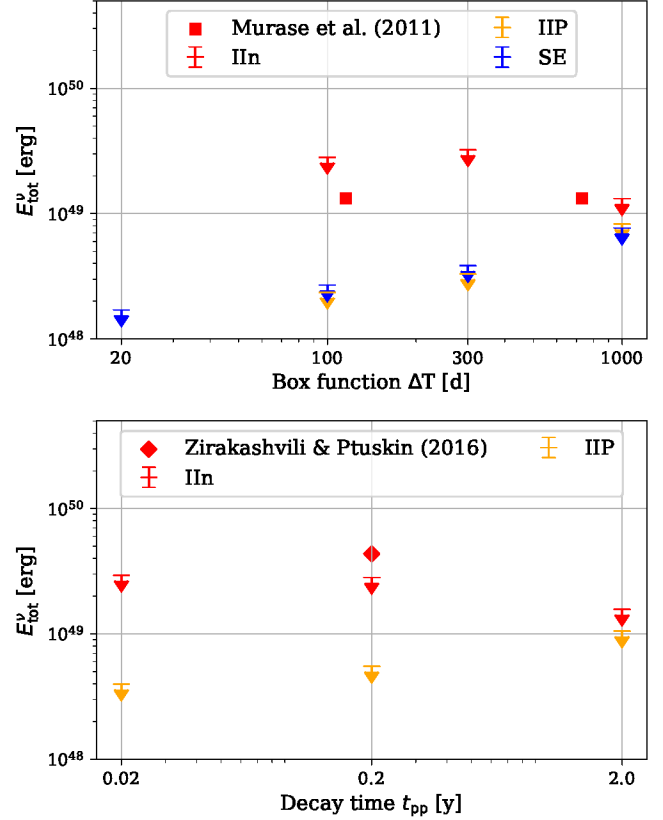


Figure 2. Upper limits on total neutrino ($\nu_\mu + \bar{\nu}_\mu$) energy assuming a box-like neutrino light curve (upper panel) and assuming a $L_\nu \propto (1 + t/t_{pp})^{-1}$ neutrino light curve as predicted by [Zirakashvili & Ptuskin \(2016\)](#). The energy ranges are the same as indicated in Figure 3. The model predictions by [Murase et al. \(2011\)](#) and [Zirakashvili & Ptuskin \(2016\)](#) are shown as red squares for comparison.

for selecting simulated signal events. We find the values where our sensitivity drops by 5% for the lower and upper bounds separately. The range between both values is our 90% energy range.

The resulting upper limits on the contribution of different SN types to the diffuse neutrino flux are shown in Fig. 3. Assuming the choked-jet scenario, stripped-envelope SNe can not contribute more than 14.6% of the observed diffuse neutrino flux. Assuming interaction with the CSM, stripped-envelope SNe and SNe type IIn can explain not more than 26.6% and 33.9%, respectively. We mildly constrain the contribution of SNe type IIP to be less than 59.9%. Note that the limit for type IIP SNe seem weaker when translating it to a component of the diffuse flux because they are the most abundant supernova type ([Li et al. 2011](#)).

This analysis has different sensitivities for different energy ranges, see Fig. 4. The region of greatest sensitivity is around 10-100 TeV. It can reach to higher energies as well, depending on the source declination. This broadly

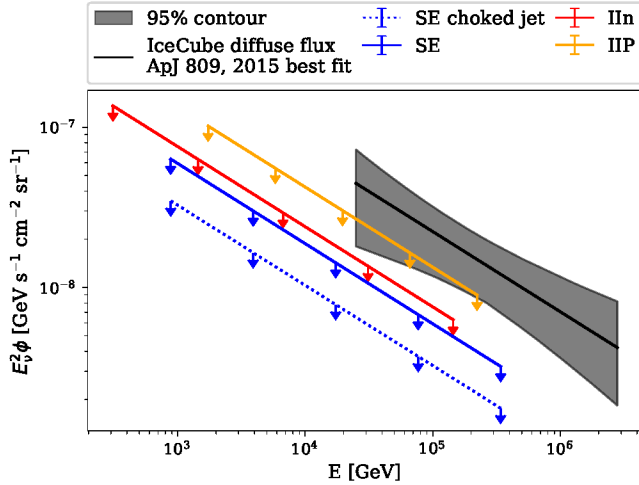


Figure 3. Upper limit on the contribution of different SN types to the diffuse neutrino flux ($\nu_\mu + \bar{\nu}_\mu$) assuming an $E^{-2.5}$ energy spectrum compared with the measured diffuse astrophysical neutrino flux (gray band). The limits are derived from the corresponding strictest limit in Figure 2. The choked-jet model refers to the 20-day box model as explained in Section 4. The energy range plotted here is the central 90% energy range of the analyzed neutrino sample.

overlaps with the energy range in which the diffuse IceCube neutrino flux global fit was measured. The quoted upper limits to the diffuse flux contribution are thus not strongly dependent on the extrapolation of the measured diffuse flux to lower energies, where the flux has not yet been measured due to large atmospheric background.

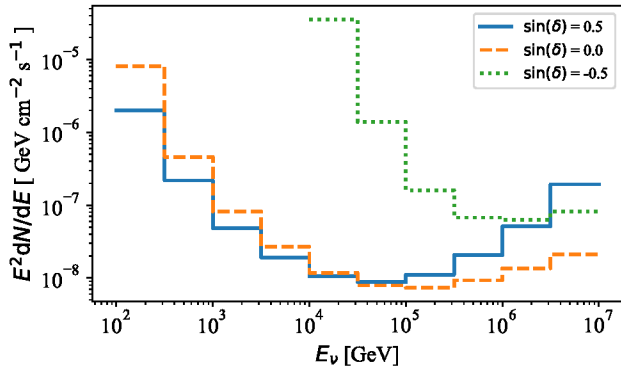


Figure 4. Differential sensitivity as a function of energy for different source declinations δ with one year of experimental data. One can see the maximum sensitivity is achieved around 10^5 GeV for sources located in the northern sky and close to the equator. For sources located in the southern sky, the overall sensitivity is much worse, but also peaks at higher energies of 10^6 GeV.

6. CONCLUSION

We have presented a search for neutrinos from certain types of CCSNe with IceCube. In a stacking analysis we correlated more than 1000 SNe from optical surveys with roughly 700,000 muon-track events recorded by IceCube. The standard stacking method was extended to allow for fitting of individual weights for each source, in order to account for expected variation in the neutrino flux from individual sources. SNe type IIn, IIP and stripped-envelope SNe were tested individually with various neutrino emission time models. No significant temporal and spatial correlation of neutrinos and the cataloged SNe was found, allowing us to set upper limits on the contribution of those SNe to the diffuse neutrino flux.

CCSNe of type IIn, IIP and stripped-envelope SNe contribute less than 34%, 60% and 27%, respectively, to the diffuse neutrino flux at the 90% confidence level, assuming CSM interaction and an extrapolation of the diffuse neutrino spectrum to low energies following an unbroken power law with index -2.5. Assuming a choked-jet, stripped-envelope SNe can not contribute more than 15%.

Upper limits on the total neutrino energy emitted by a single CSM interacting source are at levels comparable to model predictions by Murase et al. (2011) (see Fig. 2) while model predictions from Zirakashvili & Ptuskin (2016) are strongly disfavored. Note that the model prediction could easily be adjusted to lower neutrino flux predictions by assuming a lower CSM density or a lower kinetic SN energy.

Improvements to the presented limits are expected in the near future with optical survey instruments such as the Zwicky Transient Factory (Graham et al. 2019) which is able to undertake a high-cadence survey across a large fraction of the sky, providing SN catalogs with much greater completeness. In combination with next-generation neutrino telescopes, this will significantly boost the sensitivity of this type of analysis, allowing us to probe dimmer neutrino emitters and smaller contributions of CCSNe to the diffuse neutrino flux.

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Software: flarestack (Stein et al. 2022a)

APPENDIX

A. CATALOGS

Name	RA [rad]	Dec [rad]	Discovery Date	Redshift	Distance [Mpc]	Source
SN1999bw	2.70	0.79	1999-00-20	0.0032	9.80	1, 2
SN2002bu	3.22	0.80	2002-00-28	0.0030	8.90	1, 2, 3
SN2008S	5.39	1.05	2008-00-01	0.0012	5.60	4
SN2009kr	1.36	-0.27	2009-00-06	0.0075	16.00	5
SN2010jl	2.54	0.17	2010-00-03	0.0117	49.00	6
SN2011an	2.09	0.29	2011-00-01	0.0170	73.00	7
SN2011ht	2.65	0.90	2011-00-29	0.0046	19.20	8
SN2012ab	3.24	0.10	2012-00-31	0.0190	81.00	9
SN2013by	4.29	-1.05	2013-00-23	0.0038	14.80	10, 11
SN2013gc	2.13	-0.49	2013-00-07	0.0044	15.10	12
PSN J14041297-0938168	3.68	-0.17	2013-00-20	0.0038	12.55	13
CSS140111:060437-123740	1.59	-0.22	2013-00-24	0.0084	32.88	13
SN2014G	2.86	0.95	2014-00-14	0.0045	20.00	14
MASTER OT J044212.20+230616.7	1.23	0.40	2014-00-21	0.0170	72.00	15
SN2015da	3.63	0.69	2015-00-09	0.0079	32.14	16, 17

Table 1. Interacting supernovae catalogue. References: (1) Kochanek et al. (2012), (2) Smith et al. (2011), (3) Szczygiel et al. (2012), (4) Stanishev et al. (2008), (5) Steele et al. (2009a), (6) Benetti et al. (2010), (7) Marion & Calkins (2011), (8) Prieto et al. (2011), (9) Bilinski et al. (2018), (10) Margutti et al. (2013), (11) Parker et al. (2013), (12) Antezana et al. (2013), (13) Challis (2013), (14) Denisenko et al. (2014), (15) Shivvers et al. (2014), (16) Zhang & Wang (2015), (17) Tartaglia et al. (2020)

Name	RA	Dec	Discovery Date	Redshift	Distance	Source
	[rad]	[rad]			[Mpc]	
SN1999em	1.23	-0.05	1999-00-29	0.0034	7.50	1
SN2004dj	2.00	1.14	2004-00-31	0.0014	3.50	2
SN2004et	5.39	1.05	2004-00-27	0.0022	7.70	3, 4
SN2005cs	3.53	0.82	2005-00-28	0.0030	7.10	5, 6
SN2006ov	3.24	0.08	2006-00-24	0.0062	14.00	7
SN2008bk	6.27	-0.57	2008-00-25	0.0018	4.00	8
SN2009js	0.64	0.32	2009-00-11	0.0060	16.00	9
SN2009md	2.83	0.22	2009-00-05	0.0046	18.00	10
SN2009mf	0.27	0.83	2009-00-07	0.0087	23.00	11
SN2011dq	0.26	-0.13	2011-00-15	0.0055	24.40	12
SN2012A	2.73	0.30	2012-00-07	0.0034	9.80	13
SN2012aw	2.81	0.20	2012-00-16	0.0036	9.90	14
SNhunt141	3.57	-0.31	2012-00-24	0.0040	18.00	15
SN2012ec	0.72	-0.13	2012-00-12	0.0057	18.76	16
SN2013ab	3.81	0.17	2013-00-17	0.0063	23.64	17
SN2013am	2.96	0.23	2013-00-21	0.0037	12.77	18
SN2013bu	5.92	0.60	2013-00-21	0.0027	12.07	19
SN2013ej	0.42	0.28	2013-00-25	0.0020	9.00	20
SN2011ja	3.43	-0.86	2014-00-14	0.0018	3.36	21
SN2014bc	3.22	0.83	2014-00-19	0.0025	7.60	22

Table 2. IIP catalog. References: (1) Jha et al. (1999), (2) Patat et al. (2004), (3) Zwitter et al. (2004), (4) Li et al. (2005), (5) Modjaz et al. (2005), (6) Pastorello et al. (2009), (7) Li et al. (2007), (8) Morrell & Stritzinger (2008), (9) Gandhi et al. (2013), (10) Sollerman et al. (2009), (11) Steele et al. (2009b), (12) Valenti & Benetti (2011), (13) Stanishev & Porsimo (2012), (14) Quadri et al. (2012), (15) Cellier-Holzem et al. (2012), (16) Monard et al. (2012), (17) Bose et al. (2015), (18) Benetti et al. (2013), (19) Itagaki et al. (2013), (20) Dhungana et al. (2016), (21) Andrews et al. (2016), (22) Ochner et al. (2014)

Name	RA [rad]	Dec [rad]	Discovery Date	Redshift	Distance [Mpc]	Source
SN2007gr	0.71	0.65	2007-00-15	0.0027	9.30	1, 2
SN2008ax	3.28	0.73	2008-00-03	0.0029	9.60	3, 4
SN2008dv	0.95	1.27	2008-00-01	0.0084	4.20	5
SN2009dq	2.66	-1.17	2009-00-24	0.0046	16.00	6
SN2009gj	0.13	-0.58	2009-00-21	0.0053	17.00	7
SN2009mk	0.03	-0.72	2009-00-15	0.0050	22.00	8, 9
SN2009mu	2.58	-0.58	2009-00-21	0.0098	25.00	10
SN2010br	3.16	0.78	2010-00-10	0.0033	13.00	11
SN2010gi	4.55	1.32	2010-00-18	0.0041	18.20	12
SN2011dh	3.53	0.82	2011-00-01	0.0025	8.40	5
SN2011jm	3.38	0.05	2011-00-24	0.0041	14.00	13
SN2012P	3.93	0.03	2012-00-22	0.0055	20.10	14, 15
SN2012cw	2.68	0.06	2012-00-14	0.0055	19.92	16, 17
SN2012fh	2.81	0.43	2012-00-18	0.0029	8.58	18, 19, 20
SN2013df	3.26	0.55	2013-00-07	0.0033	10.58	21, 22
iPTF13bvn	3.93	0.03	2013-00-17	0.0055	19.94	15, 23, 24, 25
MASTER OT J120451.50+265946.6	3.16	0.47	2013-00-02	0.0029	8.38	26, 27, 28
SN2013ge	2.77	0.38	2013-00-08	0.0054	19.34	29, 30
SN2014C	5.92	0.60	2014-00-05	0.0037	12.07	31, 32, 33

Table 3. Stripped-envelope supernovae catalogue. References: (1) Chornock et al. (2007), (2) Valenti et al. (2008), (3) Chornock et al. (2008), (4) Pastorello et al. (2008), (5) Silverman et al. (2008), (6) Anderson et al. (2009), (7) Stockdale et al. (2009), (8) Chornock & Berger (2009), (9) Marples & Drescher (2009), (10) Stritzinger et al. (2010), (11) Maxwell et al. (2010), (12) Yamanaka et al. (2010), (13) Foley & Fong (2011), (14) Borsato et al. (2012), (15) Fremling et al. (2016), (16) Itagaki et al. (2012), (17) Wang et al. (2012), (18) Johnson et al. (2017), (19) Takaki et al. (2012), (20) Tomasella et al. (2012), (21) Ciabattari et al. (2013), (22) Van Dyk et al. (2014), (23) Cao et al. (2013), (24) Milisavljevic et al. (2013), (25) Srivastav et al. (2014a), (26) Chandra et al. (2019), (27) Singh et al. (2019), (28) Srivastav et al. (2014b), (29) Drout et al. (2016), (30) Nakano et al. (2013), (31) Kim et al. (2014), (32) Milisavljevic et al. (2015), (33) Tinyanont et al. (2016)

B. P-VALUES [%]

	Box length [days]				t_{pp} [years]		
	[-20, 0]	[0, 100]	[0, 300]	[0, 10000]	0.02	0.2	2.0
IIn	-	8.6	6.3	>50	>50	>50	30.1
IIP	-	48.6	>50	27.6	>50	>50	21.6
Stripped-envelope	>50	>50	>50	34.8	-	-	-

Table 4. Pre-trial p-values of the fitted weights scenario given as percentages for a box shaped light curve model of different length and for the CSM model of Zirakashvili & Ptuskin (2016) for different choices of t_{pp} .

C. UPPER LIMITS ON INDIVIDUAL SOURCES

This section shows upper limits on individual SNe. Sources were selected based on their expected neutrino signal. Here we assume a generic neutrino energy spectrum of E^{-2} rather than tying them to the observed diffuse spectral shape and an emission time window of 100 days.

Name	ra [rad]	dec [rad]	discovery date	distance [Mpc]	Energy Upper Limit [10^{49} erg]
CSS140111:060437-123740	1.59	-0.22	2013-12-24	31.8	49.8
PSN J13522411+3941286	3.63	0.693	2015-01-09	32.1	16.8
PSN J14041297-0938168	3.68	-0.168	2013-12-20	12.5	4.8
PTF10aaxf	2.54	0.166	2010-11-03	52.3	29.5
SN2008S	5.39	1.049	2008-02-01	5.6	5.3
SN2009kr	1.36	-0.274	2009-11-06	16.0	19.1
SN2011an	2.09	0.287	2011-03-01	73.0	65.3
SN2011ht	2.65	0.905	2011-09-29	19.2	6.6
SN2012ab	3.24	0.098	2012-01-31	81.0	64.18
SN2013gc	2.13	-0.49	2013-11-07	15.1	28.4

Table 5. Upper limits on selected SNe type IIn.

Name	ra [rad]	dec [rad]	discovery date	distance [Mpc]	Energy Upper Limit [10^{49} erg]
iPTF13aaz	2.96	0.228	2013-03-21	16.4	1.0
SN2012A	2.73	0.299	2012-01-07	9.0	1.0
SN2012aw	2.81	0.204	2012-03-16	9.6	1.0
SN2014bc	3.22	0.826	2014-05-19	7.6	3.0

Table 6. Upper limits on selected SNe type IIP.

Name	ra [rad]	dec [rad]	discovery date	distance [Mpc]	Energy Upper Limit [10^{49} erg]
iPTF13bvn	3.93	0.033	2013-06-17	25.8	4.0
MASTER OT J120451.50	3.16	0.471	2014-10-28	15.0	1.0
PTF11eon	3.53	0.823	2011-06-01	8.0	1.1
SN2008ax	3.28	0.727	2008-03-03	5.1	1.6
SN2008dv	0.95	1.267	2008-07-01	10.6	1.2
SN2010br	3.16	0.777	2010-04-10	9.9	4.1
SN2011jm	3.38	0.046	2011-12-24	14.0	1.8
SN2012cw	2.68	0.06	2012-06-14	31.3	4.3
SN2012fh	2.81	0.434	2012-10-18	8.6	1.1
SN2013df	3.26	0.545	2013-06-07	10.6	1.7
SN2014C	5.92	0.601	2014-01-05	12.1	2.3

Table 7. Upper limits on selected stripped-envelope SNe (Ib/c and IIb).

REFERENCES

- Aartsen, M. G., et al. 2013, *Science*, 342, 1242856, doi: [10.1126/science.1242856](https://doi.org/10.1126/science.1242856)
- . 2015, *Astrophys. J.*, 809, 98, doi: [10.1088/0004-637X/809/1/98](https://doi.org/10.1088/0004-637X/809/1/98)
- Aartsen, M. G., Abraham, K., Ackermann, M., et al. 2017a, *ApJ*, 835, 45, doi: [10.3847/1538-4357/835/1/45](https://doi.org/10.3847/1538-4357/835/1/45)
- Aartsen, M. G., Ackermann, M., Adams, J., et al. 2017b, *ApJ*, 843, 112, doi: [10.3847/1538-4357/aa7569](https://doi.org/10.3847/1538-4357/aa7569)
- Aartsen, M. G., et al. 2017a, *JINST*, 12, P03012, doi: [10.1088/1748-0221/12/03/P03012](https://doi.org/10.1088/1748-0221/12/03/P03012)
- . 2017b, *Astrophys. J.*, 835, 151, doi: [10.3847/1538-4357/835/2/151](https://doi.org/10.3847/1538-4357/835/2/151)
- . 2018a, *Science*, 361, X
- . 2018b, *Science*, 361, 147
- Ade, P. A. R., et al. 2016, *Astron. Astrophys.*, 594, A13, doi: [10.1051/0004-6361/201525830](https://doi.org/10.1051/0004-6361/201525830)
- Ahlers, M., & Halzen, F. 2014, *Phys. Rev.*, D90, 043005, doi: [10.1103/PhysRevD.90.043005](https://doi.org/10.1103/PhysRevD.90.043005)
- Anderson, J., Morrell, N., Folatelli, G., & Stritzinger, M. 2009, Central Bureau Electronic Telegrams, 1789, 1
- Ando, S., & Beacom, J. F. 2005, *Physical Review Letters*, 95, 061103, doi: [10.1103/PhysRevLett.95.061103](https://doi.org/10.1103/PhysRevLett.95.061103)
- Andrews, J. E., Krafton, K. M., Clayton, G. C., et al. 2016, *Monthly Notices of the Royal Astronomical Society*, 457, 3241, doi: [10.1093/mnras/stw164](https://doi.org/10.1093/mnras/stw164)
- Antezana, R., Hamuy, M., Gonzalez, L., et al. 2013, Central Bureau Electronic Telegrams, 3699, 1
- Benetti, S., Bufano, F., Vinko, J., et al. 2010, Central Bureau Electronic Telegrams, 2536, 1
- Benetti, S., Tomasella, L., Pastorello, A., et al. 2013, *The Astronomer's Telegram*, 4909, 1
- Bilinski, C., Smith, N., Williams, G. G., et al. 2018, *Monthly Notices of the Royal Astronomical Society*, 475, 1104, doi: [10.1093/mnras/stx3214](https://doi.org/10.1093/mnras/stx3214)
- Borsato, L., Nascimbeni, V., Benetti, S., et al. 2012, Central Bureau Electronic Telegrams, 2993, 2
- Bose, S., Valenti, S., Misra, K., et al. 2015, *Monthly Notices of the Royal Astronomical Society*, 450, 2373, doi: [10.1093/mnras/stv759](https://doi.org/10.1093/mnras/stv759)
- Braun, J., Baker, M., Dumm, J., et al. 2010, *Astroparticle Physics*, 33, 175, doi: [10.1016/j.astropartphys.2010.01.005](https://doi.org/10.1016/j.astropartphys.2010.01.005)
- Braun, J., Dumm, J., De Palma, F., et al. 2008, *Astropart. Phys.*, 29, 299, doi: [10.1016/j.astropartphys.2008.02.007](https://doi.org/10.1016/j.astropartphys.2008.02.007)
- Cao, Y., Kasliwal, M. M., Arcavi, I., et al. 2013, *The Astrophysical Journal*, 775, L7, doi: [10.1088/2041-8205/775/1/L7](https://doi.org/10.1088/2041-8205/775/1/L7)
- Cellier-Holzem, F., Smartt, S. J., Insnerra, C., et al. 2012, *The Astronomer's Telegram*, 4300, 1
- Challis, P. 2013, *The Astronomer's Telegram*, 5700, 1
- Chandra, P., Nayana, A. J., Björnsson, C. I., et al. 2019, *The Astrophysical Journal*, 877, 79, doi: [10.3847/1538-4357/ab1900](https://doi.org/10.3847/1538-4357/ab1900)
- Chornock, R., & Berger, E. 2009, Central Bureau Electronic Telegrams, 2086, 1
- Chornock, R., Filippenko, A. V., Li, W., et al. 2007, Central Bureau Electronic Telegrams, 1036, 1
- . 2008, Central Bureau Electronic Telegrams, 1298, 1
- Ciabattari, F., Mazzoni, E., Donati, S., et al. 2013, Central Bureau Electronic Telegrams, 3557, 1
- Coenders, S. 2016, Dissertation, Technische Universität München, München
- Denisenko, D., Lipunov, V., Gorbovskoy, E., et al. 2014, Central Bureau Electronic Telegrams, 3787, 2
- Denton, P. B., & Tamborra, I. 2018, *ApJ*, 855, 37, doi: [10.3847/1538-4357/aaab4a](https://doi.org/10.3847/1538-4357/aaab4a)
- Dhungana, G., Kehoe, R., Vinko, J., et al. 2016, *The Astrophysical Journal*, 822, 6, doi: [10.3847/0004-637X/822/1/6](https://doi.org/10.3847/0004-637X/822/1/6)
- Drout, M. R., Milisavljevic, D., Parrent, J., et al. 2016, *The Astrophysical Journal*, 821, 57, doi: [10.3847/0004-637X/821/1/57](https://doi.org/10.3847/0004-637X/821/1/57)
- Faran, T., Poznanski, D., Filippenko, A. V., et al. 2014, *MNRAS*, 442, 844, doi: [10.1093/mnras/stu955](https://doi.org/10.1093/mnras/stu955)
- Foley, R. J., & Fong, W. 2011, Central Bureau Electronic Telegrams, 2962, 2
- Fremling, C., Sollerman, J., Taddia, F., et al. 2016, *Astronomy and Astrophysics*, 593, A68, doi: [10.1051/0004-6361/201628275](https://doi.org/10.1051/0004-6361/201628275)
- Gandhi, P., Yamanaka, M., Tanaka, M., et al. 2013, *The Astrophysical Journal*, 767, 166, doi: [10.1088/0004-637X/767/2/166](https://doi.org/10.1088/0004-637X/767/2/166)
- Graham, M. J., Kulkarni, S. R., Bellm, E. C., et al. 2019, arXiv e-prints, arXiv:1902.01945, <https://arxiv.org/abs/1902.01945>
- Guillochon, J., Parrent, J., Kelley, L. Z., & Margutti, R. 2017, *ApJ*, 835, 64, doi: [10.3847/1538-4357/835/1/64](https://doi.org/10.3847/1538-4357/835/1/64)
- Hogg, D. W. 1999, arXiv e-prints, astro, <https://arxiv.org/abs/astro-ph/9905116>
- IceCube Collaboration, Abbasi, R., Ackermann, M., et al. 2022, *Science*, 378, 538, doi: [10.1126/science.abg3395](https://doi.org/10.1126/science.abg3395)
- Itagaki, K., Noguchi, T., Nakano, S., et al. 2012, Central Bureau Electronic Telegrams, 3148, 1
- . 2013, Central Bureau Electronic Telegrams, 3498, 1
- Jha, S., Challis, P., Garnavich, P., et al. 1999, *International Astronomical Union Circular*, 7296, 2
- Johnson, S. A., Kochanek, C. S., & Adams, S. M. 2017, *Monthly Notices of the Royal Astronomical Society*, 472, 3115, doi: [10.1093/mnras/stx2170](https://doi.org/10.1093/mnras/stx2170)

- Kim, M., Zheng, W., Li, W., et al. 2014, Central Bureau Electronic Telegrams, 3777, 1
- Kochanek, C. S., Szczygiel, D. M., & Stanek, K. Z. 2012, The Astrophysical Journal, 758, 142, doi: [10.1088/0004-637X/758/2/142](https://doi.org/10.1088/0004-637X/758/2/142)
- Kurahashi, N., Murase, K., & Santander, M. 2022, arXiv e-prints, arXiv:2203.11936, <https://arxiv.org/abs/2203.11936>
- Li, W., Leaman, J., et al. 2011, Monthly Notices of the Royal Astronomical Society, 412, 1441, doi: [10.1111/j.1365-2966.2011.18160.x](https://doi.org/10.1111/j.1365-2966.2011.18160.x)
- Li, W., Van Dyk, S. D., Filippenko, A. V., & Cuillandre, J.-C. 2005, Publications of the Astronomical Society of the Pacific, 117, 121, doi: [10.1086/428278](https://doi.org/10.1086/428278)
- Li, W., Wang, X., Van Dyk, S. D., et al. 2007, The Astrophysical Journal, 661, 1013, doi: [10.1086/516747](https://doi.org/10.1086/516747)
- Margutti, R., Soderberg, A., & Milisavljevic, D. 2013, The Astronomer's Telegram, 5106, 1
- Marion, G. H., & Calkins, M. 2011, Central Bureau Electronic Telegrams, 2668, 2
- Marples, P., & Drescher, C. 2009, Central Bureau Electronic Telegrams, 2080, 1
- Mauerhan, J. C., Smith, N., Silverman, J. M., et al. 2013, MNRAS, 431, 2599, doi: [10.1093/mnras/stt360](https://doi.org/10.1093/mnras/stt360)
- Maxwell, A. J., Graham, M. L., Parker, A., et al. 2010, Central Bureau Electronic Telegrams, 2245, 2
- Milisavljevic, D., Fesen, R., Pickering, T., et al. 2013, The Astronomer's Telegram, 5142, 1
- Milisavljevic, D., Margutti, R., Kamble, A., et al. 2015, The Astrophysical Journal, 815, 120, doi: [10.1088/0004-637X/815/2/120](https://doi.org/10.1088/0004-637X/815/2/120)
- Modjaz, M., Kirshner, R., Challis, P., & Hutchins, R. 2005, International Astronomical Union Circular, 8555, 1
- Monard, L. A. G., Childress, M., Scalzo, R., Yuan, F., & Schmidt, B. 2012, Central Bureau Electronic Telegrams, 3201, 1
- Moriya, T., Tominaga, N., Blinnikov, S. I., Baklanov, P. V., & Sorokina, E. I. 2011, MNRAS, 415, 199, doi: [10.1111/j.1365-2966.2011.18689.x](https://doi.org/10.1111/j.1365-2966.2011.18689.x)
- Moriya, T. J., Tominaga, N., Blinnikov, S. I., Baklanov, P. V., & Sorokina, E. I. 2012, in IAU Symposium, Vol. 279, Death of Massive Stars: Supernovae and Gamma-Ray Bursts, ed. P. Roming, N. Kawai, & E. Pian, 54–57, doi: [10.1017/S1743921312012689](https://doi.org/10.1017/S1743921312012689)
- Morrell, N., & Stritzinger, M. 2008, Central Bureau Electronic Telegrams, 1335, 1
- Murase, K., Thompson, T. A., Lacki, B. C., & Beacom, J. F. 2011, Phys. Rev., D84, 043003, doi: [10.1103/PhysRevD.84.043003](https://doi.org/10.1103/PhysRevD.84.043003)
- Nakano, S., Kiyota, S., Masi, G., et al. 2013, Central Bureau Electronic Telegrams, 3701, 1
- Nakaoka, T., Kawabata, K. S., Maeda, K., et al. 2018, The Astrophysical Journal, 859, 78, <http://stacks.iop.org/0004-637X/859/i=2/a=78>
- Necker, J., de Jaeger, T., Stein, R., et al. 2022, Monthly Notices of the Royal Astronomical Society, 516, 2455, doi: [10.1093/mnras/stac2261](https://doi.org/10.1093/mnras/stac2261)
- Ochner, P., Tomasella, L., Benetti, S., et al. 2014, The Astronomer's Telegram, 6160, 1
- Ofek, E. O., et al. 2013, Nature, 494, 65, doi: [10.1038/nature11877](https://doi.org/10.1038/nature11877)
- Parker, S., Kiyota, S., Morrell, N., et al. 2013, Central Bureau Electronic Telegrams, 3506, 1
- Pastorello, A., Kasliwal, M. M., Crockett, R. M., et al. 2008, Monthly Notices of the Royal Astronomical Society, 389, 955, doi: [10.1111/j.1365-2966.2008.13618.x](https://doi.org/10.1111/j.1365-2966.2008.13618.x)
- Pastorello, A., Valenti, S., Zampieri, L., et al. 2009, Monthly Notices of the Royal Astronomical Society, 394, 2266, doi: [10.1111/j.1365-2966.2009.14505.x](https://doi.org/10.1111/j.1365-2966.2009.14505.x)
- Patat, F., Benetti, S., Pastorello, A., Filippenko, A. V., & Aceituno, J. 2004, International Astronomical Union Circular, 8378, 1
- Pitlik, T., Tamborra, I., Angus, C. R., & Auchettl, K. 2022, ApJ, 929, 163, doi: [10.3847/1538-4357/ac5ab1](https://doi.org/10.3847/1538-4357/ac5ab1)
- Prieto, J. L., McMillan, R., Bakos, G., & Grennan, D. 2011, Central Bureau Electronic Telegrams, 2903, 1
- Quadri, U., Strabla, L., Girelli, R., et al. 2012, Central Bureau Electronic Telegrams, 3054, 1
- Razzaque, S., Mészáros, P., & Waxman, E. 2004, Physical Review Letters, 93, 181101, doi: [10.1103/PhysRevLett.93.181101](https://doi.org/10.1103/PhysRevLett.93.181101)
- Reusch, S., Stein, R., Kowalski, M., et al. 2022, Physical Review Letters, 128, 221101, doi: [10.1103/PhysRevLett.128.221101](https://doi.org/10.1103/PhysRevLett.128.221101)
- Sarmah, P., Chakraborty, S., Tamborra, I., & Auchettl, K. 2022, Journal of Cosmology and Astroparticle Physics, 2022, 011, doi: [10.1088/1475-7516/2022/08/011](https://doi.org/10.1088/1475-7516/2022/08/011)
- Senno, N., Murase, K., & Meszaros, P. 2016, Phys. Rev., D93, 083003, doi: [10.1103/PhysRevD.93.083003](https://doi.org/10.1103/PhysRevD.93.083003)
- Shivvers, I., Kelly, P. L., Clubb, K. I., & Filippenko, A. V. 2014, The Astronomer's Telegram, 6487, 1
- Silverman, J. M., Griffith, C. V., Filippenko, A. V., Chornock, R., & Li, W. 2008, Central Bureau Electronic Telegrams, 1447, 1
- Singh, M., Misra, K., Sahu, D. K., et al. 2019, Monthly Notices of the Royal Astronomical Society, 485, 5438, doi: [10.1093/mnras/stz752](https://doi.org/10.1093/mnras/stz752)

- Smith, N., Li, W., Silverman, J. M., Ganeshalingam, M., & Filippenko, A. V. 2011, *Monthly Notices of the Royal Astronomical Society*, 415, 773, doi: [10.1111/j.1365-2966.2011.18763.x](https://doi.org/10.1111/j.1365-2966.2011.18763.x)
- Sollerman, J., Ergon, M., Inserra, C., et al. 2009, *Central Bureau Electronic Telegrams*, 2068, 1
- Srivastav, S., Anupama, G. C., & Sahu, D. K. 2014a, *Monthly Notices of the Royal Astronomical Society*, 445, 1932, doi: [10.1093/mnras/stu1878](https://doi.org/10.1093/mnras/stu1878)
- Srivastav, S., Sahu, D. K., & Anupama, G. C. 2014b, *The Astronomer's Telegram*, 6639, 1
- Stanishev, V., Pastorello, A., & Pursimo, T. 2008, *Central Bureau Electronic Telegrams*, 1235, 1
- Stanishev, V., & Pursimo, T. 2012, *Central Bureau Electronic Telegrams*, 2974, 3
- Steele, T. N., Cobb, B., & Filippenko, A. V. 2009a, *Central Bureau Electronic Telegrams*, 2011, 1
- Steele, T. N., Kandrashoff, M. T., & Filippenko, A. V. 2009b, *Central Bureau Electronic Telegrams*, 2070, 1
- Stein, R. 2019, in *Proceedings of 36th International Cosmic Ray Conference — PoS(ICRC2019)*, Vol. 358, 1016, doi: [10.22323/1.358.1016](https://doi.org/10.22323/1.358.1016)
- Stein, R., Necker, J., Bradascio, F., & Garrappa, S. 2022a, *icecube/flarestack: Titan v2.4.2, v2.4.2*, Zenodo, doi: [10.5281/zenodo.6425740](https://doi.org/10.5281/zenodo.6425740)
- Stein, R., et al. 2021, *Nature Astron.*, 5, 510, doi: [10.1038/s41550-020-01295-8](https://doi.org/10.1038/s41550-020-01295-8)
- Stein, R., Reusch, S., Franckowiak, A., et al. 2022b, *arXiv e-prints*, arXiv:2203.17135
- Stockdale, C. J., Rentz, B., Vandrevalla, C. M., et al. 2009, *International Astronomical Union Circular*, 9056, 1
- Stritzinger, M., Folatelli, G., & Pignata, G. 2010, *Central Bureau Electronic Telegrams*, 2116, 1
- Strolger, L.-G., Dahlen, T., Rodney, S. A., et al. 2015, *Astrophys. J.*, 813, 93, doi: [10.1088/0004-637X/813/2/93](https://doi.org/10.1088/0004-637X/813/2/93)
- Stratjohann, N. L., Ofek, E. O., Gal-Yam, A., et al. 2021, *ApJ*, 907, 99, doi: [10.3847/1538-4357/abd032](https://doi.org/10.3847/1538-4357/abd032)
- Szczygieł, D. M., Kochanek, C. S., & Dai, X. 2012, *The Astrophysical Journal*, 760, 20, doi: [10.1088/0004-637X/760/1/20](https://doi.org/10.1088/0004-637X/760/1/20)
- Takaki, K., Itoh, R., Ueno, I., et al. 2012, *Central Bureau Electronic Telegrams*, 3263, 3
- Tartaglia, L., Pastorello, A., Sollerman, J., et al. 2020, *Astronomy and Astrophysics*, 635, A39, doi: [10.1051/0004-6361/201936553](https://doi.org/10.1051/0004-6361/201936553)
- Tinyanont, S., Kasliwal, M. M., Fox, O. D., et al. 2016, *The Astrophysical Journal*, 833, 231, doi: [10.3847/1538-4357/833/2/231](https://doi.org/10.3847/1538-4357/833/2/231)
- Tomasella, L., Turatto, M., Benetti, S., et al. 2012, *Central Bureau Electronic Telegrams*, 3263, 2
- Valenti, S., & Benetti, S. 2011, *Central Bureau Electronic Telegrams*, 2749, 2
- Valenti, S., Elias-Rosa, N., Taubenberger, S., et al. 2008, *The Astrophysical Journal*, 673, L155, doi: [10.1086/527672](https://doi.org/10.1086/527672)
- Van Dyk, S. D., Zheng, W., Fox, O. D., et al. 2014, *The Astronomical Journal*, 147, 37, doi: [10.1088/0004-6256/147/2/37](https://doi.org/10.1088/0004-6256/147/2/37)
- Wang, X. F., Liu, Q., Zhang, J. J., Zhang, T. M., & Brimacombe, J. 2012, *Central Bureau Electronic Telegrams*, 3148, 2
- Yamanaka, M., Arai, A., Sakimoto, K., Okushima, T., & Kawabata, K. S. 2010, *Central Bureau Electronic Telegrams*, 2384, 1
- Yaron, O., & Gal-Yam, A. 2012, *Publications of the Astronomical Society of the Pacific*, 124, 668, <http://stacks.iop.org/1538-3873/124/i=917/a=668>
- Yaron, O., et al. 2017, *Nature Phys.*, 13, 510, doi: [10.1038/nphys4025](https://doi.org/10.1038/nphys4025)
- Zhang, J., & Wang, X. 2015, *The Astronomer's Telegram*, 6939, 1
- Zirakashvili, V. N., & Ptuskin, V. S. 2016, *Astropart. Phys.*, 78, 28, doi: [10.1016/j.astropartphys.2016.02.004](https://doi.org/10.1016/j.astropartphys.2016.02.004)
- Zwitter, T., Munari, U., & Moretti, S. 2004, *International Astronomical Union Circular*, 8413, 1