EPJ Web of Conferences **280**, 05005 (2023) https://doi.org/10.1051/epjconf/202328005005
RICAP-22

Searching for high-energy neutrinos from the most luminous supernovae with the IceCube Neutrino Observatory

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Abstract.
The sources of the astrophysical neutrino flux discovered by IceCube remain for the most part unresolved. Extragalactic core-collapse supernovae (CCSNe) have been suggested as potentially able to produce high-energy neutrinos. In recent years, the Zwicky Transient Facility has discovered a population of exceptionally luminous supernovae, whose powering mechanisms have not yet been fully established. A fraction of these objects fall in the broader category of type IIn CCSNe, showing signs of interaction with a dense circumstellar medium. Theoretical models connect the supernova photometric properties to the dynamics of a shock-powered emission, predicting particle acceleration. In this contribution, we outline the plan for a search of high-energy neutrinos targeting the population of superluminous and type IIn supernovae with the IceCube Neutrino Observatory.

1 Introduction

The IceCube Neutrino Observatory is a large-volume neutrino detector based on an array of photomultipliers submerged in the Antarctic ice [1]. In the past decade, IceCube has discovered and characterised an astrophysical flux of high-energy neutrinos [2–4] which could be the key to identifying the origin of ultra-high-energy cosmic rays. While high-energy neutrino emission has been associated with different astrophysical objects, the majority of the flux observed by IceCube remains unresolved. Multi-messenger observations suggest that a significant fraction of the flux must originate in sources that are faint in high-energy gamma rays. Shock-powered transient phenomena observed in optical bands with suppressed gamma-ray emission are candidate neutrino sources [5]. Among these, type IIn core-collapse supernovae exhibit narrow lines in their spectrum that are a signature of interaction with a dense circumstellar medium. No high-energy neutrino excess has been previously observed from CCSNe with IceCube [6]. A search for high-energy neutrinos from a selected sample of supernovae powered by shock interaction could help in determining the origin of astrophysical neutrinos and in constraining the shock-interaction models for hadronic particle acceleration [7, 8].

2 The nature of the most luminous supernovae

In core-collapse supernovae (CCSNe), a large amount of gravitational energy is converted into low-energy neutrinos, thermal photons and kinetic energy of the ejecta. In Fig. 1, an

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overview of interesting subpopulations of CCSNe observed by the Zwicky Transient Facility Bright Transient Survey [9, 10] is given. An especially luminous subset of hydrogen-rich (type II) supernovae is represented by type IIn SNe, identified by narrow lines in their optical spectrum. This feature is a signal of interaction of the SN ejecta with the circumstellar medium (CSM). The shocks propagating in such environment may accelerate particles to relativistic energies. The interaction of the accelerated protons with the cold protons and nuclei in the dense CSM can result in the production of high-energy neutrinos [8] (see Fig. 2, left). Thanks to high-cadence wide-field astronomical surveys, populations of both hydrogen-poor (type I) and hydrogen-rich (type II) superluminous supernovae have been discovered in recent years [11]. Type II SLSNe are most likely interaction-powered and can be considered as an extension of the IIn population. Hydrogen-poor SLSNe represent a new, separate, class of SNe, likely powered by the combination of magnetar activity and CSM interaction. As both mechanisms can be responsible for particle acceleration, these sources will be considered in a future extension of this work. Type IIP SNe are excluded from this analysis, being less promising high-energy neutrino sources [7].

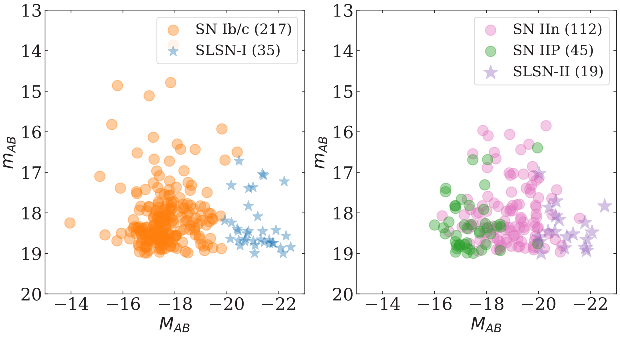

Figure 1. Distribution of the apparent magnitude (m_{AB}) as a function of absolute magnitude (M_{AB}) for selected subpopulations of type I (right) and type II (left) of core-collapse supernovae observed by the Zwicky Transient Facility in either ZTF-g or ZTF-r band. The following populations are omitted: Type-II SNe that lack a subtype classification, stripped-envelope SNe of type IIb, Ibn and Icn, and all subtypes classified as peculiar.

3 A sample of interaction-powered supernovae

A sample of type IIn SNe and type II SLSNe has been selected from the Bright Transient Survey of the Zwicky Transient Facility [9, 10]. The forced-photometry light curves for the ZTF red (ZTF-r) and green (ZTF-g) filters have been corrected for Galactic extinction and interpolated using Gaussian process regression. The sum of the interpolated light curves is taken as a *pseudo-bolometric* light curve, representing a lower limit on the optical emission of the source (see Fig. 2, right). We select events with robust spectroscopic classification, for which the time evolution has been well-observed in both bands, allowing for a reliable estimation of the rise and peak times of the supernova. The final selection includes 74 sources detected up to May 31, 2021 (end of the IceCube 2020-21 data season). The fluence at Earth for each source in the sample is calculated from the time-integrated pseudo-bolometric light curve and reported as a function of the source redshift and declination in Fig. 3.

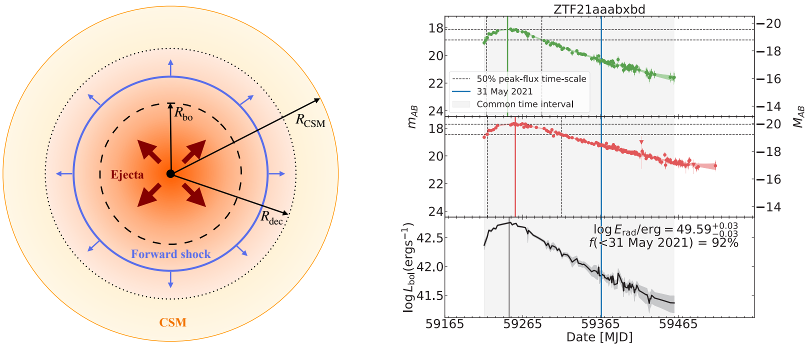

Figure 2. Left: sketch of the shock propagation in the circumstellar medium (CSM) for an interaction-powered supernova from Ref. [8]. Right: example of pseudo-bolometric light curve (bottom, see 3) obtained by the sum of interpolated ZTF-g (top) and ZTF-r (middle) band lightcurves of a type IIn CCSN observed by the Zwicky Transient Facility.

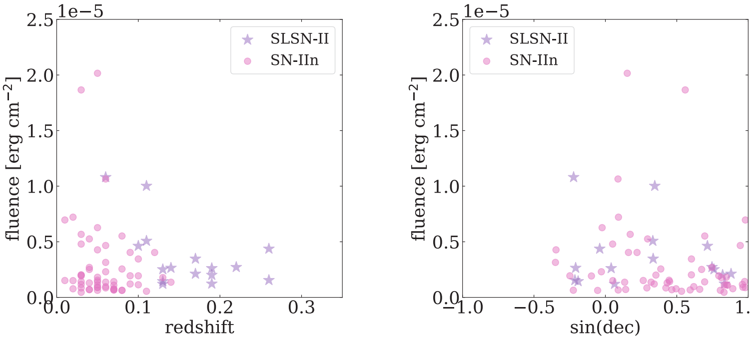

Figure 3. Pseudo-bolometric fluence as a function of redshift (left) and declination (right) for the selected sample of interaction-powered supernovae.

4 Neutrino stacking analysis and preliminary results

The analysis method for the search of astrophysical neutrinos is an unbinned stacking implemented in `flarestack` [12]. The likelihood function is defined on the neutrino sample:

$$\mathcal{L}(n_s, \gamma) = \prod_{i=0} \left[\frac{n_s}{N} \sum_{j=0}^{M} w_j \mathcal{S}_j(\theta_i, \gamma) + \left(1 - \frac{n_s}{N}\right) \mathcal{B}(\theta_i) \right] \tag{1}$$

where θ_i are the properties of the i-th neutrino (out of N), n_s is the total number of signal events from the source catalogue, w_j is the weight for source j (out of M), $\mathcal{S}$ and $\mathcal{B}$ are the signal and background probability density functions, γ is the spectral index of the signal flux. The likelihood $\mathcal{L}$ is maximised to find the best-fit values of n_s and γ. A test statistic is defined by the likelihood ratio of the *signal plus background* to the *background-only* hypotheses. The significance estimation is based on the test statistic distribution calculated from a large number of background neutrino samples, obtained by shuffling neutrino data in time and assigning random values of right ascension. Assuming a neutrino emission proportional to the optical luminosity, given that the two have a common powering mechanism, the sources are weighted according to their pseudo-bolometric fluence (see Sec. 3). A preliminary estimate of the sensitivity and discovery potential has been performed and is shown in Fig. 4. The corresponding neutrino energy fluxes are $4.5 \cdot 10^{-9}$ and $1.5 \cdot 10^{-8}$ $\mathrm{GeV^{-1}\ cm^{-2}\ s^{-1}}$. Improvements to the analysis are possible by restricting the catalogue to the Northern hemisphere (where IceCube has the best sensitivity) and by implementing a model-driven weighting of the sources based on a development of the approach described in Ref. [8].

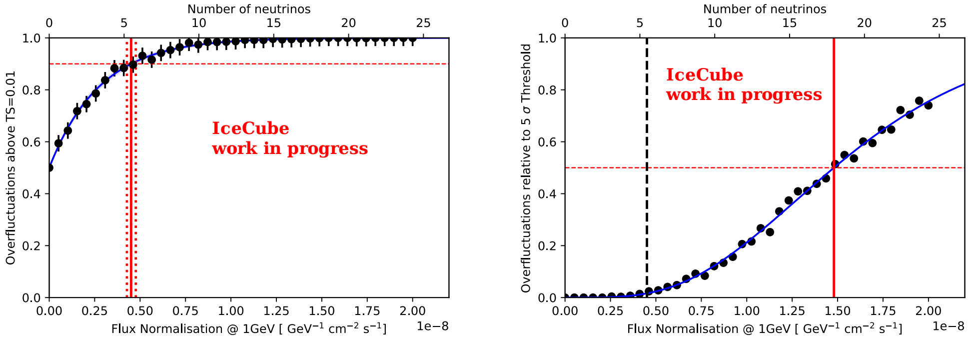

Figure 4. Sensitivity (flux at which 90% of the time the experiment yields a result above the background median; left) and discovery potential (flux at which 50% of the time the experiment yields a result above a 5 σ significance; right) for the stacking analysis estimated by evaluating the test statistic distribution for different intensity of injected signal flux.

5 Acknowledgements

The authors thank Steve Schulze for the support provided in the analysis of the ZTF data and Tetyana Pitik for providing the theoretical framework that motivates this study. The authors acknowledge funding from the German Science Foundation DFG, within the Collaborative Research Center SFB-1491 "Cosmic Interacting Matters - From Source to Signal".

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