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

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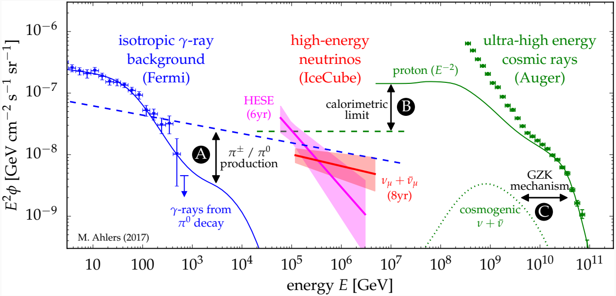
The multi-messenger dilemma

The origin of the **high-energy astrophysical neutrino flux** discovered by IceCube is still unresolved.



Above 100 TeV, the flux could be explained by *cosmic-ray reservoirs* (starburst galaxies, galaxy clusters...)

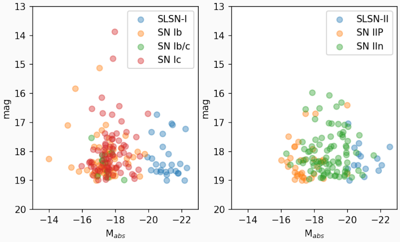
Below 100 TeV, the neutrino flux appears to overshoot the Fermi gamma ray background → **missing sources should be suppressed in high-energy gamma rays** → **optical transients**? (Fang *et al.*, ApJ 904, 4, 2020).

The atlas of core-collapse supernovae

Core-collapse supernovae (CCSNe) are a **wide and very diverse** population of luminous optical transients.

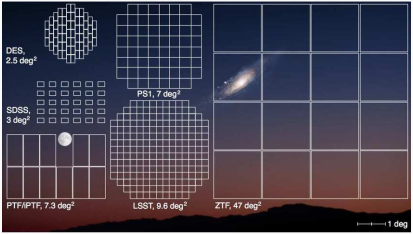
- The most luminous supernovae can be separated in hydrogen-poor (SLSN-I) and hydrogen-rich.
- Narrow lines in spectra of hydrogen-rich (type II) core-collapse supernovae are indication of interaction with the circumstellar medium (CSM) → **CCSN Type IIn**.
- The most luminous type II supernovae are believed to be part of the IIn population.

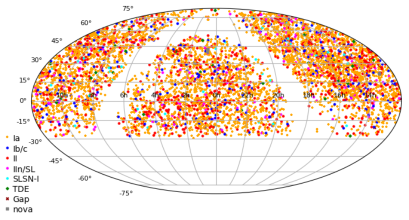
Apparent and absolute magnitude of type I and type II core-collapse supernovae from the Bright Transient Survey of ZTF.



A new era for optical transients

Wide field surveys such as the **Zwicky Transient Facility** (ZTF) are discovering optical transients at an unprecedented pace.

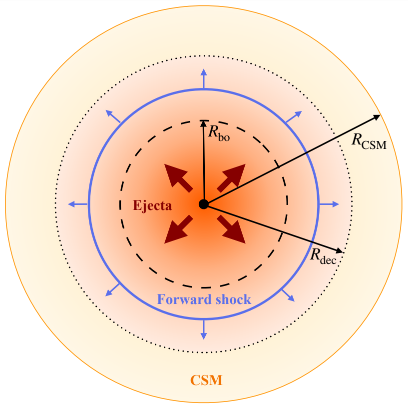




ZTF maintains a public **Bright Transient Survey** catalogue → consistent high-quality sample of optical sources.

High-energy neutrinos have been associated with **tidal disruption events** (Stein *et al.*, 2020), but not yet with supernovae (Necker, PoS(ICRC2021)).

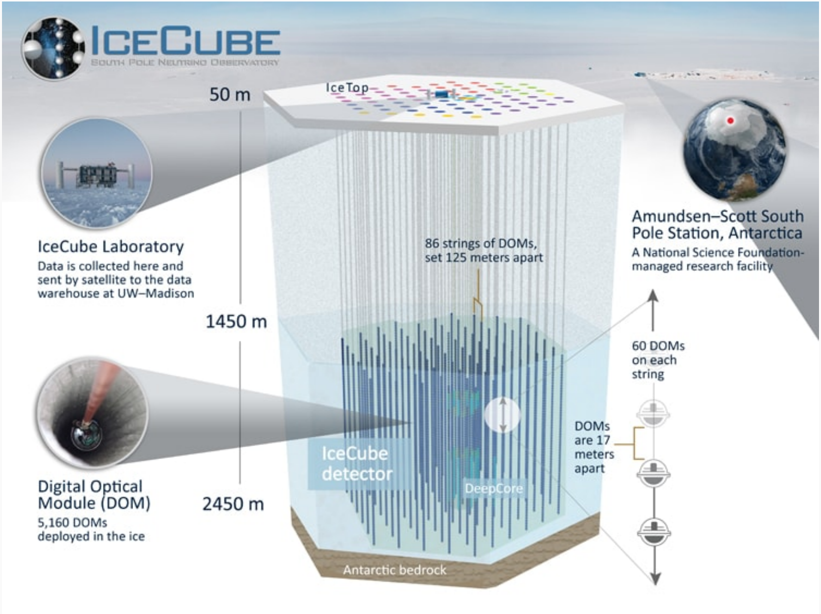
Shock-powered supernovae



Pitik *et al.*, Astrophys. J. 929 (2022) 163

- Protons are accelerated to relativistic energies in the SN forward shock.
- Neutrinos can be produced in inelastic p-p collisions between relativistic protons and the cold CSM material.
- The SN optical properties are related to the neutrino luminosity.

The IceCube Neutrino Observatory



Questions (we aim to answer)

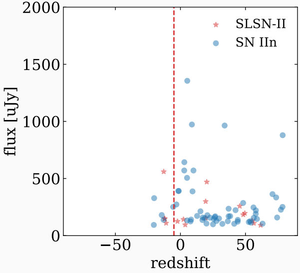
Do **interaction-powered supernovae** contribute to the diffuse astrophysical neutrino flux?

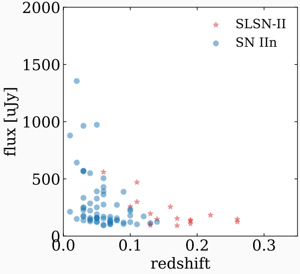
Can **novel modeling efforts** improve the IceCube sensitivity to this population of sources?

Will superluminous events (despite their higher average distance) make a difference when included in the sample?

A catalogue of interaction-powered supernovae (IPSN)

- ZTF Bright Transient Survey: 187 among SN IIn and SLSN-II reported in the 2018–2022 period.
- Require robust classification, observation in both red and green (r+g) bands, good data quality (→ 165 objects).
- Requiring good observation of rising, peak, post-peak in both g+r bands (→ 88 objects) + non-detection 20 days before the first detection (→ 82 objects).

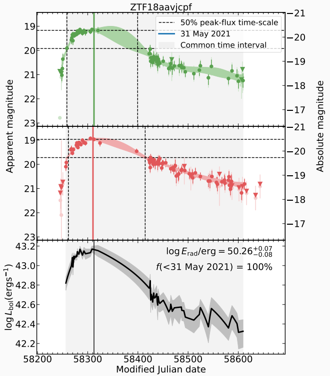




Looking at lightcurves

Lightcurve processing courtesy of S. Schulze (ZTF).

- Gaussian process interpolation of individual r, g lightcurves.
- Sum of interpolated r and g → pseudo-bolometric light curve ≈ lower bound of bolometric luminosity.



Start time = average between last non-detection and first detection in the earliest observed band.
Peak time = peak of the pseudo-bolometric light curve.
Pseudo-bolometric fluence = time-integrated pseudo-bolometric flux at Earth.

Neutrino stacking search

Unbinned likelihood stacking:

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

with $i \rightarrow$ neutrino event, $n_s \rightarrow$ number of signal events, $w_j \rightarrow$ source weight, $\mathcal{S}$ / $\mathcal{B} \rightarrow$ signal / background PDFs, $\gamma \rightarrow$ spectral index, $\delta_i \rightarrow$ declination.

Software: flarestack (Stein *et al.*, 10.5281/zenodo.5497486)

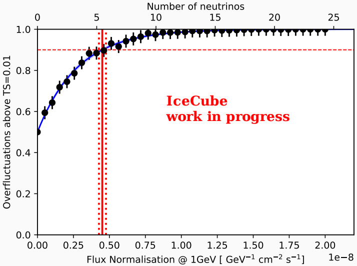
Preliminary sensitivity estimation:

- events discovered up to the end of the 2020-21 IceCube-86 season, May 31, 2021 (74 SNe);
- injection spectral index $\gamma = 2.0$;
- fixed weights based on the **pseudo-bolometric fluence** at Earth;
- **box-like time PDF** covering the observation time of the supernova lightcurve.

Sensitivity and discovery potential

Sensitivity and discovery potential are estimated using scrambled data as background.

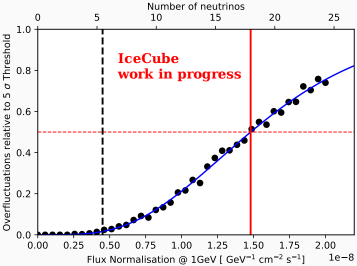
sensitivity



$\sim 4.5 \cdot 10^{-9}\ \mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

Equiv. average ν luminosity of nearest source: $6 \times 10^{41}\ \mathrm{erg\,s}^{-1}$.

discovery potential



$\sim 1.5 \cdot 10^{-8}\ \mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}$

Equiv. average ν luminosity of nearest source: $2 \times 10^{42}\ \mathrm{erg\,s}^{-1}$.

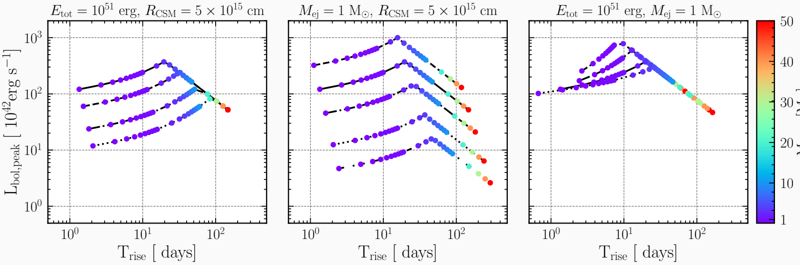
Work in progress: IceCube 2020-21 data set not yet finalized. Possible restriction to the Northern hemisphere is being considered.

Upcoming: model-driven weights

An **improved weigthing scheme** will rely on a original modeling effort by our collaborator T. Pitik (NBI).

Interaction-powered SNe → **lightcurve properties** (peak luminosity and rise time) depend on ejecta / CSM configuration (radius R_{CSM}, ejecta mass M_{ej}, CSM mass M_{CSM}).

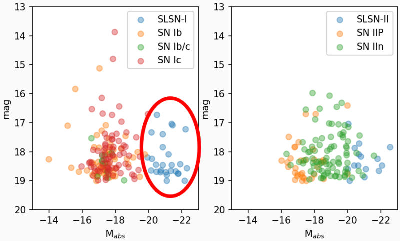
A **neutrino luminosity** can be predicted from inferred CSM properties (see Pitik *et al.*, ApJ. 929 (2022) 163).



Pitik *et al.*, in preparation

Prospects: hydrogen-poor SLSNe?

Type-I superluminous supernovae have emerged as a **new population of transients** with extreme luminosities (Gal-Yam, ARA&A, 2019). Extensive sample recently published by ZTF (Chen *et al.*, arXiv:2202.02059-60).



Their power source still undetermined . Hypotheses: magnetars, accretion on a newly formed black-hole, **interaction with a H-free CSM**. Potential connection to high-energy neutrinos is currently unexplored.

Conclusion and outlook

Thanks to the ZTF data, we can **take a new look at the core-collapse supernova population** as potential source of **high-energy neutrinos**.

A homogeneous high-quality sample of interaction-powered CCSNe has been selected, including **superluminous events**. The **photometric properties relevant to the CSM interaction** have been derived from the recorded g- and r-band optical light curves.

First estimation of the **sensitivity and discovery potential** using a bolometric fluence weighting.

Analysis will be soon improved using **model-driven weights**.

Possible **extension to type-I SLSNe** will be investigated.