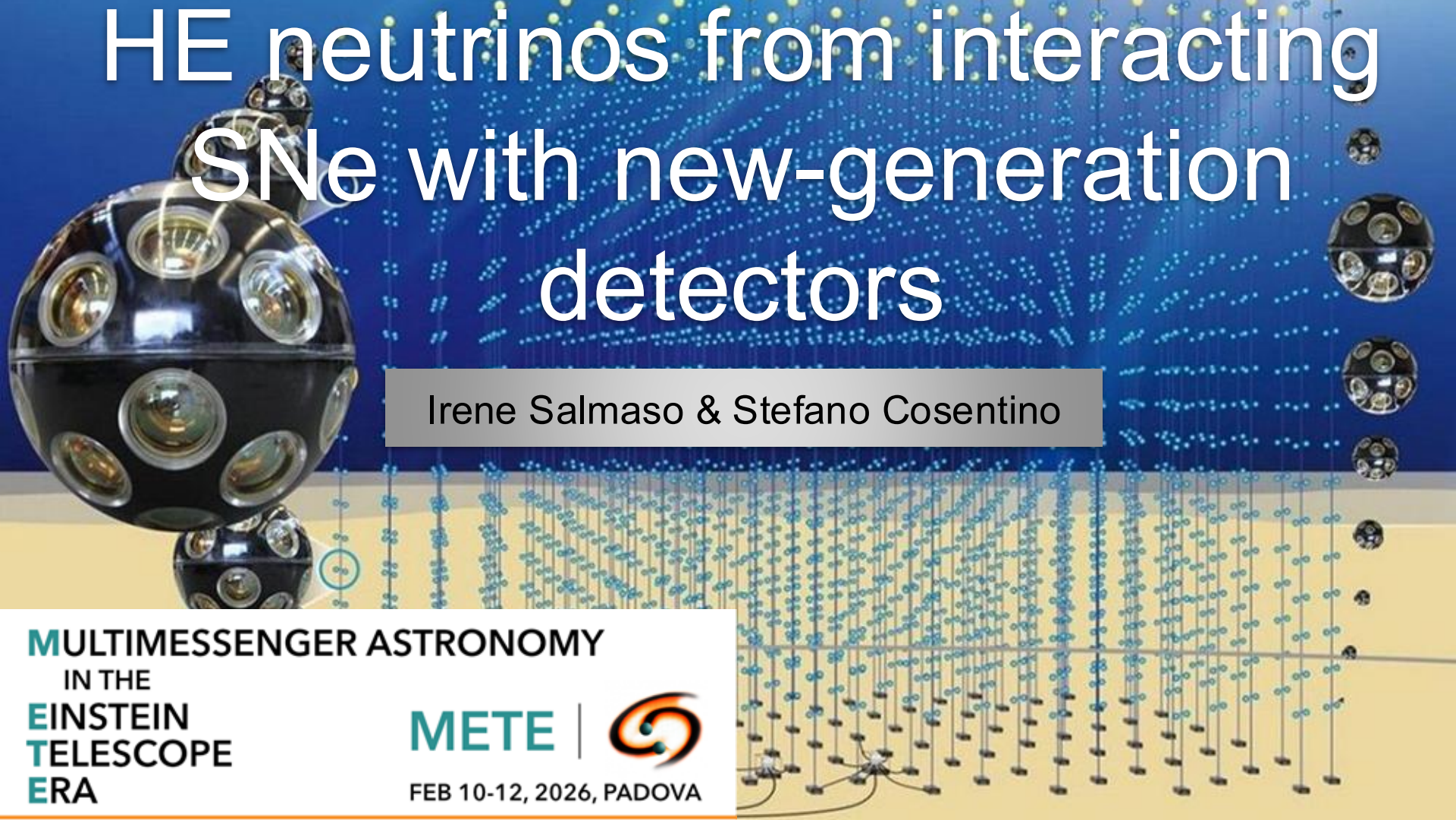
HE neutrinos from interacting SNe with new-generation detectors

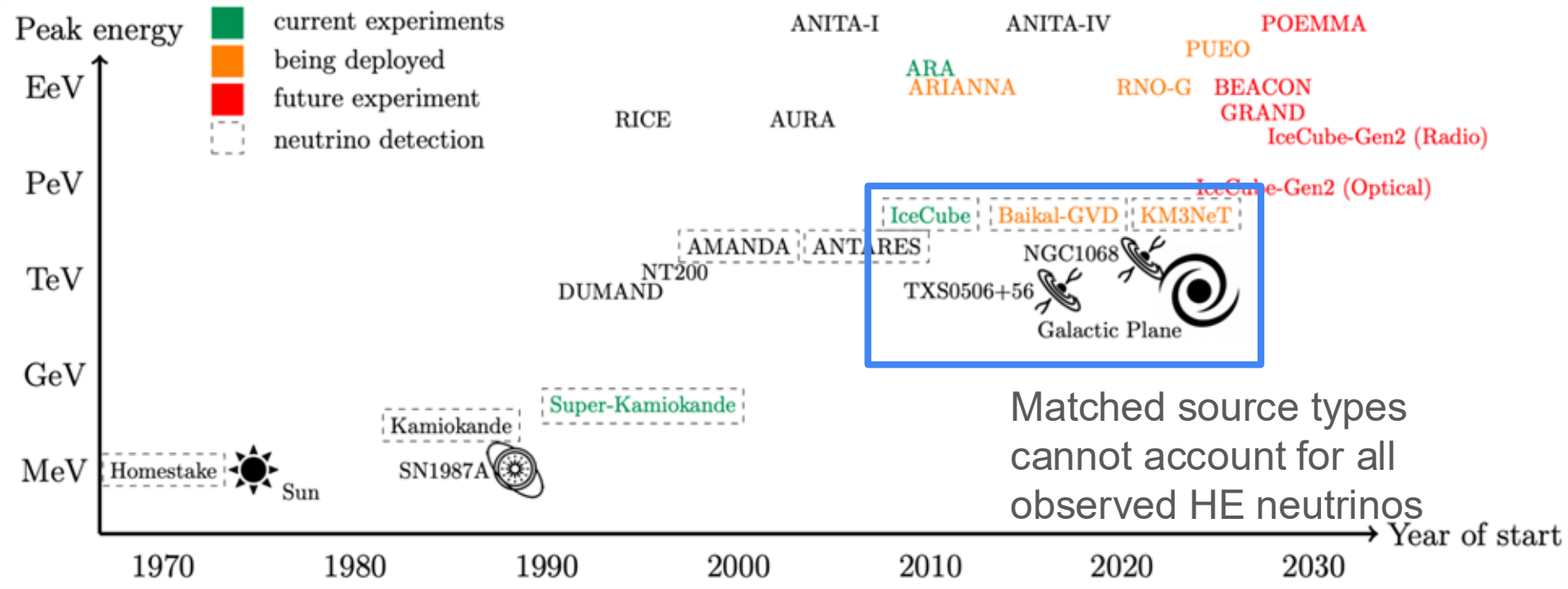
Irene Salmaso & Stefano Cosentino



MULTIMESSENGER ASTRONOMY IN THE EINSTEIN TELESCOPE ERA

METE

FEB 10-12, 2026, PADOVA

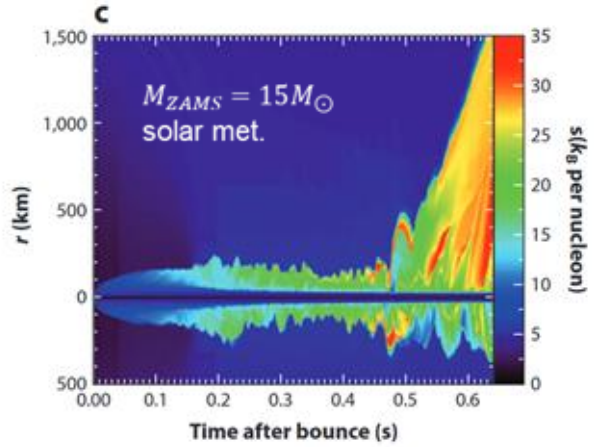


Matched source types cannot account for all observed HE neutrinos

Decoene 2023

Neutrinos from SNe

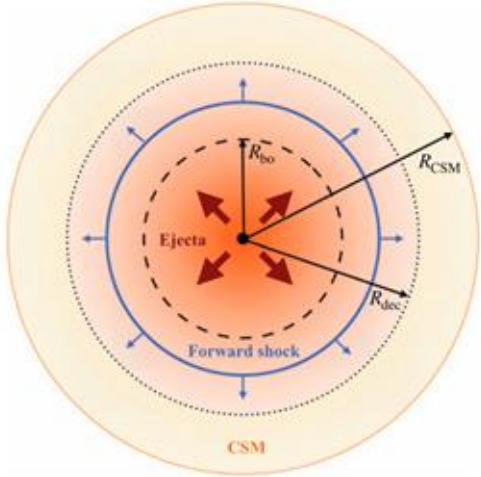
- **Neutrino-driven explosion:**



$$E \sim 9.4 \times 10^{50}\ \mathrm{erg} \left(\frac{k_B T_\nu}{4\ \mathrm{MeV}}\right)^2 \left(\frac{L_\nu}{3 \times 10^{52}\ \mathrm{erg\ s^{-1}}}\right) \times \left(\frac{M_g}{0.01\ M_\odot}\right)^2 \left(\frac{\dot{M}}{0.1\ M_\odot\ \mathrm{s^{-1}}}\right)^{-1} \left(\frac{R_g}{100\ \mathrm{km}}\right)^{-2}$$

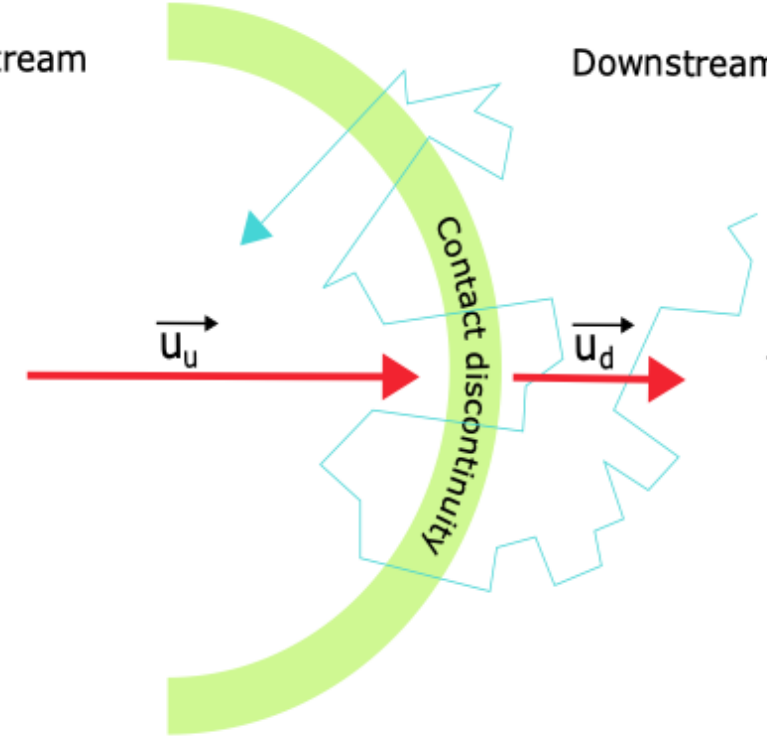
H.-T. Janka, Explosion Mechanisms of Core-Collapse Supernovae, Ann. Rev. Nucl. Part. Sci. 62 (2012) 407

- **pp-interaction neutrinos from shocked Circumstellar Medium region:**



$$Q_{\nu_\mu+\bar{\nu}_\mu}(E_\nu, R) = \frac{4 n_{\mathrm{CSM}}(R) m_p c^3}{v_{\mathrm{sh}}} \int_0^1 dx \frac{\sigma_{pp}(E_\nu/x)}{x} \times N_p\left(\frac{E_\nu}{x m_p c^2}, R\right)(F^{(1)}_{\nu_\mu}(E_\nu, x) + F^{(2)}_{\nu_\mu}(E_\nu, x)),$$

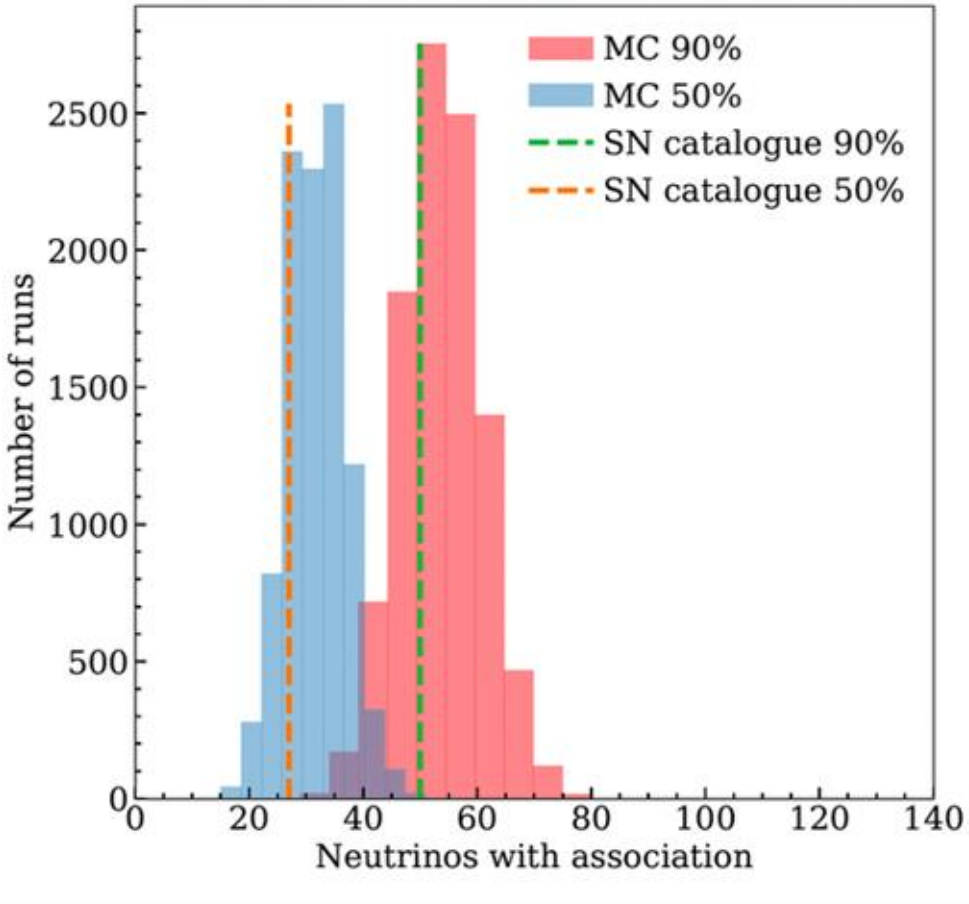
Pitik T., Tamborra I. Angus C.R. et al., 2022, ApJ, 929 163



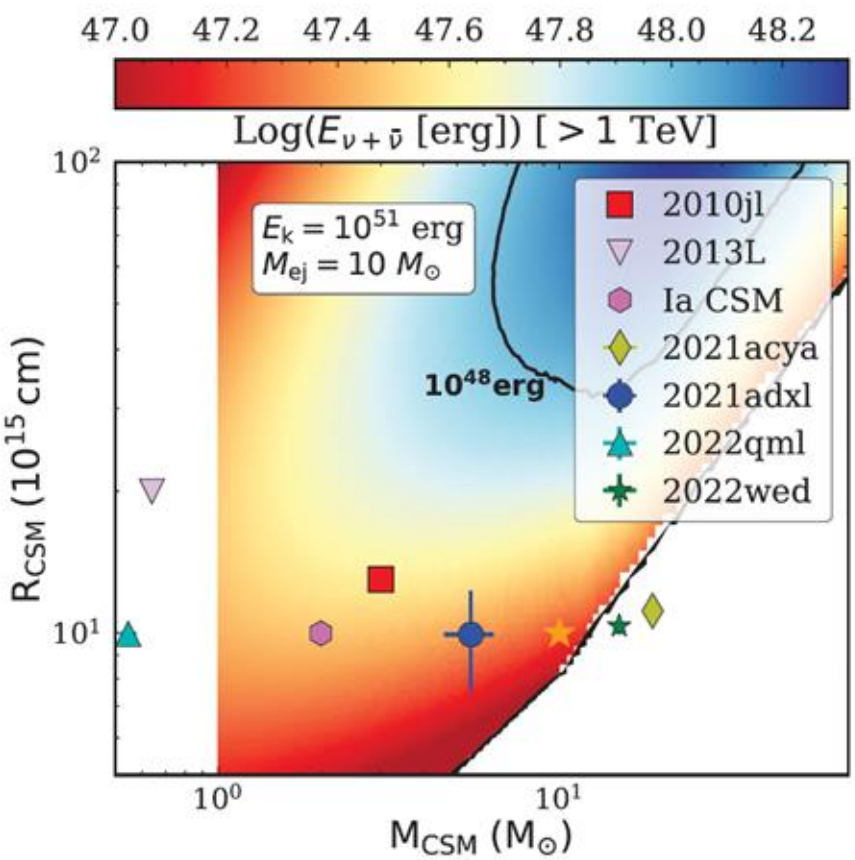
$$
\begin{aligned}
p + p/\gamma \quad &\rightarrow \quad p/n + \pi^{\pm} + \pi^0 + K^{\pm} + \cdots \\
\pi^+ \quad &\rightarrow \mu^+ + \nu_\mu \\
&\mu^+ \rightarrow e^+ + \nu_e + \bar{\nu}_\mu \\
\pi^- \quad &\rightarrow \mu^- + \bar{\nu}_\mu \\
&\mu^- \rightarrow e^- + \bar{\nu}_e + \nu_\mu \\
\pi^0 \quad &\rightarrow \gamma + \gamma \\
K^{\pm} \quad &\rightarrow \mu^+/\mu^- + \nu_\mu/\bar{\nu}_\mu
\end{aligned}
$$

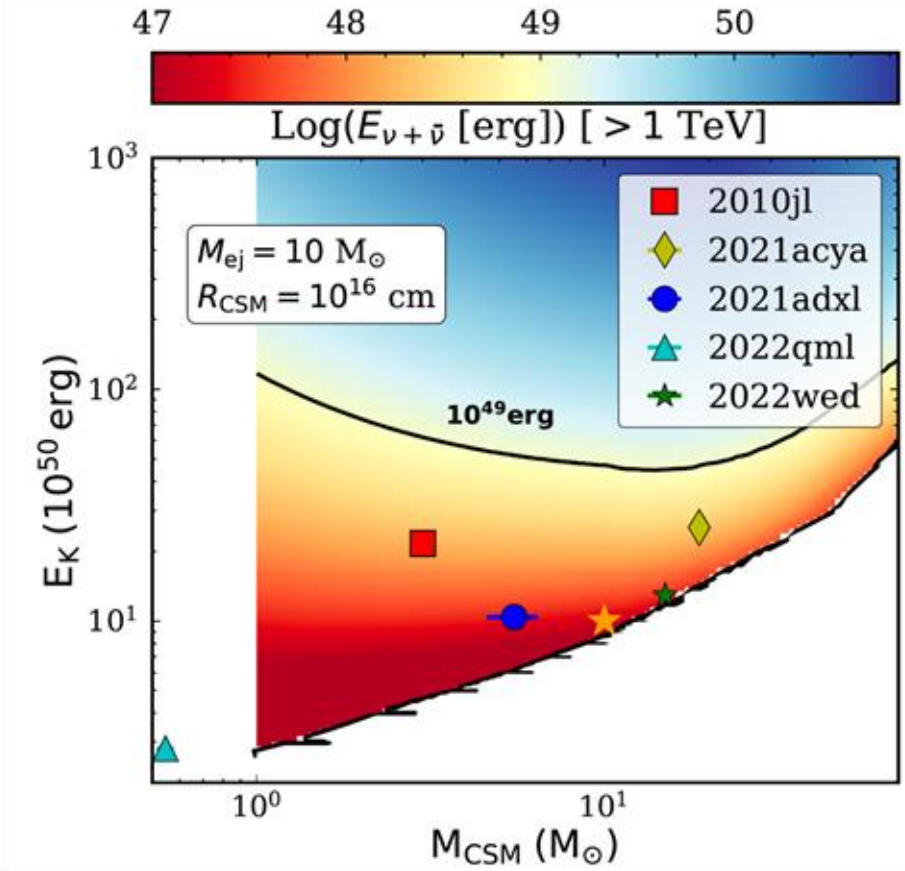
Salmaso 2024

But when will the emission happen?



Salmaso 2024





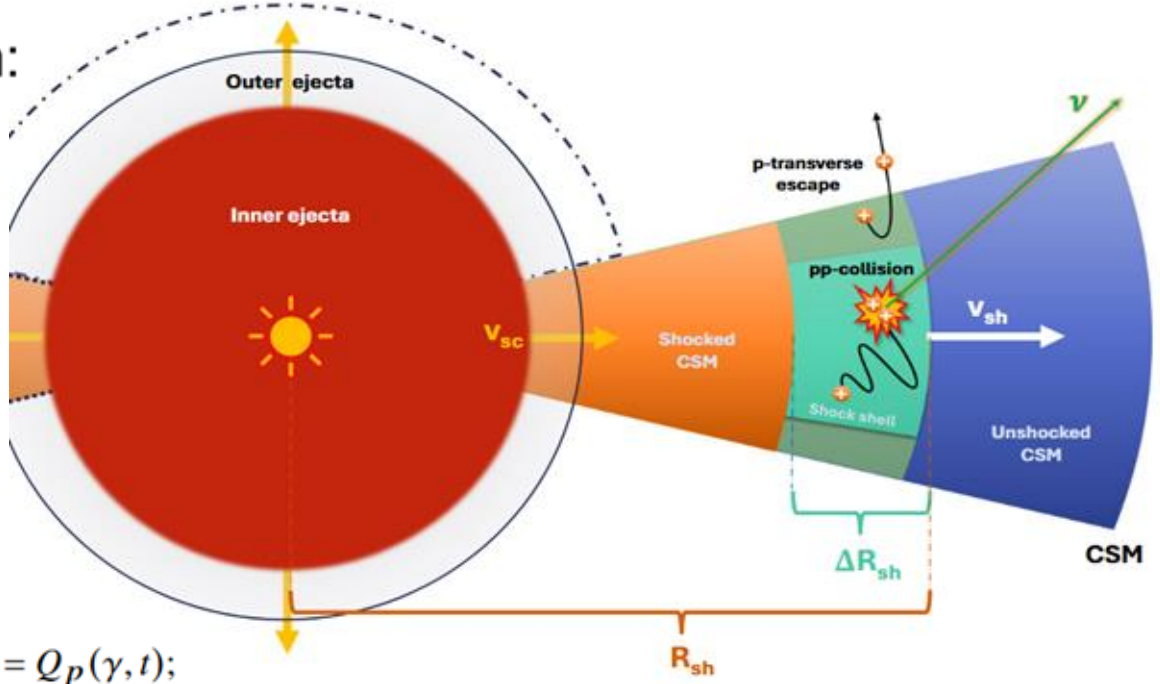
Salmaso, Cappellaro, Tartaglia, et. al 2025, A&A, 695, 29

High-energy Supernova neutrino emission

Cosentino, Pumo, Cherubini, 2025, MNRAS, 540, 2894

- Ejecta-CSM configuration:
  - $E_k, M_{ej}, R_0, \ldots$
  - $\mathrm{M}_{CSM}, \mathrm{R}_{CSM}, s$
- Proton distribution:

- Shock p-acceleration;
- Radiation cooling;
- pp-collisions;



$$\frac{\partial N_p(\gamma,t)}{\partial t} + \frac{\partial}{\partial \gamma}\left[\dot{\gamma}(t)\cdot N_p(\gamma,t)\right] + \frac{N_p(\gamma,t)}{t_{esc}(\gamma,t)} = Q_p(\gamma,t);$$

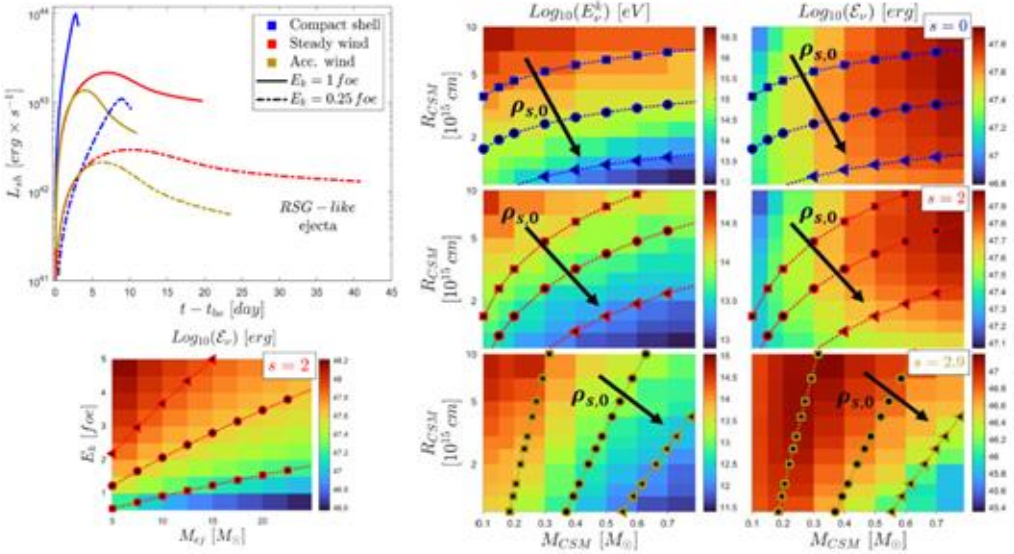
- Neutrino production rates:
  (see also Kelner et al. 2023, Phys. Rev. D)

$$\bar{Q}_{\nu+\bar{\nu}}(E_\nu,t) = \int_0^1 \sigma_{pp}\left(\frac{E_\nu}{x m_p c^2}\right)\cdot N_p\left(\frac{E_\nu}{x m_p c^2},t\right)\times F_\nu(x,E_\nu/x)\cdot d(\ln x).$$

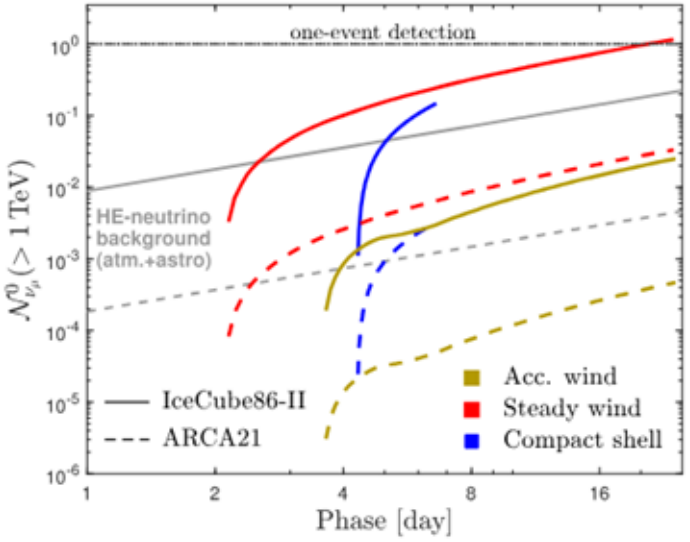
SN explosion parameters & HE-neutrinos

Cosentino, Pumo, Cherubini, 2025, MNRAS, 540, 2894; Cosentino Pumo, Cherubini, 2024,NCimC, 357

Ejecta-CSM interaction phase: e.m. & neutrino emissions



"Neutrino Signal" at Earth

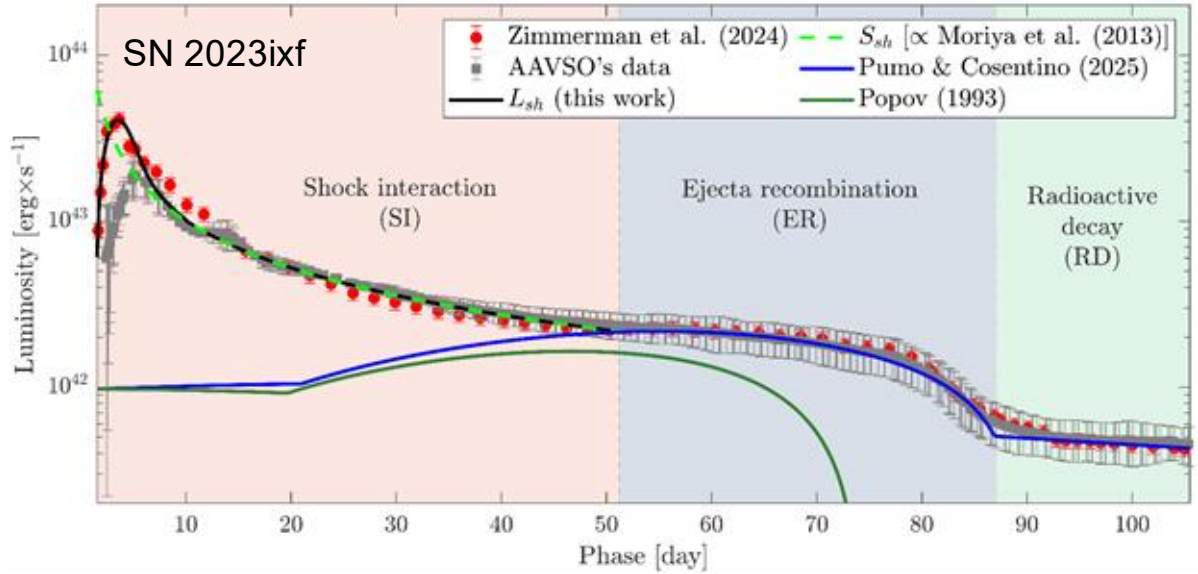


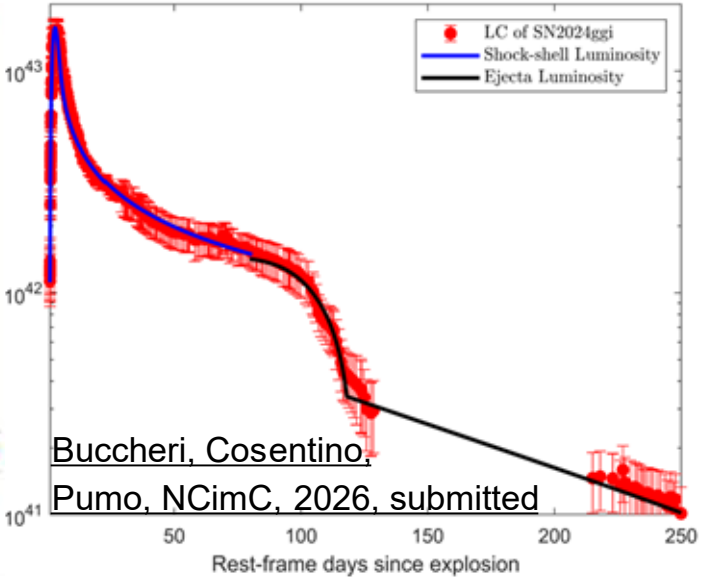
- "strong" dependence on E_k, M_{ej}, M_{CSM} and R_{CSM}, confirming what found in other works (e.g. Pitik et al. 2022, ApJ; Sarmah et al. 2022, JCAP)
- "strong" dependence on the spatial matter distribution inside the CSM
- analyzing the "whole" (i.e. also post-peak) SN e.m. emission to accurately characterize the physical condition of SN progenitor + CSM at explosion

Electromagnetic modeling of SN transients

Pumo, Cosentino, Pastorello et al., 2023, MNRAS, 521, 4801; Pumo & Cosentino, 2025, MNRAS, 538, 223; Cosentino, Pumo, Cherubini, 2025, MNRAS, 540, 2894; Cosentino, Inserra, Pumo, 2026, A&A, accepted;

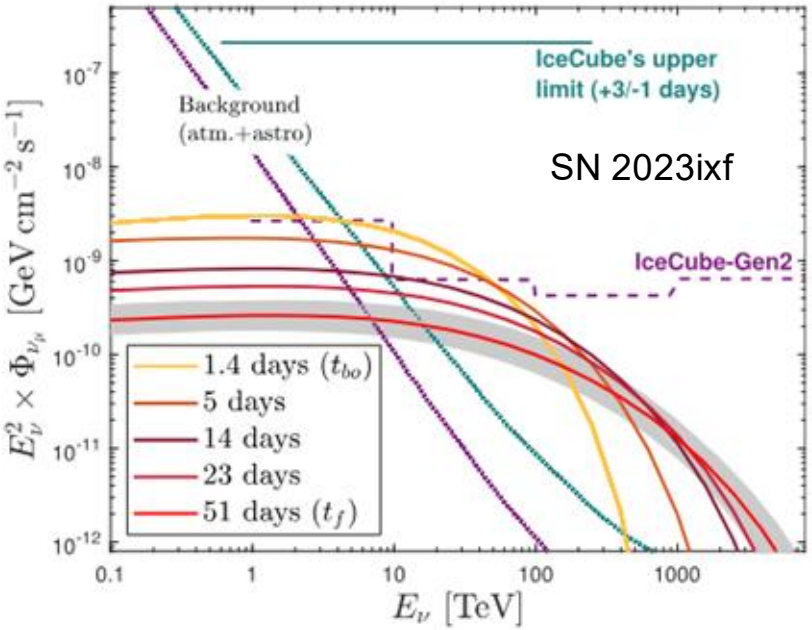
- Spectral-informed modeling through early narrow lines analysis;
- Light Curve modeling from “break-out” up to late post-explosive phases;
- Inference of Explosion and CSM parameters through bayesian and ML modeling;

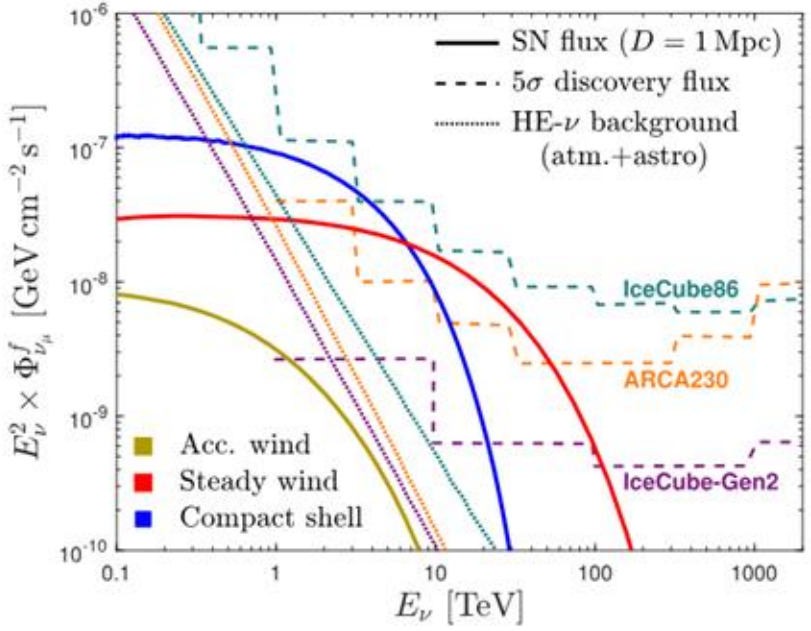




HE-ν detector sensitivity for interacting SNe

Cosentino, Pumo, Cherubini, 2025, MNRAS, 540, 2894





- Optimization of time-window for neutrino signal research through e.m. information;
- Significance of neutrino signals considering astrophysical muon background;
- Estimation of Cosmic Rays production efficiency in young SN explosion;

Further comments and future perspectives

- A physical interpretation of initial brightness and spectral narrow features can reveal the effective CSM-ejecta interaction in SN events (e.g., Tartaglia et al., 2025, A&A, 703, A177);
- Machine learning and Bayesian networks could be used to speed up the explosion parameter inference (Cosentino, Inserra, Pumo, 2026, A&A, accepted; Grassia, Cosentino, Pumo, Mangioni, 2025, IEEE, proceeding; Grassia, Cosentino, Mangioni, Pumo, Sci. Reports-Nat., submitted);
- The observation of neutrinos from SNe could provide definitive evidence of the CSM-ejecta interaction process (e.g. Cosentino, Pumo, Cherubini, 2025, MNRAS, 540, 2894);
- SNe around 5-20 Mpc, such as SN 2023ixf and SN 2024ggi, are ideal candidates for the search for high-energy neutrinos through large-volume neutrino detectors like IceCube and KM3Net (e.g. Buccheri, Cosentino, Pumo, NCimC, submitted; Pumo et al., A&A, in preparation).

Up next

Foster collaboration between supernova and neutrino researchers

Compute detection probabilities based on observations

ICECUBE
GEN2