Low- and High-energy neutrinos from SN 2023ixf in M101

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SN 2023ixf

SN 2023ixf is a type II supernova exploded on May 19 2023 in the M101 galaxy (D=6.4 Mpc):

→ Second closest Core-Collapse Supernova (CCSN) observed in the 21st century

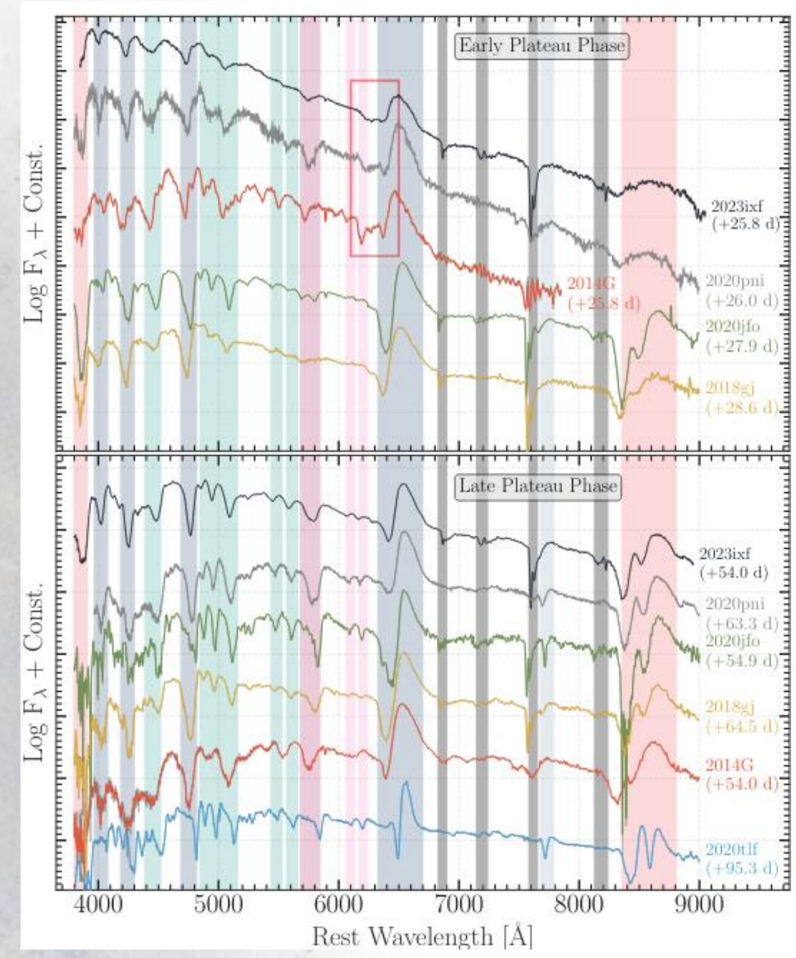
→ One of the brightest SN IIP/L ever observed in UV

→ Estimated progenitor: RSG with mass ~ <u>10-14</u> $M_\odot$, radius ~ 470 $R_\odot$

→ Estimated explosion energy: $E \approx 2 \times 10^{51}$ erg

→ Spectroscopic observations hinted to a possible interaction of the SN with a confined dense CSM

Aim of this work was to estimate the number of neutrino expected from this SN both at low energy (~ MeV) from Super-kamiokande (Super-K) and Hyper-kamiokande (Hyper-K) and at high energy (> 100 GeV) from IceCube telescope



Comparison of the early and late plateau phase spectrum of SN 2023ixf with other SNe II from the literature with signatures of CSM interaction in the top and bottom panels, respectively. Credits to [1]

Low energy neutrinos from CCSNe

CC-SNe are one of the most powerful cosmic sources of neutrinos in the Universe. It is expected that, during the burst, 99% of their energy is emitted as neutrinos with energies in the MeV energy band

→Confirmed by SN1987A data

Most favored model for CC explosion mechanism is the "Delayed neutrino-heating mechanism"

→A process where neutrinos emitted from the proto-neutron star reheat the stalled shockwave, reviving it to trigger the supernova explosion.

→All flavors of neutrinos and anti-neutrinos are expected to be produced.

The limited statistics of SN-ν prevented a full understanding of the mechanism that drives a supernova explosion. Many models have been proposed to simulate the expected neutrino emission from supernovae, employing a variety of different approximations and simplifying assumptions.

Models for low energy neutrino emission

Several models have been considered to evaluate the expected neutrino flux from SN 2023ixf:

Livermore model

- 1D simulation
- 20 $M_\odot$ progenitor
- $L_{\bar{\nu}_e} = 2.9 \cdot 10^{53}$ erg
- Until 18 s after core bounce

Nakazato model

- 1D simulation
- 13 $M_\odot$ progenitor
- $L_{\bar{\nu}_e} = 7 \cdot 10^{52}$ erg
- Until 20 s after core bounce
- Advanced neutrino transport
- Can include ν oscillations (not considered)

Fornax model

- 2D simulation
- 13 $M_\odot$ progenitor
- $L_{\bar{\nu}_e} = 8 \cdot 10^{52}$ erg
- Until 20 s after core bounce
- Can include ν oscillations (not considered)

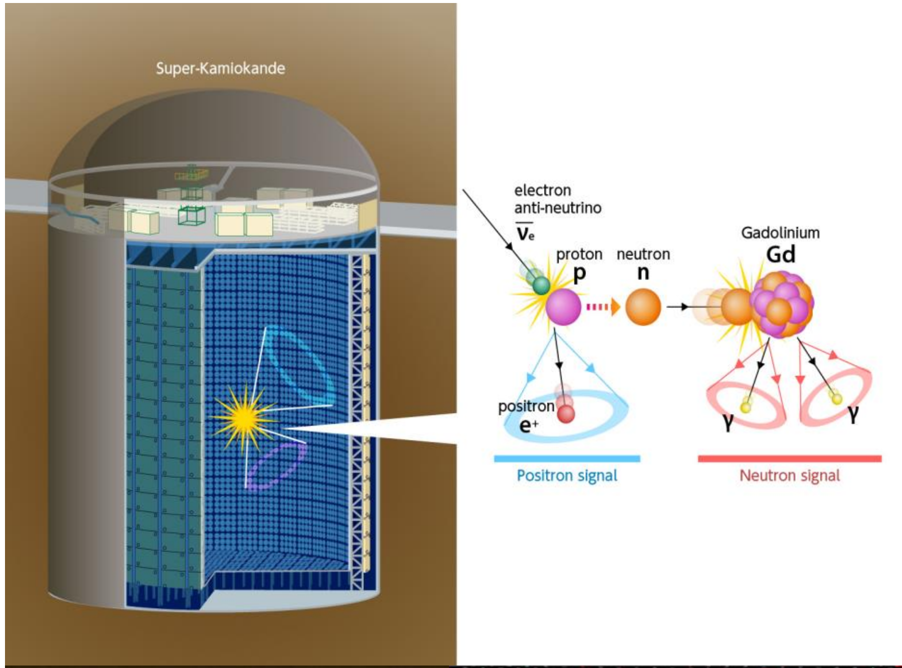
Vissani model

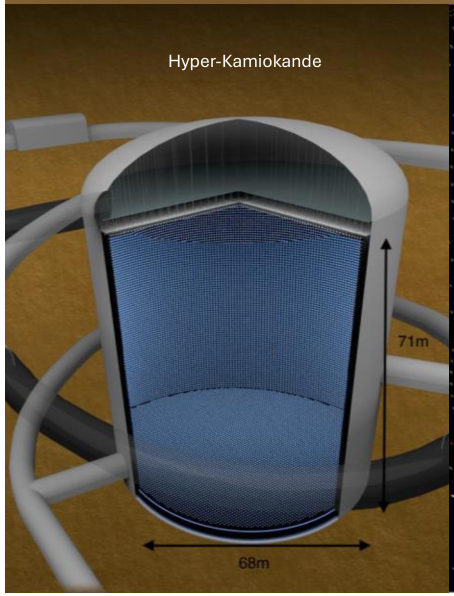
- Parametrized $\bar{\nu}_e$ flux based on SN 1987A
- 18 $M_\odot$ progenitor
- $L_{\bar{\nu}_e} = 5 \cdot 10^{52}$ erg
- Until 20 s after core bounce
- Can include ν oscillations (not considered)

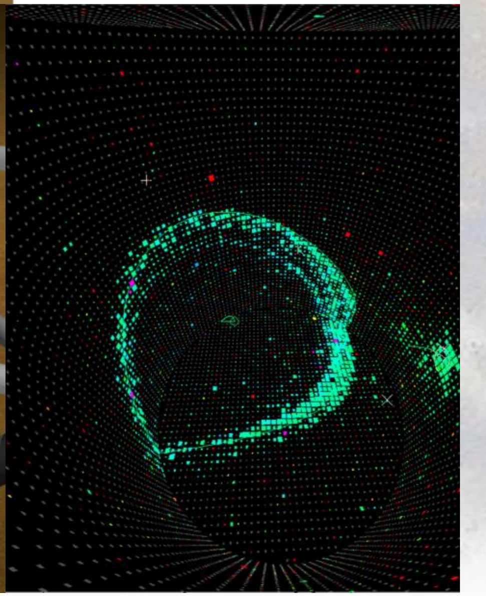
Nakamura model

- 2D simulation
- 17 $M_\odot$ progenitor
- $L_{\bar{\nu}_e} = 5 \cdot 10^{52}$ erg
- Until 7 s after core bounce
- ν oscillations included

(only for Hyper-K)







Super-Kamiokande

- Located at Kamioka, Japan.
- 50 kton of ultra pure water tank, 22.5 kton for analysis fiducial volume.
- 20-inch PMTs, 11,129 for ID.
- Water Cherenkov light technique → Energy, direction, particle ID
- Since 2020 SK-Gd → Gadolinium loading to improve neutron capture
- Currently running with 0.03% gadolinium by mass

Physics target

- Atmospheric neutrino
- Astrophysical neutrino: solar, transient sources, supernova neutrinos, Diffuse Supernova Neutrino Background (DSNB)
- Proton decay
- Reactor neutrinos
- Accelerator Neutrinos (far detector of T2K experiment)

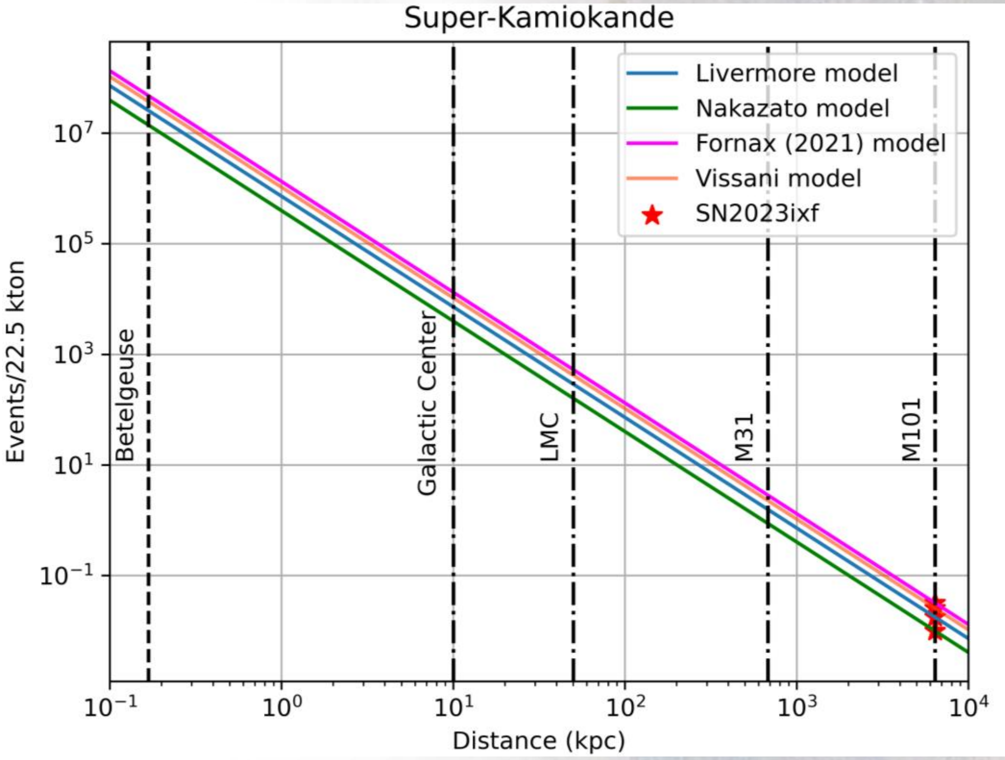
Hyper-Kamiokande

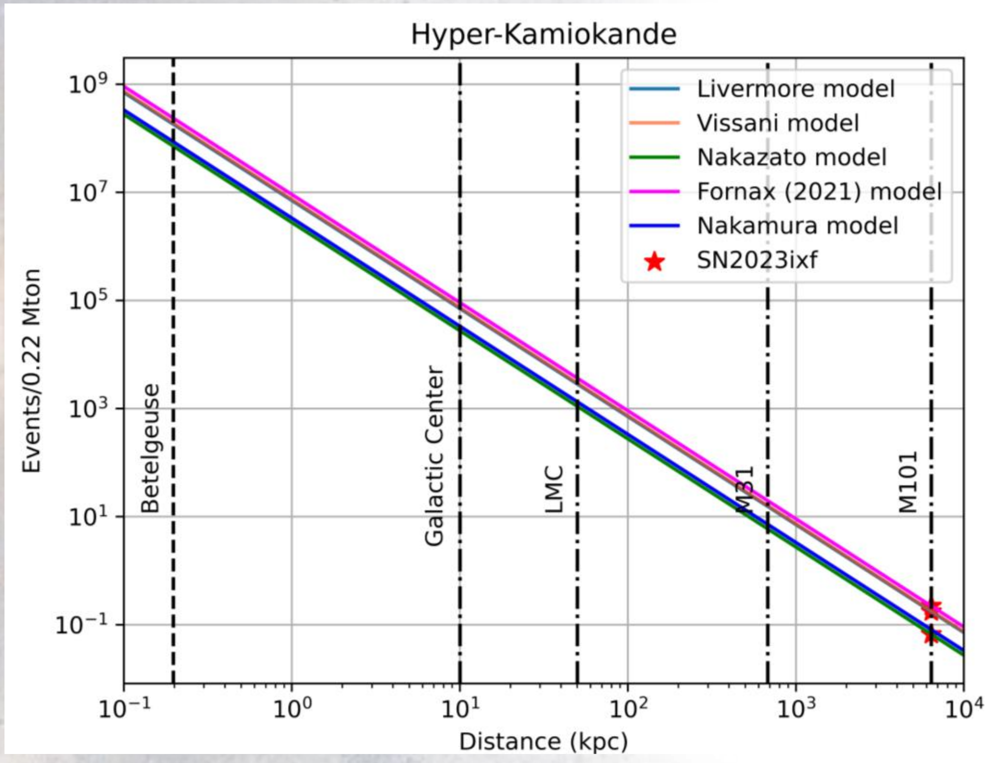
- Larger detector (x8 SK) for increased statistics
- Improved photo-sensors for better efficiency
- Higher intensity beam and updated/new near detector for accelerator neutrino part
- Construction began in 2021 and should be completed by 2027

→ Main phyisics target will be CP violation in lepton sector confirmation
→ Higher sensitivity to astrophyisical neutrinos

Low energy neutrinos from CCSNe
Super-K & Hyper-K expectations

Expected number of $\bar{\nu}_e$ as a function of ditance for Super-K and Hyper-K





→ Sub-threshold (<1) events in both cases
→ Super-Kamiokande confirmed the lack of detection of neutrinos from SN 2023ixf

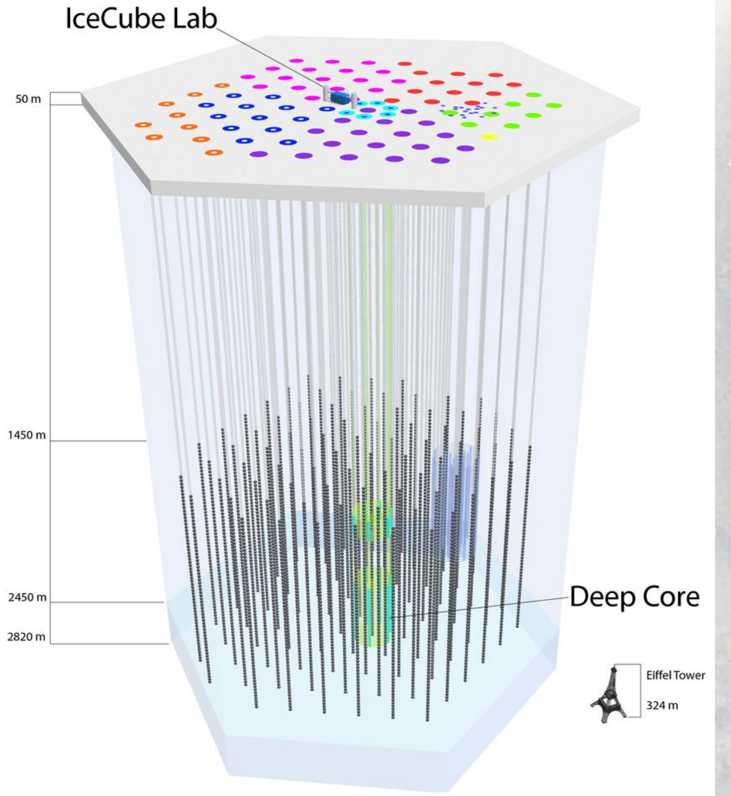
High energy neutrinos from CCSNe

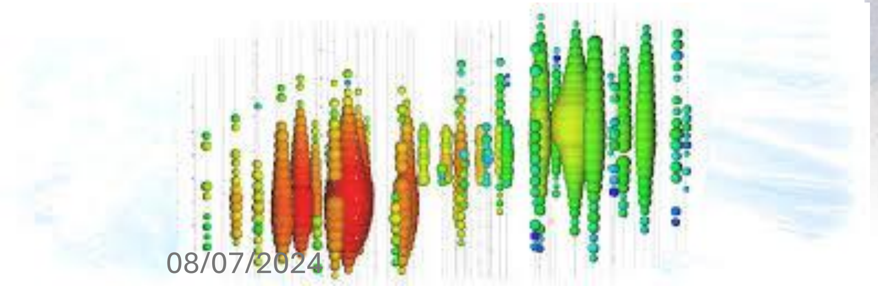
Two models were considered to evaluate the expected number of high energy neutrinos from SN 2023ixf:

1. In core-collapse events, jets form but often get trapped inside the star due to its outer layers (chocked jets). These trapped jets create energy similar to supernovae. Internal shocks in the jets can accelerate protons, producing high-energy neutrinos. If the jets can't break through the star's outer layers, only these neutrinos can escape.

2. Collisions between supernova ejecta and the dense circumstellar medium (CSM) can accelerate protons. These accelerated protons can then interact with CSM protons to produce high-energy neutrinos. If around 10% of the supernova's energy goes into accelerating protons, multi-TeV neutrinos should be detected later than the optical and infrared peaks.

IceCube telescope





- **Detector**

- Located at the geographic South Pole
- Total surface area of roughly 1 km^2
- 86 vertical strings arranged with 60 digital optical modules (DOMs) each
- Depths between 1450 m and 2450 m

- **Physics target**

- Detection and study of astrophysical neutrinos
- Investigating the sources and mechanisms of cosmic ray acceleration
- Search for dark matter
- Neutrinos properties (oscillations, mass hierarchy)
- Exotic physics

High energy neutrinos from chocked jets (1)

During jet propagation, a forward shock and a reverse shock (RS) are produced.

In the RS region, photons may be produced due to electron synchrotron emission. Due to large optical thickness, they thermalize at:

$$kT_\gamma \sim 313 eV L_{50}^{1/8} e_{e,-1}^{1/4} t_{jet,3}^{-1/4} \rho_{H,-7}^{1/8}$$

Photon density in the RS region will then follow the Planck distribution:

$$n_\gamma = \int_0^\infty \frac{dN_\gamma}{dE_\gamma} dE_\gamma \sim 16\pi\zeta(3)(\frac{kT_\gamma}{hc})^3$$

Due to inhomogenities, internal shocks (IS) can be produced and dissipate jet kinetic energy to accelarate protons. Based on [2], photon density in the IS region will be:

$$n_{\gamma,IS} = \Gamma\, n_\gamma f_{esc} \sim 1.9 \times 10^{20} cm^{-3} \Gamma_2^2 L_{50}^{-3/4} t_{jet,3}^{1/2} \rho_{H,-7}^{-1/4}$$

High energy neutrinos from chocked jets (2)

We consider neutrinos produced by photo-meson interaction between photons produced in RS region and protons accelerated in IS region. High energy cut-off due to the photo-meson cooling of protons, and the synchrotron cooling of pions and muons is taken into account.

→ Cut-off energy due to proton synchrotron radiation and adiabatic loss:

$$E^{IS}_{cut,15} \sim 0.066 \epsilon^{1/2}_{b,-1} \epsilon^{-3/4}_{e,-1} L^{5/8}_{50} \Gamma_2^{-3} t^{-1/4}_{jet,3} \rho^{1/8}_{H,-7}$$

Consequently, the following proton spectrum in the IS region is assumed:

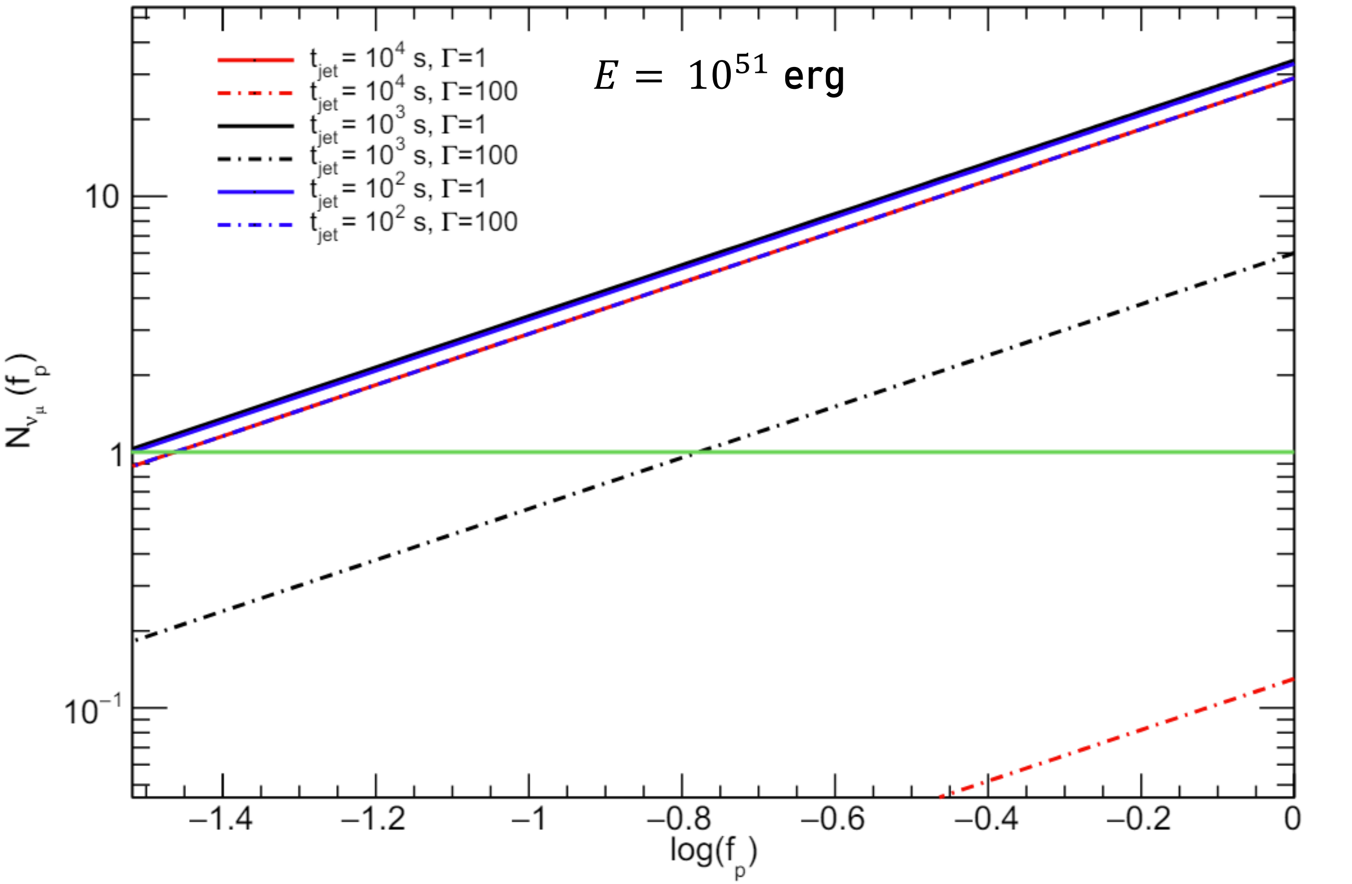
$$\frac{dN_p}{dE_p} \propto E_p^{-2} \quad \text{for } E < E_p, cut$$

$$\frac{dN_p}{dE_p} \propto E_p^{-2} e^{\frac{E_p - E_{p,cut}}{2E_{p,cut}}} \quad \text{for } E > E_p, cut$$

Neutrino spectrum distribution due to photo-meson interaction is obtained through numerical simulation.

High energy neutrinos from chocked jets (3)

IceCube expectations



Expected number of neutrinos in IceCube telescope, as a function of the baryon loading f_p for different sets of the parameters t_{jet} and Γ.

Different set of parameters have been tested:

$t = 100, 10^3, 10^4\ s$ *Duration of the jet*
$\Gamma = 1, 100$ *Lorentz factor*
$fp \in [0, 1]$ *Baryon loading*

Highest number of neutrinos expected for:
$\Gamma = 1, t = 10^3$ s

No detection expected for:
$\Gamma = 100, t = 10^4$ s

IceCube confirmed that no neutrinos were observed in a time window of +-2 days

High energy neutrinos from collision with CSM

SN ejecta may crash into the dense CSM shells. A significant fraction of the ejecta kinetic energy is converted to the internal energy of the shocked shells.

Protons can be accelerated at the shocks and interact with the protons present in the external medium via pp scattering, producing high energy neutrinos.

Expected muon neutrino fluence:

$$E_\nu^2 \phi_\nu \sim 6 \times 10^{-2}\ GeV\ cm^{-2} \min[1, f_{pp}]\, \epsilon_{cr,-1} \varepsilon_{ej,51} d_1^{-2}$$ [3]

In the case of SN 2023ixf, N~50 neutrinos with E > 1 TeV are expected.

Summary & Conclusions

Low energy neutrinos:

- Expected number of neutrinos below the detection threshold of the current Super-K and future Hyper-K neutrino telescope
- Consistent with lack of detection confirmed by Super-Kamiokande Collaboration

High energy neutrinos:

- SN 2023ixf is a standard type II core collapse with no significant high-energy neutrino emission detected by IceCube telescope.
- Lack of detection explained by:
  I. Small fraction of kinetic energy ($f_p < 10\%$) converted to proton acceleration for both models assumed. Costraint become more stringent if $E=10^{53}$ erg is assumed ($f_p < 1\%$)
  II. Long jet duration ($t_{jet} \sim 10^4$ s) and high Lorentz factor ($\Gamma \sim 100$) cause proton energy loss via synchrotron emission.
  III. Jets not driving SN 2023ixf explosion.

Future observations:

- Based on IceCube upper limit for SN 2023ixf and considering $\{E = 10^{51}$ erg, $f_p = 1$, $\Gamma = 1$, $t = 10^3$ s$\}$, the maximum distance at which this supernova could be detected by IceCube is $d_{max} = 22$ Mpc (Virgo Circle, $R_{SN} \approx 1$ per year)
- Similar results obtained for KM3NeT
- In few years, models may be confirmed by new observations

Thank you

References:

[1] Singh, A., Teja, R. S., Moriya, T. J., et al. 2024, arXiv e-prints, arXiv:2405.20989
[2] Fasano, M., Celli, S., Guetta, D., et al. 2021, JCAP, 2021, 044
[3] Murase, K., Thompson, T. A., Lacki, B. C., & Beacom, J. F. 2011, PhRvD, 84, 043003