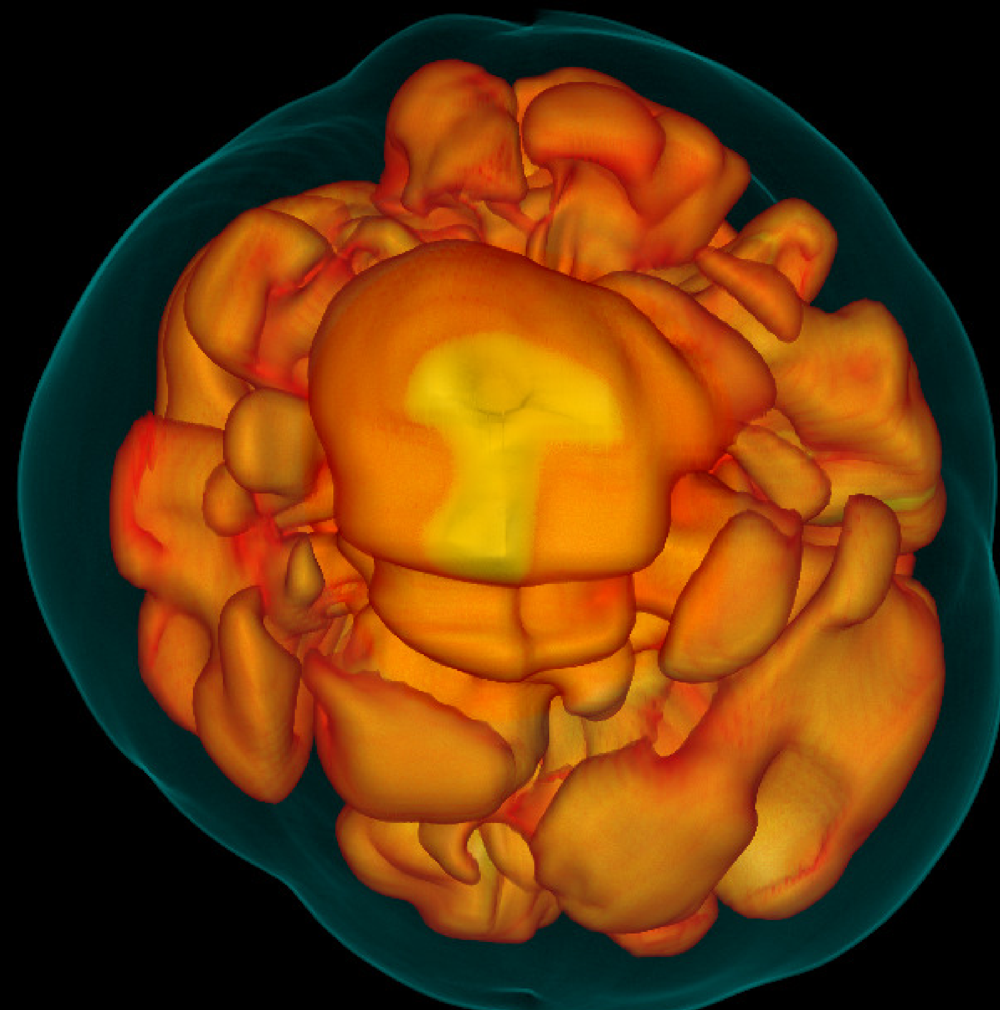
Neutrino News from the Transient Sky



Irene Tamborra (Niels Bohr Institute)

An Extraordinary Journey into the Transient Sky
Padova, April 1-4, 2025

VILLUM FONDEN

Sapere Aude

Funded by the European Union

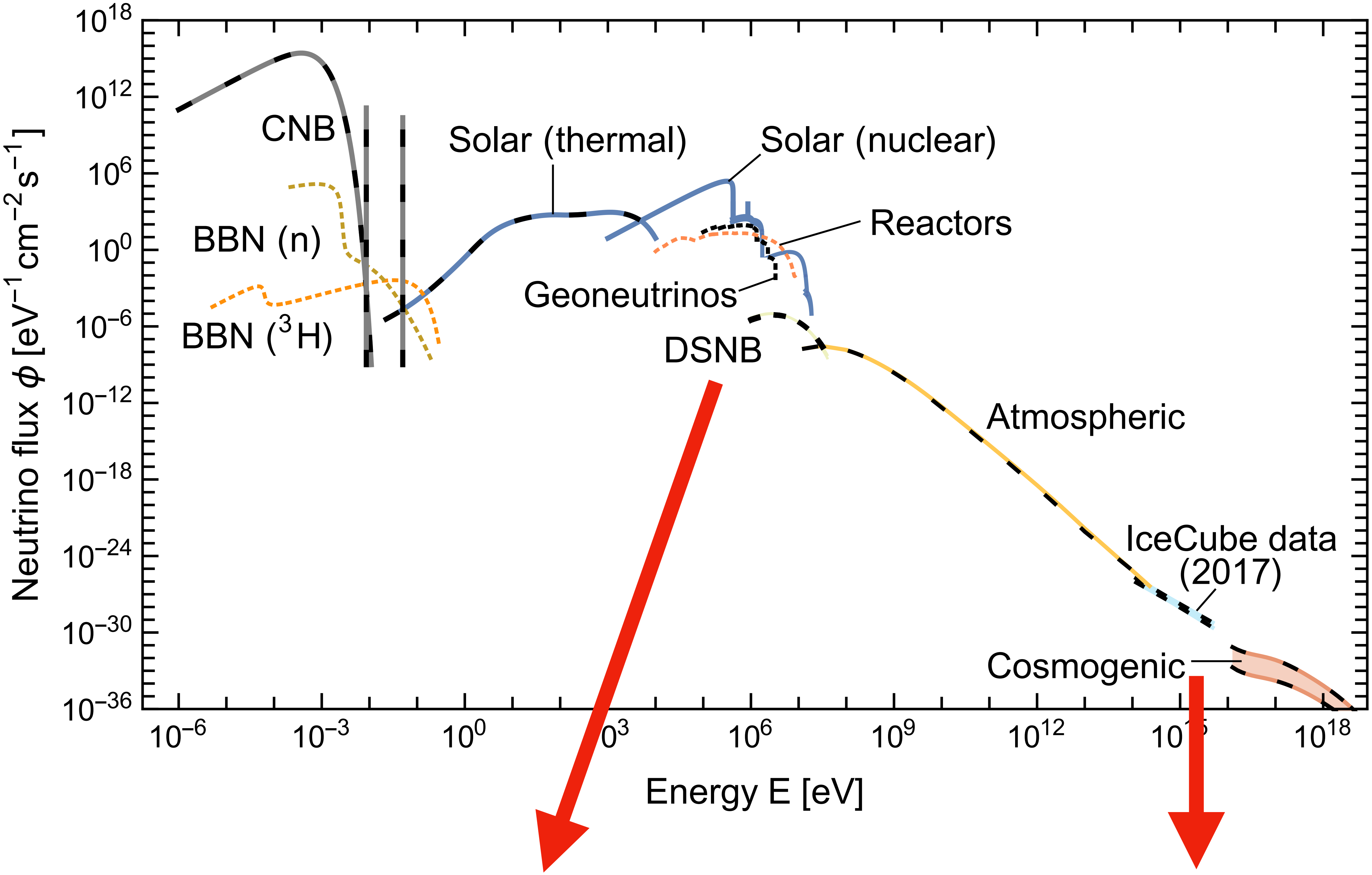
erc
European Research Council
Established by the European Commission

CARLSBERG FOUNDATION

SFB 1258
Neutrinos
Dark Matter
Messengers

The Cosmos in Neutrinos

Grand Unified Neutrino Spectrum



Produced in the stellar interiors
Super-Kamiokande [50 kton]

Produced in the stellar outskirts
IceCube, KM3NeT [Gton]

Vitagliano, Tamborra, Raffelt, Rev. Mod. Phys. (2020).

Exploring the Cosmos with Neutrinos

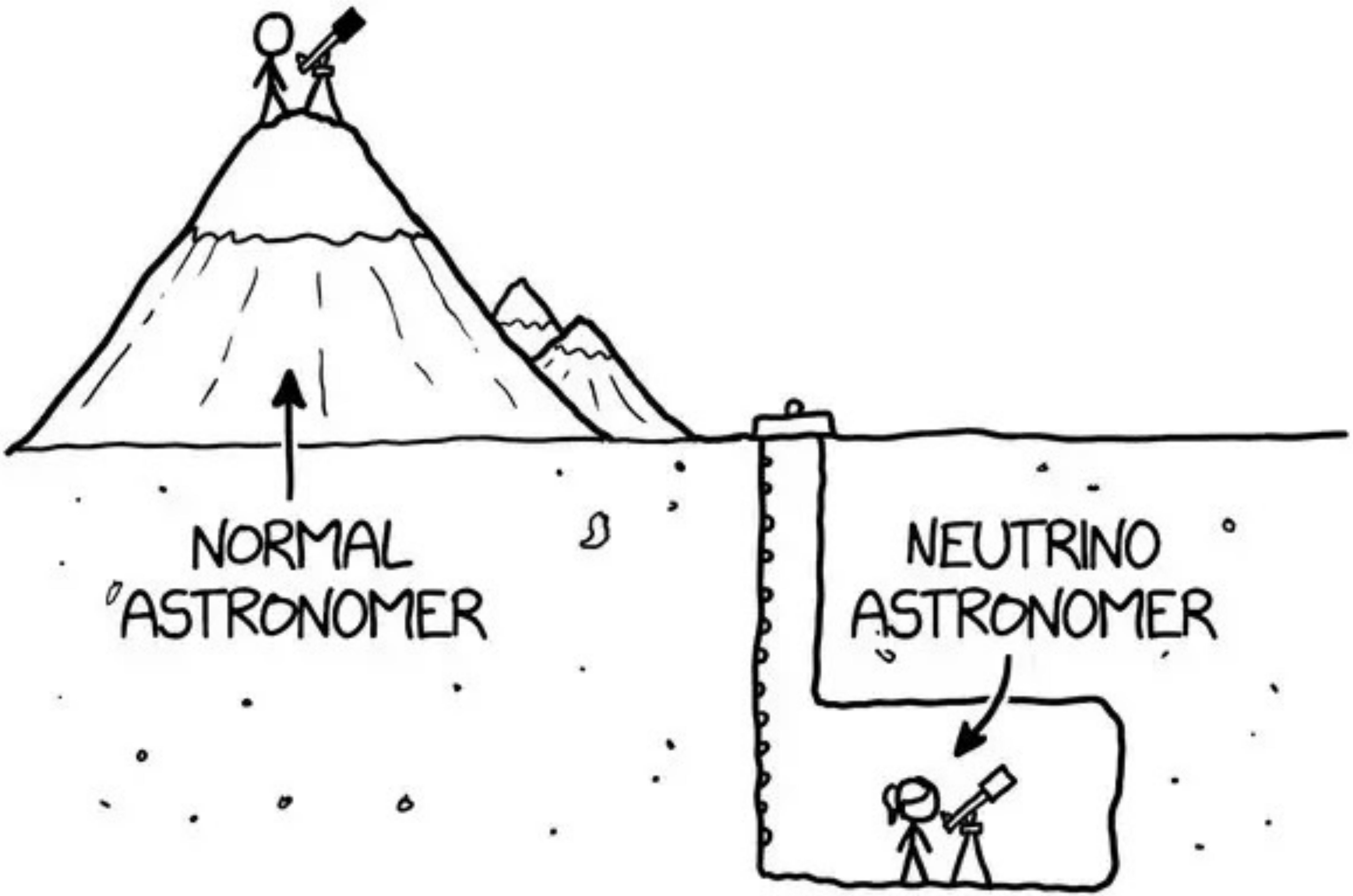


Figure credit: The New York Times.

Looking Ahed

Hyper-Kamiokande

ASAS-SN

ULTRASAT SKYLIGHT TO SPACE

LIGO VIRGO KAGRA

ICECUBE GEN2

ZWICKY TRANSIENT FACILITY

cta cherenkov telescope array

JUNO

DUNE DEEP UNDERGROUND NEUTRINO EXPERIMENT

SKA SQUARE KILOMETRE ARRAY

Pan-STARRS

ET EINSTEIN TELESCOPE

WEBB SPACE TELESCOPE

ATHENA

COSMIC EXPLORER

esa euclid

VLA SKY SURVEY

KM3NeT

P-ONE

VERA C. RUBIN OBSERVATORY

DARWIN

RES-NOVA

THE NANCY GRACE ROMAN SPACE TELESCOPE

SVOM

LISA CONSORTIUM

theseus TRANSIENT HIGH ENERGY SKY AND EARLY UNIVERSE SURVEYOR

and many more…

Neutrinos from the Supernova Interiors

Figure credits: Royal Society

The Next Local Supernova (SN 2XXXA)

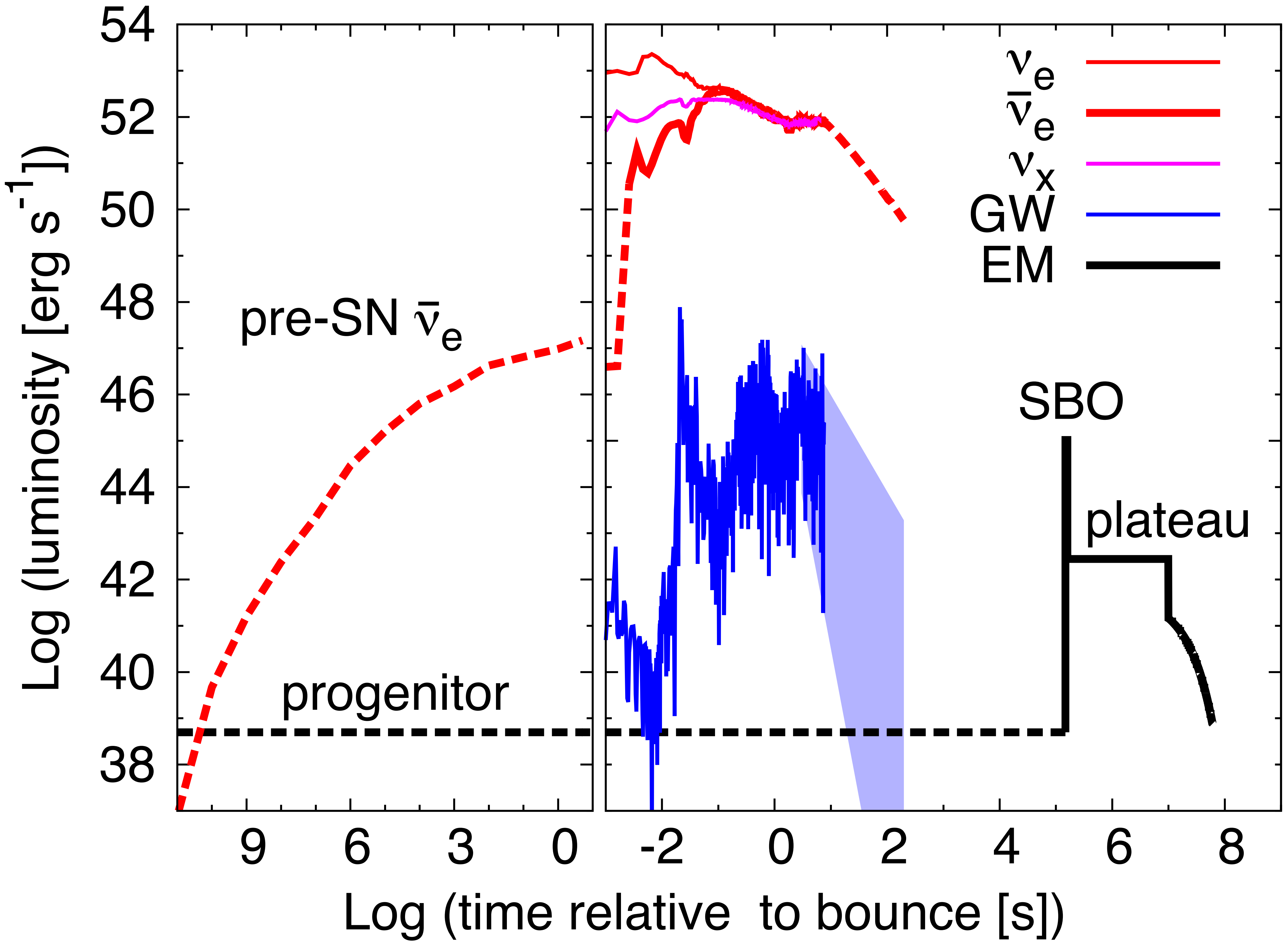
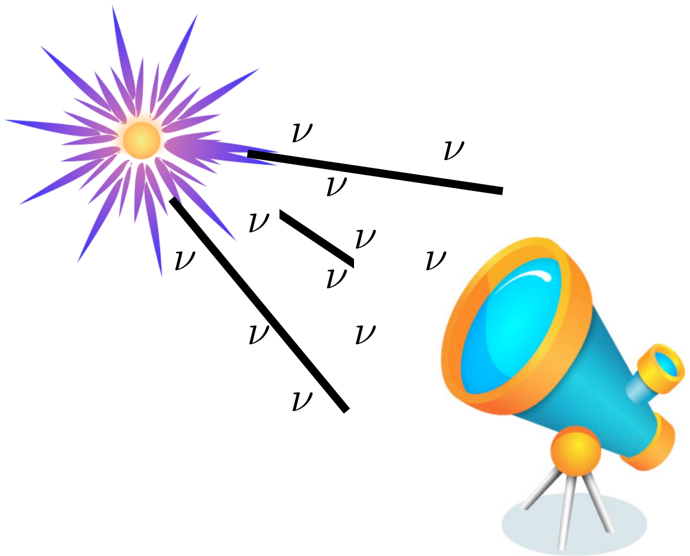
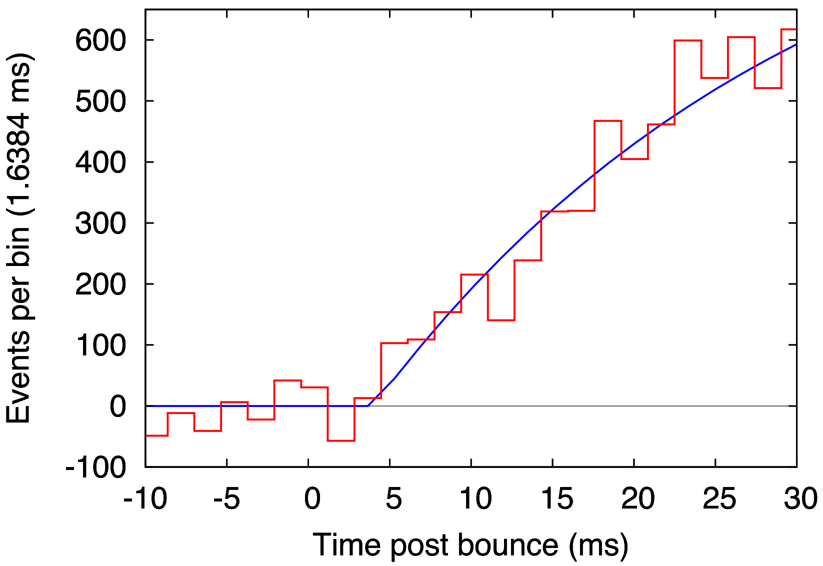


Figure from Nakamura et al., MNRAS (2016).

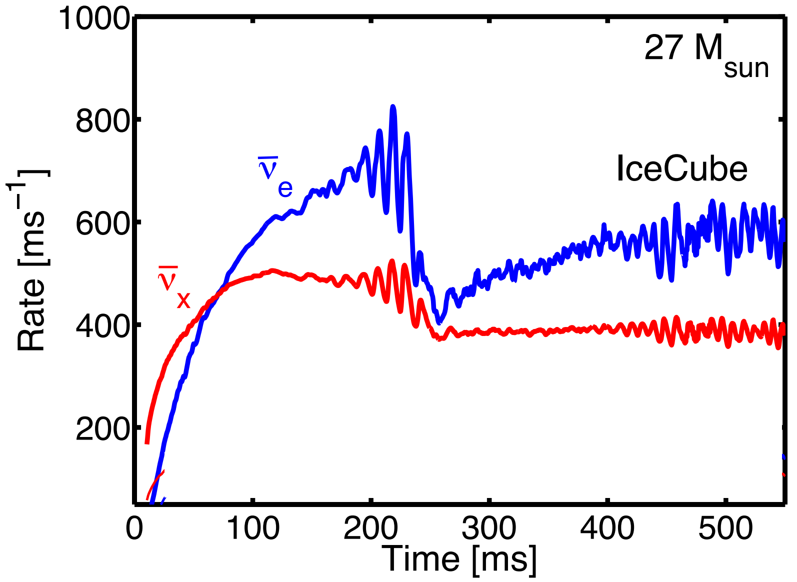
Neutrinos as Messengers



Determination of supernova direction with neutrinos.



Neutrinos as matched filter for gravitational wave detection.



Neutrinos and gravitational waves carry imprints
of supernova mechanism and proton-neutron star properties.

SNEWS 2.0, New Phys. J. (2021). Sarfati, Hansen, Tamborra, PRD (2022). Halzen & Raffelt PRD (2009). Nakamura et al., MNRAS (2016). Drago et al., PRD (2023). Tamborra et al., PRL (2013), PRD (2014). Walk, Tamborra et al., PRD (2018, 2019). Gallo Rosso et al., JCAP (2018); JCAP (2017).

The Next Nearby Supernova (SN 2XXXA)

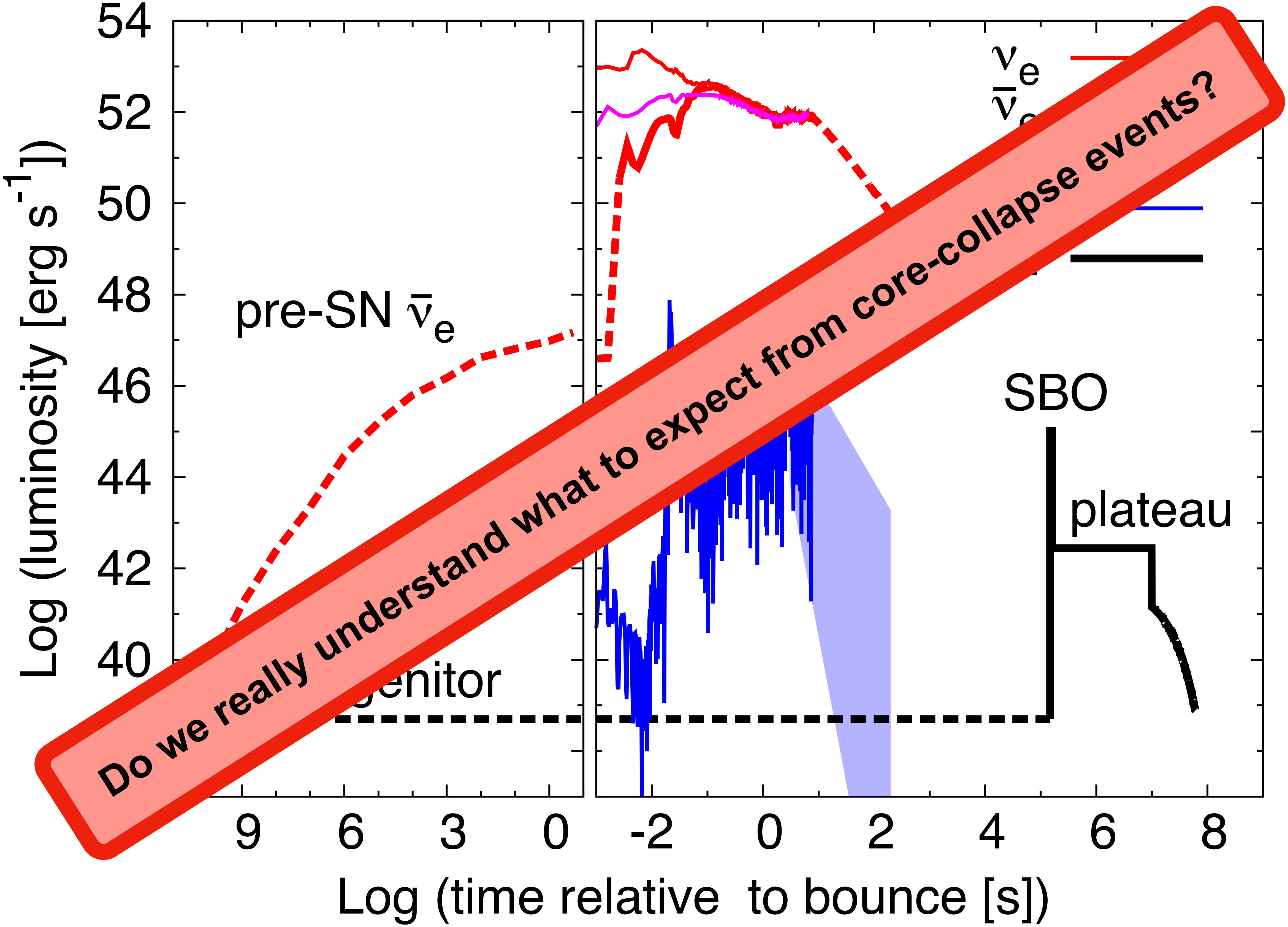
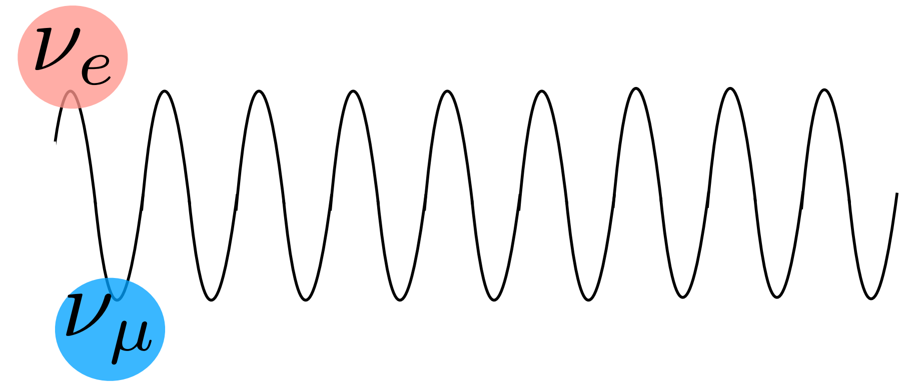


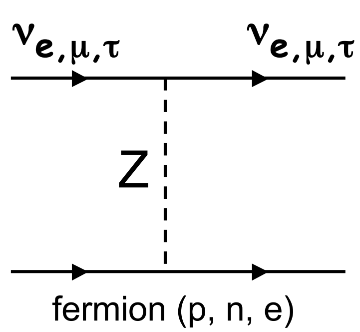
Figure from Nakamura et al., MNRAS (2016).

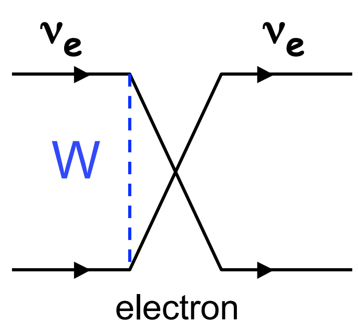
Neutrino Flavor Conversion

Vacuum

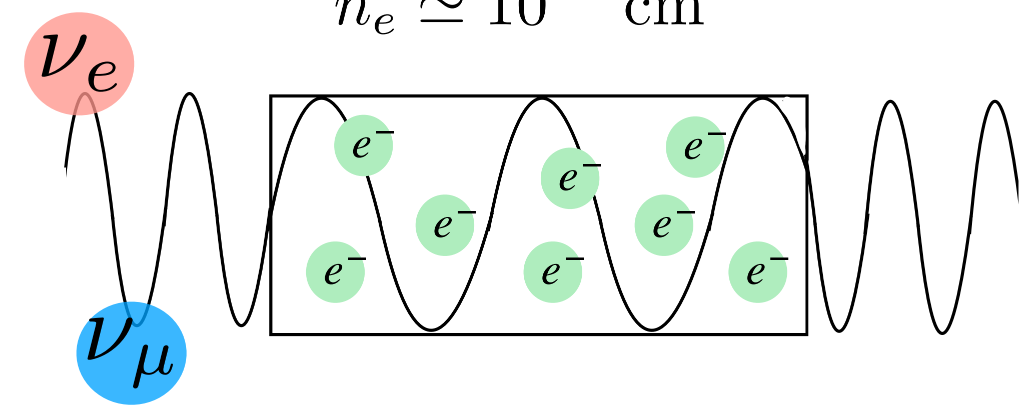


Neutrinos interact with background matter



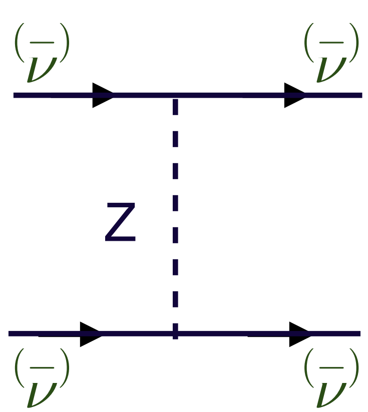


$n_e \simeq 10^{31}\ \mathrm{cm}^{-3}$

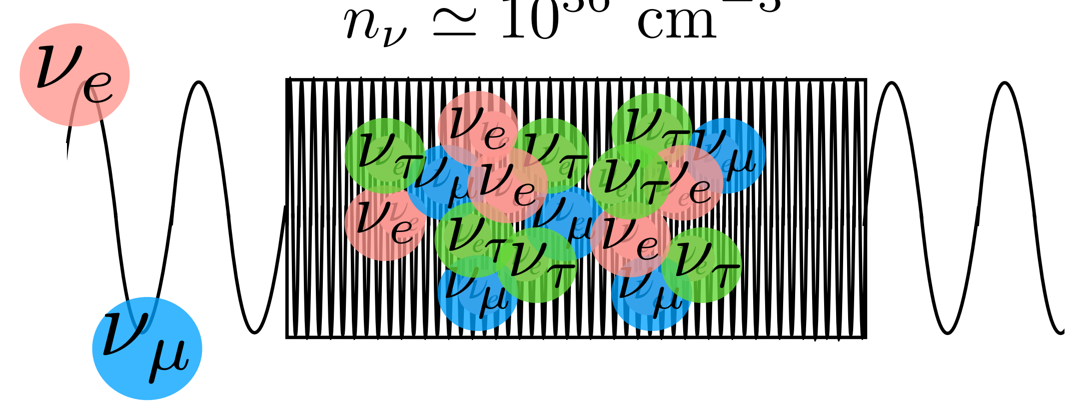


IMPACT ON FLAVOR CONVERSION POORLY UNDERSTOOD!

Neutrinos interact among themselves

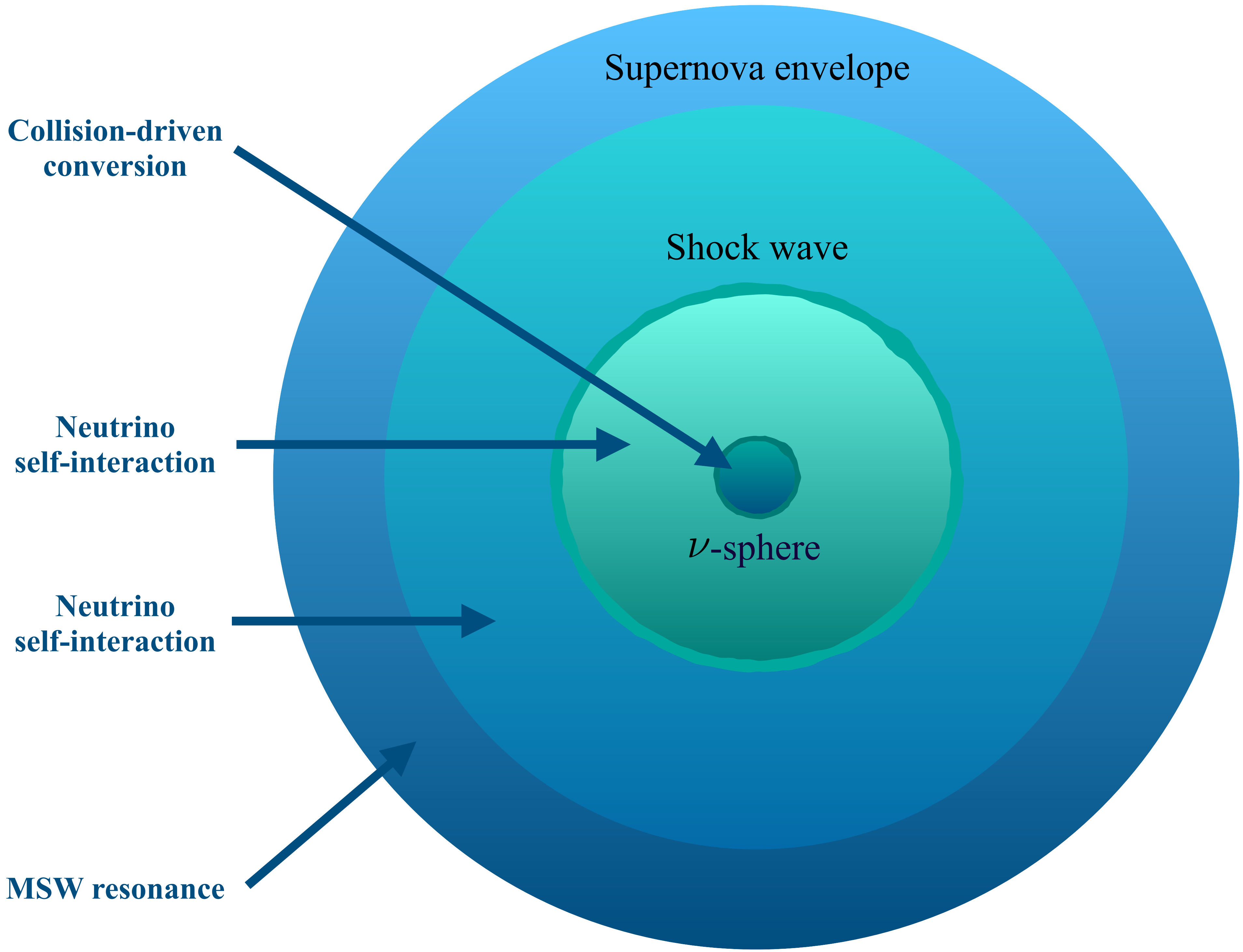


$n_\nu \simeq 10^{36}\ \mathrm{cm}^{-3}$



Recent review: Tamborra & Shalgar, Ann. Rev. Nucl. Part. Sci. (2021).

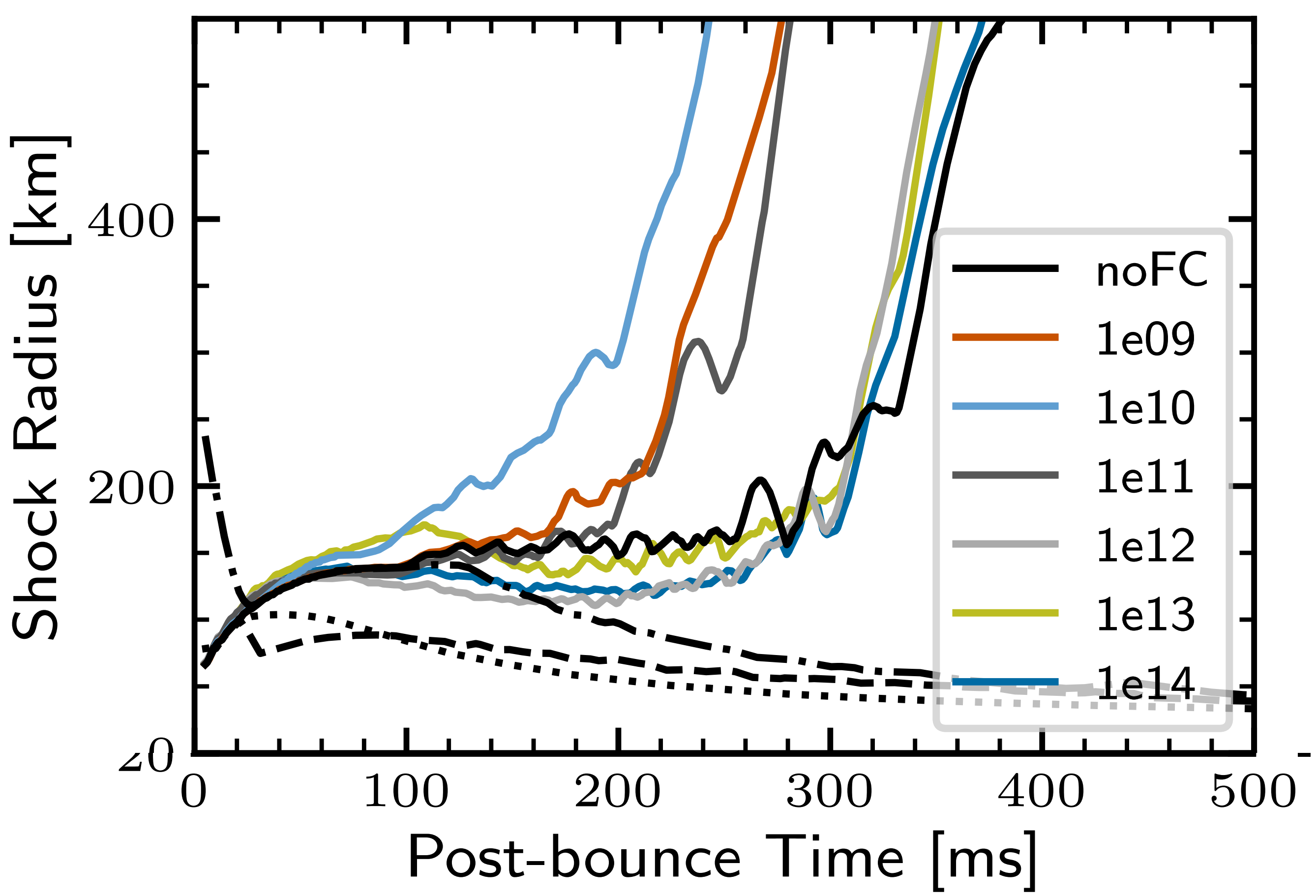
Does Flavor Conversion Affect the Supernova Mechanism & Nucleosynthesis?



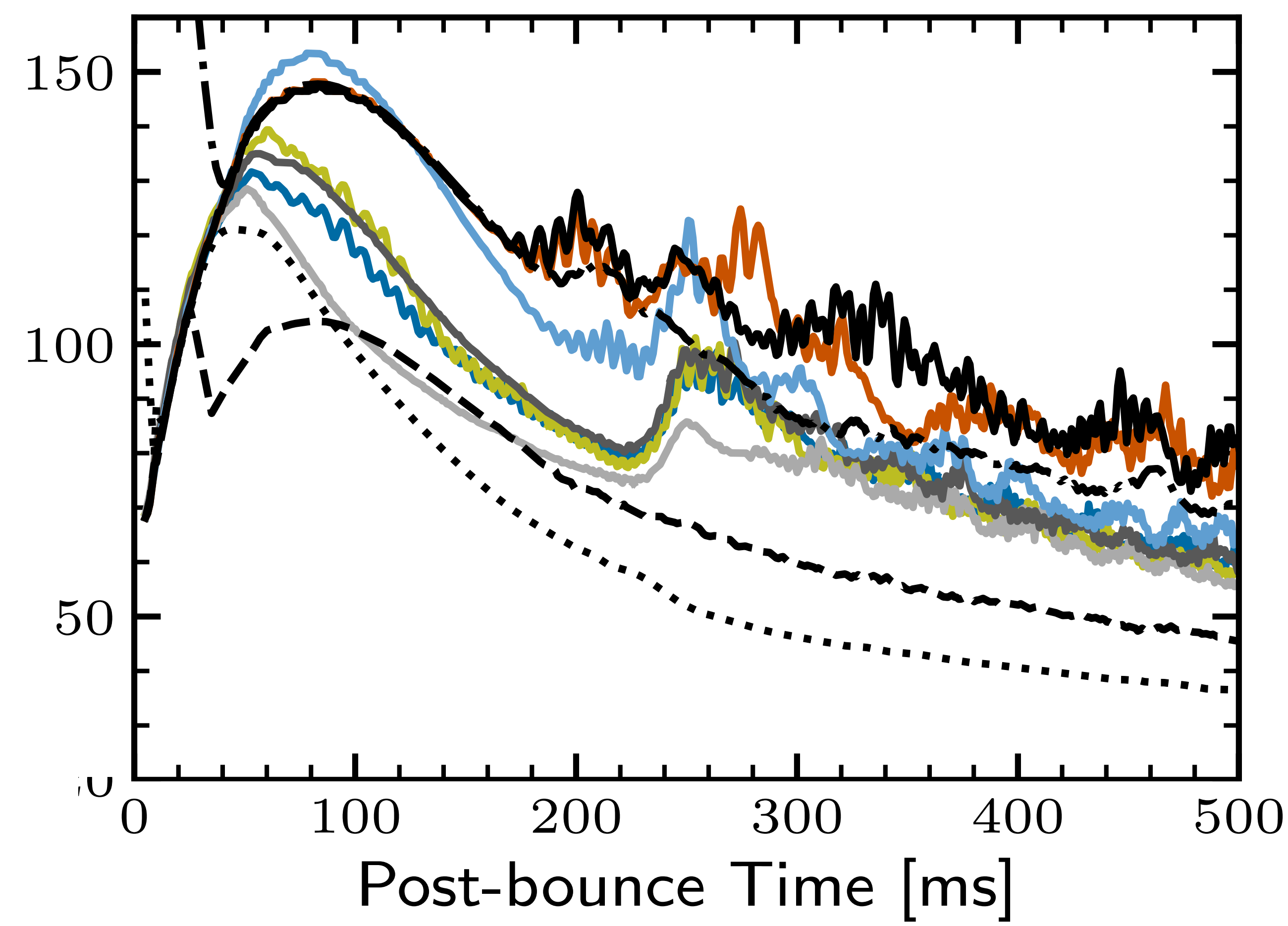
Recent review: Tamborra, arXiv: 2412.23258.

Flavor Conversion Affects the Supernova Mechanism

9 Msun



20 Msun



Flavor conversion aids the explosion for low-mass progenitors (9-12 Msun) and hinders explosion of high-mass models (20 Msun).

Ehring, Abbar, Janka, Raffelt, Tamborra, PRL (2023); PRD (2023). Nagakura, PRL (2023).

Neutrino Quantum Kinetic Equations

$$[\partial_t + \mathbf{v} \cdot \nabla_{\mathbf{x}} + \mathbf{F} \cdot \nabla_{\mathbf{p}}]\, \varrho = \mathcal{C}(\varrho, \bar{\varrho}) + \imath[\varrho, \mathbf{H}]$$

Advection

External field

Density Matrix

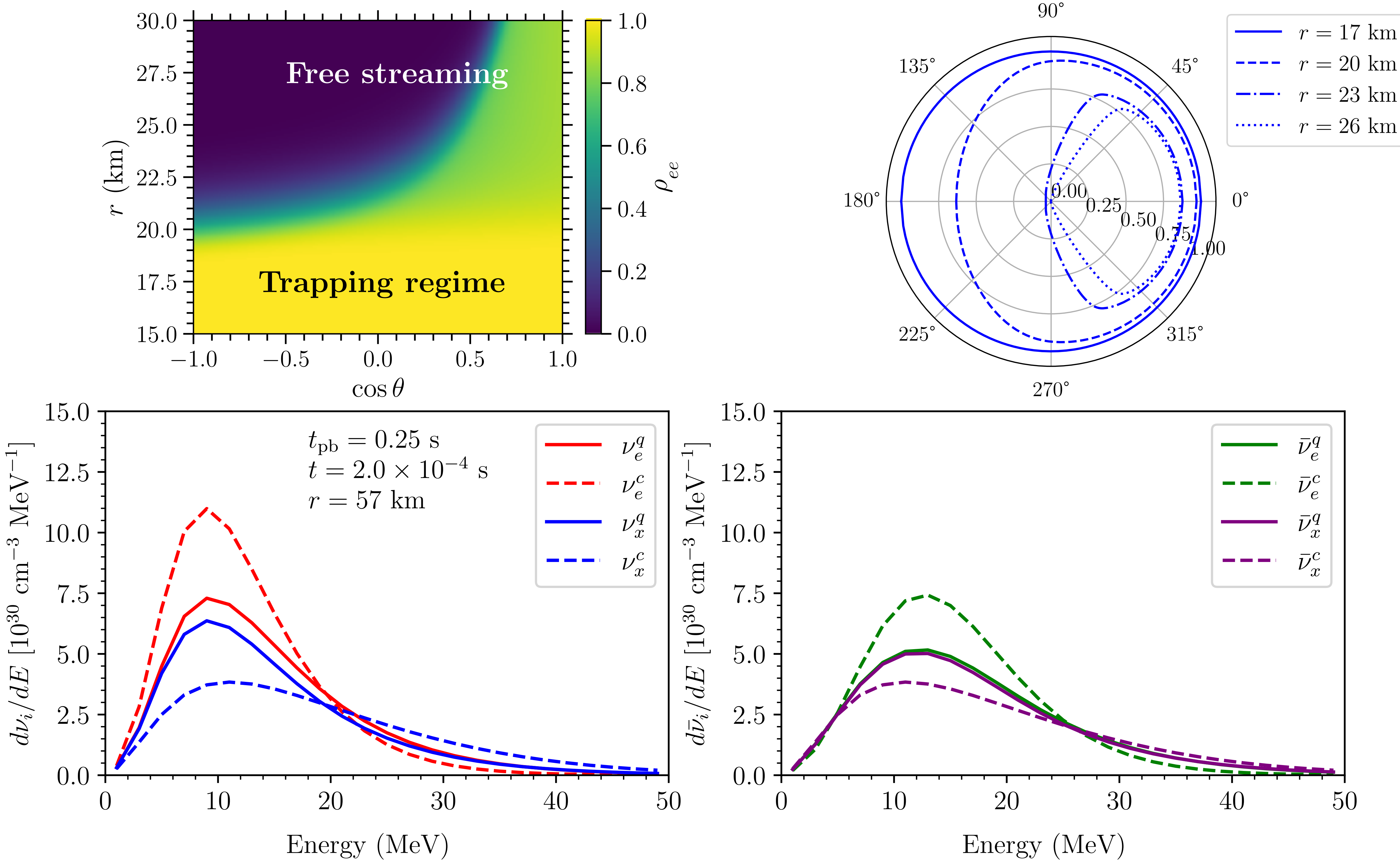
Collisions with background medium

Flavor conversion physics

with $\varrho = \varrho_{\mathbf{x},\mathbf{p},t}$.

Recent reviews: Tamborra & Shalgar, Ann. Rev. Nucl. Part. Sci. (2021). Volpe, Rev. Mod. Phys. (2024). Tamborra, arXiv: 2412.23258.

Towards the Full Solution

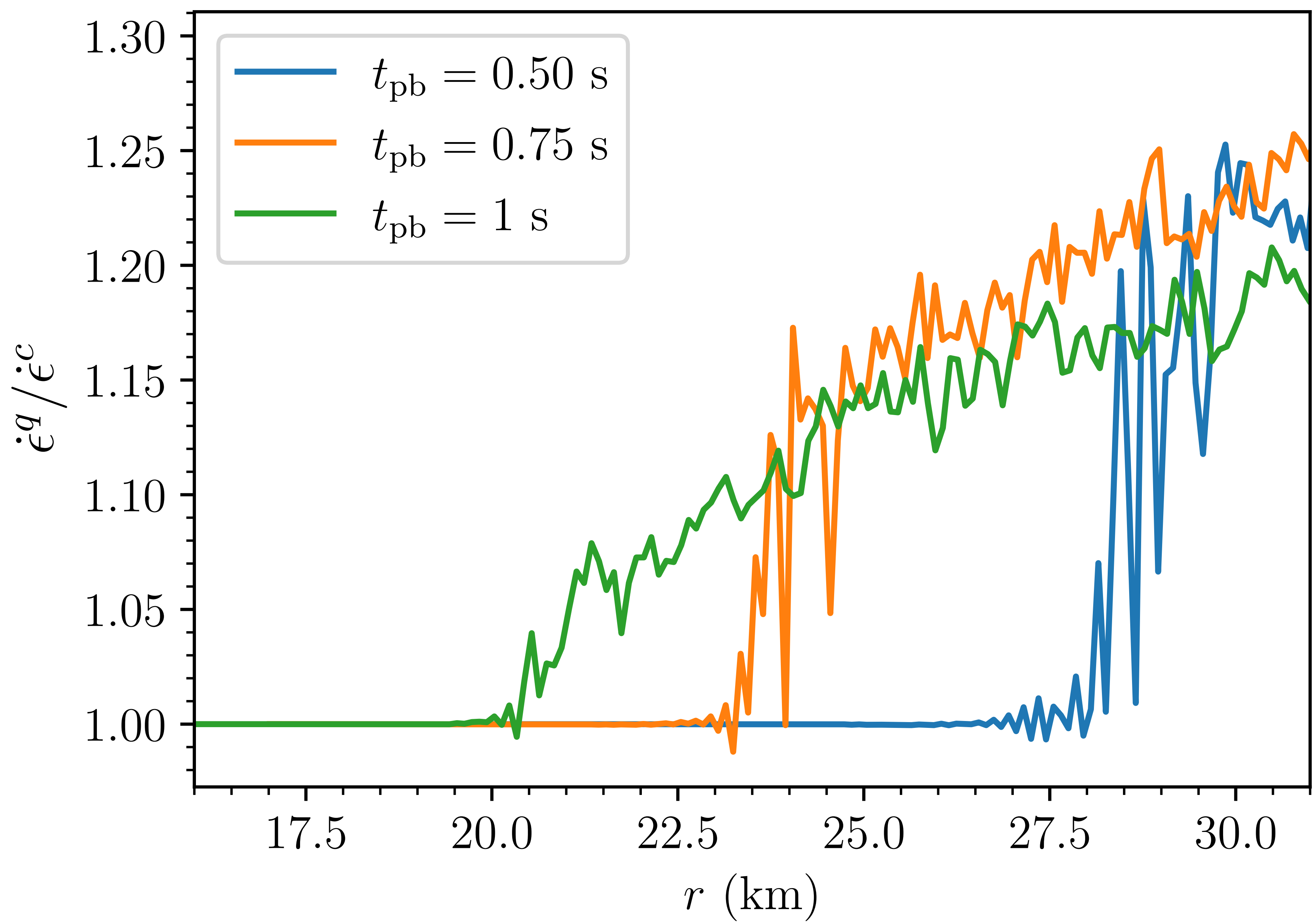


Neutrino flavor conversion occurs in the proximity of neutrino decoupling.

Flavor equipartition for antineutrinos is obtained due to flavor conversion.

Shalgar & Tamborra, arXiv: 2503.03835. Shalgar & Tamborra, JCAP (2024), PRD (2023). ApJ (2019).

Example: Core-Collapse Supernova



- The neutrino heating rate increases by 15-30% due to flavor conversion.

- Impact on multi-messenger observables?

Shalgar & Tamborra, JCAP (2024). Shalgar & Tamborra, arXiv: 2503.03835.
Ehring, Abbar, Janka, Raffelt, Tamborra, PRL (2023). Nagakura, PRL (2023).

Diffuse Supernova Neutrino Background

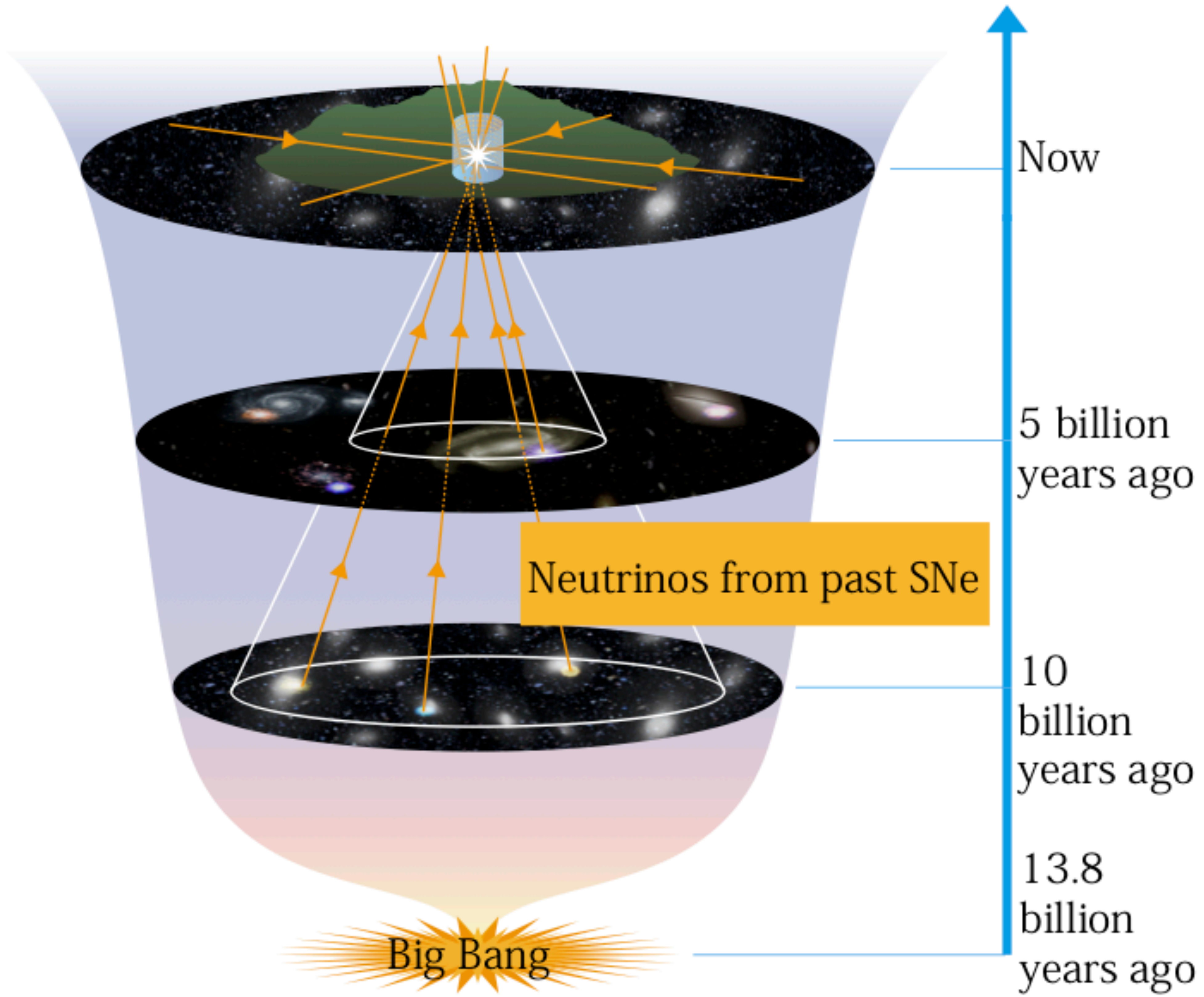
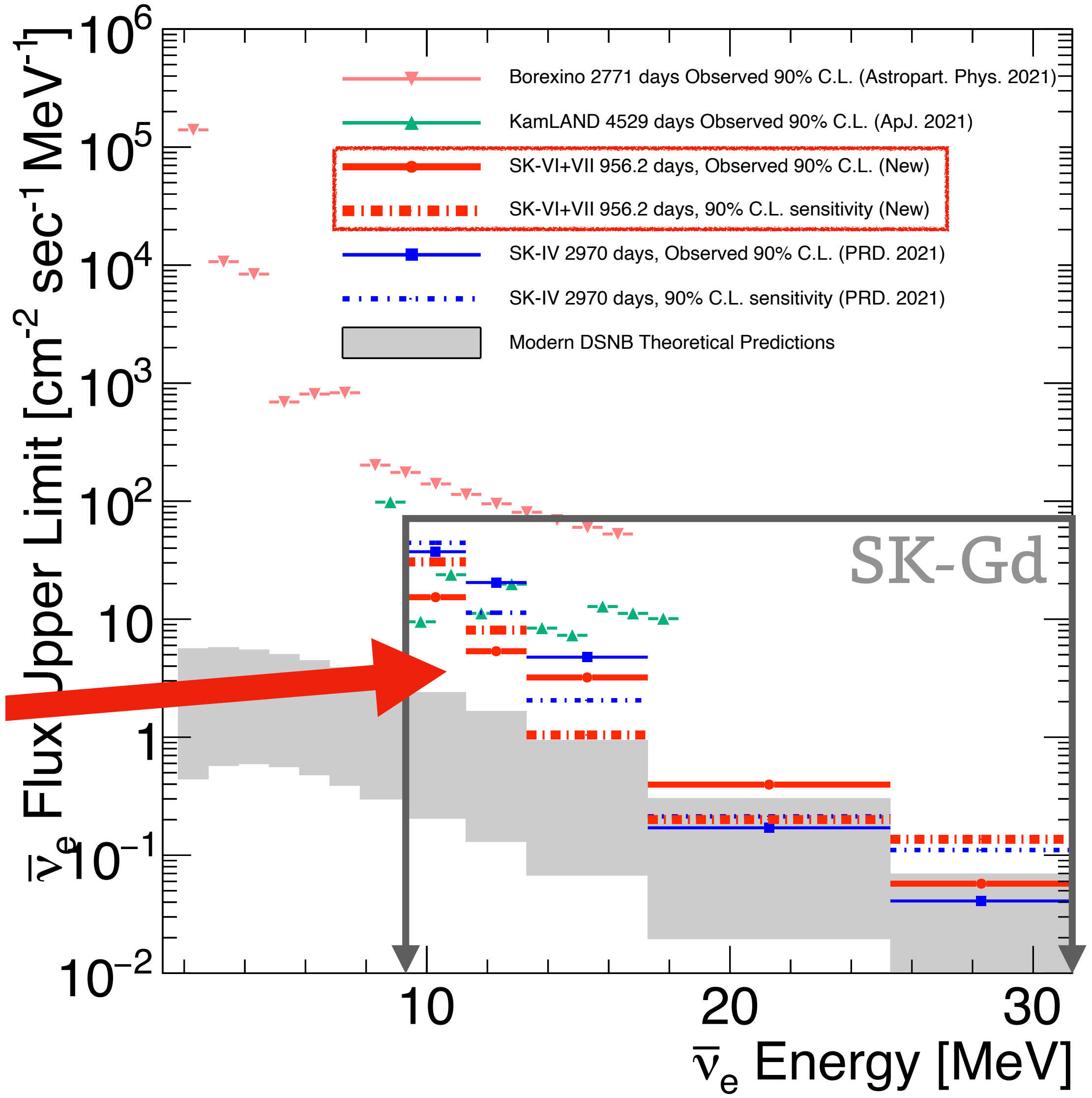
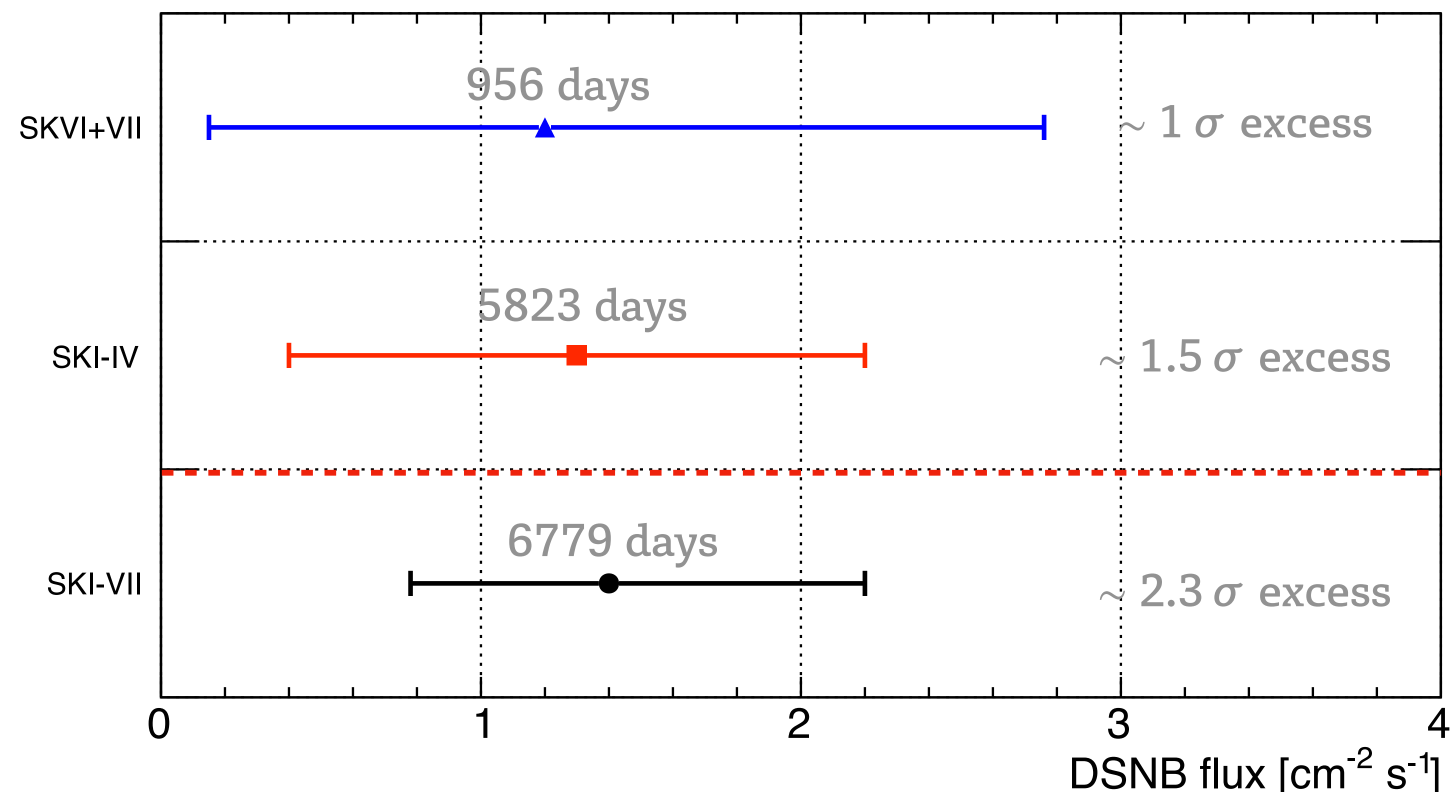


Figure credits: Kamioka Observatory.

Super-Kamiokande-Gadolinium Results





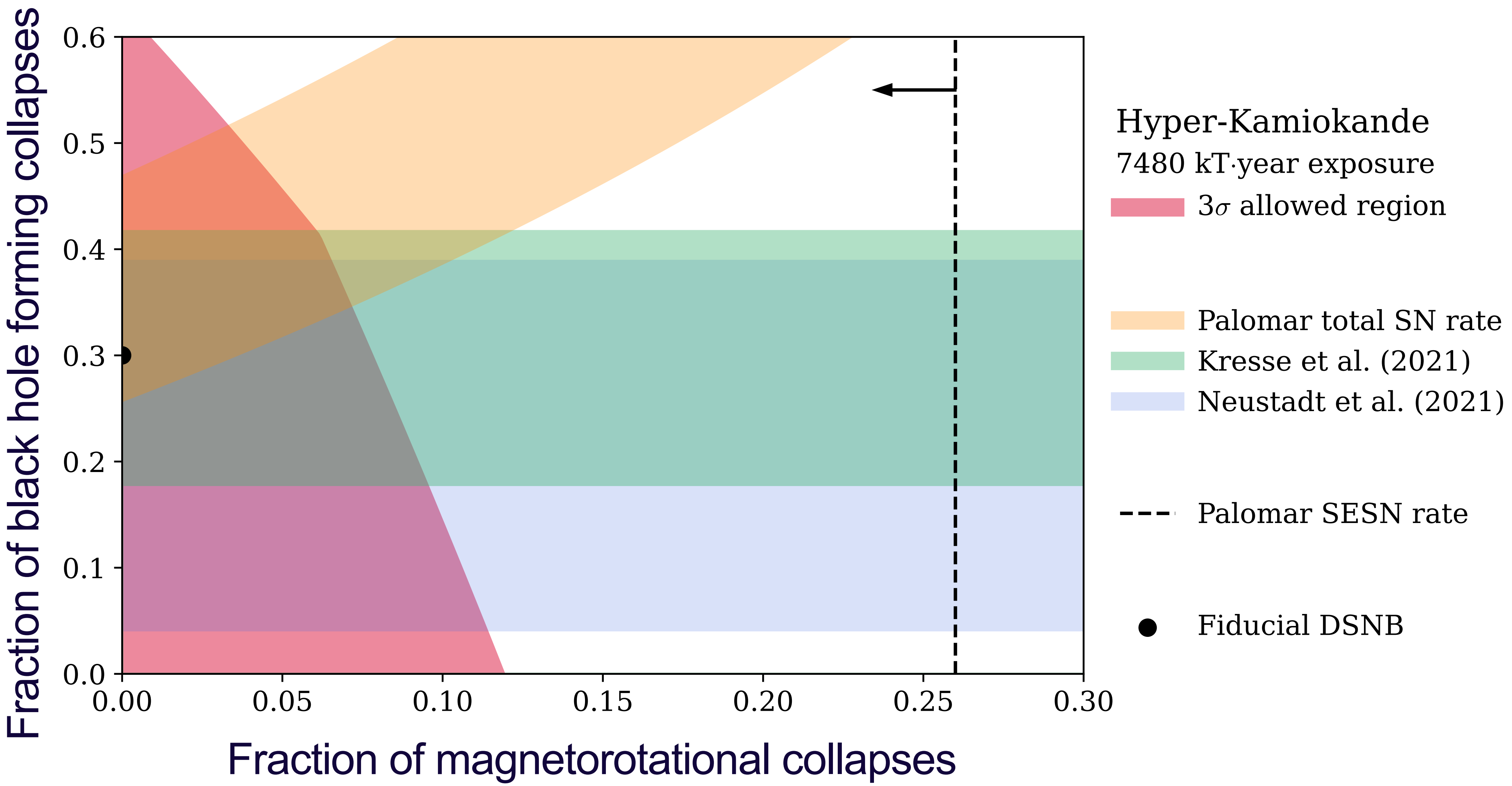
Highlight:

- Sensitivity of SK-Gd ~1000 days exposure is already comparable level it with ~6000 days of pure-water SK
- Best fit of whole SK observation is **$1.4^{+0.8}_{-0.6}$ cm^{-2} s^{-1}** for E_ν > 17.3 MeV

  ➡ **exhibit ~2.3 σ excess!!**

Figures from Harada's talk @ Neutrino 2024. Harada et al., ApJ Lett. (2023).

Constraints on the Supernova Population

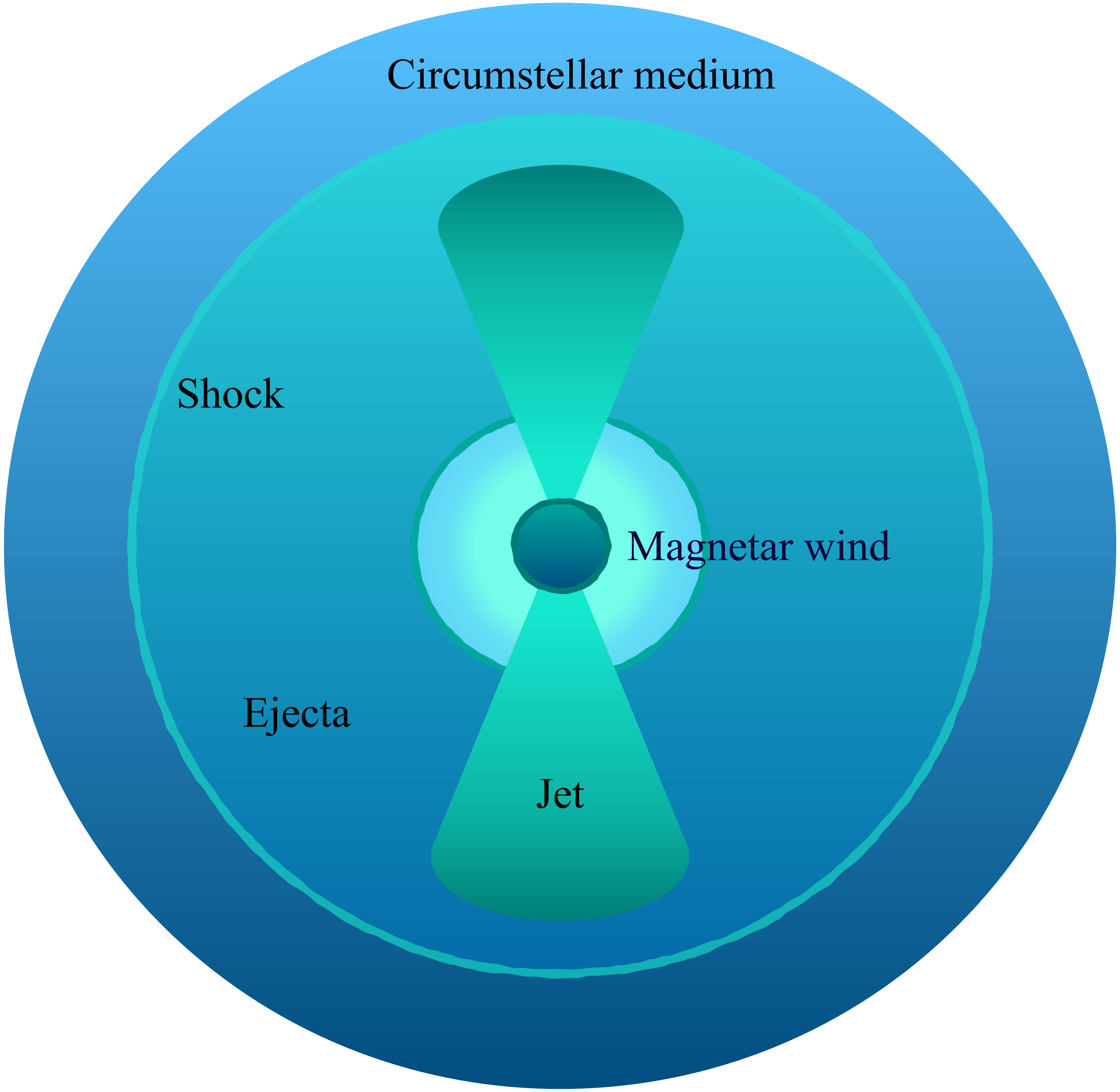


The DSNB detection, combined with EM constraints, could provide crucial insight on the population of collapsing massive stars.

Figure from Martínez-Miravé, Tamborra, Aloy, Obergaulinger, PRD (2024).

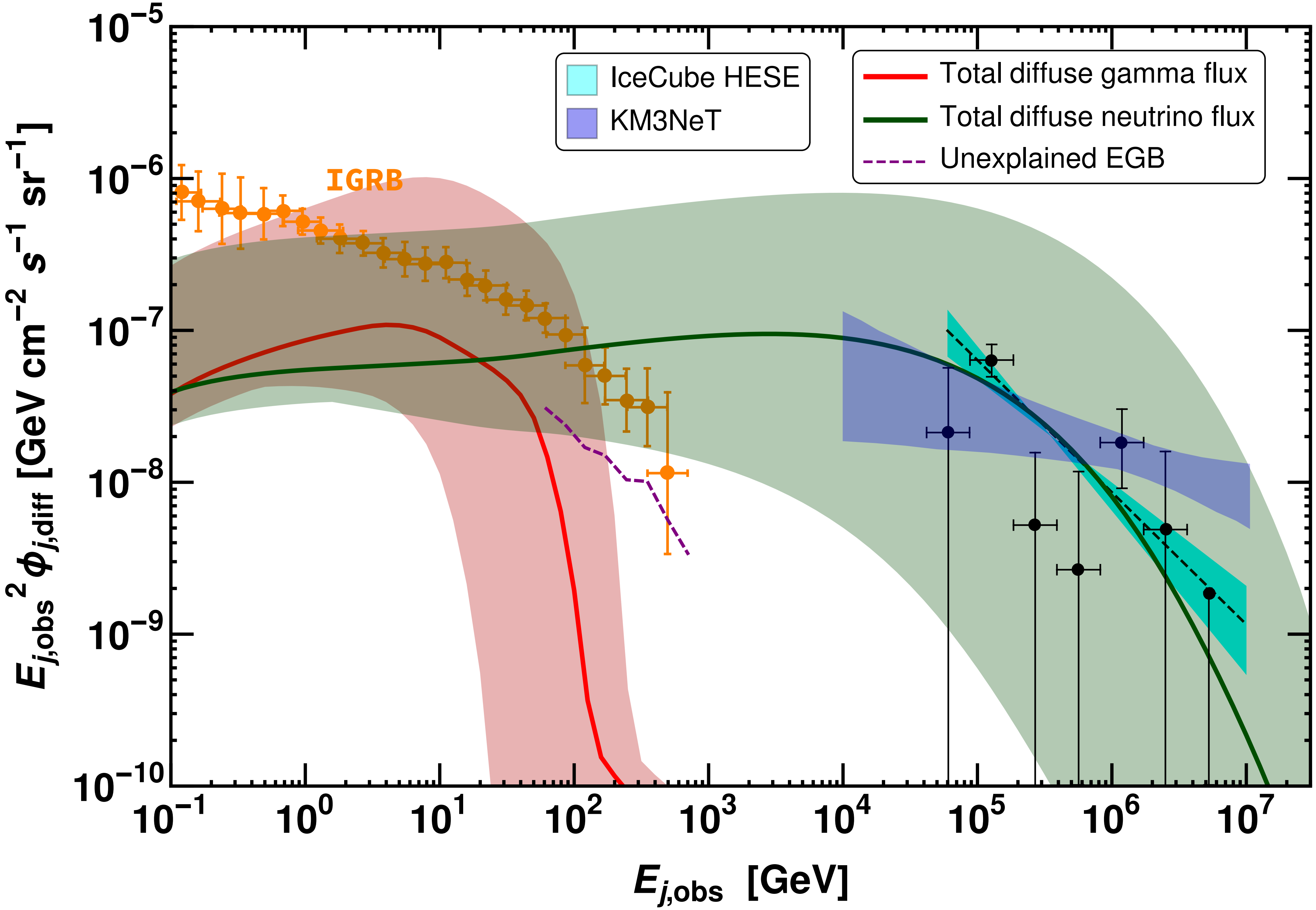

Figure credits: BBC Science Focus

Sites of Particle Acceleration



Recent review: Tamborra, arXiv: 2412.23258.

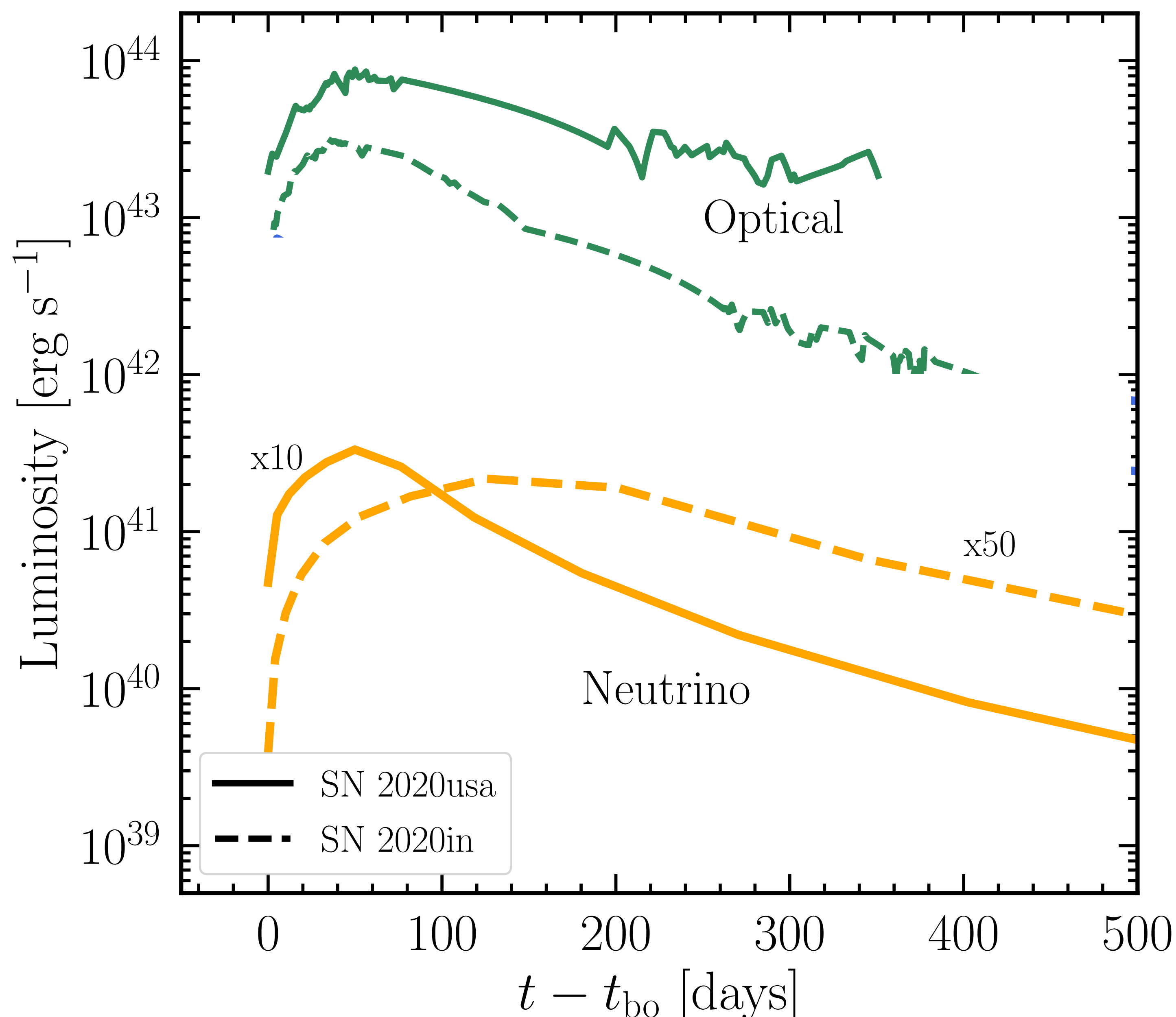
Gamma-Ray and Neutrino Diffuse Emission



- Supernovae may explain the low-energy excess observed in the diffuse background of high-energy neutrinos, without overshooting the gamma-ray diffuse background.
- SNe of Type IIn and II-P detectable in gamma-rays and neutrinos with CTA and IceCube.

Sarmah, Chackraborty, Tamborra, Auchettl, JCAP (2022). Waxman, ApJ (2025). Pitik, Tamborra, Angus, Auchettl, ApJ (2022).

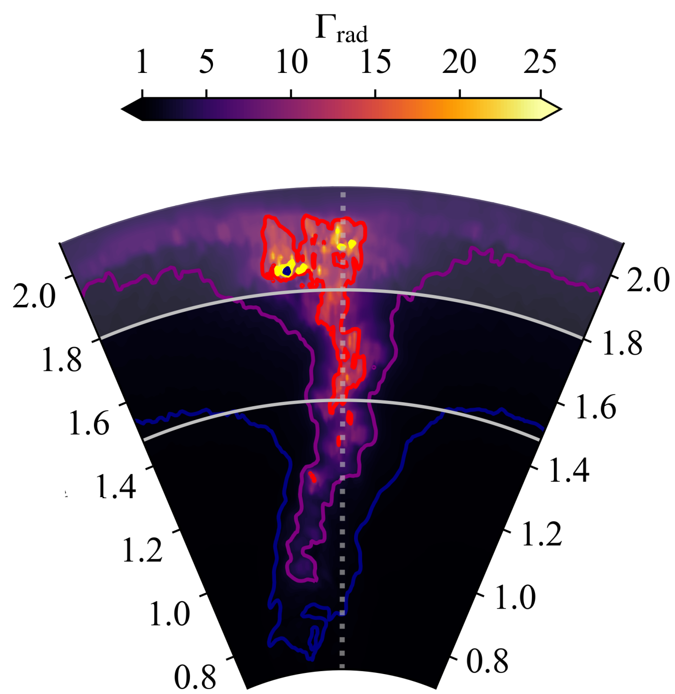
Follow-up Programs to Be Optimized



- For a given optical light curve, the neutrino signal cannot be determined exactly.
- Stacking neutrino searches based on “standard candles” are not optimal.
- The optical and neutrino light curves do not peak at the same time.
- Essential to combine X-ray/radio and UVOIR observations to aid neutrino searches.

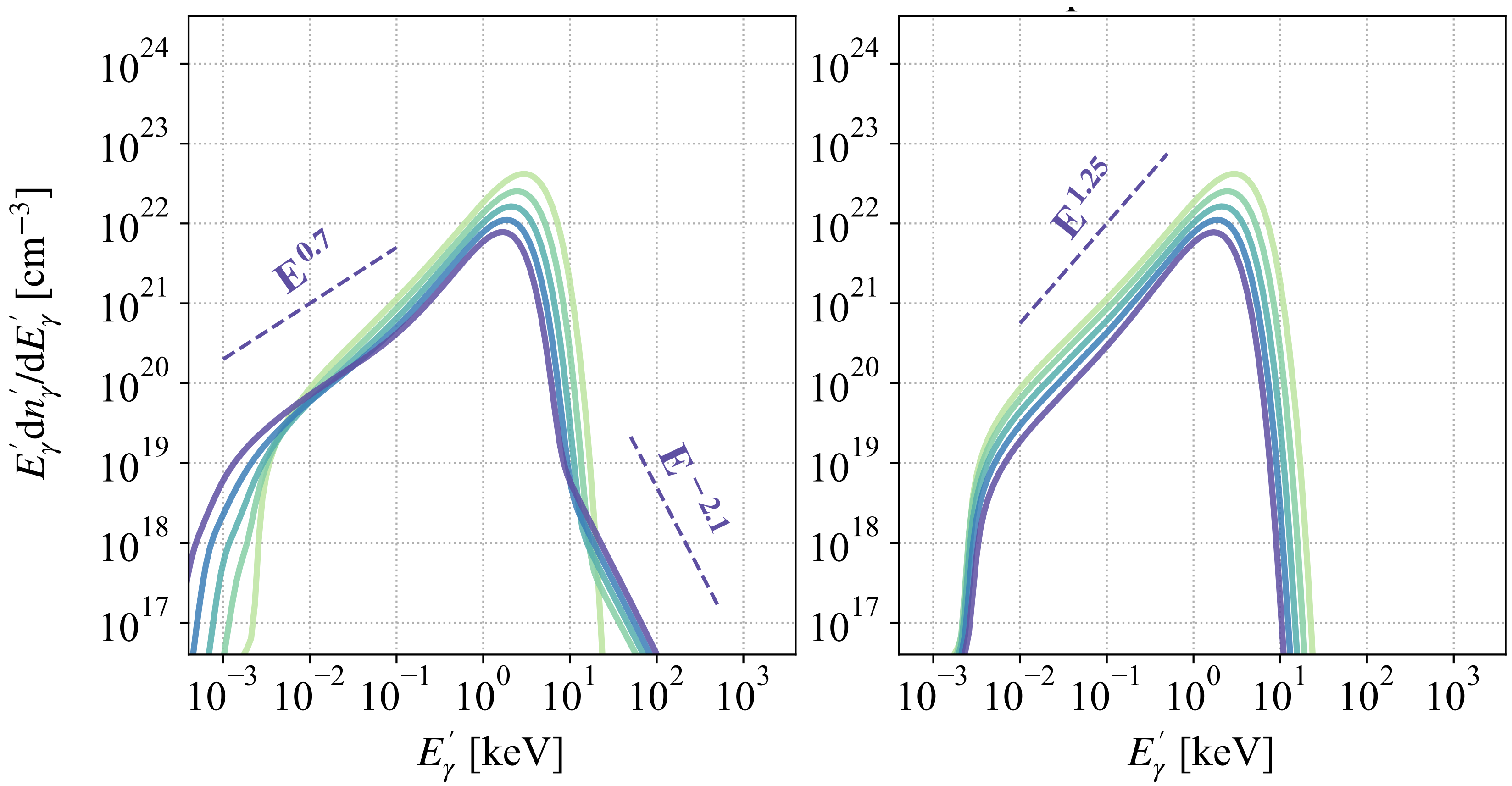
Pitik, Tamborra, Lincetto, Franckowiack, MNRAS (2023). Guarini, Tamborra, Margutti, Ramirez-Ruiz, PRD (2023).

Theoretical Models to Be Improved — 1



Leptonic + hadronic processes (our work)

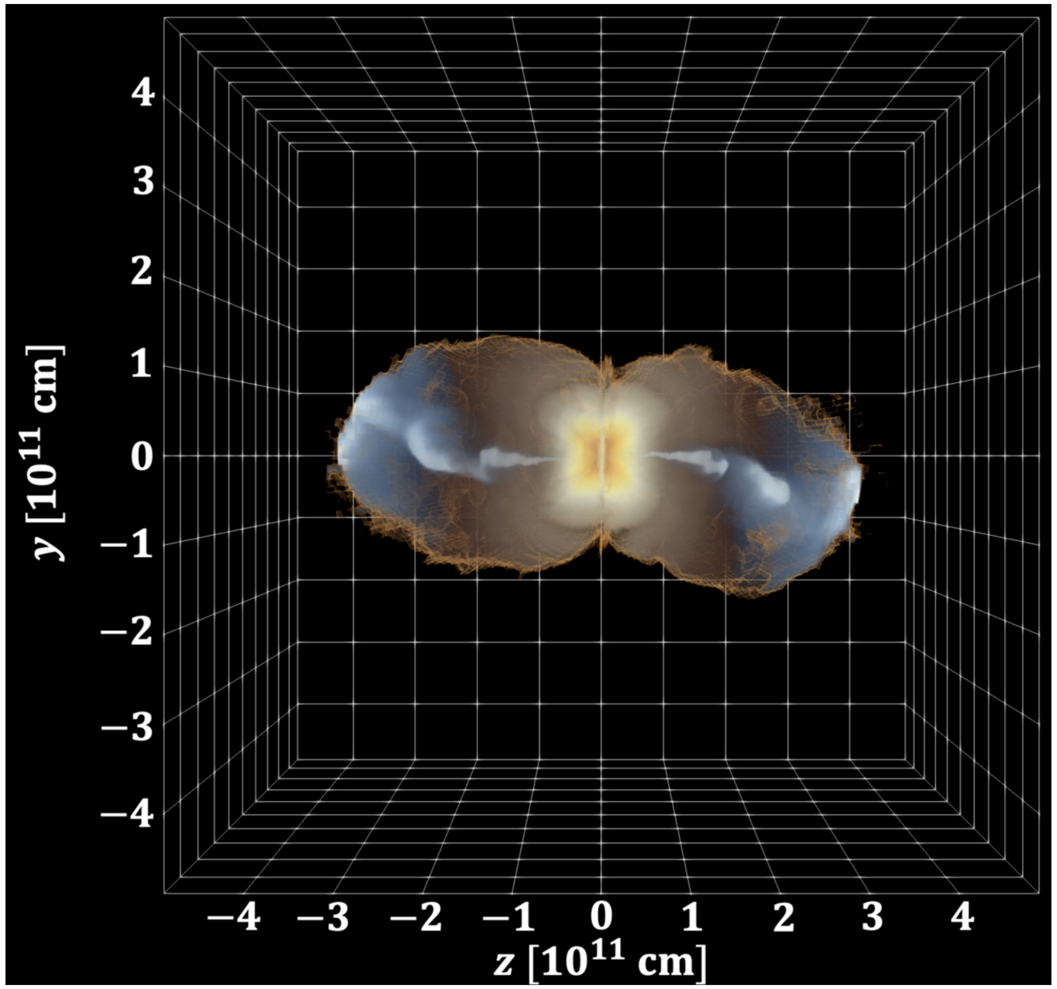
Leptonic processes only (usually considered)

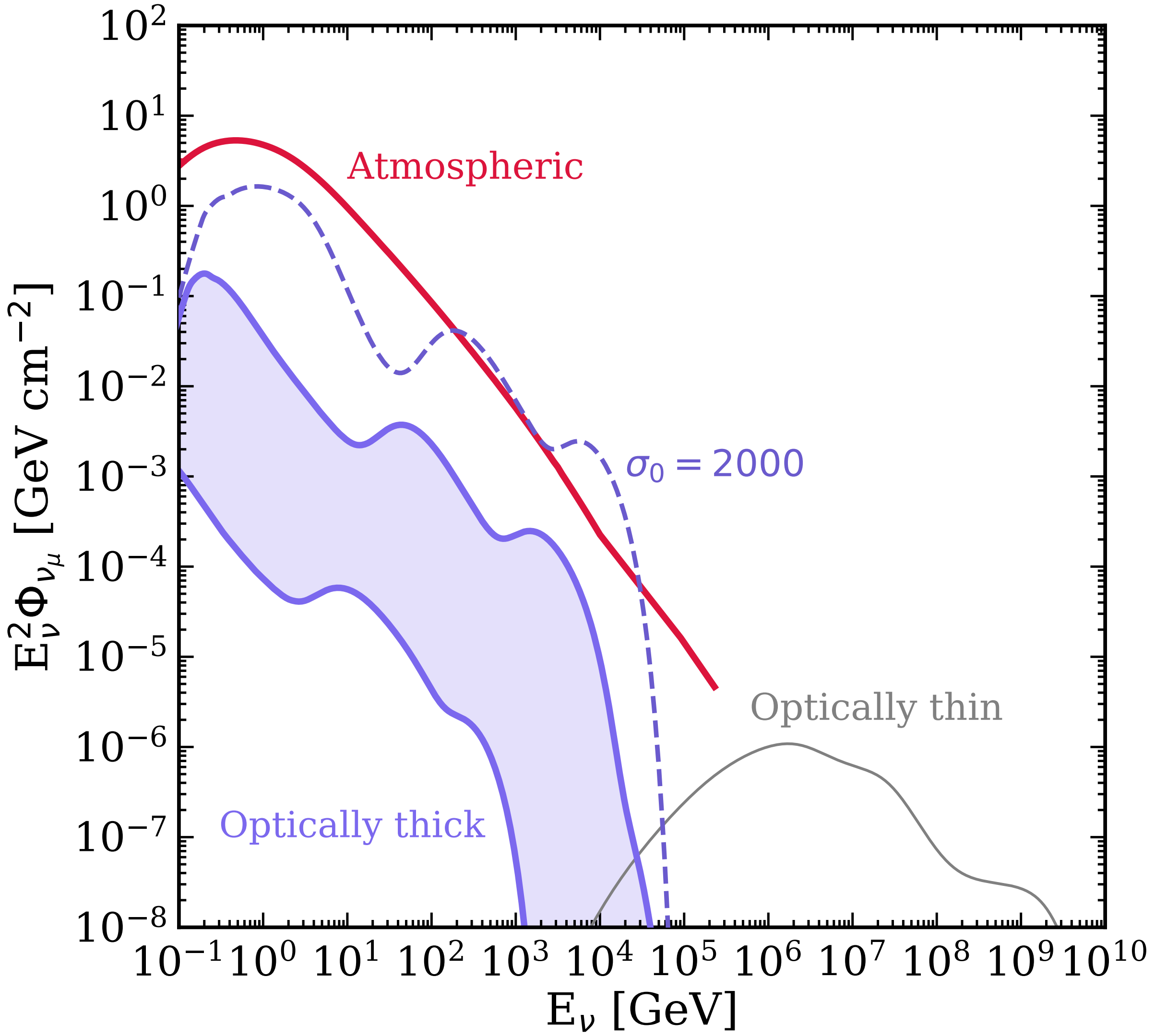


Bulk of non-thermal photon spectrum can stem from hadronic processes below the photosphere (usually just invoked for neutrino production).

Rudolph, Tamborra, Gottlieb, Astrophys. J. Lett. (2024) & ApJ (2025, in press).

Theoretical Models to Be Improved — 2





State-of-the-art collapsar jet simulations predict subphotospheric neutrinos with lower energies than previously expected.

Rudolph, Tamborra, Gottlieb, Astrophys.J. Lett. (2024) & ApJ (2025, in press). Guarini, Tamborra, Gottlieb, PRD (2023).

Conclusions

- Neutrinos are key messengers of the supernova physics and supernova population.
- Modeling of neutrino physics in the supernova core is still preliminary.
- Interpretation of multi-messenger data requires a major step forward in source modeling.
- We need to optimize multi-messenger follow-up programs to be able to test our models.

Thank you!