Messengers from the Cosmos

Irene Tamborra (Niels Bohr Institute)

GGI Program “Neutrino Frontiers”
July 15-19, 2024

VILLUM FONDEN

Sapere Aude

Funded by the European Union

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CARLSBERG FOUNDATION

SFB 1258 Neutrinos Dark Matter Messengers

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

Baikal-GVD

WEBB
SPACE TELESCOPE

ATHENA

COSMIC
EXPLORER

KM3NeT

esa
euclid

VLA
SKY SURVEY

VERA C. RUBIN
OBSERVATORY

THE NANCY GRACE
ROMAN SPACE TELESCOPE

SVOM

LISA
CONSORTIUM

DARWIN

RES-NOVA

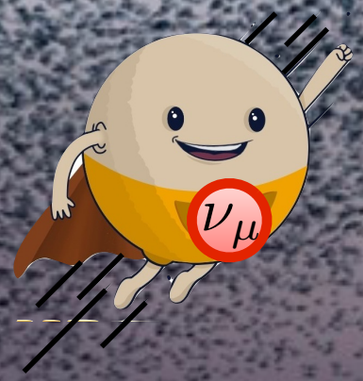
theseus
TRANSIENT HIGH ENERGY SKY AND EARLY UNIVERSE SURVEYOR

and many more…

Outline

- Neutrino quantum kinetics
- Neutrino physics and multi-messenger emission from core-collapse supernovae and neutron star mergers
- Multi-messenger emission from transient cosmic accelerators
- Outlook

Neutrino Quantum Kinetics



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

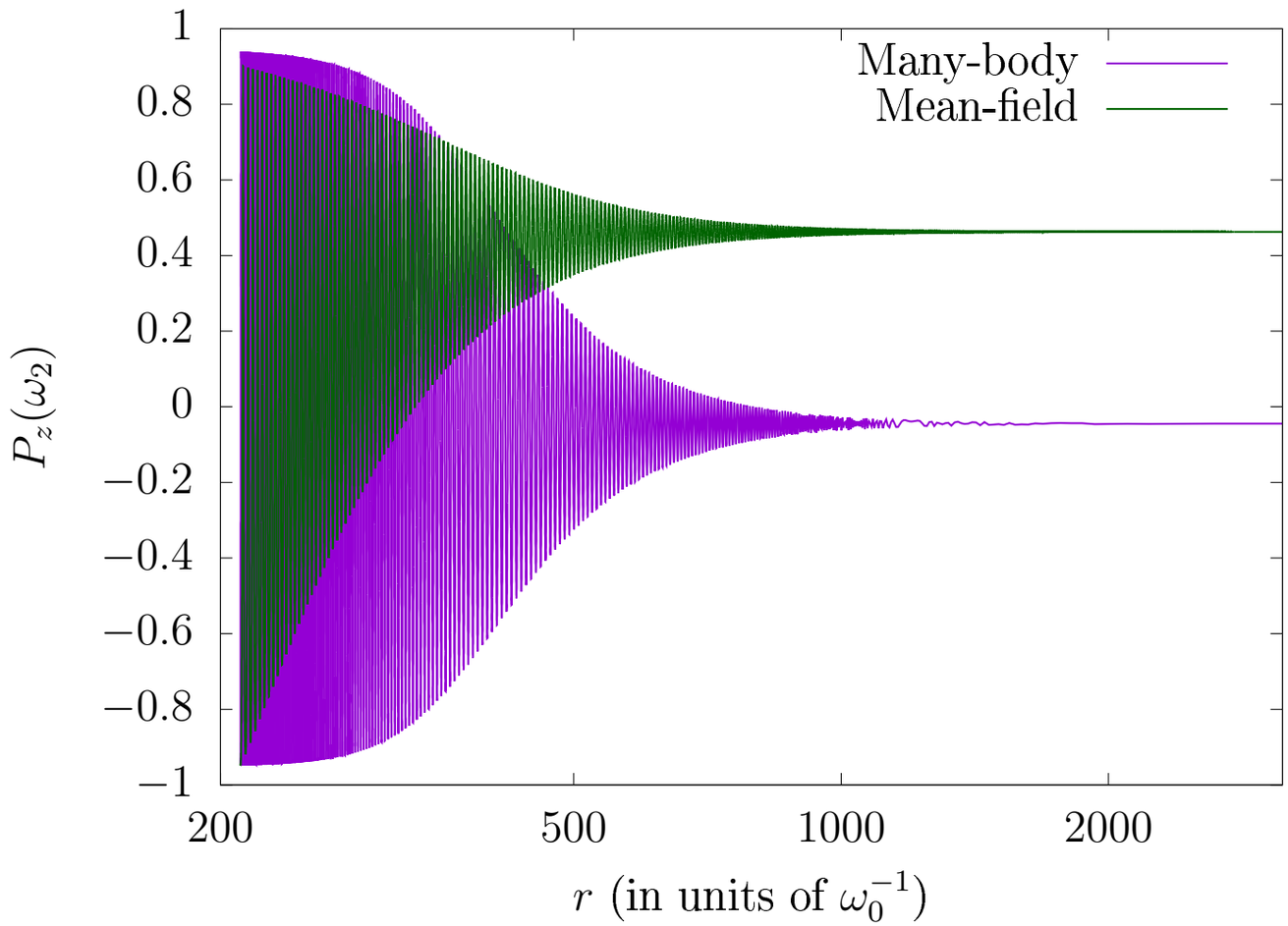
Collisions with background medium

Flavor conversion physics

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

Recent reviews: Tamborra & Shalgar, Ann. Rev. Nucl. Part. Sci. (2021). Richers & Sen, arXiv: 2207.03561. Volpe, Rev. Mod. Phys. (2024).

Do We Solve the Right Equations of Motion?



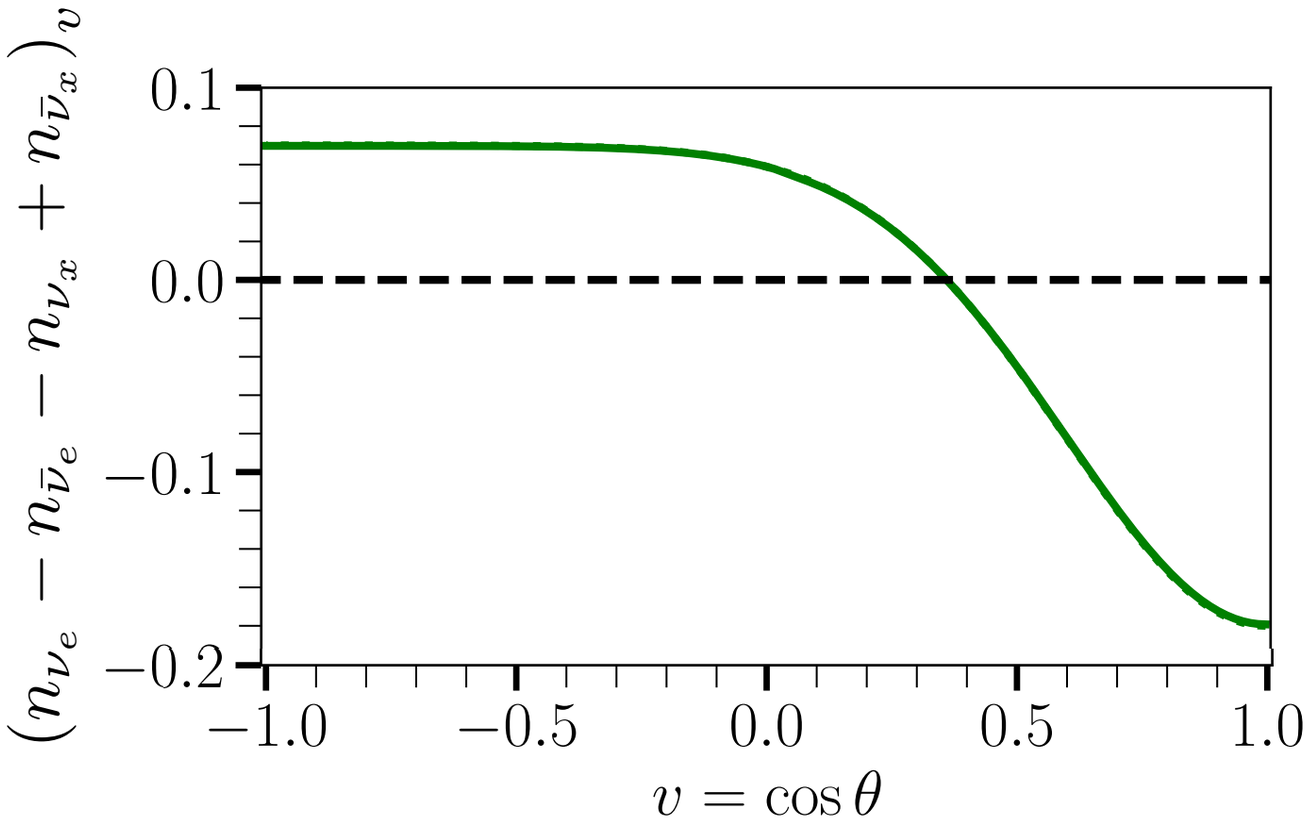
- Many-body effects are neglected in modeling of neutrino quantum kinetics.
- Existing many-body literature is based on closed neutrino systems with a finite number of particles. It is neither able to rule out nor assess the validity of mean field approximation.

Shalgar & Tamborra, PRD (2023). Johns, arXiv: 2305.04916. Kost, Johns, Duan, PRD (2024). Cirigliano, Sen, Ymauchi, arXiv: 2404.16690. Figure from Cervia, Patwardhan, Balantekin, Coppersmith, Johnson, PRD (2019). Patwardhan et al., arXiv: 2301.00342. Frosty et al., JCAP (2020). Volpe et al., PRD (2013).

Fast Neutrino Conversion

Pairwise flavor exchange by $\nu - \nu$ scattering:

$$\nu_e(p) + \bar{\nu}_e(k) \to \nu_\mu(p) + \bar{\nu}_\mu(k)$$
$$\nu_e(p) + \nu_\mu(k) \to \nu_\mu(p) + \nu_e(k)$$



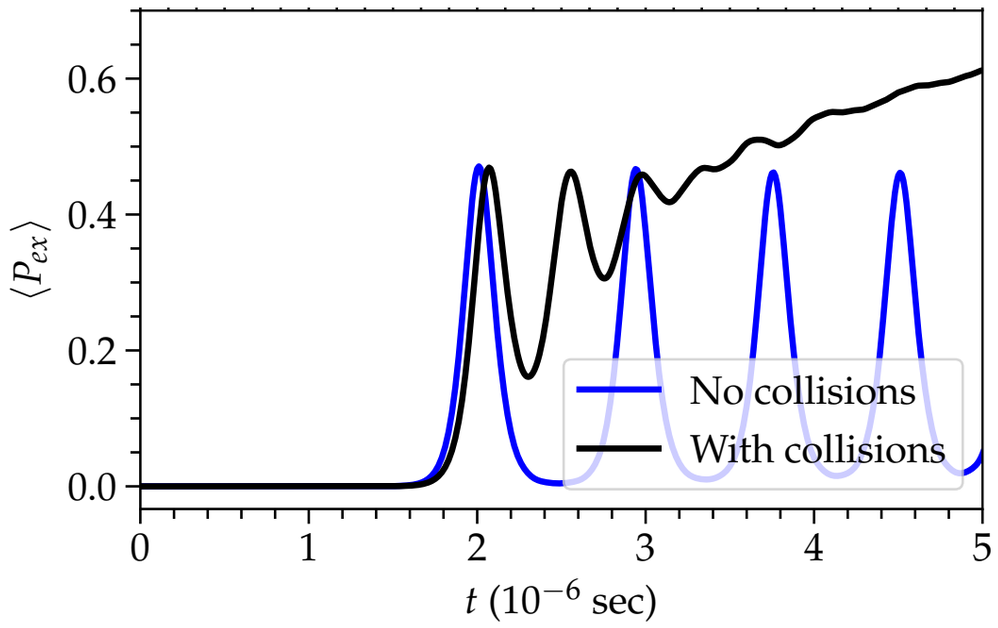
A crossing in the neutrino lepton number angular distribution is responsible for triggering fast flavor instabilities.

Characteristic scale: $\sqrt{2}G_F n_\nu$ ⇨ **“fast” conversion**

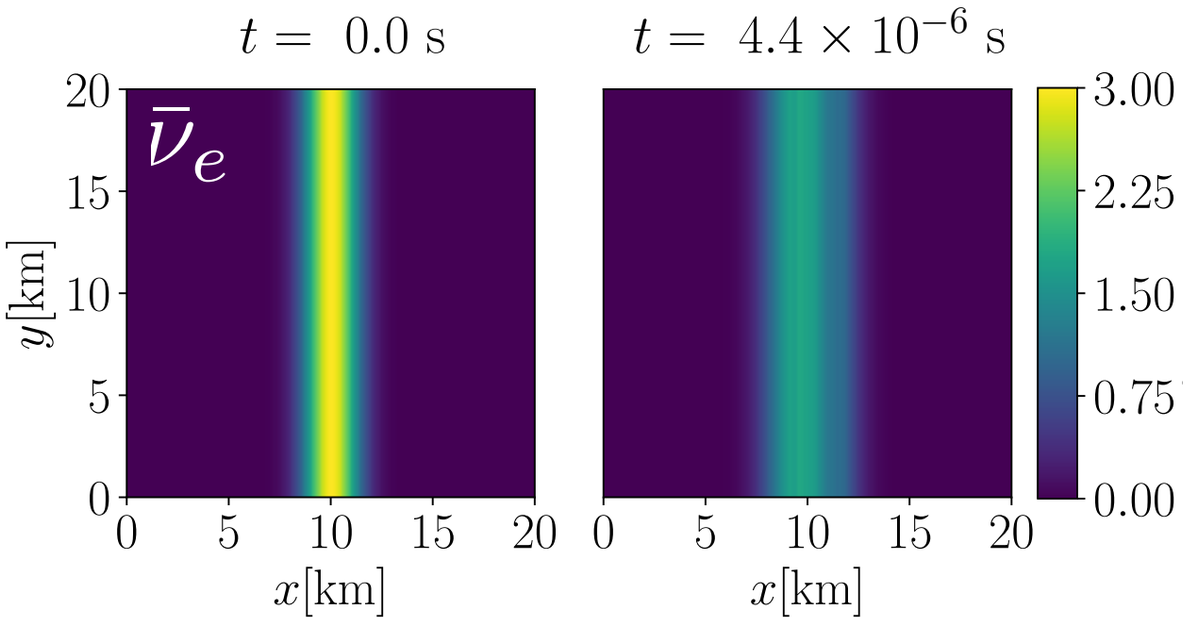
Sawyer, PRD (2005), Sawyer, PRL (2016). Izaguirre, Raffelt, Tamborra, PRL (2017). Chakraborty et al., Nucl. Phys. B (2016). Fiorillo & Raffelt, PRD (2023); arXiv: 2406.06708.

Interplay Among Flavor Conversion, Advection, and Collisions

Collisions affect flavor conversion.



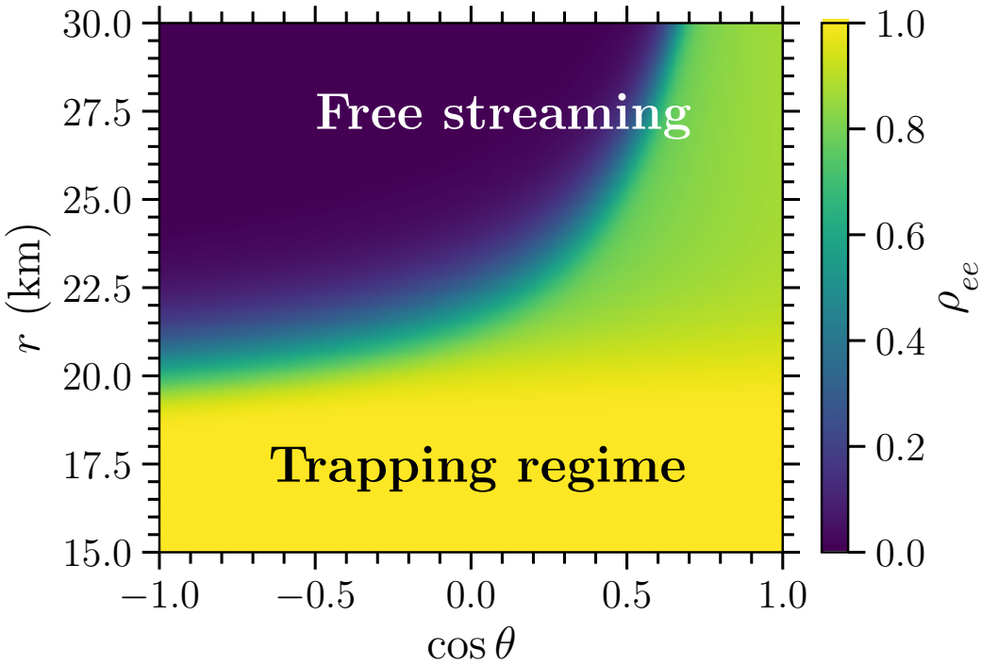
Neutrino advection
dynamically modifies flavor conversion.

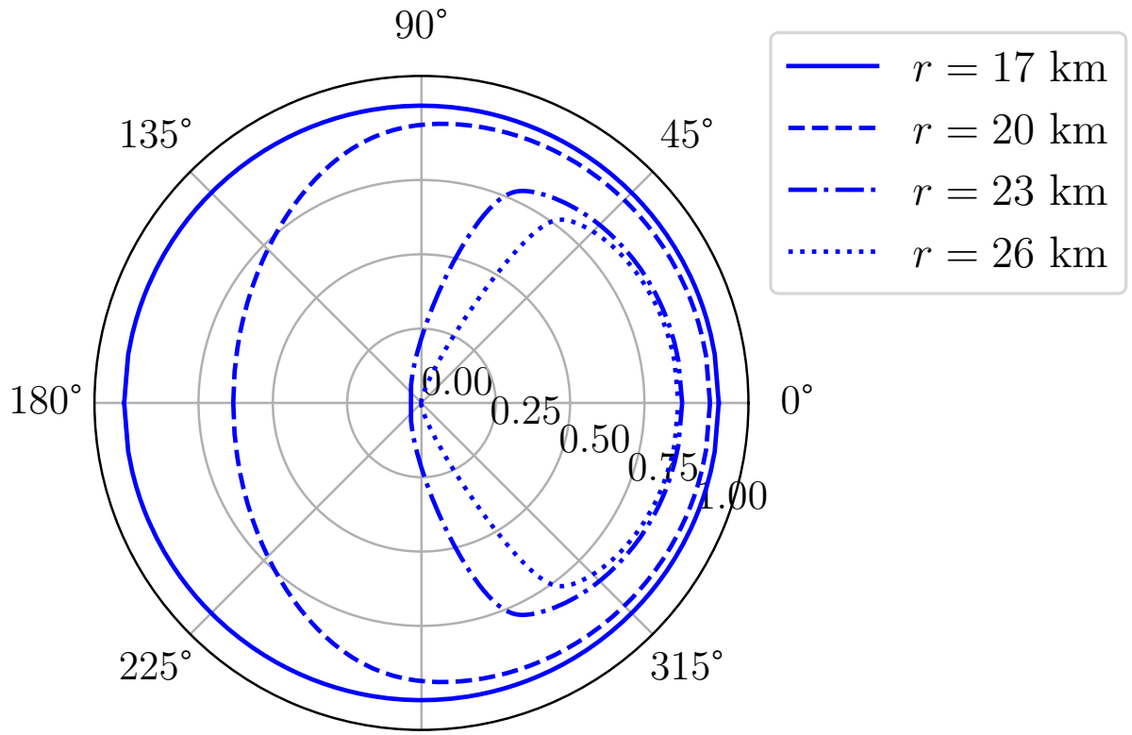


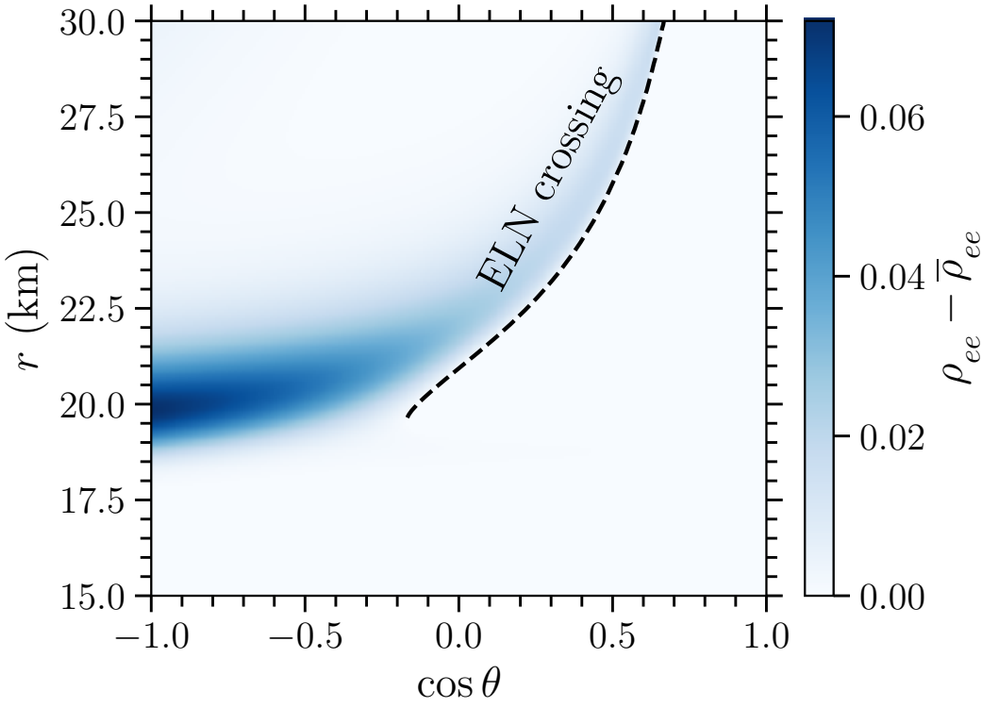
Neutrino conversion is dynamically affected by collisions and advection.

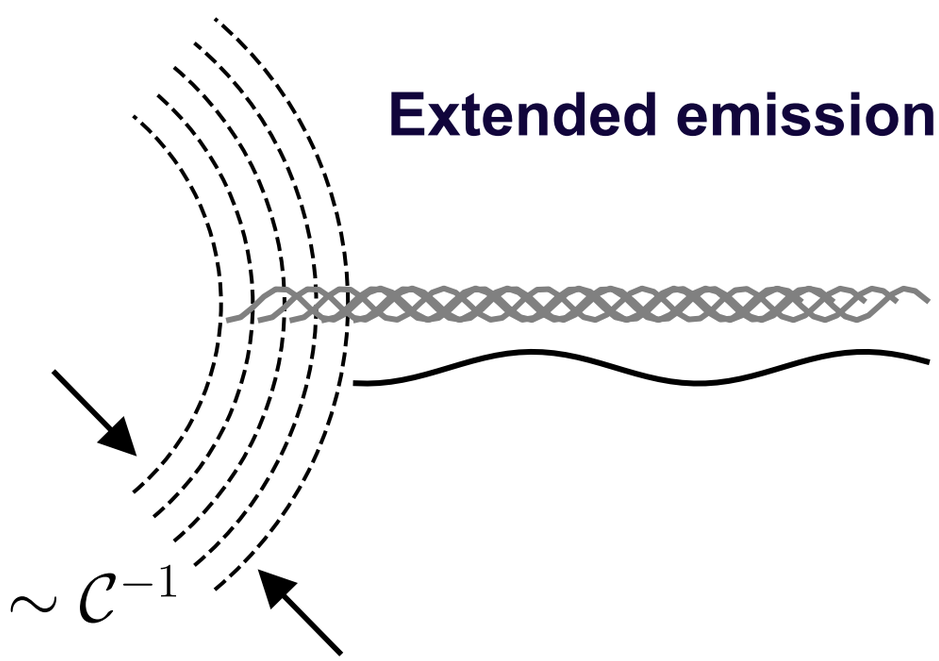
Shalgar, Padilla-Gay, Tamborra, JCAP (2020). Shalgar, Tamborra, PRD (2021). Hansen, Shalgar, Tamborra, PRD (2022). Sasaki & Takiwaki, PTEP (2022). Martin et al., PRD (2021). Sigl, PRD (2022). Richers et al., PRD (2019).

Towards the Full Solution



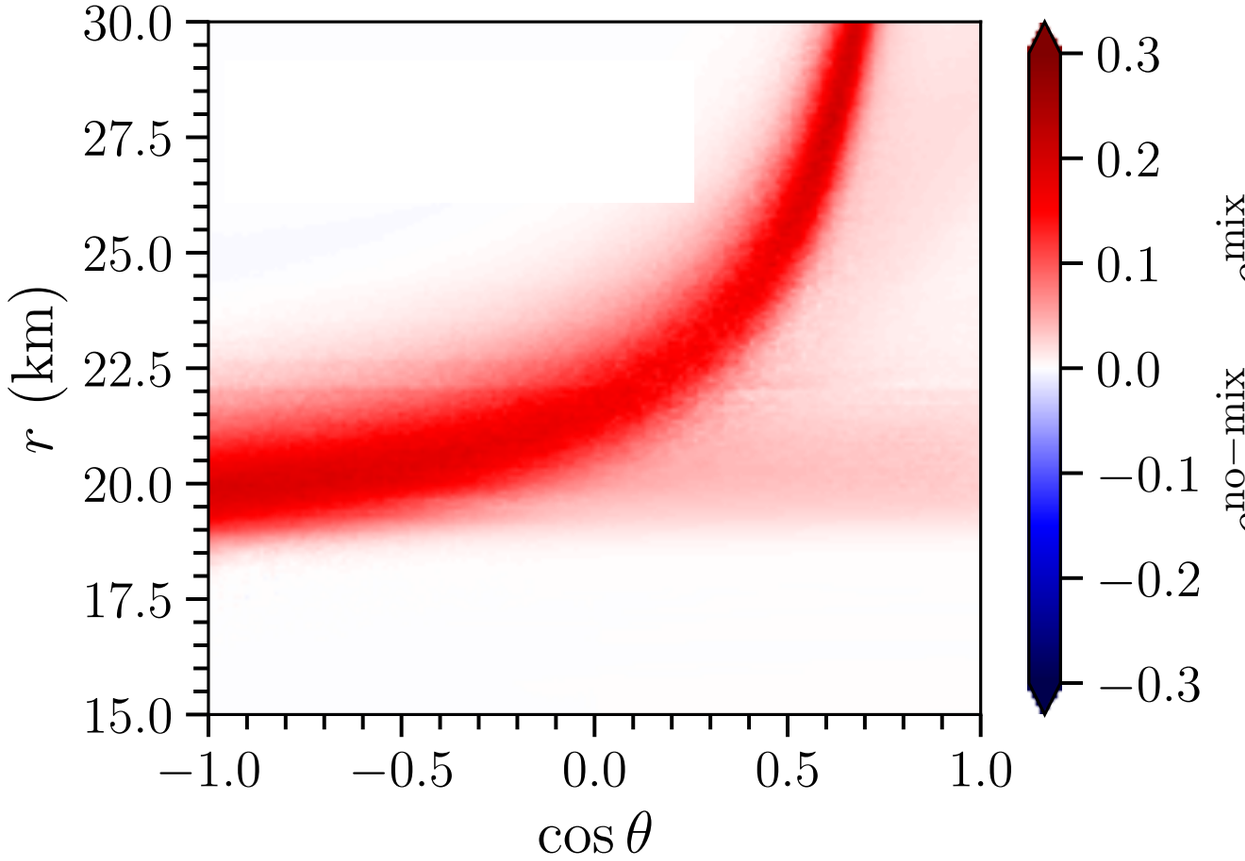


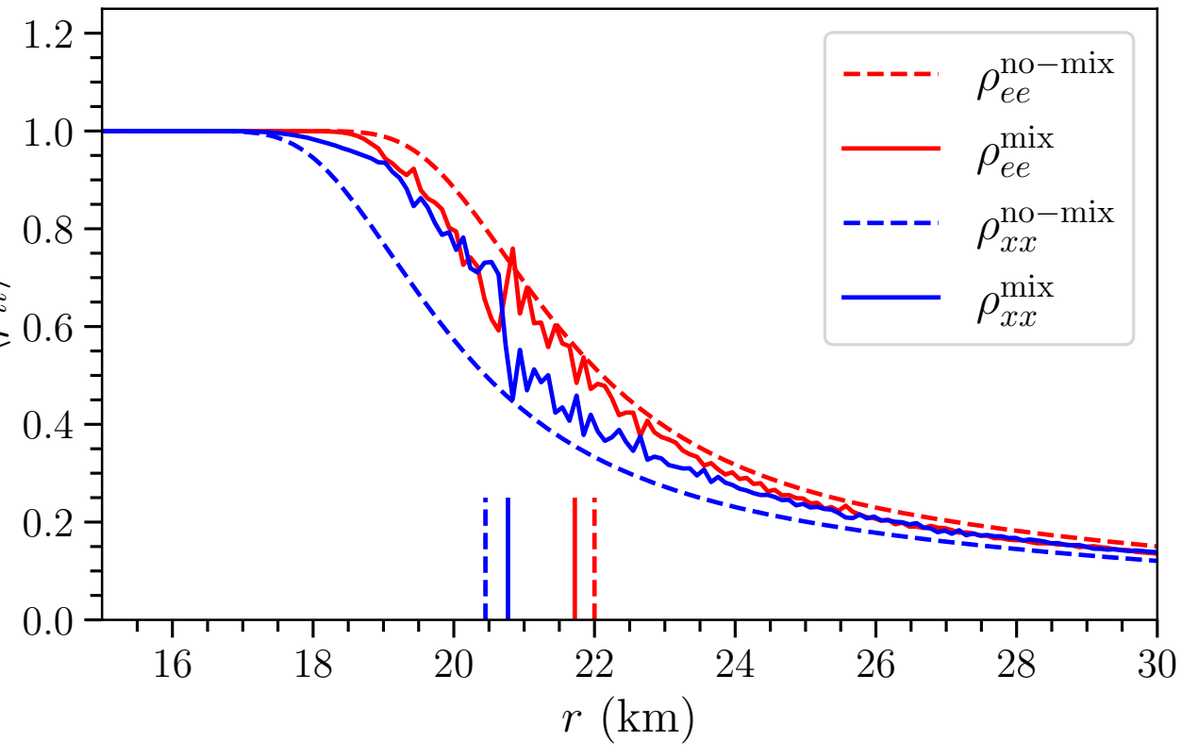




Shalgar & Tamborra, PRD (2023a), PRD (2023b). Shalgar, Padilla-Gay, Tamborra, JCAP (2020). Shalgar, Tamborra, PRD (2020, 2021), ApJ (2019). Richers et al., PRD (2021). Wu et al., PRD (2021). Fiorillo & Raffetl, arXiv: 2403.12189. Nagakura, PRD (2022), PRD (2024). Johns, arXiv: 2401.15247…

Towards the Full Solution



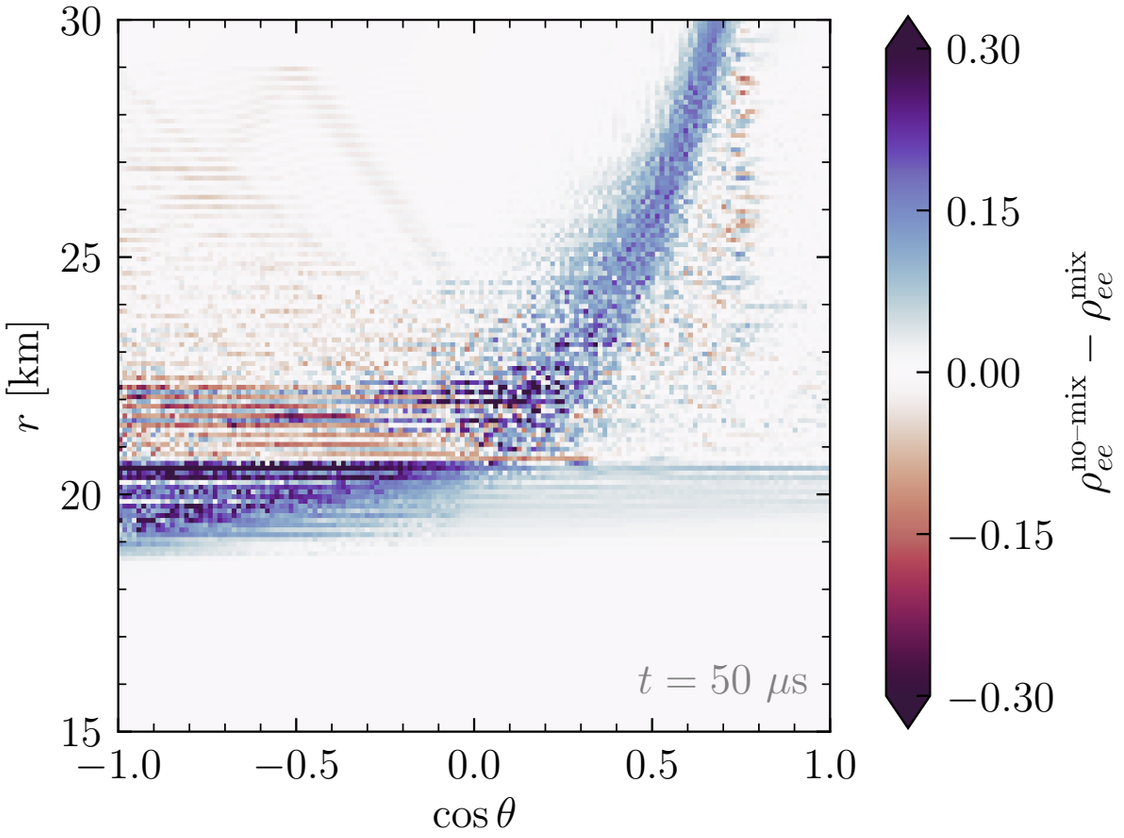


- Neutrino decoupling from matter can be affected by flavor conversion.
- Flavor equipartition is not a generic flavor outcome.

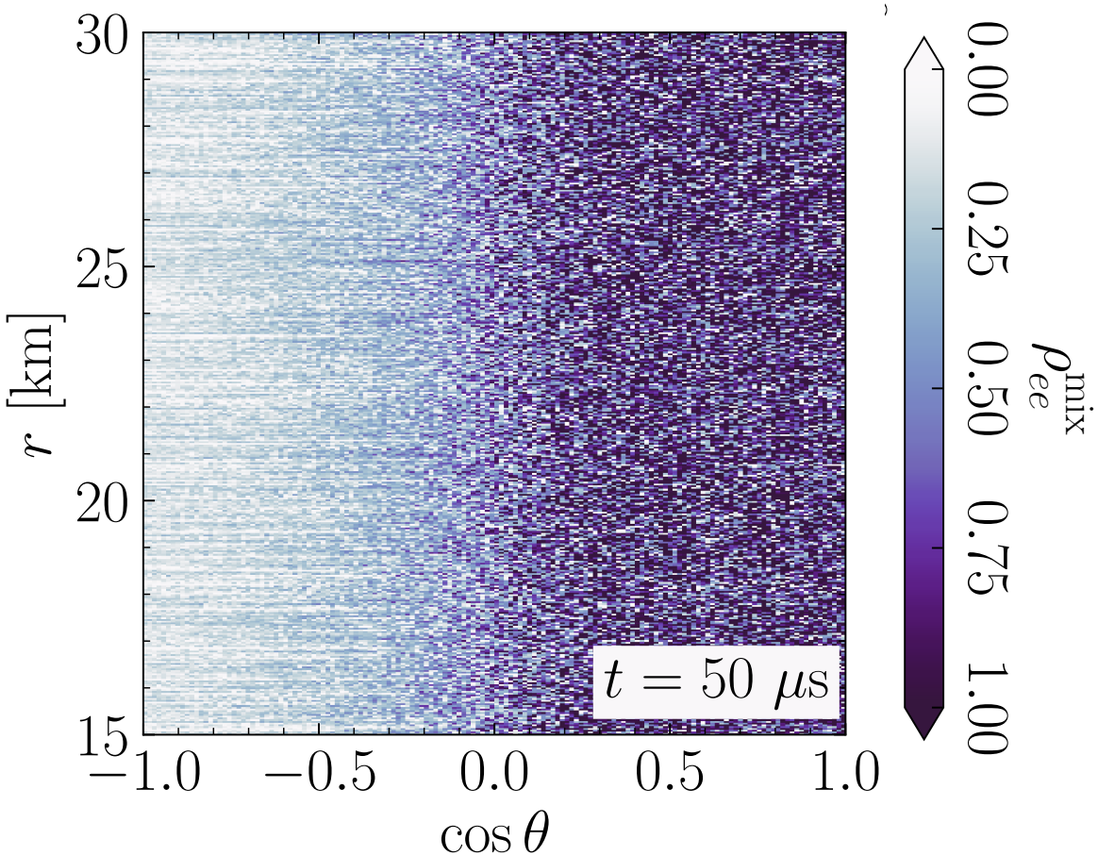
Shalgar & Tamborra, PRD (2023a), PRD (2023b).

Choice of Boundary Conditions Matters

Without periodic boundaries



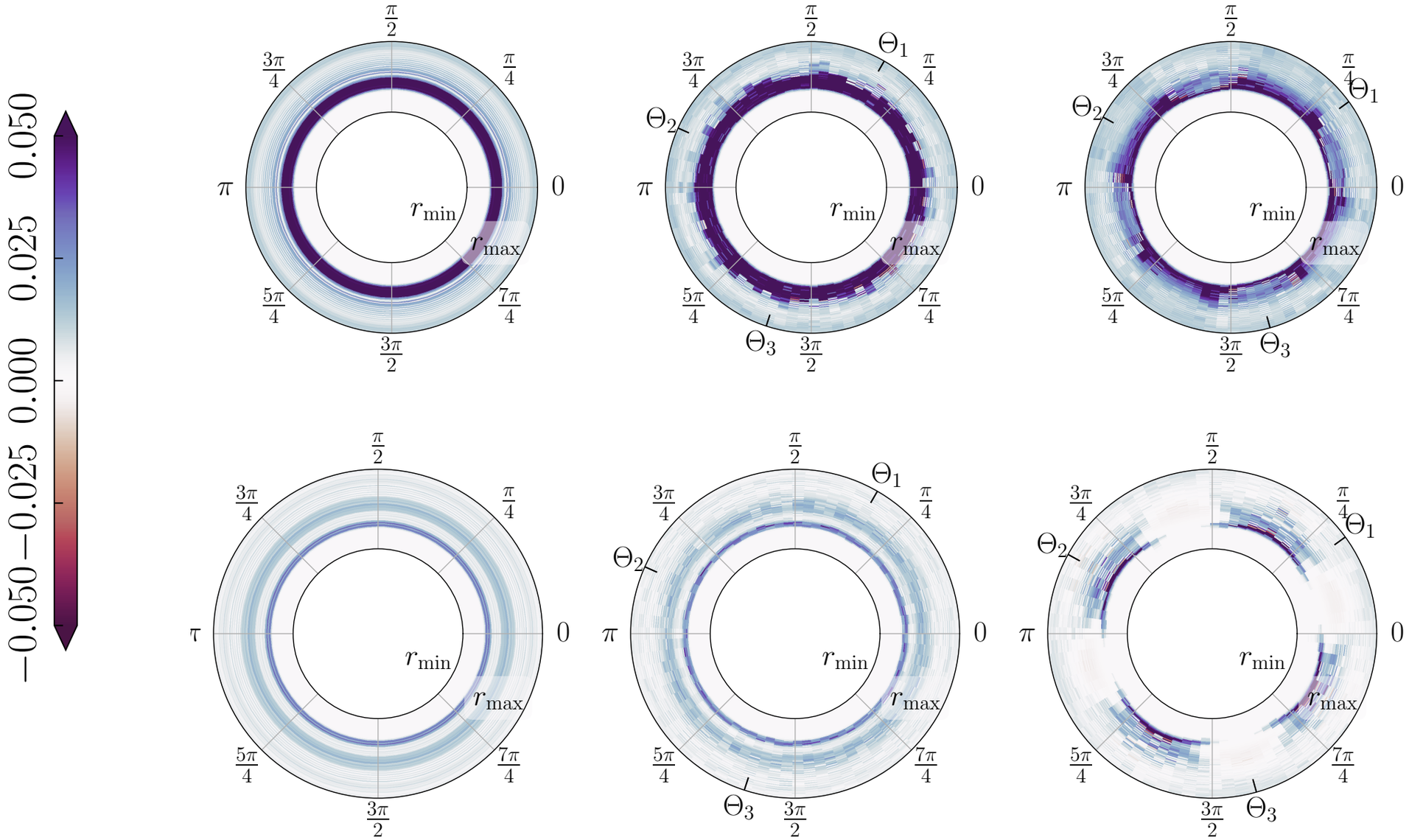
With periodic boundaries



Flavor equipartition is always obtained when periodic boundary conditions are employed, independent of ELN configuration.

Cornelius, Shalgar & Tamborra, JCAP (2024).
Xiong et al., arXiv: 2403.17269 & arXiv: 2402.19252. Martin et al., PRD (2021). Zaizen & Nagakura, PRD (2023), Richers, Willcox, Ford, PRD (2021), Bhattacharyya and Dasgupta, PRL (2021). …

Flavor Conversion in Multi-Dimensions



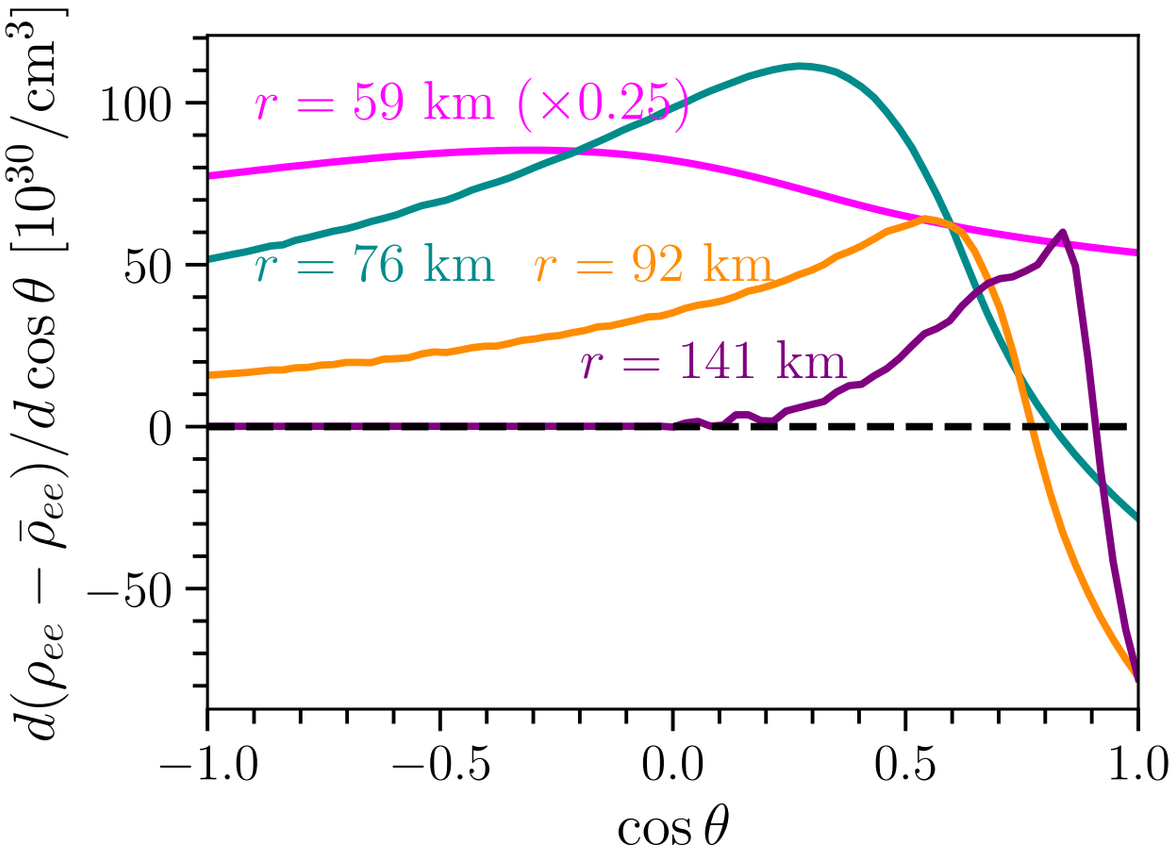
Flavor conversion in 2D (w/o perturbations)

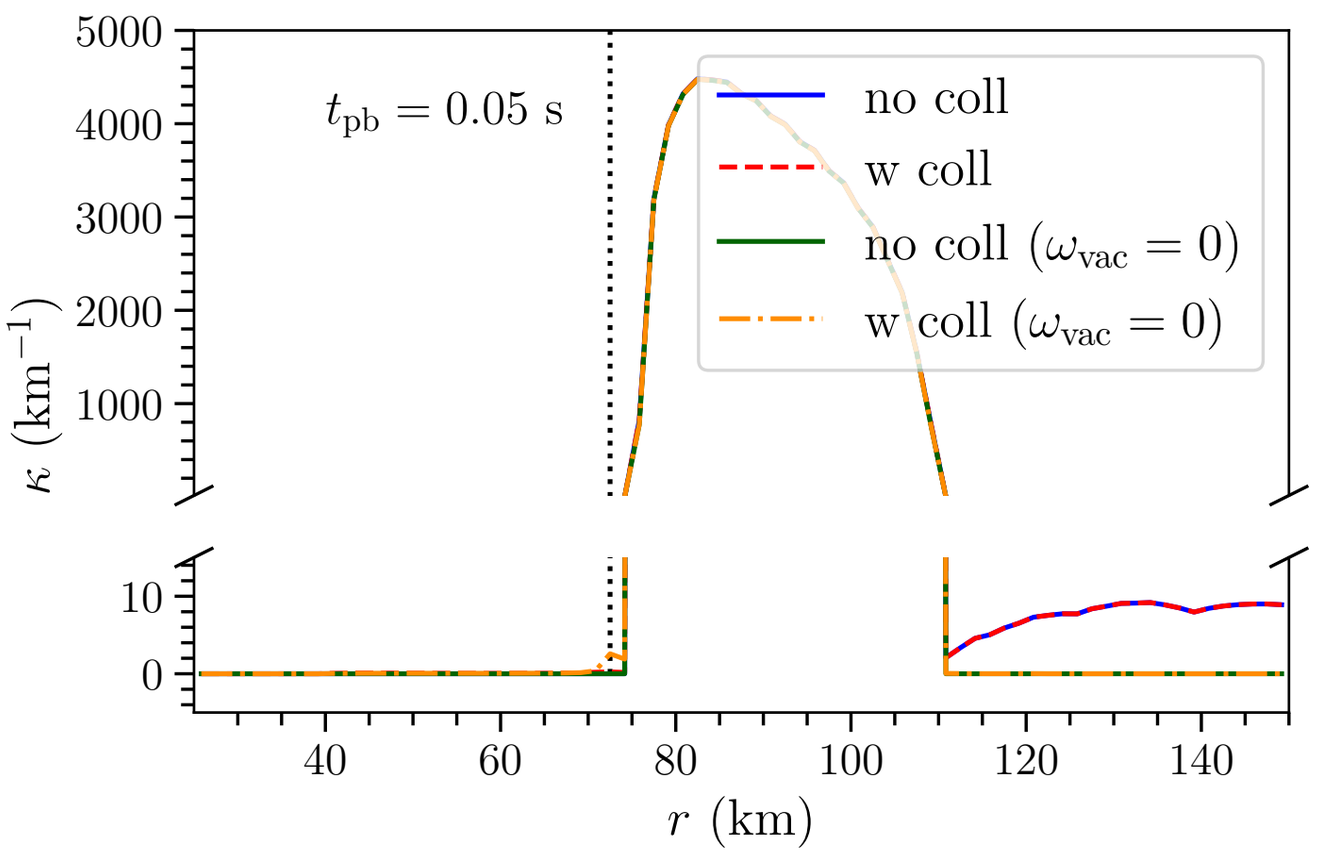
Flavor conversion in 2D (w/ perturbations)

- Flavor conversion is dynamically affected by collisions and advection.
- Background fluctuations affect the flavor conversion physics across spatial regions.

Cornelius, Shalgar & Tamborra, arXiv: 2407.04769.
Shalgar, Padilla-Gay, Tamborra, JCAP (2020). Padilla-Gay, Shalgar, Tamborra, JCAP (2021). Richers, Willcox, Ford, PRD (2021).

Collisional Flavor Instabilities

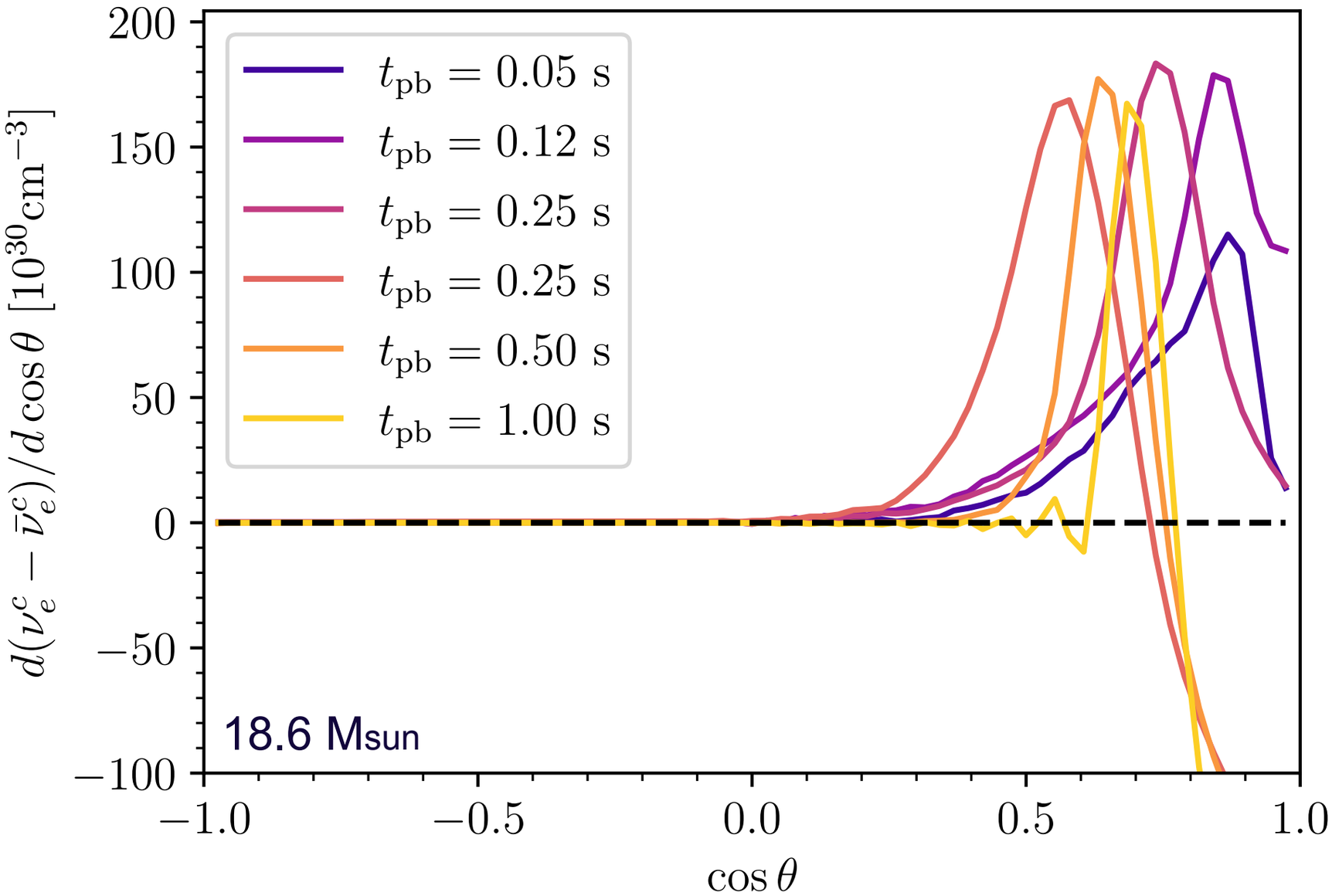




Collisional instabilities seem to have a negligible impact in the decoupling region, if ELN crossings exist. More work needed.

Shalgar & Tamborra, PRD (2024). Nagakura & Zaizen, PRD (2023). Akaho et al., PRD (2024).
Johns, PRL (2023). Johns & Xiong, PRD (2022). Xiong et al., PRD (2023). Johns & Xiong, PRD (2022). Padilla-Gay, Tamborra, Raffelt, PRD (2022).

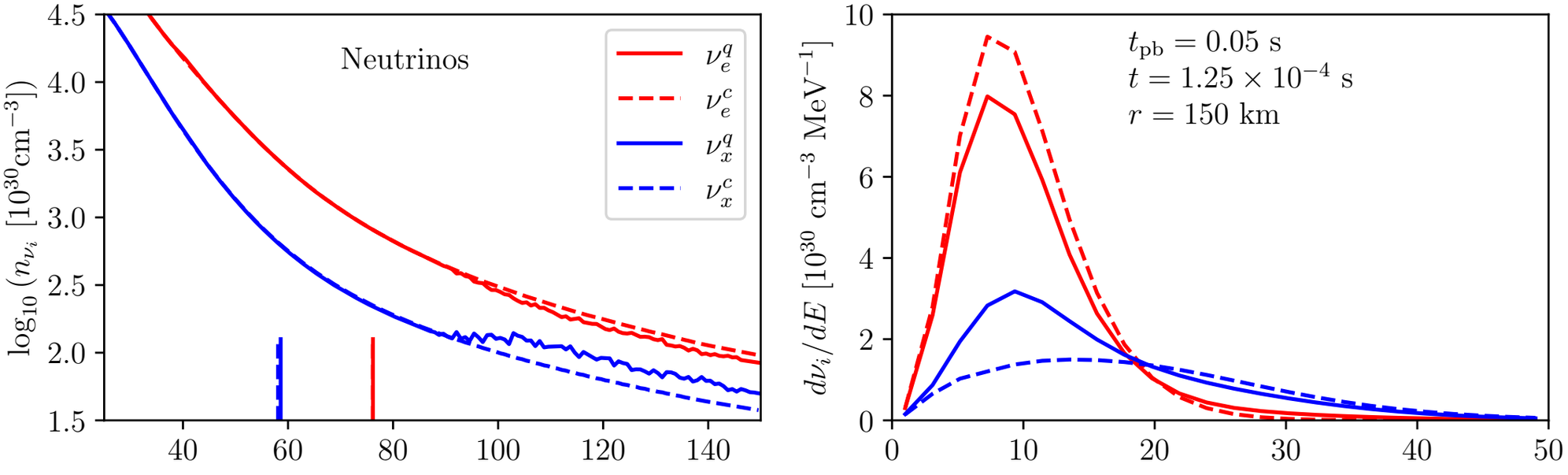
Example: Core-Collapse Supernova



Crossings in the neutrino electron number angular distribution appear for t>0.25 s.

Shalgar & Tamborra, arXiv: 2406.09504.

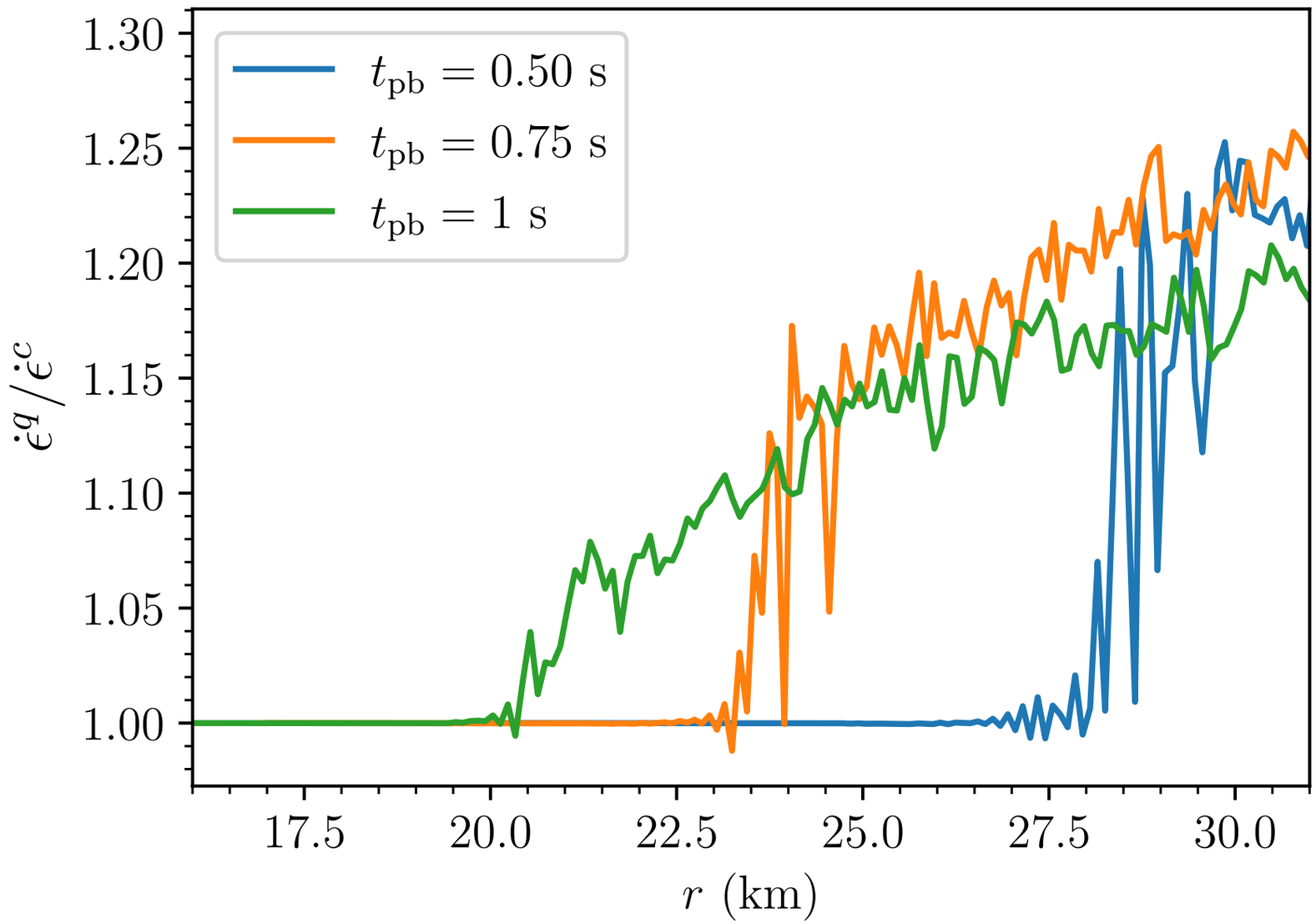
Example: Core-Collapse Supernova



Flavor equipartition due to flavor conversion depends on ELN crossing configuration.

Shalgar & Tamborra, arXiv: 2406.09504.

Example: Core-Collapse Supernova



- The neutrino heating rate increases by 15-25% due to flavor conversion.

- Impact on multi-messenger observables?

Shalgar & Tamborra, arXiv: 2406.09504.
Ehring, Abbar, Janka, Raffelt, Tamborra, PRL (2023). Nagakura, PRL (2023).

Core-Collapse Supernovae

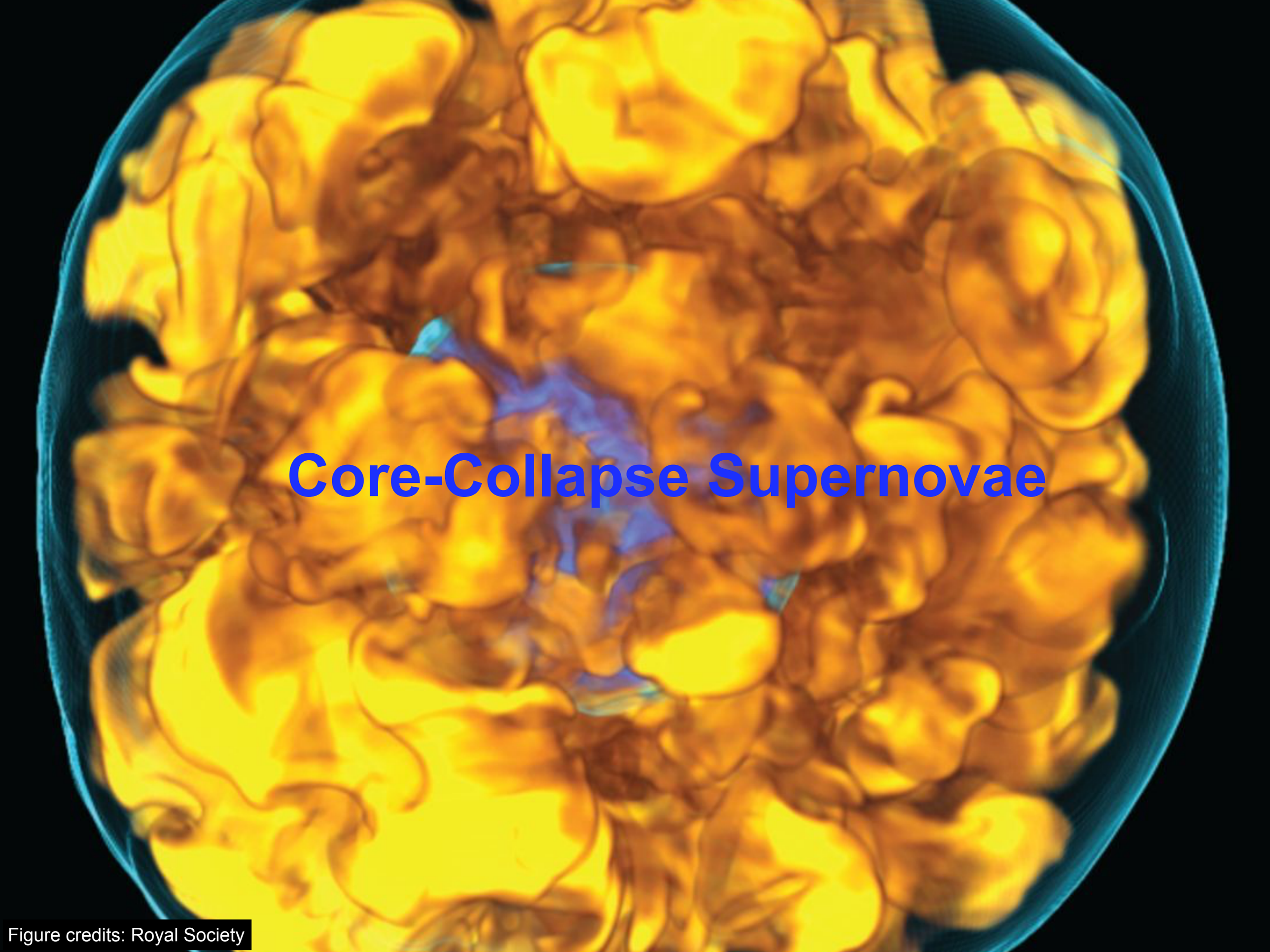
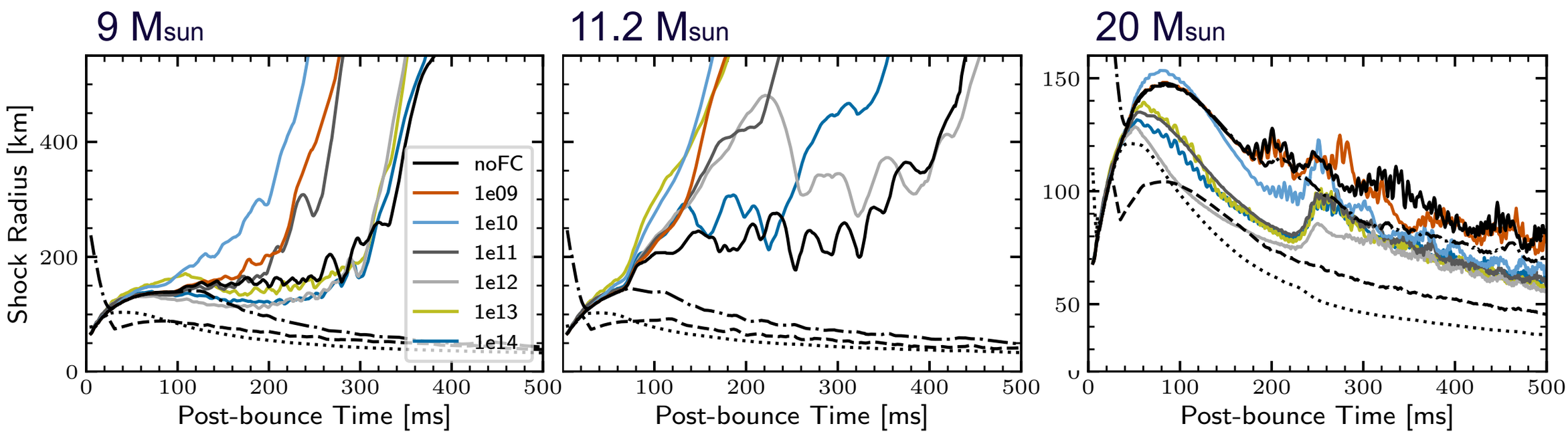


Figure credits: Royal Society

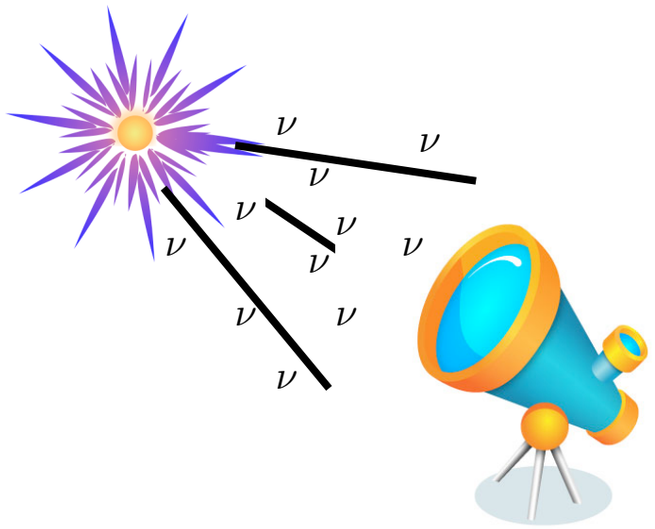
Does Flavor Conversion Affect Supernova Mechanism?



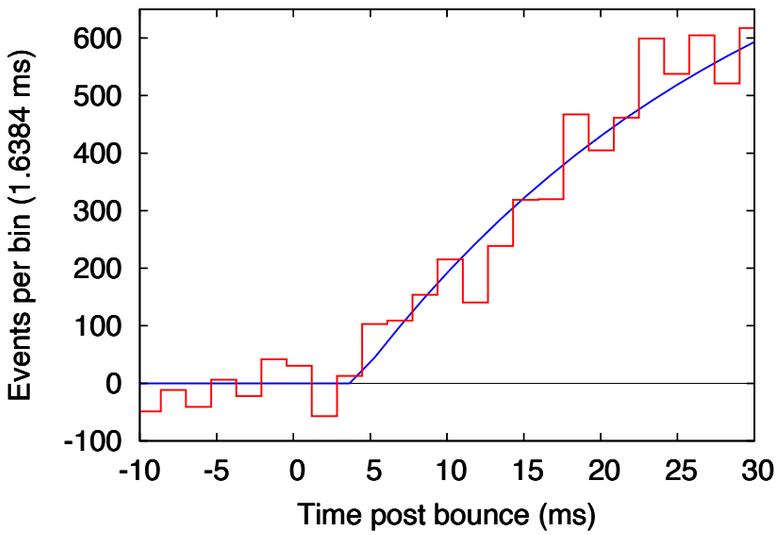
- Parametric implementation of flavor conversion in hydrodynamical simulations highlights non-trivial feedback on SN physics.
- Flavor conversion aids the explosion for low mass progenitors (9-12 Msun) and hinders explosion of higher-mass models (20 Msun).

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

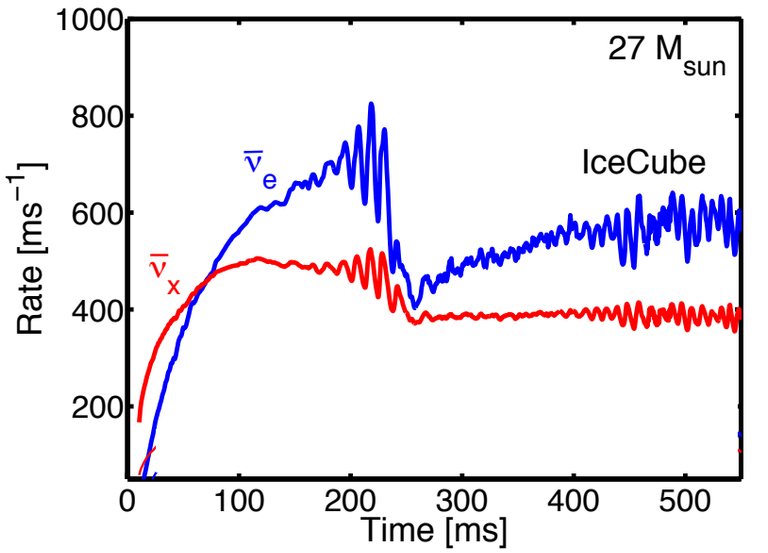
Neutrinos as Messengers



Determination of supernova direction with neutrinos.

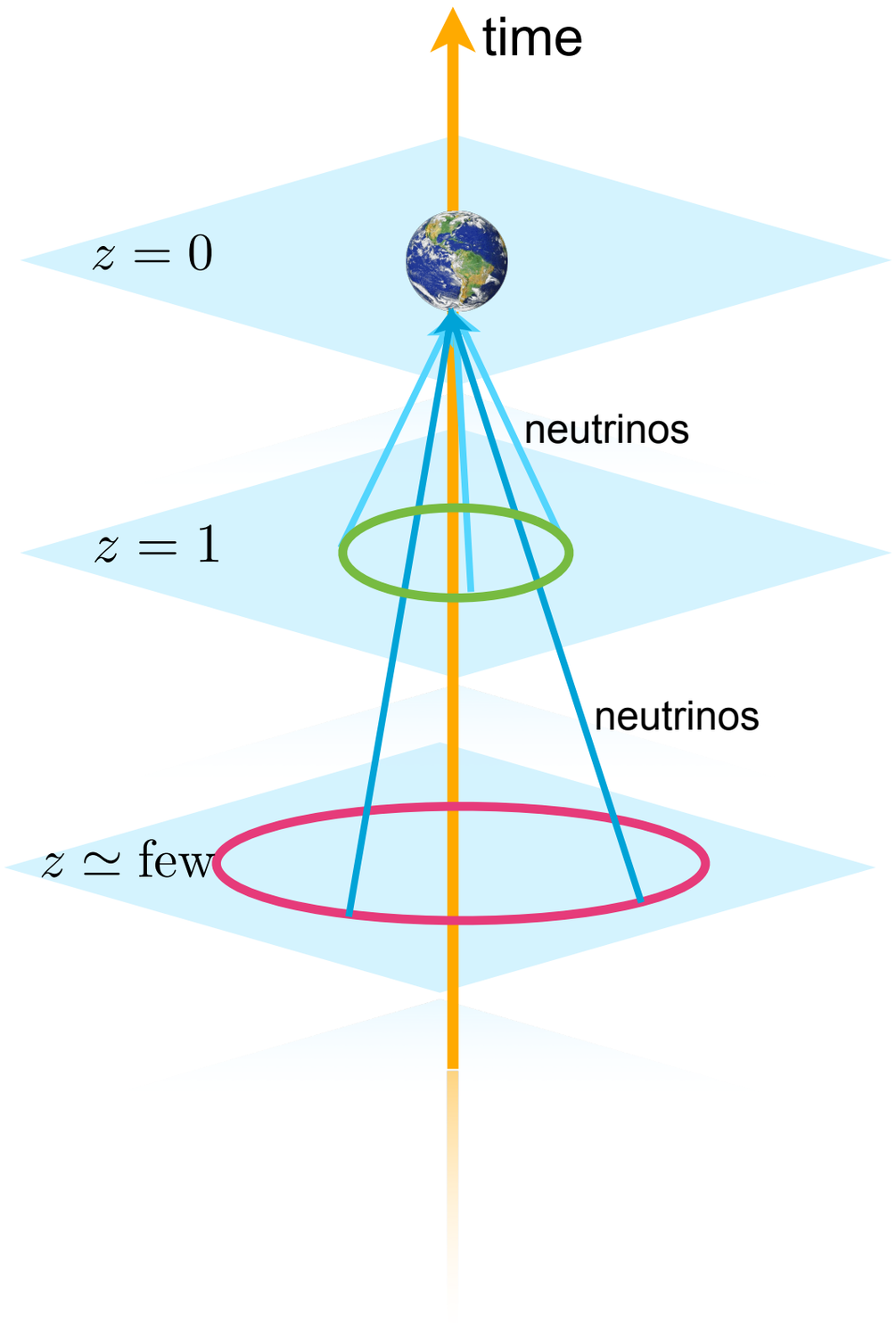


Neutrinos as matched filter for gravitational wave detection.



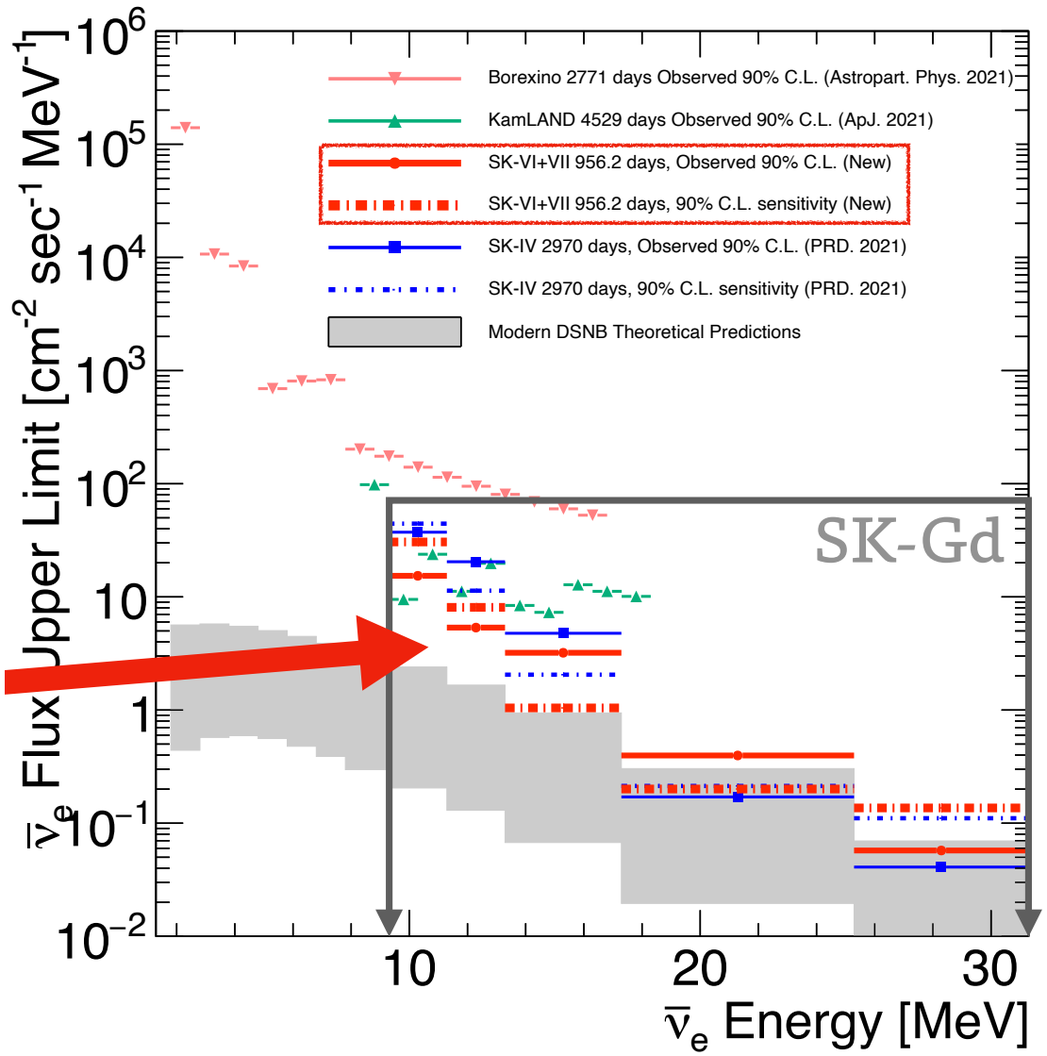
Neutrinos and gravitational waves carry imprints of supernova mechanism and proton-neutron star properties.

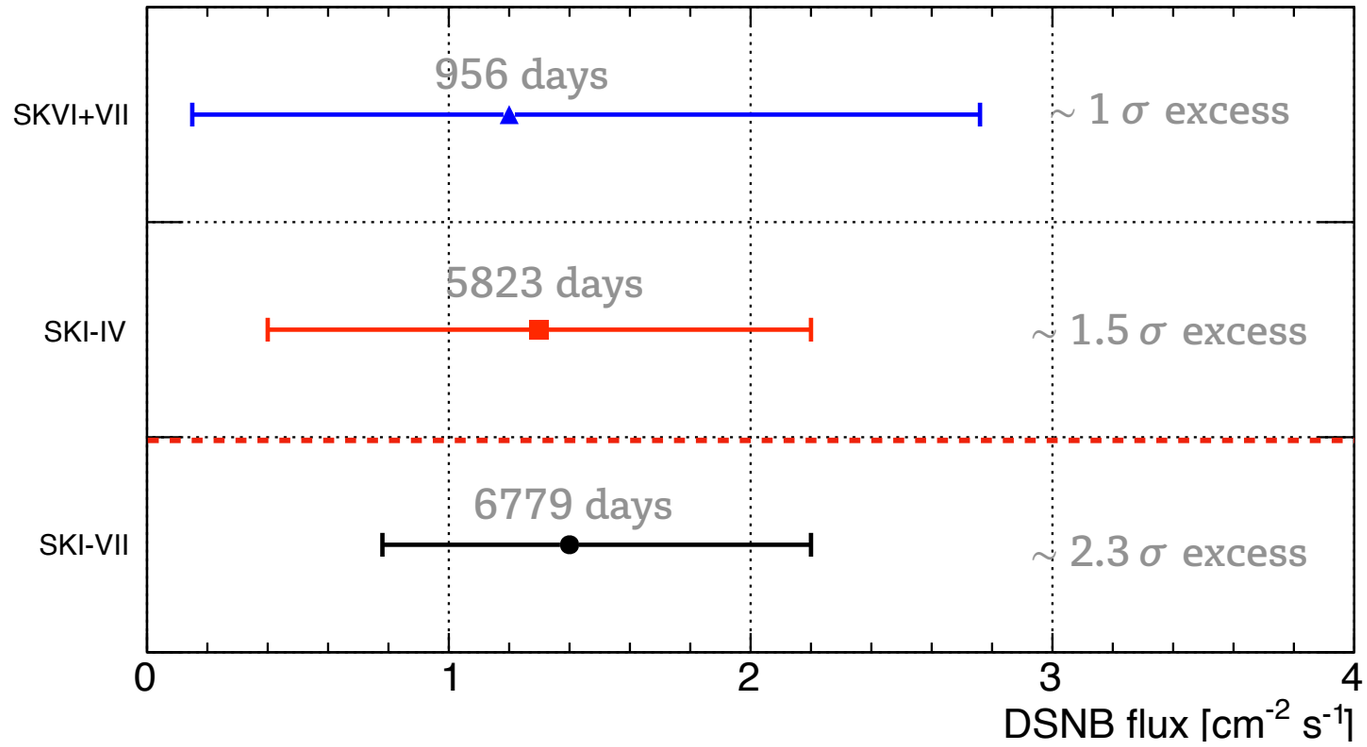
SNEWS 2.0, New Phys. J. (2021). Linzer & Scholberg, PRD (2019). Brdar et al., JCAP (2018). Sarfati, Hansen, Tamborra, PRD (2022). Pagliaroli et al., PRL (2009), Halzen & Raffelt PRD (2009). Nakamura et al., MNRAS (2016). Drago et al., PRD (2023). Tamborra et al., PRL (2013), PRD (2014). Kuroda et al.,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



Diffuse Supernova Neutrino Background

SuperK-Gd: DSNB Results





Highlight:

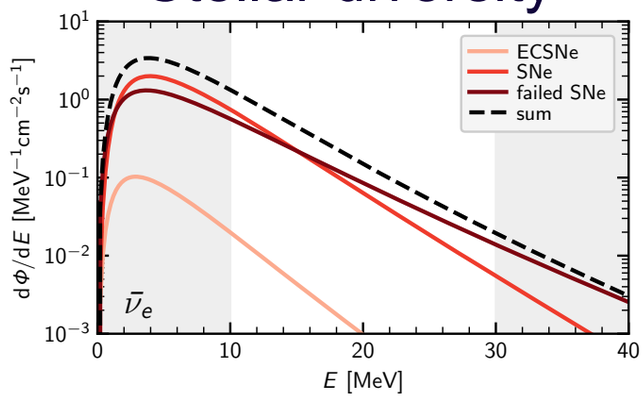
- Sensitivity of SK-Gd ~1000 days exposure is already comparable level it with ~6000 days of pure-water SK
- Best fit of whole SK observation is $\mathbf{1.4^{+0.8}_{-0.6}\ cm^{-2}\ s^{-1}}$ for $E_\nu > 17.3$ MeV

  ➡ exhibit ~2.3 σ excess!!

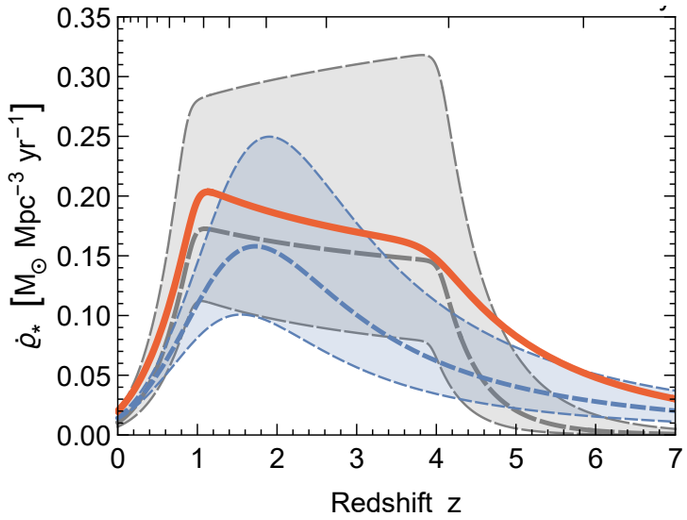
Figures from Harada's talk @ Neutrino 2024. Harada et al., ApJ Lett. (2023).

Modeling: What's Missing?

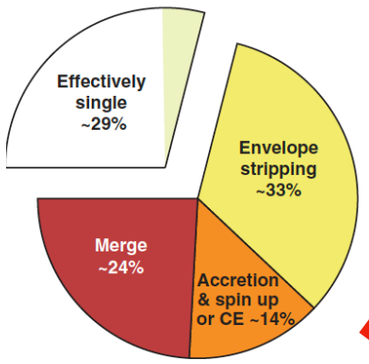
Stellar diversity



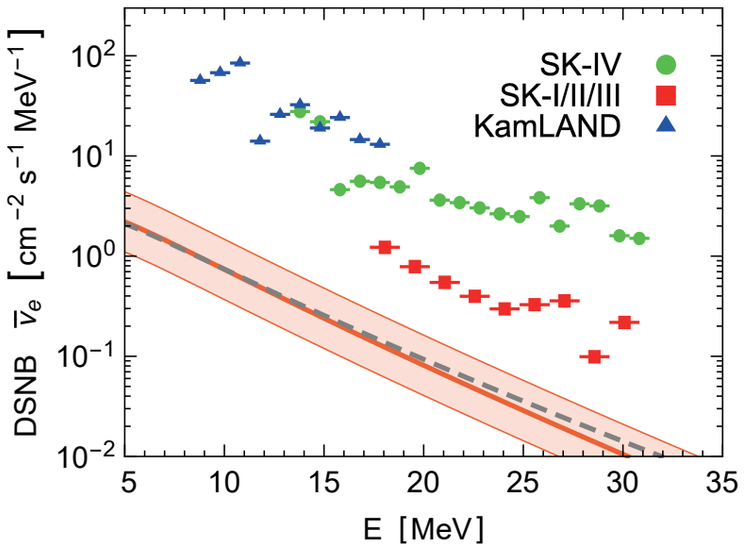
Star formation history



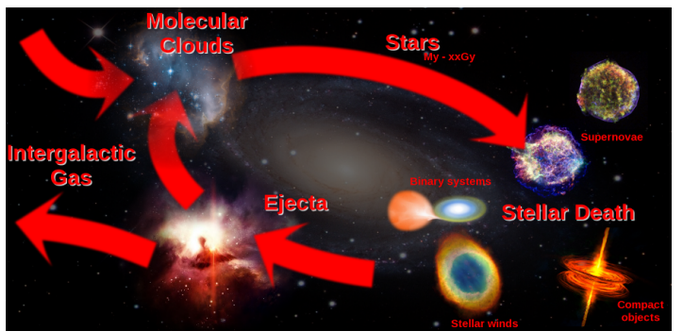
Binary interactions



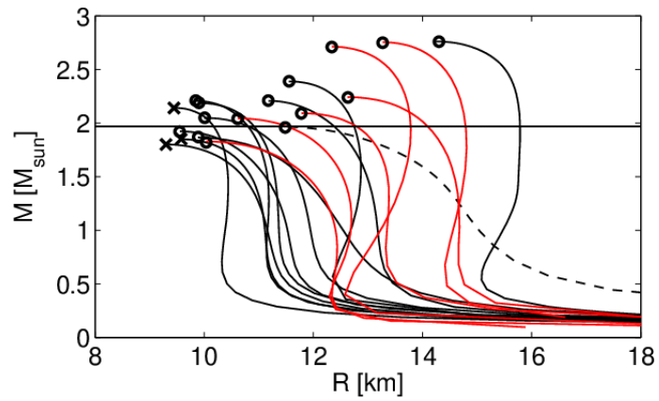
Supernova Relic Neutrinos



Galactic chemical evolution



Microphysical uncertainties (neutrino, NS properties, etc)



Lunardini, Tamborra, JCAP (2012). Moller, Suliga, Tamborra et al., JCAP (2018). Kresse, Ertl, Janka, ApJ (2020). Horiuchi et al., PRD (2021). Ziegler et al., MNRAS (2022). Ashida, Nakazato, Tsujimoto, ApJ (2023). Galais et al., PRD (2020). Ando et al., arXiv: 2306.16076.

Compact Binary Mergers

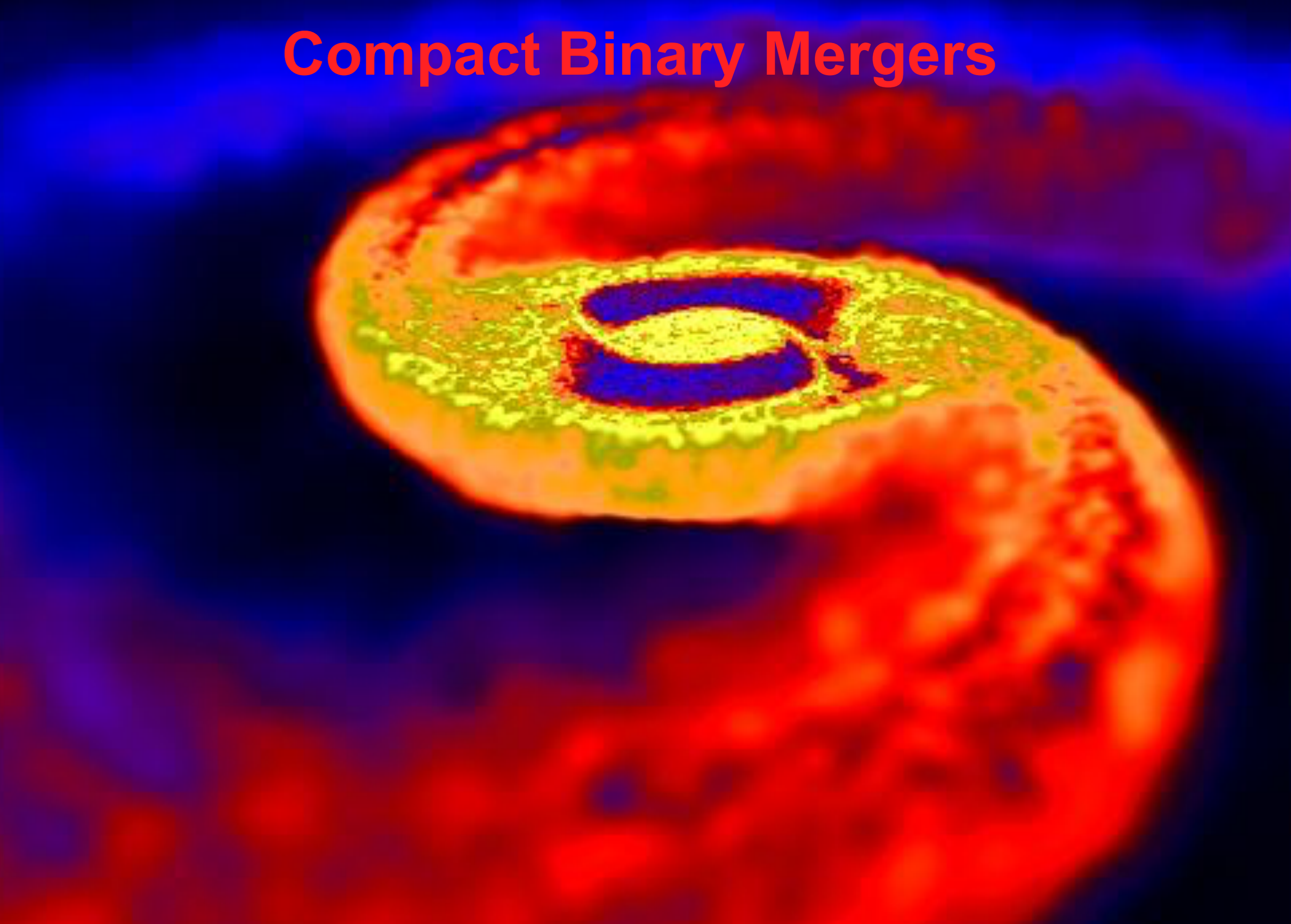
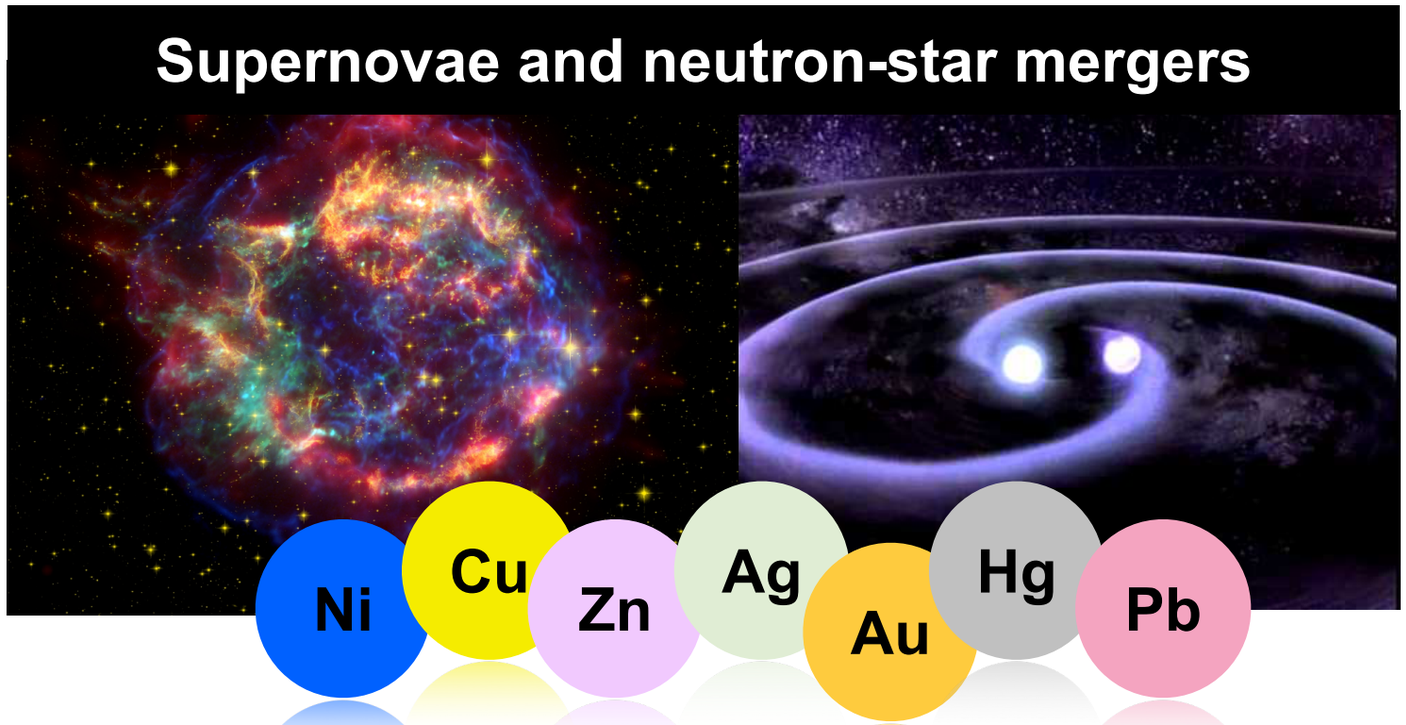
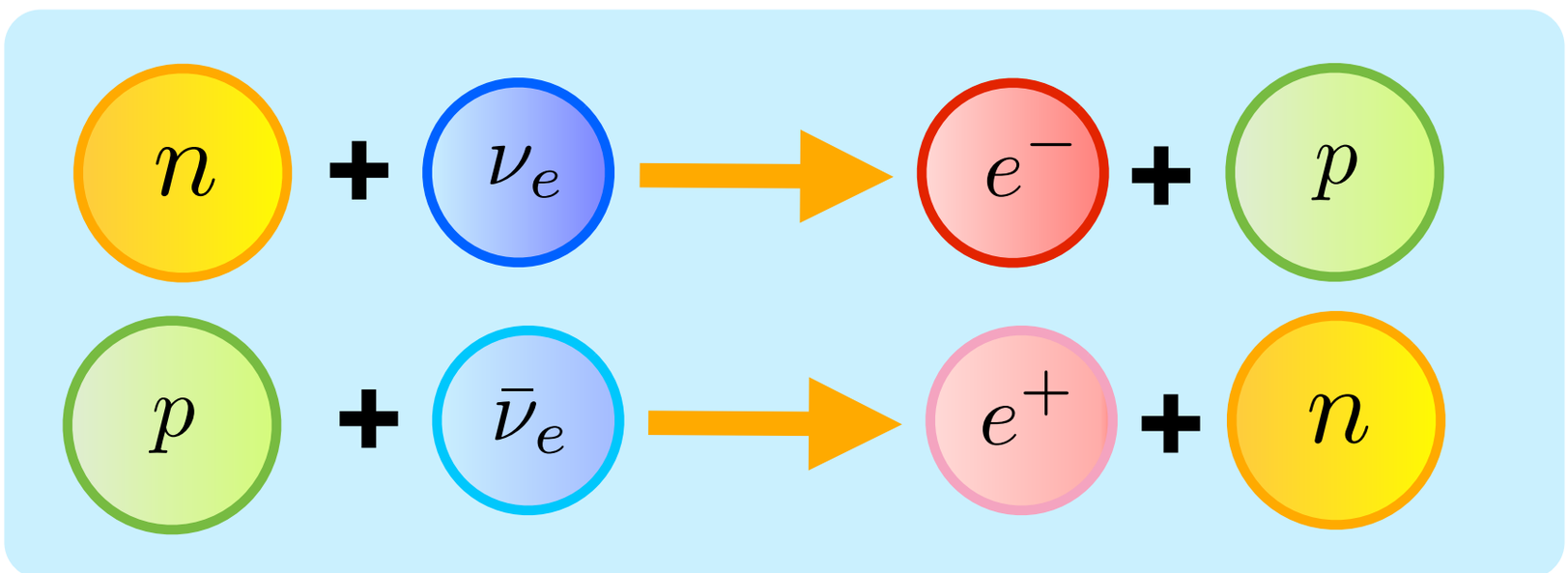


Figure credit: Price & Rosswog, Science (2006).

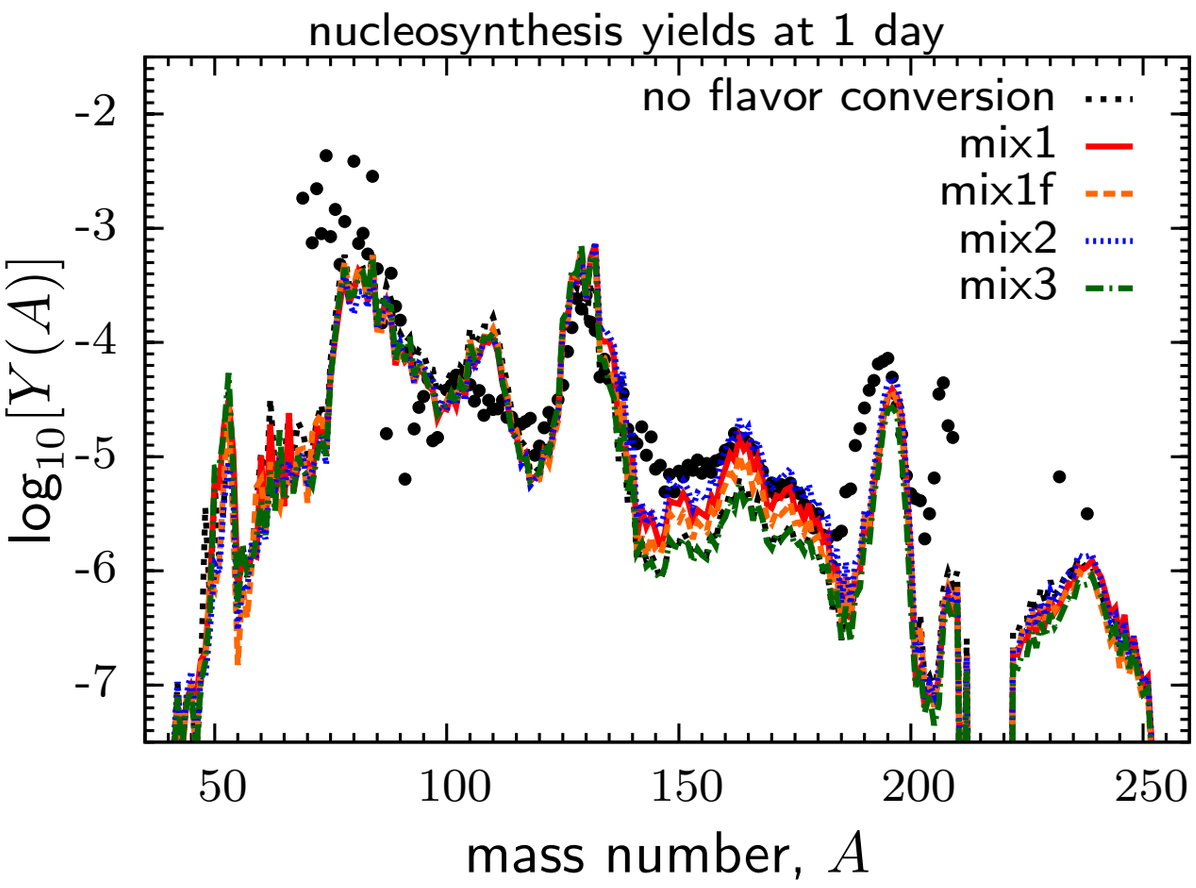
Nucleosynthesis of the Heavy Elements

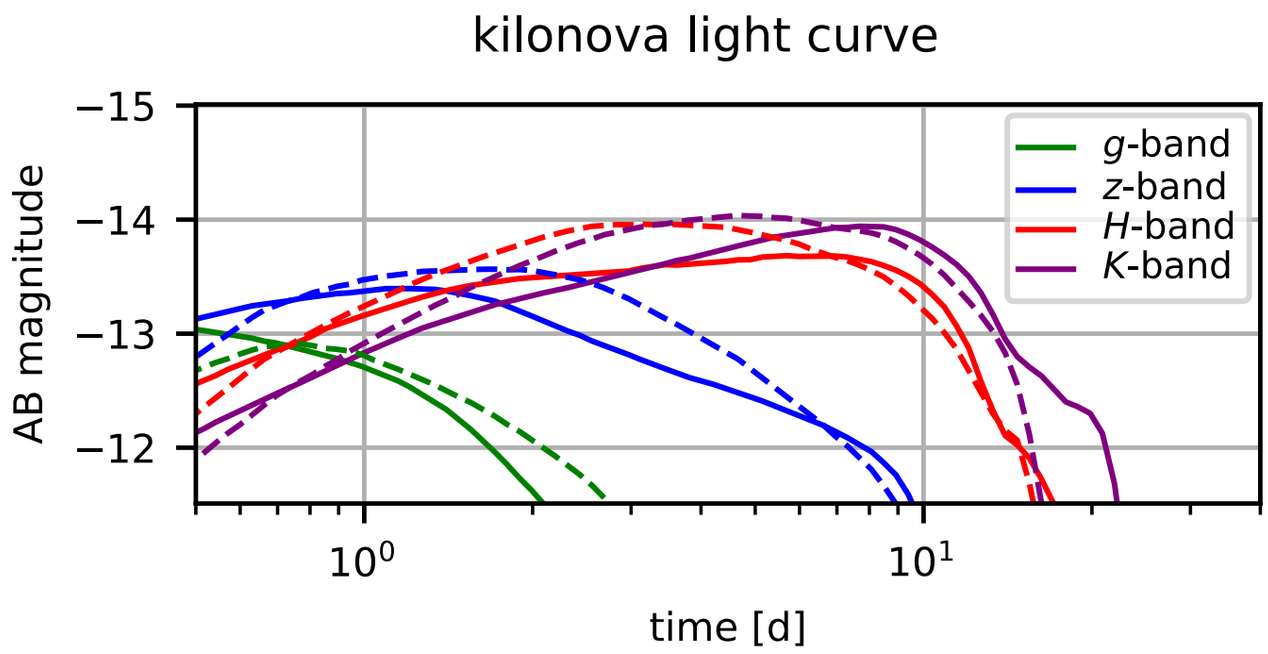


Synthesis of new elements could not happen without neutrinos.



Nucleosynthesis in Neutron Star Mergers



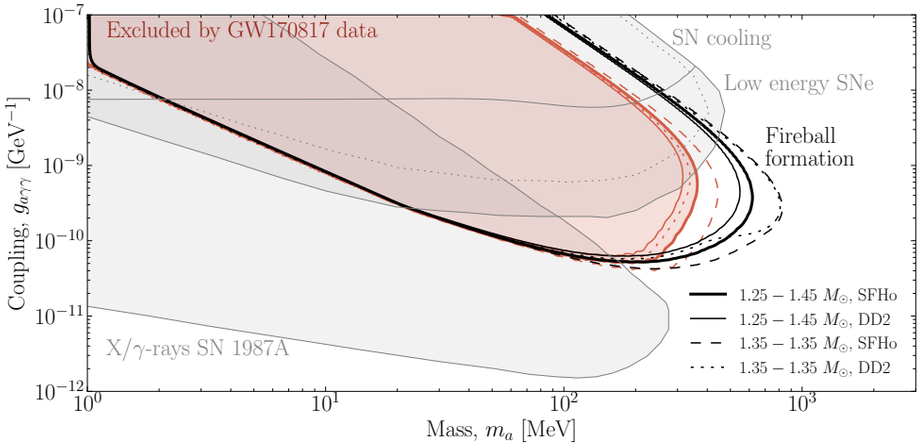


Flavor conversion affects the cooling of the disk and enhances synthesis of elements with A>130 by a factor 2-3.

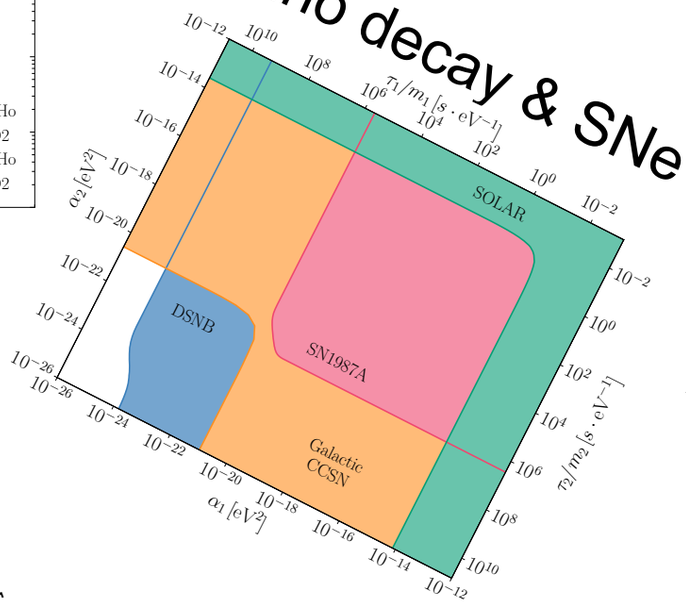
Just, Abbar, Wu, Tamborra, Janka, Capozzi, PRD (2022). Wu, Tamborra, Just, Janka, PRD (2017). Wu & Tamborra, PRD (2017). Padilla-Gay, Shalgar, Tamborra, JCAP (2021). George, Wu, Tamborra, Ardevol-Pulpillo, Janka, PRD (2020). Li & Siegel, PRL (2021). Fernandez, Richers et al., PRD (2022).

Opportunities for New Physics Discoveries

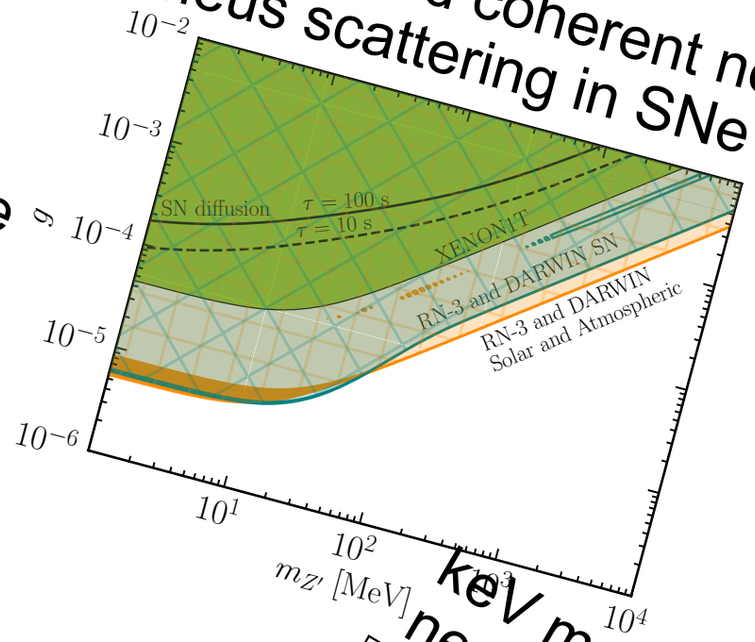
Radiatively decaying axions in mergers



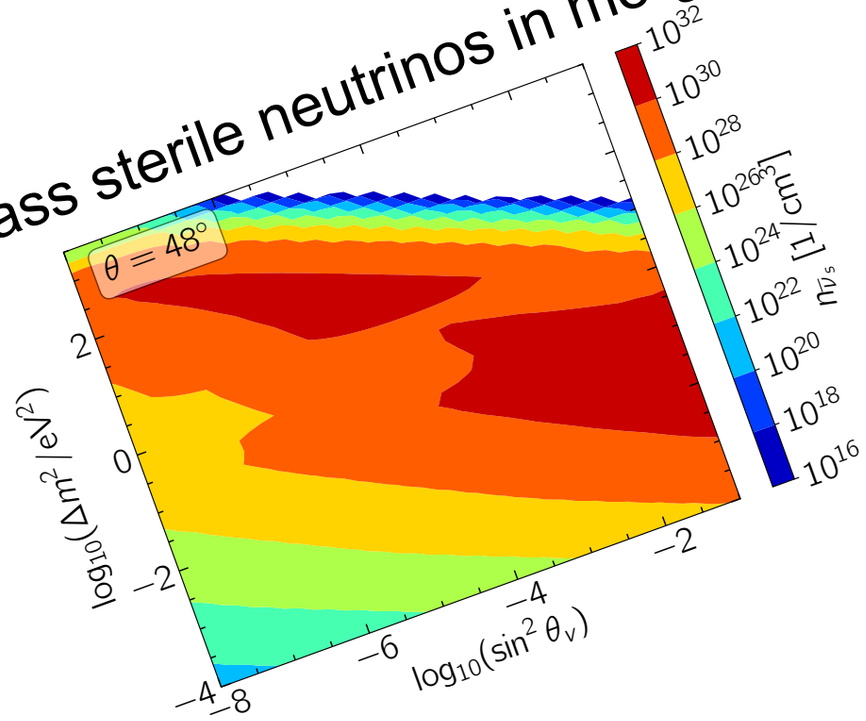
Neutrino decay & SNe



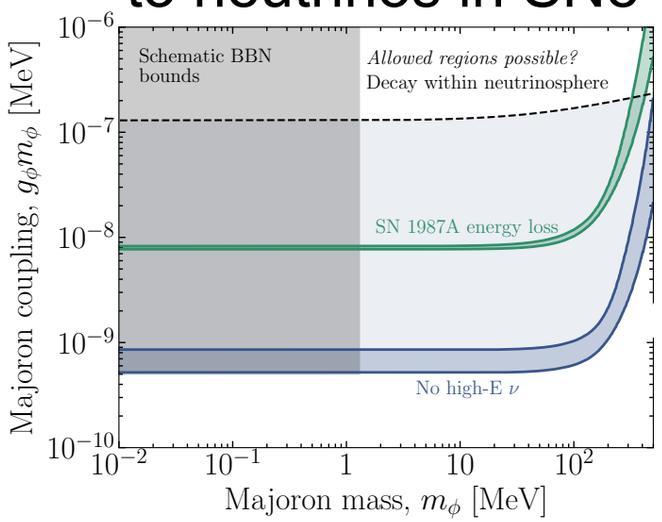
Non-standard coherent neutrino-nucleus scattering in SNe



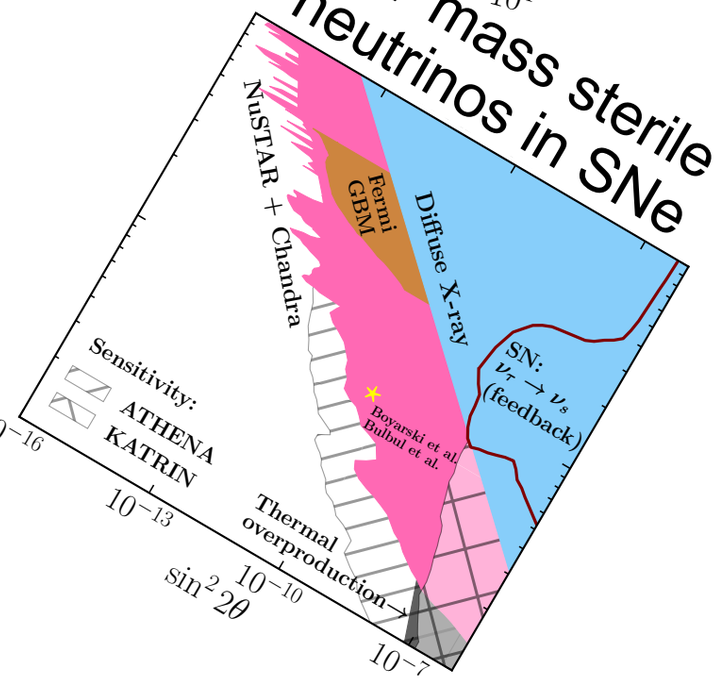
eV mass sterile neutrinos in mergers



Bosons decaying to neutrinos in SNe



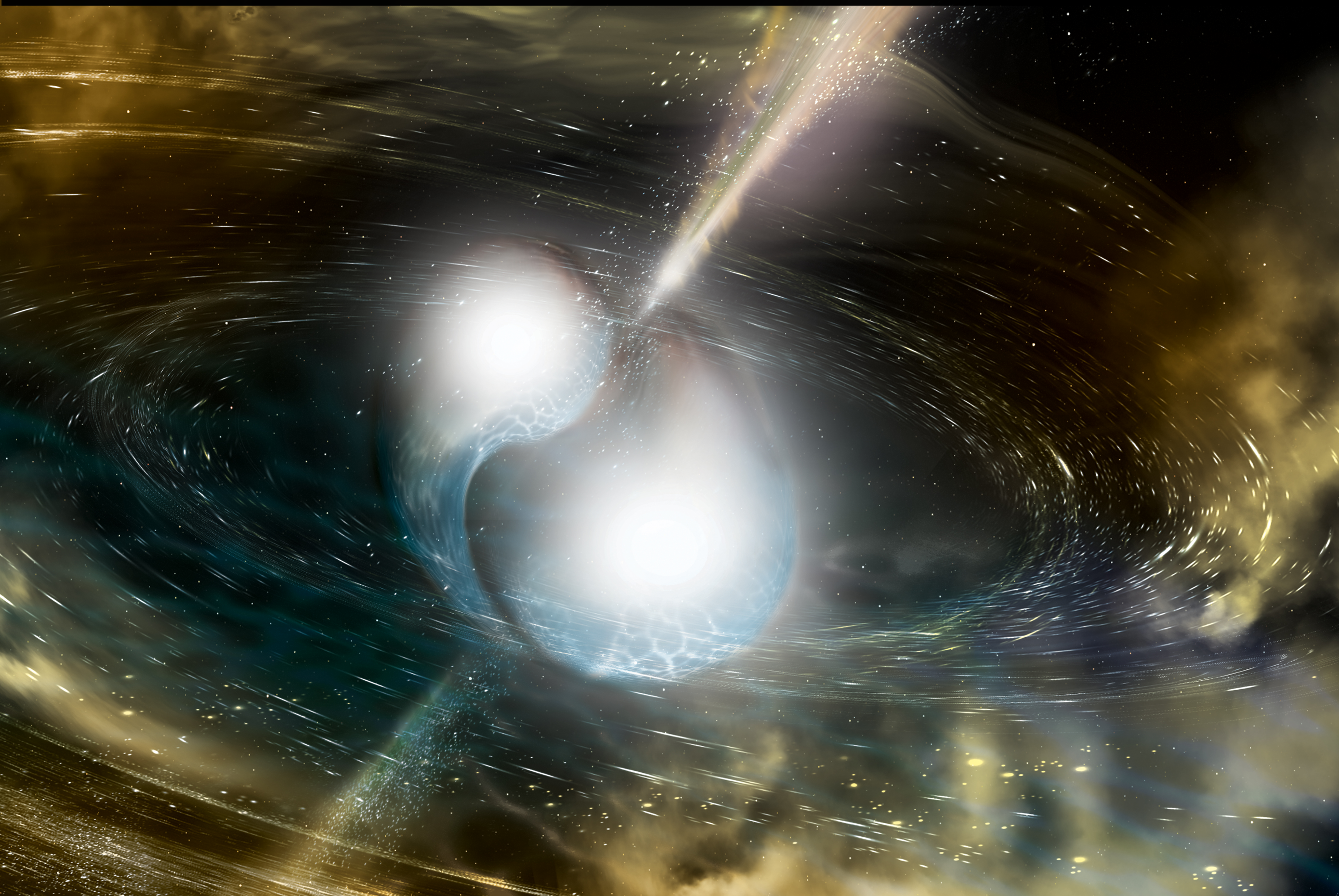
keV mass sterile neutrinos in SNe



and many more…

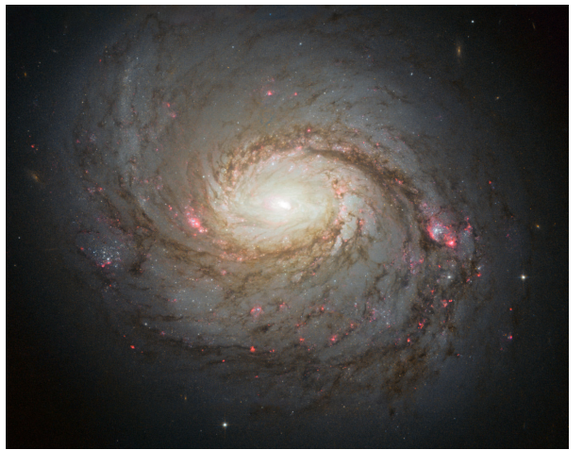
Diamond, Fiorillo, Marques-Tavares, Tamborra, Vitagliano, PRL (2024). Martinez-Mirave, Tamborra, Tortola, JCAP (2024). Sigurðarson, Tamborra, Wu, PRD (2022). Suliga & Tamborra, PRD (2021). Suliga, Tamborra, Wu, JCAP (2019), JCAP (2020). Fiorillo et al., PRL (2023), PRL (2024). Caputo et al., PRL (2022). Sung et al., PRD (2021). Tang et al., JCAP (2020). Ray, Qian, PRD (2023); arXiv: 2404.14485. Tamborra et al., JCAP (2012).

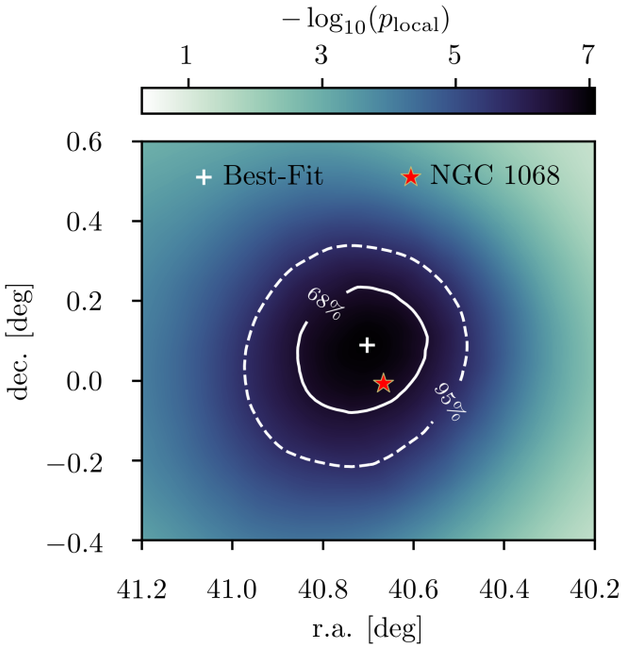
High Energy Emission



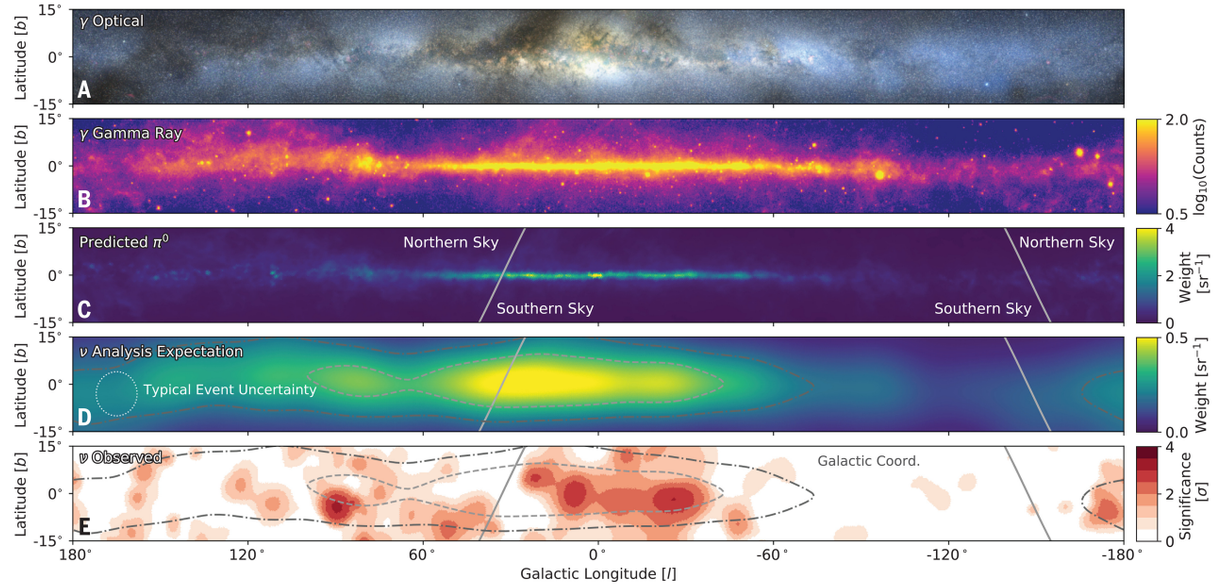
Neutrino-Electromagnetic Associations

Active Galaxies

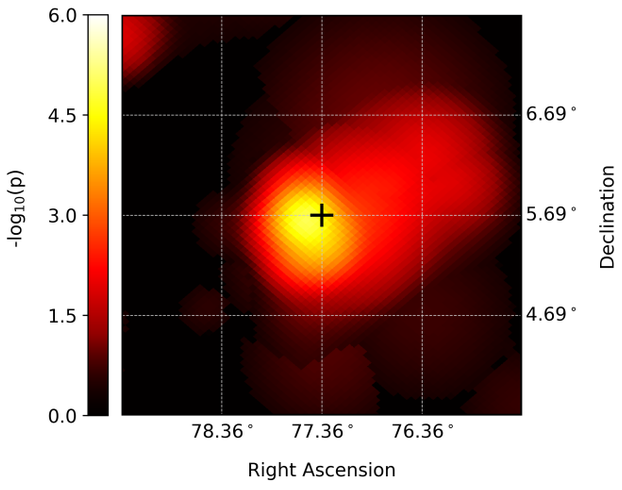




Our Galaxy



Blazars



Tidal Disruption Events/ Superluminous Supernovae?

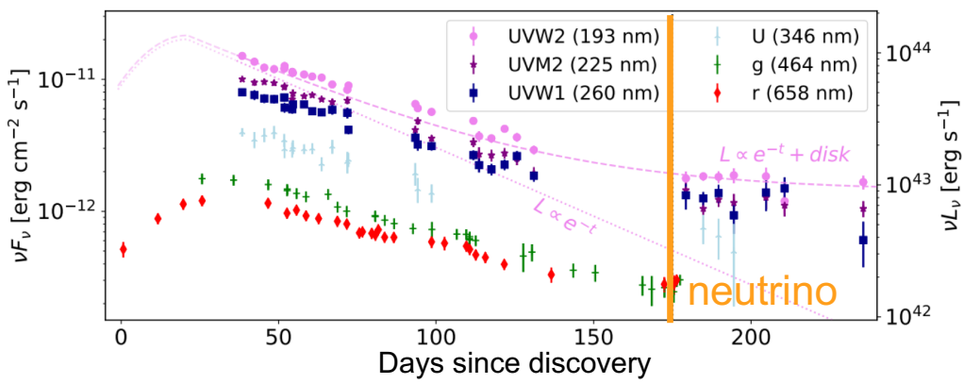
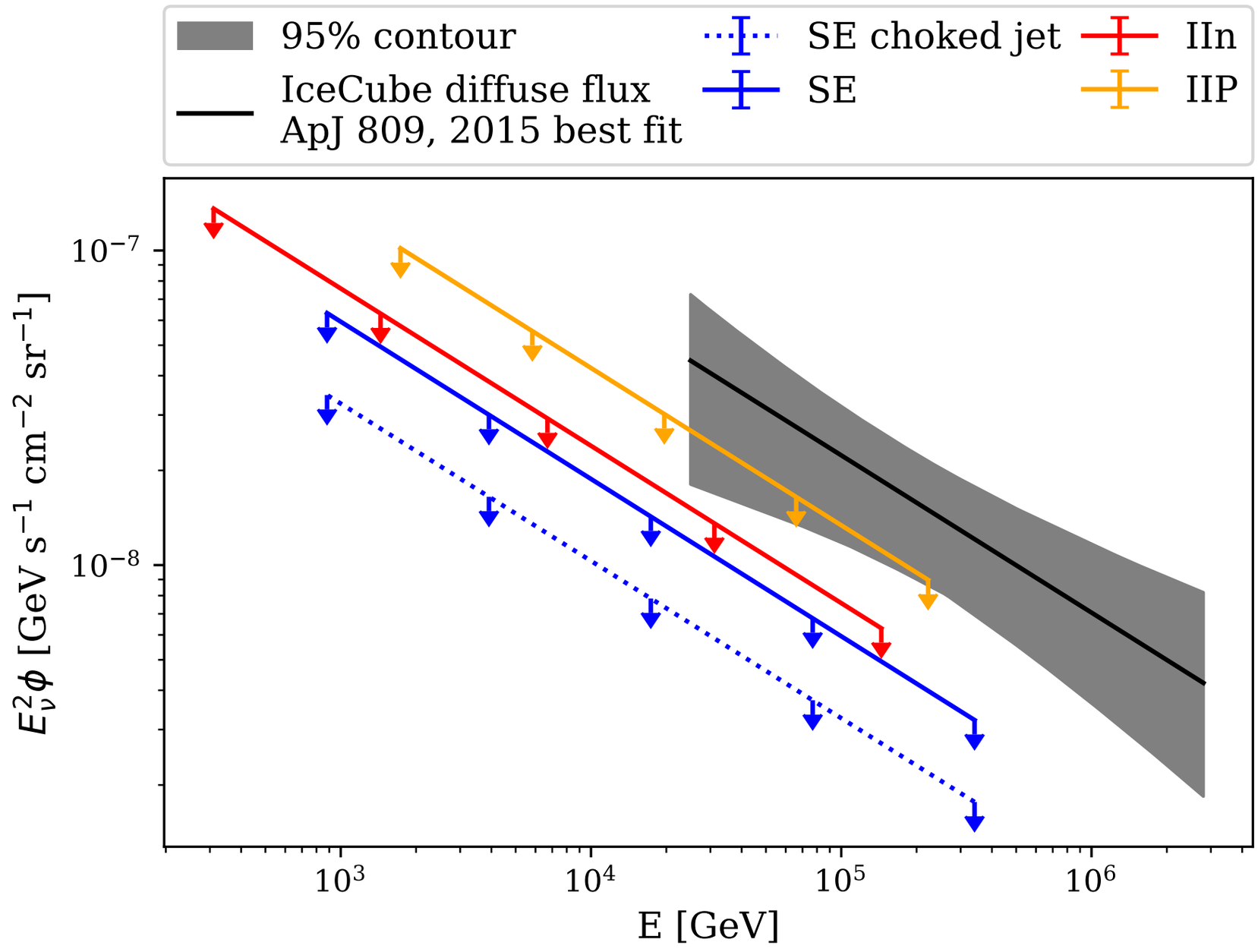


Image credits: IceCube Collaboration.

Neutrinos from Supernovae

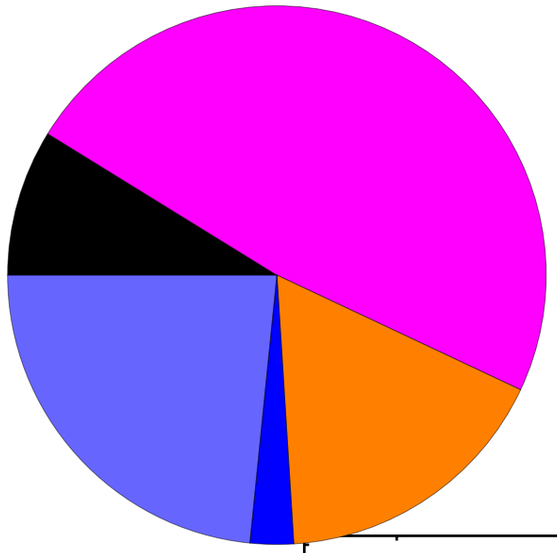


- No significant spatial or temporal correlation of high-energy neutrinos with supernovae found yet (upper limit on total energy emitted in neutrinos: 1.3×10^{49}erg for SNe IIn).

- SNe IIn (SNe IIP) do not contribute more than 33.9.6% (59.9%) to the diffuse neutrino flux observed by IceCube.

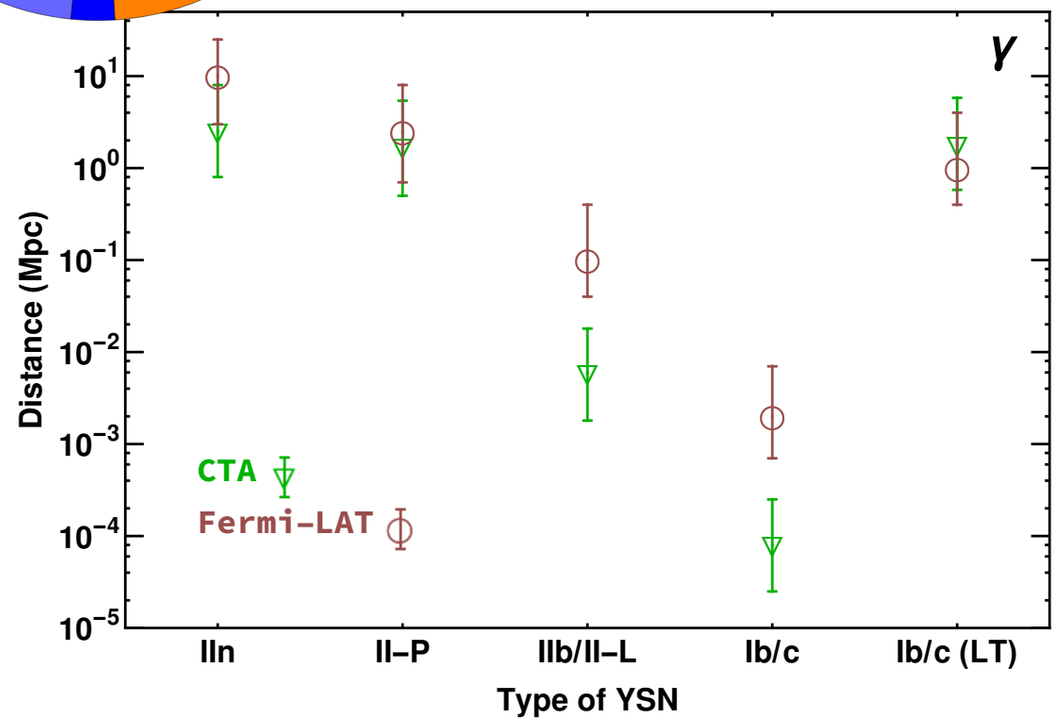
IceCube Coll., Astrophys. J. Lett. (2023).

Multi-Messenger Emission from Supernovae

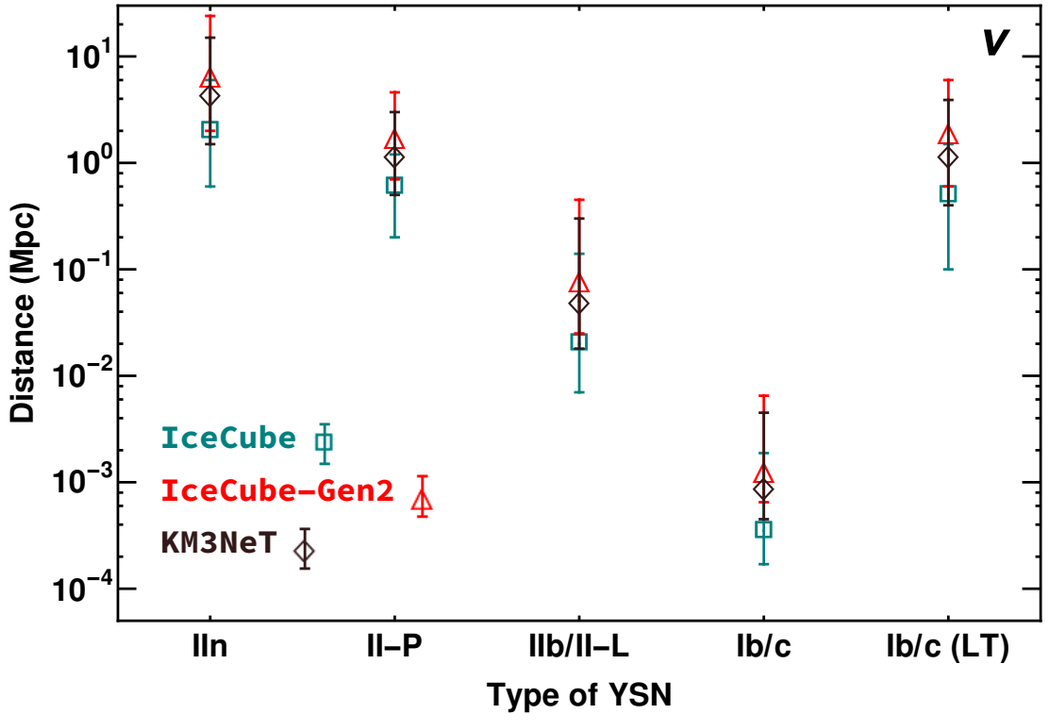


- IIn (8.8%)
- II–P (48.2%)
- IIb/II–L (17%)
- Ib/c late time (2.6%)
- Ib/c (26%)

Gamma-rays



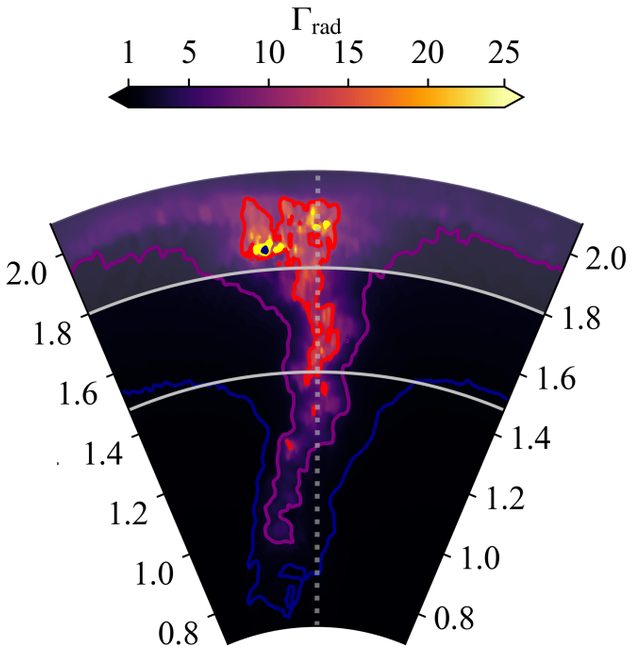
Neutrinos



- SNe of Type IIn and II-P detectable in gamma-rays and neutrinos in the local universe.
- Gamma-rays and neutrinos can probe the structure of circumstellar medium and test of particle acceleration.

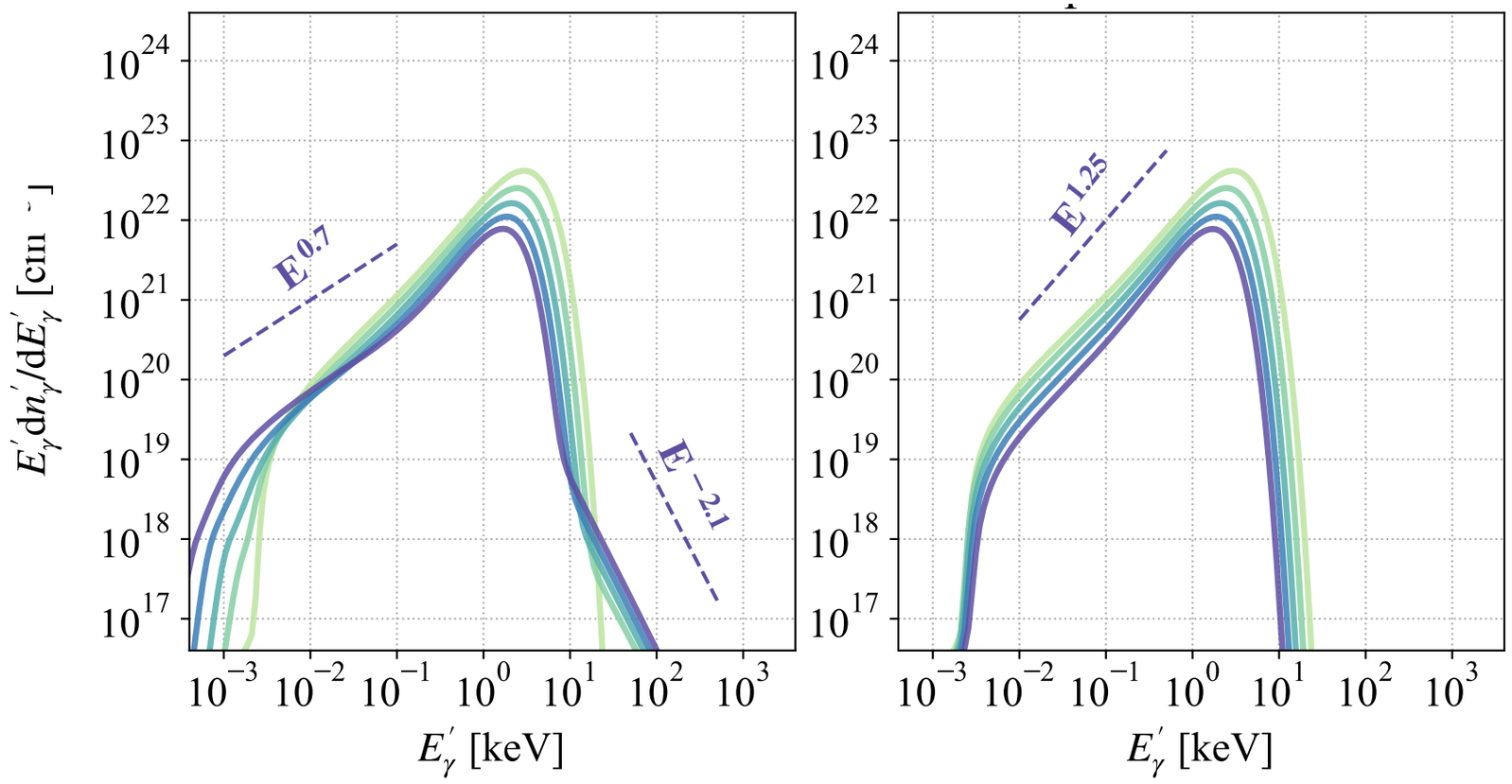
Sarmah, Chackaborty, Tamborra, Auchettl, JCAP (2022). Pitik, Tamborra, Angus, Auchettl, ApJ (2022). Pitik, Tamborra, Lincetto, Franckowiack, MNRAS (2023). Kheirandish & Murase, ApJL (2023). Cristofari et al., MNRAS (2022). Murase, PRD (2024). Murase et al., ApJ (2019).

On the Origin of the Photon Distribution



Leptonic + hadronic processes (our work)

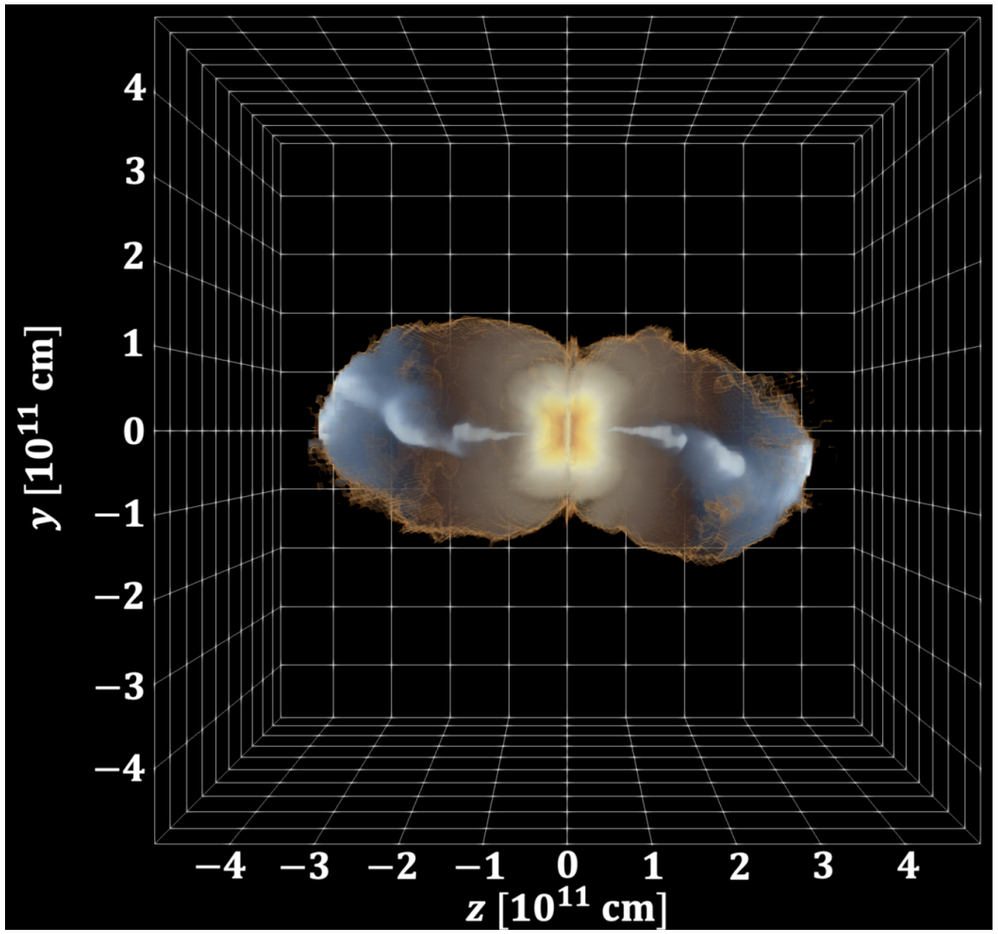
Leptonic processes only (usually considered)

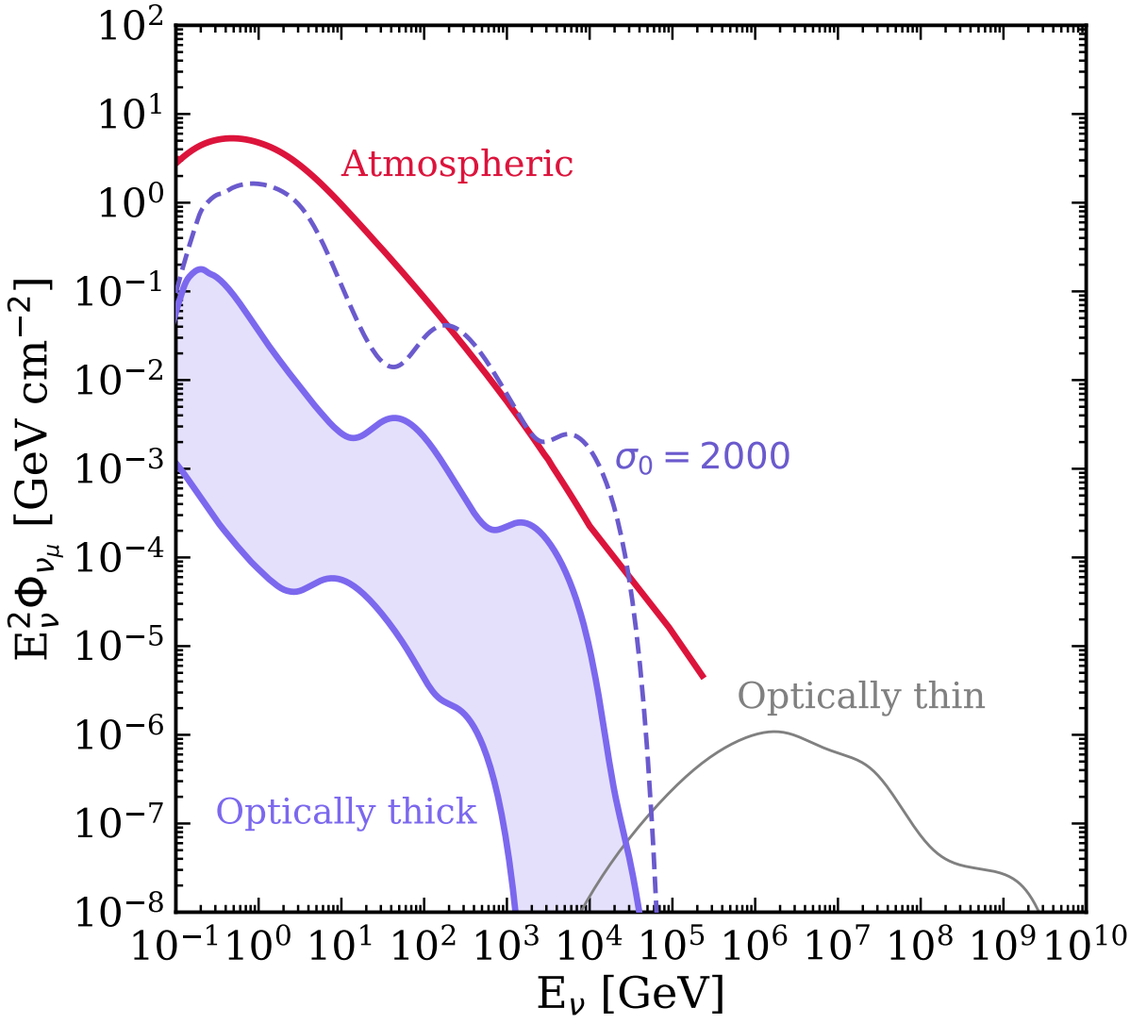


- Origin of observed Band-like photon spectrum in short GRBs is poorly understood.
- Bulk of non-thermal photon spectrum can stem from hadronic processes below the photosphere (usually just invoked for neutrino production).

Rudolph, Tamborra, Gottlieb, Astrophys. J. Lett. (2024).

On the Origin of the Neutrino Distribution

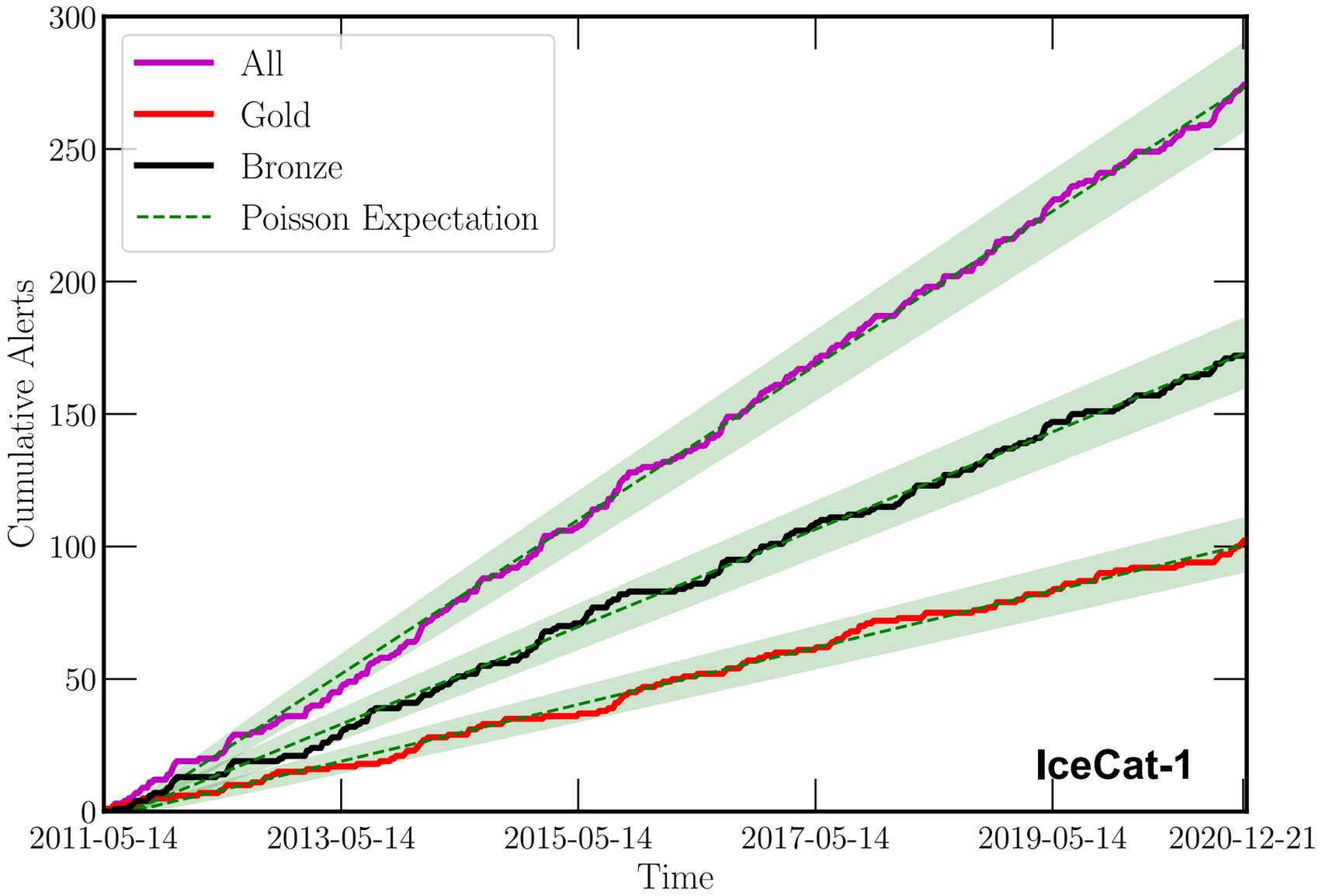




- State-of-the-art collapsar jet simulations predict neutrino signal different than expected.
- Subphotospheric neutrinos have lower energies than previously expected; detectable with IceCube DeepCore.

Rudolph, Tamborra, Gottlieb, Astrophys.J. Lett. (2024). Guarini, Tamborra, Gottlieb, PRD (2023). IceCube Coll., Astrophys. J. (2024).

Optimizing Follow-Up Programs



- Stacking neutrino searches based on “standard candles” are not optimal.
- Essential to combine X-ray/radio and UVOIR observations to aid neutrino searches.
- Neutrino bright transients may not be gamma-ray bright.

Figure credits: IceCube Collaboration, Astrophys. J. Suppl. (2023).

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

Conclusions

- Fantastic progress in multi-messenger searches of astrophysical sources.
- Modeling of neutrino quantum kinetics in compact sources advances swiftly.
- Neutrino flavor conversion impacts the supernova mechanism and kilonova lightcurve.
- The number of likely high-energy neutrino-electromagnetic associations is increasing.
- Robust 1:1 neutrino-gamma-ray connection is not so obvious as previously expected.
- We need to optimize multi-messenger follow-up programs for growing number of high-energy neutrino alerts.

Thanks!