Astrophysical Neutrinos and the Origin of the Elements: What's Next?

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INT Workshop: Astrophysical neutrinos and the origin of the elements,
Seattle, July 24-28, 2023

VILLUM FONDEN
Sapere Aude
erc European Research Council
Established by the European Commission
CARLSBERG FOUNDATION
SFB 1258 Neutrinos Dark Matter Messengers

Main Challenges

- Ab-initio simulations of the collapse of massive stars/compact binary mergers
- Supernova explosion mechanism(s)
- Formation paths for NS & BH and birth properties
- Relevance of magnetic field, rotation, general relativity
- Impact of neutrino physics
- Equation of state and nuclear uncertainties
- What are the elements synthetized in supernovae? And in mergers?
- Do we have a clear picture of the multi-messenger signals we should look for?
- How do we optimize the multi-messenger detection prospects?
- Signatures of BSM physics

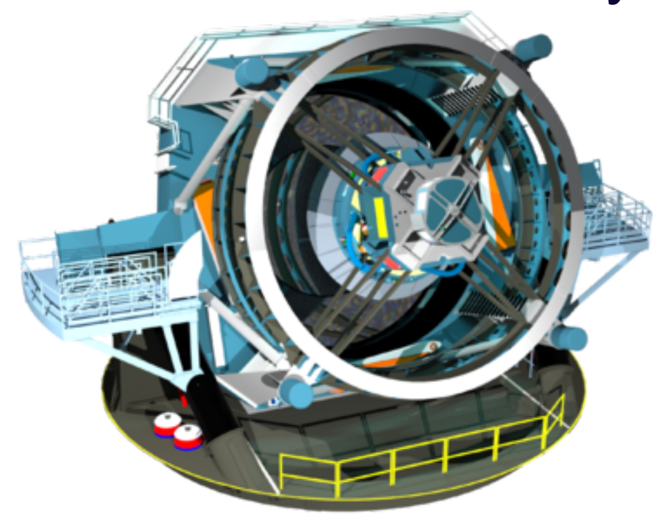
Multi-Messenger Detection Opportunities

ASAS-SN

Baikal-GVD

DARWIN

Rubin Observatory



Pan-STARRS

JUNO

DUNE
DEEP UNDERGROUND NEUTRINO EXPERIMENT

LIGO
VIRGO
KAGRA

ICECUBE GEN2

KM3NeT

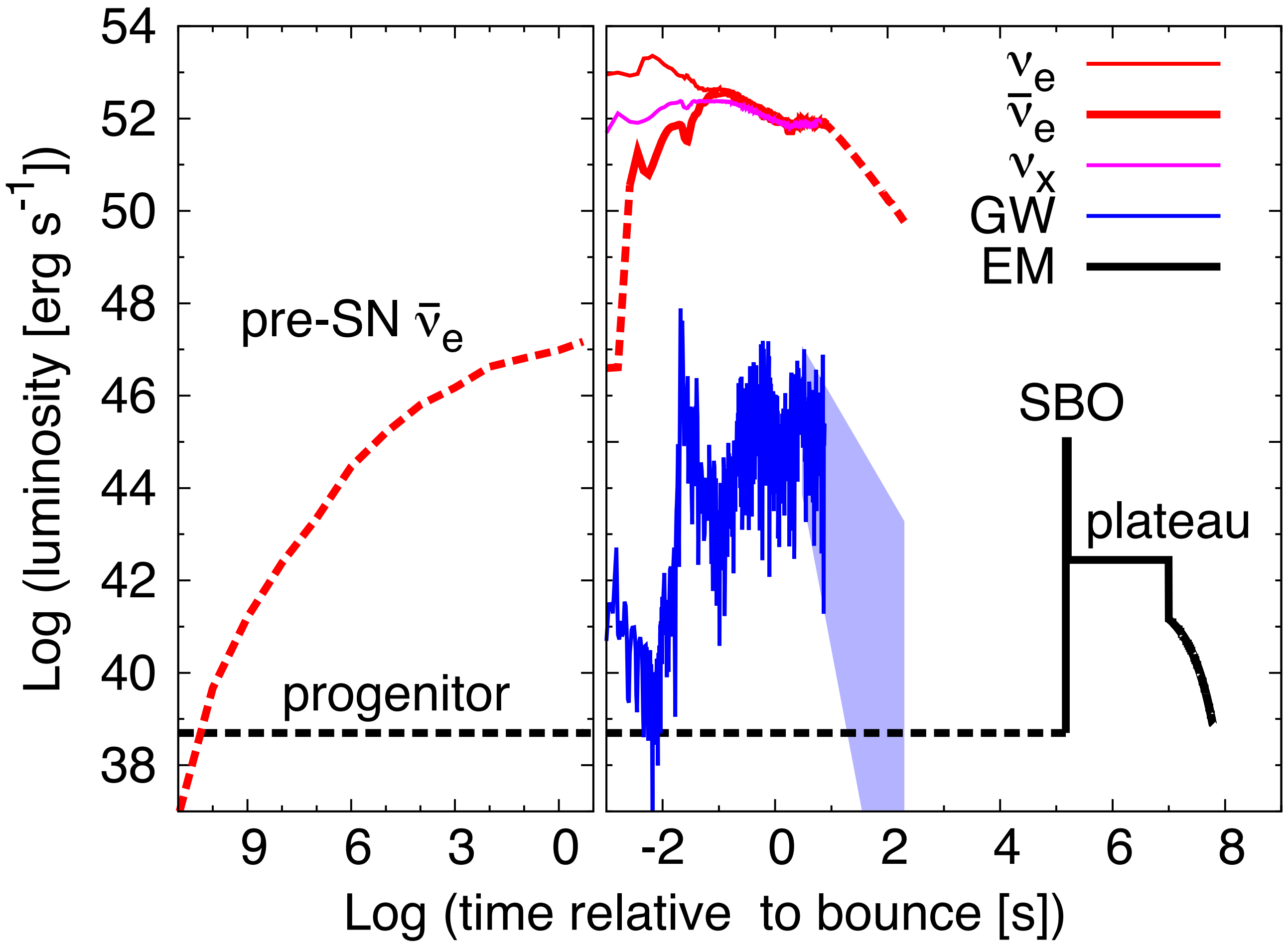
RES-NOVA

and many more…

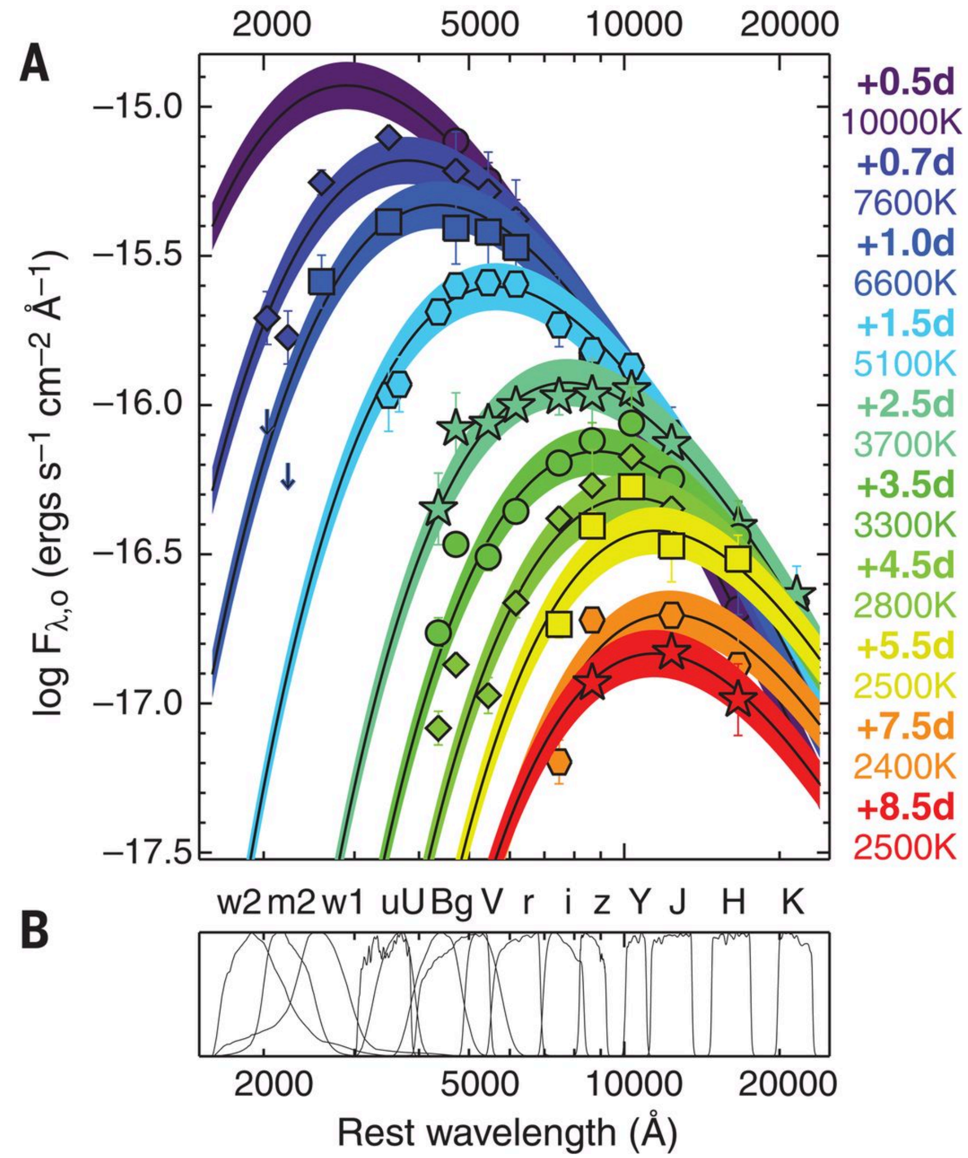
How to combine astrophysical signals from detectors employing different technologies?
What can we learn exploiting multi-waveband and multi-messenger observations?

What's Next?

The next supernova



The next kilonova



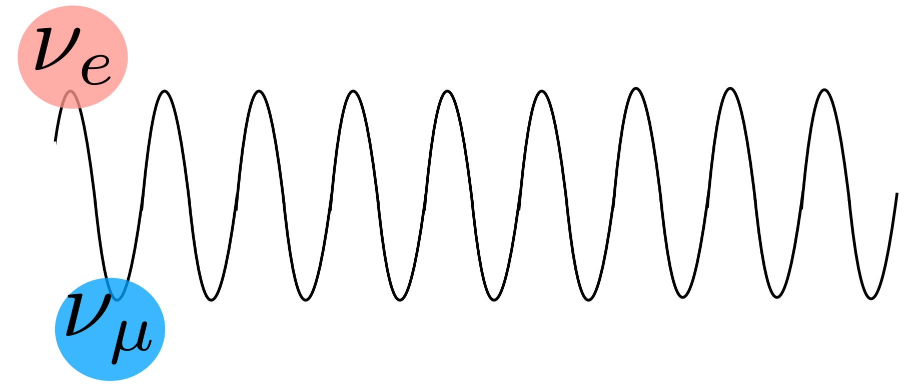
Do we really know what to expect from the next core-collapse event and neutron-star merger?

Figures from Nakamura et al., MNRAS (2016); Drout et al., Science (2017).

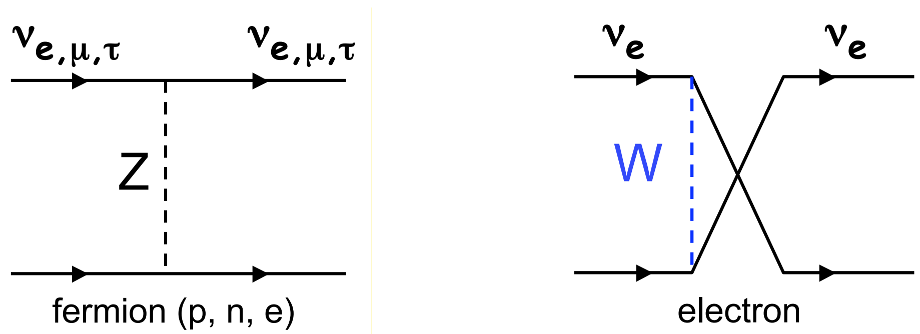
Neutrino Quantum Kinetics

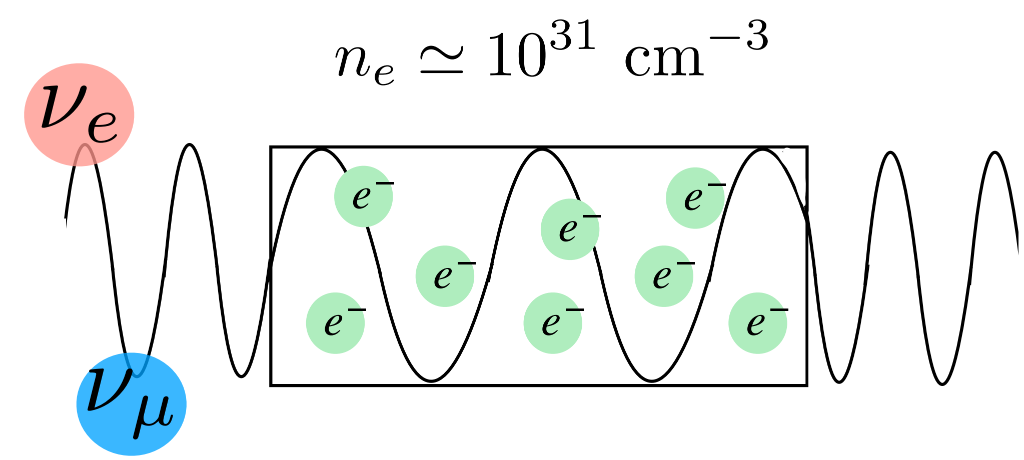
Neutrino Flavor Conversion in Dense Media

Vacuum



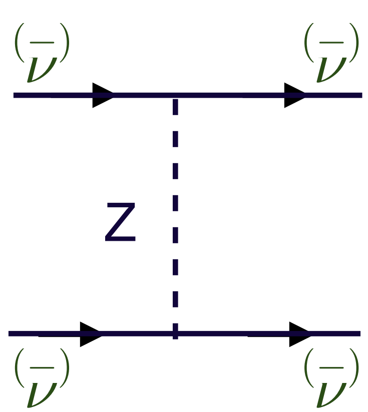
Neutrinos interact with background matter

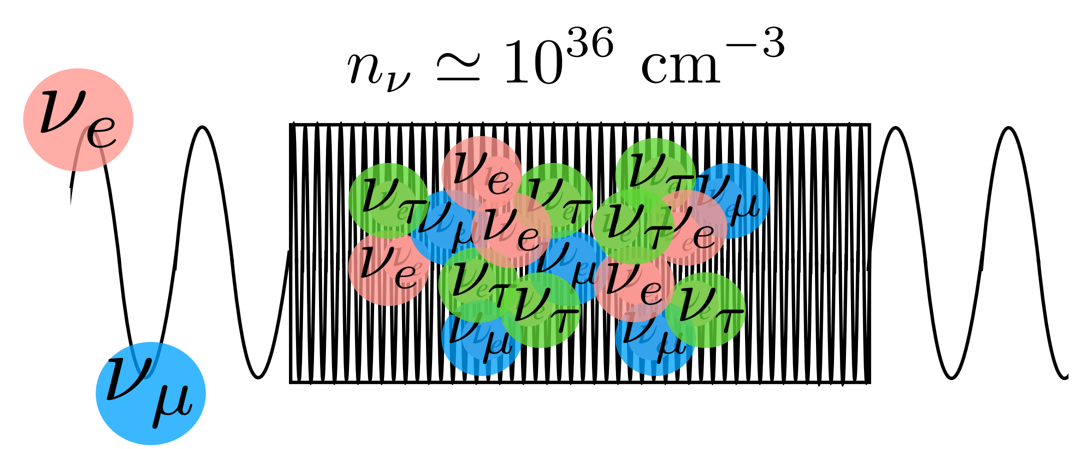




IMPACT ON FLAVOR CONVERSION POORLY UNDERSTOOD!

Neutrinos interact among themselves

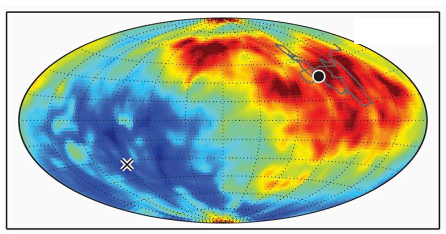




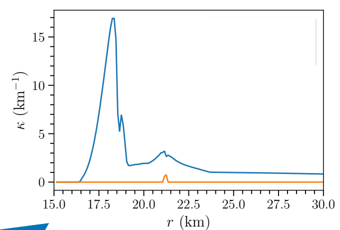
Recent review: Tamborra & Shalgar, Ann. Rev. Nucl. Part. Sci. (2021). Richers & Sen, arXiv: 2207.03561.

How Do We Tackle This?

Source physics input



Linear stability analysis
[linear regime]

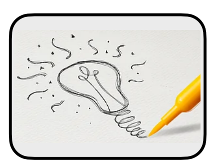


Flavor Conversion

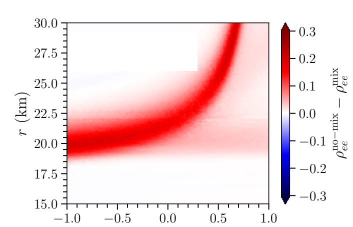
When and where? ~

How much? ✗

Parametric approach



Numerical solution
[non-linear regime]

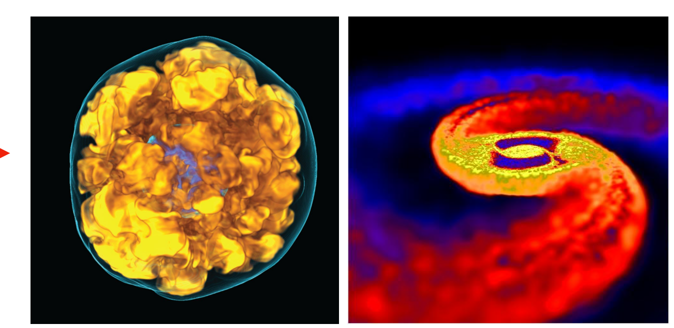


Flavor Conversion

When and where? ✓

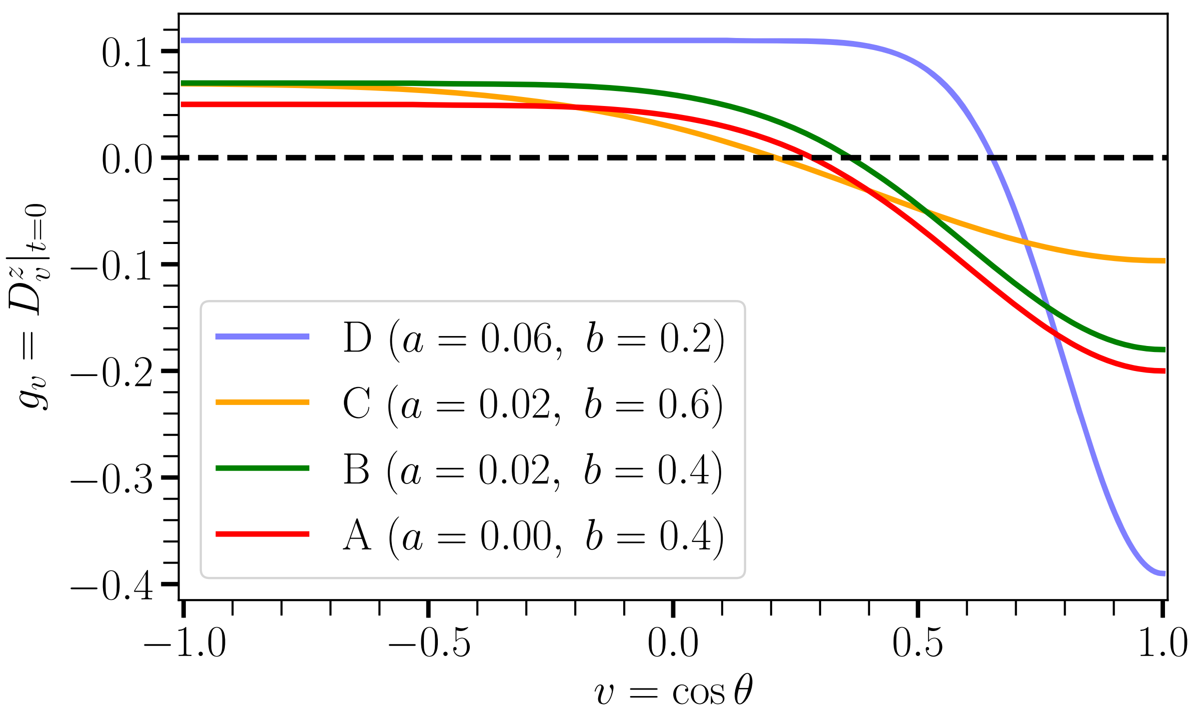
How much? ✓

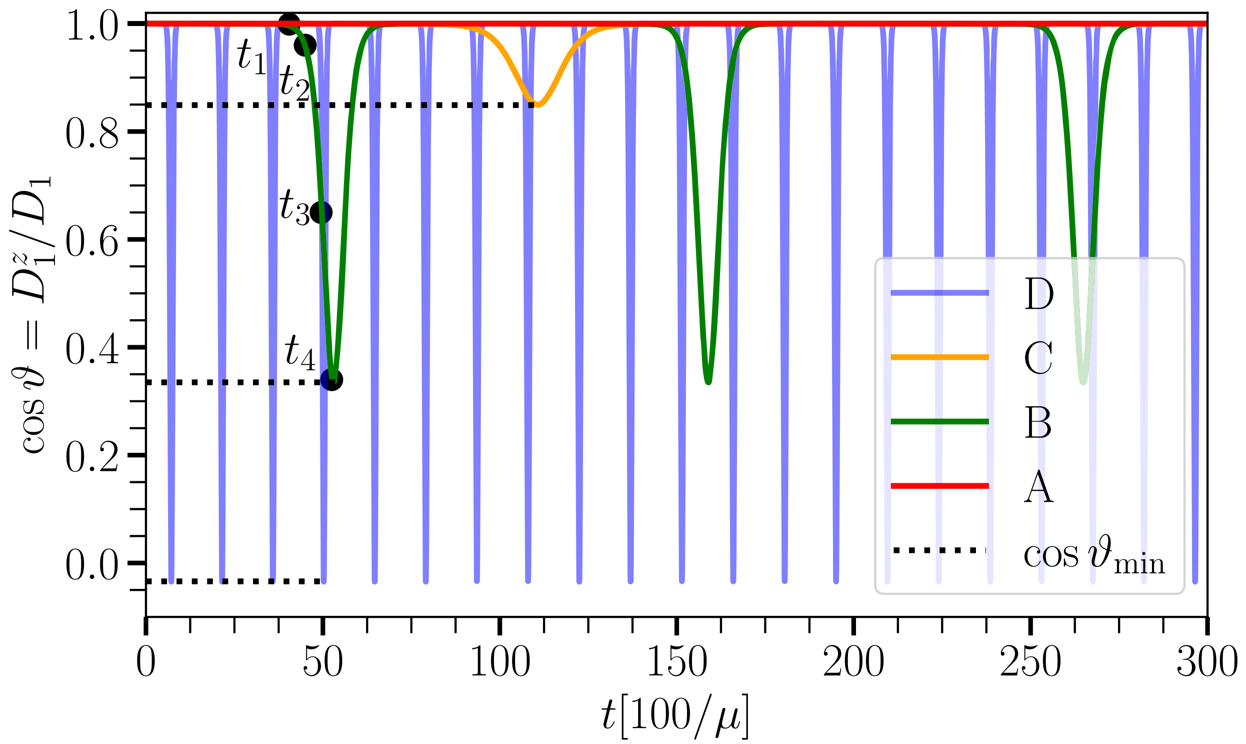
Impact on source physics, nucleosynthesis, and observables



Reliable! ✓

Advancing Parametric Approaches





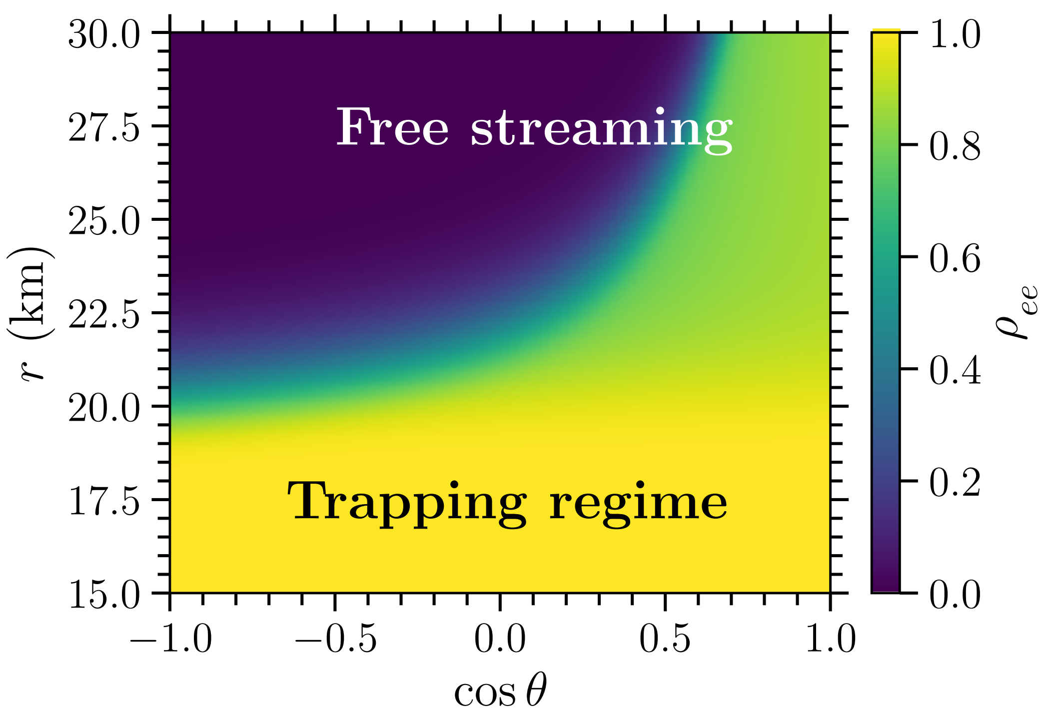
- We can predict the depth of flavor conversion without solving the evolution equations in a simple setup.

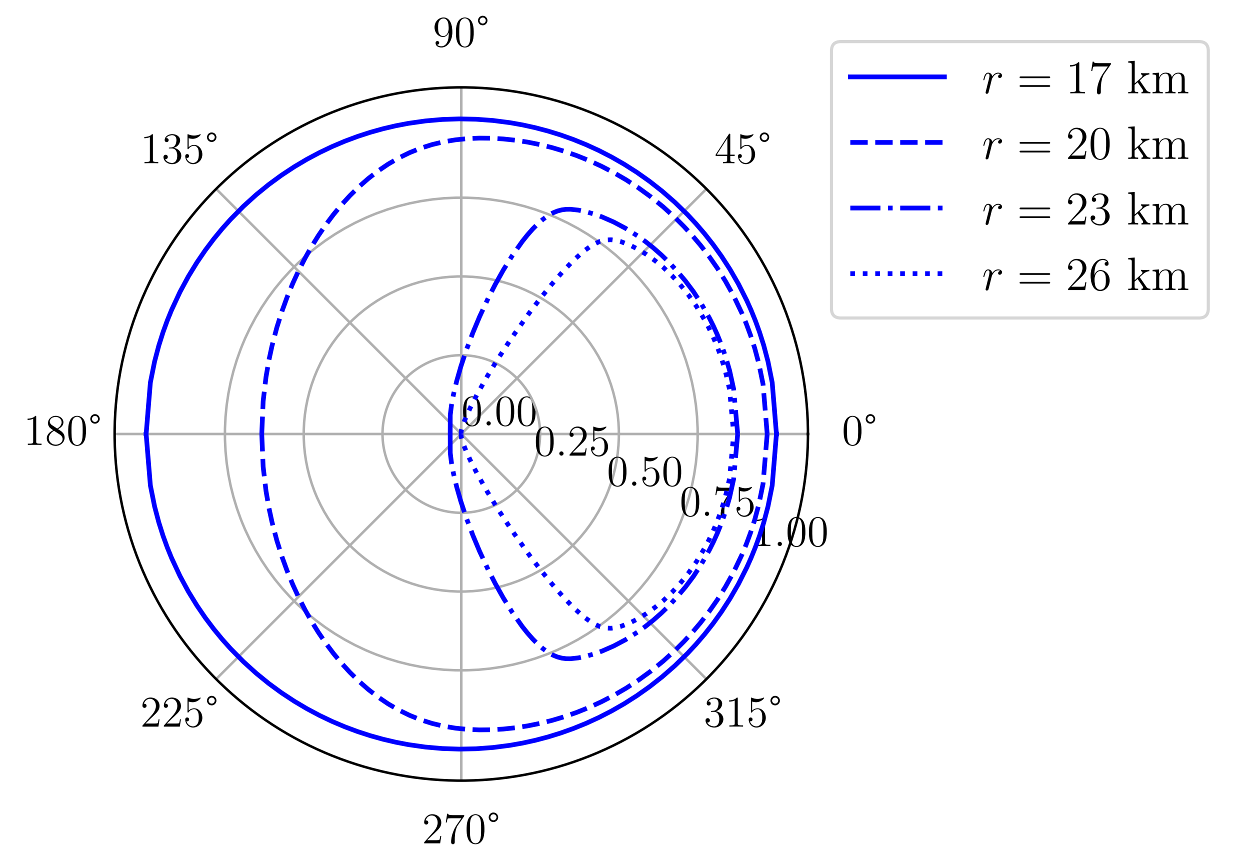
- The amount of flavor conversion does not correlate with the growth rate obtained from the linear stability analysis.

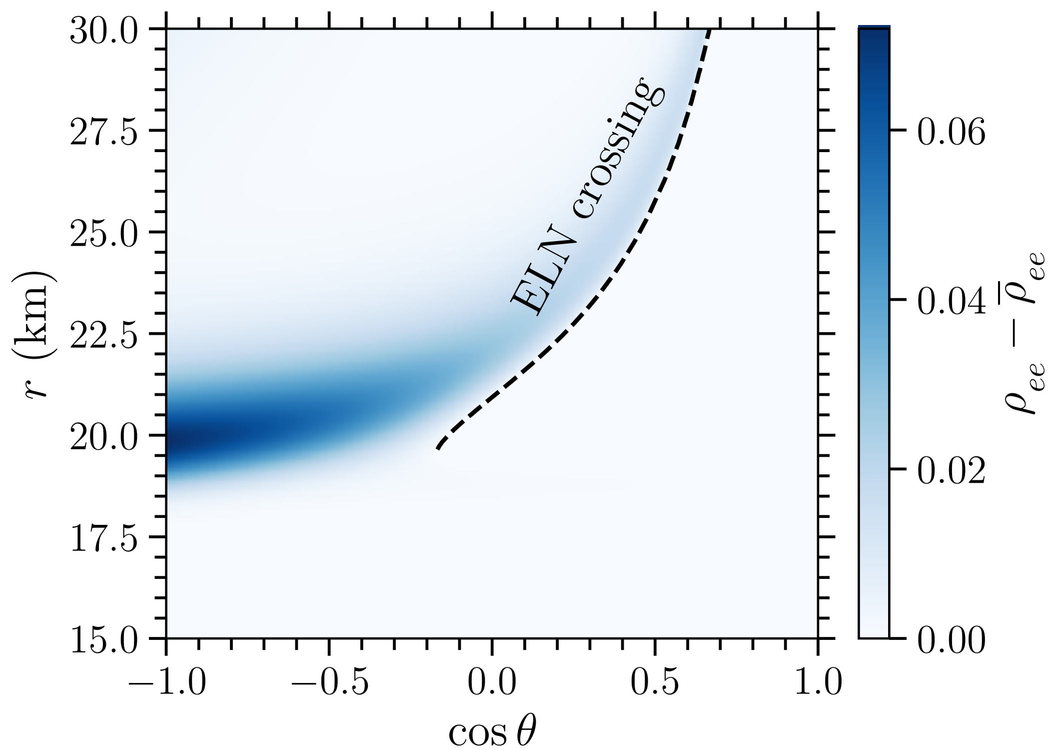
Which is the best way to implement flavor conversion physics in a parametrized fashion?

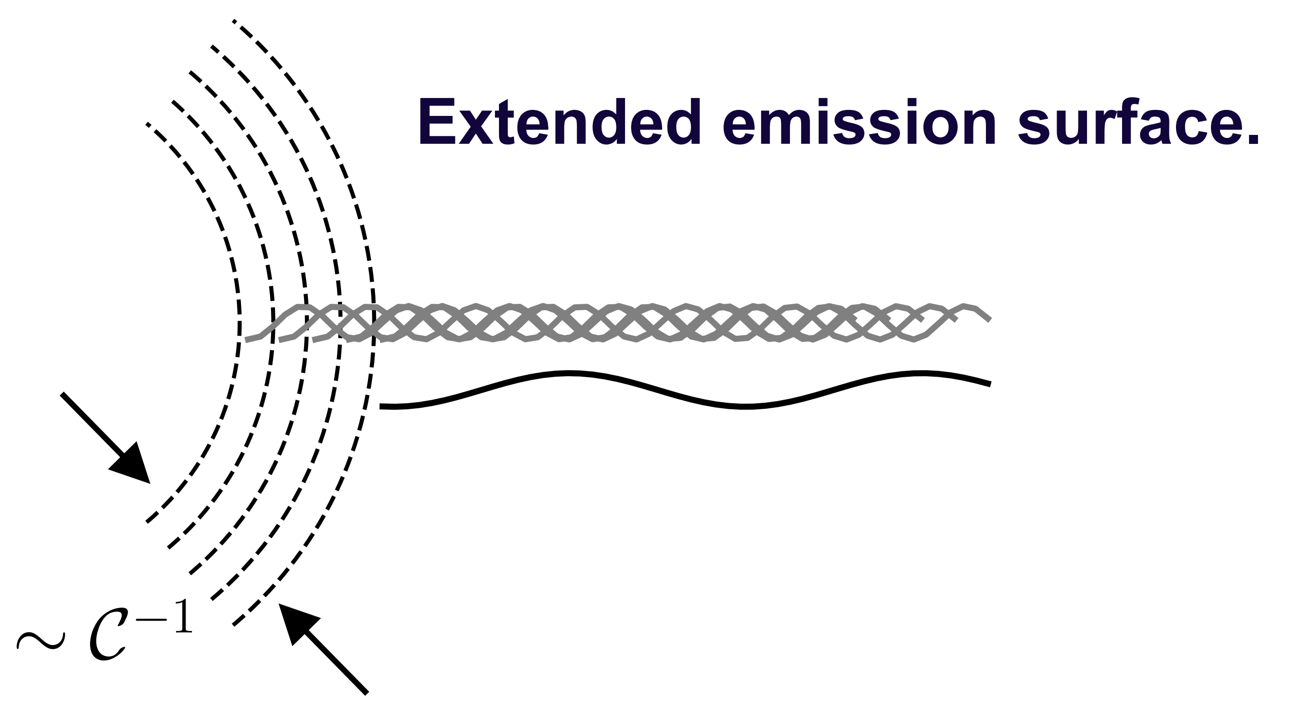
Padilla-Gay, Tamborra, Raffelt, PRL (2022). Padilla-Gay, Tamborra, Raffelt, PRD (2022). Johns, Nagakura, Fuller, Burrows, PRD (2020)

Towards the Full Solution



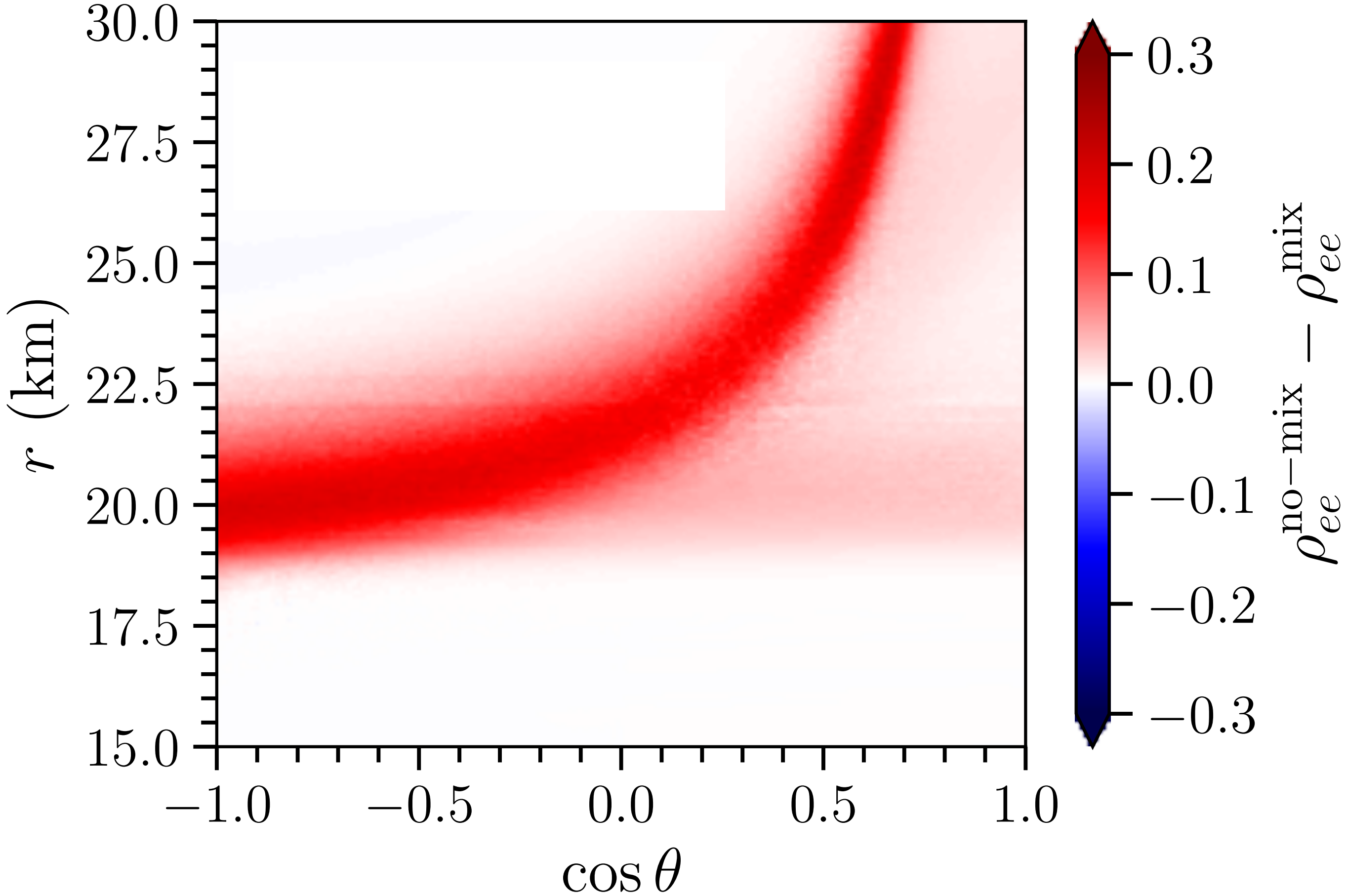


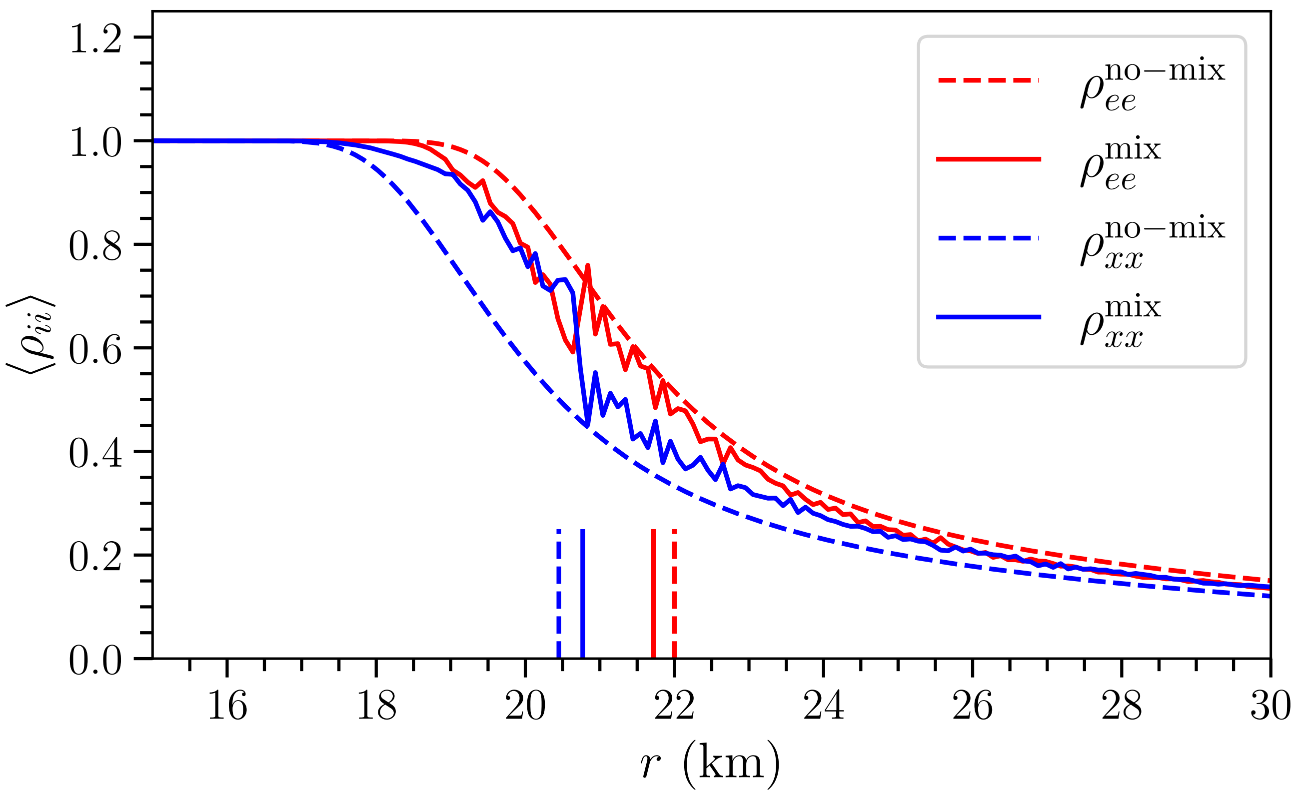




Shalgar & Tamborra, PRD (2023a), PRD (2023b, in press). Shalgar, Padilla-Gay, Tamborra, JCAP (2020). Shalgar, Tamborra, PRD (2020, 2021), ApJ (2019). Richers, Willcox, Ford, PRD (2021). Wu et al., PRD (2021). Nagakura, PRD (2022). …

Towards the Full Solution





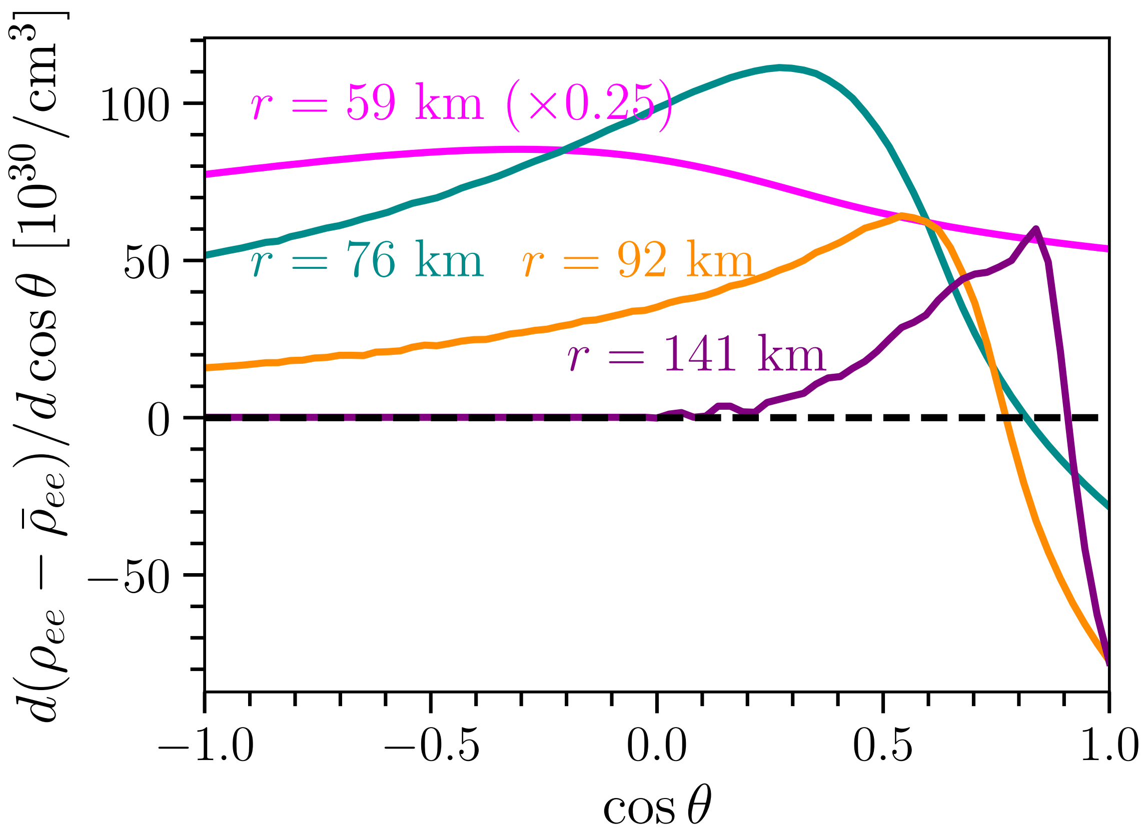
- Non trivial interplay among neutrino conversion, collisions, and advection.
- Neutrino decoupling from matter is affected by flavor conversion.
- Flavor equilibration is not a general flavor outcome.

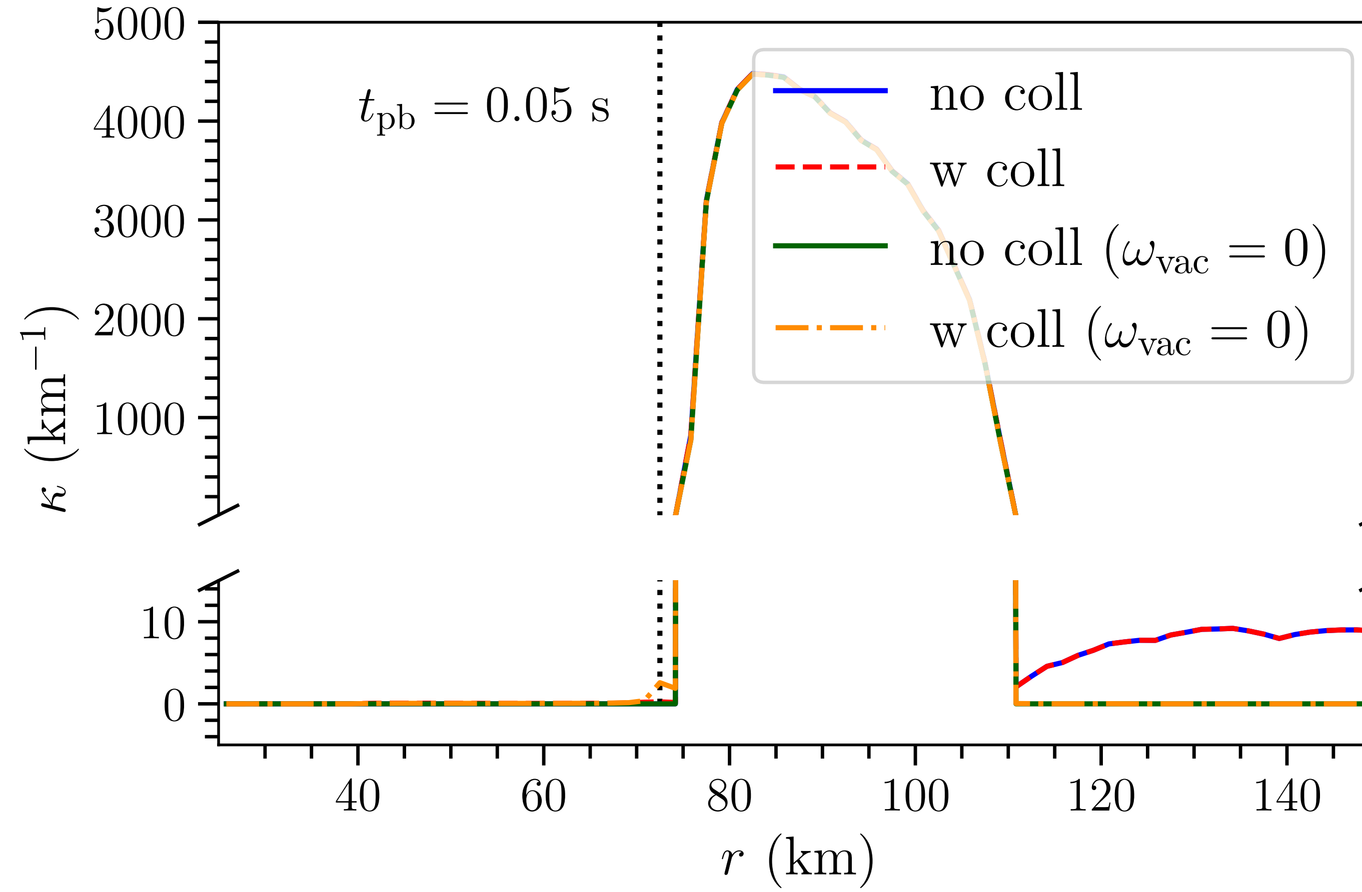
Are these conclusions still valid within in a more complex setup?

Can we predict the steady state configuration a priori?

Shalgar & Tamborra, PRD (2023a), PRD (2023b, in press). Shalgar, Padilla-Gay, Tamborra, JCAP (2020). Shalgar, Tamborra, PRD (2020, 2021), ApJ (2019). Richers, Willcox, Ford, PRD (2021). Wu et al., PRD (2021). Nagakura, PRD (2022). …

Collisional Flavor Instabilities



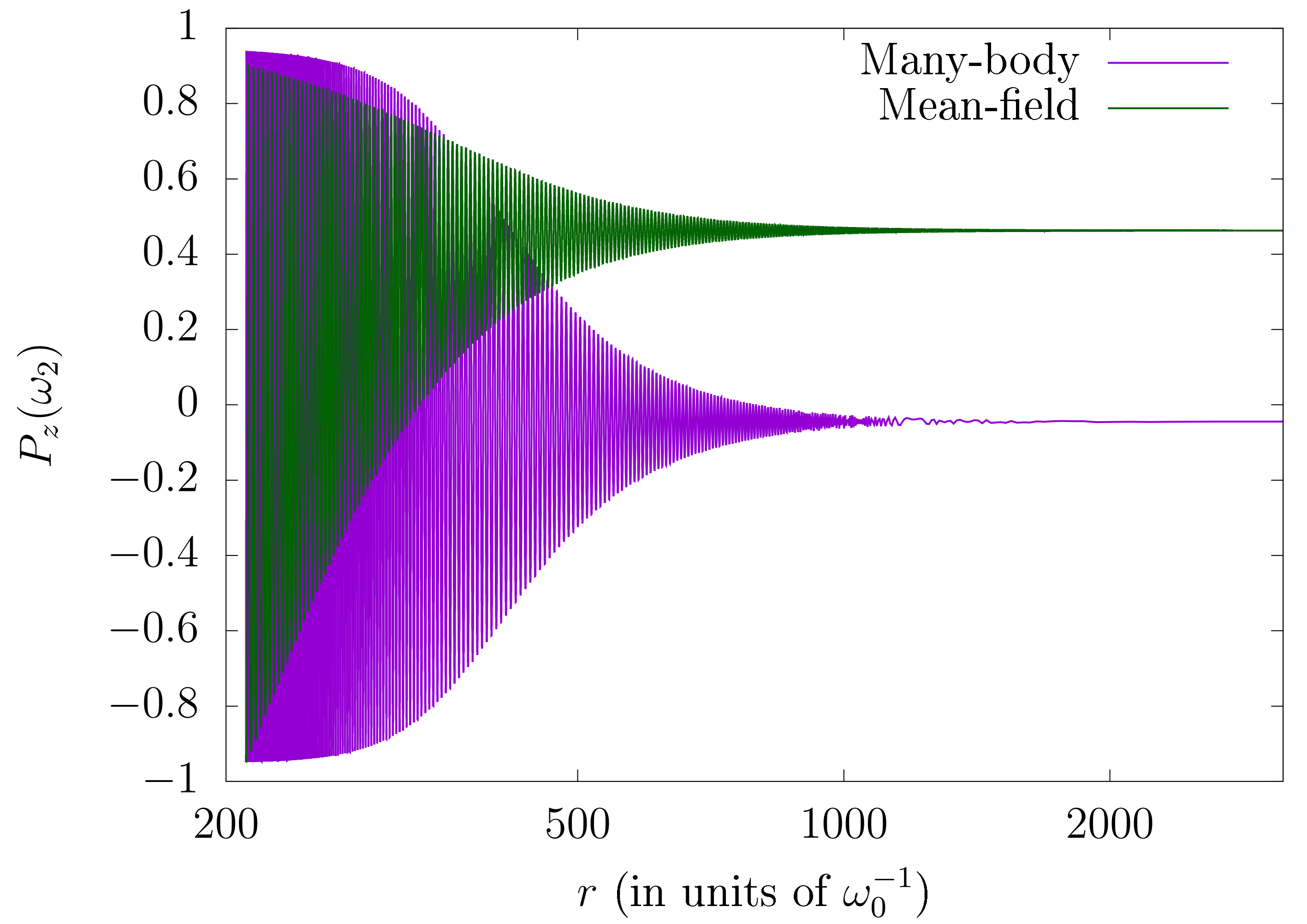


- Slow and fast flavor instabilities can coexist.
- Collisional instabilities seem to have a negligible impact in the decoupling region.

Which is the impact of collisional instabilities?

Shalgar & Tamborra, arXiv: 2307.10366.
L. Johns, PRL (2023). Johns & Xiong, PRD (2022). Xiong et al., PRD (2023), arXiv: 2212.03750. Padilla-Gay, Tamborra, Raffelt, PRD (2022).

Do We Solve the Right Equations of Motion?



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

Is the mean field approximation missing important physics? Is neutrino entanglement relevant?

Shalgar & Tamborra, PRD (2023). Johns, arXiv: 2305.04916.
Figure from Cervia, Patwardhan, Balantekin, Coppersmith, Johnson, PRD (2019). Patwardhan et al., arXiv: 2301.00342.

Core-Collapse Supernovae

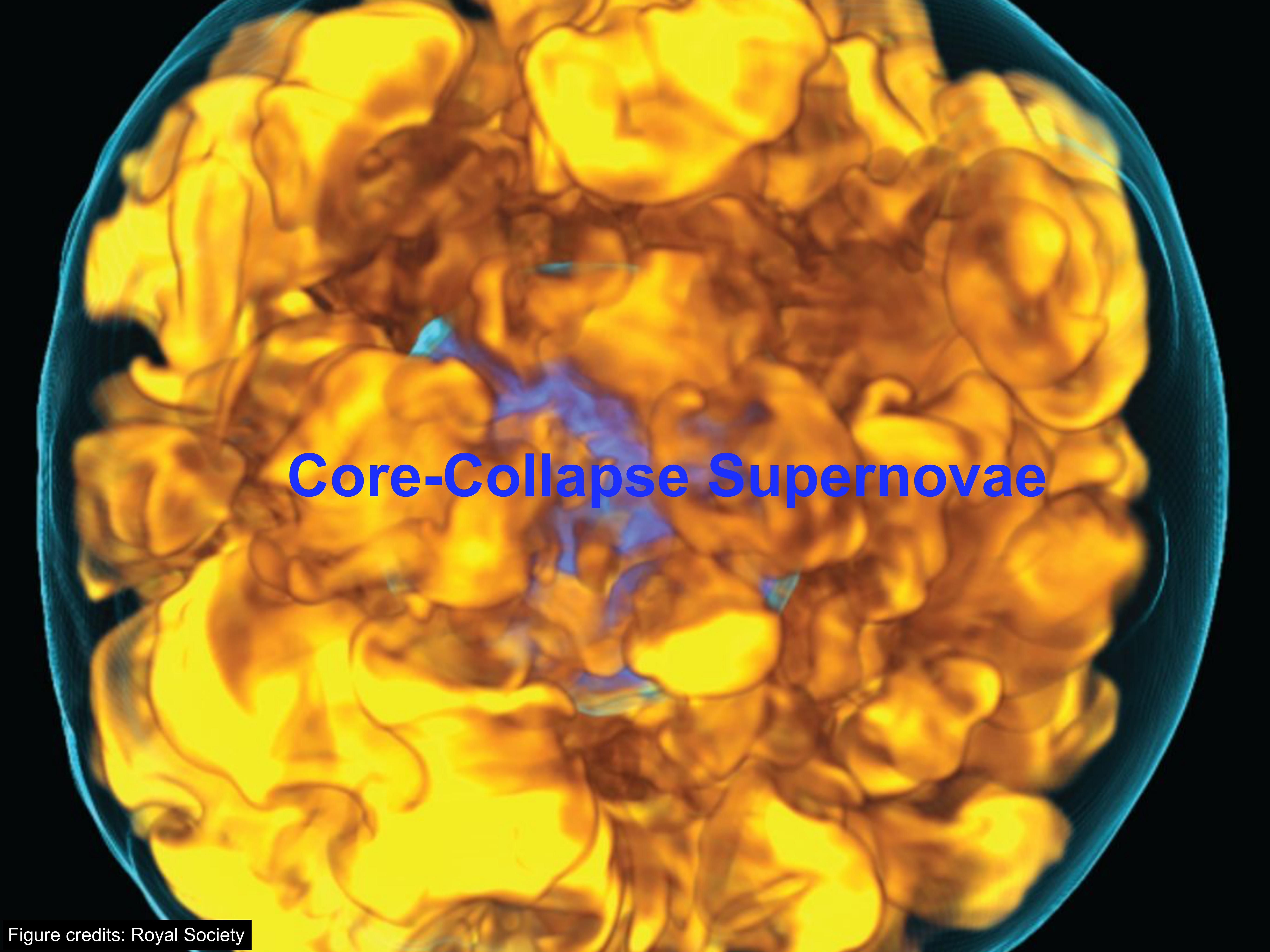
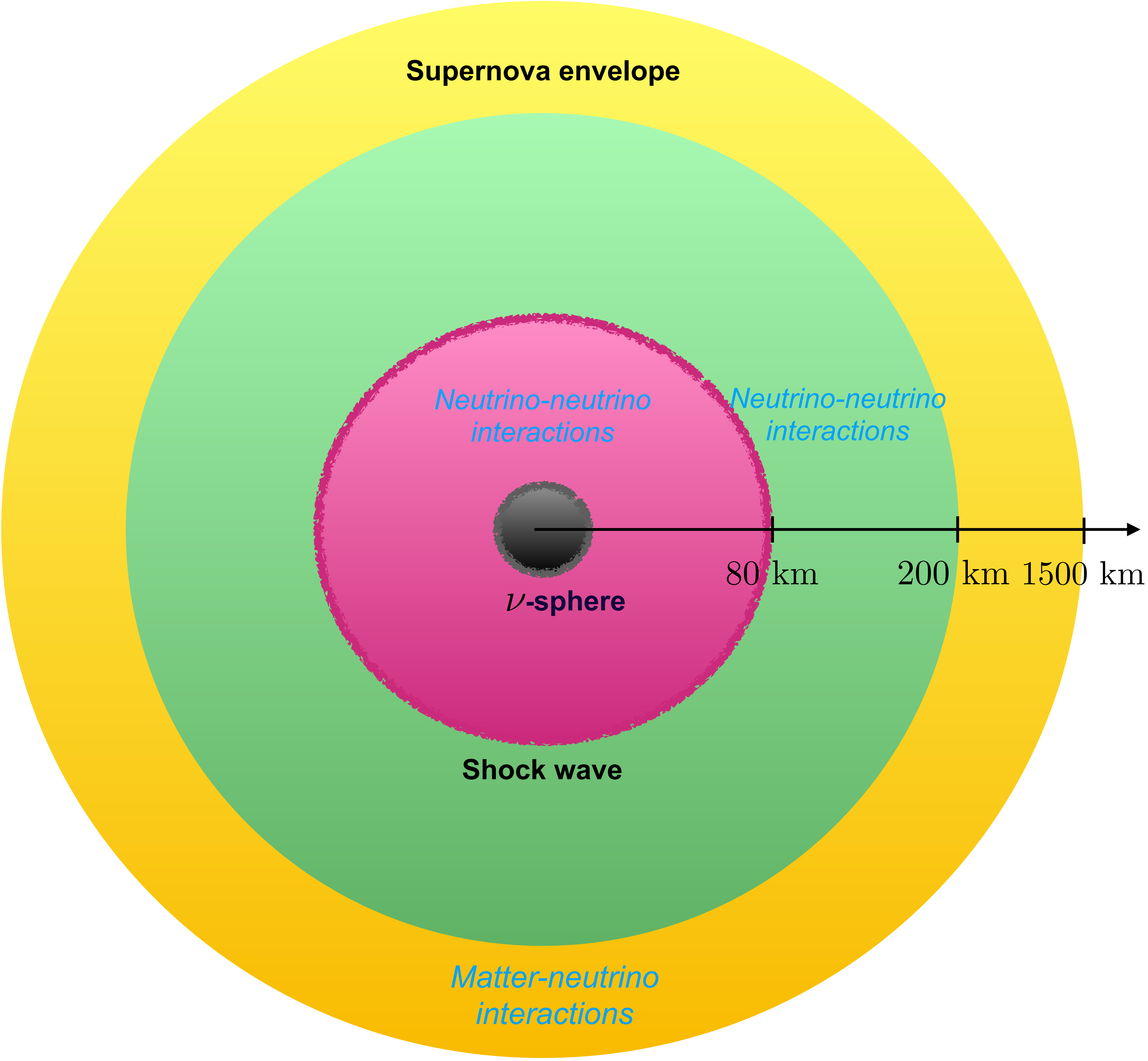
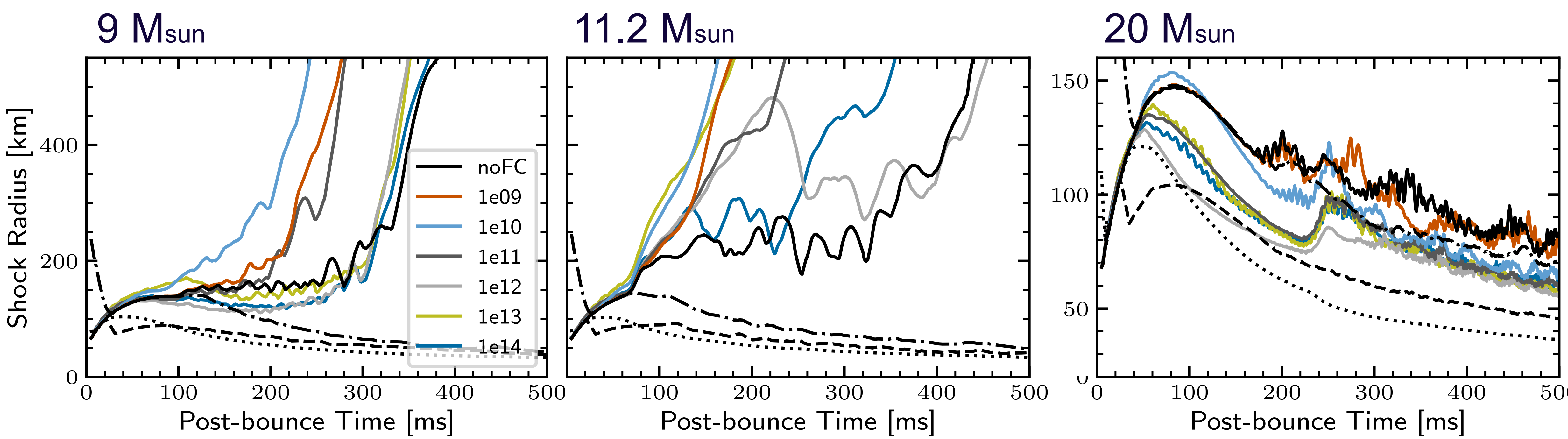


Figure credits: Royal Society

Does Flavor Conversion Affect Supernova Mechanism?



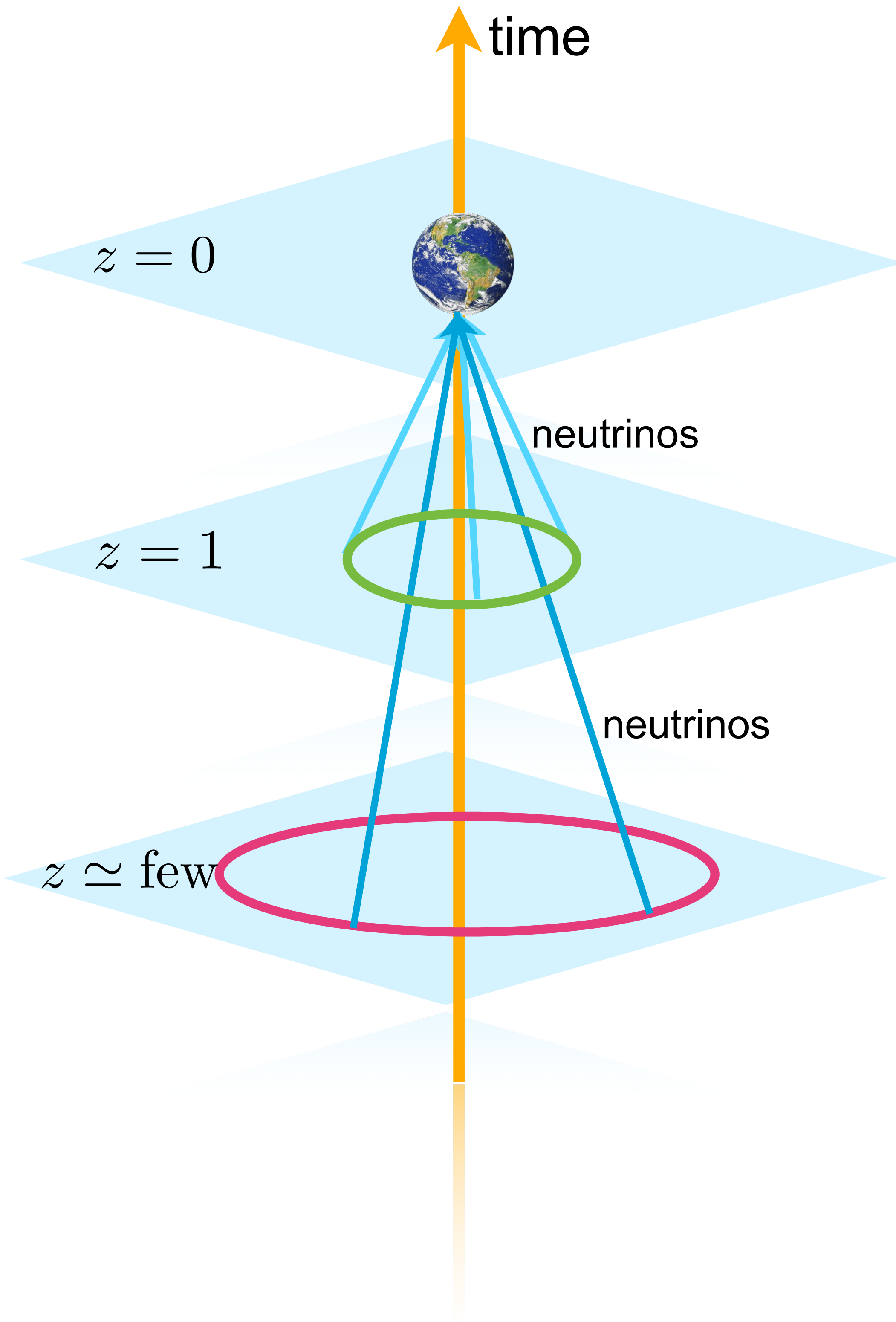
Does Flavor Conversion Affect Supernova Mechanism?



- 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).

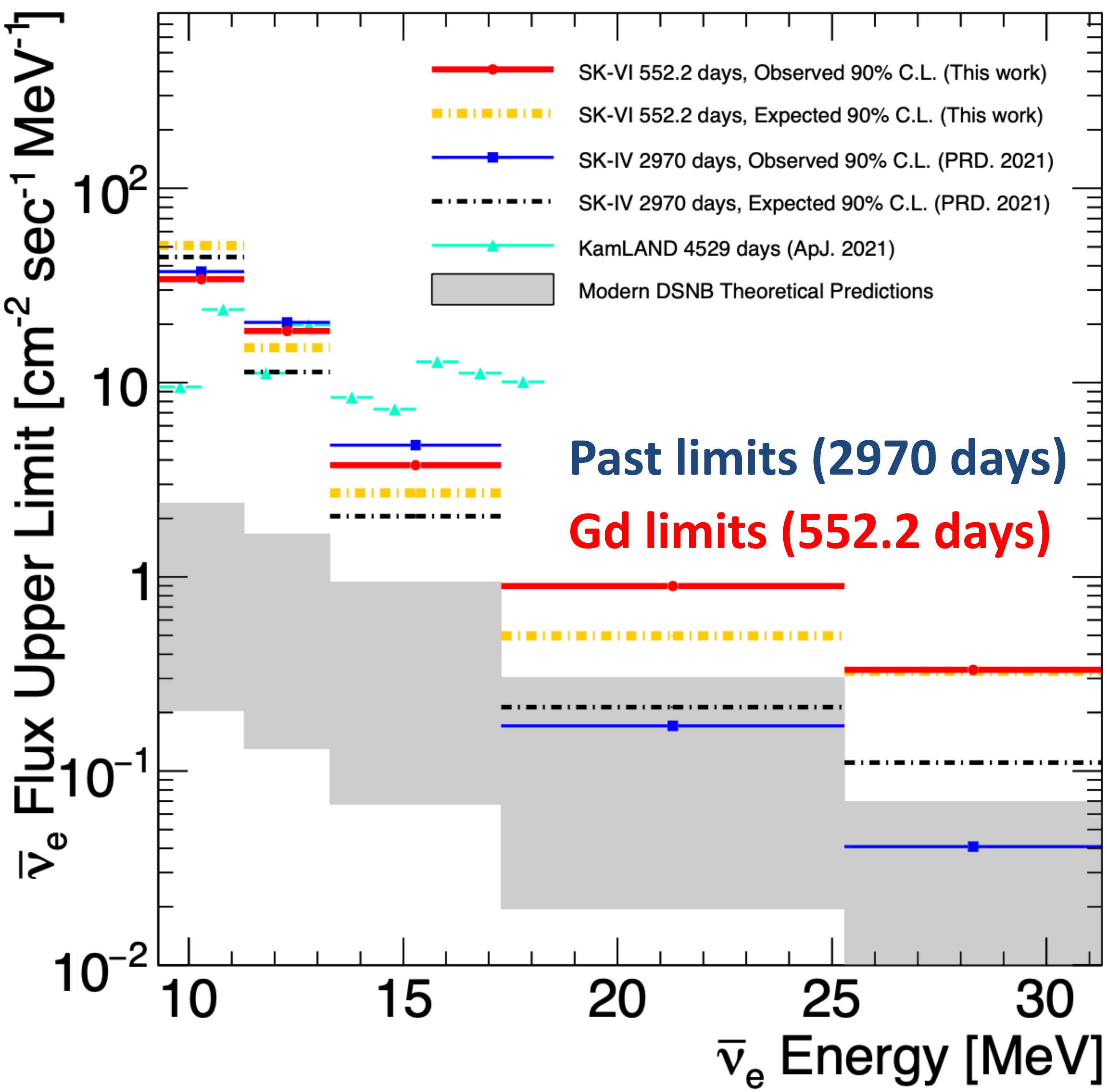
> Are these conclusions general for all ZAMS masses? Do they hold in 3D?
>
> What are the implications for multi-messenger forecasts?
>
> What are the implications for nucleosynthesis?

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



Diffuse Supernova Neutrino Background

DSNB with Super-K-Gd

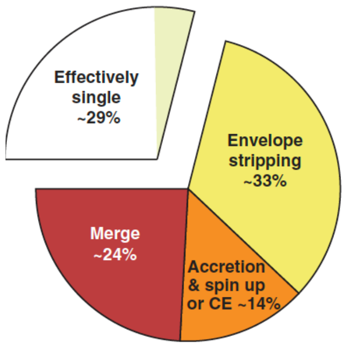


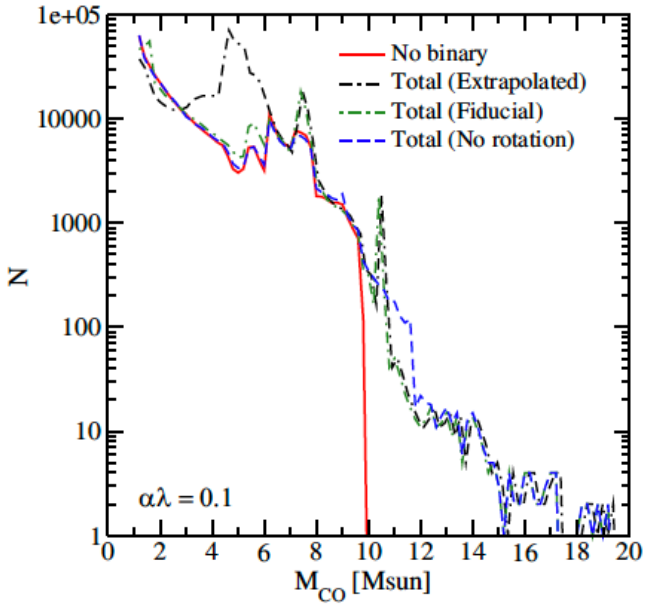
SuperK-Gd results with 0.01% Gd already comparable to ~10 years of pre-Gd results.

Figure from Harada et al., ApJ Lett. (2023).

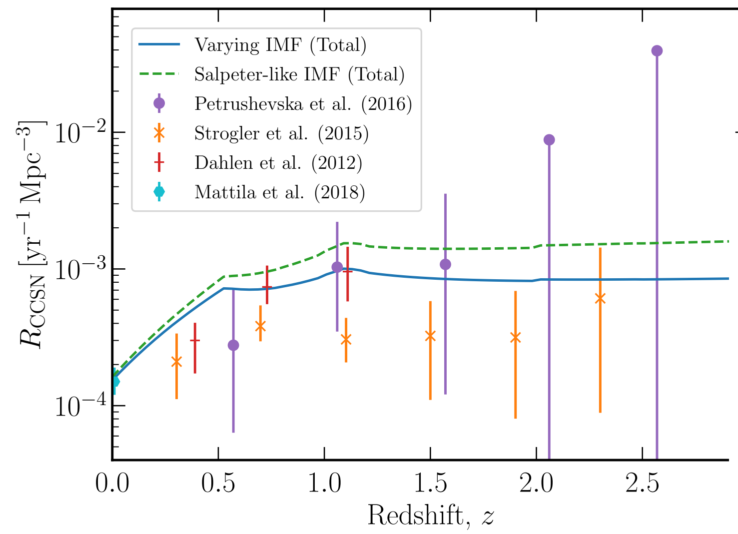
DSNB Modeling: What's Missing?

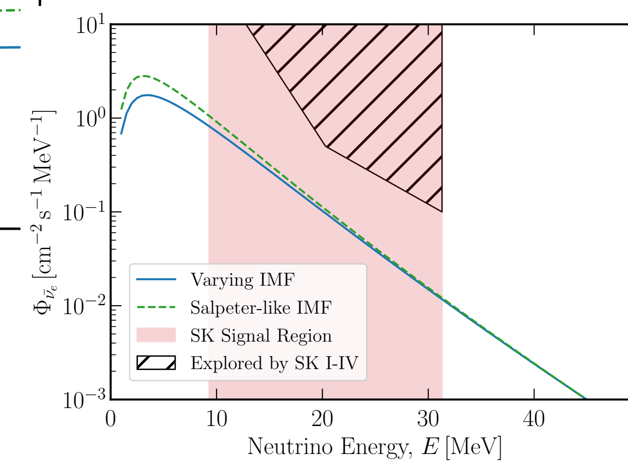
Affected by binary interactions (mass transfer and mergers)



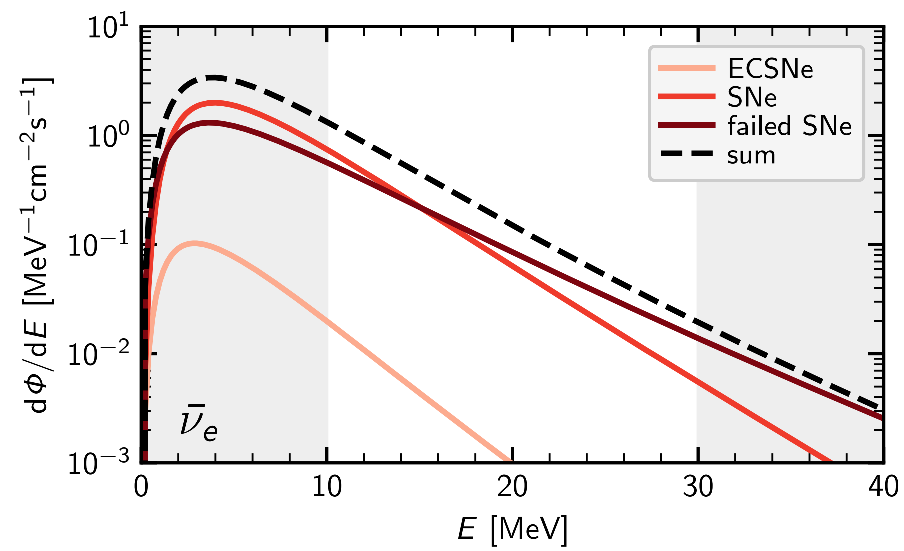


Affected by uncertainties on stellar evolution, stellar initial mass function





Affected by fraction of black hole forming collapses



Do we predict the DSNB signal reliably?

Moller, Suliga, Tamborra et al., JCAP (2018). Kresse, Ertl, Janka, ApJ (2020). Horiuchi et al., PRD (2021). Ashida, Nakazato, Tsujimoto, arXiv: 2305.13543. Ziegler et al., MNRAS (2022).

Compact Binary Mergers

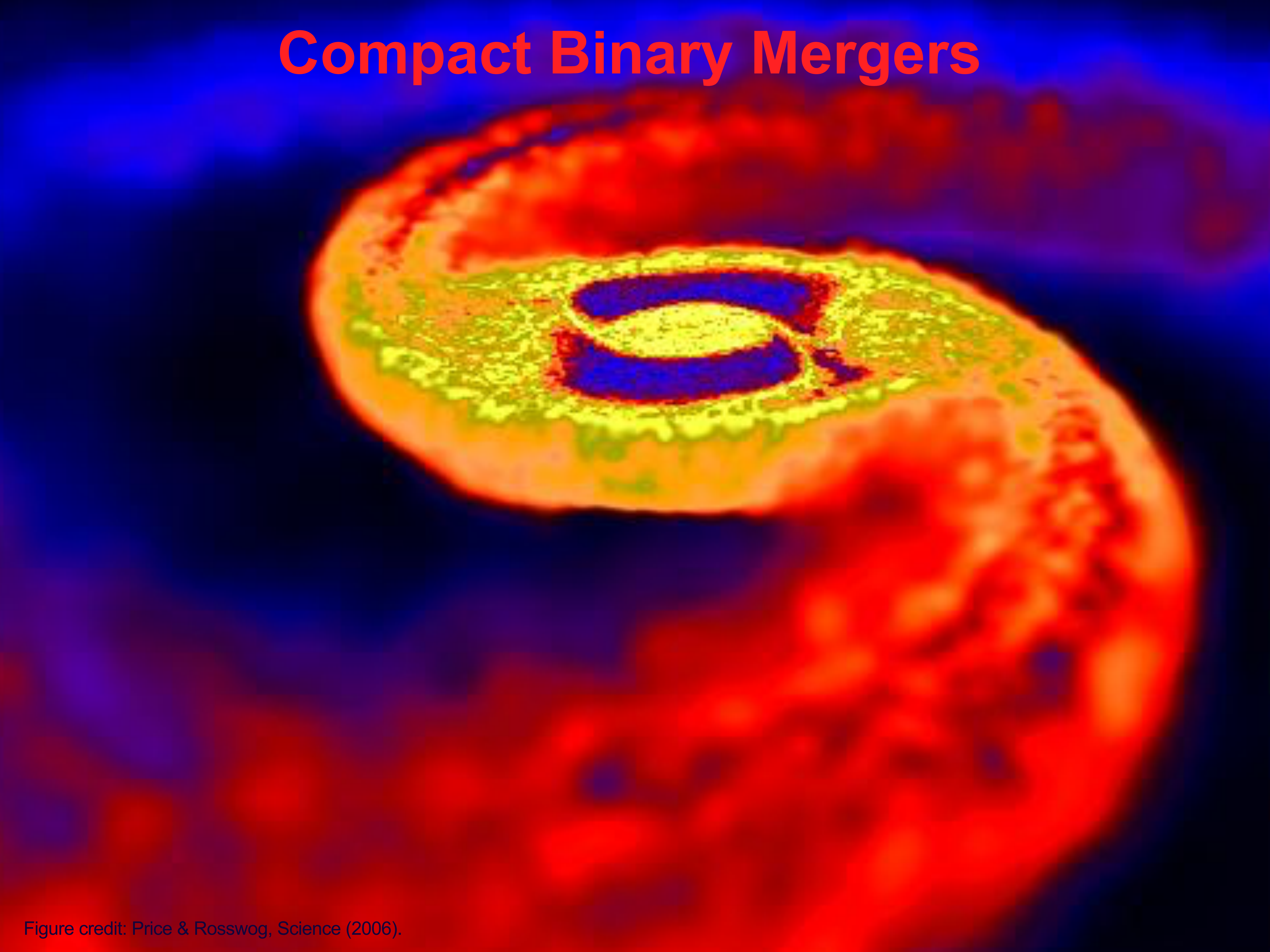
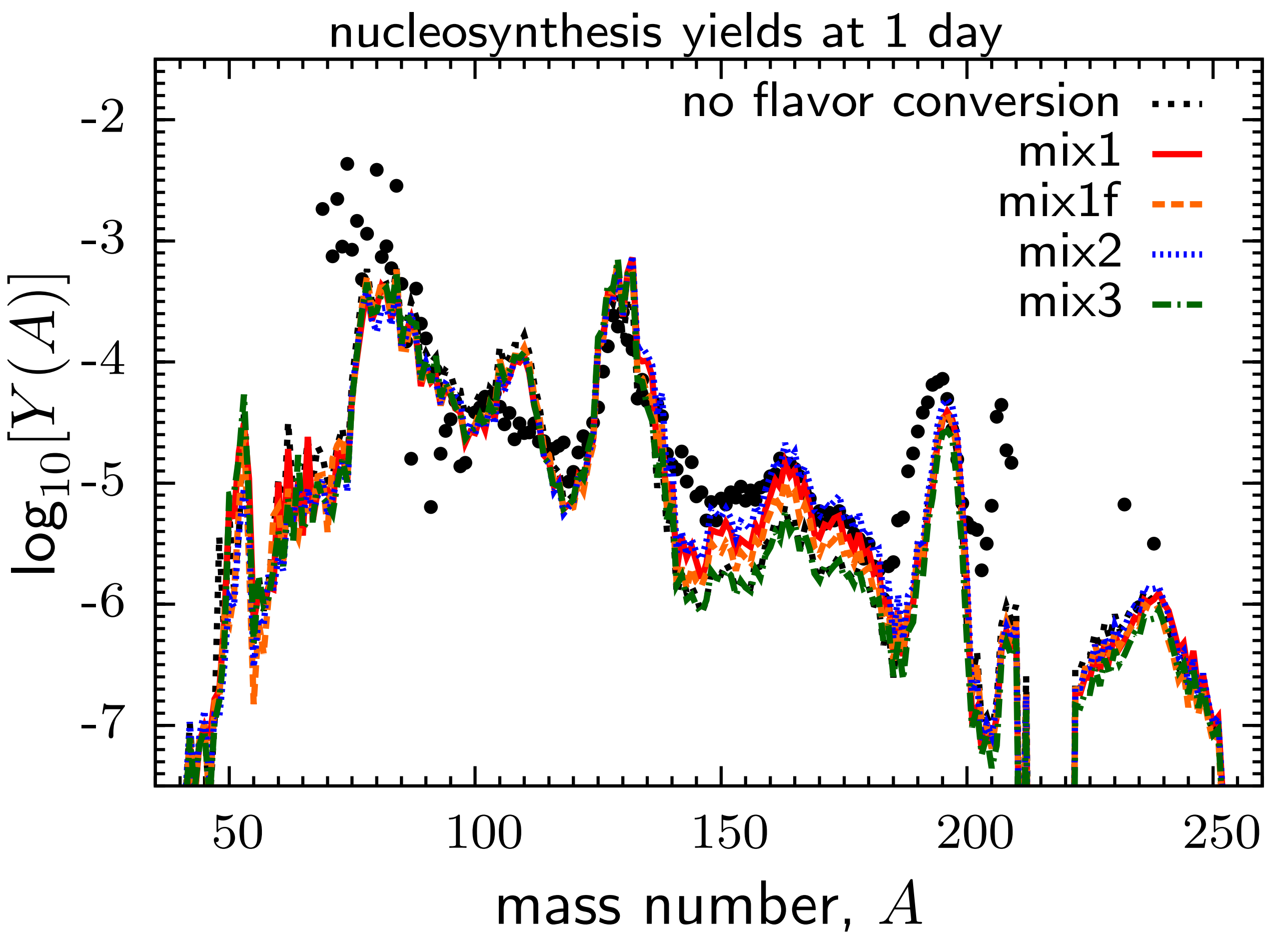
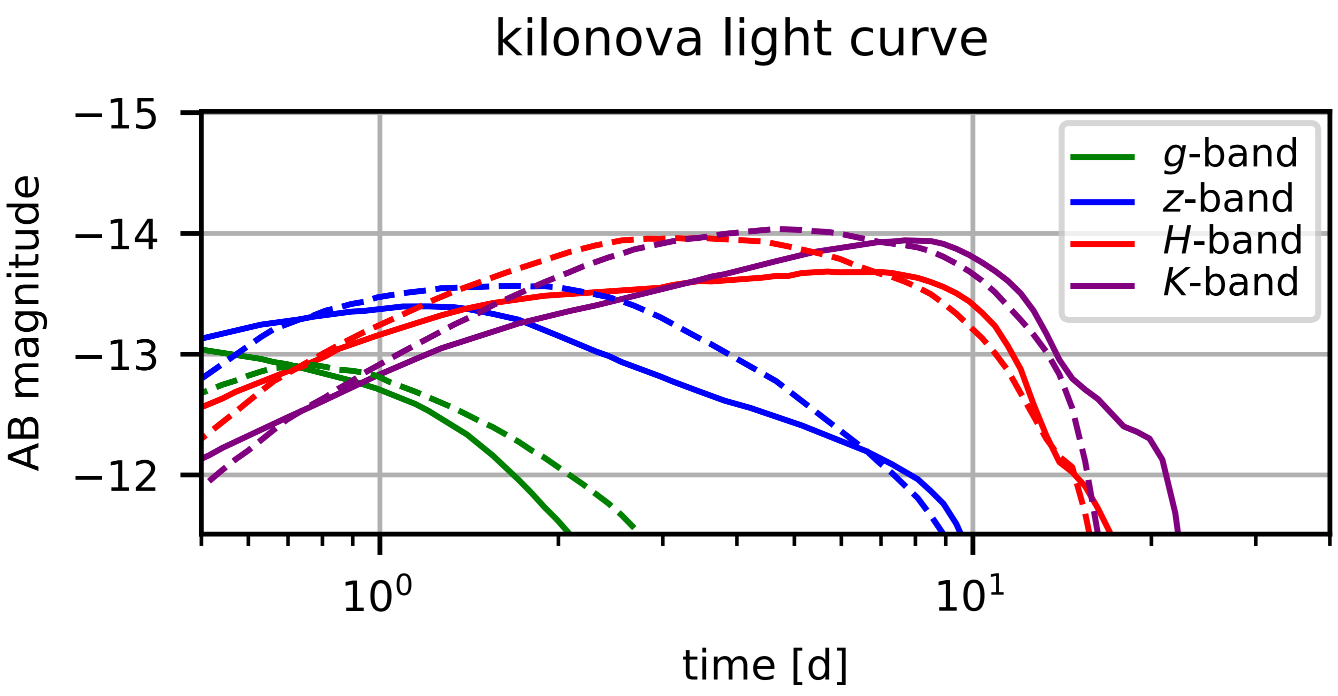


Figure credit: Price & Rosswog, Science (2006).

Neutrinos and Nucleosynthesis





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

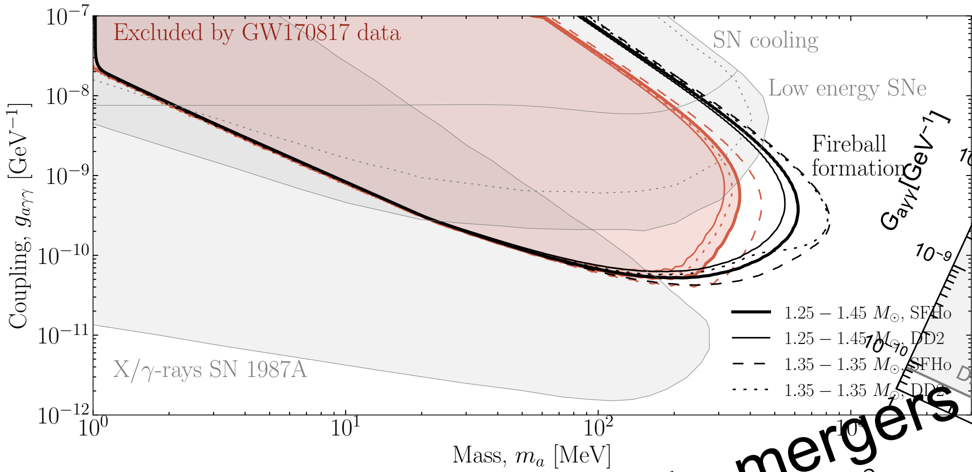
Are these conclusions robust for a range of merger properties?

More work needed to understand how neutrino physics affects kilonova properties.

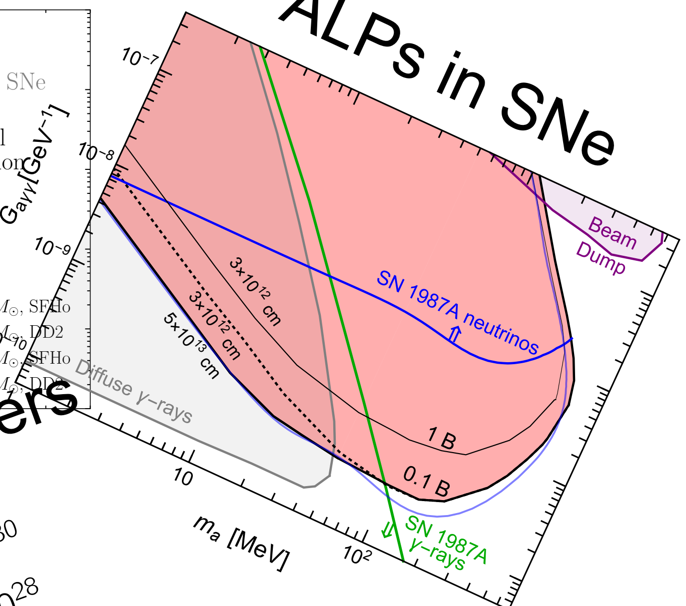
Just, Abbar, Wu, Tamborra, Janka, Capozzi, PRD (2022). Wu, Tamborra, Just, Janka, PRD (2017). Wu & Tamborra, PRD (2017). Padilla-Gay, Shalgar, Tamborra, JCAP (2021). George, Wu, Tamborra, Ardevol-Pulpillo, Janka, PRD (2020). Li & Siegel, PRL (2021). Fernandez, Richers et al., PRD (2022).

New Physics Imprints

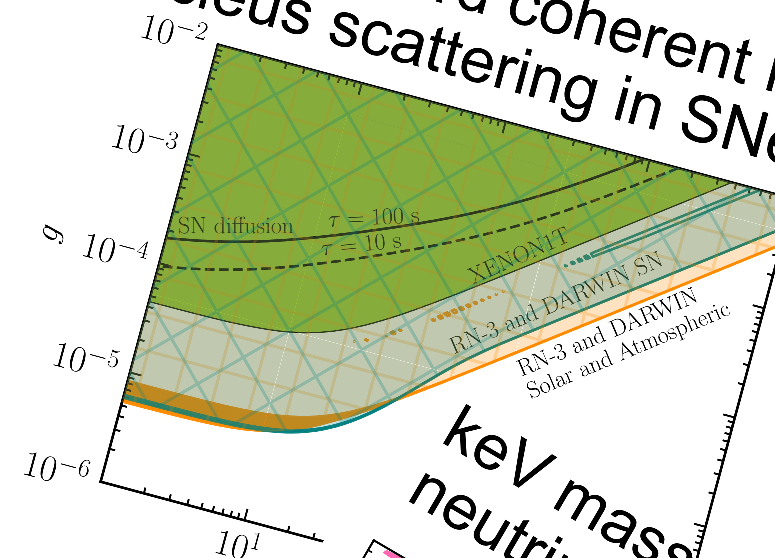
Radiatively decaying axions in mergers



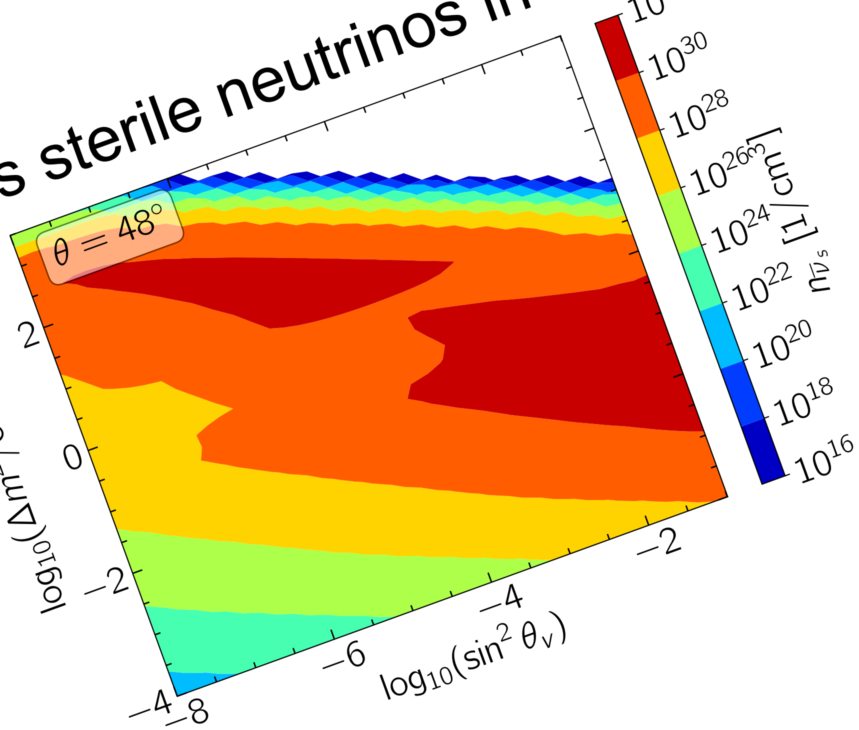
ALPs in SNe



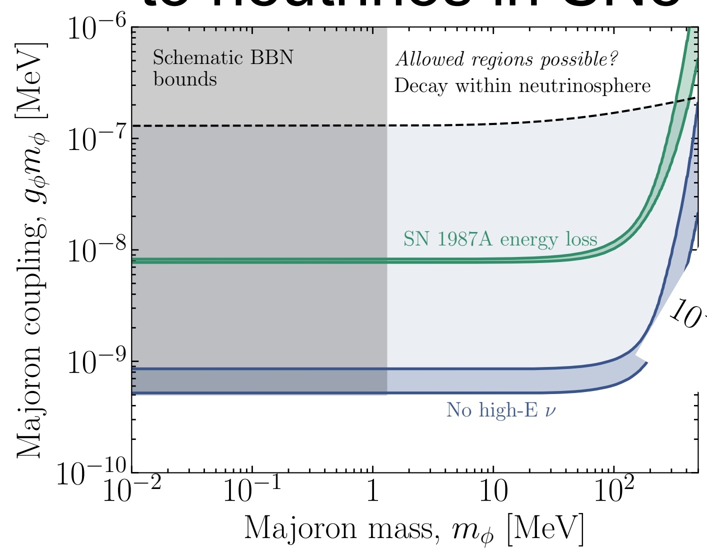
Non-standard coherent neutrino-nucleus scattering in SNe



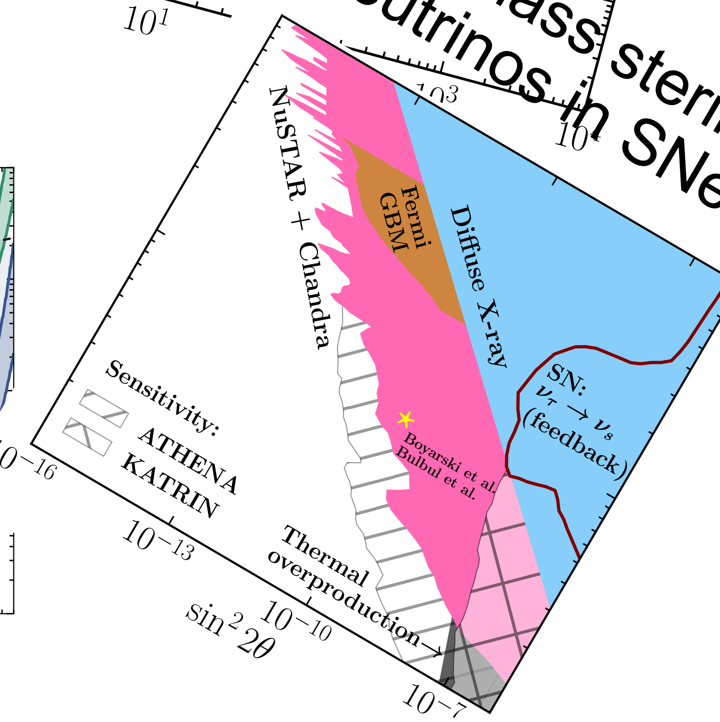
eV mass sterile neutrinos in mergers



Bosons decaying to neutrinos in SNe



keV mass sterile neutrinos in SNe



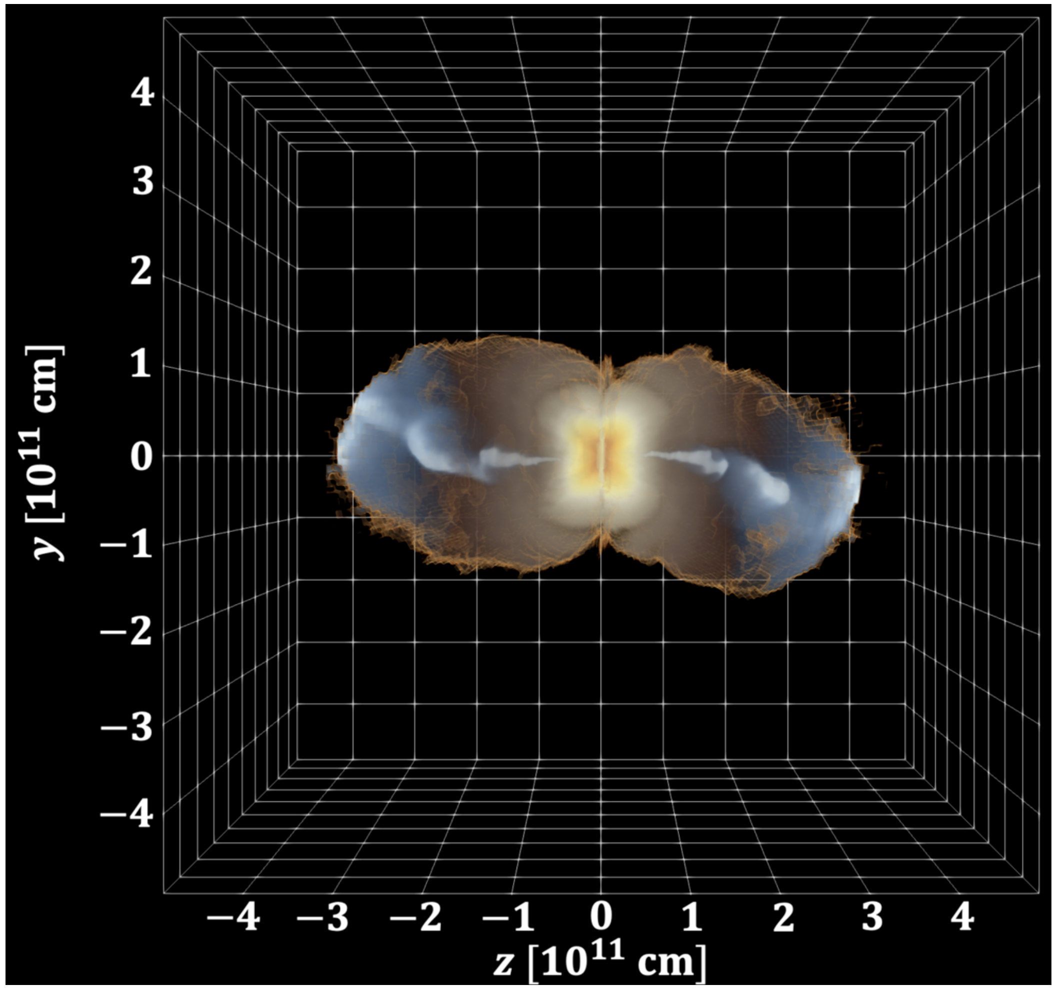
and many more…

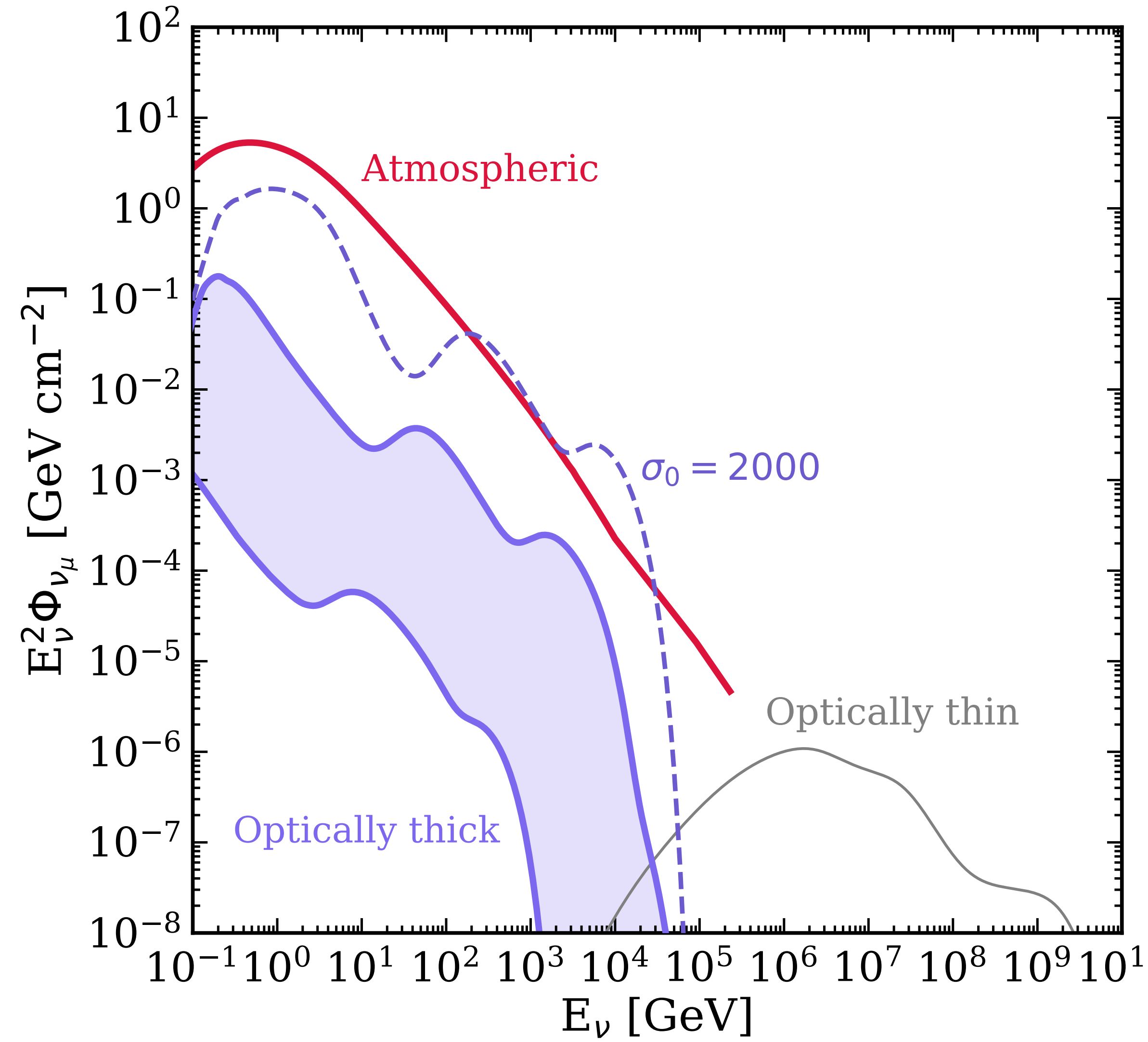
What are the signatures of BSM physics in supernovae and mergers?

Diamond, Fiorillo, Marques-Tavares, Tamborra, Vitagliano, arXiv: 2305.10327. Sigurðarson, Tamborra, Wu, PRD (2022). Suliga & Tamborra, PRD (2021). Suliga, Tamborra, Wu, JCAP (2019), JCAP (2020). Fiorillo et al., PRL (2023). Caputo et al., PRL (2022). Sung et al., PRD (2021). Tang et al., JCAP (2020). Ray, Qian, arXiv: 2306.08209. Tamborra et al., JCAP (2012). Pllumbi, Tamborra et al., ApJ (2015). ….

High Energy Emission

High Energy Particle Emission from Collapsars



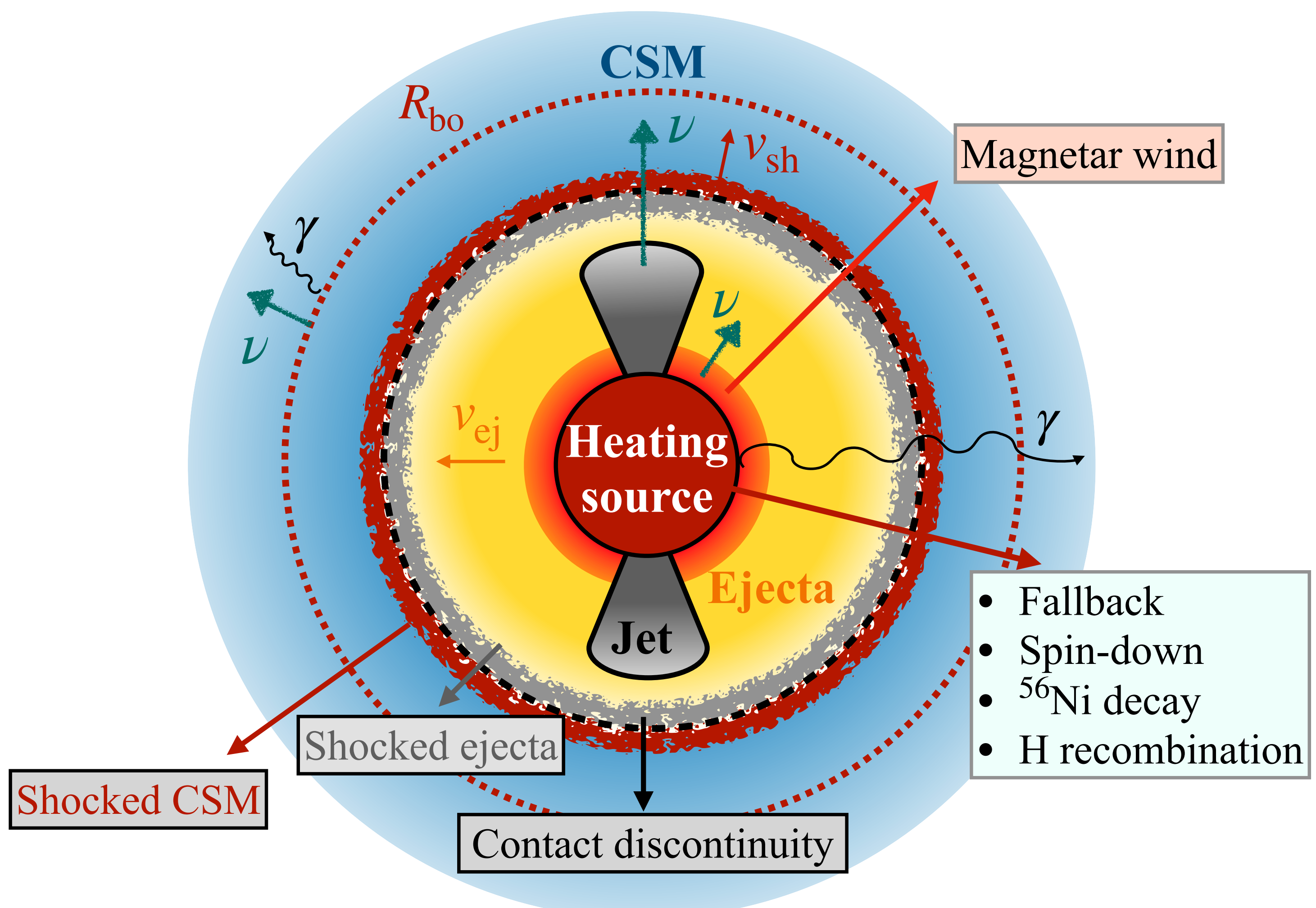


- State-of-the-art collapsar jet simulations predict neutrino signal different than expected.
- Subphotospheric neutrinos have lower energies than previously expected; detection possible with IceCube DeepCore but challenging unless source is close-by (z < 1).

Do we know which multi-messenger signals to expect?

Guarini, Tamborra, Gottlieb, PRD (2023).
Guarini, Tamborra, Margutti, ApJ (2022). Tamborra & Ando, PRD (2015). Razzaque et al., PRL (2004). Ando & Beacom, PRL (2005).

Multi-Messenger Follow-Up Programs

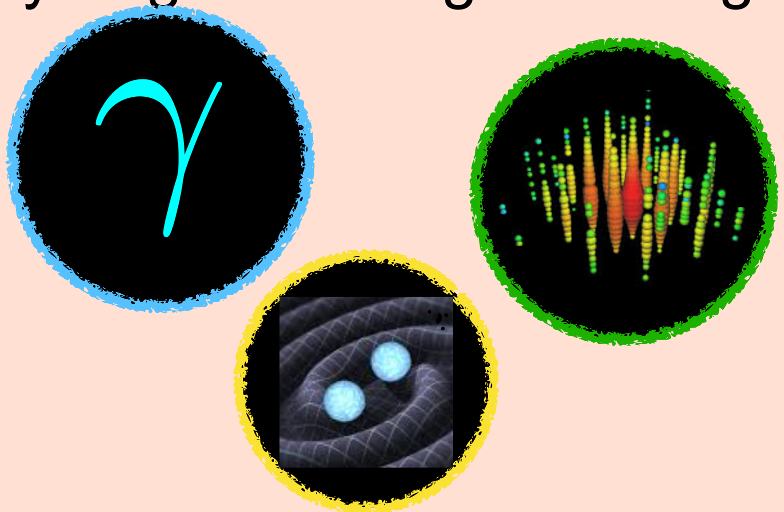


- Stacking neutrino searches relying on "standard candles" are not optimal.
- Essential to combine radio and UVOIR observations to aid neutrino searches.

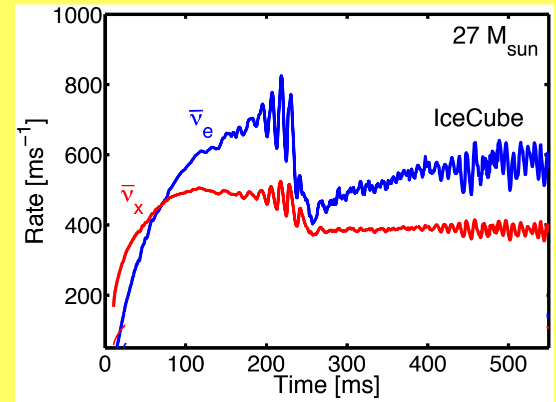
Are existing follow-up programs tailored to learn about source physics?

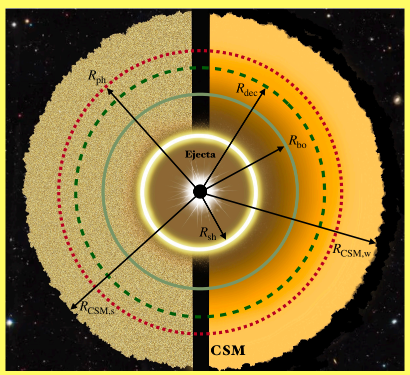
Guarini, Tamborra et al., in prep. Pitik, Tamborra, Lincetto, Franckowiack, MNRAS (2023).

Synergies among messengers

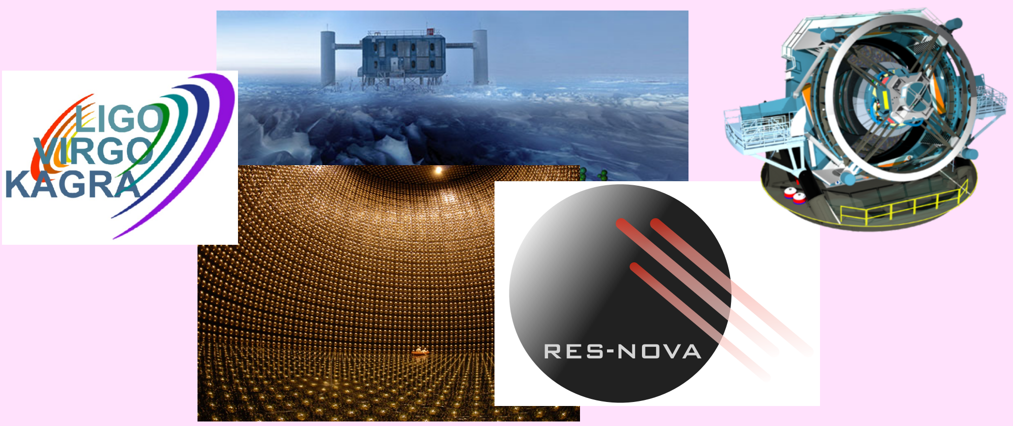


Unique opportunities to learn about source physics

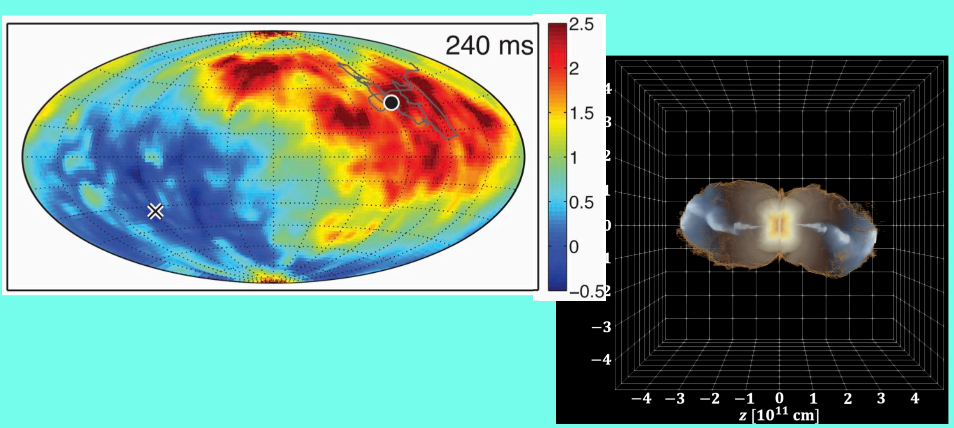




Getting ready for new discoveries



Nu & source modeling just begun



Thanks!