Max-Planck-Institut für Physik
(Werner-Heisenberg-Institut)

MPP Project Review 2024

Theoretical Astroparticle Physics

(Georg Raffelt)

LMU TUM ORIGINS Excellence Cluster

Particle Physics in Supernovae

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Max-Planck-Institut für Physik

December 9th, 2024

SFB 1258 | Neutrinos Dark Matter Messengers

(Recently extended until 12/2028)

Particle Physics in Core-Collapse Supernovae

- Neutrino flavor conversion in neutrino-dense environments:
  Standard particle physics but a very complex, collective phenomenon.

- Nonstandard particle physics impact on SNe, such as Axions.

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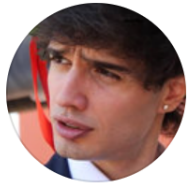

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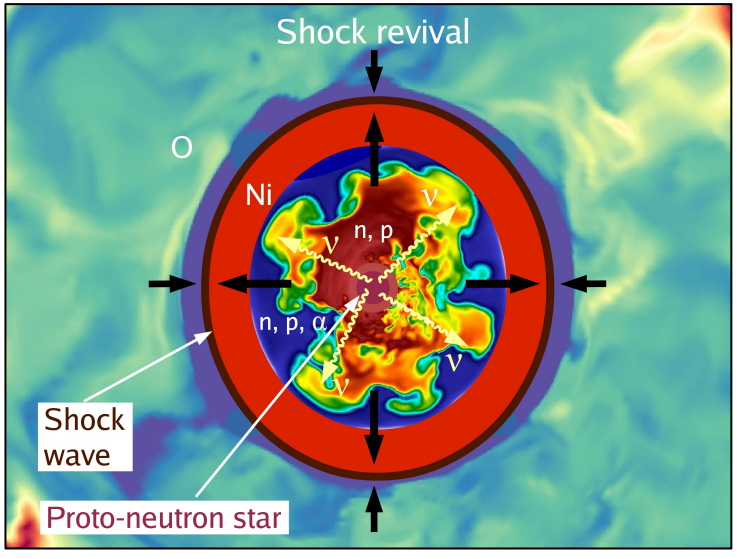
SFB 1258 | Neutrinos Dark Matter Messengers

M05

Core-Collapse Supernovae (CCSNe)



- Explosive death of very massive stars:
  Shock-wave revival by **neutrino** energy deposition.
- **Collective** neutrino oscillations:
  Interesting theoretical problem by itself.
- CCSNe are unique **laboratories** for BSM physics, such as axions.
- Possibility for neutrino (1987A) and gravitational wave detection: **Multi-messenger Astrophysics.**
- **Binary** neutron star mergers provide similar environments.

Collective Neutrino Oscillations

- Flavor-dependent phase-space densities (occupation number matrices):

$$\varrho = \begin{pmatrix} f_{\nu_e} & f_{\langle \nu_e | \nu_\mu \rangle} & f_{\langle \nu_e | \nu_\tau \rangle} \\ f_{\langle \nu_\mu | \nu_e \rangle} & f_{\nu_\mu} & f_{\langle \nu_\mu | \nu_\tau \rangle} \\ f_{\langle \nu_\tau | \nu_e \rangle} & f_{\langle \nu_\tau | \nu_\mu \rangle} & f_{\nu_\tau} \end{pmatrix}$$

Diagonal: Usual occupation numbers
Off-diag: Flavor coherence information

- **Refractive effects** due to neutrino-neutrino forward scattering can dominate the vacuum frequency in the Hamiltonian.
- One can have **flavor waves**, i.e., the amount of flavor coherence**,** supported by the nu gas (similar to plasma waves).
- Flavor coherence can grow due to the flavor **Instabilities** in nu gas.
- This can lead to the **collective oscillations** in the neutrino gas.
- A specialized but active field by ~ **50 papers** per year and active groups in Europe, USA, Japan, Taiwan, & India, dedicated workshops every year, at least 2 ERC grants

Impact of Neutrino Flavor Conversion in Supernovae

Featured in Physics

PHYSICAL REVIEW LETTERS **131,** 061401 (2023)

Fast Neutrino Flavor Conversions Can Help and Hinder Neutrino-Driven Explosions

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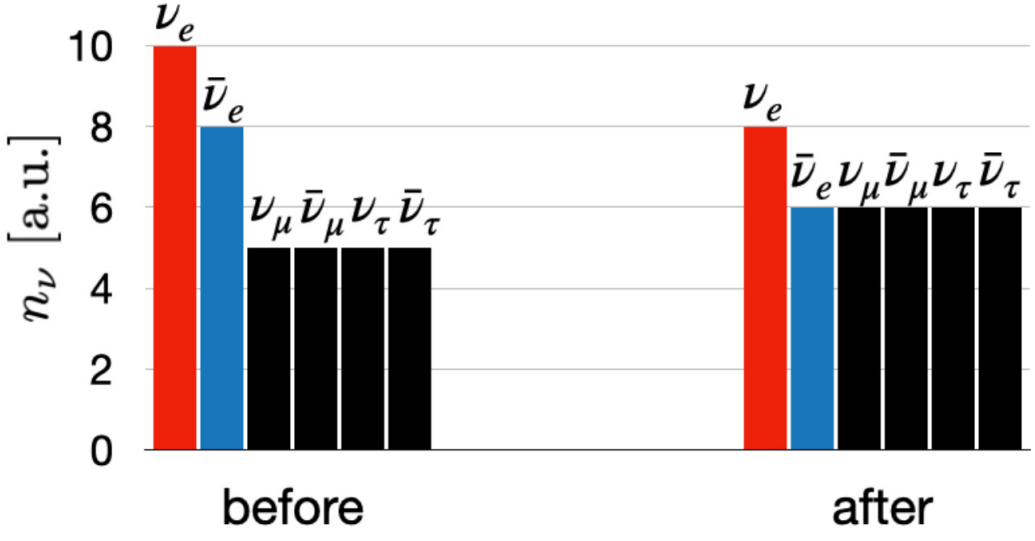
We present the first simulations of core-collapse supernovae in axial symmetry with feedback from fast neutrino flavor conversion (FFC). Our schematic treatment of FFCs assumes instantaneous flavor equilibration under the constraint of lepton-number conservation individually for each flavor. Systematically varying the spatial domain where FFCs are assumed to occur, we find that they facilitate SN explosions in low-mass (9–$12M_{\odot}$) progenitors that otherwise explode with longer time delays, whereas FFCs weaken the tendency to explode of higher-mass (around $20M_{\odot}$) progenitors.

DOI: 10.1103/PhysRevLett.131.061401

Impact of Neutrino Flavor Conversion in Supernovae

- **First parametric implementation** of neutrino flavor conversion (FC) in 1D and 2D CCSN simulations (PhD project of Jakob Ehring, now postdoc in Taiwan AS).

- Neutrinos reach flavor **equilibration** on **short** scales, which respect lepton number conservation laws.

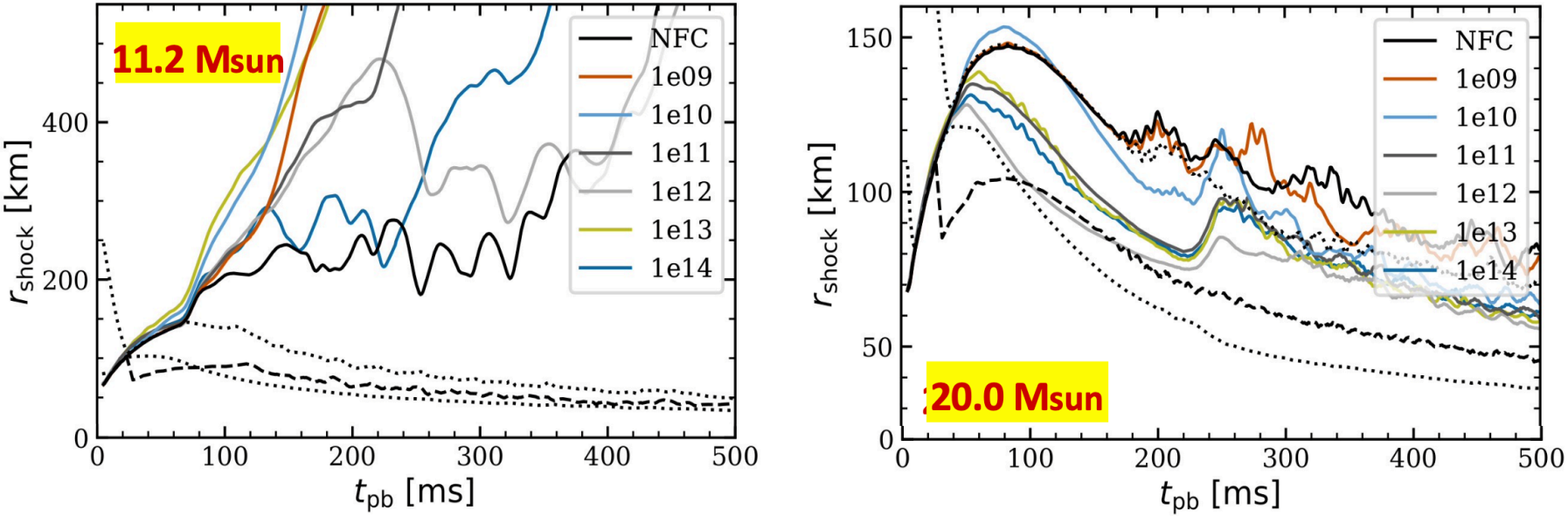


- FCs are assumed to occur for densities smaller than a **threshold** density.

Impact of Neutrino Flavor Conversion in Supernovae

- FC of heavy-lepton to electron neutrinos/antineutrinos can **boost** the neutrino **heating/cooling**.
- **Earlier** explosion of low-mass progenitors (left panel) but tends to **disfavor** explosions of high-mass progenitors (right panel).

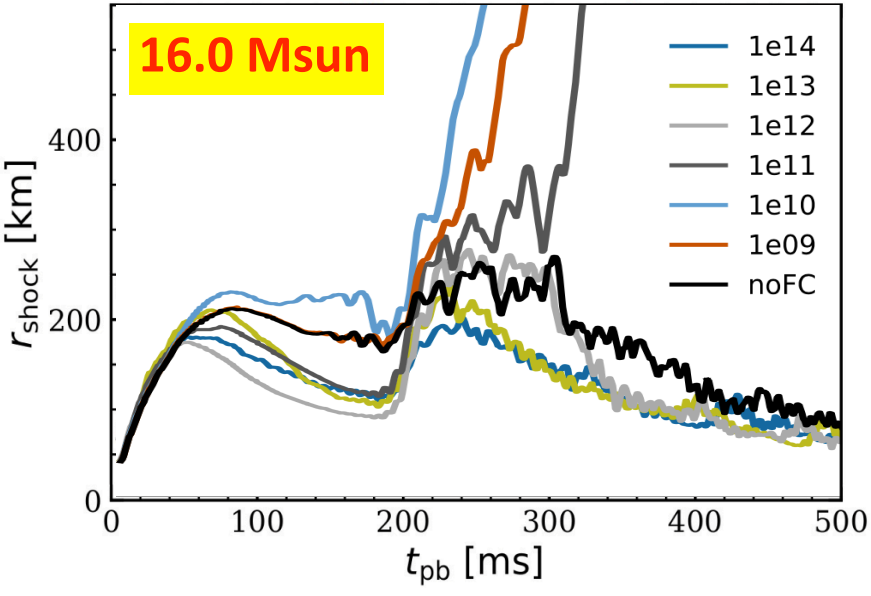
[NFC = no flavor conversion]



Ehring+, Phys. Rev. Lett. 131 (2023) 061401 , Phys. Rev. D 107 (2023) 103034

Impact of Neutrino Flavor Conversion in Supernovae

FCs can change the outcome of explosion!

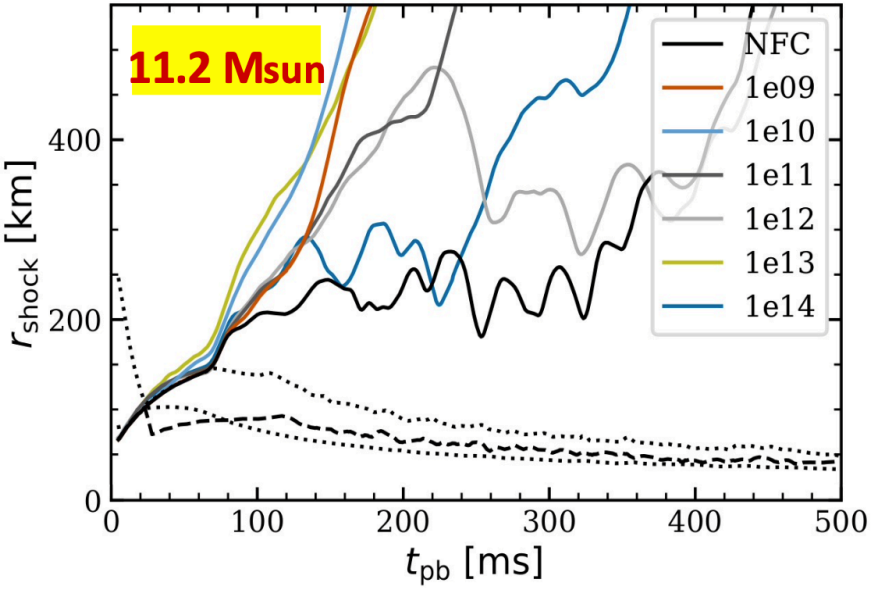


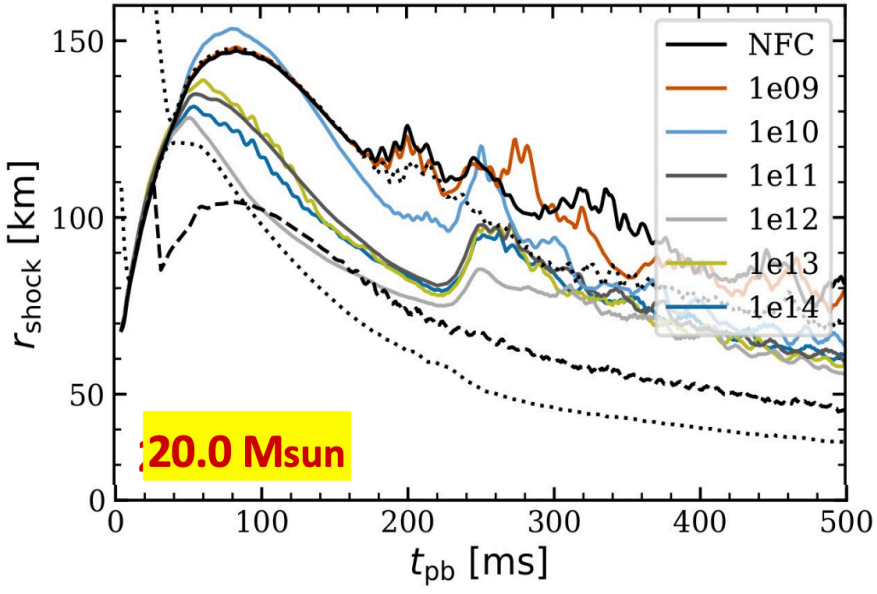
Ehring+, in prep.

Impact of Neutrino Flavor Conversion in Supernovae

Neutrino flavor conversions cannot be ignored in CCSNe!

[NFC = no flavor conversion]



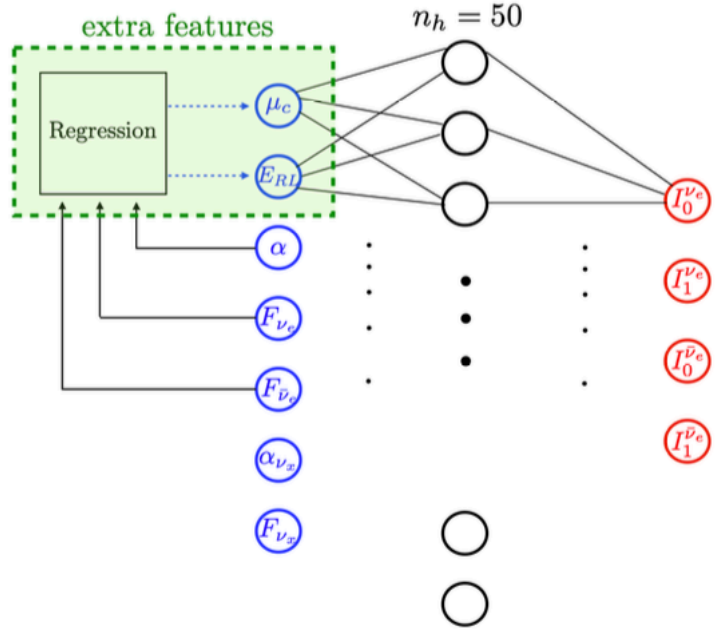


Impact of Neutrino Flavor Conversion in Supernovae

- A more realistic approach instead of parametric implementation of FCs?

  - Classical machine learning methods excel in verifying whether the criteria for the occurrence of FC are met.

  - Physics-informed neural networks also do a great job in predicting the outcomes of FCs.

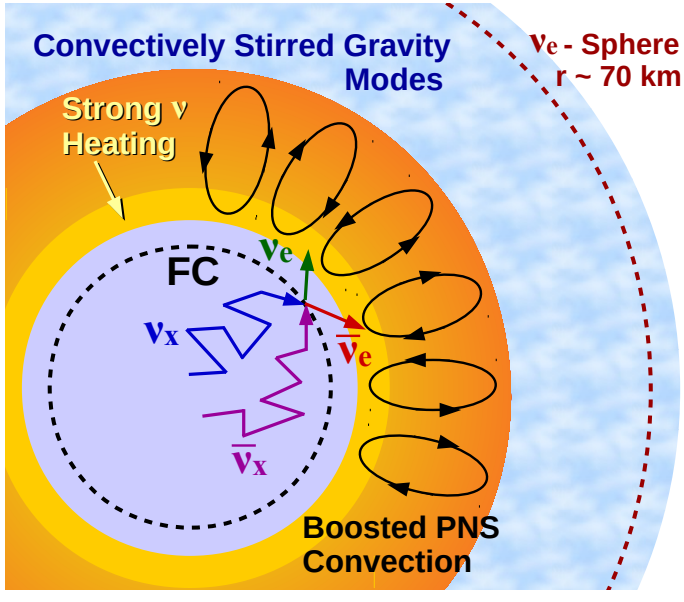


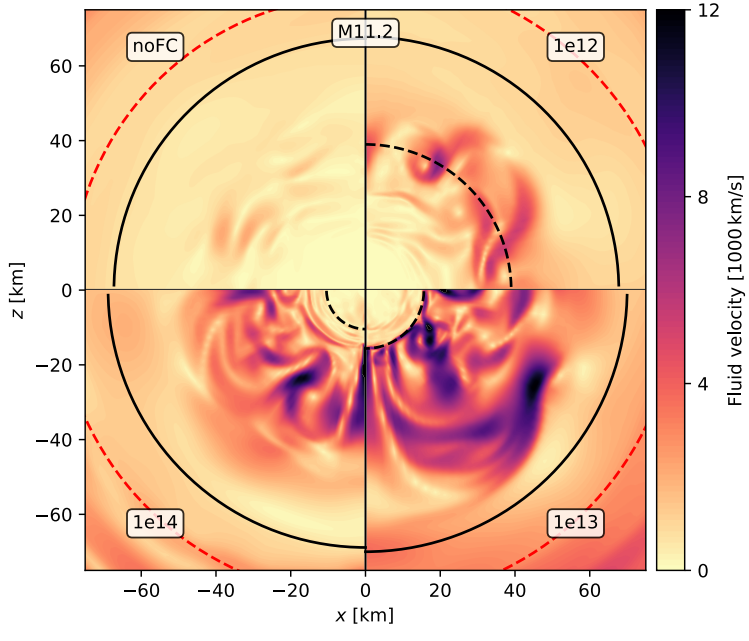
Abbar, *Phys.Rev.D* 107 (2023) 10, 103006
Abbar+, *Phys.Rev.D* 109 (2024) 2, 023033
Abbar+, *Phys.Rev.D* 109 (2024) 4, 043024
Abbar+, arXiv: 2401.10915

Gravitational Waves as Multi-Messenger Signals for Nonstandard Particle Physics in CCSNe

- High-energy heavy-lepton nu's are converted to electron neutrinos/antineutrinos, which are quickly **absorbed** by the PNS matter.

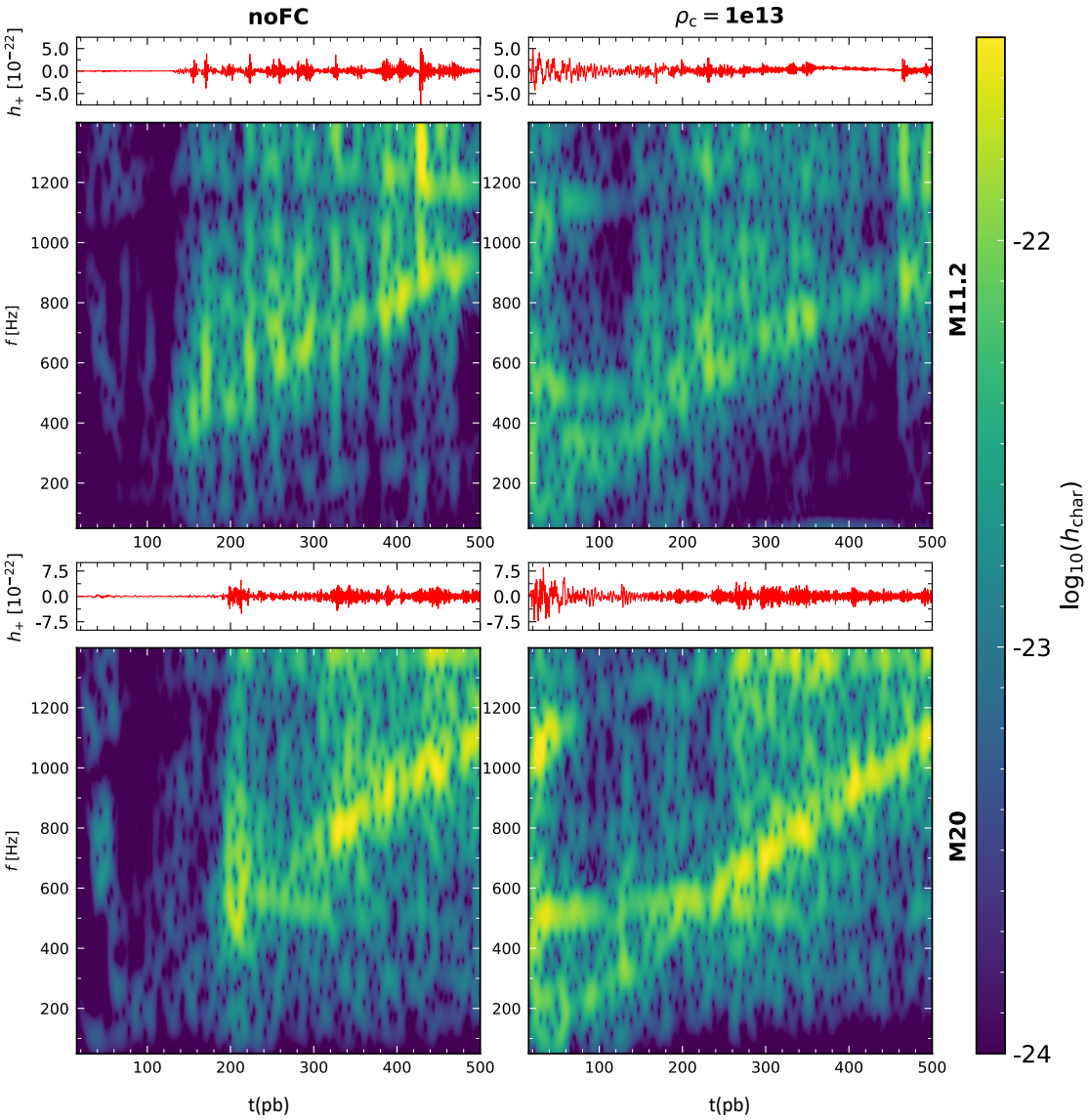
- This leads to strong local heating and thus enhances PNS **convection**.





Ehring, Abbar, et al., arXiv: 2412.02750

Gravitational Waves as Multi-Messenger Signals for Nonstandard Particle Physics in CCSNe



- The enhanced convection inside the PNS, induced by FC therein, can **generate GW** by exciting g-modes near the PNS surface

- This leads to an strong enhancement of the GWs signal right after the bounce, during the otherwise GW **quiescent** phase.

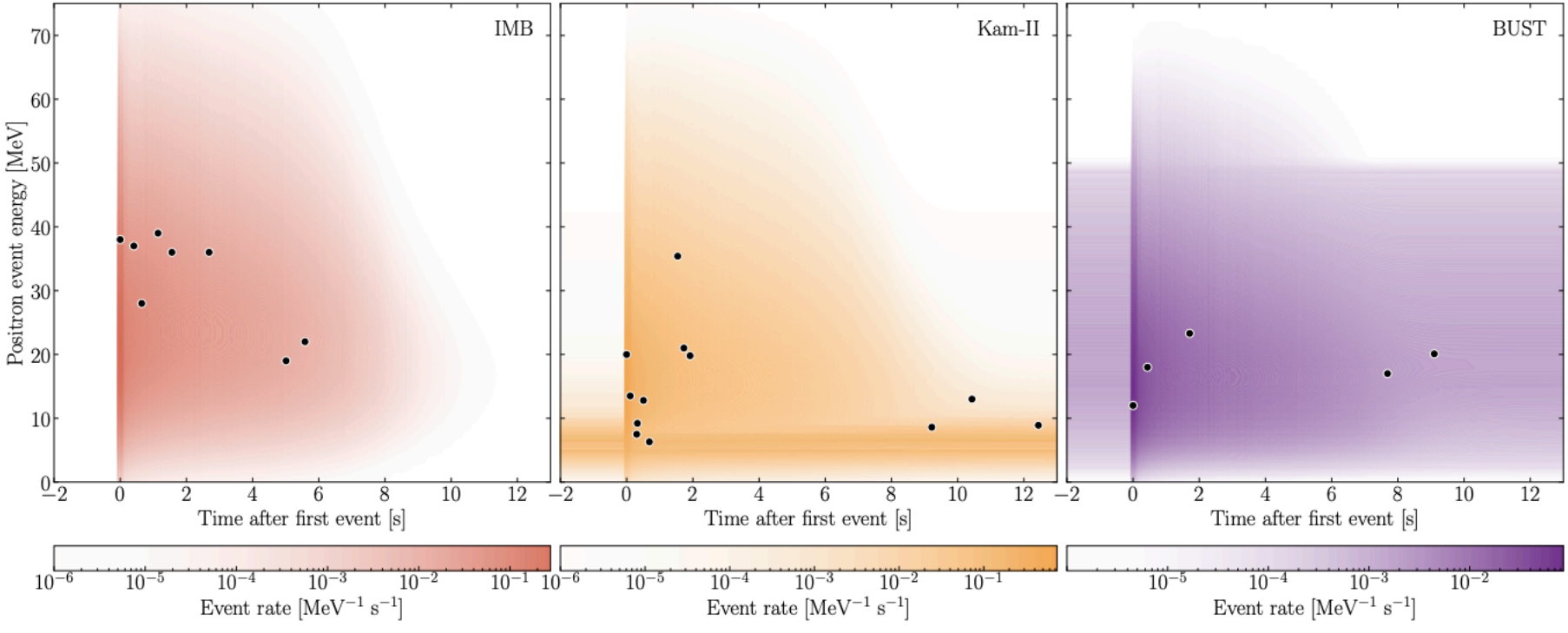
Ehring, Abbar, et al., arXiv: 2412.02750

Other Contributions:

- Theory of collective flavor evolution, mainly works of Georg Raffelt with Damiano Fiorillo (now at DESY Zeuthen)
  - D. F & G. R, arXiv: 2412.02747
  - D. F & G. R, arXiv: 2409.17232
  - D. F & G. R, JHEP 2408 (2024) 225, 47 pp. (arXiv: 2406.06708)
  - D. F & G. R, Phys. Rev. Lett. 133 (2024) 221004 (arXiv: 2403.12189)
  - D. F, G. R, & G. Sigl, Phys. Rev. Lett. 133 (2024) 021002 (arXiv: 2401.05278)
  - D. F & G. R, Phys. Rev. D 107 (2023) 123024 (arXiv: 2303.12143)
  - D. F & G. R, Phys. Rev. D 107 (2023) 043024 (arXiv: 2301.09650)
- Secret neutrino interactions
  - D. F, G. R, & E. Vitagliano, Phys. Rev. Lett. 132 (2024) 021002 (arXiv: 2307.15115)
  - D. F, G. R, & E. Vitagliano, Phys. Rev. D 109 (2024) 023017, 21 pp (arXiv: 2307.15122)
  - S. Abbar, Phys.Rev.D 107 (2023) 10, 103002 (arXiv: 2208.06023)
- Using Bayesian inference to distinguish neutrino flavor conversion scenarios
  - Abbar & Volpe, arXiv: 2401.10851

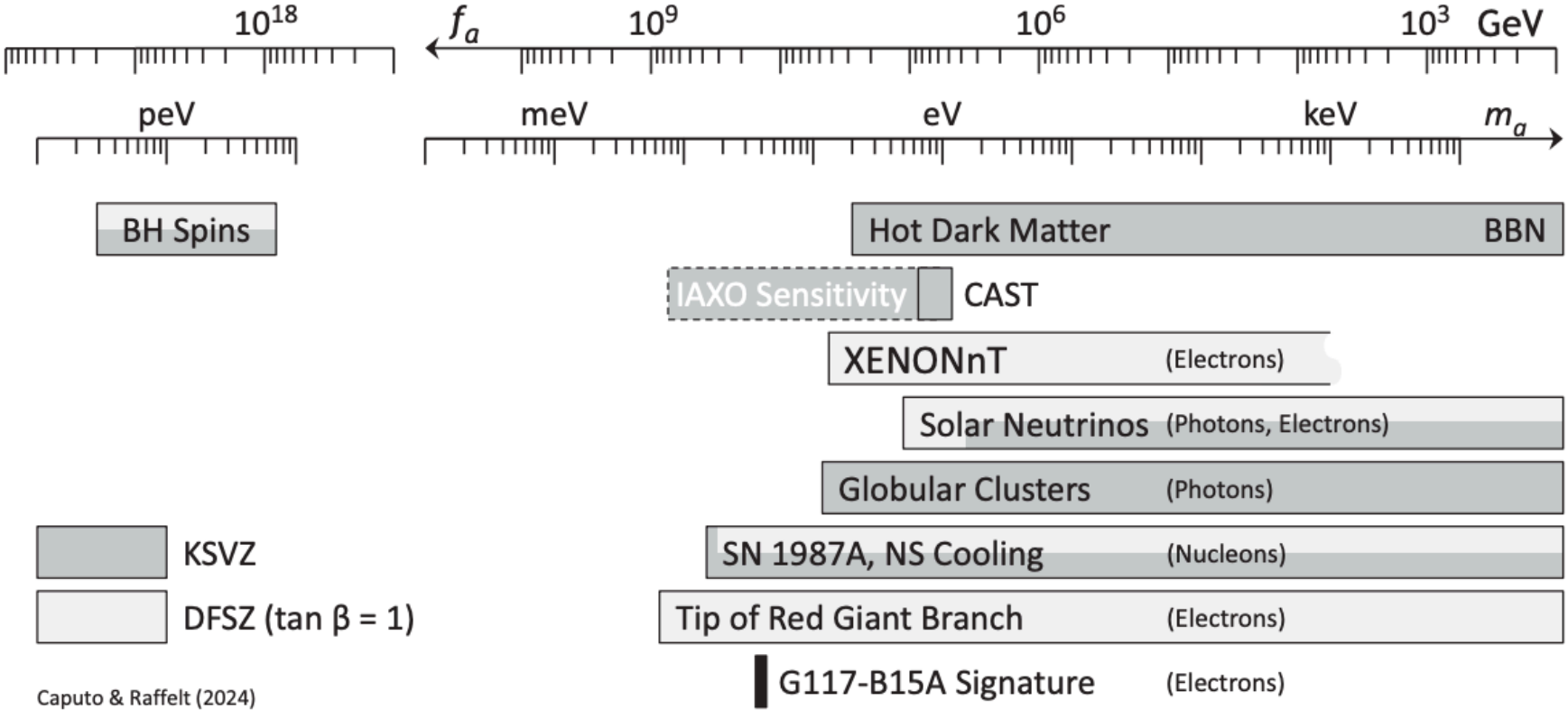
SN1987A: PNS Cools Too Fast ?

- SN1987A neutrino signal suggests that current models with PNS convection **cool too fast**, failing to explain late time events in Kamiokande-II and Baksan.
- This inconsistency drives the need to understand **PNS convection** better.
- Can axion emission switch off PNS convection?



Fiorillo, Heinlein, Janka, Raffelt & Bollig, PRD 108 (2003) 0830340

Astrophysical Axion Bounds: The 2024 Edition



Caputo & Raffelt, PoS 454 (2024) 041, 81 pp, arXiv: 2401.13728

- Restrictive bounds on new particles from low energy SNe
  - Phys. Rev. Lett. 128 (2022) 221103 (arXiv: 2201.09890)

Summary

- In the epoch of multi-messenger astronomy, collapsing stars remain powerful natural laboratories for particle physics.

- They drive the development of innovative methods, such as machine learning, while presenting complex theoretical challenges, including advancements in quantum kinetic equations.