Neutrino Flavor Conversion in Astrophysics: Towards Consistent Modeling

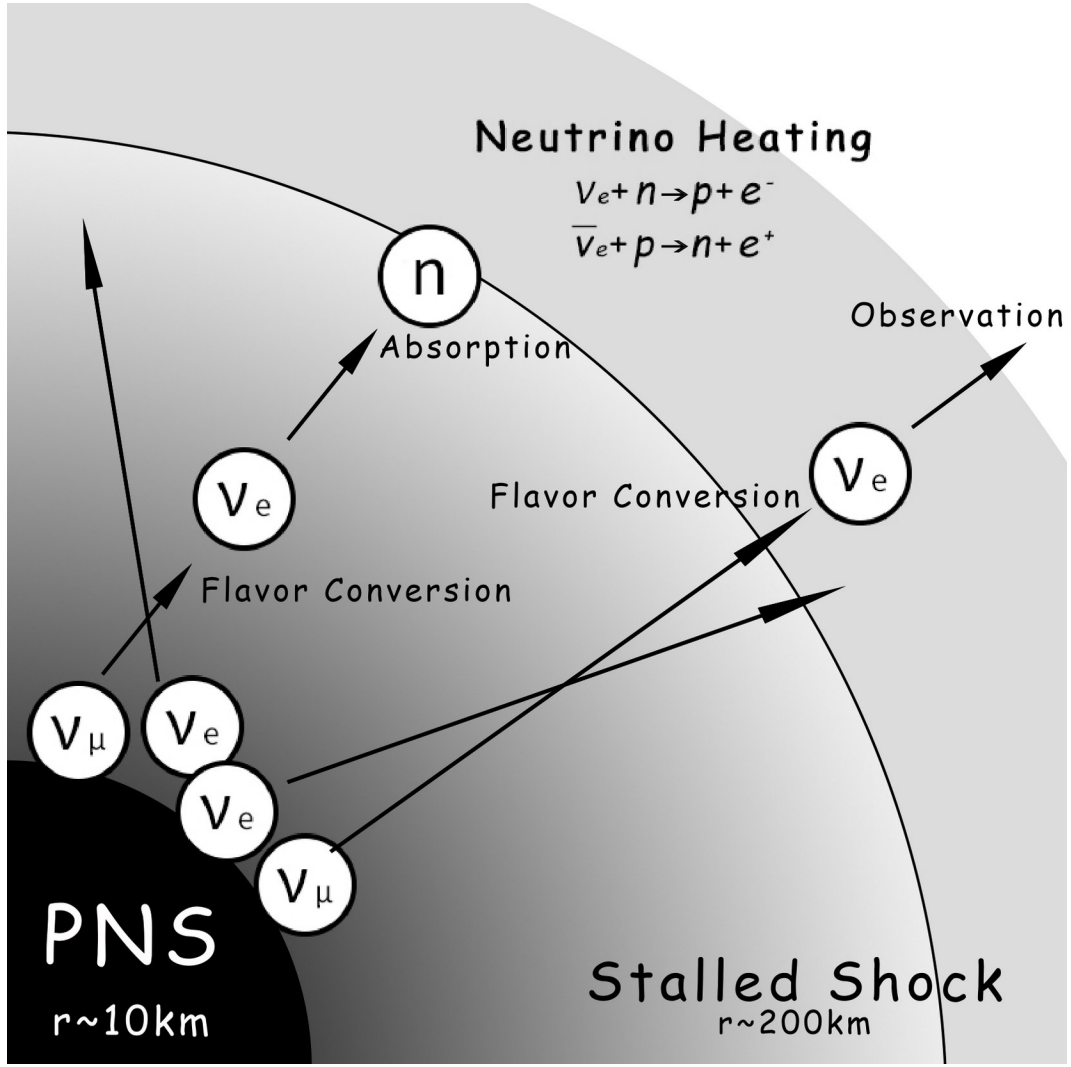
From astrophysical simulations to nonlinear flavor dynamics and effective models

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Flavor conversion can modify energy deposition and matter composition



- **Heating and dynamics**

  absorption of ν_e and $\bar{\nu}_e$ deposits energy in matter, influencing shock revival and outflows.

- **Composition and nucleosynthesis**

  These reactions change the neutron–proton balance and electron fraction Y_e, shaping nucleosynthesis conditions.

- **Why flavor conversion matters**

  Flavor conversion changes the neutrino distributions that enter these reaction rates.

- **The key question**

  Where does conversion occur, and how does it redistribute neutrinos among flavors?

From flavor instabilities to nonlinear evolution

$$(\partial_t + \boldsymbol{v}\cdot\boldsymbol{\nabla})\rho = -i[H_{\rm vac} + H_{\rm mat} + H_{\nu\nu}[\rho,\overline{\rho}],\rho] + \mathcal{C}[\rho,\overline{\rho}]$$

Slow

Fast

Collisional

Three mechanisms of collective flavor **instabilities**

Neutrino flavor **density matrix**

$$\rho(E,\boldsymbol{v}) = \begin{pmatrix} f_{\nu_e} & S_{e\mu} & S_{e\tau} \\ S_{\mu e} & f_{\nu_\mu} & S_{\mu\tau} \\ S_{\tau e} & S_{\tau\mu} & f_{\nu_\tau} \end{pmatrix}$$

f_{ν_α}: flavor α occupation number
$S_{\alpha\beta}$: flavor coherence between flavors α and β

Self-interactions couple different **energies and propagation directions**. As the neutrino state evolves, the Hamiltonian changes in turn—making the evolution **nonlinear**.

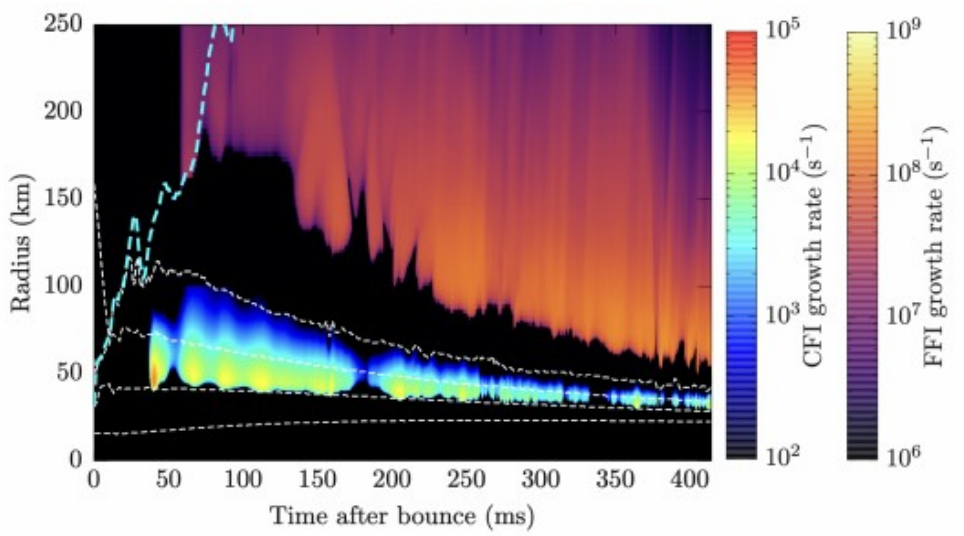
Instability analysis: which flavor-coherence perturbations grow, and how rapidly?
Nonlinear evolution: how are neutrinos redistributed among flavors?

Where do flavor instabilities occur?

Core-collapse supernova

2D CCSN simulation with Boltzmann transport

Fast + collisional instabilities

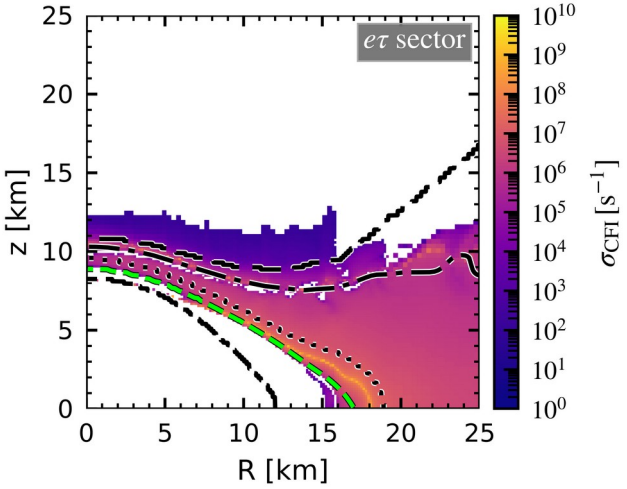


Akaho, Liu et al., PRD 109, 023012 (2024)
Figure adapted in Johns et al., arXiv:2503.05959

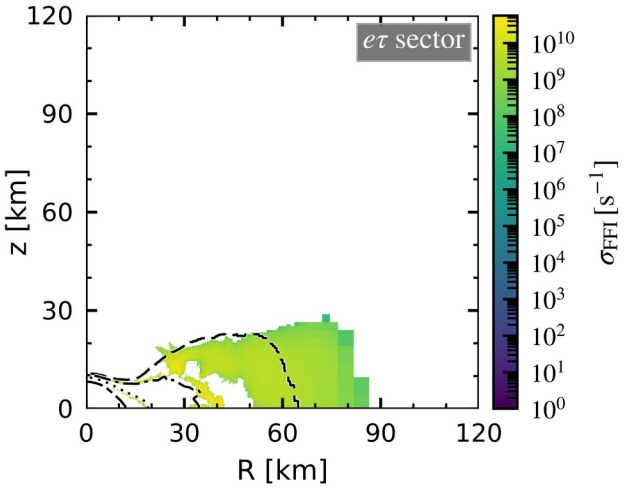
Binary-neutron-star merger

Muon-inclusive remnant · e–τ sector · 38 ms after merger

Collisional (CFI)



Fast (FFI)



Ng, Liu et al. (2026), arXiv:2610.36486
Artwork: 31 Oct manuscript; different spatial windows

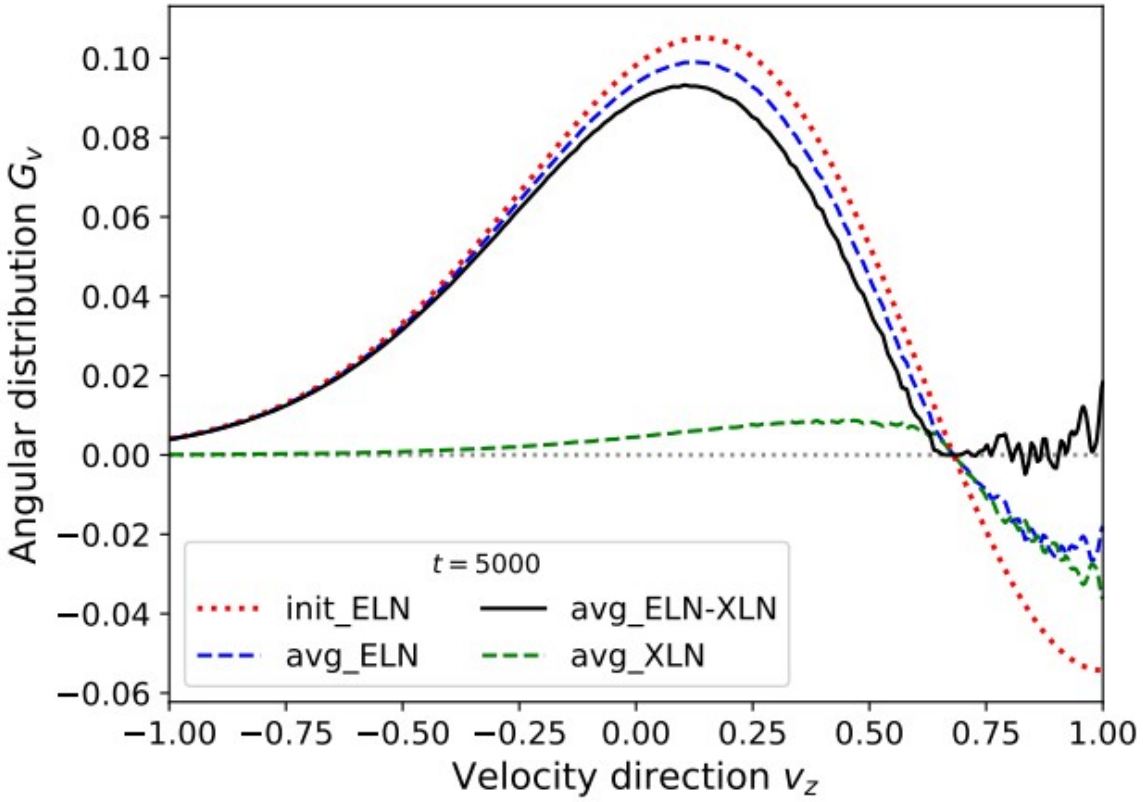
Accurate neutrino transport is essential for reliable instability diagnostics.

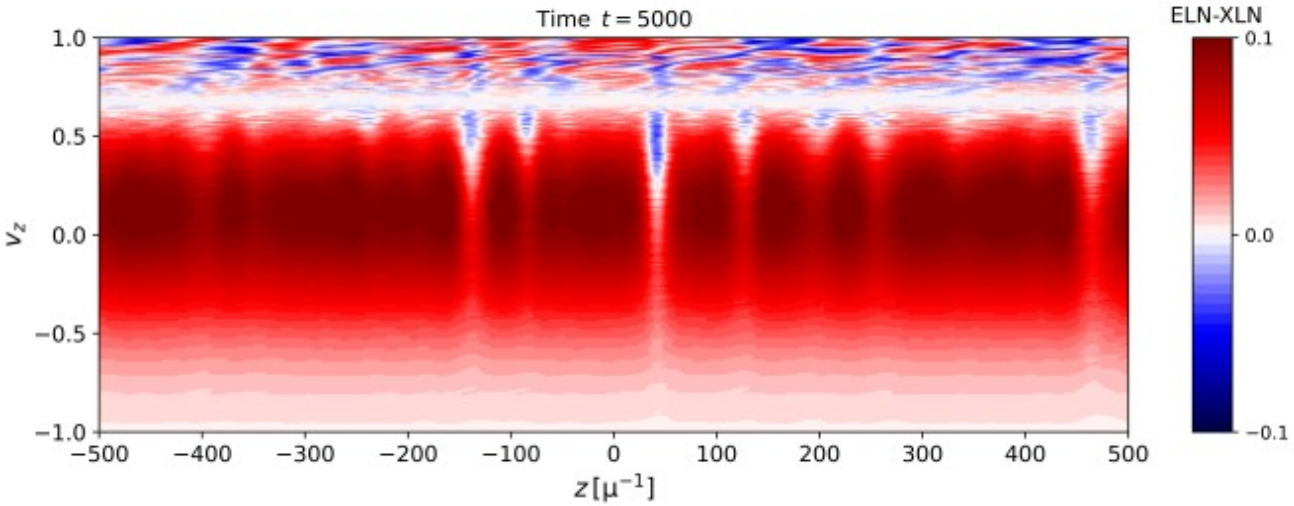
Unstable regions appear in both examples; growth alone does not determine the outcome.

Microscopic flavor scales motivate subgrid treatments in global simulations.

Asymptotic states of fast flavor conversion

Two-flavor, collisionless periodic-box benchmark





$$\mathrm{ELN} = f_{\nu_e} - f_{\bar{\nu}_e} \qquad \mathrm{XLN} = f_{\nu_x} - f_{\bar{\nu}_x}$$

Spatial average tends to be steady in time

Zaizen & Nagakura, Phys. Rev. D 107, 103022 (2023)

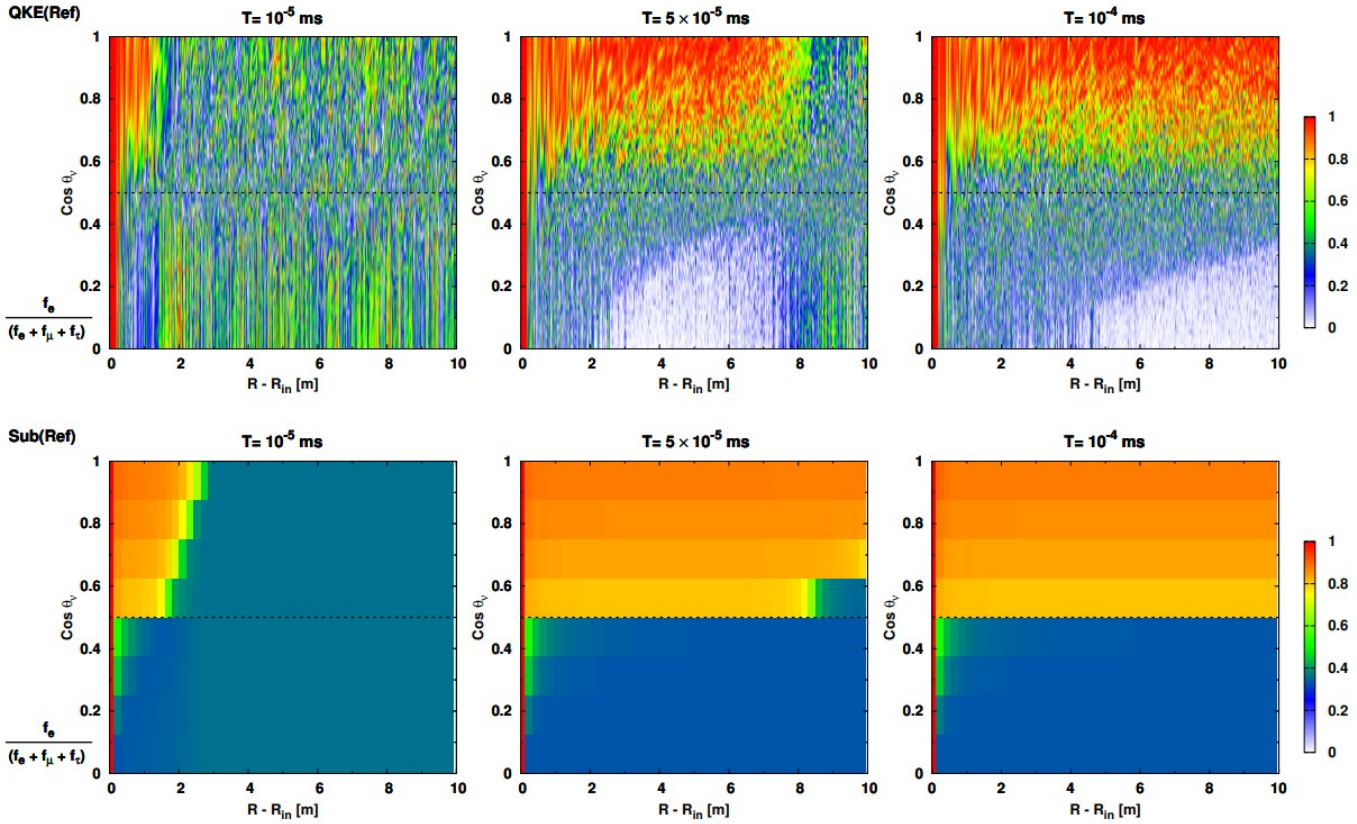
Averaged crossing removal does not require pointwise equilibration.

Crossing removal and conservation guide approximate asymptotic-state prescriptions.

A subgrid model for fast flavor conversion

$$p^\mu \frac{\partial f}{\partial x^\mu} + \frac{dp^i}{d\tau}\frac{\partial f}{\partial p^i} = -p^\mu u_\mu S + ip^\mu n_\mu [H, f]$$

$$p^\mu \frac{\partial f}{\partial x^\mu} + \frac{dp^i}{d\tau}\frac{\partial f}{\partial p^i} = -p^\mu u_\mu S + p^\mu n_\mu \frac{1}{\tau_a}(f - f^a)$$



Relaxation instead of resolved oscillations

Update two ingredients from the evolving neutrino field:

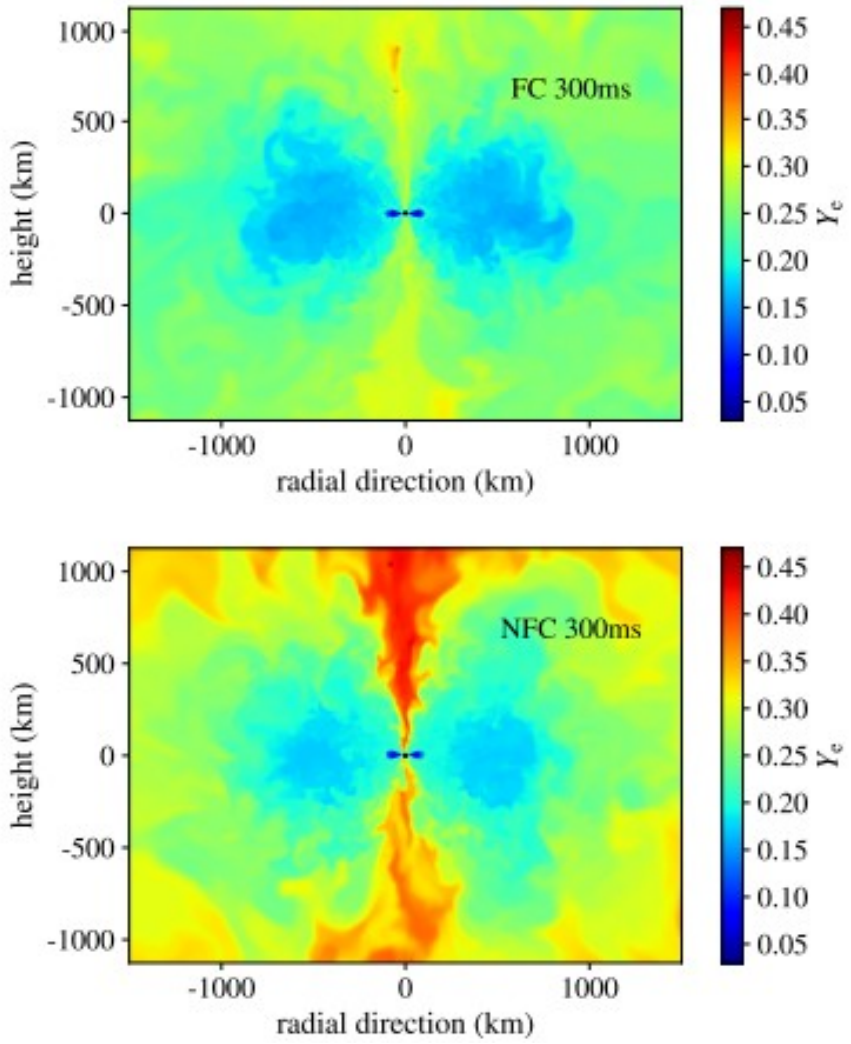
target distribution + relaxation timescale

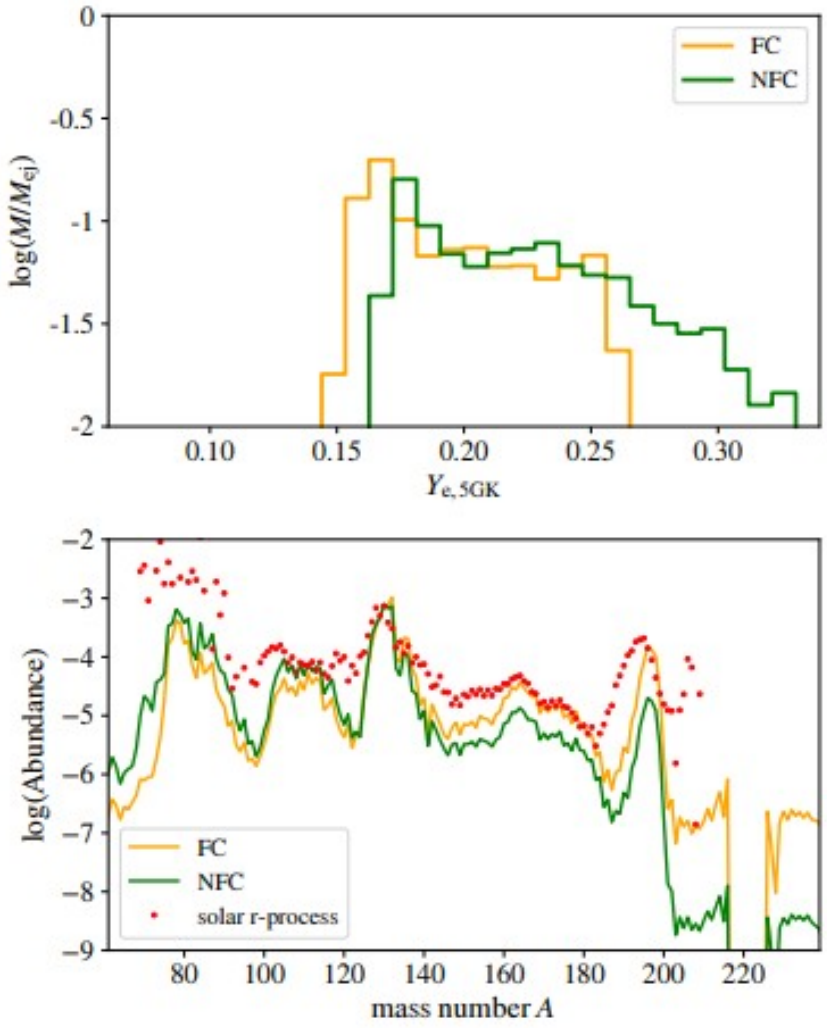
Retains classical transport variables without resolving microscopic flavor scales.

Reproduces coarse-grained redistribution in the tested QKE benchmarks—not each oscillation.

Nagakura, Johns & Zaizen, PRD 109, 083013 (2024)

Impact on neutron-star merger outflows





Postmerger accretion-disk example

With the adopted flavor prescription:

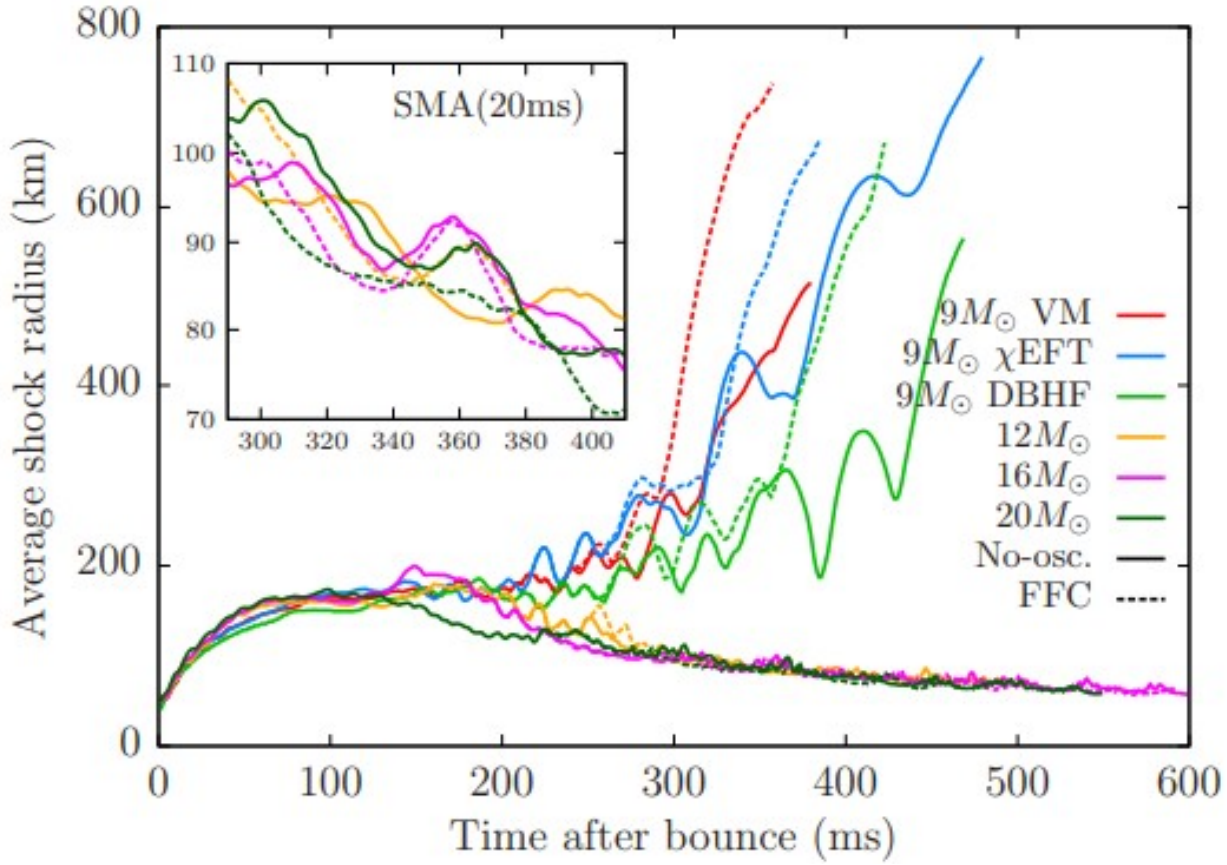
More neutron-rich outflows

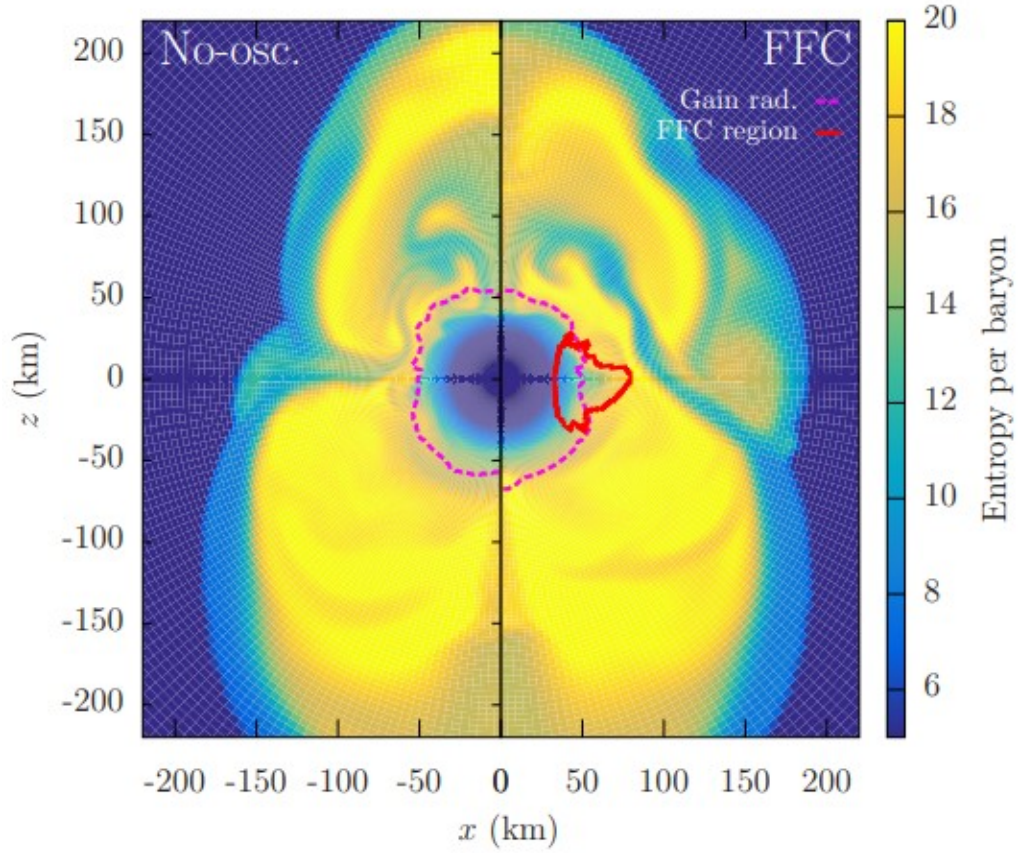
Enhanced lanthanide and third-peak r-process production

A model-dependent outcome, not a universal direction of the effect.

Li & Siegel, Phys. Rev. Lett. 126, 251101 (2021)

Impact on core-collapse supernovae





In these models, FFC promotes low-mass explosions but inhibits shock expansion at higher masses.

Spectral hardening competes with reduced neutrino luminosity.

Akaho et al., Phys. Rev. Lett. 136, 191002 (2026)

Towards consistent modeling

Beyond fast conversion

Treat slow, fast, and collisional mechanisms within one QKE framework; establish when reduced limits apply.

Test the coherence closure

Determine when population-only updates are adequate and when surviving coherence changes the averaged evolution.

Define and validate the local target

Investigate local quantum-equilibrium descriptions and their limits when relaxation is incomplete or motion persists.

Goal: predictive flavor-aware transport for dynamics and nucleosynthesis.

Local-equilibrium perspective: Johns, Phys. Rev. D 112, 063032 (2025).