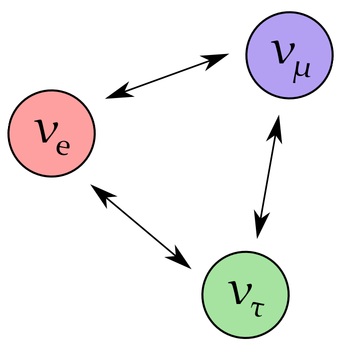
Neutrino Flavor Conversion in Supernovae: Quantum Kinetics and Astrophysical Implications



Masamichi ZAIZEN

Postdoc, Univ. of Tokyo in Japan

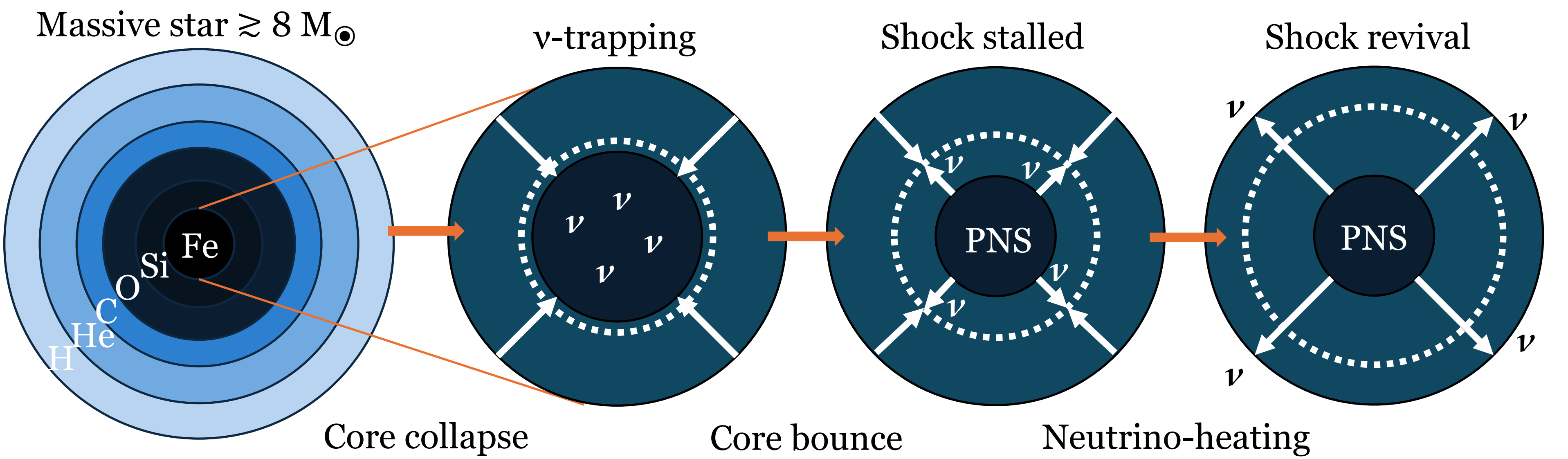
***Phys. Rev. D* 107, 103022 (2023)**

***Phys. Rev. D* 111, 103029 (2025)**

SN2025gw: First IGWN Symposium on Core Collapse Supernova Gravitational Wave Theory and Detection

University of Warsaw on Jul. 22, 2025

Roles of Neutrinos in CCSNe



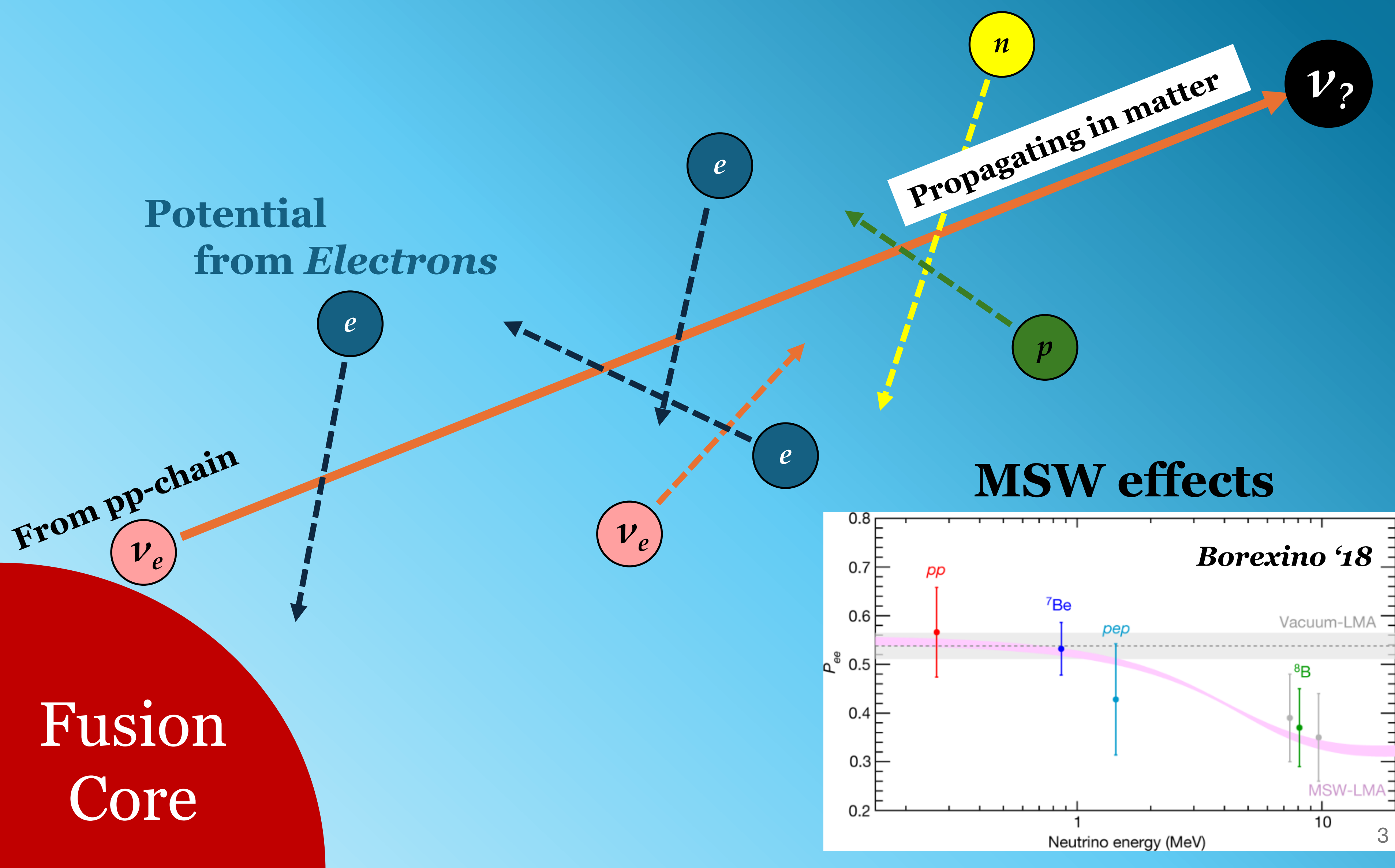
Neutrino-heating process:

- Shock wave stalls due to accreting matter and fails to explode.
- Neutrinos work as ***mediators*** because of their weakly-coupling nature with matter.
- **Neutrinos transfer their energy from the hotter core to the colder stalled shock.**

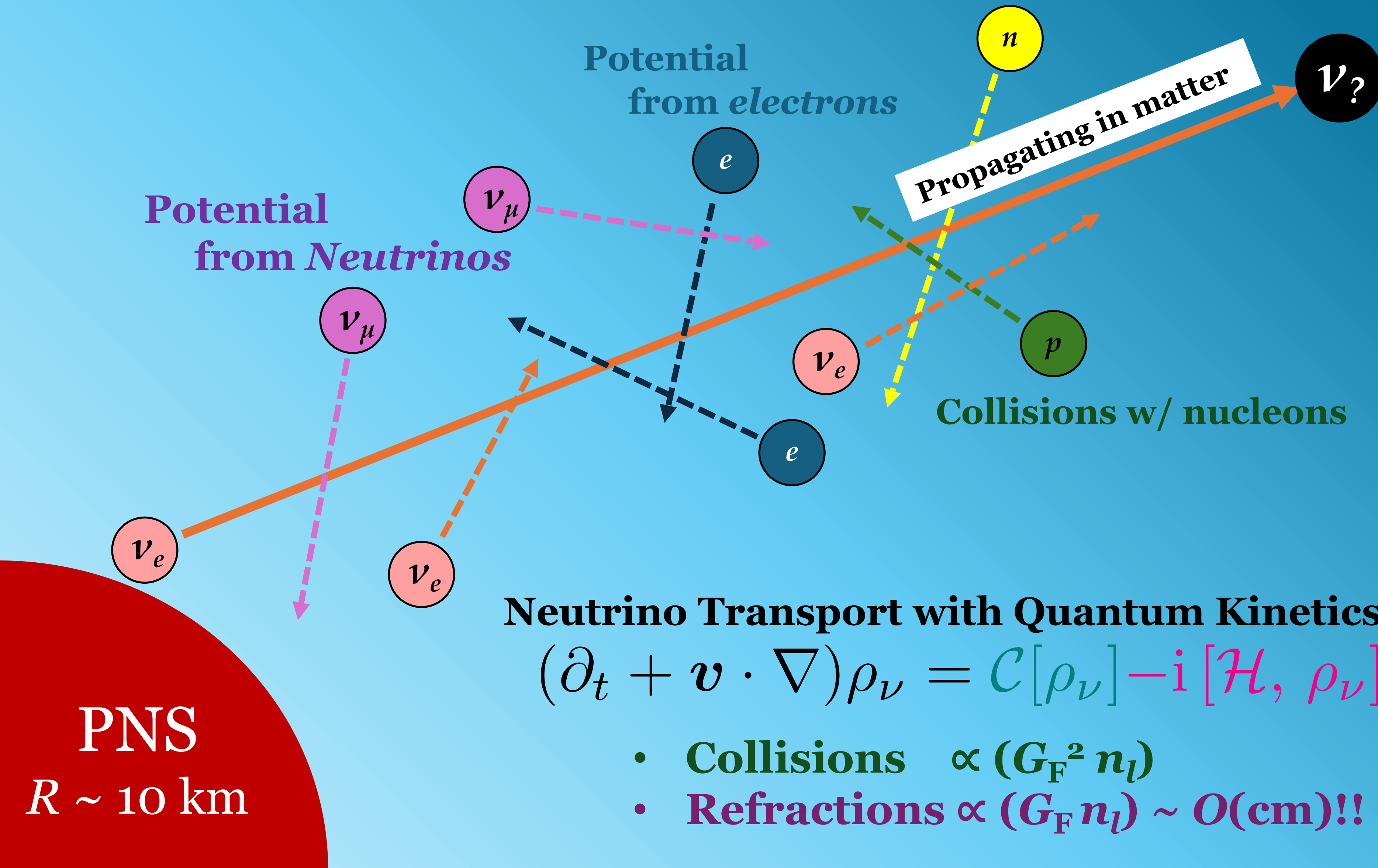
Neutrino transport is essential in the theoretical studies/predictions.

→ ***One of the uncertainties is neutrino oscillation.***

Solar Neutrino Problem



Sea of Leptons & Nucleons in CCSNe



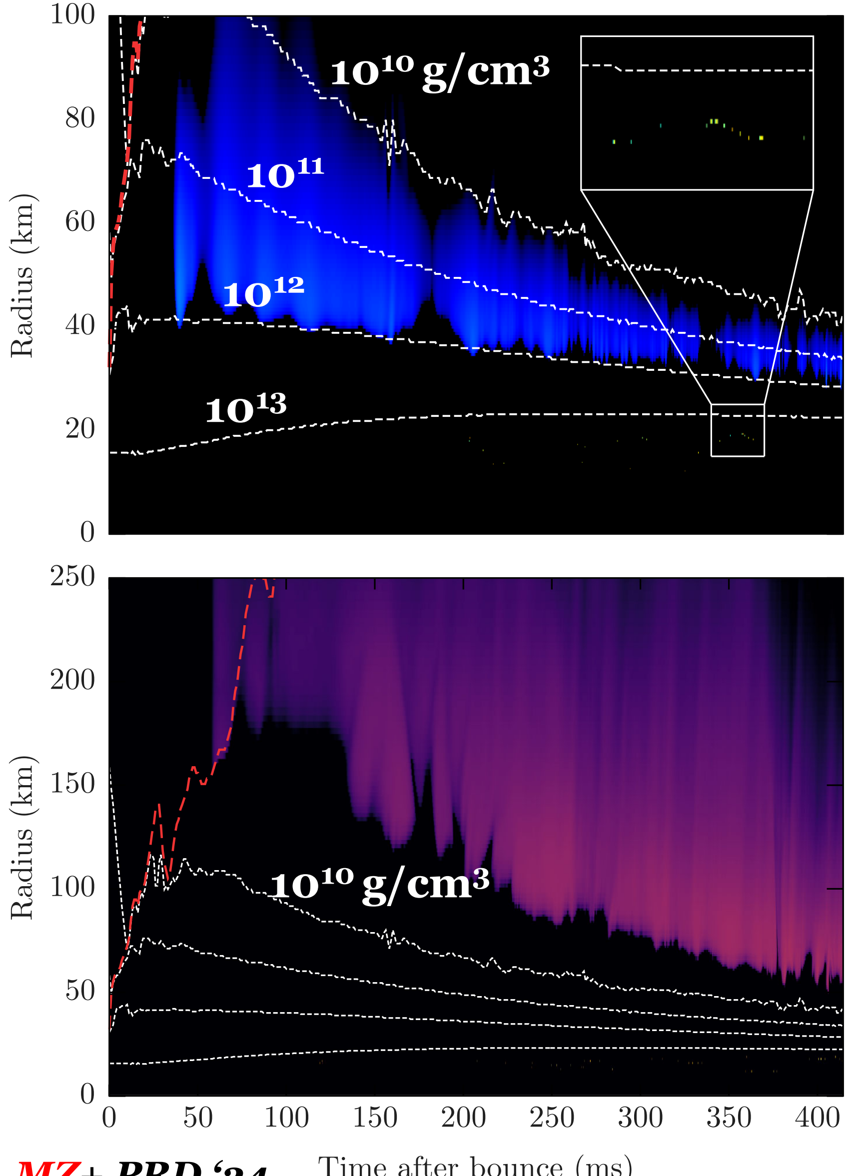
Neutrino Transport with Quantum Kinetics:

$$(\partial_t + \boldsymbol{v} \cdot \nabla)\rho_\nu = \mathcal{C}[\rho_\nu] - \mathrm{i}\,[\mathcal{H},\, \rho_\nu]$$

- **Collisions** $\propto (G_F^2\, n_l)$
- **Refractions** $\propto (G_F\, n_l) \sim O(\mathrm{cm})$!!

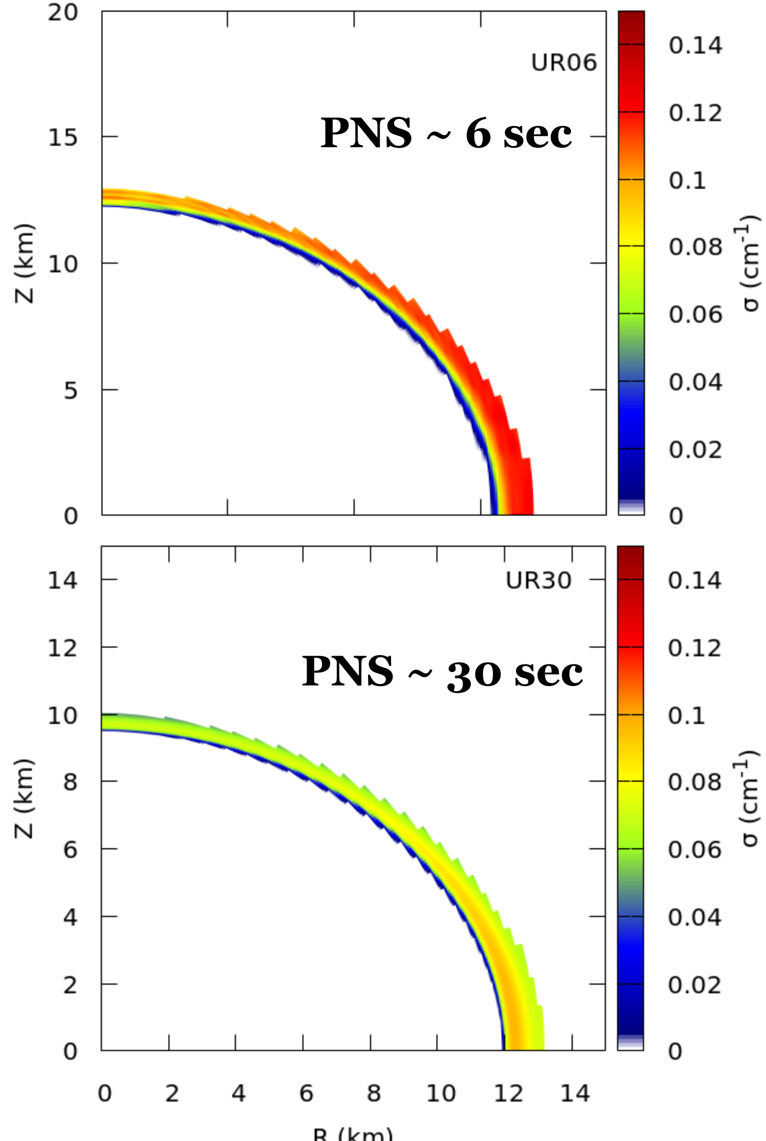
Possibility Search of Flavor Conversion

2D-CCSN



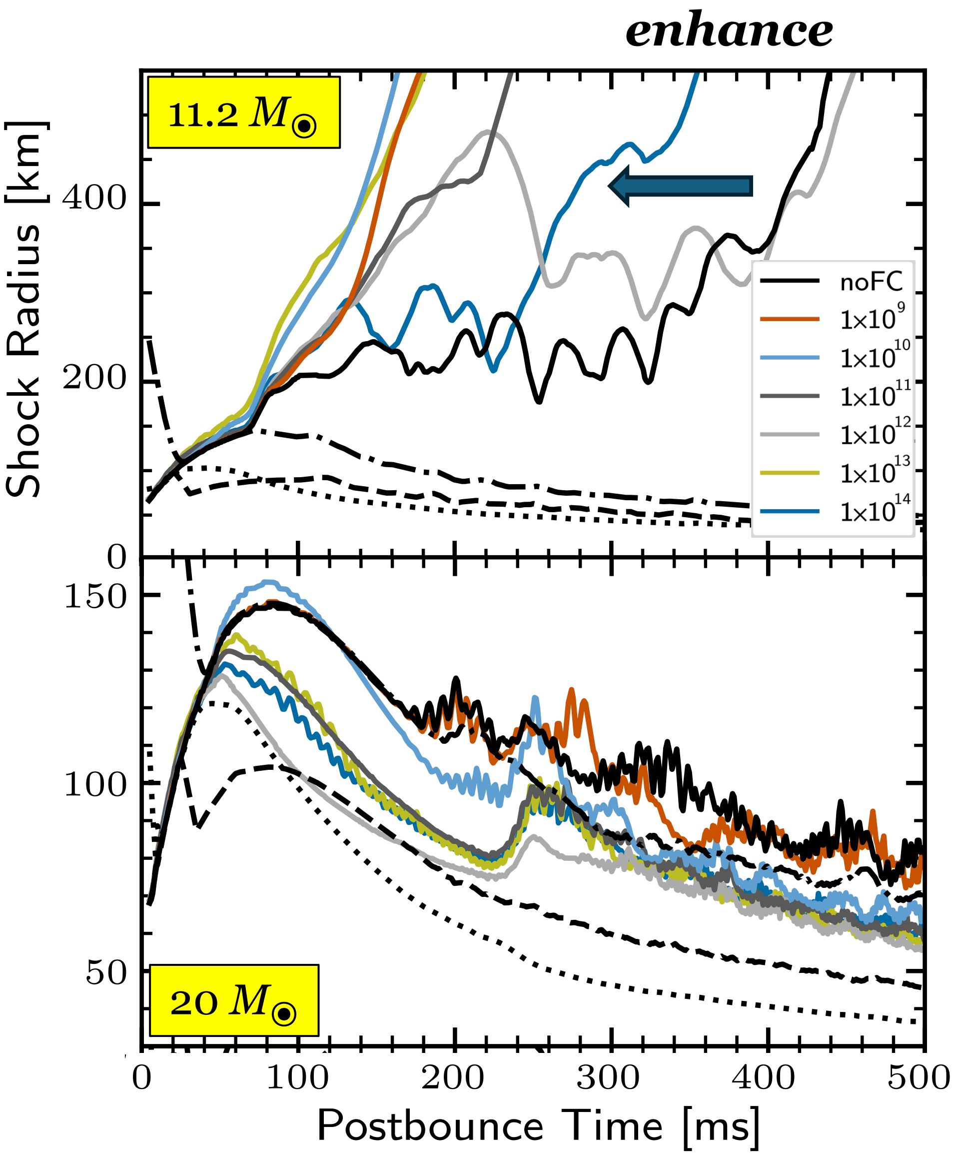
Akaho, MZ+ PRD '24

Rotating PNS Cooling

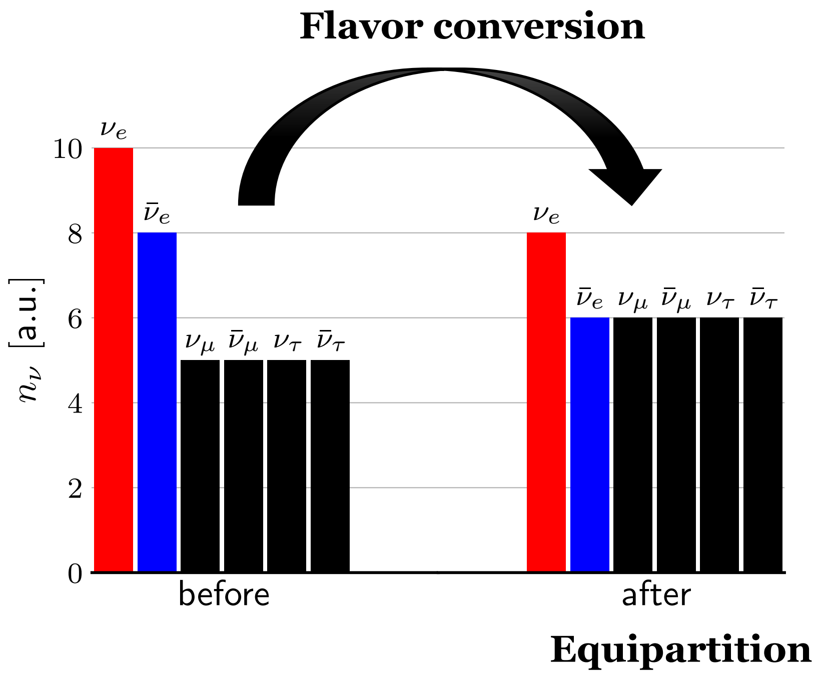


Barrio+ arXiv '25

Phenomenological Approach in 1D/2D



(noFC = traditional moment transport)



Simple prescriptions:

- Flavor equipartition below $\rho < \rho_{crit}$.

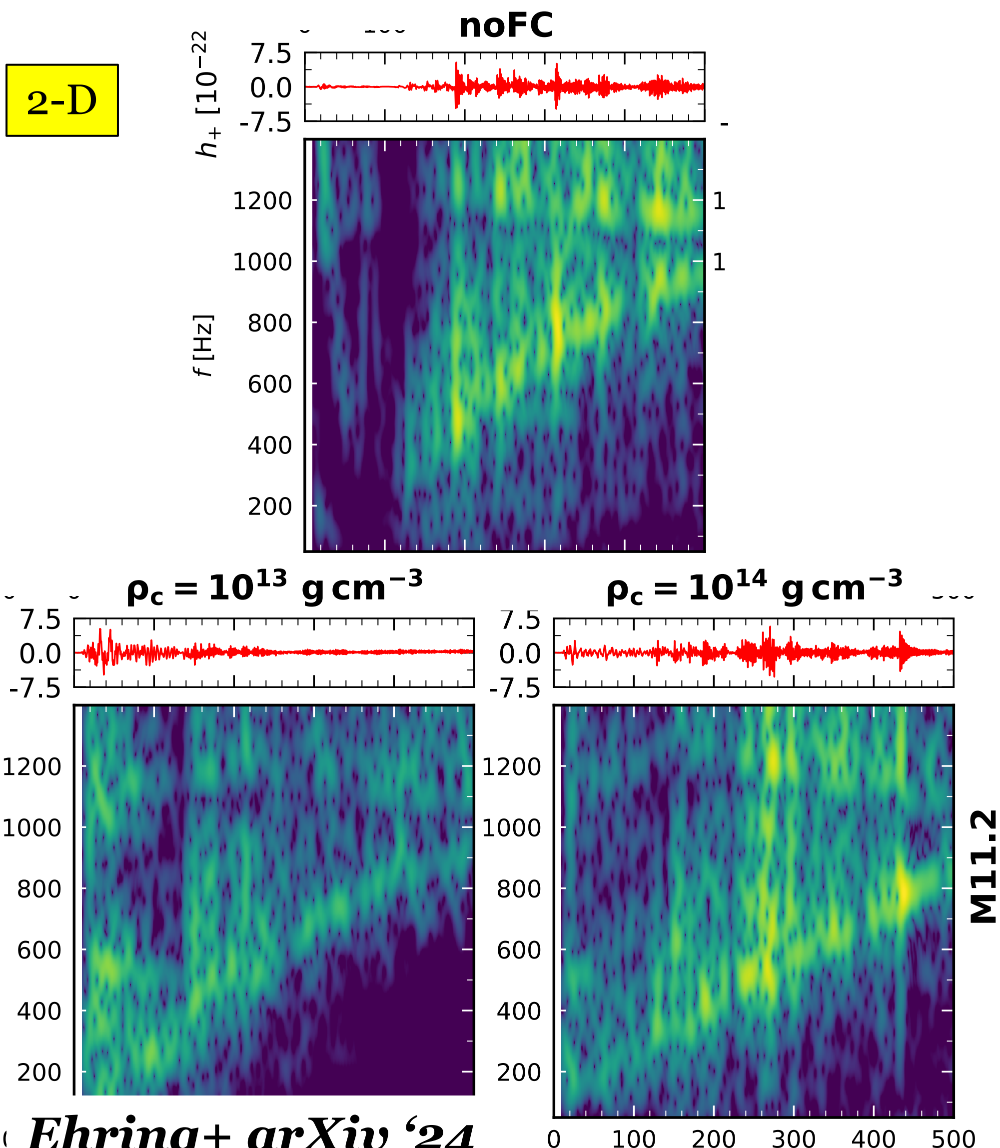
This may over-/under-estimate the impact but can change the shock dynamics.

Ehring+ PRD & PRL '23

Phenomenological Approach for GW

$\rho_{crit} \sim 10^{13\text{-}14}$ g cm^{-3}

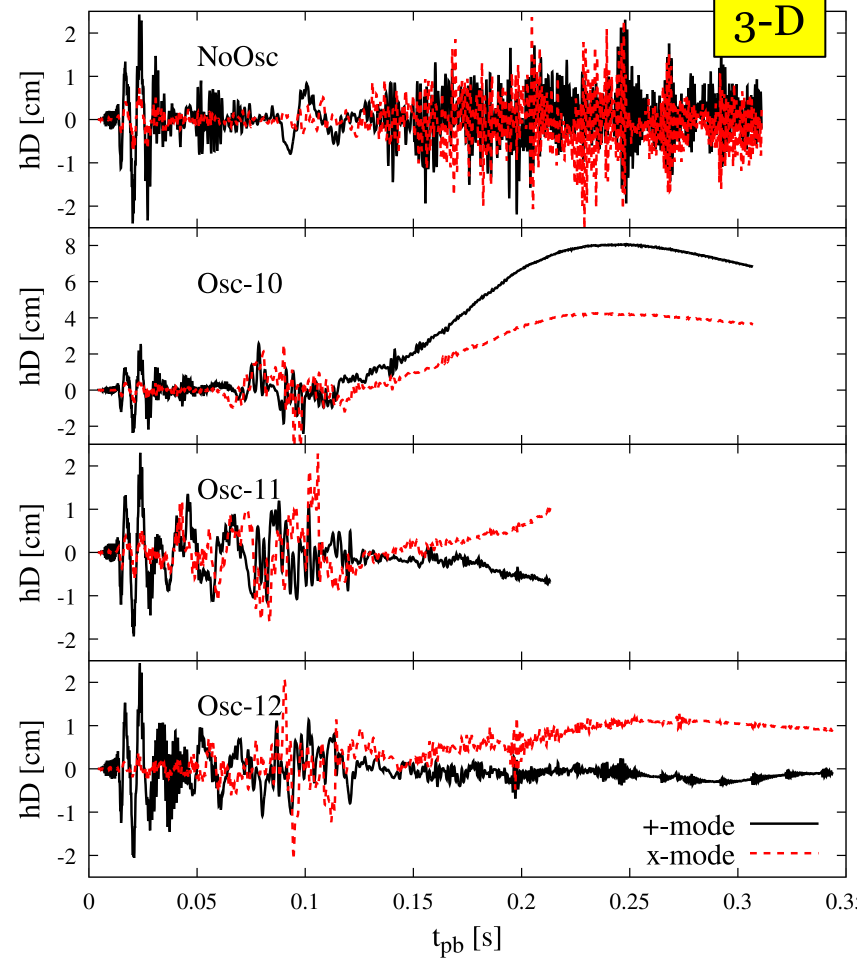
2-D



Ehring+ arXiv '24

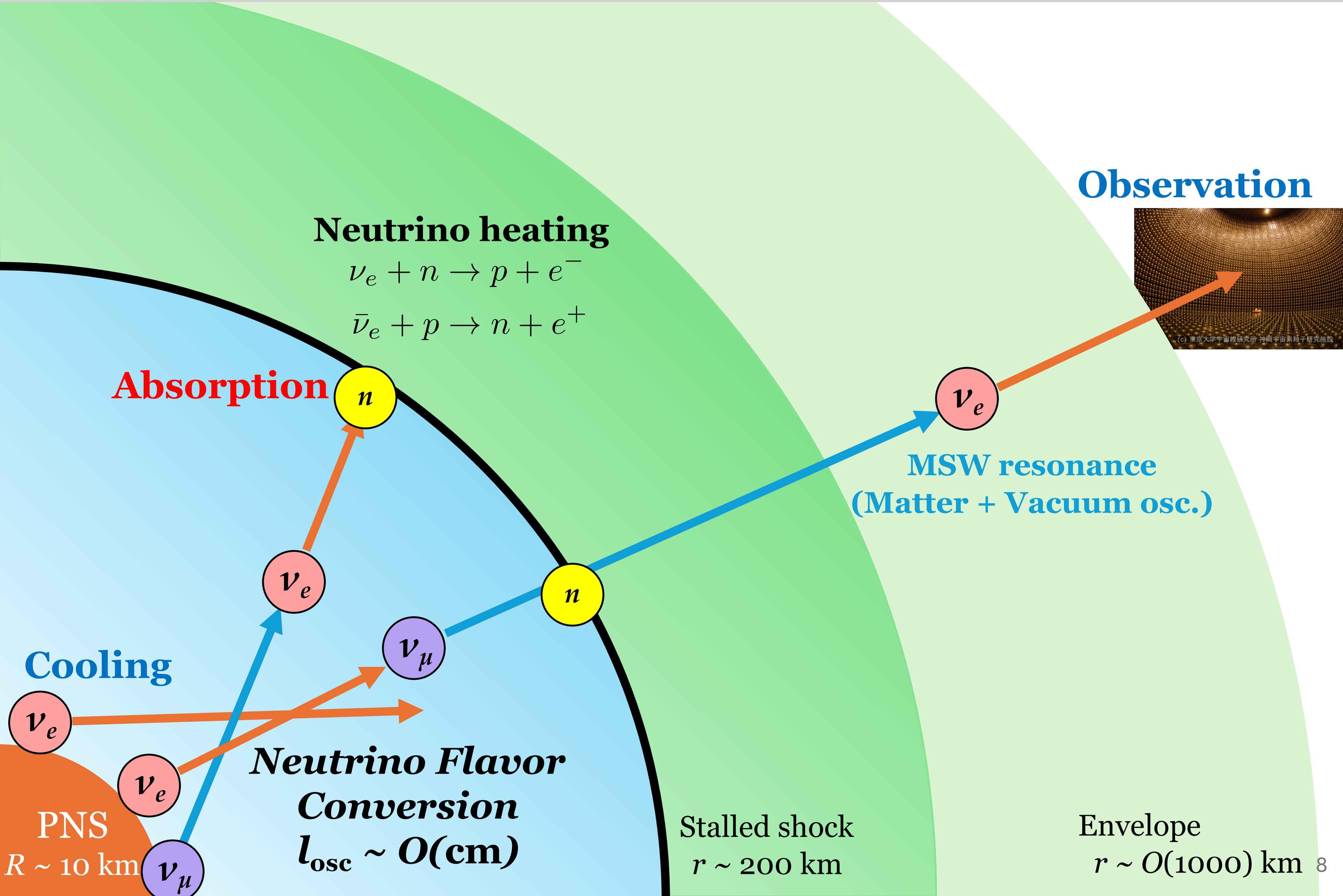
$\rho_{crit} \sim 10^{10\text{-}12}$ g cm^{-3}

3-D



Mori+ PASJ '25

Quantum Kinetic Neutrino Transport



Asymmetry Triggering Flavor Instability

Quantum Kinetic Equation:

Self-interactions

$$(\partial_t + \boldsymbol{v} \cdot \nabla)\rho = -\mathrm{i}\,[\underline{\mathcal{H}_{\mathrm{vac}}} + \mathcal{H}_{\mathrm{mat}} \boxed{+ \underline{\mathcal{H}_{\nu\nu}},}\ \rho] + \underline{\mathcal{C}_{\mathrm{col}}}$$

Collisions

e.g., ***Duan+ '06***

Slow flavor instability (SFI)

Asymmetry in ***energy***

$$\tau_{\mathrm{slow}} \sim \mathcal{O}(\sqrt{\mu\omega_{\mathrm{v}}})^{-1}$$

e.g., ***Sawyer '16***

Fast flavor instability (FFI)

Asymmetry in ***angle***

$$\tau_{\mathrm{fast}} \sim \mathcal{O}(\mu^{-1}) \sim \mathcal{O}(G_{\mathrm{F}} n_\nu)^{-1}$$

~ 1 cm

e.g., ***Johns '23***

Collisional flavor instability (CFI)

Asymmetry in ***collisions***

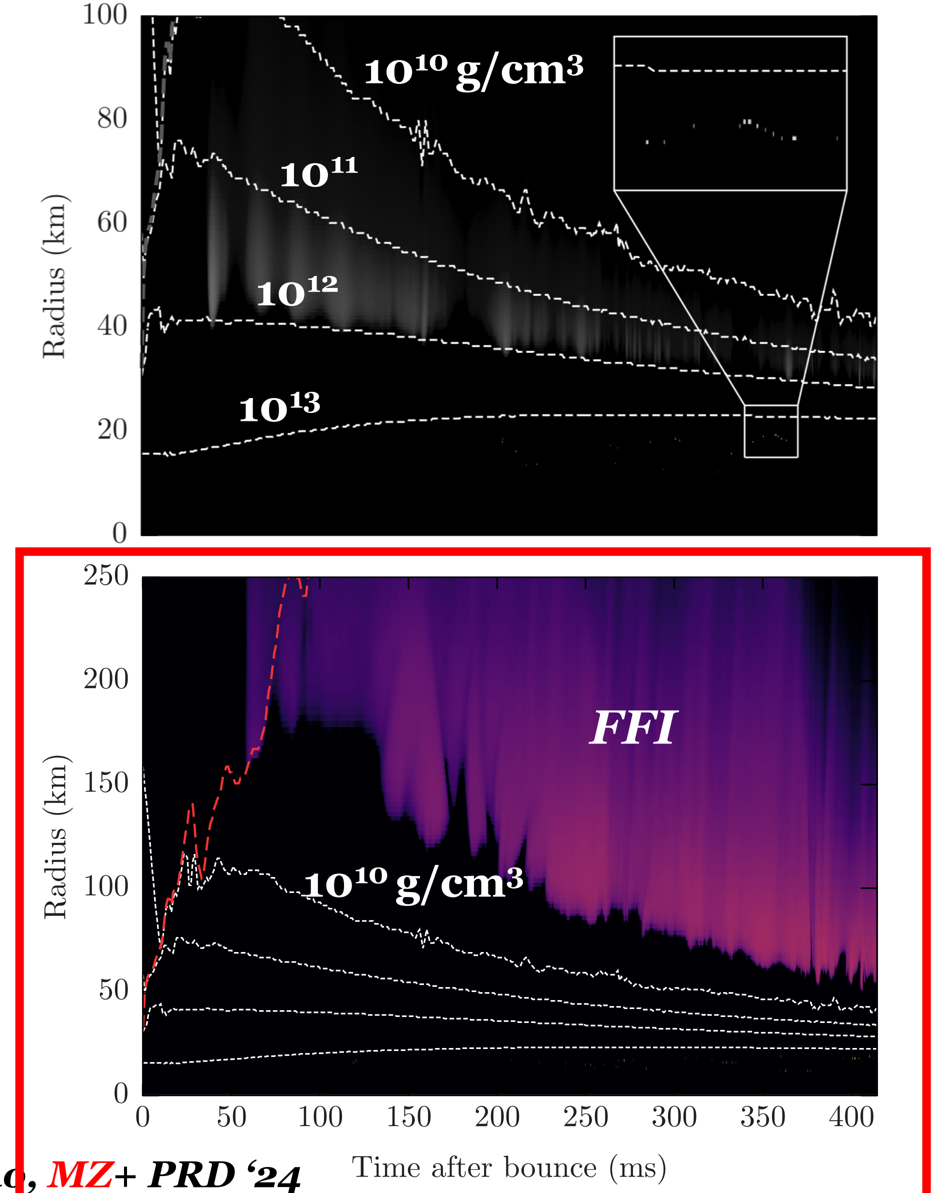
$$\tau_{\mathrm{col}} \sim \mathcal{O}(\sqrt{\mu\Gamma})^{-1} - \mathcal{O}(\Gamma)^{-1}$$

Relatively longer scale

Need separate understandings!!

Possibility Search of Flavor Conversion

2D-CCSN



Fast flavor instability (FFI)

Mechanism of instability:
- Asymmetry in angles

Neutrino distribution
- Outside decoupling regions
- Forward-peaked

→ **Angular dist. is crucial.**

Akaho, MZ+ PRD '24

Asymmetry in Angular Distributions

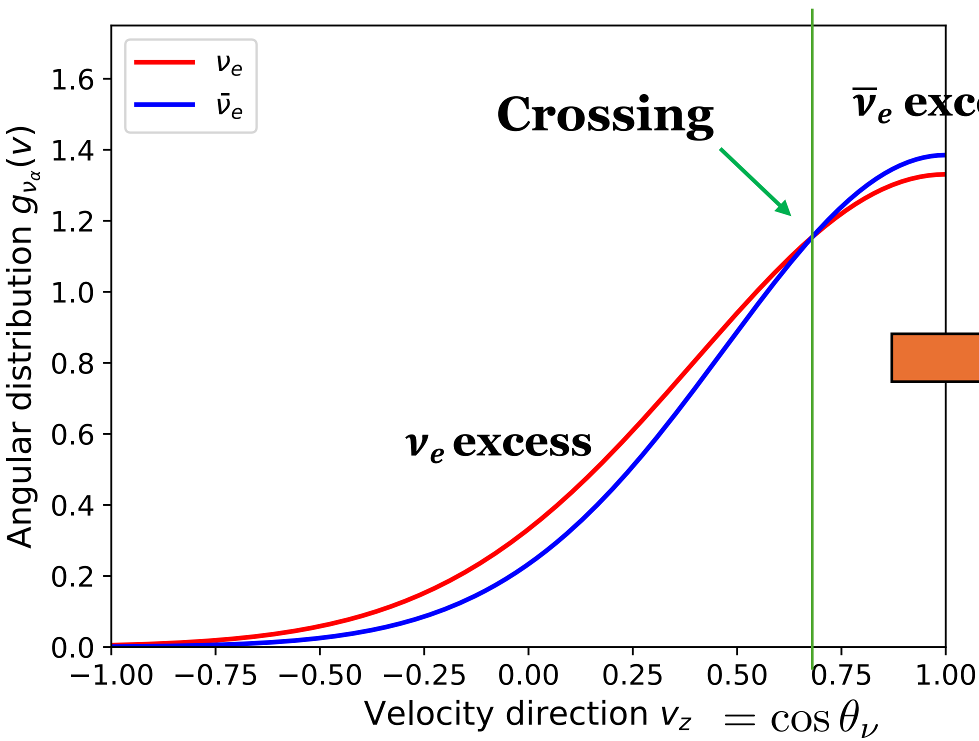
ELN-XLN angular distribution:

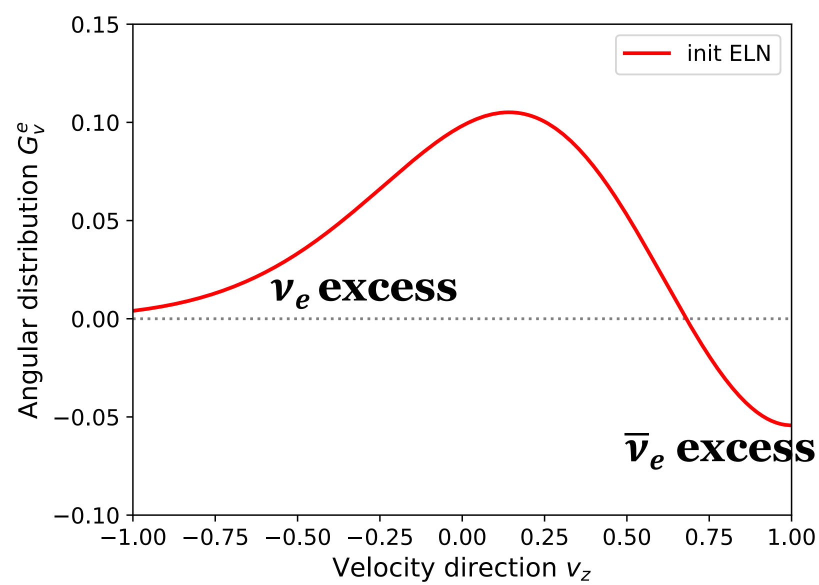
$$G_{\boldsymbol{v}}^{ex} = \sqrt{2}G_{\mathrm{F}} \int \frac{E^2 \mathrm{d}E}{2\pi^2} \left[(f_{\nu_e} - f_{\bar{\nu}_e}) - (f_{\nu_x} - f_{\bar{\nu}_x}) \right]$$

= **ELN** − **XLN**

(Electron Lepton Number) **(Heavy-Leptonic one)**

(= MuLN or TauLN)





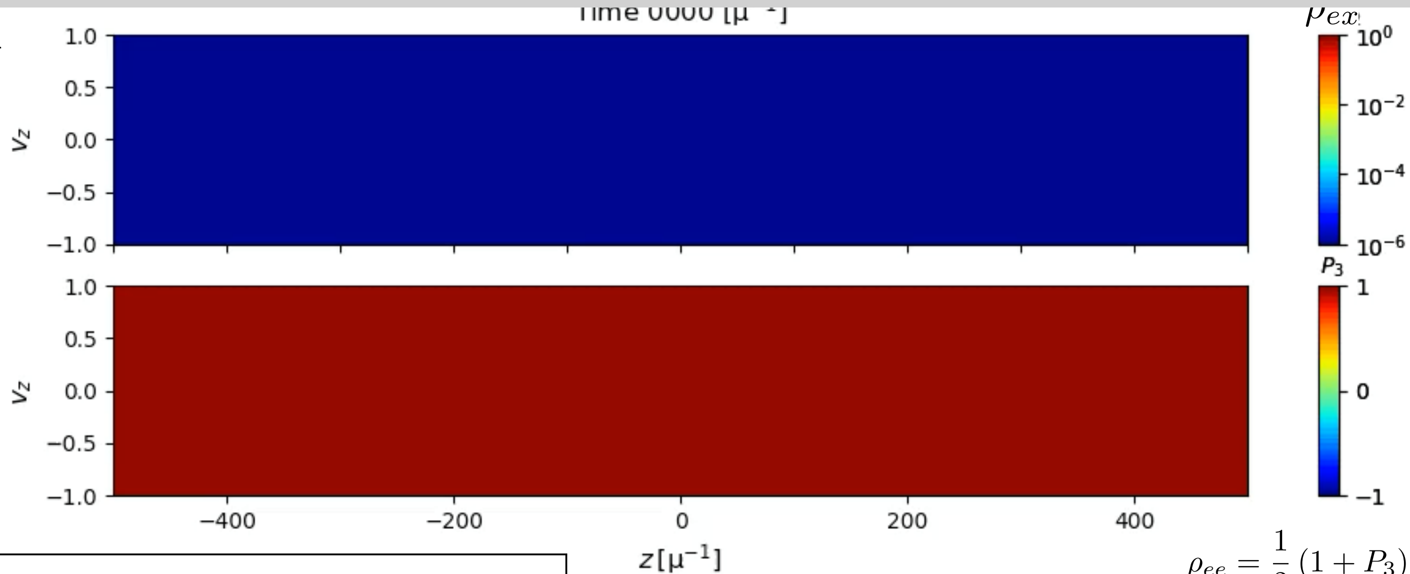
Local Simulation of Fast Instability

Flavor correlation

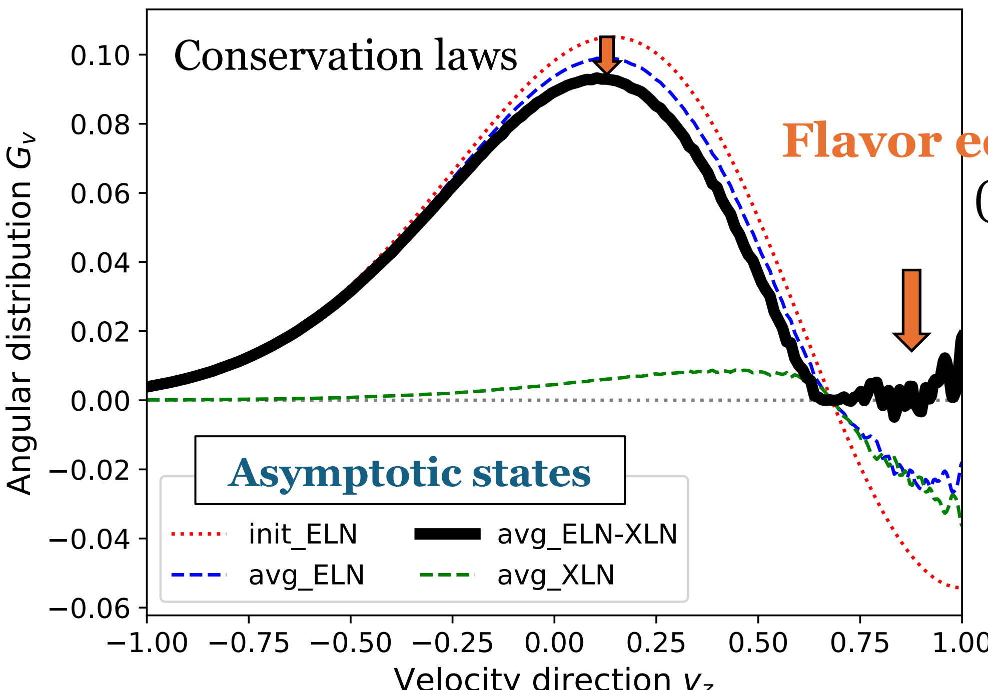
$$\langle \nu_e | \nu_X \rangle$$

Flavor content

$$\langle \nu_e | \nu_e \rangle - \langle \nu_X | \nu_X \rangle$$



$$\rho_{ee} = \frac{1}{2}(1 + P_3)$$



Flavor equipartition is established.

(= stability condition, can be modelled)

$$(f_{\nu_e} - f_{\bar{\nu}_e}) - (f_{\nu_X} - f_{\bar{\nu}_X})$$

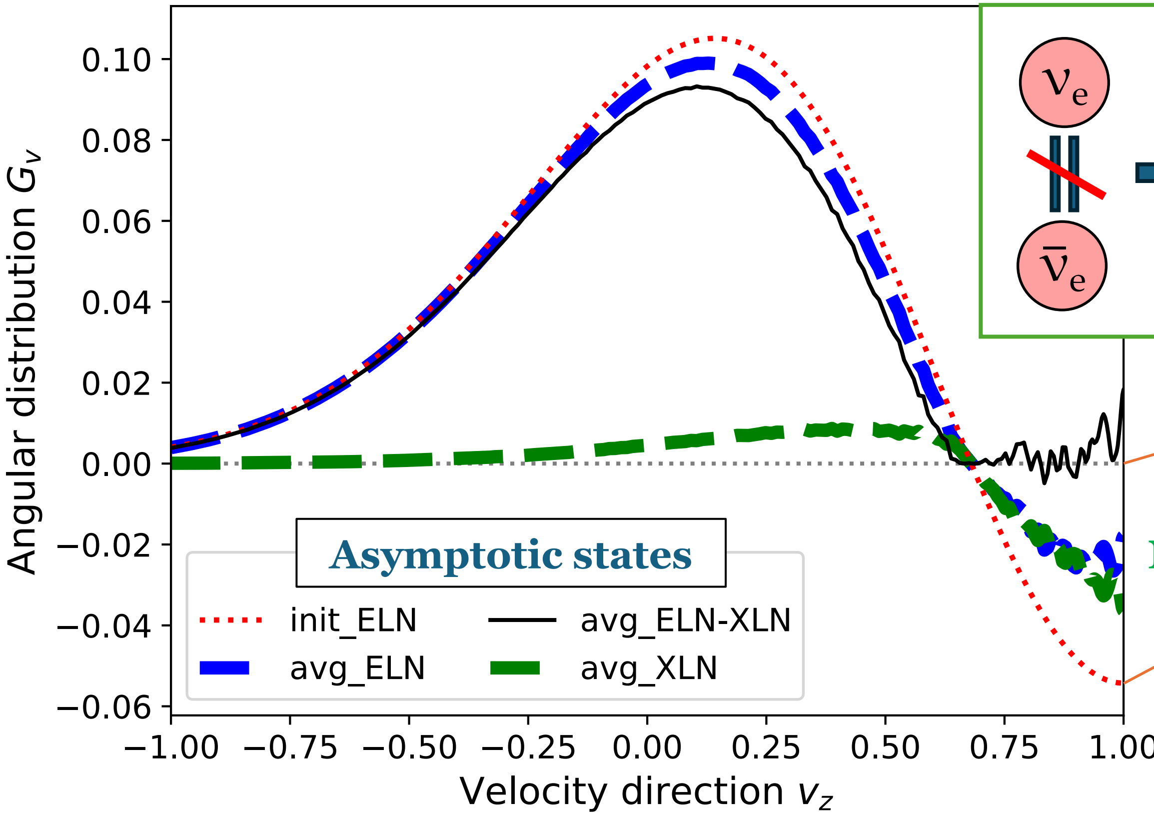
ELN – XLN angular dist.

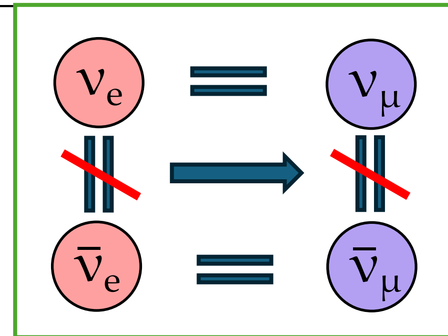
Rich angular structure!

Not just equipartition

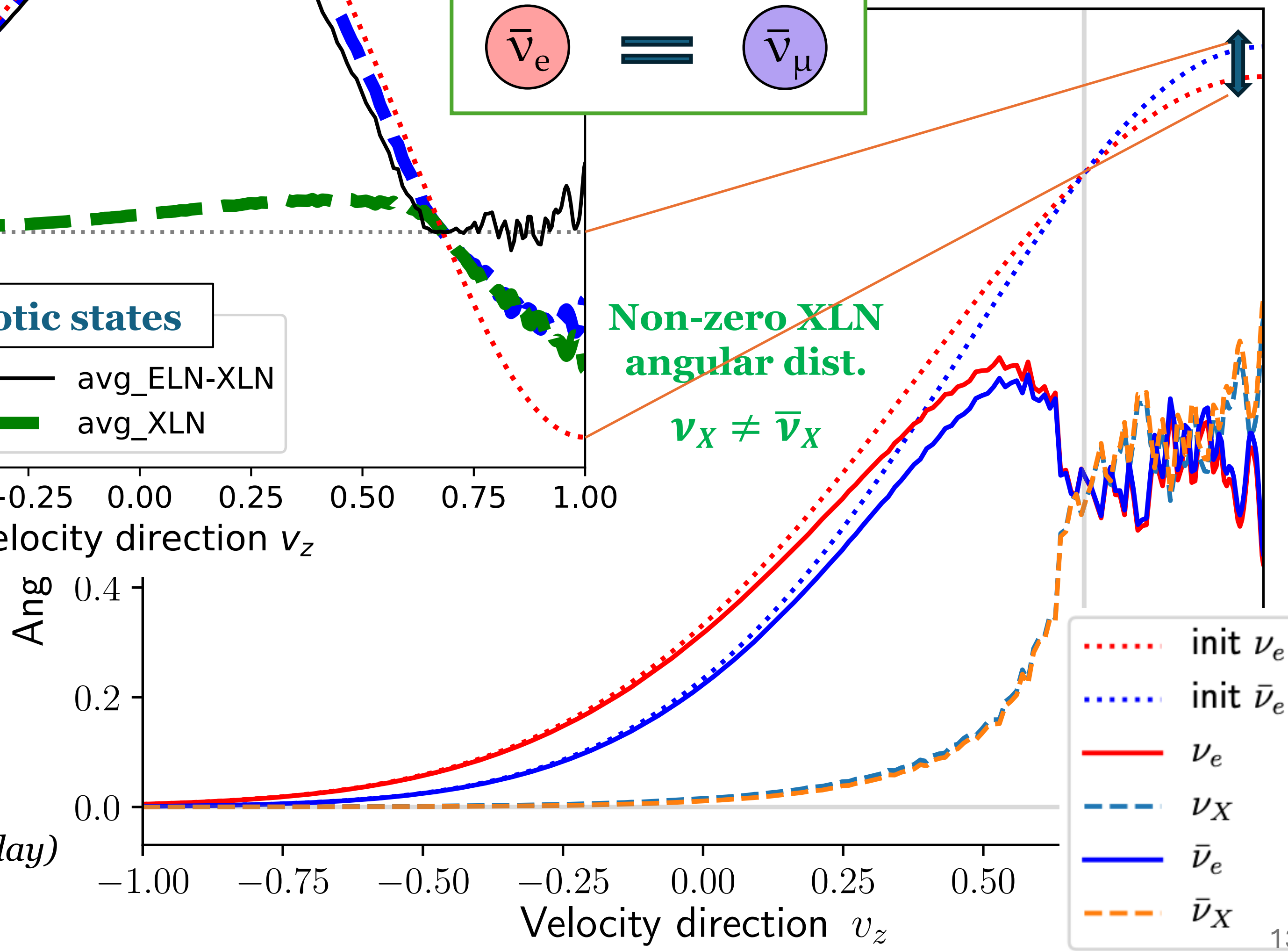
MZ & Nagakura PRD '23

Note: Flavor Equipartition for Species?





Flavor Equipartition



Non-zero XLN angular dist.

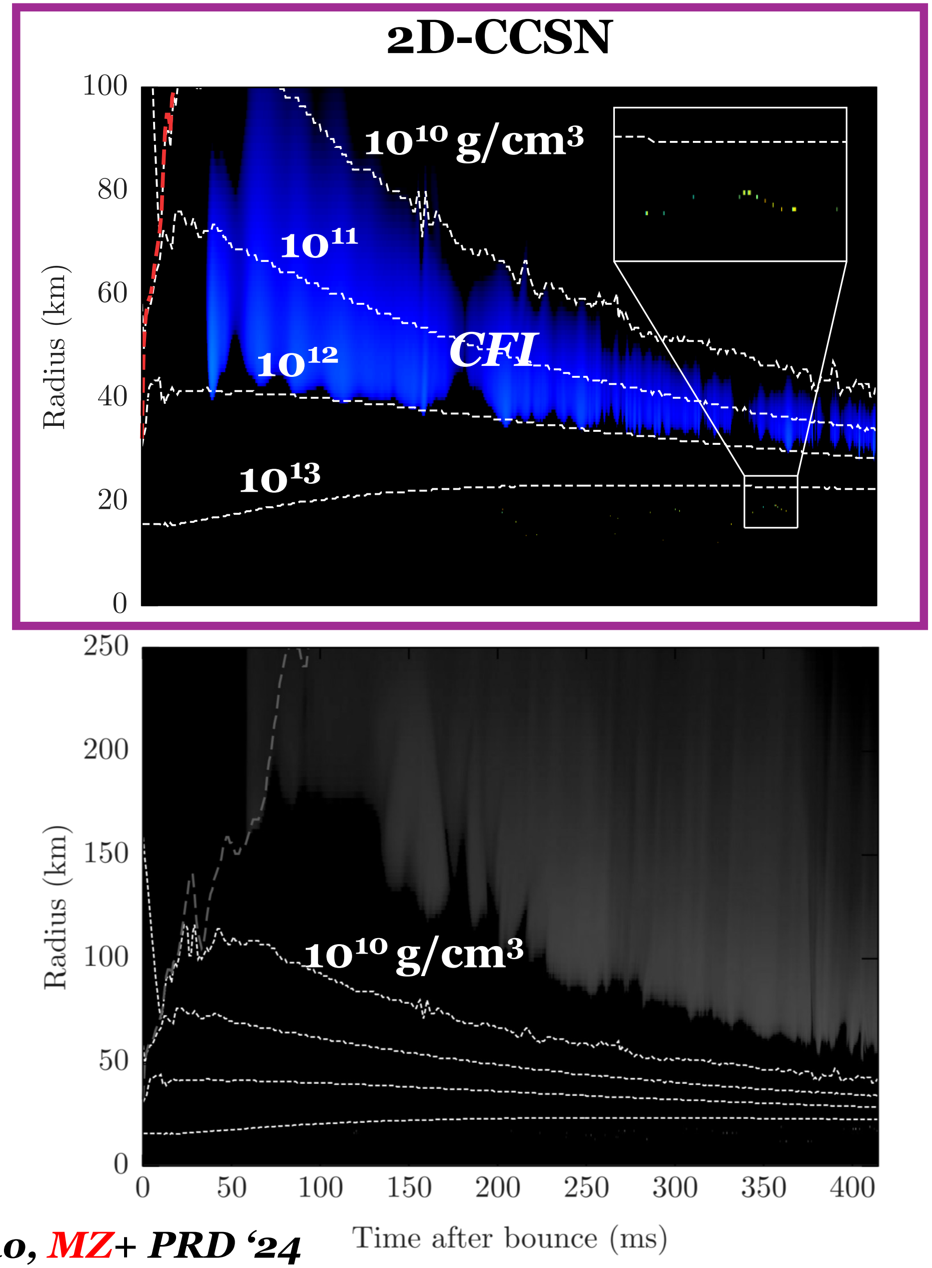
$\nu_X \neq \bar{\nu}_X$

***Four-* or *Six*-species are necessary in flavor conversion.**

See Akaho's talk (1st day)

MZ & *Nagakura PRD '23*

Possibility Search of Flavor Conversion



Mechanism of instability:
- Asymmetry in collisions

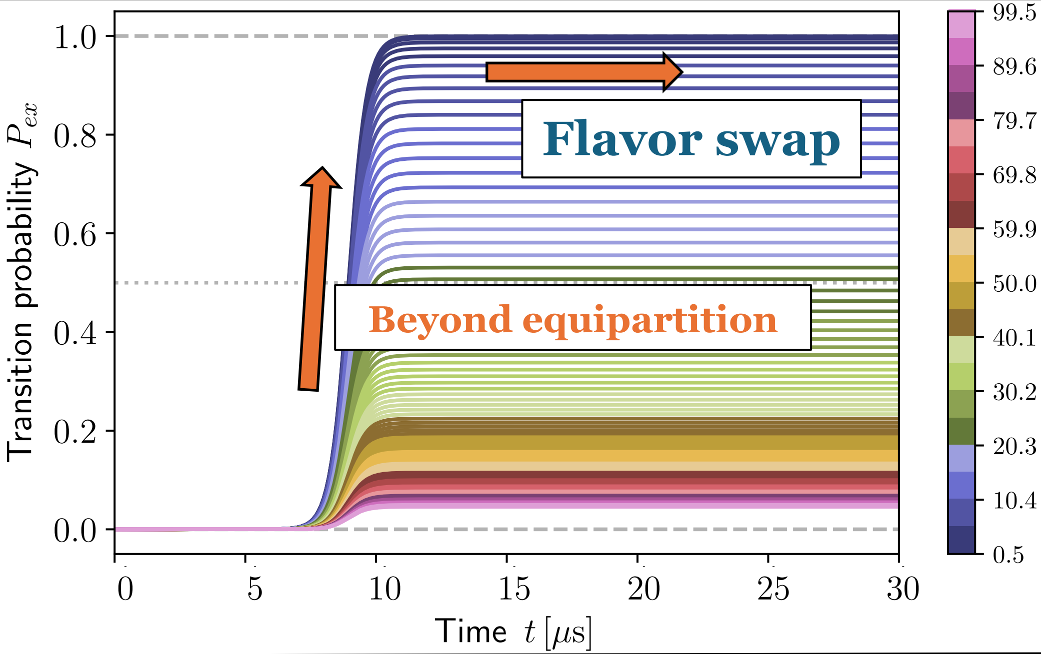
Neutrino distribution
- Inside/Outside PNS
- Close to isotropic

→ **Energy dist. is crucial.**

Collisional flavor instability (CFI)

Akaho, MZ+ PRD '24

Local Simulation of Collisional Instability



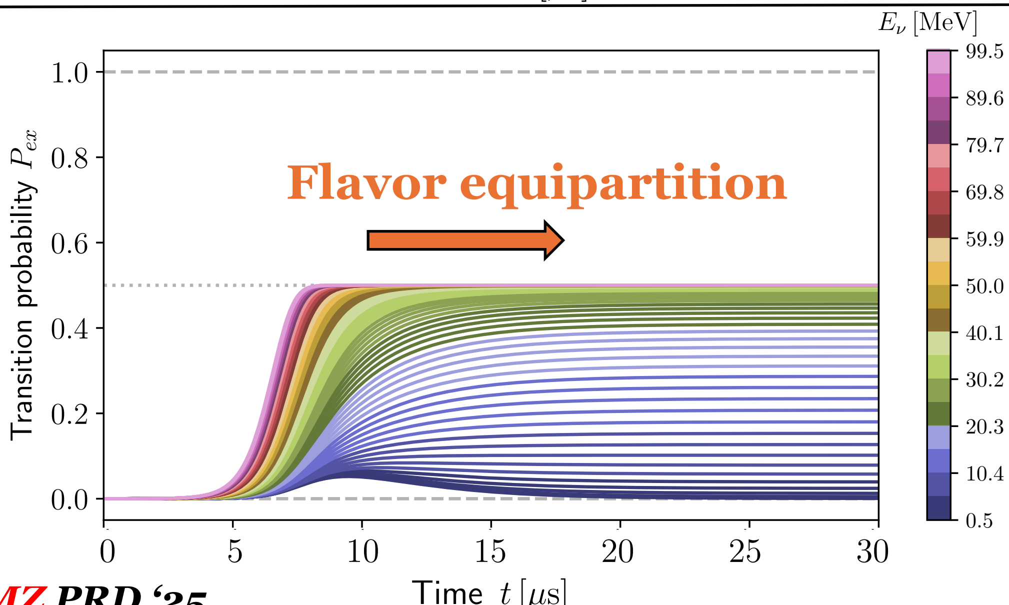
Case 1:

$$n_{\nu_e} > n_{\bar{\nu}_e}$$
$$\langle R_E \rangle > \langle \bar{R}_E \rangle$$

Same *Hierarchy*

$$(\bar{R}_E = 0.1 R_E) \quad Y_e \sim 0.1$$

$\langle R_E \rangle$: Averaged reaction rates for neutrinos



Case 2:

$$n_{\nu_e} > n_{\bar{\nu}_e}$$
$$\langle R_E \rangle < \langle \bar{R}_E \rangle$$

Twisted *Hierarchy*

$$(\bar{R}_E = R_E) \quad Y_e \sim 0.5$$

Rich spectral diversity!

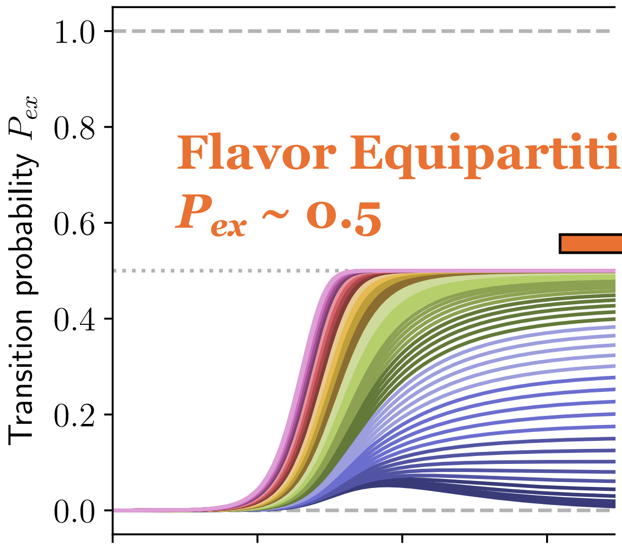
Not just equipartition

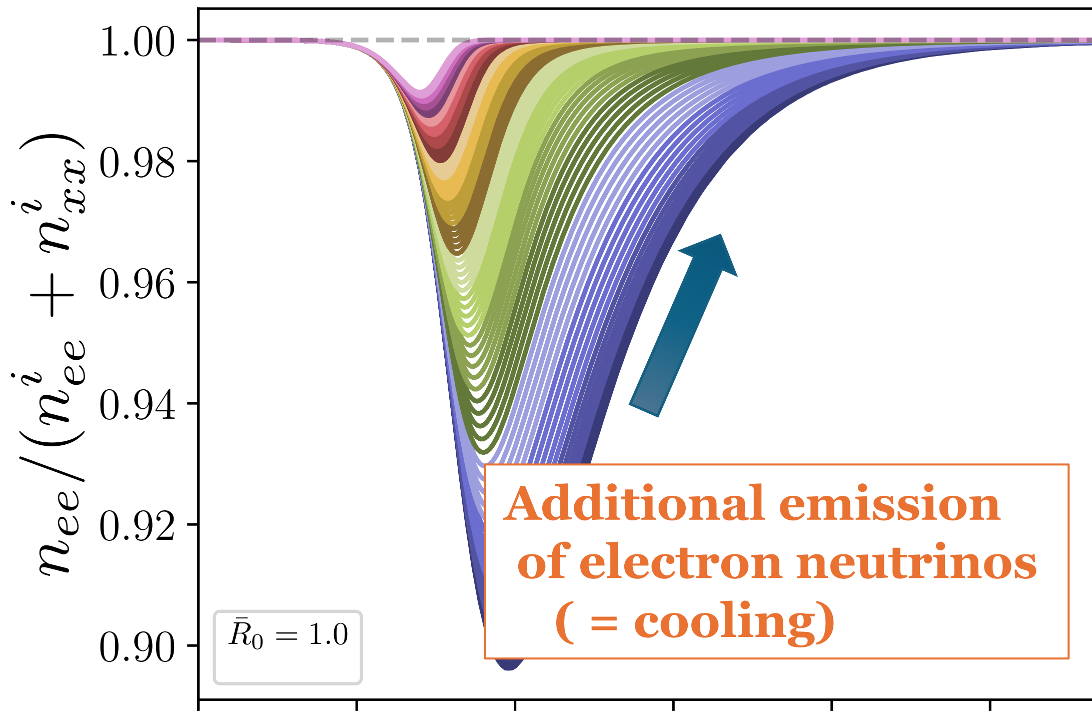
MZ ***PRD ‘25***

+ Classical β-Equilibrium (Feedback)

Case 2:

CFI can occur
near the neutrino sphere.
~ β-equilibrium with matter





$$n + e^+ \leftrightarrows p + \bar{\nu}_e$$

$$p + e^- \leftrightarrows n + \nu_e$$

Summary & Conclusions

1. Refractive effects from background matter can lead to non-negligible flavor conversion phenomena.

2. ***Neutrino flavor conversion can alter*** not only ***shock dynamics*** and neutrino signals ***but also GW signals*** from CCSN.

3. Direct computation of **fast**/**collisional** **flavor conversion** exhibits the angular / energy structure of the asymptotic states.

4. ***More accurate modeling of "Neutrino Flavor Conversion" into CCSN is running!!***