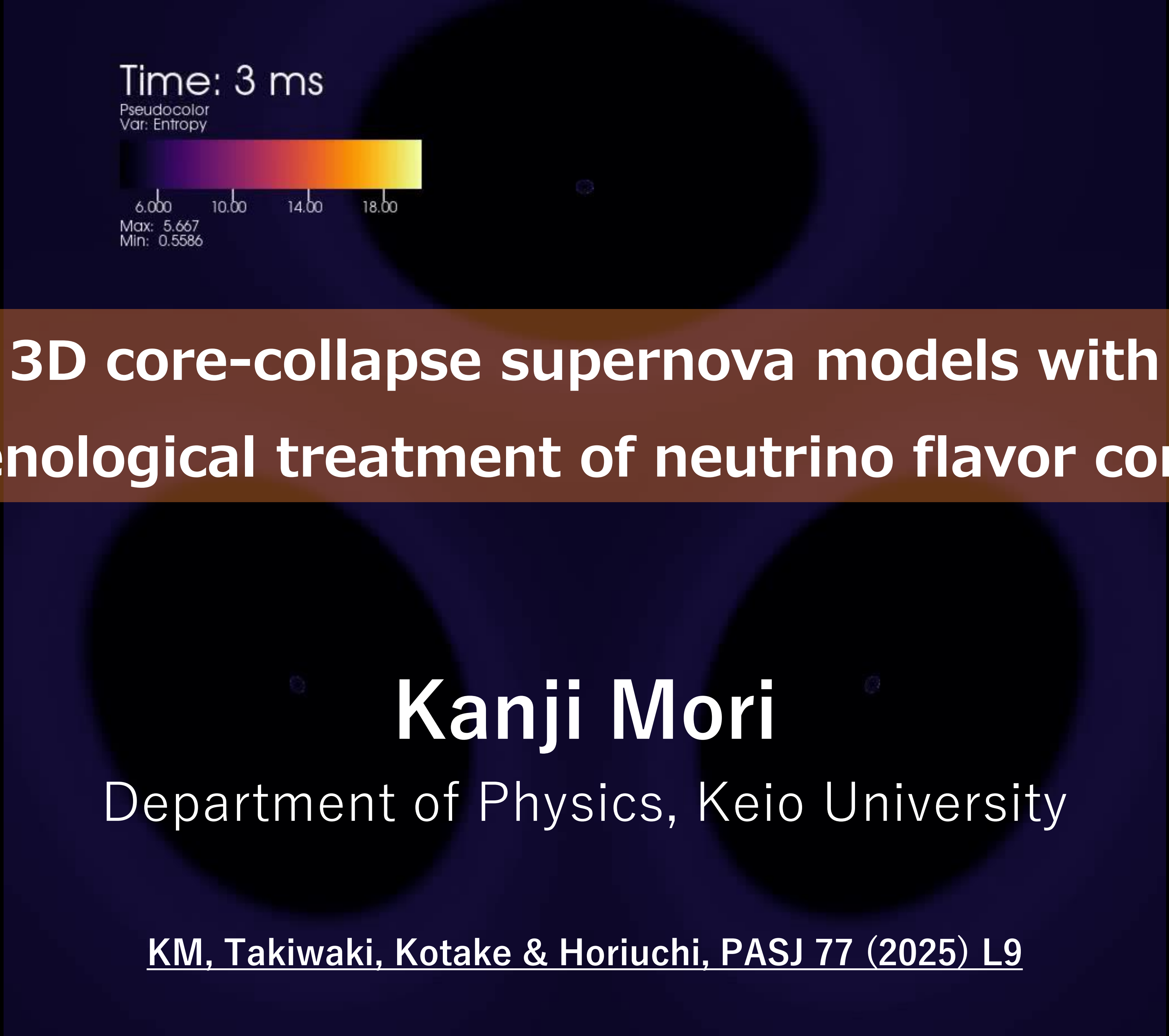


3D core-collapse supernova models with phenomenological treatment of neutrino flavor conversions

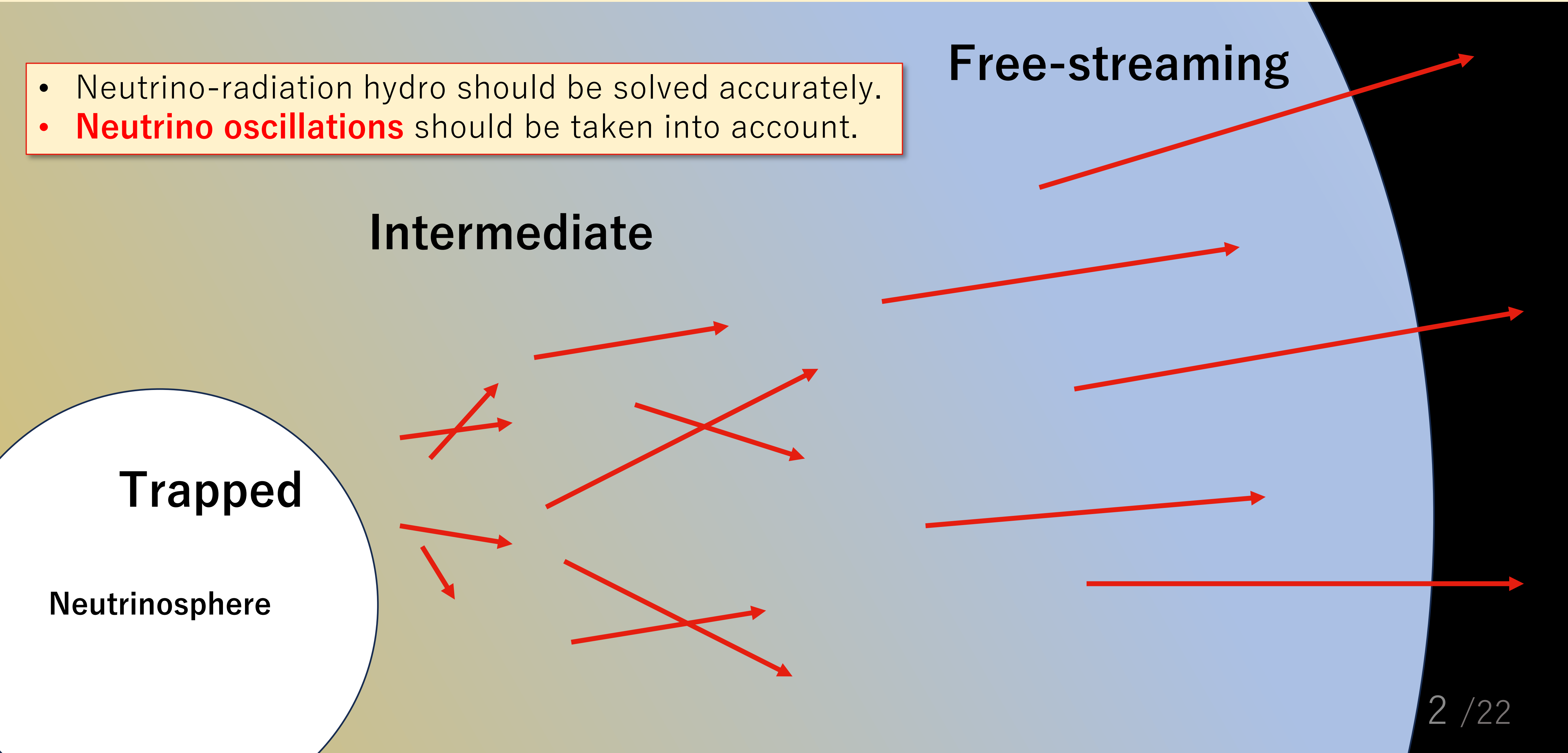
Kanji Mori

Department of Physics, Keio University

KM, Takiwaki, Kotake & Horiuchi, PASJ 77 (2025) L9

Numerical Challenges for Supernova Simulations

- Neutrino-radiation hydro should be solved accurately.
- **Neutrino oscillations** should be taken into account.



Neutrino Oscillations in Supernovae

Quantum kinetic equation

$$i(\partial_t + \mathbf{v} \cdot \nabla)\rho = [H_{\rm vac} + H_{\rm mat} + H_{\nu\nu},\ \rho] + iC$$

Density matrix (ρ) — Neutrino self-interaction ($H_{\nu\nu}$) — Collisional term (iC)

Instabilities caused by the self-interaction

- **Slow instability** [e.g. Duan et al., PRL 97 (2006) 241101]

  -Induced by energy crossing for ν and $\bar{\nu}$ distributions

- **Fast instability** [e.g. Sawyer PRD 72 (2005) 045003]

  -Induced by angular crossing for ν and $\bar{\nu}$ distributions

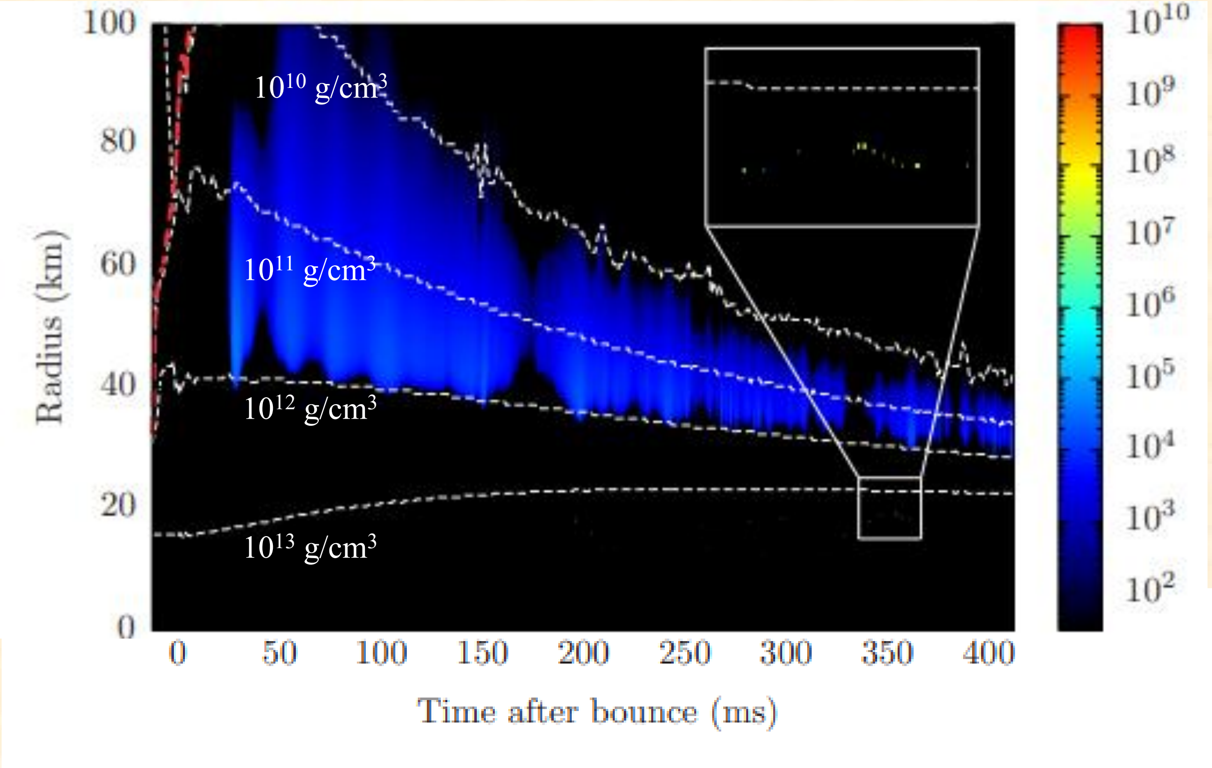
- **Collisional instability** [e.g. Johns PRL 130 (2023) 191001]

  -Induced by different reaction rates for ν and $\bar{\nu}$

Neutrino Flavor Instabilities

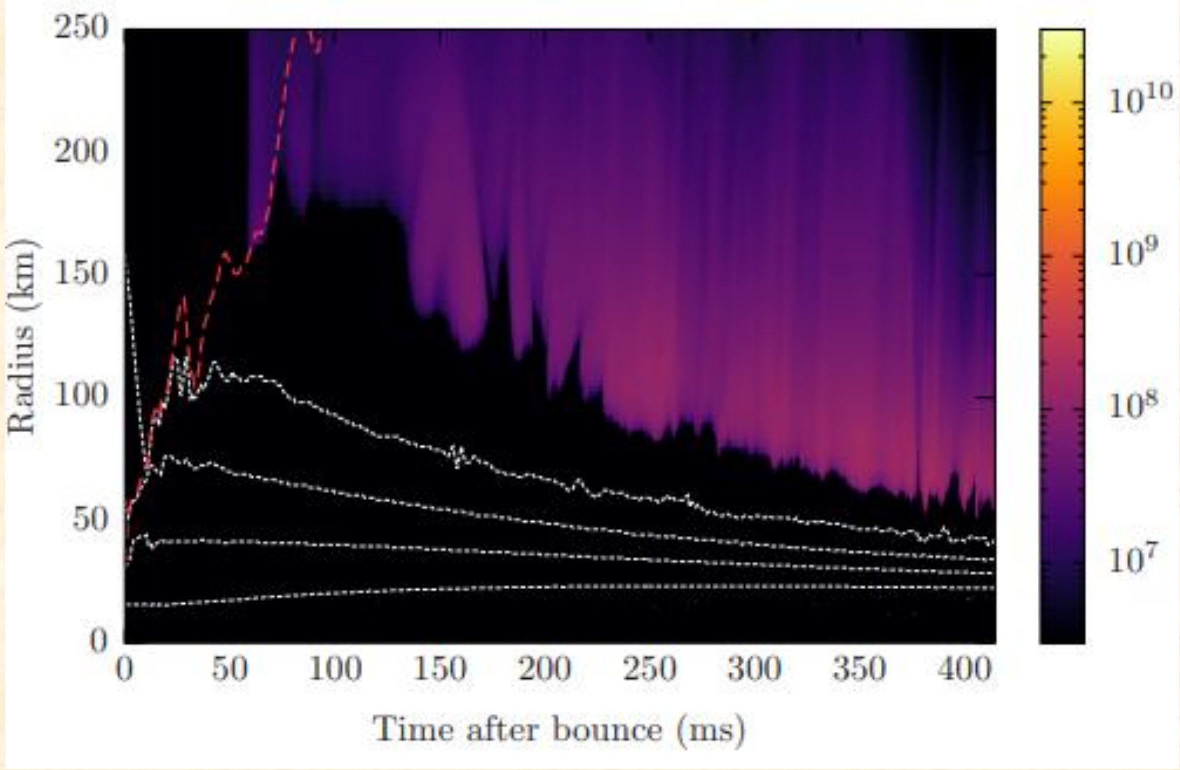
Collisional flavor instability (CFI)

Induced by different reaction rates for ν_e and $\bar{\nu}_e$



Fast flavor instability (FFI)

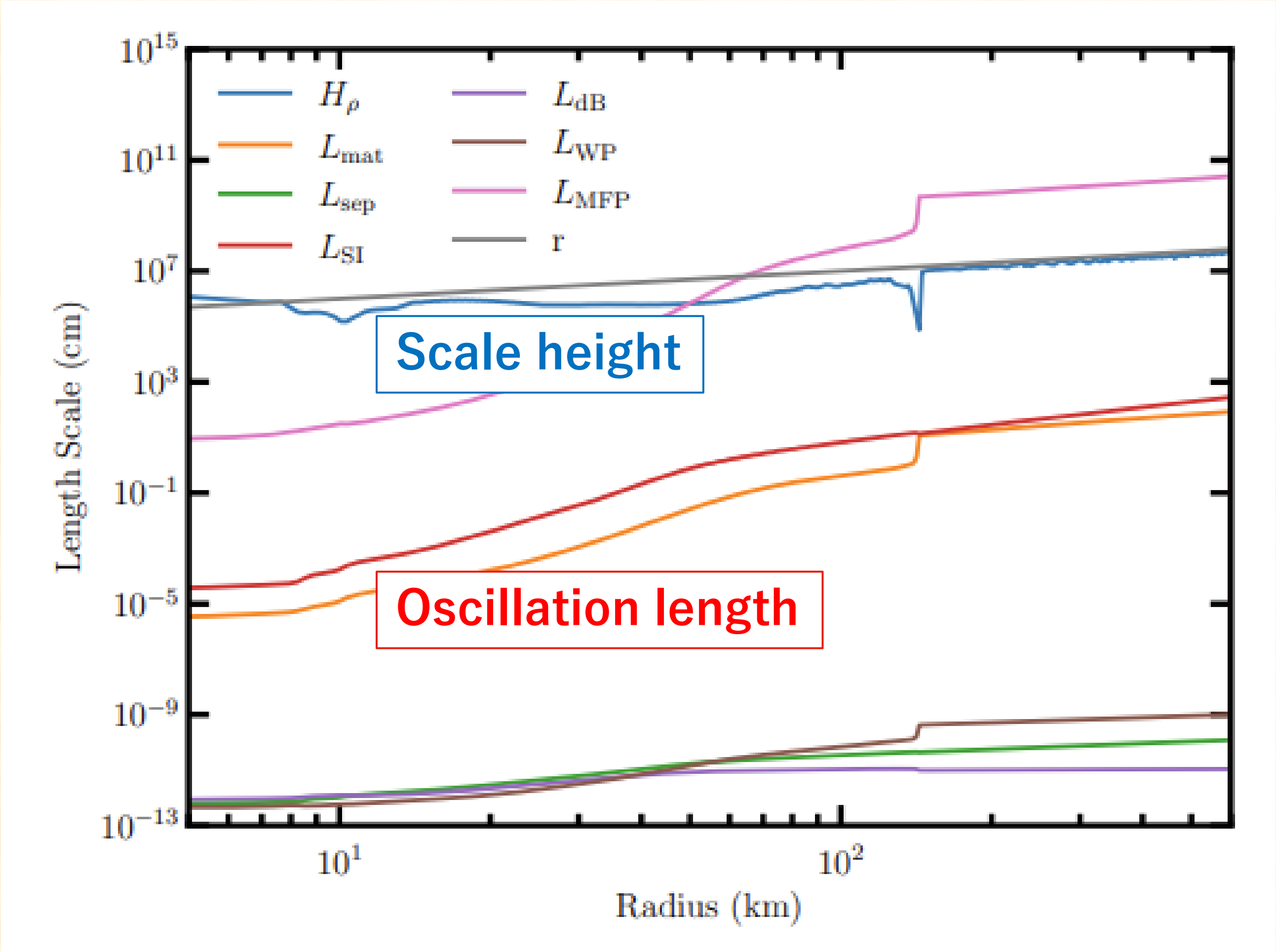
Induced by angular crossing in ν_e and $\bar{\nu}_e$ distributions



Akaho et al., PRD 109 (2024) 023012

Collective oscillations do appear in SN.
→Simulations with CFI/FFI are needed!

Difficulty in Simulating Oscillations



Johns, Richers & Wu, ARNPS, 75 (2025) 399.

$$L_{\rm SI} = (\sqrt{2} G_F n_{\nu_e})^{-1}$$

: Length scale for the collective oscillations

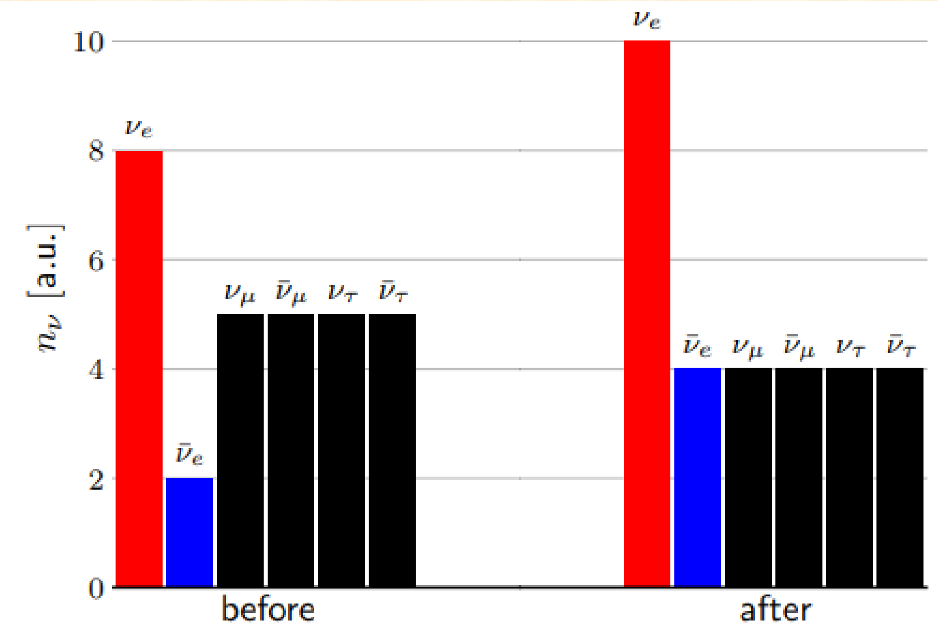
It is difficult to resolve the oscillation length scale in ν-radiation hydro simulations

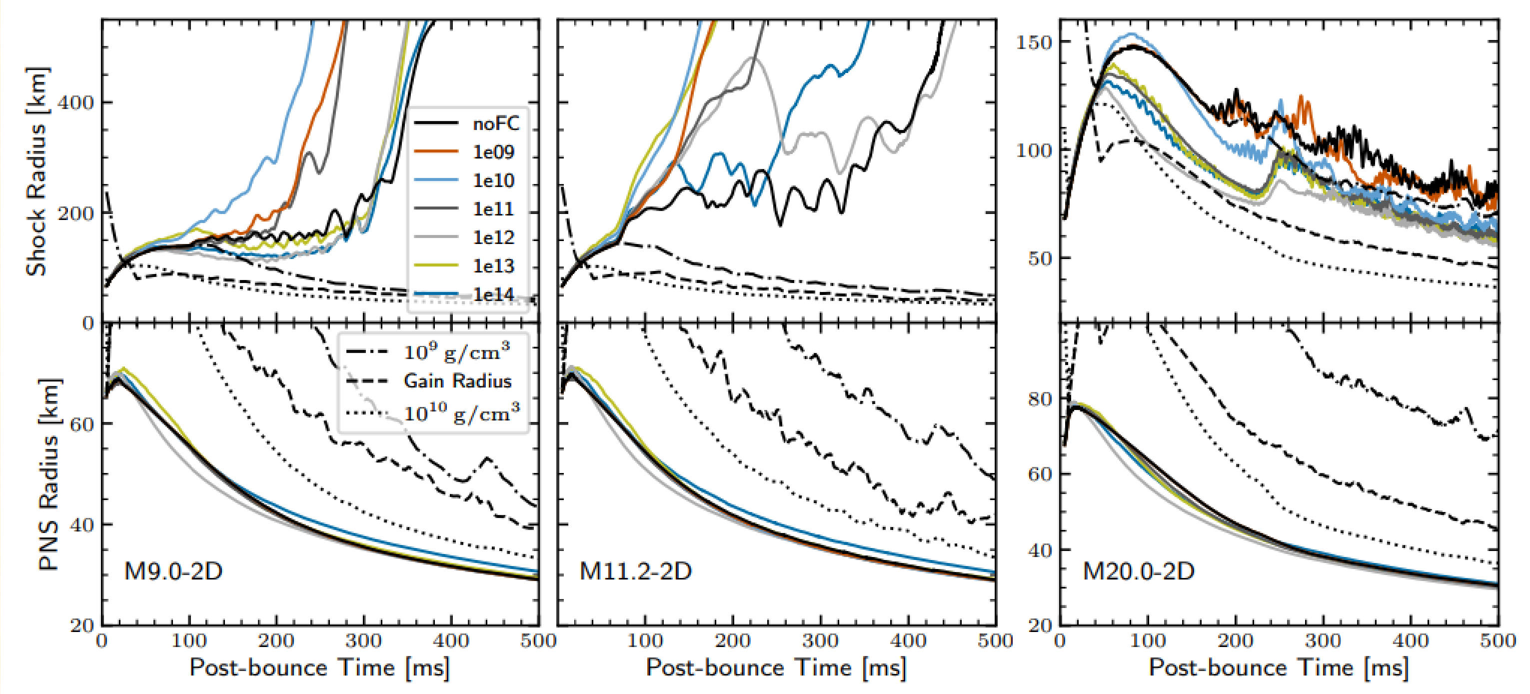
→ **Need for phenomenological / sub-grid treatment**

Phenomenological treatment for flavor conversions

Assumption [Ehring et al., PRL 131 (2023) 061401; PRD 107 (2023) 103034]

1. Collective oscillations happens when $\rho < \rho_{\text{crit.}}$
   - ρ_{crit} is treated as a free parameter.
2. Collective oscillations realize **flavor equipartition**.





3D sim. with phenomenological treatment for flavor conversions

Assumption

[Ehring et al., PRL 131 (2023) 061401; PRD 107 (2023) 103034]

1. Collective oscillations happen when $\rho < \rho_{\text{crit.}}$
   - ρ_{crit} is treated as a free parameter.
2. Collective oscillations realize **flavor equipartition.**

Setup

[KM, Takiwaki, Kotake & Horiuchi, PASJ 77 (2025) L9]

Code: 3DnSNe [Takiwaki, Kotake & Suwa MNRAS 461 (2016) L112]

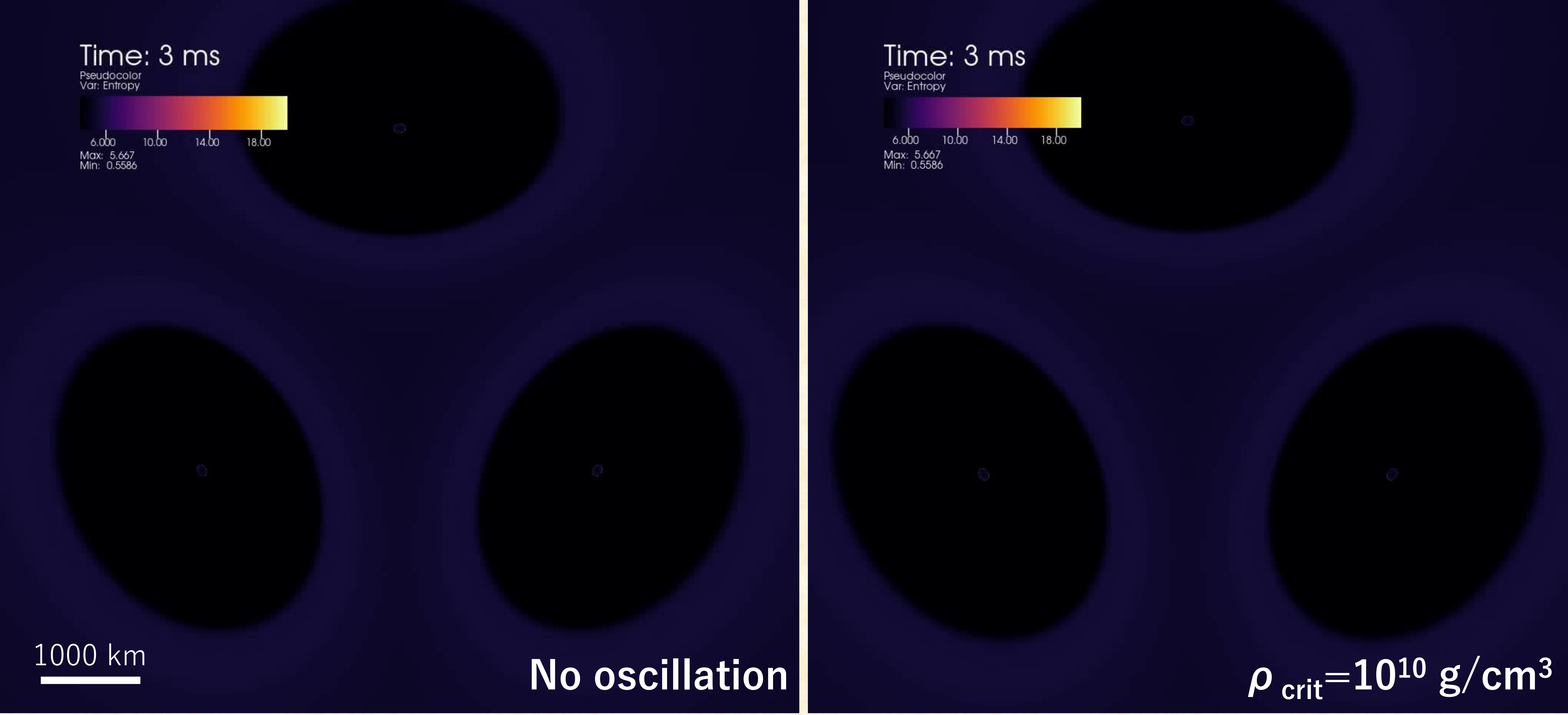
Dimension: **3D**

ν-transport: 3-flavor IDSA [Liebendörfer, Whitehouse, & Fischer ApJ 698 (2009) 1174]

Progenitor: **$11.2 M_\odot$** [Woosley, Heger & Weaver, RMP, 74 (2002) 1015]

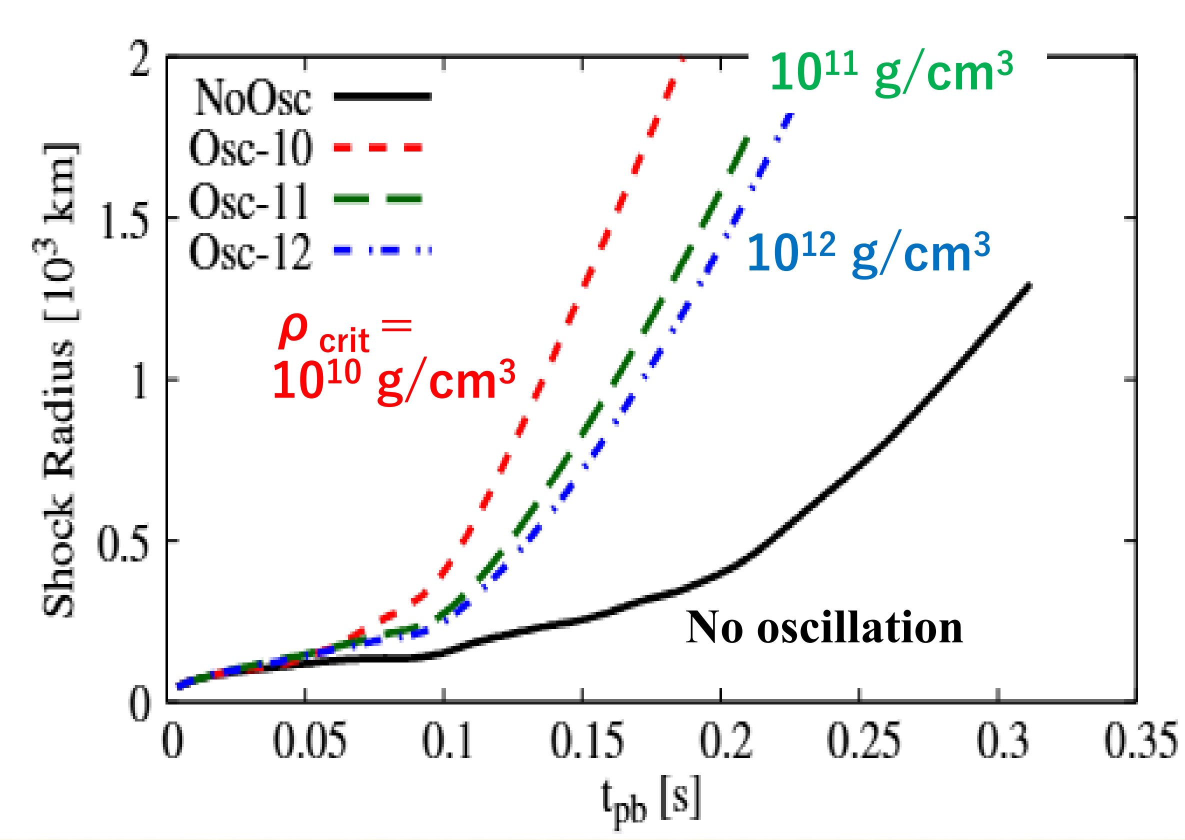
Resolution: $512 \times 64 \times 128$ EoS: LS220

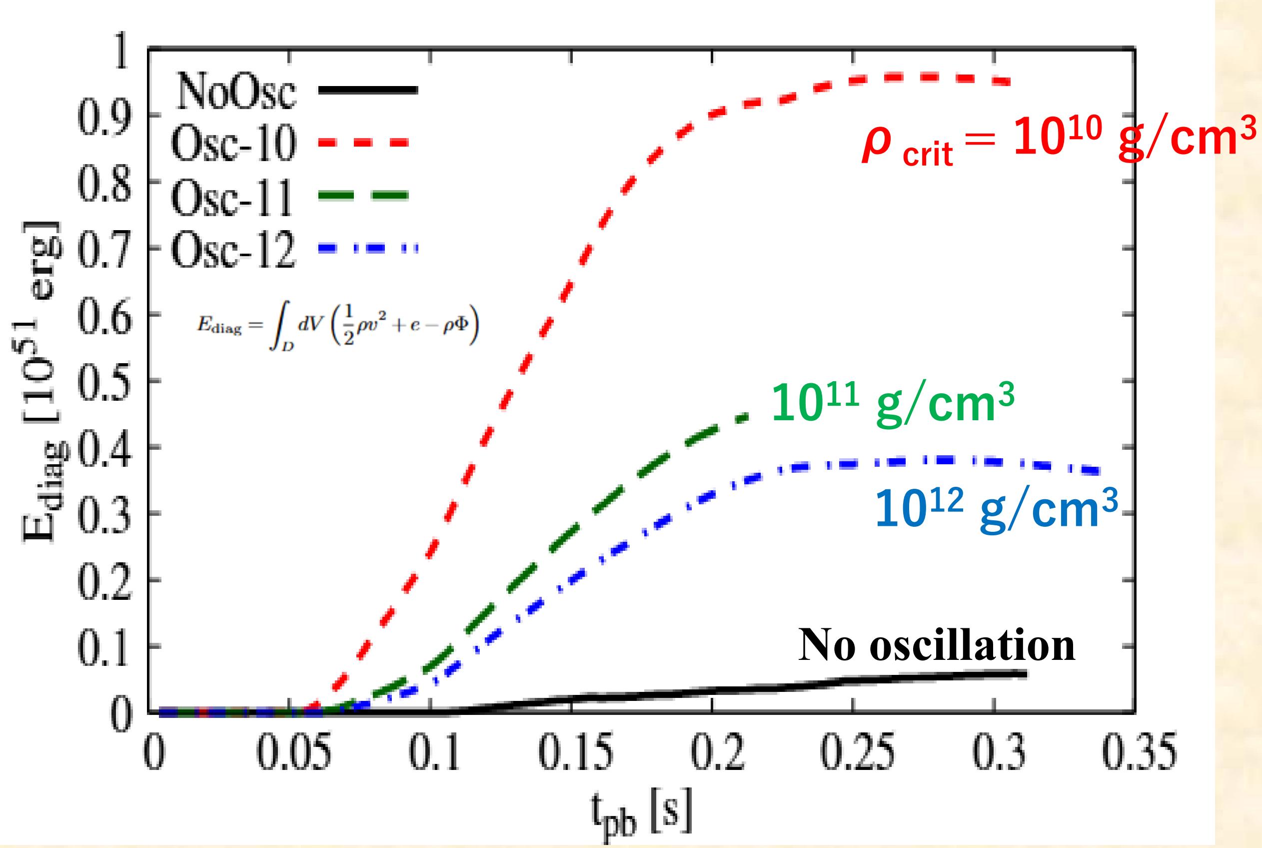
ρ_{crit}: 10^{10}, 10^{11}, 10^{12} g/cm^3



Flavor conversions can help SN explosion!

Explosion Properties

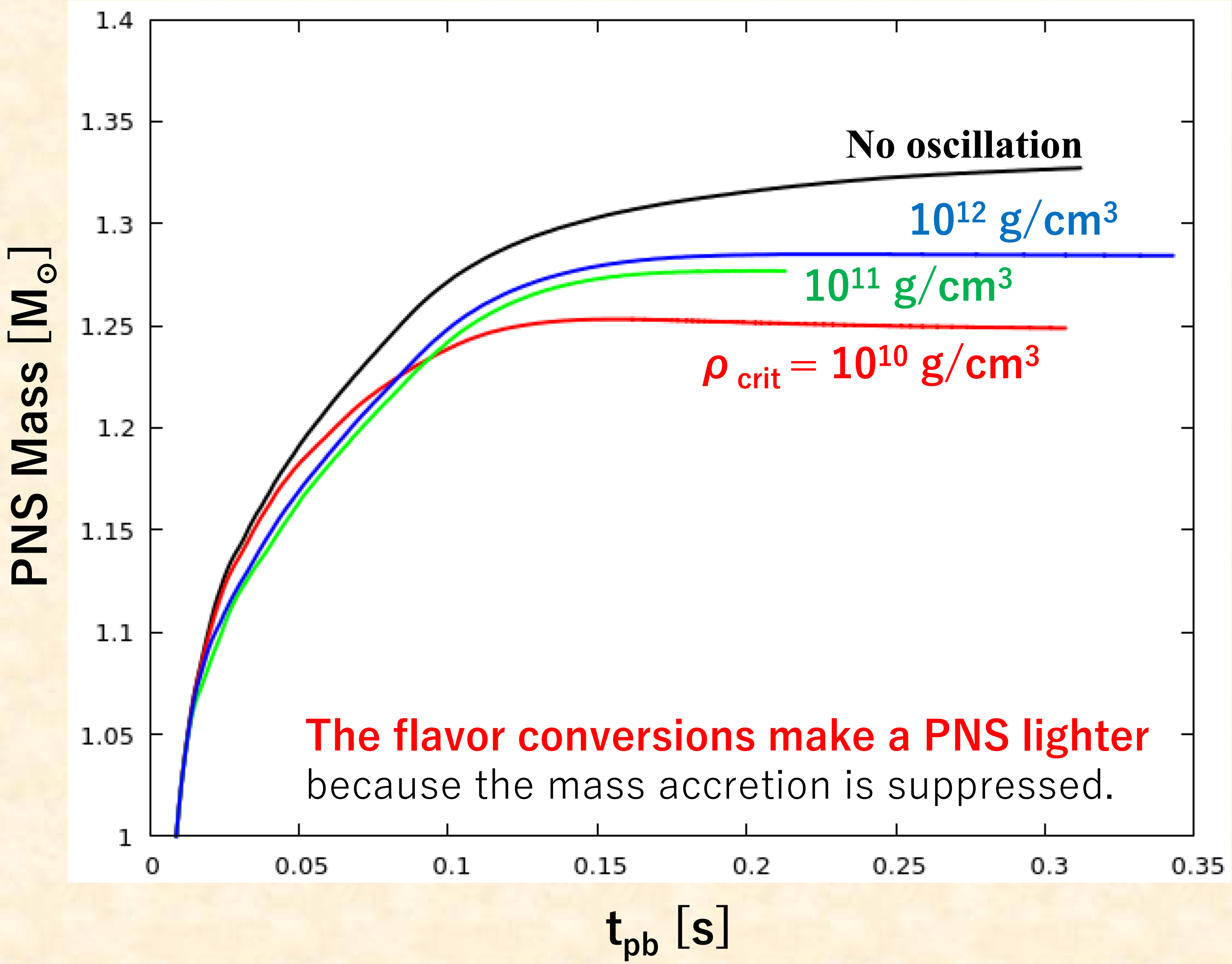




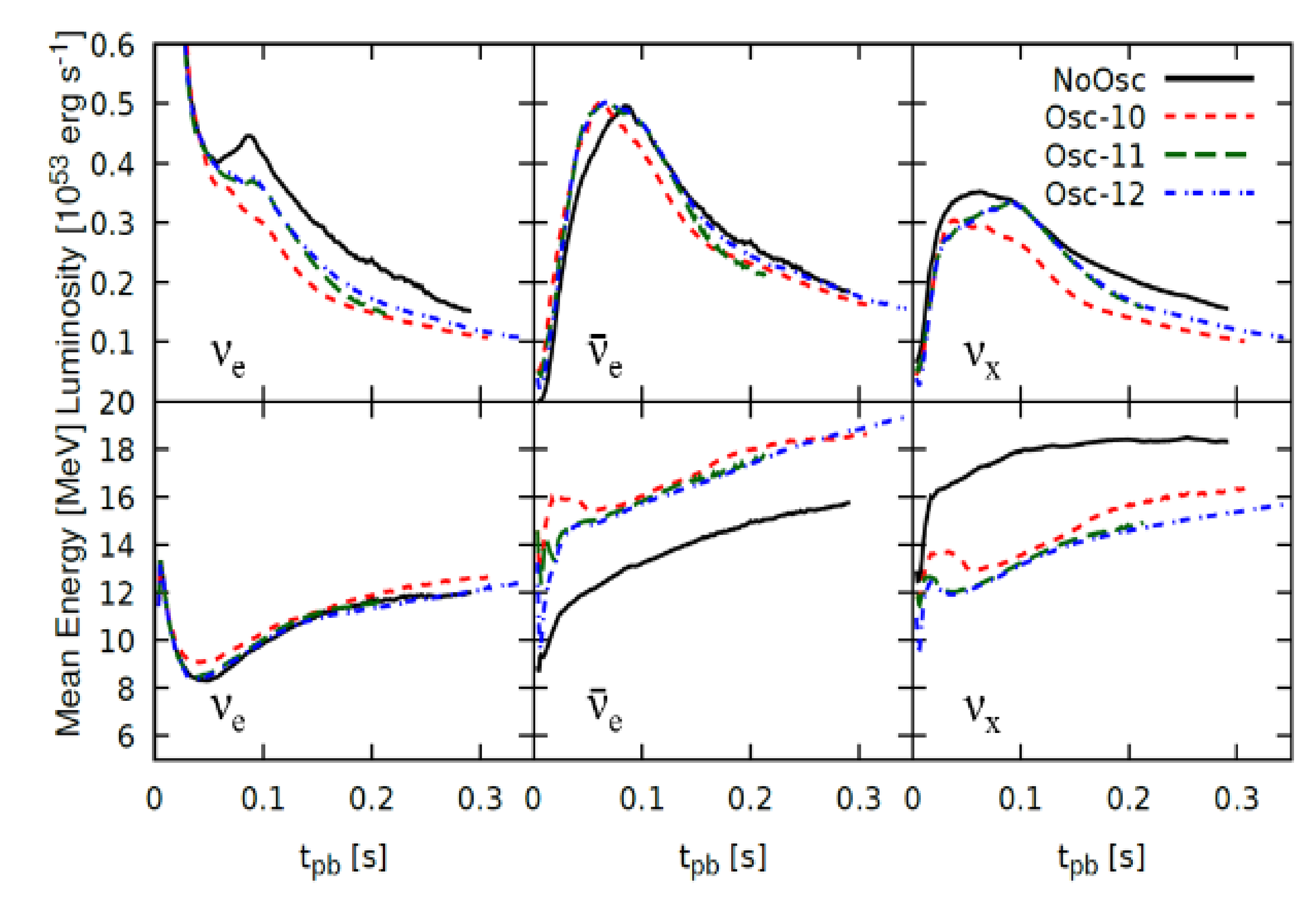
KM, Takiwaki, Kotake & Horiuchi, PASJ 77 (2025) L9

- ✓ Shock revival happens earlier.
- ✓ Explosion energy is enhanced.

Protoneutron Star Mass



Neutrinos



KM, Takiwaki, Kotake & Horiuchi, PASJ 77 (2025) L9

- Energy hierarchy changes:

$\langle E(\nu_e)\rangle < \langle E(\bar{\nu}_e)\rangle < \langle E(\nu_x)\rangle$

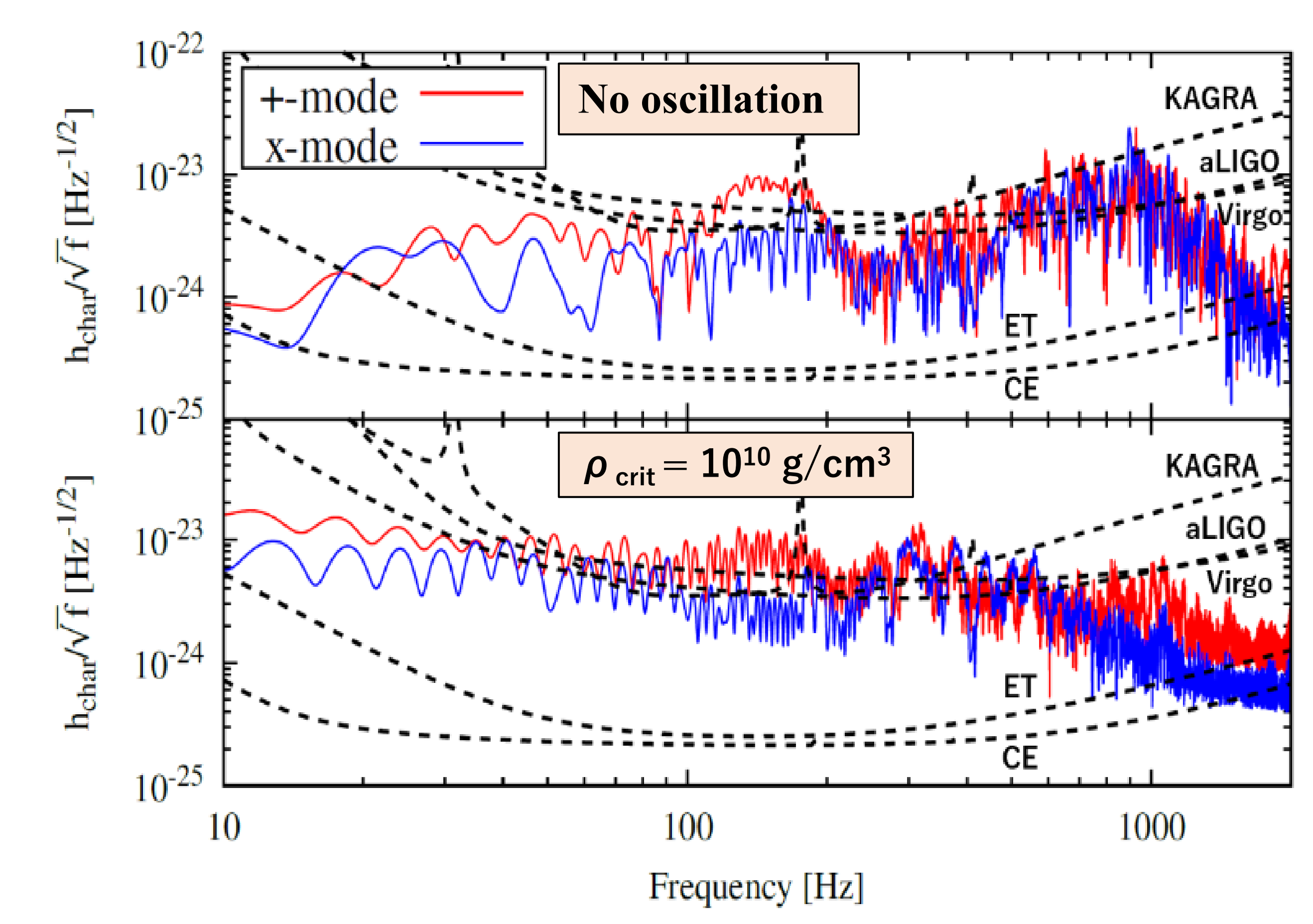
⬇

$\langle E(\nu_e)\rangle < \langle E(\nu_x)\rangle < \langle E(\bar{\nu}_e)\rangle$

- **$\nu_x \rightarrow \nu_e, \bar{\nu}_e$ enhances the neutrino heating rate**

Gravitational Waves

SN event located at the Galactic Center

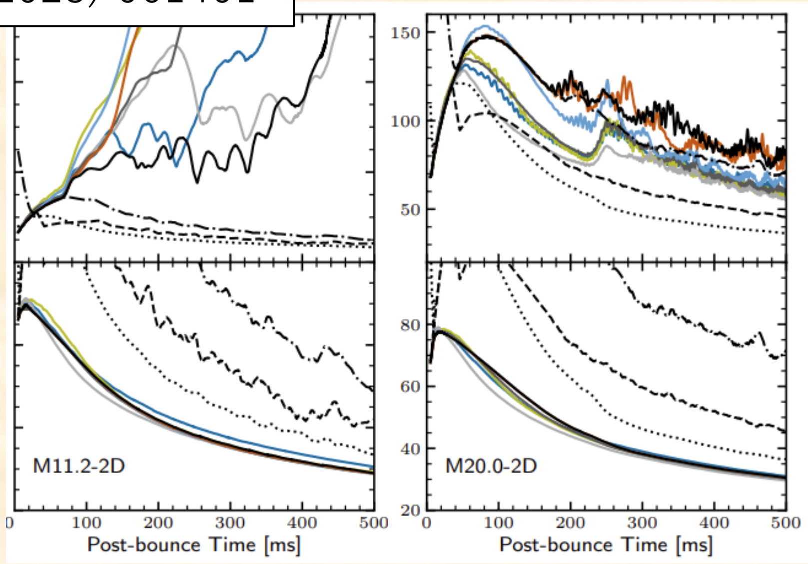


KM, Takiwaki, Kotake & Horiuchi, PASJ 77 (2025) L9

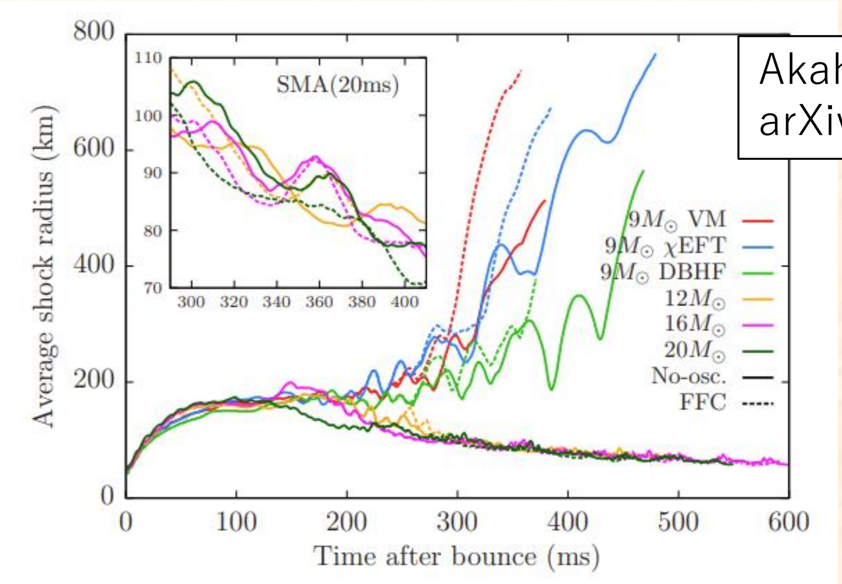
- kHz GW is weakened because the mass accretion is suppressed.
- Low-frequency GW is more prominent because of explosion asymmentry.

Progenitor Dependence

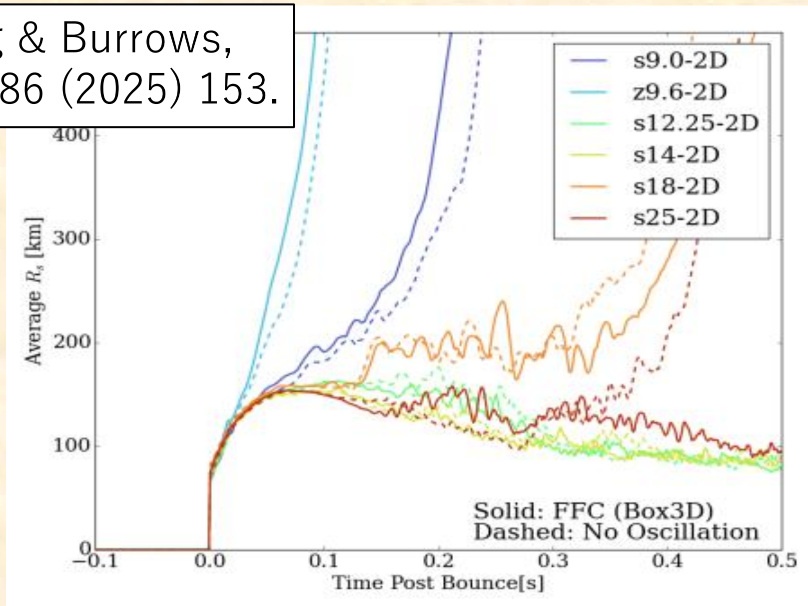
Ehring et al., PRL 131 (2023) 061401



Akaho et al. (2026), arXiv:2601.08269



Wang & Burrows, ApJ 986 (2025) 153.



Fast flavor conversion may

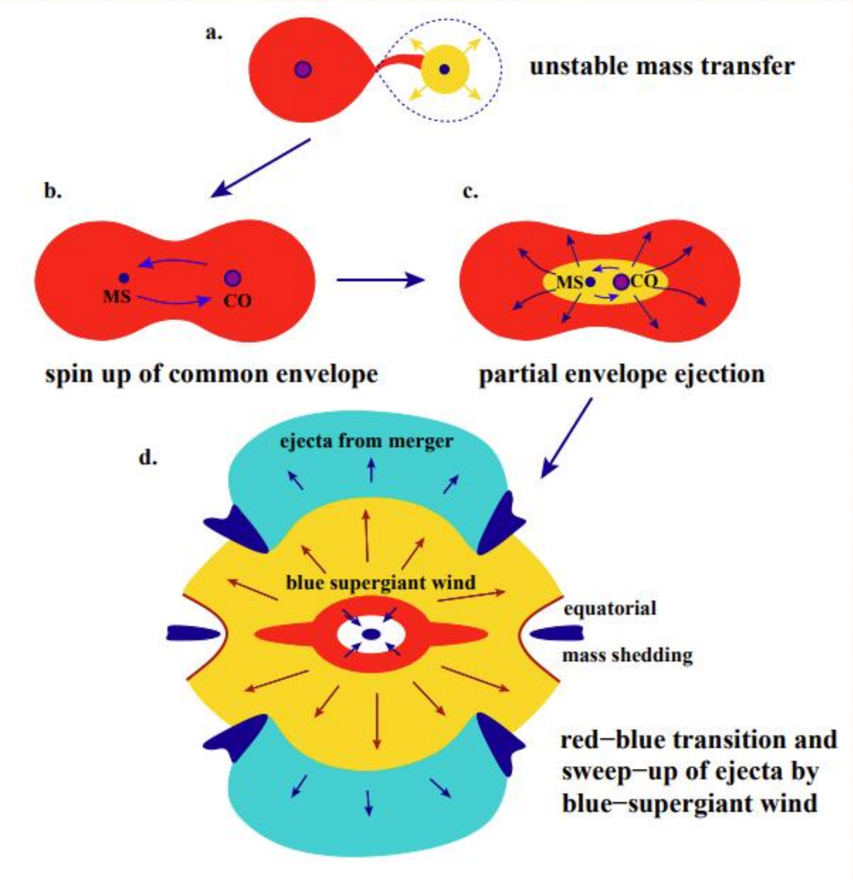
- **help** explosion for lighter stars (?)
- **hinder** explosion for heavier stars (?)

-> What happens in 3D models?

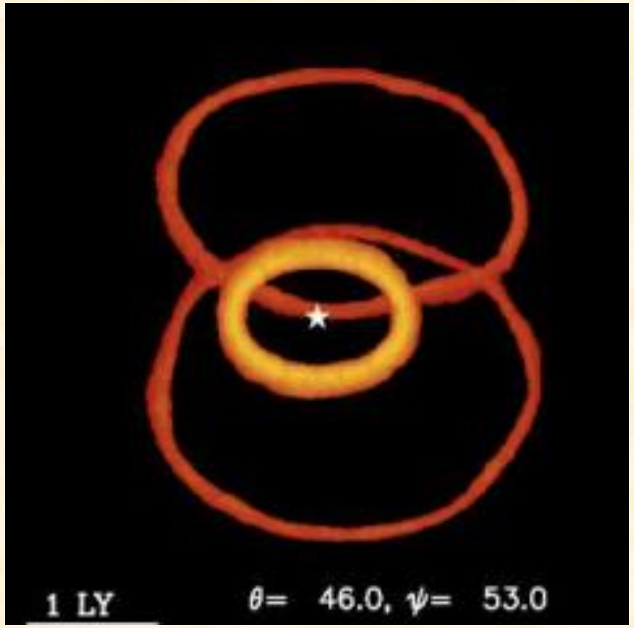
SN 1987A Progenitor Model

[Morris & Podsiadlowski, Nature 315 (2007) 1103]

Ring-like structure in SN 1987A can be reproduced by **a merger** of two stars which happened ~20 kyr before the explosion.



Simulations



Observation

©Dr. Christopher Burrows, ESA/STScI and NASA

SN 1987A Progenitor Model

[Urushibata et al., MNRAS 473 (2018) L101]

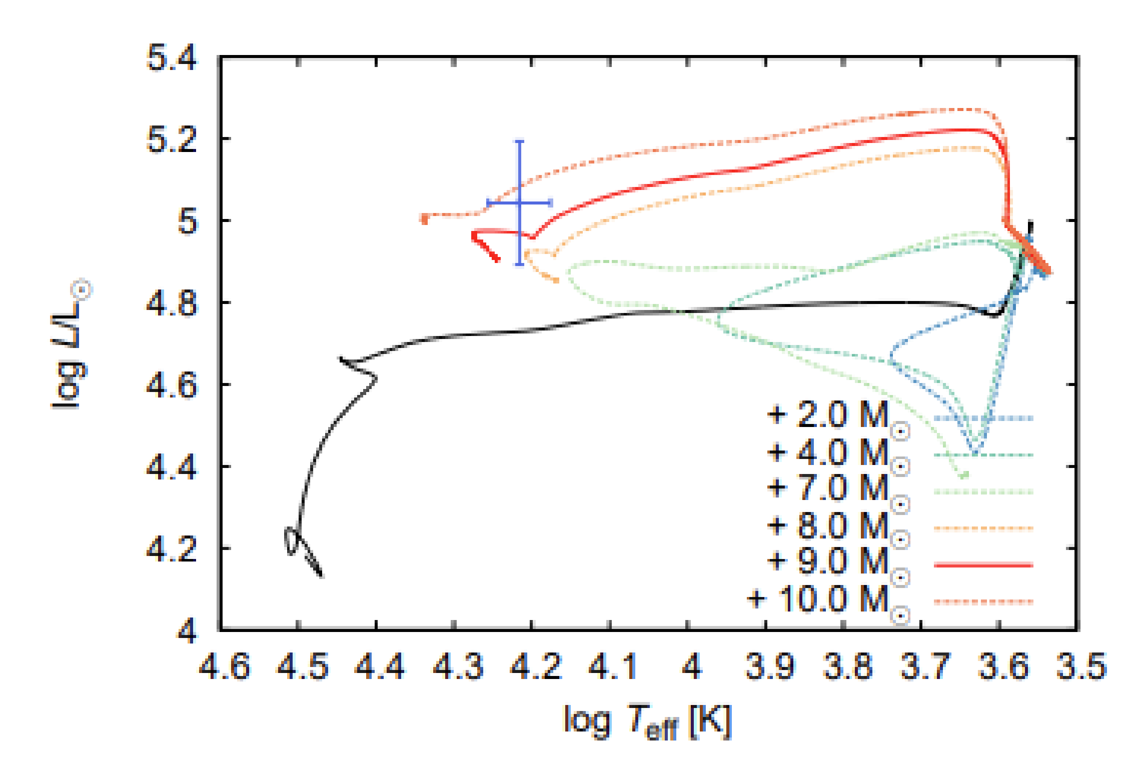
9+14$M_\odot$ model can reproduce the SN 1987A progenitor.

✓ Red to blue transition

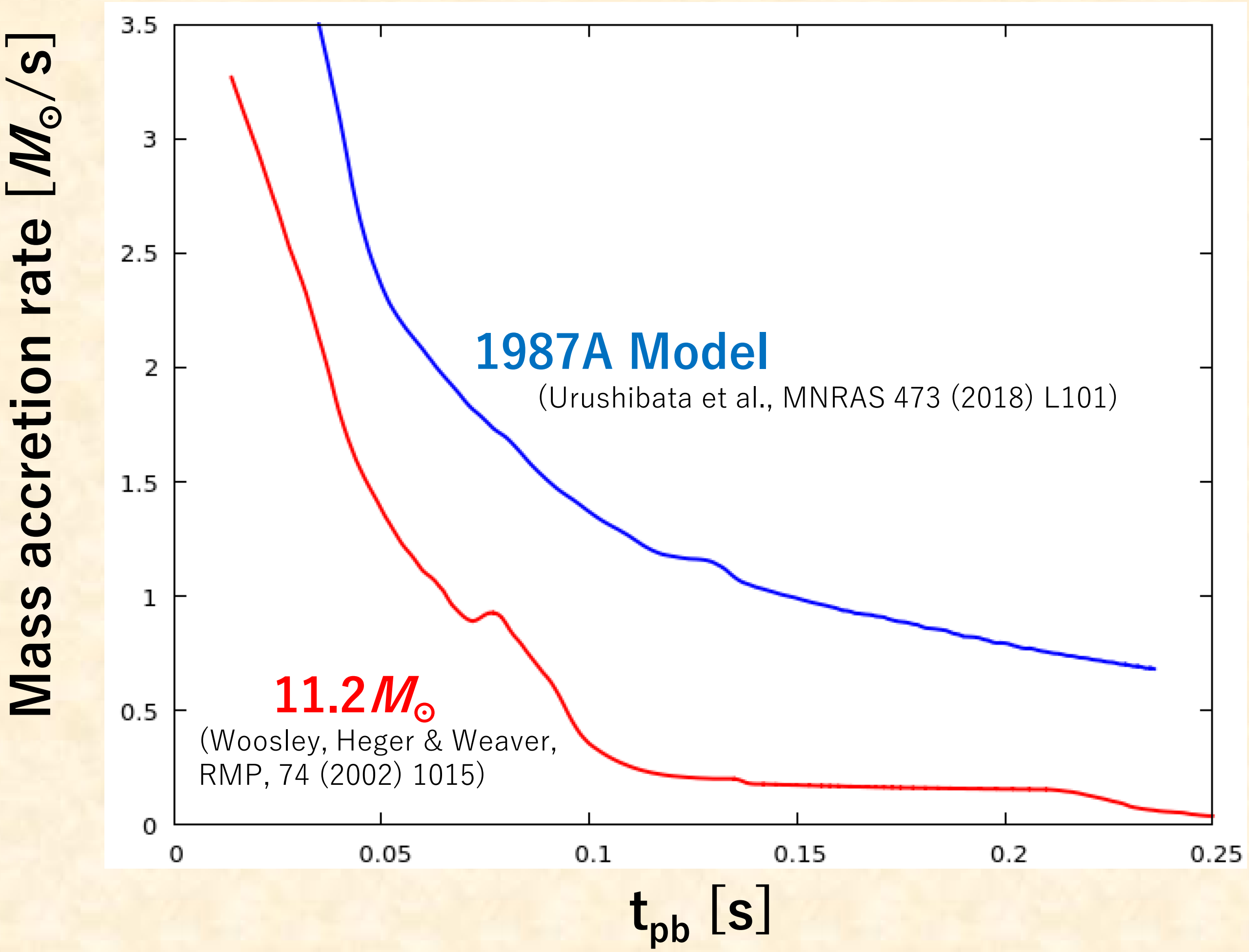
- Envelope is stripped by injection of angular momentum

✓ He and CNO abundances

	Model	Observation (Mattila et al. 2010)
He/H	0.139	0.17±0.06
N/O	1.21	1.5±0.7



Mass Accretion Rate



O'Connor & Ott, ApJ 730 (2011) 70

Compactness parameter:

$$\xi_M = \frac{M/M_\odot}{R(M_{\rm bary} = M)/1000\,{\rm km}}$$

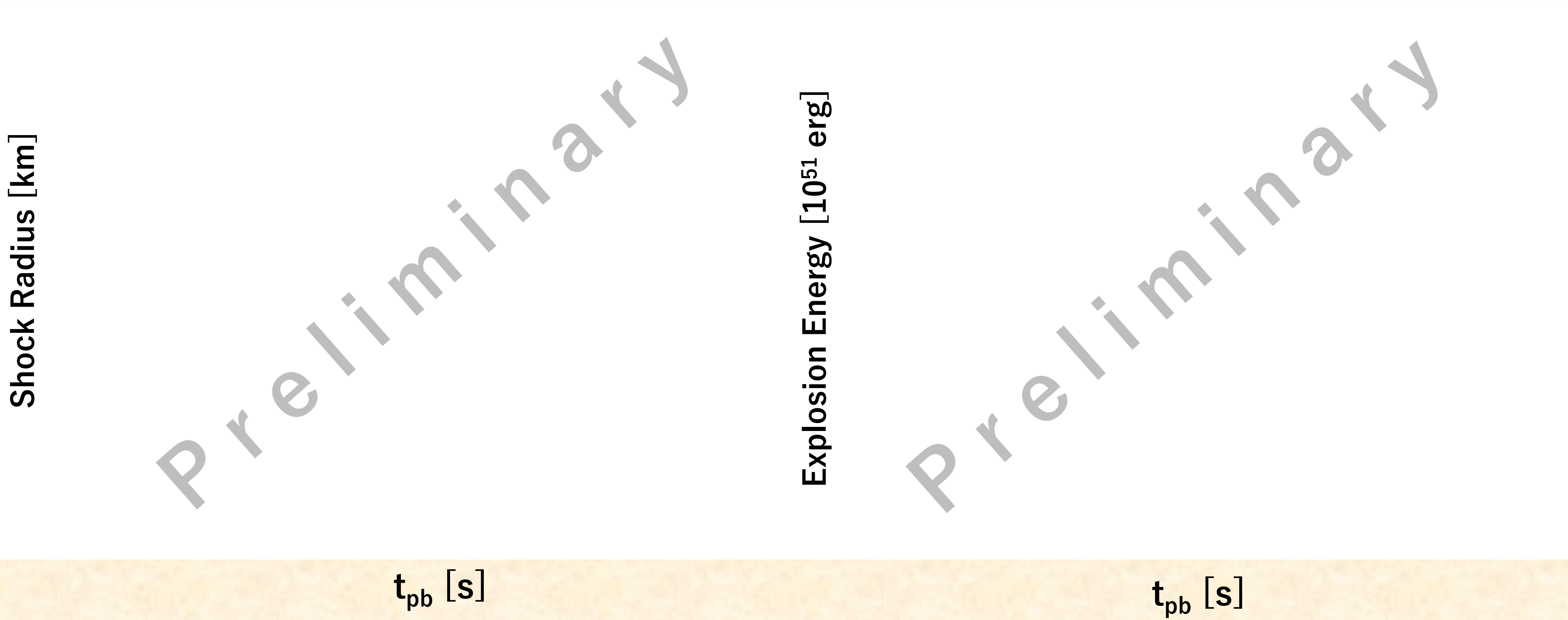
SN 1987A model $\xi_{2.5} = 0.15$

11.2 $M_\odot$ model $\xi_{2.5} = 0.05$

⬇

The SN 1987A model shows a higher mass accretion rate than **the 11.2 $M_\odot$ model**.

3D Explosion of the SN 1987A Model



As in the 11.2$M_{\odot}$ case, explosion is helped by the flavor conversion.

Diving into Beyond-Standard Model

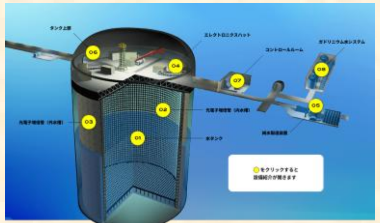
Known particles

Photons

γ

©NAOJ

Neutrinos ν



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Gravitational waves

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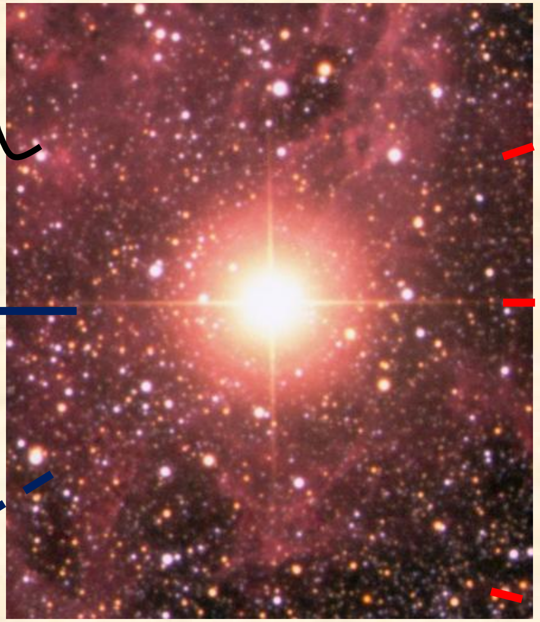
SN 1987A



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Exotic particles

Axions (ALPs)

a

KM et al., PRD 105 (2022) 063009; 108 (2023) 063027; ApJ 943 (2023) 12

KM & M. Mori, JCAP 11 (2025) 081

ν_s **Sterile neutrinos**

KM et al., PRD 110 (2024) 023031; 111 (2025) 083046

γ' **Dark photons**

KM et al., PRD, 113 (2026) L041303

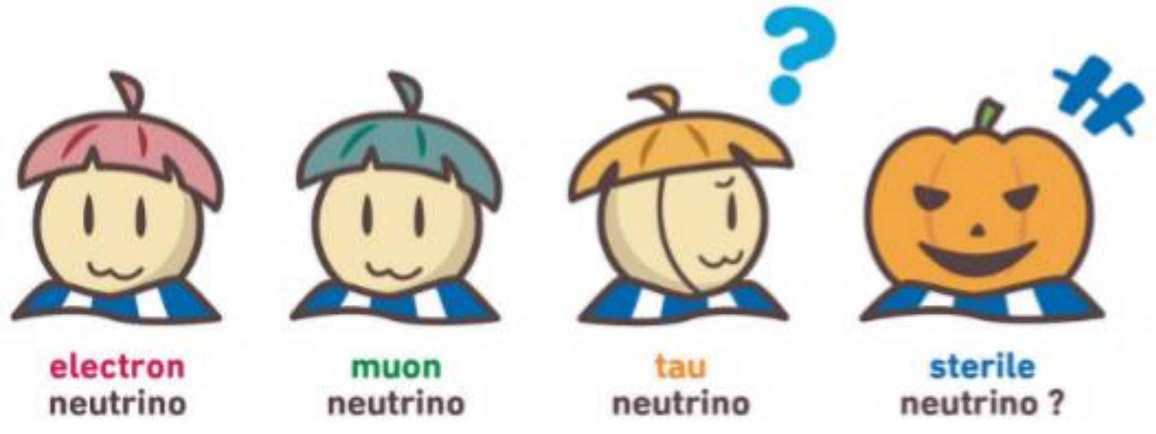
Example: eV-mass Sterile Neutrinos

- Hypothetical neutrinos that do not participate in the weak interaction
- A possible solution to the **reactor antineutrino anomaly**

Mention et al., PRD 83 (2011) 073006

- Mixing with active neutrinos
  - **In this study, we focus on mixing with ν_e**

$$\begin{aligned} \nu_e &= \cos\theta\,\nu_1 + \sin\theta\,\nu_2 \\ \nu_s &= -\sin\theta\,\nu_1 + \cos\theta\,\nu_2 \end{aligned}$$



Active-Sterile Oscillations

- ✓ MSW resonance condition:

$$\frac{\delta m_{\mathrm{v}}^2}{2E}\cos\theta_{\mathrm{v}} = \frac{3\sqrt{2}}{2}G_{\mathrm{F}}n_{\mathrm{b}}\left(Y_e - \frac{1}{3}\right)$$

[m_V : ν_s mass
θ_V : ν_e-ν_s mixing angle
G_F : Fermi coupling
Y_e : electron fraction
n_b : baryon number density]

- ✓ The conversion prob. is given by the Landau-Zener formula

$$P_{\mathrm{es}}(E_{\mathrm{res}}) = 1 - \exp\left(-\frac{\pi^2}{2}\gamma\right)$$

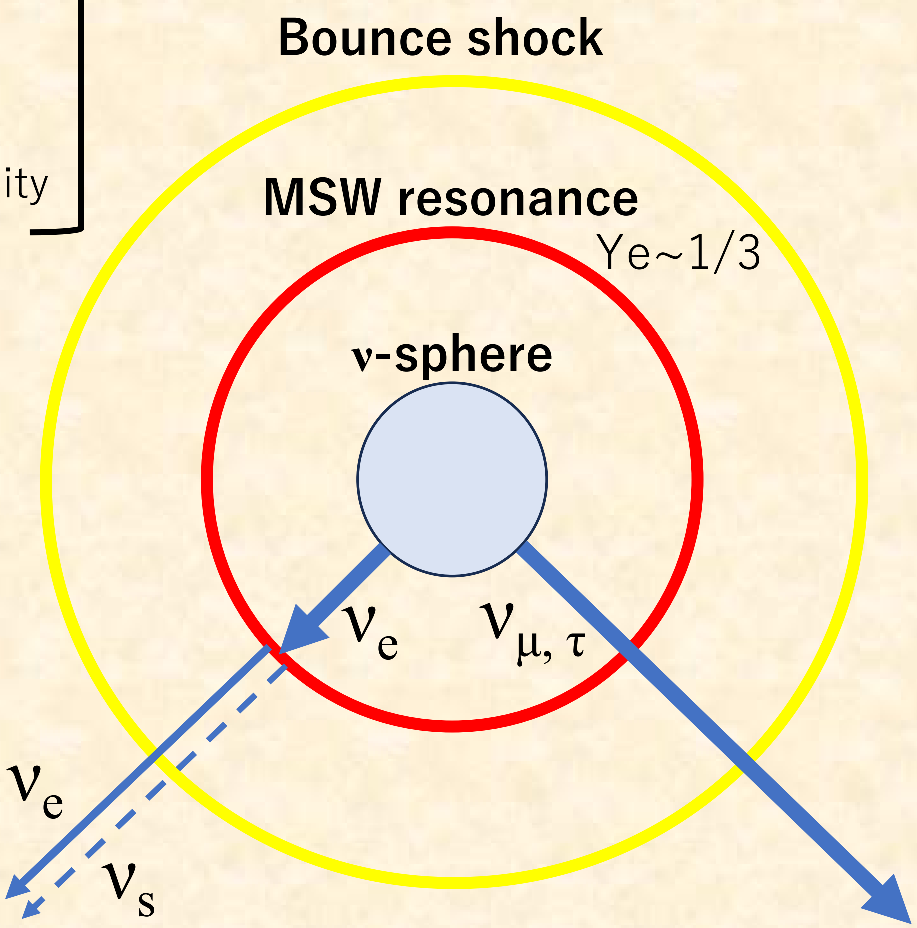
$$\gamma = \Delta_{\mathrm{res}}/l_{\mathrm{osc}}$$

$$\Delta_{\mathrm{res}} = \tan 2\theta \left|\frac{dV_{\mathrm{eff}}/dr}{V_{\mathrm{eff}}}\right|^{-1}$$

$$l_{\mathrm{osc}} = (2\pi E_{\mathrm{res}})/(m_s^2 \sin 2\theta)$$

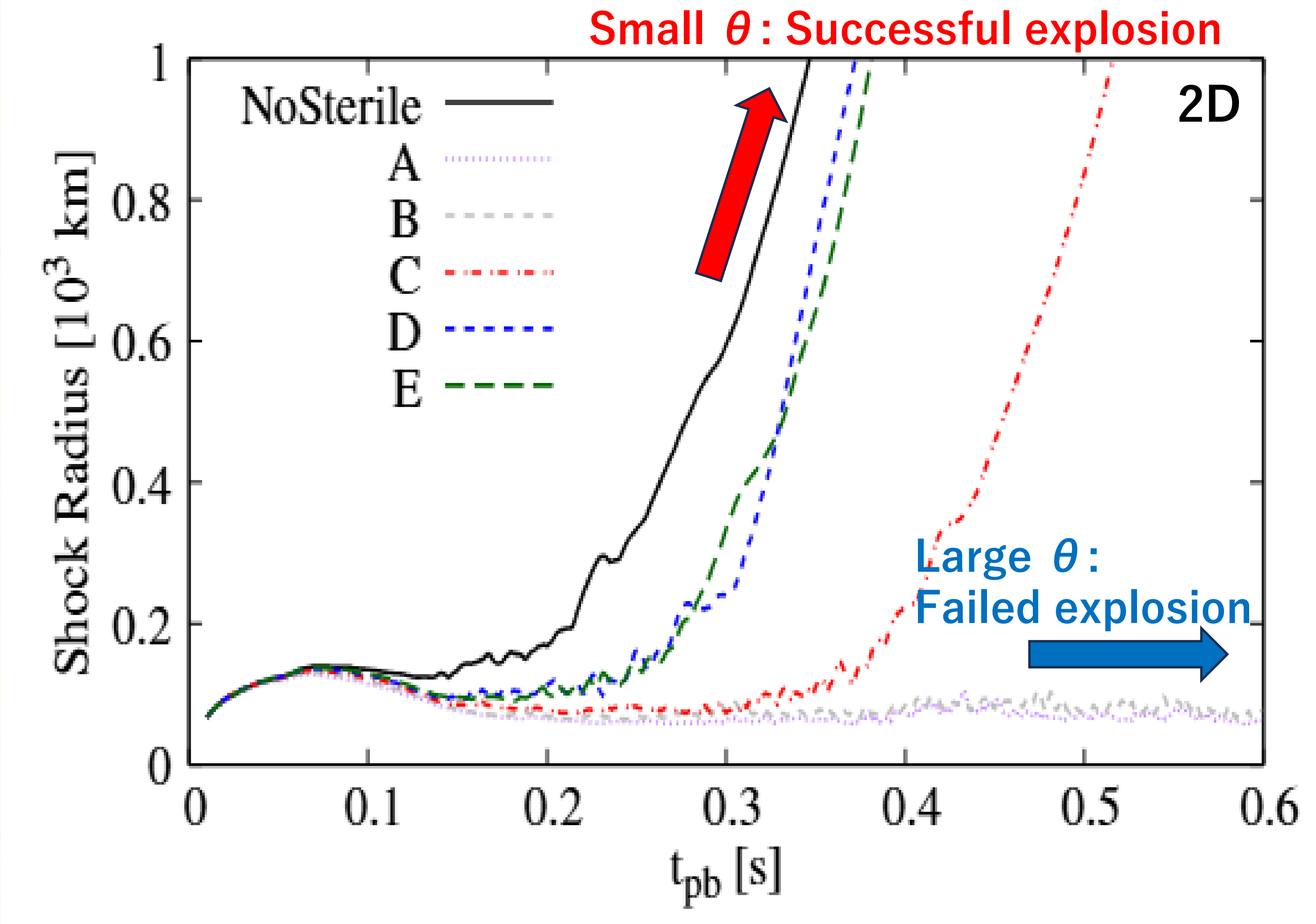
- ✓ We employ the BGK prescription for relaxation:

$$\frac{\partial f}{\partial t} = -\frac{1}{\tau_{\mathrm{osc}}}(f - f^{\mathrm{a}})$$



[Bhatnagar, Gross, & Krook, PR 94 (1954) 511.]
[Nagakura, Johns, & Zaizen, PRD 109 (2024) 083013.]

2D Supernova Simulations with Active-Sterile Neutrino Oscillations

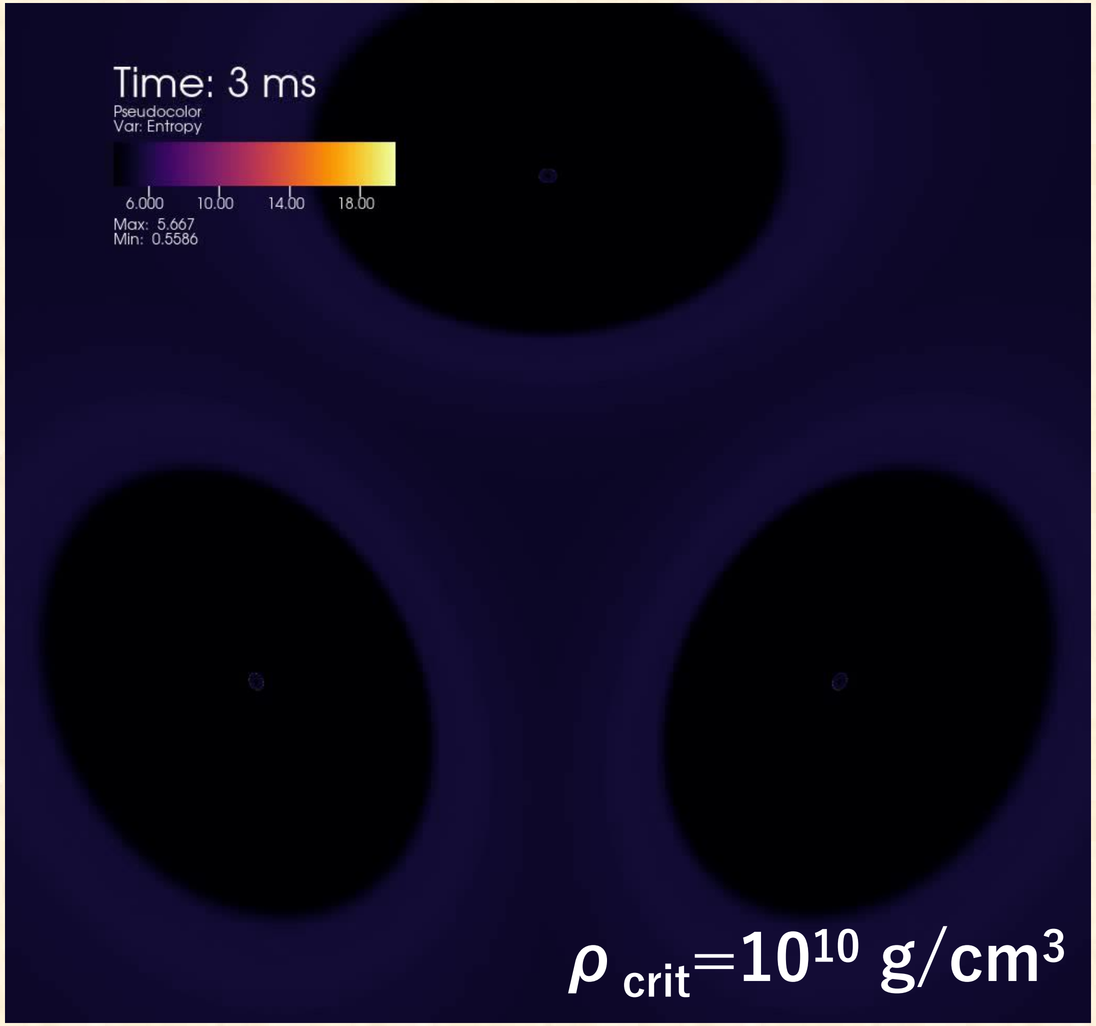


KM, Takiwaki, Kohri, & Nagakura, PRD 111 (2025) 083046.

- ✓ **The MSW active-sterile oscillations appear in the gain region.**
- ✓ When sterile neutrinos are considered, the shock revival is delayed.
- ✓ When θ is sufficiently large, the shock is not revived until the end of the simulations.

See also:
Wu et al., PRD (2014)
Xiong, Wu, & Qian, ApJ (2019)
Ko et al., ApJ (2020)
…

Summary



- We performed 3D simulations with phenomenological treatment for flavor conversion.
- Flavor conversions can help SN explosion!
- Explosion energy is significantly enhanced.
- 3D simulations with a different progenitor are ongoing.