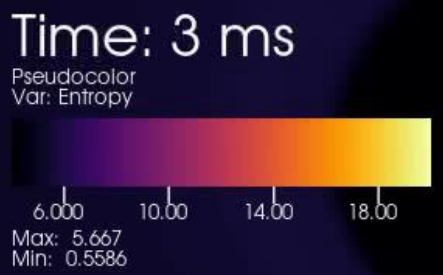


3D Core-Collapse Supernova Models with Phenomenological Treatment of Neutrino Flavor Instabilities

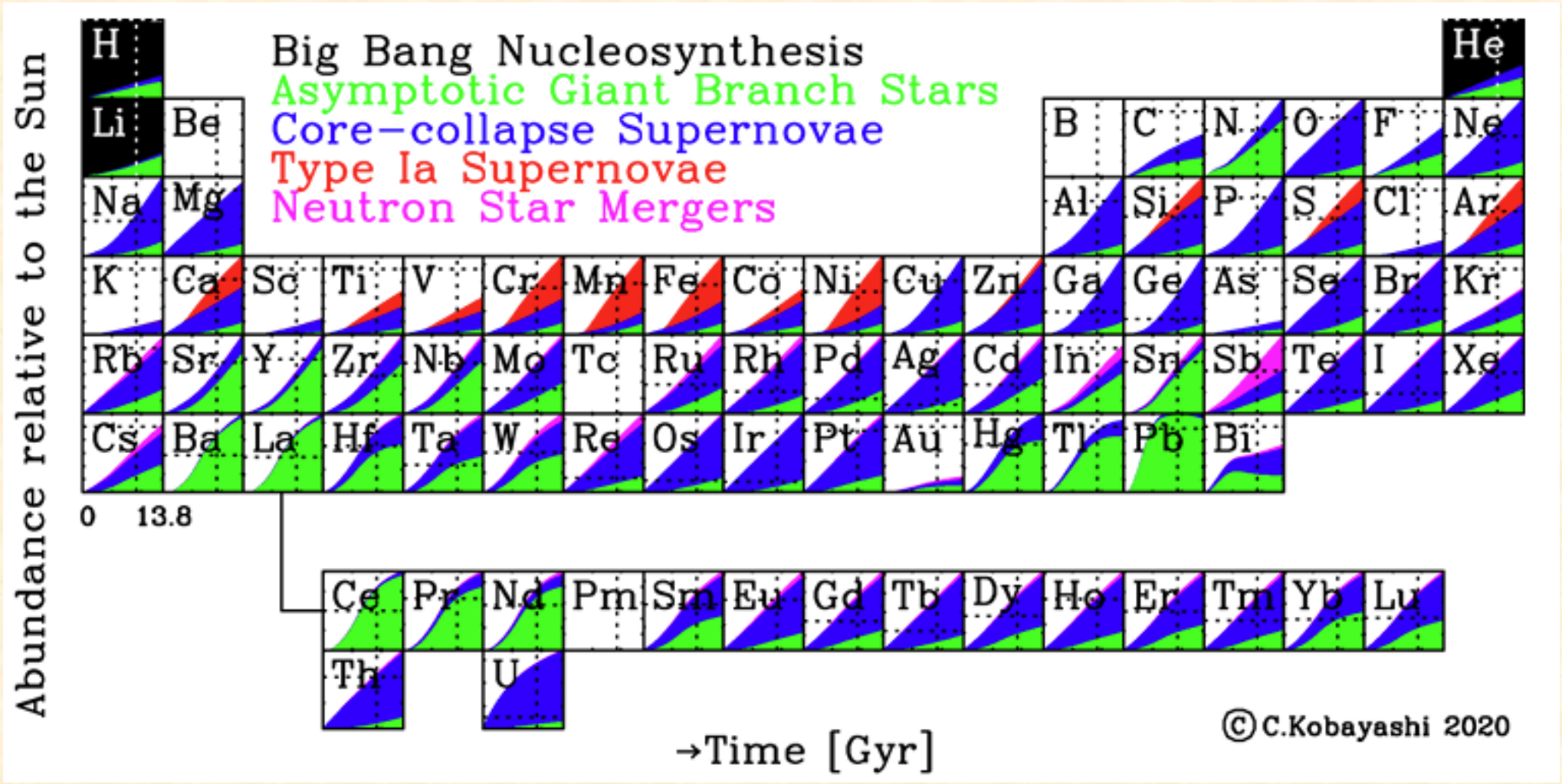
Kanji Mori

Division of Science, National Astronomical Observatory of Japan

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

Core-collapse Supernovae: an Origin of Elements!

Kobayashi, Karakas & Lugaro, ApJ 900 (2020) 179



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

Neutrino self-interaction

$$H_{\nu\nu} = \sqrt{2}G_{\rm F}\int d^3q(1-\boldsymbol{v}_p\cdot\boldsymbol{v}_q)(\rho-\bar{\rho})$$

Collisional term

Collective oscillations

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

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

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

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

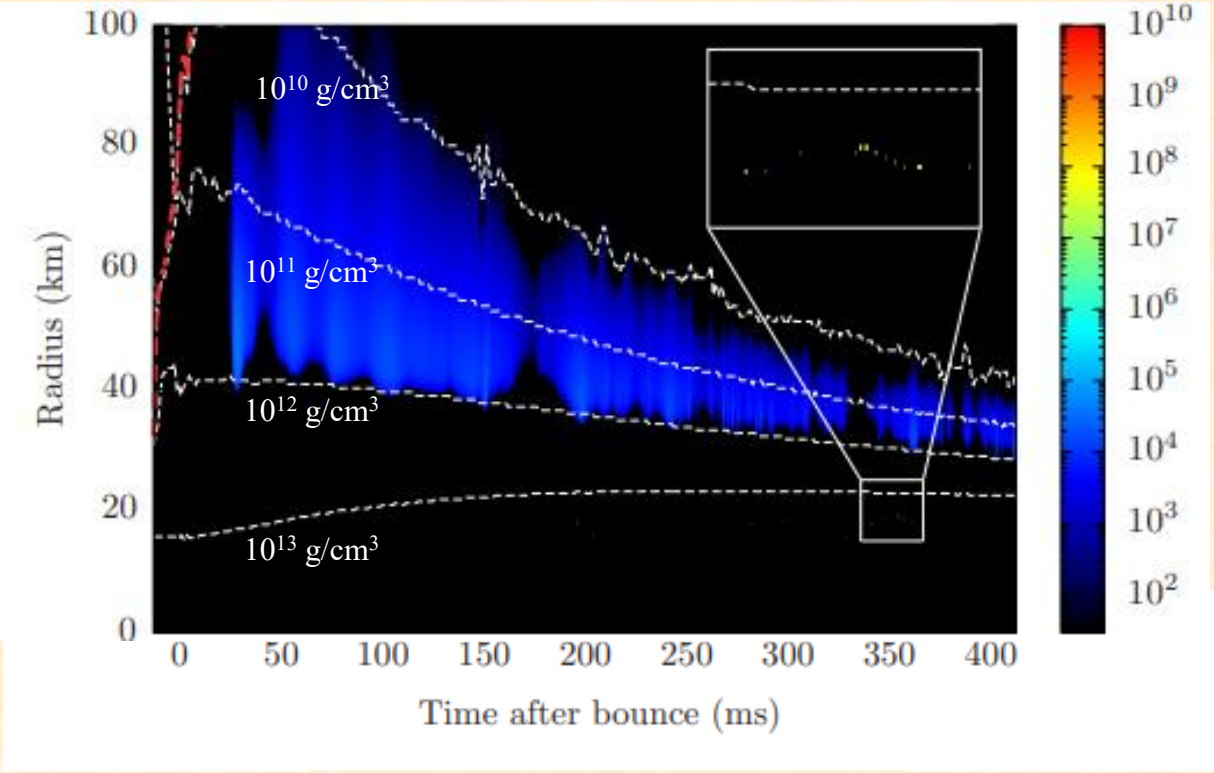
- **Collisional instability** [Johns PRL 130 (2023) 191001]

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

Neutrino collective oscillations

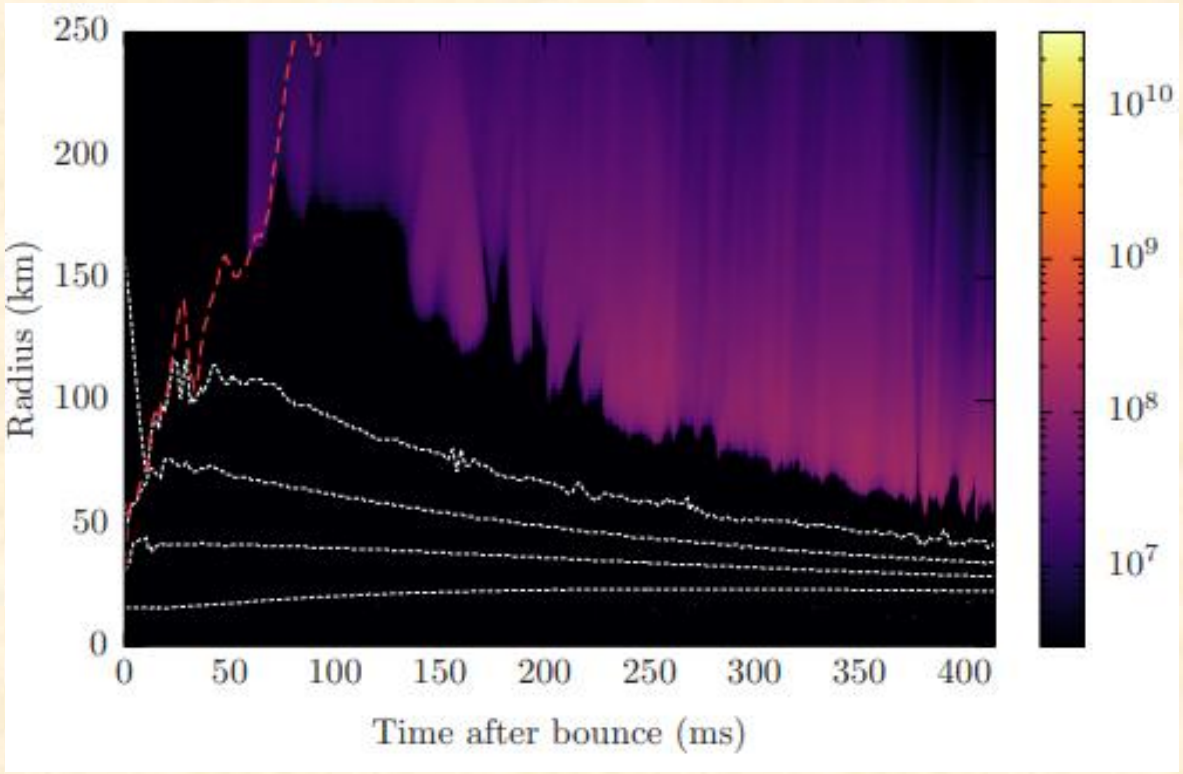
Collisional flavor instability (CFI)

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



Fast flavor instability (FFI)

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



Akaho et al., PRD 109 (2024) 023012

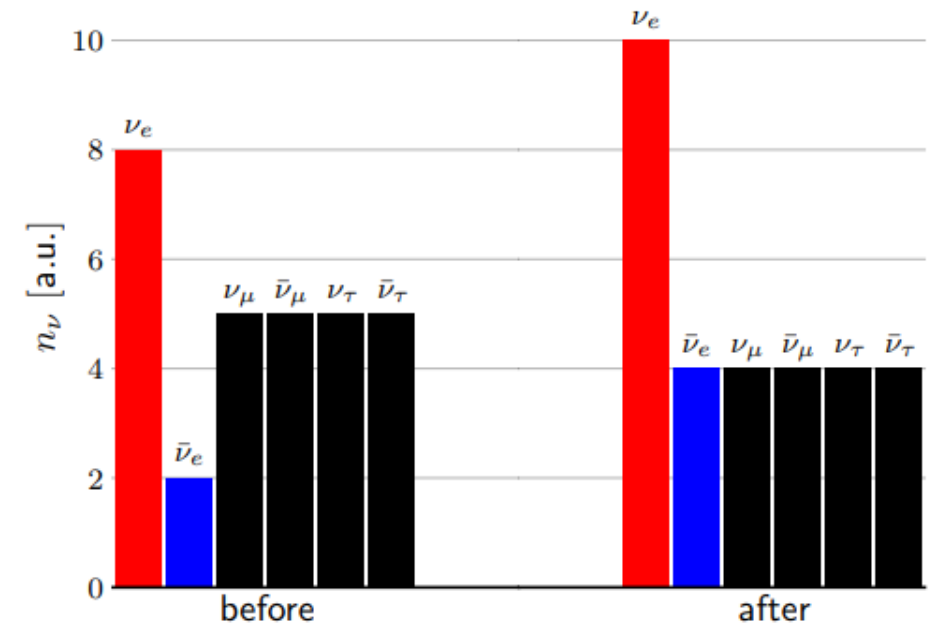
Collective oscillations do appear in supernovae
→Simulations with CFI/FFI are needed

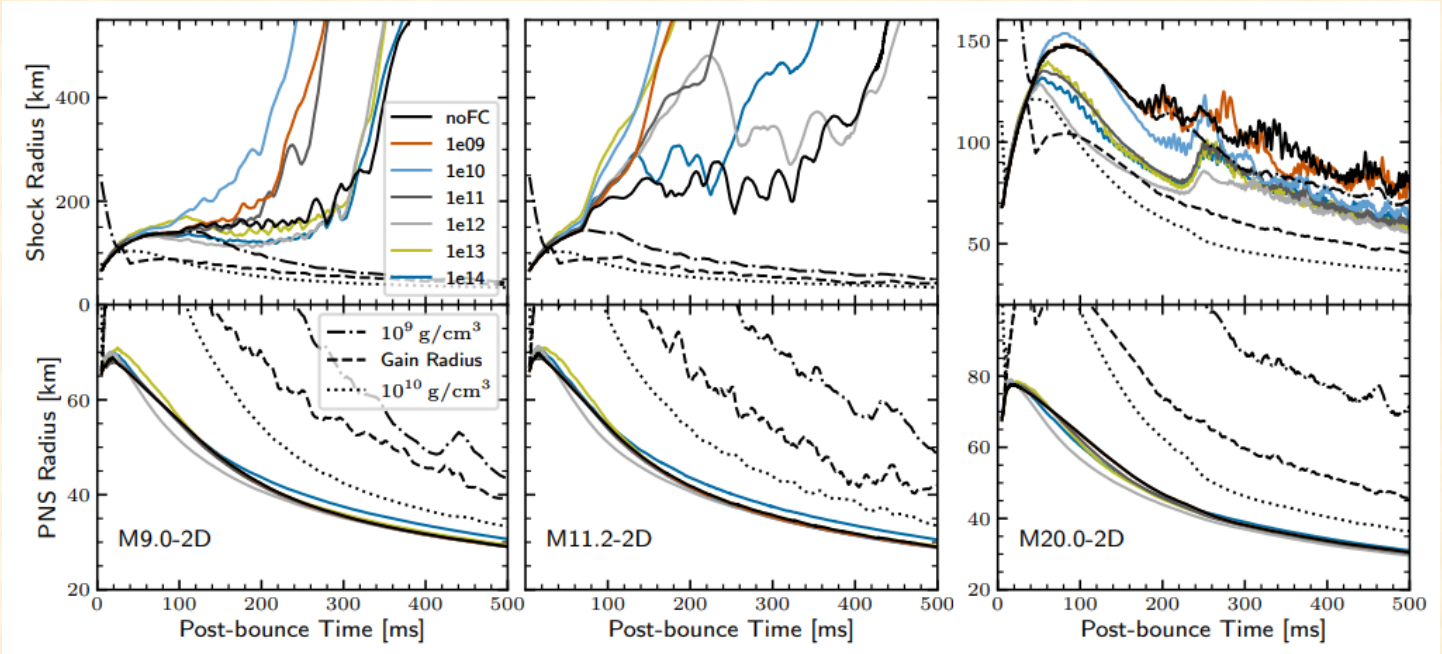
Phenomenological treatment for collective oscillations

Assumption

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

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



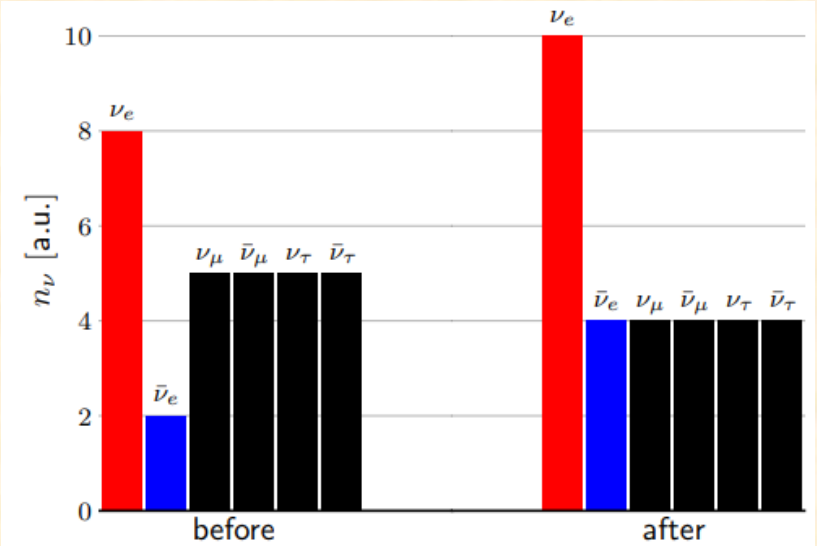


Phenomenological treatment for collective oscillations

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

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

Ehring et al. (2023)



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

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

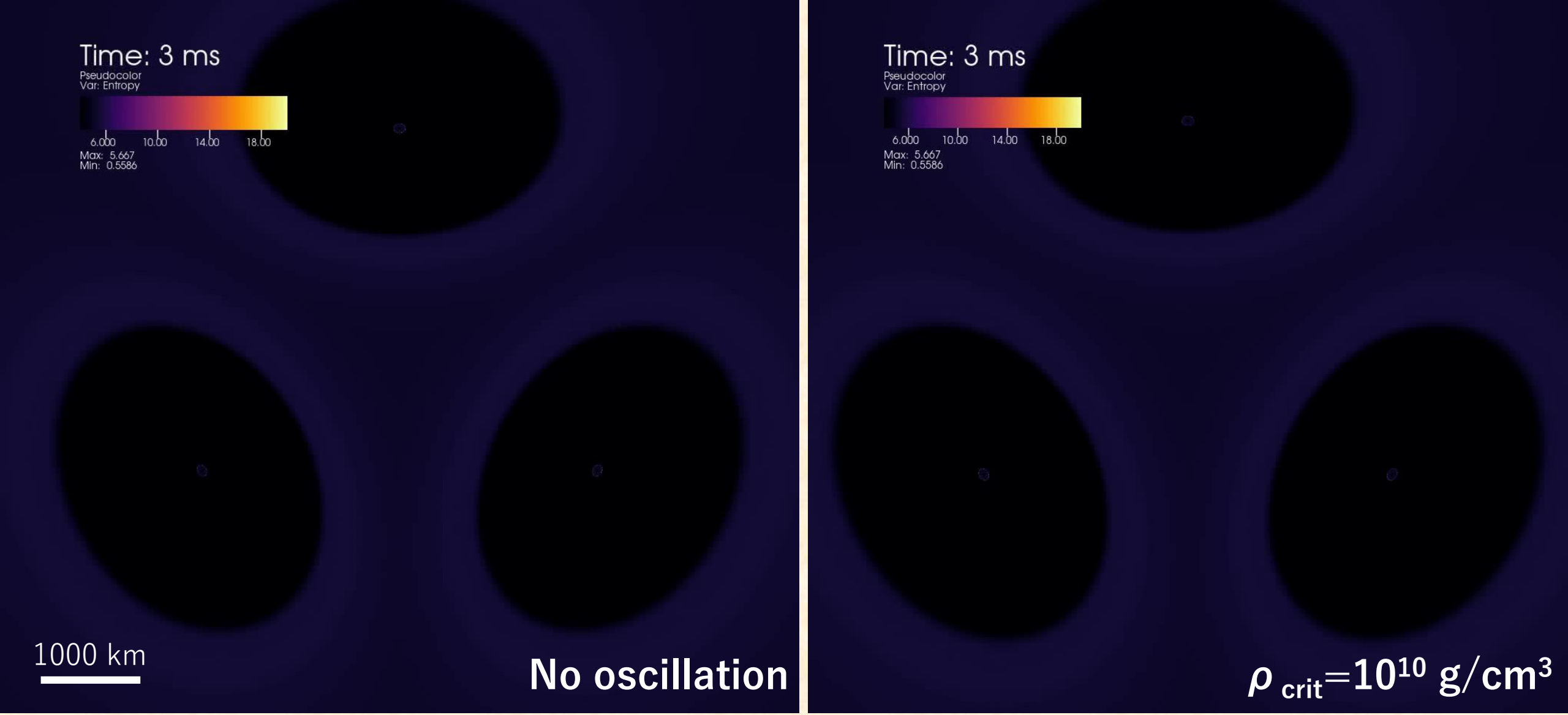
Dimension: **3D**

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

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

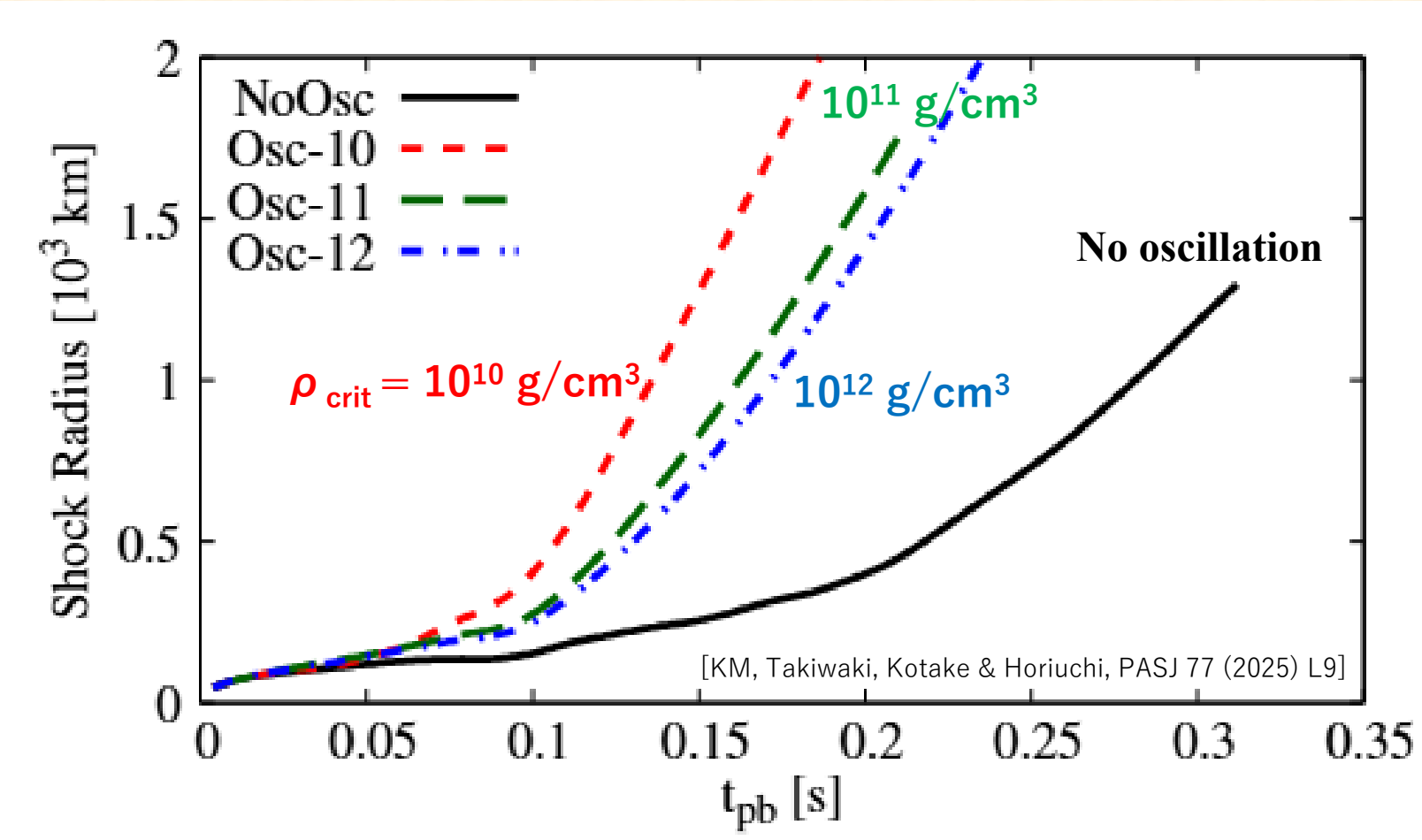
Resolution: $512 \times 64 \times 128$

$\rho_{\rm crit}$: 10^{10}, 10^{11}, 10^{12} g/cm^3



Collective oscillations help SN explosion!

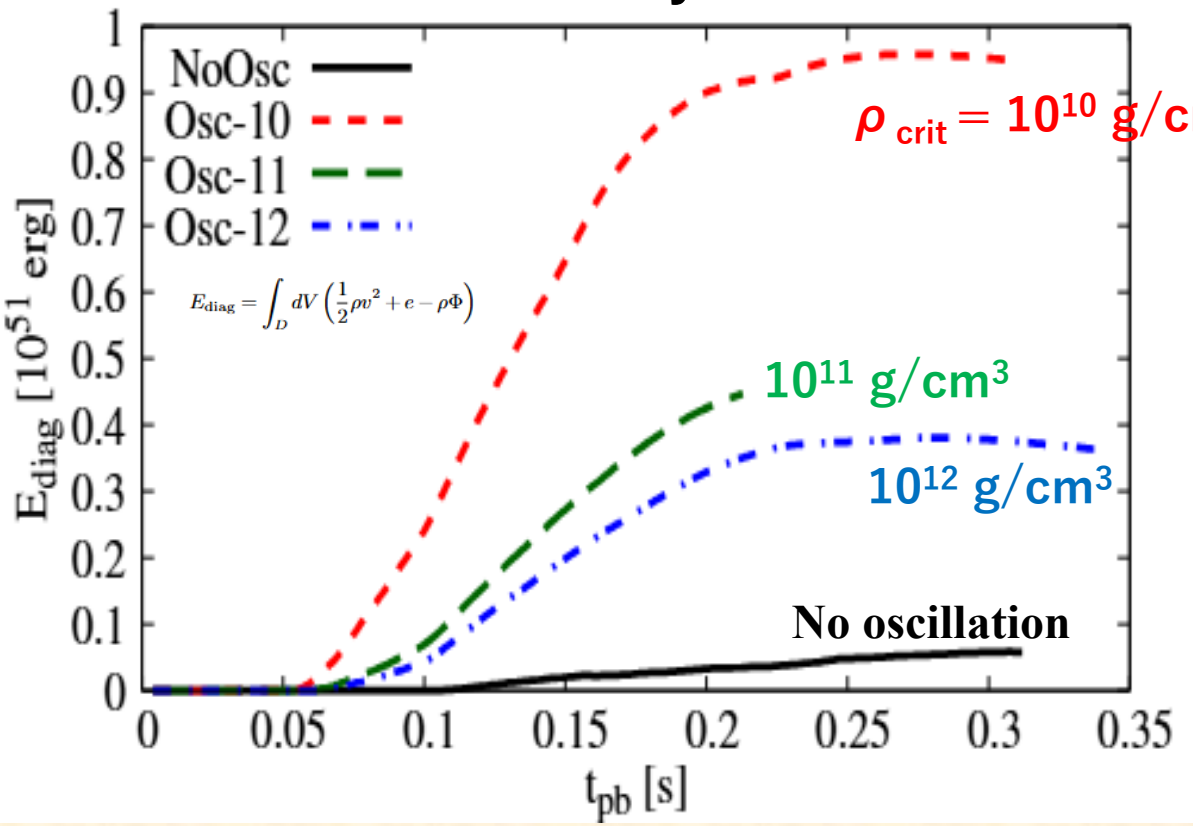
Shock Radius



The shock revives earlier when the flavor conversion is considered.

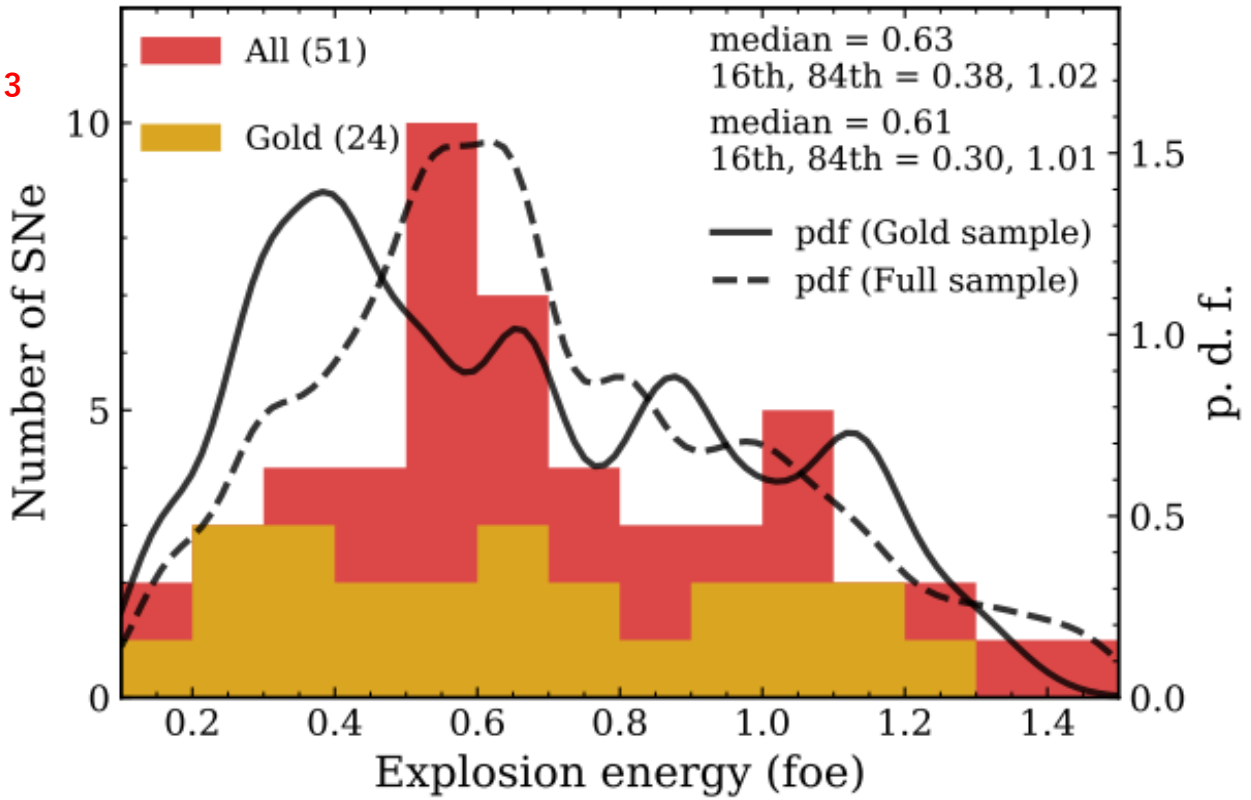
Explosion Energy

Theory



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

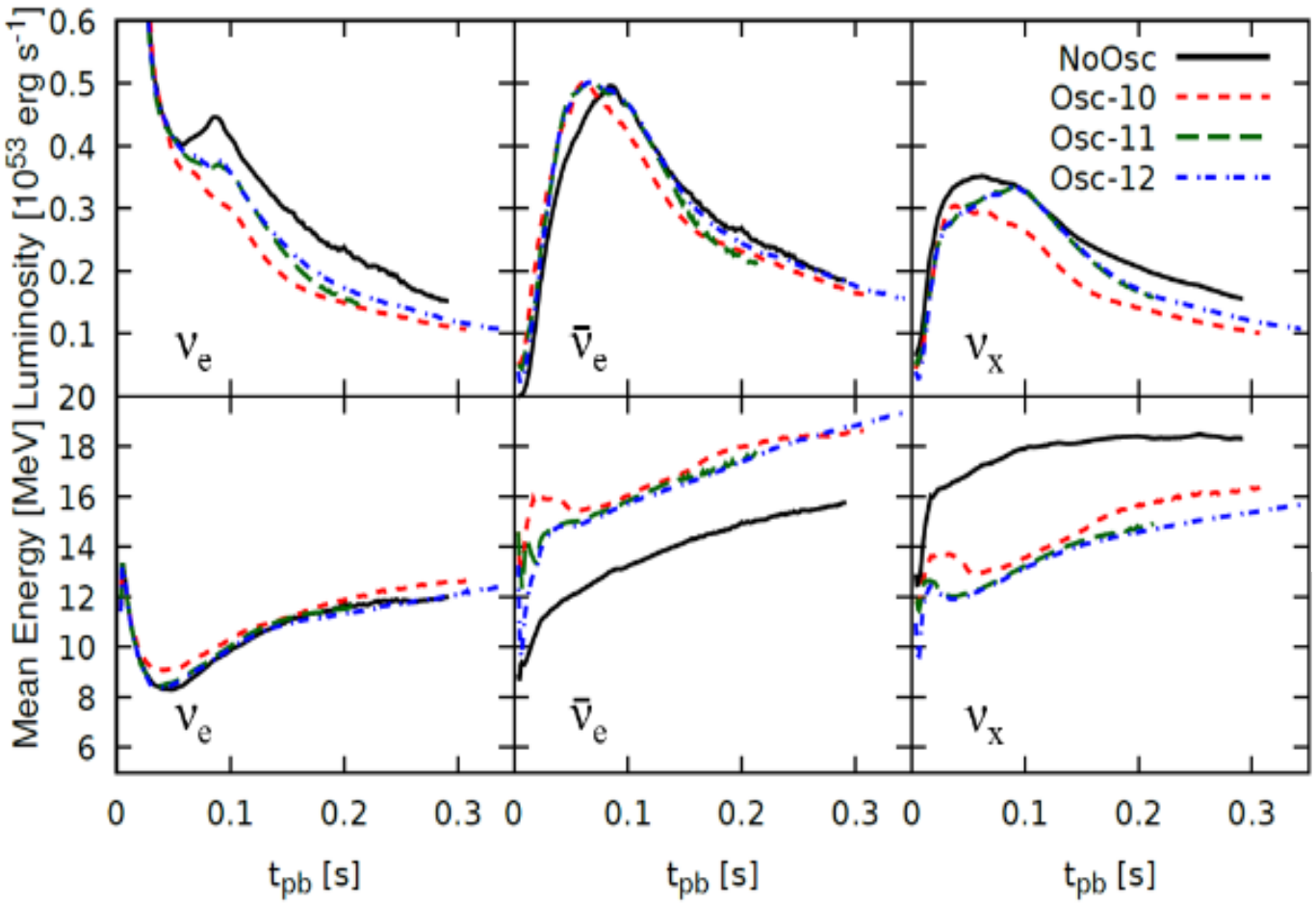
Observation



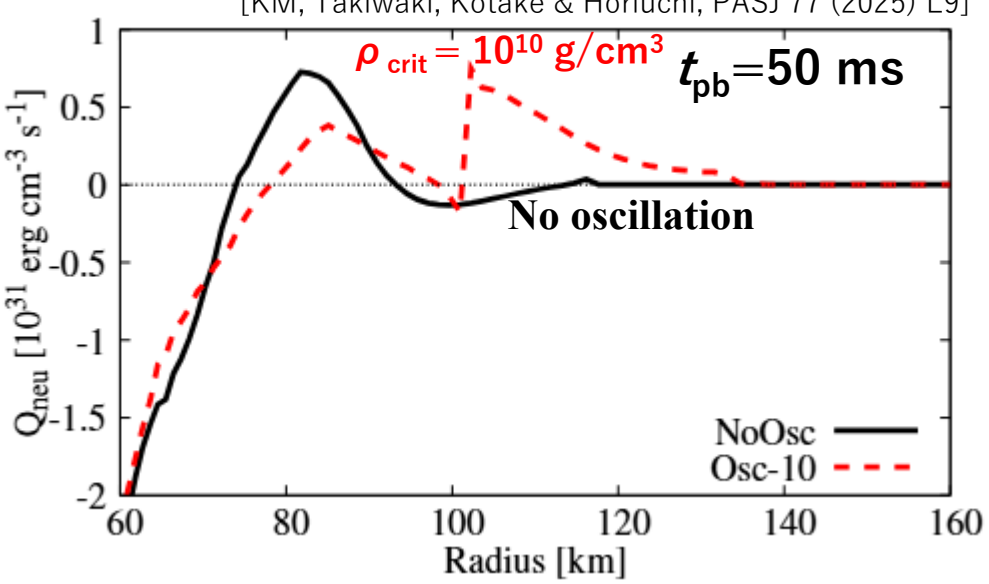
Martinez et al., A&A 660 (2022) A41

Explosion energy is enhanced
→Observed values can be reproduced

Neutrinos



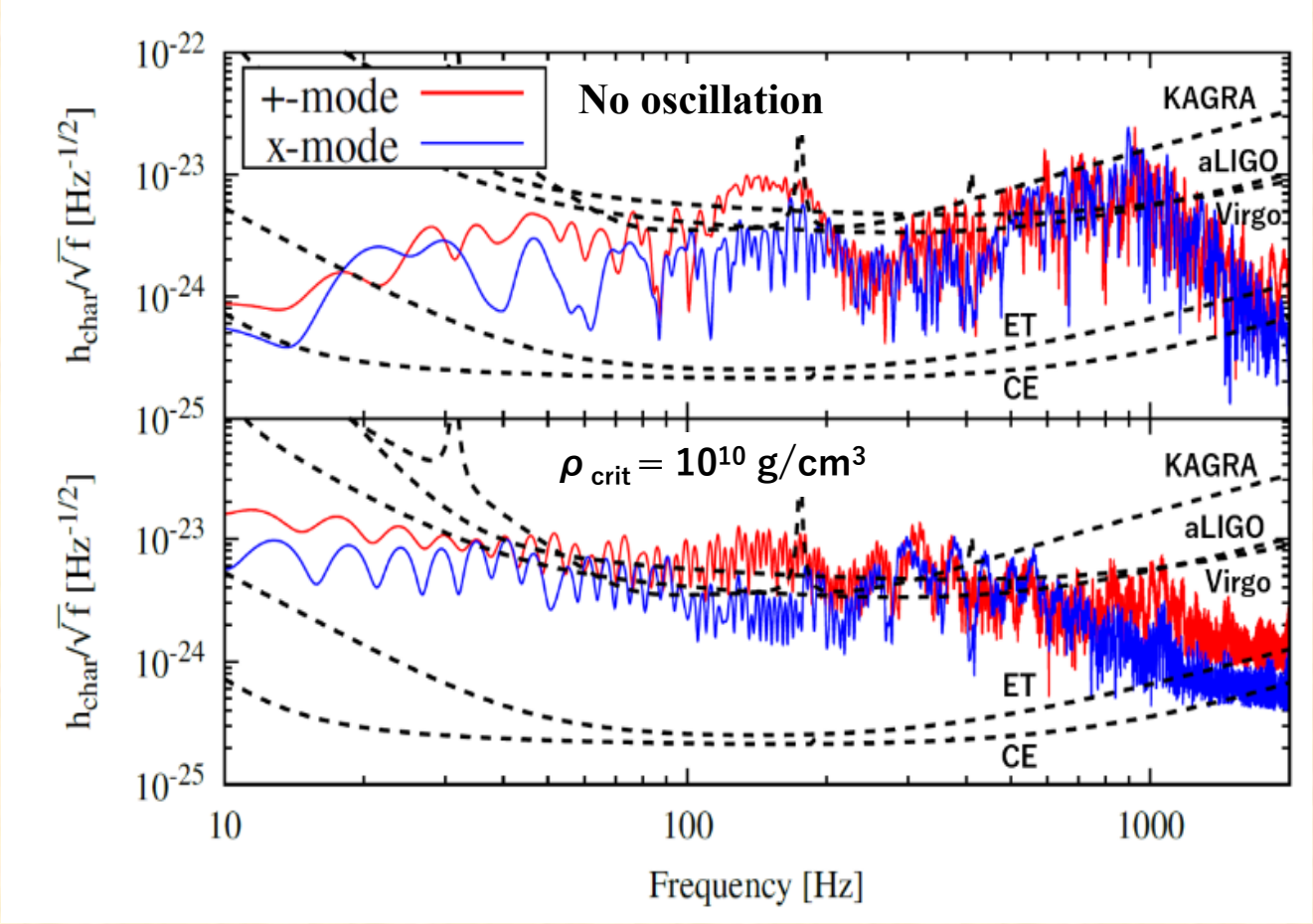
[KM, Takiwaki, Kotake & Horiuchi, PASJ 77 (2025) L9]



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

Gravitational Waves

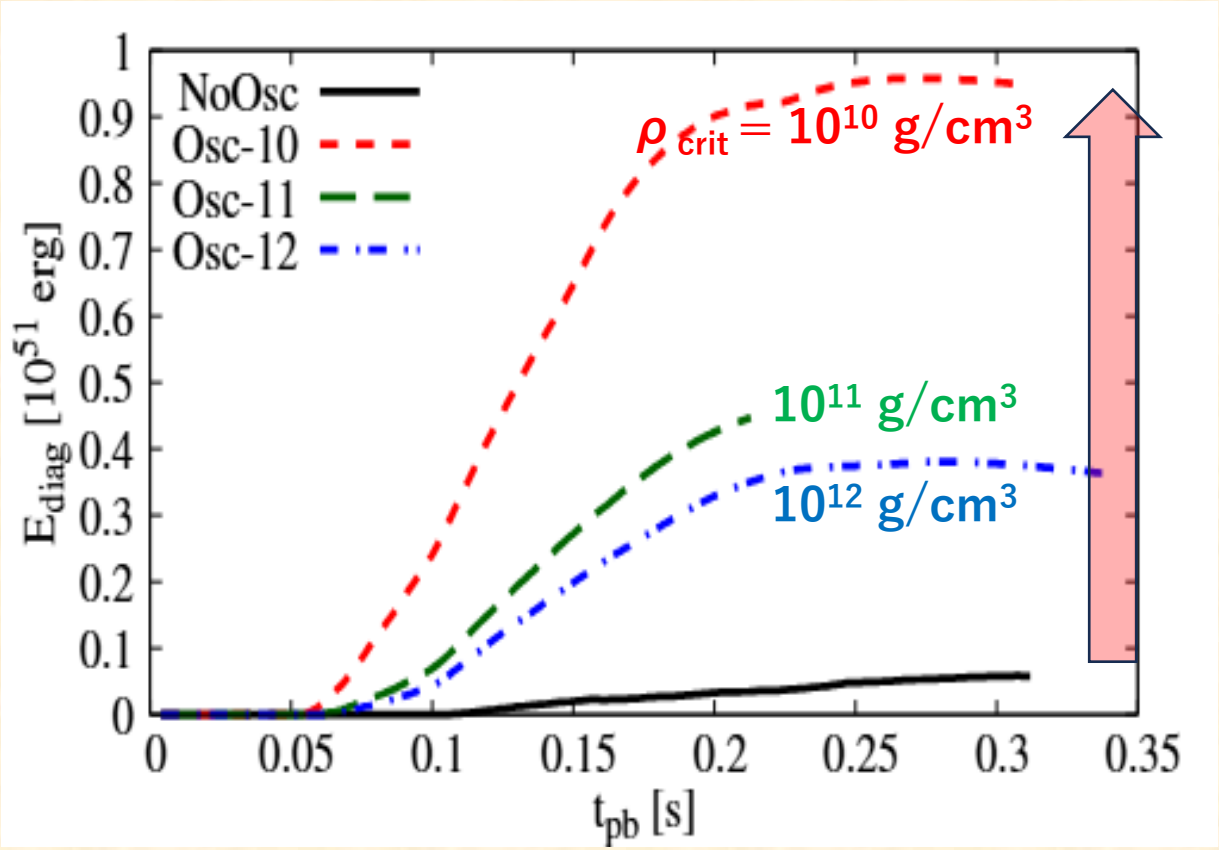
SN event located at the Galactic Center



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

- Difficult to detect with current GW detectors
- **Next-gen detectors such as Einstein Telescope and Cosmic Explorer are needed!**

Summary



Flavor instabilities can help SN explosion!

1. Discrepancy in explosion energy between theory and observation can be mitigated.
2. Systematic study on progenitors is desirable.