Impacts of sterile neutrinos on supernova dynamics

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Messengers from a Supernova

Known particles

Photons γ

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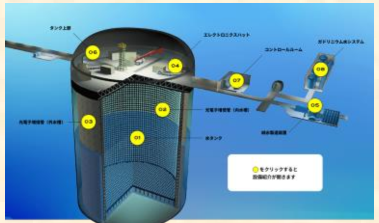
Neutrinos ν



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Gravitational waves

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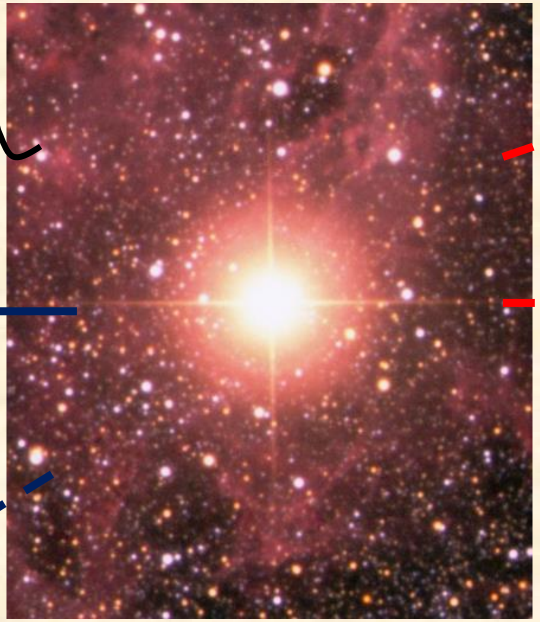
SN 1987A



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Exotic particles

Axions (ALPs) a

e.g. KM et al., PRD 105 (2022) 063009; 108 (2023) 063027
Betranhandy & O'Connor PRD 106 (2022) 063019
Fischer et al. PRD 104 (2021) 103012

ν_s **Sterile neutrinos**

e.g. KM et al. (2024), arXiv:2402.14333
Rembiasz et al. PRD 98 (2018) 103010
Warren et al. PRD 90 (2014) 103007

⋮

Contents

1. Supernova simulations with **heavy** (~200 MeV) sterile neutrinos

   KM, T. Takiwaki, K. Kotake, & S. Horiuchi, accepted by PRD, arXiv:2402.14333

2. Supernova simulations with **light** (~1 eV) sterile neutrinos

   KM, T. Takiwaki, K. Kohri, & H. Nagakura, in preparation

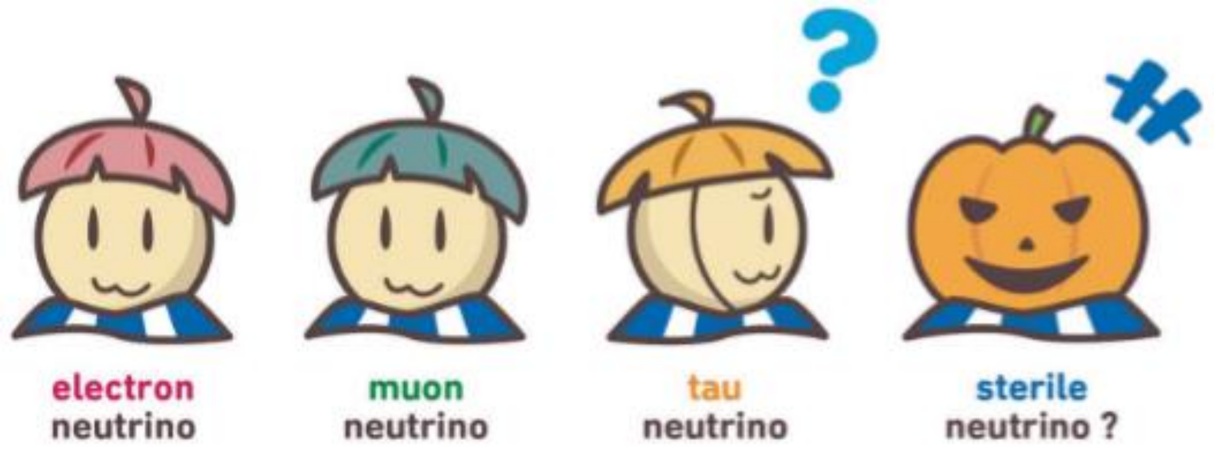
Sterile Neutrinos

- Right-handed neutrinos that do not participate in the weak interaction
- Can give light neutrino masses through the seesaw mechanism

[Gell-Mann, Ramond, Slansky (1979), Yanagida (1979)]

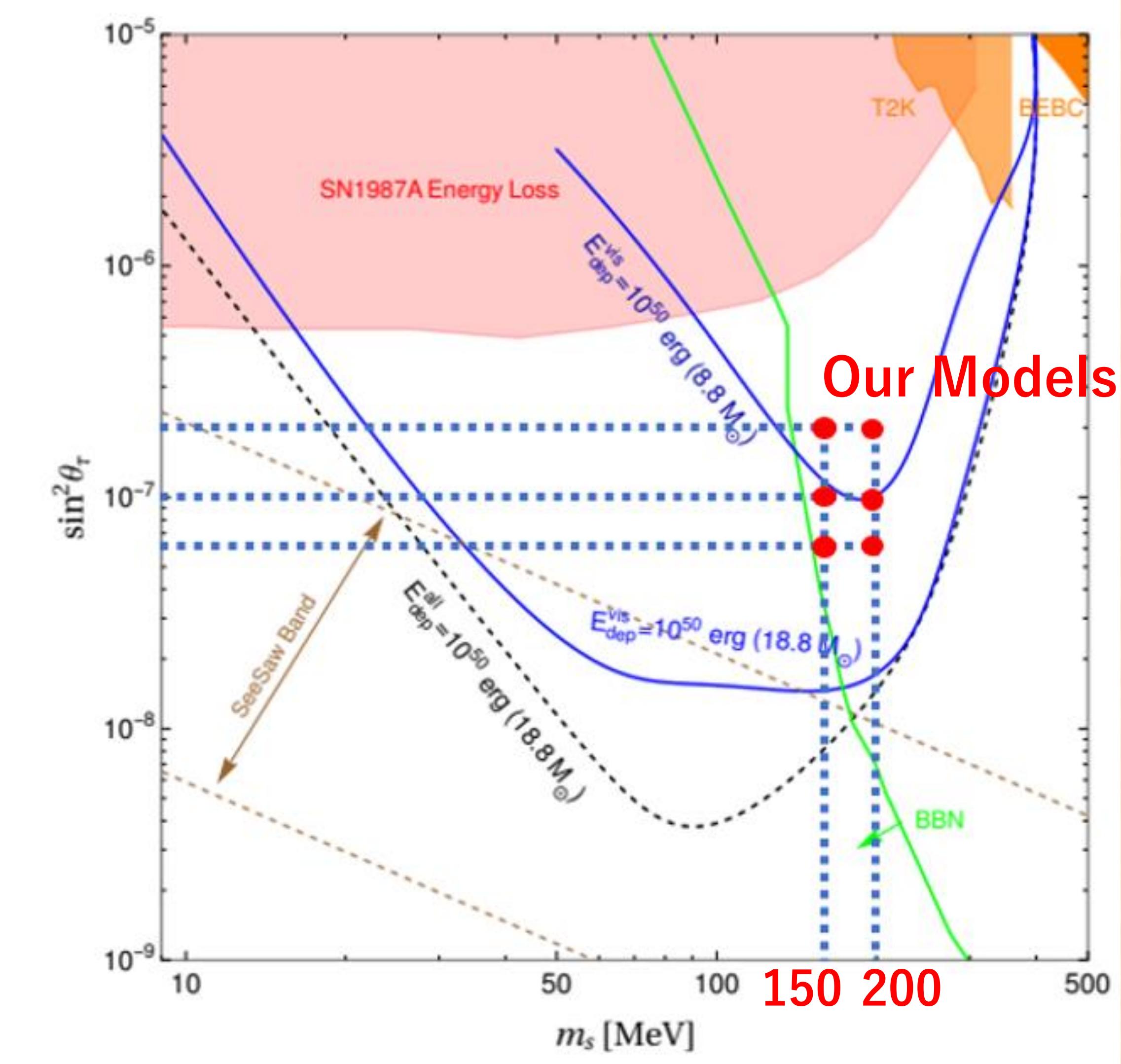
- Mixing with active neutrinos
  - ➢ **In this study, we focus on mixing with ν_τ**

$$\nu_\tau = \cos\theta_\tau\,\nu_1 + \sin\theta_\tau\,\nu_2$$
$$\nu_s = -\sin\theta_\tau\,\nu_1 + \cos\theta_\tau\,\nu_2$$



Georgescu, Nature Rev. Phys., 6 (2024) 84.

Constraints on Heavy Sterile Neutrinos



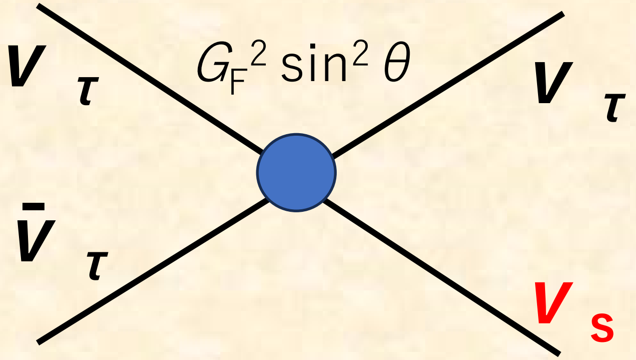
Chauhan et al. (2023), arXiv:2309.05860

- ✓ **Core-collapse supernovae** are a unique tool to investigate ν_s with m_s~100-400 MeV!
- ✓ However, multi-D simulations of SNe with ν_s have not been developed
  - ➢ For 1D SN simulations, see Rembiasz et al., PRD 98 (2018) 103010

ν_s Production Processes

Process	$S\|\mathcal{M}\|^2/(8G_F^2 \sin^2\theta_{\tau 4})$
$\nu_\tau + \bar{\nu}_\tau \to \nu_4 + \bar{\nu}_\tau(\nu_\tau)$	$4u(u - m_4^2)$
$\nu_\mu + \bar{\nu}_\mu \to \nu_4 + \bar{\nu}_\tau(\nu_\tau)$	$u(u - m_4^2)$
$\nu_\tau + \nu_\tau \to \nu_4 + \nu_\tau$	$2s(s - m_4^2)$
$\bar{\nu}_\tau + \bar{\nu}_\tau \to \nu_4 + \bar{\nu}_\tau$	$2s(s - m_4^2)$
$\nu_\mu + \nu_\tau \to \nu_4 + \nu_\mu$	$s(s - m_4^2)$
$\bar{\nu}_\mu + \bar{\nu}_\tau \to \nu_4 + \bar{\nu}_\mu$	$s(s - m_4^2)$
$\nu_\tau + \bar{\nu}_\mu \to \nu_4 + \bar{\nu}_\mu$	$u(u - m_4^2)$
$\bar{\nu}_\tau + \nu_\mu \to \nu_4 + \nu_\mu$	$u(u - m_4^2)$

Mastrototaro et al., JCAP (2019)



Collision integral:

$$\mathcal{C}_{\rm coll} = \frac{1}{2E_{\rm s}} \int d^3\hat{p}_2 d^3\hat{p}_3 d^3\hat{p}_4 (1 - f_2) f_3 f_4 \times S|M|^2 \delta^{(4)}(p_{\rm s} + p_2 - p_3 - p_4)(2\pi)^4,$$

Fitting formula (Fuller, Kusenko & Petraki, PLB 670 (2009) 281)

$$Q_{\rm cool} = 3 \times 10^{34} {\rm erg\,cm^{-3}\,s^{-1}} \times \left(\frac{\sin^2\theta_{\tau 4}}{5 \times 10^{-8}}\right) \left(\frac{T}{35\,{\rm MeV}}\right)^{7.2} \exp\left(-\frac{m_{\rm s}}{T}\right)$$

ν_s Decay Process

- Heavy sterile neutrinos are unstable:

$$\nu_s \rightarrow \pi^0 + \nu_\tau \rightarrow 2\gamma + \nu_\tau$$

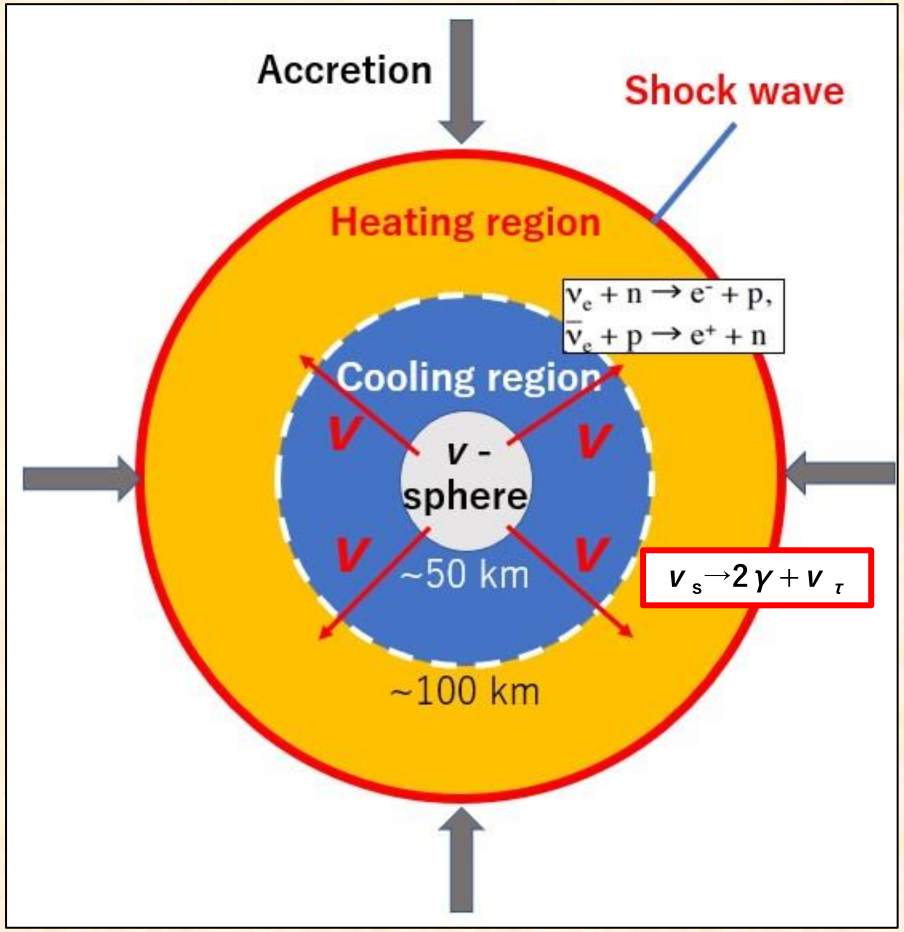
$(m > m_\pi = 135\ \mathrm{MeV})$

Heating effect

High-energy active neutrino

- Decay length:

$$\lambda_s \approx 2 \times 10^4\,\mathrm{km}\left(\frac{\sin^2\theta_{\tau 4}}{5\times 10^{-8}}\right)^{-1}\left(\frac{m_s}{200\,\mathrm{MeV}}\right)^{-3}\left(\frac{0.54}{1-\frac{m_\pi^2}{m_s^2}}\right),$$



SN Simulation Coupled with ν_s

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

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

Dimension: 2D

EoS: LS220 [Lattimer & Swesty, NPA 535 (1991) 331]

Progenitor: $20M_\odot$ [Woosley & Heger Phys. Rep. 442 (2007) 269]

Sterile neutrino transport:

$$\frac{\partial \mathcal{E}}{\partial t} + \nabla \cdot \mathcal{F} = Q_{\rm cool} - \kappa \mathcal{E}$$

$\mathcal{E}$: ν_s energy density

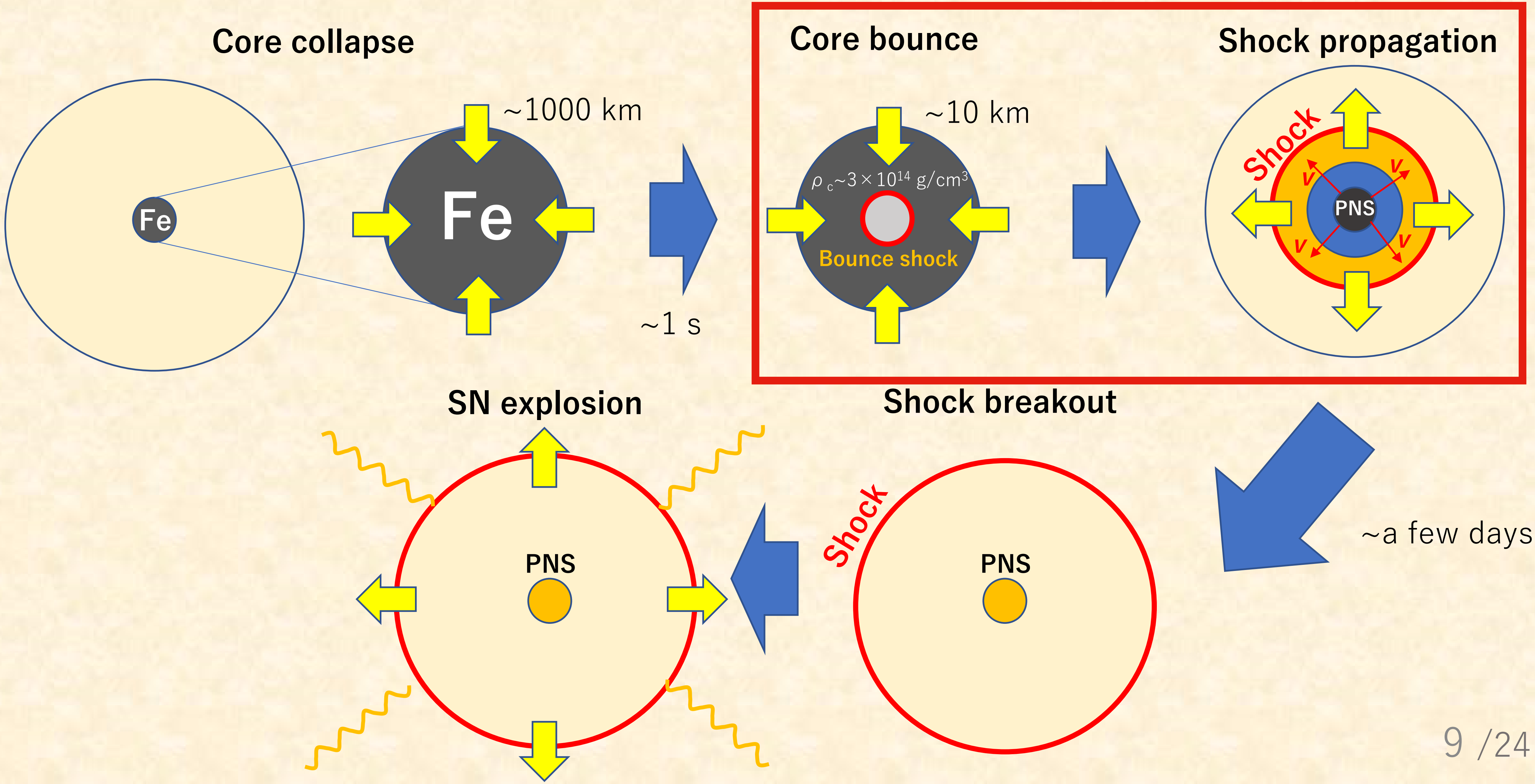
$\mathcal{F}$: ν_s flux

with the ray-by-ray approximation and a closure relation $\mathcal{F} = c\mathcal{E}$

Feedback to hydrodynamics (internal energy):

$$\left(\frac{\partial e_{\rm int}}{\partial t}\right)_{\nu_s} = Q_{\rm heat} - Q_{\rm cool}$$

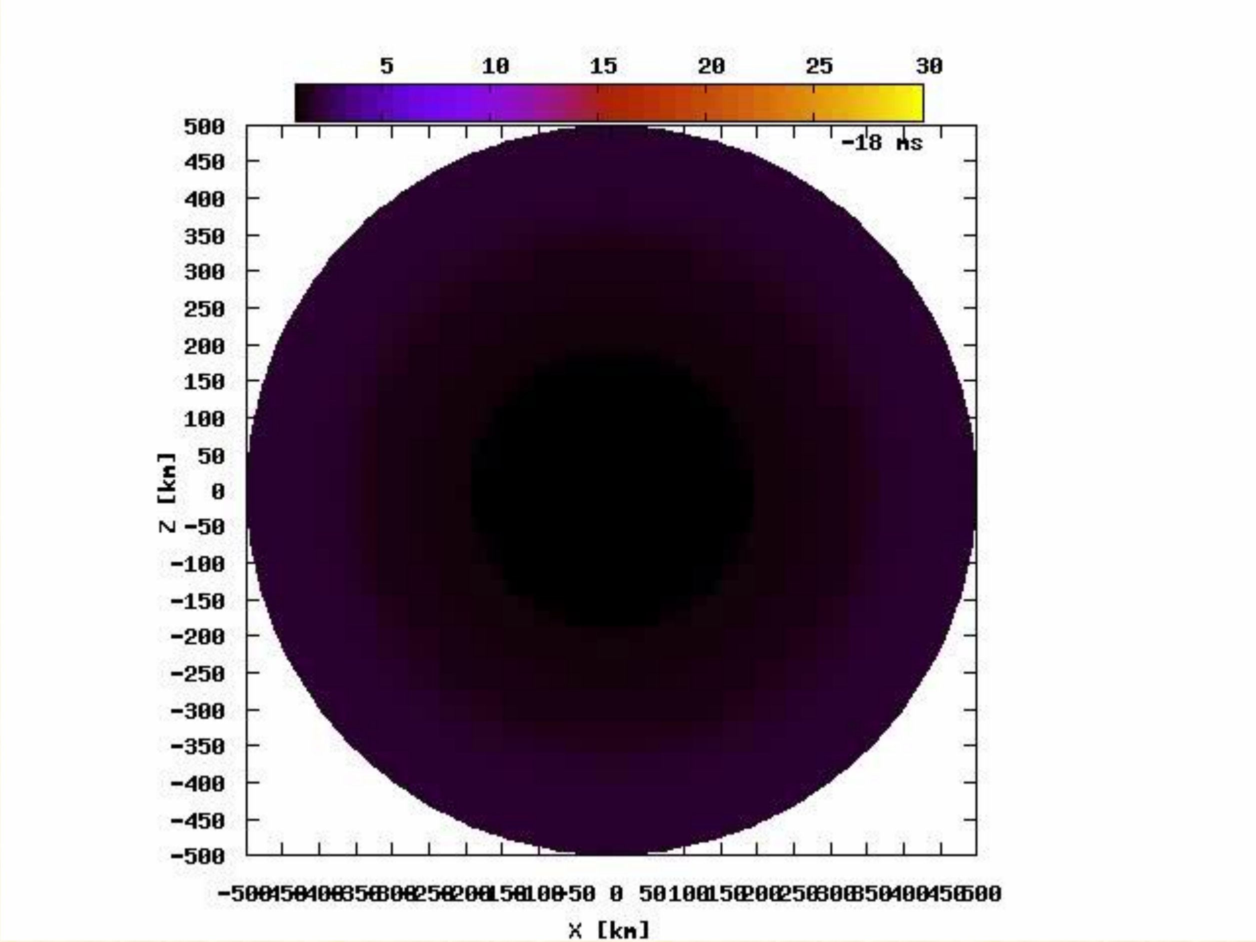
Explosion Mechanism of Core-collapse SNe



SN Models

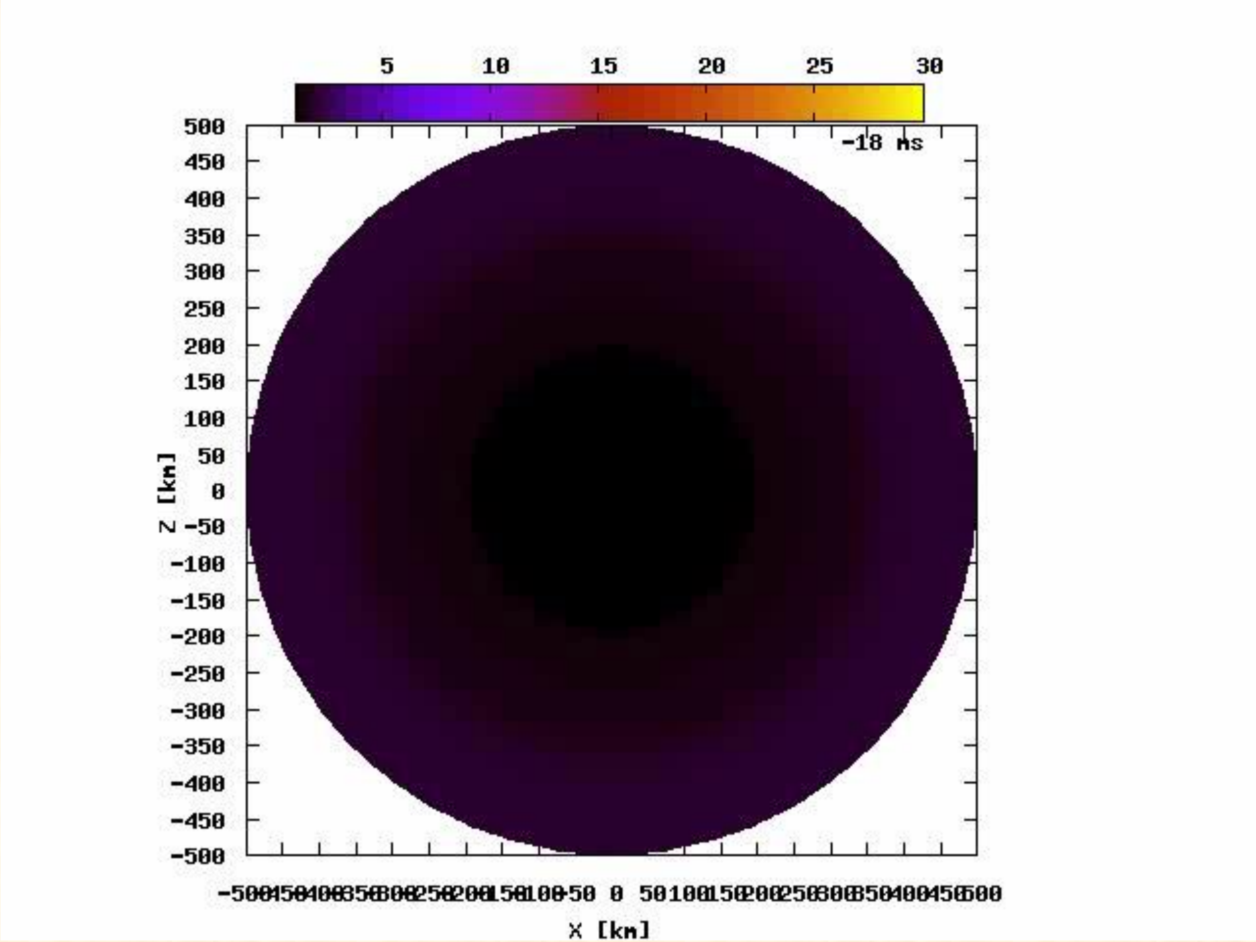
(Entropy plot)

Model without sterile neutrinos



Model with sterile neutrinos

(m_s=200 MeV, $\sin^2\theta$ $=2\times10^{-7}$)



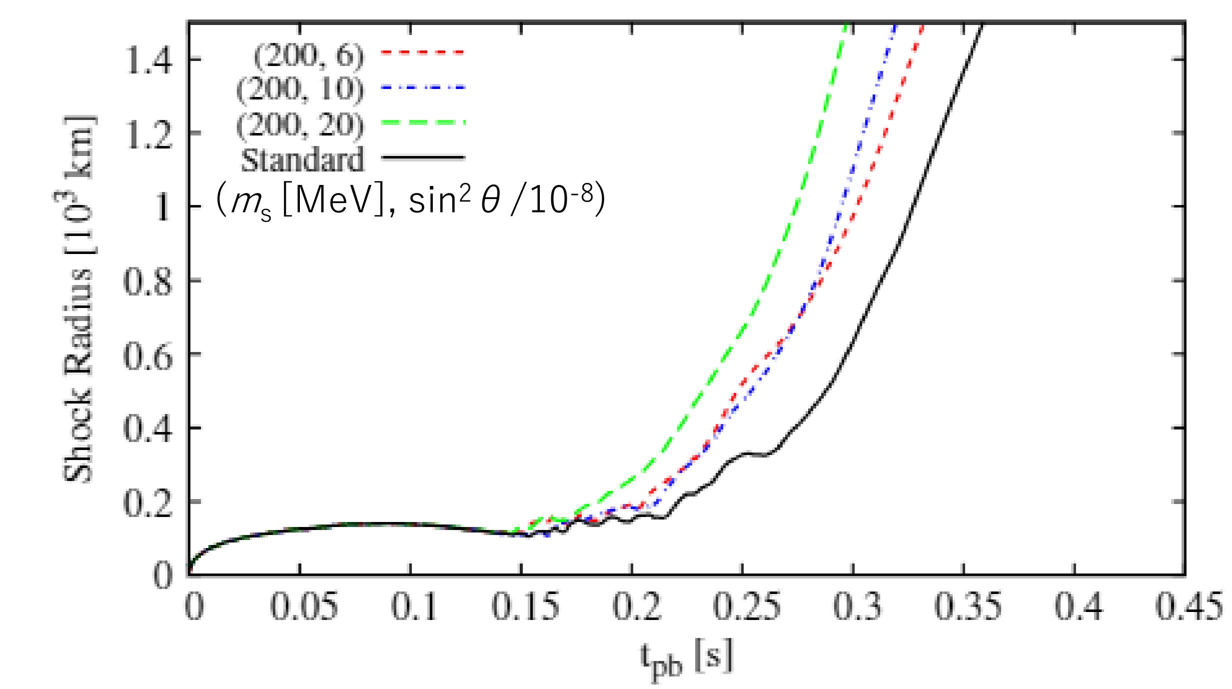
Sterile neutrinos can assist SN explosion!

Shock Radius & Explosion Energy

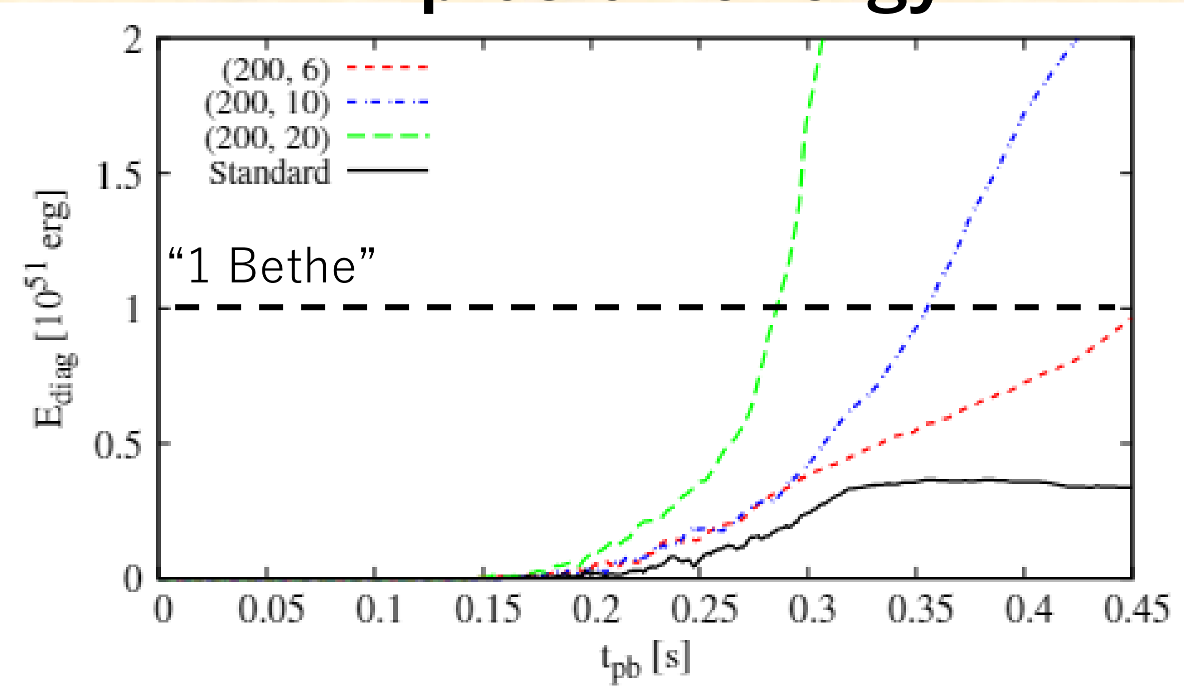
[KM, Takiwaki, Kotake, & Horiuchi, arXiv:2402.14333]

m_s=200 MeV

Shock radius



Explosion energy

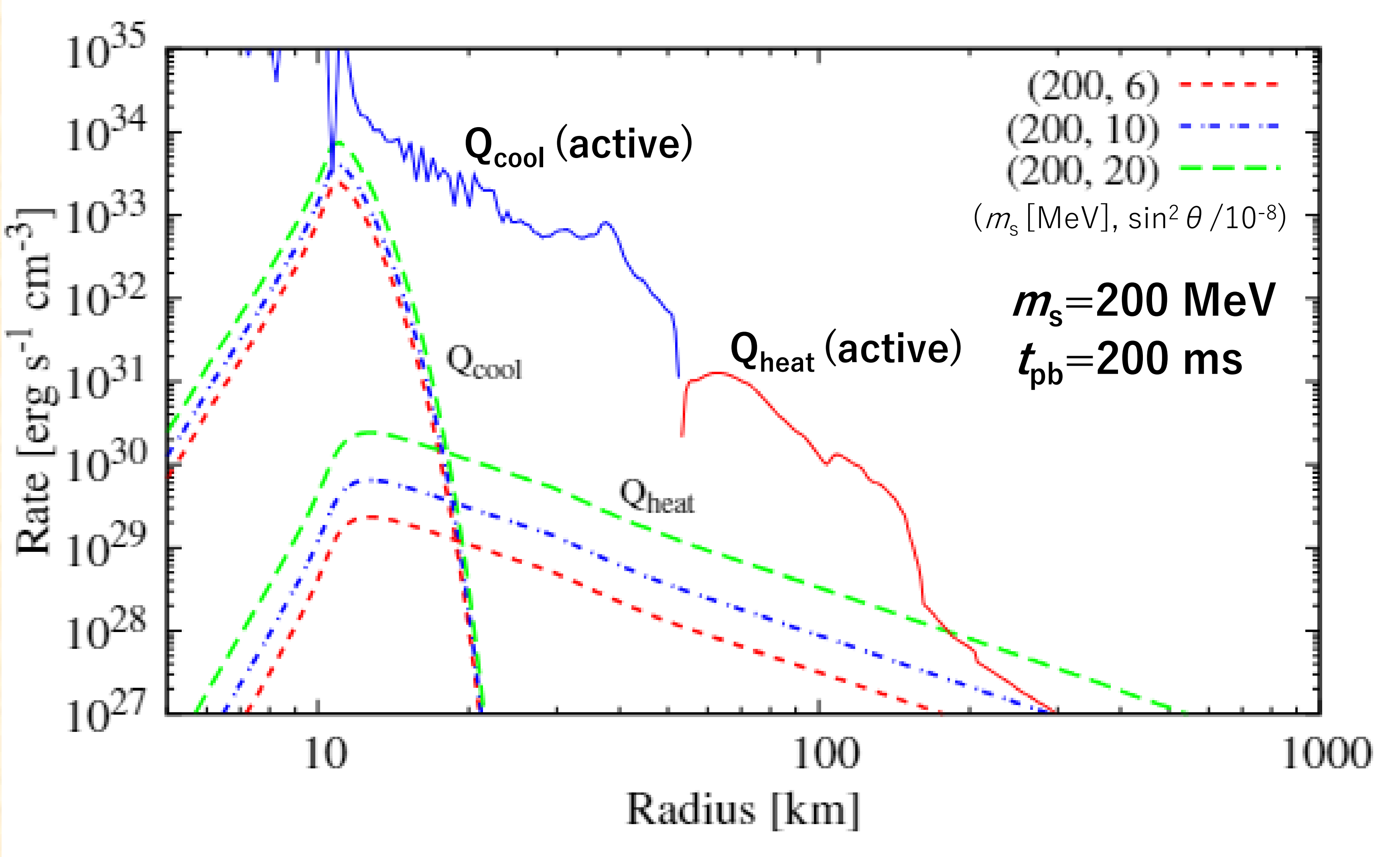


✓**Sterile neutrinos assist the explosion!**

✓Explosion energy exceeds 10^{51} erg if $\sin^2\theta$ >~10^{-7}.

Extra Cooling & Heating Rates

[KM, Takiwaki, Kotake, & Horiuchi, arXiv:2402.14333]

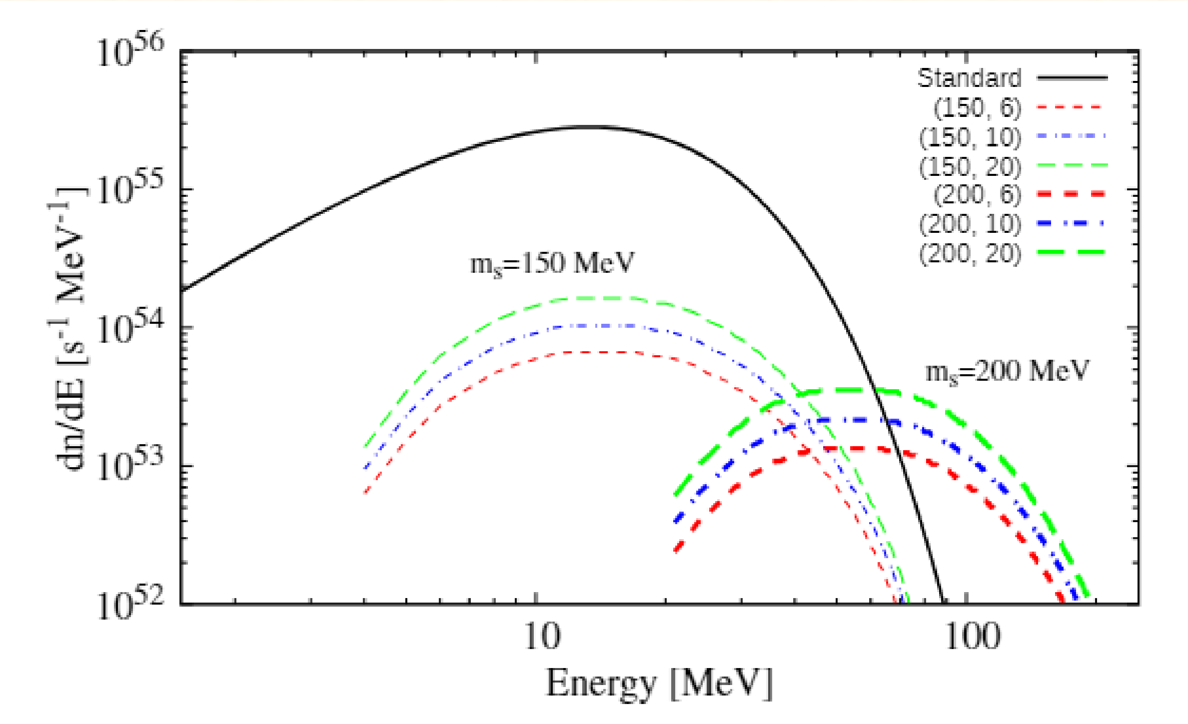


Neutrino Signal

$$\nu_s \to 2\gamma + \bar{\nu}_\tau$$

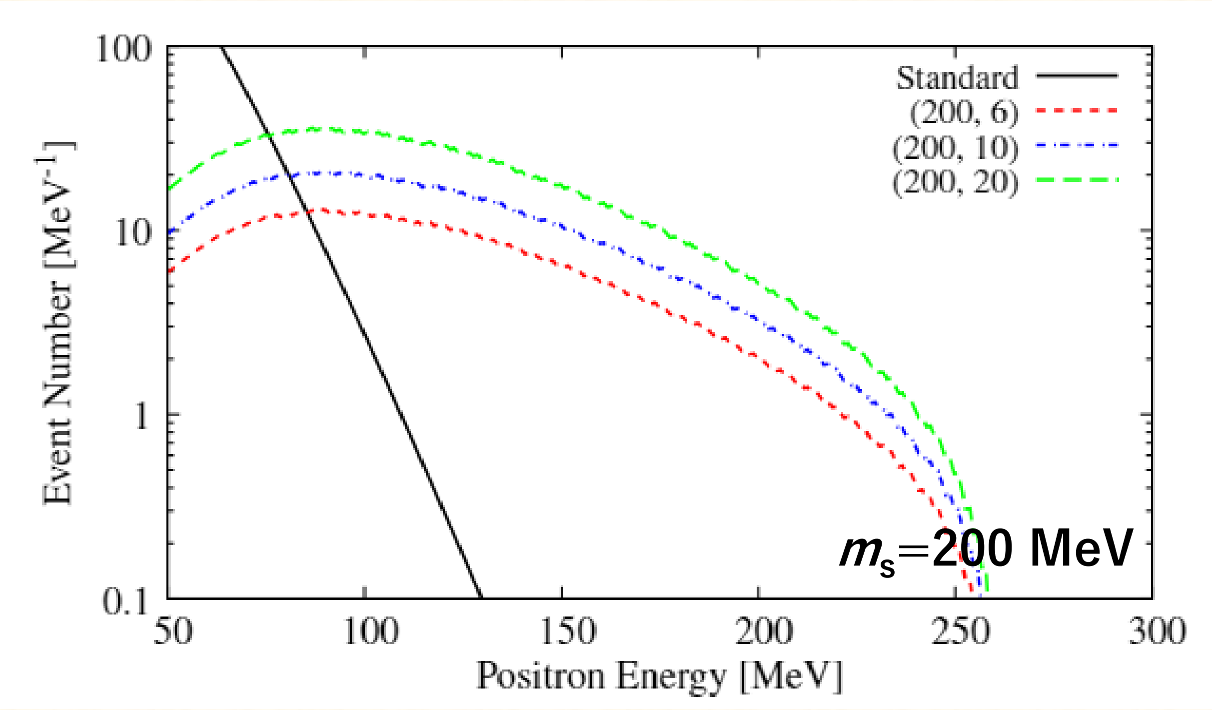
[KM, Takiwaki, Kotake, & Horiuchi, arXiv:2402.14333]

$\bar{\nu}_\tau$ spectrum



Event number @Hyper-K

(SN at the Galactic Center)

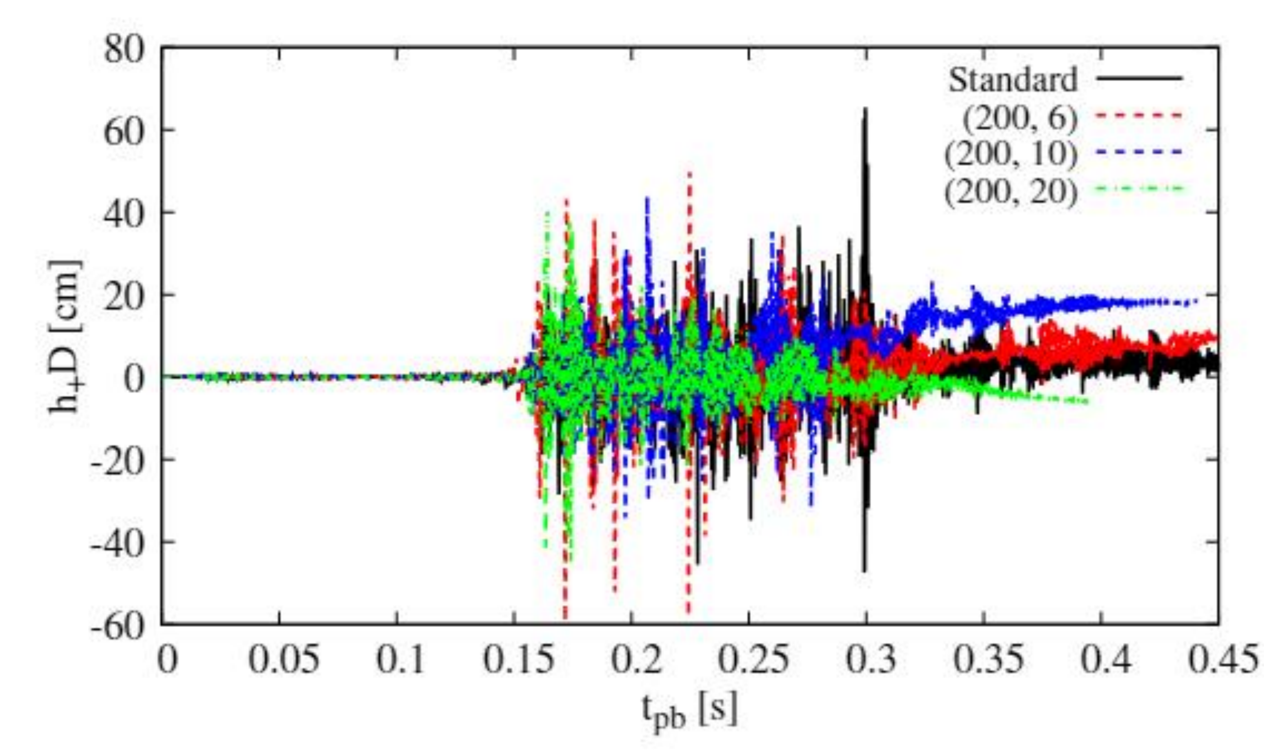


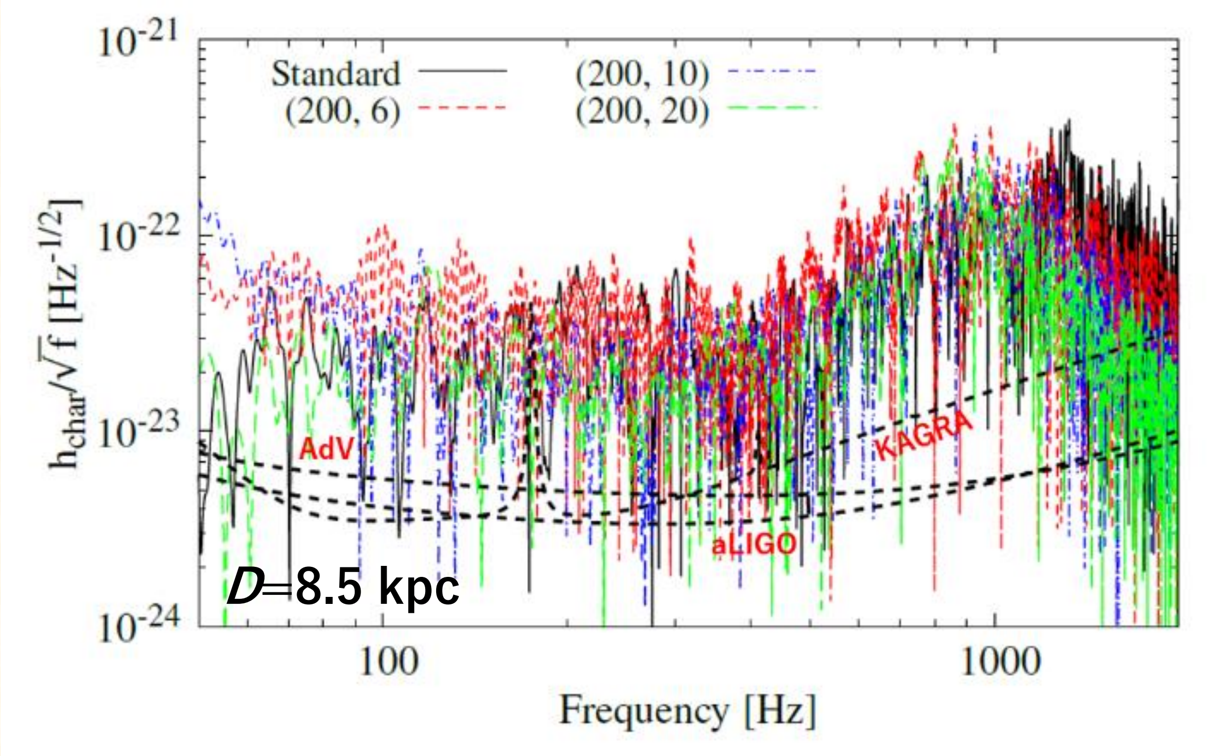
High energy neutrino bump, a smoking gun!

Gravitational Wave Signals

m_s=200 MeV

[KM, Takiwaki, Kotake, & Horiuchi, arXiv:2402.14333]





- **GW signals are weakened.**
- Extra heating prevents the mass accretion.

Summary

Heavy sterile neutrinos (m_s~150-200 MeV) would help SN explosion.

1. Explosion becomes more energetic.
2. A high-energy bump of neutrino signals can appear.
3. GW signals become weaker.

Results for light sterile neutrinos (m_s~1 eV) are under preparation!