# Core-collapse Supernova Explosions Assisted by Heavy Sterile Neutrinos

**Kanji Mori** (NAOJ)

## 1. Sterile neutrinos

**Sterile neutrinos**: Hypothetical right-handed neutrinos

**Motivation**:

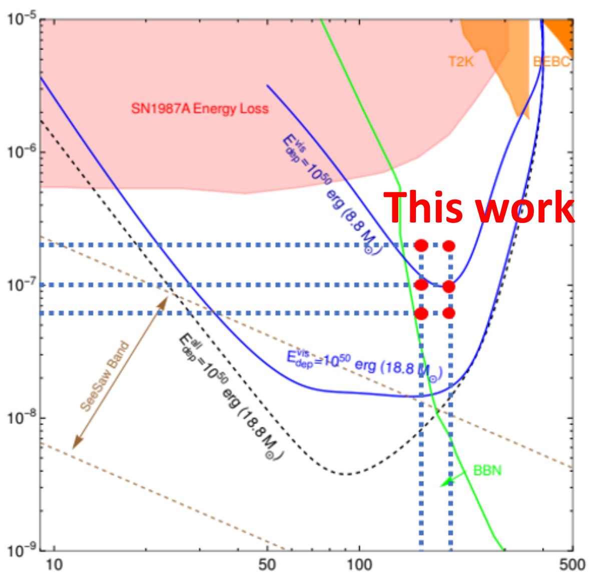
$m_s$ ~ eV → Reactor antineutrino anomaly

$m_s$ ~ keV → Candidate for dark matter

$m_s \gtrsim 100$ MeV → explains active neutrino masses through the seesaw mechanism

We consider mixing between $\nu_s$ and $\nu_\tau$:

$$\nu_\tau = \cos\theta_{\tau 4}\nu_1 + \sin\theta_{\tau 4}\nu_2$$
$$\nu_s = -\sin\theta_{\tau 4}\nu_1 + \cos\theta_{\tau 4}\nu_2,$$




The parameter space for heavy sterile neutrinos [1].

This mixing induces production processes of $\nu_s$ in SNe [1-5]:

$\bar{\nu}_\tau + \nu_\tau \rightarrow \bar{\nu}_\tau + \nu_s$

$\bar{\nu}_\mu + \nu_\mu \rightarrow \bar{\nu}_\tau + \nu_s$

$\nu_\mu + \nu_\tau \rightarrow \nu_\mu + \nu_s$

$\bar{\nu}_\mu + \nu_\tau \rightarrow \bar{\nu}_\mu + \nu_s$

+ their charge conjugate

→ Additional **cooling** of a proto-neutron star

If $\nu_s$ is heavier than $\pi^0$, $\nu_s$ can decay:

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

→ Additional **heating** in a collapsing star

**Question: How can heavy sterile neutrinos affect supernova dynamics?**

## 2. Supernova simulations

We performed SN simulations coupled with the $\nu_s$ transport [6]

**Code:** 3DnSNe-IDSA [7]
**EoS**: LS220 [8]
**Dimension**: 2D
**Progenitor**: $20M_\odot$ [9]

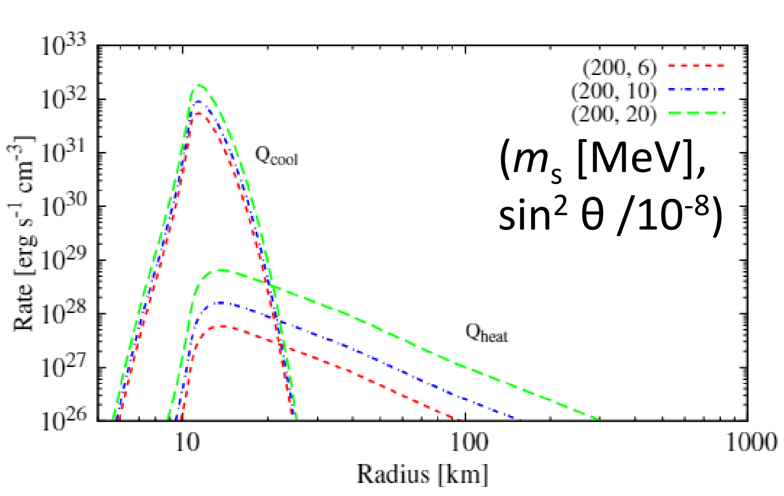
We solve the $\nu_s$ transport equation

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

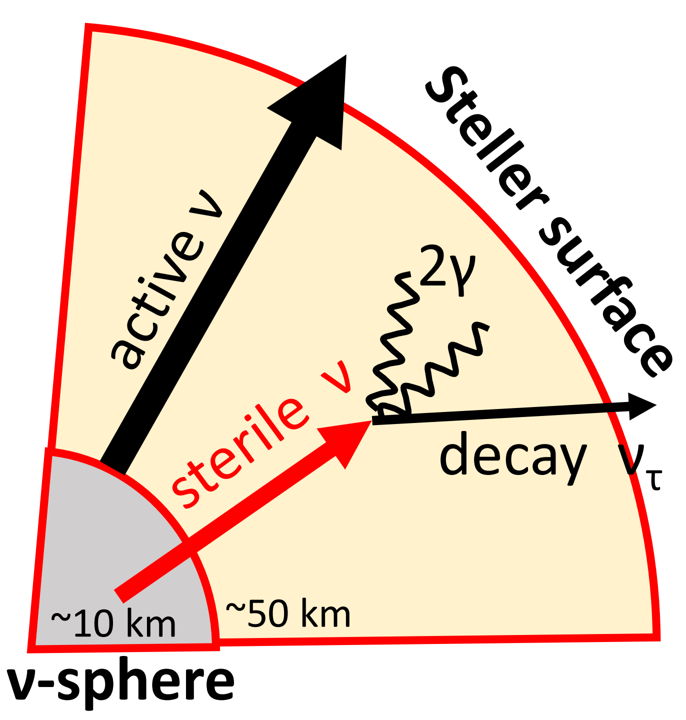
with the ray-by-ray approximation and a closure relation $\mathcal{F} = c\mathcal{E}$.

$\mathcal{E}$ : $\nu_s$ energy density
$\mathcal{F}$ : $\nu_s$ energy flux
κ : $\nu_s$ opacity

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




Cooling and heating rates induced by sterile neutrinos at 0.1 s after the core bounce.

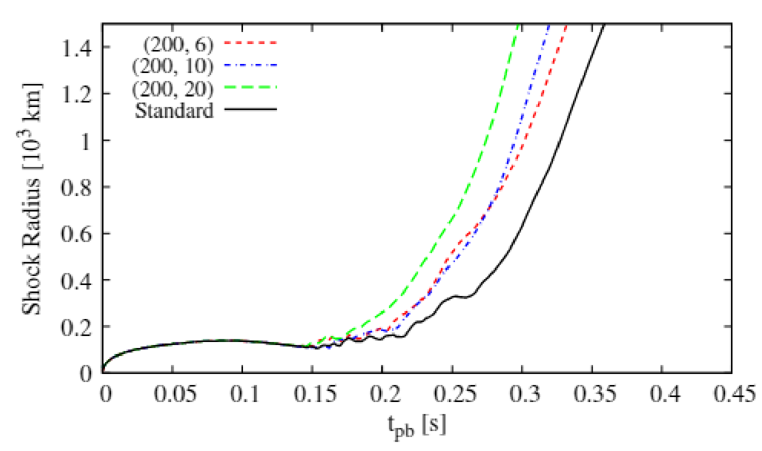



Schematic picture for an SN model with sterile neutrinos.

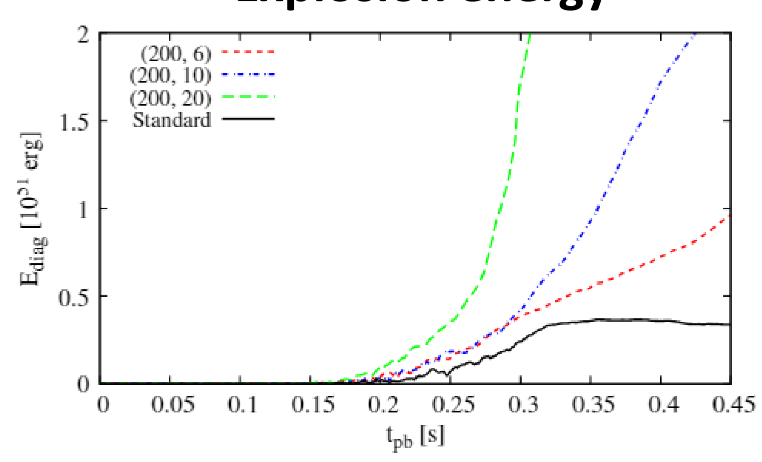
## 3. Results

### 3-A. Explosion properties

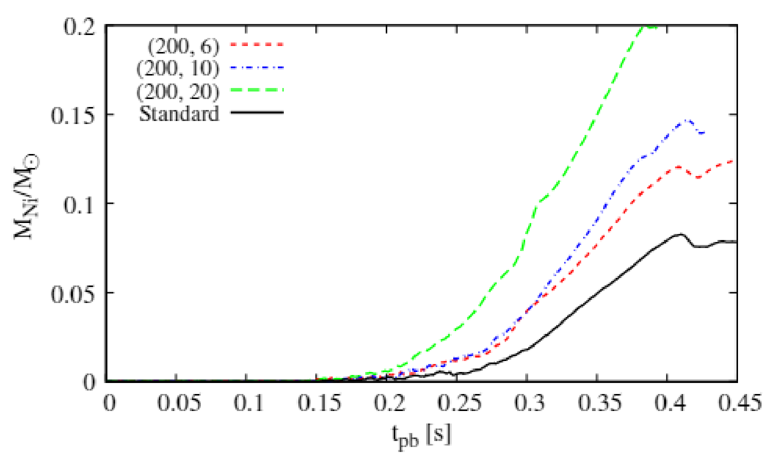
Shock radius




Explosion energy



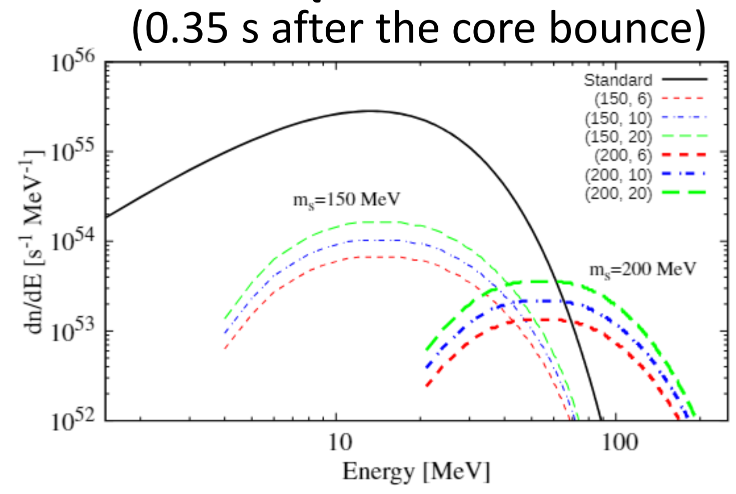

Ni mass




Because of additional heating, $r_{sh}$, $E_{exp}$, and $M_{Ni}$ increase.

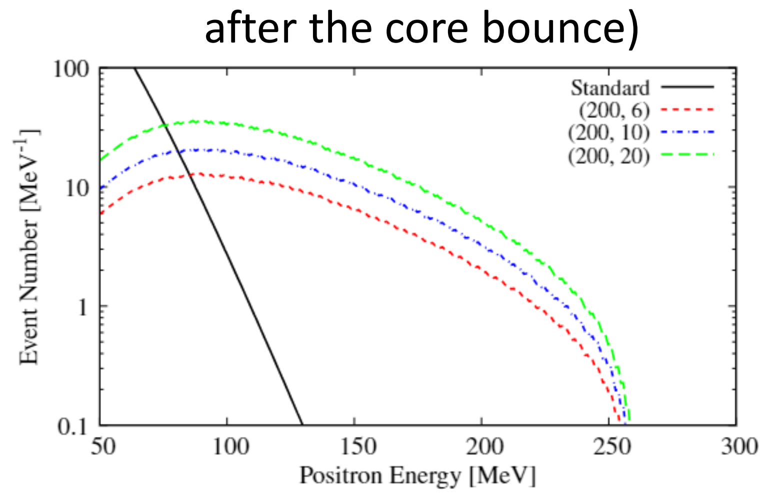
### 3-B. Decay Neutrinos: $\nu_s \rightarrow \pi^0 + \nu_\tau \rightarrow 2\gamma + \nu_\tau$

**$\nu_\tau$ spectrum**
(0.35 s after the core bounce)




When $m_s$=200 MeV, sterile neutrino decay induces a high-energy bump in the $\nu_\tau$ spectrum.

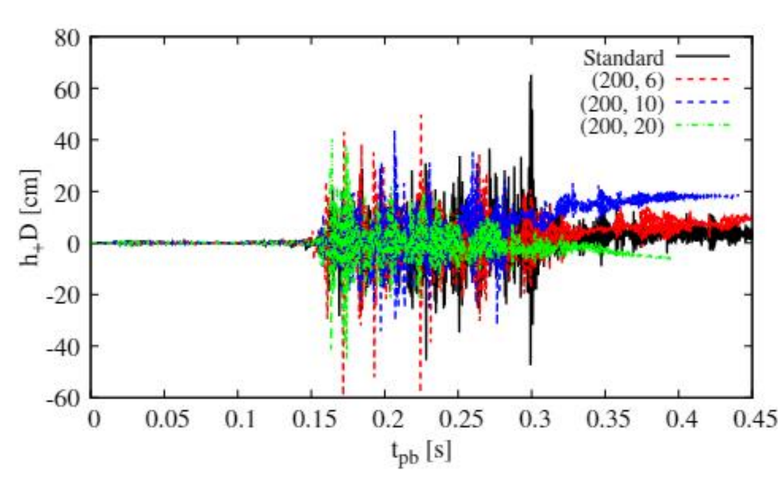
**Event number observed by Hyper-K**
($d$=8.5 kpc, integrated until 0.4 s after the core bounce)




Decay neutrinos could be observed by Hyper-K, if a supernova happens at the Galactic Center.

Decay neutrinos are a smoking gun of sterile neutrinos!

### 3-C. Gravitational waves




Gravitational wave signal becomes weaker because the mass accretion is suppressed.

## 4. Conclusion

We performed 2D SN simulations coupled with heavy sterile neutrinos [6]. We found that the explosion becomes more energetic. A high-energy neutrino bump produced by the sterile neutrino decay would work as a smoking gun of the particles. GW signals would become weaker, but they are still observable if $d$~10 kpc. We are working on eV-mass $\nu_s$ as well, which could explain the reactor anomaly.


**References:**
[1] Chauhan et al. (2023), arXiv:2309.05860
[2] Carenza et al. (2023) arXiv:2311.00033
[3] Mastrototaro et al. JCAP 2020, 010 (2020)
[4] Rembiasz et al. PRD 98, 103010 (2018)
[5] Fuller, Kusenko, & Petraki, PLB 670, 281 (2009)
[6] Mori, Takiwaki, Kotake, & Horiuchi, submitted to PRD, arXiv.2402.14333
[7] Takiwaki, Kotake & Suwa MNRAS 461, L112 (2016)
[8] Lattimer & Swesty NPA 535, 331 (1991)
[9] Woosley & Heger, Phys. Rep. 442, 269 (2007)