軽いステライル・ニュートリノの出現による超新星爆発の失敗

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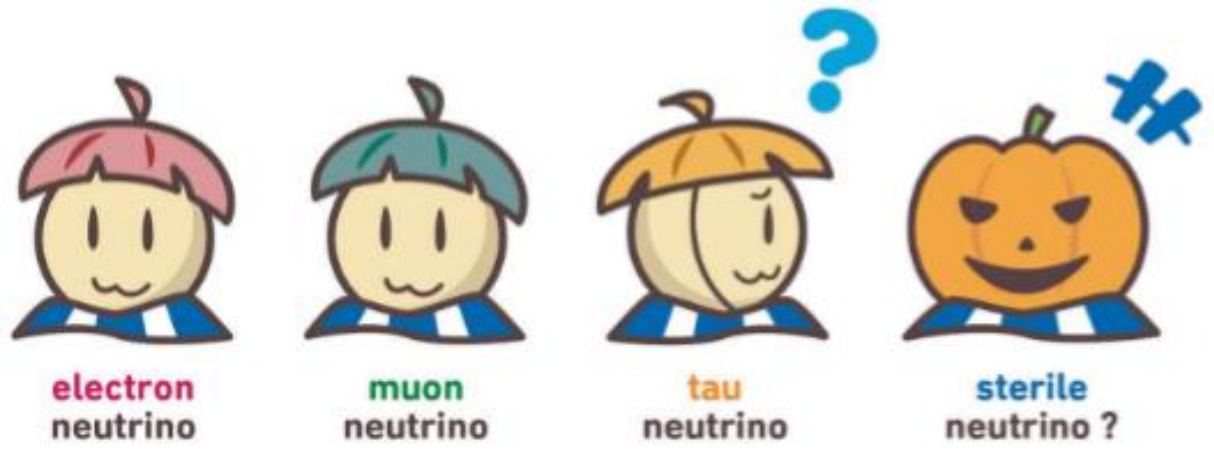
KM, T. Takiwaki, K. Kohri, & H. Nagakura, PRD 111 (2025) 083046.

Light Sterile Neutrinos

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

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

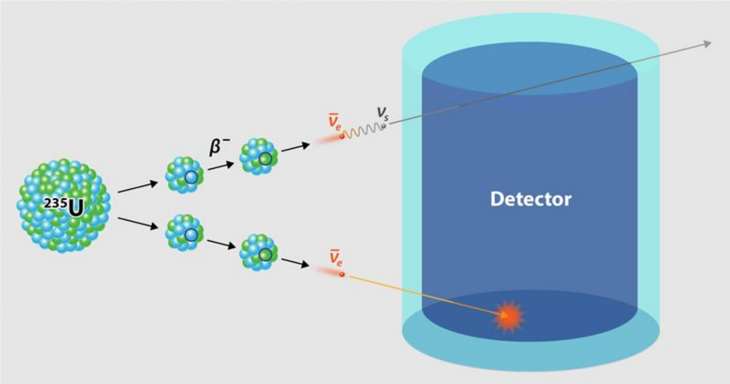
$$\nu_e = \cos\theta\,\nu_1 + \sin\theta\,\nu_2$$
$$\nu_s = -\sin\theta\,\nu_1 + \cos\theta\,\nu_2$$



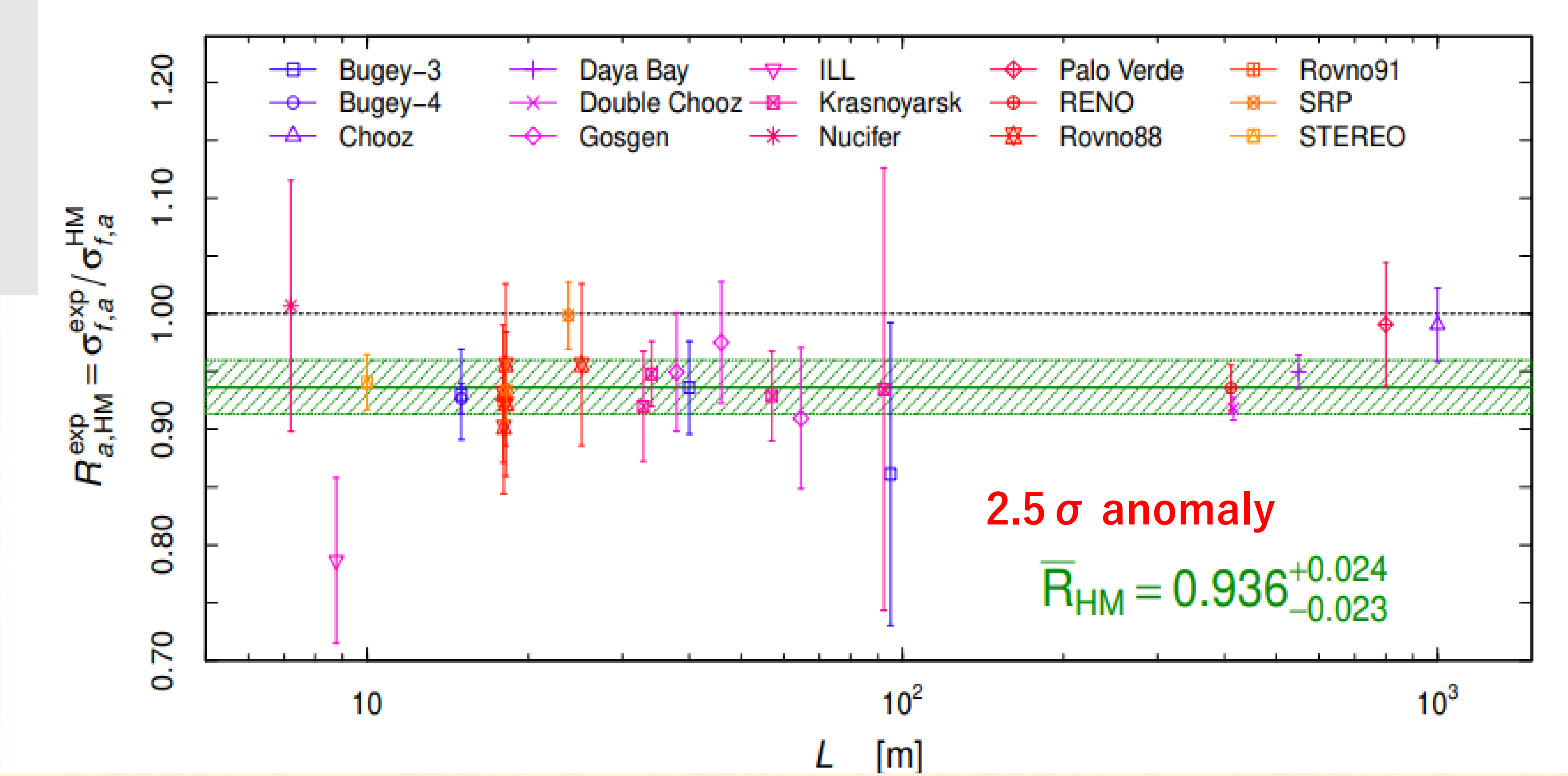
Georgescu, Nature Rev. Phys., 6 (2024) 84.

Reactor Antineutrino Anomaly

[Mention et al., PRD 83 (2011) 073006]



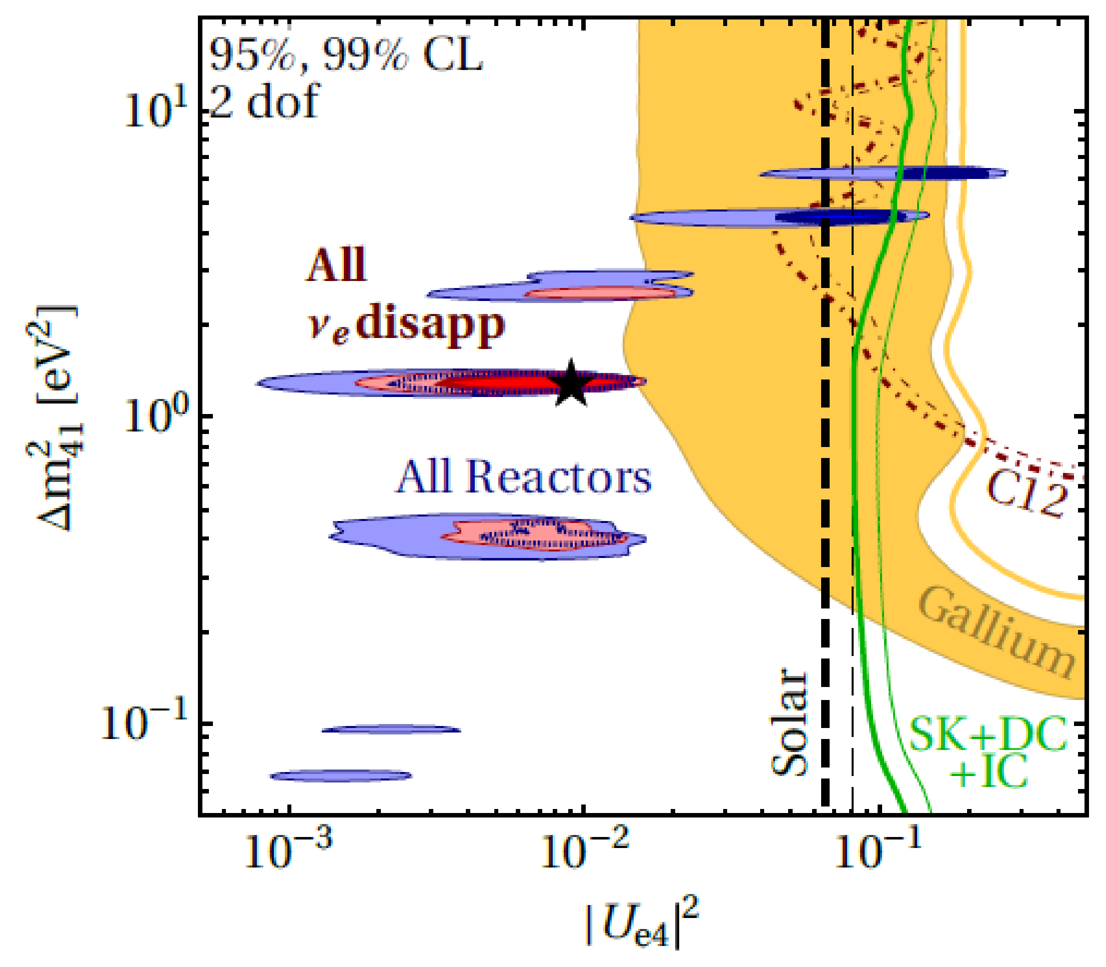
https://physics.aps.org/articles/v10/66



Giunti et al., PLB, 829 (2022) 137054

Deficit in reactor neutrino flux -> A hint of sterile neutrinos?

Parameter Space of Light Sterile Neutrinos

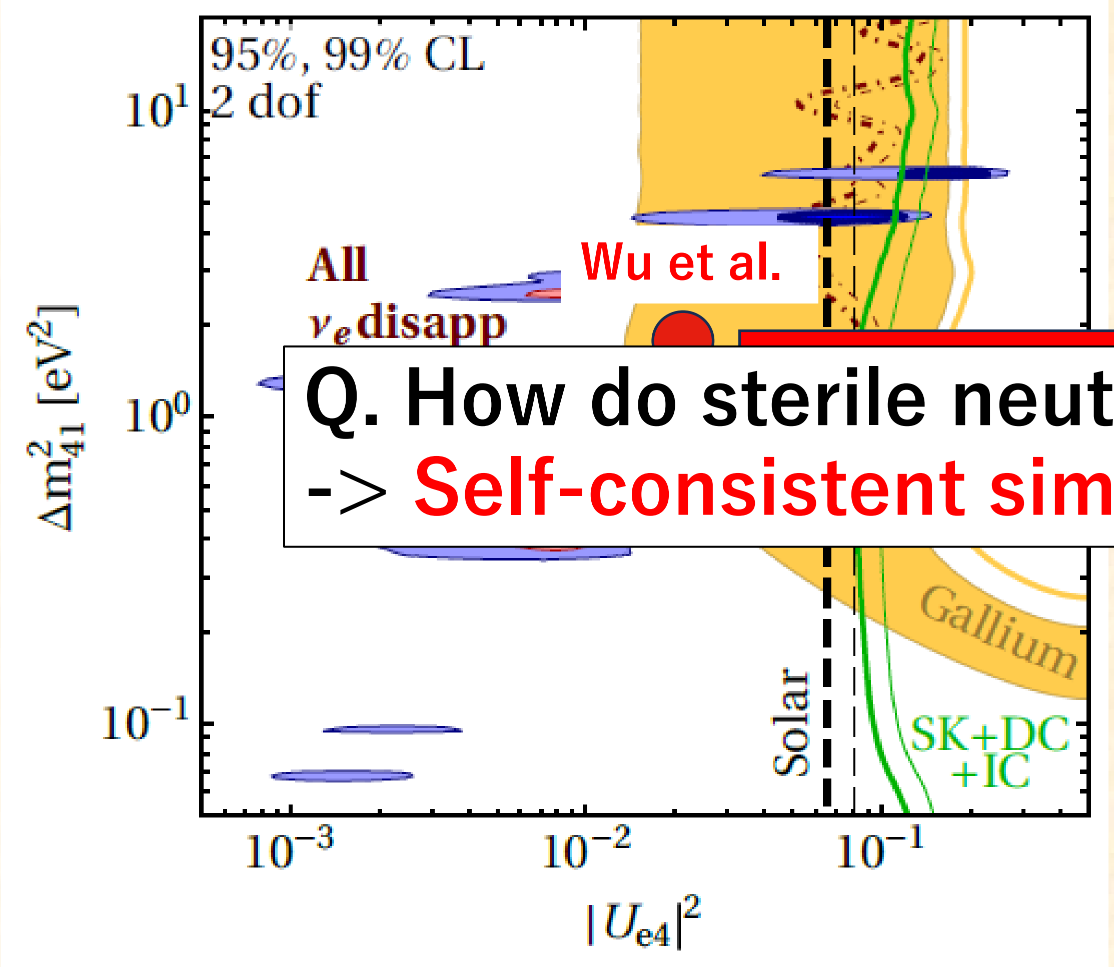


Dentler et al., JHEP 08 (2018) 010

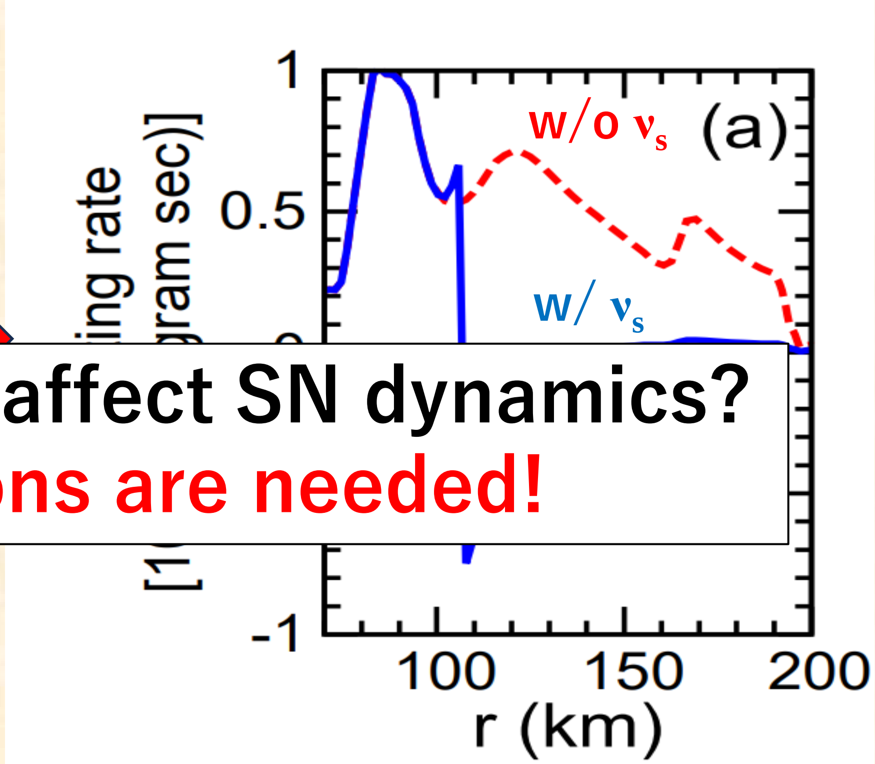
Idea: Active-sterile oscillations can happen in SNe as well.

Kainulainen, Maalampi, Peltoniemi, NPB (1991)
Peltoniemi, A&A (1992)
Raffelt & Sigl, Astropart. Phys. (1993)
Nunokawa et al., PRD (1997)
McLaughlin et al., PRC (1999)
Caldwell et al., PRD (2000)
Fetter et al., Astropart. Phys. (2003)
Beun et al., PRD (2006)
Keranen et al. PRD (2007)
Tamborra et al. JCAP (2012)
Wu et al., PRD (2014)
Pllumbi et al. ApJ (2015)
Xiong, Wu, & Qian, ApJ (2019)
Tang, Wang, & Wu, JCAP (2020)
Ko et al., ApJ (2020)
…

Parameter Space of Light Sterile Neutrinos



Dentler et al., JHEP 08 (2018) 010



Wu et al., PRD 89 (2014) 061303

Q. How do sterile neutrinos affect SN dynamics?
-> Self-consistent simulations are needed!

Neutrino heating rate is significantly reduced.

Neutrino Oscillations in Matter

Neutrino oscillations can be described by the Schrödinger-like equation:

$$i\frac{d}{dr}\vec{\psi}(E,\, r) = H(E,\, r)\vec{\psi}(E,\, r),$$

where the Hamiltonian is

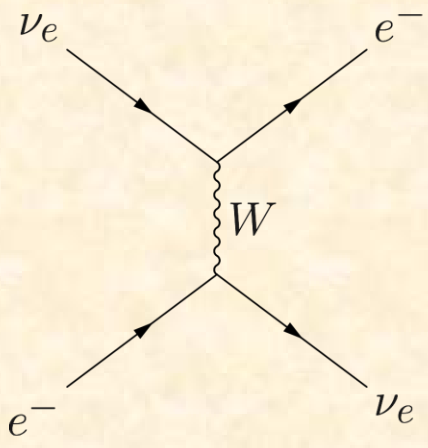
In vacuum

$$H = \frac{\delta m_{\mathrm{v}}^2}{4E}\begin{pmatrix} -\cos 2\theta_{\mathrm{v}} & \sin 2\theta_{\mathrm{v}} \\ \sin 2\theta_{\mathrm{v}} & \cos 2\theta_{\mathrm{v}} \end{pmatrix}$$

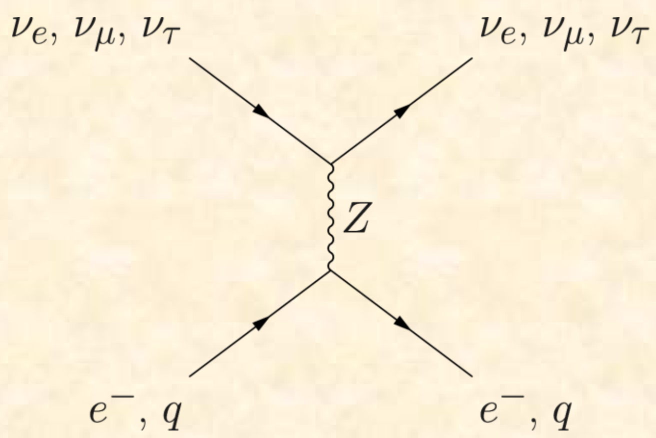
In matter

$$H = \frac{\delta m_{\mathrm{m}}^2}{4E}\begin{pmatrix} -\cos 2\theta_{\mathrm{m}} & \sin 2\theta_{\mathrm{m}} \\ \sin 2\theta_{\mathrm{m}} & \cos 2\theta_{\mathrm{m}} \end{pmatrix}$$

Charged current



Neutral current



https://docs.neutrino.xyz/matter/index.html

$$\tan 2\theta_{\mathrm{m}} = \frac{\tan 2\theta_{\mathrm{v}}}{1 - \frac{2EV_{\mathrm{m}}}{\delta m_{\mathrm{v}}^2 \cos 2\theta_{\mathrm{v}}}}$$ (V_{m}: Matter potential)

When $\frac{\delta m_{\mathrm{v}}^2}{2E}\cos 2\theta_{\mathrm{v}} = V_{\mathrm{m}}$ is satisfied, $\theta_{\mathrm{m}} = \pi/4$.

→ **MSW resonance!**

Active-Sterile Oscillations

MSW resonance condition: $\frac{\delta m_\nu^2}{2E}\cos 2\theta_\nu = V_\mathrm{m}$

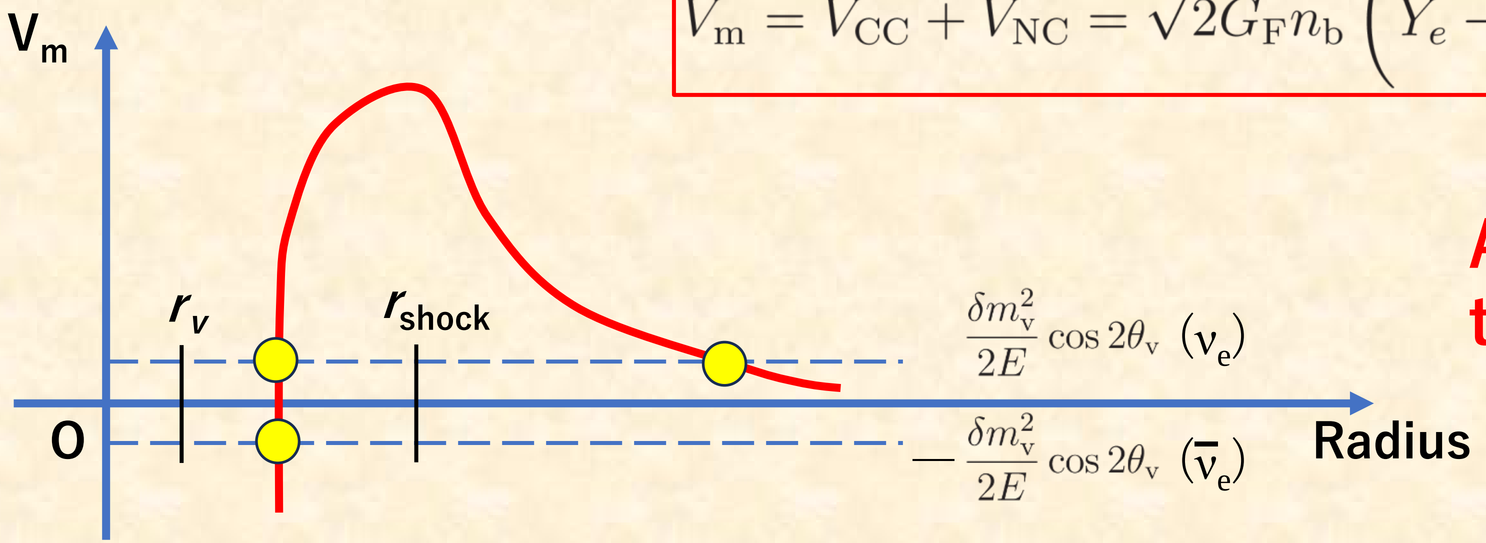
	ν_e	$\nu_{\mu,\tau}$	ν_s
CC	✅	✕	✕
NC	✅	✅	✕

In the case of **active-active oscillations**,
only the charged-current potential is considered:

$$V_\mathrm{m} = V_\mathrm{CC} = \sqrt{2}G_\mathrm{F} n_\mathrm{b} Y_e$$

However, in the case of **active-sterile oscillations**,
the neutral-current potential should be included:

$$V_\mathrm{m} = V_\mathrm{CC} + V_\mathrm{NC} = \sqrt{2}G_\mathrm{F} n_\mathrm{b}\left(Y_e - \frac{1}{2}Y_n\right) = \frac{3\sqrt{2}}{2}G_\mathrm{F} n_\mathrm{b}\left(Y_e - \frac{1}{3}\right)$$



A resonance appears in the post-shock region!

Active-Sterile Oscillations

MSW resonance condition:

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

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

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

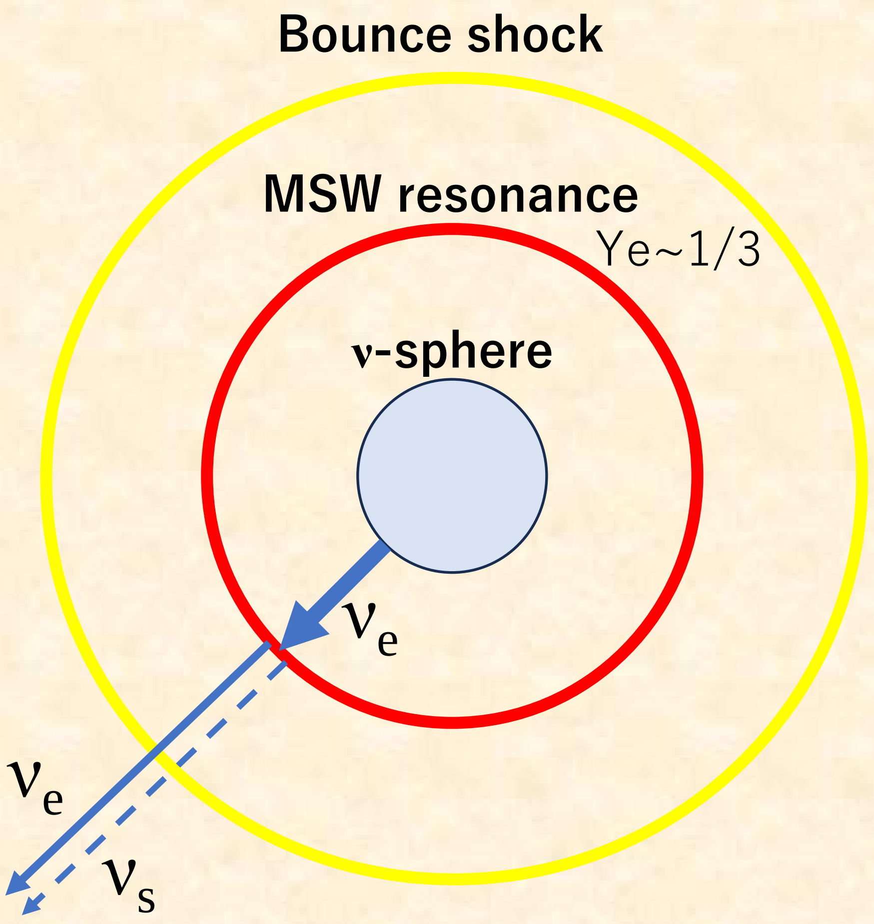
$$\gamma = \Delta_{\mathrm{res}}/l_{\mathrm{osc}}$$

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

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

Since the outer resonance is located at r>1000 km,

we only consider the inner resonance in the simulations.



SN Simulation Coupled with ν_s

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

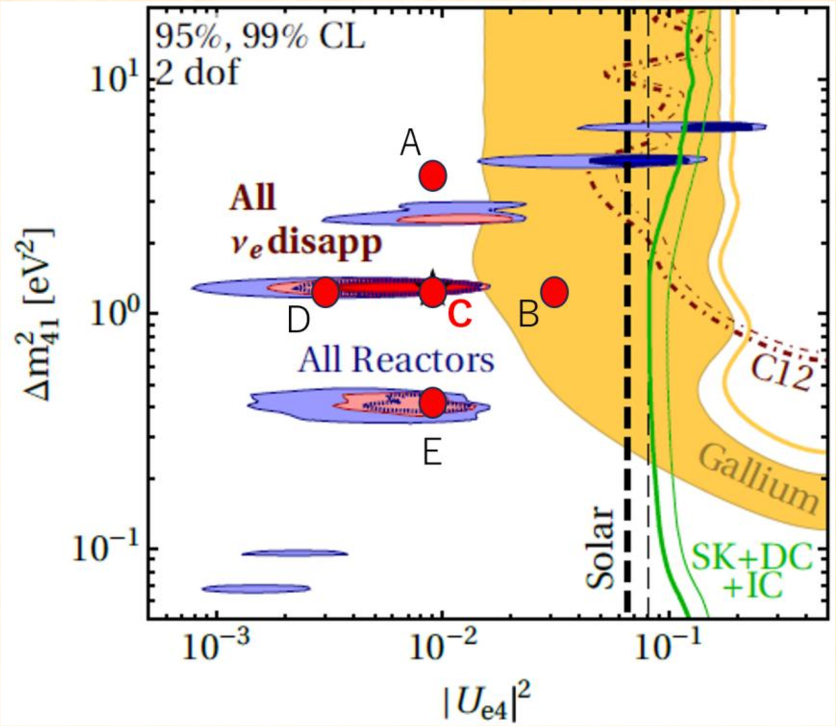
Neutrino transport: IDSA [Liebendörfer, Whitehouse, & Fischer ApJ 698 (2009) 1174]

Dimension: 2D **EoS**: LS220 **Progenitor**: 14+9$M_\odot$ merger model

"SN 1987A progenitor model"

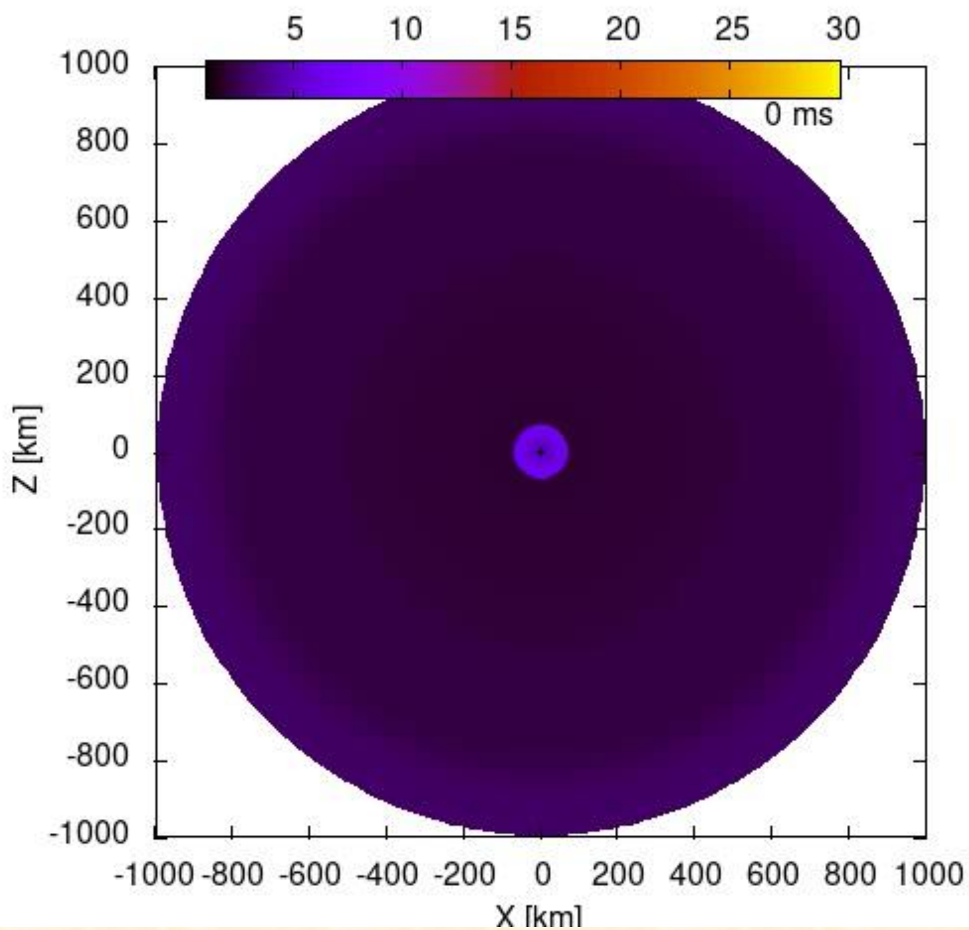
[Urushibata et al., MNRAS 473 (2018) L101]

ν_s mass and
ν_e- ν_s mixing angle:



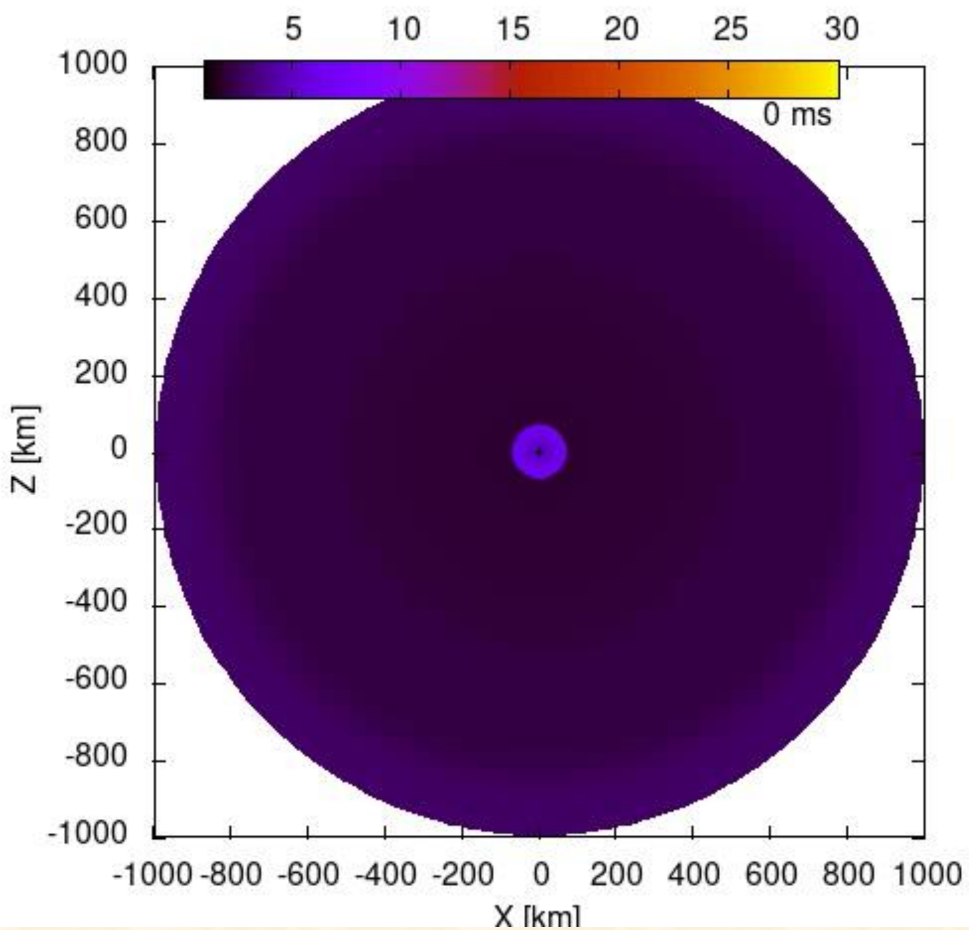
Dentler et al., JHEP 08 (2018) 010

Model NoSterile



Model A

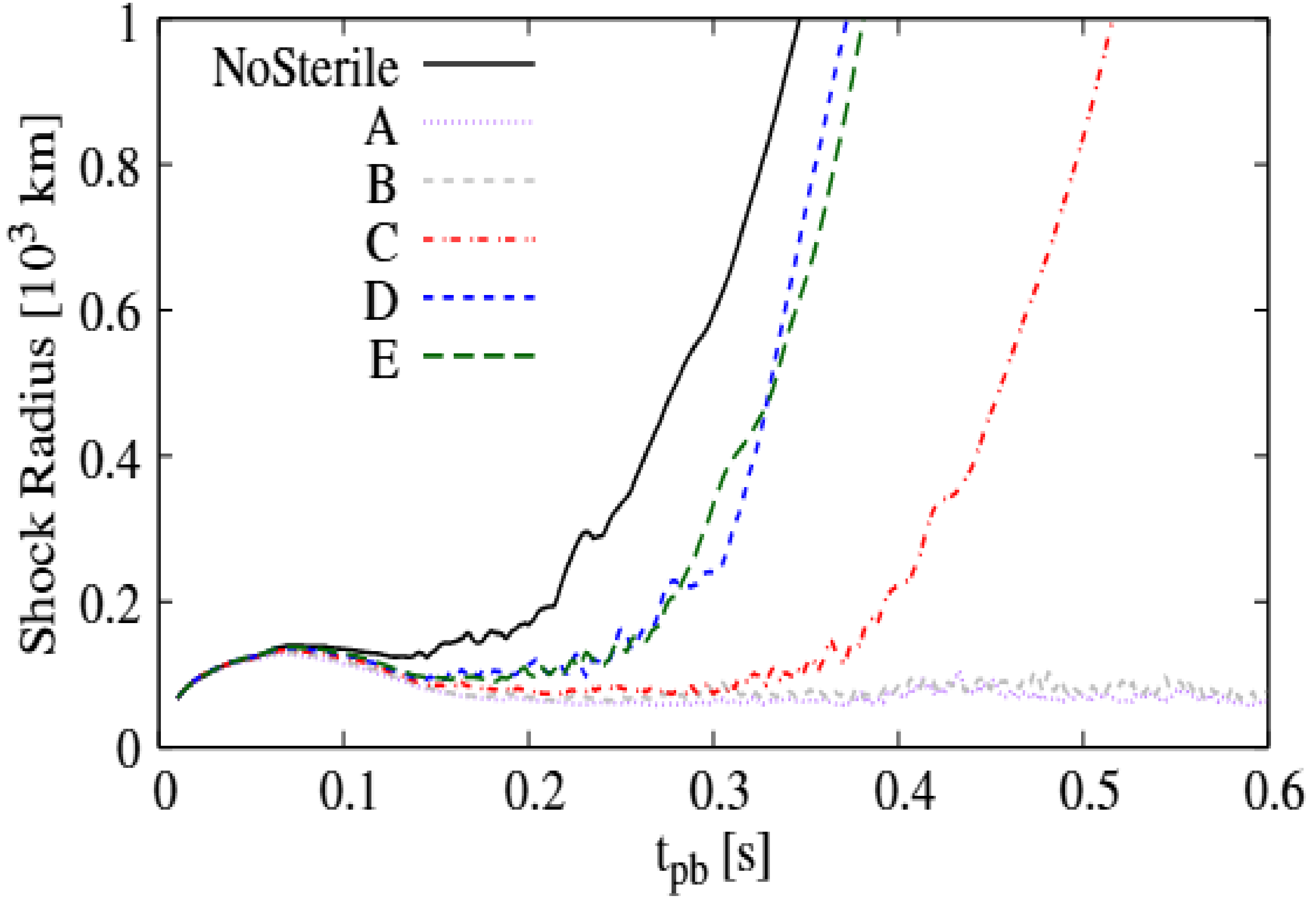
($\delta m^2 = 3.90$ eV^2, $\sin^2 2\theta = 0.040$)



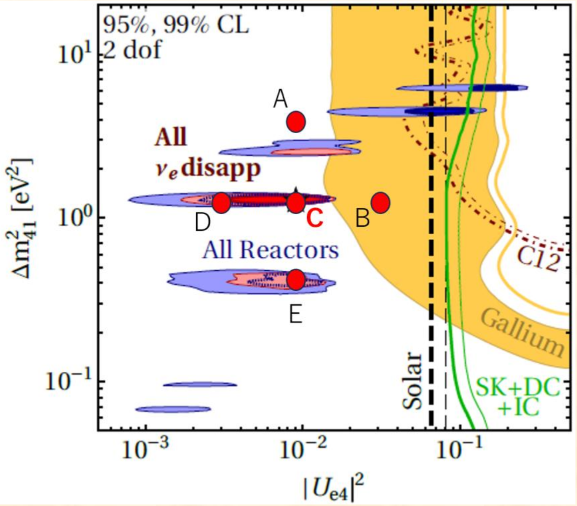
Sterile neutrinos hinder SN explosion!

Shock Radius

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

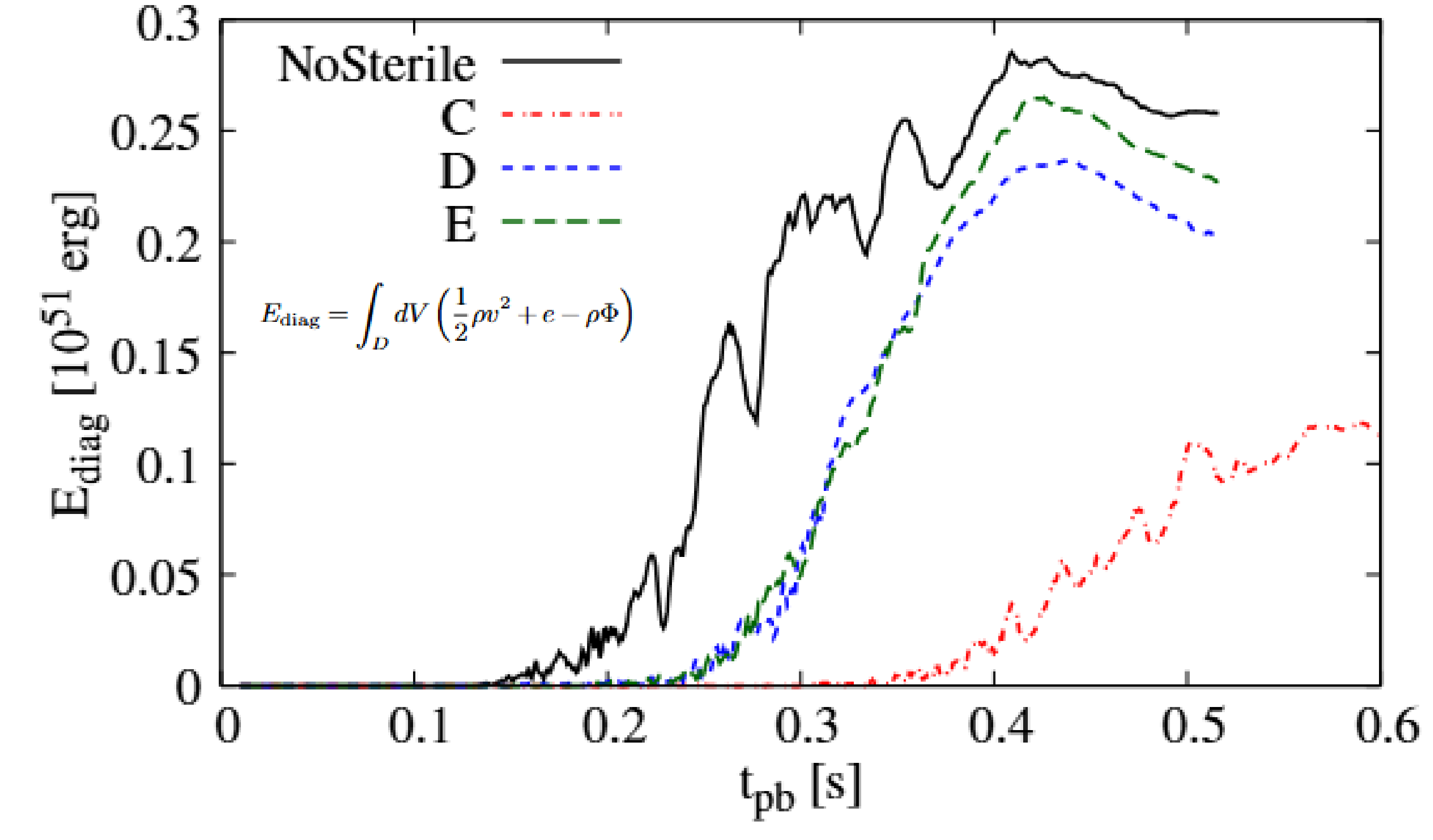


- ✓ When sterile neutrinos are considered, the shock revival is delayed.
- ✓ When $\delta m_s^2 \sin 2\theta$ is sufficiently large, the shock is not revived until the end of the simulations.



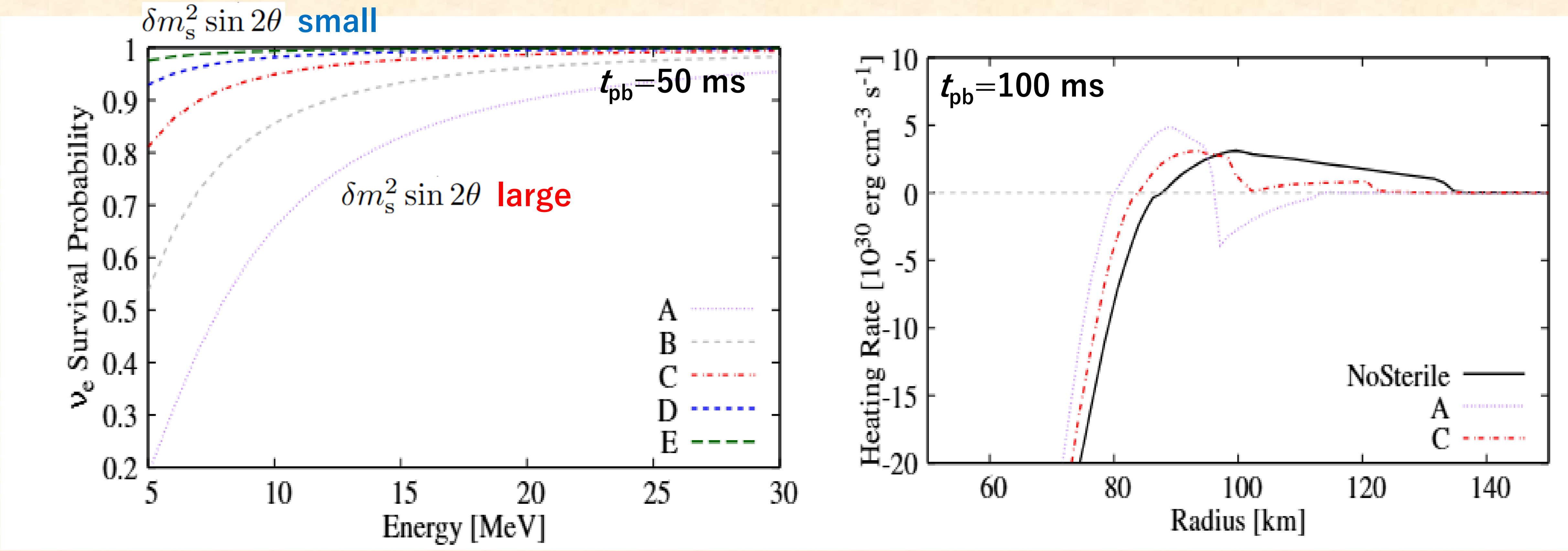
Explosion Energy

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



When sterile neutrinos are considered, **the explosion energy is reduced**.

Active-Sterile Oscillation



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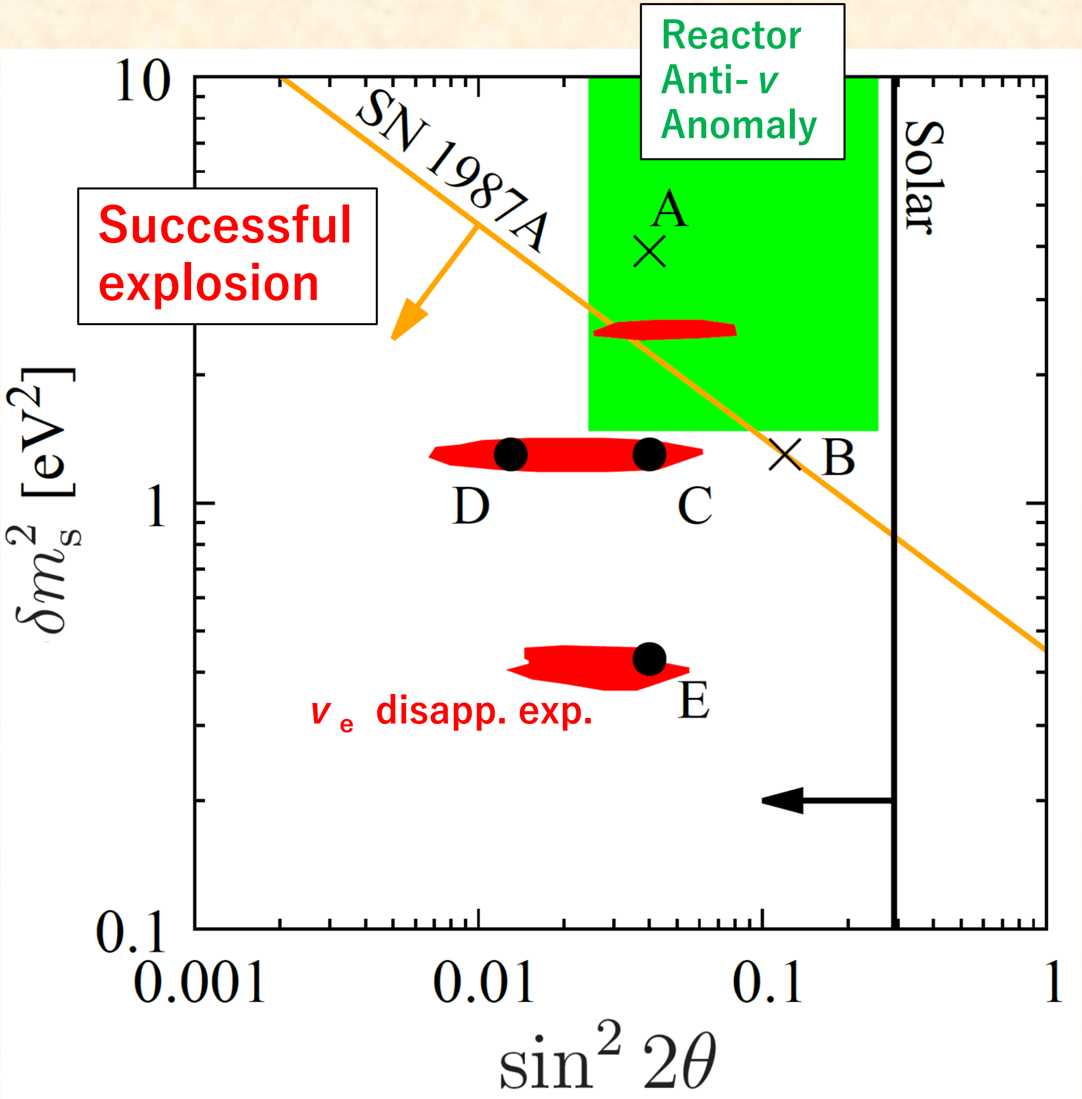
✓ The ν_e survival prob. depends on $\delta m_s^2 \sin 2\theta$

✓ **The neutrino heating rate is reduced!**

SN 1987A Explosion Condition



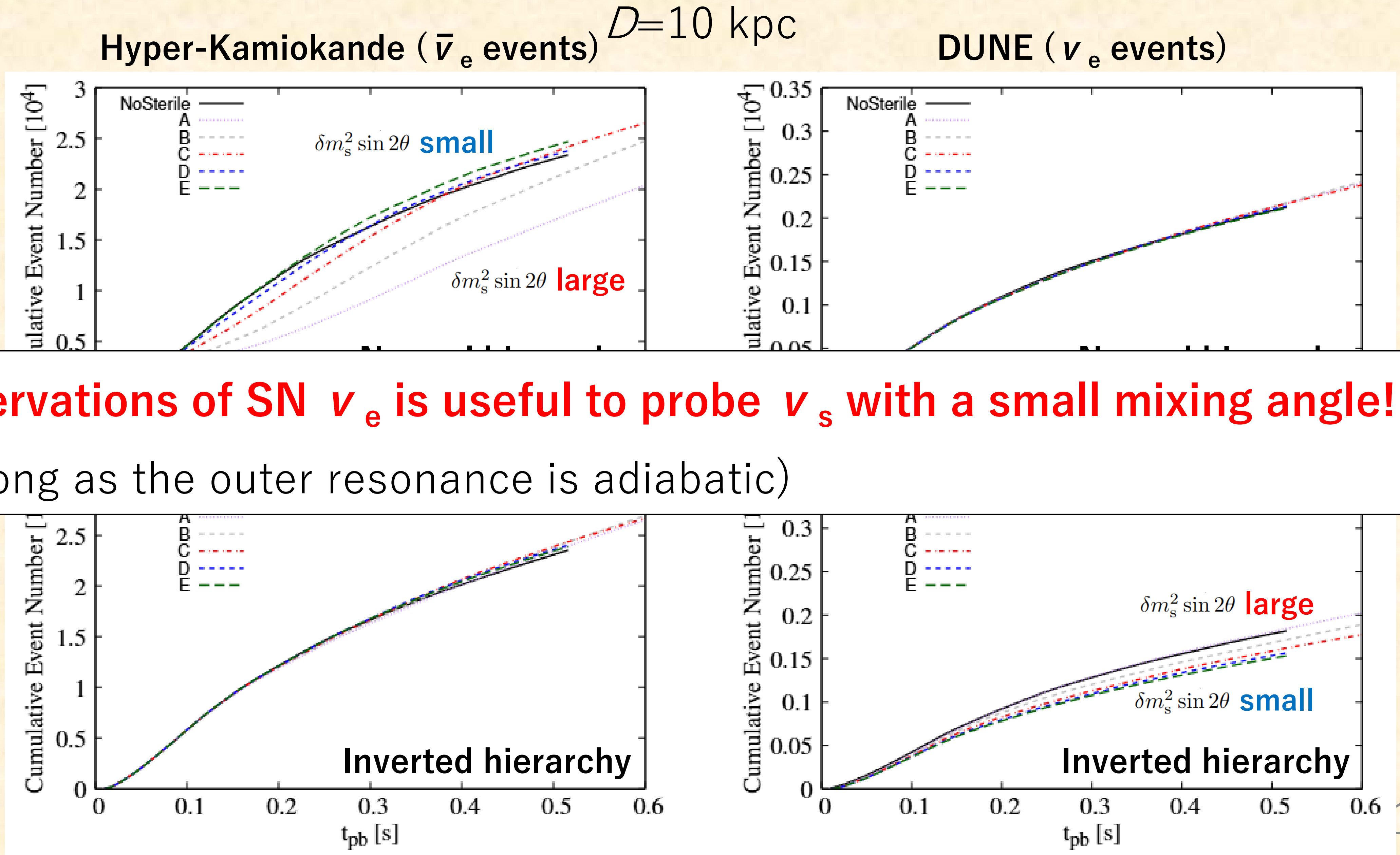
KM, Takiwaki, Kohri, & Nagakura, PRD 111 (2025) 083046.

Condition for successful SN 1987A explosion:

$$\sin 2\theta \lesssim 0.45\,\mathrm{eV}^2/\delta m_s^2$$

SN explodability can provide a new constraint on sterile neutrinos!

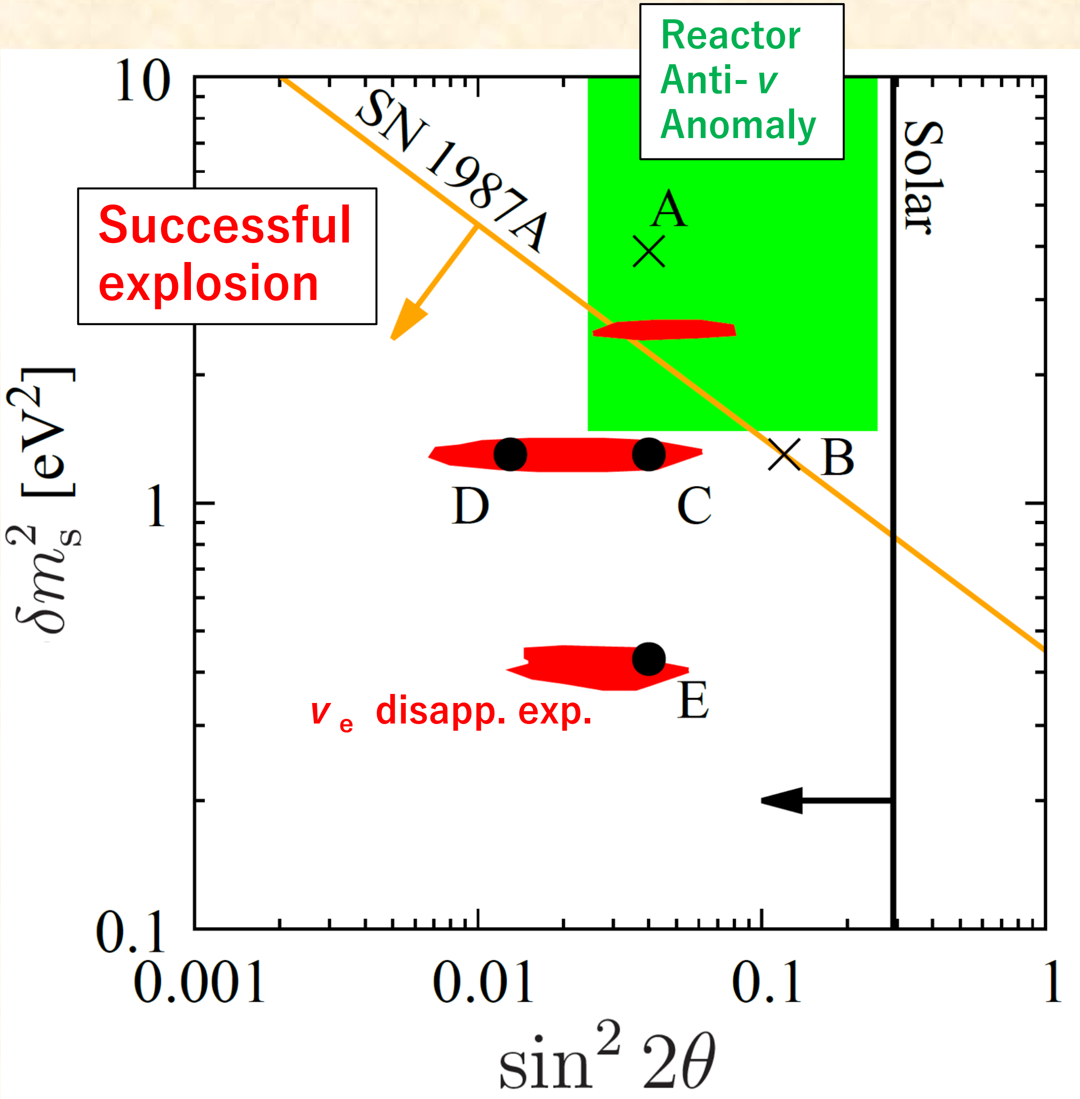
Neutrino Signals



Observations of SN ν_e is useful to probe ν_s with a small mixing angle!

(as long as the outer resonance is adiabatic)

Summary



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

Light sterile neutrinos (m_s~1 eV) would hinder SN explosion.

- A new constraint can be obtained based on explodablity.
- ν_e signals from a nearby SN would provide a stringent constraint on sterile neutrinos.