ステライル・ニュートリノを考慮した多次元超新星爆発シミュレーションの実現

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Messengers from a Supernova

Known particles

Photons γ

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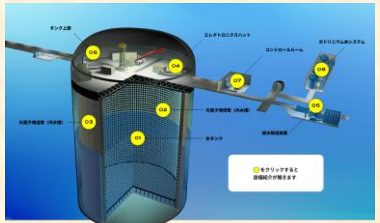
Neutrinos ν



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Gravitational waves

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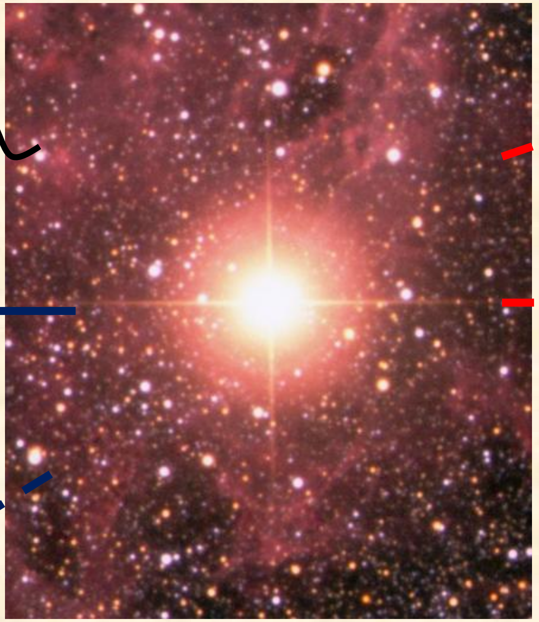
SN 1987A



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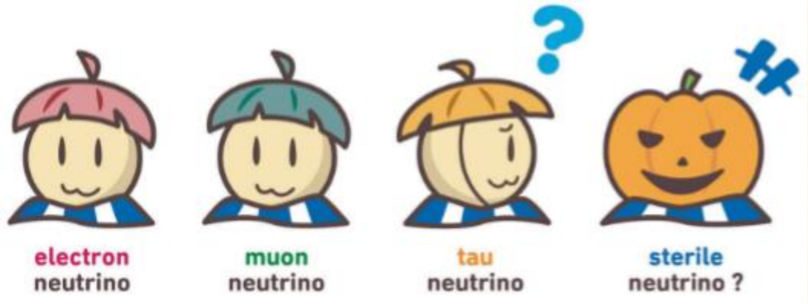
Exotic particles

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**

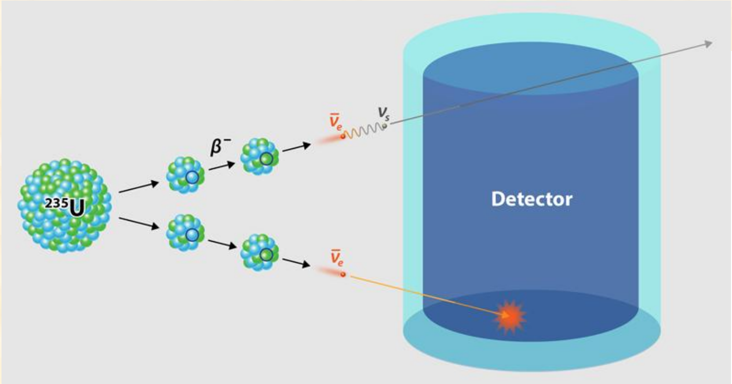
e.g. KM et al., PRD 111 (2024) 083046.
Rembiasz et al., PRD 98 (2018) 103010



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

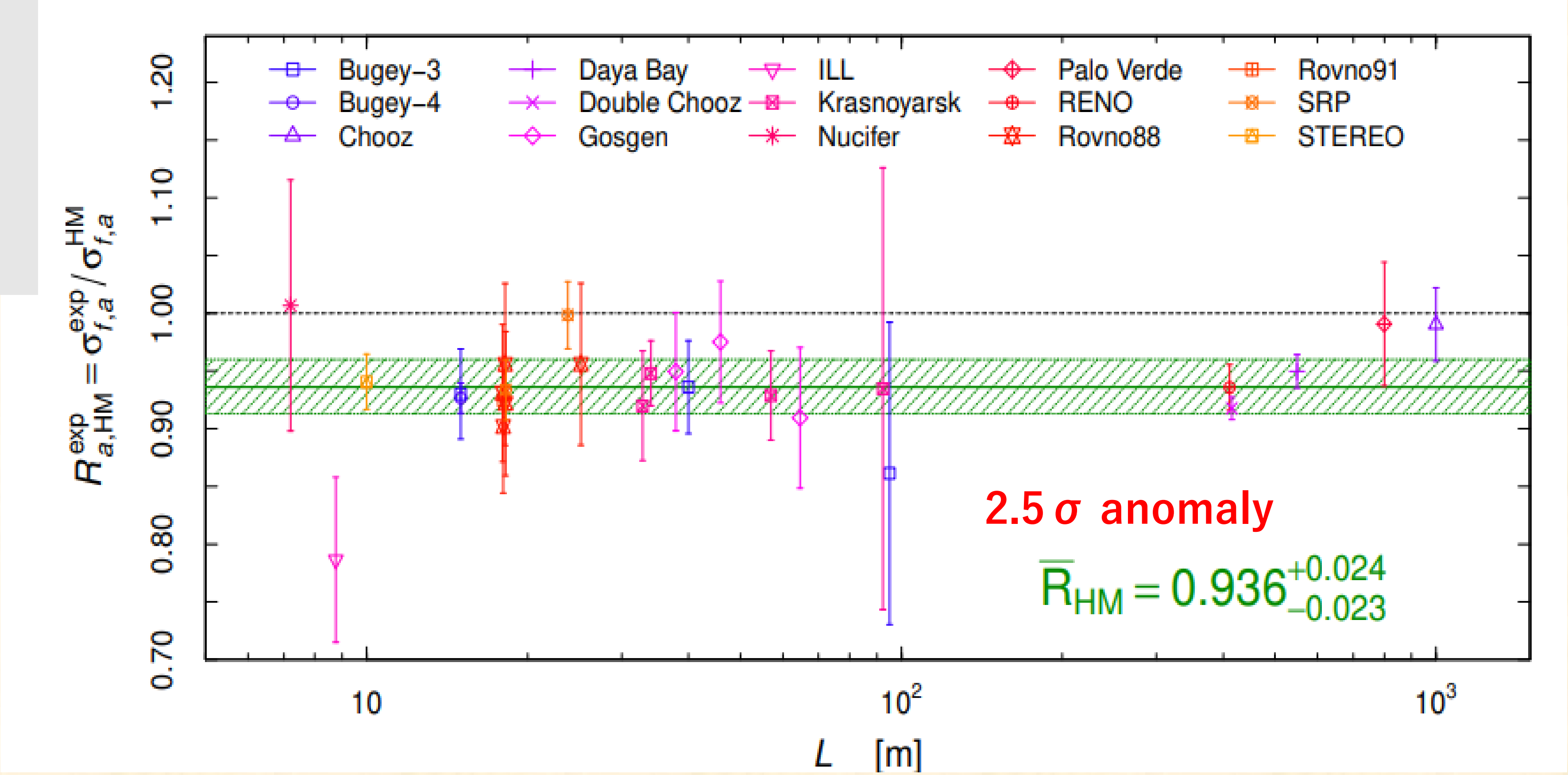
Reactor Antineutrino Anomaly

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



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

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



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

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

keV-mass Sterile Neutrinos as Dark Matter

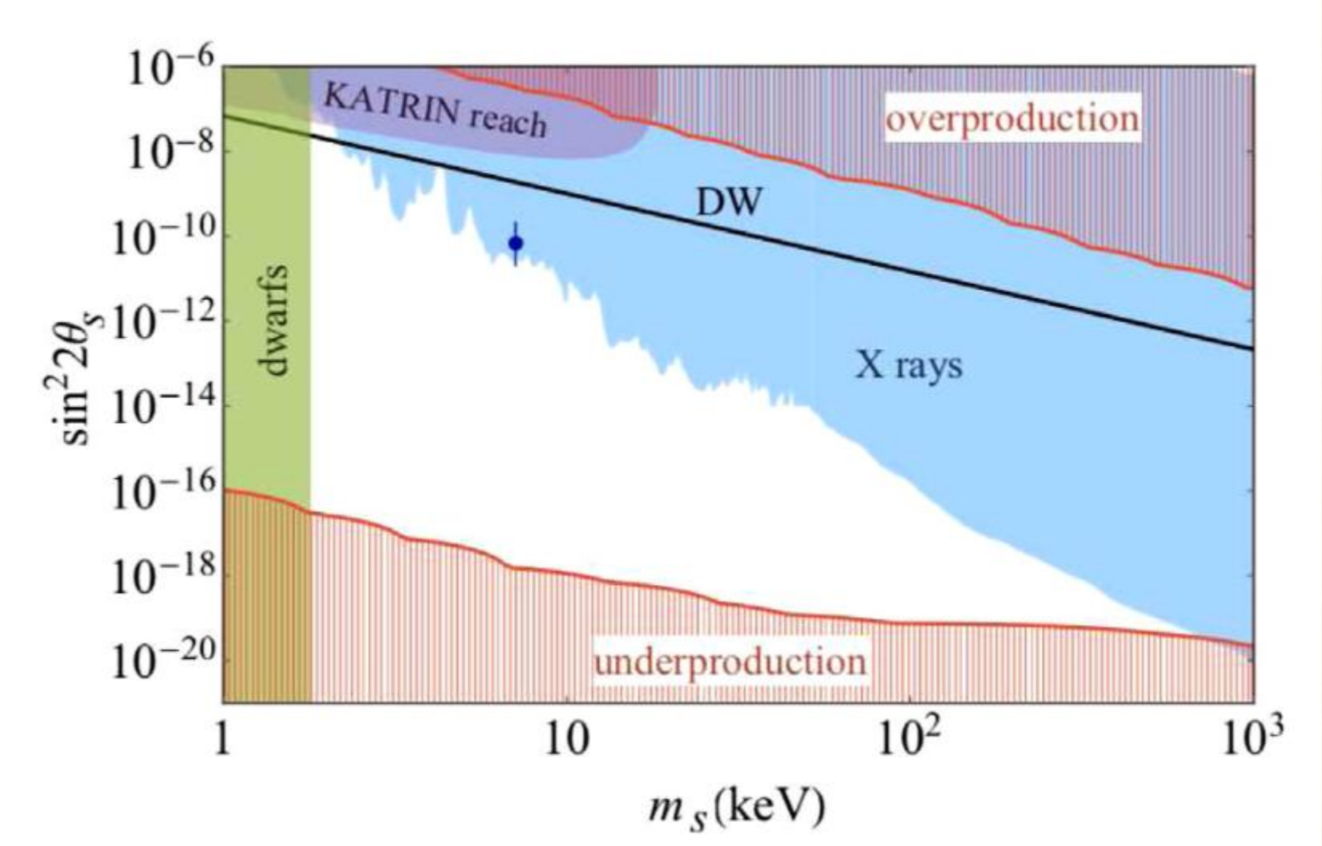
Cosmological production

- Collisional production

  [Dodelson & Widrow, PRL 72 (1994) 17]

- MSW effect

  [Shi & Fuller PRL 82 (1999) 2832]



Gouvêa et al., PRL 124 (2020) 081802

keV-mass sterile neutrinos can make up all the DM!

Towards Multi-D SN Simulations with Sterile Neutrinos

	原子炉ニュートリノ異常の説明	暗黒物質の正体	シーソー機構
ν_s質量	~eV	~keV	>MeV
3D	本研究計画	本研究計画	本研究計画
2D	Mori et al. (2025)	本研究計画	Mori et al. (2024)
1D	Xiong et al. (2019)	Warren et al. (2014)	Rembiasz et al. (2018)
ポストプロセス	Wu et al. (2014)	Fuller et al. (2003)	Fuller et al. (2009)

現実的超新星モデル

Active-Sterile Oscillations

[e.g. KM, Takiwaki, Kohri, & Nagakura, PRD 111 (2025) 083046]

MSW resonance condition:

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

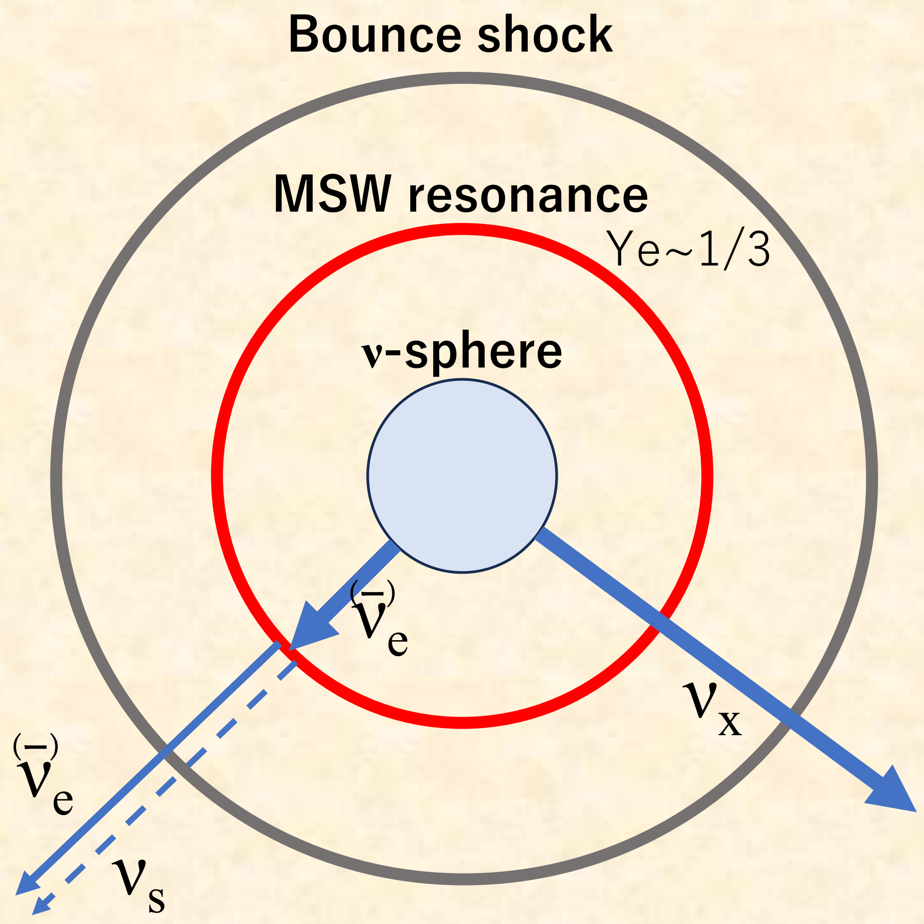
The conversion prob. is given by the Landau-Zener formula

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

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

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

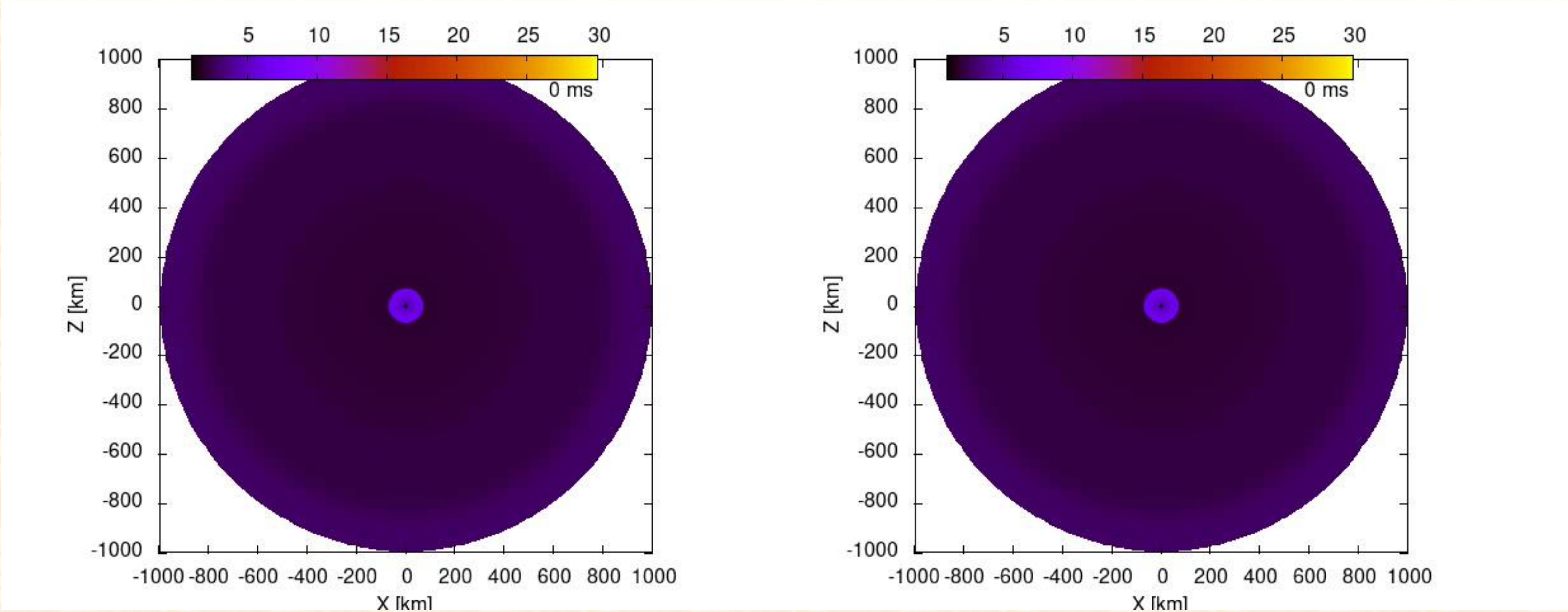
$$l_\mathrm{osc} = (2\pi E_\mathrm{res})/(m_s^2 \sin 2\theta)$$



Model NoSterile

Model A

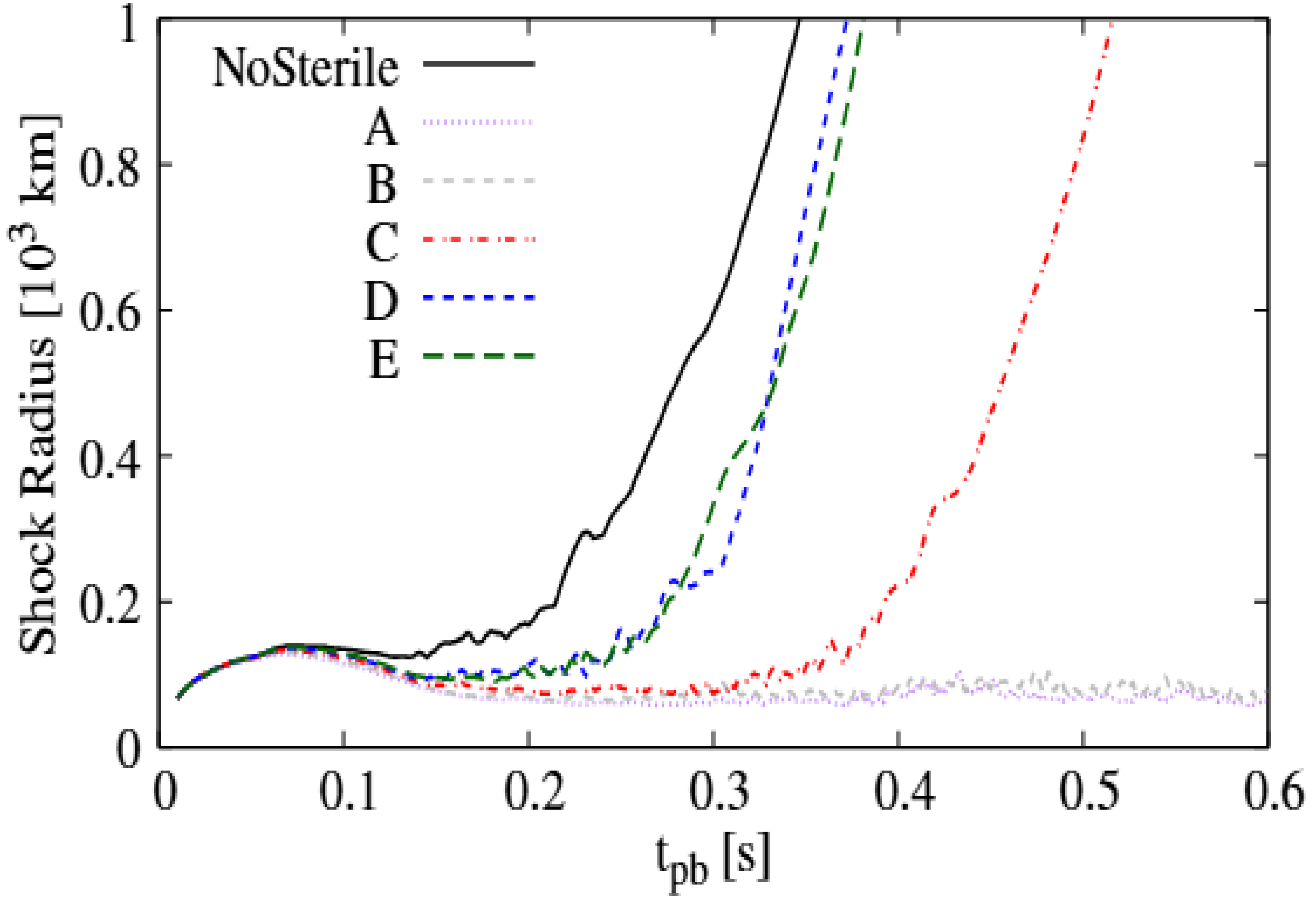
($\delta m^2 = 3.90\ eV^2$, $\sin^2 2\theta = 0.040$)



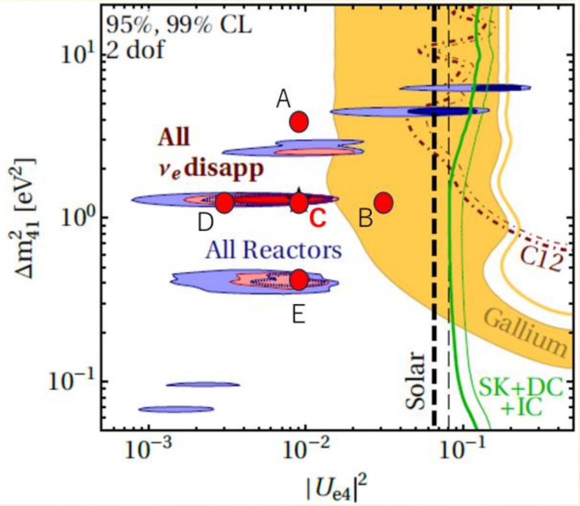
Sterile neutrinos hinder SN explosion!

Shock Radius

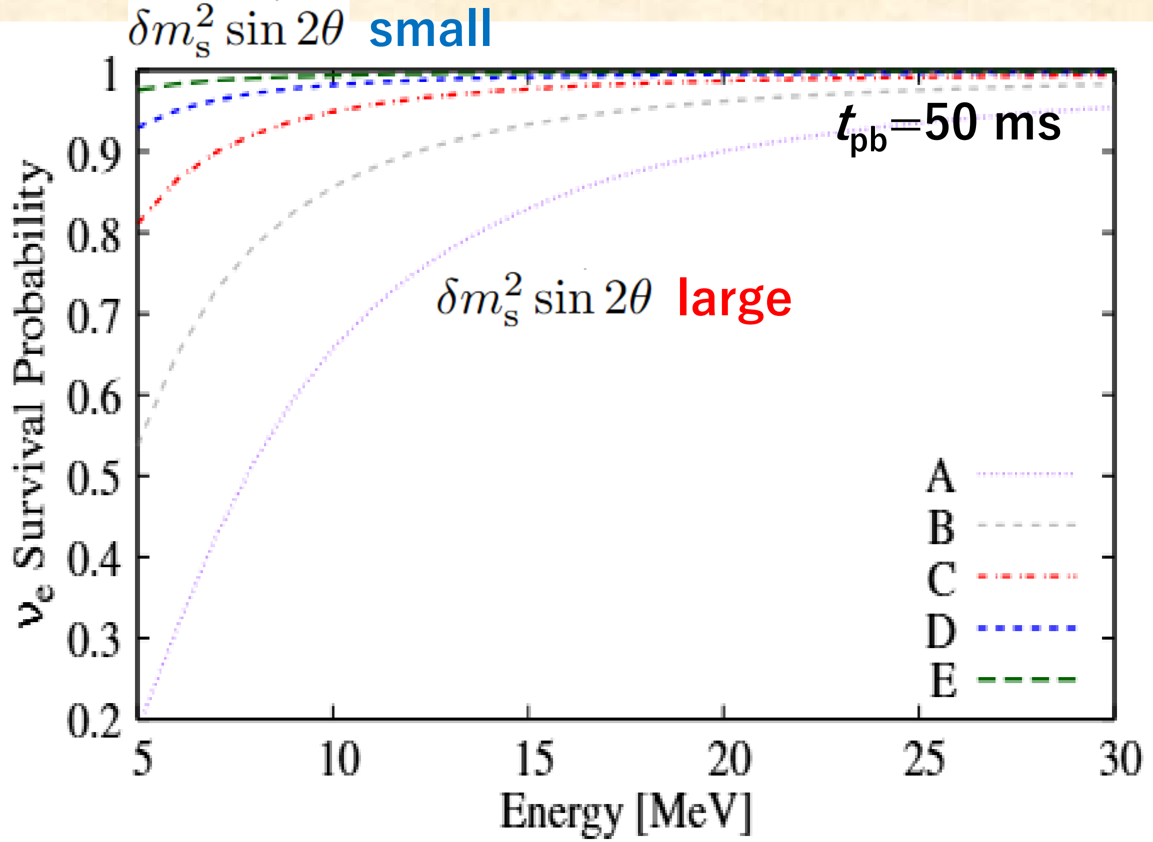
KM, Takiwaki, Kohri, & Nagakura, PRD 111 (2025) 083046.

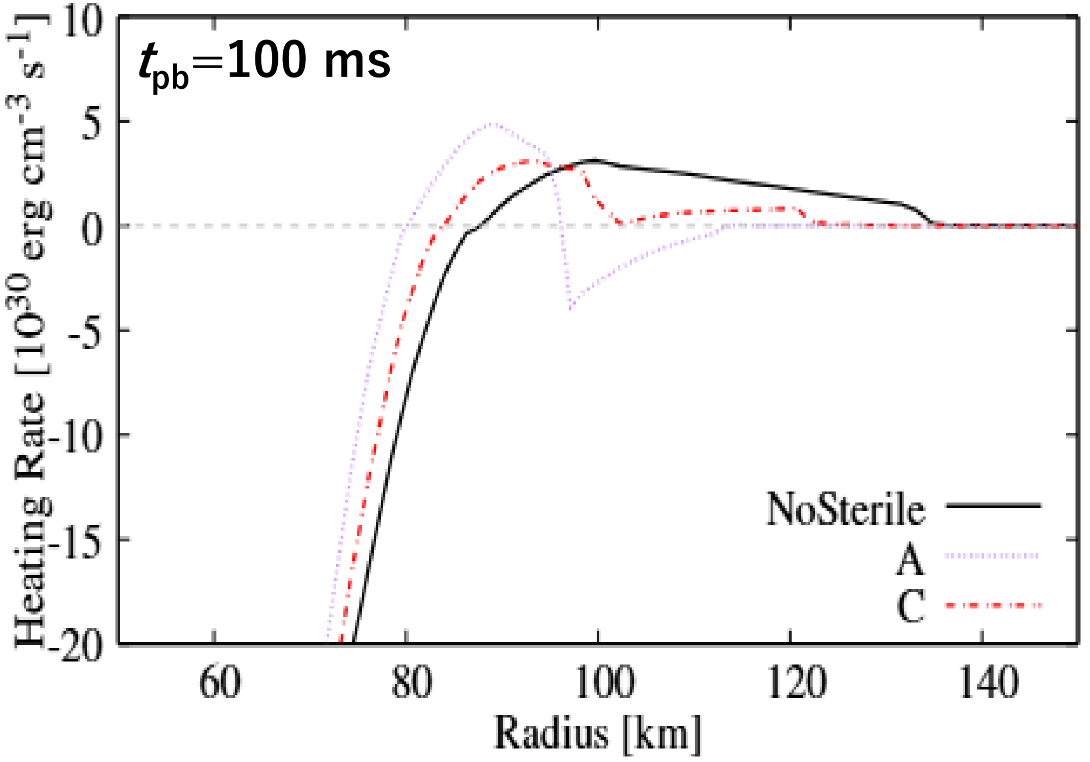


- ✓ When sterile neutrinos are considered, the shock revival is delayed.
- ✓ When $\delta m_s^2 \sin 2\theta$ is sufficiently large, the shock is not revived until the end of the simulations.



Active-Sterile Oscillation

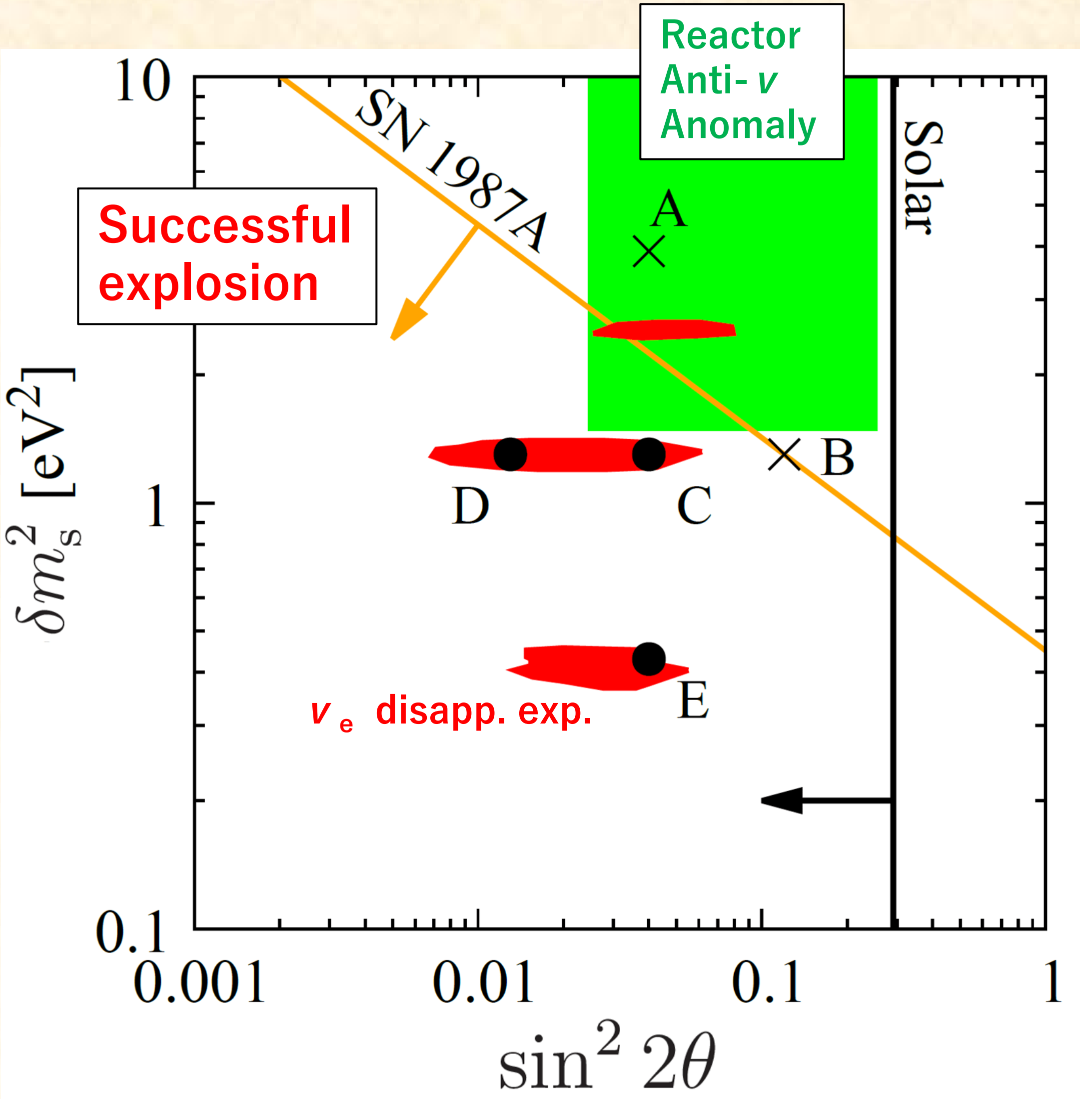




KM, Takiwaki, Kohri, & Nagakura, PRD 111 (2025) 083046.

- ✓ 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:

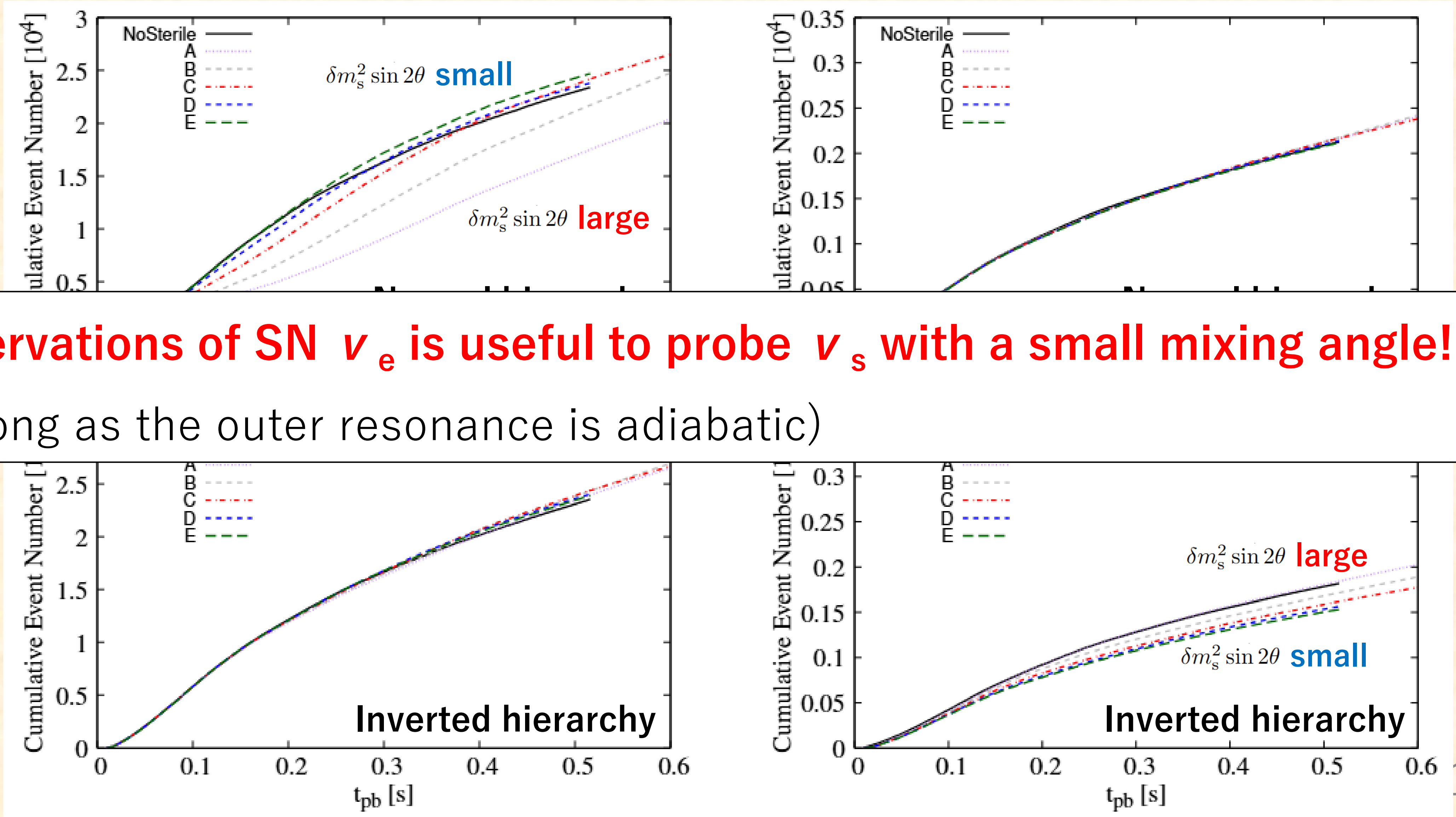
$$\sin 2\theta \lesssim 0.45\,\mathrm{eV}^2/\delta m_s^2$$

SN explodability can provide a new constraint on sterile neutrinos!

Neutrino Signals

D=10 kpc

Hyper-Kamiokande ($\bar{\nu}_e$ events) | **DUNE (ν_e events)**



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

(as long as the outer resonance is adiabatic)

まとめ

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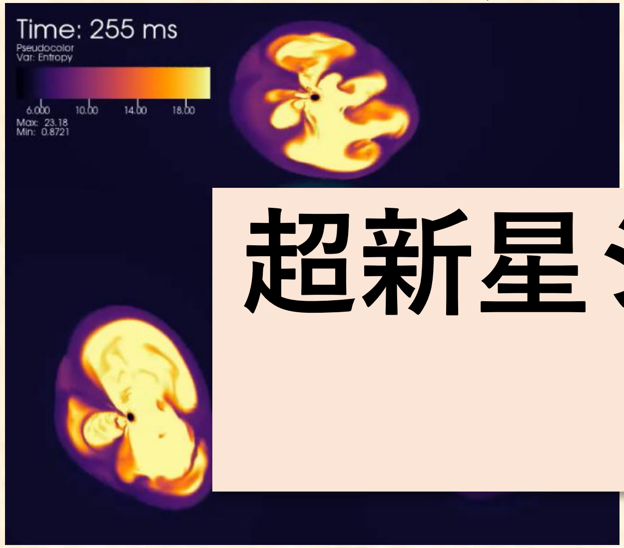

ステライル・ニュートリノ

原子炉ニュートリノ異常の説明	暗黒物質の正体	シーソー機構

>MeV

ori et al. (2024)

現実的超			
1D	Xiong et al. (2019)	Warren et al. (2014)	Rembiasz et al. (2018)
ポストプロセス	Wu et al. (2014)	Fuller et al. (2003)	Fuller et al. (2009)

超新星シミュレーションを活用した新物理の制限へ!

アクシオン

$$\mathcal{L} = \sum_{N=p,\,n} \frac{g_{aN}}{2m_N}\bar{N}\gamma^\mu\gamma_5 N\partial_\mu a - \frac{g_{a\gamma}}{4}aF_{\mu\nu}\tilde{F}_{\mu\nu}$$

ダーク・フォトン

$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2}m'^2 A'_\mu A'^\mu - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} - \frac{\epsilon}{2}F'_{\mu\nu}F^{\mu\nu}$$