素粒子標準模型を超えた物理に対する超新星の爆発可能性に基づく新たな制限

Exploring New Physics with Supernova Explodability

森　寛治 (Kanji Mori)
慶應義塾大学理工学部物理学科

KM, T. Takiwaki, K. Kohri, & H. Nagakura, PRD 111 (2025) 083046;
KM, T. Takiwaki, & K. Kohri, accepted by PRD, arXiv:2511.18122

Messengers from a Supernova

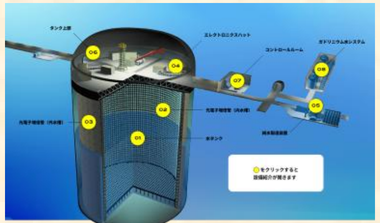
Known particles

Photons

ⒸNAOJ

γ

Neutrinos ν



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Gravitational waves

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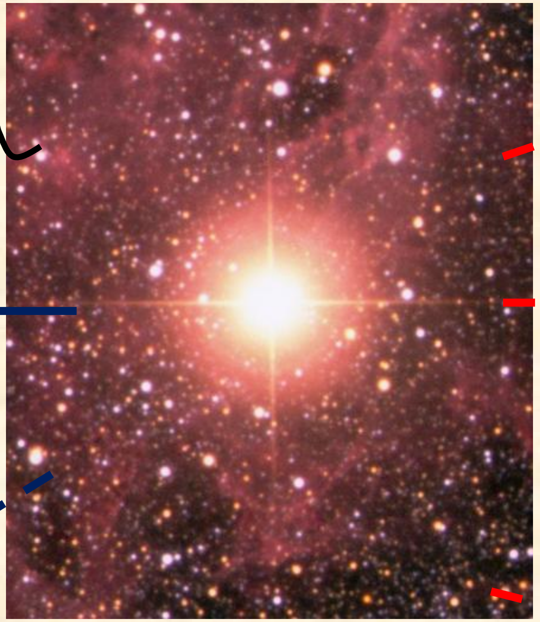
SN 1987A



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Exotic particles

Axions (ALPs)

a

KM et al., PRD 105 (2022) 063009;
108 (2023) 063027;
ApJ 943 (2023) 12

KM & M. Mori, JCAP 11 (2025) 081

ν_s

Sterile neutrinos

KM et al., PRD 110 (2024) 023031;
111 (2025) 083046

γ'

Dark photons

KM et al., (2026) accepted.

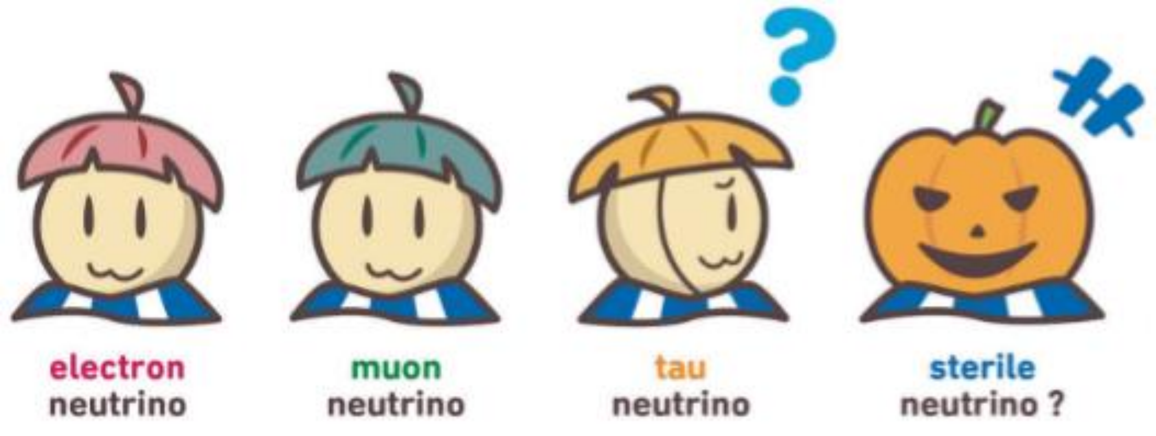
Light Sterile Neutrinos

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

[see Mention et al., PRD 83 (2011) 073006, and Giunti et al., PLB, 829 (2022) 137054 for recent development]

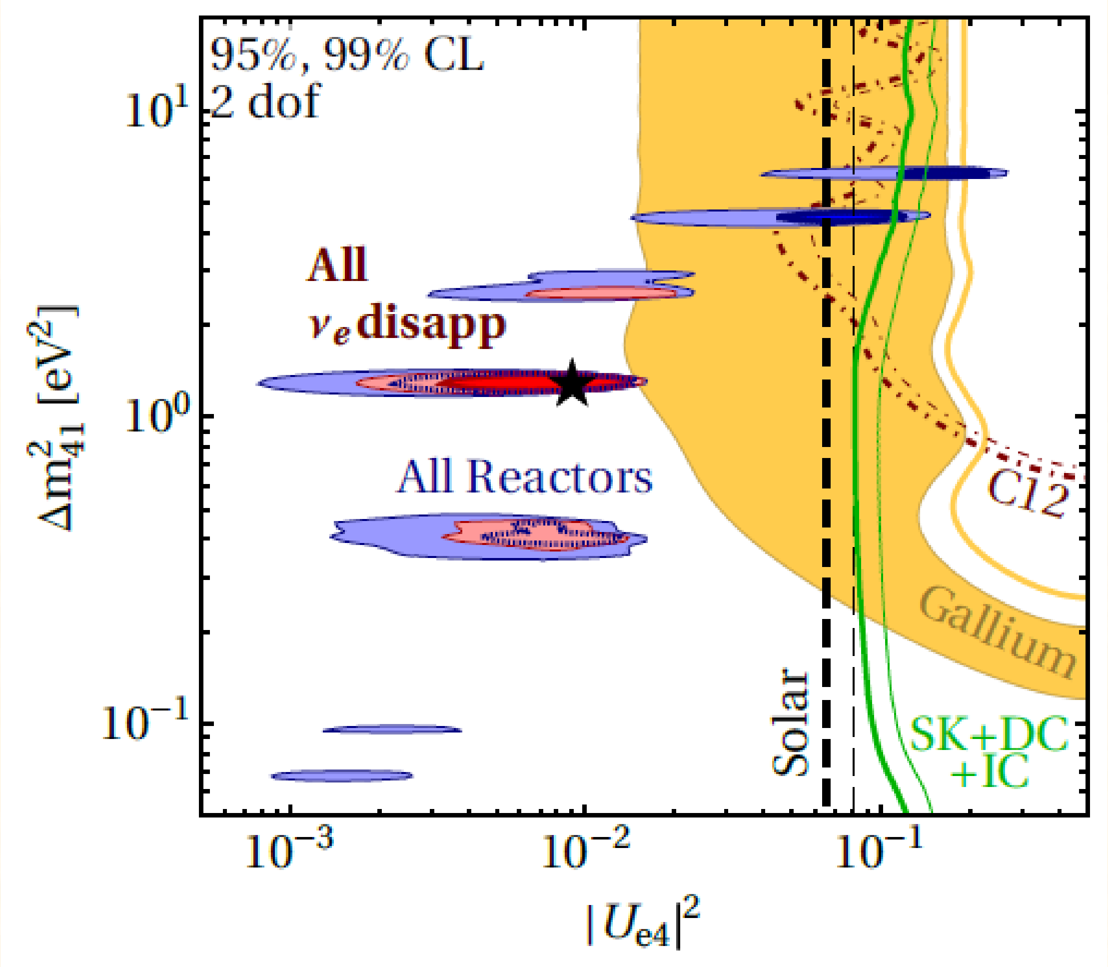
- Mixing with active neutrinos
  - **In this study, we focus on mixing with ν_e**

$$
\begin{aligned}
\nu_e &= \cos\theta\,\nu_1 + \sin\theta\,\nu_2 \\
\nu_s &= -\sin\theta\,\nu_1 + \cos\theta\,\nu_2
\end{aligned}
$$



ⒸHiggs-tan

Parameter Space of Light Sterile Neutrinos

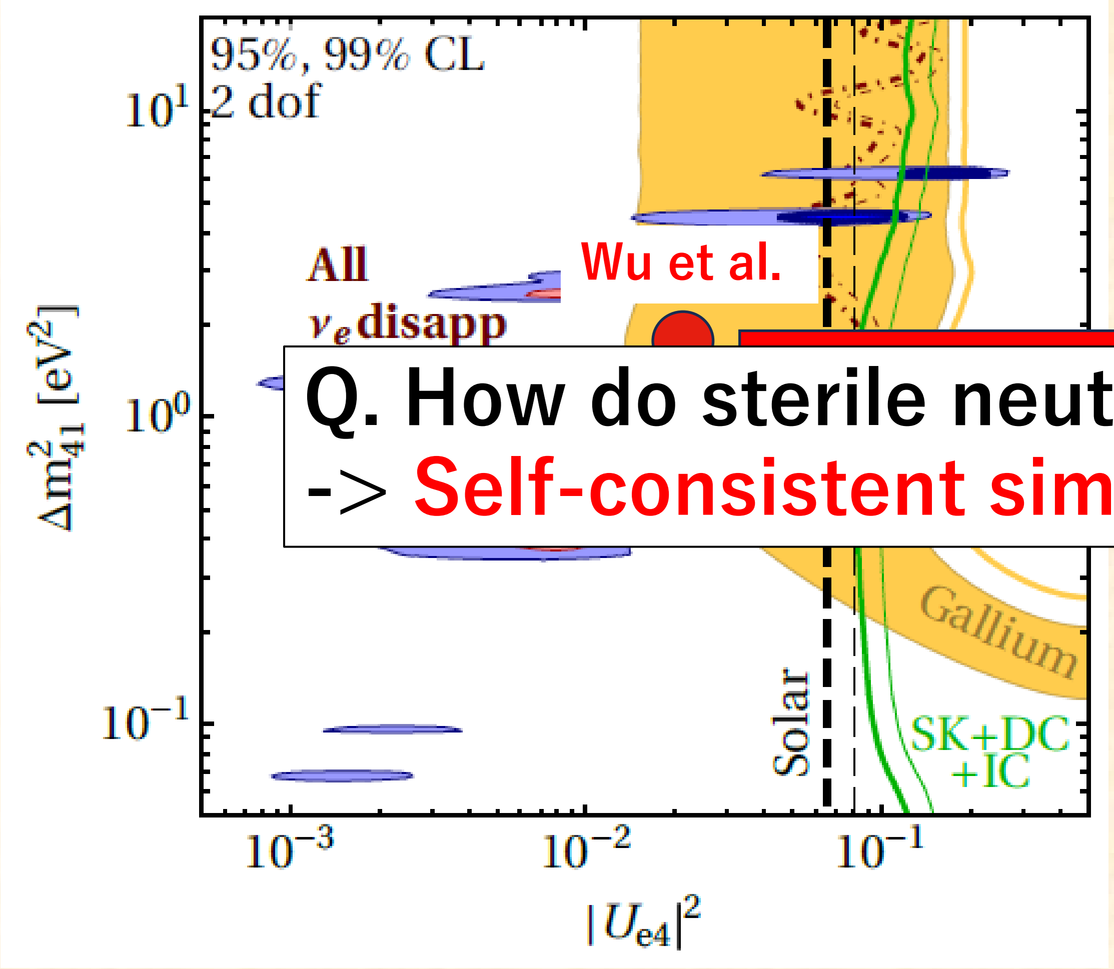


Dentler et al., JHEP 08 (2018) 010

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

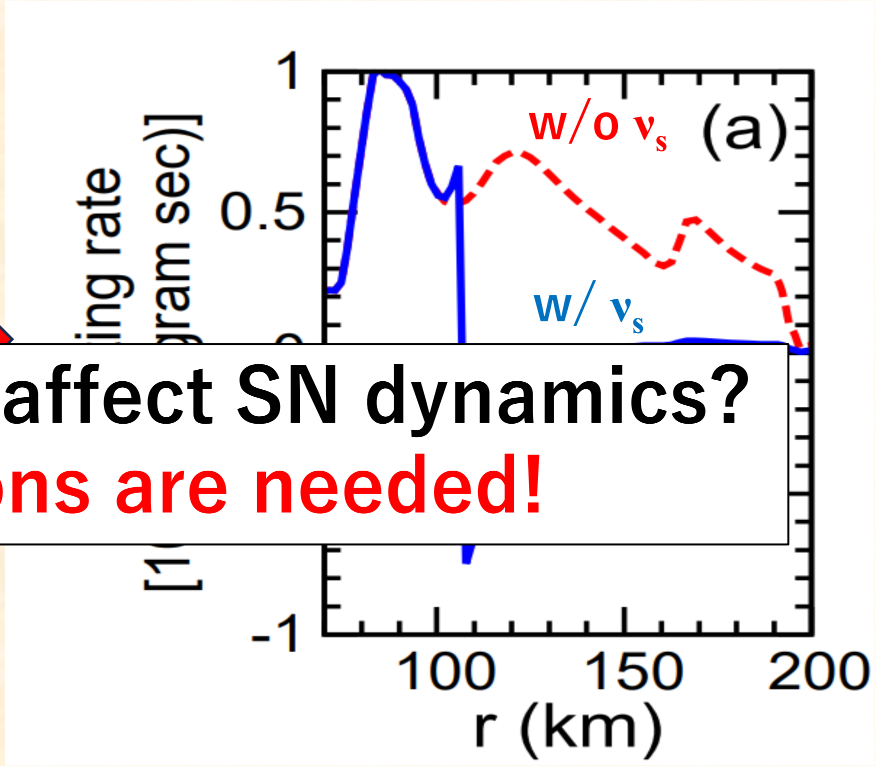
Kainulainen, Maalampi, Peltoniemi, NPB (1991)
Peltoniemi, A&A (1992)
Raffelt & Sigl, Astropart. Phys. (1993)
Nunokawa et al., PRD (1997)
McLaughlin et al., PRC (1999)
Caldwell et al., PRD (2000)
Fetter et al., Astropart. Phys. (2003)
Beun et al., PRD (2006)
Keranen et al. PRD (2007)
Tamborra et al. JCAP (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

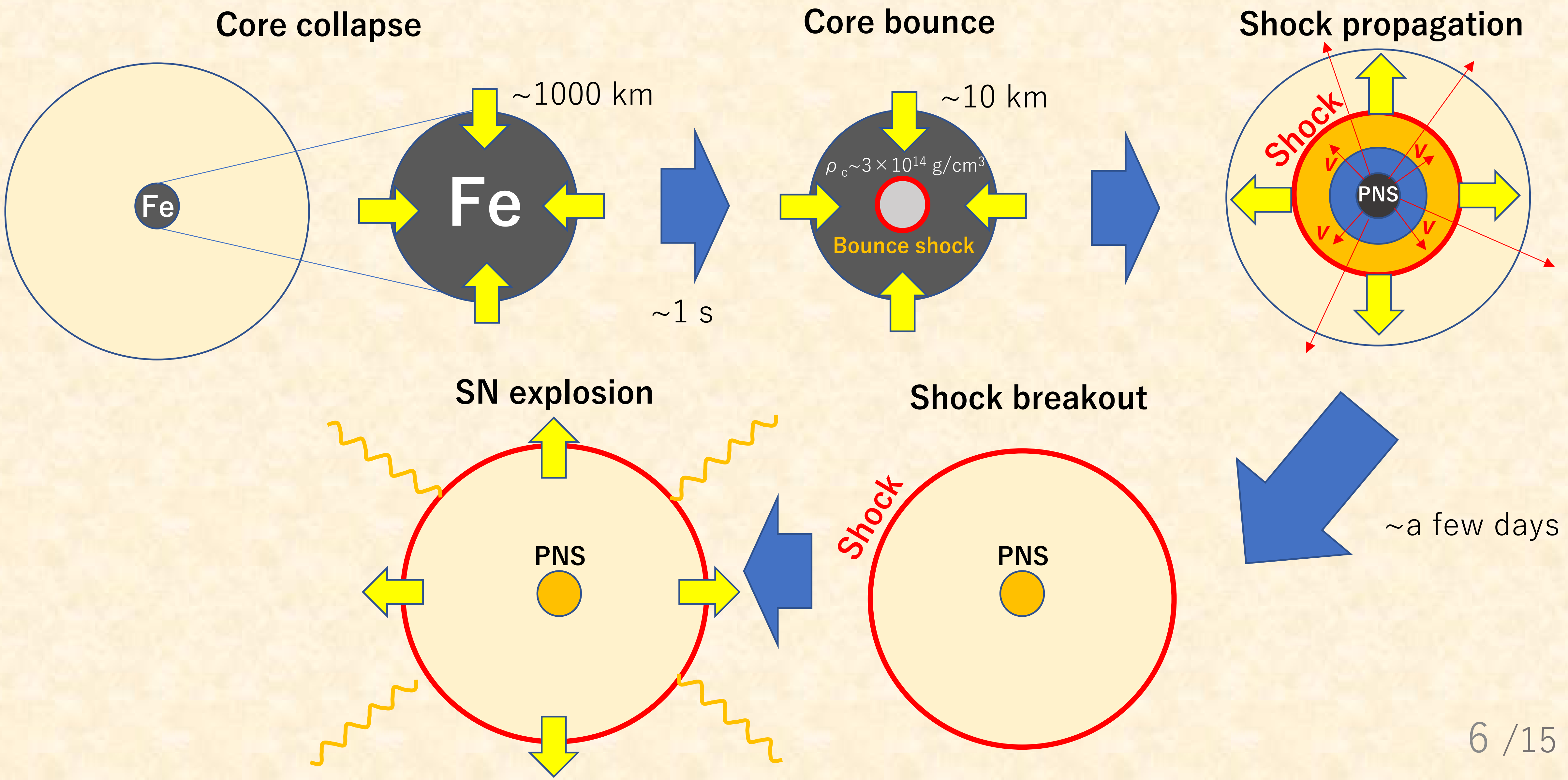
Q. How do sterile neutrinos affect SN dynamics?
-> Self-consistent simulations are needed!



Wu et al., PRD 89 (2014) 061303

Neutrino heating rate is significantly reduced.

Explosion Mechanism of Core-collapse SNe



Active-Sterile Oscillations

- ✓ Sterile neutrinos are produced by the **neutrino oscillation**
- ✓ MSW resonance condition:

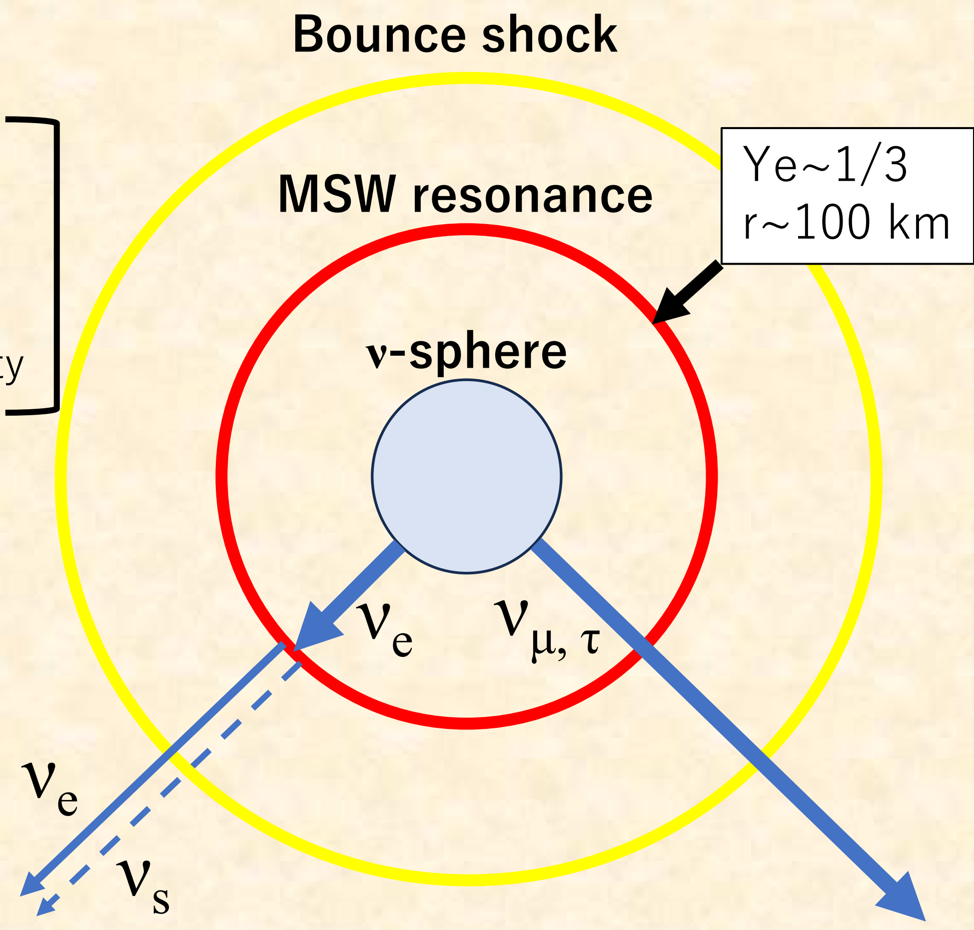
$$\frac{\delta m_{\mathrm{v}}^2}{2E}\cos\theta_{\mathrm{v}} = \frac{3\sqrt{2}}{2}G_{\mathrm{F}}n_{\mathrm{b}}\left(Y_e - \frac{1}{3}\right)$$

[
m_{V} : ν_s mass
θ_{V} : ν_e-ν_s mixing angle
G_F : Fermi coupling
Y_e : electron fraction
n_b : baryon number density
]

- ✓ The conversion probability is given by Landau-Zenar formula:

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

$$\left(\begin{aligned} \gamma &= \Delta_{\mathrm{res}}/l_{\mathrm{osc}} \\ \Delta_{\mathrm{res}} &= \tan 2\theta \left|\frac{dV_{\mathrm{eff}}/dr}{V_{\mathrm{eff}}}\right|^{-1} \\ l_{\mathrm{osc}} &= (2\pi E_{\mathrm{res}})/(m_s^2 \sin 2\theta) \end{aligned}\right)$$



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

Progenitor: 14+9$M_\odot$ merger model

"SN 1987A progenitor model"

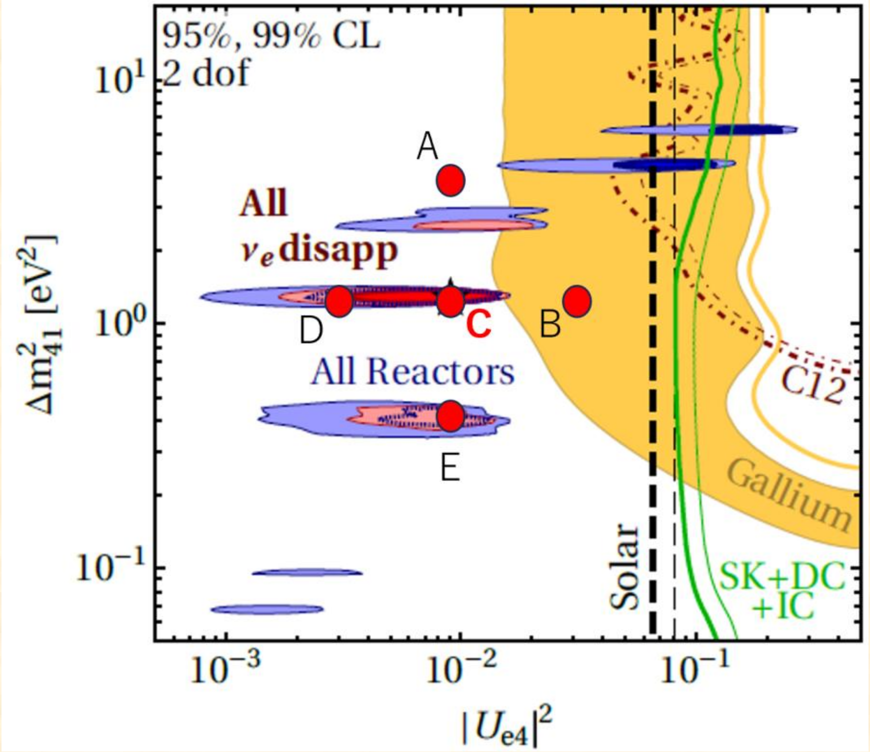
[Urushibata et al., MNRAS 473 (2018) L101]

Resolution: $N_r \times N_\theta = 512 \times 128$

Resource: XD2000 & XC50

~4 k nodes hours

ν_s mass and
ν_e- ν_s mixing angle:

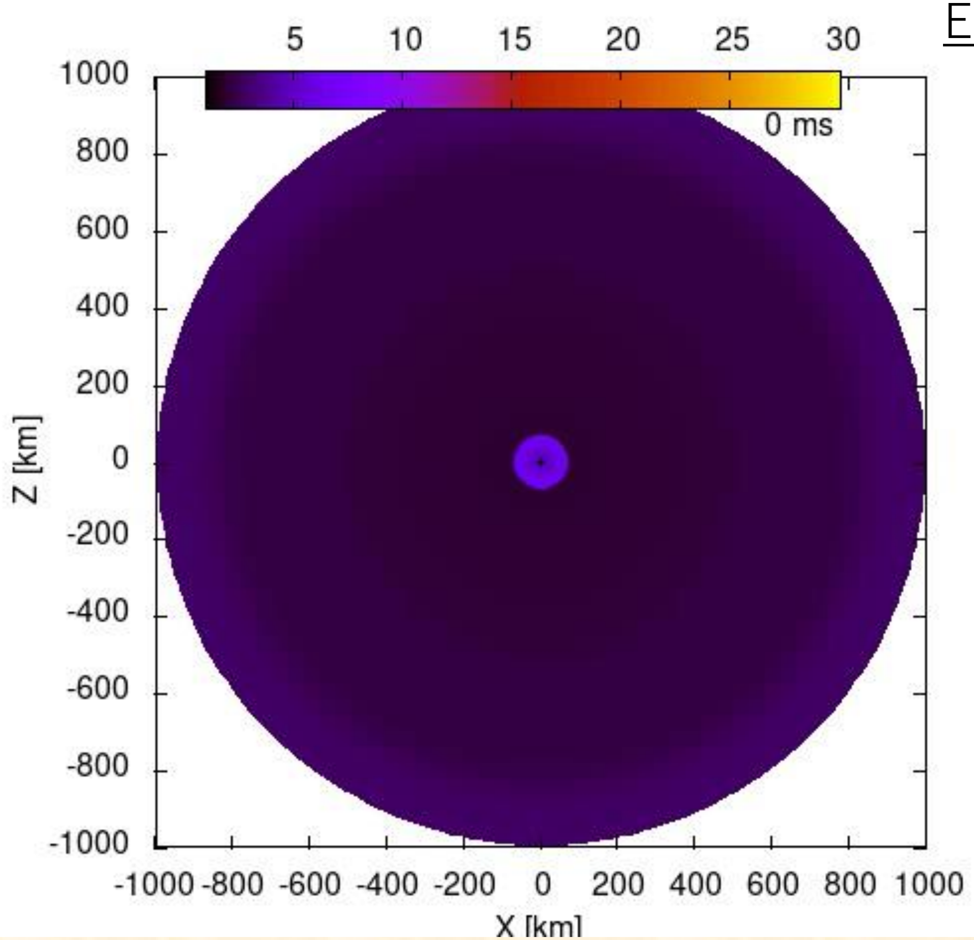


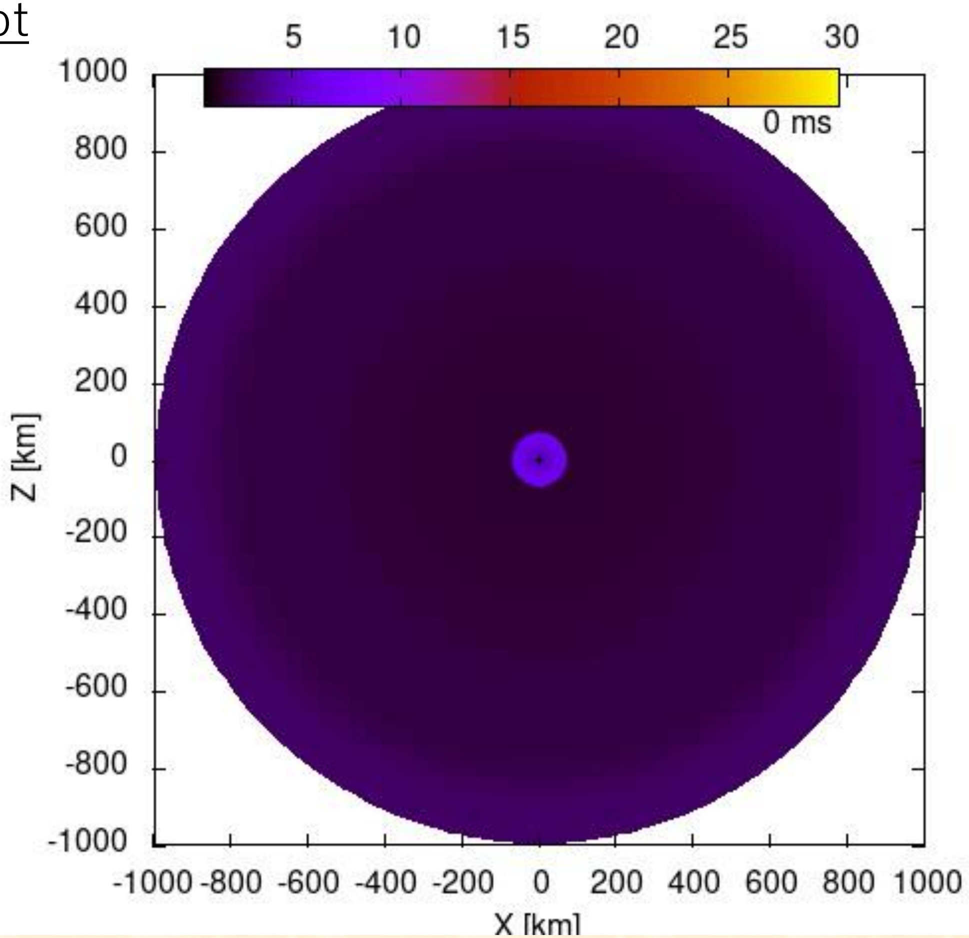
Dentler et al., JHEP 08 (2018) 010

Model NoSterile

Model A
(δm^2=3.90 eV^2, $\sin^2 2\theta$=0.040)

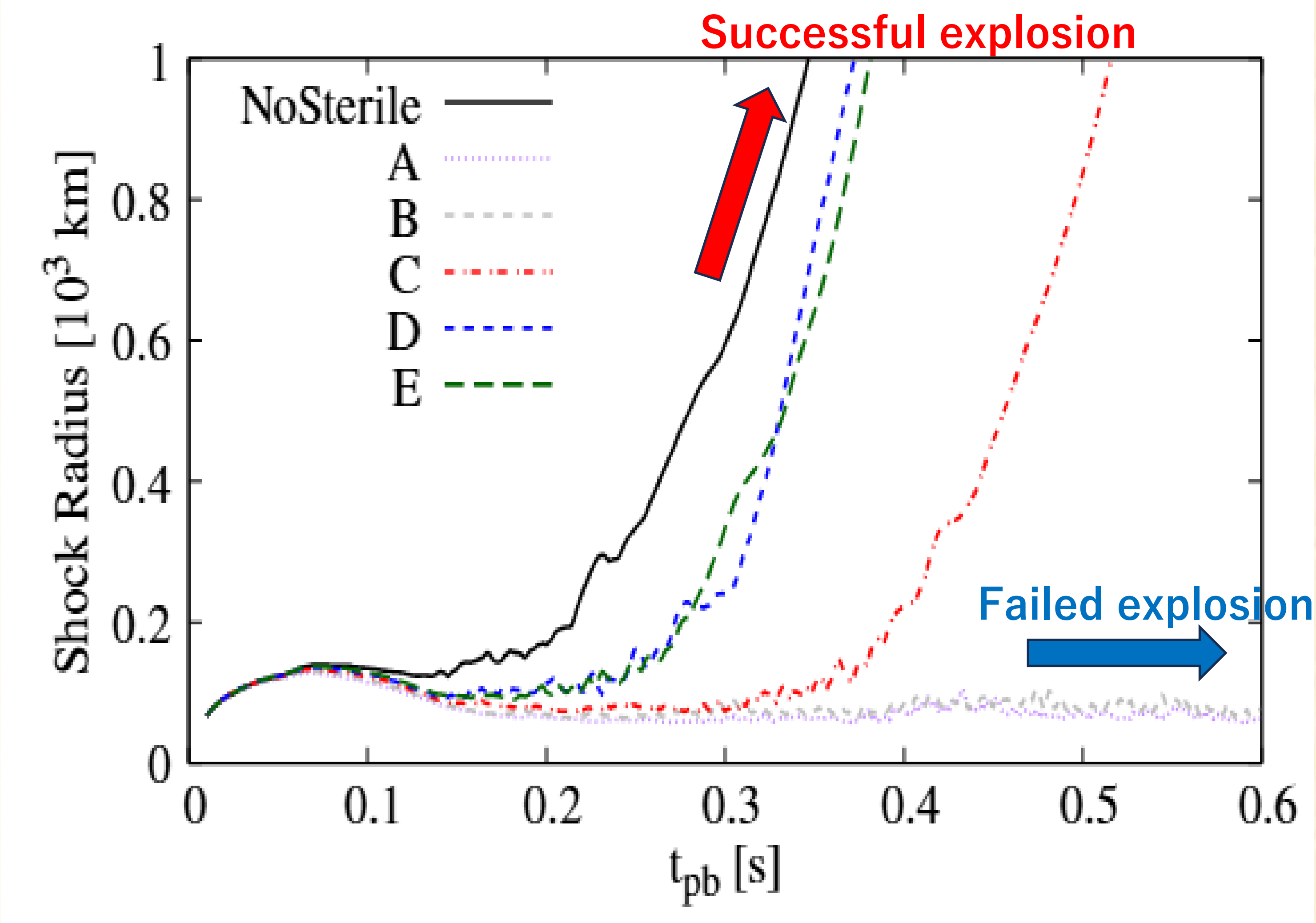
Entropy plot



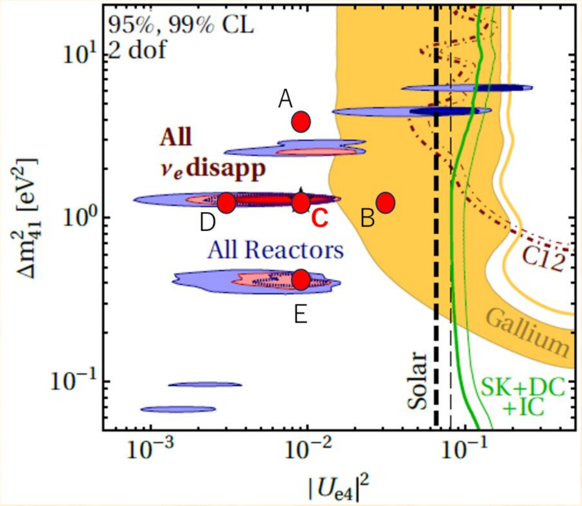


Sterile neutrinos hinder SN explosion!

Shock Radius



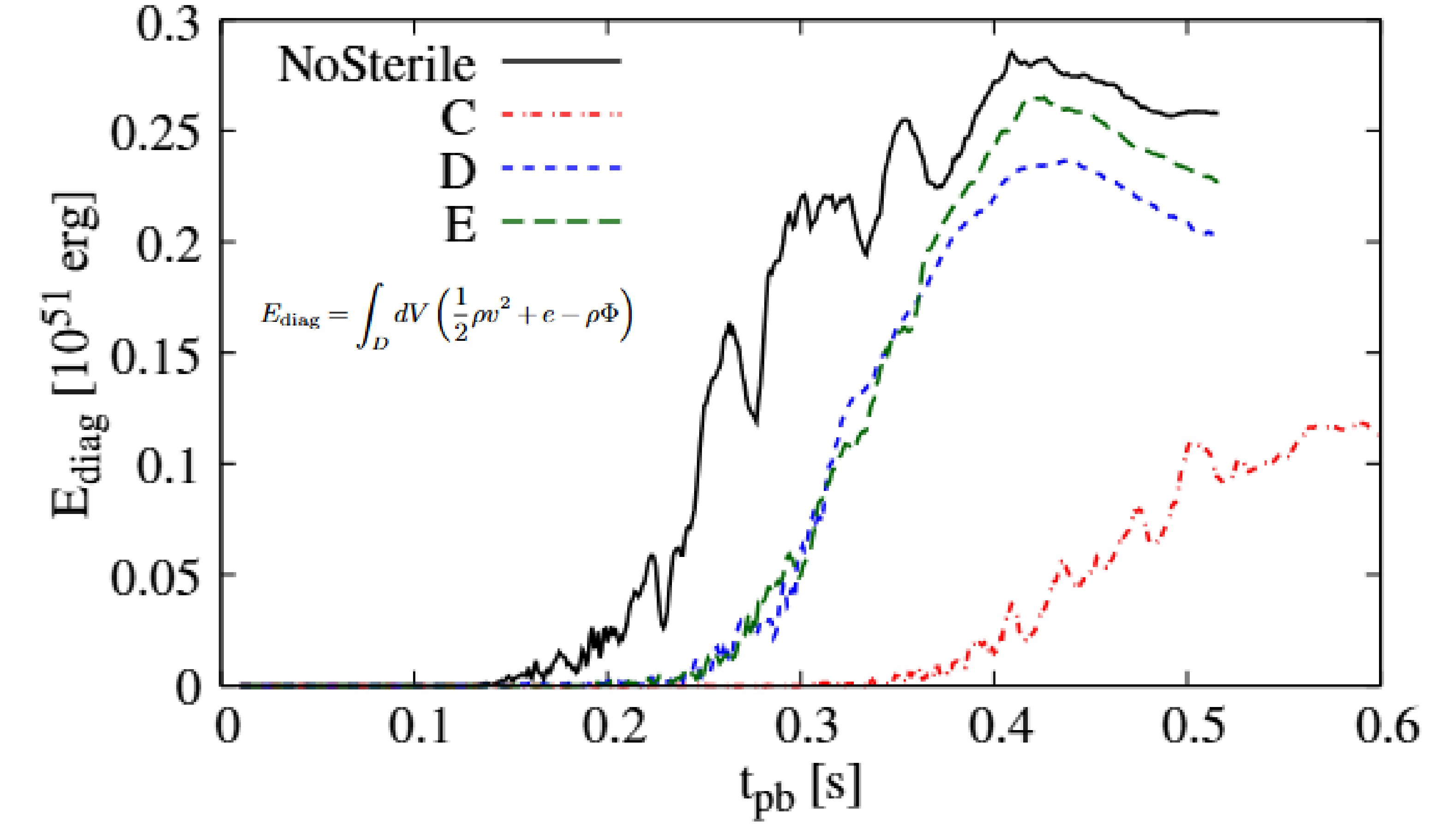
- ✓ When sterile neutrinos are considered, the shock revival is delayed.
- ✓ When $\delta m_s^2 \sin 2\theta$ is sufficiently large, the shock is not revived until the end of the simulations.



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

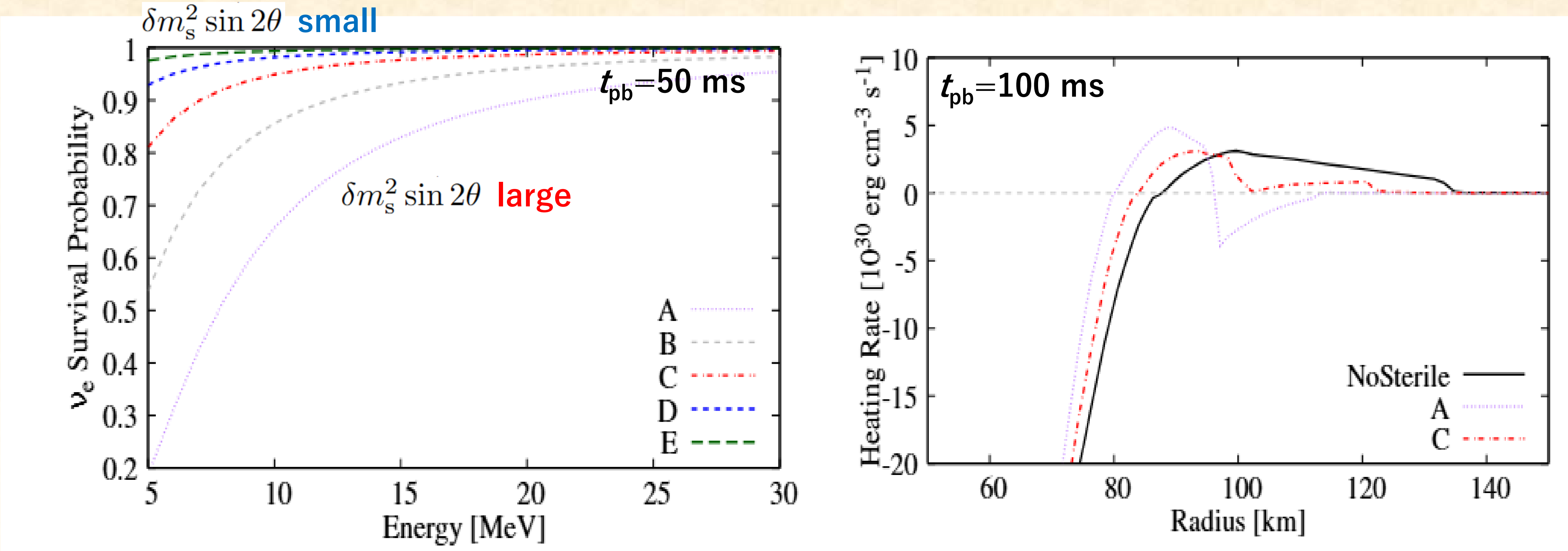
Explosion Energy

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



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

Active-Sterile Oscillation

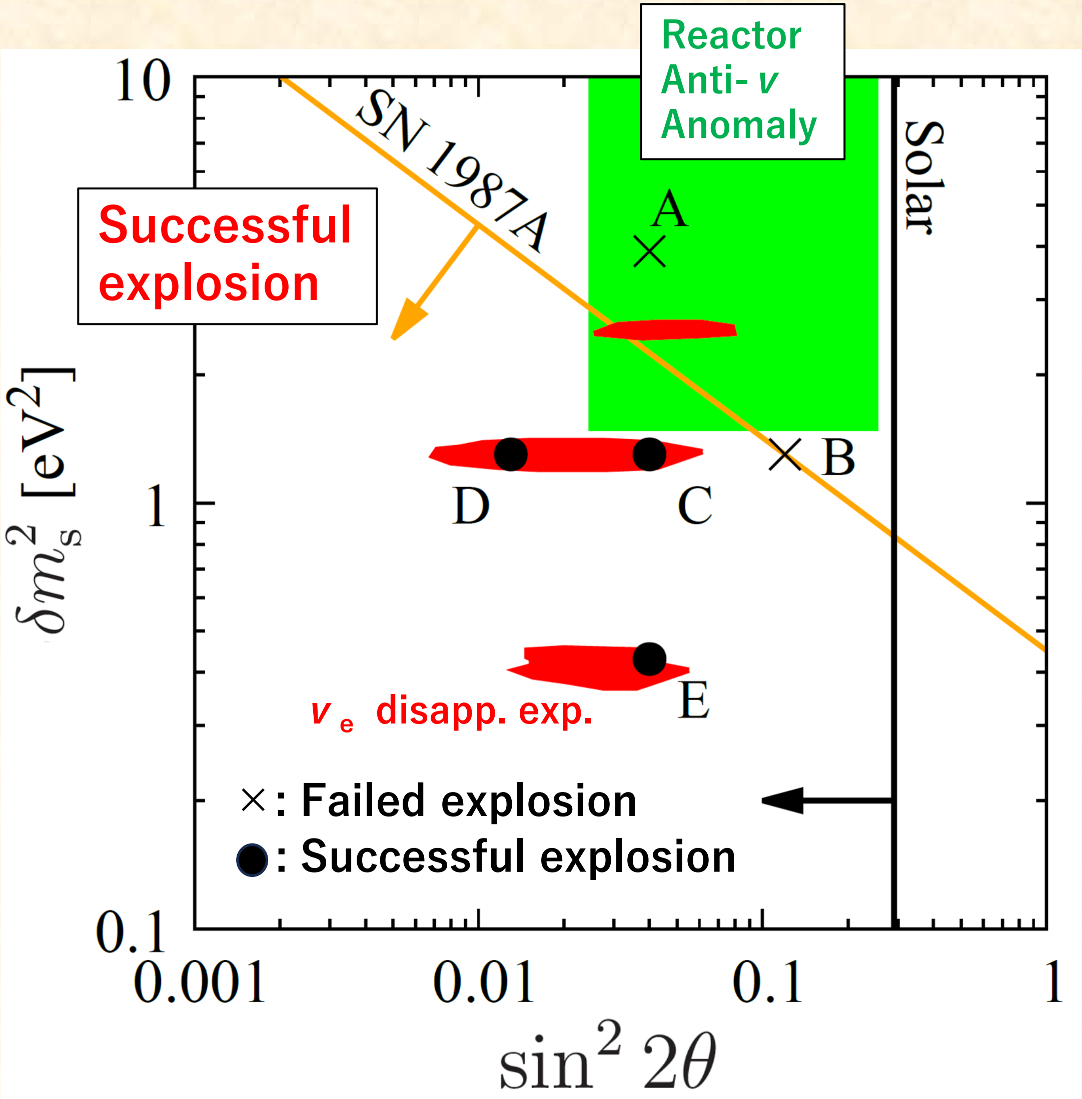


KM, Takiwaki, Kohri, & Nagakura, PRD 111 (2025) 083046.

✓ The ν_e survival probability 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.

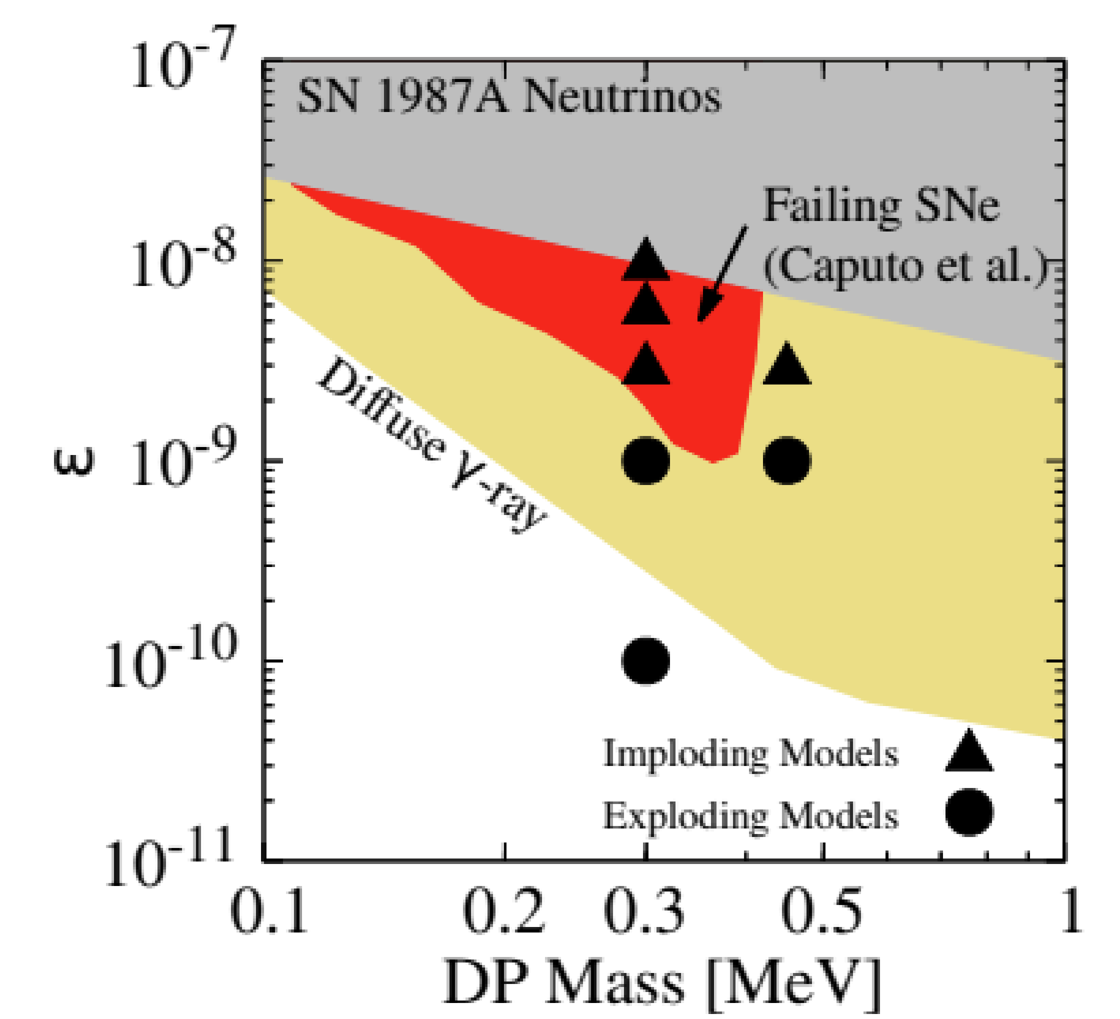
Condition for successful SN 1987A explosion:

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

- ✓ **SN explodability can provide a new constraint on sterile neutrinos!**
- ✓ A part of the area preferred by the reactor anomaly is excluded.

SN Constraint on Dark Photons

KM, T. Takiwaki, & K. Kohri, accepted by PRD

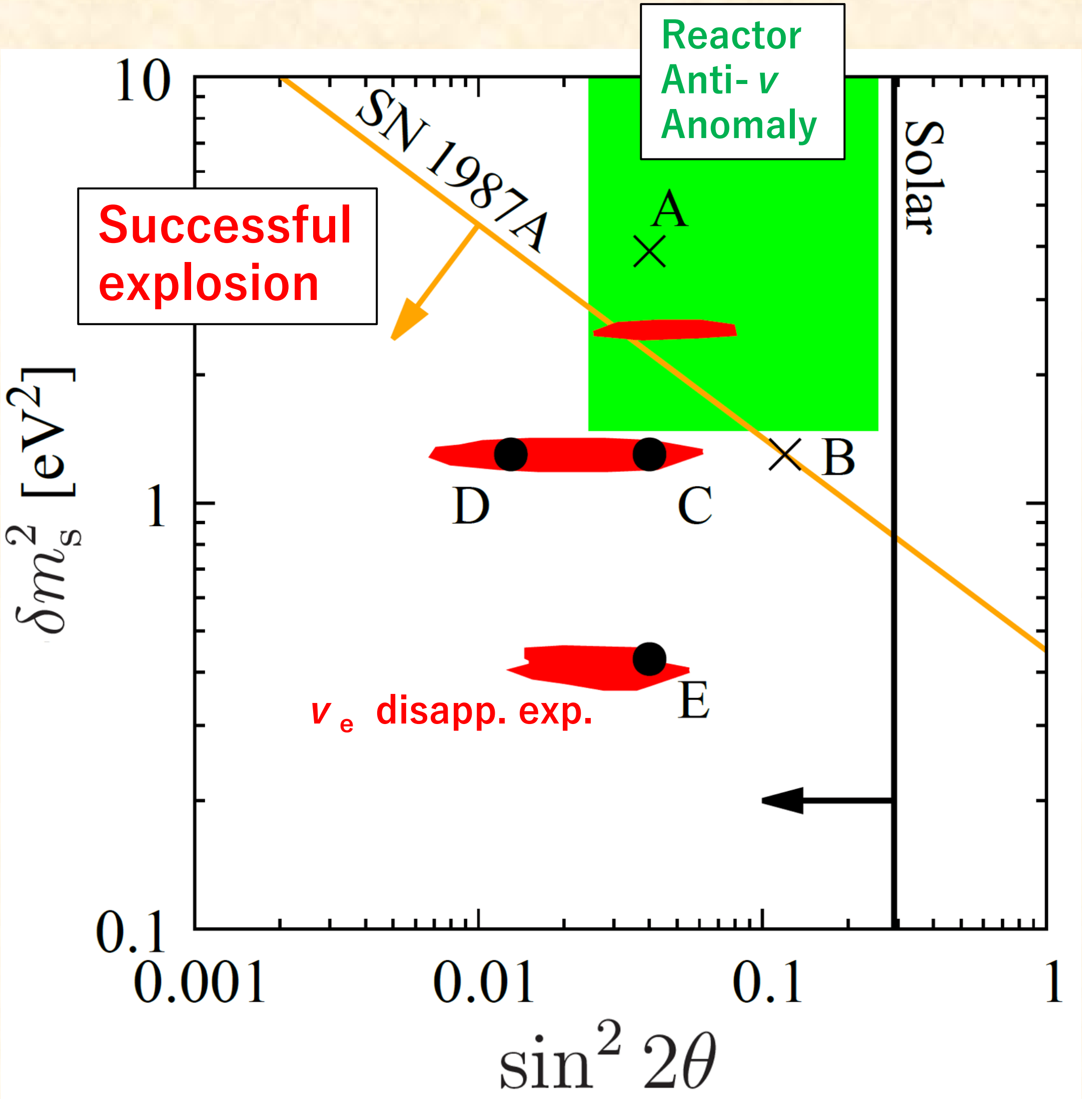


$$\mathcal{L} = \mathcal{L}_{\rm SM} + \frac{1}{2} m_{\gamma'}^2 A'_\mu A'^\mu - \frac{1}{4} F'_{\mu\nu} F'^{\mu\nu} - \frac{\epsilon}{2} F'_{\mu\nu} F^{\mu\nu}$$

Interaction with photons

- ✓ When the mixing parameter, ε, is sufficiently large, supernovae do not explode.
- ✓ **SN explodability is useful to constrain various exotic particles!**

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.
- This argument can be applicable to other particle models such as dark photons.