Core-collapse Supernova Models with Heavy Axion-like Particles

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1. Heavy Axion-like Particle (ALP)

Axion-like particle: Hypothetical pseudoscalar boson that can couple with photons.

ALP-photon interaction:

$$\mathcal{L}_{a\gamma\gamma} = -\frac{1}{4} g_{a\gamma} a \tilde{F}^{\mu\nu} F_{\mu\nu}$$

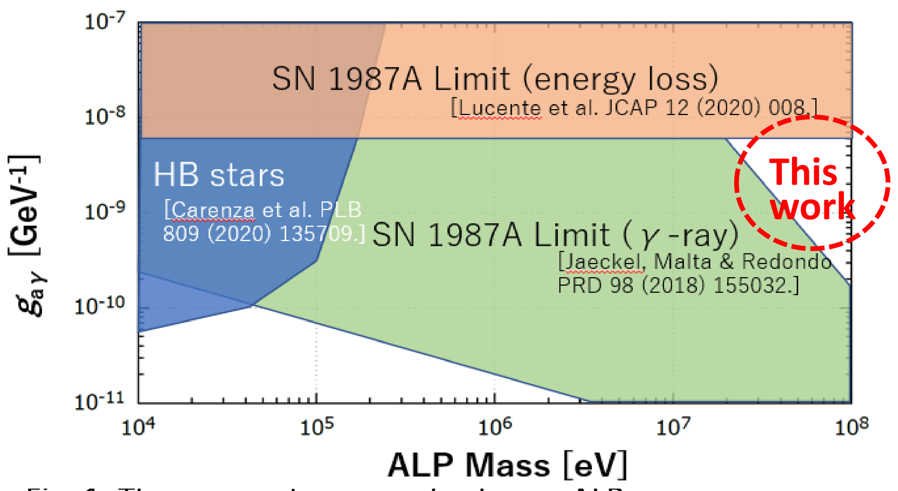
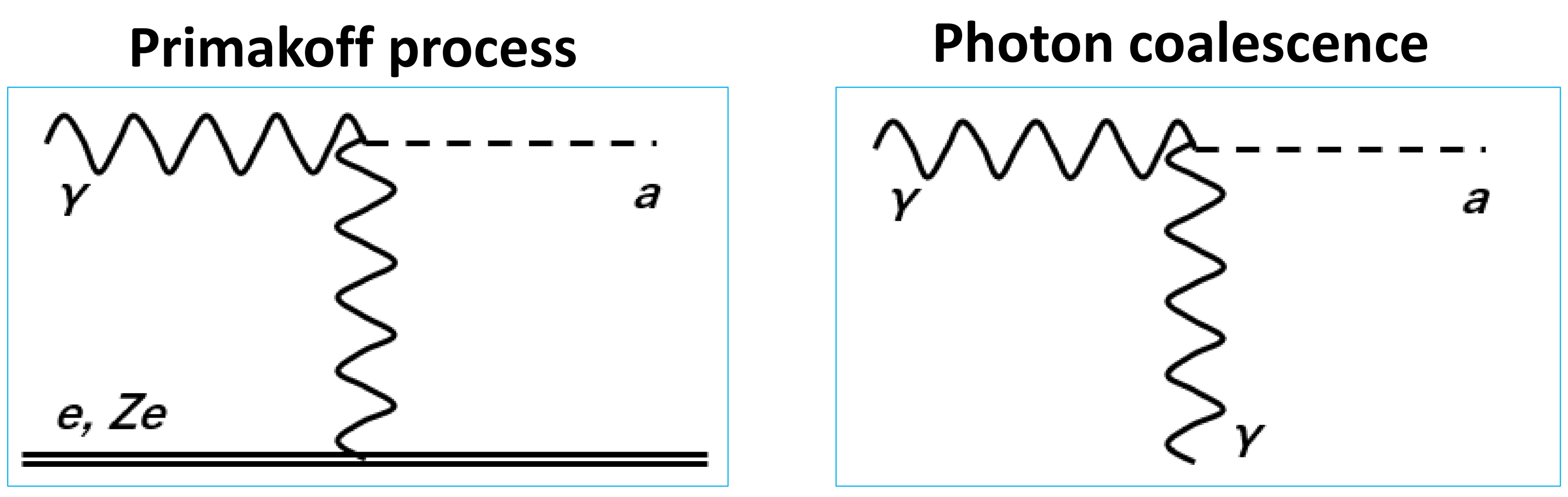


Fig. 1. The parameter space for heavy ALPs.

Extra cooling [e.g. 2]



$$\Gamma_{\gamma\to a} = g_{a\gamma}^2 \frac{T\kappa^2}{32\pi}\frac{p}{E}\left(\frac{((k+p)^2+\kappa^2)((k-p)^2+\kappa^2)}{4kp\kappa^2} \times \ln\left(\frac{(k+p)^2+\kappa^2}{(k-p)^2+\kappa^2}\right) - \frac{(k^2-p^2)^2}{4kp\kappa^2}\ln\left(\frac{(k+p)^2}{(k-p)^2}\right) - 1\right)$$

$$\frac{d^2 n_a}{dt\,dE} = g_{a\gamma}^2 \frac{m_a^4}{128\pi^3} p \left(1-\frac{4\omega_{pl}^2}{m_a^2}\right)^{\frac{3}{2}} e^{-\frac{E}{T}}$$

Possible only when $m_a > 2\omega_{pl}$ (ω_{pl}: plasma frequency)

Extra heating

ALP radiative decay ($a \to \gamma+\gamma$):

$$\mathrm{MFP} = \frac{E_a}{m_a}\sqrt{1-\frac{m_a^2}{E_a^2}}\frac{64\pi}{g_{a\gamma\gamma}^2 m_a^3} \sim \frac{4\times 10^{15}\ \mathrm{cm}}{g_{10}^2}\frac{E_{100}}{m_{10}^4}$$

Q. How do extra cooling and heating affect supernova dynamics?

2. Core-collapse Model

Code: 3DnSNe-IDSA [3] **EoS**: LS220

Dimension: 1D **Progenitor**: $20M_\odot$

SN model		ALPs
• Temperature • Density • Composition	Hydro info → ← Backreaction	• Production rate (->cooling) • Absorption rate (->heating)

3. Extra Cooling & Heating

$$\nabla\cdot\mathbf{F} = Q_{\rm cool} - Q_{\rm heat}$$

$$Q_{\rm cool} = \int_{m_a}^{\infty} dE_a E_a \frac{d^2 n_a}{dt\,dE_a}$$

↓ Discretized

$$L_{i+\frac{1}{2}} = L_{i-\frac{1}{2}} + (Q_{{\rm cool},\,i} - Q_{{\rm heat},\,i})\Delta V_i$$

$$Q_{{\rm heat},\,i}\Delta V_i = L_{i-\frac{1}{2}}\left(1-\exp\left(-\frac{r_{i+1}-r_i}{\lambda_{a,\,i}}\right)\right)$$

Modification to the internal energy:

$$e_{{\rm int},\,i}^{n+1} = e_{{\rm int},\,i}^{n} + (Q_{{\rm heat},\,i}^{n} - Q_{{\rm cool},\,i}^{n})\Delta t$$

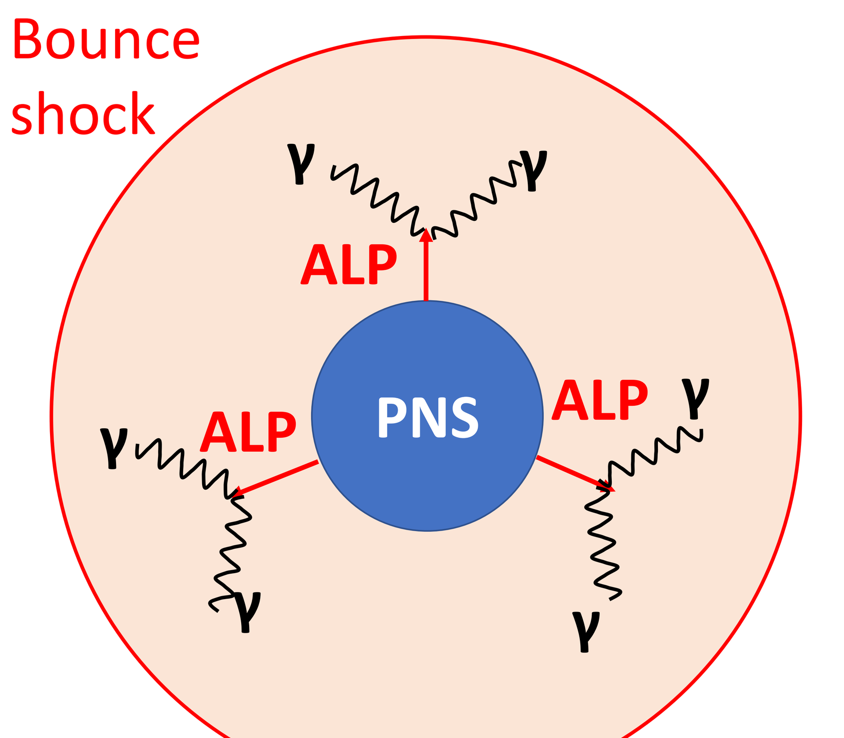


Fig. 2. A schematic picture for the extra heating induced by ALPs.

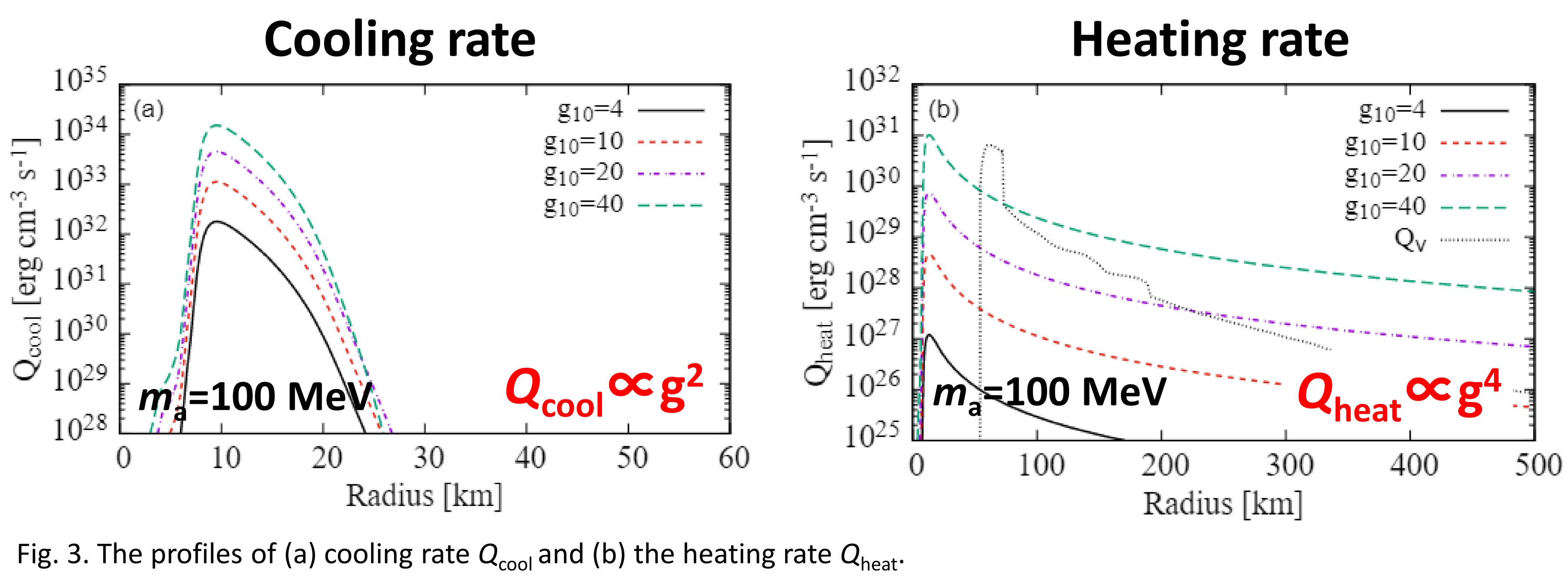


Fig. 3. The profiles of (a) cooling rate $Q_{\rm cool}$ and (b) the heating rate $Q_{\rm heat}$.

✓ALPs are efficiently produced at r~10 km because of the temperature peak.

✓The produced ALPs radiatively decay after propagation and heat the surrounding material.

4. Supernova Explosion with ALPs

4-1. Shock Radius

✓In the standard 1D models without ALPs, the shock wave stalls at r~100 km.

✓When $g_{a\gamma}$ is sufficiently high, the bounce shock is revived and the star successfully explodes!

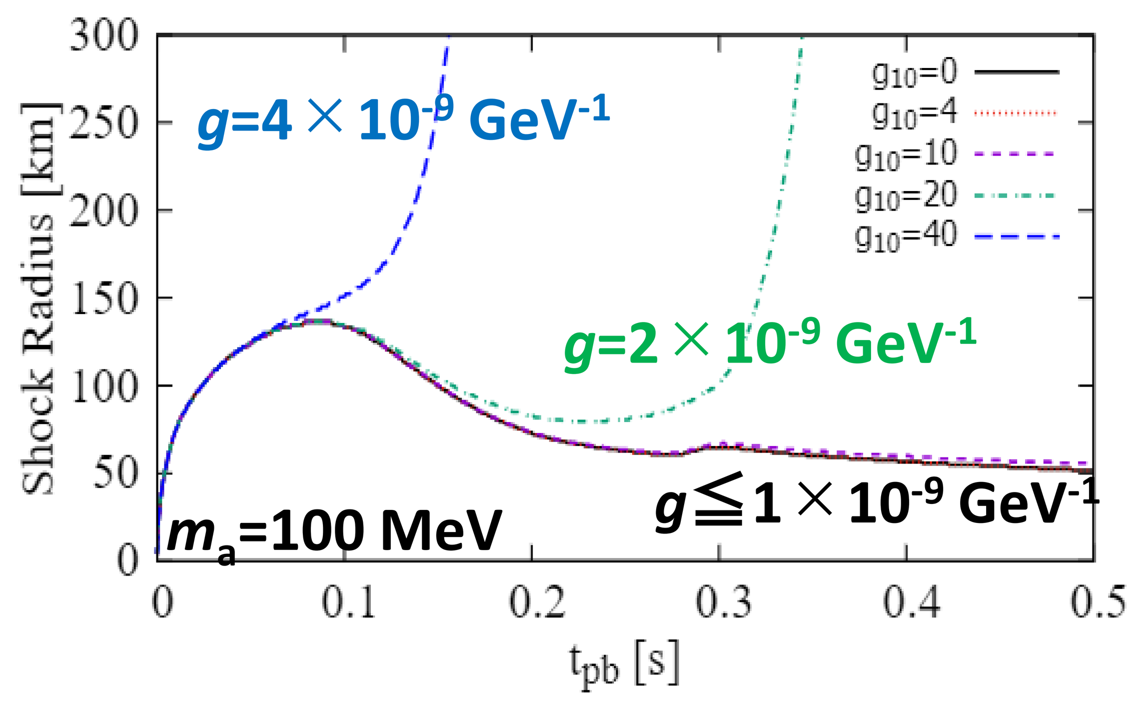


Fig. 3. The time evolution of the shock radius.

4-2. Explosion Energy

✓In general, larger $g_{a\gamma}$ leads to more energetic explosion

✓Some models approach $E_{\rm exp}$=10^{52} erg, which is much larger than the typical value for SNe II.

→ Constraint on (m_a, $g_{a\gamma}$) ?

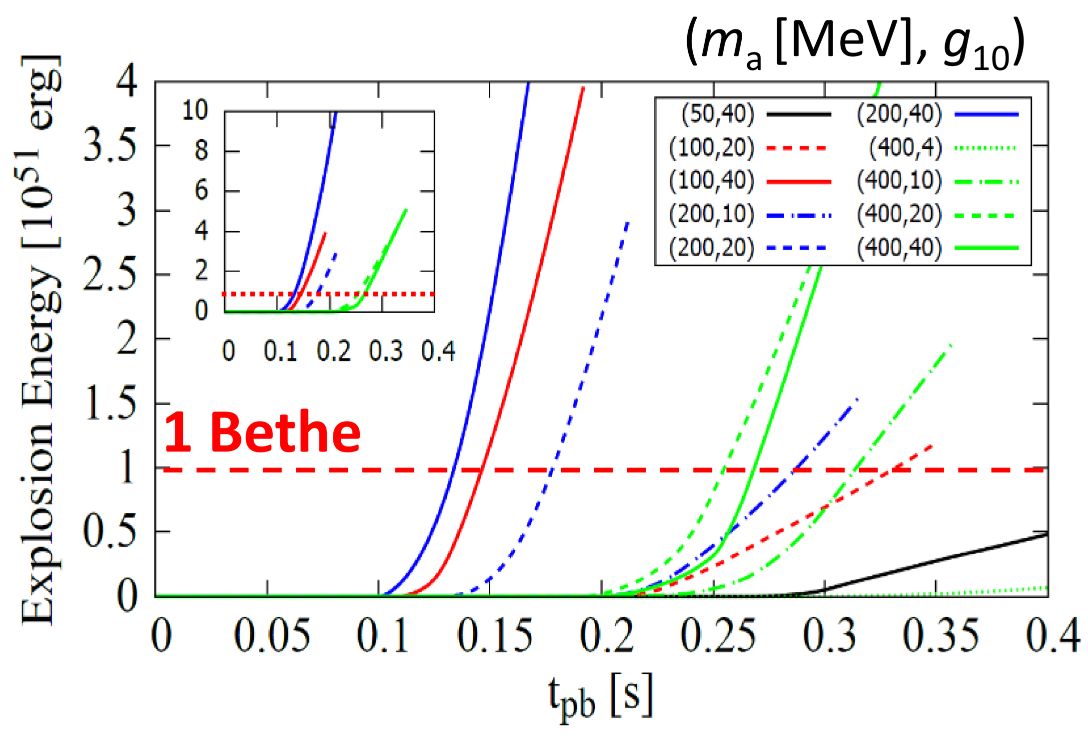


Fig. 4. The time evolution of the explosion energy.

4-3. Parameter Dependence

✓Heavy ALPs tend to induce successful explosion because of shorter MFP.

✓ALPs with m_a=800 MeV do not lead to explosion because T in the core is not high enough.

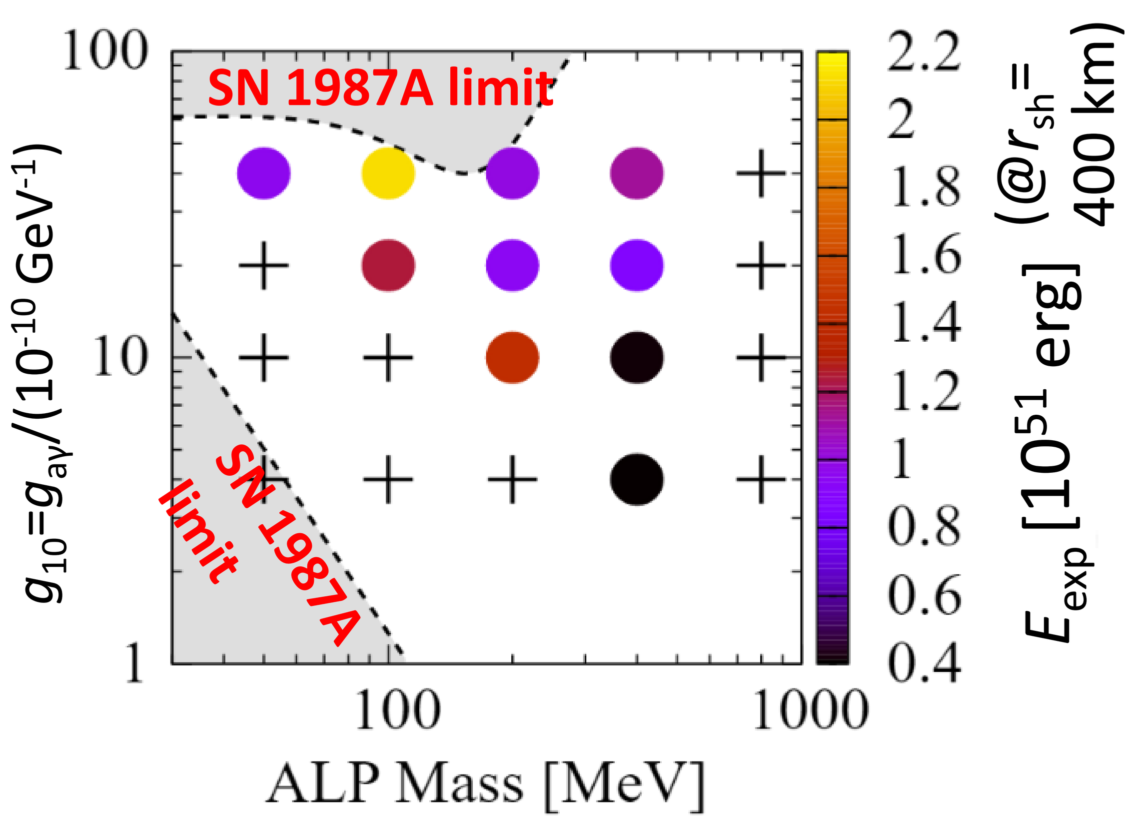


Fig. 5. The models on the parameter space. The crosses show the models that fail to explode and the circles show the models that explode.

5. Summary & Discussion

We developed core-collapse supernova models coupled with heavy ALPs with m_a~100 MeV. The radiative decay of ALPs can heat the material and help the revival of the bounce shock. We found that a supernova successfully explodes when $g_{a\gamma}$ is sufficiently high even in 1D models.

As Fig. 4 shows, some models result in very energetic explosion with $E_{\rm exp}$~10^{52} erg, which may be interpreted as hypernovae or broad-line SNe Ic. However, such energetic explosion is much rarer than usual SNe II. It is hence more likely that the parameter region with high $E_{\rm exp}$ is excluded. In order to obtain solid constraints, it is desirable to perform sensitivity studies on the equation of state and progenitors.

We are planning to perform multi-D simulations to predict the signature of ALPs in multi-messenger signals, which would provide information on the supernova core. Also, we are exploring the ALP effects on different astrophysical objects such as SNe Ia [4], massive stars [5], and pair-instability supernovae [6].

References

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[2] di Lella et al. PRD 62 (2000) 125011.
[3] Takiwaki, Kotake & Suwa MNRAS 461 (2016) L112.
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[5] Mori, Takiwaki & Kotake PRD 105 (2022) 023020.
[6] Sakstein, Croon & McDermott PRD 105 (2022) 095038.