超新星爆発に対する アクシオン加熱の影響

森　寛治

福岡大学爆発天体研究所

Mori, Takiwaki, Kotake & Horiuchi, PRD 105 (2022) 063009

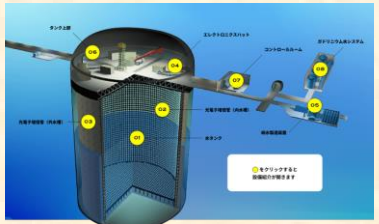
Messengers from a Supernova

SM particles

Photons γ

©NAOJ

Neutrinos ν



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Gravitational waves

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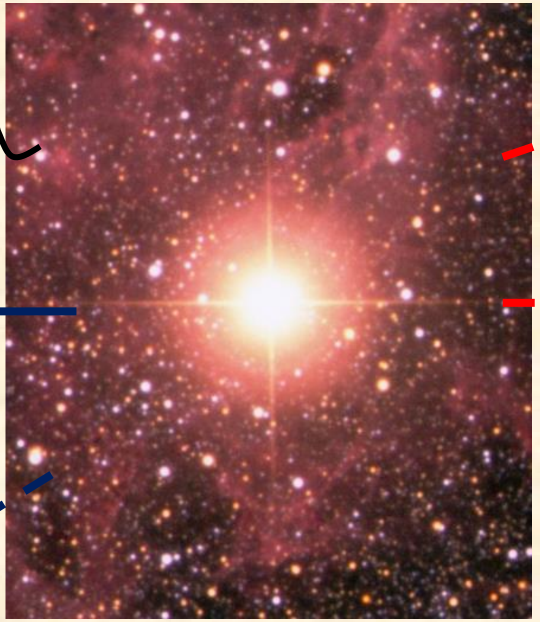
SN 1987A



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Exotic particles

a **Axions**

ν_s Sterile neutrinos

⋮

Axion-like Particles (ALPs)

- Axions are first introduced to solve the strong-CP problem in QCD [Wilczek PRL 40 (1978) 279, Weinberg PRL 40 (1978) 223.]
- However, more fundamental theories such as the string theory can suggest the presence of particles similar to axions [Svrcek & Witten JHEP 2006 (2006) 51, Arvanitaki et al., PRD 81 (2010) 123530.]
- Hypothetical particles which are similar to QCD axions are called **axion-like particles (ALPs)**

Interaction with SM particles

- **ALP-photon coupling**

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

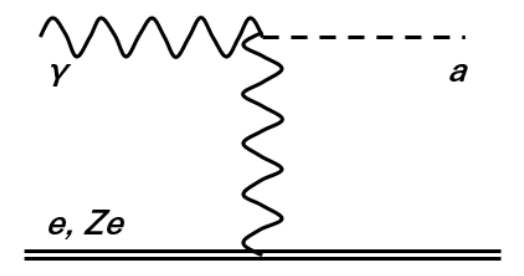
- ALP-electron coupling

$$\mathcal{L}_{ae} = \frac{g_{ae}}{2m_e} \bar{e} \gamma_\mu \gamma_5 e \partial^\mu a$$

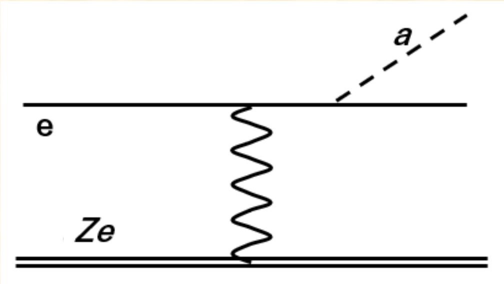
- ALP-nucleon coupling

$$\mathcal{L}_{aN} = \sum_{i=p,n} \frac{g_{ai}}{2m_N} \bar{N}_i \gamma_\mu \gamma_5 N_i \partial^\mu a$$

Primakoff process

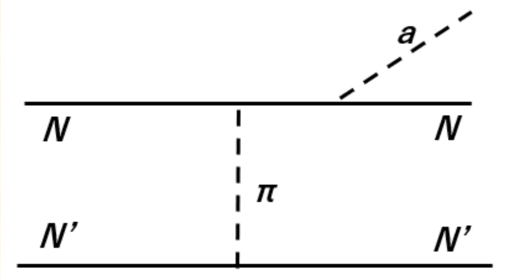


electron-ion bremsstrahlung



e.g. Lucente & Carenza
PRD 104 (2021) 103007

nuclear bremsstrahlung



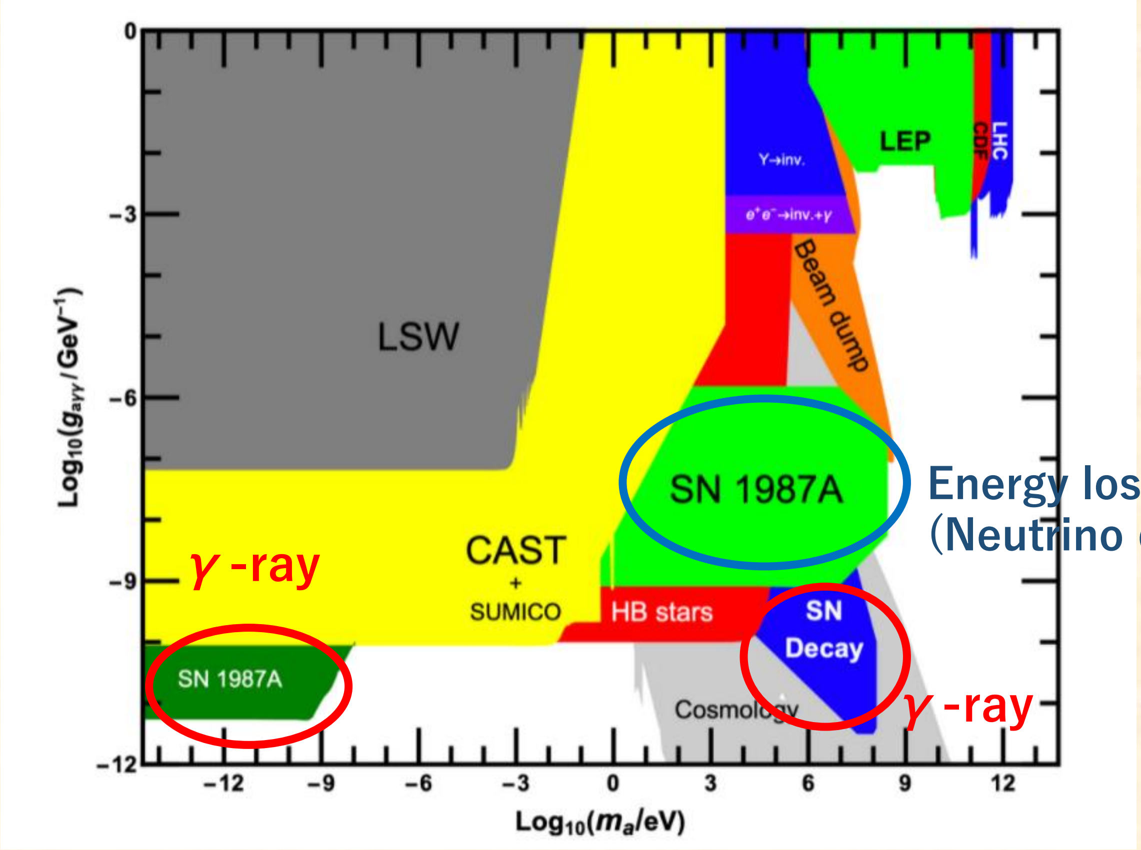
e.g. Carenza et al. JCAP 10 (2019) 016
Turner, PRL 60 (1988) 1797

Constraints on ALP-photon Coupling

ALP-photon coupling

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

✓Supernovae have provided information on the mass m_a and ALP-photon coupling $g_{a\gamma}$



γ-ray

Energy loss
(Neutrino duration)

γ-ray

Jaeckel & Spannowsky PLB 753 (2016) 482

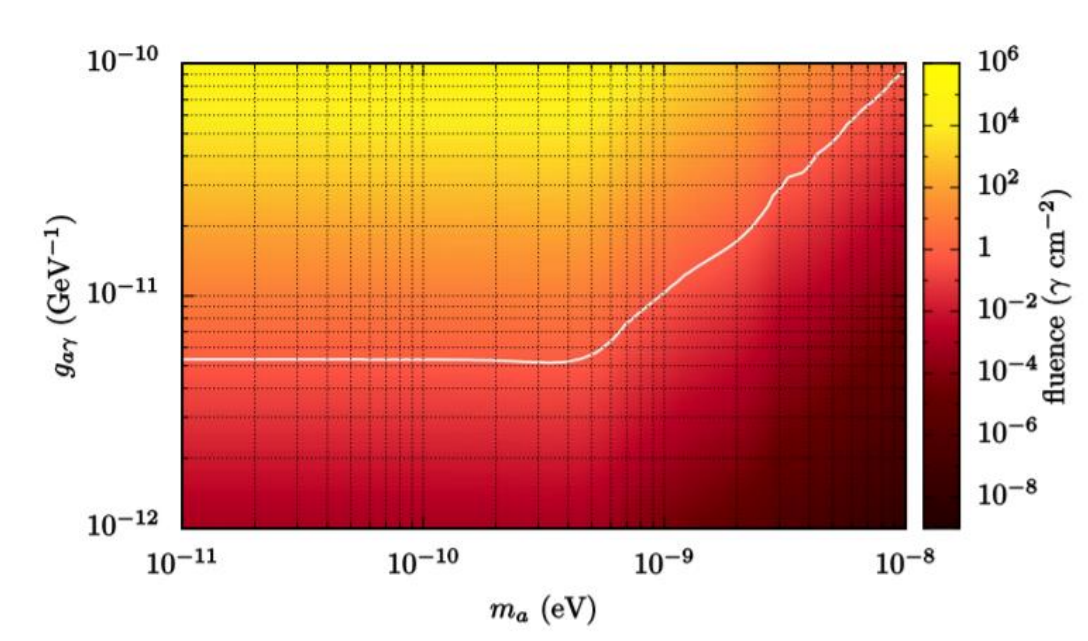
γ-ray Constraints on ALPs

γ-rays from SN 1987A

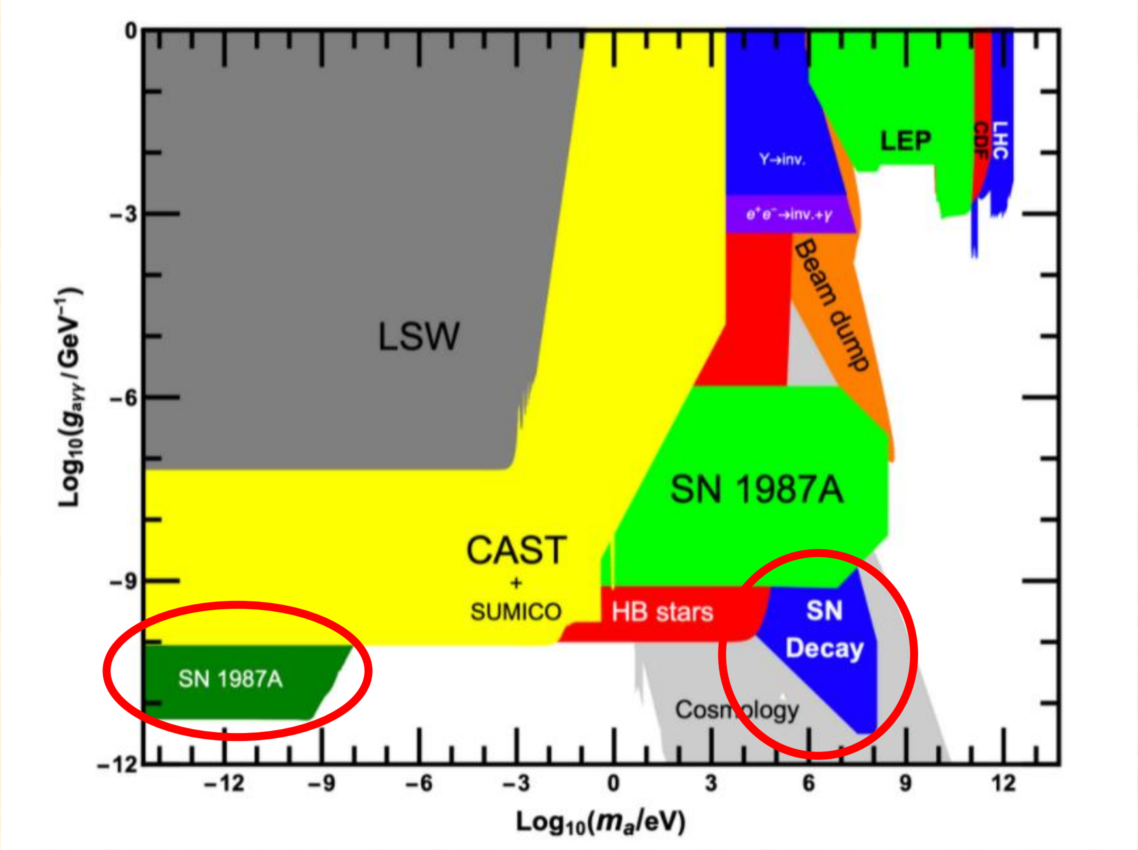
Observation: F(25-100 MeV)<0.6 γ/cm^2

Chupp, Vestrand & Reppin PRL 62 (1989) 505

Theory



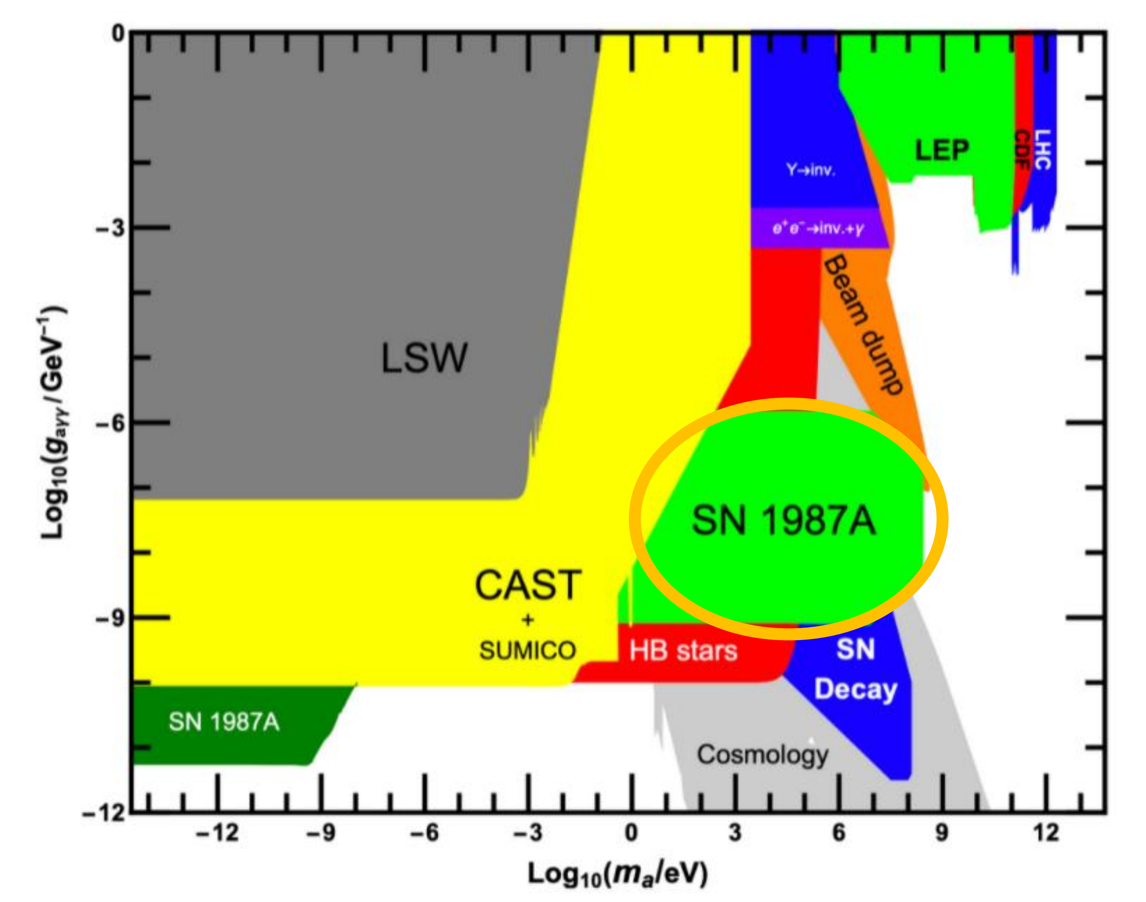
Payez et al., JCAP 1502 (2015) 006



Non-detection of γ-rays from SN 1987A has provided constraints on ALPs

Additional Energy Loss from SNe

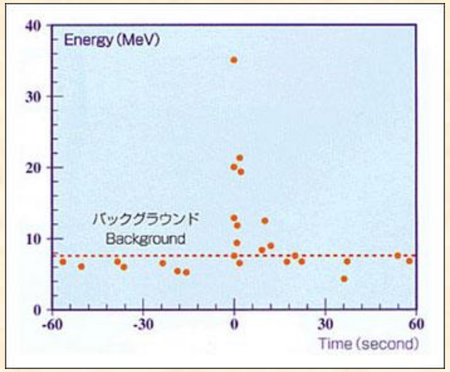
[Lucente et al. JCAP 12 (2020) 008.]



Jaeckel & Spannowsky PLB 753 (2016) 482

- The ALP luminosity L_a is so large that the neutrino burst duration (~10 s) cannot be explained.

Neutrinos from SN 1987A



http://www-sk.icrr.u-tokyo.ac.jp/sk/_images/photo/sk/shinsei_gazou02.jpg

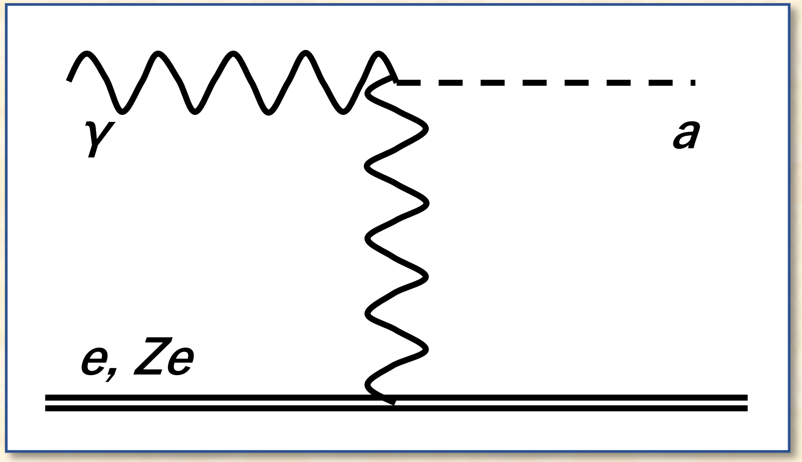
- A criterion $L_a < L_\nu \sim 30 \times 10^{51}$ erg/s is often adopted.

ALP Production Processes

[e.g. di Lella et al. PRD 62 (2000) 125011.]

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

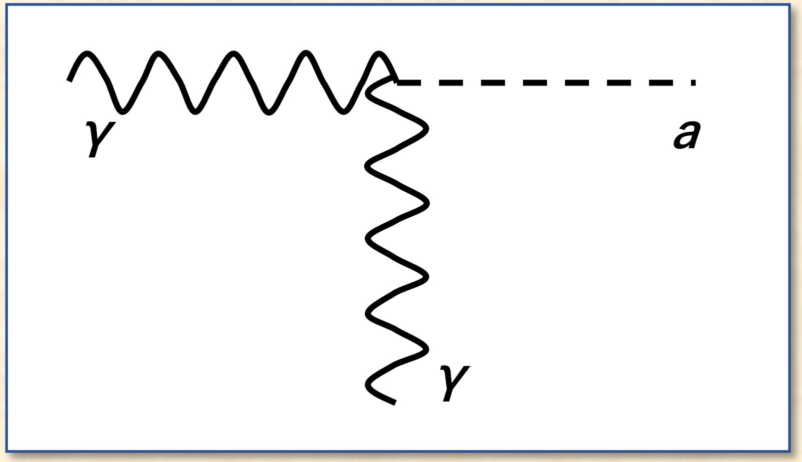
Primakoff process



$$\frac{d^2 n_a}{dtdE} = g_{a\gamma}^2 \frac{T\kappa^2}{32\pi^3} \frac{kp}{e^{\frac{E}{T}} - 1} \left(\frac{((k+p)^2+\kappa^2)((k-p)^2+\kappa^2)}{4kp\kappa^2} \ln\left(\frac{(k+p)^2+\kappa^2}{(k-p)^2+\kappa^2}\right) - \frac{(k^2-p^2)^2}{4kp\kappa^2} \ln\left(\frac{(k+p)^2}{(k-p)^2}\right) - 1 \right)$$

k: photon wave number in plasma
p: ALP momentum
κ : Debye-Hückel scale

Photon coalescence

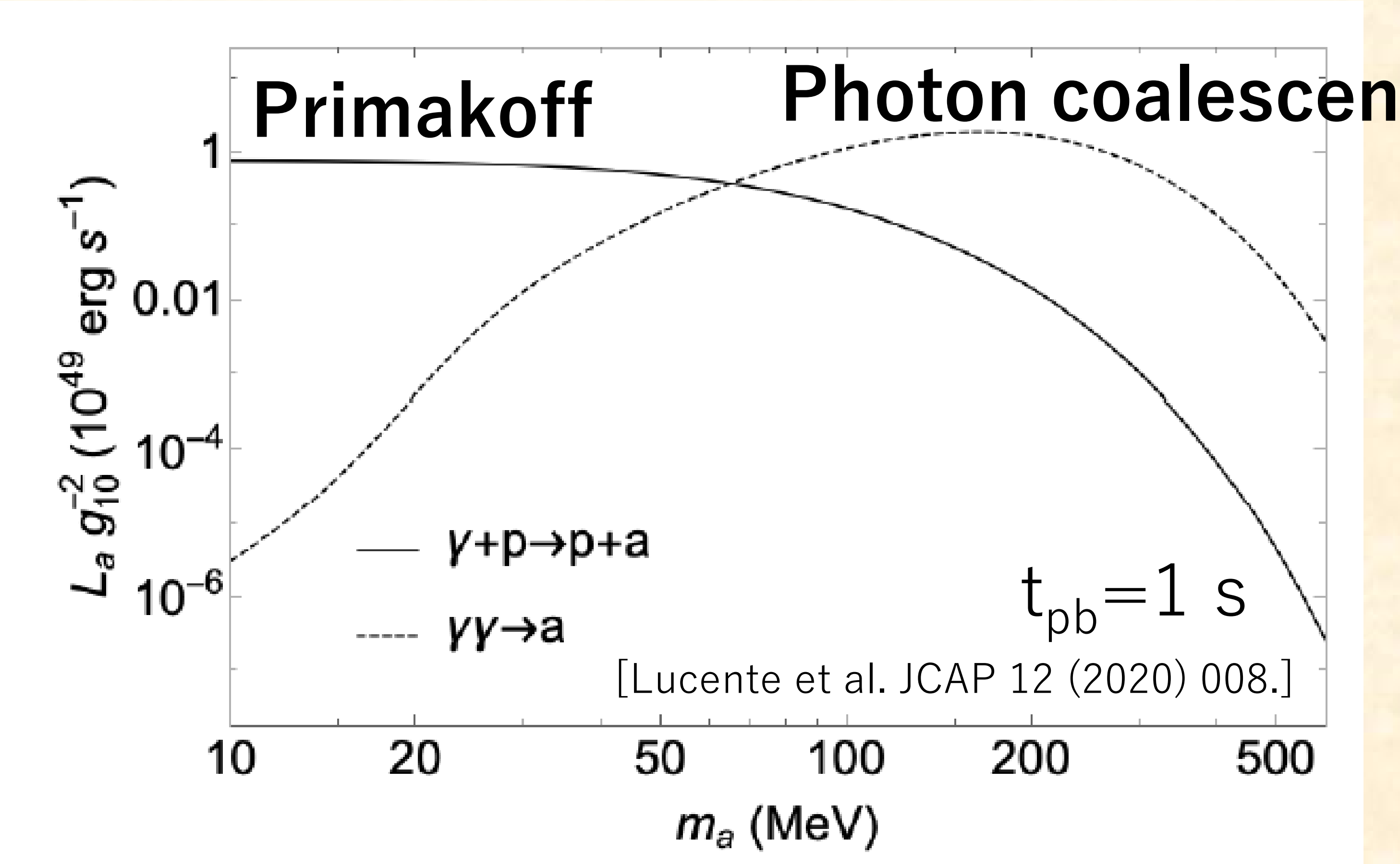


$$\frac{d^2 n_a}{dtdE} = g_{a\gamma}^2 \frac{m_a^4}{128\pi^3} p \left(1 - \frac{4\omega_{\rm pl}^2}{m_a^2}\right)^{\frac{3}{2}} e^{-\frac{E}{T}}$$

$\omega_{\rm pl}$: plasma frequency

Possible only when $m_a > 2\omega_{\rm pl}$

ALP Luminosity from a SN



Primakoff

Photon coalescence

$t_{pb}=1$ s

[Lucente et al. JCAP 12 (2020) 008.]

When we discuss heavy ALPs,
photon coalescence cannot be ignored.

Radiative Decay of Heavy ALPs

- Heavy ALPs are unstable:

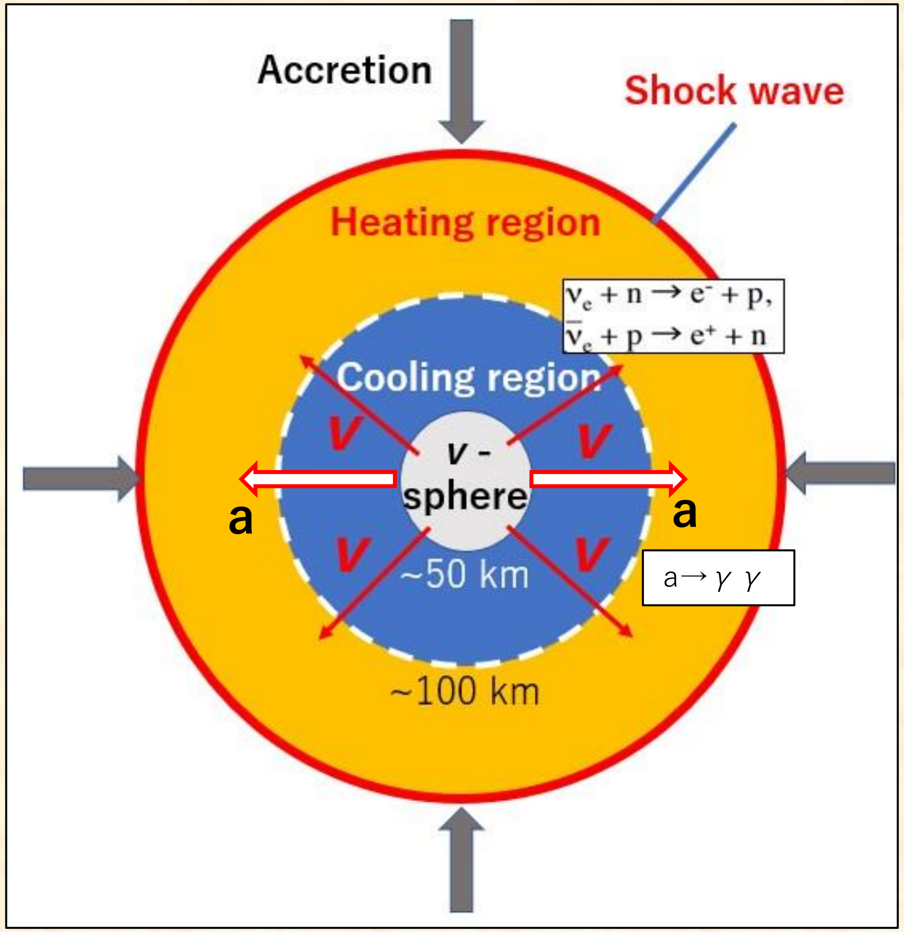
  $$a \to \gamma + \gamma$$

- Mean free path:

$$\lambda_{a\to\gamma\gamma} \sim 6\times10^{4}\ \mathrm{km}\left(\frac{g_{a\gamma}}{10^{-9}\ \mathrm{GeV}^{-1}}\right)^{-2}\left(\frac{E}{150\ \mathrm{MeV}}\right)\left(\frac{m_a}{100\ \mathrm{MeV}}\right)^{-4}$$

- When ALPs are heavy enough, ALPs decay in a star

→**Heating effect in SNe**



SN Simulation Coupled with ALPs

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

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

Dimension: 1D **EoS**: LS220 **Progenitor**: $20M_\odot$ [Woosley & Heger Phys. Rep. 442 (2007) 269]

ALP production:
- Primakoff process
- Photon coalescence

ALP absorption:
- Inverse Primakoff process
- Radiative decay

What we solve:

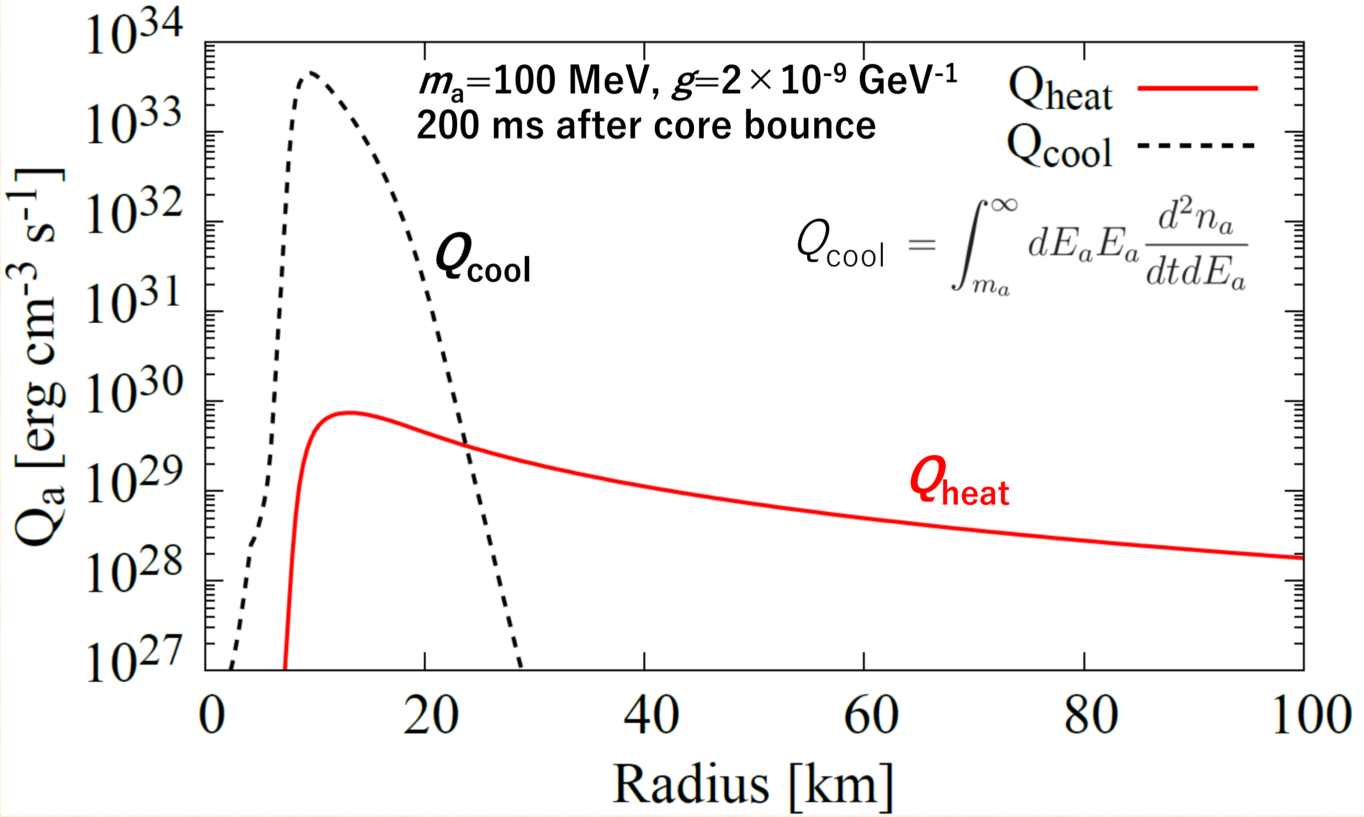
$$\cancelto{0}{\frac{\partial \mathcal{E}}{\partial t}} + \nabla \cdot \mathcal{F} = \mathcal{S}$$

→

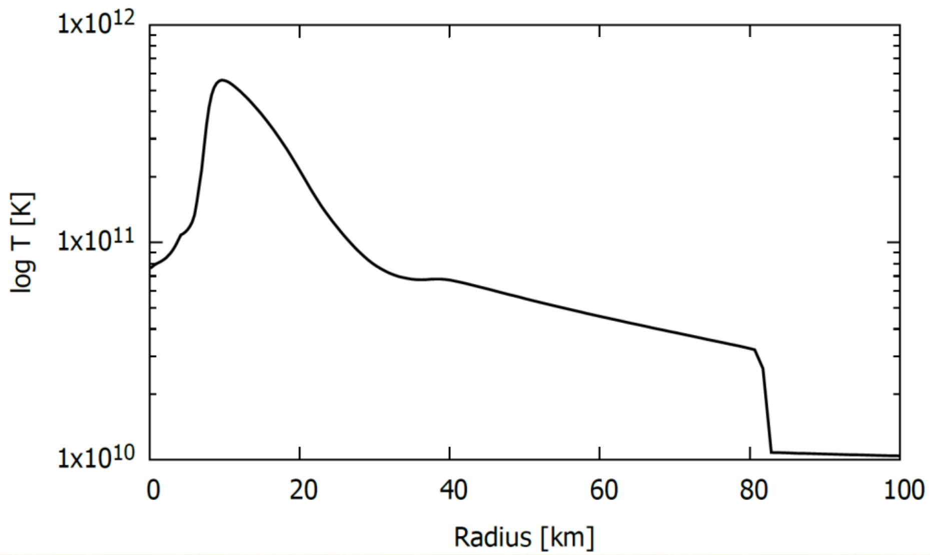
Modification on internal energy:

$$e^{n+1}_{\mathrm{int},\, i} = e^{n}_{\mathrm{int},\, i} + (Q^{n}_{\mathrm{heat},\, i} - Q^{n}_{\mathrm{cool},\, i})\Delta t$$

ALP Cooling & Heating Rates



Temperature profile



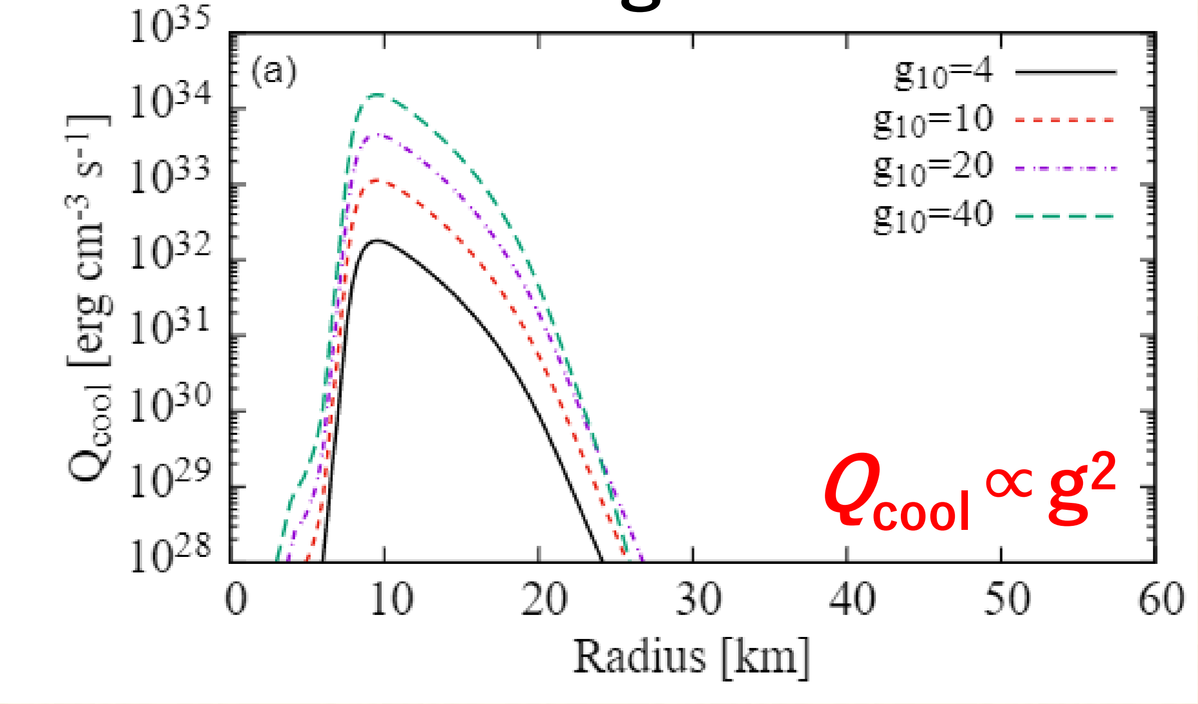
✓ALPs are produced at ~10 km

✓ALPs decay after propagation → **additional heating**

ALP Cooling & Heating Rates

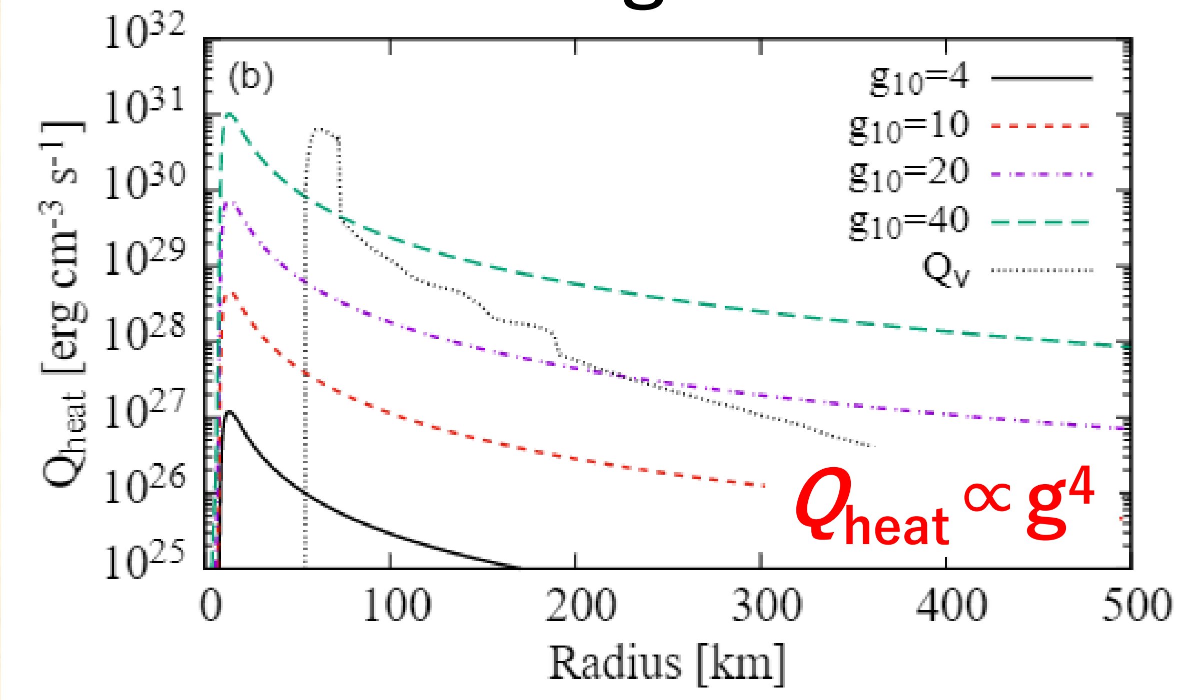
ALP mass is fixed: m_a=100 MeV

Cooling rate



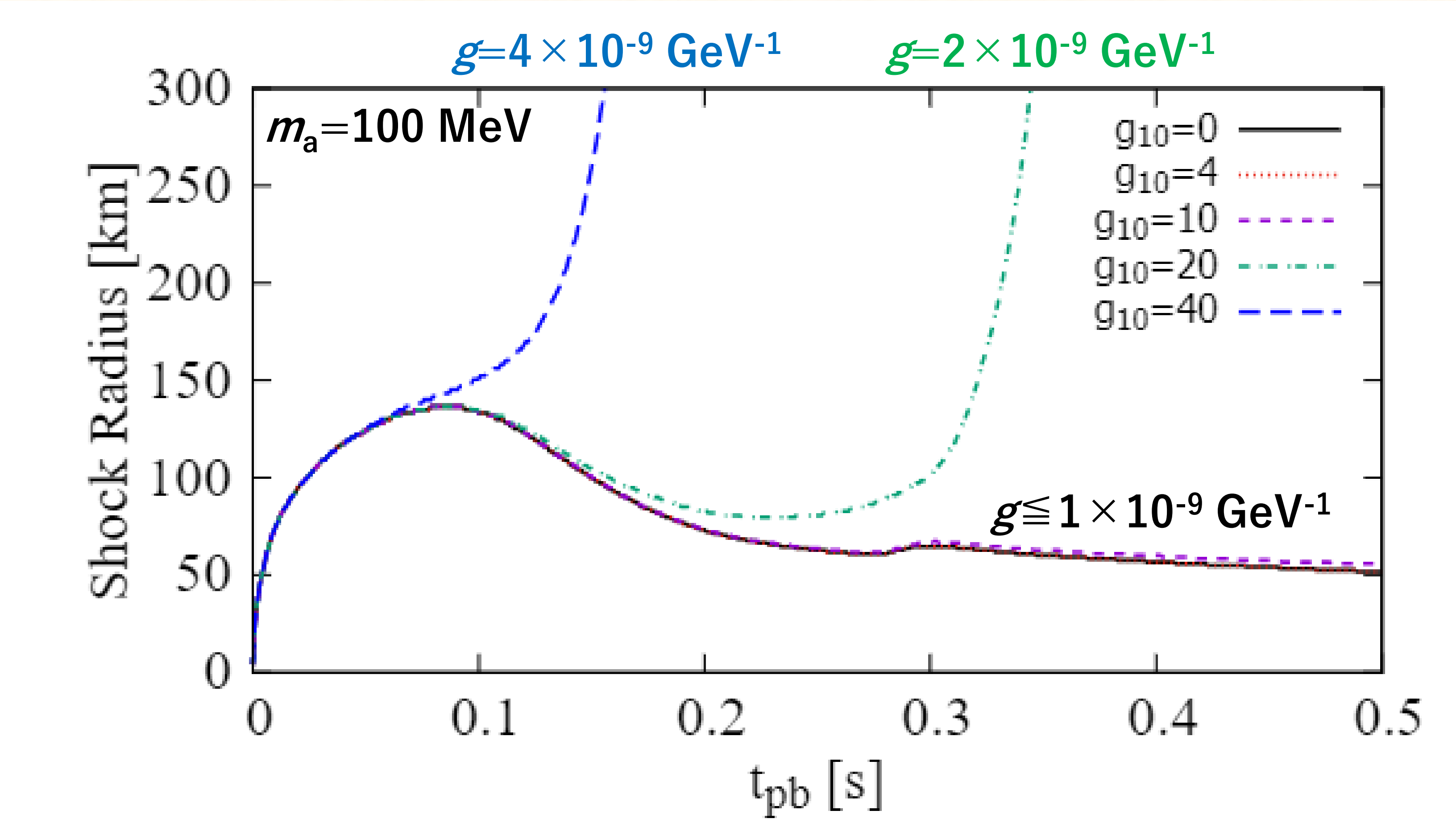
$Q_{\mathrm{cool}} \propto g^2$

Heating rate



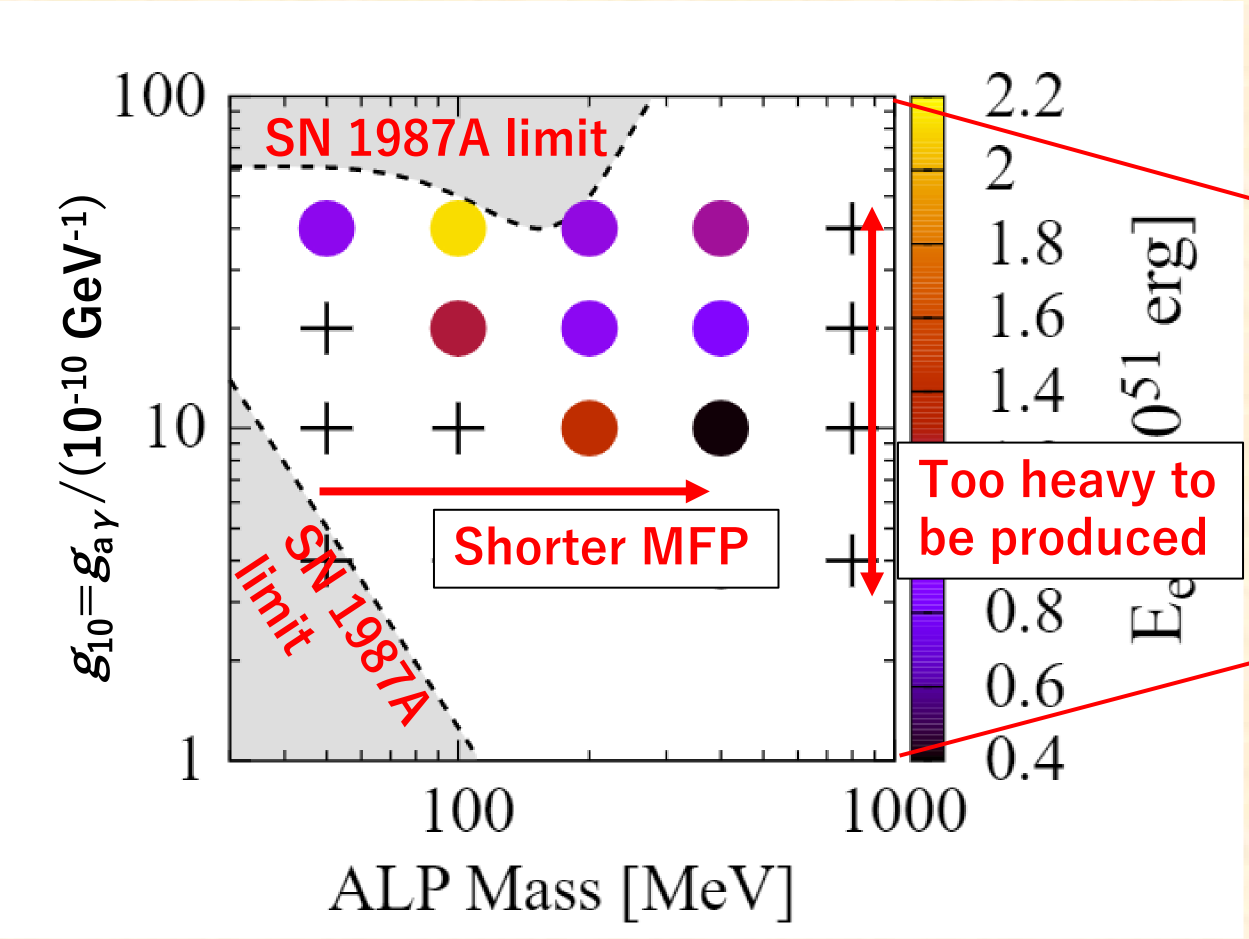
$Q_{\mathrm{heat}} \propto g^4$

Shock Revival Assisted by ALPs



ALP heating can lead to shock revival even in 1D models!

Explodability of 1D Models

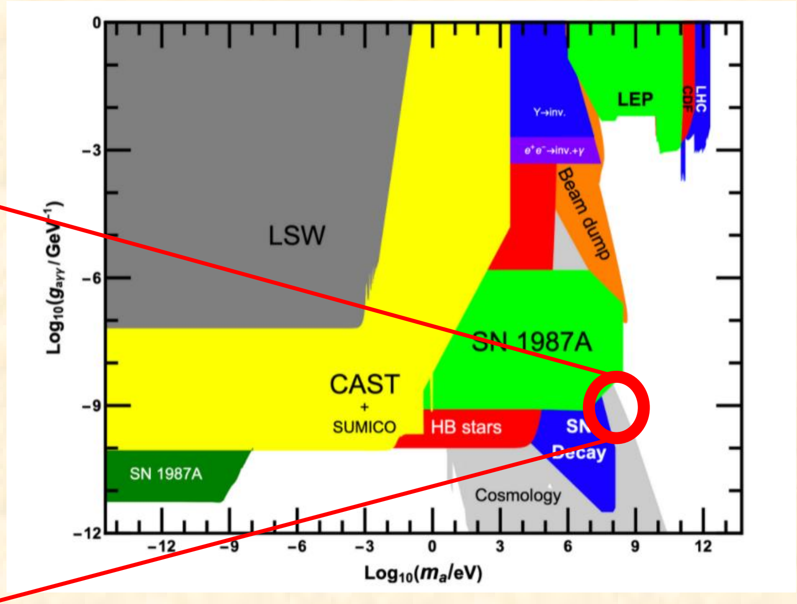


SN 1987A limit

SN 1987A limit

Shorter MFP

Too heavy to be produced



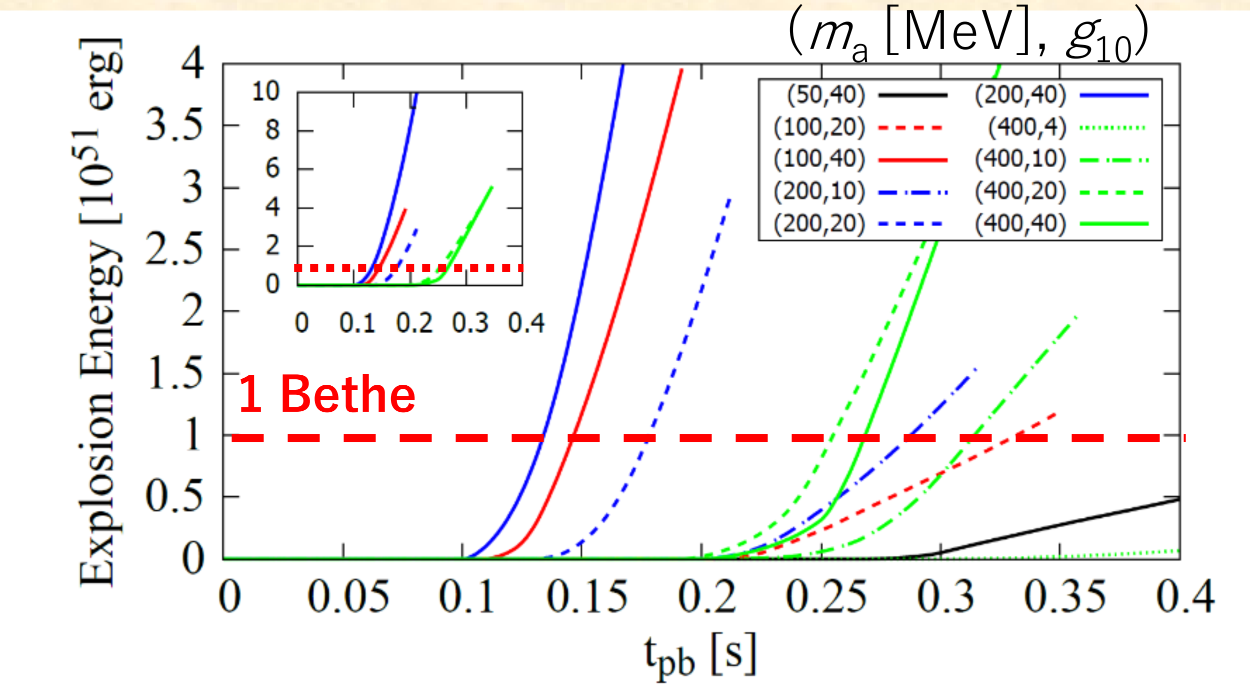
ALPs with m_a=O(100) MeV significantly affect SN dynamics.

●: Successful explosion

+: Failed Explosion

Explosion Energy

- In general, larger coupling constants lead to more energetic explosion
- The ALP parameters with $E_{\mathrm{exp}} > 10^{51}$ erg would be excluded



$$\left[\quad E_{\mathrm{exp}} = \int_D dV\left(\frac{1}{2}\rho v^2 + e - \rho\Phi\right)\quad\right]$$

Summary

- Astrophysical objects such as core-collapse SNe offer opportunities to explore ALPs.
- We performed stellar core-collapse simulations with ALP transport.
- Heavy ALPs with m_a~100 MeV can assist the shock revival in SNe.
- If $g_{a\gamma}$ is too high, the explosion energy exceeds 10^{51} erg.

→Additional constraint on ALPs