Multi-messenger signals of heavy axion-like particles in core-collapse supernovae

Kanji Mori (森寛治)
Division of Science, National Astronomical Observatory of Japan

KM, Takiwaki, Kotake & Horiuchi,
PRD 105 (2022) 063009; PRD in press (arXiv:2304.11360)

Axions

[Peccei & Quinn (1977), Wilczek (1978), Weinberg (1978).]

- Hypothetical particles introduced to solve the strong CP problem in QCD

$\mathcal{L}_{\mathrm{QCD}} \supset \theta \frac{g_s^2}{32\pi^2} G^{a\,\mu\nu} \tilde{G}^a_{\mu\nu}$:CP-violating term ⟺ ? Exp: $\theta < 10^{-10}$

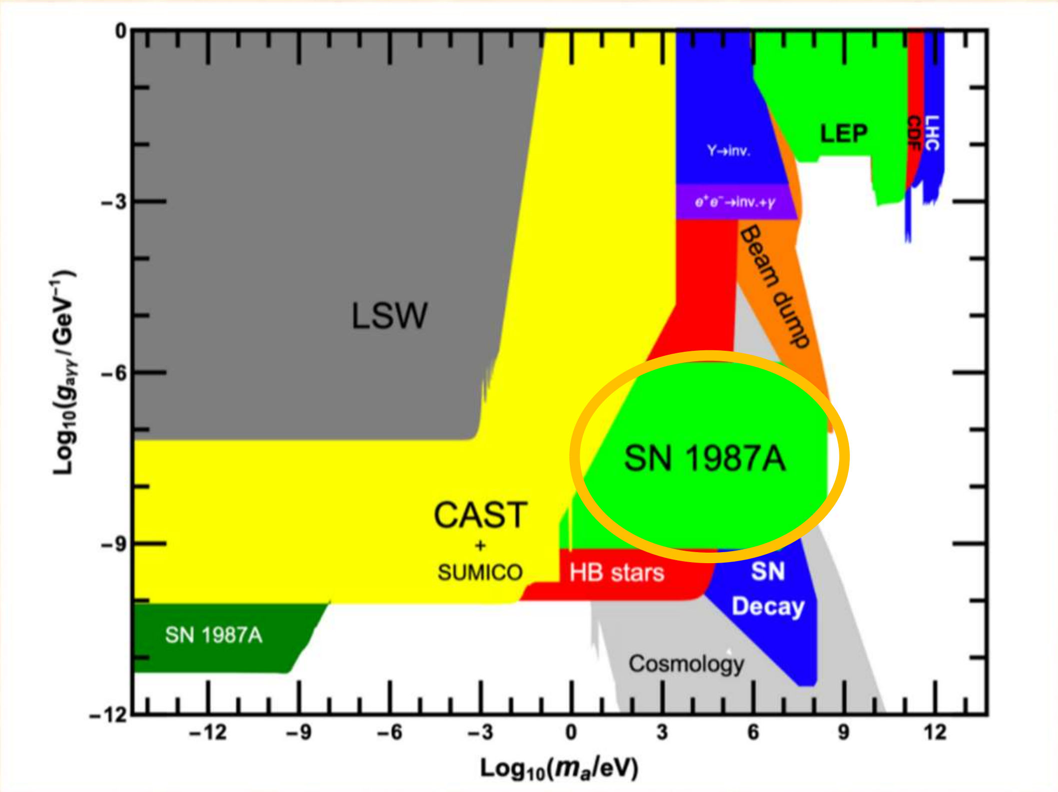
- Possible coupling with photons: $\mathcal{L}_{a\gamma\gamma} = -\frac{1}{4} g_{a\gamma} a \tilde{F}^{\mu\nu} F_{\mu\nu}$

→ Axions can be produced in astrophysical plasma

- Other types of particles that share some features with QCD axions: **Axion-like particles** (ALPs)

Additional Energy Loss from Proto-NS

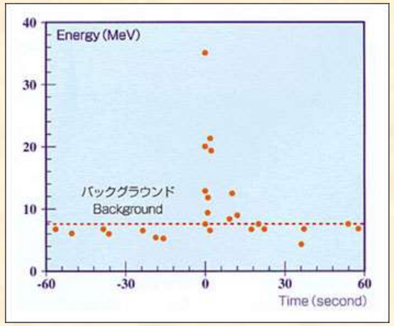
[Lucente et al. JCAP 12 (2020) 008.]



Jaeckel & Spannowsky PLB 753 (2016) 482

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

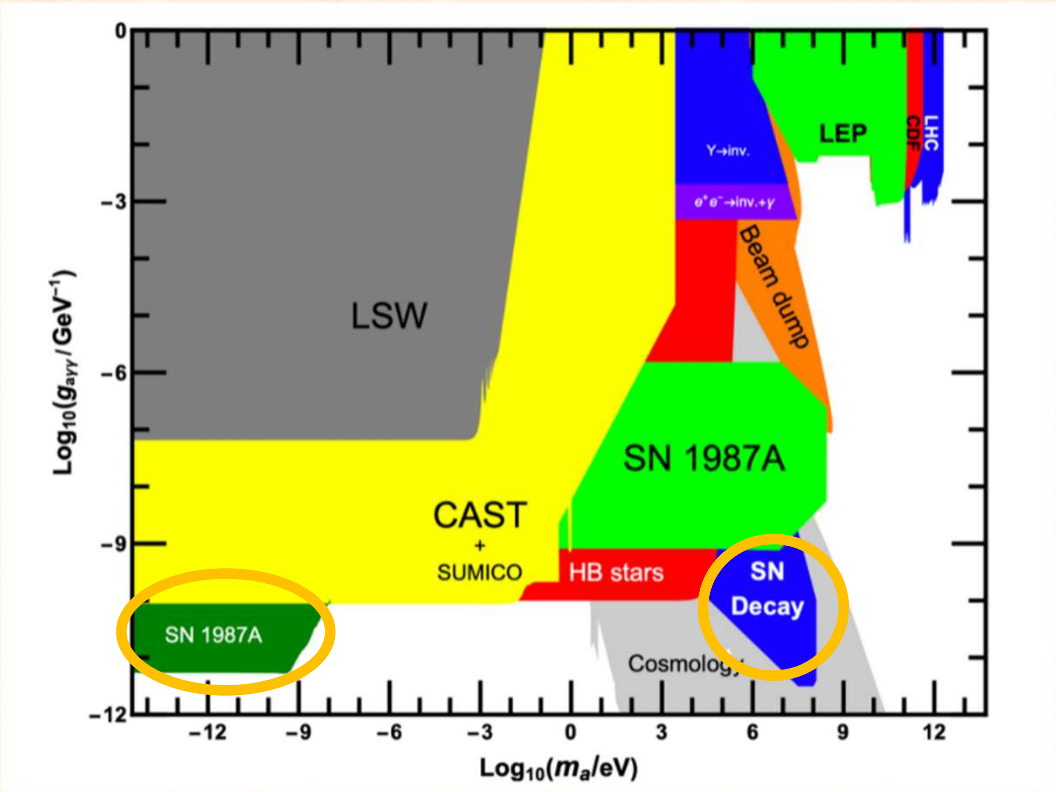
Neutrinos from SN 1987A



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.

Supernova Gamma-ray Limit



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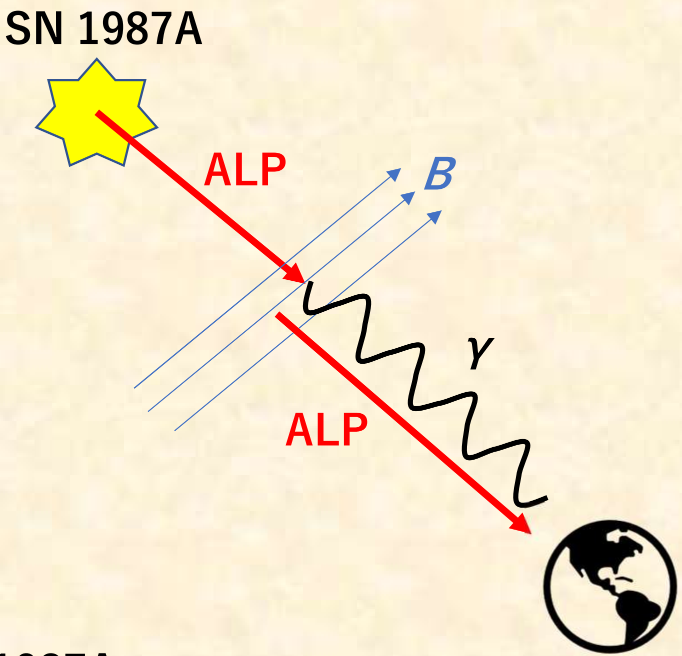
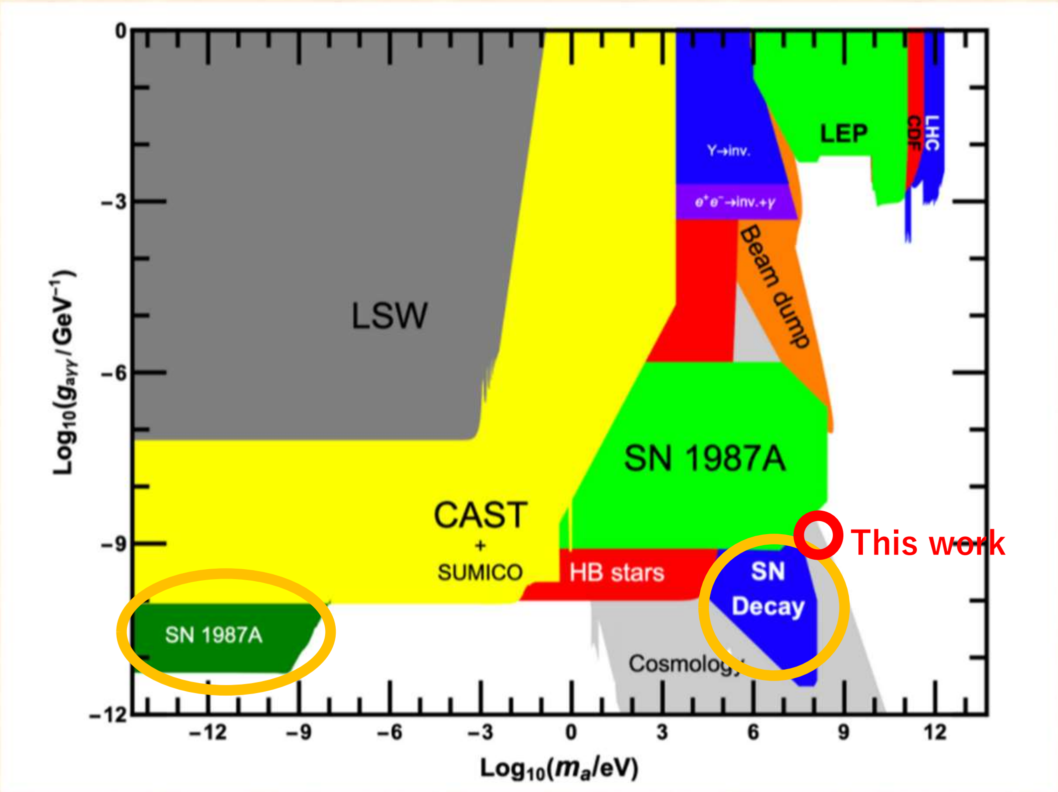


SN 1987A
Observation: F(25-100 MeV)<0.6 γ/cm^2

Chupp, Vestrand & Reppin PRL 62 (1989) 505

Supernova Gamma-ray Limit



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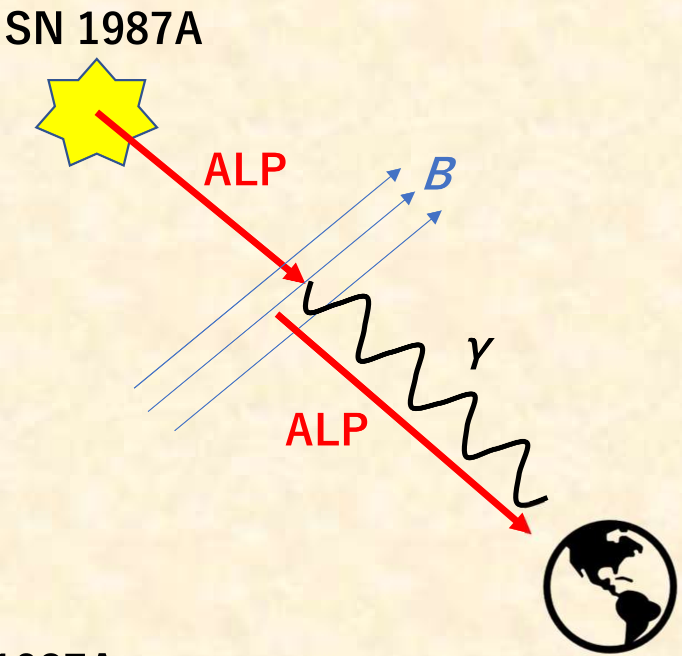

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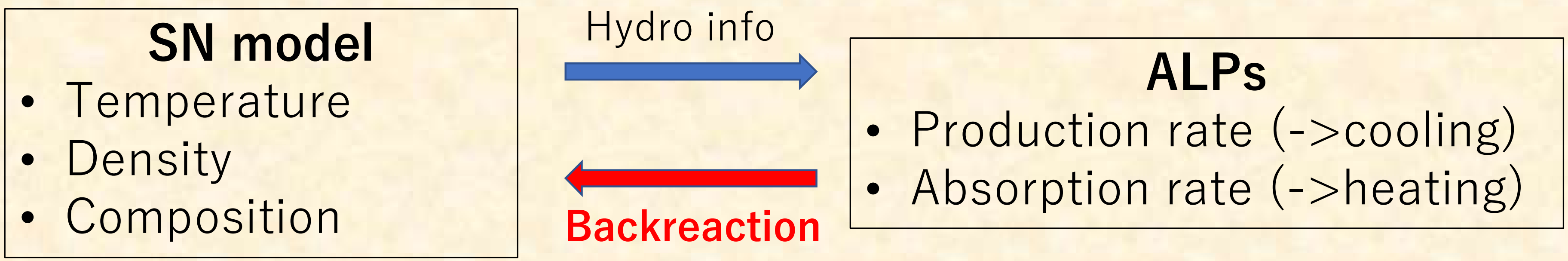
Beyond Post-processing

- Previous calculations are mainly performed with post-process: hydrodynamics and ALPs are decoupled
- In order to predict the signature of ALPs in neutrino and gravitational wave signals, one should go beyond post-processing
- **We developed a new method to calculate the backreaction of ALPs**

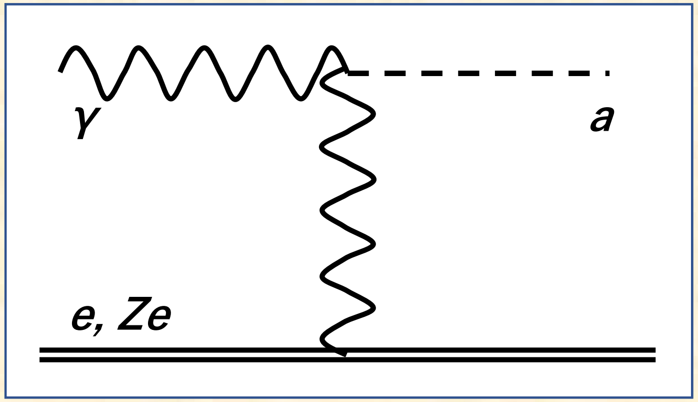


ALP Production Processes

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

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

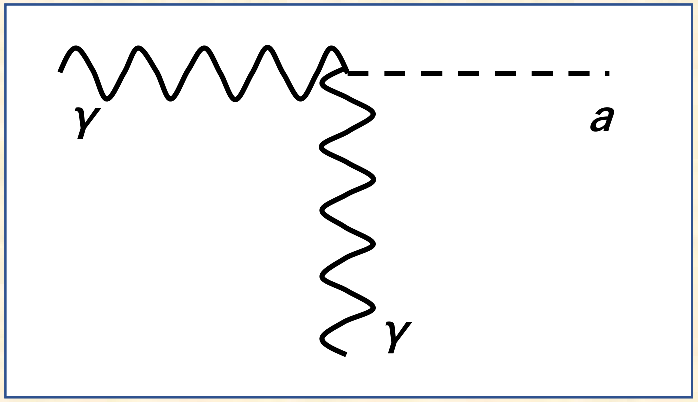
Primakoff process



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

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

Photon coalescence



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

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

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

Radiative Decay of Heavy ALPs

- Heavy ALPs are unstable:

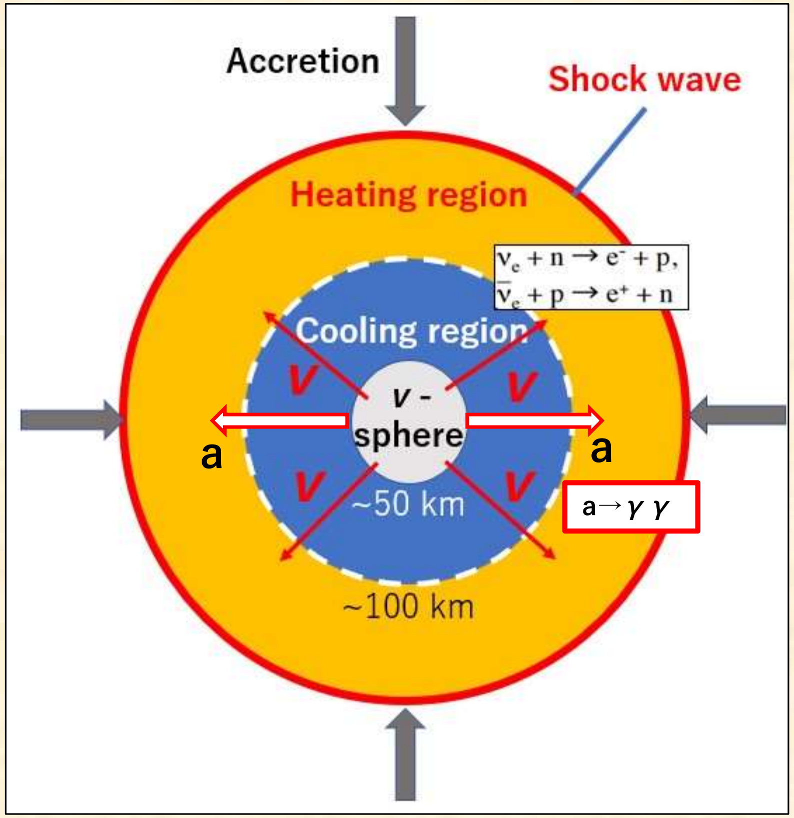
  a→ $\gamma + \gamma$

- Mean free path:

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

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

→**Effect on SN dynamics?**



SN Simulation Coupled with ALPs

Code: 3DnSNe [Takiwaki, Kotake & Suwa MNRAS 461 (2016) L112]
with IDSA [Liebendörfer, Whitehouse, & Fischer ApJ 698 (2009) 1174]

Dimension: **2D** **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

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

$Q_{\rm cool}$: ALP production
$Q_{\rm heat}$: ALP absorption

discretize →

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

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

for the *i*-th cell

Modification on internal energy:

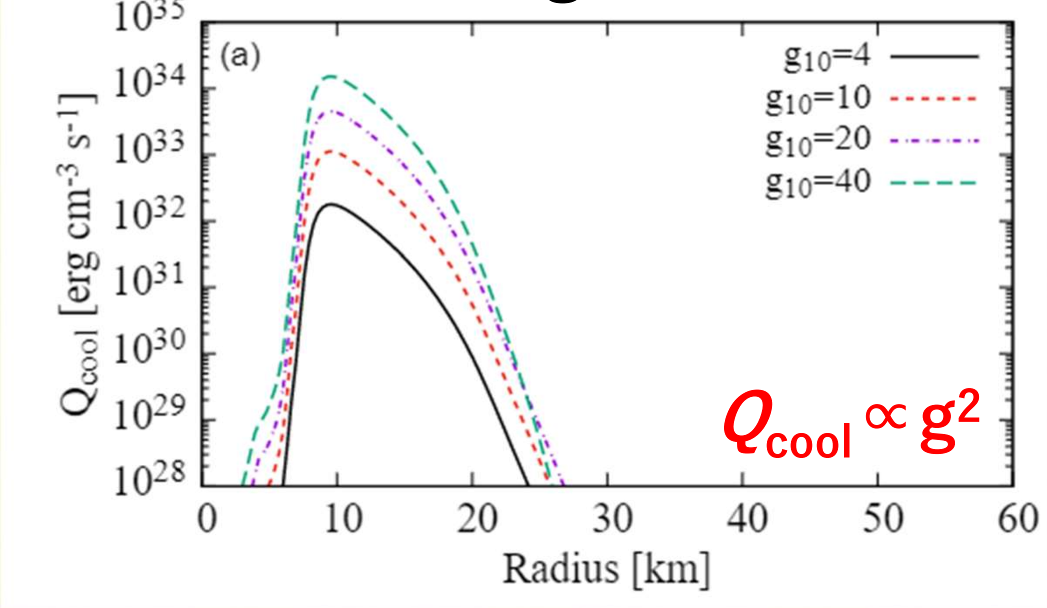
$$e^{n+1}_{{\rm int},\, i} = e^{n}_{{\rm int},\, i} + (Q^n_{{\rm heat},\, i} - Q^n_{{\rm cool},\, i})\Delta t$$

ALP Cooling & Heating Rates

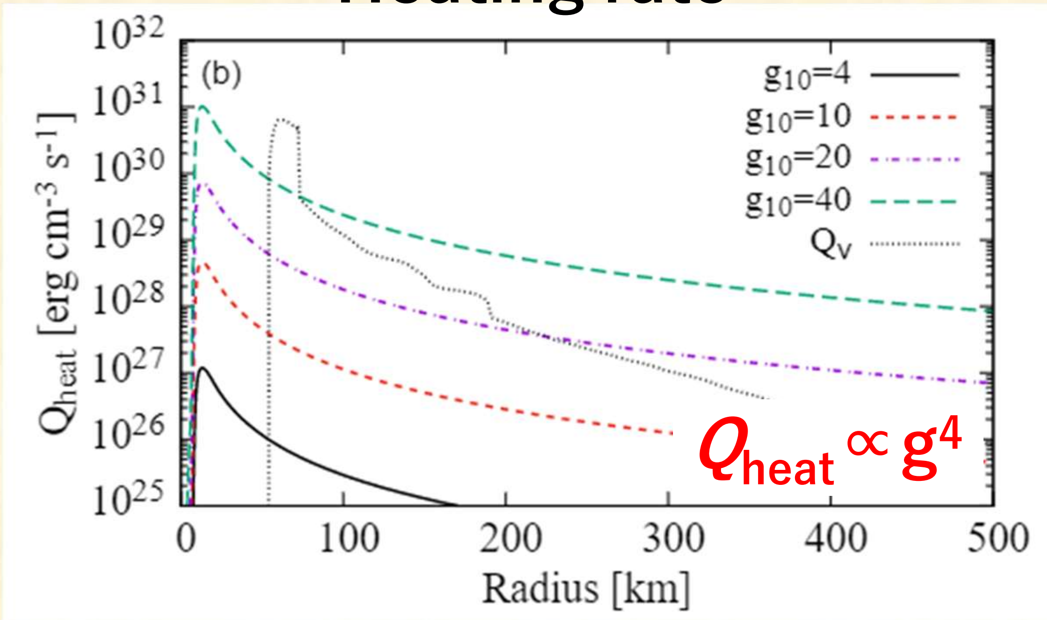
[KM et al., PRD 105 (2022) 063009]

m_a=100 MeV
t_{pb}=200 ms

Cooling rate



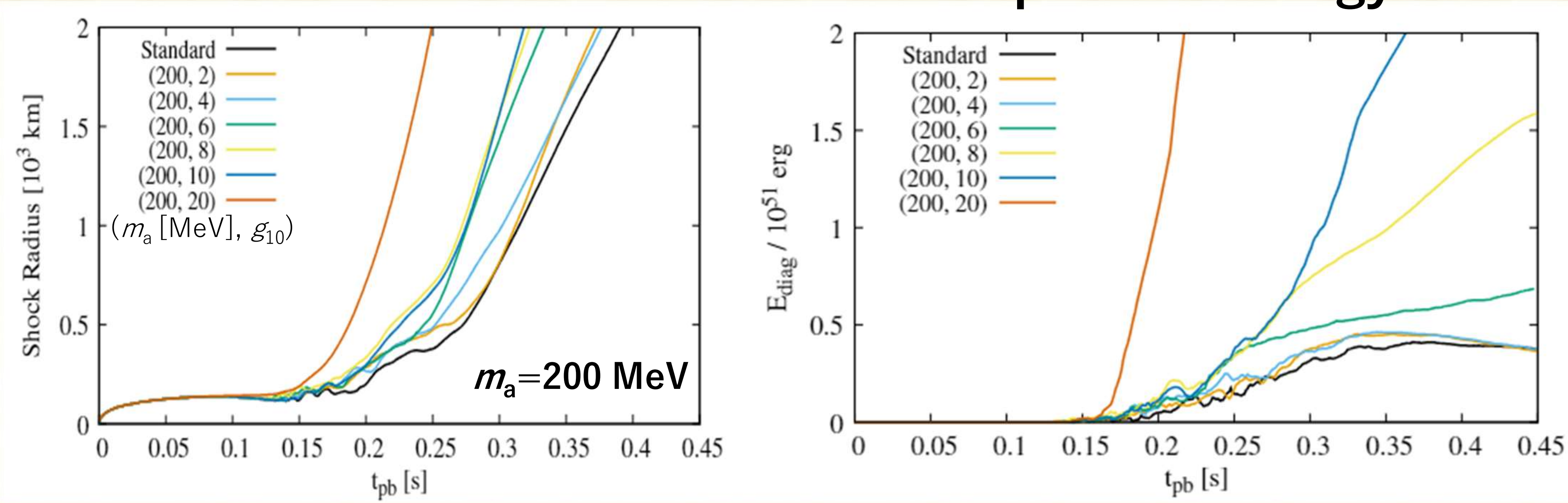
Heating rate



Q_{heat} is a steep function of the ALP-photon coupling constant g.

Shock Radius & Explosion Energy

Shock radius **Explosion energy**



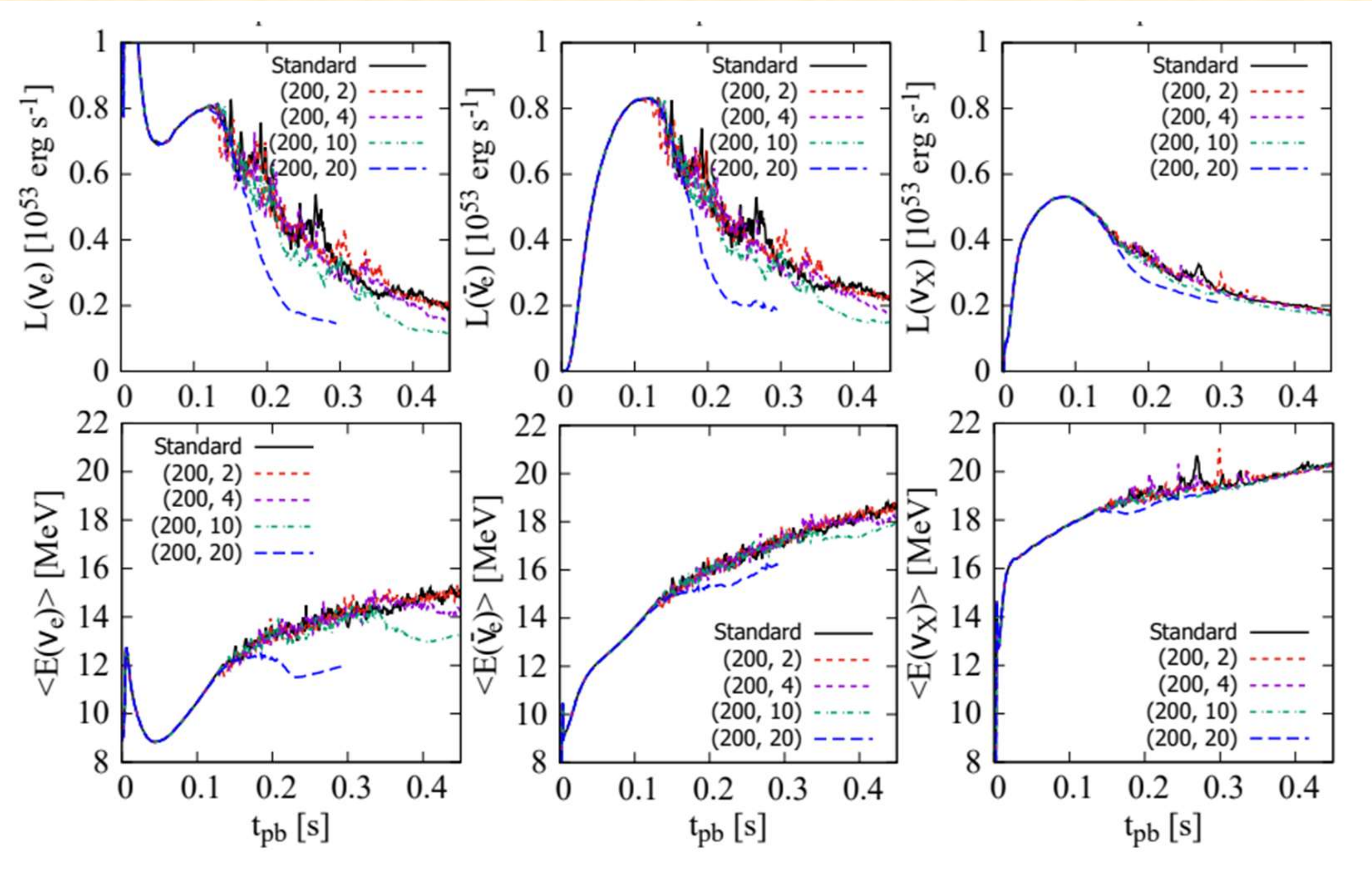
[KM et al., PRD in press (arXiv:2304.11360)]

✓**ALPs assist the explosion!**

✓Explosion energy exceeds 10^{51} erg if $g_{a\gamma}$ >~6×10^{51} erg.

Neutrino Signals

m_a=200 MeV



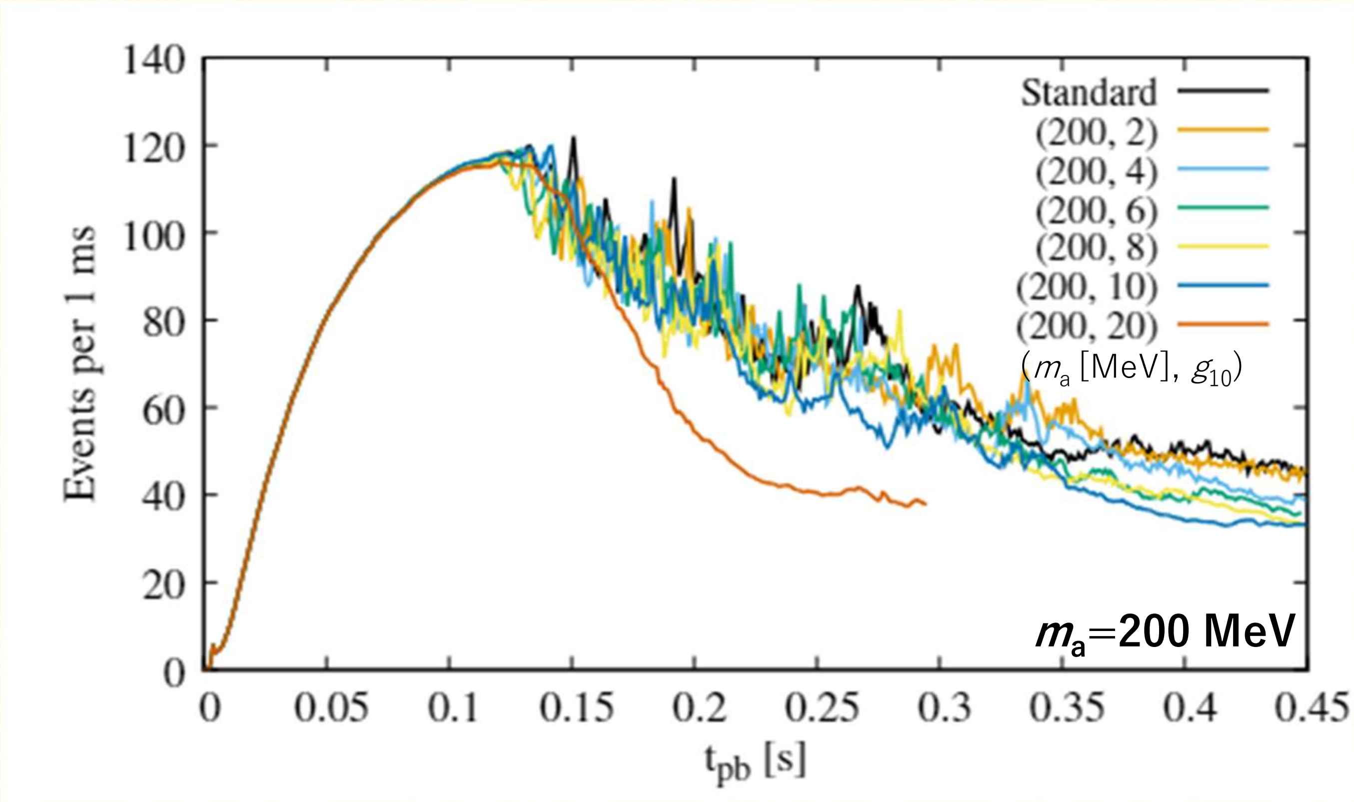
✓Both neutrino luminosity and mean energy decrease because of ALPs.

✓ALP production induces additional cooling of PNS.

[KM et al., PRD in press (arXiv:2304.11360)]

Neutrino Signals

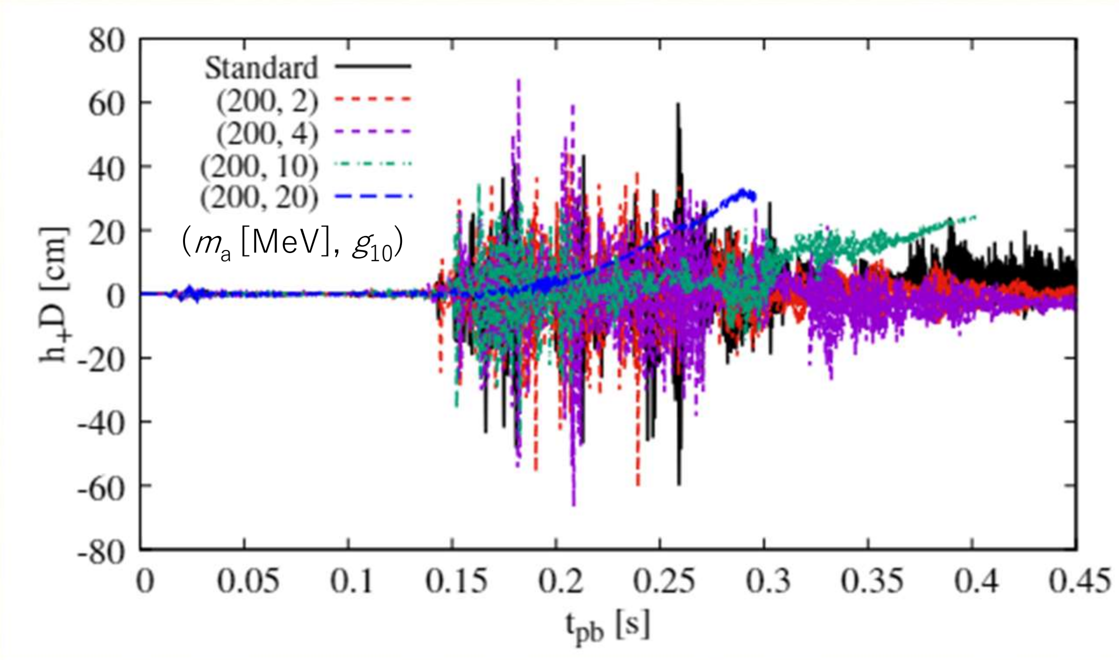
Hyper-kamiokande, inverse β -decay, D=8.5 kpc (*i.e.* Galactic center)
Normal mass hierarchy

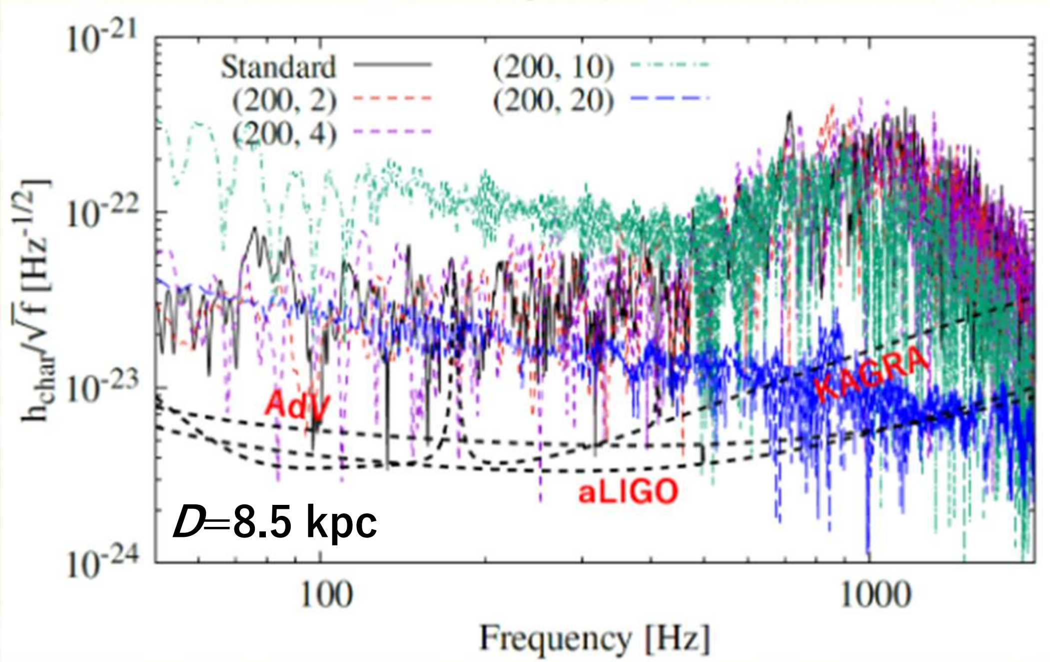


[KM et al., PRD in press (arXiv:2304.11360)]

Neutrino events from a nearby SN event decrease!

Gravitational Wave Signals





[KM et al., PRD in press (arXiv:2304.11360)]

- **GW signals are weakened.**
- ALP heating prevents the mass accretion.

Summary

- Astrophysical objects such as core-collapse SNe offer unique opportunities to explore ALPs.
- Heavy ALPs with m_a~100 MeV can assist the shock revival in SNe.
- If the ALP-photon coupling is large enough, the explosion becomes more energetic than observed events.
- Both neutrino and GW signals are weakened (but still observable!).

ALP-photon Conversion

[Raffelt & Stodolsky PRD 37 (1988) 1237.]

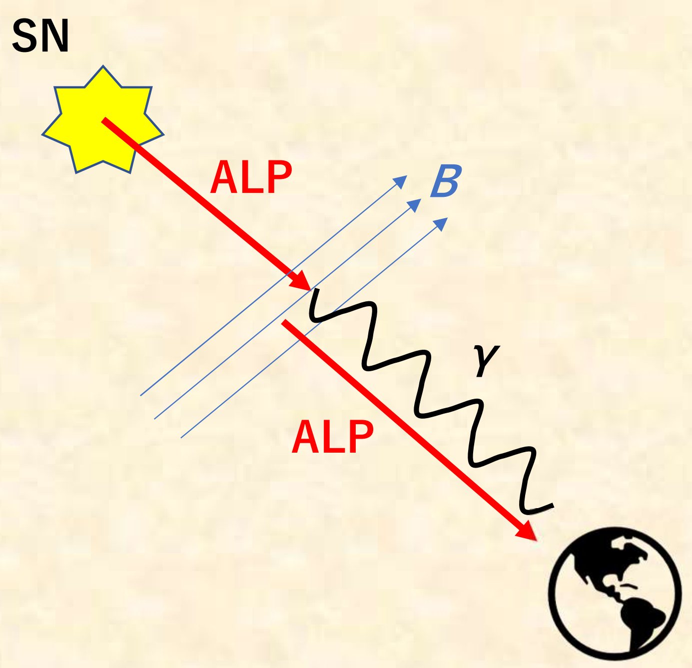
ALPs are converted into photons by Galactic magnetic field

→ **γ -ray may be observable**

$$P_{a\gamma} = (\Delta_{a\gamma} d)^2 \frac{\sin^2\left(\frac{\Delta_{\rm osc} d}{2}\right)}{\left(\frac{\Delta_{\rm osc} d}{2}\right)^2}$$

$$\Delta_a = -\frac{m_a^2}{2E},\ \Delta_{\rm pl} = -\frac{\omega_{\rm pl}^2}{2E}$$

$$\Delta_{a\gamma} = g_{a\gamma}\frac{B_{\rm T}}{2} \qquad \Delta_{\rm osc} = \sqrt{(\Delta_a - \Delta_{\rm pl})^2 + 4\Delta_{a\gamma}^2}$$



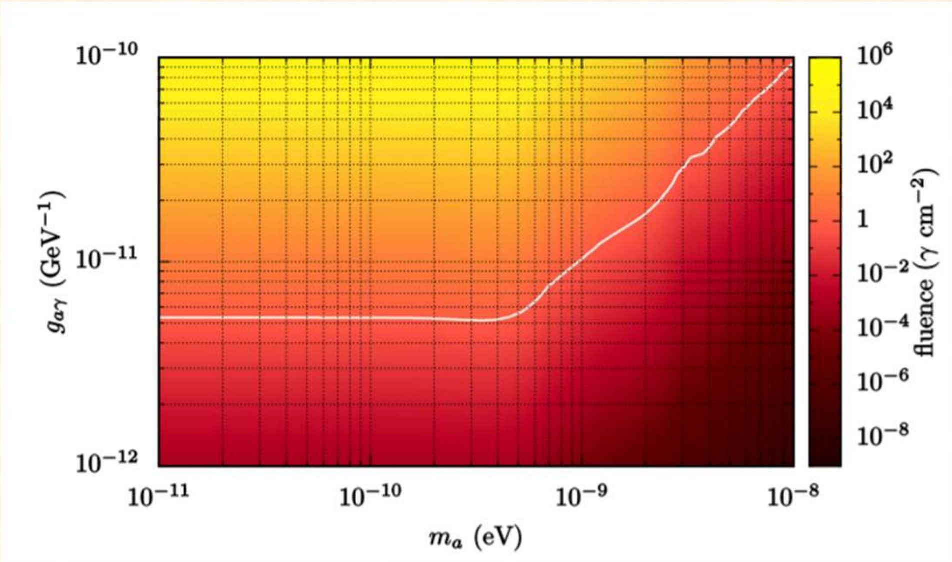
SN 1987A Constraints on ALPs

γ-rays from SN 1987A

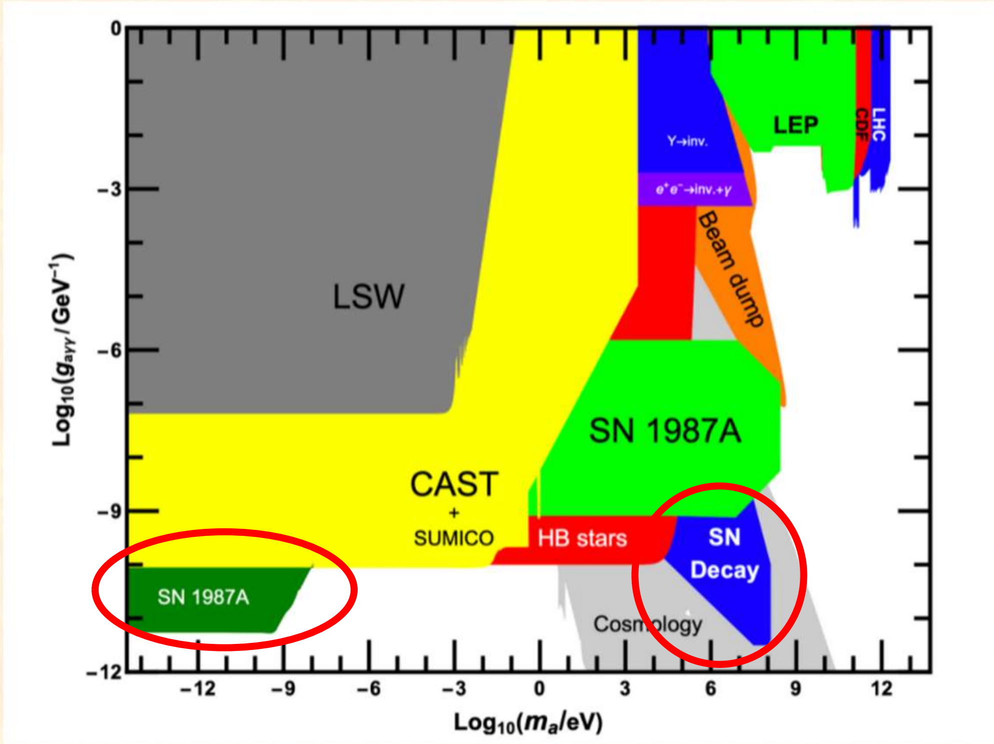
Observation: F(25-100 MeV)<0.6 γ/cm^2

Chupp, Vestrand & Reppin PRL 62 (1989) 505

Theory

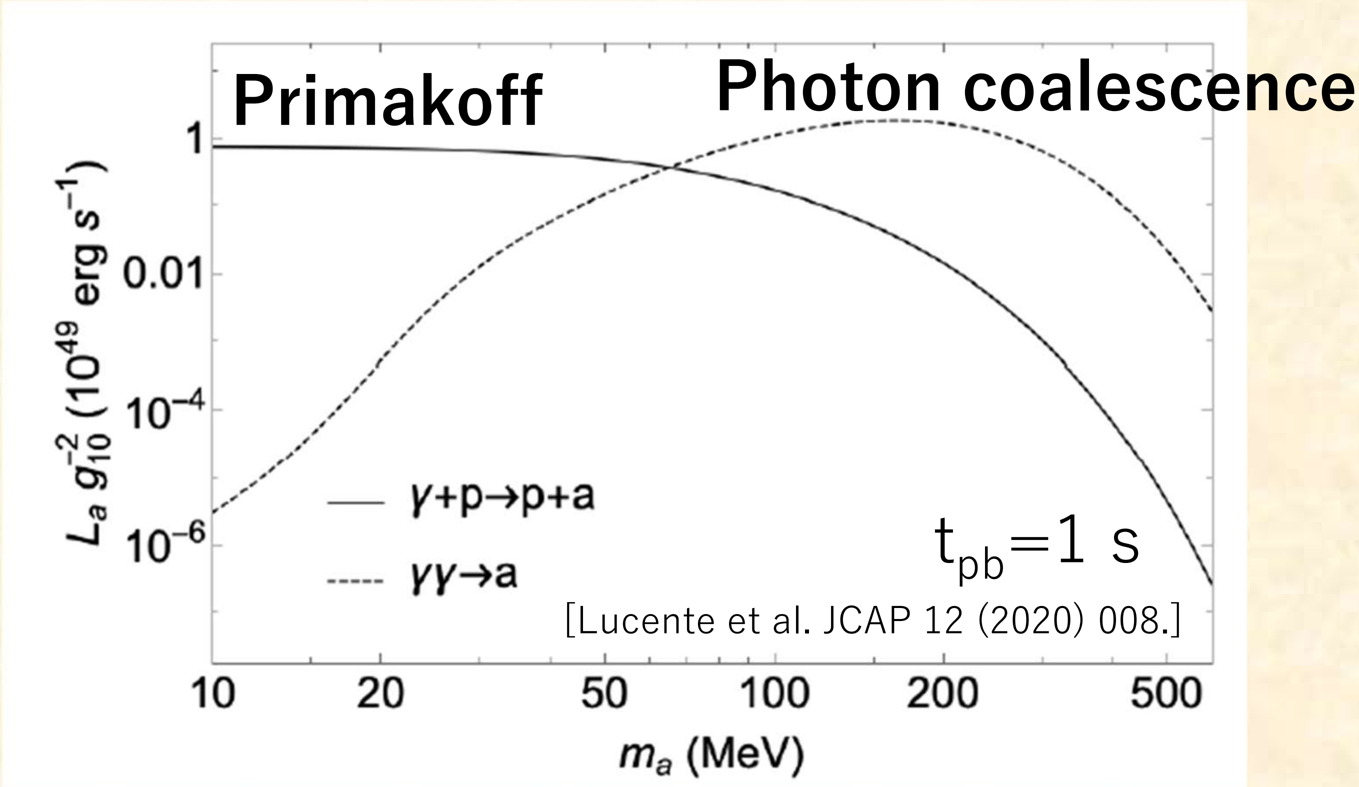


Payez et al., JCAP 1502 (2015) 006



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

ALP Luminosity from a SN



Supernovae can create ALPs lighter than ~300 MeV.