Core-collapse Supernova Models with Heavy Axion-like Particles

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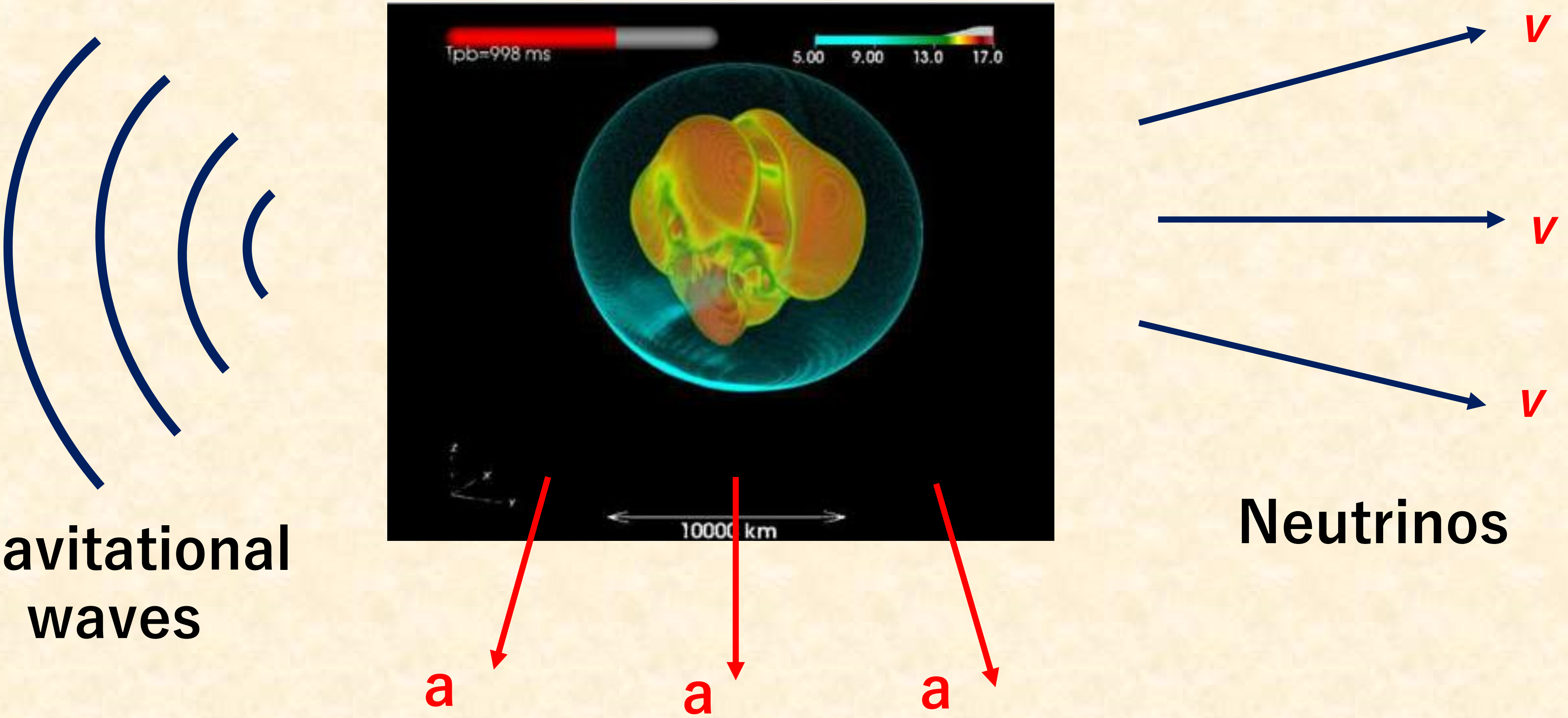
Fukuoka University

Messengers from Supernova Core

Nakamura, Takiwaki & Kotake PASJ 71 (2019) 98.



ν

ν

ν

Gravitational waves

Neutrinos

a

a

a

Axion-like particles (?)

Outline

1. Brief review on supernova limits on axion-like particles (ALPs)

2. Possible impacts of ALPs on supernova dynamics

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

3. Pair-instability supernova models with ALPs (preliminary)

   Mori, Moriya, Sakstein, Croon, Takiwaki, Kotake & Horiuch,
   in preparation.

Axions

[Wilczek PRL 40 (1978) 279,
Weinberg PRL 40 (1978) 223.]

- 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 $\xleftrightarrow{?}$ Exp: $\theta < 10^{-10}$

- Possible coupling with photons and nucleons

→ Axions can be produced in astrophysical plasma

- A candidate of the dark matter

- Signature in a recent experiment?

[XENON Collaboration PRD 102 (2020) 072004]

Axion-like Particles (ALPs)

- A class of hypothetical pseudo-scalar bosons

- Many models

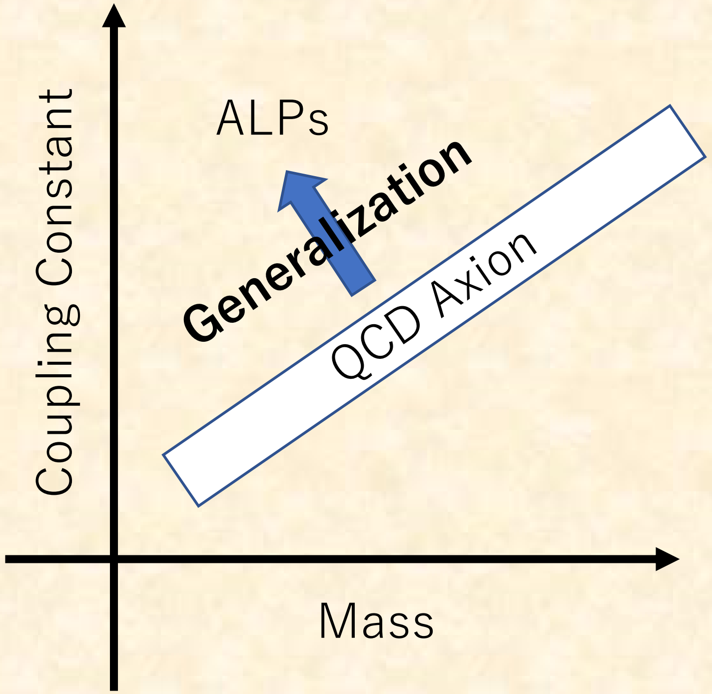
  ✓QCD axions

  ✓String axions [Svrcek & Witten JHEP 2006 (2006) 51. Arvanitaki et al., PRD 81 (2010) 123530.]

  ✓…

- **ALPs are generalization of axions**

Parameter space of ALPs



Interaction with SM particles

- **ALP-photon coupling**

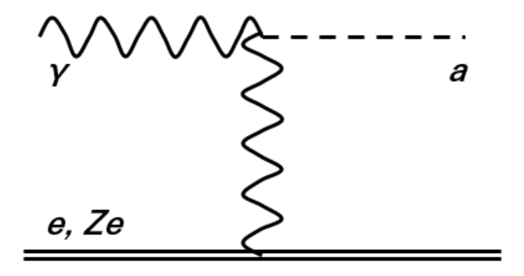
$$\mathcal{L}_{a\gamma\gamma} = -\frac{1}{4} g_{a\gamma} a \tilde{F}^{\mu\nu} F_{\mu\nu}$$

- ALP-electron coupling

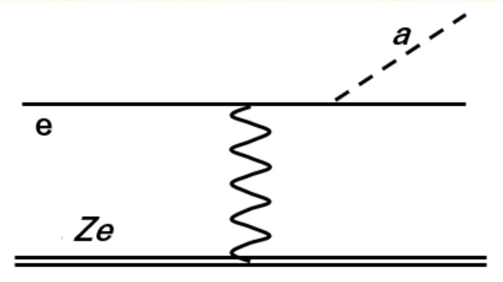
$$\mathcal{L}_{ae} = \frac{g_{ae}}{2m_e} \bar{e} \gamma_\mu \gamma_5 e \partial^\mu a$$

- ALP-nucleon coupling

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

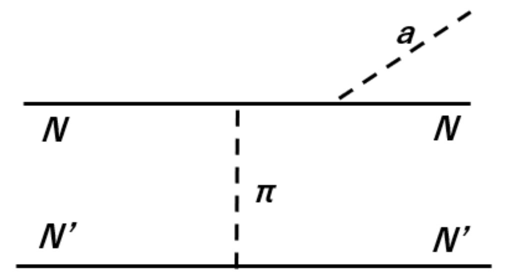


Primakoff process



electron-ion bremsstrahlung

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



nuclear bremsstrahlung

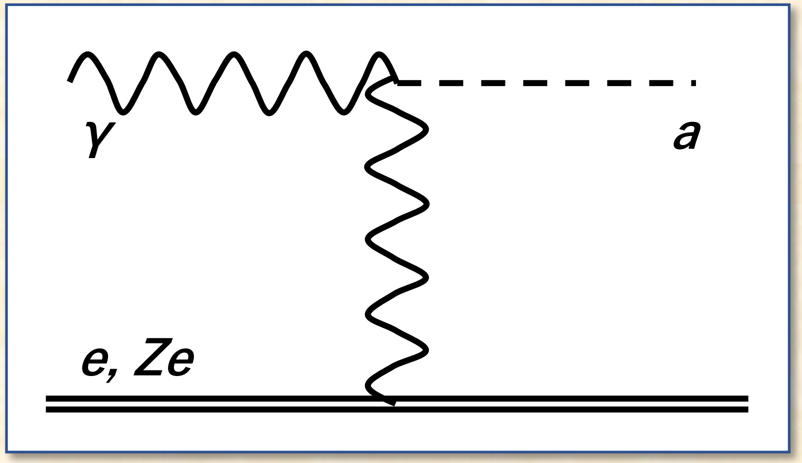
→**Prof. Fischer's talk**

ALP Production Processes

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

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

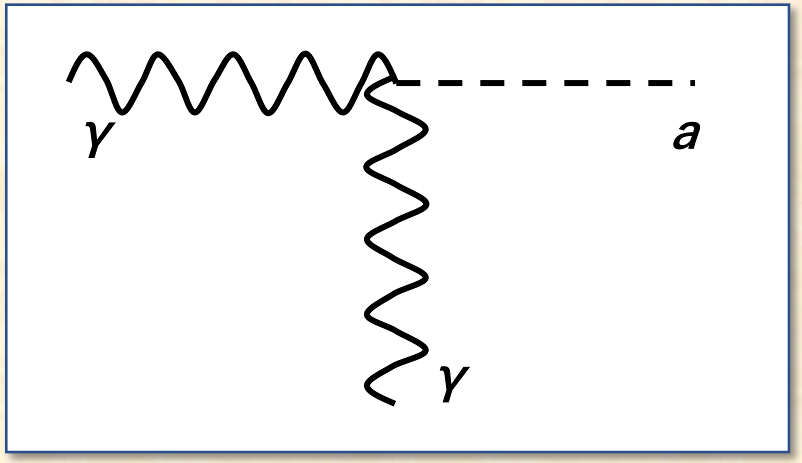
Primakoff process



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

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

Photon coalescence

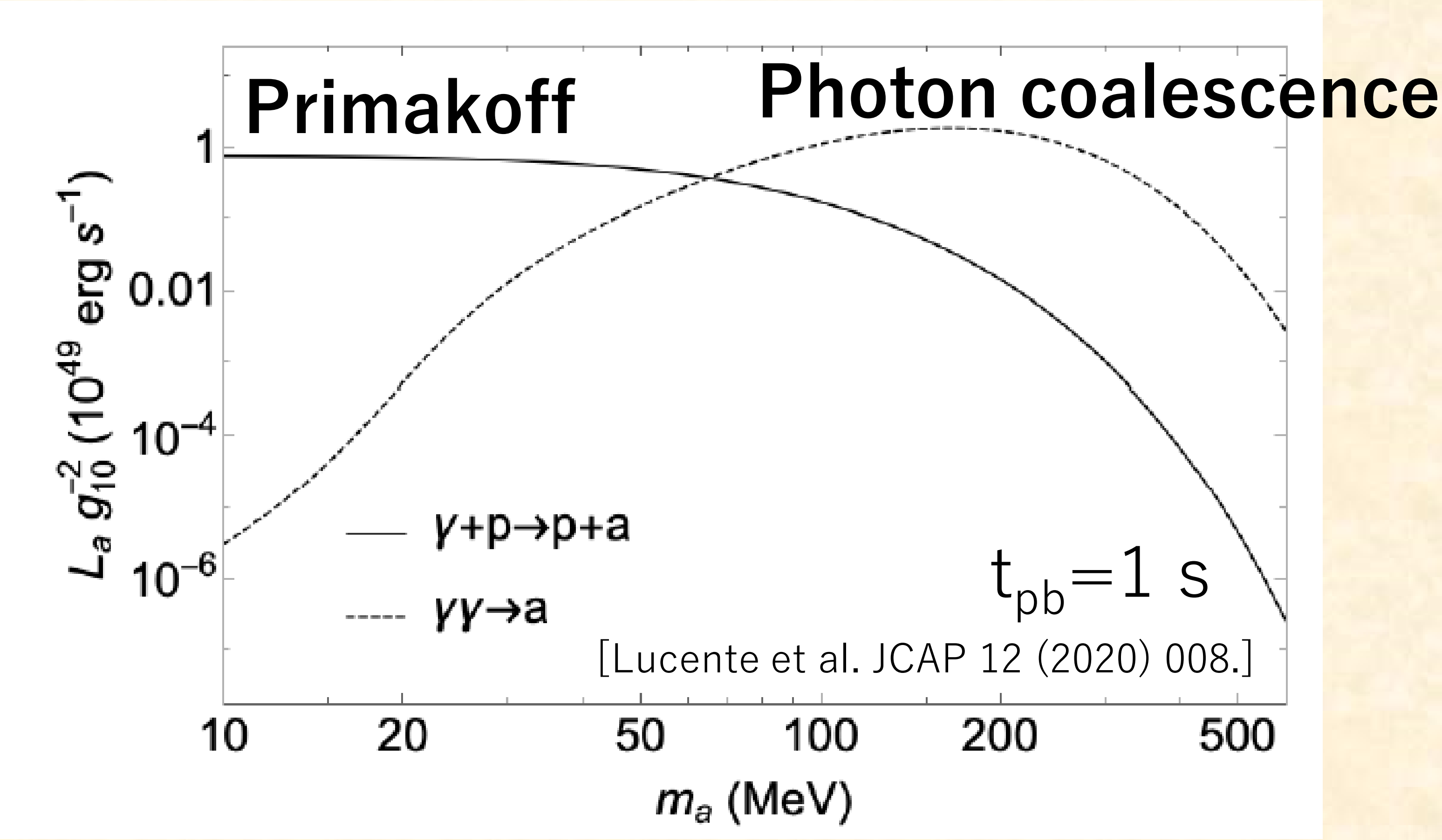


$$\frac{d^2 n_a}{dtdE} = g_{a\gamma}^2 \frac{m_a^4}{128\pi^3} p \left(1 - \frac{4\omega_{\mathrm{pl}}^2}{m_a^2}\right)^{\frac{3}{2}} e^{-\frac{E}{T}}$$

ω_{pl}: plasma frequency

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

ALP Luminosity from a SN

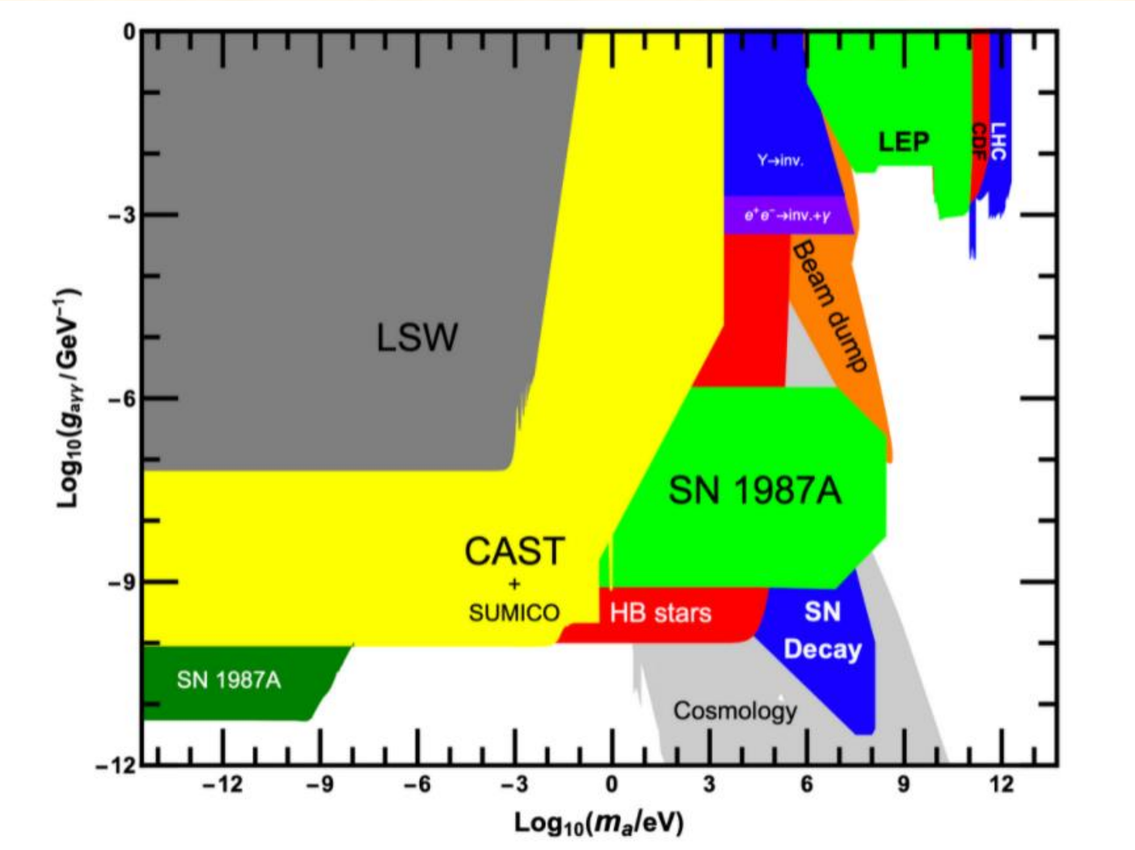


[Lucente et al. JCAP 12 (2020) 008.]

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

Constraints on ALPs

The ALP-photon coupling $g_{a\gamma}$ has been explored experimentally and astrophysically



Jaeckel & Spannowsky PLB 753 (2016) 482

SN 1987A limits

1. γ -ray limits
2. Energy-loss argument

ALP-photon Conversion

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

ALPs are converted into photons

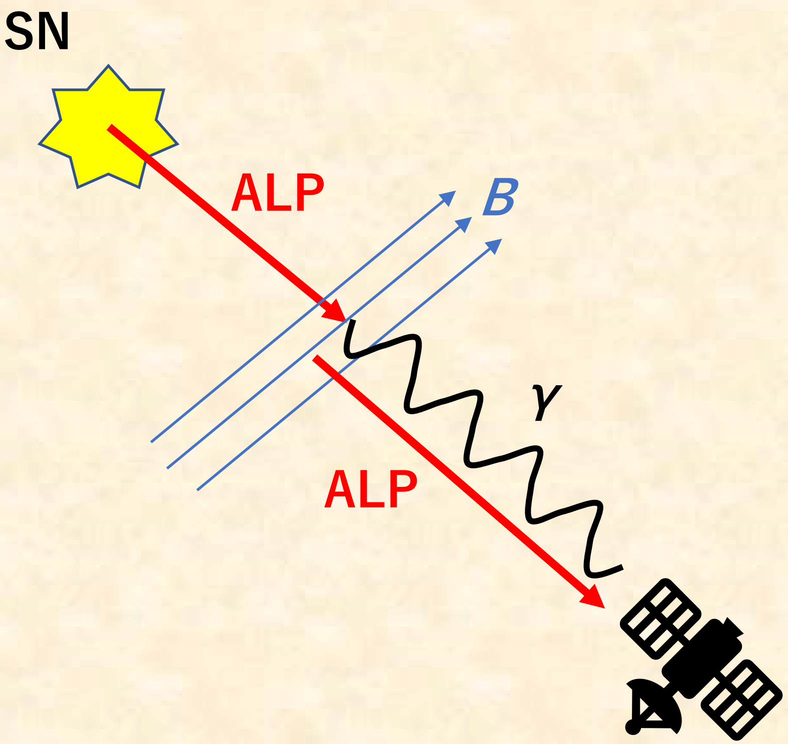
by Galactic magnetic field

→ **γ -ray may be observable**

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

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

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



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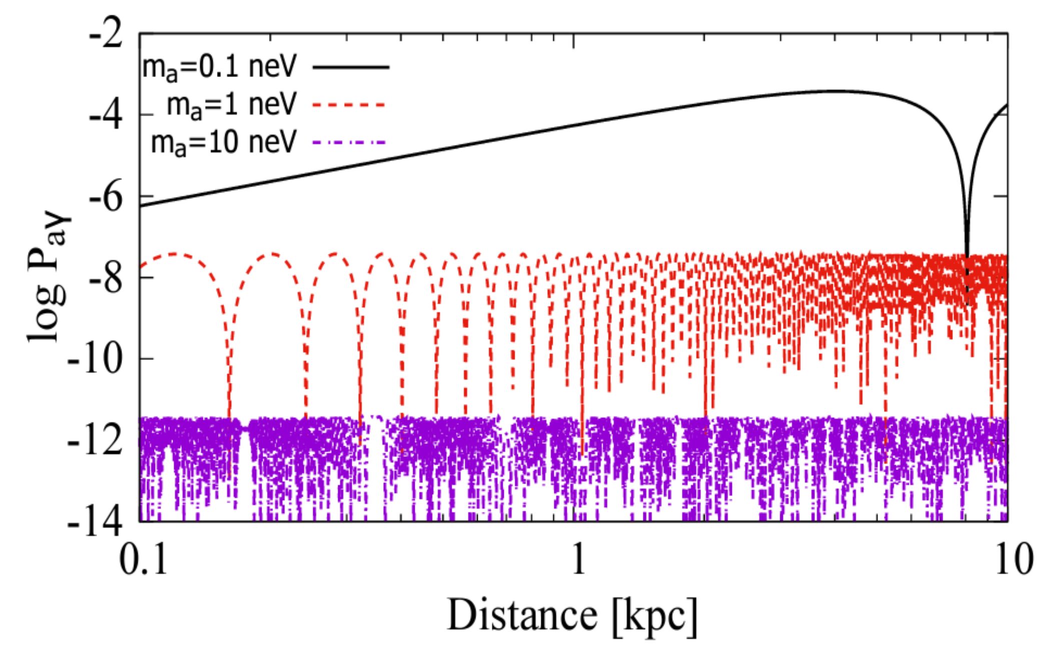
a-γ conversion prob. with B=1 μG and g=5×10^{-12} GeV^{-1}



Mori, Takiwaki & Kotake, PRD 105 (2022) 023020.

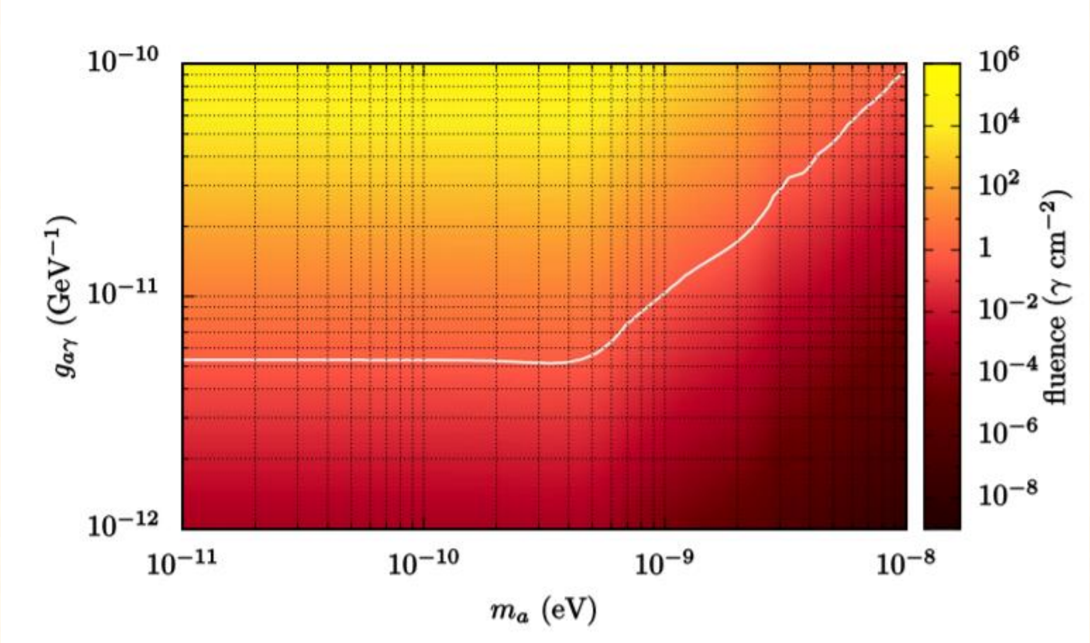
SN 1987A Constraints on ALPs

γ -rays from SN 1987A

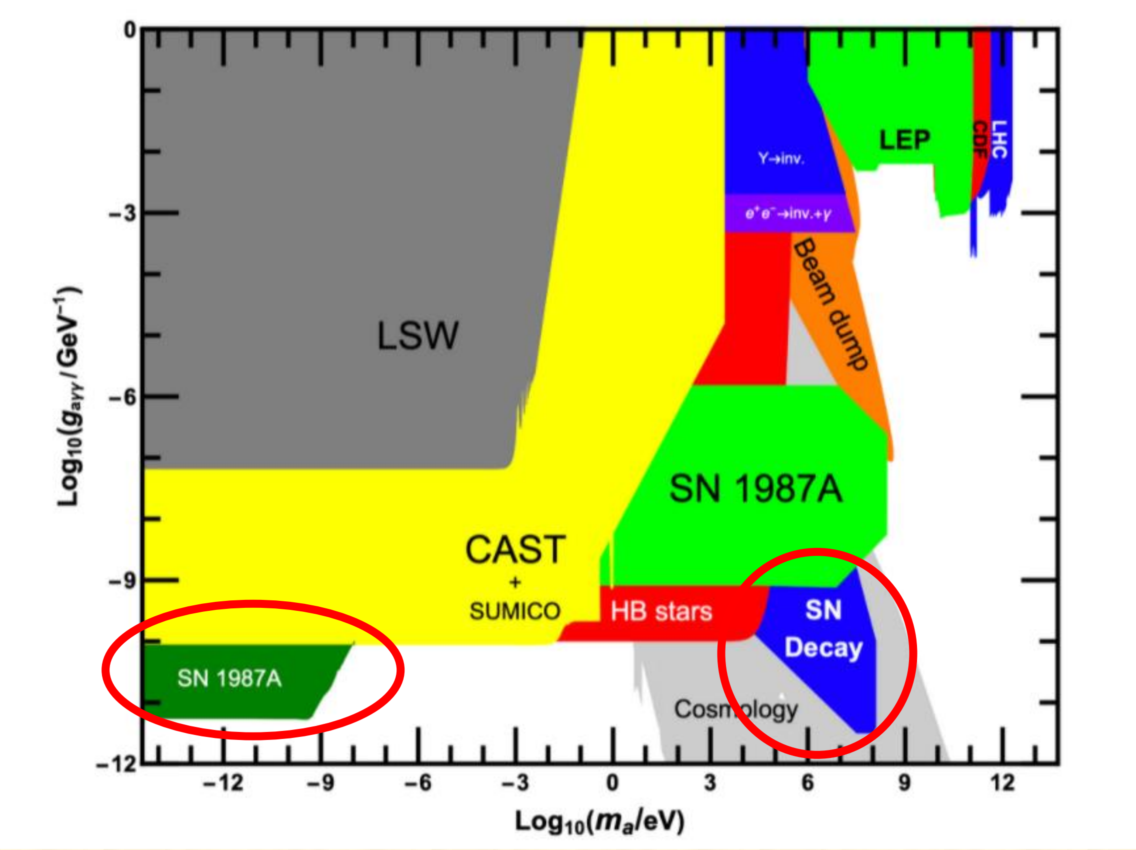
Observation: F(25-100 MeV)<0.6 γ /cm^2

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

Constraints on ALPs

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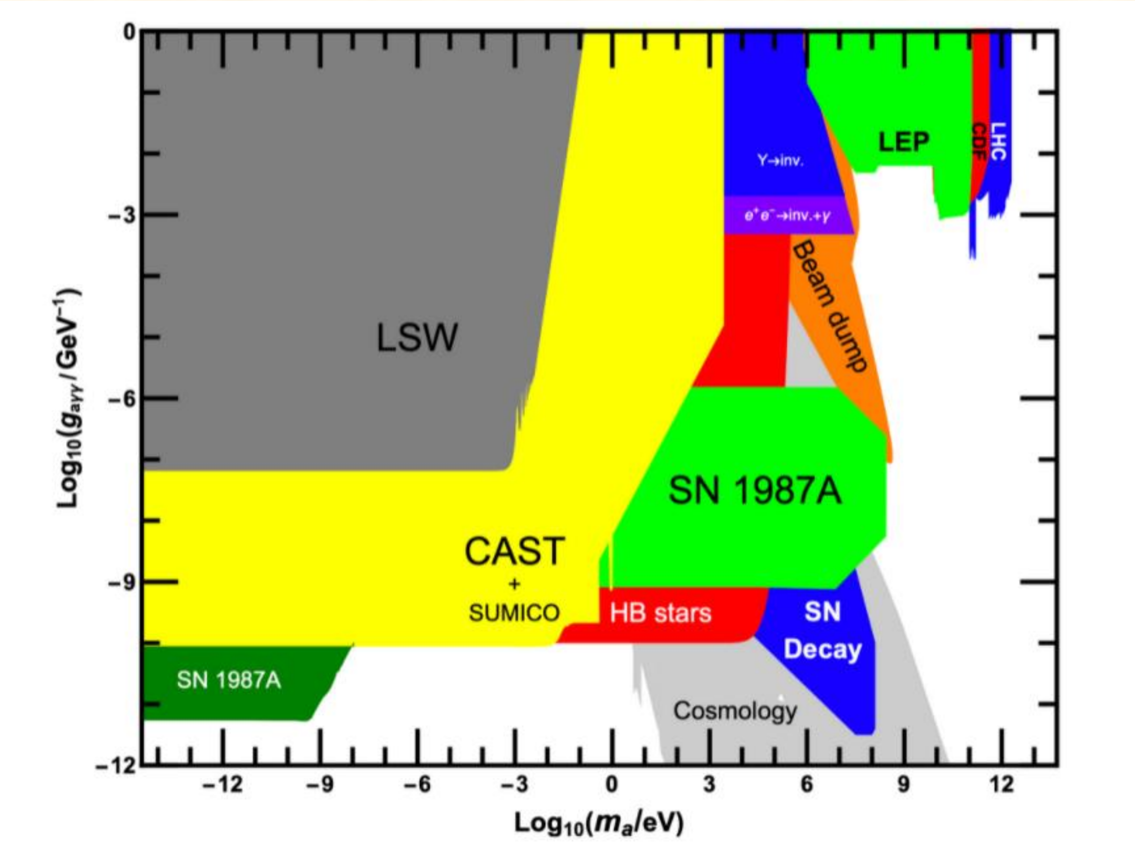


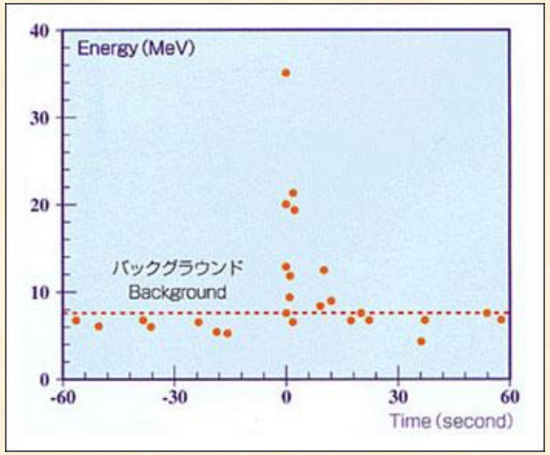
Jaeckel & Spannowsky PLB 753 (2016) 482

SN 1987A limits

1. γ -ray limits
2. **Energy-loss argument**

Energetics of Core-collapse SNe

- Gravitational energy release $E_g = \left(-\frac{GM^2}{R_{star}}\right) - \left(-\frac{GM^2}{R_{NS}}\right) \approx 10^{53}$ erg
- Kinetic energy $E_k = \frac{1}{2} M_{ejecta} v_{ejecta}^2 \approx 10^{51}$ erg (= 1 Bethe)
- Radiation $E_r \approx 10^{49}$ erg
- Neutrino (**SN 1987A obs.**) $E_\nu \approx 10^{53}$ erg

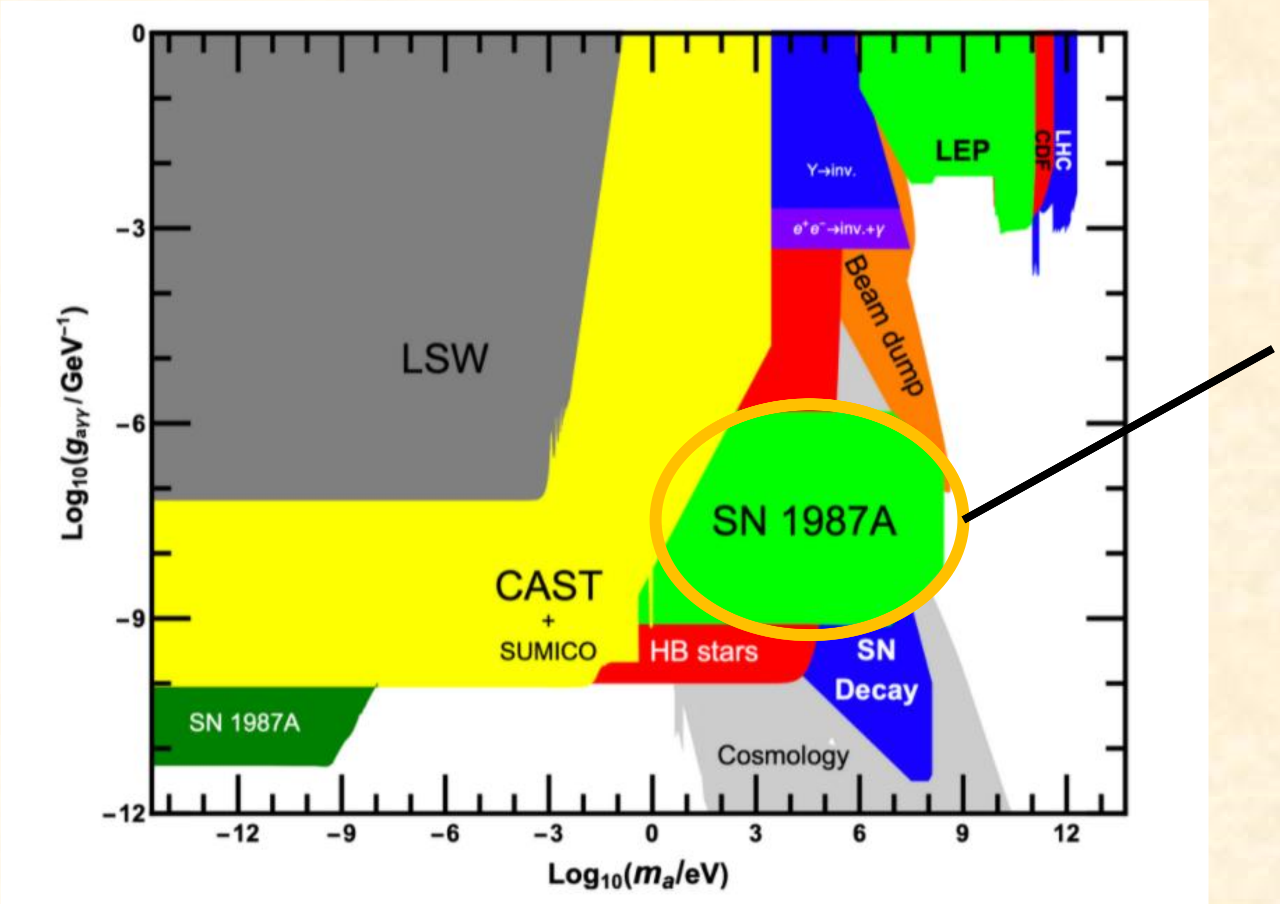


http://www-sk.icrr.u-tokyo.ac.jp/sk/_images/photo/sk/shinsei_gazou02.jpg

Energy budget: $E_g = \underset{\sim 1\%}{\underline{E_k}} + \underset{\sim 0.01\%}{\underline{E_r}} + \underset{\sim 99\%}{\underline{E_\nu}}$

Additional Energy Loss from SNe

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



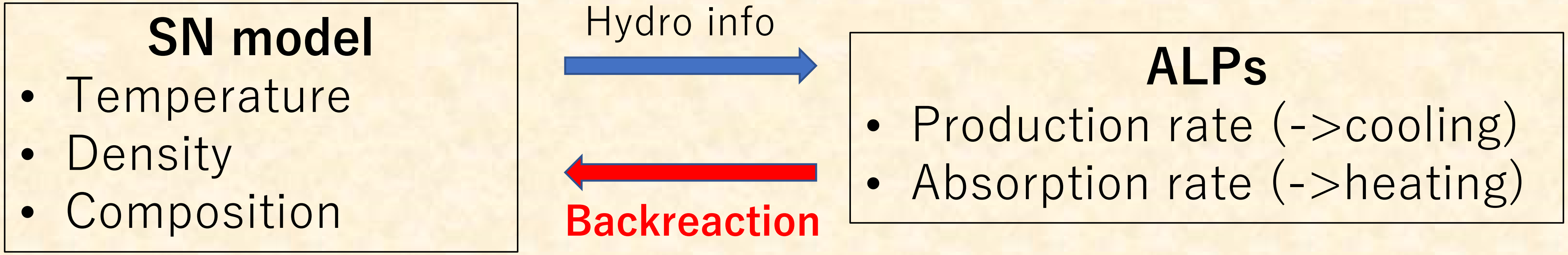
Jaeckel & Spannowsky PLB 753 (2016) 482

$$E_g = E_k + E_r + E_\nu + E_{axion}$$

- The ALP luminosity L_a is so large that the neutrino burst duration (~10 s) cannot be explained.
- A criterion $L_a < 20 \times 10^{51}$ erg/s is often adopted.

Beyond Post-processing

- Previous calculations are mainly performed with hydrodynamics and ALPs 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**



SN model
- Temperature
- Density
- Composition

Hydro info

Backreaction

ALPs
- Production rate (->cooling)
- Absorption rate (->heating)

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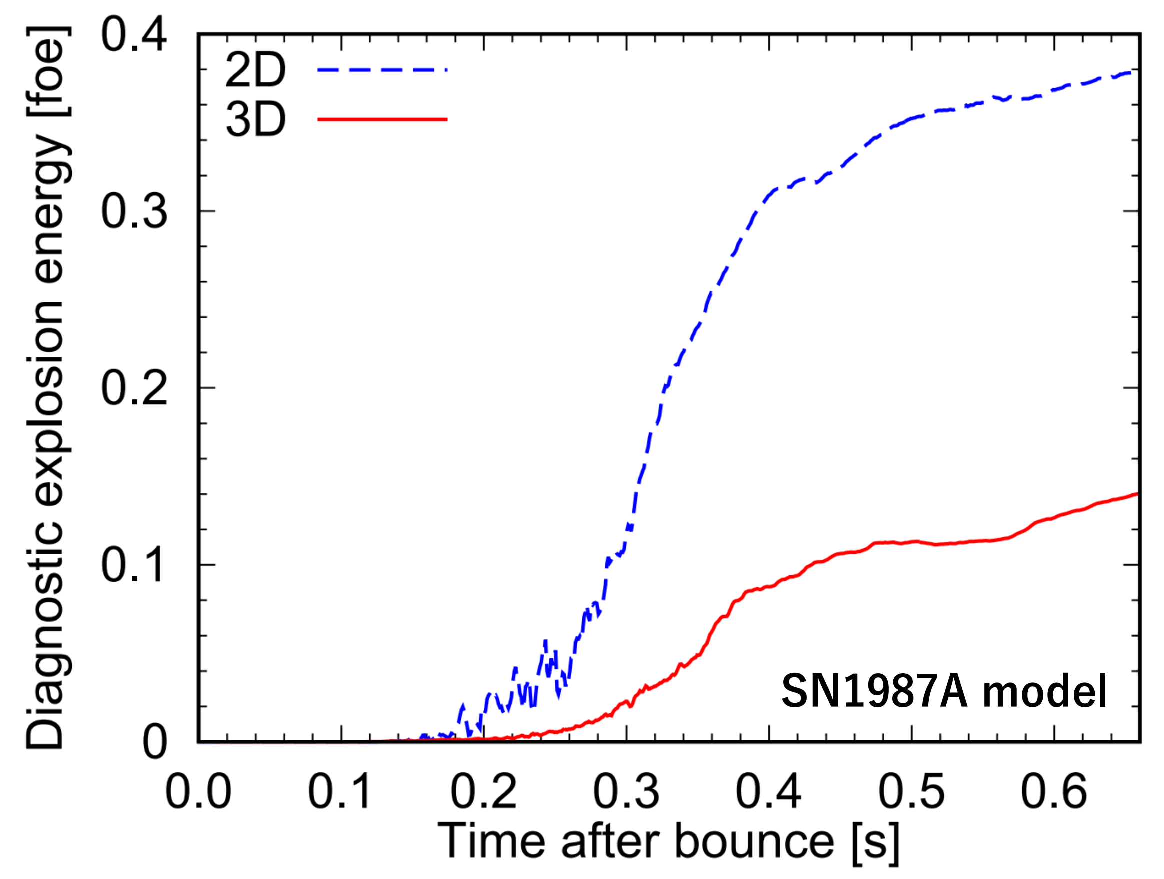
E_{exp} Problem in Supernova Models



Nakamura, Takiwaki & Kotake MNRAS 514 (2022) 3941

Modern multi-D models tend to show E_{exp}<1 B 😥

Radiative Decay of Heavy ALPs

- Heavy ALPs are unstable:

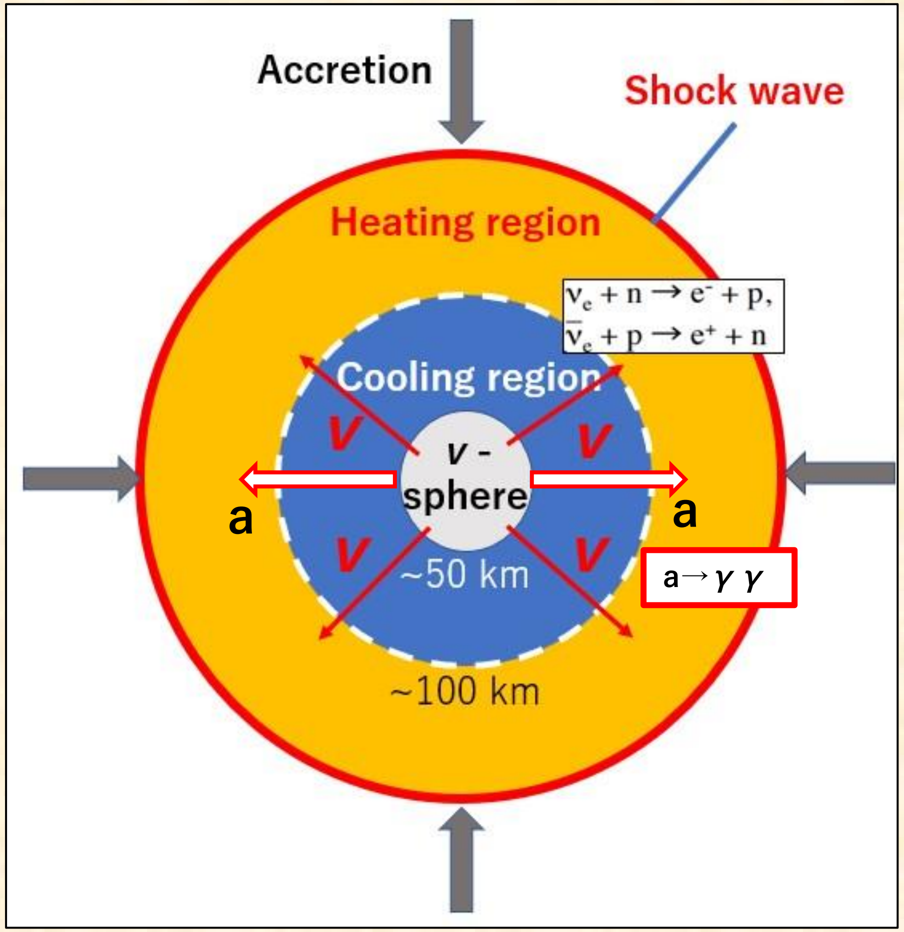
$$a \to \gamma + \gamma$$

- Mean free path:

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

- 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: 1D **EoS**: LS220 **Progenitor**: $20M_\odot$

ALP production:

Primakoff process
Photon coalescence

ALP absorption:

Inverse Primakoff process
Radiative decay

$$\nabla \cdot \mathbf{F} = \underset{\text{ALP production}}{\underline{Q_{\text{cool}}}} - \underset{\text{ALP absorption}}{\underline{Q_{\text{heat}}}} \xrightarrow{\textbf{discretize}}$$

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

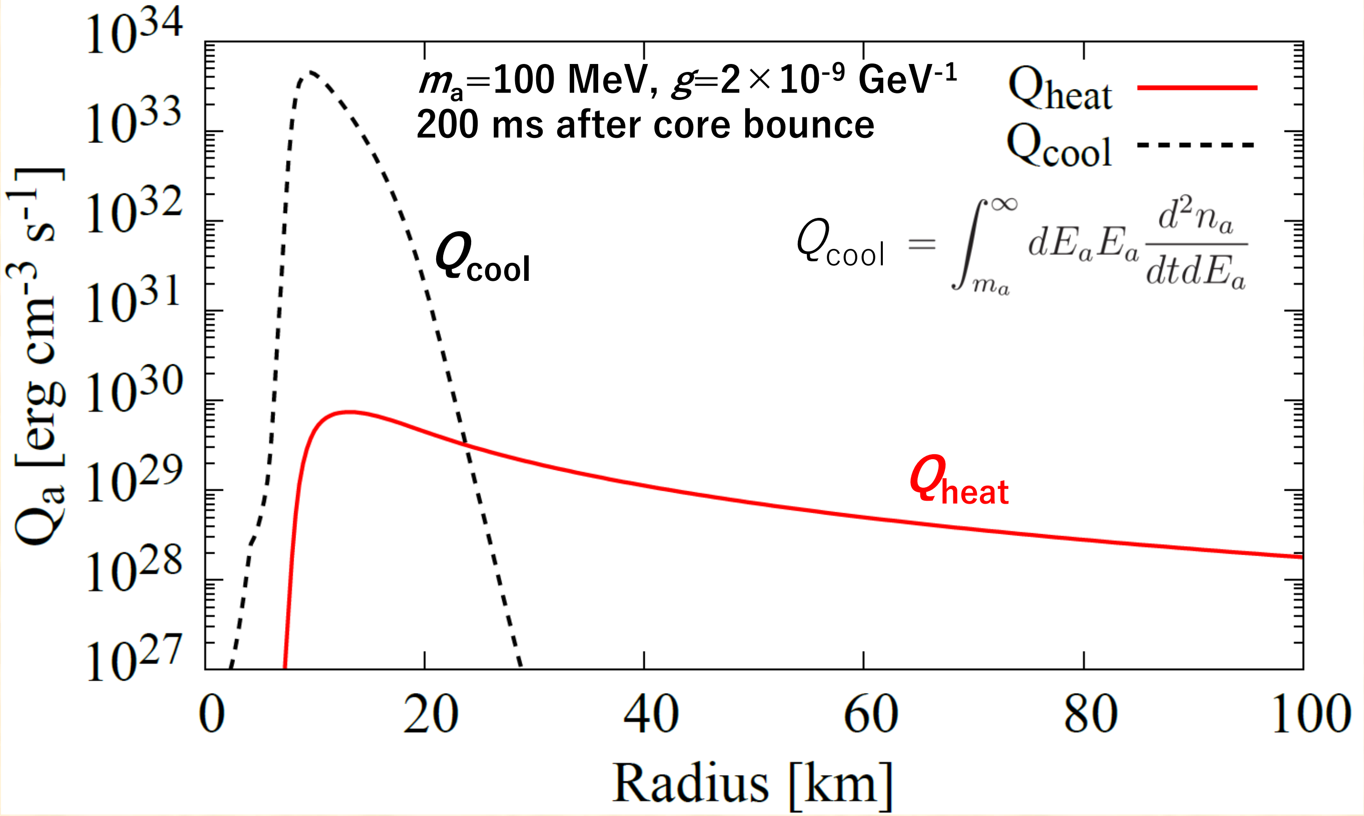
$$Q_{\text{heat},\,i}\Delta V_i = L_{i-\frac{1}{2}}\left(1 - \exp\left(-\frac{r_{i+1}-r_i}{\lambda_{a,\,i}}\right)\right)$$

for the i-th cell

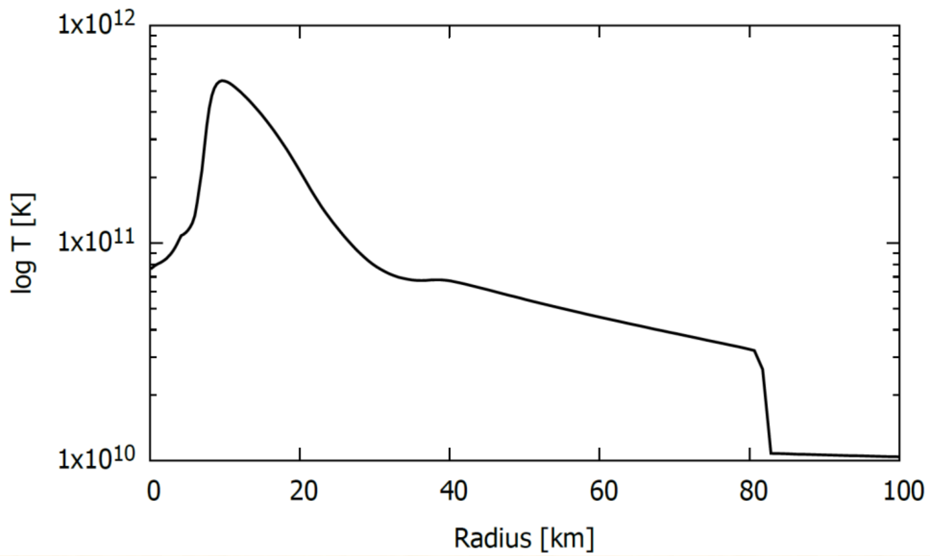
Modification on internal energy:

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

ALP Cooling & Heating Rates



Temperature profile

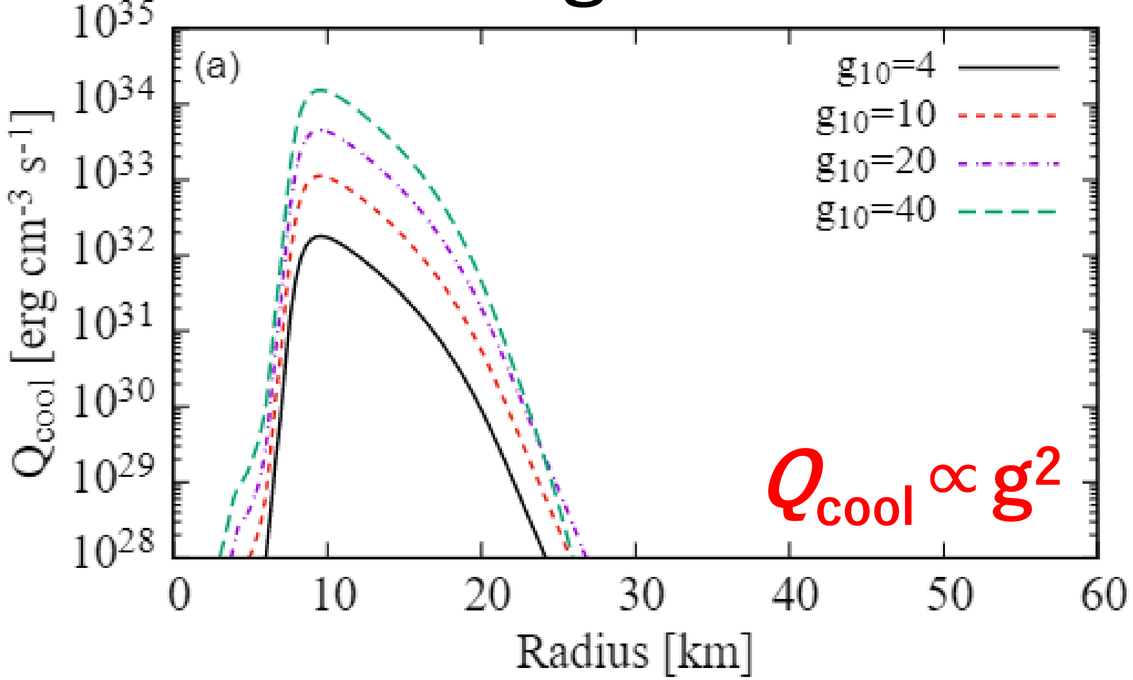


- ✓ ALPs are produced at ~10 km
- ✓ ALPs decay after running a mean free path → **additional heating**

ALP Cooling & Heating Rates

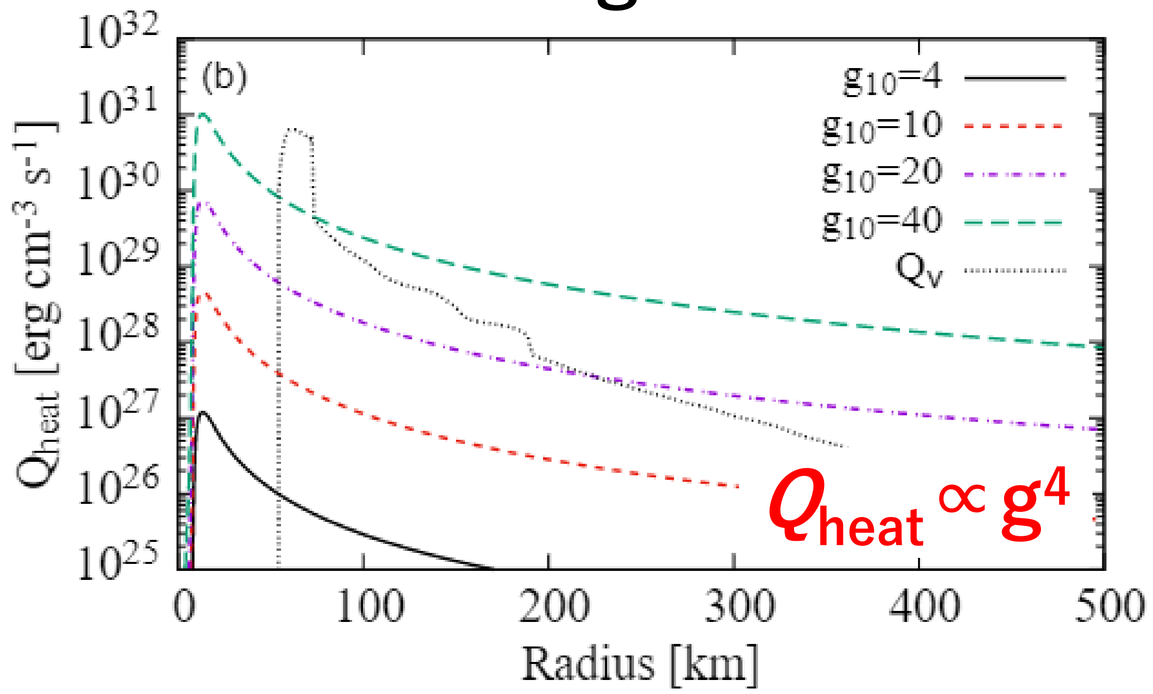
ALP mass is fixed: m_a=100 MeV

Cooling rate



$Q_{cool} \propto g^2$

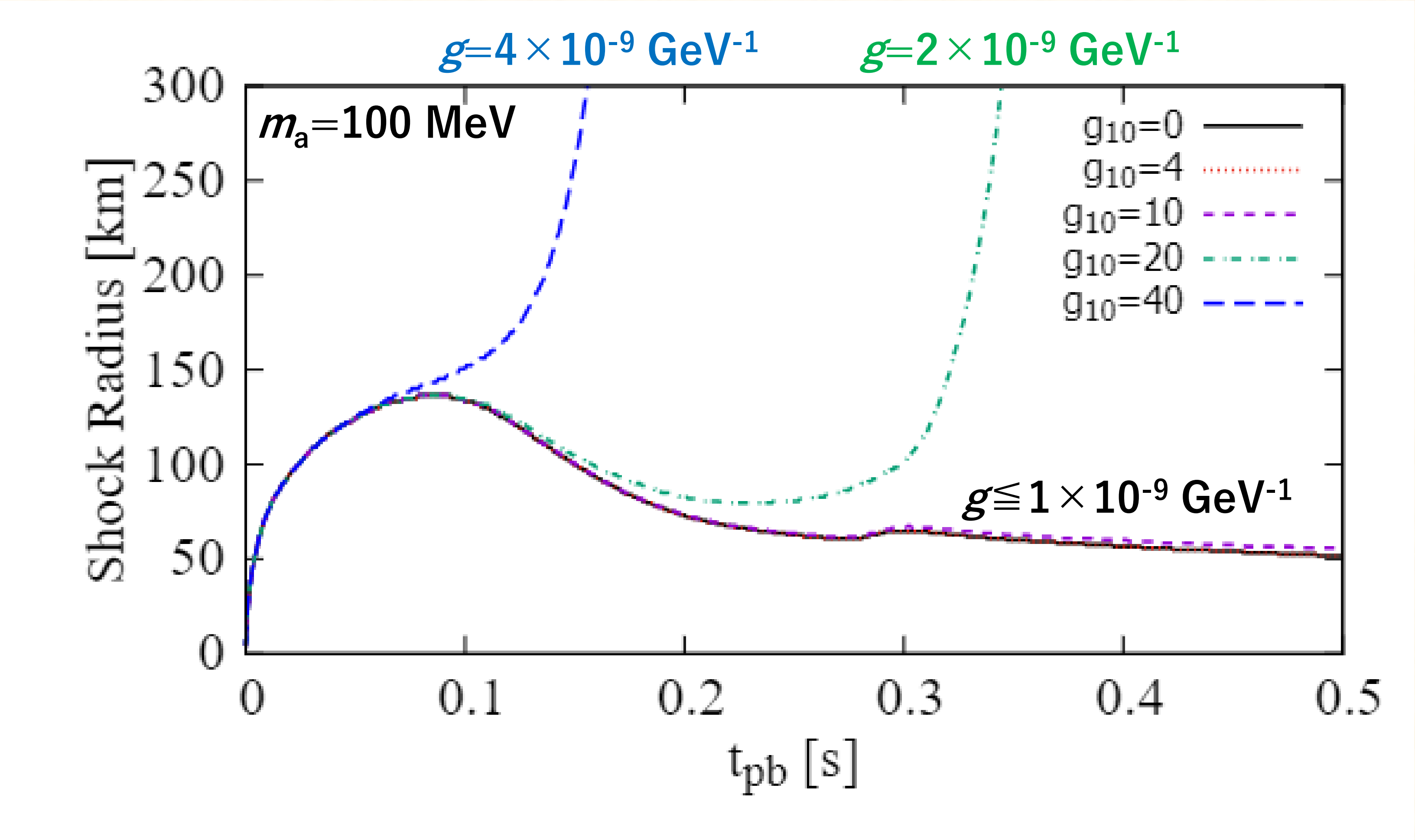
Heating rate



$Q_{heat} \propto g^4$

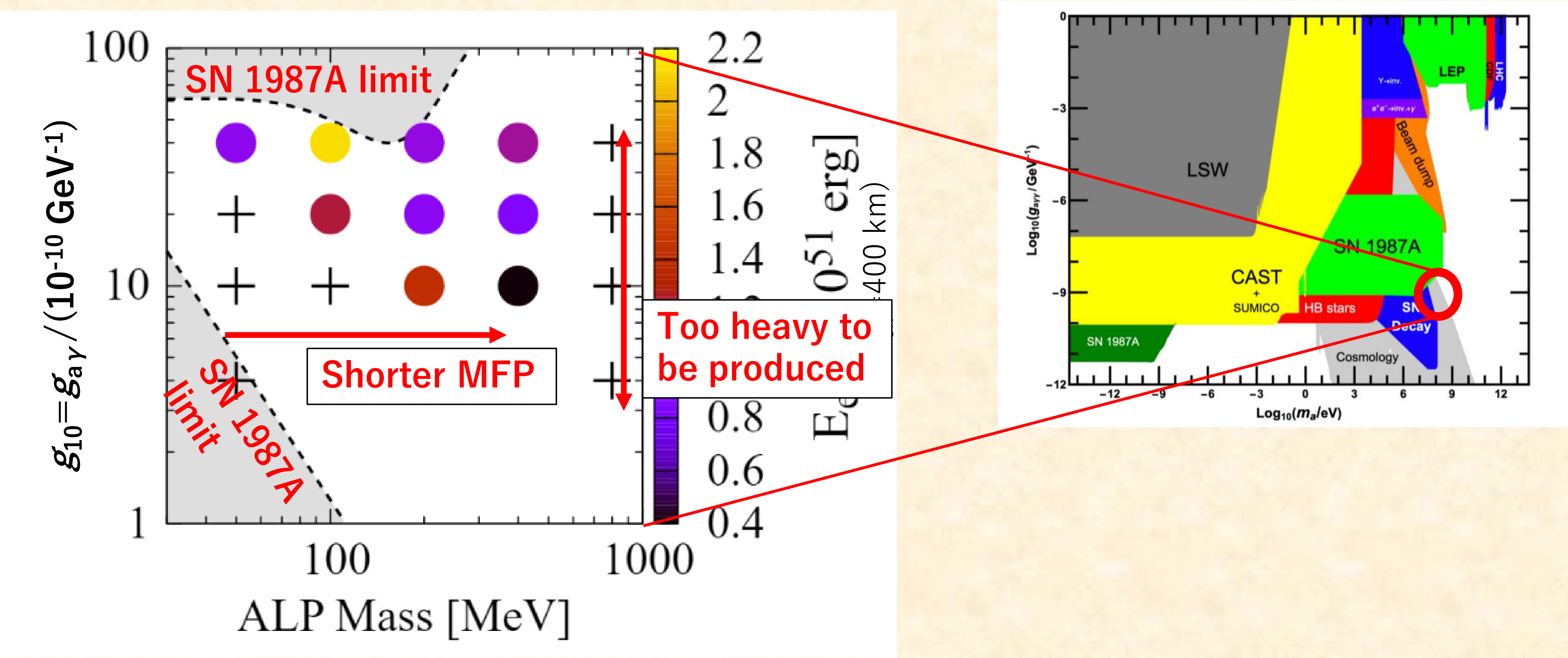
Q_{heat} is a steep function of the ALP-photon coupling constant g

Shock Revival Assisted by ALPs



ALPs may heat the shock wave and lead to shock revival

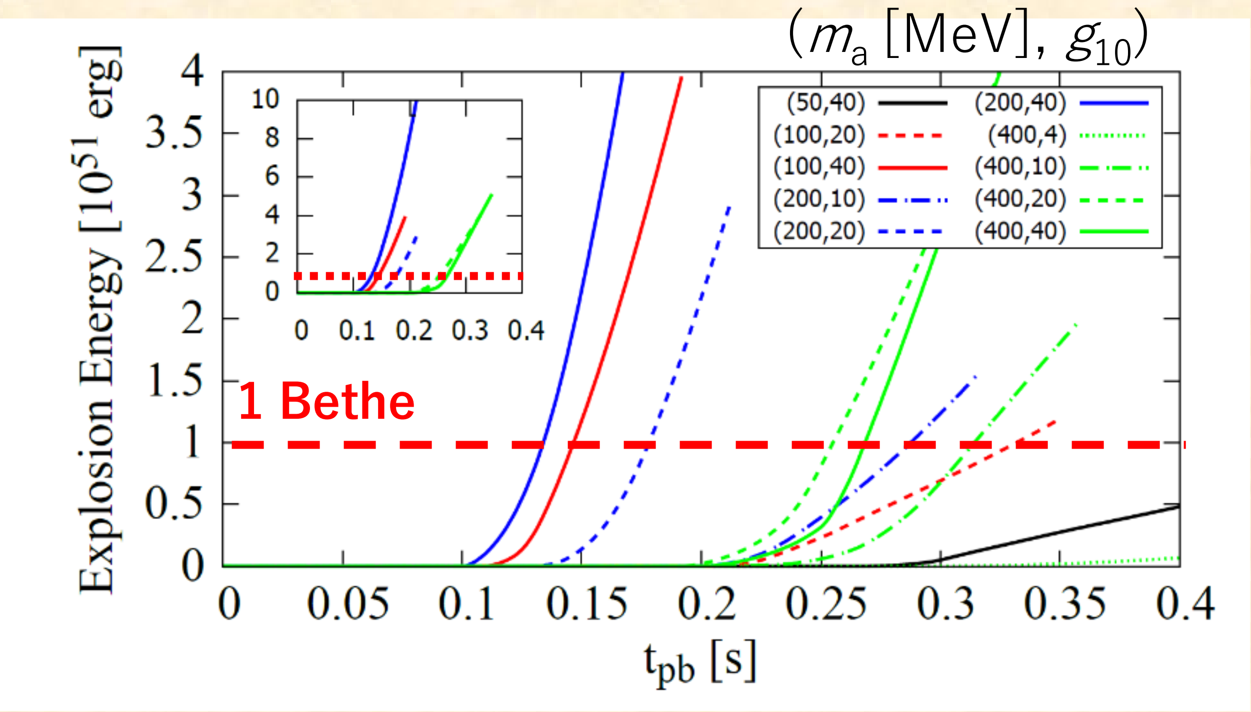
Explodability



Successful explosions with ALP heating even in 1D models!

Explosion Energy

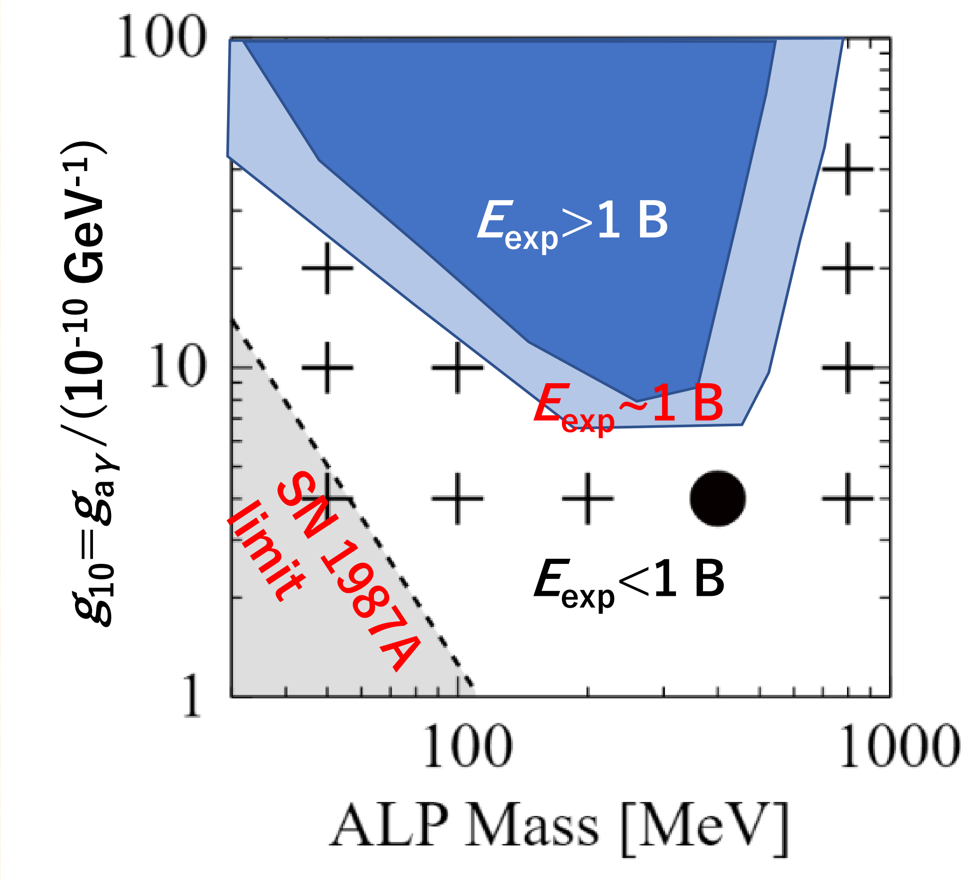
- Some models approach 10^{52} erg
- In general, larger coupling constants lead to more energetic explosion



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

Explosion Energy

SN explosion energy
(**schematic**)



$E_{\mathrm{exp}}>1$ B → Excluded

$E_{\mathrm{exp}}\sim1$ B → Possible solution for the E_{exp} problem (?)

$E_{\mathrm{exp}}<1$ B → Allowed

We need …

- Long-term simulations
- Multi-D simulations
- Parameter studies (progenitor, EoS, …)

Summary (1)

- Astrophysical objects such as core-collapse SNe and stars 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 can be more energetic than >1 B.
- I am planning to perform multi-D simulations to predict GW signals.

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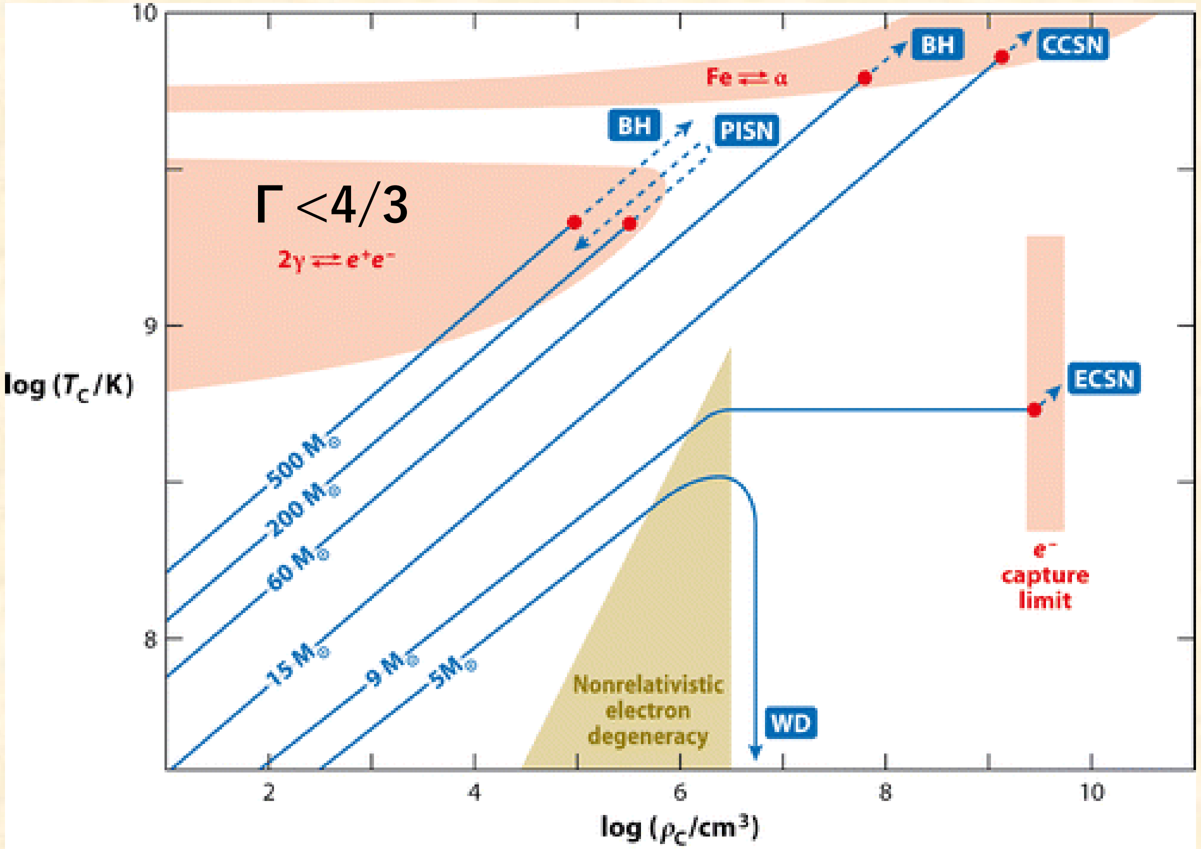
Pair-instability Supernova (PISN)

- Very massive stars with $M_{\mathrm{ZAMS}} \sim 150\text{-}250\, M_{\odot}$
- Explosive O-burning

→Total disruption of the star

- No confirmed event



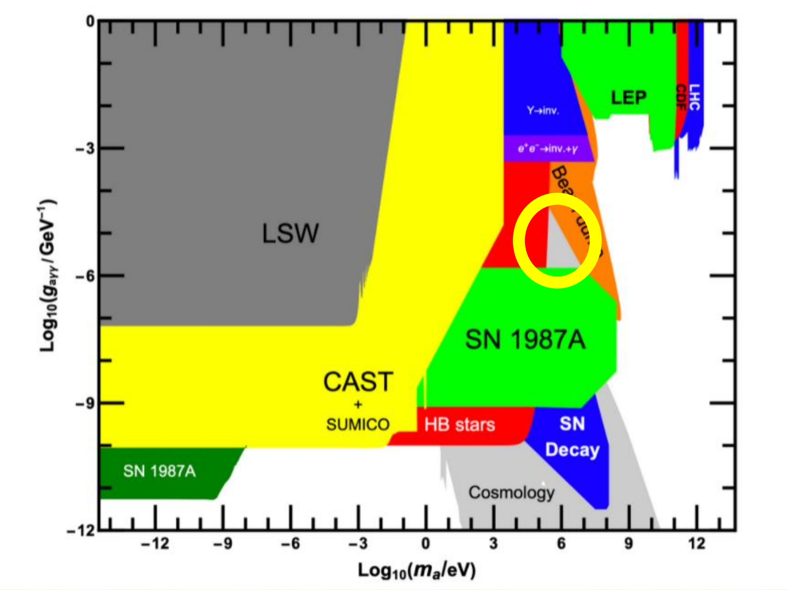
Langer N. 2012.
Annu. Rev. Astron. Astrophys. 50:107–64

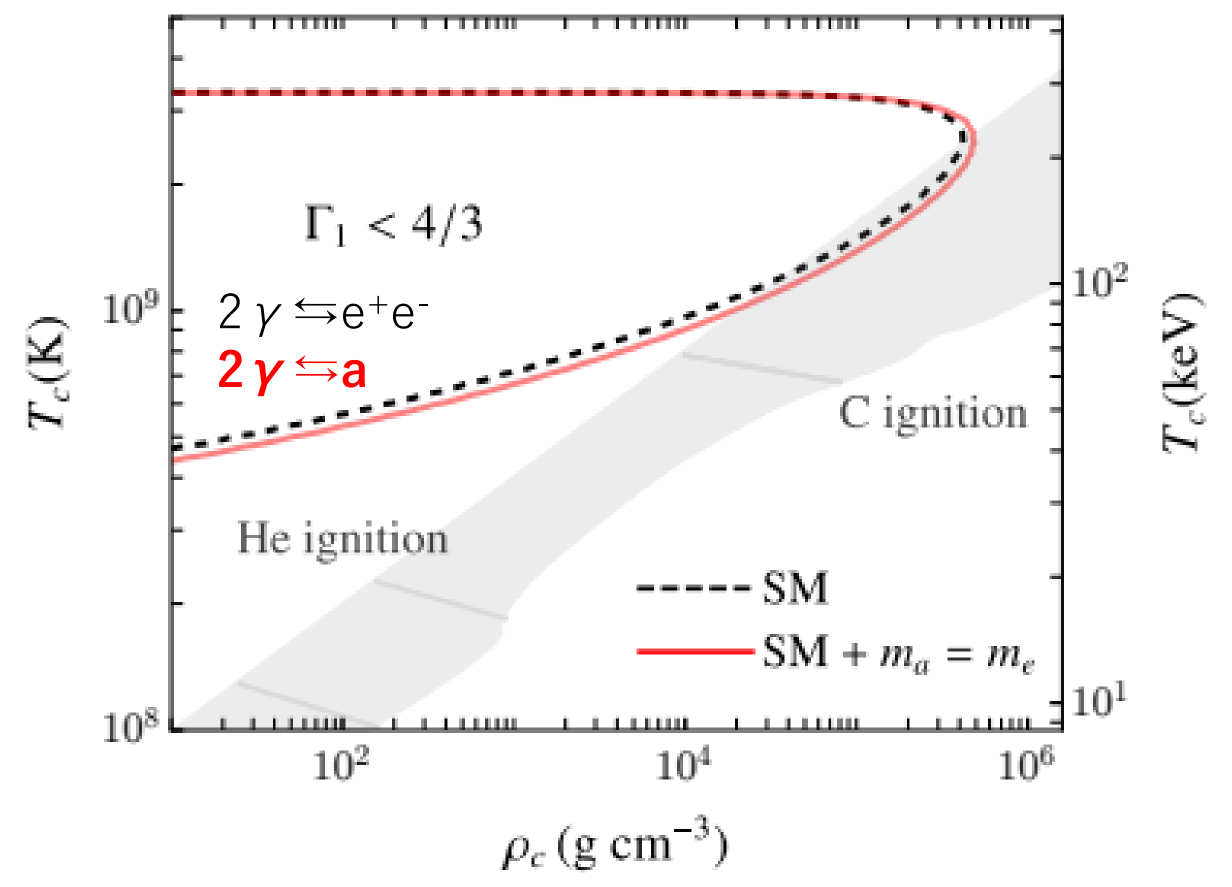
ALP Effect on PISNe

ALPs with $m_a <\sim 2m_e$ can be effectively produced

→ If g is sufficiently large,

ALPs can reach equilibruin and soften the EoS





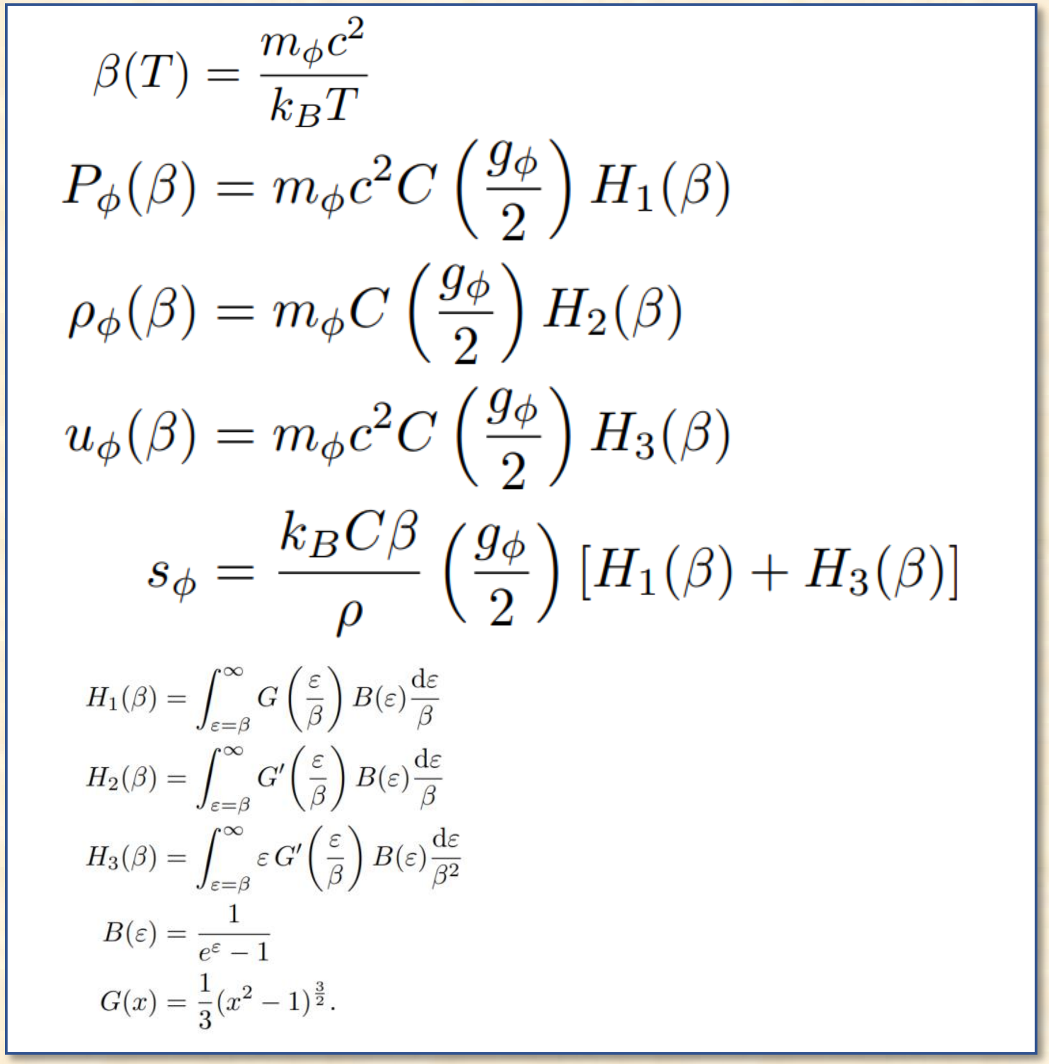
$2\gamma \leftrightarrows e^+e^-$

$2\gamma \leftrightarrows a$

Sukstein et al. PRD 105 (2022) 095038

EoS Modification

[Sukstein et al. PRD 105 (2022) 095038]



$$\beta(T) = \frac{m_\phi c^2}{k_B T}$$

$$P_\phi(\beta) = m_\phi c^2 C \left(\frac{g_\phi}{2}\right) H_1(\beta)$$

$$\rho_\phi(\beta) = m_\phi C \left(\frac{g_\phi}{2}\right) H_2(\beta)$$

$$u_\phi(\beta) = m_\phi c^2 C \left(\frac{g_\phi}{2}\right) H_3(\beta)$$

$$s_\phi = \frac{k_B C \beta}{\rho} \left(\frac{g_\phi}{2}\right) [H_1(\beta) + H_3(\beta)]$$

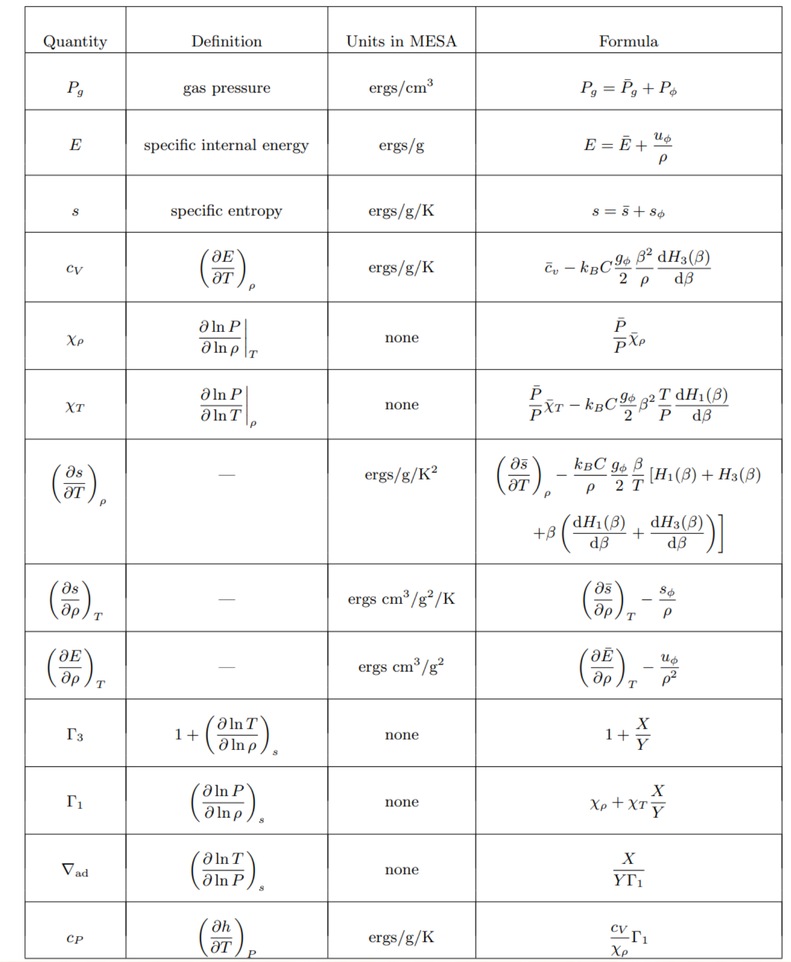
$$H_1(\beta) = \int_{\varepsilon=\beta}^{\infty} G\left(\frac{\varepsilon}{\beta}\right) B(\varepsilon) \frac{\mathrm{d}\varepsilon}{\beta}$$

$$H_2(\beta) = \int_{\varepsilon=\beta}^{\infty} G'\left(\frac{\varepsilon}{\beta}\right) B(\varepsilon) \frac{\mathrm{d}\varepsilon}{\beta}$$

$$H_3(\beta) = \int_{\varepsilon=\beta}^{\infty} \varepsilon G'\left(\frac{\varepsilon}{\beta}\right) B(\varepsilon) \frac{\mathrm{d}\varepsilon}{\beta^2}$$

$$B(\varepsilon) = \frac{1}{e^\varepsilon - 1}$$

$$G(x) = \frac{1}{3}(x^2 - 1)^{\frac{3}{2}}.$$



Quantity	Definition	Units in MESA	Formula
P_g	gas pressure	ergs/cm^3	$P_g = \bar{P}_g + P_\phi$
E	specific internal energy	ergs/g	$E = \bar{E} + \frac{u_\phi}{\rho}$
s	specific entropy	ergs/g/K	$s = \bar{s} + s_\phi$
c_V	$\left(\frac{\partial E}{\partial T}\right)_\rho$	ergs/g/K	$\bar{c}_v - k_B C \frac{g_\phi}{2} \frac{\beta^2}{\rho} \frac{\mathrm{d}H_3(\beta)}{\mathrm{d}\beta}$
χ_ρ	$\frac{\partial \ln P}{\partial \ln \rho}\Big\vert_T$	none	$\frac{\bar{P}}{P}\bar{\chi}_\rho$
χ_T	$\frac{\partial \ln P}{\partial \ln T}\Big\vert_\rho$	none	$\frac{\bar{P}}{P}\bar{\chi}_T - k_B C \frac{g_\phi}{2} \beta^2 \frac{T}{P} \frac{\mathrm{d}H_1(\beta)}{\mathrm{d}\beta}$
$\left(\frac{\partial s}{\partial T}\right)_\rho$	—	ergs/g/K^2	$\left(\frac{\partial \bar{s}}{\partial T}\right)_\rho - \frac{k_B C}{\rho} \frac{g_\phi}{2} \frac{\beta}{T} [H_1(\beta) + H_3(\beta)$ $+\beta\left(\frac{\mathrm{d}H_1(\beta)}{\mathrm{d}\beta} + \frac{\mathrm{d}H_3(\beta)}{\mathrm{d}\beta}\right)]$
$\left(\frac{\partial s}{\partial \rho}\right)_T$	—	ergs cm^3/g^2/K	$\left(\frac{\partial \bar{s}}{\partial \rho}\right)_T - \frac{s_\phi}{\rho}$
$\left(\frac{\partial E}{\partial \rho}\right)_T$	—	ergs cm^3/g^2	$\left(\frac{\partial \bar{E}}{\partial \rho}\right)_T - \frac{u_\phi}{\rho^2}$
Γ_3	$1 + \left(\frac{\partial \ln T}{\partial \ln \rho}\right)_s$	none	$1 + \frac{X}{Y}$
Γ_1	$\left(\frac{\partial \ln P}{\partial \ln \rho}\right)_s$	none	$\chi_\rho + \chi_T \frac{X}{Y}$
∇_{ad}	$\left(\frac{\partial \ln T}{\partial \ln P}\right)_s$	none	$\frac{X}{Y\Gamma_1}$
c_P	$\left(\frac{\partial h}{\partial T}\right)_P$	ergs/g/K	$\frac{c_V}{\chi_\rho}\Gamma_1$

ALP Effect on PISNe

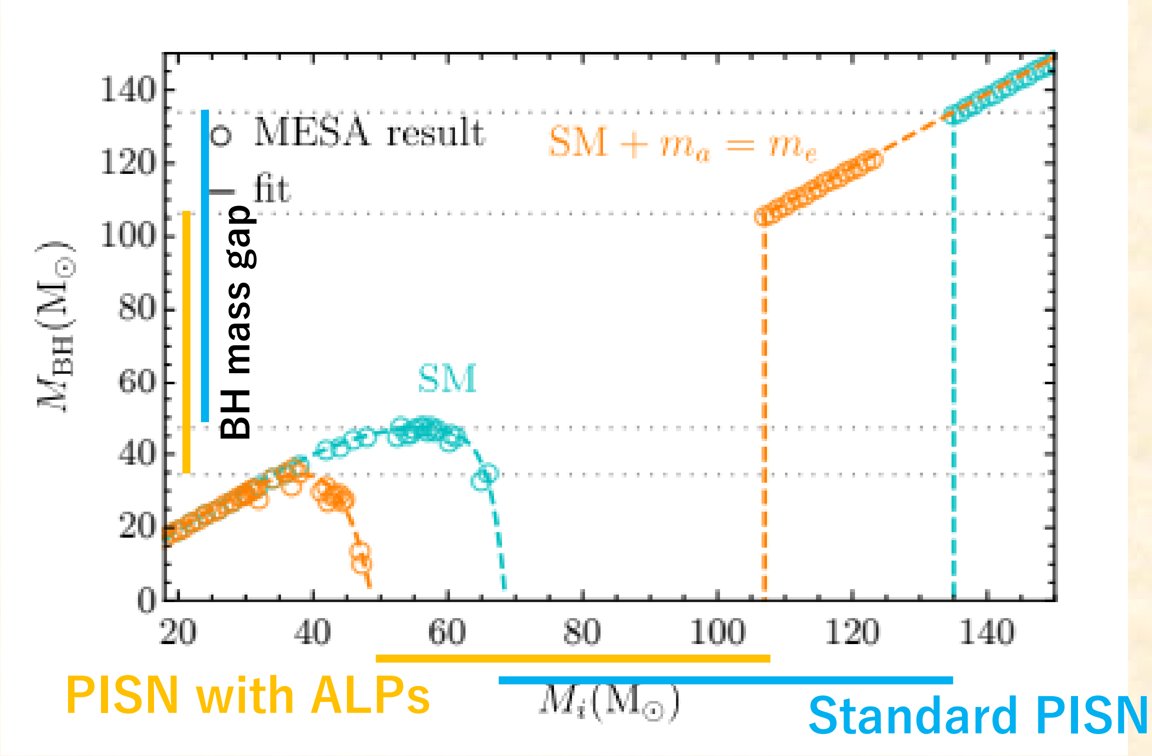
- ALPs can soften the EoS

→ **Lighter stars can cause PISNe**

- ALPs can lower the edges of the BH mass gap

→ Comparison with GW observations of BH binaries

- **Effects on optical signals?**



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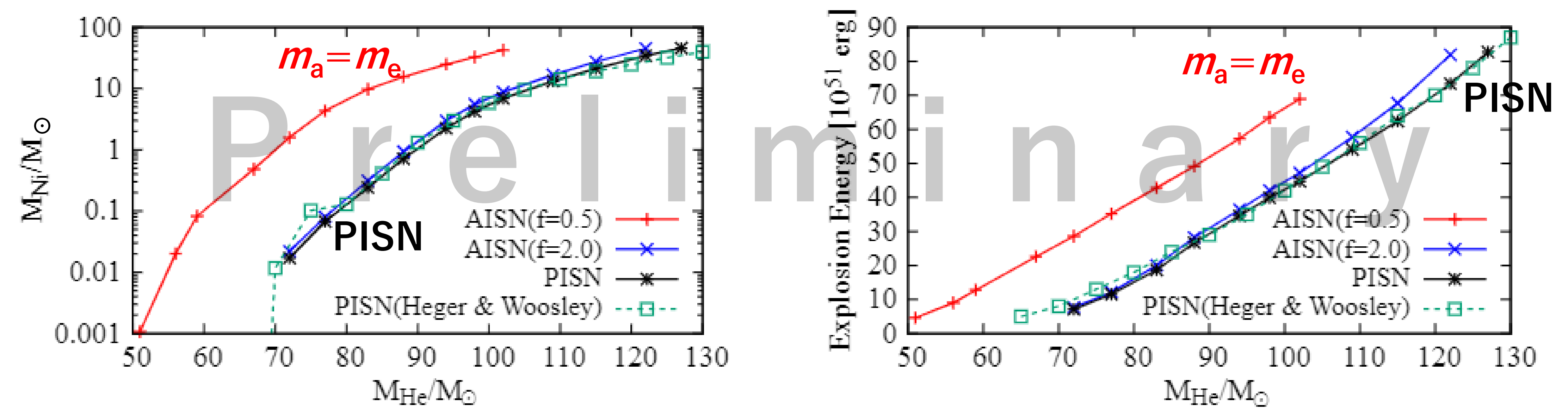
^{56}Ni Mass & Explosion Energy

MESA models with EoS modification

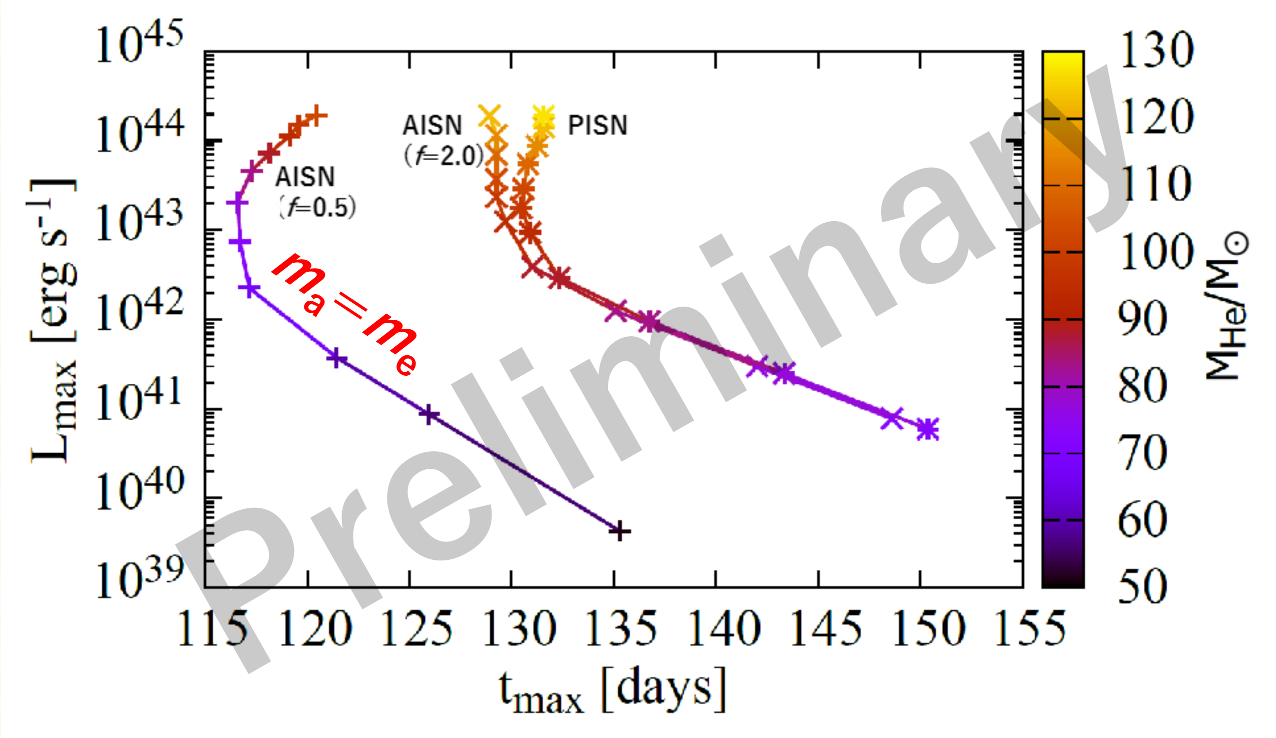
(He star, Z=10^{-5})

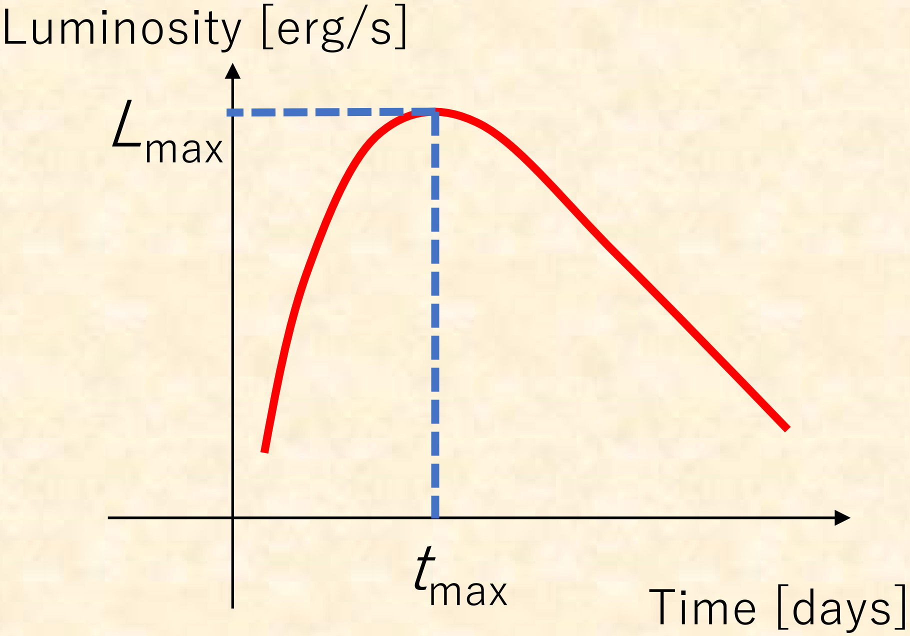


ALPs can increase M_{Ni} and E_{exp} in PISNe

Effect on Light Curves

Light curves estimated with Arnett's law (heating by the ^{56}Ni decay chain)





$$t_{max} \simeq \frac{1}{4}(\kappa/\mathrm{c})^{1/2}(M^3/E_k)^{1/4}$$

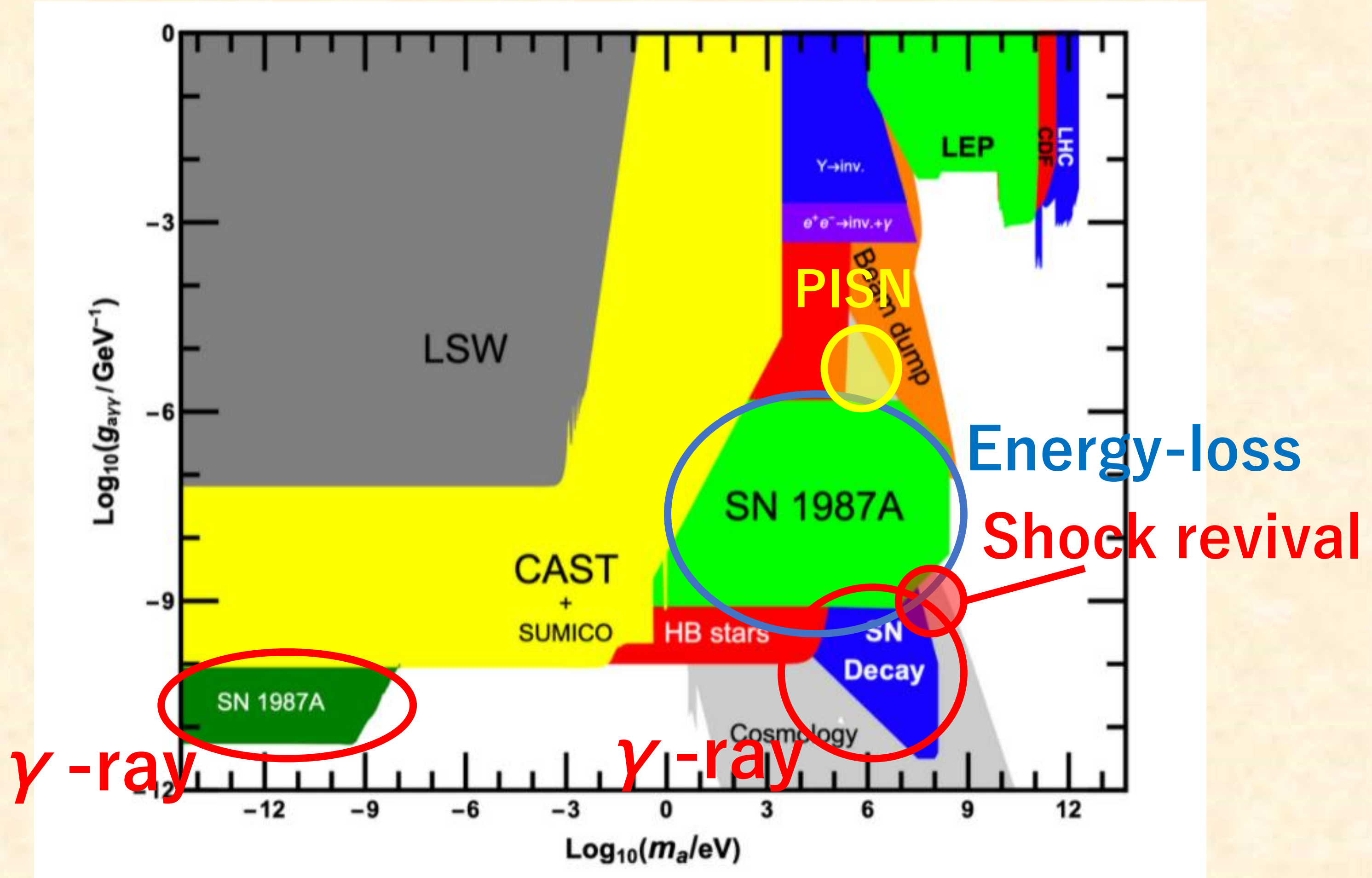
ALPs shorten t_{max} because of higher explosion energy

Summary (2)

- PISNe may be affected by ALPs if $m_a <\sim 2 m_e$
- Lighter stars can become PISNe
- The edges of the BH mass gap can be lighter
- ^{56}Ni mass and explosion energy can become higher
- **The peak time of the light curves can be shorter**
- Future optical/GW observations may find these signatures

Summary

Supernovae are a laboratory for ALPs!



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