# Exploring Axion-like Particles with Nearby Supernovae

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# Contents

1. Introduction – What are **axion-like particles** (ALPs)?

2. ALPs from nearby **supernova progenitors**

   [Mori, Takiwaki & Kotake, submitted (arXiv:2107.12661).]

3. Impacts of ALPs on **core-collapse supernovae**

   [Mori, Takiwaki & Kotake, in prep.]

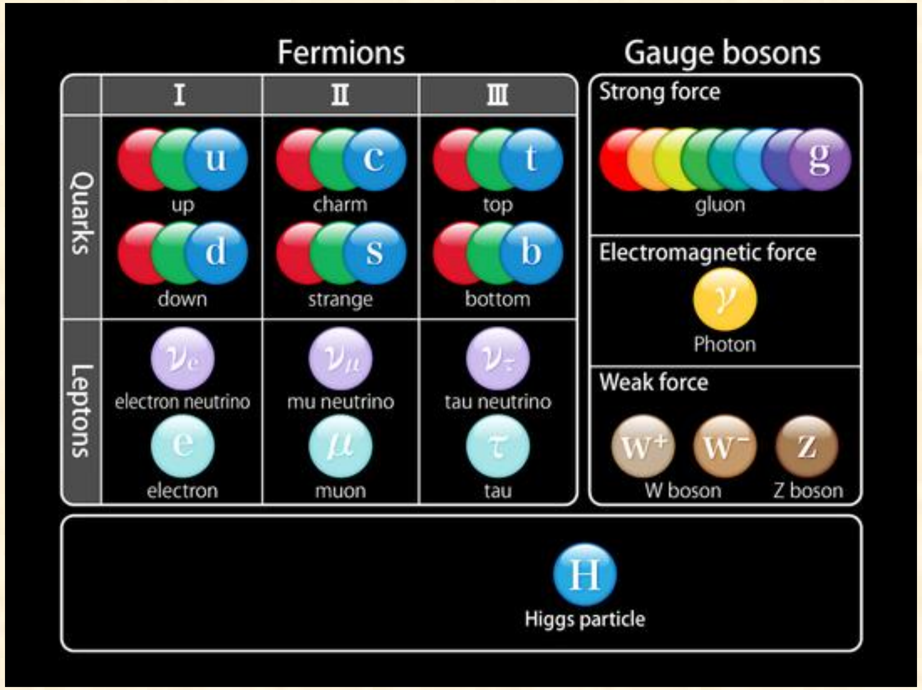
# Standard Model

SM is a successful theory for the most fundamental level of Nature, but:

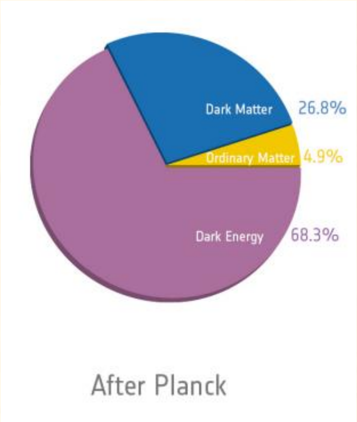
✓Where is **gravity**?

✓What are **dark matter** and **dark energy**?

✓What is **neutrino mass**?




https://www.kek.jp/old/en/Research/IPNS/201402123_%E9%BB%92_en.jpg




https://sci.esa.int/web/planck/-/51557-planck-new-cosmic-recipe

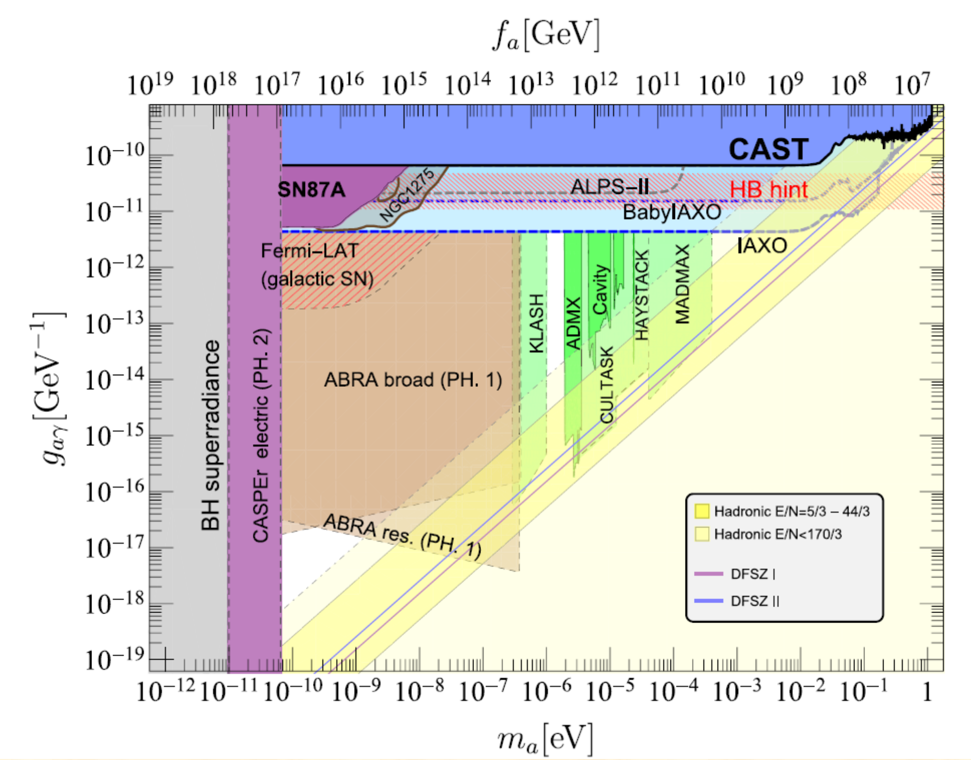
# Axion-like Particles (ALPs)

- A class of hypothetical pseudo Nambu-Goldstone bosons associated with U(1) symmetries
- Many models
  - ✓QCD axions [Wilczek PRL 40 (1978) 279, Weinberg PRL 40 (1978) 223.]
  - ✓String axions [Svrcek & Witten JHEP 2006 51.]
  - ✓…
- A candidate of **dark matter**!

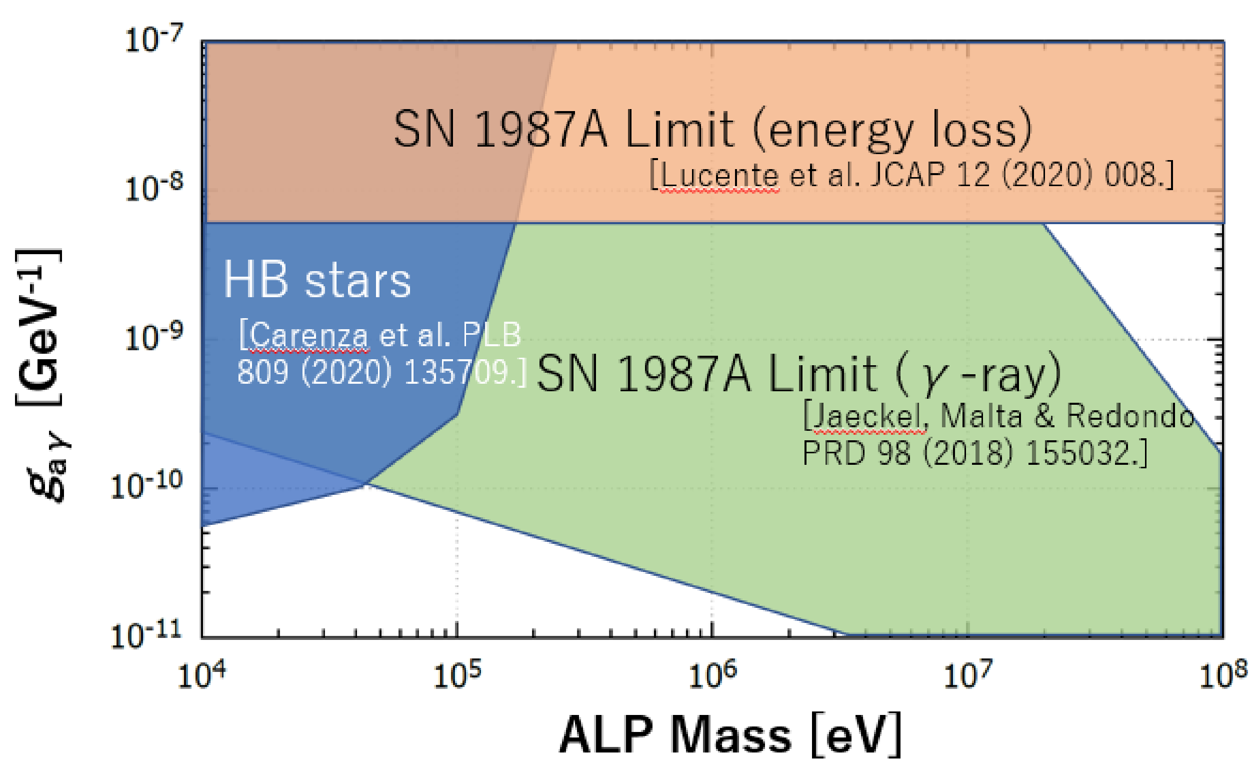

https://www.tuhogar.com/es-mx/productos/axion/limon

# Constraints on ALPs

- ALPs can couple with photons: $\mathcal{L}_{a\gamma\gamma} = -\frac{1}{4} g_{a\gamma} a \tilde{F}^{\mu\nu} F_{\mu\nu}$
- The ALP-photon coupling $g_{a\gamma}$ has been explored experimentally and astrophysically

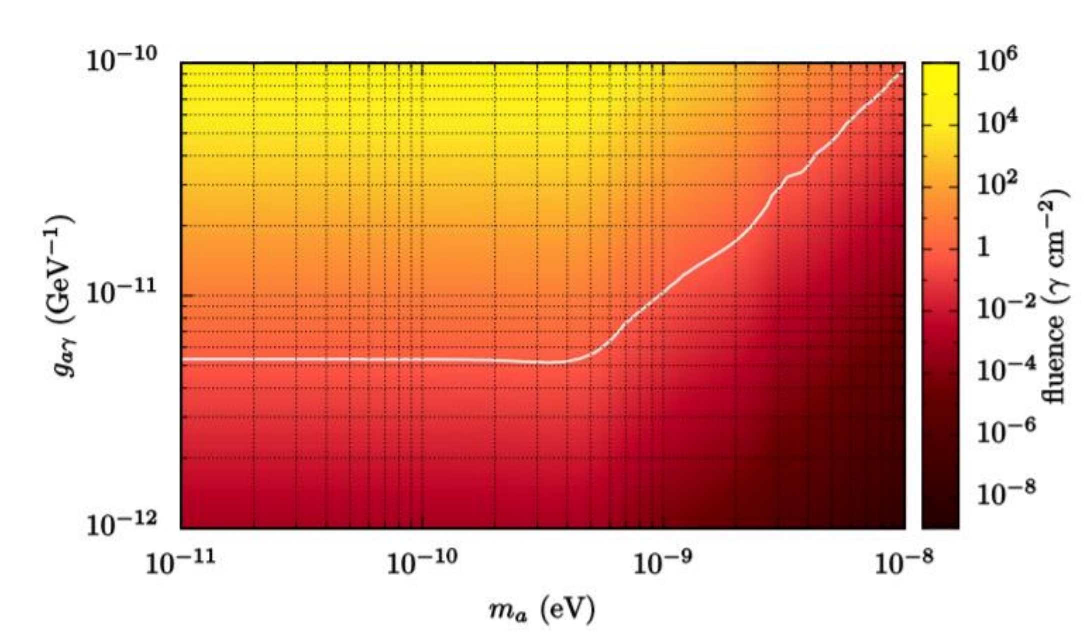


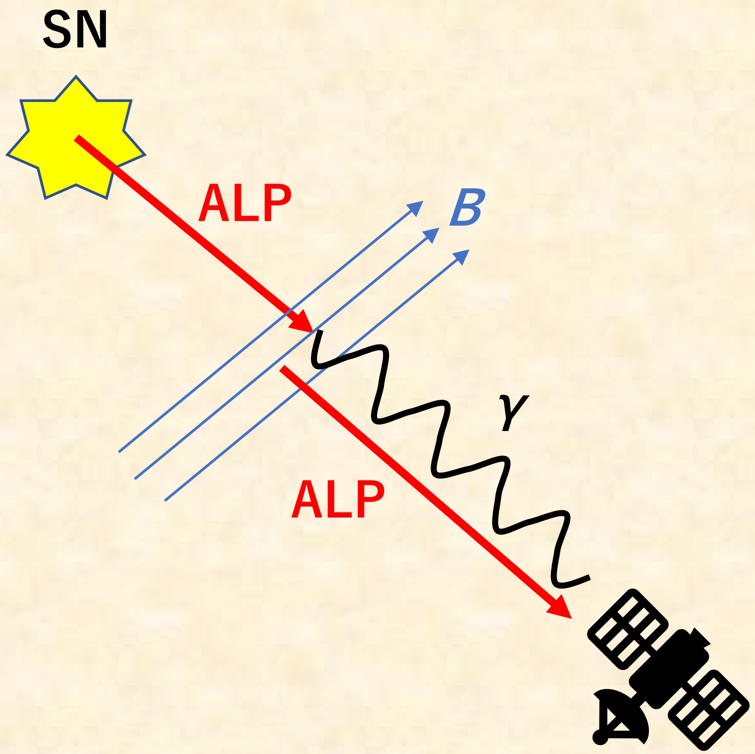

Di Luzio et al. Phys. Rep. 870 (2020) 1.



# SN 1987A Constraints on ALPs

- Non-detection of $\gamma$-rays




Payez et al., JCAP 1502 (2015) 006

Observation: $F$(25-100 MeV)<0.6 $\gamma$/cm$^2$

Chupp, Vestrand & Reppin PRL 62 (1989) 505

# Impact on Stellar Evolution

- Horizontal branch stars

TABLE IV. Time scale for helium burning for a $1.3 M_\odot$ star for various values of $G$.

| $G_9$ | $t_{\rm He}$ (yr) |
|---|---|
| 0.0 | $1.2\times 10^8$ |
| 0.1 | $6.9\times 10^7$ |
| 0.3 | $1.6\times 10^7$ |

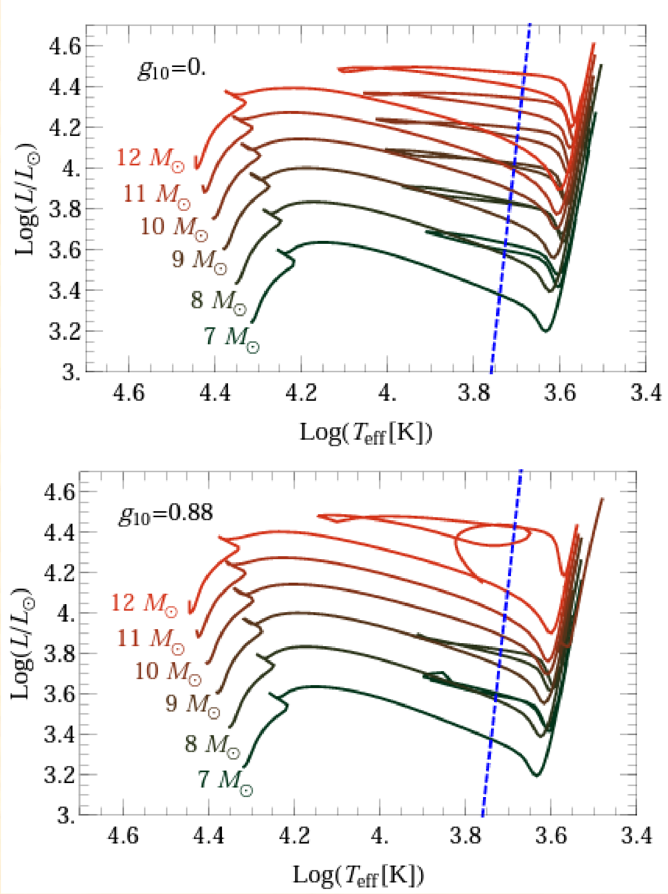
accelerated

Raffelt & Dearborn PRD 36 (1987) 2211

**Globular clusters**


- Massive stars

**Hertzsprung-Russell diagrams**




Friedland, Giannotti & Wise PRL 110 (2013) 061101

# Astrophysical Constraints

- Core-collapse supernovae

  Calore et al. PRD 102 (2020) 123005; Lucente et al. JCAP 2020 (2020) 008; Ge et al. JCAP 2020 (2020) 059; Sung, Tu & Wu PRD 99 (2019) 121305; Meyer et al. PRL 118 (2017) 011103; Fisher et al. PRD 94 (2016) 085012; Payez et al. JCAP 2015 (2015) 006; Giannotti, Duffy & Nita JCAP 2011 (2011) 015; Jaeckel, Malta & Redondo JCAP 2011 (2011) 015; Grifols, Masso & Toldra PRL 77 (1996) 2372; Brockway, Carlson & Raffelt PLB 383 (1996) 439

- Stellar evolution

  Xiao et al. PRL 126 (2021) 031101; Dolan, Hiskens & Volkas JCAP 2021 (2021) 010; Croon, McDermott & Sakstein PRD 102 (2020) 115024; Straniero et al. ApJ 881 (2019) 158; Carenza et al. PLB 809 (2020) 135709; Ayala et al. PRL 113 (2014) 191302; Friedland, Giannotti & Wise PRL 110 (2013) 061101; Raffelt & Dearborn PRD 36 (1987) 2211

- Sun

  IAXO Collaboration, JCAP 2019 (2019) 047; TASTE Collaboration, JINST 12 (2017) P11019; CAST Collaboration, Nature Physics 13 (2017) 584; Inoue et al. PLB 668 (2008) 93; Bernabei et al. PLB 515 (2001) 6; Moriyama et al. PLB 434 (1998) 147; Lazarus et al. PRL 69 (1992) 2333

- Others

**Pros**

Extreme environment far beyond terrestrial experiments
→Tight constraints on ALPs

**Cons**

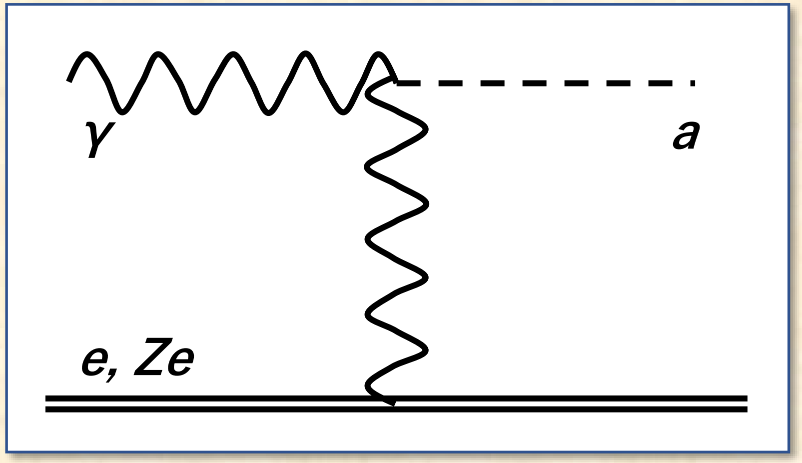
Ignorance on astrophysical objects
→Possibly large systematic uncertainties

It is important to propose **independent** methods to explore ALPs

# ALP Production Process

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

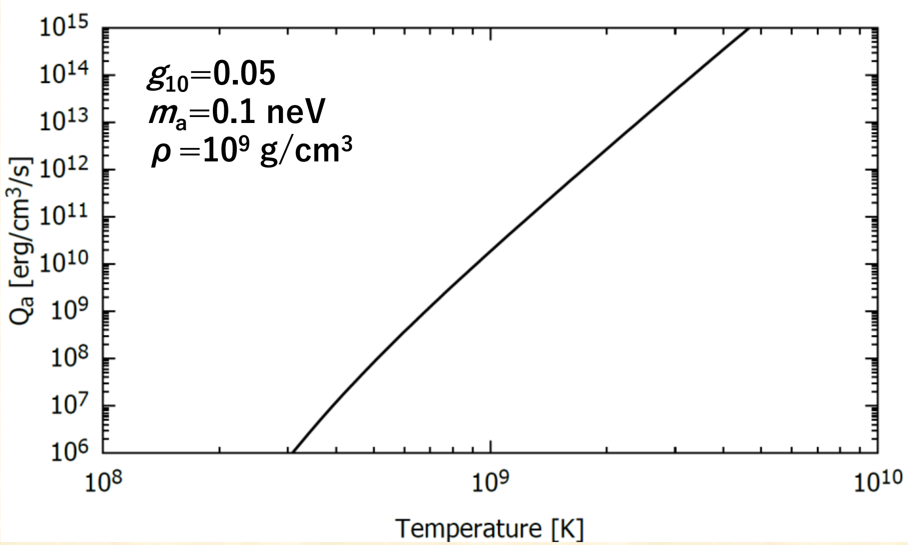
## Primakoff process




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

$k$: photon wave number in plasma
$p$: ALP momentum
$\kappa$ : Debye-Hückel scale

## ALP Emissivity
## $Q_a$ [erg/cm³/s]




$$Q_a = \int_{m_a}^{\infty} dE_a E_a \frac{d^2 n_a}{dtdE_a}$$

ALP emissivity is a steep function of $T$
→**Hot** astrophysical plasma is preferred

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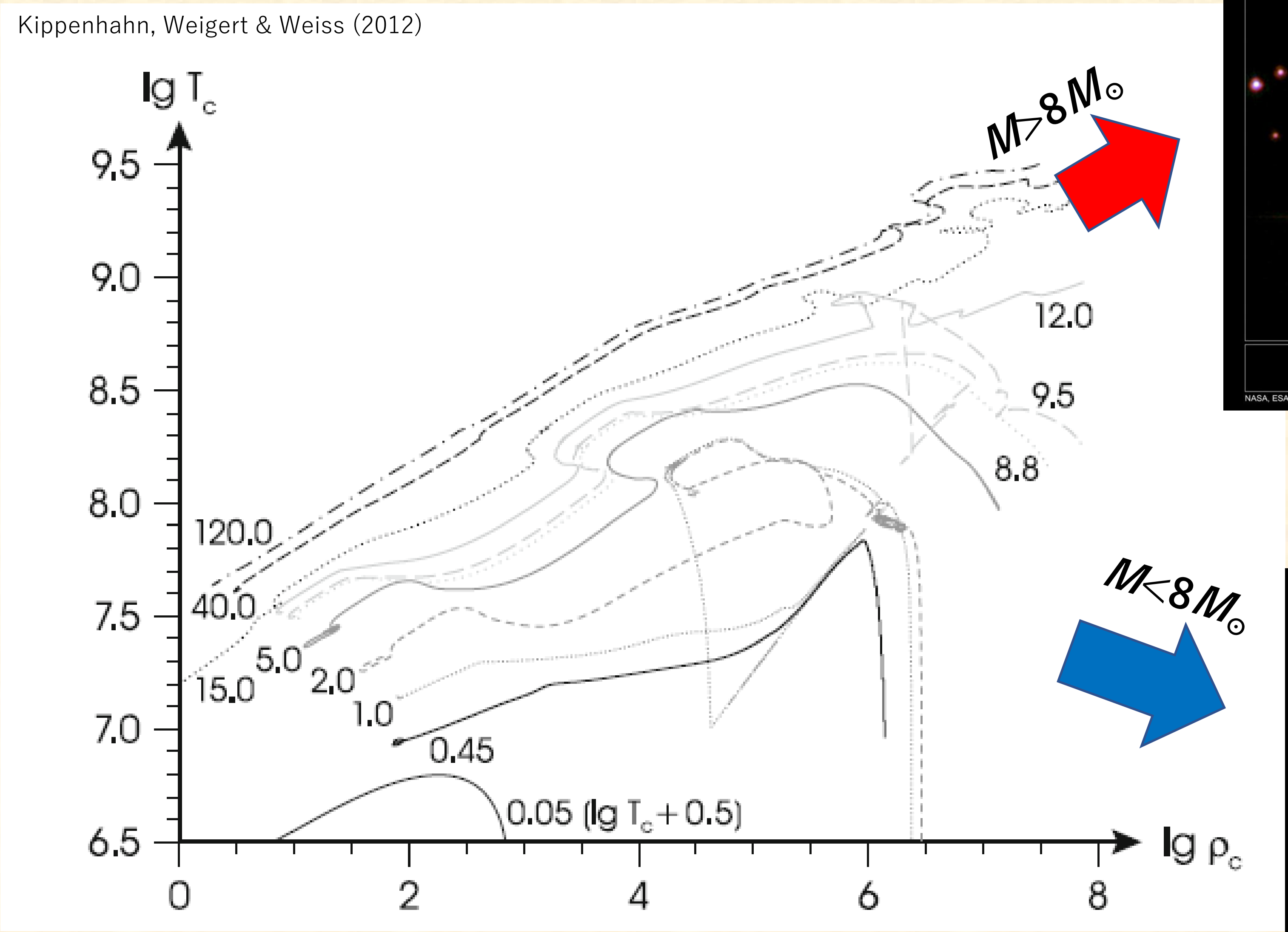
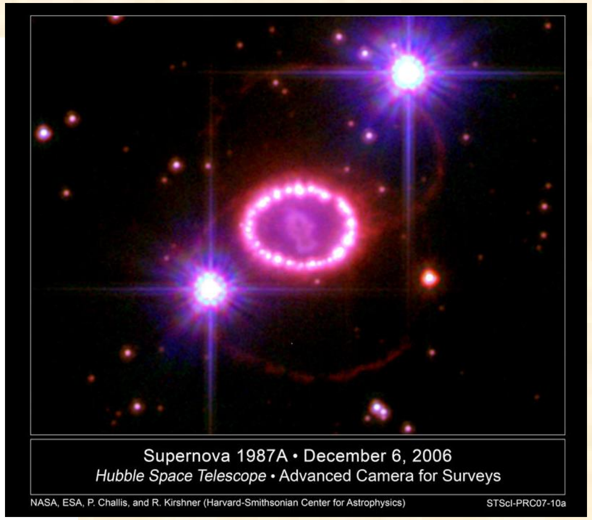
   [Mori, Takiwaki & Kotake, in prep.]

# Stellar Evolution

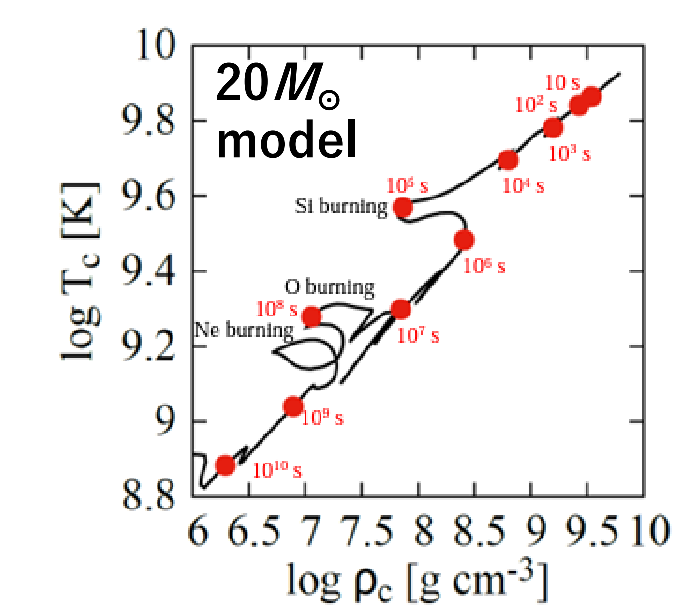



## Core-collapse SN




## White dwarf

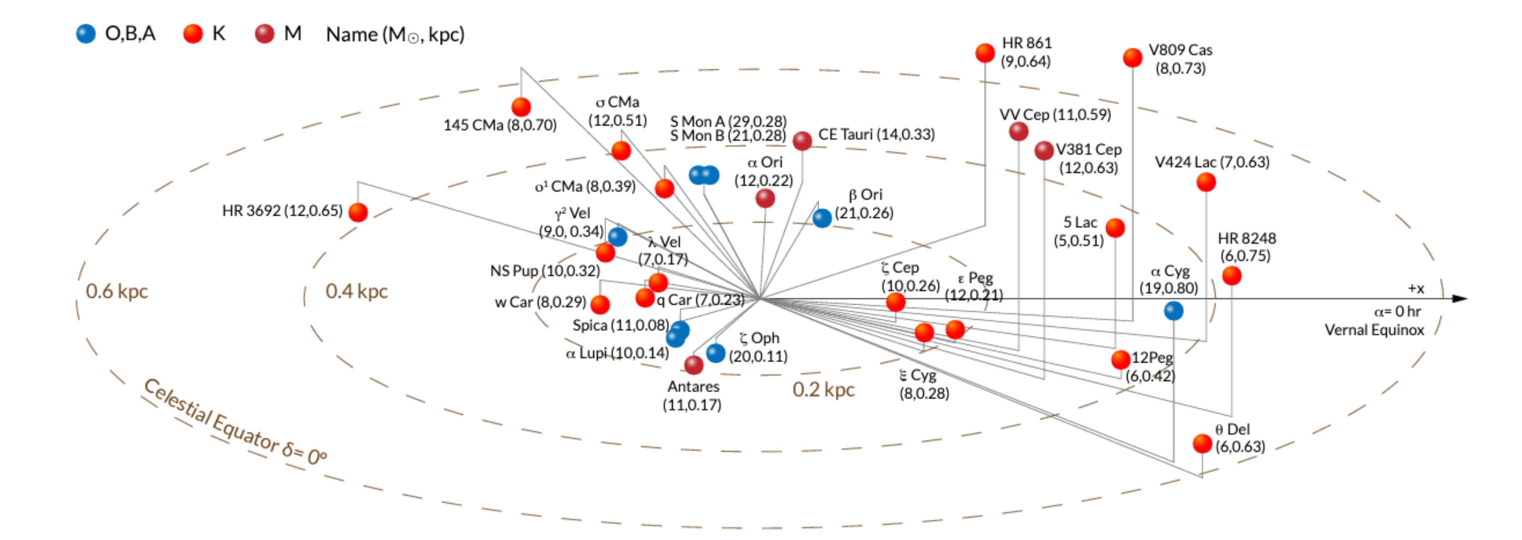
# Supernova Progenitors




Temperature becomes higher as the star evolves

→Massive stars in O- and Si-burning phases as an ALP factory?

Mukhopadhyay et al. ApJ 899 (2020) 153.




There are ~30 SN candidates within ~1 kpc

# ALP-photon Conversion by Magnetic Field

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

ALPs are converted into photons by Galactic magnetic field
→ $\gamma$ -ray may be observable

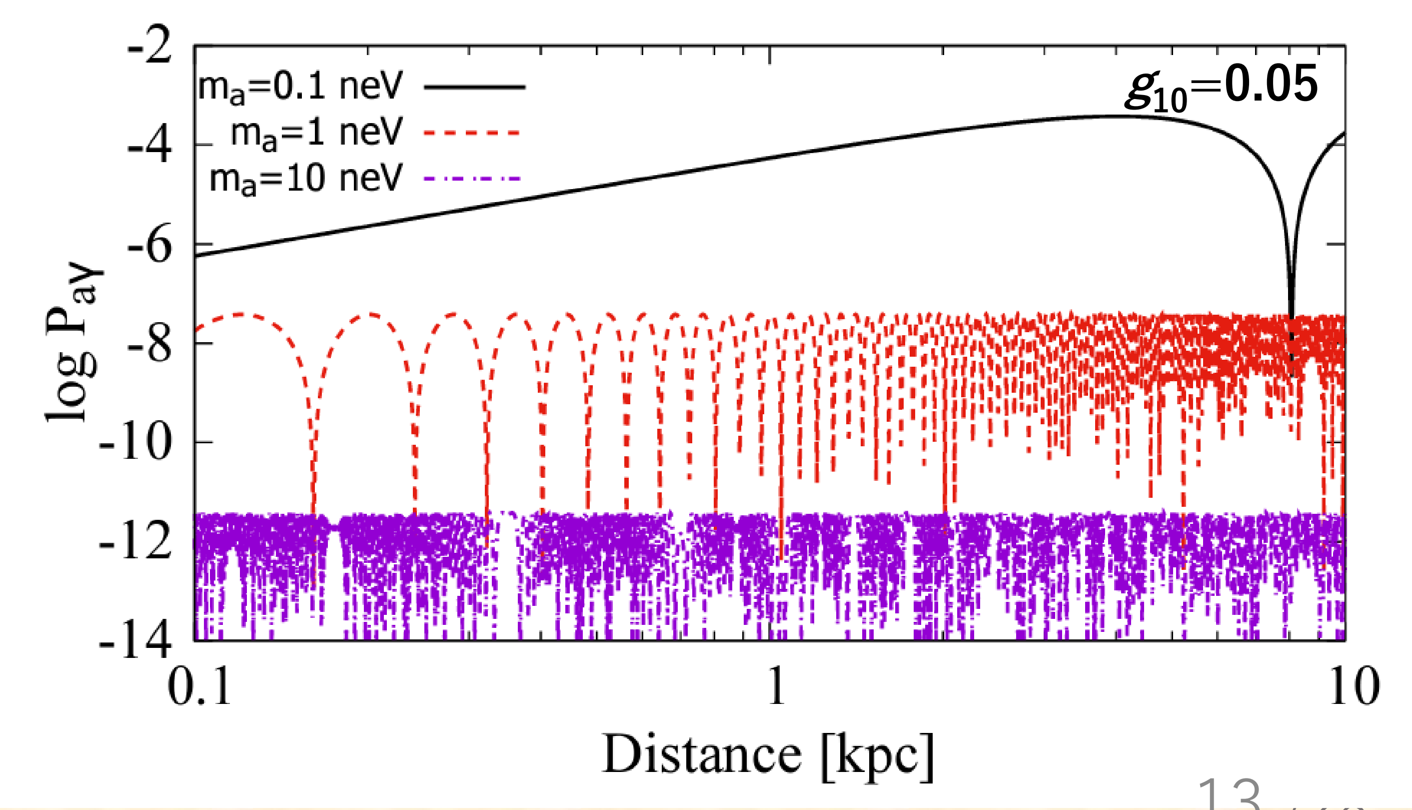
$$P_{a\gamma} = (\Delta_{a\gamma} d)^2 \frac{\sin^2\left(\frac{\Delta_{\rm osc} d}{2}\right)}{\left(\frac{\Delta_{\rm osc} d}{2}\right)^2}$$

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

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

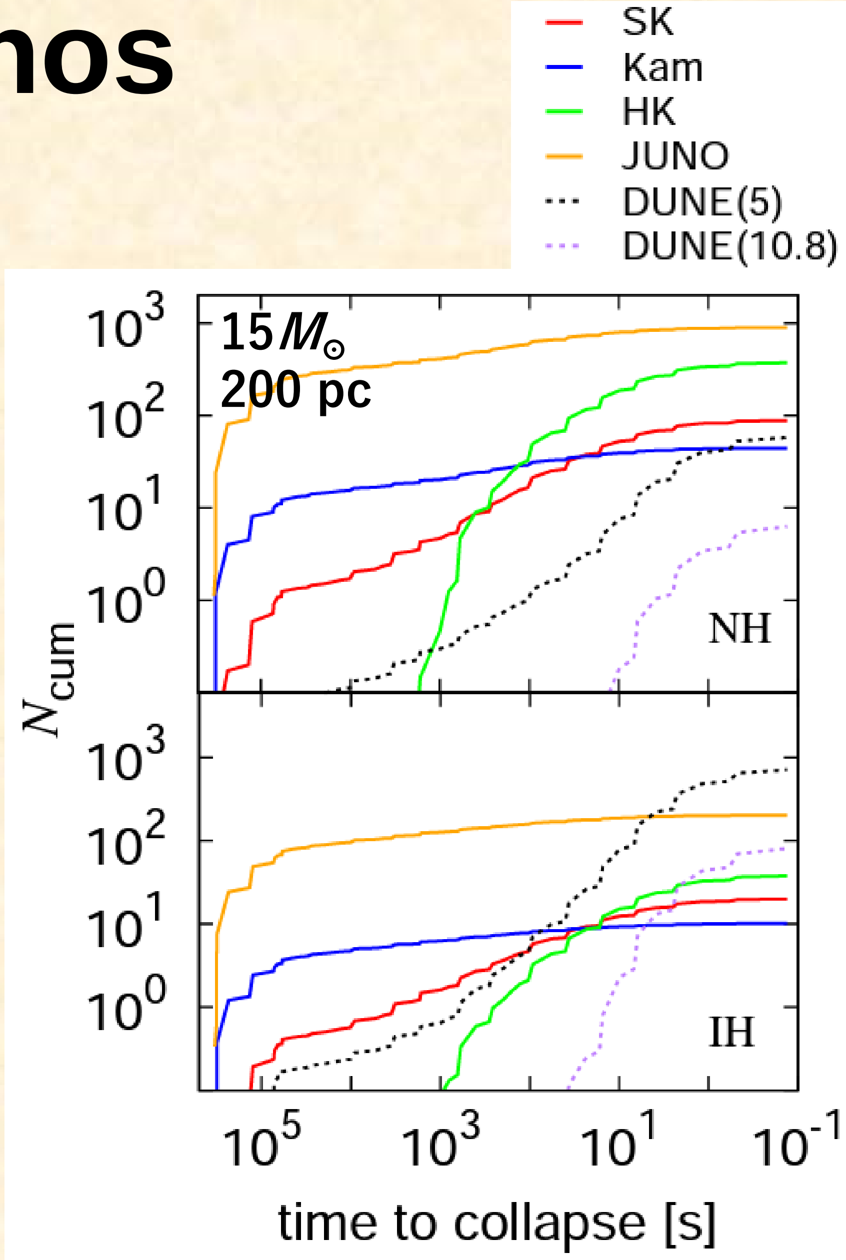
$$\Delta_{a\gamma} = g_{a\gamma}\frac{B_{\rm T}}{2}$$

**a-$\gamma$ conversion prob. with $B$=1 $\mu$G**



# Pre-SN Neutrinos

- **Pre-SN alarm** would be provided by observing pre-SN neutrinos
- Target-of-opportunity observations of $\gamma$-rays may find signatures of **pre-SN ALPs**



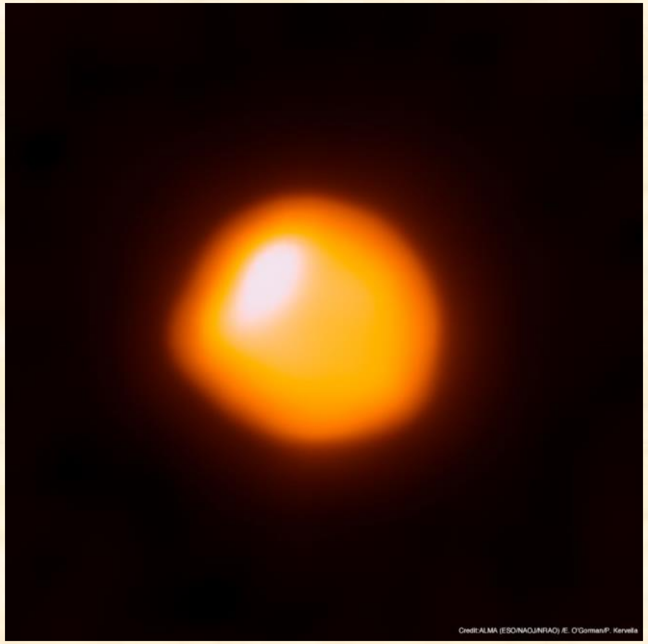

Kato et al., ApJ 848 (2017) 48.

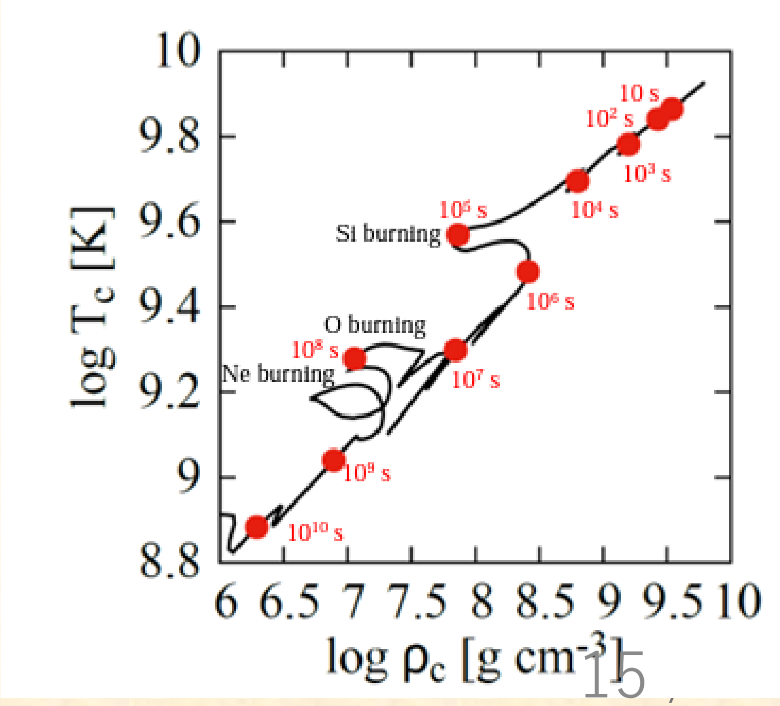
# Stellar Model

- We adopt parameters for Betelgeuse as a benchmark
- MESA [Paxton et al. ApJS]
- $M = 20 M_\odot$
- $d = 168^{+27}{}_{-15}$ pc

  [Joyce et al. ApJ 902 (2020) 63.]
- $B = 1\ \mu$G

**Betelgeuse**



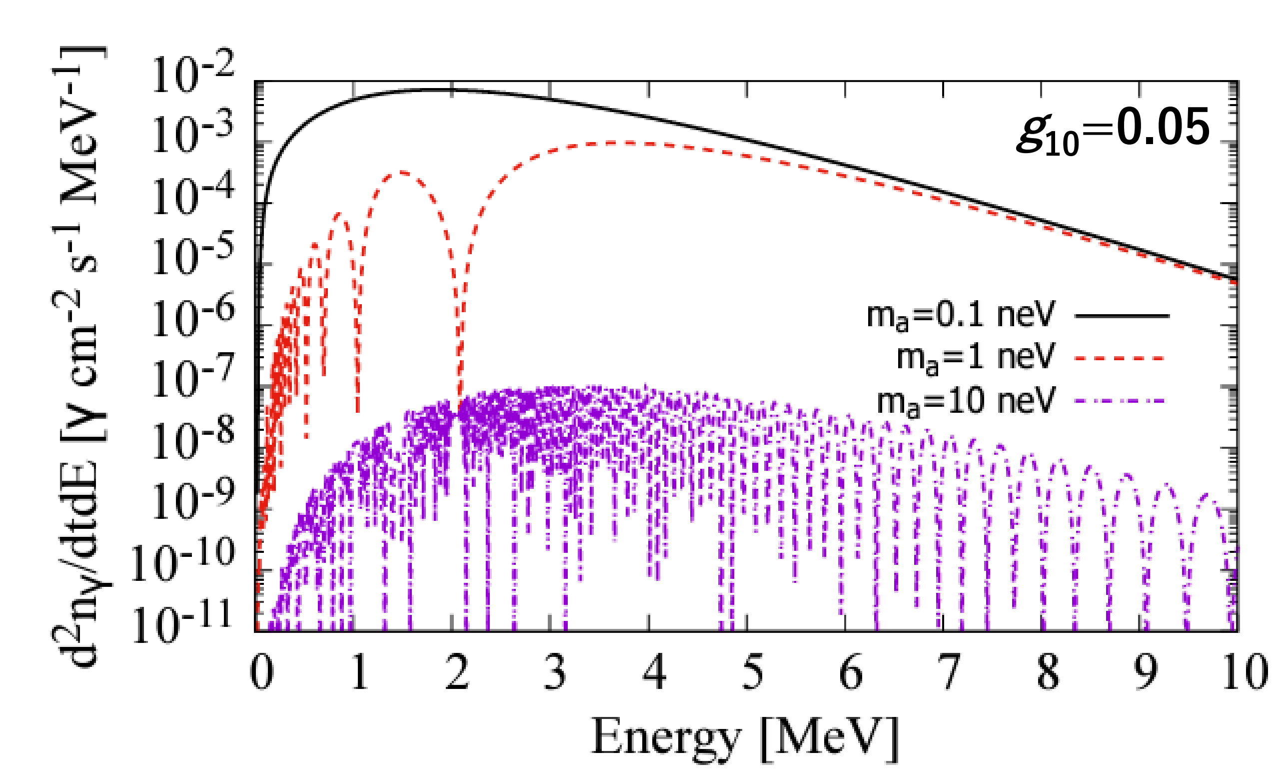


# γ-ray Spectrum

- $20\,M_\odot$ model **just before core-collapse**
- $d$=168 pc (Betelgeuse)
- The peak is at ~1-5 MeV

→may be observed by **MeV γ-ray telescopes**

- Spectral irregularity by $P_{a\gamma}$

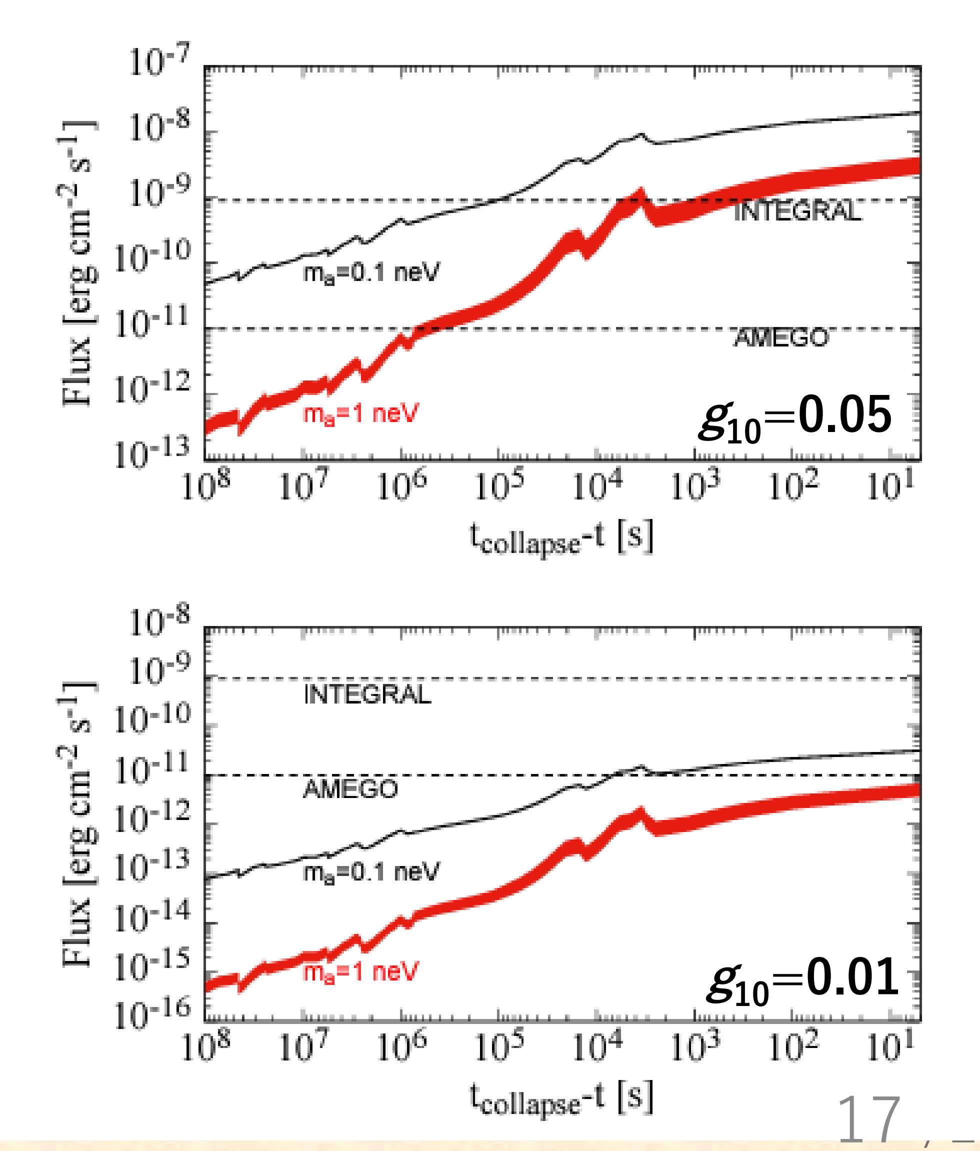



$$\frac{d^2 n_\gamma}{dt dE} = \frac{1}{4\pi d^2} 4\pi P_{a\gamma} \int_0^R \frac{d^2 n_a}{dt dE} r^2 dr$$

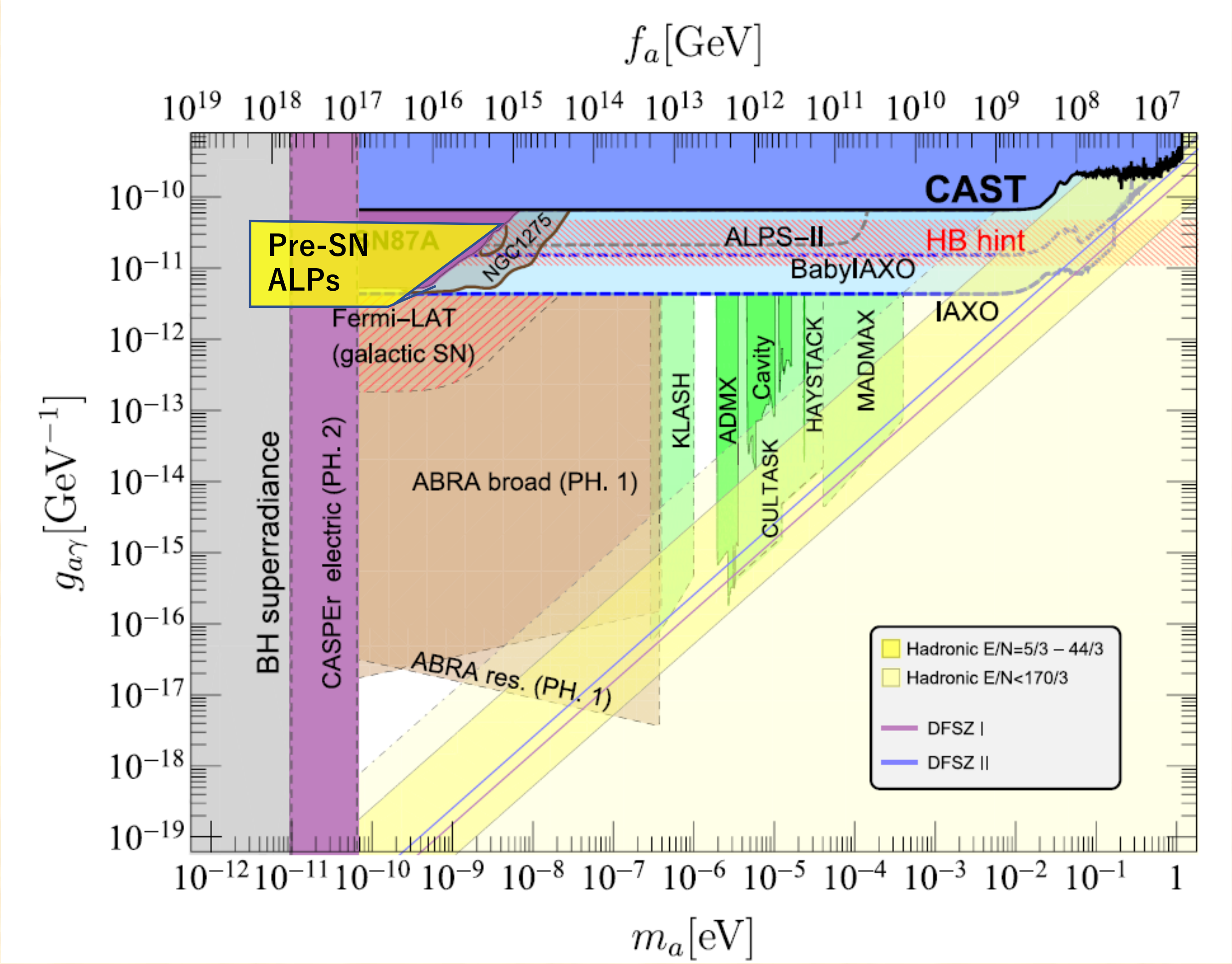
# γ-ray Flux and its Observability

- $\gamma$ -ray flux increases as a function of time
- $\gamma$ -ray may be observable

→ToO observations following **pre-SN neutrino alarms** are desirable



# Summary



$f_a$[GeV]
$10^{19}$ $10^{18}$ $10^{17}$ $10^{16}$ $10^{15}$ $10^{14}$ $10^{13}$ $10^{12}$ $10^{11}$ $10^{10}$ $10^{9}$ $10^{8}$ $10^{7}$
$g_{a\gamma}$[GeV$^{-1}$]
$10^{-10}$ $10^{-11}$ $10^{-12}$ $10^{-13}$ $10^{-14}$ $10^{-15}$ $10^{-16}$ $10^{-17}$ $10^{-18}$ $10^{-19}$
CAST
Pre-SN ALPs
SN87A
NGC1275
ALPS–II
HB hint
BabyIAXO
IAXO
Fermi–LAT (galactic SN)
BH superradiance
CASPEr electric (PH. 2)
ABRA broad (PH. 1)
ABRA res. (PH. 1)
KLASH
ADMX
Cavity
CULTASK
HAYSTACK
MADMAX
Hadronic E/N=5/3 – 44/3
Hadronic E/N<170/3
DFSZ I
DFSZ II
$10^{-12}$ $10^{-11}$ $10^{-10}$ $10^{-9}$ $10^{-8}$ $10^{-7}$ $10^{-6}$ $10^{-5}$ $10^{-4}$ $10^{-3}$ $10^{-2}$ $10^{-1}$ 1
$m_a$[eV]

# Contents

# Multi-messenger Astronomy of SNe

- SN 1987A provided much information on ALPs
- Previous calculations are (mainly) post-processing
- Much information will be obtained by multi-messenger observations of SNe

→**SN models coupled with ALPs** are needed

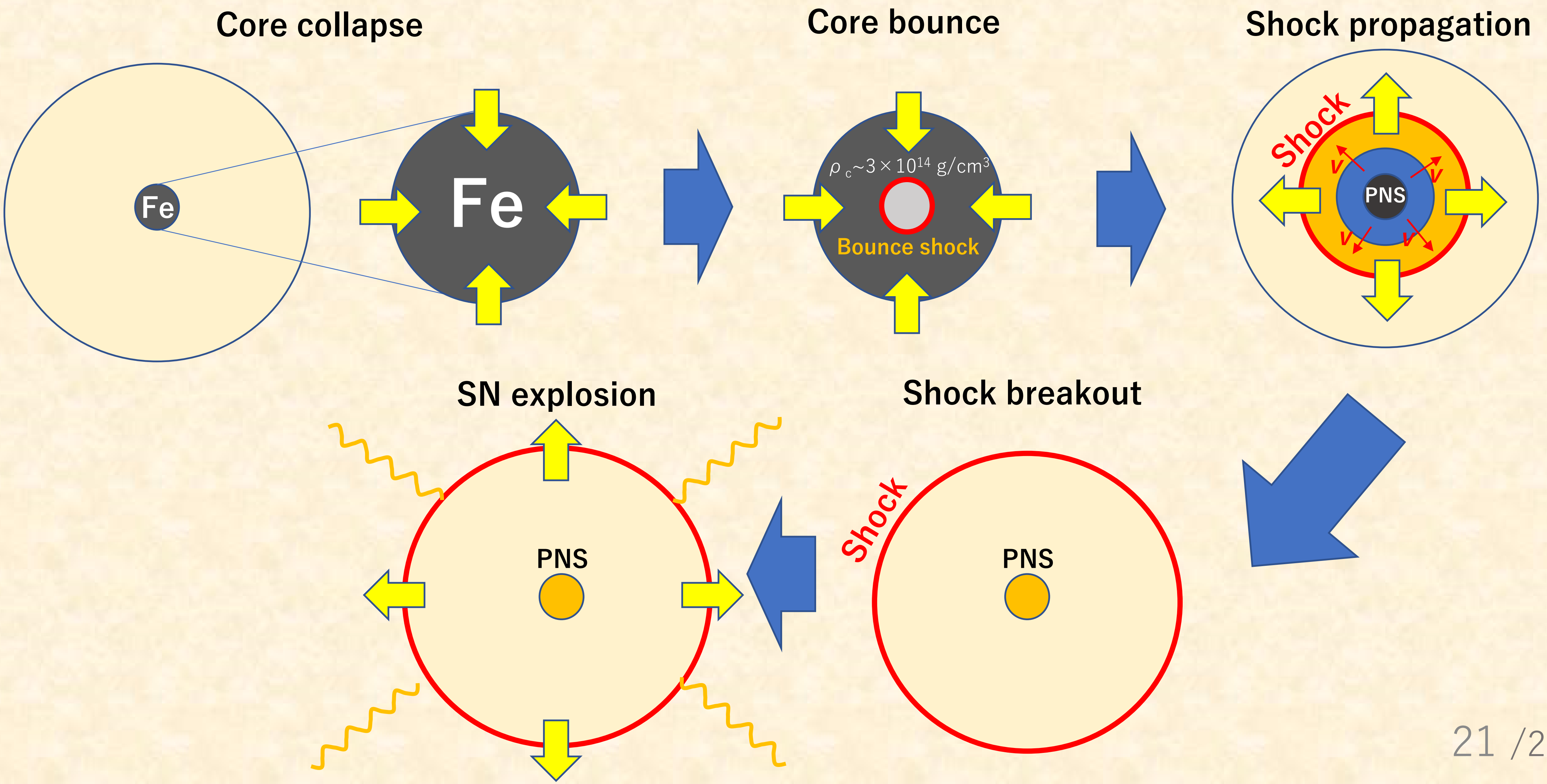
**Gravitational waves**

Ⓒ Caltech/MIT/LIGO Lab

**Neutrinos**

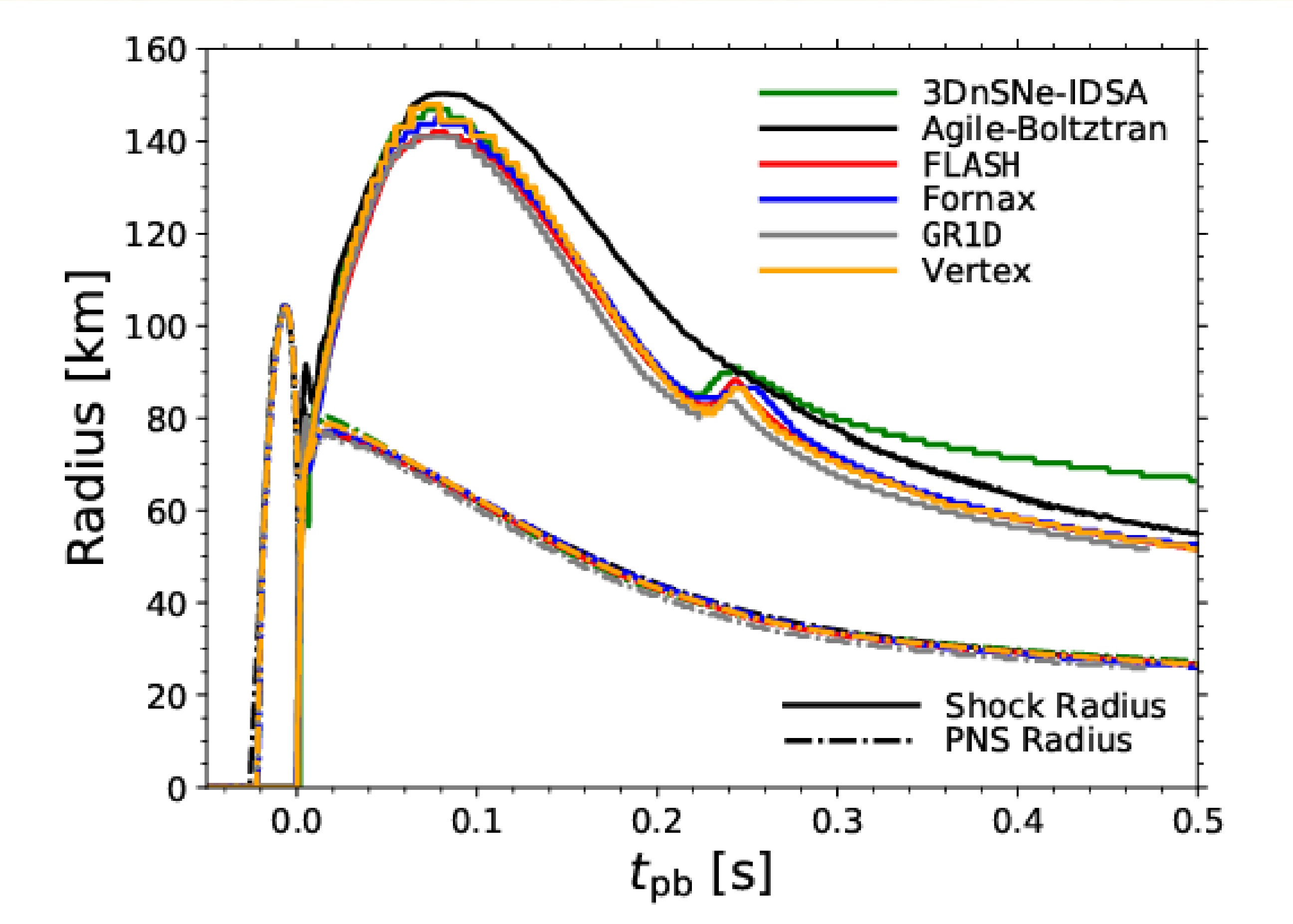
ⒸKamioka Observatory, ICRR (Institute for Cosmic Ray Research), The University of Tokyo

# Explosion Mechanism of Core-collapse SNe



# Stalled Shock

- The bounce shock stalls in 1D simulations
- Photodisintegration of heavy elements (**cooling**) v.s. **neutrino heating**
- Long-standing problem in SN physics
- Neutrino heating + multi-*D* effect?




O'Connor et al., JPhG 45 (2018) 104001.

# SN Simulation Coupled with ALPs

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

**ALP Production**:

Primakoff process
Photon coalescence

**ALP absorption**:

Inverse Primakoff process
Radiative decay

$$\nabla \cdot \mathbf{F} = \underline{Q_{\mathrm{cool}}} - \underline{Q_{\mathrm{heat}}} \xrightarrow{\text{discretize}} L_{i+\frac{1}{2}} = L_{i-\frac{1}{2}} + (Q_{\mathrm{cool},\, i} - \underline{Q_{\mathrm{heat},\, i}})\Delta V_i$$

ALP production — ALP absorption — for the *i*-th cell — **ALP heating rate**

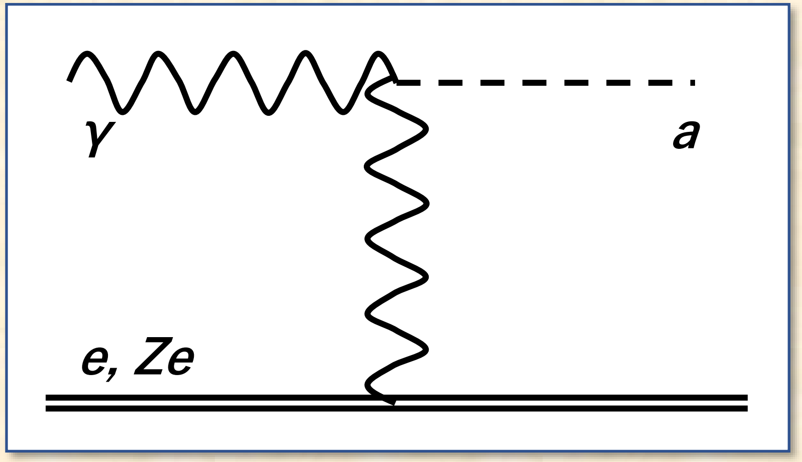
**Modification on internal energy**:

$$E_{\mathrm{int},\, i} \to E_{\mathrm{int},\, i} + (Q_{\mathrm{heat},\, i} - Q_{\mathrm{cool},\, i})\Delta t$$

# ALP Production Processes

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

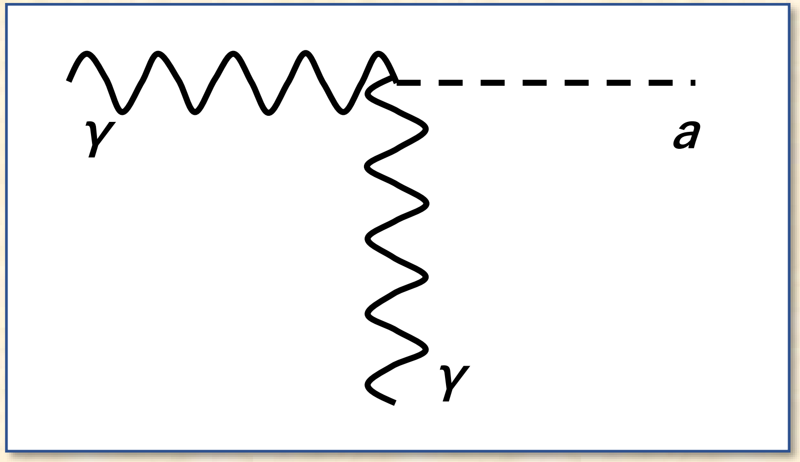
## Primakoff process




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

$k$: photon wave number in plasma
$p$: ALP momentum
$\kappa$ : Debye-Hückel scale

## Photon coalescence

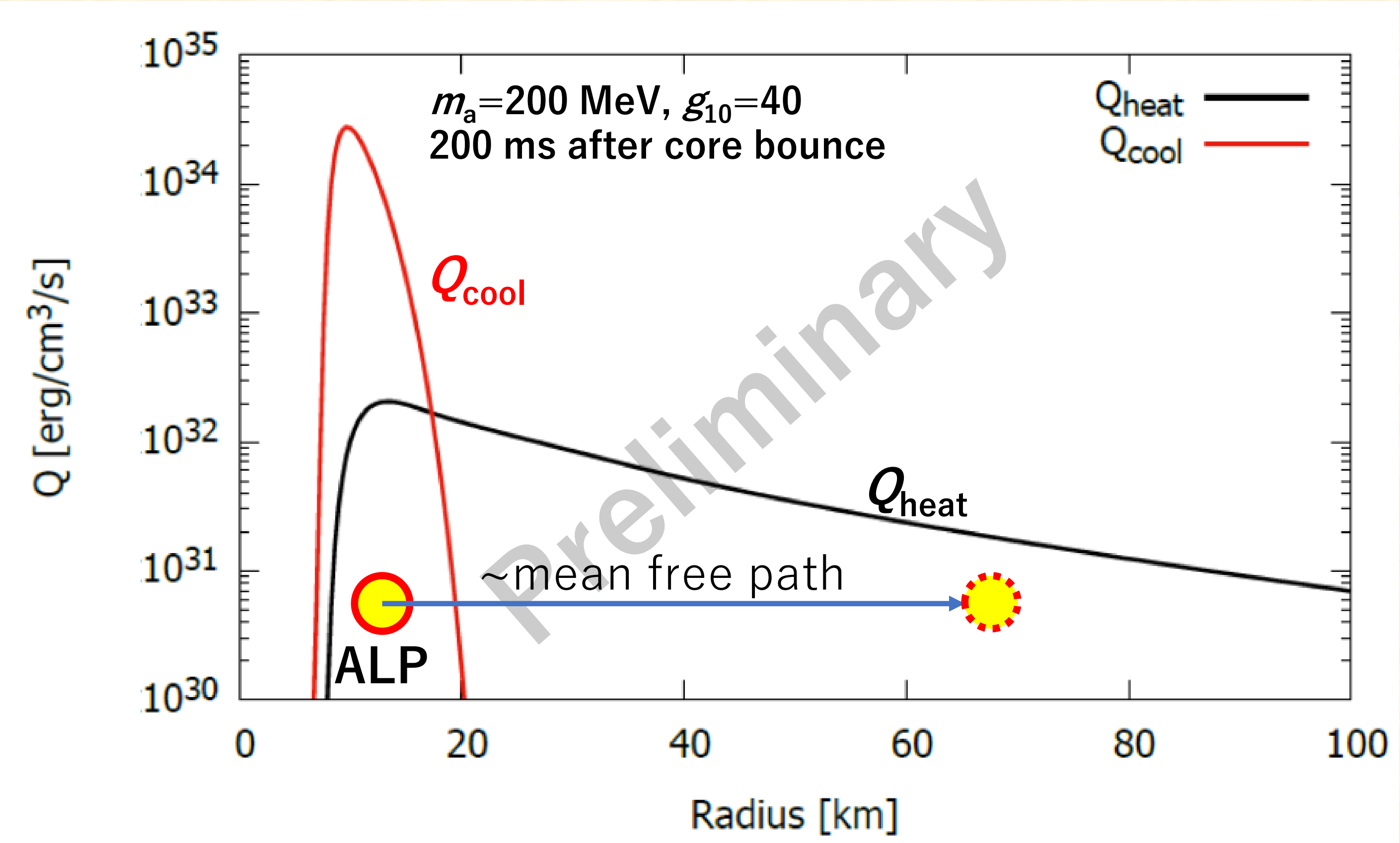



$$\frac{d^2 n_a}{dtdE} = g_{a\gamma}^2 \frac{m_a^4}{128\pi^3} p \left(1 - \frac{4\omega_{\rm pl}^2}{m_a^2}\right)^{\frac{3}{2}} e^{-\frac{E}{T}}$$

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

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

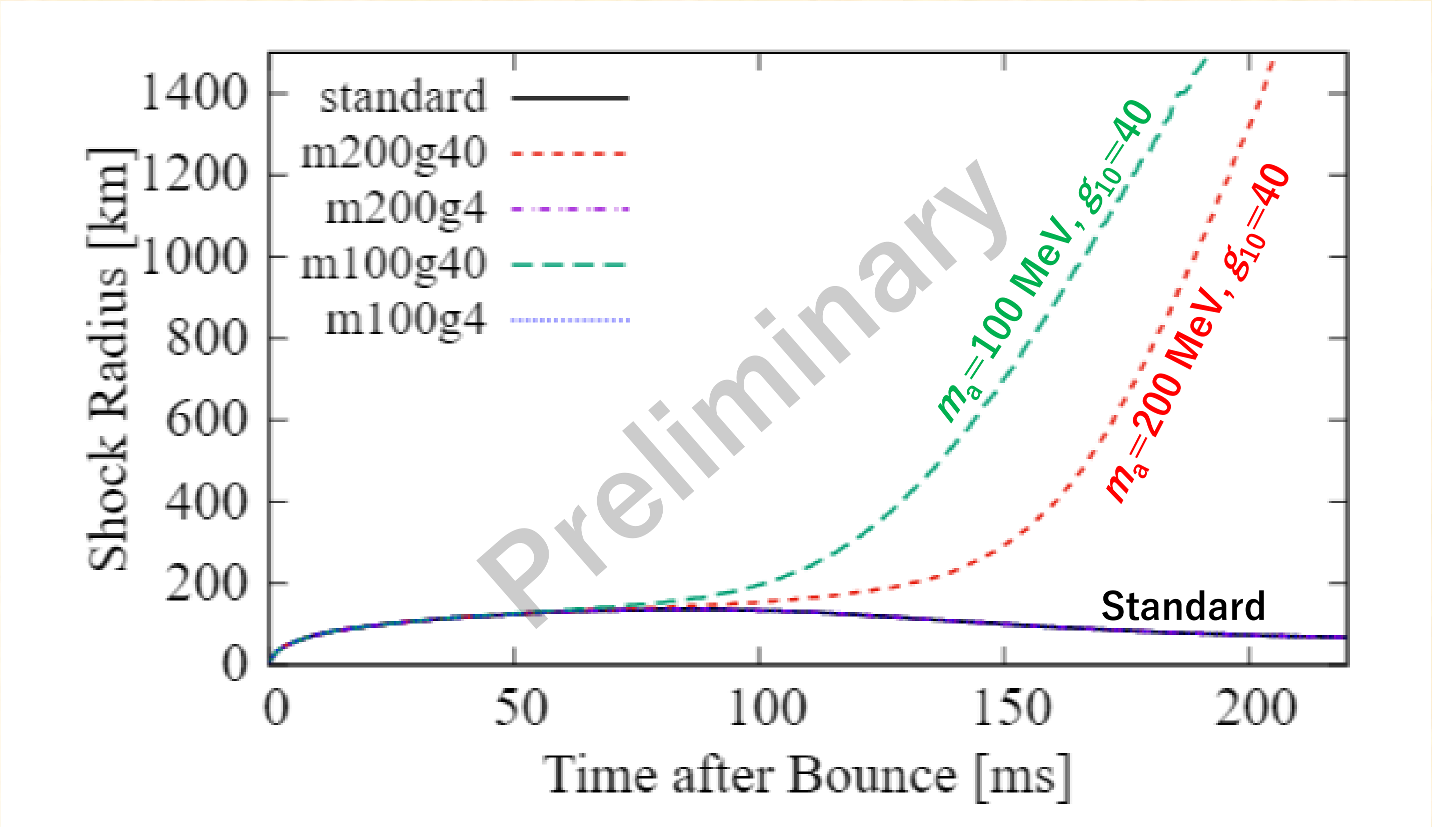
# SN Simulation Coupled with ALPs

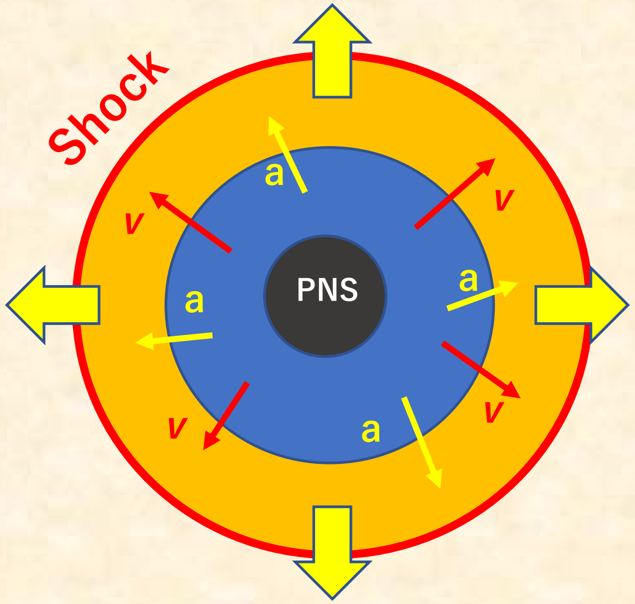



✓ ALPs are produced at ~10 km

✓ ALPs decay after running a mean free path → additional heating

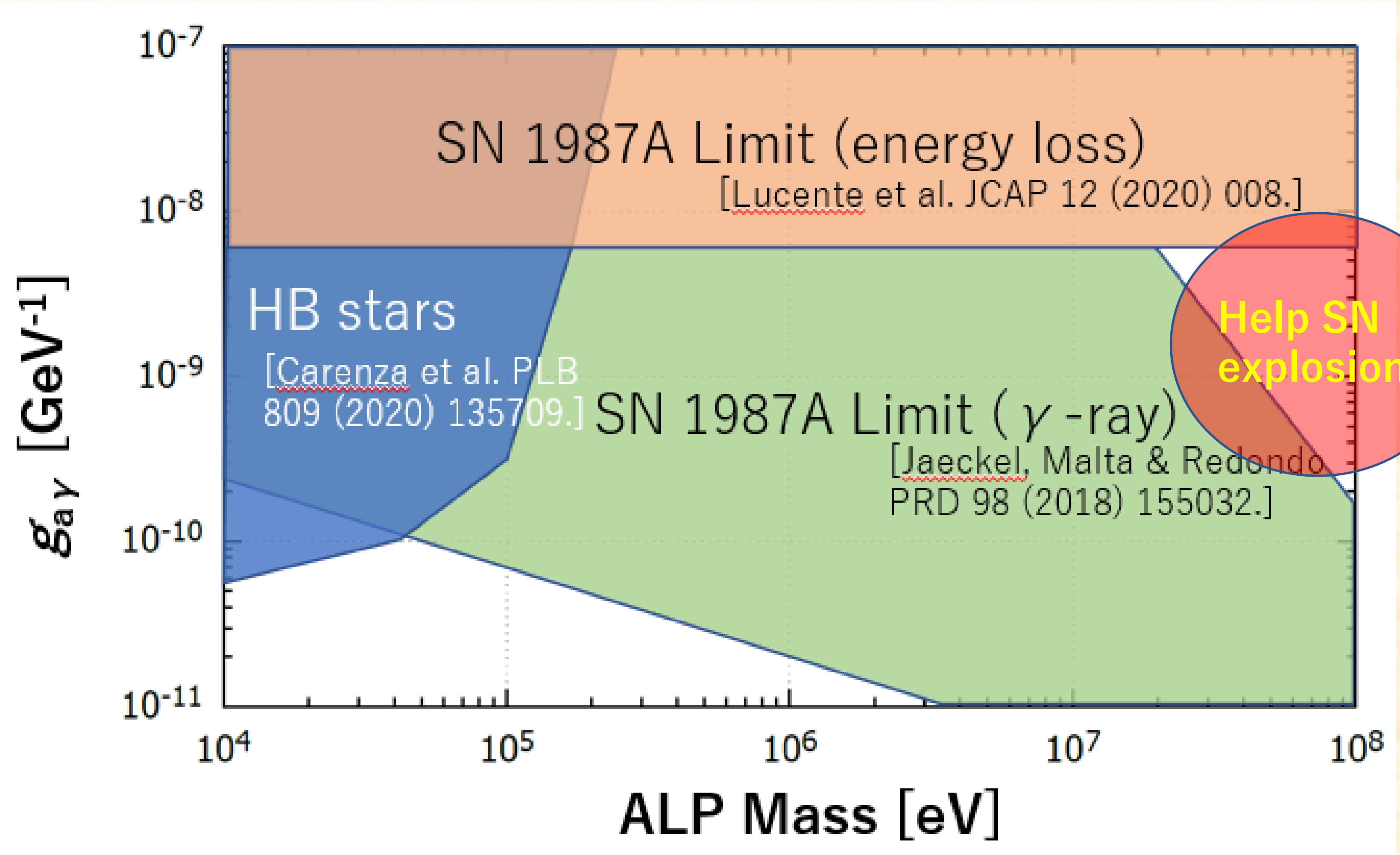
# Shock Revival by ALPs




ALPs may heat the shock wave and lead to shock revival

# Summary



SN 1987A Limit (energy loss)
[Lucente et al. JCAP 12 (2020) 008.]
HB stars
[Carenza et al. PLB 809 (2020) 135709.]
SN 1987A Limit (γ-ray)
[Jaeckel, Malta & Redondo PRD 98 (2018) 155032.]
Help SN explosion?
$g_{a\gamma}$ [GeV-1]
ALP Mass [eV]
10-7
10-8
10-9
10-10
10-11
104
105
106
107
108

# Summary

- Astrophysical objects such as SNe offer unique opportunities to explore ALPs.
- Observations of nearby SN progenitors with next-generation $\gamma$-ray telescopes may provide independent information on ALPs.
- ALPs in a specific parameter region may significantly affect explosion mechanism of core-collapse SNe.