Pre-supernova Axion-like Particles and Their Detectability

Kanji Mori (森寛治)
Research Institute of Stellar Explosive Phenomena,
Fukuoka University

Mori, Takiwaki & Kotake (2021) submitted (arXiv:2107.12661)

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**!

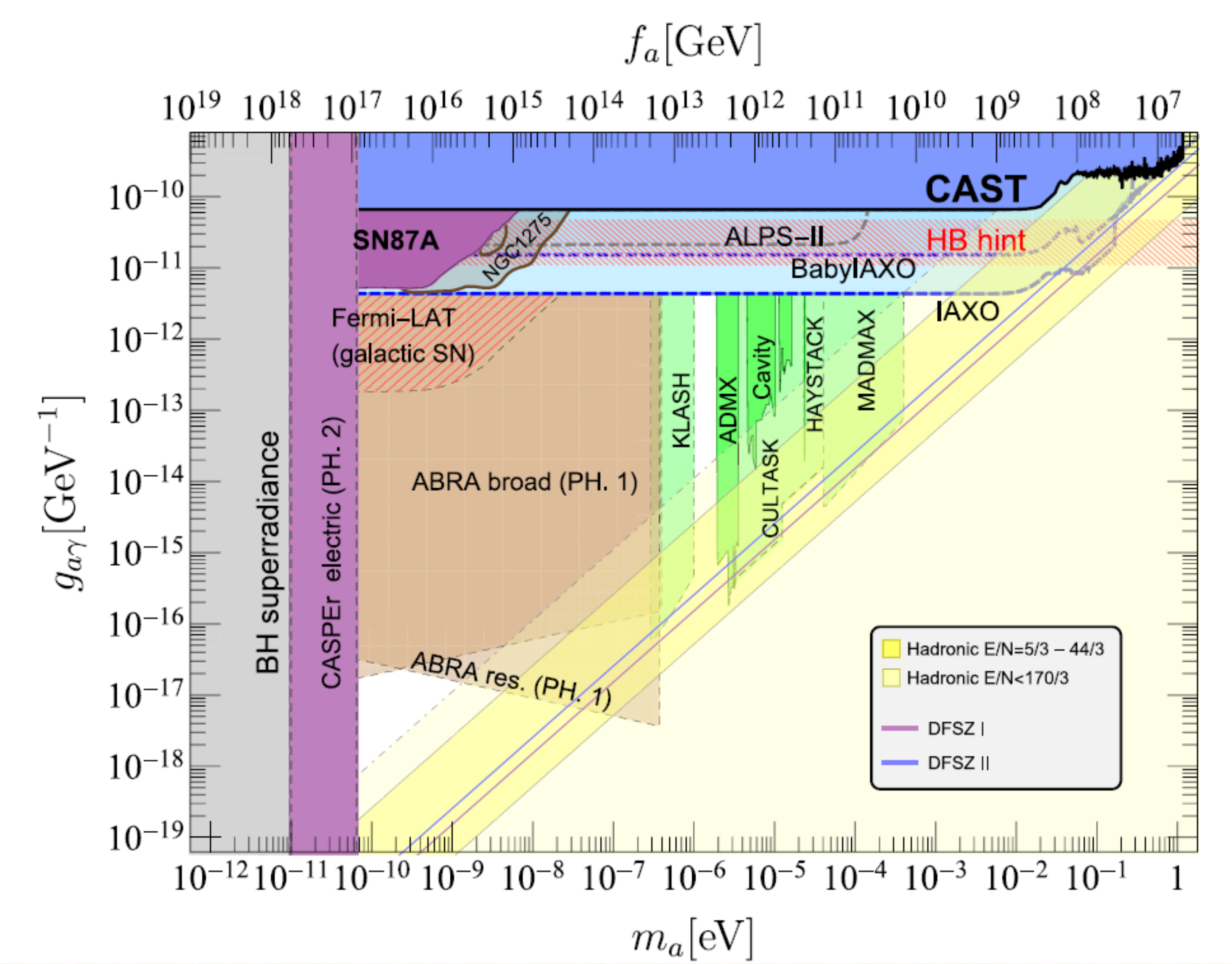
https://www.tuhogar.com/es-mx/productos/axion/limon

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
- ALPs with m_a~1 neV are tightly limited by astrophysical γ-rays

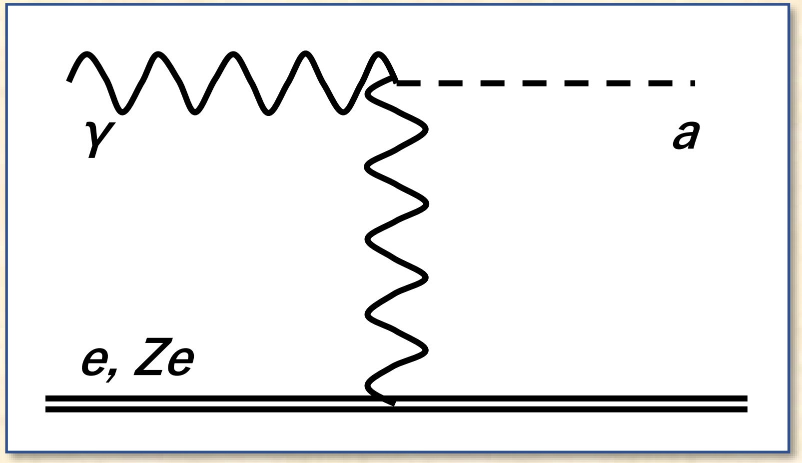


Di Luzio et al. Phys. Rep. 870 (2020) 1.

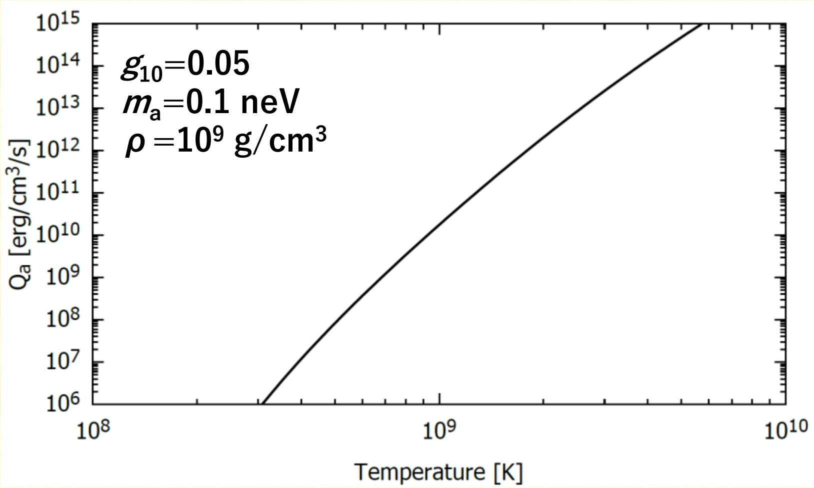
ALP Production Process

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

Primakoff process



ALP Emissivity Q_a [erg/cm³/s]



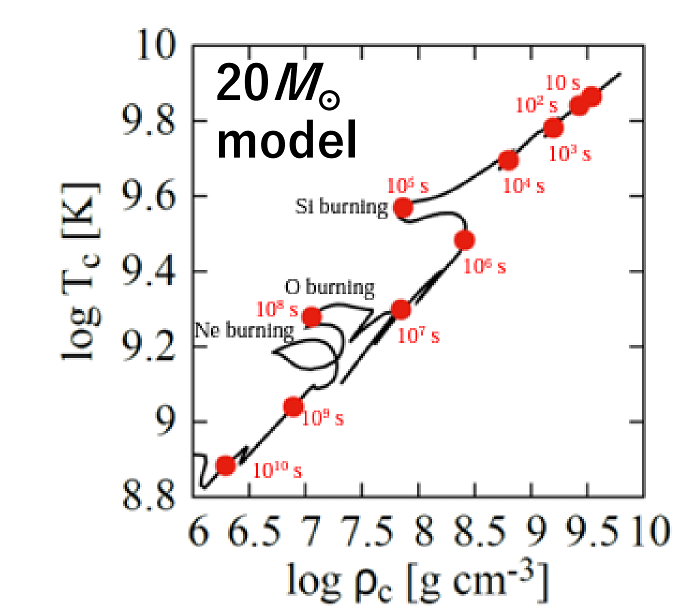
$$\frac{d^2 n_a}{dtdE} = g_{a\gamma}^2 \frac{T\kappa^2}{32\pi^3} \frac{kp}{e^{\frac{E}{T}} - 1} \left(\frac{((k+p)^2+\kappa^2)((k-p)^2+\kappa^2)}{4kp\kappa^2} \ln \left(\frac{(k+p)^2+\kappa^2}{(k-p)^2+\kappa^2} \right) - \frac{(k^2-p^2)^2}{4kp\kappa^2} \ln \left(\frac{(k+p)^2}{(k-p)^2} \right) - 1 \right)$$

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

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

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

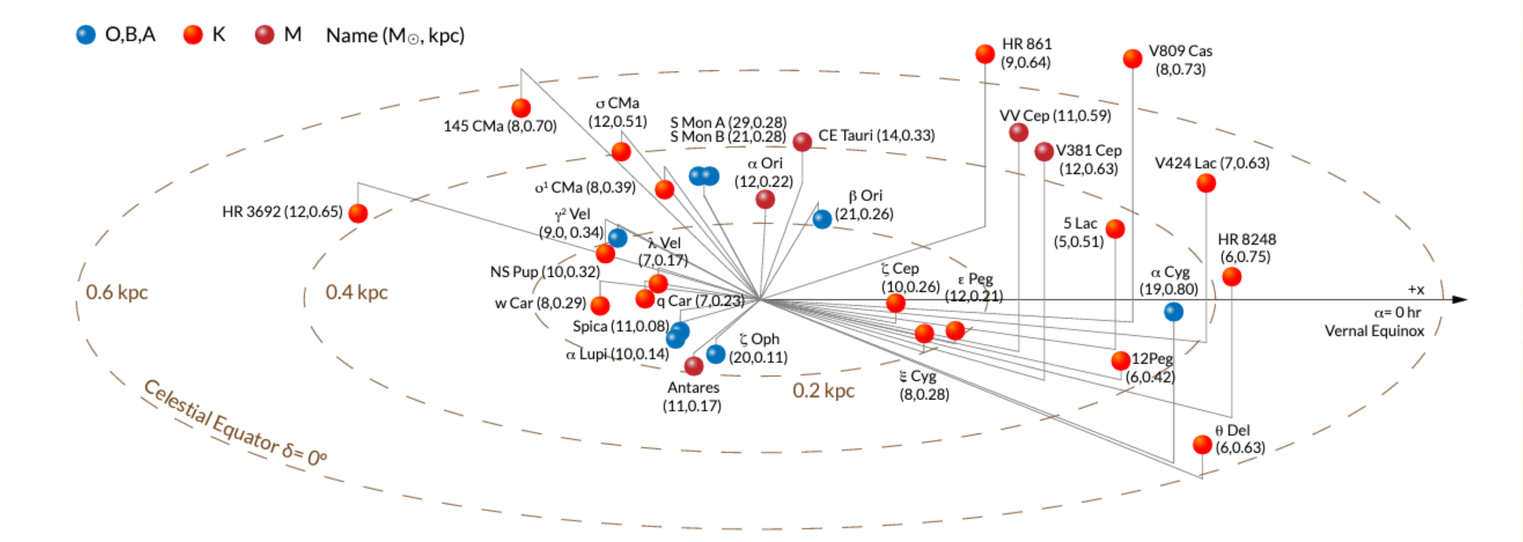
Supernova Progenitors



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

→ γ -ray may be observable

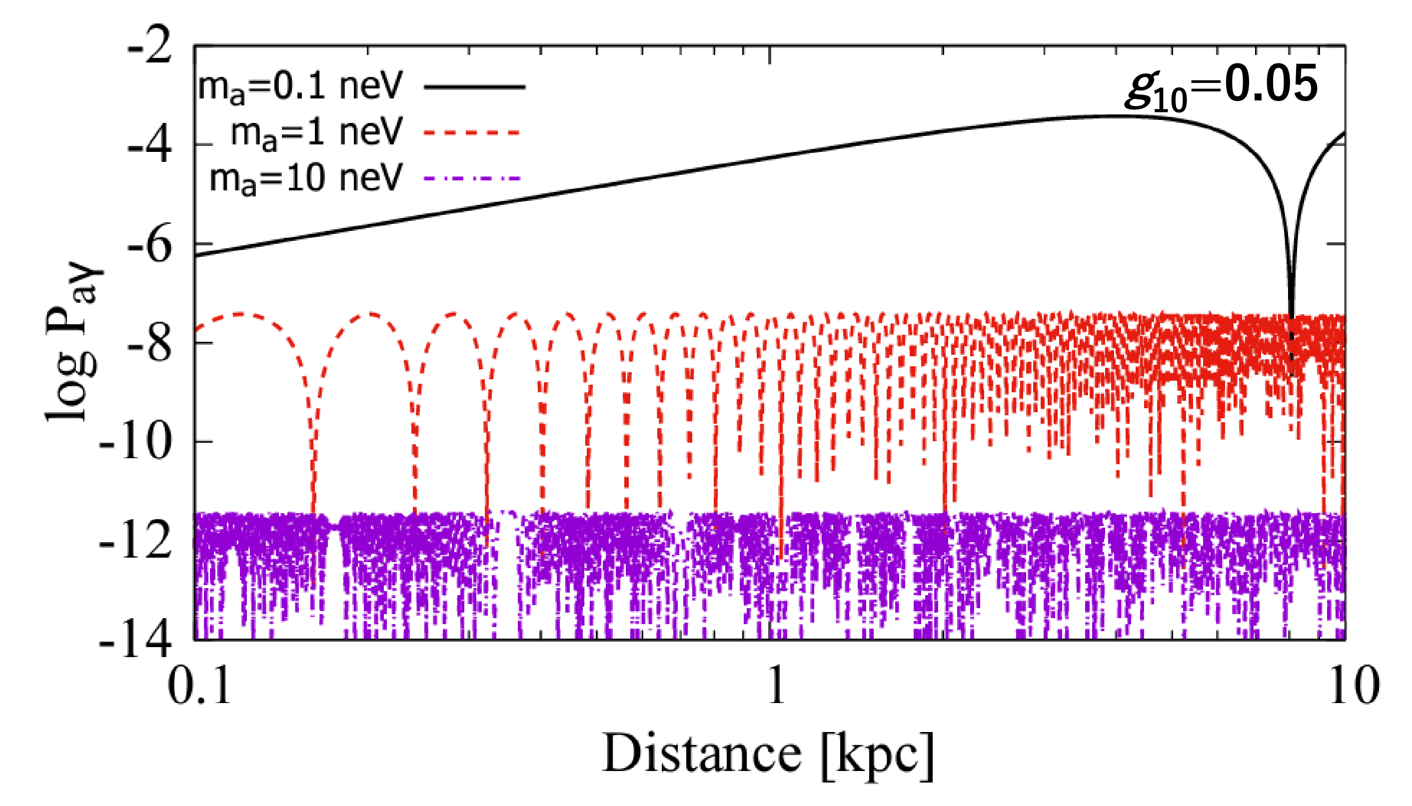
$$P_{a\gamma} = (\Delta_{a\gamma} d)^2 \frac{\sin^2\left(\frac{\Delta_{\rm osc} d}{2}\right)}{\left(\frac{\Delta_{\rm osc} d}{2}\right)^2}$$

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

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

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

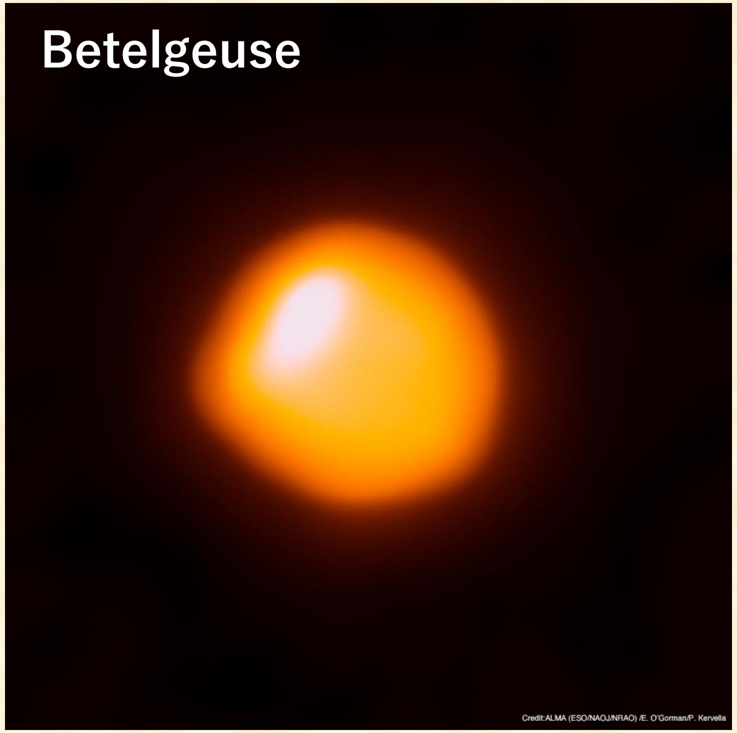
a-γ conversion prob. with B=1 μG

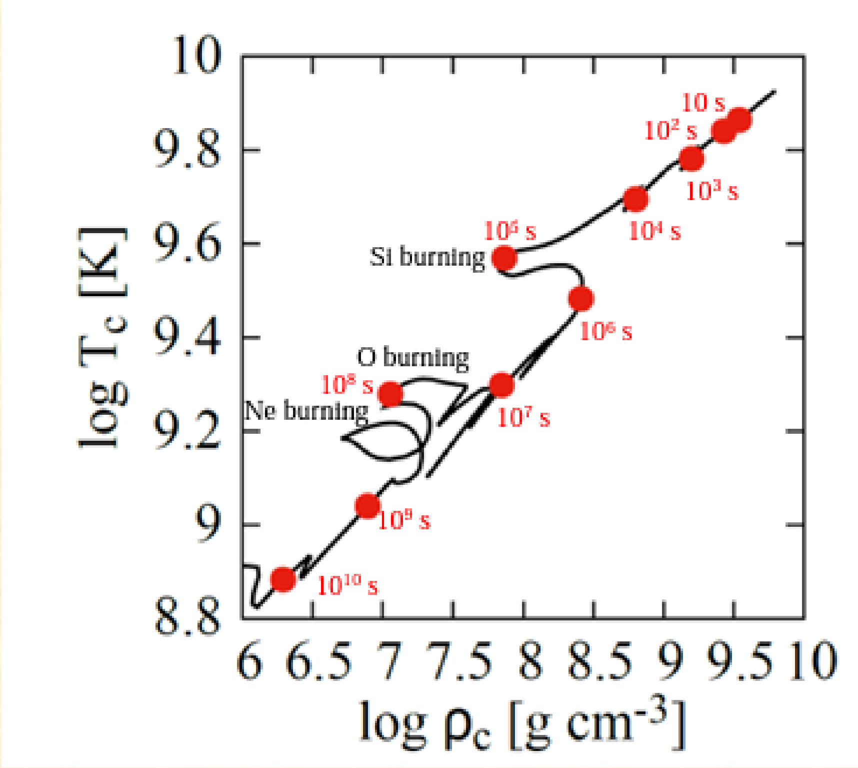


Stellar Model

[Joyce et al. ApJ 902 (2020) 63.]

- We adopt parameters for Betelgeuse as a benchmark
- MESA [Paxton et al. ApJS]
- $M = 20\,M_\odot$
- $d = 168^{+27}_{-15}$ pc
- $B = 1\ \mu$G



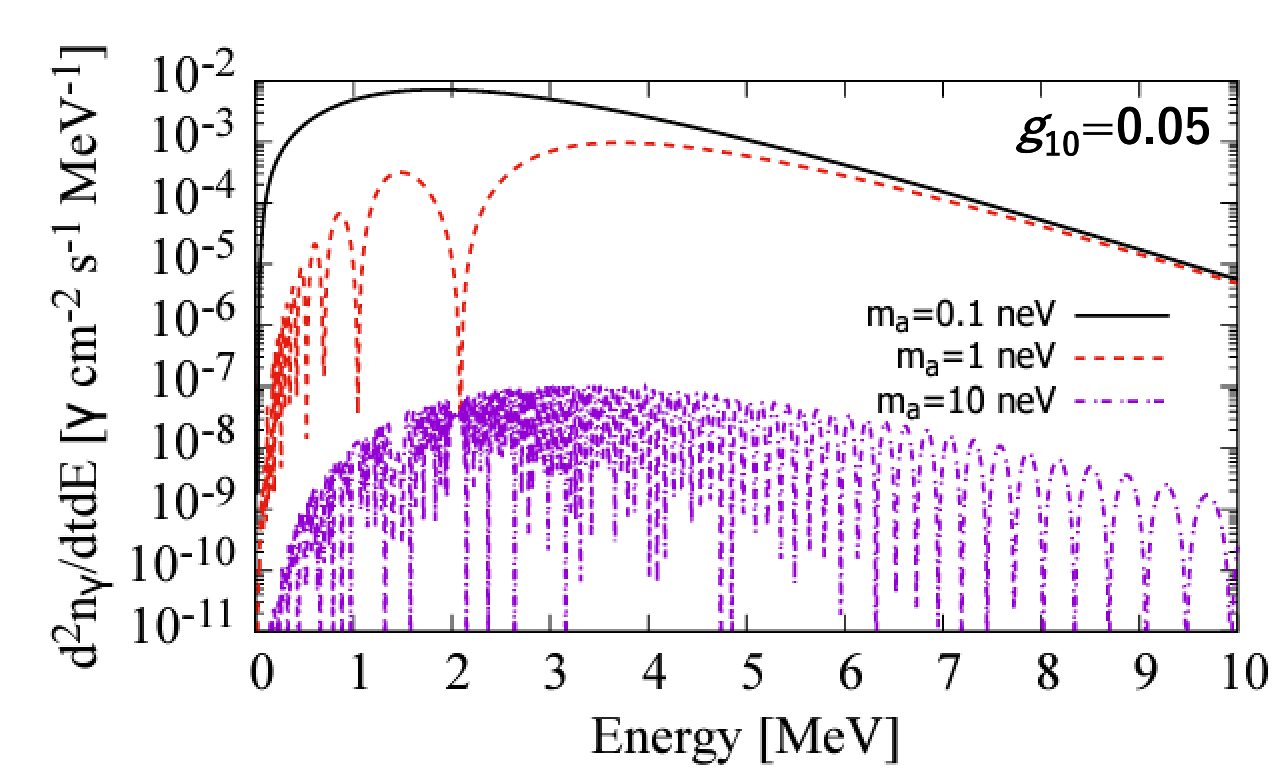


γ-ray Spectrum

- $20M_\odot$ 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 $P_{a\gamma}$

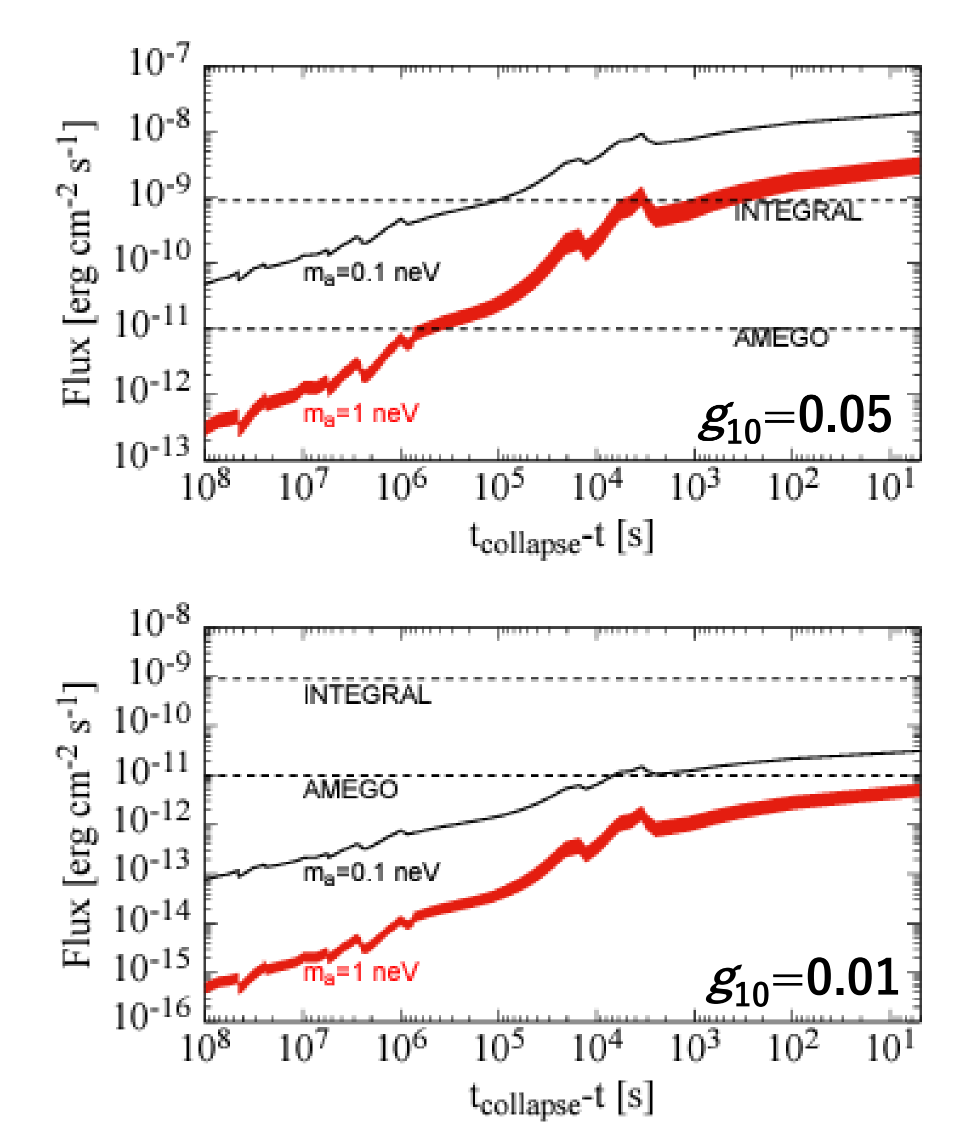


$$\frac{d^2n_\gamma}{dtdE} = \frac{1}{4\pi d^2} 4\pi P_{a\gamma} \int_0^R \frac{d^2n_a}{dtdE} r^2 dr$$

γ-ray Flux and its Observability

- γ -ray flux increases as a function of time
- γ -ray may be observable

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



Summary

- We calculated ALP emission from an SN progenitor
- γ-ray from a nearby star (e.g. Betelgeuse) may be observable by MeV γ-ray telescopes
- γ-ray observations following pre-SN neutrino alarms may provide an independent constraint on ultralight ALPs