Probing Heavy Axion-Like Particles from Massive Stars with X-rays and Gamma rays

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based on

[1] arXiv: 2412.21163 with James Buckley, Francesc Ferrer and Takuya Okawa

[2] *In preparation* with Chris Cappiello, Takuya Okawa and Soebur Razzaque

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ALP Motivation

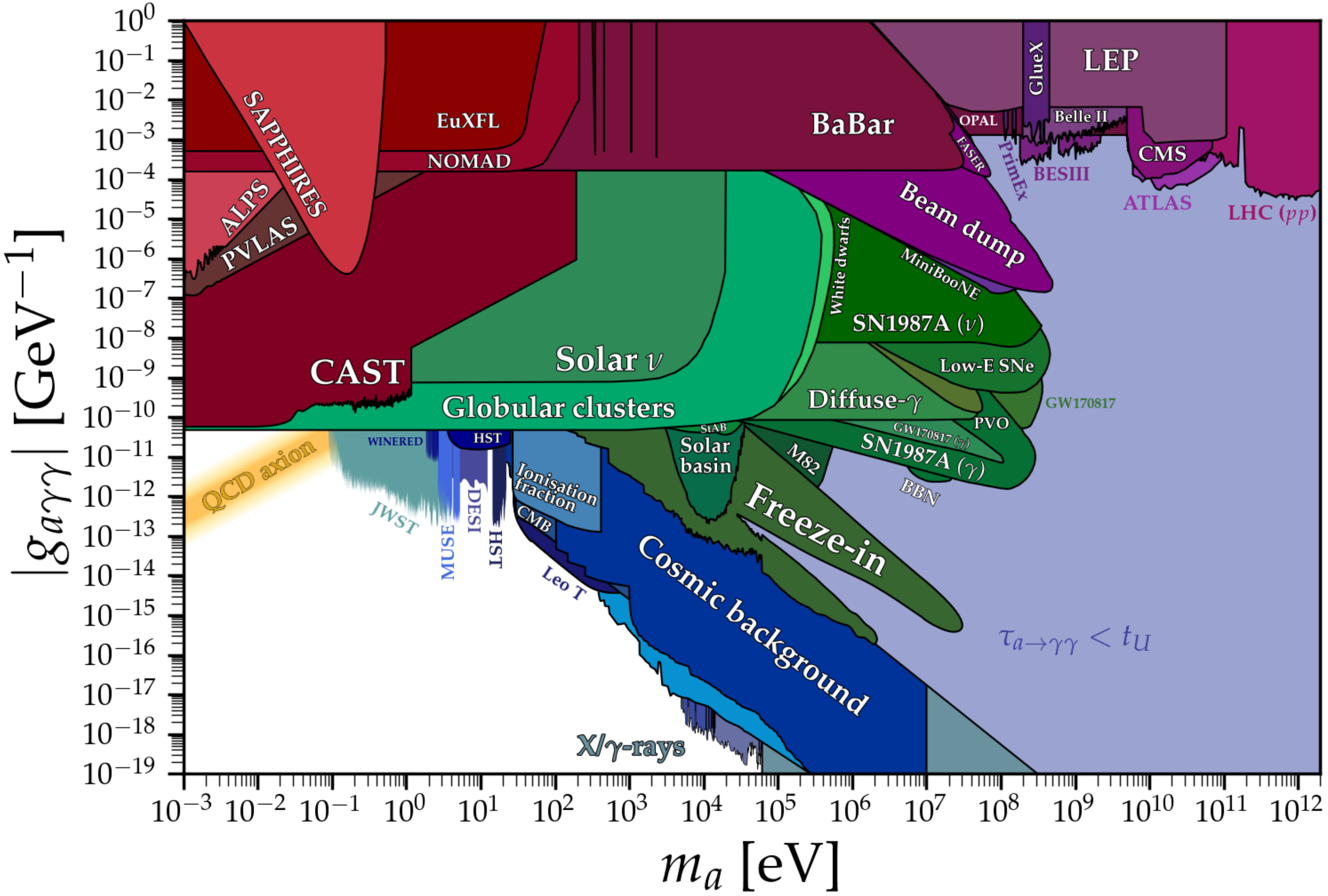
- Axions were originally proposed to solve the strong CP problem. [Peccei, Quinn (PRL '77); Weinberg (PRL '78); Wilczek (PRL '78)]
- Axion-like particles (ALPs) are ubiquitous in many BSM constructions.
- String theory provides a strong motivation. [Svrcek, Witten (hep-th/0605206); Arvanitaki, Dimopoulos, Dubovsky, Kaloper, March-Russell (0905.4720)]
- In this talk, we only focus on ALP couplings to photons: $\mathscr{L}_{a\gamma} = -\frac{g_{a\gamma}}{4} a F_{\mu\nu} \widetilde{F}^{\mu\nu}$
- Consider heavy ALPs in the keV-MeV range. Not a dark matter candidate.

$$\tau_a = \frac{64\pi}{g_{a\gamma}^2 m_a^3} \simeq 10^{17}\ \mathrm{s} \left(\frac{10^{-12}\ \mathrm{GeV}^{-1}}{g_{a\gamma}}\right)^2 \left(\frac{10\ \mathrm{keV}}{m_a}\right)^3$$

- Astrophysical environments provide an ideal testing ground. [Raffelt (Phys. Rep. '90)]

Current Status

https://cajohare.github.io/AxionLimits/docs/ap.html



Stellar Plasma as ALP Laboratory

Main sequence stars (e.g. Sun)

$R \sim 1R_\odot,\ T_{\rm core} \sim \mathcal{O}(\text{keV})$

[Nguyen, Tanin, Kamionkowski, 2307.11216]

Red giants, horizontal branch stars

$R \sim \mathcal{O}(10^{2-3}\ R_\odot),\ T_{\rm core} \sim \mathcal{O}(10\ \text{keV})$

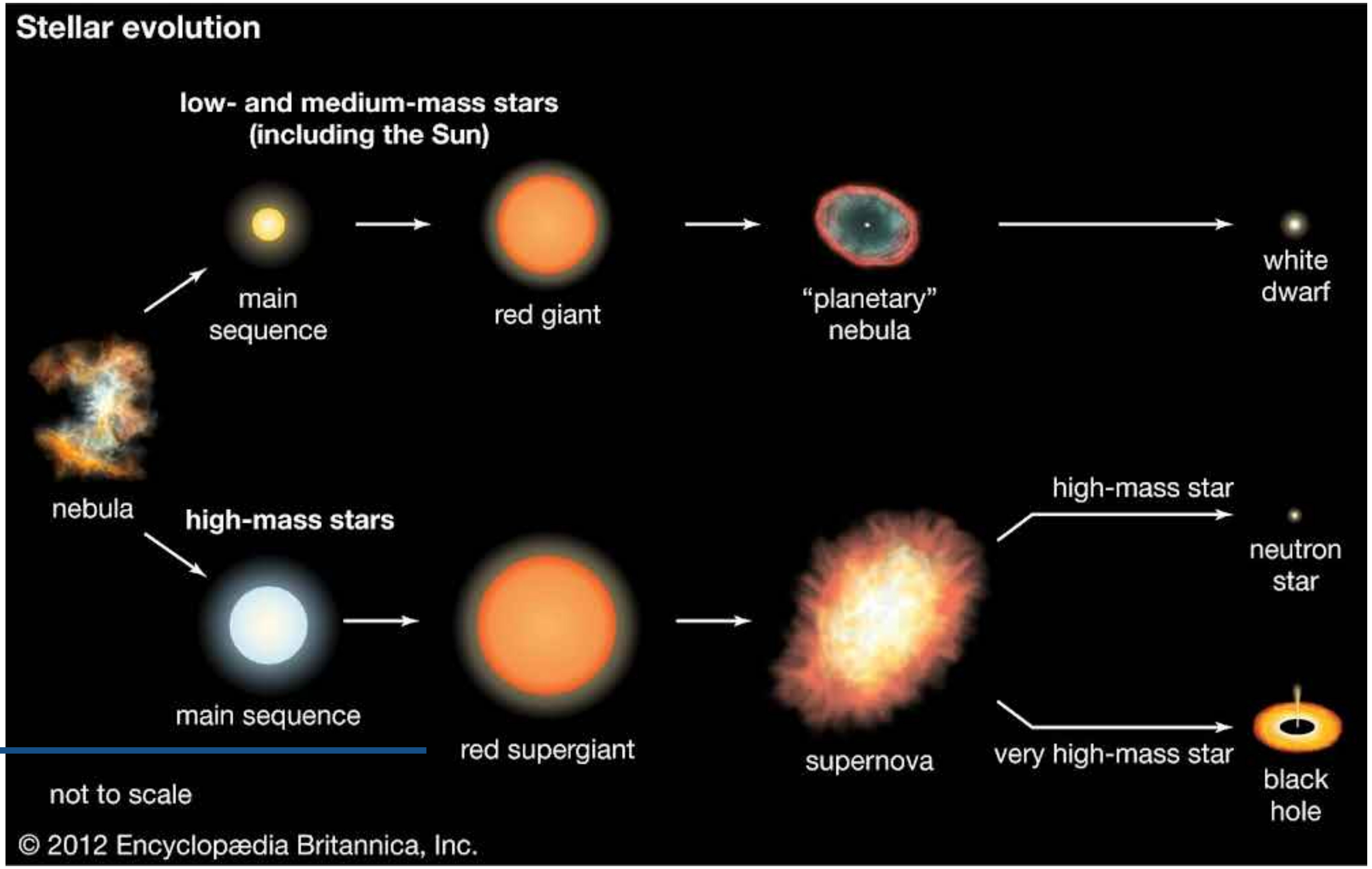
[Capozzi, Raffelt, 2007.03694]

White dwarfs

$R \sim \mathcal{O}(10^{3-4}\ \text{km})$

$T_{\rm core} \lesssim \mathcal{O}(\text{keV})$

[Dolan, Hiskens, Volkas, 2102.00379]



Supernovae,

Neutron star mergers

$R \sim \mathcal{O}(10\ \text{km}),$

$T_{\rm core} \sim \mathcal{O}(10\ \text{MeV})$

[Muller et al, 2304.01060; BD et al, 2305.01002; Diamond et al, 2305.10327]

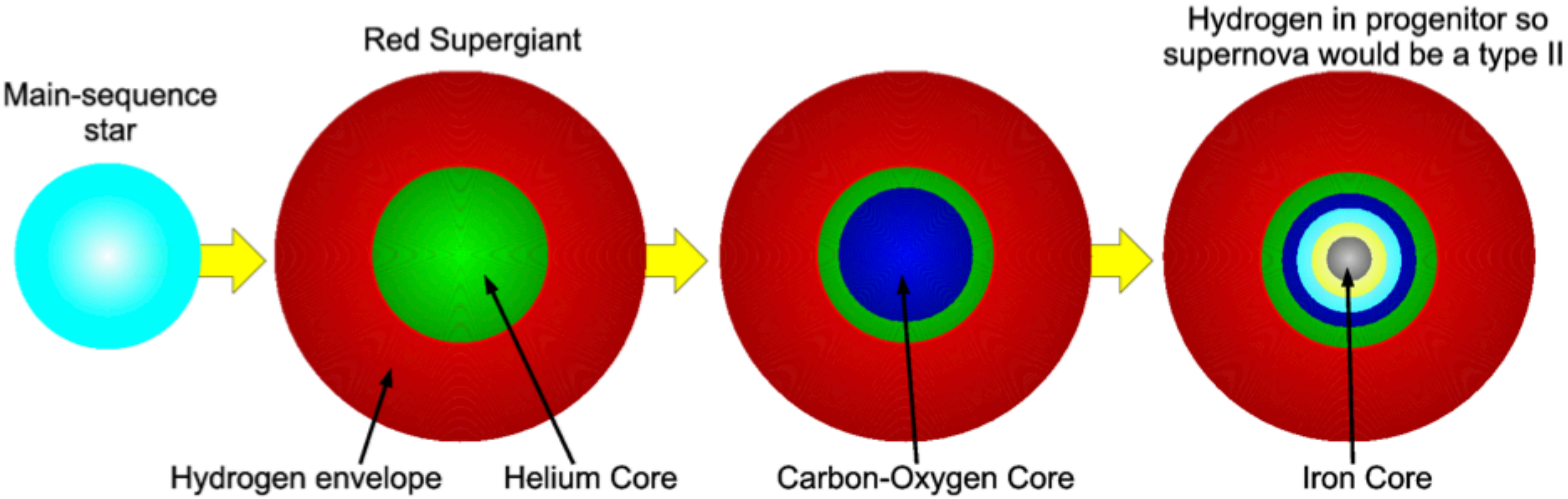
Wolf-Rayet stars

$T_{\rm core} \simeq 20\ \text{keV}, R \sim 1 - 2R_\odot$

(2412.21163, this talk)

Wolf-Rayet Stars

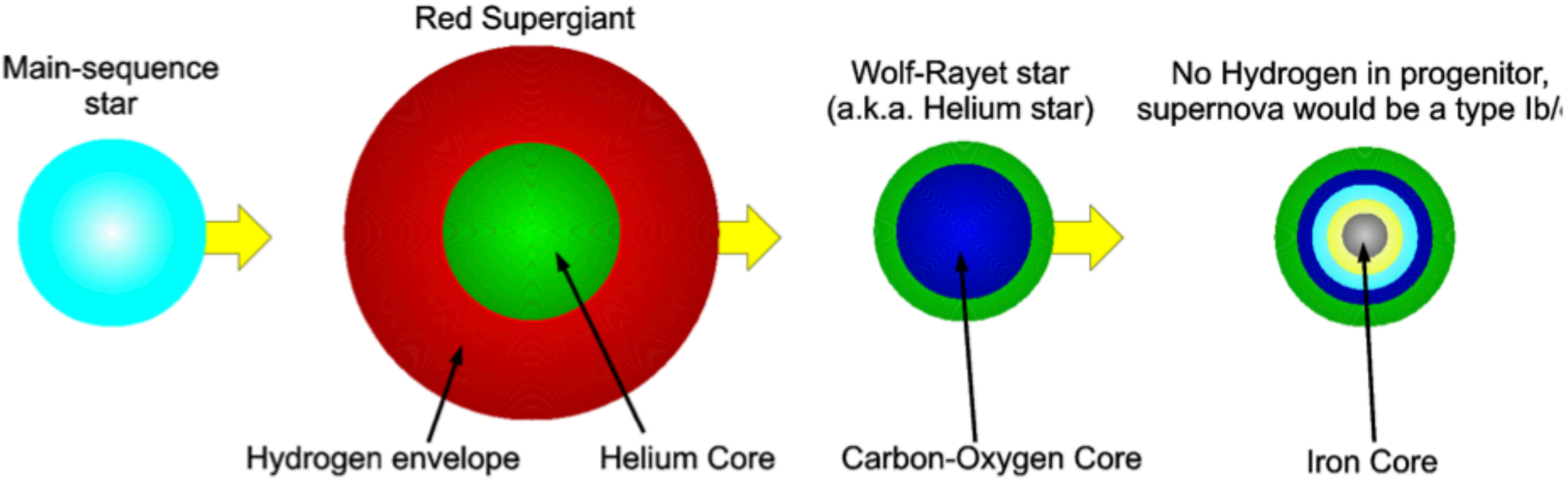
[Eldridge, 0809.1245]



Typical fate of a massive star ($M \gtrsim 8M_\odot$). Ends up as type-II supernova.

Wolf-Rayet Stars

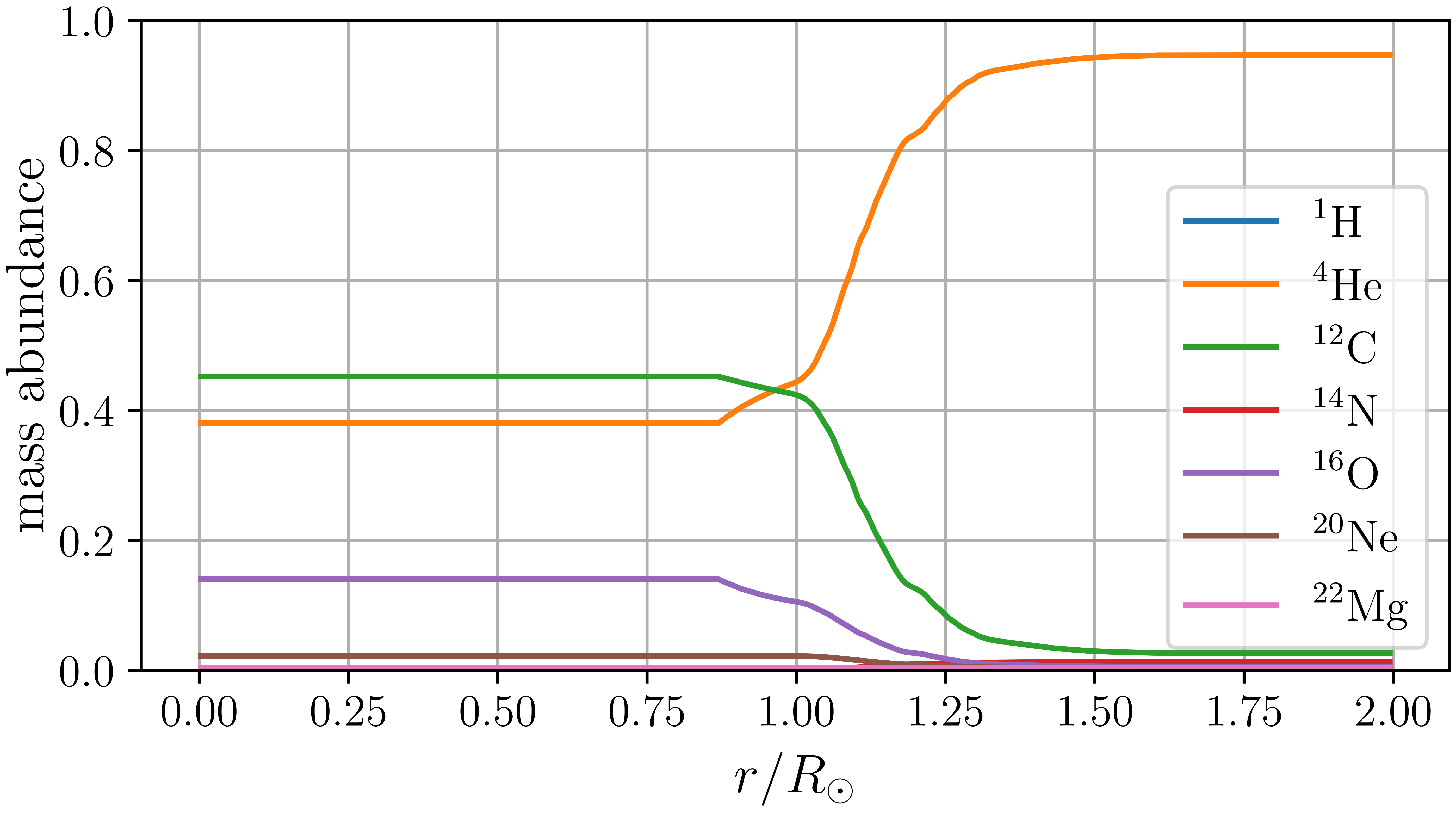
[Eldridge, 0809.1245]



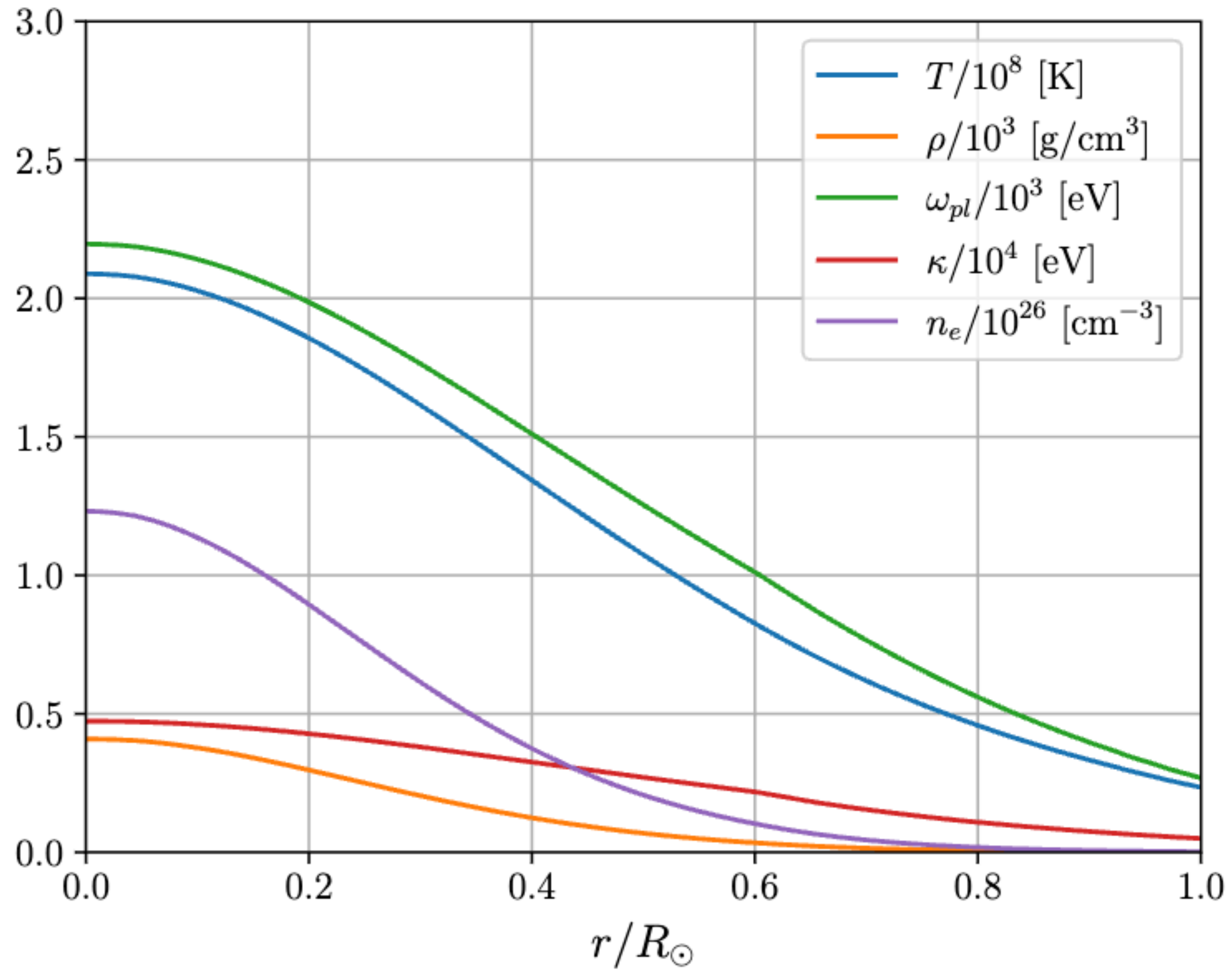
Exception: High-mass stars $> 25 M_\odot$ with large rotational velocity.

Strong stellar wind (or binary interaction) removes the Hydrogen envelope.

Wolf-Rayet Stars



Generated using full stellar evolution implemented in MESA code [1009.1622]

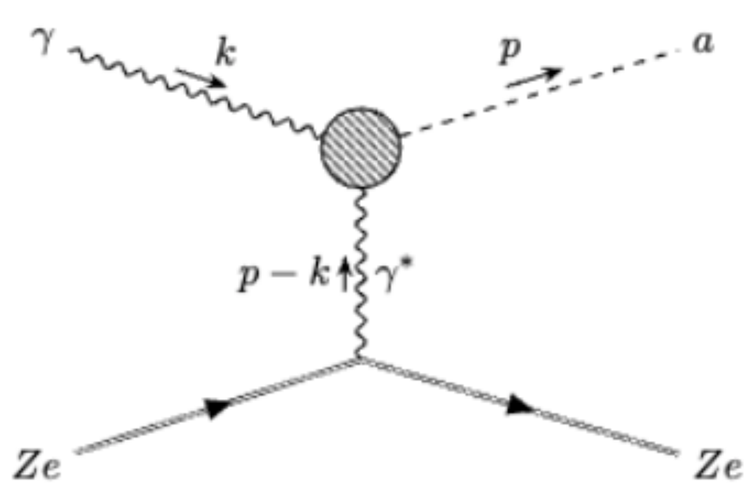


$$T_{\rm core} \simeq 20 \text{ keV}, R \sim 1 - 2R_\odot$$

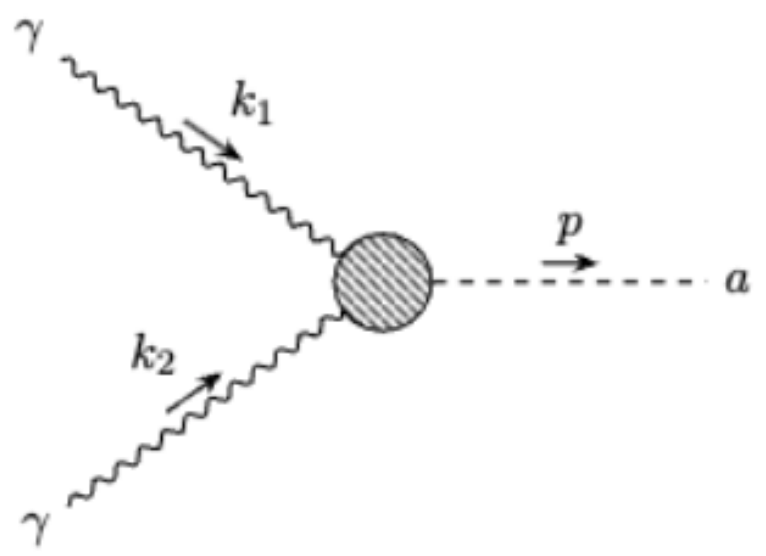
Efficient ALP production and high escape probability

ALP Production in WR Stars

Primakoff process ($\gamma + Ze \to a + Ze$)



Photon coalescence ($2\gamma \to a$)



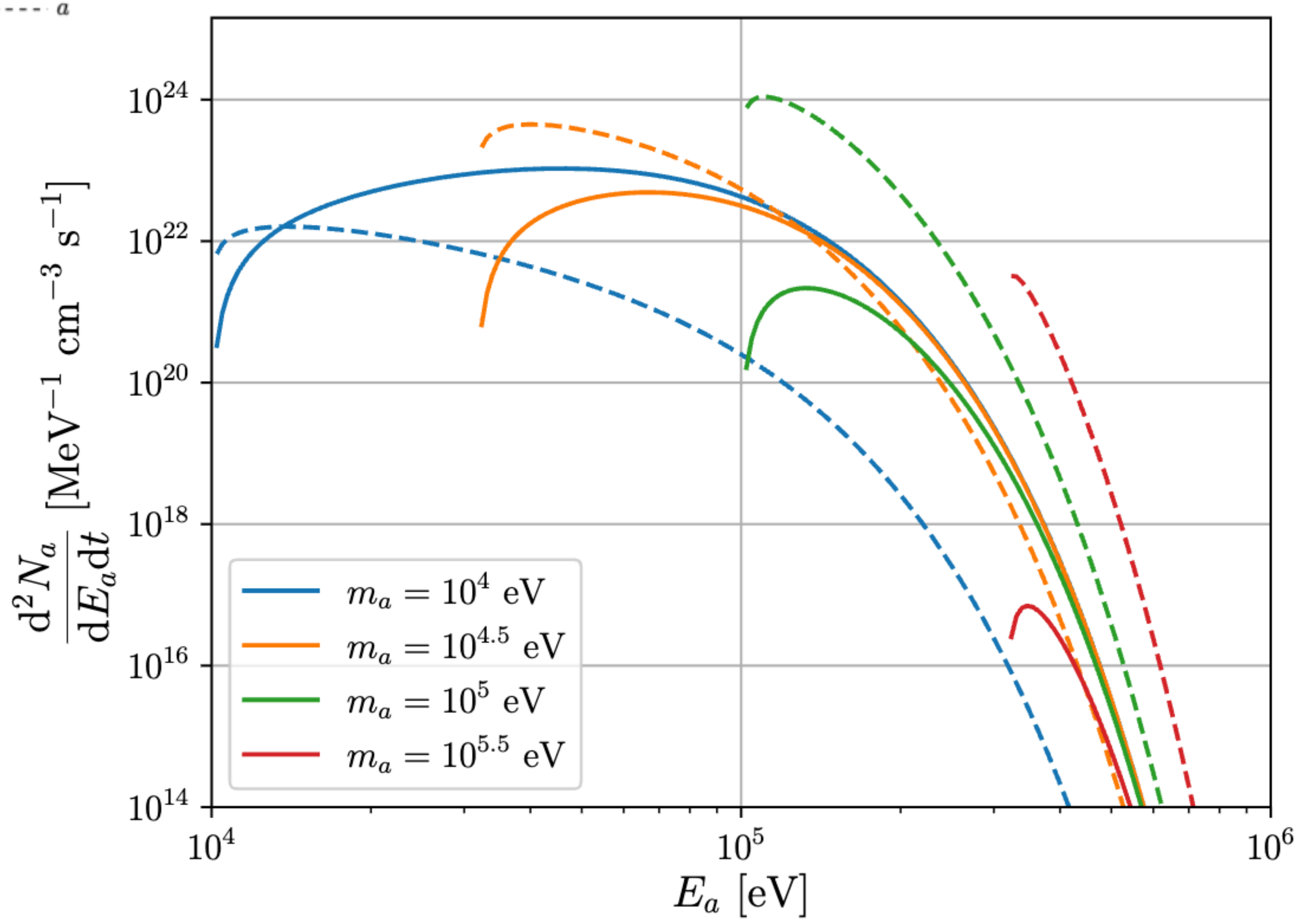
- The ALPs production rate density of each process has different dependence on T, m_a

- Dominant process:

  $m_a \ll T \to$ Primakoff process

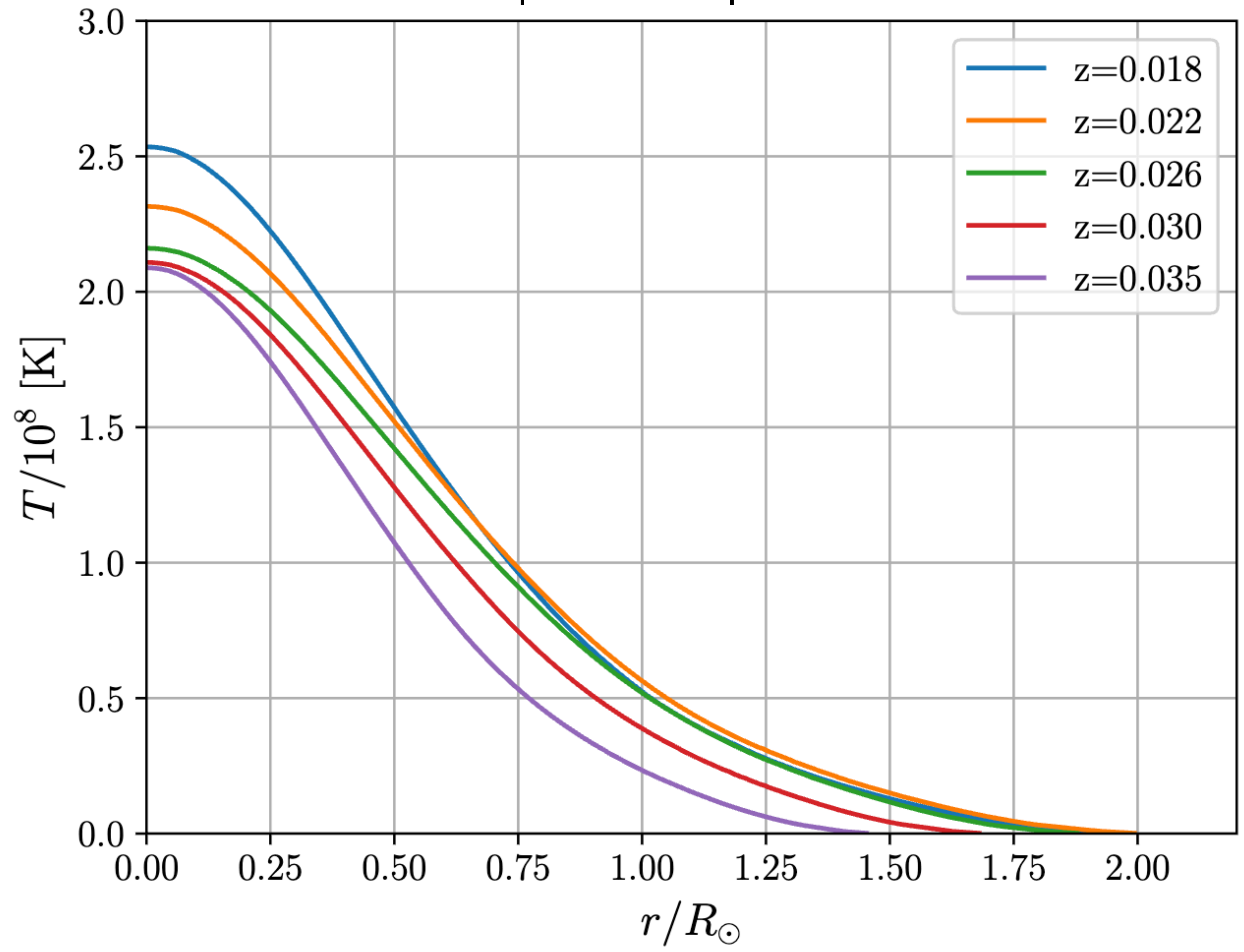
  $m_a \gg T \to$ photon coalescence

Primakoff (solid) coalescence (dashed)



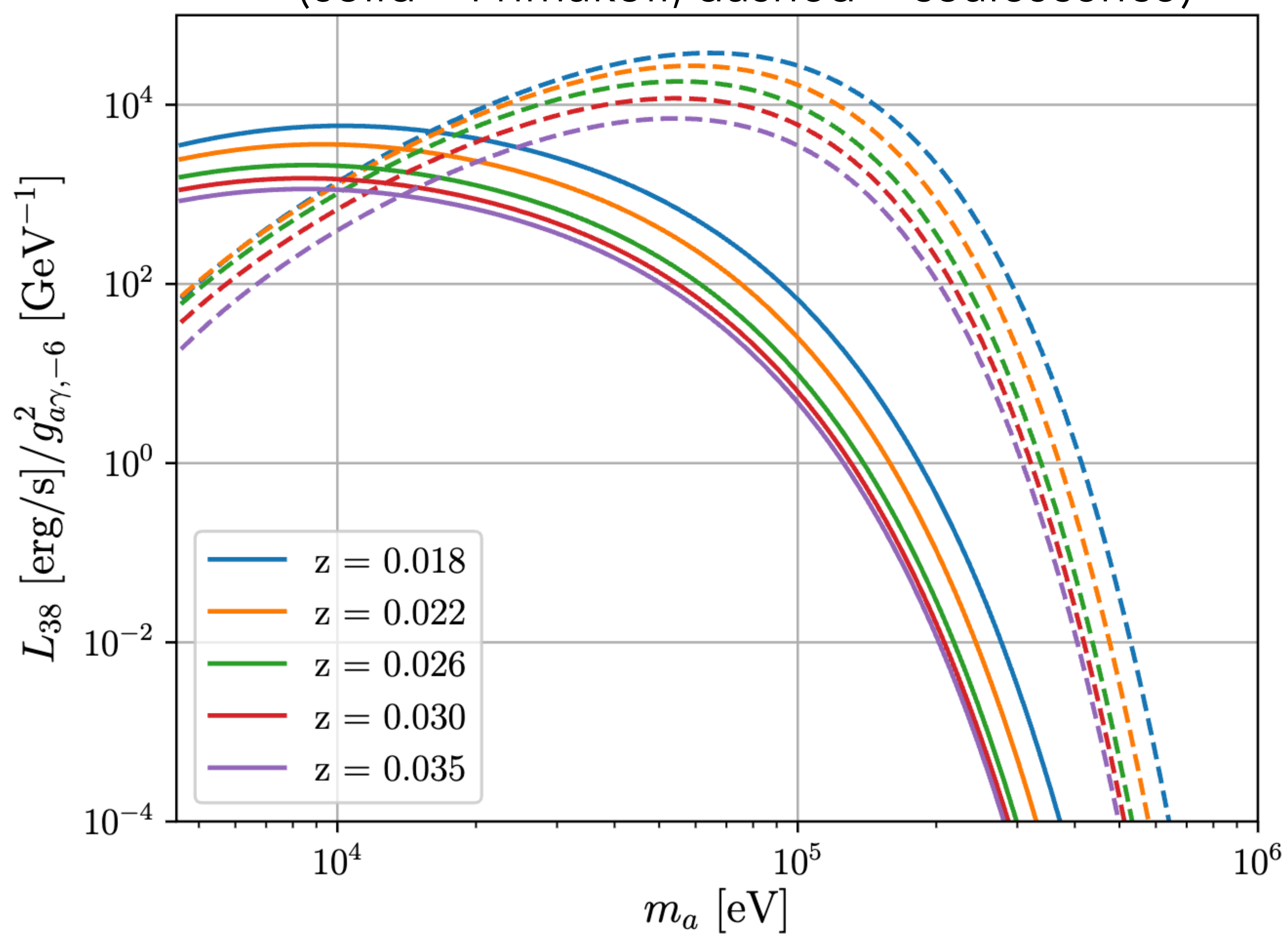
Dependence on Metallicity

Temperature profile



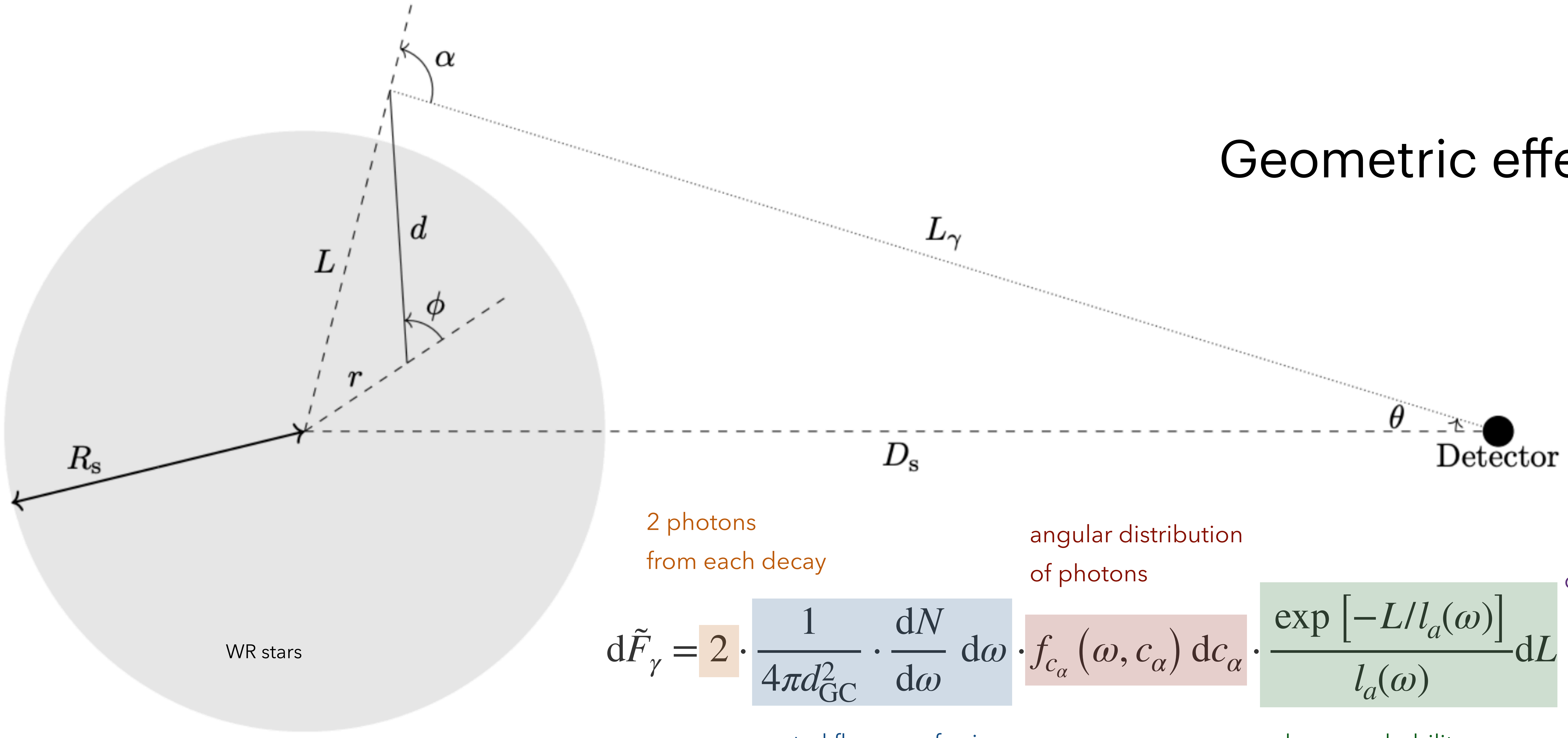
ALP luminosity

(solid – Primakoff, dashed – coalescence)



- Some uncertainty on the exact metallicity of the WR stars, $z \in [0.018, 0.035]$.
- Lower metallicity results in higher plasma temperature, producing more ALPs.

Photon Flux on Earth



Geometric effect included

2 photons from each decay

angular distribution of photons

constraints on ω, c_α, L

$$d\tilde{F}_\gamma = 2 \cdot \frac{1}{4\pi d_{GC}^2} \cdot \frac{dN}{d\omega}\, d\omega \cdot f_{c_\alpha}(\omega, c_\alpha)\, dc_\alpha \cdot \frac{\exp\left[-L/l_a(\omega)\right]}{l_a(\omega)} dL \cdot \Theta_{\text{cons.}}(\omega, c_\alpha, L)$$

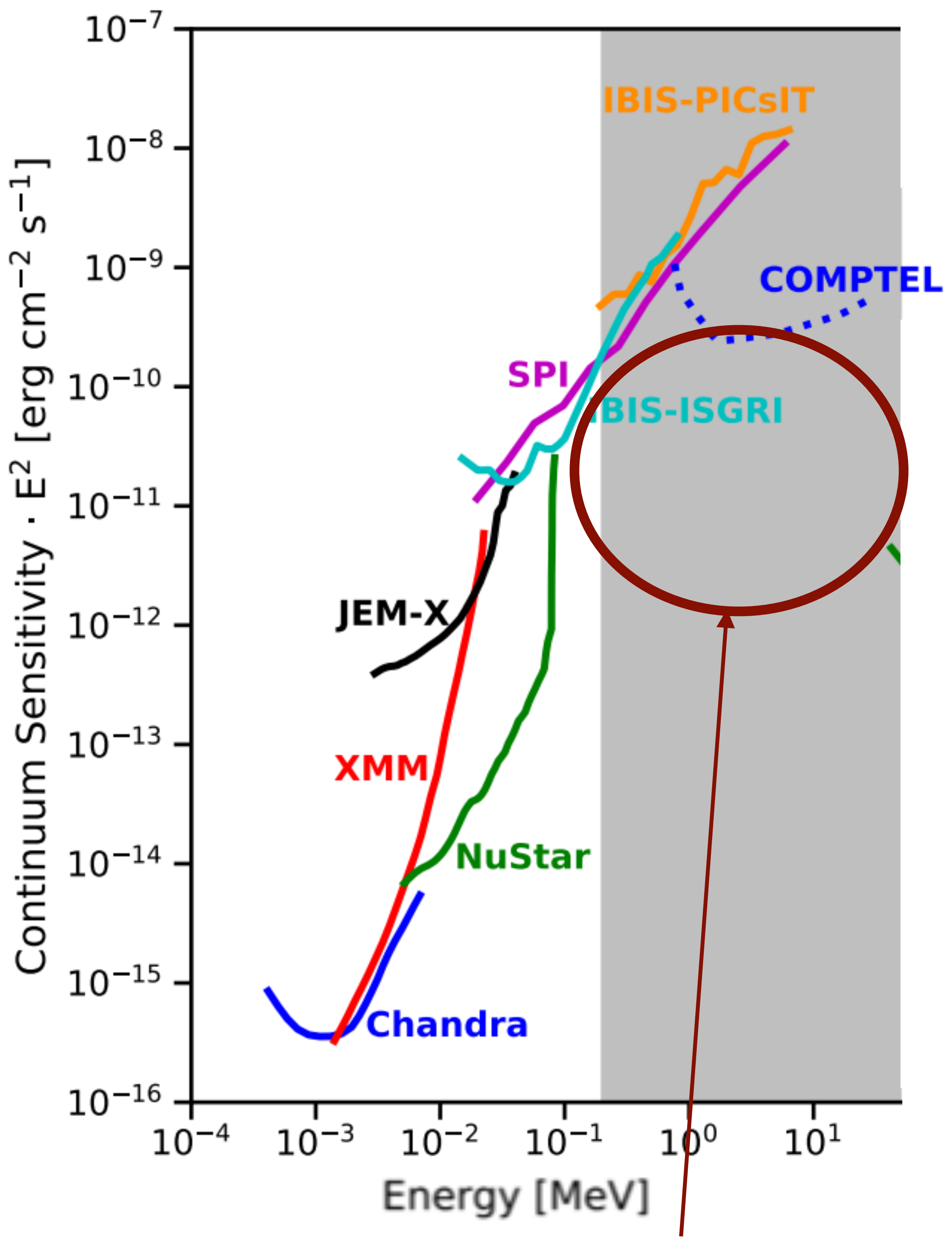
spectral fluence of axions at the earth

decay probability

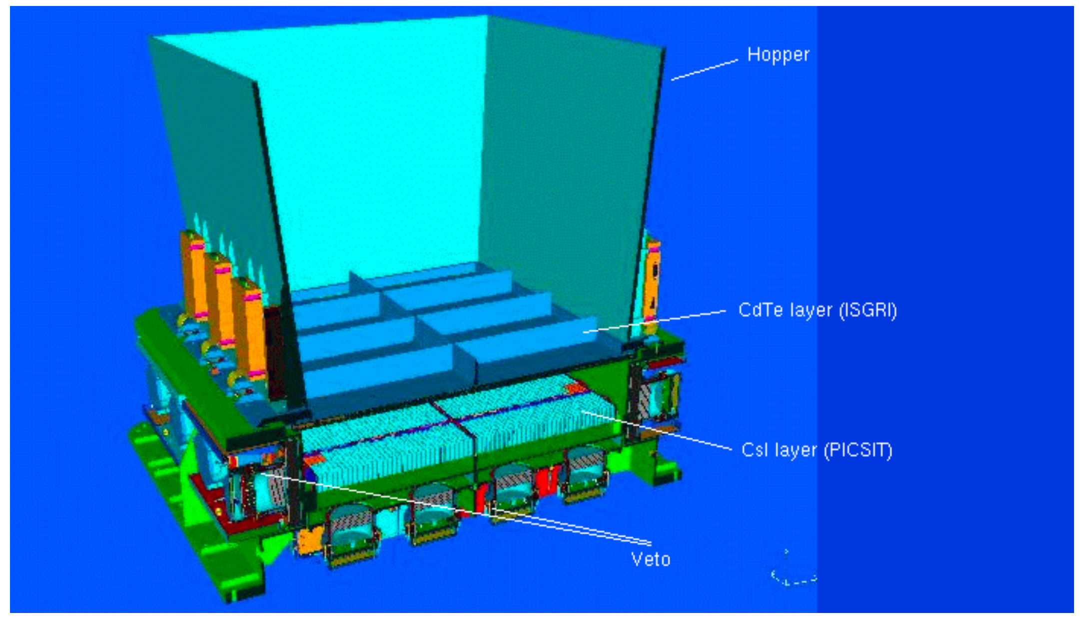
Telescopes Considered

Mission	Sensitivity Range	Angular Resolution (at Energy)	Mission Status	Effective Area	Observation Time
XMM-Newton [89]	0.1-15 keV	$12''$ (2-10 keV)	1999-present	~ 3000 cm^2	10^4 s
NuSTAR [90]	5 keV - 80 keV	$18''$	2012-present	~ 1000 cm^2	10^6 s
INTEGRAL IBIS/ISGRI [91]	15 keV - 1 MeV	$12'$	2002-2023	250 cm^2	10^5 s
INTEGRAL IBIS/PICsIT [92]	170 keV - 10 MeV	$12'$	2002-2023	~ 1400 cm^2	10^5 s
INTEGRAL SPI [93]	20 keV - 8 MeV	$2.5°$	2002-2023	~ 3000 cm^2	10^6 s
INTEGRAL JEM-X [94]	3 keV - 35 keV	$3'$	2002-2023	400 cm^2	10^6 s
SWIFT (BAT) [95]	15-150 keV	$22'$	2004-present	5200 cm^2 (15 keV)	0.7×19 yrs
eROSITA [96]	0.2-10 keV	$35''$ (2-8 keV)	2019-present	1500 cm^2	10^5 s
Insight-HXMT/HE [97]	20 keV - 250 keV	$6'$	2017-present	4096 cm^2	$\sim 10^5$ s
COSI [98]	200 keV - 5 MeV	$\sim 4°$ (1 MeV)	2027 (planned)	$\sim$ 300 cm^2	2 yrs
AMEGO (Compton) [99]	200 keV - 10 MeV	$\sim 4°$ (1 MeV)	Concept	~ 300 cm^2	$0.24\times$ 5 yrs
AMEGO-X [100]	100 keV - 1 GeV	$\sim 10°$	Concept	3500 cm^2	3 yrs
APT (Compton) [101]	200 keV - 10 MeV	$\sim 5°$ (1 MeV)	Concept	10,000 cm^2	$0.82\times$ 5 yrs
ASTROGAM [102]	100 keV - 1 GeV	$\sim 1.5°$	Concept	1000 cm^2	1 yr
e-ASTROGAM [103]	300 keV - 3 GeV	$\sim 2°$	Concept	9025 cm^2	1 yr
GECCO [104]	100 keV - 10 MeV	$2°$	Concept	2000 cm^2	10^6 s

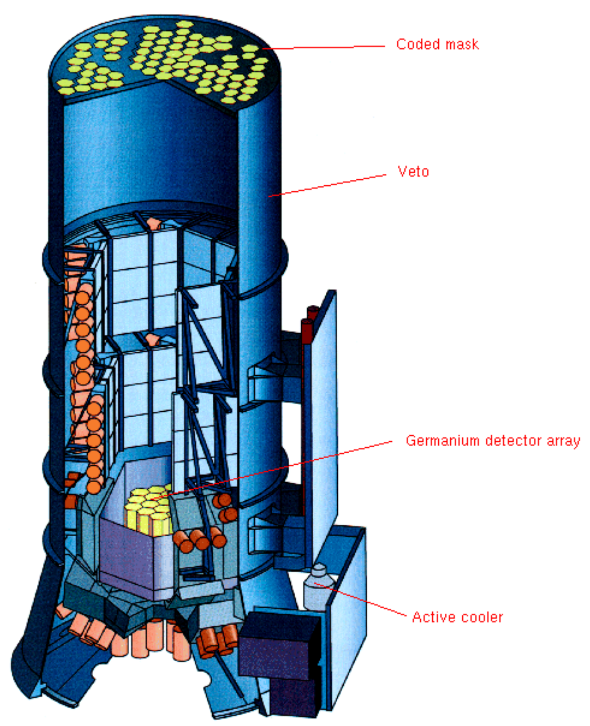
G. Lucchetta et al. 2204.01325



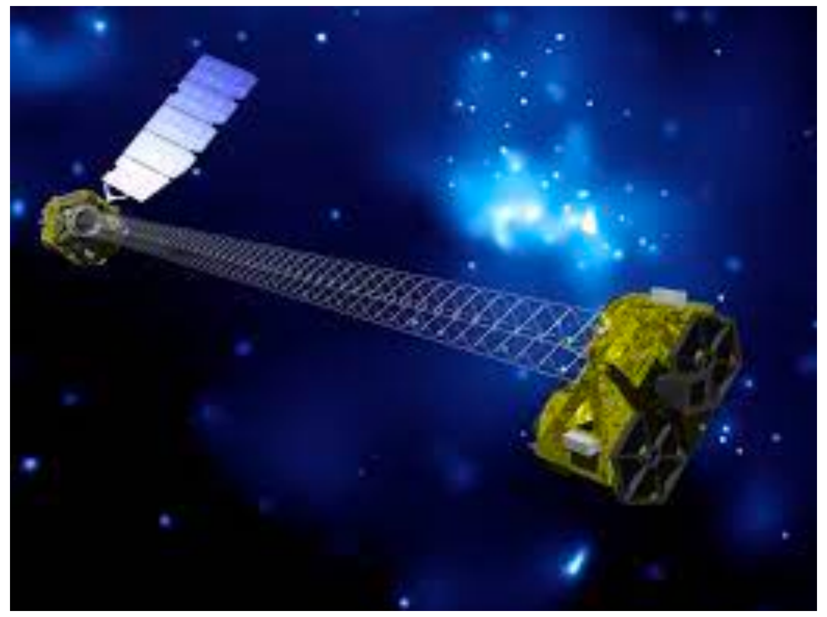
IBIS-ISGRI
IBIS-PICsIT



SPI



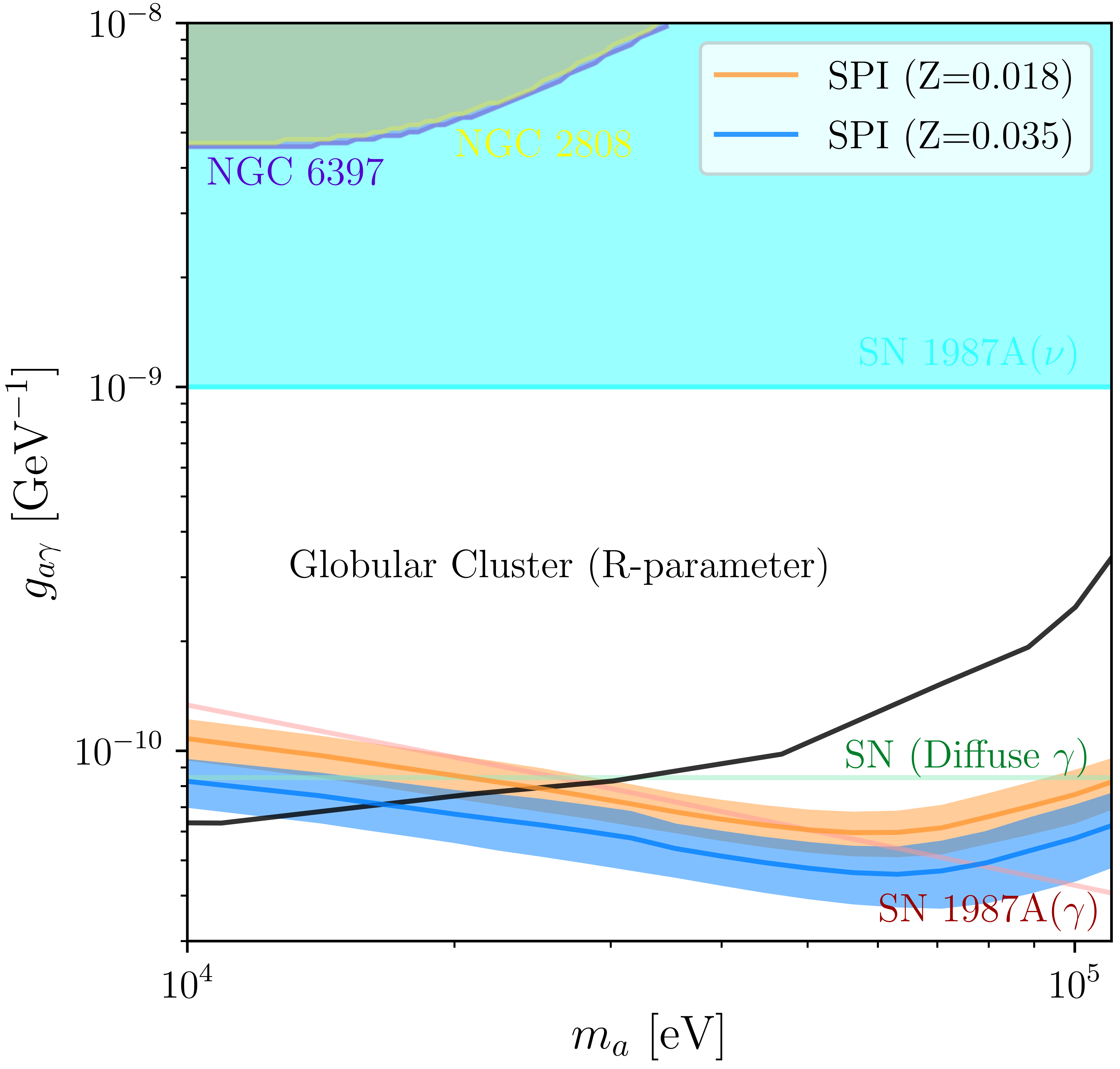
NuSTAR



Best limit obtained from INTEGRAL-SPI

Future telescopes:
- ASTROGAM — A. De Angelis et al. 2102.02460
- AMEGO-X — R. Caputo et al. 1907.07558
- GECCO — E Orlando et al.2112.07190

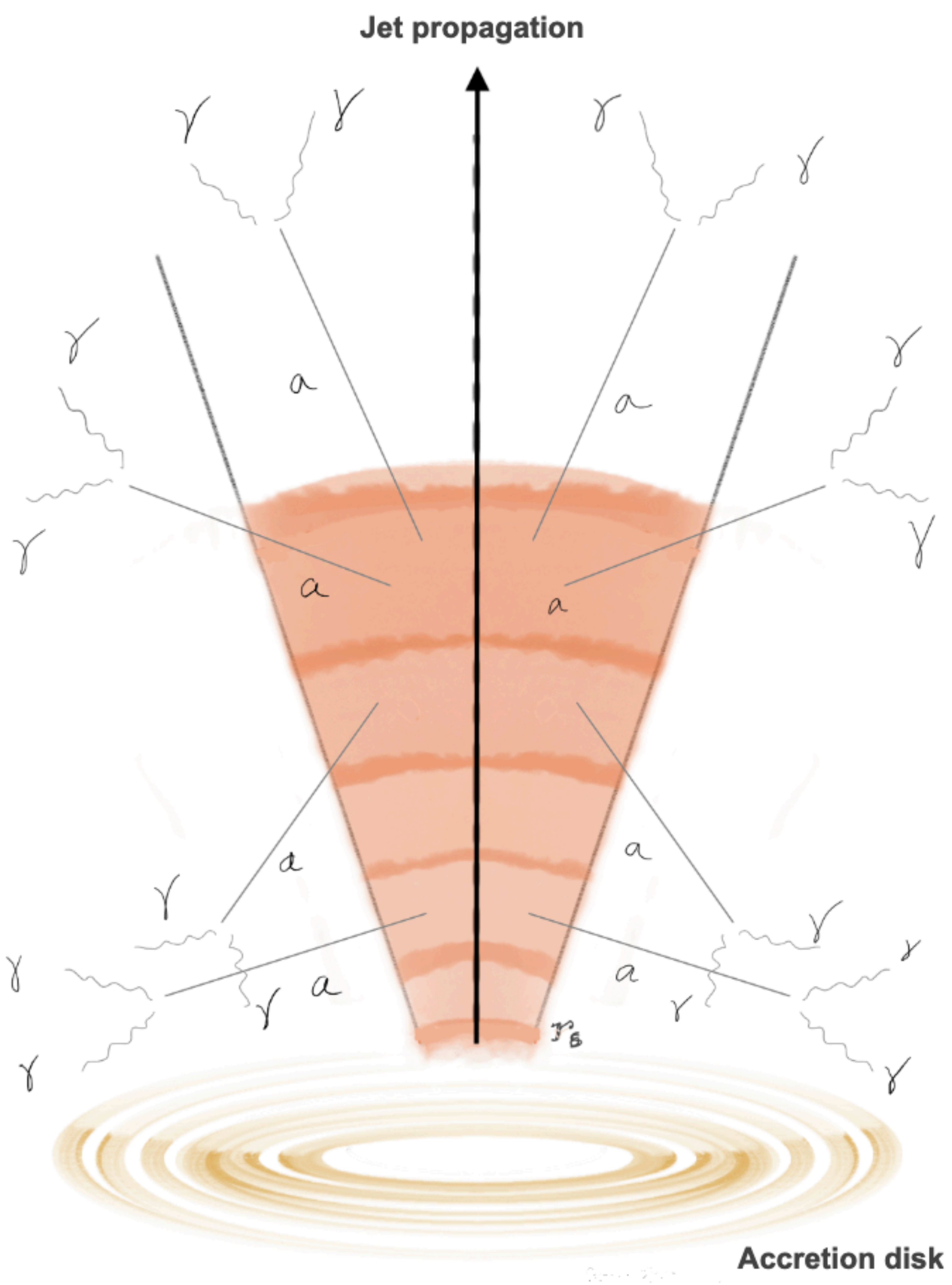
Results for WR Star Analysis

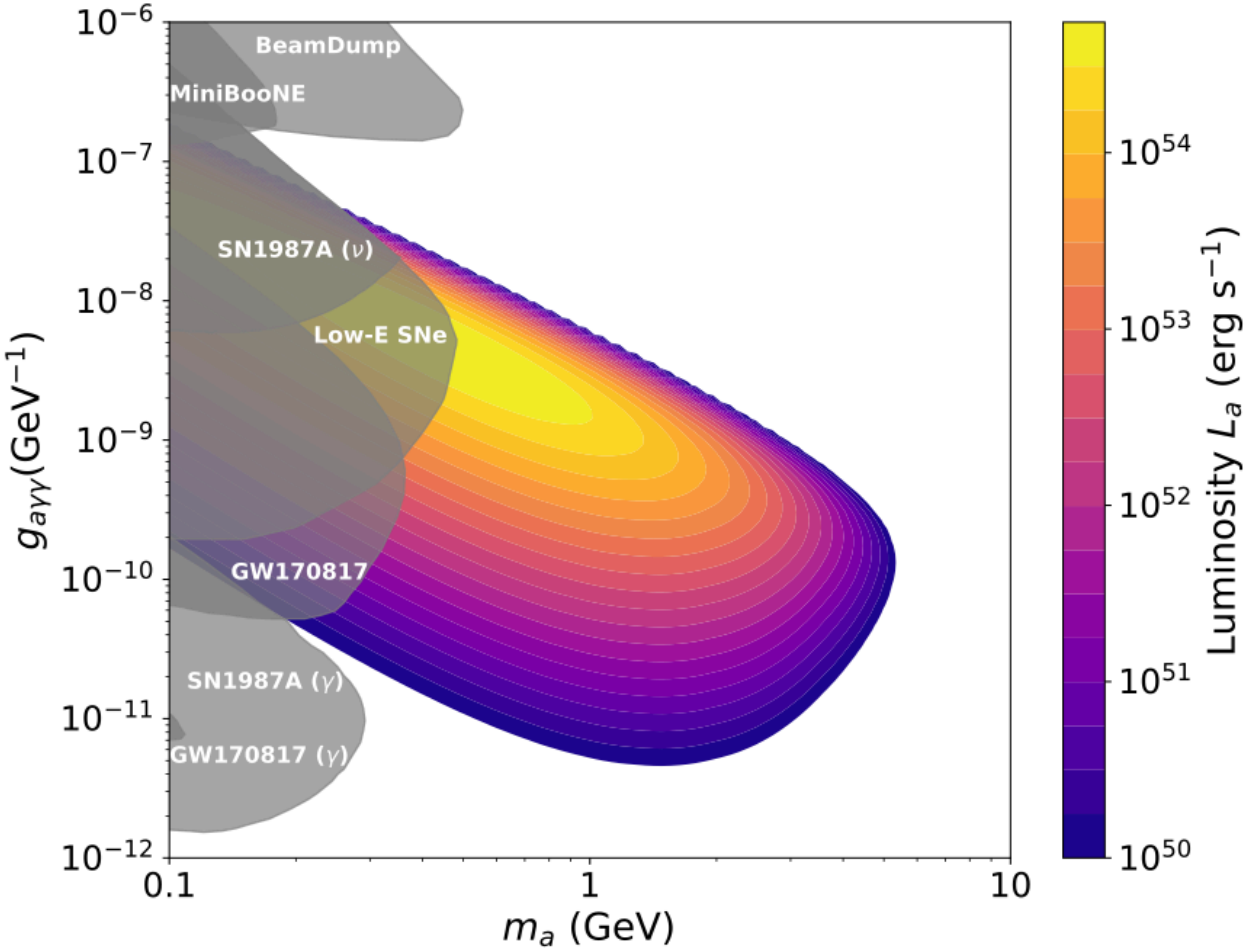


- Used super star cluster Quintuplet located near the galactic center, which hosts 71 massive stars.
- 13 (WC)+1 (WN) are in the WR phase.
- Stellar evolution parameters taken from a previous study. [Dessert, Foster, Safdi, 2008.03305]
- INTEGRAL-SPI gives the best limit in the parameter space of interest.
- New NuSTAR bound from starburst galaxy M82. [Candon, Fiorillo, Lucente, Vitagliano, Vogel, 2412.03660]

ALPs from GRB Fireball

Ghosh, Jacobsen, Linden, 2501.08978





Fireball ALP-induced Diffuse Gamma-ray Bkg

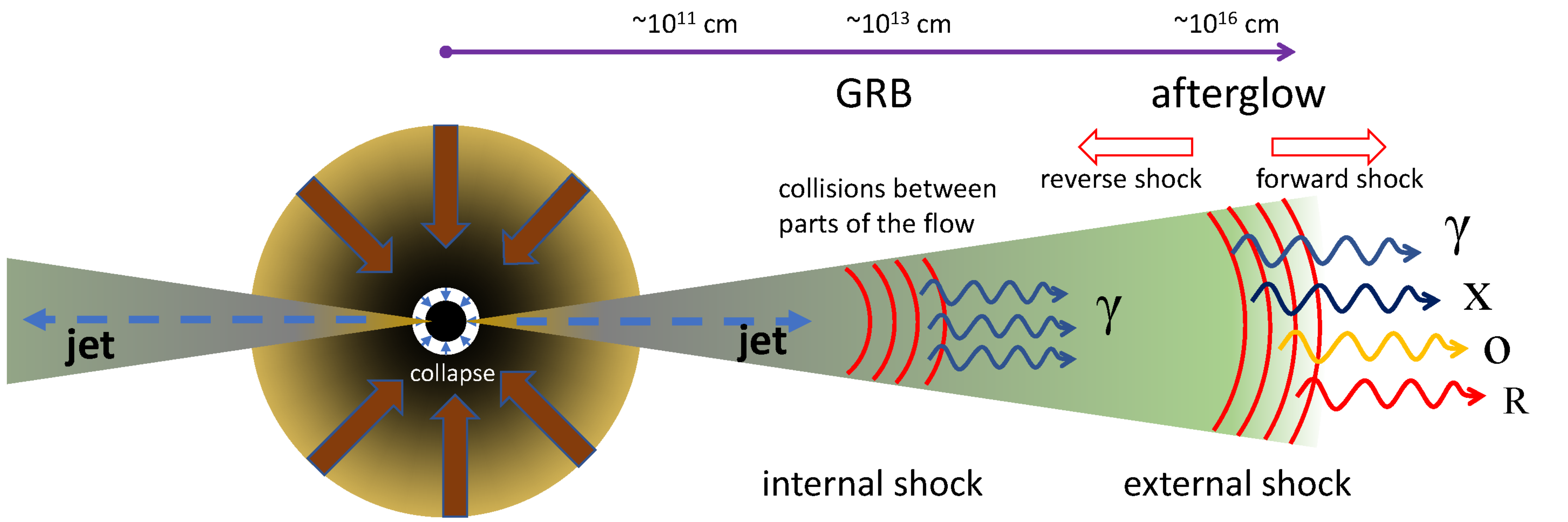


Image credit: S. Dado et al., Universe 2022, 8(7), 350

- The innermost (radiation-dominated) region follows

$$T(r) = T_i \frac{r_i}{r}, \qquad \gamma(r) = \frac{r}{r_i}$$

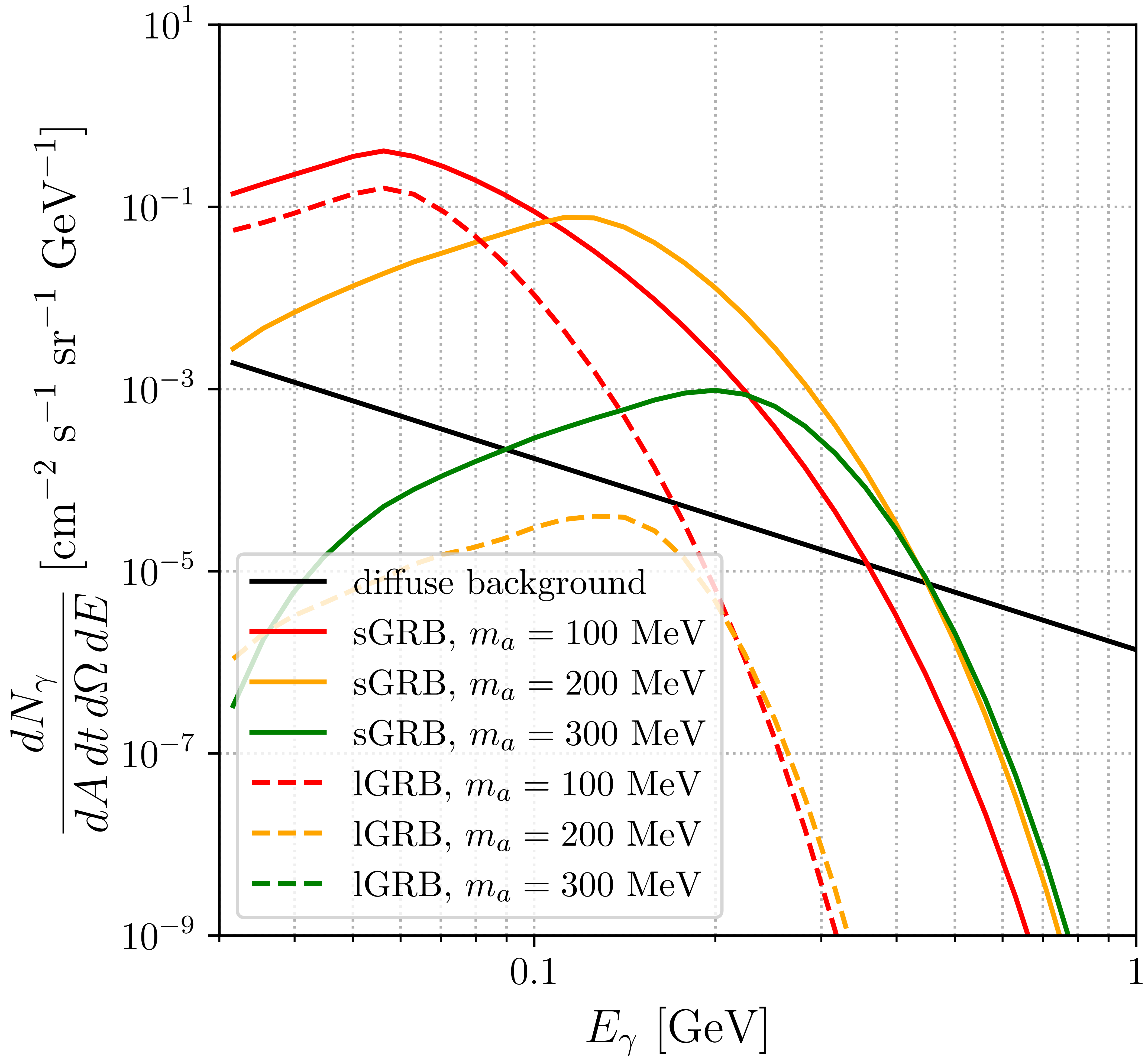
- Launched at $r_i \approx (2-3) \times r_s$ where $T_i \approx \mathcal{O}(10\ \mathrm{MeV})$
- Extended to $r_m \approx 10^{7-9}$ cm

Integrate over a fireball volume — energy loss per unit volume

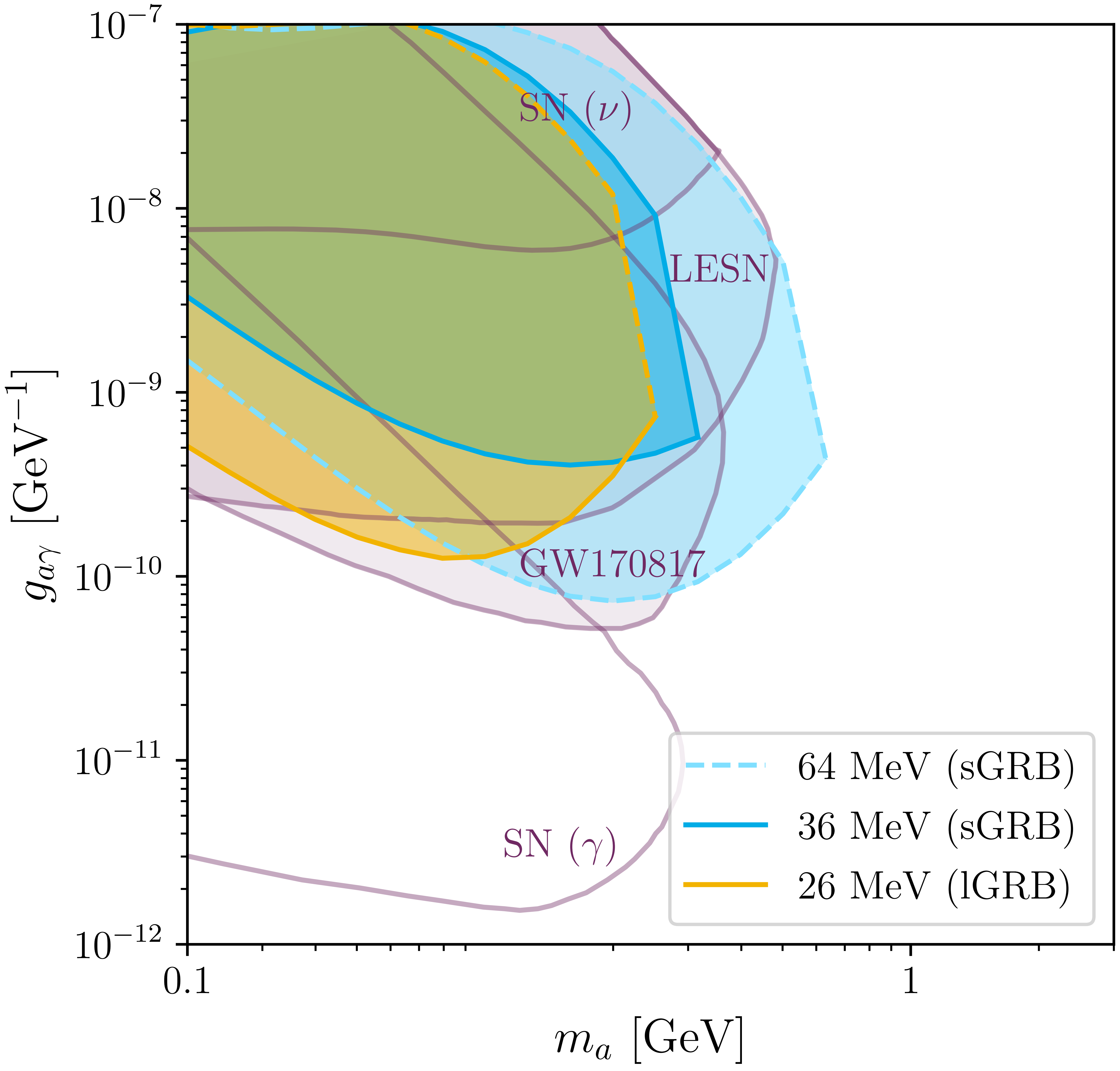
$$L_a = \Delta\Omega \int_{r_i}^{r_m} \mathrm{d}r\, r^2 \int_{m_a}^{\infty} \mathrm{d}E_a\, E_a \frac{d\dot{n}_a}{dE_a} \times \Theta\left(E_a - \frac{m_a}{\sqrt{1-\frac{2GM_r}{rc^2}}}\right) f_{\mathrm{decay}},$$

condition for ALPs to escape from a gravitational potential — escape probability

Diffuse γ-ray background spectrum



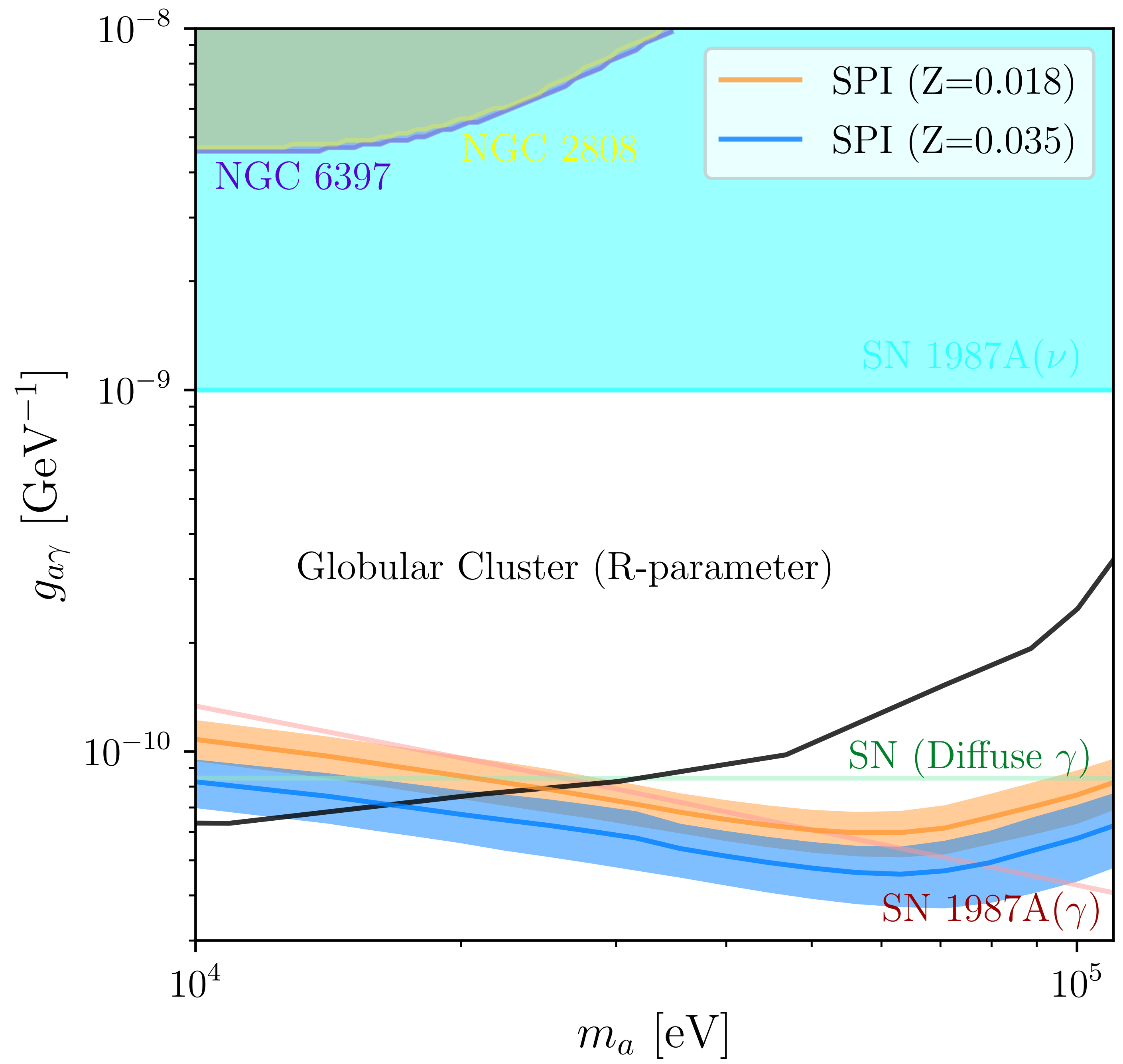
New ALP Bounds



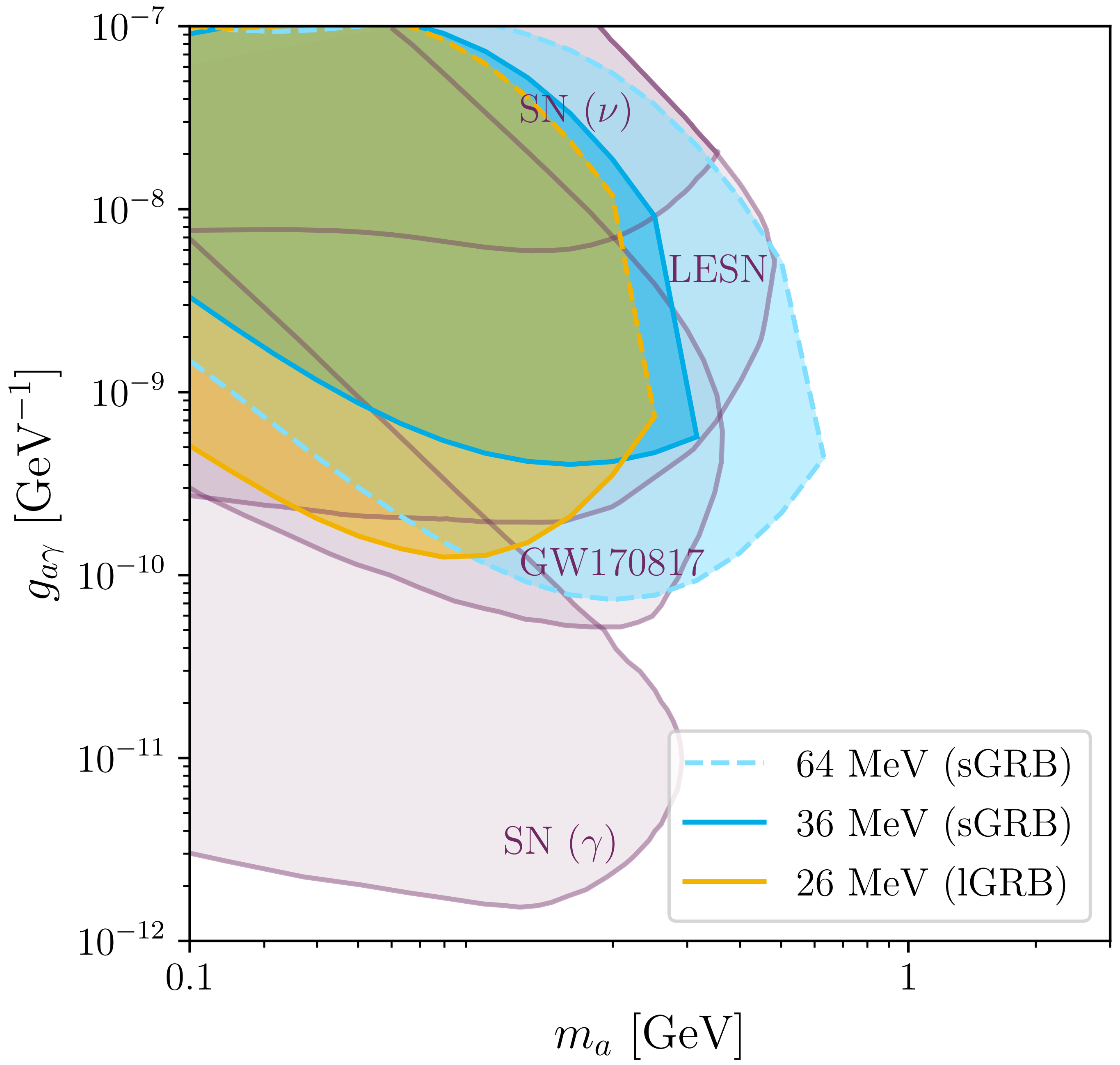
- Strongly depends on initial GRB fireball temperature and launch radius.
- Previous study used an explosion model which predicts higher temperatures $T \sim \mathcal{O}(100\ \text{MeV})$.
- Detailed modeling of GRB jet flow suggests a wind model with lower temperatures $T \sim \mathcal{O}(10\ \text{MeV})$.
- Results in significantly weaker ALP bounds than those shown in [Ghosh, Jacobsen, Linden, 2501.08978].

Conclusions

- ALPs are well-motivated BSM candidates.
- Astrophysical plasma is an efficient ALP production site.
- Considered massive Wolf-Rayet stars and GRB fireball as two examples.
- Derived new astrophysical bounds on heavy ALPs in the keV-MeV range.



WR Star



GRB Fireball