# Probing Axion-like Particles from Massive Stars with X-rays and Gamma Rays

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# axions - motivation

- QCD axion solves the strong CP problem

$$\mathscr{L}_{\rm QCD} \supset -\left(\bar{\mathbf{q}}_L m_q e^{i\theta_Y}\mathbf{q}_R + \text{ h.c. }\right) - \frac{\alpha_s}{8\pi} G^a_{\mu\nu}\widetilde{G}^{\mu\nu}_a \theta_{\rm QCD} = -\frac{\alpha_s}{8\pi} G^a_{\mu\nu}\widetilde{G}^{\mu\nu}_a \theta$$

$|\theta| \lesssim 10^{-10}$

**C. Abel et al. 2001.11966**

- Heavy ($m_a \gtrsim \mathcal{O}(\mathrm{keV})$) DSFZ and KSVZ axions are excluded

- motivation for Heavy QCD axion/axion-like particles
  - compactifications in string theory **J. M. Pendlebury et al. 1509.04411**
  - explain anomalous TeV gamma-ray transparency **M. Meyer et al. 1302.1208**
  - relaxion models **P. W. Graham et al. 1504.07551**
  - high quality QCD axion **V. A. Rubakov (1997) 9703409, etc.**

# Stellar evolution

- Main sequence stars
  consists of $^1$H, burning $^1$H, $T_{\rm core} \sim 1$ keV

- Red giant
  $^1$H shell + $^4$He core, burning $^1$H

- Horizontal branch stars
  $^1$H shell + $^4$He core
  burning $^1$H and $^4$He, $T_{\rm core} \sim 10$ keV

- Asymptotic giant branch stars
  $^1$H, $^4$He shell + $^{12}$C, $^{16}$O core

- neutron stars $T_{\rm core} \sim 10$ MeV

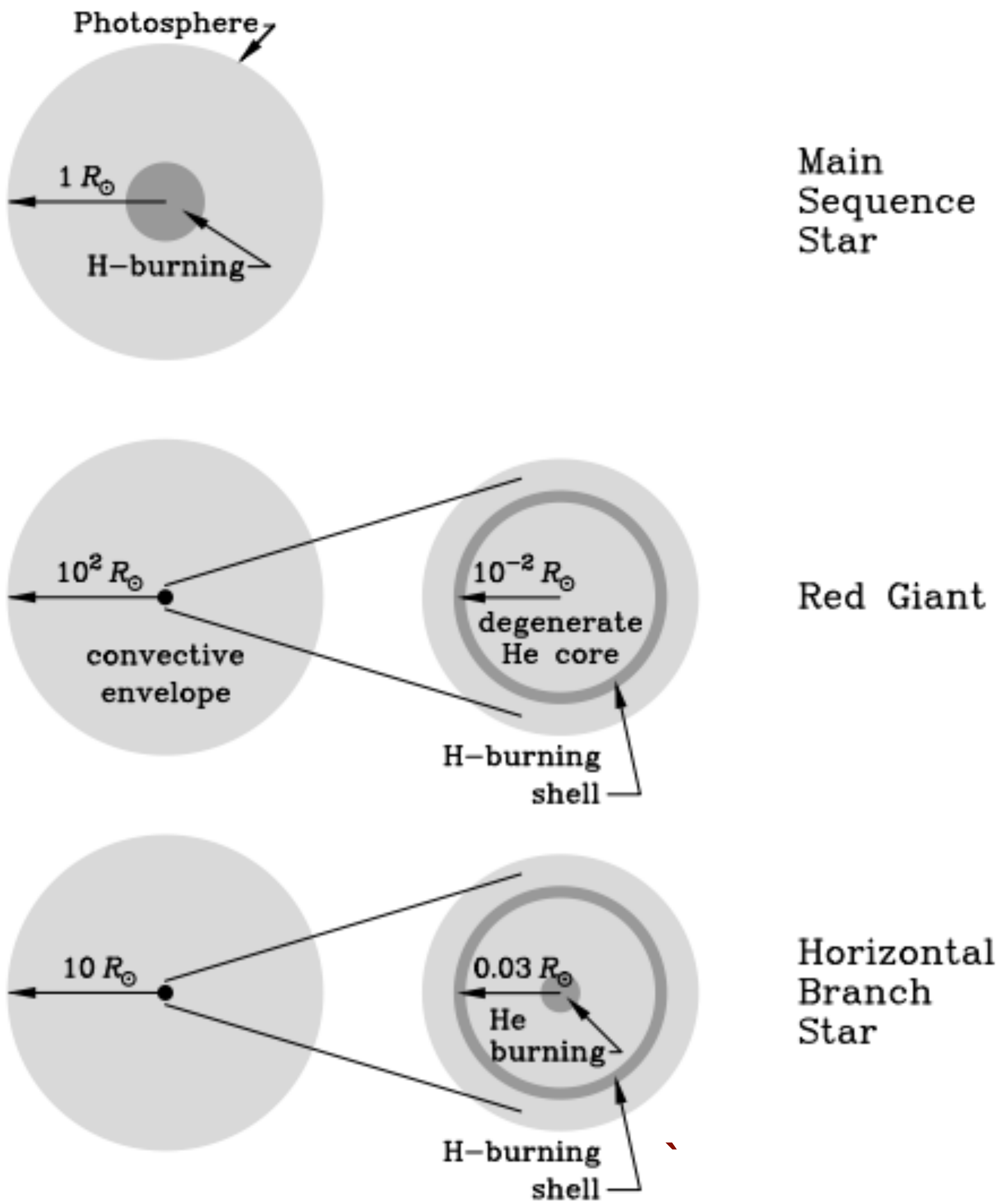
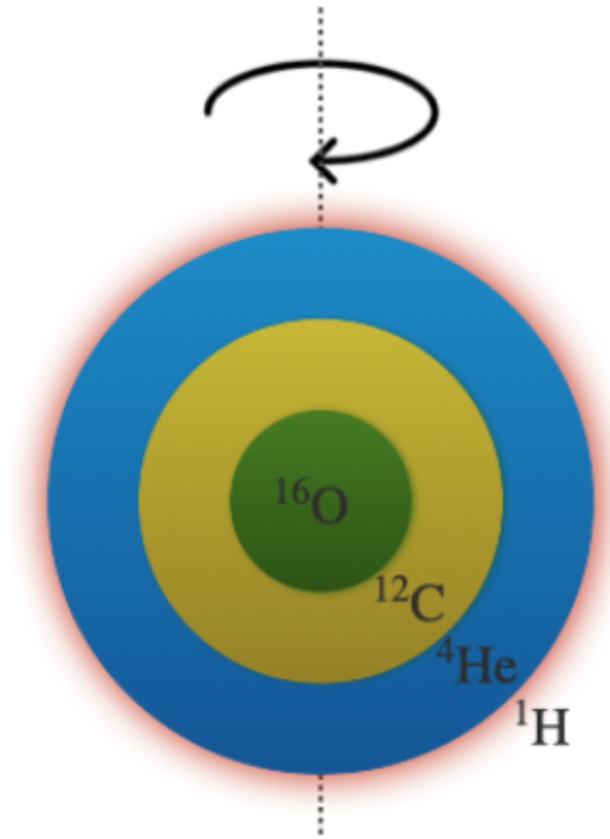


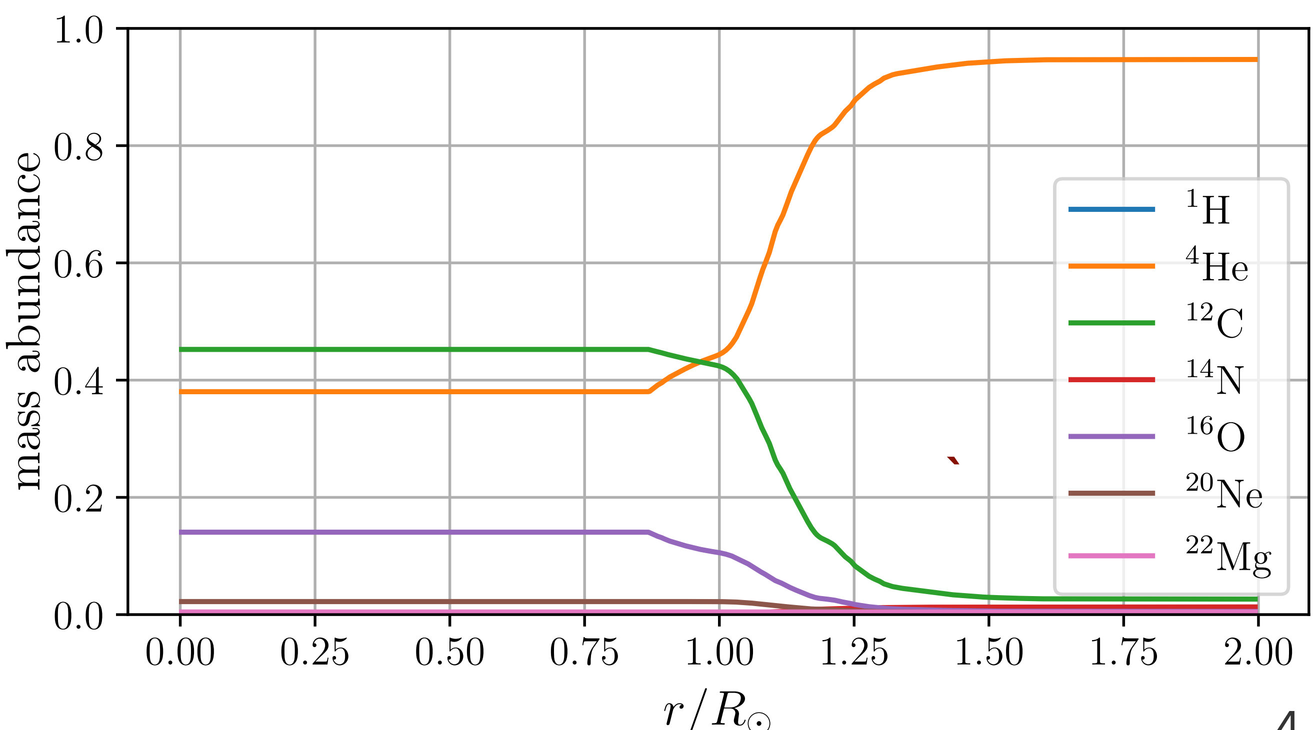

Image: G.G. Raffelt, Stars as laboratories for fundamental physics

# WR stars

- Wolf-Rayet (WR) stars
  - Massive + high rotational velocity
  - $^1\mathrm{H}$ shell is stripped out
  - WN → WC → WO phase
  - $T_{\mathrm{core}} \simeq 20\ \mathrm{keV}, R \sim 1 - 2R_\odot$




- Quintuplet cluster **C. Dessert et al., 2008.03305**
  - near the Galactic Center
  - has 13 WC stars
  - metallicity $z \in [0.018, 0.035]$
  - $\mu_{\mathrm{rot}} = 100\ \mathrm{km/s}, \sigma_{\mathrm{rot}} = 140\ \mathrm{km/s}$
  - $t_{\mathrm{age}} \in [3.0, 3.6]\ \mathrm{Gyr}$
  - Kroupa initial mass function

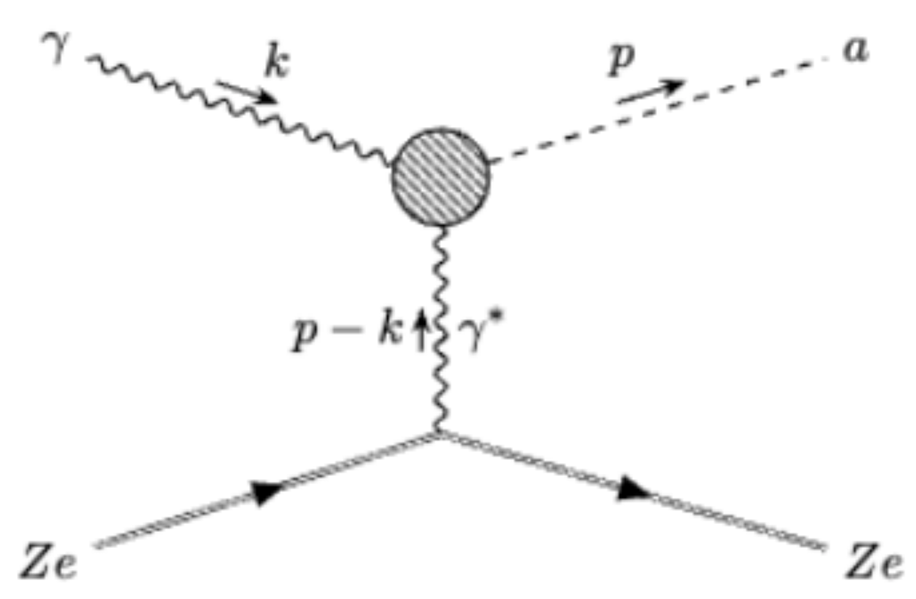


# Axions produced in stars

- Consider keV-MeV QCD axions/ALPs with:

$$\mathscr{L}_{a\gamma} = -\frac{g_{a\gamma}}{4} F_{\mu\nu} \widetilde{F}^{\mu\nu} a$$

- axions are produced by
  - Primakoff process ($\gamma + Ze \rightarrow a + Ze$)
  - photon coalescence ($\gamma + \gamma \rightarrow a$)

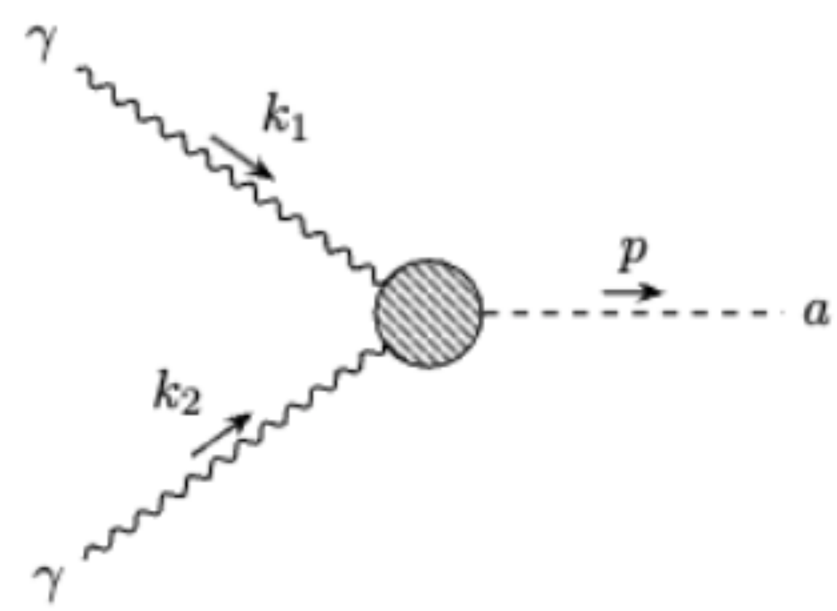



- include finite temperature correction:

$$\omega^2 = k^2 + \omega_{\rm pl}^2$$

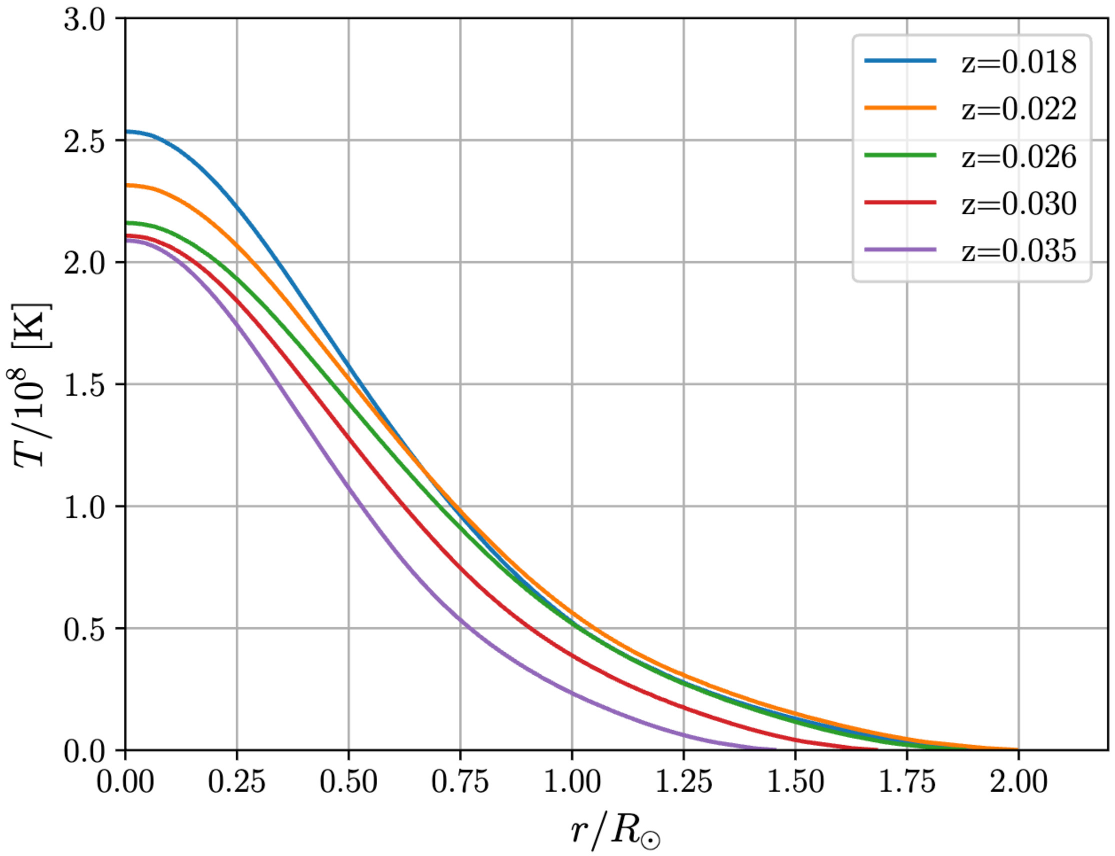
$$\frac{1}{q^4} \rightarrow \frac{1}{q^2(q^2+\kappa^2)}$$

G. G. Raffelt (1986)
T. Altherr et. al. (1993)




$$\kappa^2 = \frac{4\pi\alpha}{T}\left(n_e^{eff} + \sum_j Z_j^2 n_j^{eff}\right) \qquad n_{\rm eff} = g\int \frac{d^3\mathbf{p}}{(2\pi)^3} f_{B/F}\left(1 \pm f_{B/F}\right)$$

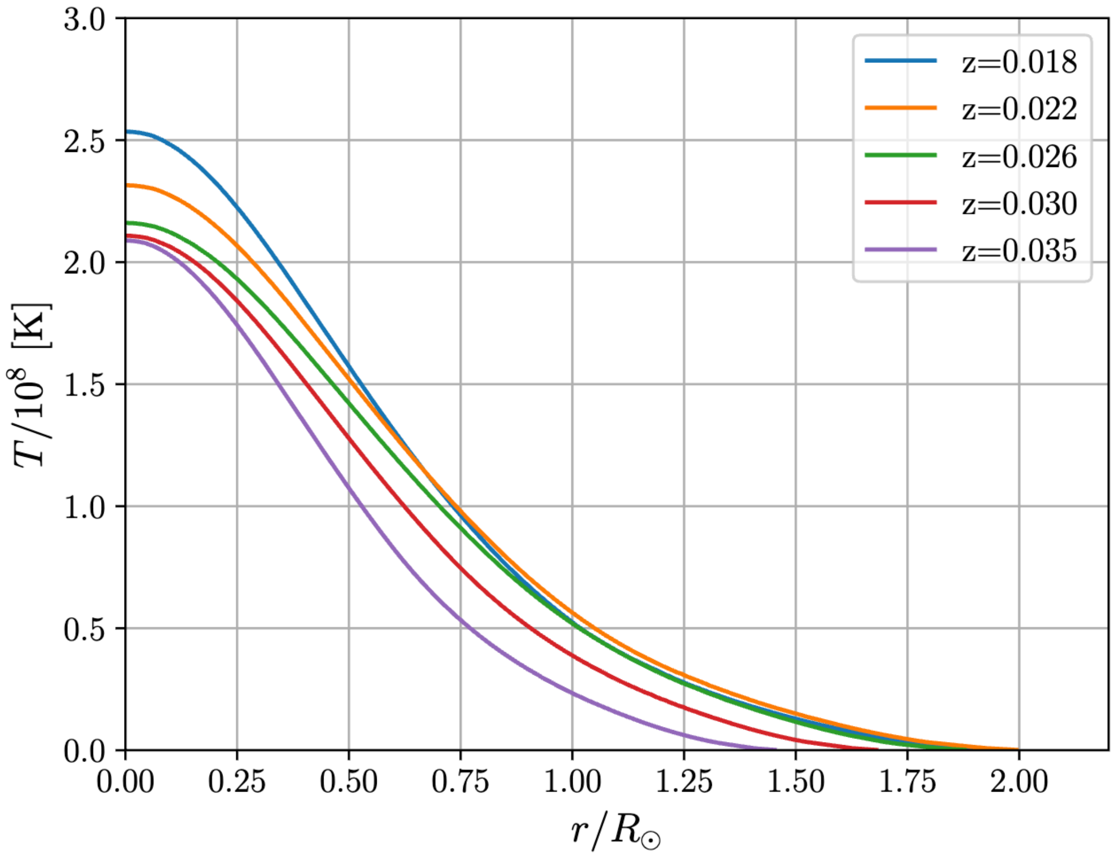
# Axions produced in stars

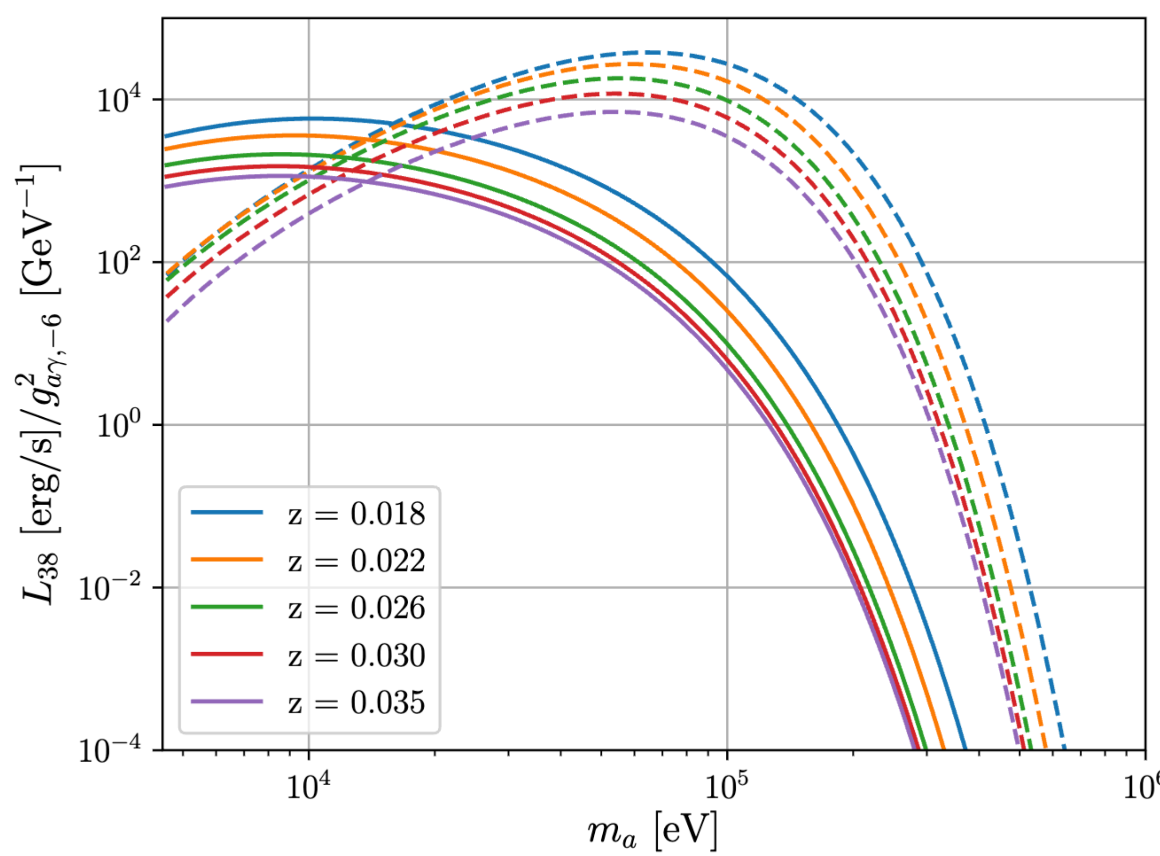



left: temperature profile of a WR stars with a different initial metallicity $z$

$(M_{\rm init} = 85 M_\odot,\ v_{\rm rot} = 150\ \rm km/s)$

# Axions produced in stars



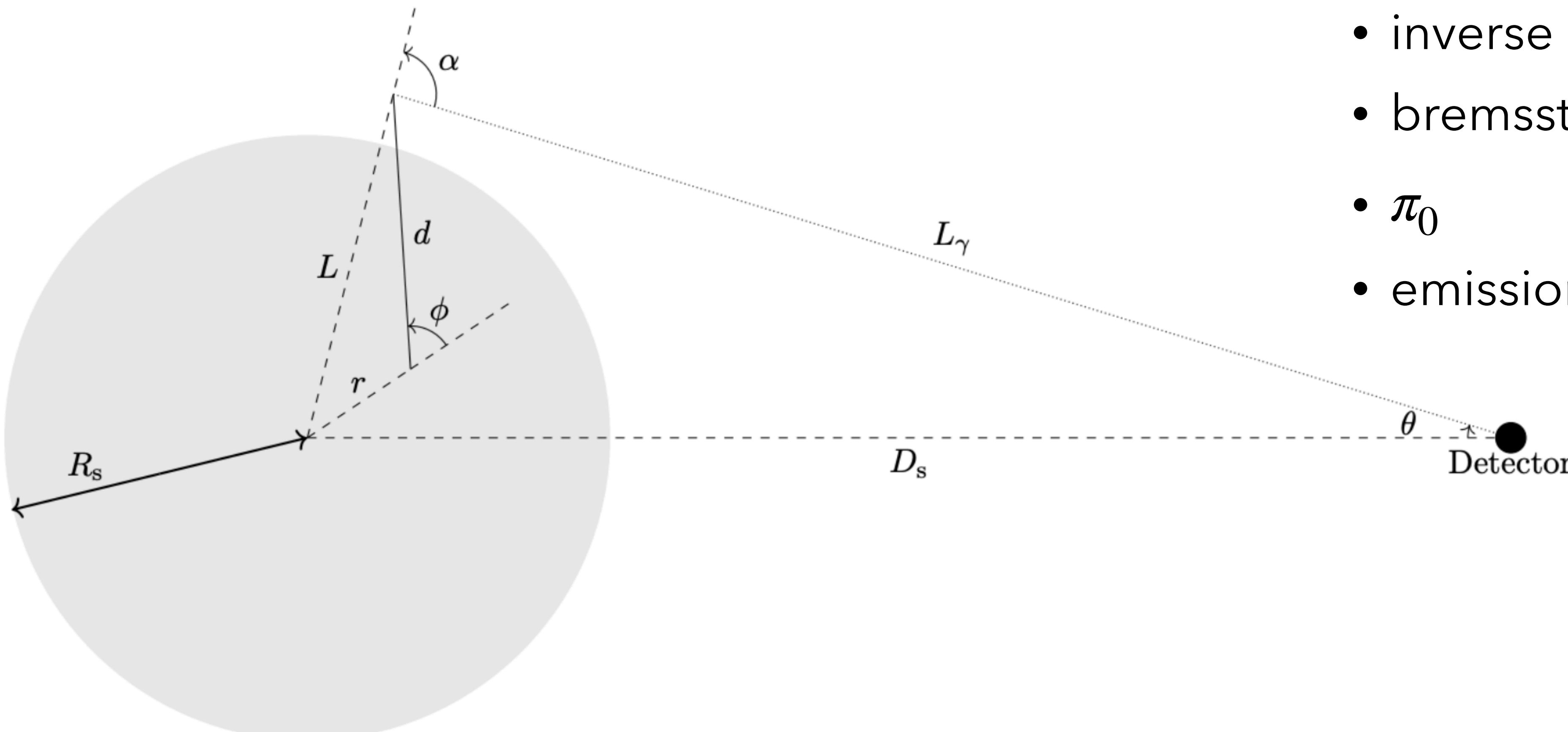

left: temperature profile of a WR stars with a different initial metallicity $z$

$$(M_{\rm init} = 85 M_\odot,\ v_{\rm rot} = 150\ \text{km/s})$$

right: luminosity of axions as a function of axion mass

$$(g_{a\gamma} = 10^{-6}\ \text{GeV}^{-1})$$

# Photon flux at the earth




Possible backgrounds:

- inverse compton
- bremsstrahlung
- $\pi_0$
- emissions from pulsars

2 photons from each decay

angular distribution of photons

constraints on $\omega, c_\alpha, L$

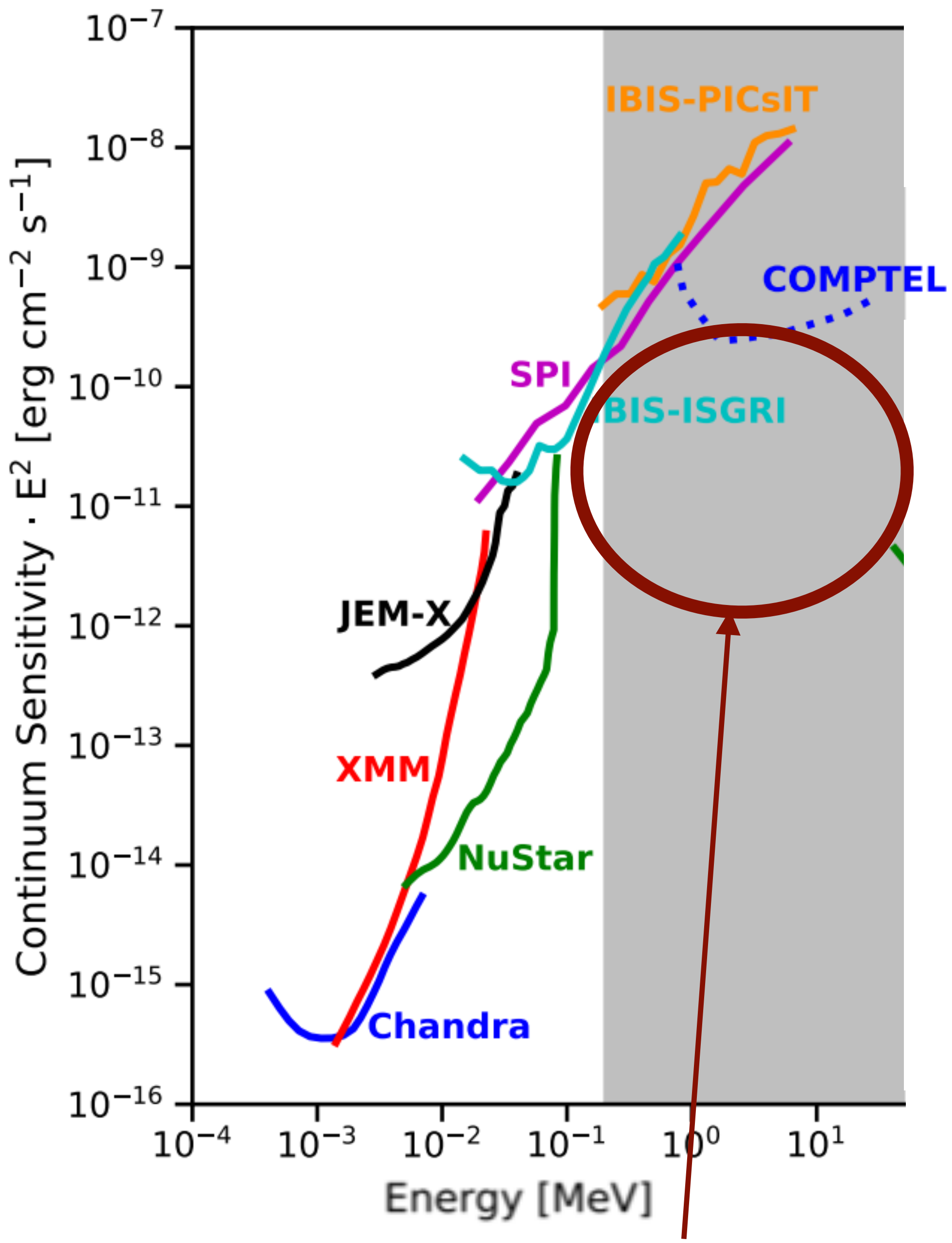
$$d\tilde{F}_\gamma = 2 \cdot \frac{1}{4\pi D_s^2} \cdot \frac{dN}{d\omega}\, d\omega \cdot f_{c_\alpha}(\omega, c_\alpha)\, dc_\alpha \cdot \frac{\exp\left[-L/l_a(\omega)\right]}{l_a(\omega)} dL \cdot \Theta_{\text{cons.}}(\omega, c_\alpha, L)$$

spectral fluence of axions at the earth

decay probability

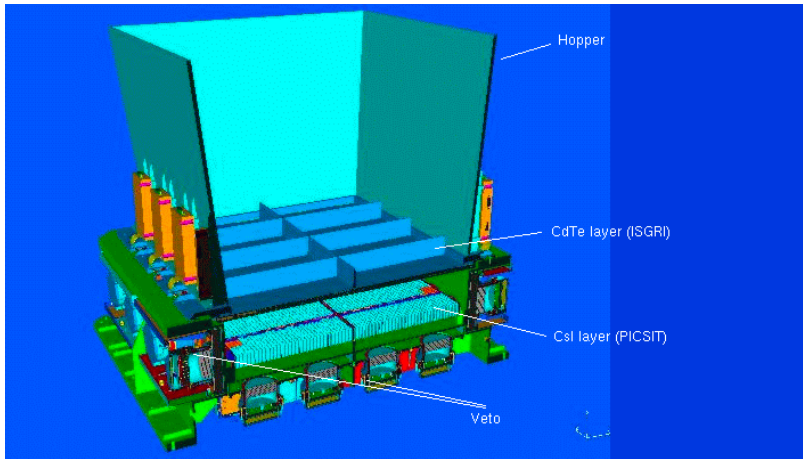
# Telescopes

G. Lucchetta et al. 2204.01325

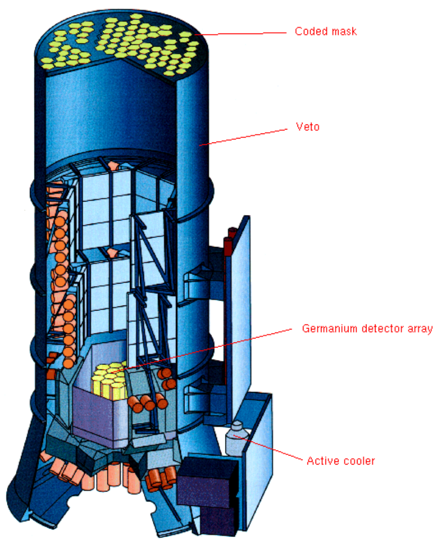



IBIS-ISGRI **G. Di Cocco et al. A&A 411 1 (2003)**

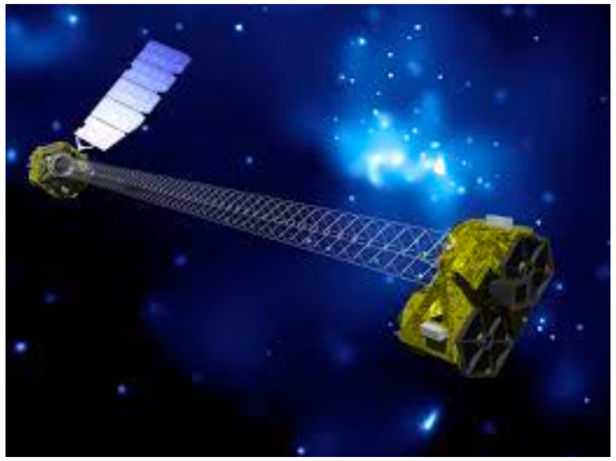
IBIS-PICsIT **G. Vedrenne et al. A&A 411 1 (2003)**




SPI **G. Vedrenne et al. A&A 411 1 (2003)**



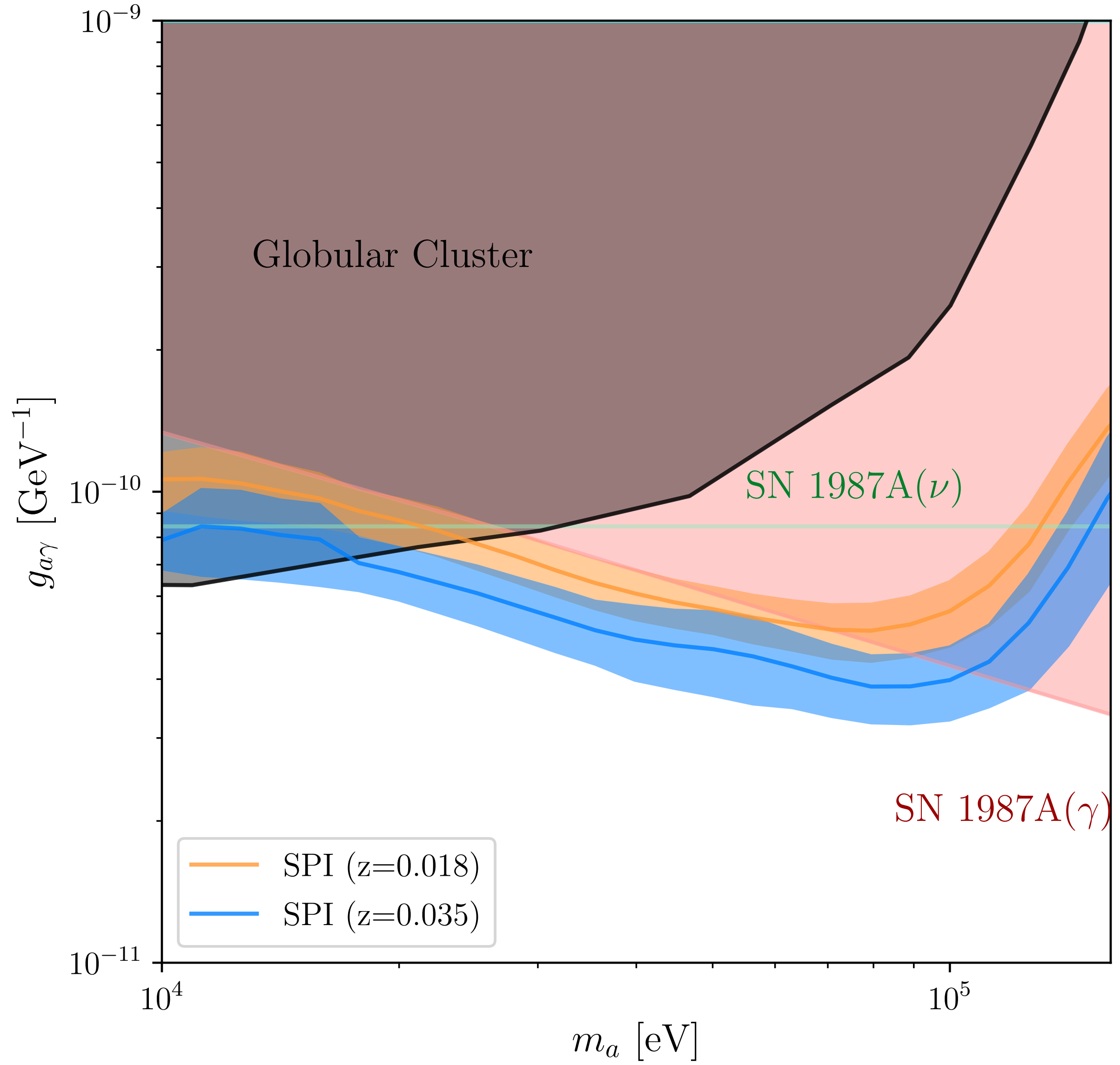

NuSTAR **F. A. Harrison et al. 1301.7307**



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




- can exclude $g_{a\gamma} \gtrsim 10^{-10}$ GeV$^{-1}$ for $10\ \mathrm{keV} \lesssim m_a \lesssim 200\ \mathrm{keV}$
- WR star bound outperforms Globular cluster and SN 1987A bound at $20\ \mathrm{keV} \lesssim m_a \lesssim 100\ \mathrm{keV}$

# Summary

- heavy keV-MeV axions are predicted in several models
- WR stars: massive star with a high rotational velocity whose $^{1}\mathrm{H}$ shell is peeled out
- a large number of axions are produced in WR stars via the Primakoff process and photon coalescence
- Photons from their spontaneous decays will be detected by the current telescope with $3\sigma$ significance if $g_{a\gamma} \gtrsim 10^{-10}$ GeV$^{-1}$ for $10\ \mathrm{keV} \lesssim m_a \lesssim 200\ \mathrm{keV}$

# Backup slides

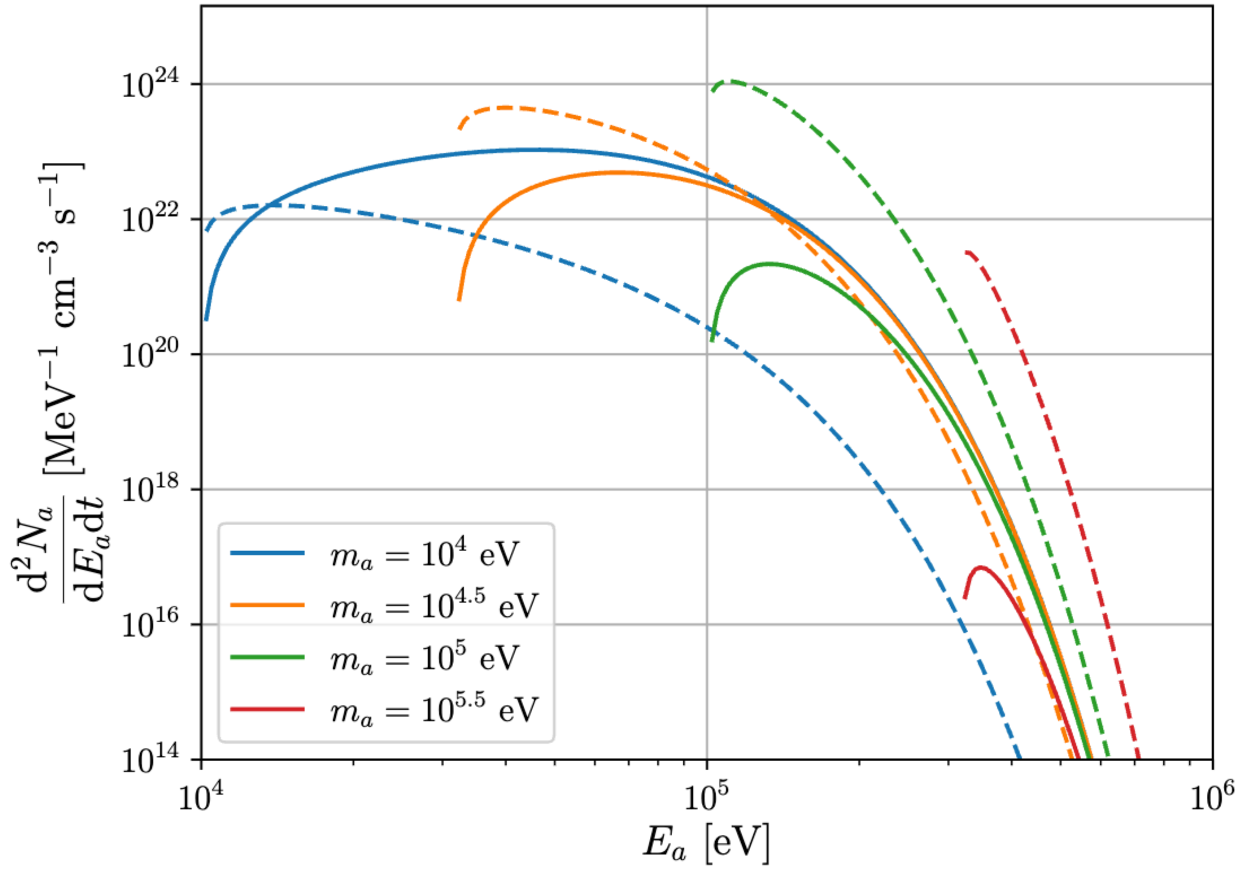
# Production spectra

Primakoff process:

$$\frac{d^2N_a}{dEdt}(r,t,E) = \frac{\beta_\gamma}{e^{E/T}-1}\frac{g_{a\gamma}^2 T\kappa^2}{32\pi^3}pE$$
$$\left\{\frac{\left[(k+p)^2+\kappa^2\right]\left[(k-p)^2+\kappa^2\right]}{4pk\kappa^2}\ln\left[\frac{(k+p)^2+\kappa^2}{(k-p)^2+\kappa^2}\right] - \frac{\left(k^2-p^2\right)^2}{4kp\kappa^2}\ln\left[\frac{(k+p)^2}{(k-p)^2}\right]-1\right\}$$

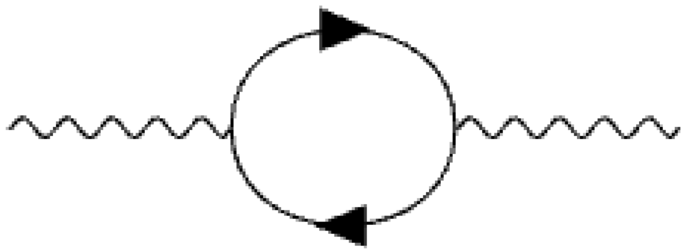
Photon coalescence:

$$\frac{d^2N_a}{dEdt}(r,t,E) = \frac{g_{a\gamma}^2}{128\pi^3}m_a^4\sqrt{E^2-m_a^2}\left(1-\frac{4\omega_{pl}^2}{m_a^2}\right)^{3/2}e^{-E/T}$$



# Finite temperature effect

$$\Pi^{\mu\nu}(K) = 16\pi\alpha \int \frac{d^3p}{(2\pi)^3}\frac{1}{2E}\left[f(E)+\bar{f}(E)\right]\frac{P\cdot K\left(P^\mu K^\nu + K^\mu P^\nu\right) - K^2 P^\mu P^\nu - (P\cdot K)^2 g^{\mu\nu}}{(P\cdot K)^2 - \left(K^2\right)^2/4}$$



- the photon propagator:

$$\Delta_{00} = \frac{1}{K^2 - \Pi_L}\frac{K^2}{|\mathbf{k}|^2} \qquad \Delta_{0i} = 0 \qquad \Delta_{ij} = \frac{P_{\mu\nu}}{K^2 - \Pi_T}$$

- a location of a pole determines the dispersion relation

$$\omega_T^2 = |\mathbf{k_T}|^2 + \omega_p^2\left(1 + \frac{|\mathbf{k_T}|^2}{\omega_T^2}\frac{T}{m_e}\right)$$

$$\omega_L^2 = \omega_p^2\left(1 + 3\frac{|\mathbf{k_L}|^2}{\omega_L^2}\frac{T}{m_e}\right)$$

# Telescopes

| Mission | Sensitivity Range | Angular Resolution (at Energy) |
|---|---|---|
| XMM | 0.1-15 keV | $12''$ (2-10 keV) |
| NuSTAR | 5 keV - 80 keV | $18''$ |
| INTEGRAL IBIS/ISGRI | 15 keV - 1 MeV | $12'$ |
| INTEGRAL IBIS/PICsIT | 170 keV - 10 MeV | $12'$ |
| INTEGRAL SPI | 20 keV - 8 MeV | $2.5^\circ$ |
| INTEGRAL JEM-X | 3 keV - 35 keV | $3'$ |
| SWIFT (BAT) | 15-150 keV | $22'$ |
| eROSITA | 0.2-10 keV | $35''$ (2-8 keV) |
| COSI | 200 keV - 5 MeV | $\sim 4^\circ$ (1 MeV) |
| AMEGO (Compton) | 200 keV - 10 MeV | $\sim 4^\circ$ (1 MeV) |
| APT (Compton) | 200 keV - 10 MeV | $\sim 5^\circ$ (1 MeV) |
| ASTROGAM | 100 keV - 1 GeV | $\sim 1.5^\circ$ |
| Insight-HXMT/HE | 20 keV - 250 keV | $6'$ |
| e-ASTROGAM | 300 keV - 3 GeV | $\sim 2^\circ$ |
| GECCO | 100 keV - 10 MeV | $2^\circ$ |