PHYSICAL REVIEW LETTERS **134**, 241001 (2025)

Searching for Axionlike Particles with X-Ray Observations of Alpha Centauri

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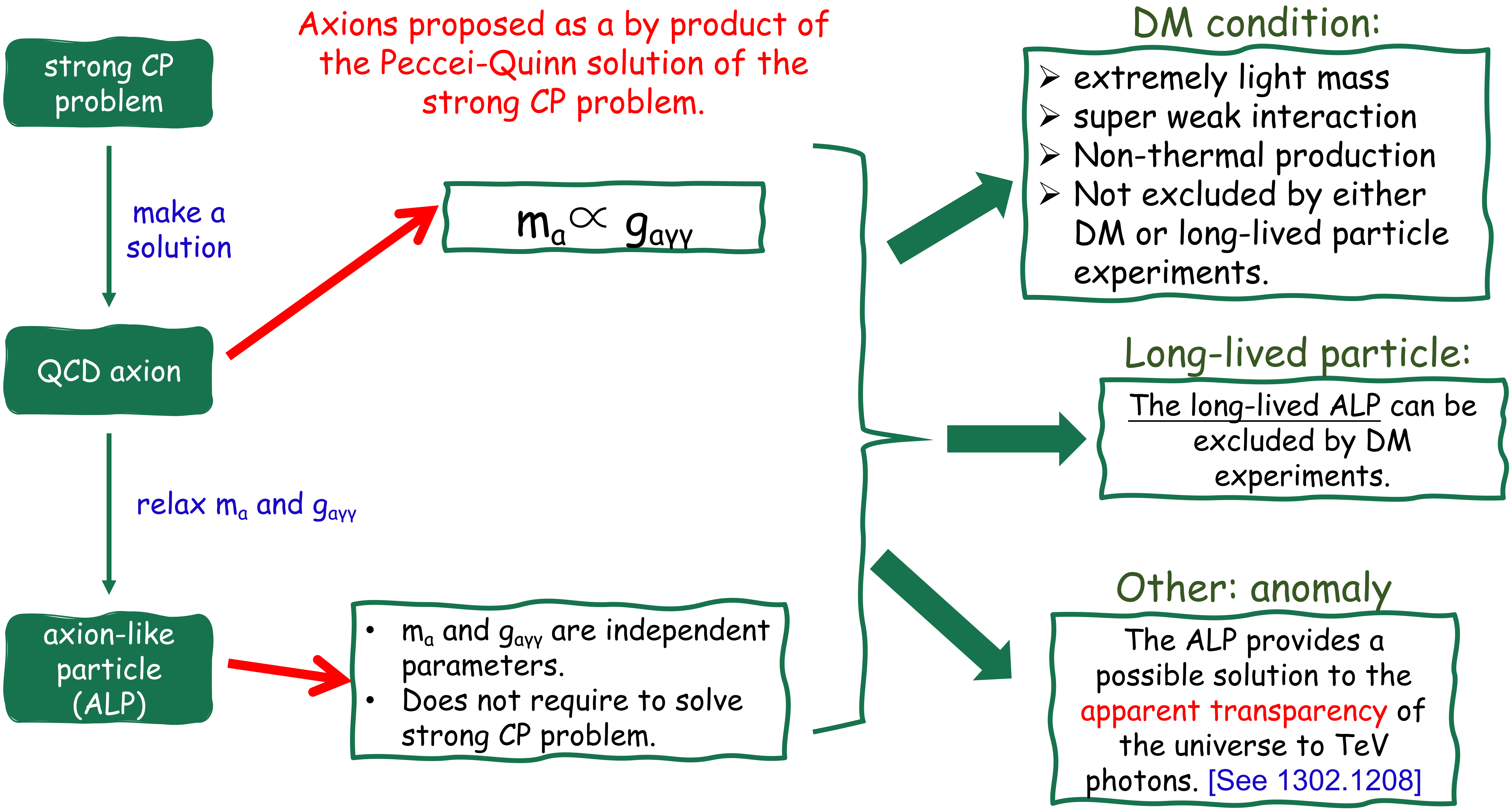
Z. Guo, Y. Tsai, L. Wu and Z. Xia, ***Constraints on Axion-Like Particles from 16.5 Years of Fermi-LAT Data and Prospects for VLAST***, arXiv:2507.07786

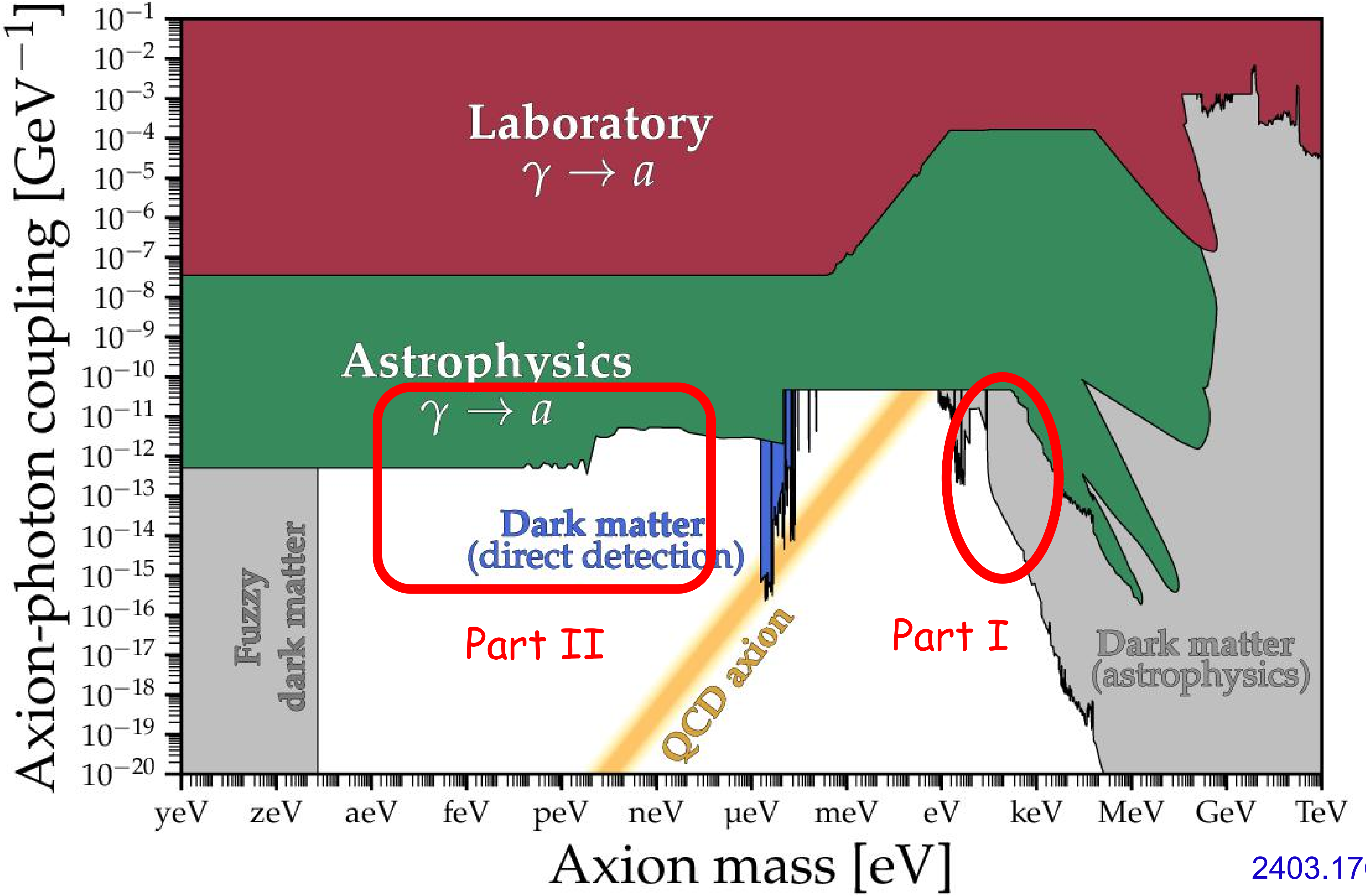
Detecting Axion-like Particles: Long-Lived Particles and Dark Matter

Yue-Lin Sming Tsai

(Purple Mountain Observatory)

Talk@TAUP2025 (2025.08.25)


strong CP problem
make a solution
QCD axion
relax m_a and $g_{a\gamma\gamma}$
axion-like particle (ALP)
Axions proposed as a by product of the Peccei-Quinn solution of the strong CP problem.
$m_a \propto g_{a\gamma\gamma}$
• m_a and $g_{a\gamma\gamma}$ are independent parameters.
• Does not require to solve strong CP problem.
DM condition:
➢ extremely light mass
➢ super weak interaction
➢ Non-thermal production
➢ Not excluded by either DM or long-lived particle experiments.
Long-lived particle:
The long-lived ALP can be excluded by DM experiments.
Other: anomaly
The ALP provides a possible solution to the apparent transparency of the universe to TeV photons. [See 1302.1208]



Laboratory
$\gamma \to a$
Astrophysics
$\gamma \to a$
Dark matter
(direct detection)
Fuzzy
dark matter
QCD axion
Part II
Part I
Dark matter
(astrophysics)
Axion-photon coupling [GeV^{-1}]
10^{-1}
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}
10^{-7}
10^{-8}
10^{-9}
10^{-10}
10^{-11}
10^{-12}
10^{-13}
10^{-14}
10^{-15}
10^{-16}
10^{-17}
10^{-18}
10^{-19}
10^{-20}
yeV zeV aeV feV peV neV µeV meV eV keV MeV GeV TeV
Axion mass [eV]

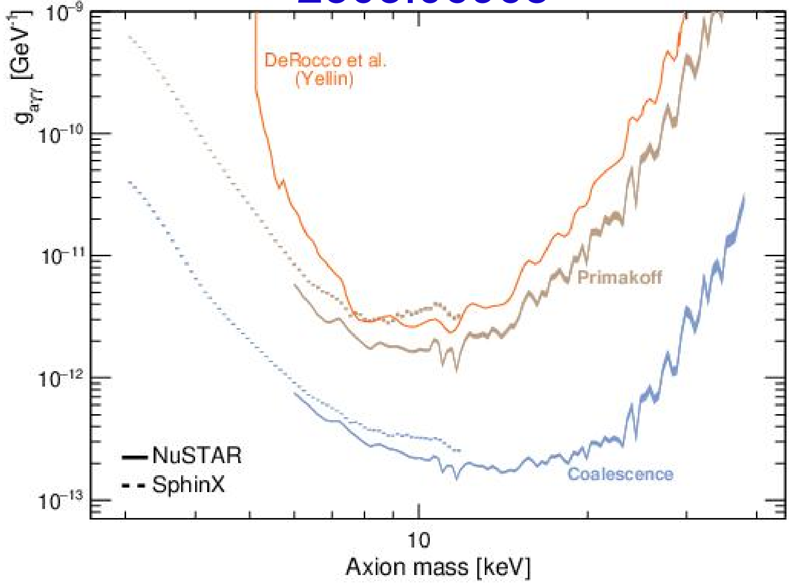
2403.17697

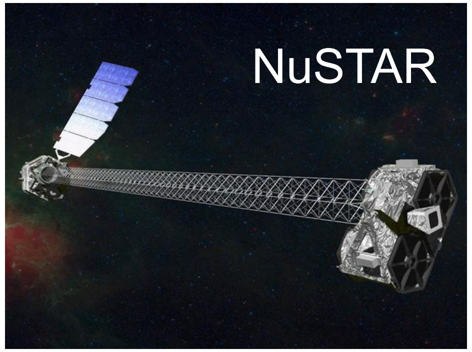
If ALP is not DM, but long-lived particle, then...

Y. Chen, L. Lei, Z. Xia, Z. Wang, **Y. Tsai** and Y. Fan,
Searching for Axionlike Particles with X-Ray Observations of Alpha Centauri,
Phys. Rev. Lett. 134, no.24, 241001 (2025)

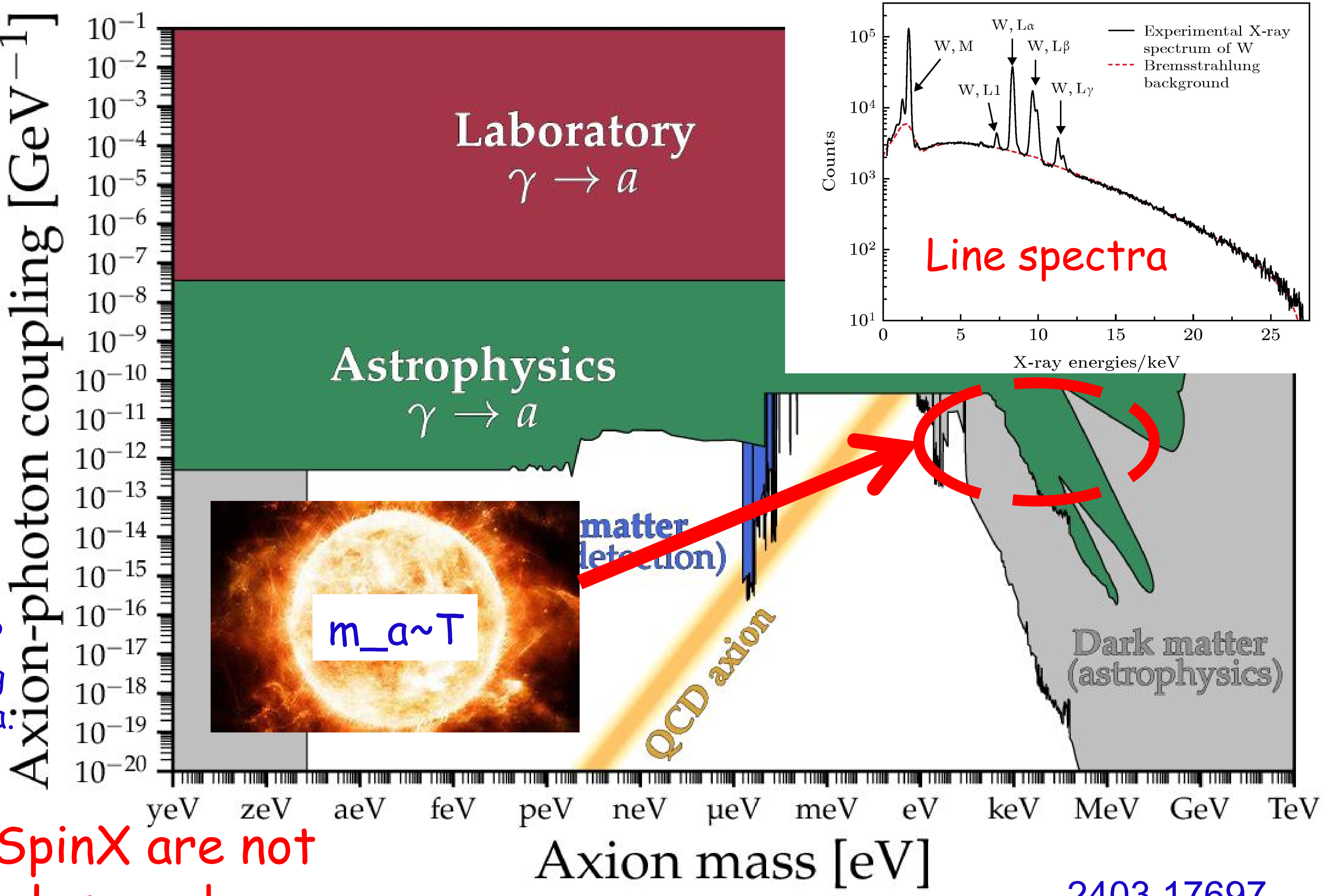
Axion-like particle: a long-lived particle

2303.06968





Detect non-relativistic ALP by using looking for line spectra:



However, NuSTAR and SpinX are not the most senstive telescope!

2403.17697

Could we improve the result from the Sun?

However, the Sun is **too bright to be seen** in Chandra or other sensitive X-ray telescope!

TABLE I. The basic information of some nearby stars.

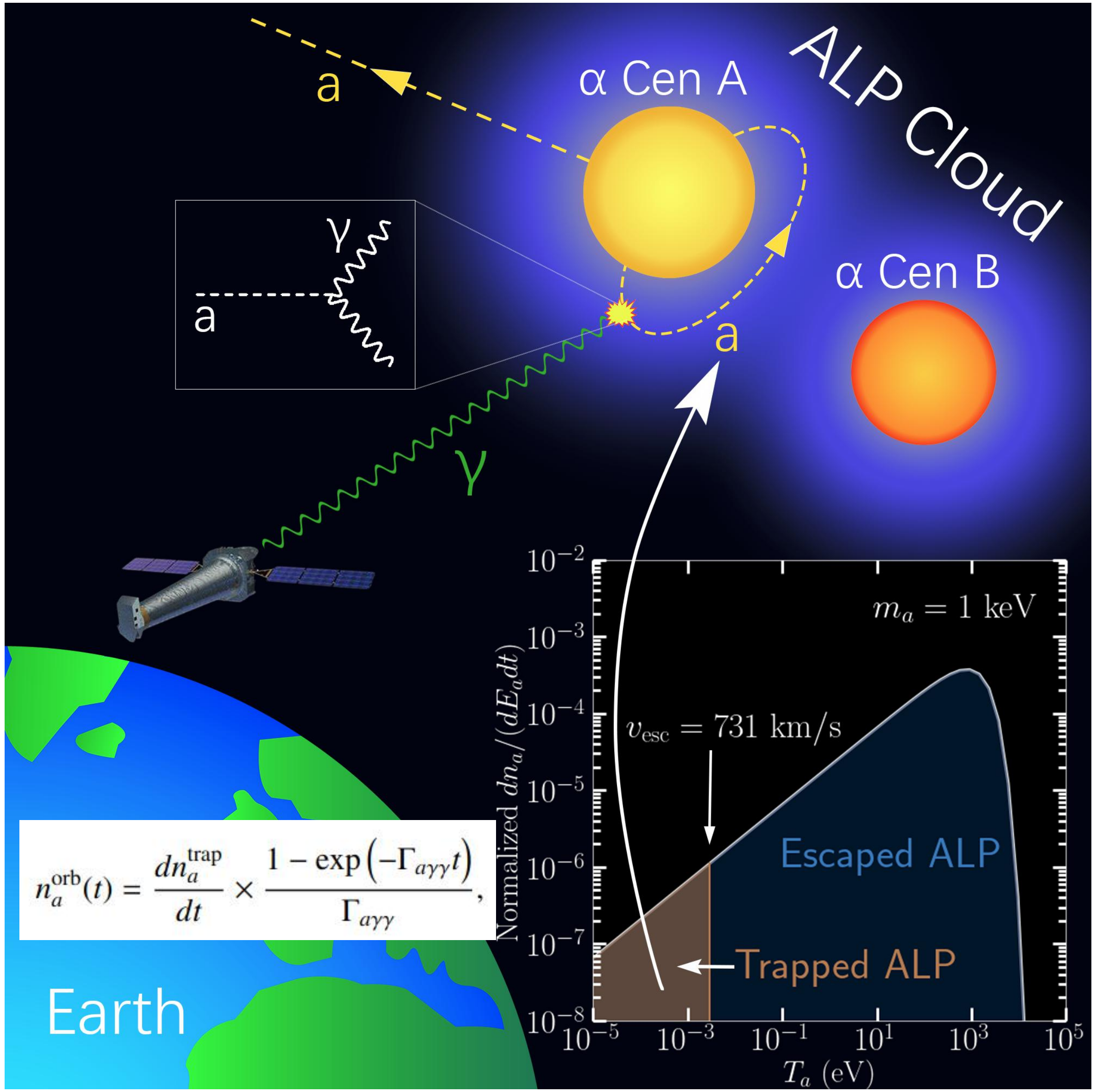
Name†	D⋆ [pc]	M♣ [$M_\odot$]	T⁎ [K]	Age [Gyr]
Sun	4.85×10^{-6}	1.00	5772	4.60
Proxima Centauri	1.30	0.12	2992	4.85
Alpha Centauri A	1.33	1.08	5804	4.85
Alpha Centauri B	1.33	0.91	5207	5.30
Barnard's Star	1.83	0.16	3195	~ 10
Wolf 359	2.41	0.11	2749	0.1–1.5
Lalande 21185	2.55	0.39	3547	8.05
Sirius A	2.64	2.06	9845	0.24

† The stars we list have masses greater than 0.1 $M_\odot$ and the furthest distance reaches up to Sirius A. The basic information of these nearest stars can be found in https://en.wikipedia.org/wiki/List_of_nearest_stars.
⋆ D is the distance from the Earth to the star.
♣ M is the star's mass.
⁎ T is the star's effective temperature.

Closer?
(Not possible)

Hotter?
Heavier?
Older?

eROSITA and Chandra X-ray telescope

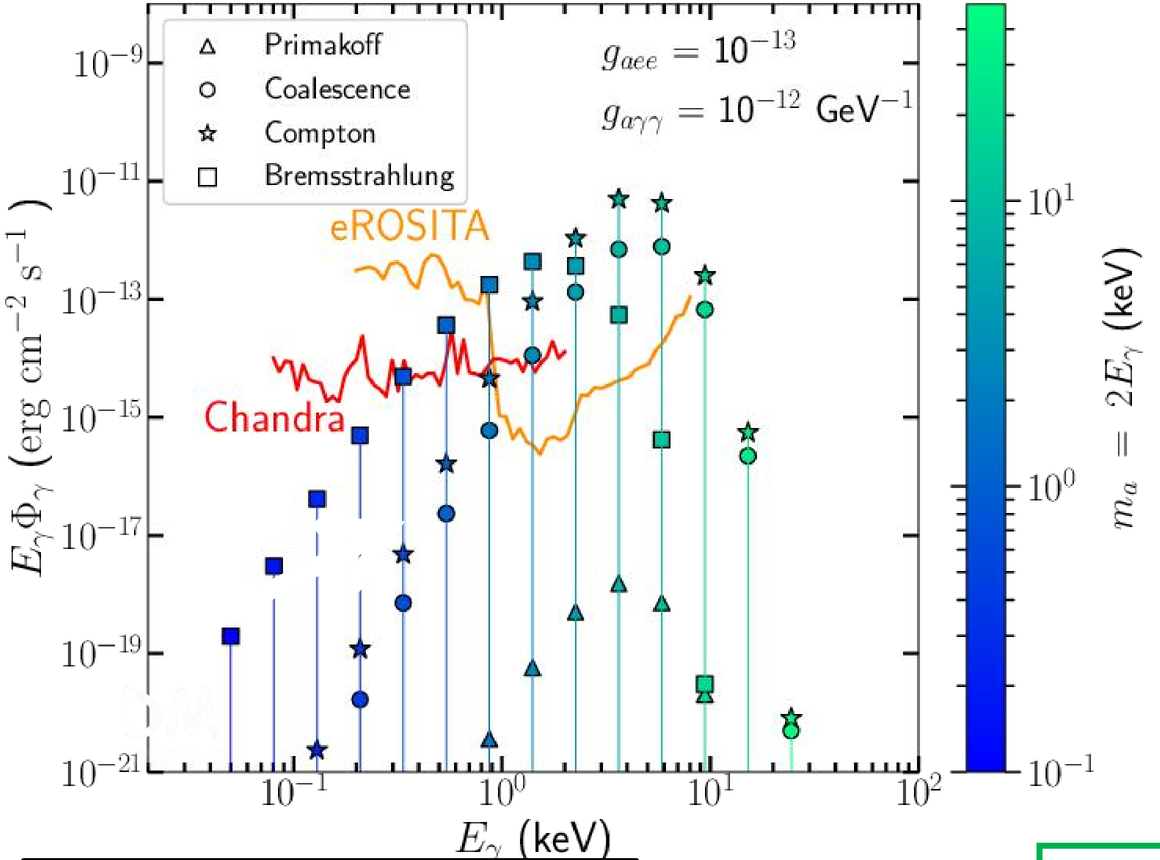


- eROSITA
  - wide-field X-ray telescope on-board.
  - Hardly distinguish X-ray from alpha-Centauri A and B.
  - Photon energy range between 0.2 kev to 8 keV.

- Chandra
  - Higher spatial resolution.
  - Photon energy range between 0.1 keV to 3 keV.

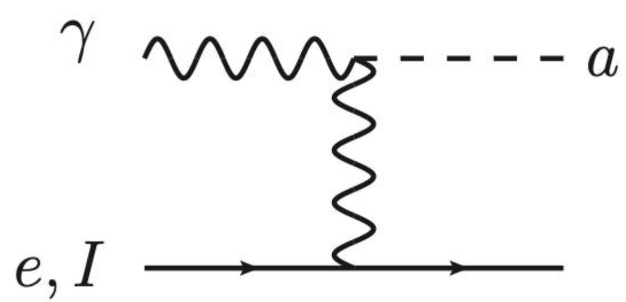
ALP production and capture

$$\mathcal{L} = \frac{1}{2}\partial^\mu a \partial_\mu a - \frac{1}{2}m_a^2 a^2 - \frac{1}{4}g_{a\gamma\gamma} a F^{\mu\nu}\widetilde{F}_{\mu\nu} - \frac{1}{2}g_{aee} a \bar{\psi}\gamma^5\psi$$

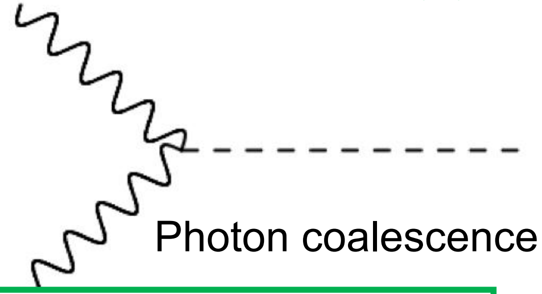


$$\Phi_{E,\gamma}(t) = \frac{1}{4\pi D^2}\int_{R_s}^{\infty} dr \cdot 4\pi r^2 n_a^{\rm orb}(t)\Gamma_{a\gamma\gamma},$$

$$\Gamma^{\rm Primakoff} \simeq \frac{g_{a\gamma\gamma}^2 T\kappa^2}{32\pi^2}\left[\frac{8p^2}{3(\kappa^2+m_a^2)} + O(p^4)\right].$$

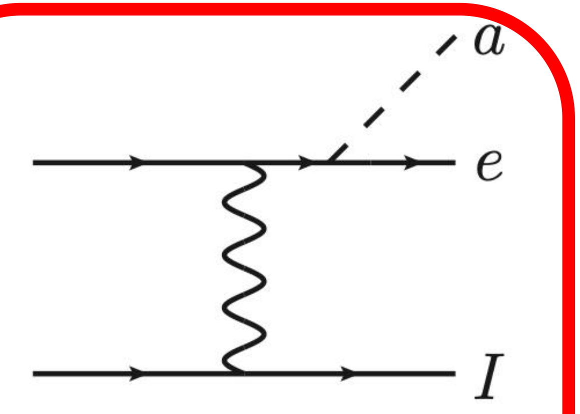


$|\mathcal{M}|^2 \propto g_{a\gamma\gamma}^2$

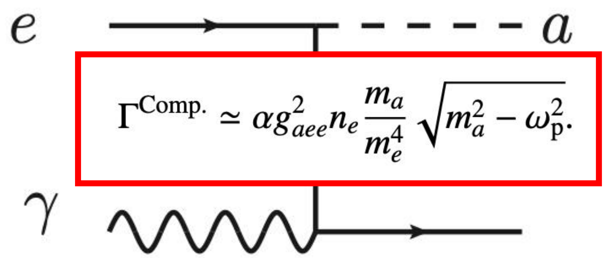


$$\Gamma^{\rm coal.}(T) = \Gamma_{a\gamma\gamma}\frac{m_a^2 - 4\omega_{\rm p}^2}{m_a^2}\left(\frac{m_a}{E_a}\right)\left[1 + \frac{2T}{p}\ln\frac{1-e^{-(E_a+p)/2T}}{1-e^{-(E_a-p)/2T}}\right]$$

$$\Gamma^{\rm brem.} \simeq \frac{\alpha^2 g_{aee}^2 \bar{n}_N n_e}{32\sqrt{2}\pi^{5/2} m_e^{7/2} T^{3/2}} \times \int d\epsilon \left[\log\frac{2+2\sqrt{1-\epsilon}-\epsilon+\xi}{\epsilon+\xi} \times \exp\{-\frac{m}{\epsilon T}\}\right],$$



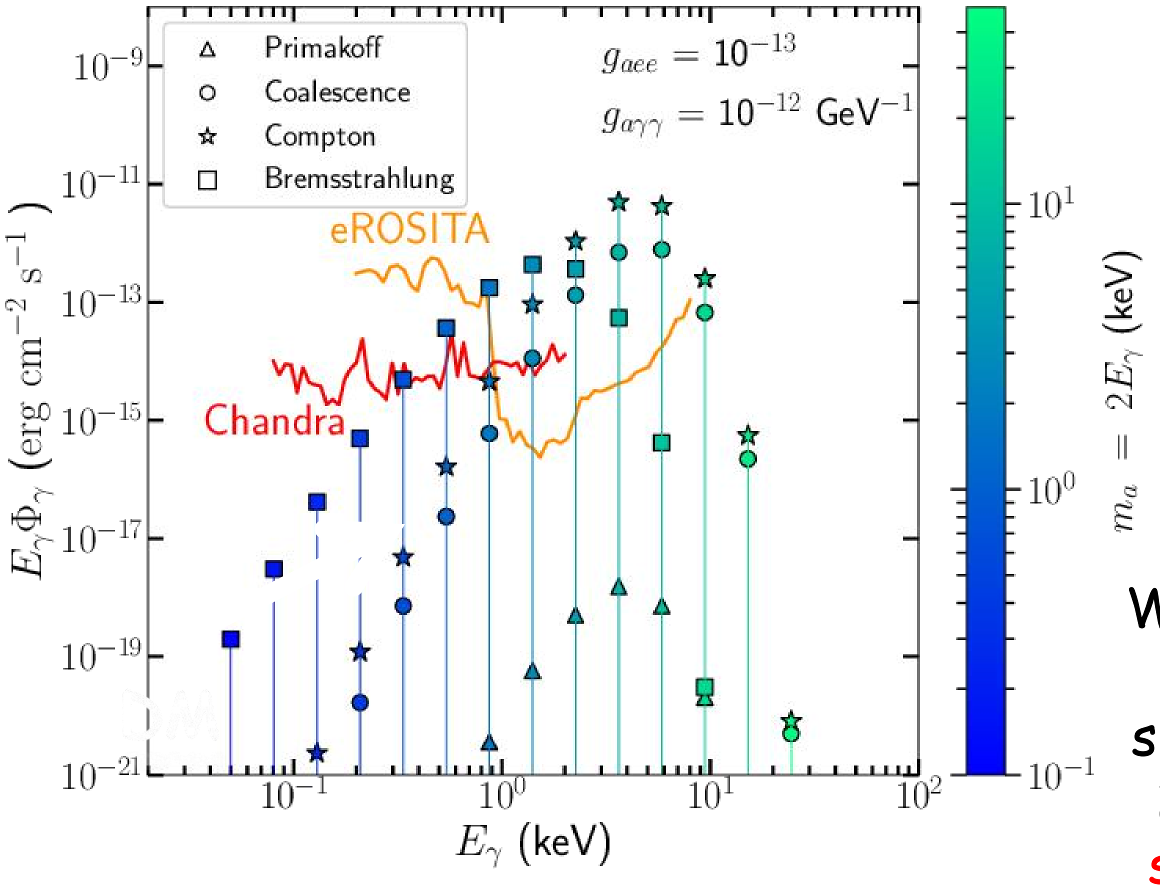
$|\mathcal{M}|^2 \propto g_{aee}^2$

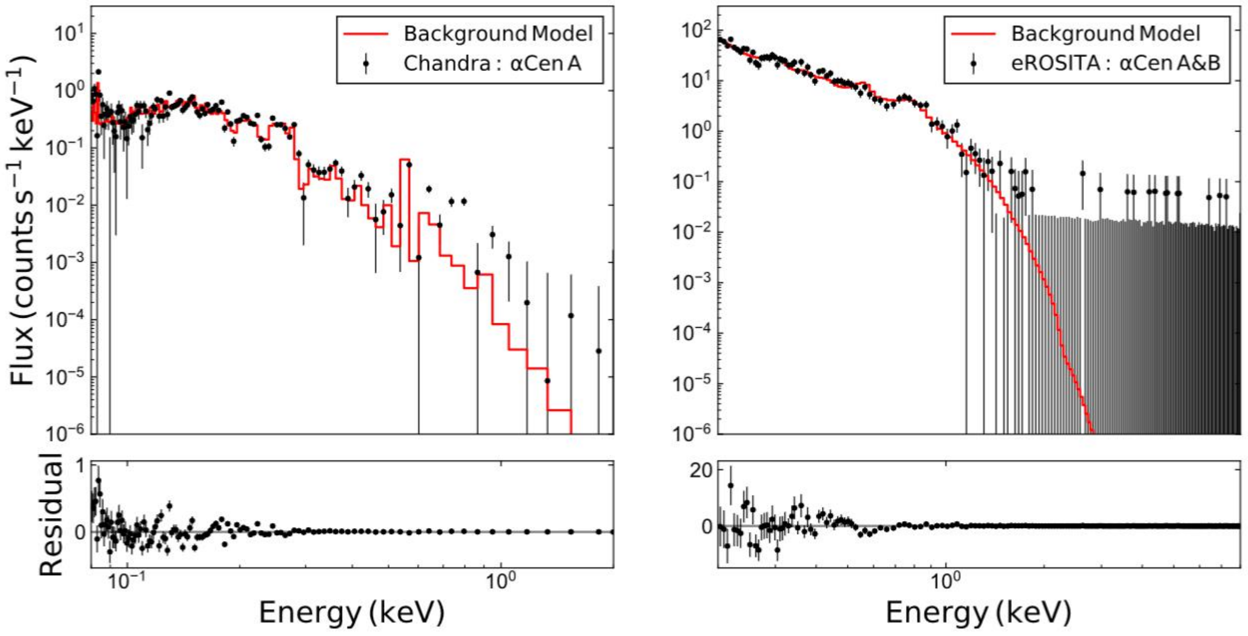


$$\Gamma^{\rm Comp.} \simeq \alpha g_{aee}^2 n_e \frac{m_a}{m_e^4}\sqrt{m_a^2 - \omega_{\rm p}^2}.$$

ALP production and capture

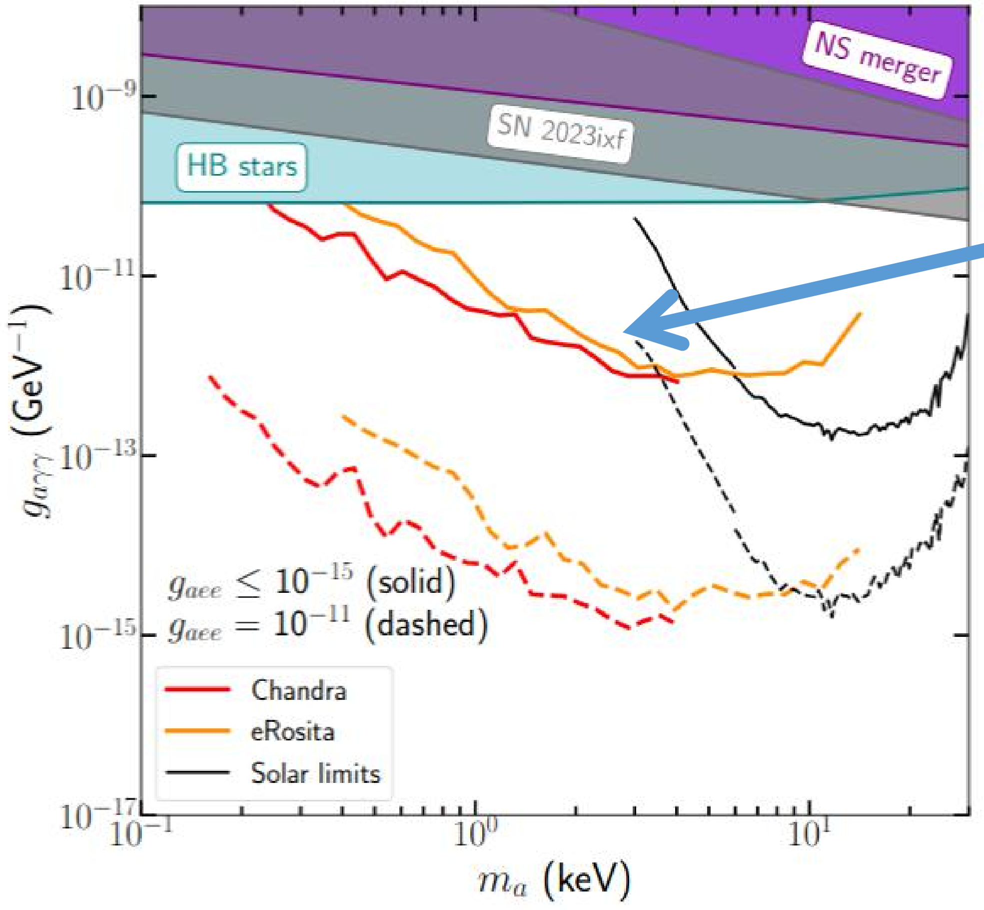
$$\Phi_{E,\gamma}(t) = \frac{1}{4\pi D^2}\int_{R_s}^{\infty} dr \cdot 4\pi r^2 n_a^{\rm orb}(t)\Gamma_{a\gamma\gamma},$$

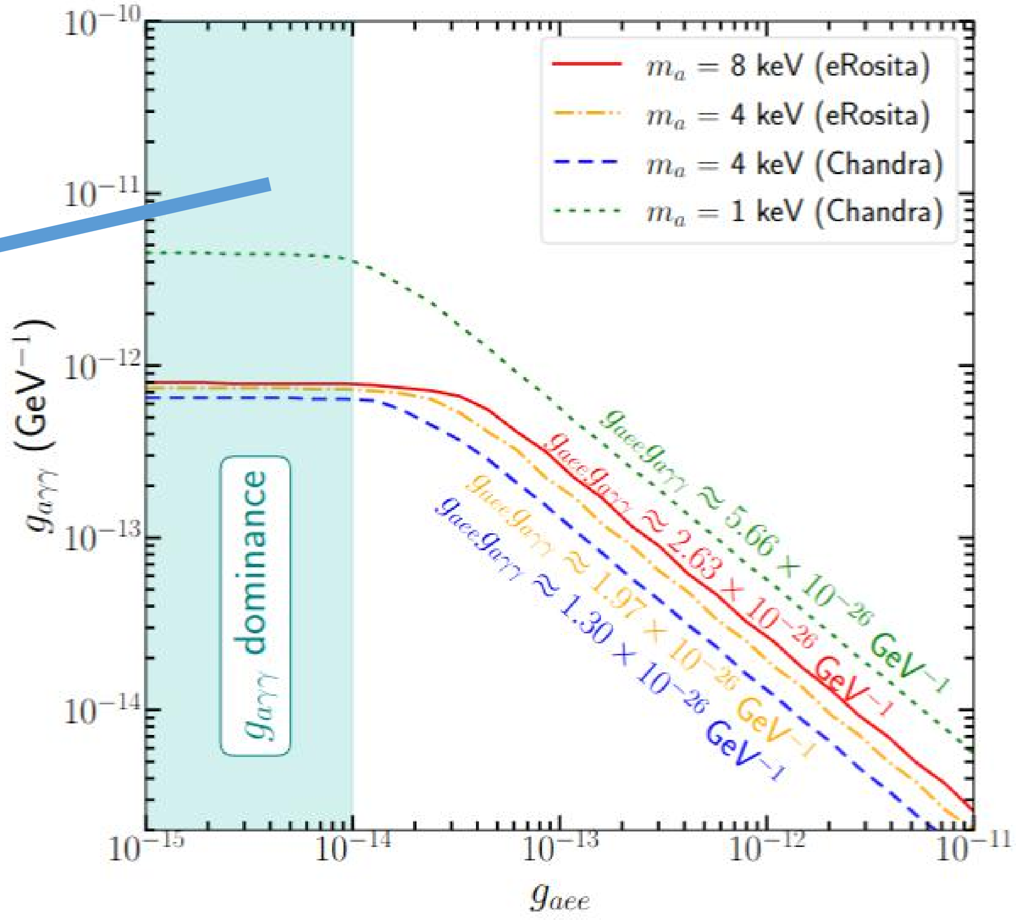




While we detect some excesses of emission lines, none reaches 5σ significance. The line with the most significant deviation (TS[without line]- TS[with line] = 22.4) locates at 0.2142 keV, corresponding to a 4.3σ significance based on a Chi-squared distribution with 2 degrees of freedom.

Results





Our limits on $g_{a\gamma\gamma}$ extend to ALP masses as low as 0.16 keV, benefiting from the lower X-ray energy threshold of Chandra and eROSITA.

Uncertainties

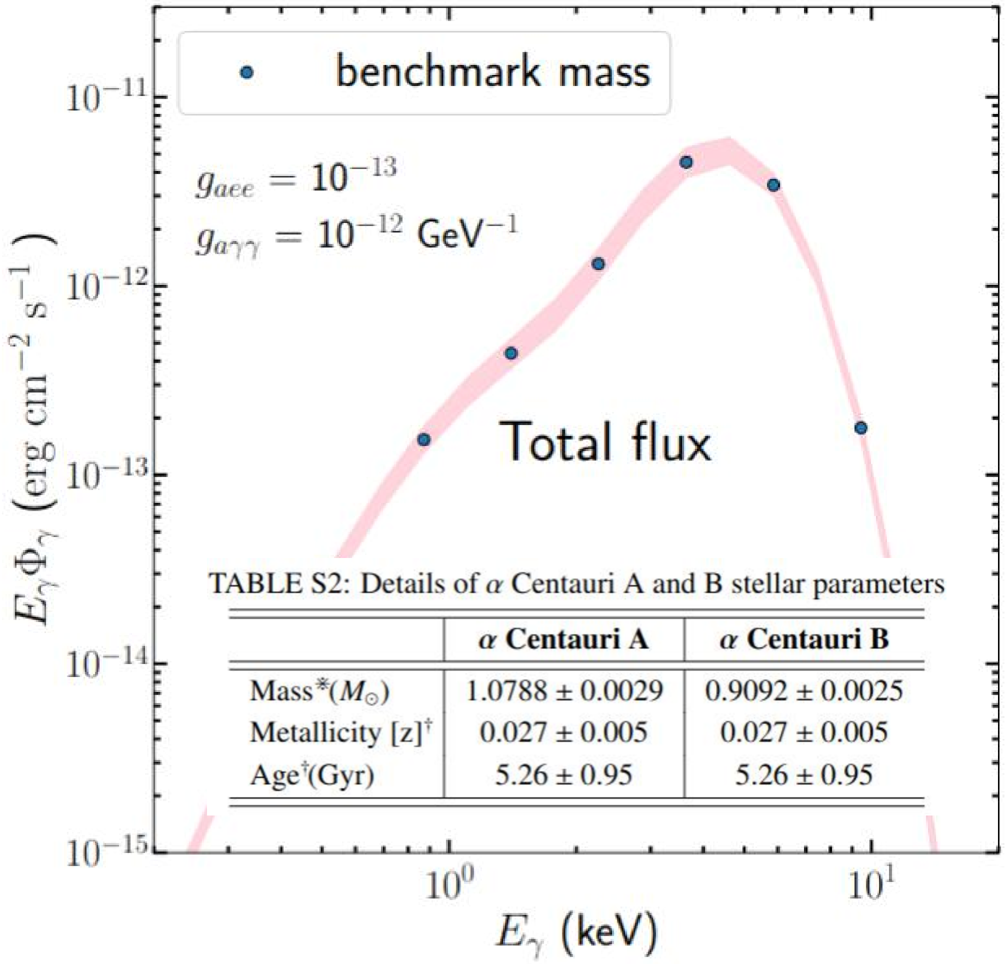
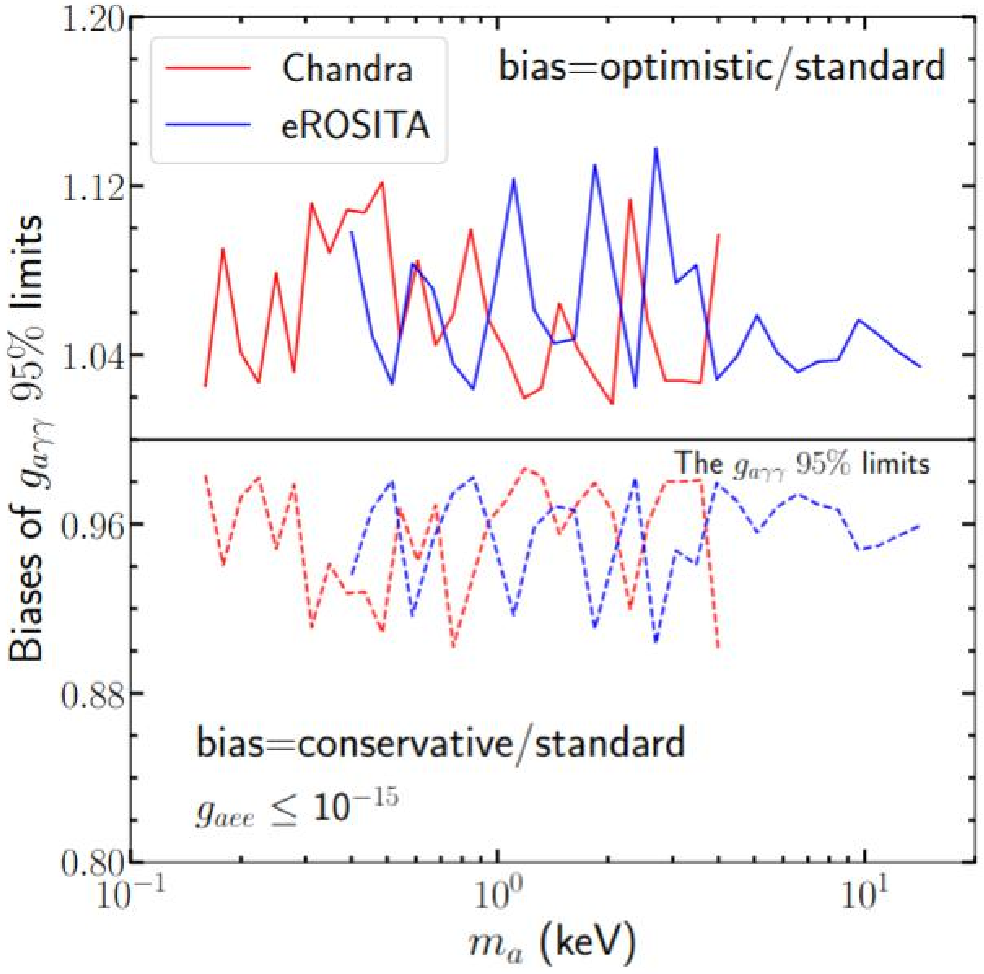


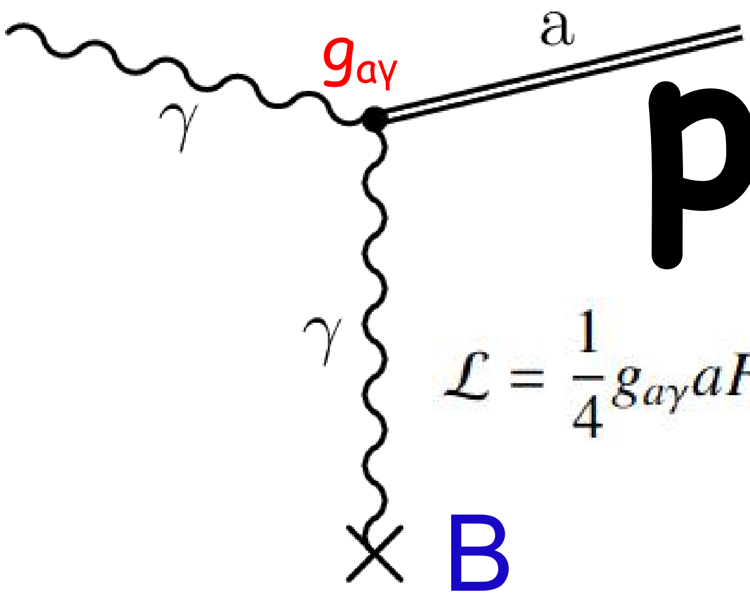
TABLE S2: Details of α Centauri A and B stellar parameters

	α **Centauri A**	α **Centauri B**
Mass*($M_\odot$)	1.0788 ± 0.0029	0.9092 ± 0.0025
Metallicity [z]†	0.027 ± 0.005	0.027 ± 0.005
Age†(Gyr)	5.26 ± 0.95	5.26 ± 0.95



Sources: stellar parameters, mixing length, the Schwarzschild and Ledoux criteria, and convective overshooting. It is at most 12%.

If ALP can be DM particle...



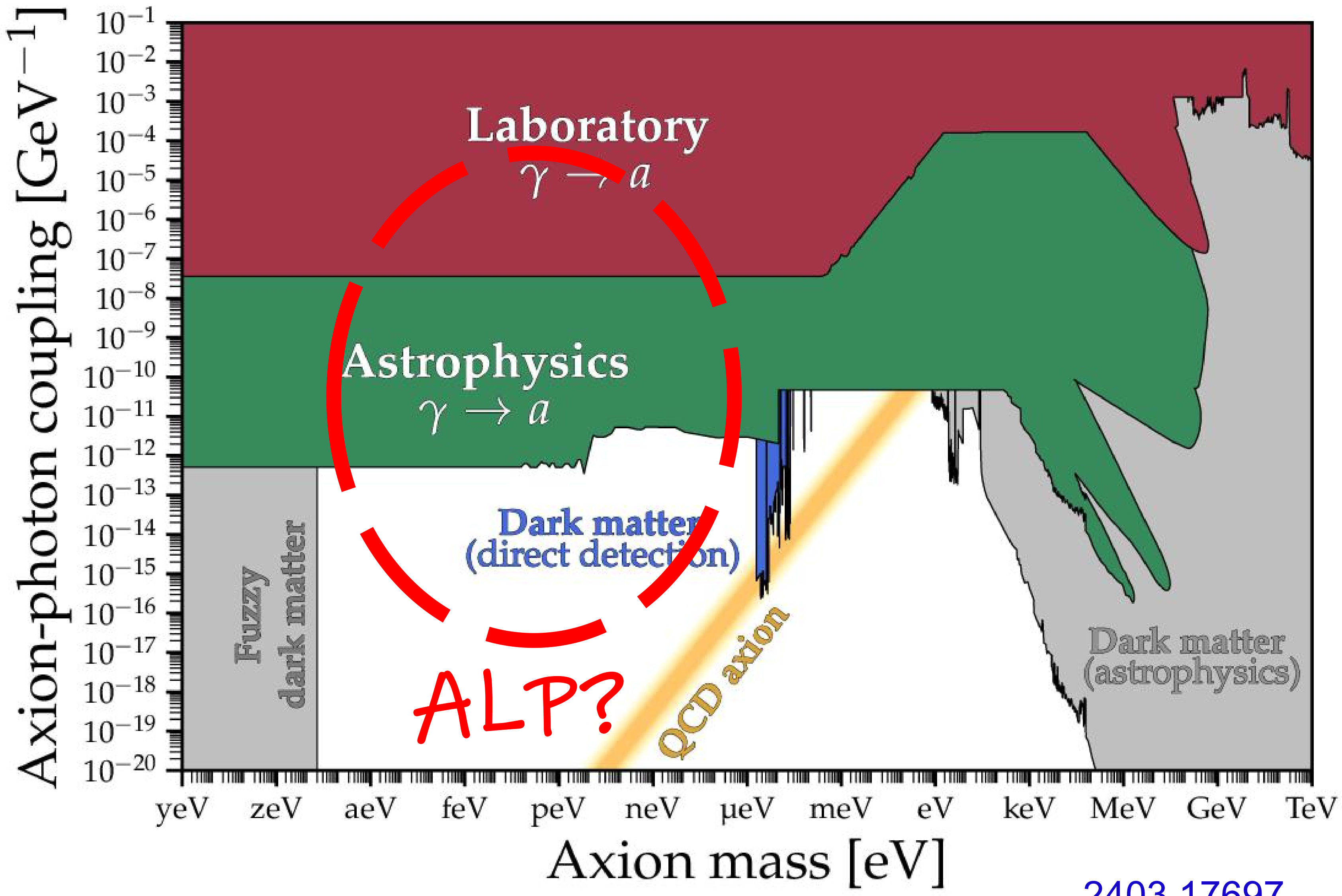
Primakoff Process

$$\mathcal{L} = \frac{1}{4} g_{a\gamma} a F^{\mu\nu} \tilde{F}_{\mu\nu} = g_{a\gamma} a E \cdot B$$

Z. Guo, **Y. Tsai**, L. Wu and Z. Xia, ***Constraints on Axion-Like Particles from 16.5 Years of Fermi-LAT Data and Prospects for VLAST***, arXiv:2507.07786

ALP can be both a LLP and DM

There is no "DM detection", so ALPs in this mass range could be either long-lived particles or dark matter.



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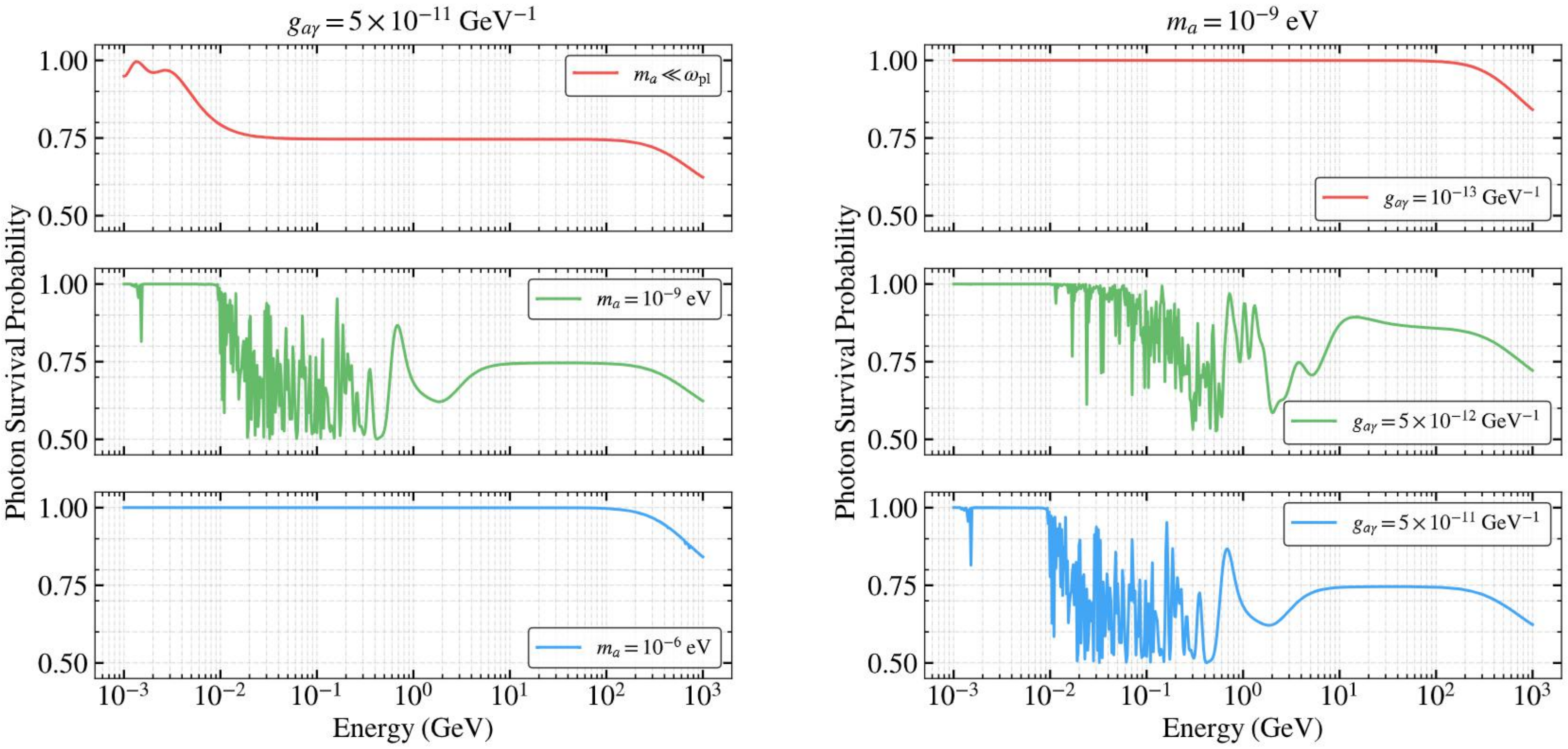
Giant elliptical galaxy: NGC 1275

Property	Details
Object Type	Active Galaxy (AGN), Seyfert 2 Galaxy
Redshift (z)	0.0176
Distance from Earth	70.7 Mpc
Galactic Coordinates	l = 144.4°, b = -10.7°
Host Galaxy	Perseus Cluster (NGC 1275 is the central galaxy of the Perseus cluster)
Core Activity	Strong AGN, radio emission, X-ray emissions, and possible central black hole
X-ray Luminosity	~10^{24} erg/s (from central region)
Radio Emission	Strong radio source, part of the Perseus cluster's radio halo
Supermassive Black Hole Mass	~3.5×10^9 M_{sol} (solar masses)
Radius (Galaxy)	~30 kpc (kiloparsecs)
Average Magnetic Field	~10 μG (microgauss) at the center of the cluster
Mass (Galaxy)	~2×10^{12} M_{sol} (solar masses)

- NGC 1275 is highly gamma-ray bright, with Fermi-LAT significance >100 sigma.
- Its broadband spectrum follows the synchrotron self-Compton model.
- Located in the Perseus cluster, it offers precise magnetic field constraints via rotation measures.

B_T is more or less understood

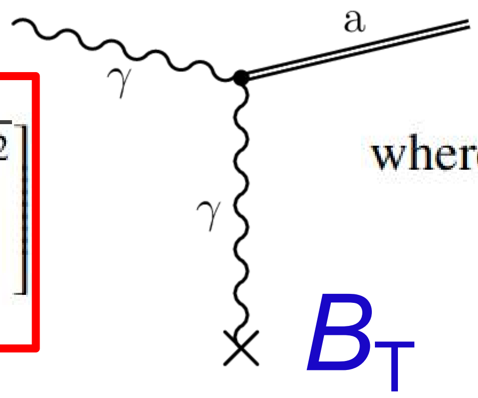
PHOTON-ALP OSCILLATION



E_c is an important quantity to determe oscillation. When m_a>>ω_{pl}, E_c is no longer sensitive to ω_{pl}.

Photon surviving probabilities

$$1-P_{\gamma\to a} = 1-\frac{1}{1+\left(E_c/E_\gamma\right)^2}\sin^2\left[\frac{g_{a\gamma}B_\mathrm{T}l}{2}\sqrt{1+\left(\frac{E_c}{E_\gamma}\right)^2}\right]$$

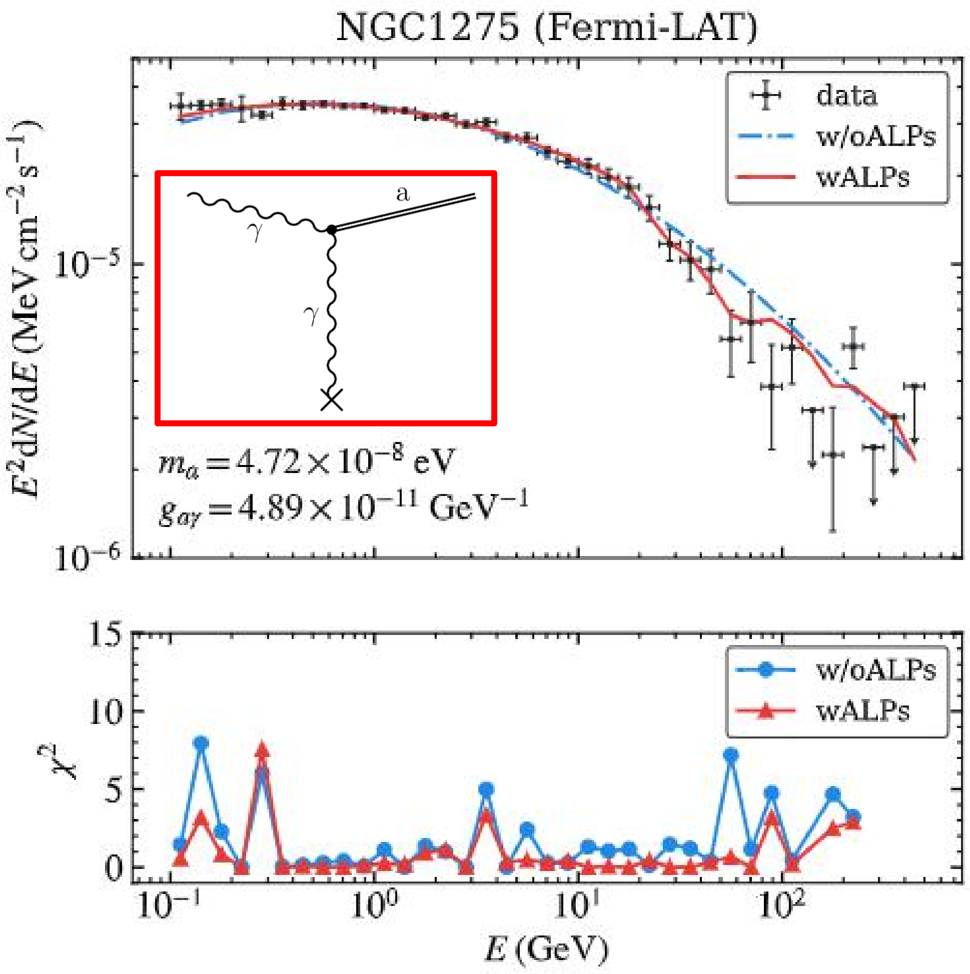


$$E_c = \frac{\left|m_a^2-\omega_\mathrm{pl}^2\right|}{2g_{a\gamma}B_\mathrm{T}},$$

where ω_pl is the plasma frequency:

$$\omega_\mathrm{pl} = \sqrt{4\pi\alpha n_e/m_e},$$

ALP-induced gamma-ray spectrum



$$\left(\frac{\mathrm{d}N}{\mathrm{d}E}\right)_{\mathrm{w/oALPs}} = N_0\left(\frac{E}{E_b}\right)^{-[\alpha+\beta\ln(E/E_b)]}, \quad (8)$$

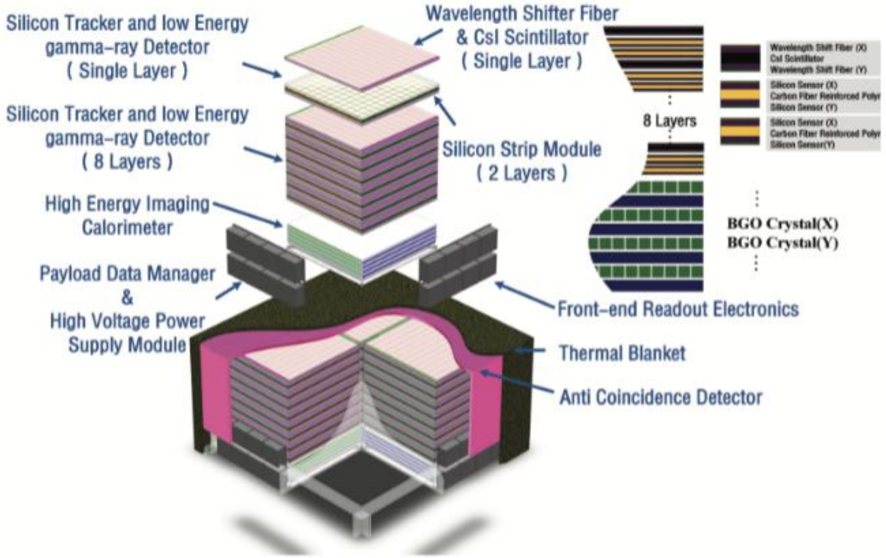
where N_0 is the normalization constant, α is the spectral index, β is the curvature parameter, and E_b is the scale parameter, typically fixed to the characteristic energy value near the low-energy region of the fitted spectrum. In this study, it is set to 0.9578 GeV.

Incorporating the photon-ALP oscillation effect, the intrinsic spectrum is multiplied by the photon survival probability to obtain the oscillatory spectrum for the alternative hypothesis (labeled as wALPs):

$$\left(\frac{\mathrm{d}N}{\mathrm{d}E}\right)_{\mathrm{wALPs}} = P\left(g_{a\gamma}, m_a, E\right)\left(\frac{\mathrm{d}N}{\mathrm{d}E}\right)_{\mathrm{w/oALPs}}. \quad (9)$$

Free parameters to fit data are: $\{\alpha, \beta, N_0\}$ for background and $\{g_{a\gamma}, m_a\}$ for ALP.

VLAST-closing the MeV gap



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甚大面积伽马射线空间望远镜计划*

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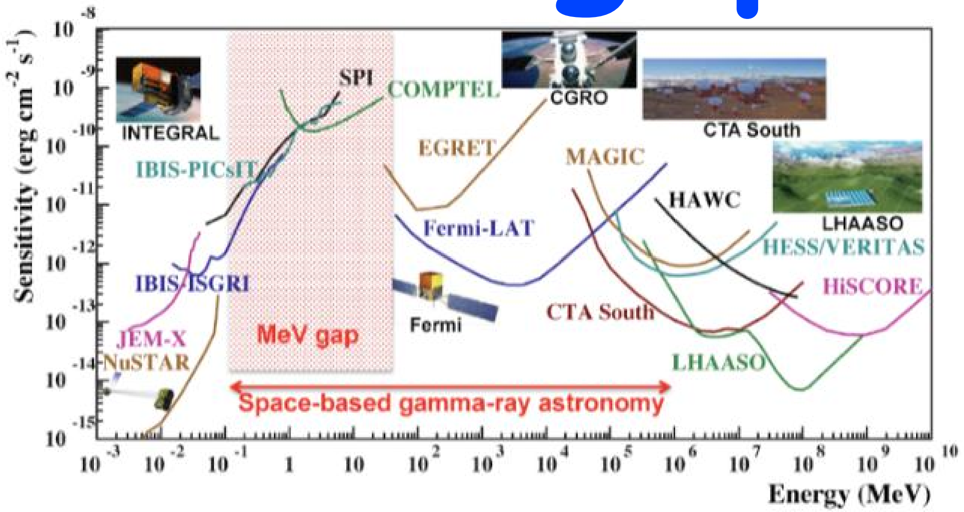
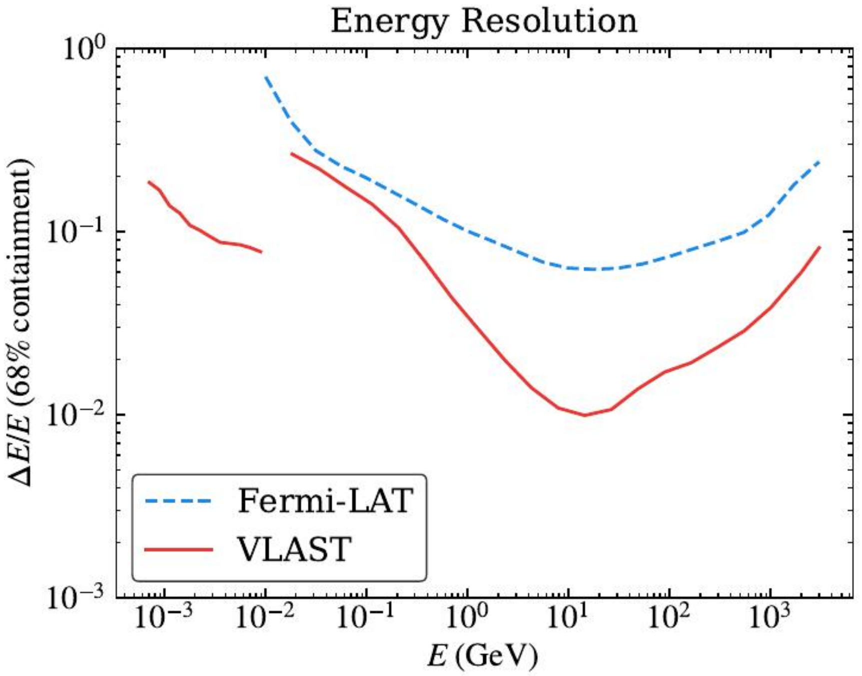
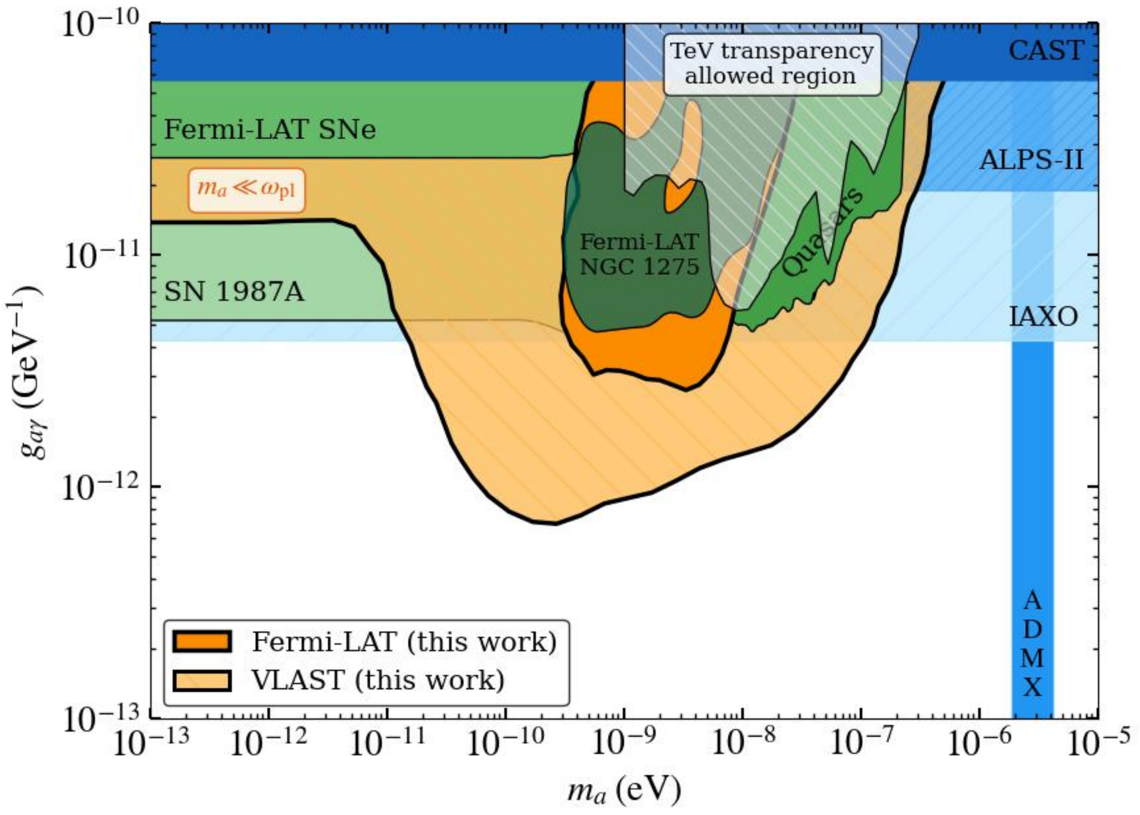
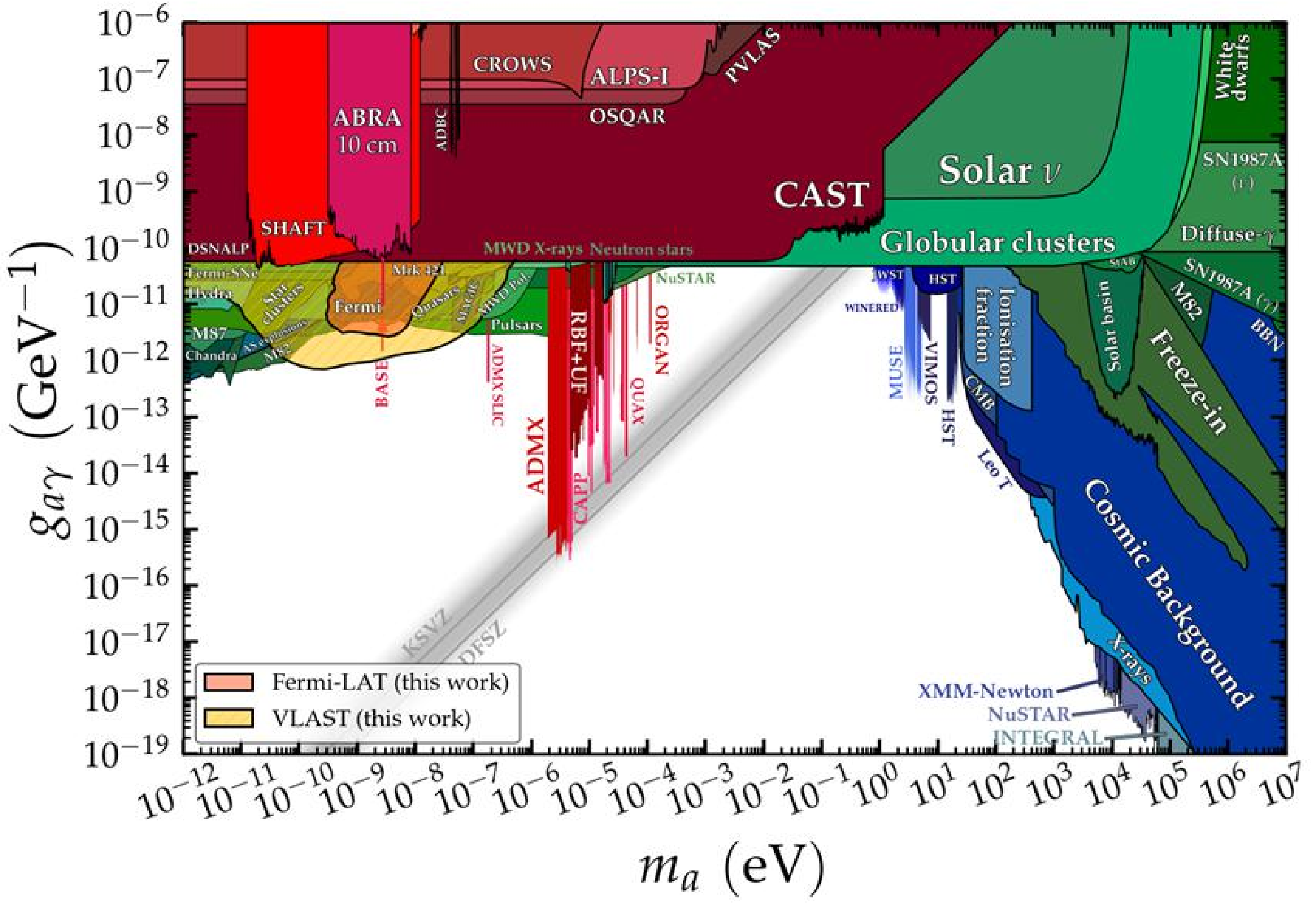




- Very Large Area gamma-ray Space Telescope (VLAST), the successor of DAMPE
- The first 10 m^2 sr level gamma-ray satellite (~20 tons)
- Leading the research on dark matter detection and time-domain astronomy based on MeV - TeV gamma-rays

VLAST prospect

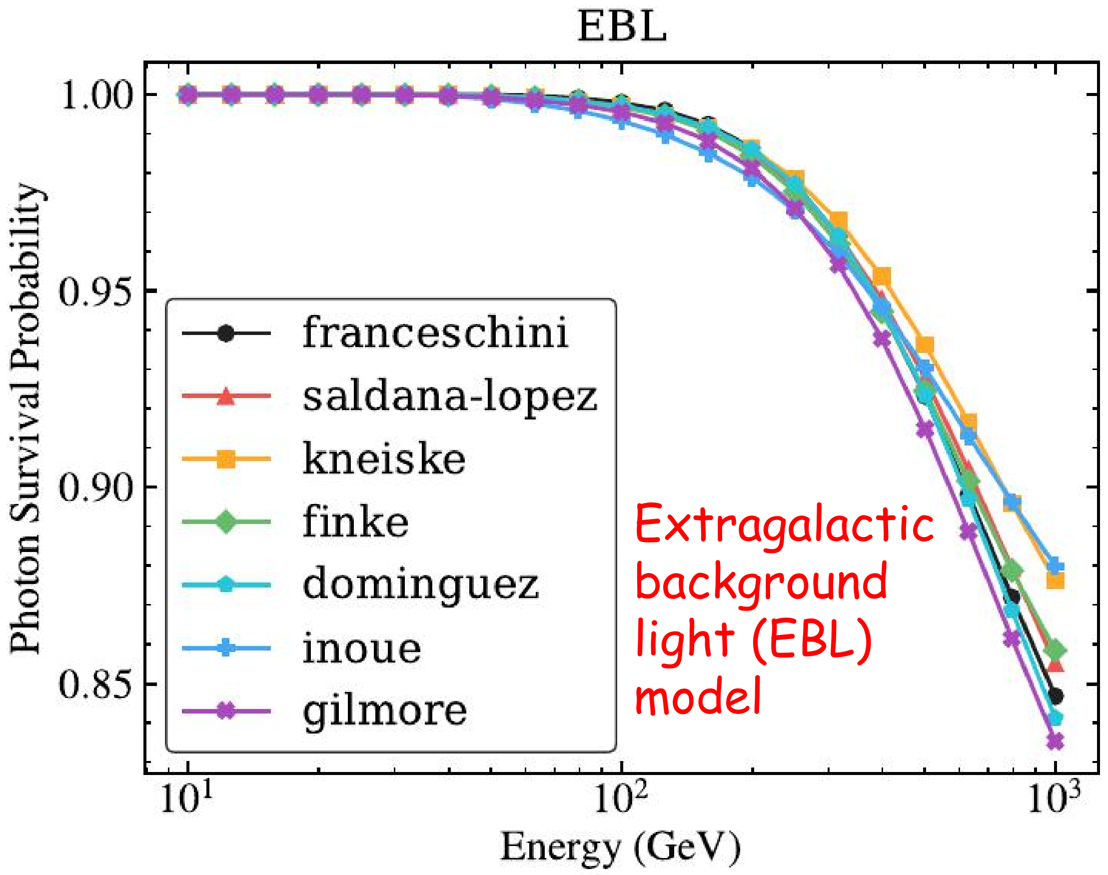




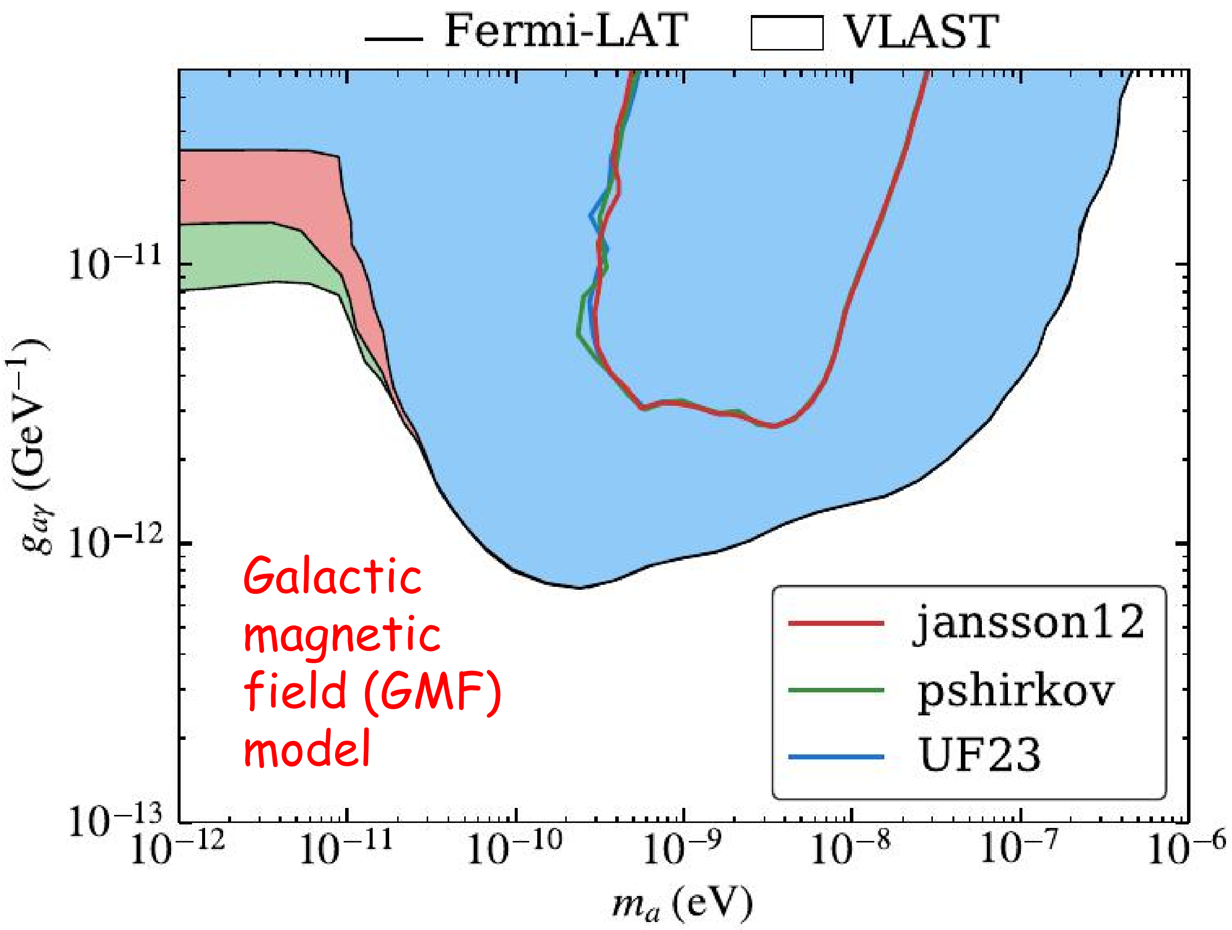
Fermi NGC 1275+Quasars totally cover TeV transparency region.

VLAST will probe $g_{a\gamma}$~10^{-12} at m_a~10^{-10} region.

Uncertainties



Extragalactic background light (EBL) model



Galactic magnetic field (GMF) model

Neither EBL nor GMF affects our result significantly.

Summary (1) long-lived ALP

- Gravitationally trapped in the orbits of stars and subsequently decay into two photons -> monochromatic line spectra -> best senstivities.

- New target (Alpha Centauri) for observation instead of the Sun.

- Use of sensitive X-ray detectors like Chandra and eROSITA.

- Most strigent limits are given even in a conservative setup.

- Theoretical uncertainties are studied.

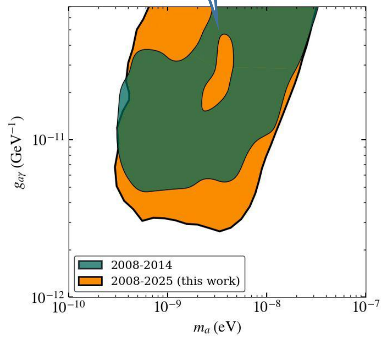
Summary (2) ALP dark matter

- Our study tightens constraints on ALPs for masses ~10^{-9} and 10^{-7} eV and couplings around 10^{-11} and 10^{-10} GeV^{-1}.

- Our results exclude previously viable regions ("holes") in ALP parameter space.

- Simulated result indicate that VLAST could further enhance sensitivity—especially extending reach to slightly heavier ALPs or weaker couplings.

No hole now



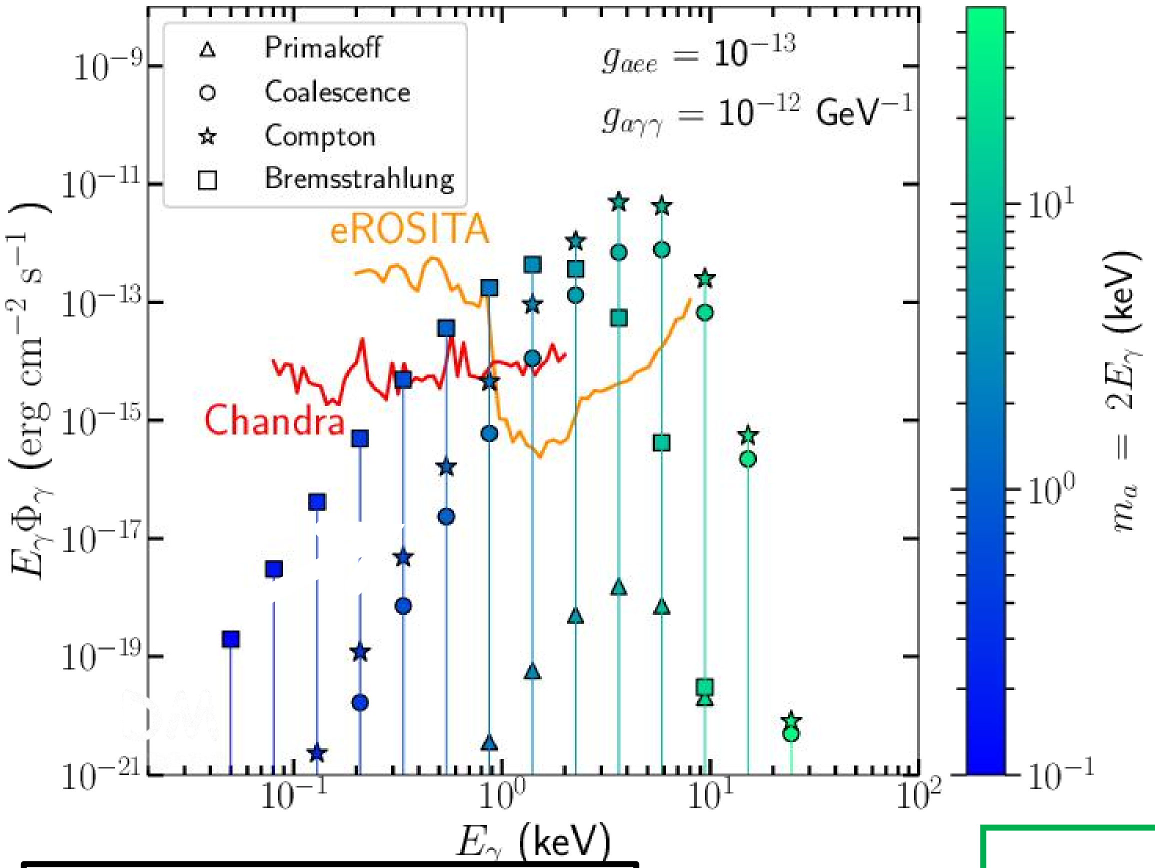
Thank you for listening!

ALP production and capture

$$\mathcal{L} = \frac{1}{2}\partial^\mu a \partial_\mu a - \frac{1}{2}m_a^2 a^2 - \frac{1}{4}g_{a\gamma\gamma} a F^{\mu\nu}\widetilde{F}_{\mu\nu} - \frac{1}{2}g_{aee} a \bar{\psi}\gamma^5\psi$$

$$\Gamma^{\text{Primakoff}} \simeq \frac{g_{a\gamma\gamma}^2 T \kappa^2}{32\pi^2}\left[\frac{8p^2}{3(\kappa^2+m_a^2)} + O(p^4)\right].$$

$$\Gamma^{\text{brem.}} \simeq \frac{\alpha^2 g_{aee}^2 \bar{n}_N n_e}{32\sqrt{2}\pi^{5/2} m_e^{7/2} T^{3/2}} \times \int d\epsilon \left[\log\frac{2+2\sqrt{1-\epsilon}-\epsilon+\xi}{\epsilon+\xi} \times \exp\{-\frac{m}{\epsilon T}\}\right],$$



$$\Phi_{E,\gamma}(t) = \frac{1}{4\pi D^2}\int_{R_s}^{\infty} dr \cdot 4\pi r^2 n_a^{\text{orb}}(t)\Gamma_{a\gamma\gamma},$$

$|\mathcal{M}|^2 \propto g_{a\gamma\gamma}^2$

- Primakoff process has never be the dominant, because p^2.
- Photon coalescence is only important when g_{aee}^2 is suppressed.

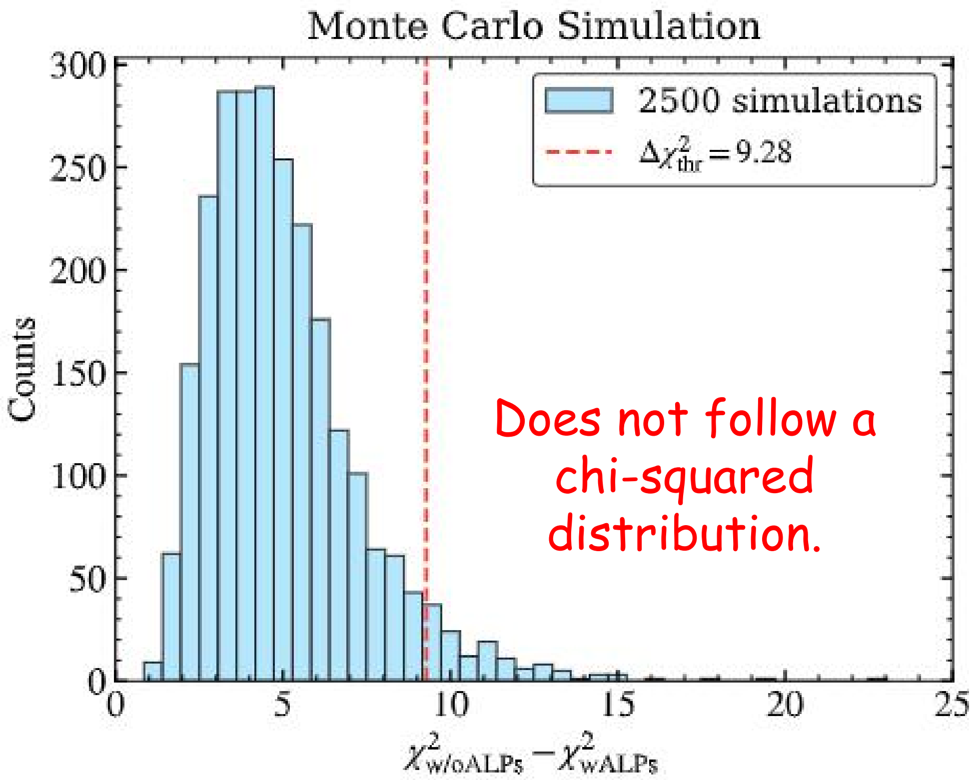
$$\Gamma^{\text{coal.}}(T) = \Gamma_{a\gamma\gamma}\frac{m_a^2 - 4\omega_p^2}{m_a^2}\left(\frac{m_a}{E_a}\right)\left[1 + \frac{2T}{p}\ln\frac{1-e^{-(E_a+p)/2T}}{1-e^{-(E_a-p)/2T}}\right]$$

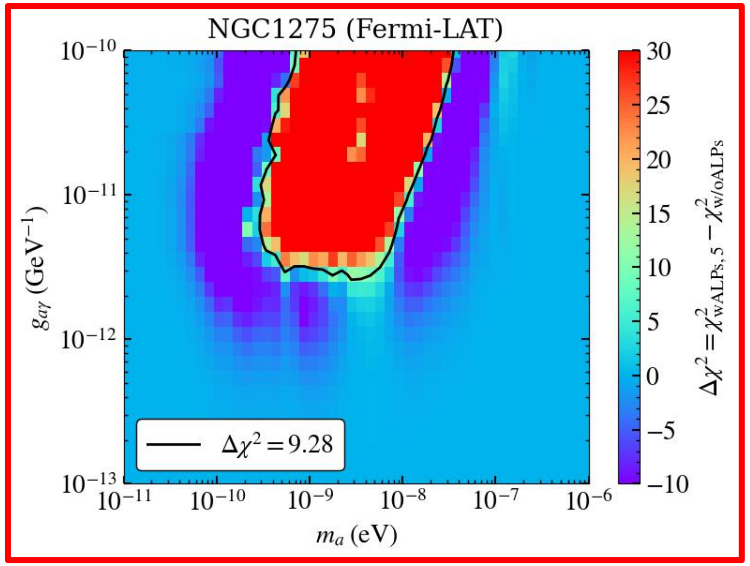
$|\mathcal{M}|^2 \propto g_{aee}^2$

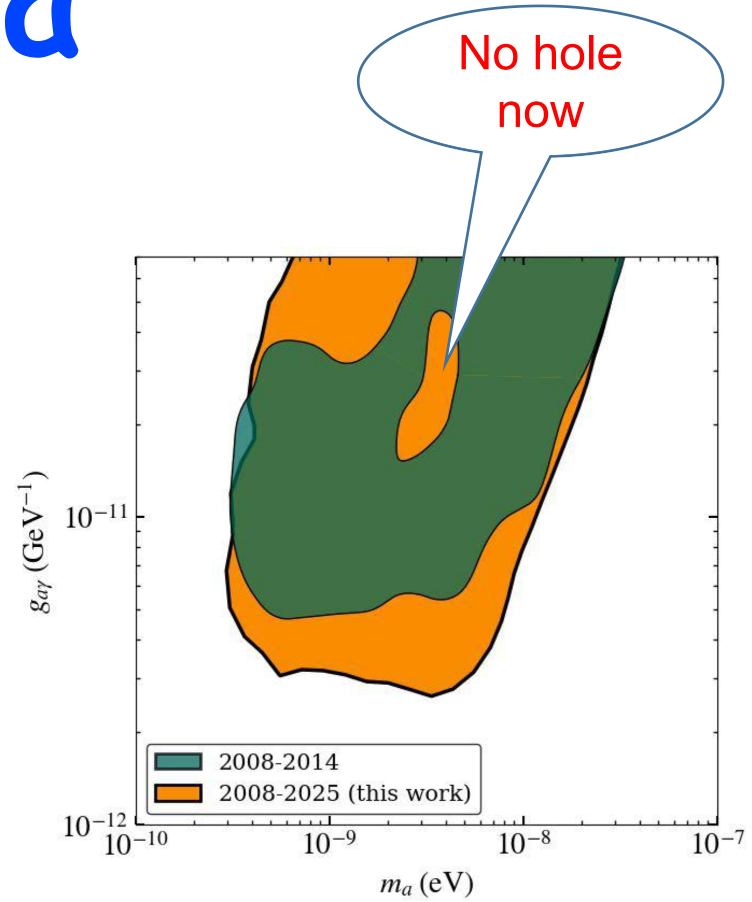
- Bremsstrahlung is important for ALP mass less than 10 keV when g_{aee}^2 is NOT suppressed.
- Compton dominant the region where the ALP mass greater than 10 keV.

$$\Gamma^{\text{Comp.}} \simeq \alpha g_{aee}^2 n_e \frac{m_a}{m_e^4}\sqrt{m_a^2 - \omega_p^2}.$$

Constraints from 16.5 Years of Fermi-LAT Data

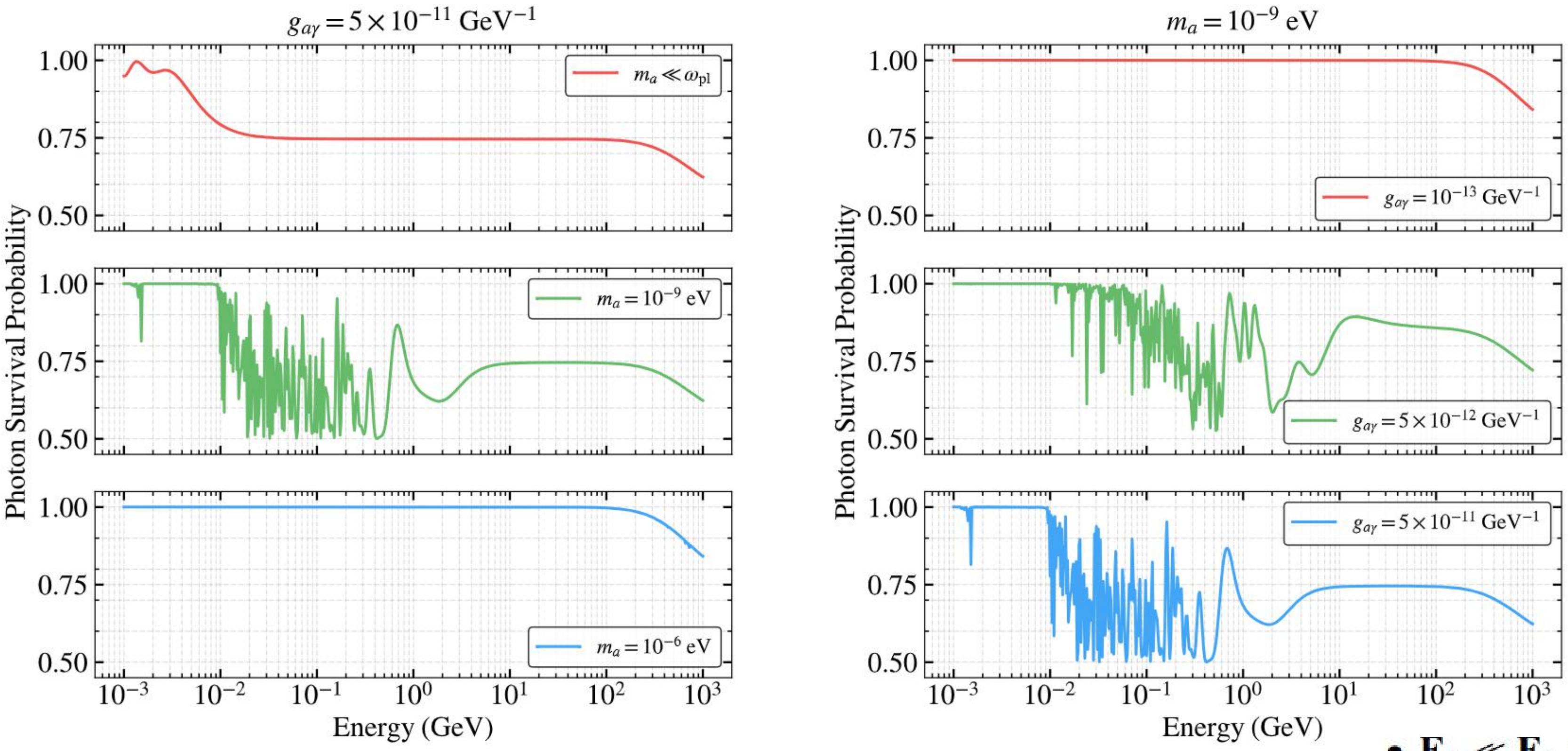






We perform a Monte Carlo simulation to include 100 random realizations of Gaussian turbulent magnetic fields.

PHOTON-ALP OSCILLATION



Clearly, the detectable mass range (oscillation signature) is more sensitive to E_c than to the detectors' energy upper limits.

Photon surviving probabilities

$$1 - P_{\gamma\to a} = 1 - \frac{1}{1+(E_c/E_\gamma)^2}\sin^2\left[\frac{g_{a\gamma}B_\mathrm{T}l}{2}\sqrt{1+\left(\frac{E_c}{E_\gamma}\right)^2}\right], \quad (2)$$

- $\mathbf{E_\gamma \ll E_c}$: the photon-ALP oscillation is weak, with a low conversion probability, and the photon survival probability is close to 1.
- $\mathbf{E_\gamma \sim E_c}$: photons and ALPs undergo strong mutual conversion, leading to obvious oscillation.
- $\mathbf{E_\gamma \gg E_c}$: the conversion probability is still large, however, the photon survival probability in Equation (2) mildly varies with E_γ and becomes gradual.