New Constraints on Axion-Like Particles from IXPE Polarization Data for Magnetars

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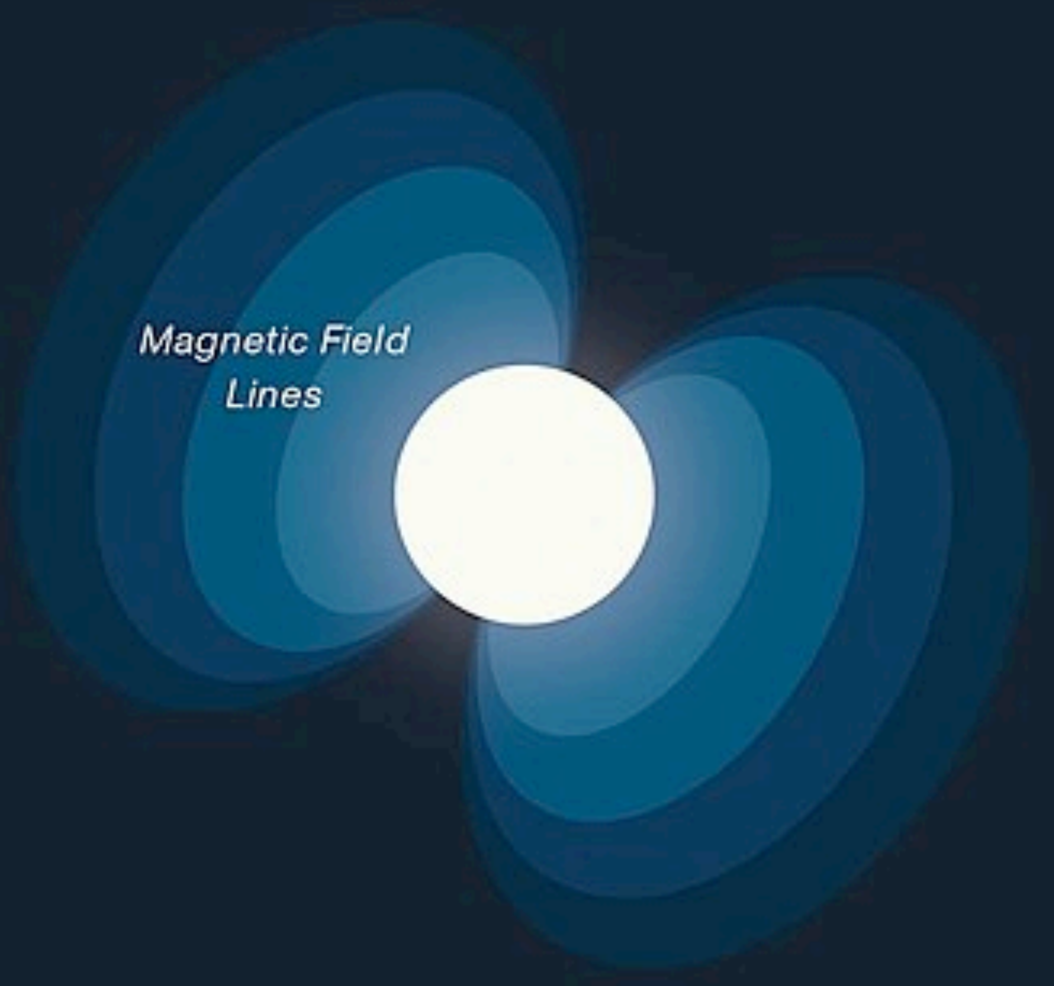
DIFFERENT NEUTRON STAR TYPES

A neutron star is a dense core left behind after a massive star goes supernova and explodes. Though only about 10 to 20 miles (15 to 30 kilometers) wide, they can have three times the mass of our Sun, making them some of the densest objects in the universe, second only to black holes. A teaspoon of neutron star material would weigh 4 billion tons on Earth. There are several types of neutron stars.

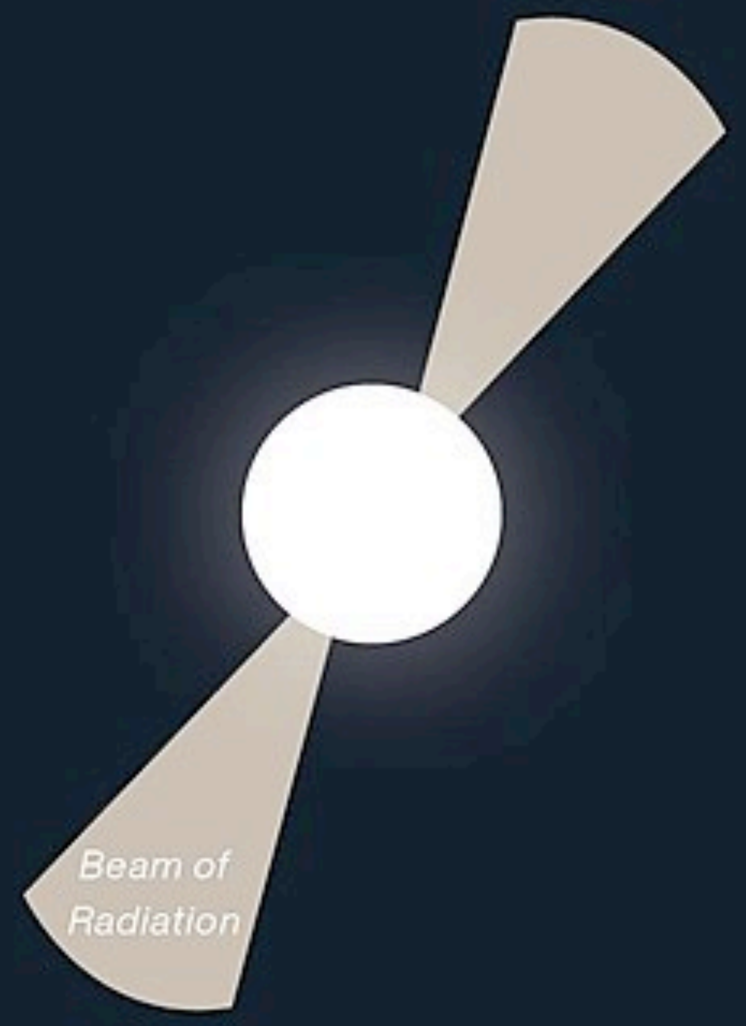
MAGNETAR

A magnetar is a neutron star with a particularly strong magnetic field, about 1,000 times stronger than a normal neutron star. That's about a trillion times stronger than Earth's magnetic field and about 100 million times stronger than the most powerful magnets ever made by humans. Scientists have only discovered about 30 magnetars so far.



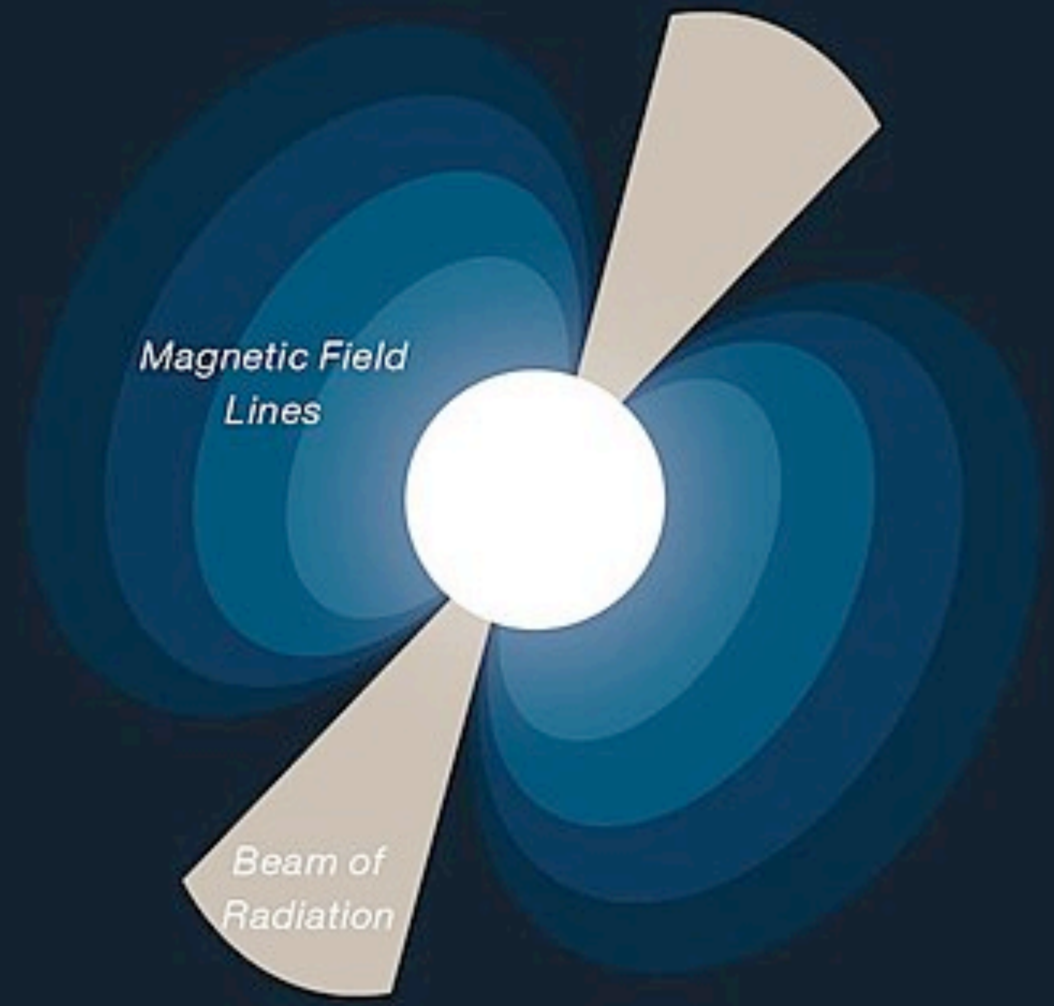
PULSAR

Most of the roughly 3,000 known neutron stars are pulsars, which emit twin beams of radiation from their magnetic poles. Those poles may not be precisely aligned with the neutron star's rotation axis, so as the neutron star spins, the beams sweep across the sky, like beams from a lighthouse. To observers on Earth, this can make it look as though the pulsar's light is pulsing on and off.



MAGNETAR + PULSAR

There are now six known neutron stars that are both pulsars and magnetars.



Facts accurate as of June 2020

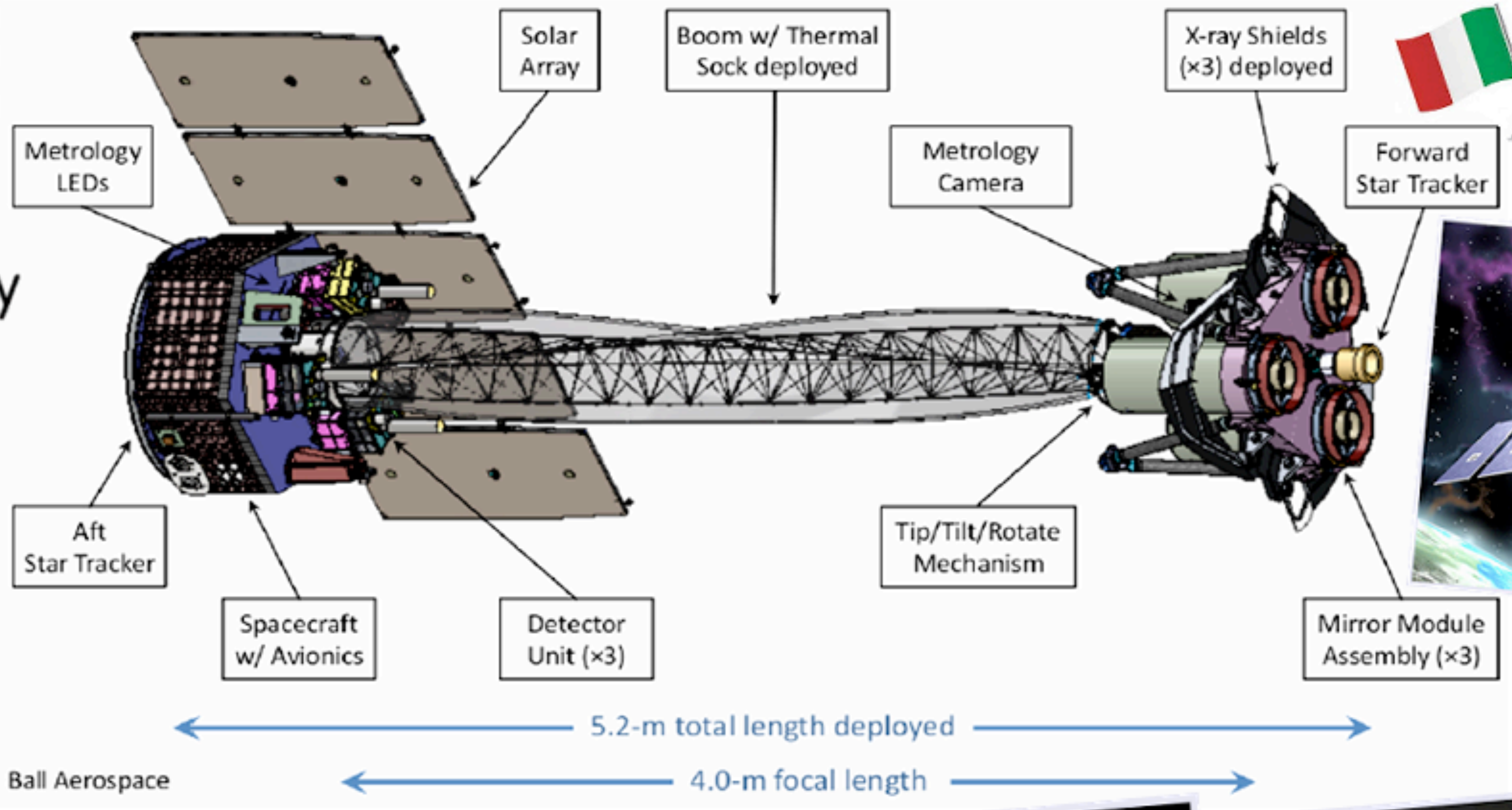
IXPE

Imaging X-Ray Polarimetry Explorer

Marshall Space Flight Center

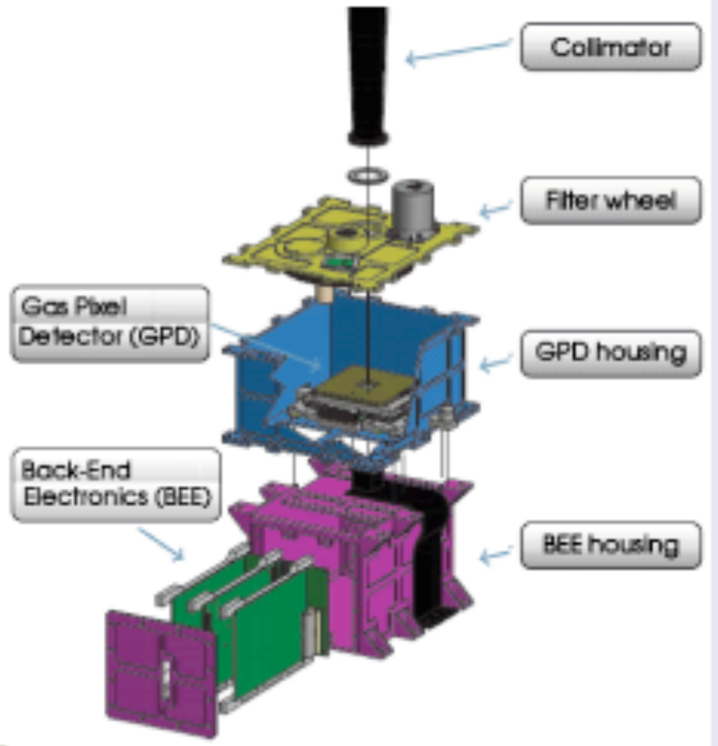
Agenzia Spaziale Italiana

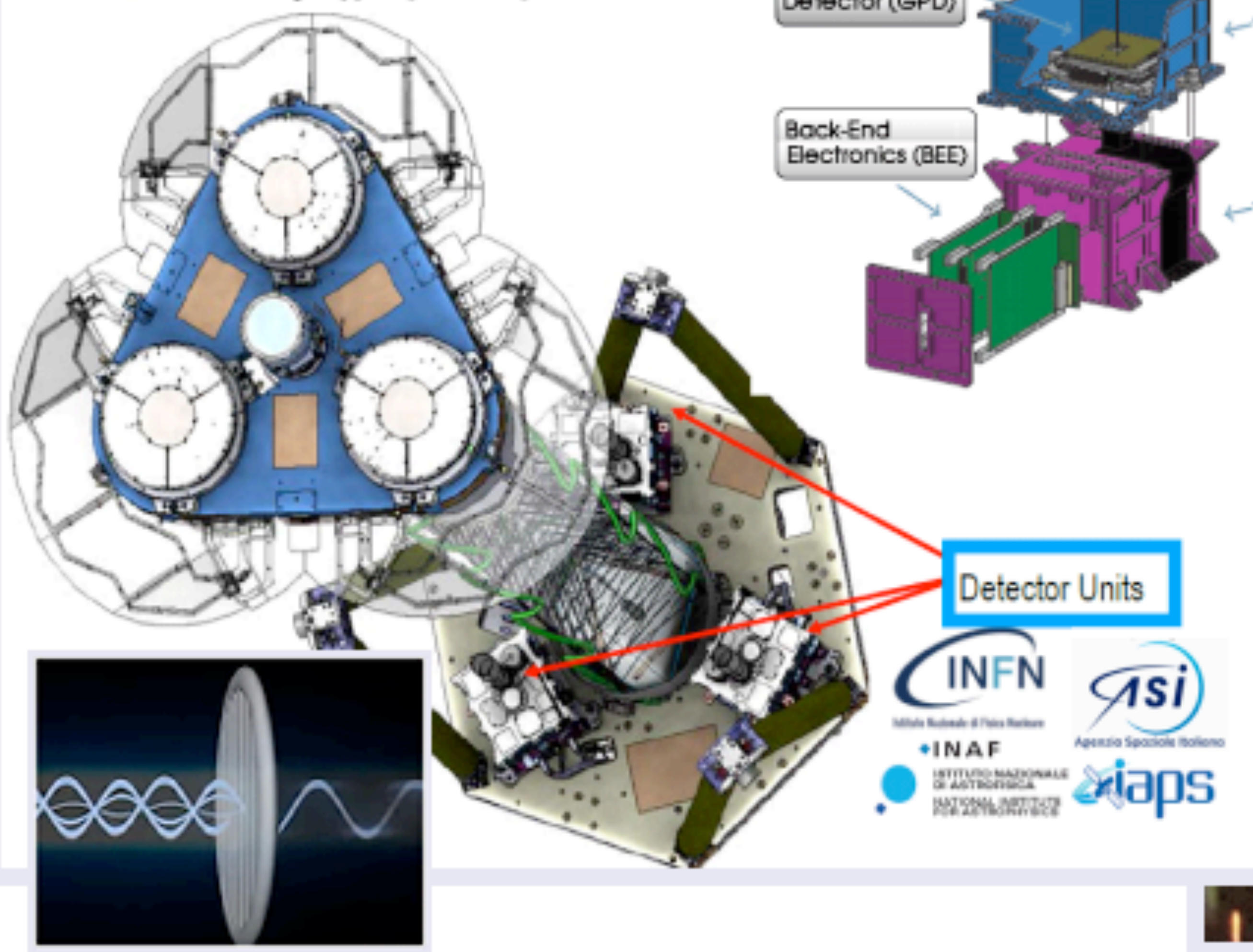
Ball Aerospace

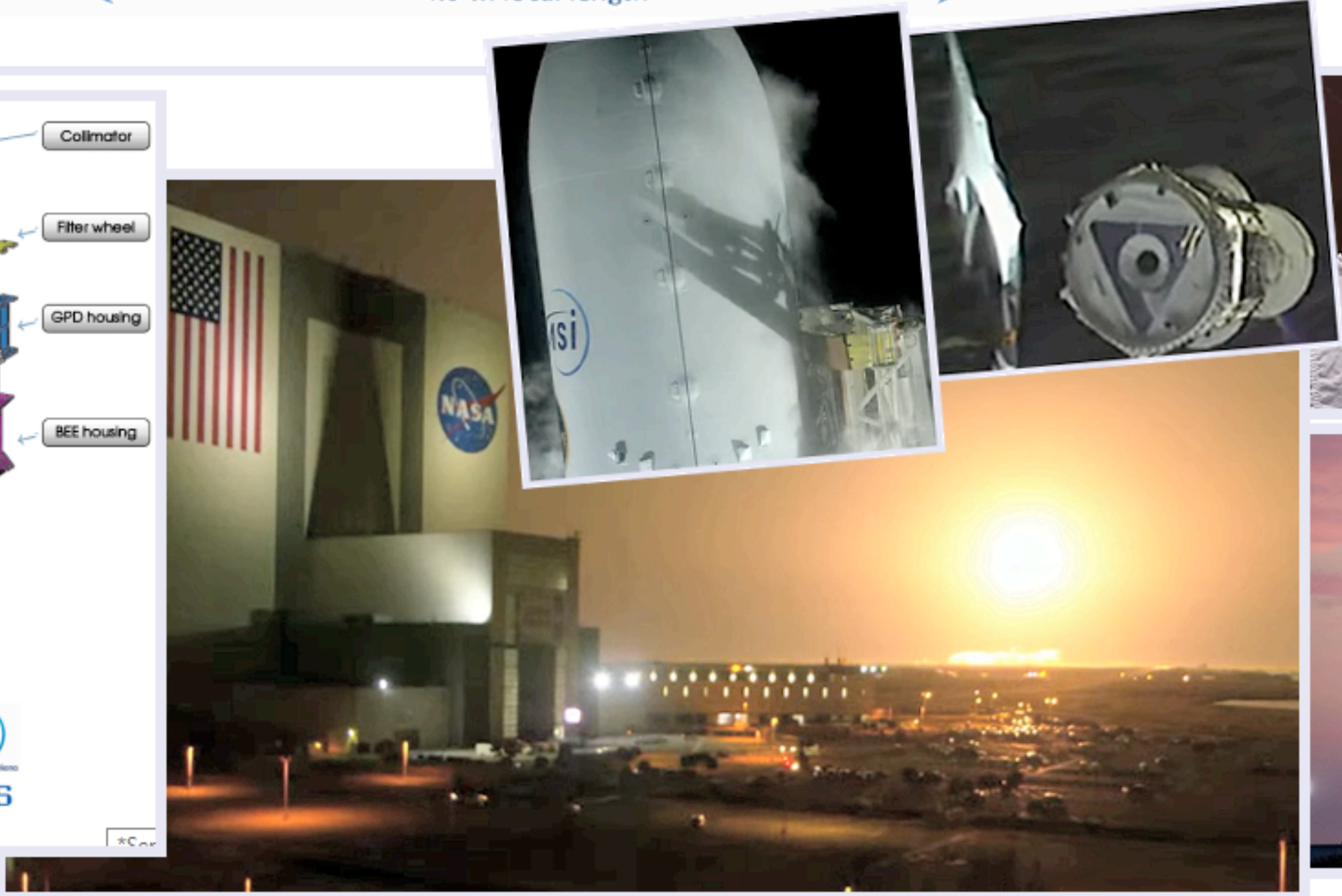


DETECTOR UNIT

- DU design & analysis
- DU Product & Quality assurance
- DU CAD, TMM/GMM
- GPD Design & Development
- DAQ, collimator, housing design & procurement
- HV board & FCW interface def & procurement supp
- DU AIT/AIV and environmental tests
- Post-delivery support (till launch)







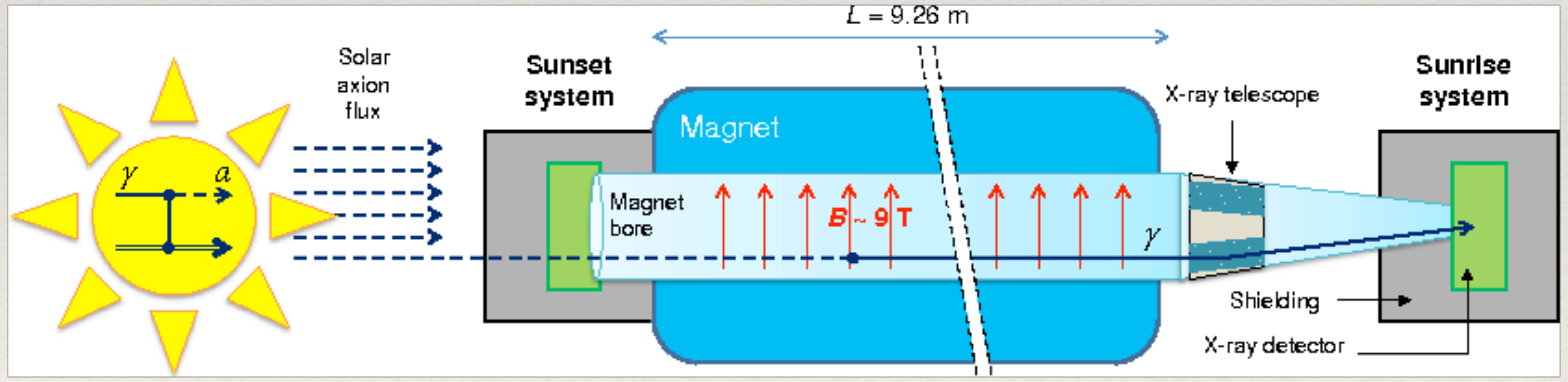
Axion and its Interactions with Standard Model Particles

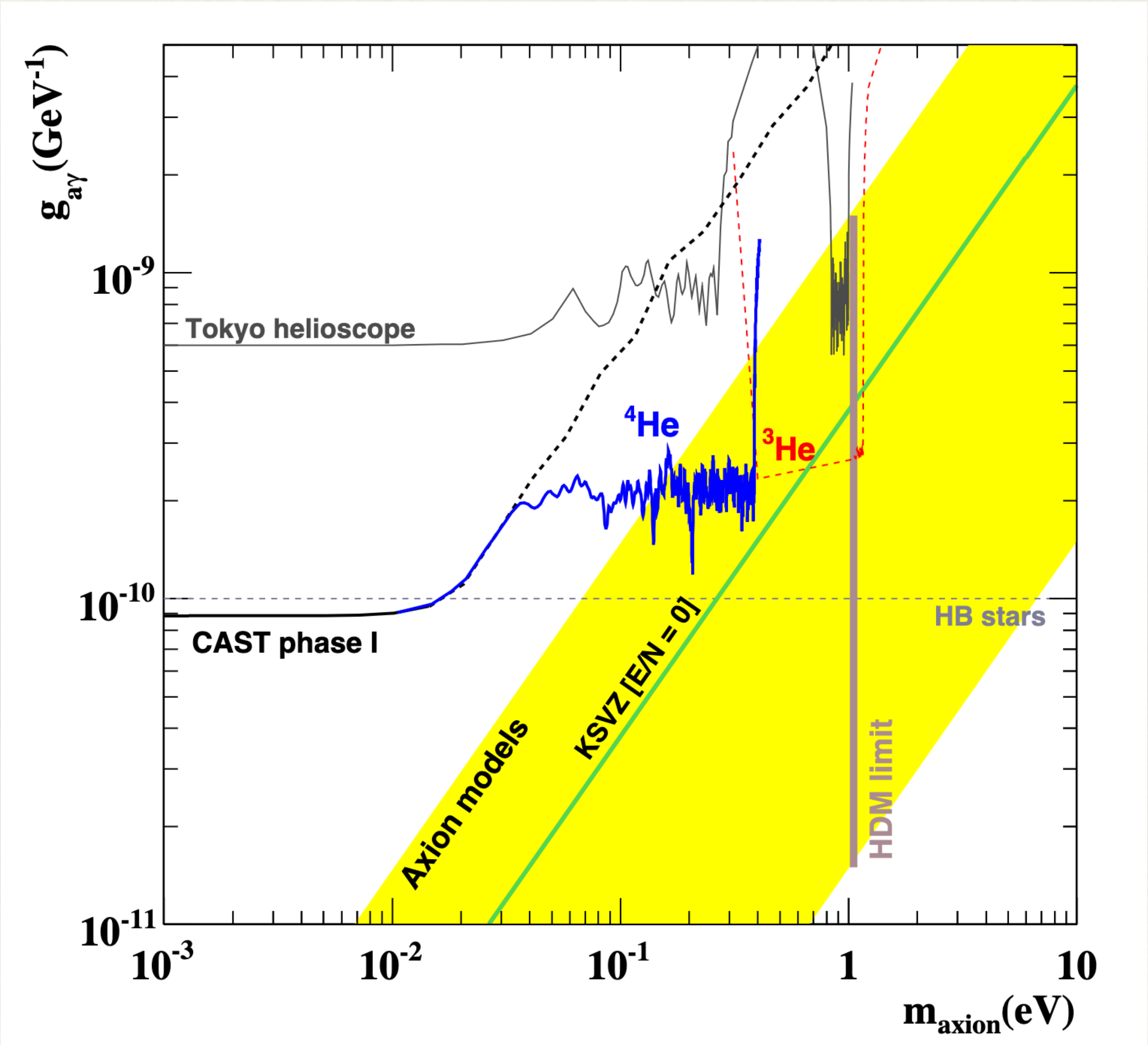
We consider ALPs that have a coupling to nucleons as well as to photons:

$$\mathcal{L} \supset -\frac{g_{a\gamma}}{4} a F_{\mu\nu} \tilde{F}^{\mu\nu} + g_{aN} (\partial_\mu a) \bar{N} \gamma^\mu \gamma_5 N$$

Axion Haloscope:

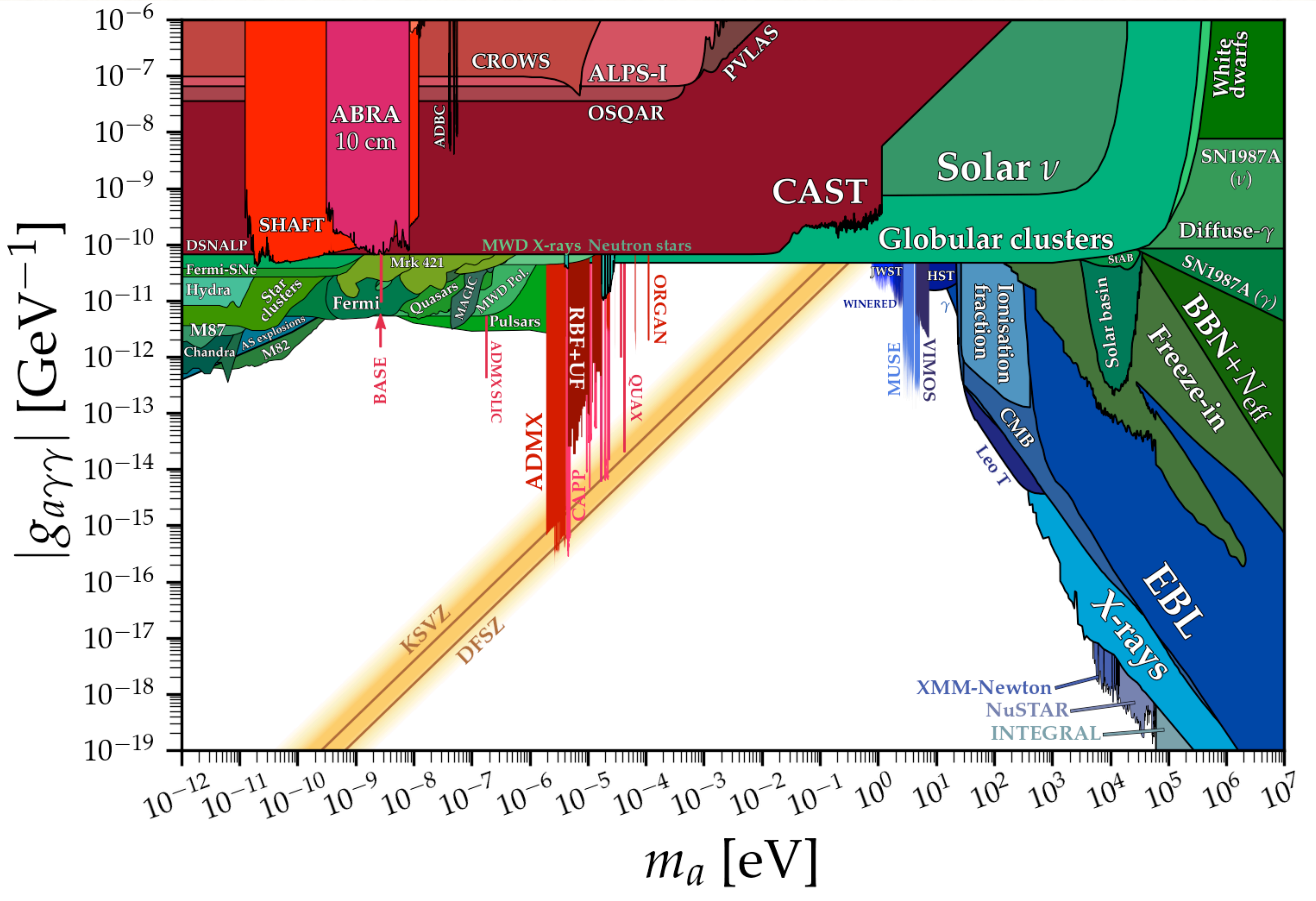
Cast Experiment





arXiv:hep-ex/0702006

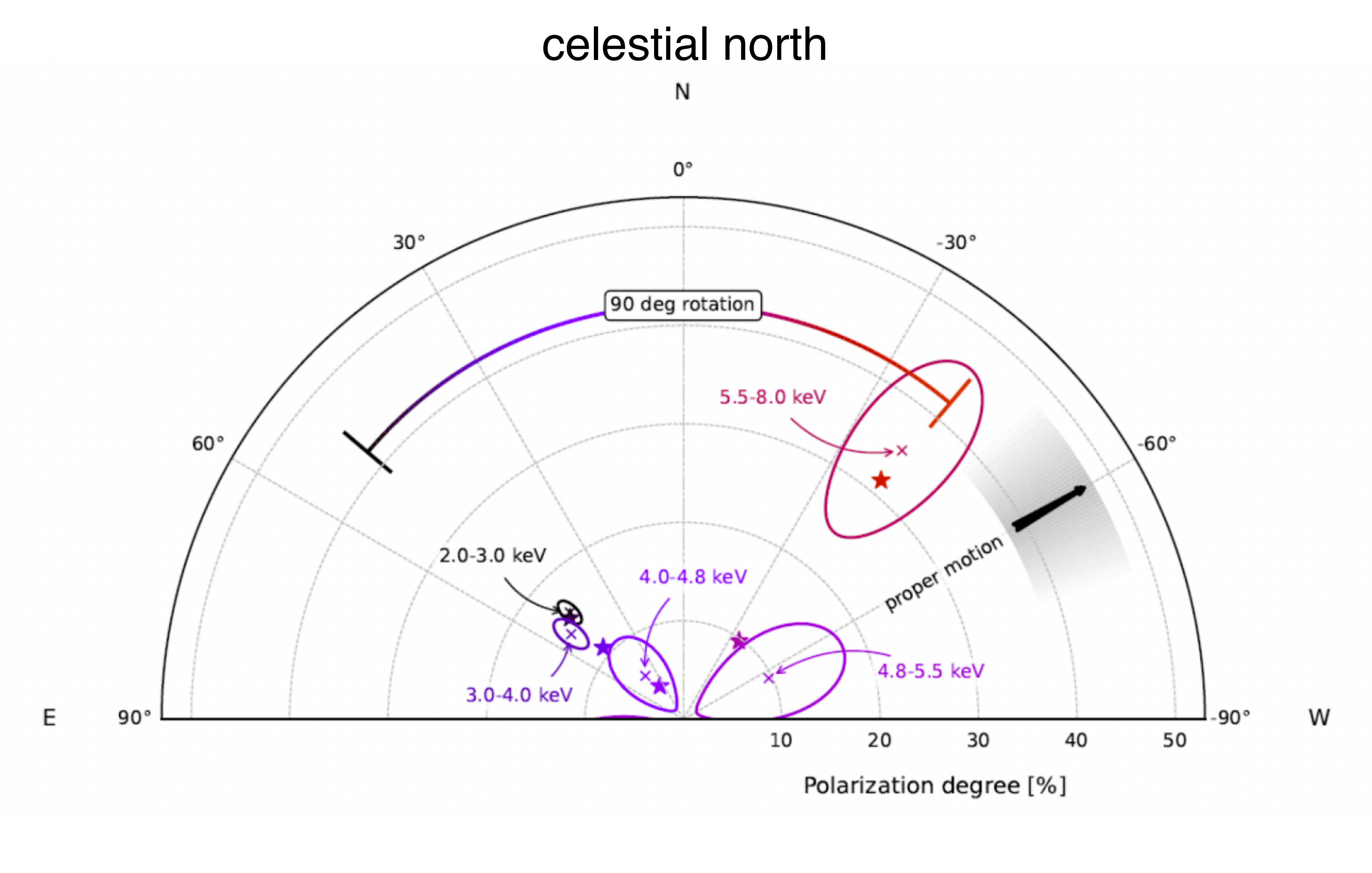
Experimental Constraints on Axion-Photon Coupling

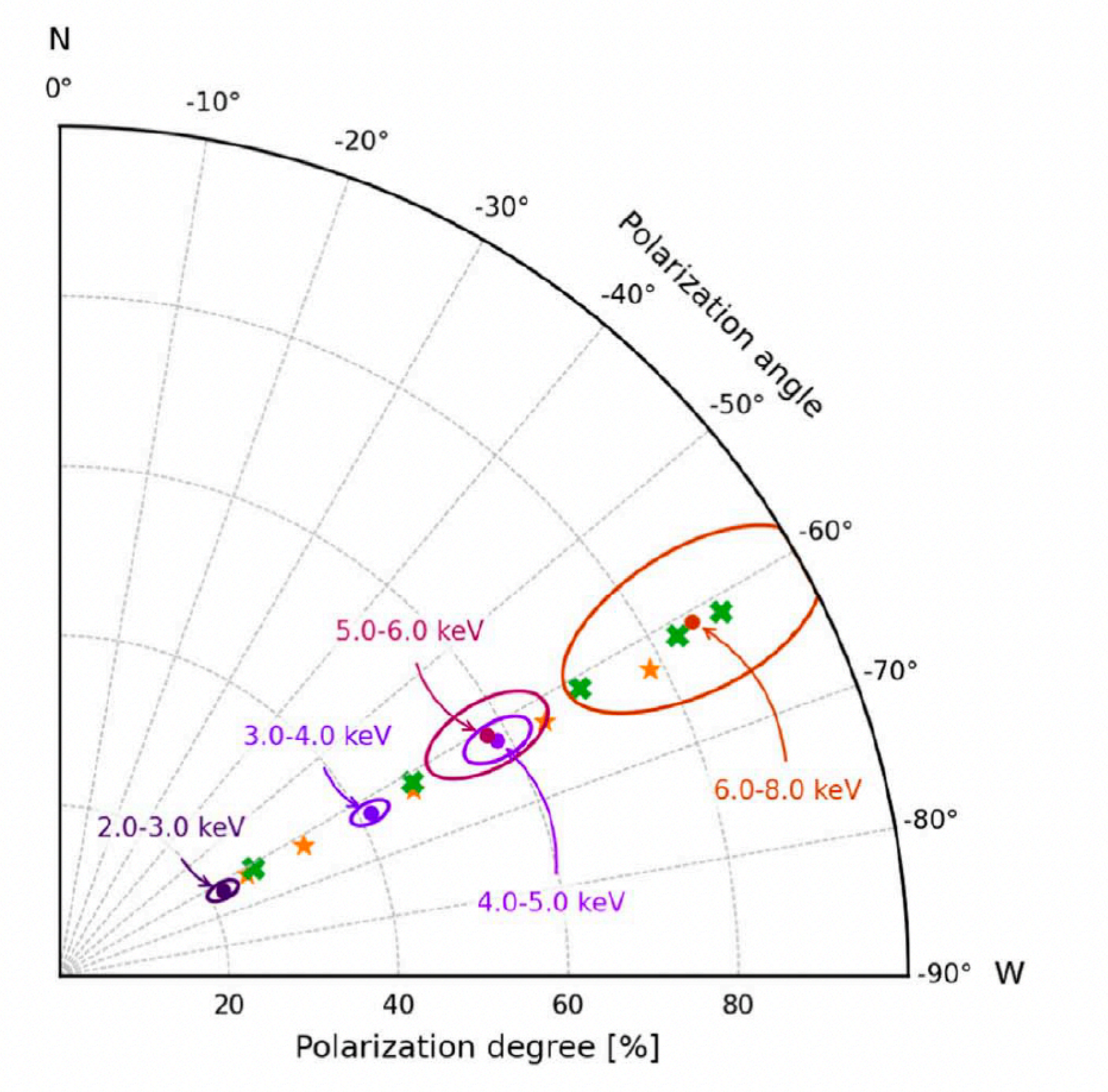


Polarization Data of Magnetars

Magnetar	Field Strength	Distance	Period	Age
4U 0142+61	2.6×10^{14} G	3.6(4) kpc	8.68869249(5) s	68 kyr
1RXS J170849.0-400910	9.4×10^{14} G	3.8(5) kpc	11.00502461(17) s	9.0 kyr

Key parameters for the two magnetars

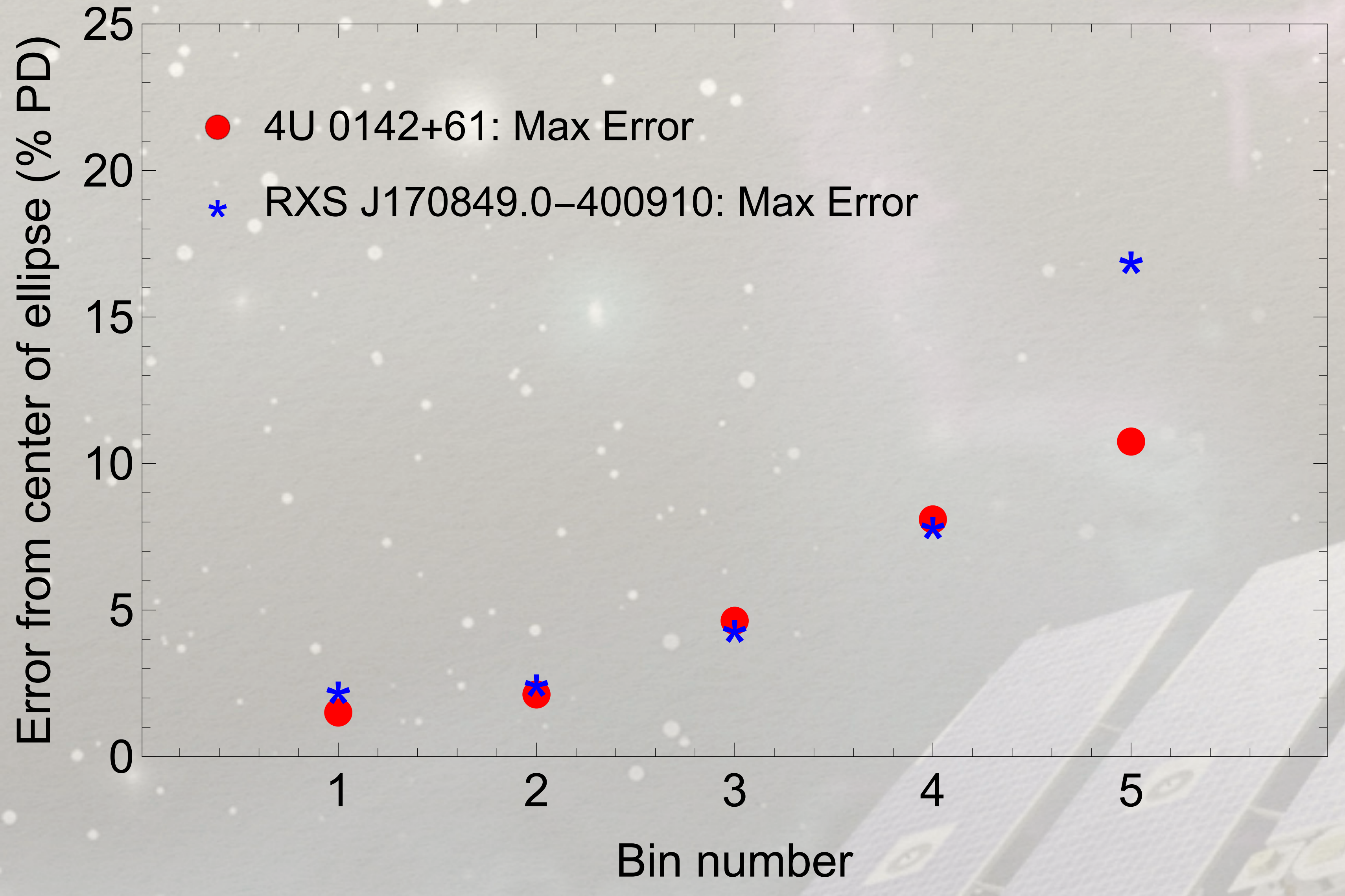




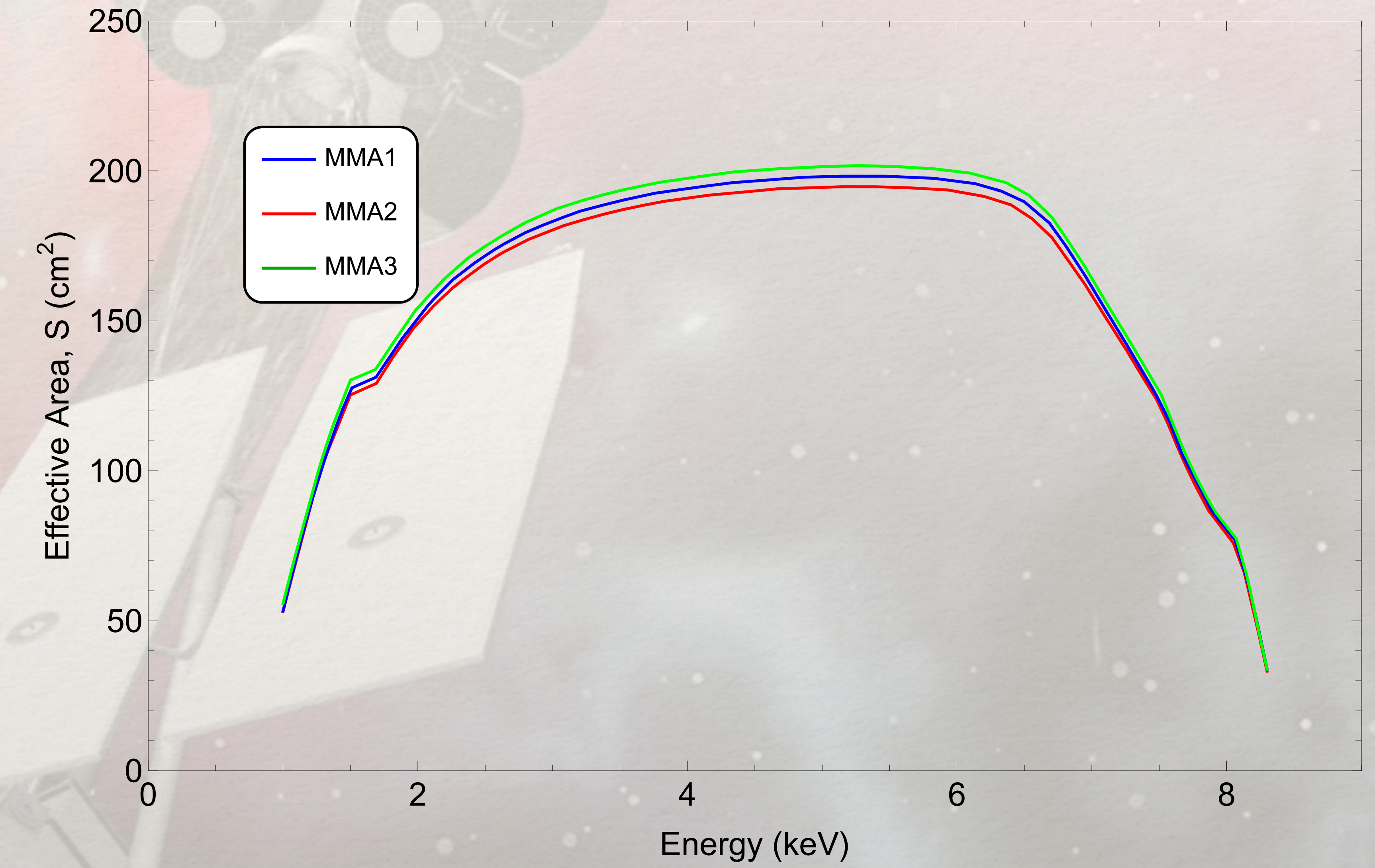
Polarisation data for first magnetar: 4U 0142+61

Polarisation data for second magnetar: RXS J170849.0-400910

Polarization Measurement Uncertainty and Detector Effective Area



The maximum error (in percentage) from the observational central data point to the edge of the ellipses (68% and 50% C.L. uncertainty contours) in the (PD, PA) plane of polar plots, for magnetars 4U 0142+61 and RXS J170849.0-400910, respectively. The horizontal axis depicts the energy bin number in the sequence of five bins between 2 – 8 keV.



The best-fit models of the effective area of each of the three Mirror Module Assemblies (MMAs, i.e., the three detectors) of IXPE as a function of photon energy.

arXiv: 2307.02259

Axion Emissivity from Nucleons Scattering

ALP emissivity spectrum from nucleon interactions inside magnetar:

$$n + n \to n + n + a$$
$$n + p \to n + p + a$$
$$p + p \to p + p + a.$$

$$\frac{dQ^0_{nn}}{d\omega_a} = \frac{1}{36\pi^7} C_\pi \left(\frac{m_N}{m_\pi}\right)^4 f^4 g^2_{aN} p_{Fn} F(c) \omega_a^3 \frac{\omega_a^2 + 4\pi^2 T^2}{e^{\omega_a/T} - 1}.$$

$$\frac{dQ^S_{np}}{d\omega_a} = \frac{2}{3\pi^7} C_\pi \left(\frac{m_N}{m_\pi}\right)^4 f^4 g^2_{aN} p_{Fp} G(c,d) T^3 \omega_a^2 I^S_{np}(y = \omega_a/T, n_B, T),$$

$$\frac{dQ^S_{pp}}{d\omega_a} = \frac{2}{3\pi^7} C_\pi \left(\frac{m_N}{m_\pi}\right)^4 f^4 g^2_{aN} p_{Fp} F(d) T^3 \omega_a^2 I^S_{pp}(y = \omega_a/T, n_B, T).$$

Axion emissivity in general form:

$$\frac{dL^\infty}{d\omega_a^\infty} = 4\pi \int_0^{R_\mathrm{crust}} dr \, \frac{r^2 e^{\phi(r)}}{\sqrt{1 - \frac{2m(r)G}{r}}} \frac{dQ_\mathrm{total}}{d\omega_a},$$

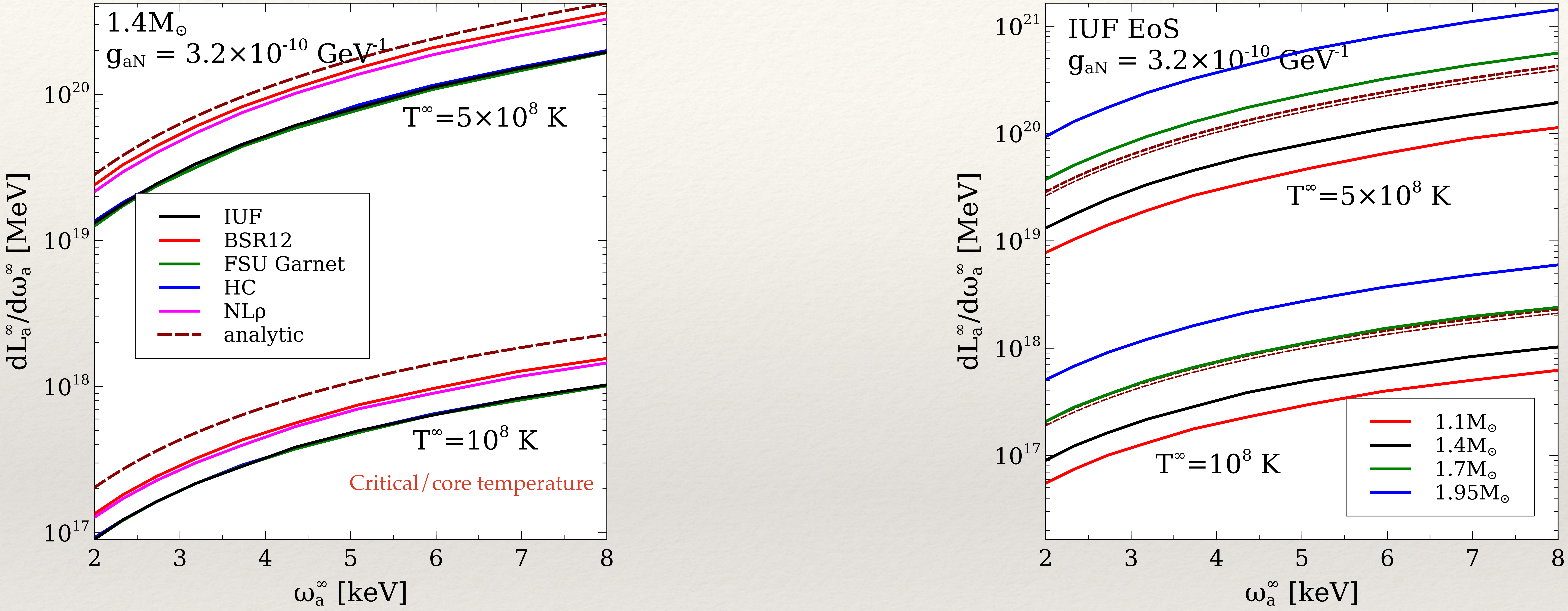
Axion emissivity analytical:

$$\frac{dL}{d\omega_a} = \frac{1}{3^{5/3}\pi^{16/3}} \frac{m_N^{11/3}}{m_\pi^4} g^2_{aN} R^3 \rho^{1/3} \frac{\omega_a^3(\omega_a^2 + 4\pi^2 T^2)}{e^{\omega_a/T} - 1}$$

Nuclear saturation density:

$$\rho_0 \approx 2.8 \times 10^{14}\,\mathrm{g} \cdot \mathrm{cm}^{-3}$$

Axion Emissivity Rates



Left panel: Various ALP spectra found from varying the nuclear EoS, while fixing the magnetar mass at $1.4M_\odot$. The upper (lower) set of curves corresponds to a redshifted core temperature $T^\infty = 5\ (1) \times 10^8$K. Right panel: Various ALP spectra for different magnetar masses, fixing the EoS to be IUF. In both panels, the dashed dark red lines correspond to the analytic estimate of the spectrum. In the right panel, there is a set of four, essentially overlapping, dashed red lines for each temperature, showing that the analytic approximation of the spectra is essentially independent of the magnetar mass, while the full calculation of the spectra has significant dependence on the magnetar mass. The ALP-nucleon coupling is taken to be the maximum value allowed by SN1987A, $g_{aN} = 3.2 \times 10^{-10}$ GeV^{-1}.

arXiv:1708.02111

Interaction of Axion and Photon Around the Magnetar

Spatial evolution of the ALP-photon system:

$$i\frac{d}{dx}\begin{pmatrix} a \\ E_{\|} \\ E_{\perp} \end{pmatrix} = \begin{pmatrix} \omega R + \Delta_a R & \Delta_M R & 0 \\ \Delta_M R & \omega R + \Delta_{\|} R & 0 \\ 0 & 0 & \omega R + \Delta_{\perp} R \end{pmatrix} \begin{pmatrix} a \\ E_{\|} \\ E_{\perp} \end{pmatrix}$$

x = r/R,
r is the distance
from the center of
the magnetar.

$$\Delta_a = -\frac{m_a^2}{2\omega}, \qquad \Delta_{\|} = \frac{1}{2} q_{\|} \omega \sin^2\theta, \qquad \Delta_{\perp} = \frac{1}{2} q_{\perp} \omega \sin^2\theta, \qquad \Delta_M = \frac{1}{2} g_{a\gamma} B \sin\theta$$

Axion mass term   Euler-Heisenberg term   Mixing term

$$q_{\|} = \frac{7\alpha}{45\pi} b^2 \hat{q}_{\|}, \qquad \hat{q}_{\|} = \frac{1 + 1.2b}{1 + 1.33b + 0.56b^2},$$

$$q_{\perp} = \frac{4\alpha}{45\pi} b^2 \hat{q}_{\perp}, \qquad \hat{q}_{\perp} = \frac{1}{1 + 0.72b^{5/4} + (4/15)b^2},$$

$$b = B/B_c, \; B_c = m_e^2/e = 4.414 \times 10^{13}\,\mathrm{G}$$

The photon electric fields parallel and perpendicular to the local magnetic field $B = B_0\,(R/r)^3$ (in the dipole regime) are denoted by $E_{\|}(x)$ and $E_{\perp}(x)$.

The energy of the (axion or photon) particle is ω, and the angle between the dipolar magnetic field and the ALP propagation direction is denoted by θ.

Axion-Photon Interaction and Intensities

As the ALPs are emitted and climb out of the gravitational potential well of the magnetar, their energy is redshifted. ALP conversion to photons is most probable at a distance of r~ 1000 R (R~12 km: equatorial radius of the magnetar)

$$
\begin{aligned}
a(x) &= A\cos[\chi(x)]e^{-i\phi_a(x)}, \\
E_{\parallel}(x) &= A\sin[\chi(x)]ie^{-i\phi_{\parallel}(x)}, \\
E_{\perp}(x) &= A_{\perp}e^{-i\phi_{\perp}(x)},
\end{aligned}
$$

Conservation of probability:

$$\frac{d}{dx}[|a(x)|^2 + |E_{\parallel}(x)|^2] = 0$$

$A_a = A\cos[\chi(x)]$, $A_{\parallel} = A\sin[\chi(x)]$, and $A_{\perp}$ are the amplitudes at position x of the ALP field, the parallel photon field, and the perpendicular photon field. Intensities of the fields:

Axion mode

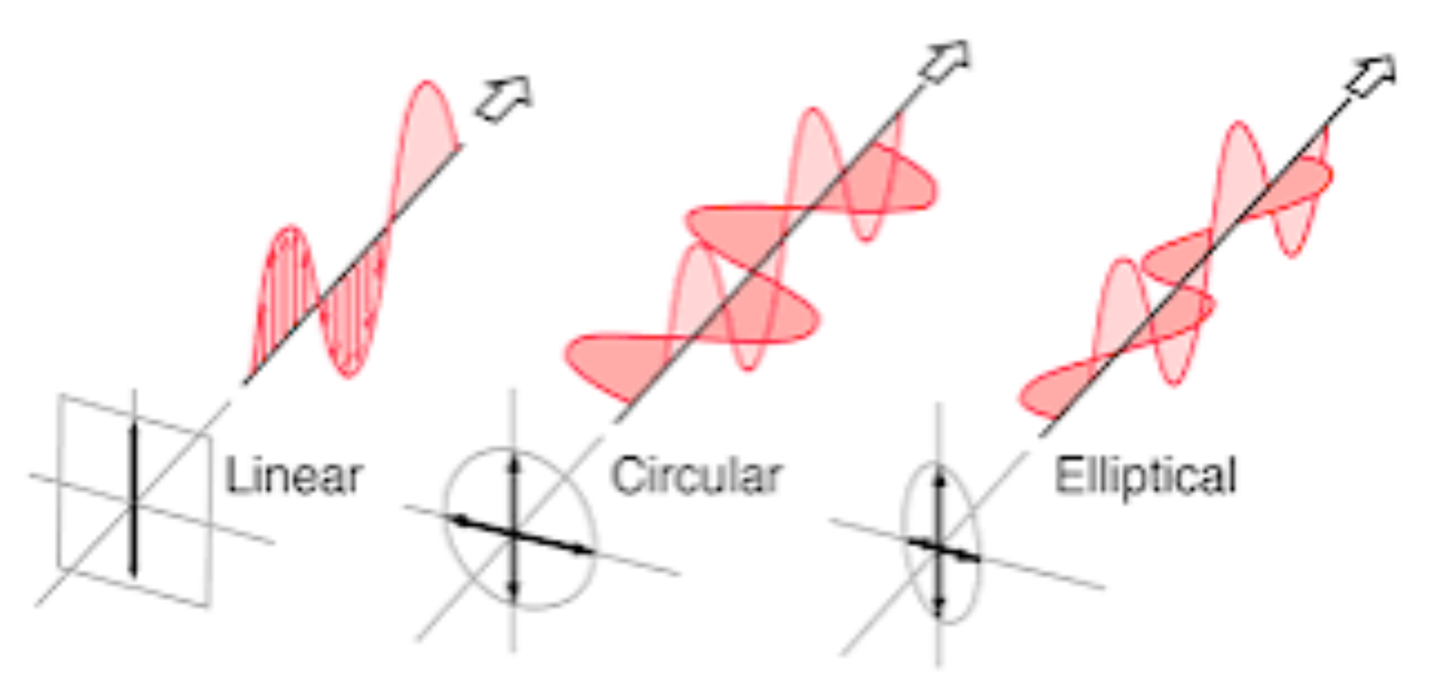
O-mode

X-mode

$$
\begin{aligned}
I_a(x) &= A^2\cos^2[\chi(x)], \\
I_{\parallel}(x) &= A^2\sin^2[\chi(x)], \\
I_{\perp}(x) &= A_{\perp}^2,
\end{aligned}
$$

$$I_a(x) + I_{\parallel}(x) = A^2$$

$$I_{\perp}(x) = A_{\perp}^2$$



arXiv:2303.17641

Photon Modes

Calculation of ALP Intensity and Polarization Effect

As the emitted ALPs and photons propagate in the magnetosphere, the spatial evolution of the ALP-photon system can be described by a set of coupled equations

$$\frac{d\chi(x)}{dx} = -\Delta_M r_0 \cos[\Delta\phi(x)],$$
$$\frac{d\Delta\phi(x)}{dx} = (\Delta_a - \Delta_{\|}) r_0 + 2\Delta_M r_0 \cot[2\chi(x)] \sin[\Delta\phi(x)],$$
$$\frac{d\delta\phi(x)}{dx} = (\Delta_\perp - \Delta_{\|}) r_0 + \Delta_M r_0 \{\cot[2\chi(x)] + \csc[2\chi(x)]\} \sin[\Delta\phi(x)],$$
$$\frac{d\phi_\perp(x)}{dx} = (\omega + \Delta_\perp) r_0,$$

$$\Delta\phi(x) = \phi_a(x) - \phi_{\|}(x), \qquad \delta\phi(x) = \phi_\perp(x) - \phi_{\|}(x),$$

We solve this set of differential equations numerically!

Probability of axion conversion to photon (x=r/R):

$$P_{a\to\gamma}(x) = \sin^2[\chi(x)]$$

I: intensity, Q, U: linear polarisations, V: circular polarisation

$$I^2 = Q^2 + U^2 + V^2$$

The Stokes parameters Q, U, and V are generally frame-dependent, as opposed to the intensity I that can be used to constrain ALPs with the hard X-ray emission.

arXiv:1804.01992

arXiv:1807.10773

Calculation of ALP Intensity and Polarization Effect

$\Delta\psi$ is the (unconstrained) relative angle between the detector and magnetar frames.

Stokes parameters in detector frame:

$$
\begin{aligned}
I_{\rm obs}^{\rm det} &\approx I_{\rm ast}^{\rm det} + I_a(1)P_{a\to\gamma} = (1+p_a)I_{\rm ast}^{\rm det}\,,\\
Q_{\rm obs}^{\rm det} &\approx Q_{\rm ast}^{\rm det} - I_a(1)P_{a\to\gamma}\cos(2\Delta\psi) = [q - p_a\cos(2\Delta\psi)]I_{\rm ast}^{\rm det}\,,\\
U_{\rm obs}^{\rm det} &\approx U_{\rm ast}^{\rm det} + I_a(1)P_{a\to\gamma}\sin(2\Delta\psi) = [u + p_a\sin(2\Delta\psi)]I_{\rm ast}^{\rm det}\,,\\
V_{\rm obs}^{\rm det} &\approx \pm V_{\rm ast}^{\rm det}\,,
\end{aligned}
$$

Stokes parameters in magnetar frame:

$$
\begin{aligned}
I_{\rm obs}^{\rm mag} &= I_{\rm ast}^{\rm mag} + \left[I_a(1) - \frac{I_{\rm ast}^{\rm mag} - Q_{\rm ast}^{\rm mag}}{2}\right]P_{a\to\gamma},\\
Q_{\rm obs}^{\rm mag} &= Q_{\rm ast}^{\rm mag} - \left[I_a(1) - \frac{I_{\rm ast}^{\rm mag} - Q_{\rm ast}^{\rm mag}}{2}\right]P_{a\to\gamma},\\
U_{\rm obs}^{\rm mag} &= [U_{\rm ast}^{\rm mag}\cos(\delta\phi_a) - V_{\rm ast}^{\rm mag}\sin(\delta\phi_a)]\sqrt{1-P_{a\to\gamma}},\\
V_{\rm obs}^{\rm mag} &= [V_{\rm ast}^{\rm mag}\cos(\delta\phi_a) + U_{\rm ast}^{\rm mag}\sin(\delta\phi_a)]\sqrt{1-P_{a\to\gamma}},
\end{aligned}
$$

for small ALP-photon coupling $\delta\phi_a = \phi_a(\infty) - \phi_a(1) \ll 1$ and $P_{a\to\gamma} \ll 1$

$$
\begin{aligned}
I_{\rm obs}^{\rm mag} &\approx I_{\rm ast}^{\rm mag} + I_a(1)P_{a\to\gamma},\\
Q_{\rm obs}^{\rm mag} &\approx Q_{\rm ast}^{\rm mag} - I_a(1)P_{a\to\gamma},\\
U_{\rm obs}^{\rm mag} &\approx U_{\rm ast}^{\rm mag},\\
V_{\rm obs}^{\rm mag} &\approx V_{\rm ast}^{\rm mag},
\end{aligned}
$$

Estimation for axion intensity:

$$
I_a(1) = \frac{S}{4\pi D^2}\frac{1}{\omega_a^\infty}\frac{dL_a^\infty}{d\omega_a^\infty} = \frac{Sf^4}{2^2 3^{5/3}\pi^{19/3}D^2}\frac{m_N^{11/3}}{m_\pi^4}g_{aN}^2T^4R^3\rho^{1/3}\frac{y^2(y^2+4\pi^2)}{e^y-1}
$$

$$
y = \omega_a^\infty/T^\infty = \omega_a/T
$$

$$
p_a = \frac{I_a(1)P_{a\to\gamma}}{I_{\rm ast}^{\rm det}}, \qquad q = \frac{Q_{\rm ast}^{\rm det}}{I_{\rm ast}^{\rm det}}, \qquad u = \frac{U_{\rm ast}^{\rm det}}{I_{\rm ast}^{\rm det}}.
$$

D is the distance from the magnetar to Earth

Estimation of Photon Polarization due to Axions

Sufficiently light mass and sufficiently weak coupling:

Conversion Probability $$P_{a\to\gamma} \approx \left(\frac{\Delta_{M0}R^3}{r_{a\to\gamma}^2}\right)^2 \frac{\Gamma\left(\frac{2}{5}\right)^2}{25|\Delta_a r_{a\to\gamma}/5|^{\frac{4}{5}}}$$

Radius of Conversion $$r_{a\to\gamma} = \left(\frac{7\alpha}{45\pi}\right)^{1/6}\left(\frac{\omega}{m_a}\frac{B_0}{B_c}|\sin\theta|\right)^{1/3} R$$

Validity of mass independent bound on axion:

$$m_a \lesssim \frac{3^{7/5}}{2^{4/5}5^{1/2}7^{1/10}}\left(\frac{m_e^2\omega^2}{\alpha R^3 B_0|\sin\theta|}\right)^{1/5}$$

Polarisation degree and polarisation angle in terms of Stokes parameters are Q, U , and V :

IXPE is only able to detect linear X-ray polarization!

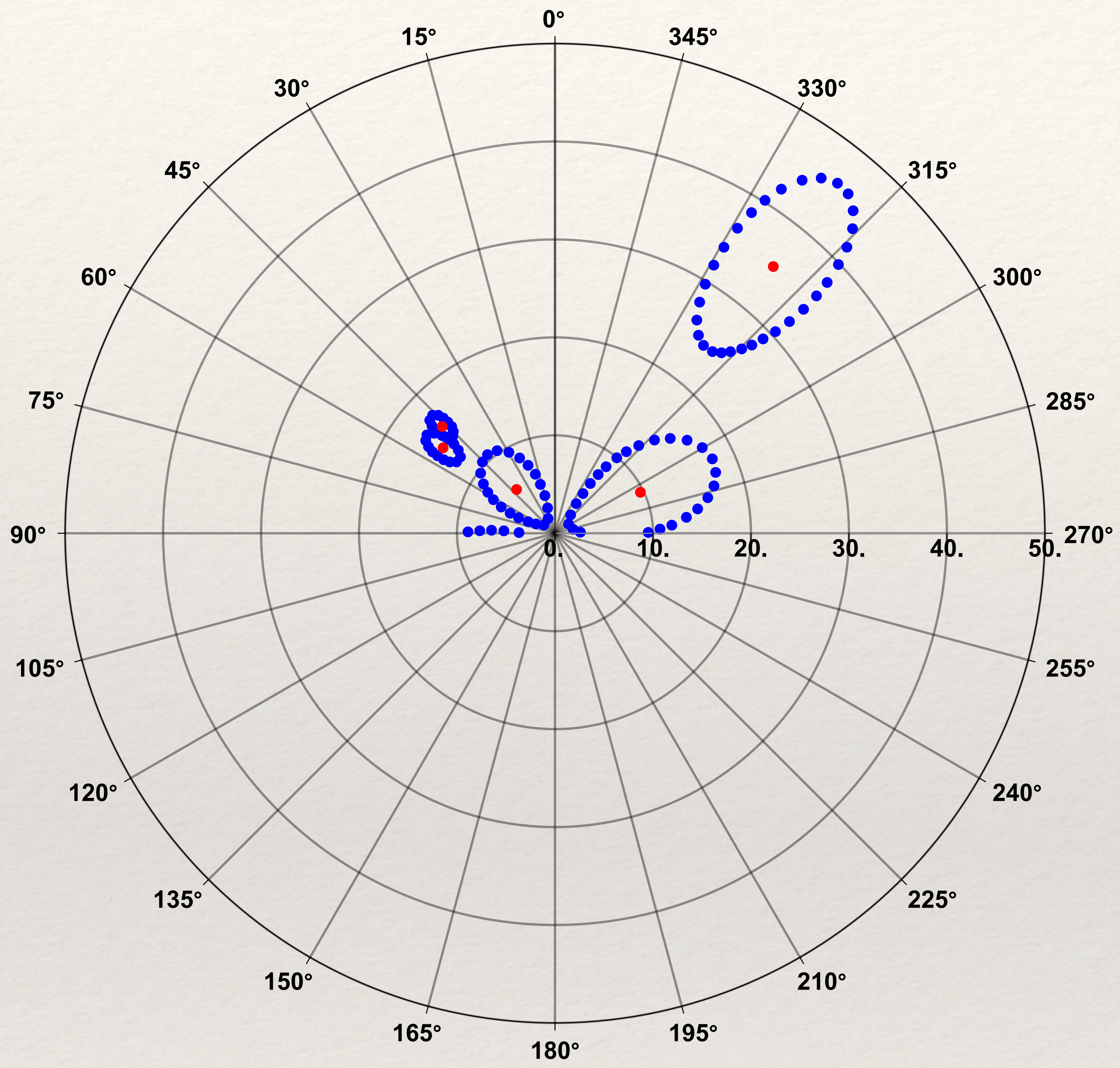
No V!

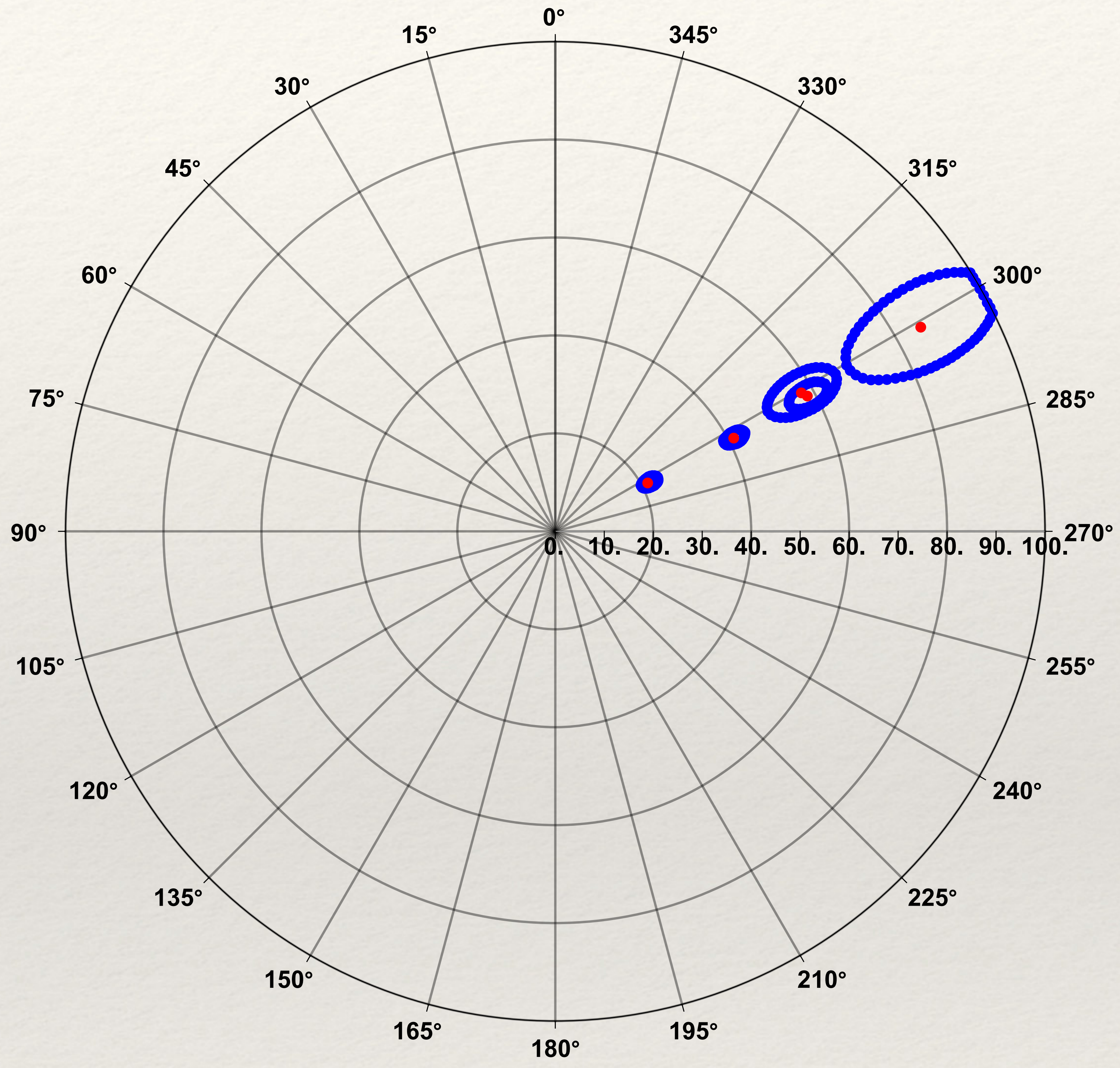
$$\mathrm{PD} = \frac{\sqrt{Q^2+U^2}}{I},$$
$$\mathrm{PA} = \frac{1}{2}\arctan\left(\frac{U}{Q}\right).$$

We do a scan over the relevant parameters to find the bound on axion!

Axion mass, couplings, polarisation angle

Probing Axion Parameter Space

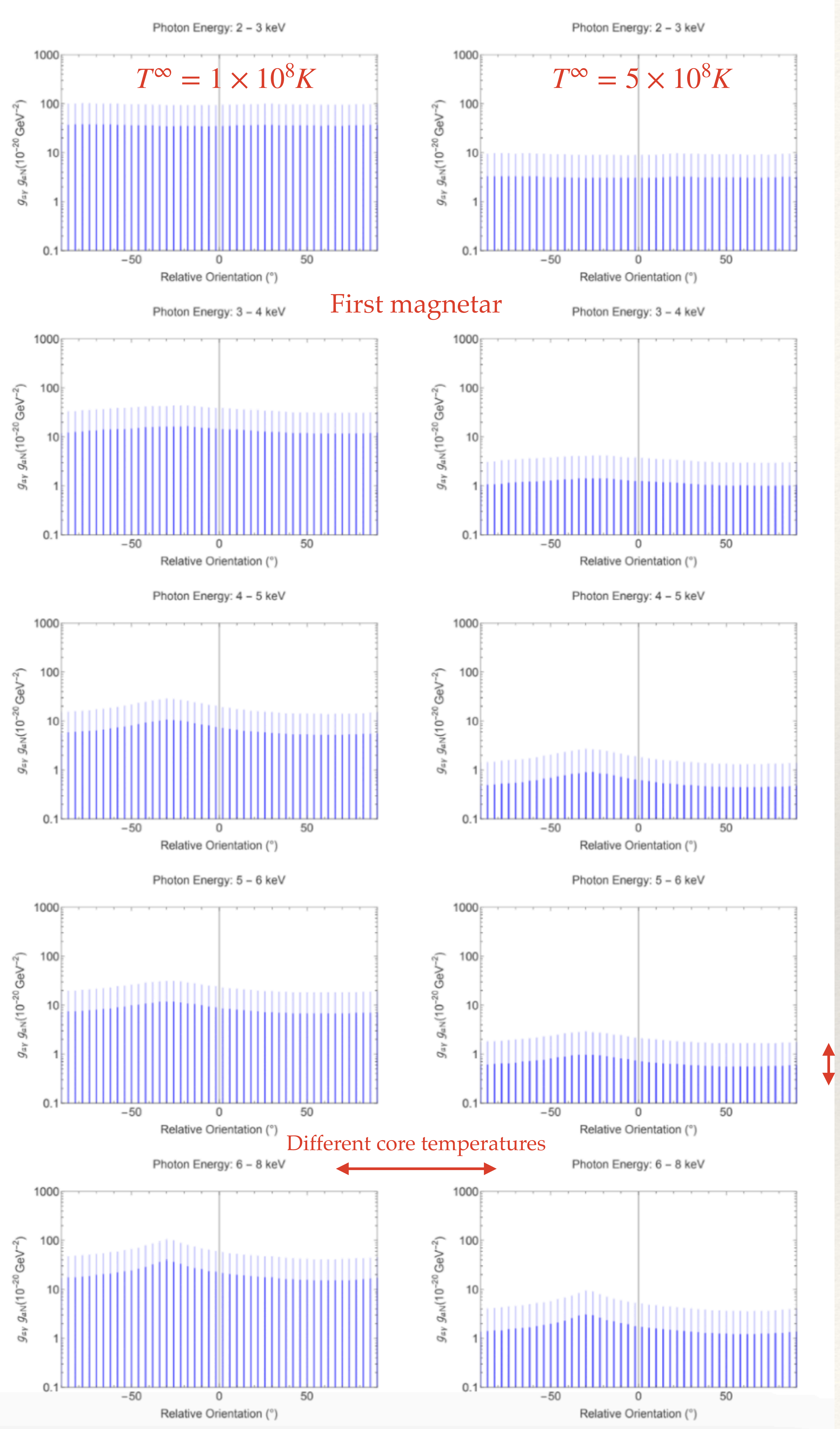




arXiv:2312.14153

For mass independent region of bounds: small masses

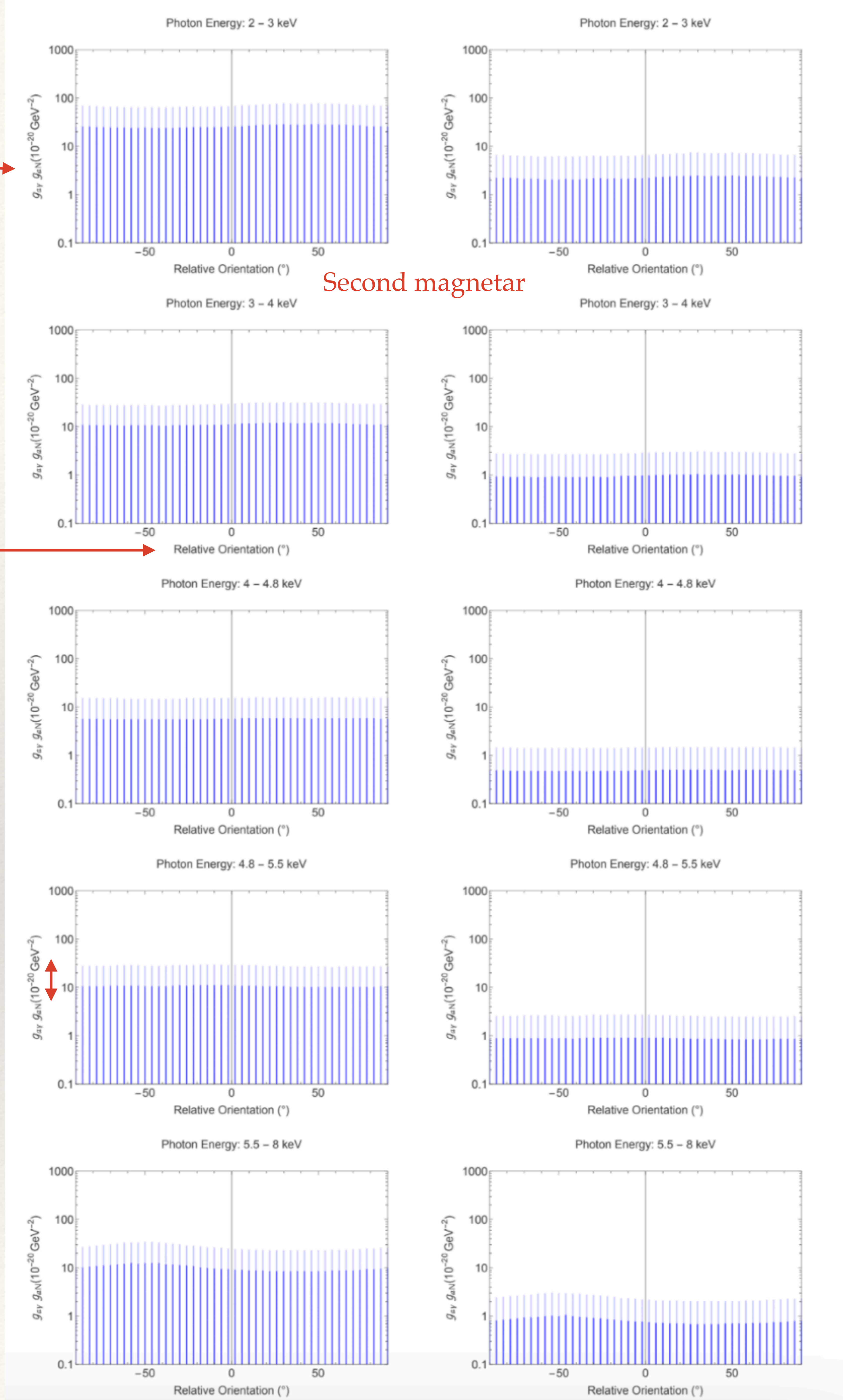
Different energy bins



Axion-photon-nucleon couplings

Relative orientation

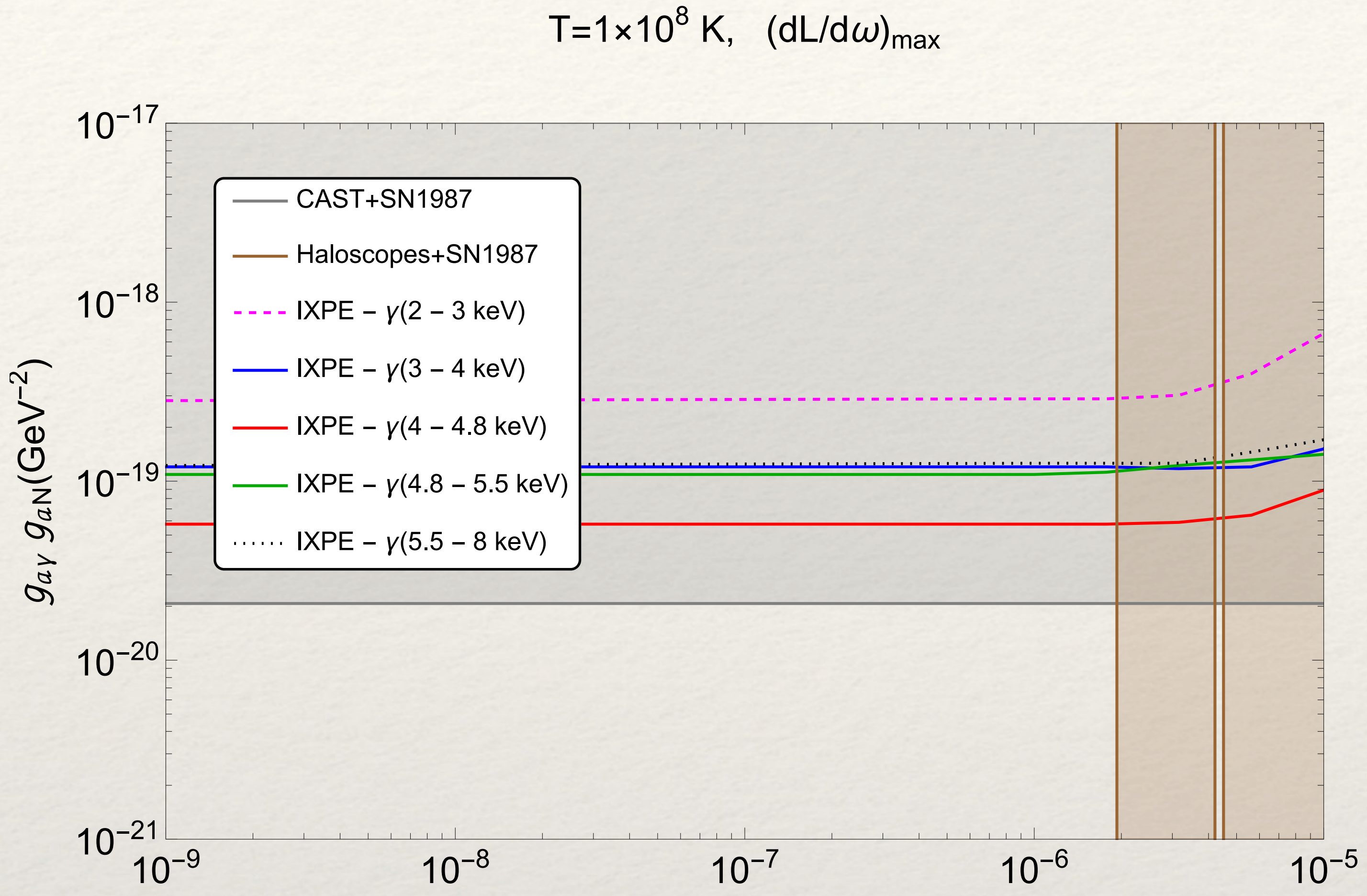
Maximum and minimum luminosity



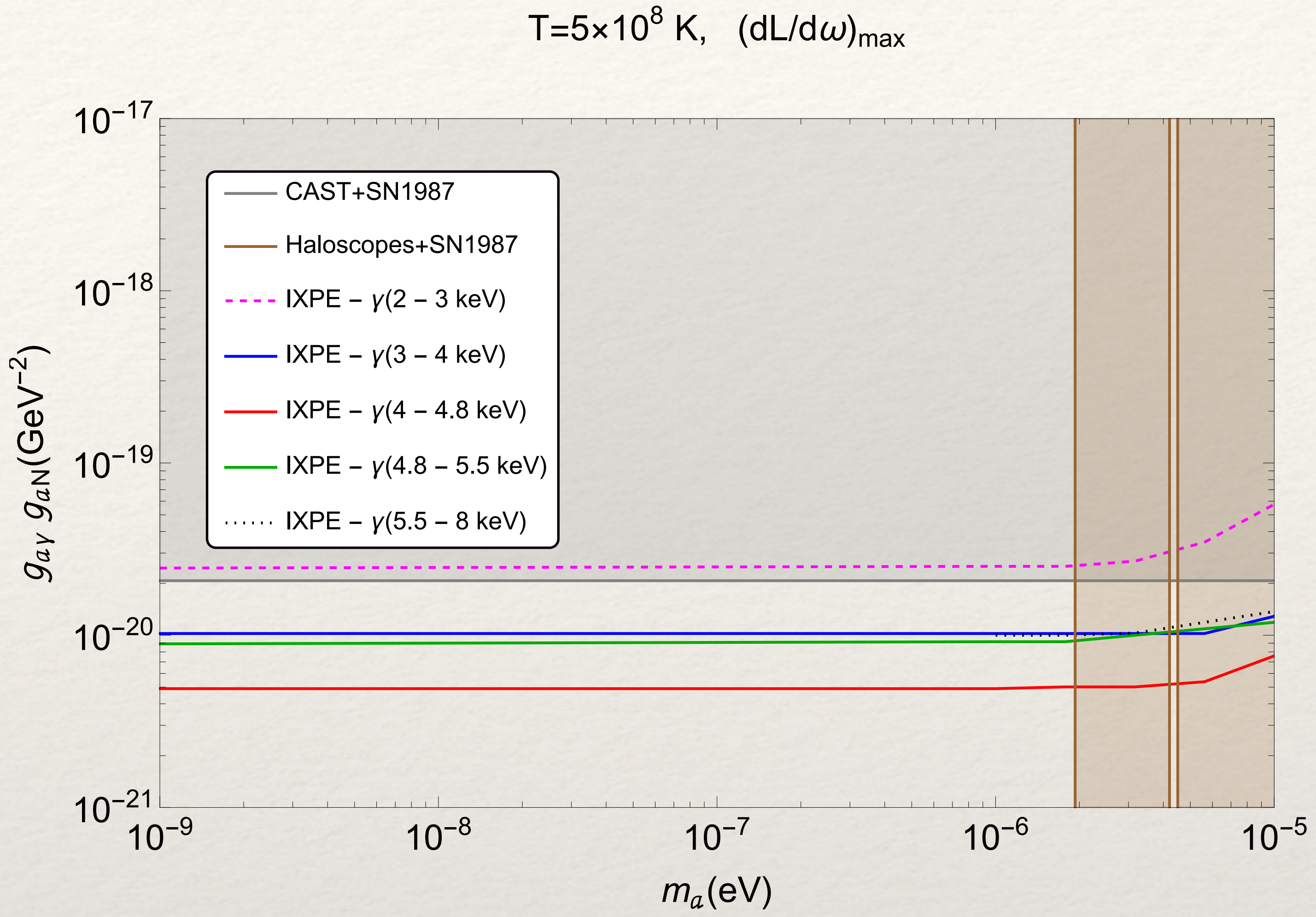
arXiv:2312.14153

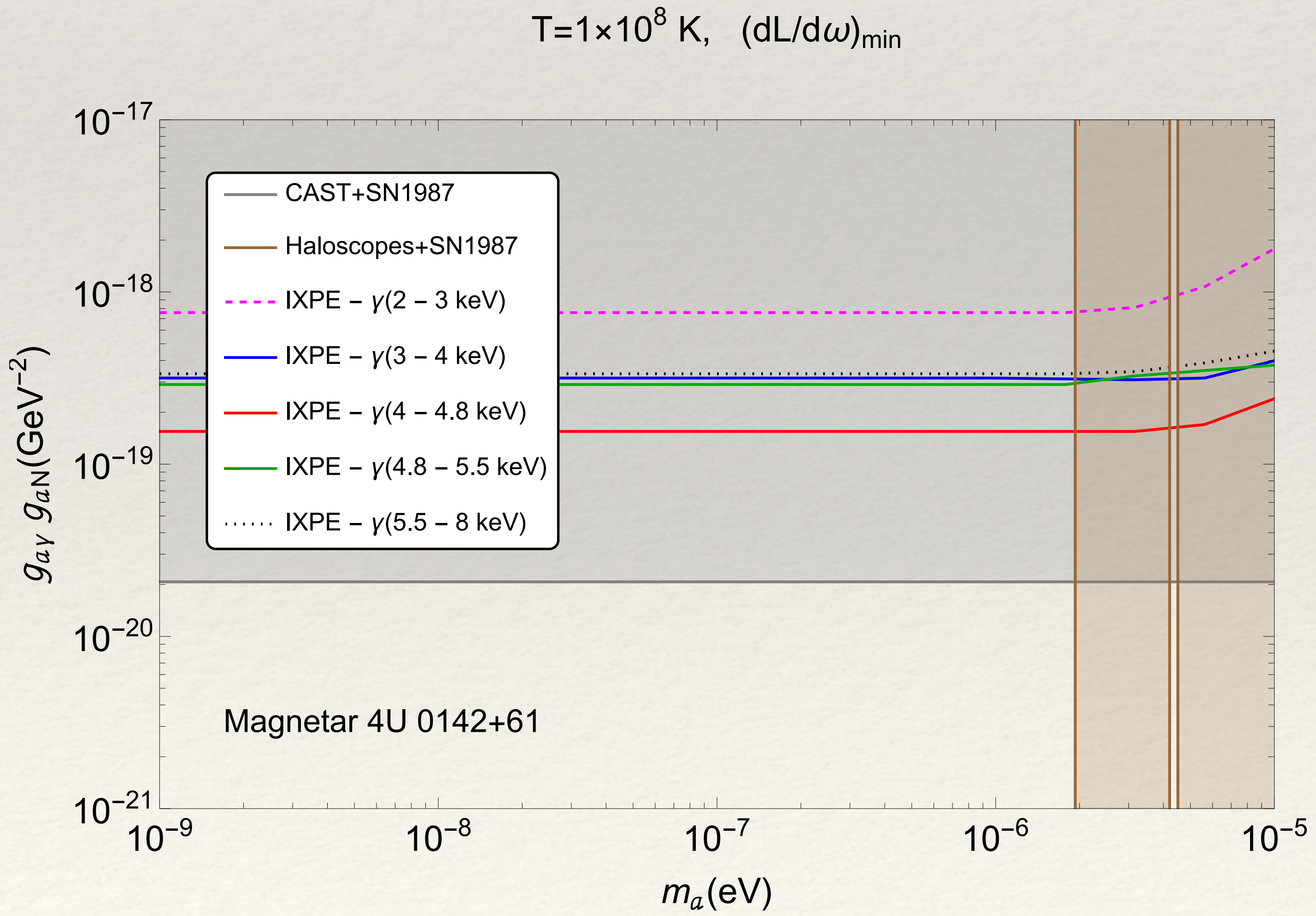
Bounds on Axion Couplings from First Magnetar

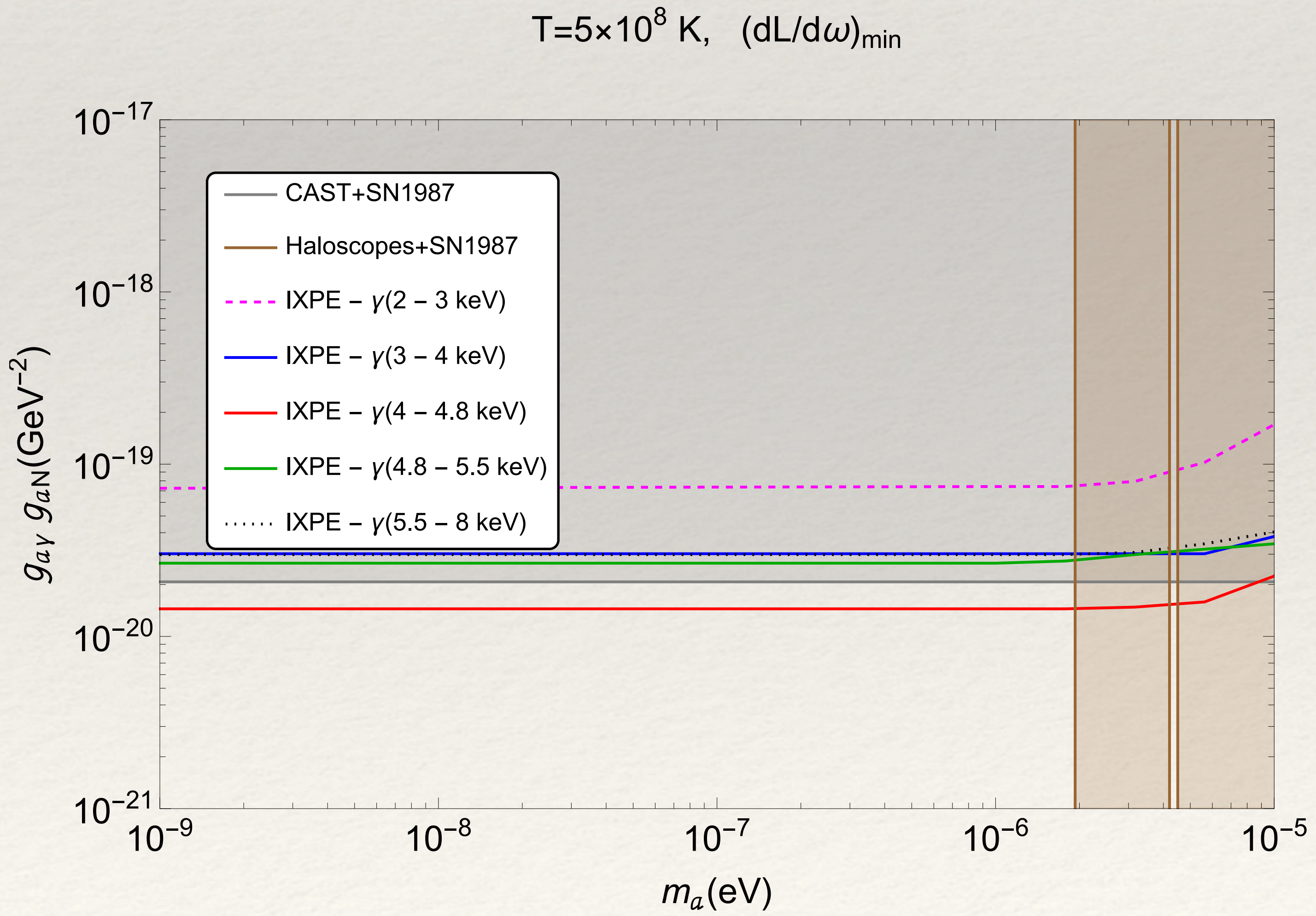
Multiplication of axion-photon and nucleon couplings



Axion mass

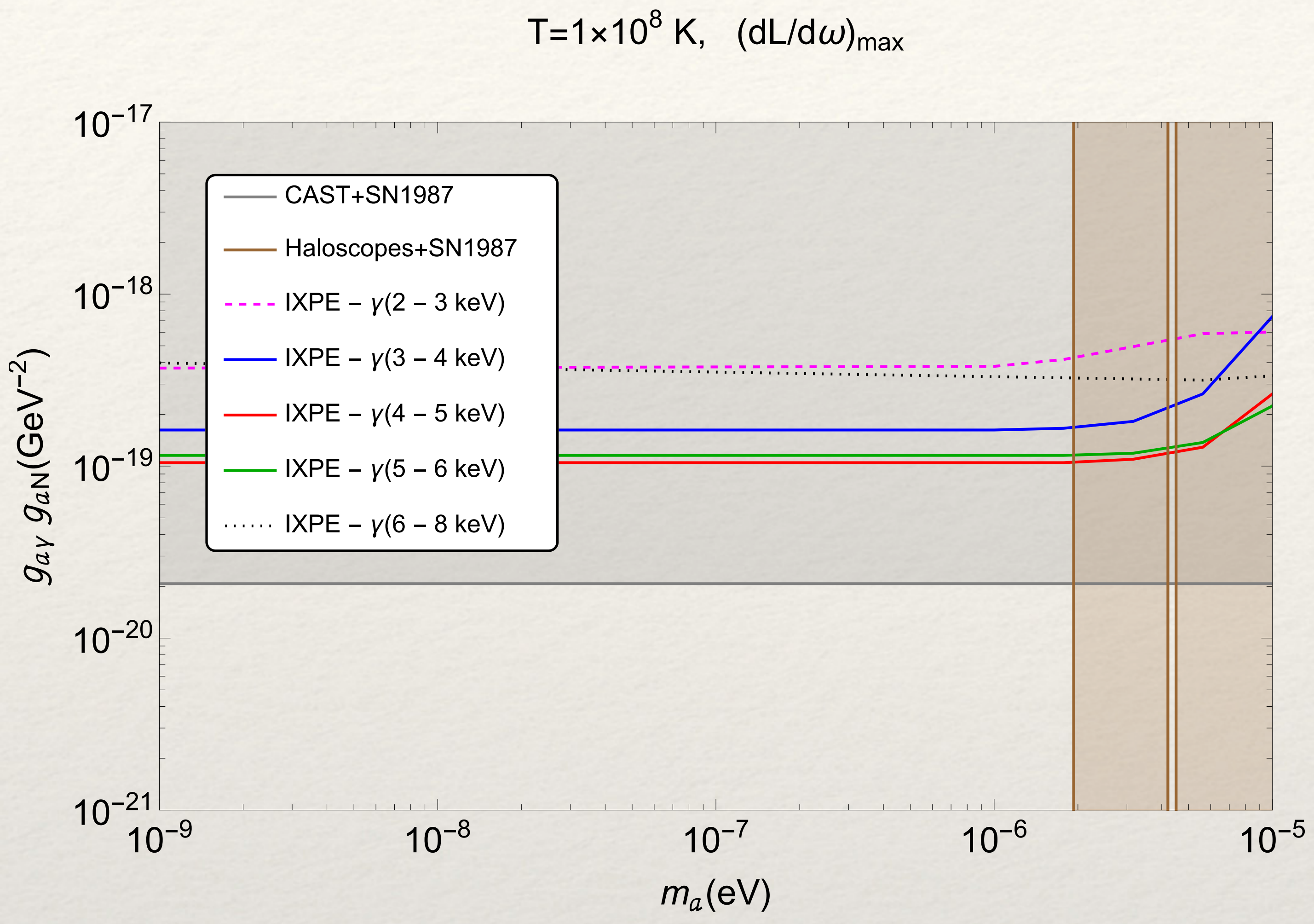


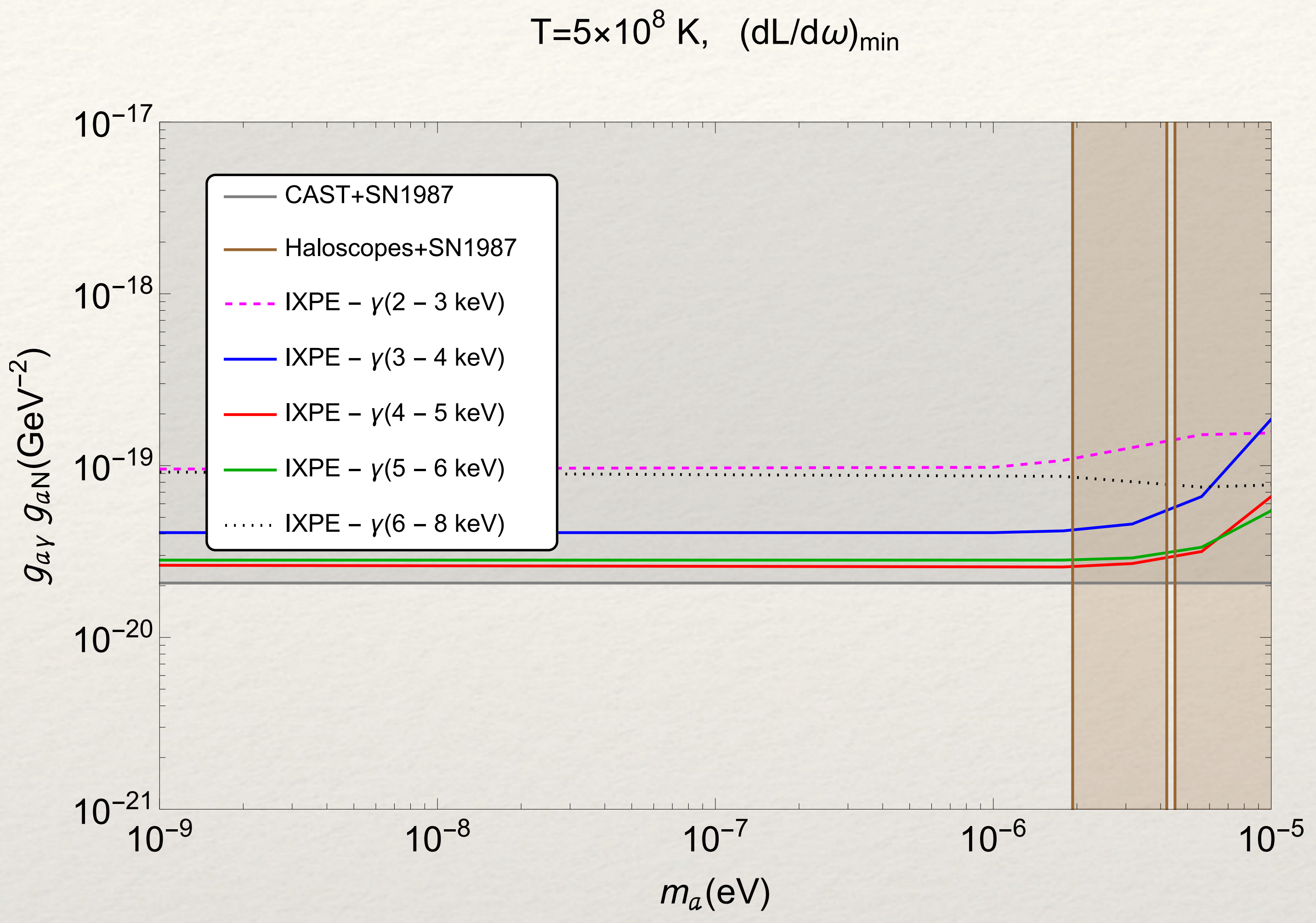


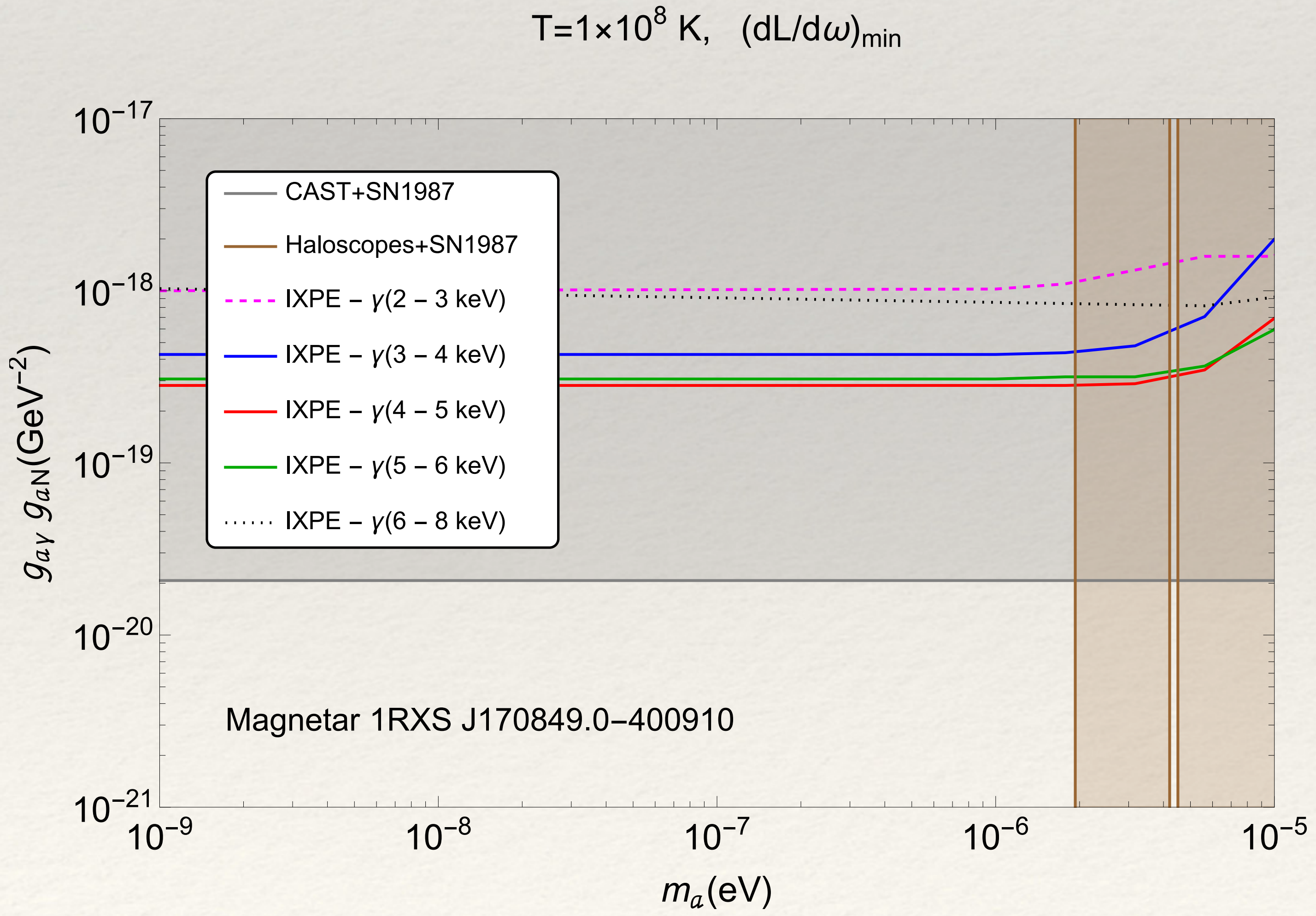


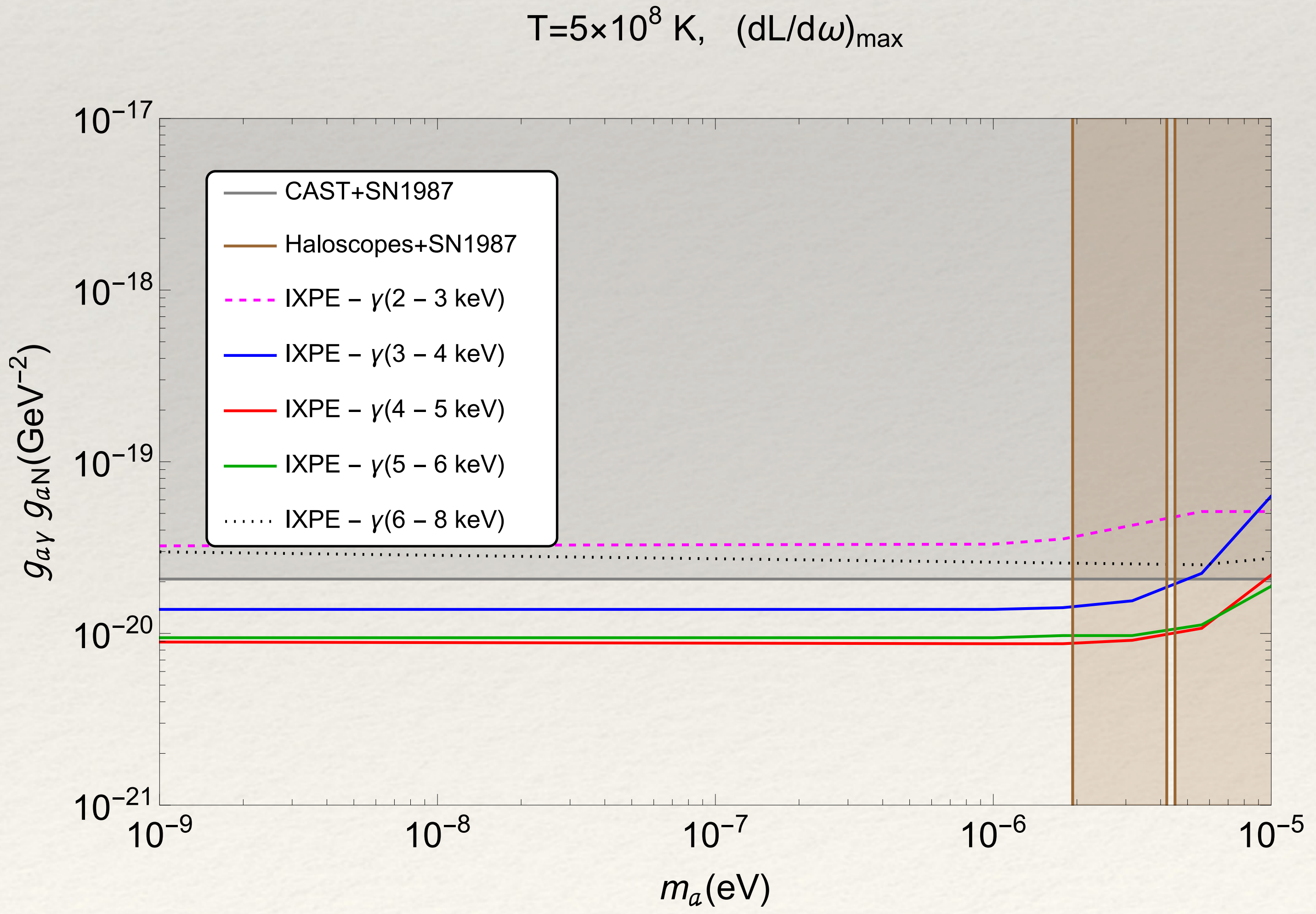
arXiv:2312.14153

Bounds on Axion Couplings from Second Magnetar









arXiv:2312.14153

Summary

- Light polarisation measurement is a novel way to probe the parameter space of QCD axion and axion-like particles
- Measuring light polarization from astrophysical sources can constrain the axion coupling to photons at different ranges of mass —> XL-Calibur, , IXPE and EHT
- Future experiments with more sensitive polarimeters can put a stronger bound on $g_{a\gamma}g_{aN}$ and $g_{a\gamma}$ depending on the interactions


Thanks for your attention!