Neutron Star Eclipses as Axion Laboratories

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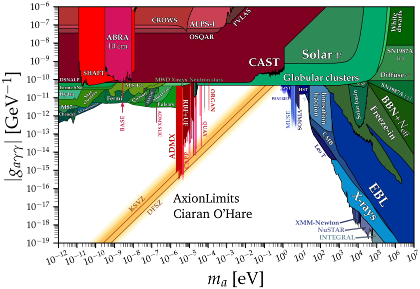
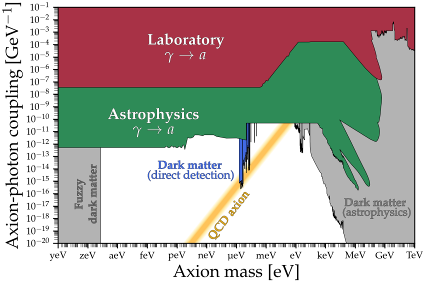
Axion-Photon Interaction

- axion's two-photon interaction plays a key role in the majority of the experimental searches

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

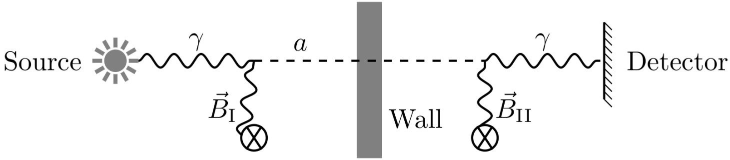
- here, $g_{a\gamma} \propto f_a^{-1}$ and $m_a f_a \approx m_\pi f_\pi \sim (100\,\mathrm{MeV})^2$
- fo the case of axion-like particles (ALPs), particle's mass and its decay constant are treated as independent parameters





Light-Shining-Through-Walls

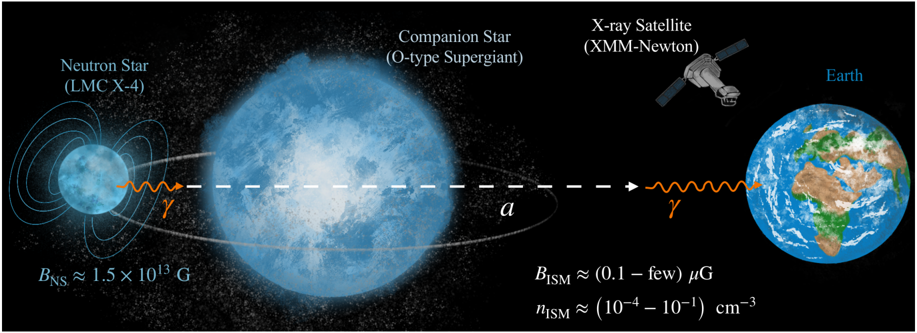
$$\mathscr{L} \supset -\frac{1}{4} g_{a\gamma}\, a\, F^{\mu\nu} \tilde{F}_{\mu\nu}$$



- Lab-based experiments: OSQAR, CROWS, ALPS ($g_{a\gamma} \simeq 10^{-7}\mathrm{GeV}^{-1}$)
  ALPS II ($g_{a\gamma} \simeq 10^{-9}\mathrm{GeV}^{-1}$)

- we utilize the light-shining-through-walls concept and apply it to astrophysical scales (eclipsing binary system)

Schematic Diagram



- eclipsing binary system composed of:

  1) neutron star → bright source of X-rays
  2) larger companion star that serves as a "wall"

$\gamma \to a$ Transition Near Binary Systems

- 2-level system featuring ALP and photon states:

$$\mathcal{H}_{\mathrm{eff}} = -\begin{pmatrix} \Delta_\gamma & \Delta_{a\gamma} \\ \Delta_{a\gamma} & \Delta_a \end{pmatrix}$$

$$\Delta_\gamma = -\frac{m_{\mathrm{eff}}^2}{2E_\gamma} \qquad \Delta_a = -\frac{m_a^2}{2E_\gamma} \qquad \Delta_{a\gamma} = \frac{1}{2} g_{a\gamma} |\vec{B}_T|$$

effective photon mass: $m_{\mathrm{eff}}^2(r) = \frac{4\pi\alpha}{m_e} n_e(r) - \frac{88\,\alpha^2 E_\gamma^2}{270\,m_e^4} B(r)^2$

- model the magnetic field like that of a dipole: $B(r) = B^{(0)}\,(r/10\,\mathrm{km})^{-3}$
- $n_e(r) = n_e^{(0)}\,(r/10\,\mathrm{km})^{-3}$
- $B^{(0)}$ and $n_e^{(0)}$ are magnetic field and electron number density at the surface of the neutron star

Finding the Ideal System: LMC X-4

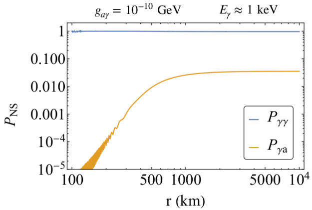
- Optimal candidate – high out-of-eclipse to eclipse flux ratio, large $B^{(0)}$, large distance from Earth

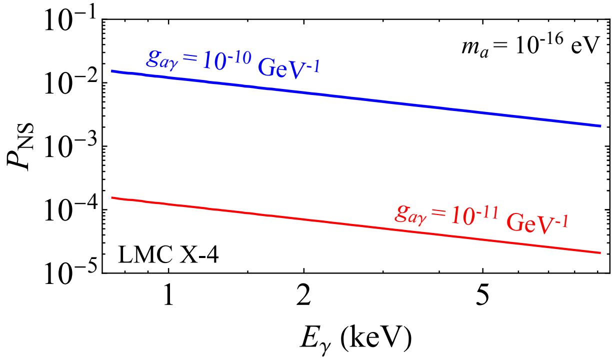
		Distance	NS Mag. field	Flux ratio	Location
HMXB	**LMC X-4**	~50 kpc	3×10^{13} G	**~237**	LMC
HMXB	**Vela X-1**	1.6 kpc	2.6×10^{12} G	**~100**	MW
HMXB	**Cen X-3**	~7.2 kpc	3×10^{12} G	**~70**	MW
LMXB	**MXB 1659-298**	9-15 kpc	$(10^8 - 10^9)$ G	~ **30**, 250	Towards GC
LMXB	**EXO 0748-676**	~7 kpc	$(10^8 - 10^9)$ G	~ **50**, 600	Galactic disk
LMXB	**XTE 1710-281**	12-16 kpc	$(10^8 - 10^9)$ G	~**129**, 500	Towards GC

90% LMXBs have weaker magnetic fields, while ~10% have magnetic field at ~10^{12} G

$\gamma \to a$ Process Near LMC X-4

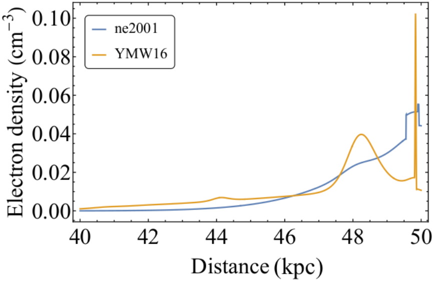
- solve $i\frac{d}{dr}\begin{pmatrix}\gamma(r)\\a(r)\end{pmatrix} = \mathscr{H}_{\rm eff}\begin{pmatrix}\gamma(r)\\a(r)\end{pmatrix}$ and compute $|a(r)|^2$
- the large transition probability, $P_{\rm NS}$, originates from the resonance achieved for $m_{\rm eff}^2 = m_a^2$

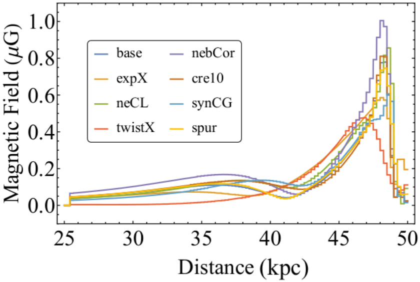




$a \to \gamma$ Transition in the Interstellar Medium (ISM)

- ISM n_e and B will affect the oscillation probabilities
- we use UF23 (x8) magnetic field, and the YMW16 electron density model



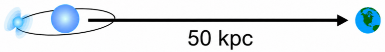


$$\Delta_\gamma \approx 1.1 \left(\frac{n_e}{10^{-2}\,\mathrm{cm}^{-3}} \right) \left(\frac{E_\gamma}{1\,\mathrm{keV}} \right)^{-1} \mathrm{kpc}^{-1}$$

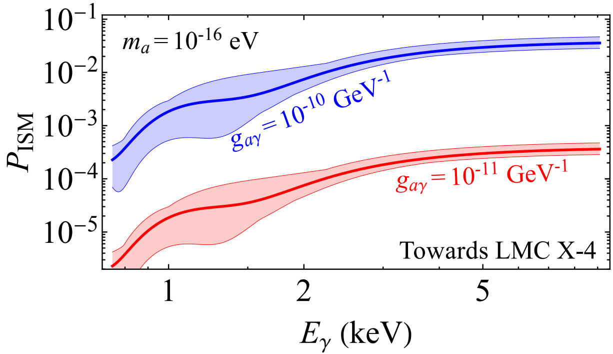
$$\Delta_{a\gamma} \approx 0.15 \left(\frac{g_{a\gamma}}{10^{-10}\,\mathrm{GeV}^{-1}} \right) \left(\frac{B_T}{1\,\mu\mathrm{G}} \right) \mathrm{kpc}^{-1}$$

$$P_{\mathrm{ISM}} = 4(\Delta_{a\gamma}^2/\Delta_\gamma^2)\sin^2(\tfrac{\Delta_\gamma L}{2})$$

$a \to \gamma$ Transition in the Interstellar Medium (ISM)



- $\sim$ kpc distances necessary for efficient transition probability P_{ISM}
- we consider conversion in Milky Way (LMC and IGMF not considered)



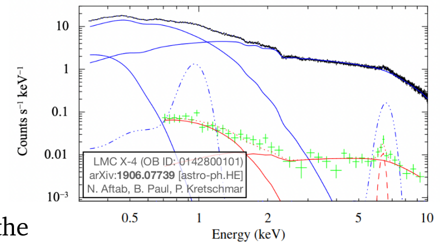
Constraining the ALP-Photon Coupling

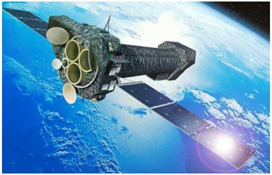
- The total number of photons observed during the eclipse must exceed the number of photons produced through the γ-ALP-γ process

$$F_{\text{eclipse}} \gtrsim F_{\text{out-of-eclipse}} P_{\text{NS}} P_{\text{ISM}}$$

- $P_{\text{NS}} \sim 10^{-2}$ and $P_{\text{ISM}} \sim 10^{-2}$ for $g_{a\gamma} = 10^{-10}$ GeV^{-1} and $E_\gamma = 3$ keV

- Given the $g_{a\gamma}^2$ dependence of both the $\gamma \to a$ and $a \to \gamma$ processes, and the out-of-eclipse to eclipse flux ratio of about 10^3, one would expect to set a limit around $g_{a\gamma} \sim 2 \times 10^{-10}$ GeV^{-1}

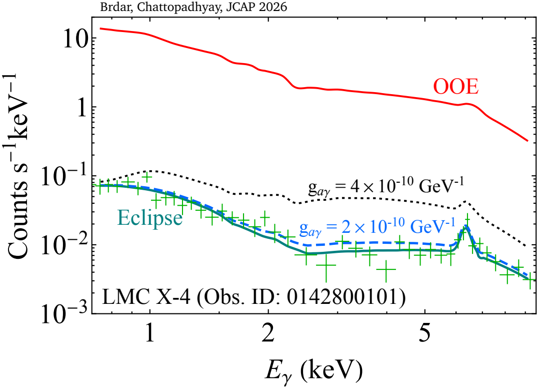




XMM-Newton

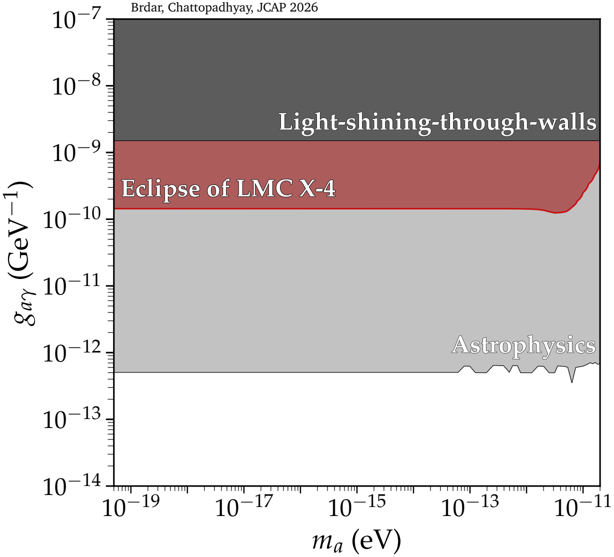
Constraining the ALP-Photon Coupling

$$\chi^2_{\rm ALP} \equiv \chi^2_{\rm ALP+ecl.} - \chi^2_{\rm ecl.} \qquad \chi^2_{\rm ecl.} = \sum_i \frac{(\tilde{F}_{\rm ecl.} - F_{\rm ecl.})^2}{\delta F^2_{\rm ecl.}} \qquad \chi^2_{\rm ALP+ecl.} = \sum_i \frac{(\tilde{F}_{\rm ALP+ecl.} - F_{\rm ecl.})^2}{\delta F^2_{\rm ecl.}}$$



- $P_{\rm NS} P_{\rm ISM}$ is maximum in $E_\gamma \approx (3-6)$ keV range
- ISM conversion becomes inefficient at higher ALP masses
- 90% CL limit at $g_{a\gamma} = 1.44 \times 10^{-10}\,{\rm GeV}^{-1}$ for $m_a \lesssim 10^{-11}$ eV

Constraining the ALP-Photon Coupling



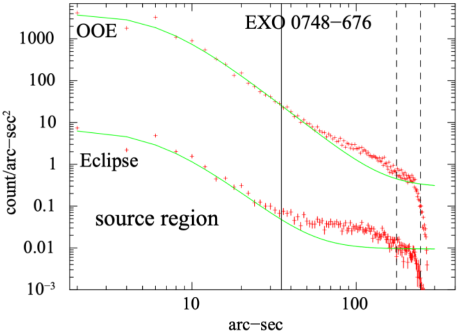
Towards the Ideal Candidate

- an eclipsing system located towards the Galactic Center would be ideal due to the stronger magnetic fields (factor of 10 in P_{ISM})

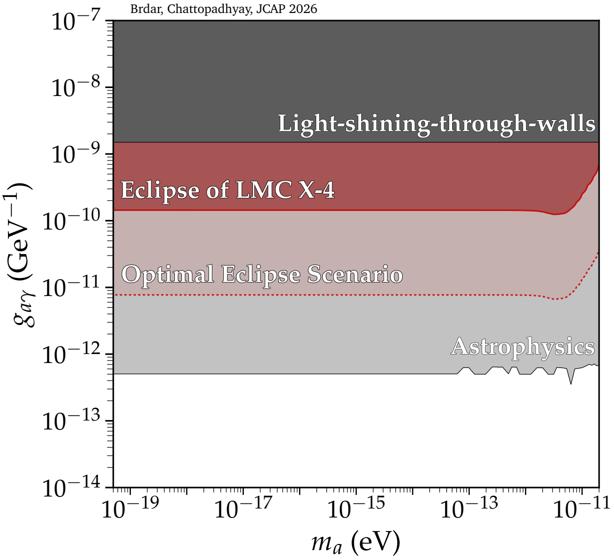
- a stronger magnetic field of the candidate neutron star (e.g., an eclipsing magnetar) could increase P_{NS} by $\mathcal{O}(10)$

- future observations may achieve unprecedented angular resolution for such a system, enhancing the out-of-eclipse to eclipse flux ratio by $\mathcal{O}(100)$

N. Aftab, B. Paul, [arXiv:2308.03916]



Constraining the ALP-Photon Coupling



Take-Home Message

- Light-shining-through-walls in astrophysics
- Eclipsing neutron stars as a novel system to look for ALPs
- LMC X-4 system gives constraints of $g_{a\gamma} \sim 10^{-10}\,\mathrm{GeV}^{-1}$
- Optimal eclipse scenario can yield $g_{a\gamma} \sim 10^{-11}\,\mathrm{GeV}^{-1}$