Looking for lights from the darkness

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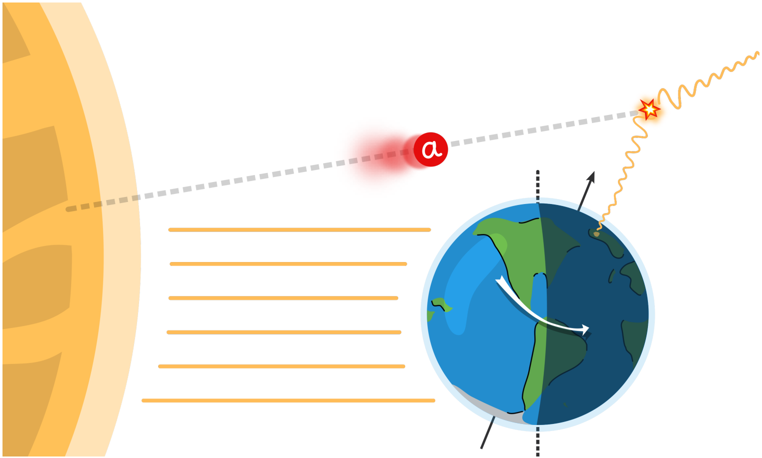
Based on 2604.18397 with **Yongchao Zhang** (*Southeast University*)

Overview



ALP

Introduction

Axion and Axion-like particle (ALP)

- Strong CP problem $\rightarrow$ axion field
- String landscape $\rightarrow$ flat moduli, axion-like particle

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Phenomenology: (anomalous) approximate shift symmetry

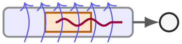
$$\mathcal{L} = \frac{1}{2}(\partial a)^2 - \underbrace{\frac{1}{2}m_a^2 a^2}_{\text{explicit breaking}} - \underbrace{C_\gamma \frac{a}{f_a} F\tilde{F}}_{\text{anomaly terms}} - \underbrace{\frac{\partial a}{f_a}(\cdots)}_{\text{derivative coupling}} + \underbrace{\mathcal{O}\left((\partial a)^4\right)}_{\text{non-linear}}$$

- Technically natural, can be ultralight, $m_a \ll f_a$
- Cosmologically interesting, DM, DE, etc.

Introduction

Axion and Axion-like particle (ALP)

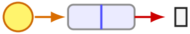
Haloscopes



dark-matter axion → microwave photon

ADMX, HAYSTAC, ORGAN, MADMAX

Helioscopes



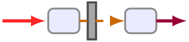
solar axion → X-ray photon

CAST, IAXO

ALP couplings

$g_{a\gamma}$, g_{ae}, g_{aN}

Light shining through wall



photon → ALP → photon

ALPS II, OSQAR

Precision probes

spin precession / oscillating forces

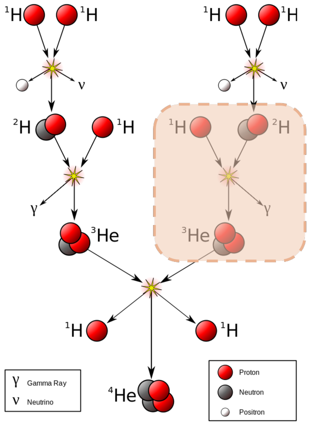
CASPEr, ARIADNE, atomic clocks

Core idea: search for weak ALP-induced conversion, absorption, or precision-sensing signals.

Solar Production

Solar Production

MeV axions

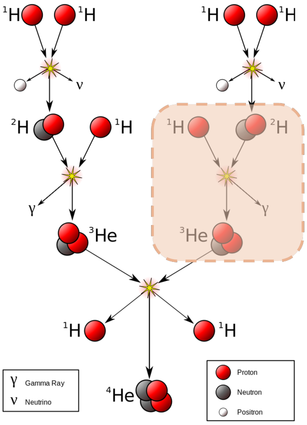


99% solar energy from

$$p + D \to {}^3\text{He} + \gamma \ (5.5\ \text{MeV})$$

Solar Production

MeV axions



99% solar energy from

$$p + D \to {}^3\text{He} + \gamma \ (5.5 \text{ MeV})$$

IF axion couple to nucleon,

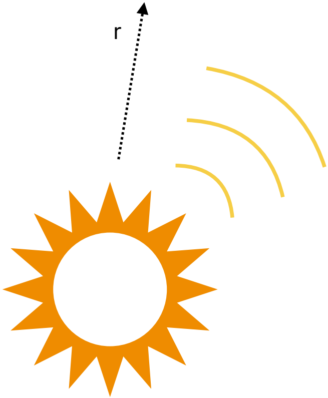
$$g_{aN} a N \gamma^5 N \quad \Longrightarrow \quad p + D \to {}^3\text{He} + a \ (5.5 \text{ MeV})$$

$$\mathcal{Q} \simeq 9.1 \times 10^{17} \left(\frac{g_{aN}}{10^{-10}} \right)^2 \underbrace{\left(1 - \frac{m_a^2}{\omega_a^2} \right)^{3/2}}_{\text{velocity}^3} \text{s}^{-1}$$

$$\omega_a = 5.5 \text{ MeV}$$

Solar Production

axion number density



$$dn(r) \propto \frac{1}{4\pi r^2} \times \underbrace{\frac{e^{-r/\ell_a}}{\ell_a}}_{\text{decay}}$$

$$\ell_a \sim 10^5 \mathrm{AU} \left(\frac{m_a}{3\ \mathrm{MeV}}\right)^{-4} \left(\frac{g_{a\gamma}}{10^{-11}\ \mathrm{GeV}^{-1}}\right)^2$$

Decay geometry

$a \to \gamma\gamma$ via $g_{a\gamma} a F \tilde{F}$

Two-body decay

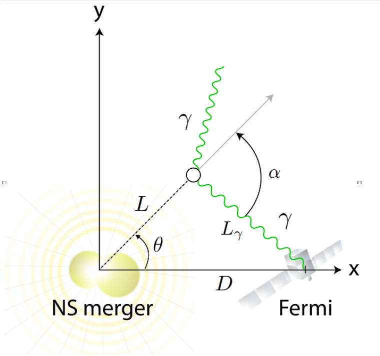


Figure: From Dev, Fortin, Harris, Sinha & **YCZ**, PRL132 (2024) 101003.

Triangular geometry

- Supernova Astropart.Phys. 1 (1993) 377; astro-ph/9601104; 1702.02964; 1910.10249; 2109.03244; 2205.07896; 2206.06852; 2212.09764; 2302.10965; 2303.11395; 2304.01060; 2312.13627; 2404.19191; 2406.15506; 2412.13247; 2503.13607; 2511.15785; 2603.08695
- Neutron stars 2305.01002
- Horizontal-branch stars 2412.21163
- Wolf-Rayet stars 2412.21163
- Starburst galaxy M82 2412.03660

$a \to \gamma\gamma$ via $g_{a\gamma} aF\tilde{F}$

Two-body decay

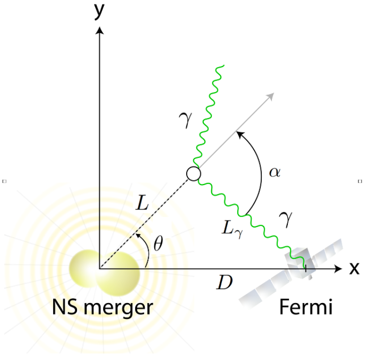


Figure: From Dev, Fortin, Harris, Sinha & **YCZ**, PRL132 (2024) 101003.

Deflection angle α is fixed by ω_γ

$$\cos\alpha = \frac{1}{\beta_a} - \frac{\omega_a(1-\beta_a^2)}{2\beta_a\omega_\gamma}$$

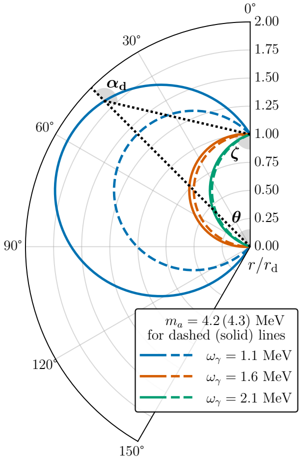
Observation angle ζ is fixed by α

$$\zeta = \alpha - \theta$$

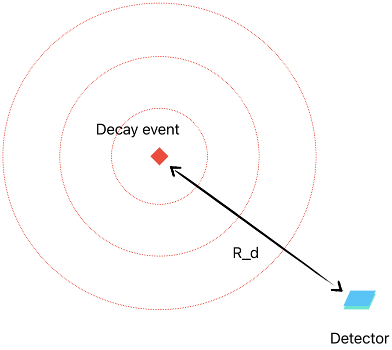
Decay geometry

Two-body decay

- For certain photon energy ω_γ (deflection α_d is fixed), only if it was emitted from certain locations p, it can be reach the Earth (detector).
- Such ps form a curve in (r, θ) plane.
- The maximal observation angle ζ is α_d.



Detection Suppression



$$\int d\Pi_{\mathrm{eff}} \propto \frac{S_d}{R_{\mathrm{d}}^2}$$

- S_d: detector effective crosssection

Photon energy flux

The photon energy rate

$$\frac{dE_\gamma}{dt} = \int_{\mathcal{M}} \frac{dn}{dt} \times r^2 dr d\cos\theta d\varphi \times \int d\Pi_{\text{eff}} \times \omega_\gamma$$

- $\mathcal{M}$: certain decay locations that fits geometry
- $dn \propto \mathcal{Q}$: the production
- $d\Pi_{\text{eff}}$: the detection suppression

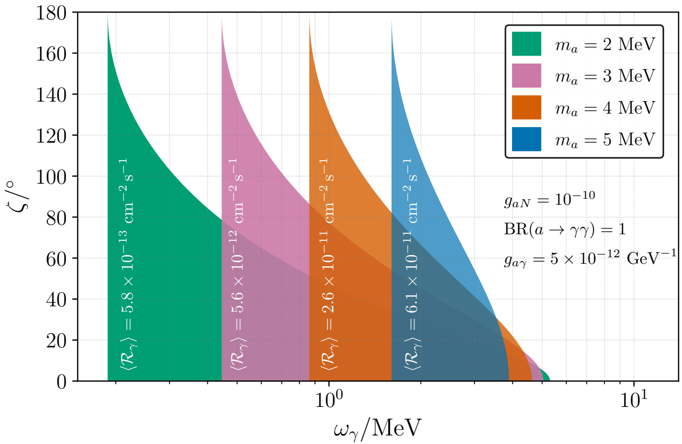
The photon energy flux

Re-parametrize in detection parameter:

$$drd\cos\theta \to d\omega_\gamma d\zeta \ , \quad \mathcal{R}_\gamma \equiv \frac{d^2\dot{F}_\gamma}{d\omega_\gamma d\zeta}$$

- $\dot{F}_\gamma = d^2E_\gamma/dS_d dt$: photon energy flux
- $[\dot{F}_\gamma] = \mathrm{erg}\cdot\mathrm{cm}^{-2}\cdot\mathrm{s}^{-1}$

The photon energy flux



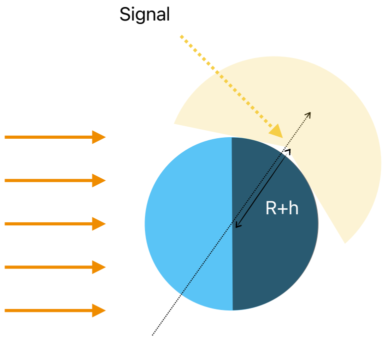
Detection

Detection

How can we observe such signal?

- Space: Satellite telescope (NuSTAR, Fermi-LAT, etc)
- Terrestrial: Pole region!

Pole detection



$$\Omega = 2\pi\left(1 + \sqrt{1 - \frac{R^2}{(R+h)^2}}\right)$$

- R: Earth radius
- h: balloon height

The flux from pole region

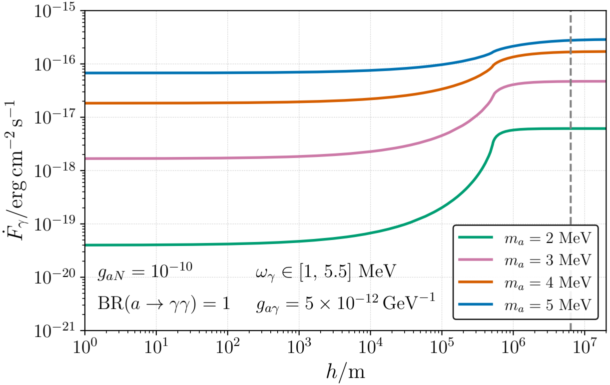


Figure: Flux at the Pole during pole night. Dash: Earth radius $\sim 6 \times 10^3$ km.

The parameter space

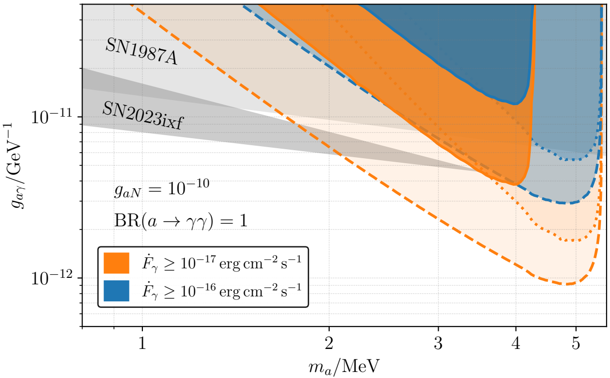


Figure: Solid: $\omega_\gamma \in [1, 5]$ MeV. Dashed: $\omega_\gamma \in [0.01, 1]$ MeV. Dotted: Balloon at 50 km height.

MeV gap?

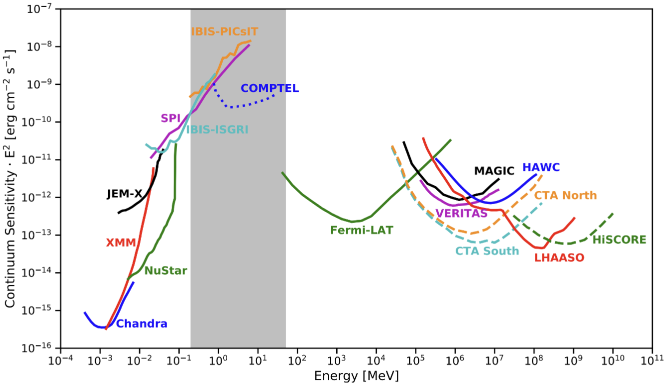
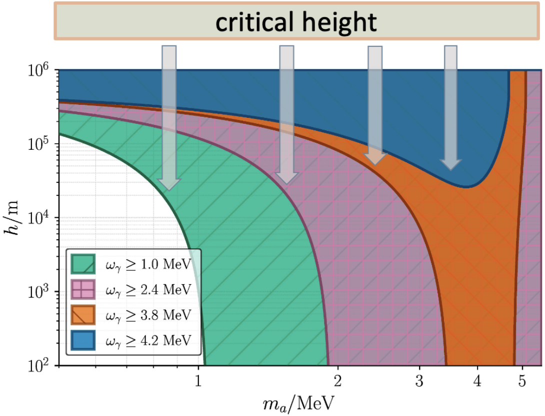


Figure: Lucchetta, Ackermann, Berge & Bühler, 2204.01325

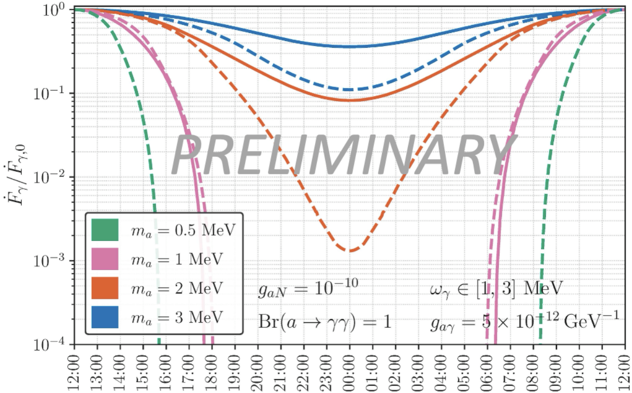
Critical height



Given certain detection channel (ω_γ range), critical height exists h_{crit}, below which $\dot{F}_\gamma \to 0$.

Modulation?

- If not exactly at the pole, earth self-rotation gives rise to modulation during the day.
- how about seasonal modulation?
- stay-tuned for the next episode



Summary

Summary

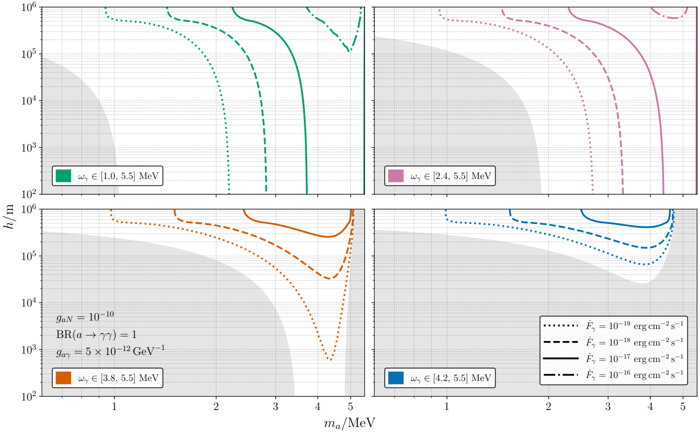
- We explored MeV $a \to \gamma\gamma$ from solar production.
- Triangle geometry give interesting detection strategy. (critical height, modulation, Light from the Darkness)
- One can extend to any two-body decay. $\nu_j \to \nu_i \gamma$, etc
- One can extend to any production source.

Thank You

Questions and comments are welcome

Flux contour

for different detection channel



Borexino limit

From 2504.19135