ALP Anarchy

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Outline

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Axion-like particles

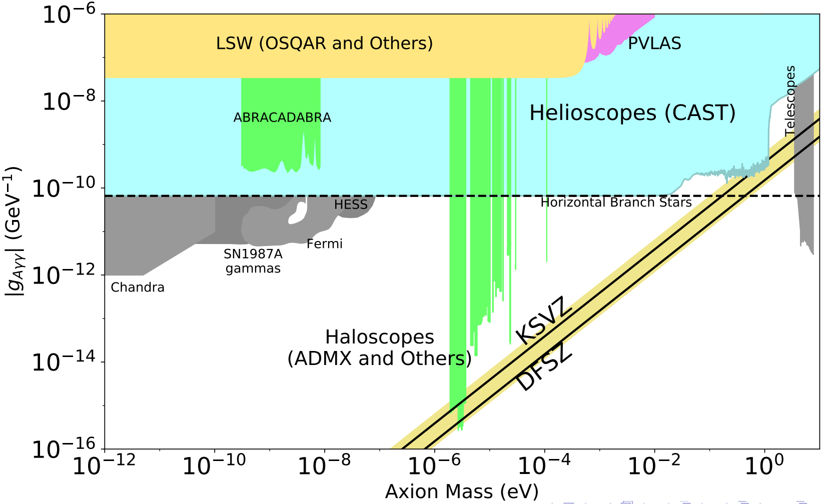
- ALPs are ultra-light particles that exist in many extensions of the Standard Model.
- They are pseudo-Nambu Goldstone bosons of global $U(1)$ symmetries.
- ALPs do not necessarily couple to gluons or solve the neutron EDM problem.
- String theory compactificiations typically give rise to many ALPs at a range of masses.
- An axiverse can also arise from a sector of dark quarks (Alexander, Manton and McDonough, 2404.11642).

Interactions

$$\mathcal{L} = \frac{1}{2}\partial_\mu\phi\partial^\mu\phi - \frac{1}{2}m^2\phi^2 + g^g\phi G\tilde{G} - g^\gamma\phi F\tilde{F} + g^f\overline{\Psi}_f\gamma^\mu\gamma_5\Psi_f\partial_\mu\phi$$

- $g \sim \frac{1}{f_a}$
- QCD axion: $mf_a \sim m_\pi f_\pi$
- General ALP: m and f_a are free parameters.

Bounds on the ALP-photon interaction



Axiverse signatures

- The string axiverse may lead to a complex, multi-component dark sector.
- Avoiding overproduction of string ALPs is a significant constraint (M. Stott *et al*, 1706.03236).
- Constraints on the axiverse mass spectrum from Black Hole superradiance (Stott & Marsh, 1805.02016; V. Mehta *et al*, 2103.06812)
- ...

The Axiverse Lagrangian

$$\mathcal{L} \supset \sum_i \Big(-\frac{1}{2}\partial^\mu \phi_i \partial_\mu \phi_i - \frac{1}{2} m_i^2 \phi_i^2 \\ - g_i^\gamma \phi_i \tilde{F}^{\mu\nu} F_{\mu\nu} + g_i^e \bar{\psi} \gamma^\mu \gamma_5 \psi \partial_\mu \phi_i \Big)$$

The Axiverse Lagrangian

Change basis so that only one ALP couples to electromagnetism:

$$\phi_\gamma = \frac{\sum_i g_i^\gamma \phi_i}{\sqrt{\sum_i {g_i^\gamma}^2}}.$$

See Halverson *et al*, 1909.05257.

The other *hidden* ALP fields are orthogonal to ϕ_γ and do not interact directly with the photon.

The Axiverse Lagrangian

$$\mathcal{L} \supset \sum_i \frac{1}{2}\partial^\mu \phi_i \partial_\mu \phi_i - \sum_{i,j} \frac{1}{2} M_{ij}\phi_i\phi_j + \sum_i g_i^e \bar{\psi}\gamma^\mu\gamma_5\psi\partial_\mu\phi_i - g^\gamma \phi_\gamma \tilde{F}^{\mu\nu}F_{\mu\nu}$$

As the mass matrix is not diagonal, we will see oscillations between ϕ_γ and the other hidden ALP fields, similar to neutrino oscillations.

ALP Oscillations

Transformation between mass and electromagnetic bases:

$$|\phi_i^{\text{mass}}\rangle = U_{ji}^{\gamma}\,|\phi_j^{\text{EM}}\rangle\,,$$

This leads to oscillations between the ALP fields akin to neutrino oscillations.

ALP Oscillations

We can similarly define a basis where only one ALP state couples to the electron:

$$\phi_e = \frac{\sum_i g_i^e \phi_i}{\sqrt{\sum_i g_i^{e2}}}.$$

$$\left|\phi_i^{\text{mass}}\right\rangle = U_{ji}^e \left|\phi_j^{\text{electron}}\right\rangle ,$$

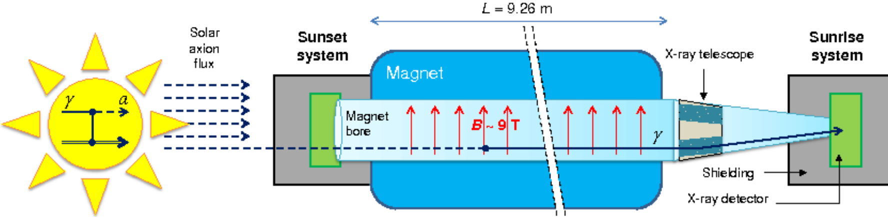
ALP Oscillations

- **Mass basis**: mass matrix is diagonal, no oscillations between propagating ALP states.
- **Electromagnetic basis**: only one ALP couples to the photon with coupling g^γ.
- **Electronic basis**: only one ALP couples to the electron with coupling g^e.
- The electromagnetic and electronic ALPs are in general neither orthogonal nor colinear.
- For the QCD basis see Gavela, Quílez & Ramos, 2305.15465.

ALP Anarchy

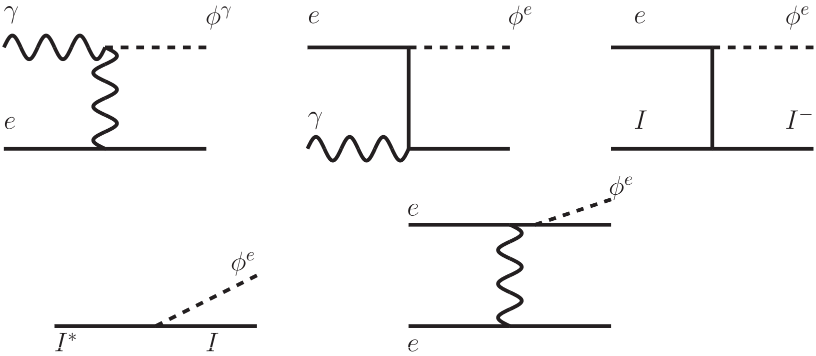
- The ALP masses and couplings are determined by the string or other UV model.
- String axiverse masses and photon couplings are calculated in Halverson *et al*, 1909.05257 and Gendler *et al*, 2309.13145.
- No such calculation has been performed for the ALPs' electron couplings.
- We will remain agnostic to the ALPs' UV physics by randomly sampling the basis transformation matrices U^γ and U^e from $SO(N)$.
- Motivated by the neutrino anarchy framework.

CAST



Reproduced from 1705.02290.

Solar ALP production



CAST

- Assume that ALP masses are $m_i \ll 10^{-2}$ eV.
- ALP states ϕ_γ and ϕ_e are produced in the sun.
- CAST with evacuated magnet bores detects the state ϕ_γ.
- ALPs produced in the Sun may oscillate into hidden ALPs as they travel to Earth, and therefore be unobservable to CAST.
- Seek to compare bounds on g^e and g^γ for different values of the number of relevant ALP states N.

ALP Oscillations

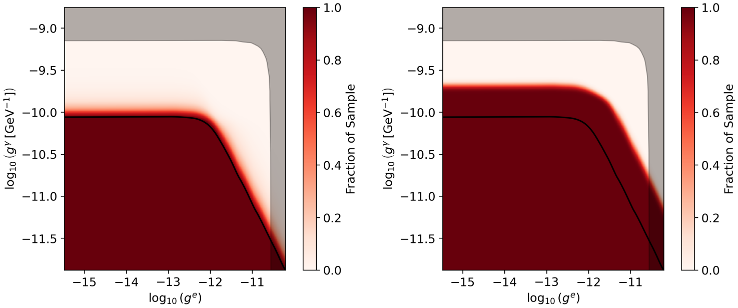
Mass eigenstates propagate as $|\phi_i(L)\rangle = \mathrm{e}^{-i\frac{m_i^2 L}{2\omega}} |\phi_i(0)\rangle$.

For $\Delta m^2 > 10^{-12}\mathrm{eV}^2$, the ALP oscillation probability becomes independent of Δm^2 when we average over the CAST energy range:

$$P_{\gamma\to\gamma} = \frac{\sum_i^N g_i^{\gamma 4}}{\left(\sum_i^N g_i^{\gamma 2}\right)^2},$$

$$P_{e\to\gamma} = \frac{\sum_i^N g_i^{e2} g_i^{\gamma 2}}{\sum_i^N g_i^{e2} \sum_i^N g_i^{\gamma 2}}.$$

CAST bounds



The fraction of ALP anarchy realisations consistent with non-detection as a function of coupling (g^e and g^γ) shown for two different values of N – Left: $N = 2$; Right: $N = 30$.

Transparency of intergalactic space

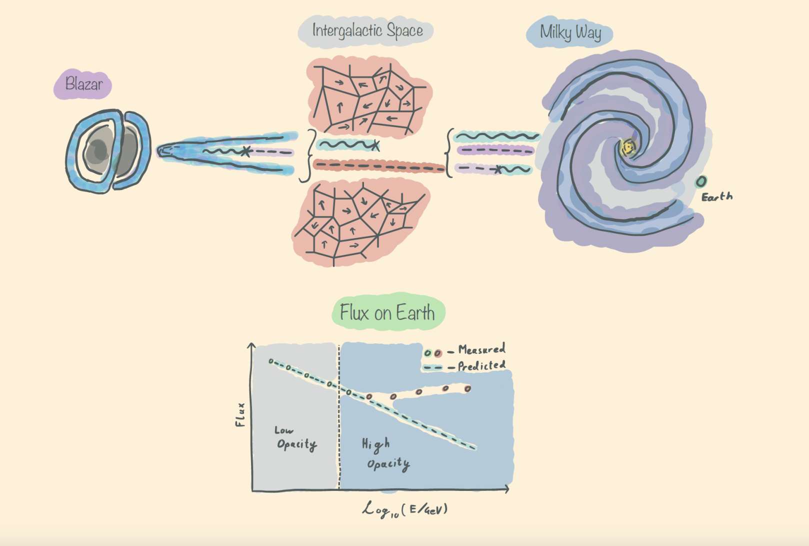


Image by James Maxwell

Anomalous Transparency Hint

- ALPs and photons can interconvert in the magnetic fields of galaixes, galaxy clusters, AGN and intergalactic space.
- Photons above ~ 100 GeV are attenuated in intergalactic space due to pair production with extra-galactic background light.
- The universe might be more transparent to such very high energy photons than expected (Horns & Meyer 1201.4711).
- This anomaly can be explained by interconversion with ALPs, as an intergalactic example of light shining through a wall.

Transparency of intergalactic space

- ALP-photon interconversion has been postulated to explain the anomalous transparency of intergalactic space to very high energy photons (see e.g. Meyer *et al* 1302.1208)

- Photons may convert to ALPs in the cluster magnetic field, propagate freely through the intergalactic medium, and convert back to photons in the Milky Way magnetic field

- How would this effect change in a many ALP model?

Transparency of intergalactic space

- Oscillation from the electromagnetic ALP to hidden ALPs could decrease final photon signal.
- The ALP mass is relevant in this environment, so it will be easiest to work in the mass basis.

ALP-photon conversion

$$\left(\omega + \begin{pmatrix} \Delta_\gamma & 0 & \Delta_{\gamma ax} \\ 0 & \Delta_\gamma & \Delta_{\gamma ay} \\ \Delta_{\gamma ax} & \Delta_{\gamma ay} & \Delta_a \end{pmatrix} - i\partial_z\right)\begin{pmatrix} \mid \gamma_x\rangle \\ \mid \gamma_y\rangle \\ \mid \phi\rangle \end{pmatrix} = 0$$

- $\Delta_\gamma = \frac{-\omega_{pl}^2}{2\omega}$
- Plasma frequency: $\omega_{pl} = \left(4\pi\alpha\frac{n_e}{m_e}\right)^{\frac{1}{2}}$
- $\Delta_a = \frac{-m_a^2}{\omega}$.
- Mixing: $\Delta_{\gamma ai} = g^\gamma B_i$

$$P_{a\to\gamma}(L) = \mid \langle 1,0,0|f(L)\rangle \mid^2 + \mid \langle 0,1,0|f(L)\rangle \mid^2$$

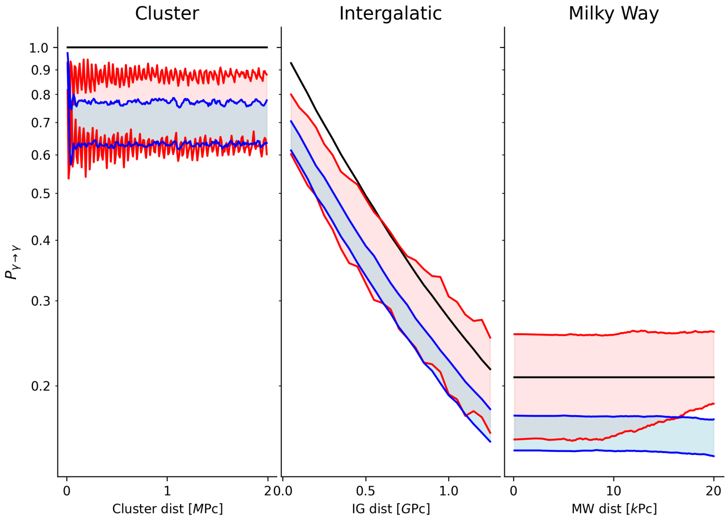
ALP-photon conversion

$$\left(\omega + \begin{pmatrix} \Delta_\gamma & 0 & \Delta_{\gamma a x1} & \Delta_{\gamma a x2} \\ 0 & \Delta_\gamma & \Delta_{\gamma a y1} & \Delta_{\gamma a y2} \\ \Delta_{\gamma a x1} & \Delta_{\gamma a y1} & \Delta_{a1} & 0 \\ \Delta_{\gamma a x2} & \Delta_{\gamma a y2} & 0 & \Delta_{a2} \end{pmatrix} - i\partial_z \right) \begin{pmatrix} \mid \gamma_x \rangle \\ \mid \gamma_y \rangle \\ \mid \phi_1 \rangle \\ \mid \phi_2 \rangle \end{pmatrix} = 0$$

ALP-photon conversion

- Model magnetic field and electron density in galaxy cluster, intergalactic space and Milky Way.
- Draw realisations of magnetic fields and ALP anarchy realisations.
- Density matrix approach to model attenuation of photon component in intergalactic space.
- Calculate photon survival probabilities for each realisation.
- Compare to single ALP case with the same g^{γ}.

In ALP anarchy models



Photon survival probability for 400 GeV photon produced by 1ES0414+009. The zero ALP case is shown in black, with the central third of samples shown in red and blue for the 1 ALP and 20 ALP cases.

Summary

- String axiverse scenarios contain an ‘electromagnetic’ ALP and a number of ‘hidden’ ALPs.
- These ALPs undergo oscillations similar to neutrino oscillations.
- ALP oscillations may significantly reduce the experimental signals when an ALP is produced and then *travels a long distance* before being detected.

Discussion

- This may effect ALP bounds from CAST, VHE blazars, white dwarfs and SN1987A.
- Effects that only probe ALP production (e.g. stellar cooling) are not significantly affected by ALP oscillations.
- Comparisons between different ALP search strategies become harder.
- The effect of oscillations could be very large when many ALP mass eignstates couple to SM particles.
- String axiverse phenomenology is very rich and warrants further study.