ALP Anarchy

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Light Dark World
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Outline

1. The String Axiverse
2. ALP Oscillations
3. ALP Anarchy
4. CAST
5. Very High Energy Blazars
6. Discussion

2107.12813, FCD
2311.13658, FCD, James Maxwell and Jessica Turner

Collaborators

Jessica Turner

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Axion-like particles

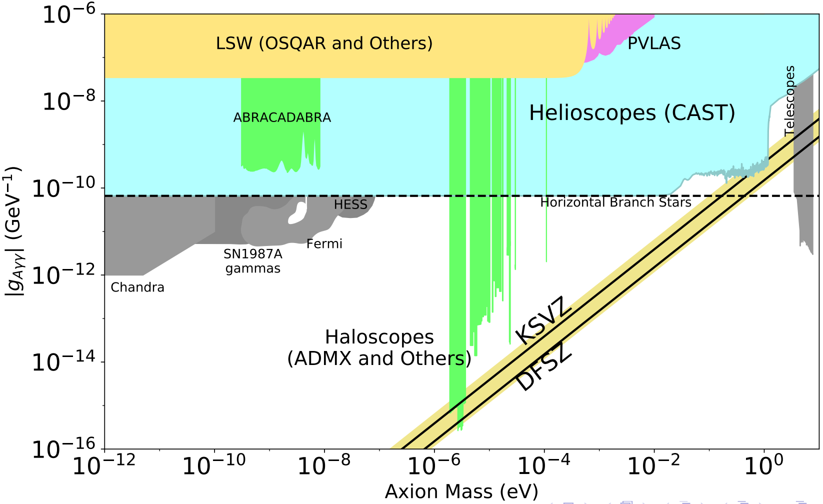
- ALPs are ultra-light particles that exist in many extensions of the Standard Model.
- They are pseudo-Nambu Goldstone bosons of global $U(1)$ symmetries.
- ALPs do not necessarily couple to gluons or solve the neutron EDM problem.
- String theory compactificiations typically give rise to many ALPs 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

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

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:

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

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

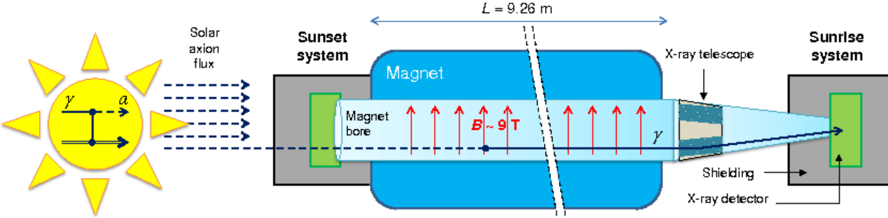
ALP Oscillations

- **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

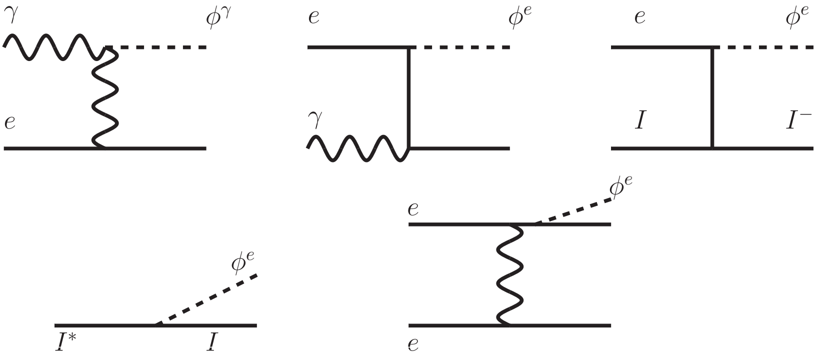
- The ALP masses and couplings are determined by the string or other UV model.
- String axiverse masses and photon couplings are calculated in Halverson *et al*, 1909.05257 and Gendler *et al*, 2309.13145.
- No such calculation has been performed for the ALPs' electron couplings.
- We will remain agnostic 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

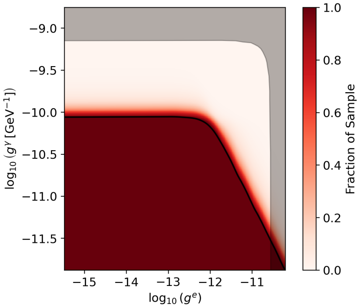
Mass eigenstates propagate as $|\phi_i(L)\rangle = \mathrm{e}^{-i\frac{m_i^2 L}{2\omega}}\,|\phi_i(0)\rangle$.

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

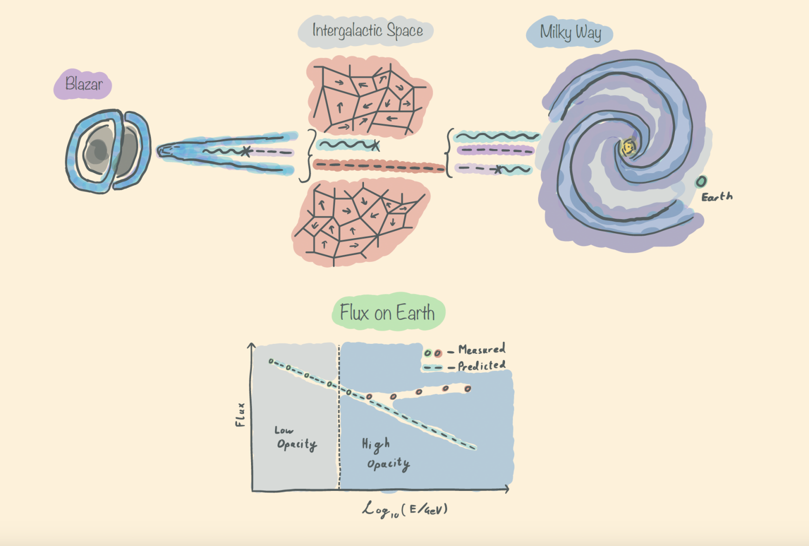


Image by James Maxwell

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

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

- $\Delta_\gamma = \frac{-\omega_{pl}^2}{2\omega}$
- 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: $\Delta_{\gamma a i} = g^\gamma B_i$

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

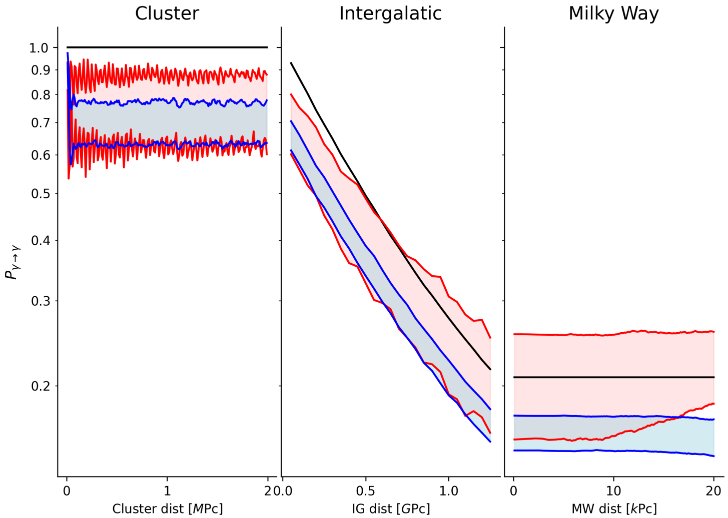
ALP-photon conversion

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

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.