# Axions and dark sectors

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# Overview

Dark sectors to search for at the intensity frontier:

- The strong CP problem
- The QCD axion
- Properties of the axion and ALPs
- Constraints ... and hints!
- Hidden photons/$Z'$ bosons

# The strong CP problem

In the lagrangian of the strong force we can write a term which violates CP:

$$\mathcal{L} \supset \frac{\theta}{64\pi^2} G^a_{\mu\nu} G^a_{\rho\kappa} \epsilon^{\mu\nu\rho\kappa}.$$

Such a term would (through pion loops) induce an electric dipole moment for the neutron, of the order

$$d_n \sim |\theta| e \frac{m_\pi^2}{m_N^2} \simeq 10^{-16}\ e\,\mathrm{cm}.$$

However, the current limit is

$$d_n \leqslant 3.0 \times 10^{-26}\ e\,\mathrm{cm}, \longrightarrow |\theta| < 10^{-10}\ !$$

Even if we suppose that the strong force preserves $CP$ and set $\theta = 0$, CP is violated in the Standard Model and, when we diagonalise the quark masses and remove their complex phases, we find

$$\delta\theta = \arg\det \mathcal{M}_f$$

where $\mathcal{M}_f$ is the mass matrix of all the quarks.

- We know the CKM angles, e.g. $\delta_{13} \simeq 1.2$.
- Therefore there seems to be some extreme fine-tuning of this parameter in the lagrangian.

# Solutions

There are three widely-known proposed “solutions:”

1. The lightest quark is massless. This seems to be excluded by lattice QCD data.
2. Spontaneous breaking of CP. This would prohibit a “bare” $\theta$ term in the action, and there are mechanisms that allow for the generation of CP-violation in the CKM matrix without a phase in $\det \mathcal{M}_f$ – at leading order. These fit into Grand Unified Models and/or left-right symmetric models. However, to prevent a phase being generated at higher orders again introduces tuning.
3. An “axion,” that promotes $\theta$ to $\theta + \frac{a}{f}$. This is the most widely accepted solution.

# Axions mix with pions

The interactions of the QCD axion can be parametrised as

$$\mathcal{L} \supset \frac{1}{2}\partial_\mu a \partial^\mu a + (\theta + \frac{a}{f_a})\frac{g_3^2}{32\pi^2} G^a_{\mu\nu}\tilde{G}^{a\,\mu\nu} + \frac{a}{f_a} C_{a\gamma\gamma}\frac{e^2}{32\pi^2} F_{\mu\nu}\tilde{F}^{\mu\nu}$$
$$+ \sum_f \left[\bar{f}(i\gamma^\mu\partial_\mu - m_f)f + \frac{C_{aff}}{2f_a}\partial_\mu a(\bar{f}\gamma^\mu\gamma_5 f)\right].$$

We can remove the QCD anomaly by making the rotations

$$u \to e^{-i\alpha_u\gamma_5}u, \qquad d \to e^{-i\alpha_d\gamma_5}d, \qquad \alpha_u + \alpha_d = -\frac{1}{2}(\theta + \frac{a}{f_a}).$$

Now at low energies the quarks form into the pions. We can write

$$u = \exp(\frac{i\pi^0}{2f_\pi}\gamma_5)\nu, \qquad d = \exp(-\frac{i\pi^0}{2f_\pi}\gamma_5)\nu, \qquad \bar{\nu}\gamma_5\nu = 0$$

The mass terms become

$$-m_u\overline{u}\exp(-2i\alpha_u\gamma_5)u \to -m_u\bar{\nu}\nu\cos(\frac{\pi^0}{f_\pi} - 2\alpha_u)$$
$$-m_d\overline{d}\exp(-2i\alpha_d\gamma_5)d \to -m_d\bar{\nu}\nu\cos(-\frac{\pi^0}{f_\pi} - 2\alpha_d)$$

# Axion properties

Axion mixing with pions is very important:

- Allow us to calculate the mass:

$$m_a^2 = \frac{m_\pi^2 f_\pi^2}{f_a^2} \frac{z}{(1+z)^2}.$$

- $z \equiv m_u/m_d \simeq 0.56$. The latest calculations give

$$m_a = 5.70(7) \text{ meV} \times \left( \frac{10^9 \text{ GeV}}{f_a} \right).$$

- Allow us to produce axions in pp collisions (gives a lower bound on $f_a$ for QCD axion)
- Places bounds on axions from rare decays

# Axion coupling to photons

The same calculation also gives a contribution to the photon anomaly:

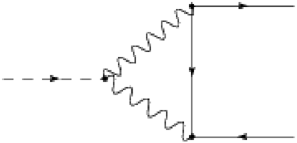
$$\begin{aligned}\delta\mathcal{L} =& \frac{e^2}{8\pi^2} F_{\mu\nu}\tilde{F}^{\mu\nu}\,\mathrm{tr}(Q^2(\alpha_u + \alpha_d)) \\ =& \frac{e^2}{8\pi^2} F_{\mu\nu}\tilde{F}^{\mu\nu} \times \underbrace{3}_{\text{colours}} \times \left(\frac{4}{9}\alpha_u + \frac{1}{9}\alpha_d\right) \\ \to \Delta C_{a\gamma\gamma} =& -\frac{2}{3}\frac{4+z}{1+z}.\end{aligned}$$

This is a very important result! It tells us that even if we try to set $C_{a\gamma\gamma} = 0$, then the interaction with the quarks/pions will generate one.

# Fermions

The other very important couplings are to electrons and nucleons, which will be generated – at least – by photon loops:

$$\Delta C_{aee} \simeq \frac{3\alpha^2}{4\pi^2} C_{a\gamma\gamma} \log \frac{f_a}{m_e}$$



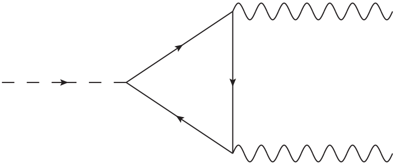
- For nucleons, a coupling will be generated from the quark couplings, and can be calculated from matrix elements of $\langle N|\overline{q}\gamma^\mu\gamma_5 q|N\rangle$.
- So $C_{a\gamma\gamma}, C_{aee}, c_{aNN}$ are model dependent but have minimum reasonable values for the QCD axion: we cannot assume that they are zero.

# Top-down motivation

So where does the axion come from?

- In field theory, it is a Goldstone boson of a Global symmetry that is anomalous under QCD.

$\phi = f_a e^{ia/f_a}$, $\mathcal{L} \supset -y\phi\psi_1\psi_2 + h.c.$



- $f_a \leftrightarrow$ expectation value of "Higgs" that breaks the symmetry → a harbinger of physics at a (very) high energy scale!
- Fields are ubiquitous in e.g. string theory, $f_a \sim M_{\text{string}} \rightarrow$ there is a *string axiverse* with many axions having different logarithmically distributed masses.
- So why not consider axions that are anomalous under just $U(1)_Y \times SU(2)_W$? → Axion-Like-Particles?
- Or more recently: allow an ALP that couples to QCD, but has a large mass explicitly breaking the symmetry.

# Misalignment dark matter

- An axion or ALP is a periodic field: it can take any initial value in $[0, 2\pi f_a]$ since the potential energy in the field is negligible compared to energies in early universe.
- During inflation any scalar field will undergo quantum fluctuations of magnitude $\frac{H_I}{2\pi} \rightarrow \sigma_\Theta = \frac{H_I}{2\pi f_a}$
- At later times, the scalar field behaves classically with equation of motion

$$\ddot{\phi} + 3H\dot{\phi} + m_\phi^2 \phi = 0$$

- While $3H > m$, the field is damped and retains its initial vev.
- When $3H = m$, it starts to oscillate and will behave like a bath of particles; the energy stored in the field is $\frac{1}{2} m^2 \phi_0^2 \sim \frac{1}{2} m_a^2 f_a^2 \theta^2$ which starts to red-shift like matter $\propto a^{-3}$.
- One complication: for the QCD axion, the mass decreases rapidly as the temperature increases; instanton calculations give

$$V_{\text{inst}} \sim \frac{m_u m_d m_s \Lambda_{QCD}^9}{(\pi T)^8} \rightarrow m_a \sim T^{-4}$$

# ALP vs axion dark matter

- So for the QCD axion we find

$$\frac{\Omega_a h^2}{0.112} \simeq 6 \times \left(\frac{f_a}{10^{12}\mathrm{GeV}}\right)^{7/6} \left(\frac{\theta_a}{\pi}\right)^2$$

- While for an ALP we find

$$\frac{\Omega_a h^2}{0.112} \simeq 1.4 \times \left(\frac{m_{a_i}}{\mathrm{eV}}\right)^{1/2} \times \left(\frac{f_{a_i}}{10^{11}\mathrm{GeV}}\right)^2 \left(\frac{\theta_a}{\pi}\right)^2$$

This means that the parameter space can be very different:

- For the QCD axion we are restricted by dark matter at high $f_a$
- The QCD axion always mixes with pions and therefore has restrictions coming from nucleon couplings
- It will always have a minimal coupling to electrons and photons coming from this too (more later) which bound $f_a \gtrsim 10^9$ GeV.
- For an ALP, we have no such restrictions except that it should not couple strongly to QCD!
- In fact we have a “maximum” allowed coupling to the photon:

$$g_{i\gamma} \equiv \frac{\alpha}{2\pi}\frac{C_{a_i}}{f_{a_i}} \lesssim \frac{\alpha}{2\pi f_{a_i}}$$

- Gives the lifetime of

$$\tau_{a_i} = \frac{64\pi}{g_{i\gamma}^2 m_{a_i}^3} \simeq 1.3 \times 10^{25}\,\mathrm{s} \left(\frac{g_{i\gamma}}{10^{-10}\mathrm{GeV}^{-1}}\right)^{-2} \left(\frac{m_{a_i}}{\mathrm{eV}}\right)^{-3}$$

# Classic axion window

Axions and ALPs face different exclusions depending on what they couple to, and are strongest for the QCD axion:

- $\frac{f_a}{C_{a\gamma\gamma}} \gtrsim 10^7$ GeV from measurements of lifetime of HB stars
- $\frac{f_a}{C_{aee}} \gtrsim 2 \times 10^9$ GeV from delay of helium ignition in low-mass red giants.
- $\frac{f_a}{C_{aNN}} \gtrsim 3 \times 10^9$ GeV $\leftrightarrow f_a \gtrsim 0.6 \times 10^9$ GeV from the duration of neutrino signal from Supernova SN1987A

So the classic QCD axion window is

$$10^9 \text{ GeV} \lesssim f_a \lesssim 10^{12} \text{ GeV} \leftrightarrow 5\ \mu\text{eV} \lesssim m_a \lesssim 5 \text{ meV}$$

Caveats:

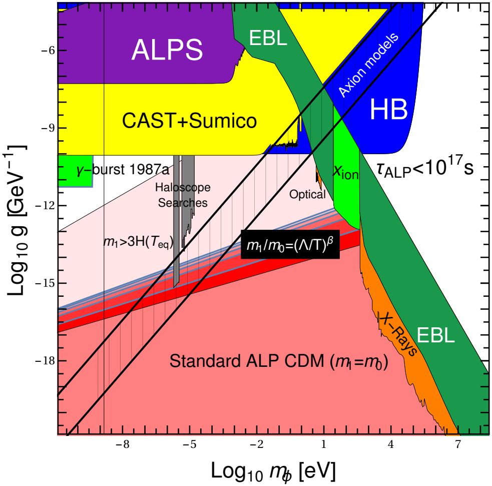
- The upper bound on $f_a$ is only based on *naturalness*: people argue that anthropic reasoning allows any value
- Explorations of string theory and quantum gravity imply $f_a \lesssim M_P$.
- On the other hand, having late-time entropy injection before BBN could allow $f_a \lesssim 10^{14}$ GeV while staying fully natural.

# Where can ALPs be?

For ALPs, we usually assume only $C_{a\gamma\gamma}$ so that $C_{aNN}$, $C_{aee}$ are much smaller (generated by loops). But for light ALPs, the most important is the HB bound:

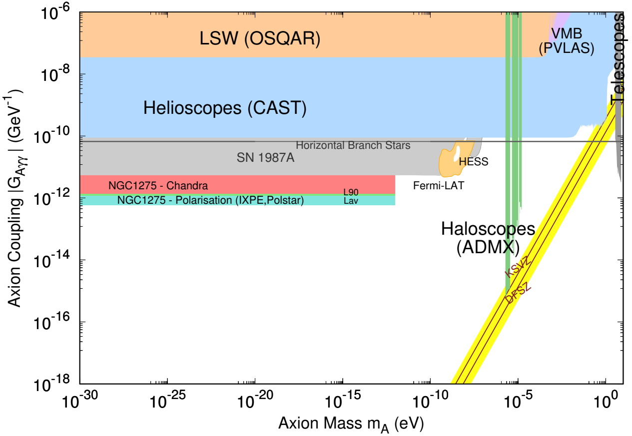
$$\frac{f_a}{C_{a\gamma\gamma}} \gtrsim 10^7 \text{ GeV} \leftrightarrow g_{a\gamma} = \frac{C_{a\gamma\gamma}}{f_a}\frac{\alpha}{2\pi} \lesssim 10^{-10} \text{ GeV}^{-1}$$

If ALPs are dark matter, we have the following summary:



# Polarisation

... and including a paper from today (Day & Krippendorf 1801.10557) polarisation could set the best bounds:



# Hints of ALPS

But there are also *many* hints of a light ALP:

- Anomalous transparency of the universe for VHE gamma rays

$$f_i/C_{i\gamma} \sim 10^8 \text{ GeV}$$

- ... and for same value of $f_i/C_{i\gamma}$, steps is power spectrum at critical energy of 100 GeV, hinting at $m_{\text{ALP}} \sim 10^{-9} \div 10^{-10}$ eV.
- X-ray hint of ALPs from the Coma cluster (Conlon, Marsh, Powell, ...)

$$\frac{f_a}{C_{a\gamma\gamma}} \lesssim 10^{10} \text{GeV} \sqrt{0.5/\Delta N_{eff}}$$

- Observation of spectral modulations in NGC1275 (Conlon et al)

$$\frac{f_a}{C_{a\gamma\gamma}} \sim 10^9 \text{ GeV}$$

- Solution to non-standard energy loss of white dwarfs

$$f_i/C_{ie} \simeq (0.2 \div 2.6) \times 10^9 \text{ GeV}$$

- These are compatible (need $C_{i\gamma}/C_{ie} \gtrsim 10$) and could be searched for in future experiments!!

Also the dark matter could decay to an ALP to fit the 3.55 keV line:

$$\mathcal{L} \supset \frac{1}{M} \bar{\chi}_2 \gamma^5 \chi_1 \partial^\mu a, \qquad M \sim 10^{17} \text{ GeV}$$

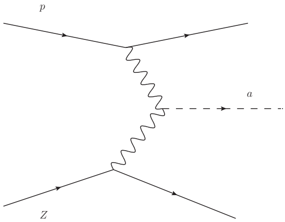
# Very light ALPs and fuzzy DM

- There exist bounds just on the mass of an ALP coming from *black hole superradiance* and also gravitational waves, removing windows of masses around $10^{-13}$ to $10^{-11}$ eV.
- However, a possibility receiving a lot of attention is *fuzzy dark matter* with $m_a > 10^{-25}$ eV.
- Fuzzy DM could solve problems of WIMPs e.g. the cusp-core problem.
- It can also be constrained by cosmological observations, see e.g. papers of DJE Marsh.

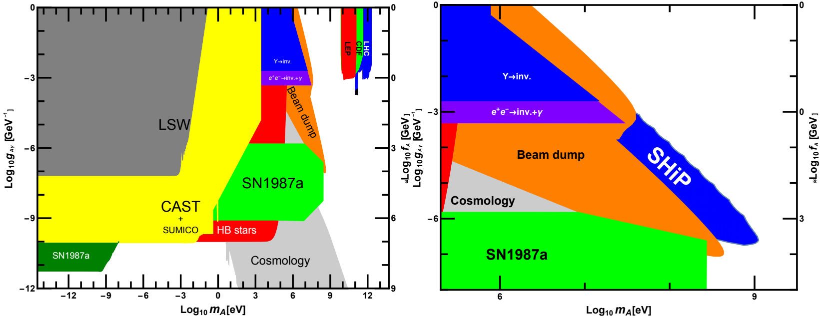
# ALPs at colliders

Going instead in the opposite direction in energy and looking at large mass/coupling ALPs, there has been a lot of interest in ALPs at colliders/beam dumps/SHiP etc:

At beam dumps such as SHiP and ALP-Traum, look at Primakoff process:

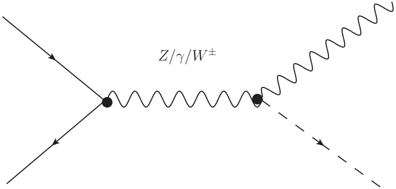


Constraints/prospects on $g_{a\gamma}$ are given by (from the SHiP proposal):

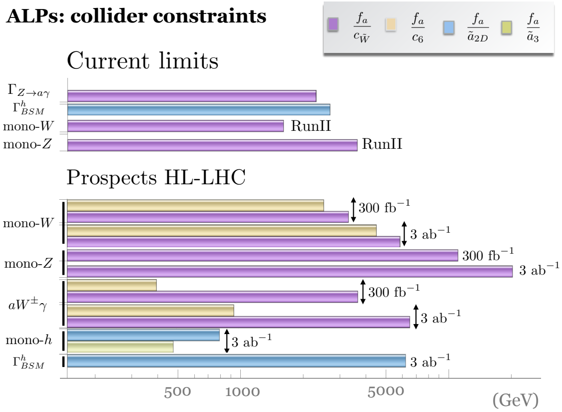


# LHC

Classic signature at the LHC is a monophoton/mono-Z/W/monojet:



Constraints just from these couplings from 1701.05379 (Brivio et al):



# Other WISPs

*Hidden Photons* or $Z'$ bosons are the other dark sector particles of major interest, which interact via *kinetic mixing*:

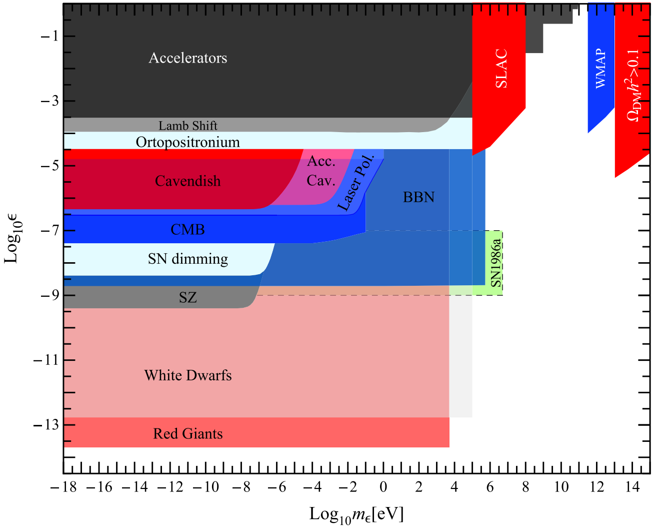
$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}X_{\mu\nu}X^{\mu\nu} + \frac{m_{\gamma'}^2}{2}X_\mu X^\mu - \frac{\chi}{2}F_{\mu\nu}X^{\mu\nu} + J_V^\mu A_\mu + J_H^\mu X_\mu$$

- Hidden photons/$Z'$ obtain masses through either a hidden Higgs or the Stückelberg mechanism.

Also have phenomenon of milicharges:

- If $m_{\gamma'}$ is small (compared to $E_\gamma$) can make transformation $X_\mu \to X_\mu - \chi X_\mu \to J_H$ picks up interaction with $A_\mu$ proportional to $\chi \to$ millicharges.
- ... but then the photon can oscillate into the hidden photon (like neutrino oscillations) and e.g. pass through walls!
- If $E_\gamma \ll m_{\gamma'}$ make the transformation $A_\mu \to A_\mu - \chi X_\mu \to J_V$ picks up interactions with $X_\mu$ but no millicharges.

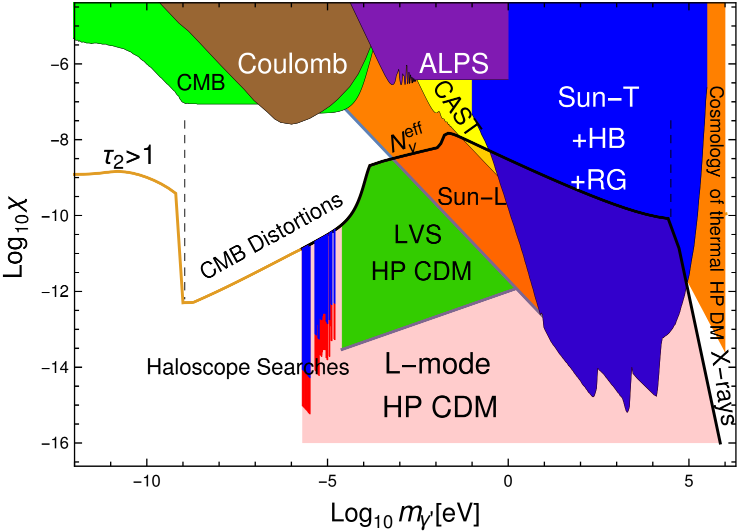
# Minicharge bounds



# Motivation

- Hidden photons/$\mathrm{Z}'$ appear ubiquitously in string theory <u>and can make predictions about their masses and kinetic mixings!</u>
- Constantly invoked to explain anomalies: $\mathrm{B} \to \mathrm{K}^*$, neutron lifetime discrepancy, proton radius puzzle, ...
- Kinetic mixing is <u>renormalisable</u> so is not suppressed by any high energy scale!
- Stückelberg mass is protected by gauge symmetry $\to$ no new hierarchy problem, in contrast to extra Higgs sectors.
- Can also be a candidate for dark matter after misalignment production!
- Can search for them in the lab: light-shining-through walls, helioscopes, haloscopes, ...

# Dark matter parameter space



# Conclusions

- Axions and related dark sectors present a huge opportunity for the intensity frontier
- The QCD axion is possibly the best motivated new physics that we have, and would be a direct link to physics above $10^9$ GeV!
- Similarly ALPs must have their origins in very heavy scales, but the parameter space is huge!
- Axions, ALPs and hidden photons have many motivations from the top-down and bottom up: they present a spectacular opportunity for disovery at the intensity frontier!