Axion Phenomenology, Dark Matter, and ADMX

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290e Underground Physics Seminar

Strong-CP Problem I

SM is one of the most successful theories in history of physics. However, it contains a serious blemish: Strong-CP problem of QCD.

Non-abelian gauge theories have rich vacuum structure ('t Hooft):

$$n = \frac{ig^3}{24\pi^3} \int d^3x \mathrm{Tr}[\epsilon_{ijk} A^i(x) A^j(x) A^k(x)],$$

where $|n\rangle$ is "winding number" that characterizes non-trivial degenerate vacuum configurations.
Correct vacuum of the theory is a superposition of these topologically distinct configurations $|\theta\rangle = \sum e^{-in\theta} |n\rangle$. θ is a phase that tells us how these different solutions (instantons) should be added together.
Analogous to quantum tunneling $\Rightarrow$ necessarily suppressed by $e^{-8\pi^2/g^2}$.

Strong-CP Problem II

The effect of the θ-vacuum can be recast as

$$\mathcal{L}_{QCD} = \mathcal{L}_{pert} + \bar{\theta}\frac{g^2}{32\pi^2}G\tilde{G},$$

where $\bar{\theta} = \theta + \text{arg det}[Q]$ includes contribution from phase of the quark mass matrix.
Note that $G\tilde{G}$ term violates CP, and this leads to a neutron electric dipole moment $d_n \simeq 5 \times 10^{-16}\bar{\theta}\, e \cdot \text{cm}$. Present day bounds constrain $\bar{\theta} < 10^{-10}$.

Strong-CP: why is $\bar{\theta}$, which arises from two separate effects (QCD instantons and flavor physics) so small? What are some solutions?

- $m_u = 0$ so $\bar{\theta}$ is unphysical (chiral rotation). However, this contradicts known experimental evidence.
- QCD instanton effects are, for some reason, unimportant. But this is precisely what solves the $U(1)_A$ problem.
- There exists a spontaneously broken global symmetry $U(1)_{PQ}$ that also has a mixed anomaly under QCD $\Rightarrow$ axion! .

Axion Solution to Strong-CP

Suppose $U(1)_{PQ}$ is spontaneously broken at a high scale $f_a \Rightarrow$ axion a is the goldstone boson. But if symmetry is also anomalous under QCD (true for generic assignment of PQ charges), then

$$\mathcal{L} \supset (\partial_\mu a)^2 + \frac{a}{f_a} G\tilde{G}.$$

Basic idea is simple: $\bar{\theta}$ promoted to a field $\bar{\theta} \to \bar{\theta} + \frac{a}{f_a}$. Instantons give rise to a potential $V(a) \sim \Lambda^4_{QCD} \cos\left(\bar{\theta} + \frac{a}{f_a}\right)$ that is minimized at $\left(\bar{\theta} + \frac{a}{f_a}\right) = 0$.

One can show that (expanding around the axion minimum),

$$m_a \sim \frac{\Lambda^2_{QCD}}{f_a} \sim 6\,\mu\text{eV}\left(\frac{10^{12}\,\text{GeV}}{f_a}\right)$$

Exact relation depends on the precise model (i.e. KSVZ, DFSZ, etc.) but ultimately only 1 free parameter f_a.

Axion-like Particles (ALPs)

Simply goldstone bosons ϕ of a global symmetry spontaneously broken at high scale f_ϕ. Defined to have no QCD anomaly. Can generate mass if:

- associated symmetry anomalous under some other gauge group with strong dynamics.
- explicit breaking of symmetry (quantum gravity?).

Mass depends on additional unconstrained physics, so we generally treat (m_ϕ, f_ϕ) as 2D parameter space.

Although no connection to Strong-CP, ALPs are still well-motivated.

- Any string theory contains perhaps a large number of ALPs, with f_ϕ near the characteristic string scale $10^{16} - 10^{19}\,\mathrm{GeV}$.
- Can act as inflaton in certain models of slow-roll inflation.
- Key ingredient in cosmological relaxation models to solve electroweak hierarchy problem, CC problem.
- **Unique probe of UV physics**

Axion Phenomenology

Axion defined by $\frac{a}{f_a} G\tilde{G}$ coupling. In addition, axions (and ALPs) can have

- Coupling to photons $\frac{a}{f_a} F\tilde{F}$. Arises because, for generic assignment of PQ charges, there is an E/M anomaly.
- Coupling to fermions $\frac{\partial_\mu a}{f_a} \bar{\psi}_f \gamma^\mu \gamma_f \psi_f$. Goldstone boson $\Rightarrow$ derivative structure.

Both couplings will contain model-dependent coefficients, but parametrically all interactions suppressed by scale f_a.

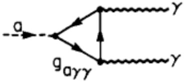
Generally, low-energy phenomenology does not change significantly for different axion models.

Axion-Photon Coupling

Axion coupling to photons described by effective Lagrangian

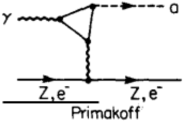
$$\mathcal{L} \supset -g_{a\gamma\gamma} a F\tilde{F} = -g_{a\gamma\gamma} a \vec{E}\cdot\vec{B},$$

where $g_{a\gamma\gamma} \equiv \frac{\alpha}{\pi}\frac{g_\gamma}{f_a}$. $g_\gamma \sim \mathcal{O}(1)$ is model-dependence.



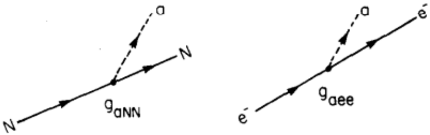
$$\Gamma(a\to\gamma\gamma) \sim 1.1\times 10^{-24}\,\mathrm{s}^{-1}\left(\frac{m_a}{\mathrm{eV}}\right)^5$$

Primakoff effect: Conversion of $a \leftrightarrow \gamma$ in an external B-field or interaction with E-field of Ze. Can be treated as an oscillation (like neutrinos).

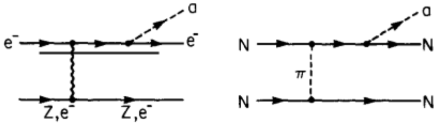


Axion-Fermion Coupling

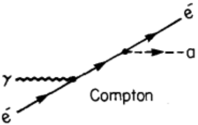
Axion couplings to fermions also characterized by (model-dependent) parameters $g_{aee}, g_{aNN}, \ldots$ Note that the coupling to nucleons arises from 2 roughly equal contributions: tree-level coupling to quarks + $a \leftrightarrow \pi^0$ mixing. There are even models ("hadronic axion") where the tree-level coupling to electrons vanishes.



Consequently, there are important axion production processes:



Bremsstrahlung



Astrophysical Bounds

Axions and Stars

- Light, weakly-coupled particles can accelerate the evolutionary process of stars by more efficiently transporting energy away.
- Best bounds come from Globular Clusters. Can compare Horizontal Branch stars (He burning stage) to known evolutionary time-scales $\Rightarrow g_{a\gamma\gamma} < 10^{-10}\,\mathrm{GeV}^{-1}$
- White dwarf cooling $\Rightarrow g_{aee} < 1.3 \times 10^{-13}\,\mathrm{GeV}^{-1}$

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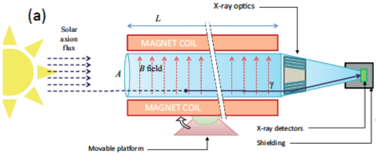
- Requirement that ν signal (Kamiokande II) not excessively shortened by axion losses.
- Burst duration + number of events $\Rightarrow m_a \lesssim 10\,\mathrm{meV},\, f_a < 10^9\,\mathrm{GeV}$.

Solar Axions

Axions produced in the sun's interior by Primakoff effect.

Searches for solar axions - helioscope experiments ("Staring at the Sun").



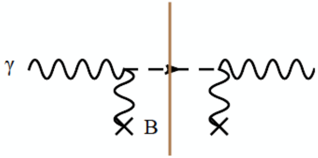
Current bounds come from the CERN Axion Solar Telescope (CAST):

$$g_{a\gamma\gamma} < 10^{-10}\,\mathrm{GeV}^{-1}, \quad m_a < 0.02\,\mathrm{eV}.$$

Future planned experiment (IAXO) will improve reach.

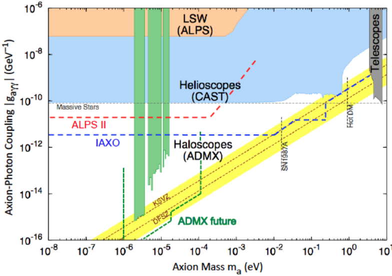
Purely Laboratory Experiments

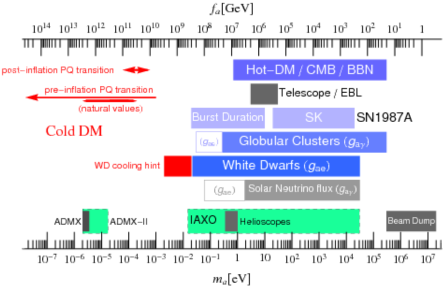
Source and detect axion in the lab - photon regeneration experiments ("Light Shining Through a Wall")



- Look for $a \leftrightarrow \gamma$ oscillations in a static B-field $\propto g^2_{a\gamma\gamma}$.
- Enhanced in high-Q cavities, can also use optical cavities.
- ALPs experiment most sensitive $\Rightarrow$ $g_{a\gamma\gamma} \lesssim 10^{-11}\,\mathrm{GeV}^{-1}$.

Axion Constraints and Parameter Space

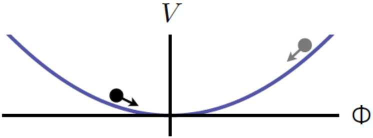




Cosmic Axions

A cosmic population of axions can arise in the early universe by two main production mechanisms.

- Thermal: axions produced by processes involving quarks and gluons (i.e. $\pi + \pi \leftrightarrow \pi + a$). Resulting axion density would constitute a hot DM component (freeze-out while still relativistic, analogous to massive neutrinos). Cosmological precision data $\Rightarrow m_a \lesssim \mathrm{eV}$.
- **Misalignment**: when PQ symmetry is spontaneously broken, axion acquires a random initial field value a_0. This is generally displaced from the CP-conserving minima $\langle a \rangle = -f_a \bar{\theta}$, and will lead to a cosmological abundance due to coherent oscillations of the field.



Axion Cosmology

In the early universe, axion field obeys Klein-Gordon EOM in an expanding universe $\ddot{\phi} + 3H\dot{\phi} + m^2\phi = 0$ (ignoring spatial gradients and interactions).

Two different limits:

- $H > m_\phi \Rightarrow \dot{\phi} \simeq 0$, so field value a_0 and energy density $\rho_\phi \sim m_\phi^2 \phi_0^2$ remain roughly constant.
- $H < m_\phi \Rightarrow$ Hubble friction cannot hold the field anymore, ϕ rolls down potential and starts to oscillate ("Cosmic Oscillator"). As universe expands, can show that amplitude of oscillations $\phi \propto \left(\frac{1}{a}\right)^{3/2} \Rightarrow \rho_\phi \sim m_\phi^2 \phi^2 \propto \left(\frac{1}{a}\right)^3$.
  Energy density of field redshifts exactly like Cold DM!

How much DM will you have? Should depend on:

- initial field value, i.e. "misalignment angle" $\theta_0 \equiv \frac{\phi_0}{f_\phi} \in [0, \pi]$.
- axion mass.

Axion DM Abundance

Recall axion mass turns on when instantons effects explicitly break PQ symmetry ("tilting of the mexican hat potential"), which occurs at $T \sim \Lambda_{QCD}$. The precise temperature dependence of m_a is

$$m_a(T) \simeq m_a \left(\frac{\Lambda_{QCD}}{T}\right)^{3.7}, \quad T > \Lambda_{QCD}.$$

Actual calculation is a bit involved, but can show

$$\Omega_a h^2 \sim 0.7 \left(\frac{f_a}{10^{12}\,\mathrm{GeV}}\right)^{1.175} \left(\frac{\theta_0}{\pi}\right)^2.$$

Note: this relation is specific to QCD axion since for general ALPs, mass generation mechanism is unknown.

Parametric behavior:

- As θ_0 increases, Ω_a increases. Makes sense since larger initial angle means larger initial energy density $\sim \Lambda_{QCD}^4 \theta_0^2$.
- As m_a increases, Ω_a decreases. For larger axion mass, oscillations turn on earlier $\Rightarrow$ energy density has more time to redshift.

Axions and Inflation

Misalignment is a general production mechanism for cosmic axions.
It is sometimes stated that too high an f_a will overclose the universe,
$\Rightarrow$ cosmological lower bound $f_a \gtrsim 10^{12}\,\mathrm{GeV}$

However, this is a bit premature! Consider two different cosmologies:

- PQ broken after inflation: most likely value of misalignment angle is $\theta_0 \simeq \mathcal{O}(\pi/2)$. Any other θ_0 would require some fine-tuning. Additionally, there are contributions to Ω_a from topological defects (production from decay of cosmic strings). Hard to quantify.

- PQ broken before or during inflation: θ_0 is randomly scanned, but our entire observable universe lands in a single θ_0 patch.
  Key point: θ_i could take any value $\in [0, \pi]$. No clear way to define probabilities in an inflationary spacetime, so all values equally likely. Sometimes dubbed "Anthropic Axion window". CMB constraints?

Features of Axion DM

We normally think of DM in a very "particle" way, which is certainly true for some popular candidates:

$$\rho_{\text{DM}} \sim 0.2\,\text{GeVcm}^{-3},\ m_{\text{WIMP}} \sim 100\,\text{GeV} \Rightarrow n_{\text{WIMP}} \sim 10^{-3}\,\text{cm}^{-3}.$$

But for axions $m_a \sim \frac{\Lambda_{QCD}^2}{f_a}$, and for reasonable masses

$$m_a \sim 10^{-5}\,\text{eV} \Rightarrow n_a \sim 10^{14}\,\text{cm}^{-3}.$$

This is a huge occupation number, so axion DM better thought of as background classical field oscillating at frequency equal to its mass

$$a(t) = a_0 \cos(m_a t).$$

$$\lambda \sim \frac{2\pi}{m_a v} \sim 10\,\text{km}\left(\frac{10^{-8}\,\text{eV}}{m_a}\right) \qquad \tau \sim \frac{2\pi}{m_a v^2} \sim 0.4\,\text{s}\left(\frac{10^{-8}\,\text{eV}}{m_a}\right),$$

where $v \sim 10^{-3}$ is the DM virial velocity in the galactic halo.
Axion DM has correlation length (random field) that is small on galactic scales, but ideal for lab-detection on human scales!

Microwave Cavity Experiments

Primary way to detect DM axions using coupling to photons.

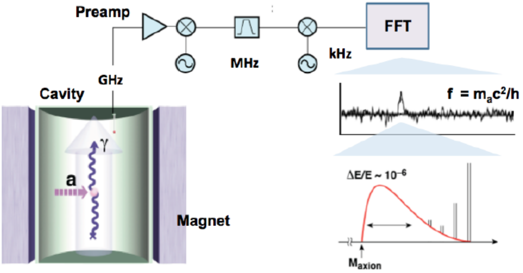
- Place a high-Q cavity in large, static B-field (Sikivie, 1983).
- Cavity fixes mass range to cavity size, allows for a resonant conversion of DM $a \to \gamma$ by Primakoff effect.

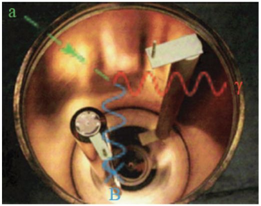
$$P_{sig} \sim g_{a\gamma\gamma}^2 \frac{\rho_{\mathsf{DM}}}{m_a} B_0^2 V Q.$$

- Resonant conversion condition: $\nu = \frac{m_a}{2\pi}\left[1 + \frac{v^2}{2}\right]$.
- Expect a quasi-monochromatic signal of $\frac{\delta\nu}{\nu} \sim 10^{-6}$ width.

Axion Dark Matter eXperiment (ADMX)

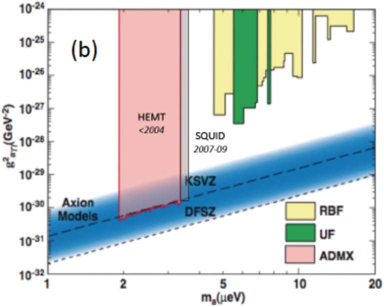
Leading microwave cavity experiment to detect DM axions and ALPs.





- $Q \sim 10^5, \quad B_0 \sim 8\,\mathrm{T}, \quad V \sim 1\,\mathrm{m}^3.$
- Two tuning rods to adjust cavity size, maintain resonant enhancement while scanning m_a .

ADMX parameter reach



ADMX reaches the QCD axion in narrow mass range. Fundamental limitations?

- Achieve sensitivity by resonance ⇒ mass pinned to size of cavity.
- Signal $\propto \left(\frac{1}{f_a}\right)^4$ suppressed, hard to probe high f_a, lower mass axions (ADMX-HF can probe slightly higher masses).

Other approaches?

Axion Electrodynamics Revisted

Recall $a(t) = a_0 \cos(m_a t) = \frac{\sqrt{2\rho_{\mathrm{DM}}}}{m_a} \cos(m_a t)$. ADMX is looking for an energy deposition from this background classical field.

However, light bosonic DM behaves collectively. Should think in terms of charges and currents (not Feynman diagrams). $\mathcal{L} \supset g_{a\gamma\gamma} a F \tilde{F}$ term can also be expressed as a modification to Maxwell Equations:

$$\nabla \times B_r = \frac{\partial E_r}{\partial t} - g_{a\gamma\gamma} \left(E_0 \times \nabla a - B_0 \frac{\partial a}{\partial t} \right), \qquad \nabla \cdot E_r = -g_{a\gamma\gamma} B_0 \cdot \nabla a$$

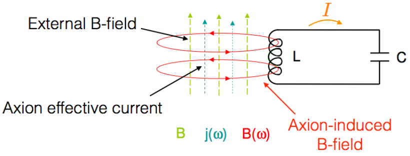
In presence of background E/M fields, axion-photon coupling induces oscillating response fields. Ignoring spatial gradients, can show that there is an effective current due to the axion

$$J_{\mathrm{eff}} \sim g_{a\gamma\gamma} \sqrt{\rho_{\mathrm{DM}}} B_0 \cos(m_a t),$$

that follows a static B-field and oscillates at a frequency equal to m_a. How to detect this oscillating current?

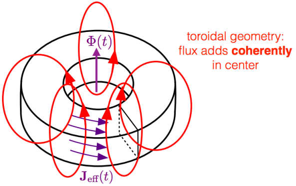
New Ideas in Axion DM Detection

Measure time-varying local flux $\propto g_{a\gamma\gamma}$!
Pickup-loop couples to induced B-field, resonant enhancement by LC circuit + SQUID magnetometer (Thomas, Cabrera; Sikivie, et al).

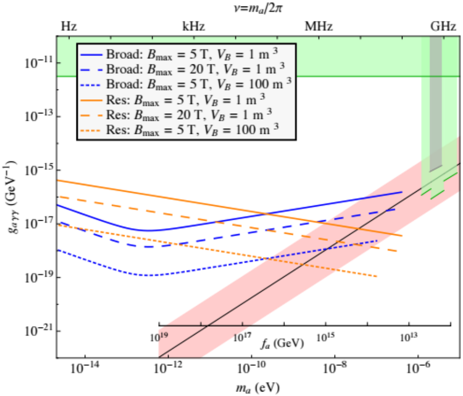


$$I = \frac{Q}{L} V_B g_{a\gamma\gamma} \sqrt{2\rho_{\rm DM}} B_0$$

Can also place LC circuit in region of zero static-field (Thaler, et al).



Sensitivity and Drawbacks



- Proposal also includes a broadband approach to detection.
- Only valid in the quasistatic regime, limits upper mass reach.
- Requires a larger "volume" for signal enhancement.