Ultra-light Dark Matter
Theory and Overview

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Sub-eV Dark Matter

Dark Matter is one of the most concrete clues of physics beyond the Standard Model.

The mass scale for dark matter spans many orders of magnitude.

For masses $\lesssim eV$, the dark matter has to be bosonic, non-thermal, and is aptly described by a classical field.

Large range of parameter space that requires particular search strategy.
Bosonic Sub-eV Dark Matter

A number of well-motivated models fall in this category

Why are these light?

(Pseudo-)Nambu - Goldstone bosons
   QCD Axion
   Axion-like particles
   :

Light spin-1 particles
   Dark photons

Very weakly coupled scalars
   Modulus / dilaton fields

Expected to be ubiquitous in theories of quantum gravity
The QCD axion

A solution to the strong CP problem

The QCD Lagrangian

\[ \mathcal{L}_{QCD} = -\frac{1}{4} G^a_{\mu\nu} G^{a,\mu\nu} - \frac{\alpha_s \theta}{8\pi} G^a_{\mu\nu} \tilde{G}^a_{\mu\nu} + y_u Q H u^c + y_d Q \tilde{H} d^c \]

Two sources of CP violation

\[ \delta_{\text{CKM}} = \arg \det \left[ y_u y^\dagger_u, y_d y^\dagger_d \right] \sim \mathcal{O}(1) \]

\[ \bar{\theta} = \arg \det \left( e^{i\theta} y_u y^\dagger_d \right) \lesssim 10^{-10} \]

The vacuum energy of QCD is minimized at \( \bar{\theta} = 0 \)

Make \( \bar{\theta} \) a dynamical field

Peccei - Quinn symmetry: (anomalous) chiral rotations of colored fermions

PQ symmetry spontaneously broken at scale \( F_a \)

(Pseudo) Nambu - Goldstone boson of spontaneous breaking of PQ symmetry: Axion
QCD Axion parameter space

Mass and decay constant

The number $f_a$ characterizes axion couplings

$$\left( \theta + \frac{a}{f_a} \frac{\alpha_s}{8\pi} \right) G_{\mu\nu}^a \tilde{G}^{\mu\nu,a} + \frac{a}{f_a} \frac{\alpha E}{8\pi N} F_{\mu\nu} \tilde{F}^{\mu\nu} + c' \frac{\partial_{\mu} a}{f_a} \bar{\psi} \gamma^\mu \gamma^5 \psi$$

QCD generated potential

$$V(a) \simeq - f_\pi^2 m_\pi^2 \cos \left( \theta + \frac{a}{f_a} \right)$$
QCD Axion parameter space

Coupling to photons

The coupling to photons is phenomenologically important

Model dependent UV contribution: charges of PQ fermions

Model independent IR contribution: axion-meson mixing

\[
\frac{a}{f_a} \frac{\alpha}{8\pi} \left[ \frac{E}{N} - 1.92 \right] F_{\mu\nu} \tilde{F}^{\mu\nu} 
\]

\[
\frac{1}{4} g_{a\gamma\gamma}
\]

Kim [Phys. Rev. Lett. 43 (1979)]
Zhitnitsky [Sov. J. Nucl. Phys. 31 (1980)]
Constraints and Hints

Axion-photon coupling is constrained by many observations.
Constraints and Hints

Phenomenological hints for axions

Excessive energy losses in stars

Giannotti et al [1512.08108]

Gamma-ray transparency

Sánchez-Conde et al [0905.3270]
Axion Cosmology

There are a number of mechanisms to populate axion dark matter

Misalignment (PQ breaking before inflation)

\[ \Omega_a h^2 \approx 0.1 \left( \frac{f_a}{10^{12} \text{ GeV}} \right)^{7/6} \theta_i^2 \]

Topological defects (post-inflation)

Significant uncertainty in predictions currently

Extended cosmological mechanisms

Entropy dump
Particle production

Daido, Takahashi, Wen [1702.03284]
PA, Marques-Tavares, Xue [1708.05008]
Co, Hall, Harigaya [1711.1048]

Should look for QCD axions everywhere!
Axion target space

Traditional target space: variants of the KSVZ and DFSZ models

Some guiding principles

Small representations
Unification
No Landau poles

Giudice, Rattazzi, Strumia
[1204.5465]
Luzio, Mescia, Nardi
[1610.07593], [1705.05370]

In general, a much wider target space is possible in extended models

\[ g_{a\gamma} \text{[GeV}] \]
\[ m_a \text{[eV]} \]
Hypercharge / PQ charge

Models where the PQ fermions have large hypercharge or Peccei-Quinn charge have moderately enhanced couplings to photons

\[ \frac{1}{4} g_{\alpha \gamma \gamma} = \frac{\alpha}{8\pi} \left[ \frac{E}{N} - 1.92 \right] \]

Hypercharge

- Landau pole above Planck scale
  \[ Y \lesssim 6 \]
- Enhancement: \( 2Y^2 \)

PQ charge

- Mass of fermions suppressed
  \[ M_\psi \lesssim f_a \left( \frac{f_a}{\Lambda} \right)^{m-1} \]
- Enhancement: \( 2m \)
Kinetic mixing

String-inspired theories predict a large number of axions

Two axion model

\[
\frac{1}{2} \partial_{\mu} a \partial^{\mu} a + m_{\pi}^2 f_{\pi}^2 \cos \frac{a}{f_a} + \epsilon \partial_{\mu} a \partial^{\mu} b + \frac{1}{2} \partial_{\mu} b \partial^{\mu} b + \frac{b}{f_b} \frac{\alpha}{8\pi} F \tilde{F} \\

b \rightarrow b - \epsilon a
\]

Enhanced coupling

\[
\frac{\epsilon f_a}{f_b} \frac{\alpha}{8\pi} a F \tilde{F}
\]

If generated in QFT, effect of kinetic mixing is expected to be small

String compactifications can have larger kinetic mixing

Cicoli, Goodsell, Ringwald [1206.0819]
Alignment mechanism

Aligned two axion model

\[ \frac{a}{f_a} \frac{\alpha_a}{8\pi} F_a \tilde{F}_a \rightleftharpoons \frac{b}{f_b} \frac{\alpha_b}{8\pi} F_b \tilde{F}_b + \Lambda^4 \cos \left( \frac{a}{f_a} + \frac{Qb}{f_b} \right) \]

The light eigenstate

\[ \phi = \frac{-Qf_a a + f_b b}{\sqrt{f_b^2 + Q^2 f_a^2}} \]

Enhanced couplings to photons

\[ \frac{Q\phi}{f_{\text{eff}}} \frac{\alpha_a}{8\pi} F_a \tilde{F}_a + \frac{\phi}{f_{\text{eff}}} \frac{\alpha_b}{8\pi} F_b \tilde{F}_b \]

\[ f_{\text{eff}} = \sqrt{f_b^2 + Q^2 f_a^2} \]


SU(M), M ∈ [3, 10]
Clockwork

N-site alignment model

Aligned multi-axion model

\[ \frac{a_1}{f} \frac{\alpha_1}{8\pi} F_a \tilde{F}_a + \Lambda^4 \cos \left( \frac{a_1}{f} + \frac{Qa_2}{f} \right) + \ldots + \Lambda^4 \cos \left( \frac{a_{n-1}}{f} + \frac{Qa_n}{f} \right) + \frac{a_n}{f} \frac{\alpha_n}{8\pi} F_b \tilde{F}_b \]

The light eigenstate

\[ \phi \approx a_1 + \frac{a_2}{Q} + \ldots + \frac{a_n}{Q^{n-1}} \]

Exponential enhancement

\[ \frac{Q^{n-1} \phi}{f_{\text{eff}}} \frac{\alpha_1}{8\pi} F_a \tilde{F}_a + \frac{\phi}{f_{\text{eff}}} \frac{\alpha_n}{8\pi} F_b \tilde{F}_b \]

\[ f_{\text{eff}} \approx f Q^{n-1} \]

[1404.6209] Choi, Kim, Yun
[1511.00132] Choi, Im
[1511.01827] Kaplan, Rattazzi
[1611.0985] Farina, Pappadopulo, Rompineve, Tesi
[1709.06085] PA, Fan, Reece, Wang
Enhanced Photon-Axion coupling

Wider target for QCD axion searches

\[ g_{\gamma\gamma} \text{ [GeV}^{-1}] \]

\[ m_a \text{ [eV]} \]

\[ \epsilon = (f_b/f_a)^{1/3} \]

\[ U(1)_Y, Y = \{0, 6\} \]

\[ U(1)_{PQ}, m = \{1, 16\} \]

\[ SU(M), M \in [3, 10] \]

\[ (SU(3)_h)^{2n-1}, n \in [3, 6] \]
Extended QCD Axion target space

1/$f_a$ [GeV$^{-1}$] vs $m_a$ [eV]

- Clockwork
- Dark photon production
- UV instantons

References:
- [1611.0985] Farina et al
- [1709.06085] PA, Fan, Reece, Wang
- [1708.05008] PA, Marques-Tavares, Xue
- [1710.04213] PA, Howe
Dark Photon Dark Matter

Spin-1 fields with very small masses

Dark electric field $\sim 50$ V/cm

Challenging to populate light dark photon dark matter

- Very limited misalignment mechanism
- Couplings to curvature

Tachyonic particle production

- Store energy in an axion, transfer to dark photons

Arias, Cadamuro, Goodsell, Jaeckel, Redondo, Ringwald [1201.5902]

PA, Kitajima, Reece, Sekiguchi, Takahashi, [1810.07188]
Bastero-Gil, Santiago, Ubaldi, Vega-Morales [1810.07208]
Co, Pierce, Zhang, Zhao [1810.07196]
Dror, Harigaya, Narayan [1810.07195]

Common / Complementary probes with the axion

Kinetically mixed with photons
Light scalar dark matter

[+ CP violating axion coupling]

Light scalars (moduli) appear ubiquitously in higher dimensional theories

These set the masses and coupling strengths for particles

Constrained by fifth force / equivalence principle tests

Dark matter \(\rightarrow\) oscillating masses / couplings

Other probes

Absorption in molecules

Gravitational wave detectors (MAGIS/AION)

Modulation of atomic transition energies

Atomic clocks

Atomic spectroscopy

GPS

A vast effort in tabletop / GW experiments leveraging new advances in sensors technology
Conclusions

Ultralight dark matter models are compelling, and constitute a large part of theory space for possible dark matter candidates.

Some of the best-motivated part of the parameter space is being probed now.

Very rich experimental program is underway / being planned / being proposed.

Very active field of research:

- new theoretical ideas are expanding where we might find dark matter
- new experimental ideas are increasingly covering the preferred parameter space

We stand to learn quite a bit about new physics from axion searches.