Ultralight Particle Dark Matter.

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Introduction

> Plenty of dark matter (DM) candidates spanning huge parameter range in masses and couplings

> Two classes stand out because of their convincing physics case and the variety of experimental and observational probes:

- Weakly Interacting Massive Particles (WIMPs), such as neutralinos
- Very Weakly Interacting Slim (=ultra-light) Particles (WISPs), such as axions

> Plan:

- Physics case for axions and axion-like particles (ALPs)
- Probes of axions and ALPs

[Kim, Carosi `10]
Physics case for axions: Strong CP problem

- Most general gauge invariant Lagrangian of QCD up to dimension four:

\[ \mathcal{L} = -\frac{1}{4} G^a_{\mu\nu} G^{a,\mu\nu} + \bar{q} (i\gamma_\mu D^\mu - \mathcal{M}_q) q - \frac{\alpha_s}{8\pi} \theta G^a_{\mu\nu} \tilde{G}^{a,\mu\nu} \]

- Fundamental parameters of QCD: strong coupling $\alpha_s$, quark masses $m_u, m_d, \ldots$, and theta parameter

\[ \overline{\theta} = \theta + \arg \det \mathcal{M}_q \]

- Theta term $\propto G^a_{\mu\nu} \tilde{G}^{a,\mu\nu} \propto E^a \cdot B^a$ violates P and T, and thus CP

- Most sensitive probe of P and T violation in flavor conserving interactions: electric dipole moment (EDM) of neutron; experimentally

\[ |d_n| < 2.9 \times 10^{-26} \ e \ cm \]

- Strong CP problem:

\[ d_n(\bar{\theta}) \sim \frac{e\bar{\theta}m_u m_d}{(m_u + m_d)m_n^2} \sim 6 \times 10^{-17} \ \bar{\theta} \ e \ cm \Rightarrow |\bar{\theta}| \lesssim 10^{-9} \]
Physics case for axions: Strong CP problem

- **Peccei-Quinn (PQ) solution of strong CP problem based on observation that the vacuum energy in QCD, inferred from chiral QCD Lagrangian,**

  \[ V(\bar{\theta}) = \frac{m^2 f^2_\pi}{2} \frac{m_u m_d}{(m_u + m_d)^2} \bar{\theta}^2 + O(\bar{\theta}^4) \]

  has localised minimum at vanishing theta parameter:

  If theta were a dynamical field, its vacuum expectation value (vev) would be zero

- **Introduce field \( A(x) \) as dynamical theta parameter, respecting a non-linearly realized \( U(1)_{PQ} \) symmetry, i.e. a shift symmetry, \( A(x) \rightarrow A(x) + \text{const} \). broken only by anomalous couplings to gauge fields,**

  \[
  \mathcal{L} \supset -\frac{\alpha_s}{8\pi} \left( \bar{\theta} + \frac{A}{f_A} \right) G^a_{\mu\nu} \tilde{G}^a_{\mu\nu}
  \]

  - Can eliminate theta by shift \( A(x) \rightarrow A(x) - \bar{\theta} f_A \); QCD dynamics (see above) leads then to vanishing vev, \( <A> = 0 \), i.e. P, T, and CP conserved

  - Particle excitation of A: Nambu-Goldstone boson “axion” [Weinberg 78; Wilczek 78]

  - Strength of its interactions with SM controlled by PQ scale \( f_A \)
Physics case for axions: Strong CP problem

> Because of mixing with the neutral pion, described by the chiral QCD Lagrangian, the axion is a pseudo Nambu-Goldstone boson, with see-saw relation between chiral symmetry breaking scale and PQ scale $f_A$,

\[ m_A \sim \frac{m_\pi f_\pi}{f_A} \sim \text{meV} \times \left( \frac{10^9 \text{GeV}}{f_A} \right) \]

It has a universal coupling to photons

\[ \mathcal{L} \supset -\frac{g_{A\gamma}}{4} A F_{\mu\nu} \tilde{F}^{\mu\nu} \]

of size

\[ g_{A\gamma} \sim \frac{\alpha}{2\pi f_A} \sim 10^{-12} \text{ GeV}^{-1} \left( \frac{10^9 \text{GeV}}{f_A} \right) \]

> For large PQ scale: axion prime paradigm of a WISP [Kim 79; Shifman et al 80; Zhitnitsky 80; Dine et al 81]

> Constraints from astrophysics (e.g. duration of $\nu$ signal of SN1987A) : 

\[ f_A \gtrsim 4 \times 10^8 \text{ GeV} \Rightarrow m_A \lesssim 16 \text{ meV} \]
Physics case for axions and ALPs: Cold dark matter

- For $f_A \gtrsim 10^9$ GeV, axions produced pre-dominantly non-thermally in the early universe by vacuum-realignment and, in some cases and under certain circumstances, also via decay of topological defects

- Vacuum-realignment: [Preskill et al. 83; Abbott,Sikivie 83; Dine,Fischler 83]
  - Homogeneous mode of axion field frozen at random initial value, $A(t_i) = \theta_i f_A$, because of cosmic expansion, as long as $t \lesssim 1/m_A$. Later, at $t > 1/m_A$, axion field oscillates around zero.
  - Classical, spatially coherent oscillating fields = coherent state of extremely non-relativistic dark matter, i.e. cold dark matter

![Graph showing oscillations](graph.png)
Physics case for axions and ALPs: Cold dark matter

> If reheating temperature after inflation below $f_A$ and no dilution by late decays of particles beyond SM,
\[
\Omega_A h^2 \approx 0.71 \left( \frac{f_A}{10^{12} \text{ GeV}} \right)^{7/6} \left( \frac{\theta_i}{\pi} \right)^2
\]

> If reheating temperature after inflation is above $f_A$, initial misalignment angles take on different values in different patches of universe,
\[
\Omega_A h^2 \approx 0.3 \left( \frac{f_A}{10^{12} \text{ GeV}} \right)^{7/6}
\]

[Raffelt]
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  Decay of cosmic strings and domain walls may provide for additional sources for axion CDM

[Hiramatsu et al. 12]
Physics case for axions and ALPs: Cold dark matter

- Other bosonic WISPs, such as axion-like particles (ALPs) (pseudo NG bosons from further $U(1)_{PQ}$s) would also be produced via the vacuum-realignment mechanism,

$$\Omega_a h^2 \approx 0.16 \left( \frac{m_a}{\text{eV}} \right)^{1/2} \left( \frac{f_a}{10^{11} \text{ GeV}} \right)^2 \left( \frac{\theta_i}{\pi} \right)^2$$

- Natural range for axion/ALP CDM: cosmic axion window,

$$10^9 \text{ GeV} \lesssim f_A, f_a \lesssim 10^{12} \text{ GeV}$$

- Large search space for axion and ALP CDM in photon coupling $g_{i\gamma} \sim \alpha/(2\pi f_i)$ vs. mass

  [Arias et al. 12]

adapted from [Hewett et al. 1205.2671]
Physics case for axions and ALPs: NGBs of SSB

> In 4D field theoretic extensions of the Standard Model (SM), axion and ALP fields realised as phases of complex SM singlet scalar fields whose vevs break global anomalous chiral $U(1)^{PQ_i}$ symmetries,

$$\Phi_i(x) = \frac{v_{PQ_i} + \rho_i(x)}{\sqrt{2}} e^{ia_i(x)/f_{a_i}}$$

- At energies much below the symmetry breaking scales $v_{PQ_i}$ the low-energy effective field theory is that of (pseudo-)Nambu-Goldstone bosons (NGB) with decay constants $f_{a_i} = v_{PQ_i}$

> Decay constants naturally in cosmic axion window

$$10^9 \text{ GeV} \lesssim f_{a_i} \lesssim 10^{12} \text{ GeV}$$

- in models where PQ symmetry breaking scales are tied to the scale of lepton number violation, featuring intermediate scale Majorana neutrinos to explain the masses of SM neutrinos via seesaw mechanism [Mohapatra,Senjanovic 83; Shafi,Stecker 84; Langacker,Peccei,Yanagida 86;...;Dias,Pleitez 05;...;Altarelli,Meloni 13]; axion plus ALPs plus heavy Majorana neutrinos occur automatically in big classes of heterotic string orbifold compactifications [Buchmüller et al. 07; Choi et al. 09]

- in Large Volume IIB string scenarios; in these the axion plus ALPs are occurring automatically [Conlon 06; Cicoli,Goodsell,AR 12]
Physics case for ALPs: VHE transparency of universe

- VHE photon spectra from distant Active Galactic Nuclei (AGN) should show absorption features due pair production at Extragalactic Background Light (EBL)

[Manuel Meyer 12]
Physics case for ALPs: VHE transparency of universe

> In conflict with observations? 

[Aharonian et al. 07; Albert et al. 08; Mirizzi et al. 07;...]

[Horns, Meyer 12]
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Possible explanation in terms of photon <-> ALP conversions in astrophysical magnetic fields with $g_{a\gamma} \gtrsim 10^{-12} \text{ GeV}^{-1}$; $m_a \lesssim 10^{-7} \text{ eV}$

[De Angelis et al 07; Simet et al 08; Sanchez-Conde et al 09; Horns, Meyer, Raue 13]
Experimental probes of axions and ALPs

- Direct detection of dark matter axions or axion-like particles (ALPs) (haloscopes)

- Detection of solar axions and ALPs (helioscopes)

- Direct production and detection of ALPs (light shining through walls experiments)
Direct detection of axion or ALP dark matter: Cavities

- Axion or ALP DM -> photon conversion in electromagnetic cavity placed in a magnetic field [Sikivie `83]

- Best sensitivity: mass = resonance frequency

\[ m_a = 2\pi\nu \sim 4 \, \mu\text{eV} \left( \frac{\nu}{\text{GHz}} \right) \]

\[ P_{\text{out}} \sim g^2 |B_0|^2 \rho_{\text{DM}} V Q / m_a \]
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- Operational: ADMX (Seattle), takes decade for mass scan over two orders of magnitude
Direct detection of axion or ALP dark matter: Cavities

adapted from [Hewett et al 12]
Available building blocks (DESY)
- HERA proton ring accelerator cavity
- H1 superconducting solenoid

Interested partner institute (MPIfR)
- Receiver, amplifier, FFT, ...

Operational: pilot study for WISPDMX
> WISPDMX may probe mass region below ADMX:
[Horns et al. (DESY,MPIfR,UHH)]

adapted from [Hewett et al 12]
Direct detection of axion or ALP DM: Dish Antenna

> Proposed broadband search method, based on

- radiation emitted by conducting surfaces when excited by axionic
- focussed into detector by using spherically shaped surface (dish antenna)

\[ P_{\text{center}} \sim g^2 |B_0|^2 \rho_{\text{DM}} A_{\text{dish}}/m_a^2 \]

[Horns et al. 12]
Detection of solar axions and ALPs: Helioscopes

- Sun strong source of axions and ALPs

- Helioscope searches for axions and ALPs

  \[ P(a \leftrightarrow \gamma) = 4 \frac{(g_a \gamma \omega B)^2}{m_a^4} \sin^2 \left( \frac{m_a^2}{4 \omega} L_B \right) \]

  - Ongoing: CAST … CERN Axion Solar Telescope

  [Sikivie 83]
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- Ongoing: CAST … CERN Axion Solar Telescope
- LoI currently written: IAXO (International Axion Observatory)
Detection of solar axions and ALPs: Helioscopes

adapted from [Hewett et al 12]
Direct production and detection of ALPs: LSW

- ALPs can pass walls  
  [Anselm 85; van Bibber et al. 87]
- Light-shining-through-walls experiments: (here ALPS-I (@DESY)):

\[ P(a \leftrightarrow \gamma) = 4 \frac{(g_{a\gamma B})^2}{m_a^4} \sin^2 \left( \frac{m_a^2}{4\omega L_B} \right) \]
Direct production and detection of ALPs: LSW

ALPS-I: [AEI, DESY, UHH]

- HERA dipole (8.4 m, 5 T)
- Primary laser: enhanced LIGO laser (1064 nm, 35 W)
- Frequency doubled: 532 nm
- 300-fold power build-up in cavity
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> ALPS-II:
  - 5000-fold power build-up in cavity
  - Cavity also on regeneration part with 40000-fold power build-up \((2014)\)
  - 10 + 10 HERA dipoles \((2017)\)
  - Single photon detection with TES
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  [AEI,DESY,UHH] [ALP-II TDR 12]

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Direct production and detection of ALPs: LSW

- Sensitivity improves by more than 3 orders of magnitude compared to ALPS-I (another order of magnitude doable, but needs new efforts in laser and magnet technology)

adapted from [Hewett et al 12]
Summary

Strong physics case for axion and ALPs:

- Solution of strong CP problem gives particularly strong motivation for existence of axion
- For intermediate scale decay constant, $10^9 \text{ GeV} \lesssim f_A, f_a \lesssim 10^{12} \text{ GeV}$, axion and ALPs are natural cold dark matter candidates
- In many theoretically appealing UV completions of SM, in particular in completions arising from strings, there occur intermediate scale axions and ALPs automatically
- ALPs can explain the anomalous transparency of the universe for VHE gamma rays

Intermediate scale region in axion and ALPs parameter space can be tackled in the upcoming decade by a number of experiments:

- Haloscopes
- Helioscopes
- Light-shining-through-a-wall experiments

Stay tuned!