The Quest for Axions and Other WISPs.

Andreas Ringwald (DESY)

COSMO 2013
Centre for Theoretical Cosmology, Cambridge, UK
2-6 September 2013
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:

\[
\mathcal{L} = -\frac{1}{4} G^{a}_{\mu\nu} G^{a,\mu\nu} + \bar{q} (i\gamma_{\mu} D^{\mu} - M_{q}) q - \frac{\alpha_{s}}{8\pi} \theta \ G^{a}_{\mu\nu} \tilde{G}^{a,\mu\nu}
\]

- Fundamental parameters of QCD: strong coupling $\alpha_{s}$, quark masses $m_u, m_d, ...$, and theta parameter

\[
\bar{\theta} = \theta + \arg \det M_{q}
\]

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

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

\[
|d_{n}| < 2.9 \times 10^{-26} \text{ e cm}
\]

- Strong CP problem:

\[
d_{n}(\bar{\theta}) \sim \frac{e\bar{\theta}m_{u}m_{d}}{(m_{u} + m_{d})m_{n}^{2}} \sim 6 \times 10^{-17} \bar{\theta} \text{ e cm} \Rightarrow |\bar{\theta}| \lesssim 10^{-9}
\]
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, has localised minimum at vanishing theta parameter:  
  \[ V(\theta) = \frac{m_{\pi}^2 f_\pi^2}{2} \frac{m_u m_d}{(m_u + m_d)^2} \theta^2 + O(\theta^4) \]  
  If theta were a dynamical field, its 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 coupling to \( G \tilde{G} \),

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

- Can eliminate theta by shift \( A(x) \rightarrow A(x) - \tilde{\theta} f_A \); QCD dynamics (see above) leads then to vanishing vev, \( \langle A \rangle = 0 \), 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]
Physics case for axions: Strong CP problem

Constraints from astrophysics: \( f_A \gtrsim 4 \times 10^8 \text{ GeV} \Rightarrow m_A \lesssim 16 \text{ meV} \)

adapted from [Hewett et al. 1205.2671]
Physics case for axions and ALPs: Cold dark matter

- For \( f_A \gtrsim 10^9 \text{GeV} \), axions produced pre-dominantly non-thermally in the early universe.

- 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.

  \[
  \frac{A(t)}{A(t_i)} \quad t \sim 1/m_A
  \]

  - Classical, spatially coherent oscillating fields = coherent state of extremely non-relativistic dark matter, i.e. cold dark matter
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,
  \[ \Omega_A h^2 \approx 0.3 \left( \frac{f_A}{10^{12} \text{ GeV}} \right)^{7/6} \]
  - 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”,

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

(“intermediate scale”)

- 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]
Minimalistic global $U(1)_{PQ}$ extension of the SM by

- singlet complex scalar field with PQ charge $PQ \sigma = 1$
- vector-like color triplet (a la KSVZ) with PQ charges $PQ_{Q_R} = -1/2, PQ_{Q_L} = 1/2$
- right handed singlet Majorana neutrinos with PQ charges $PQ_{N_{iR}} = -1/2$
  - PQ charges of left and right handed charged leptons $PQ_{L_i} = -1/2, PQ_{l_{iR}} = -1/2$

\[
\mathcal{L} \supset G_{ij} \tilde{L}_i H l_{jR} + F_{ij} \tilde{L}_i H N_{jR} + y_{ij} (\tilde{N}_{iR})^c \sigma N_{jR} + yQ_L \sigma Q_R + h.c.
\]

\[
V(H, \sigma) = \lambda_H (H^\dagger H - \frac{v^2}{2})^2 + \lambda_\sigma (|\sigma|^2 - \frac{v^2_{PQ}}{2})^2 + 2\lambda_H \sigma \left( H^\dagger H - \frac{v^2}{2} \right) \left( |\sigma|^2 - \frac{v^2_{PQ}}{2} \right)
\]

can explain simultaneously, for intermediate $v_{PQ}$, [Dias,Machado,Nishi,AR,Vaudrevange in prep.]

- absence of strong CP violation; PQ scale: $f_A = v_{PQ}$
  - axion: NG boson from PQ breaking $\sigma(x) = [(v_{PQ} + \rho(x))/\sqrt{2}] \exp[iA(x)/f_A]$ which couples to $GG$ via anomalous triangle graph due to exotic color triplet
- dark matter by axion if $10^9 \text{ GeV} \lesssim f_A = v_{PQ} \lesssim 10^{12} \text{ GeV}$
- masses of active neutrinos (seesaw): $m_\nu = -F y^{-1} F^T \frac{v^2}{v_{PQ}} = 0.06 \text{ eV} \left( \frac{-F y^{-1} F^T}{10^{-3}} \right) \left( \frac{10^{12} \text{ GeV}}{v_{PQ}} \right)$
- baryon asymmetry of universe through thermal leptogenesis ($N_R \rightarrow HL$ decays ...); works best if $M_{N_R} = y v_{PQ} \gtrsim 10^9 \text{ GeV}$
- stability of electroweak vacuum through scalar threshold effect [Lebedev 12; Elias-Miro et al. 12]
Top-down theory motivation for intermediate scale

4D low-energy effective field theory emerging from string theory predicts natural candidates for the axion, often even an `axiverse´, containing many additional ALPs

- KK zero modes of 10D antisymmetric tensor fields, the latter belonging to the massless spectrum of the bosonic string
  - shift symmetry from gauge invariance in 10D; # ALPs depends on topology;
  - PQ scale of order the string scale, i.e. GUT scale, $10^{16}$ GeV, in the heterotic string case; typically lower, the intermediate scale, $10^{10}$ GeV, in IIB compactifications realising brane worlds with large extra dimensions [Witten 84; Conlon 06; Arvanitaki et al. 09; Acharya et al. 10; Cicoli, Goodsell, AR 12]

- NGBs from accidental PQ symmetries appearing as low energy remnants of discrete symmetries from compactification, PQ scale decoupled from string scale [Lazarides, Shafi 86; Choi et al. 09; Dias et al. in prep.]
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]
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]
Physics case for ALPs: VHE transparency of universe

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

[De Angelis et al 07; Simet et al 08; Sanchez-Conde et al 09; Meyer,Horns,Raue 13]

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

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

Possible explanation in terms of photon <-> ALP conversions in astrophysical magnetic fields with \( g_{\alpha\gamma} \gtrsim 10^{-12} \text{ GeV}^{-1} \); \( m_a \lesssim 10^{-7} \text{ eV} \)

[De Angelis et al 07; Simet et al 08; Sanchez-Conde et al 09; Meyer,Horns,Raue 13]

\[ E^2 \frac{dN}{dE} \left[ \text{GeV}^{-1} \text{ cm}^{-2} \text{ s}^{-1} \right] \]

\[ E \left[ \text{TeV} \right] \]

[Simet,Hooper,Serpico 08]
Possible explanation in terms of photon <-> ALP conversions in astrophysical magnetic fields with $g_{a\gamma} \gtrsim 10^{-12}$ GeV$^{-1}$; $m_a \lesssim 10^{-7}$ eV.

- CAST
- SN $\gamma$ burst
- general-source 1.3 $\times$ $\tau_{TRV}$
- optimistic-IGMF 1.3 $\times$ $\tau_{TRV}$
- optimistic-ICM 1.3 $\times$ $\tau_{TRV}$
- ALPSII
- IAXO
- WD cooling hint

---

### Table

<table>
<thead>
<tr>
<th>Name</th>
<th>$B^0_{IGMF}$ (nG)</th>
<th>$\lambda^0_{IGMF}$ (Mpc)</th>
<th>$n^0_{el,IGMF}$ ($\times 10^{-7}$ cm$^{-3}$)</th>
<th>$B^0_{ICMF}$ ($\mu$G)</th>
<th>$\lambda^0_{ICMF}$ (kpc)</th>
<th>$r_{cluster}$ (Mpc)</th>
<th>$n^0_{el,ICMF}$ ($\times 10^{-3}$ cm$^{-3}$)</th>
<th>$r_{core}$ (kpc)</th>
<th>$\eta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>General source</td>
<td>5</td>
<td>50</td>
<td>Only conversion in GMF, but $\rho_{init} = 1/3\text{diag}(e^{-\tau}, e^{-\tau}, 1)$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Optimistic IGMF</td>
<td>$\cdots$</td>
<td>$\cdots$</td>
<td>$\cdots$</td>
<td>1</td>
<td>$\cdots$</td>
<td>$\cdots$</td>
<td>$\cdots$</td>
<td>$\cdots$</td>
<td>$\cdots$</td>
</tr>
<tr>
<td>Optimistic ICM</td>
<td>$\cdots$</td>
<td>$\cdots$</td>
<td>$\cdots$</td>
<td>10</td>
<td>$\cdots$</td>
<td>$\cdots$</td>
<td>$\cdots$</td>
<td>2</td>
<td>10</td>
</tr>
<tr>
<td>Fiducial</td>
<td>0.01</td>
<td>10</td>
<td>Only conversion in GMF, but $\rho_{init} = 1/3\text{diag}(e^{-\tau}, e^{-\tau}, 1)$</td>
<td>1</td>
<td>1</td>
<td>2/3</td>
<td>1</td>
<td>200</td>
<td>0.5</td>
</tr>
</tbody>
</table>

[Meyer, Horns, Raue 13]
More astro hints for intermediate scale axions/ALPs

- Anomalous cooling of white dwarfs (WDs) apparent in [Isern et al. 08-12]
  - luminosity function
  - period decrease of pulsating WDs G117-B15A and R548
    \[ \frac{f_A}{C_{Ae}}, \frac{f_a}{C_{ae}} \sim 10^9 \text{ GeV}, \]
    \[
    \text{for } m_A, m_a \lesssim \text{keV}
    \]

- Hints of relativistic ALP background (dark radiation) in CMB, generated by modulus decay; ALP decay to photons in magnetic fields of galaxy clusters, e.g. COMA, may explain observed soft X-ray excesses [Marsh, Conlon 13]
Intermediate scale axions/ALPs may be found in lab exps

Axions and ALPs with decay constants in the intermediate scale range

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

can be searched for in the laboratory with

- haloscpes: direct detection of DM axions/ALPs \([\text{Sikivie 83}]\)
- light-shining-through-a-wall: production and detection of ALPs \([\text{Anselm 85; van Bibber et al 87}]\)
- helioscopes: detection of solar axions/ALPs \([\text{Sikivie 83}]\)
Haloscope searches

- Axion or ALP DM – photon conversion in microwave cavity placed in magnetic field

Best sensitivity: mass = resonance frequency $m_a = 2\pi \nu \sim 4 \mu eV \left( \frac{\nu}{\text{GHz}} \right)$

\[ P_{\text{out}} \sim g^2 | B_0 |^2 \rho_{\text{DM}} V Q / m_a \]
Haloscope searches

Axion or ALP DM – photon conversion in microwave cavity placed in magnetic field

- Ongoing: ADMX at University of Washington, Seattle, exploiting high Q cavity in 8 T superconducting solenoid; search starts at 1 GHz towards higher frequencies
- Pilot study: WISPDMX at DESY, Hamburg, exploiting high Q HERA p acceleration cavity and H1 solenoid (1.1 T); search starts at 208 MHz towards higher frequencies
Haloscope searches

> Proposed broadband dish antenna search

- Non-relativistic DM axions/ALPs are converted into monochromatic photons emitted from the surface of a spherical dish antenna placed in a background magnetic field
- Photons are focused in the centre, where a broadband detector is placed

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

[Horns et al. 12]
Haloscope searches

- Sensitivity of microwave cavity (ADMX) and dish antenna haloscopes:

adapted from [Hewett et al 12]
Proposed searches for axion and ALP dark matter exploiting time-varying CP-odd nuclear moments acquired by interactions with the background axion dark matter, e.g.

\[ d_N \equiv g_{Ad} A(t) \sim e \frac{m_um_d}{(m_u + m_d)m_N^2} \frac{A(t)}{f_A} \sim 10^{-16} \frac{A(t)}{f_A} \text{ e cm} \]

\[ \frac{A(t)}{f_A} \sim \frac{\sqrt{\rho_{DM}}}{m_A f_A} \cos(m_A t) \sim \frac{\sqrt{\rho_{DM}}}{m_\pi f_\pi} \cos(m_A t) \sim 10^{-19} \cos(m_A t) \]

- Moments cause precession of nuclear spins in material sample in presence of background electric field
- Can be searched for with precision magnetometry [Graham,Rajendran 13; Budker et al 11]

Window of opportunity for GUT scale axions, \( m_a \sim m_\pi f_\pi / f_a \sim \text{MHz} \left(10^{16} \text{ GeV} / f_a \right) \)
Haloscope searches

> Sensitivity of CASPEr (Cosmic Axion Spin Precession Experiment)

[Budker et al 13]
Most sensitive until now: Any Light Particle Search I (ALPS-I) at DESY

- One superconducting HERA dipole (5 T)
- 1.2 kW cw green (2.3 eV) laser
- CCD camera

\[ P(a \leftrightarrow \gamma) = 4 \left( \frac{g_a \gamma \omega B}{m_a^4} \right)^2 \sin^2 \left( \frac{m_a^2}{4\omega L_B} \right) \]
Presently being set up: ALPS-II at DESY (data taking planned for 2017)

- 10 + 10 superconducting HERA dipoles
- 150 kW infrared (1.17 eV) laser light stored before wall; resonant regeneration behind wall
- Transition Edge Sensor

[Bähre et al (ALPS-II TDR) 13]
Light-shining-through-a-wall searches

Sensitivity of light-shining-through-a-wall (LSW) searches:

adapted from [Hewett et al 12]
Helioscope searches

Most sensitive until now: CERN Axion Solar Telescope (CAST)

- Superconducting LHC dipole magnet
- X-ray detectors

\[ P(a \leftrightarrow \gamma) = 4 \frac{(g_a \gamma \omega B)^2}{m_a^4} \sin^2 \left( \frac{m_a^2 L_B}{4\omega} \right) \]
Proposed successor: International Axion Observatory (IAXO)

- Dedicated superconducting toroidal magnet with much bigger aperture than CAST
- Extensive use of X-ray optics
- Low background X-ray detectors

[Armengaud et al (IAXO LoI) 13]
Helioscope searches

> Sensitivity of helioscope searches:

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
- ALPs may explain soft X-ray excesses from galaxy clusters

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

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

> Stay tuned!