Experimental Searches for Axions and Axion-Like Particles.

Andreas Ringwald (DESY)

DaMESyFla: CP Violation 50 Years after Discovery
SISSA, Trieste, Italy
22-23 September 2014
Strong case for particles beyond the Standard Model

- Standard Model (SM) of particle physics describes basic properties of known matter and forces
- SM not a complete theory:
  - No explanation of dark sector
Strong case for particles beyond the Standard Model

- Standard Model (SM) of particle physics describes basic properties of known matter and forces

- SM not a complete theory:
  - No explanation of dark sector

- Well-motivated SM extensions provide dark matter candidates:
  - Neutralinos and other Weakly Interacting Massive Particles (WIMPs)
  - Axions and other very Weakly Interacting Slim (=ultra-light) Particles (WISPs)

- Plan:
  - Physics case for axions and axion-like particles (ALPs)
  - Terrestrial probes of axions and ALPs

(Kim, Carosi 10)
Physics case for WISPs: Theoretical motivations

> Nambu-Goldstone bosons arising from SSB of global U(1)s at scale $f_a$

- Low energy effective field theory has shift symmetry $a(x) \rightarrow a(x) + \text{const.}$, forbidding explicit mass terms, $\propto m^2_a a^2(x)$, in the Lagrangian
- Effective couplings to SM particles suppressed by powers of high energy scale $f_a$

- Examples:
  
  - Axion from breaking of global chiral symmetry; axion field acts as dynamical theta parameter,
    $$\mathcal{L} \supset - \frac{\alpha_s}{8\pi} A \frac{A}{f_A} G^{a\mu\nu}_\mathcal{G}^{a,\mu\nu}$$
    
    spontaneously relaxing to zero, $\langle A \rangle = 0$ (thus CP conserved)
    - mass due to mixing with pion, $m_A \sim m_\pi f_\pi / f_A$
    - has universal coupling to photons,
      $$\mathcal{L} \supset - \frac{\alpha}{8\pi} C_0 \frac{A}{f_A} F_{\mu\nu} \tilde{F}^{\mu\nu}$$
  
  - Majoron from breaking of global lepton number symmetry
    
    - high scale explains small neutrino mass, $m_\nu \sim v^2 / f_L$
    - Familon from breaking of family symmetry

> Axion-like particle (ALP): no coupling to gluons, but nonzero coupling to photons,

$$\mathcal{L} \supset - \frac{\alpha}{8\pi} C_{a\gamma} \frac{a}{f_a} F_{\mu\nu} \tilde{F}^{\mu\nu}$$
Physics case for WISPs: Theoretical motivations

- 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. 14]
Physics case for axions and ALPs: Cold dark matter

> At $T < f_a$, axion or ALP field

$$\theta_a(x) = a(x)/f_a \in [-\pi, \pi]$$

satisfies

$$\ddot{\theta}_a + 3H(T)\dot{\theta}_a - \nabla^2 \theta_a/R^2 + m_a^2(T) \sin \theta_a = 0$$

- First, at $3H > m_a$, Hubble friction freezes field at initial value
- Then, at $3H(T_{osc}) \approx m_a(T_{osc})$, field feels pull of mass towards $\theta_a = 0$
- Oscillating zero mode corresponds to coherent state of many nonrelativistic axions or ALPs. After a few oscillations,

$$\overline{N}_a = \overline{\rho}_a R^3/m_a = \text{const.}$$

and therefore

$$\overline{\rho}_a(T_0) \approx \overline{\rho}_a(T_{osc}) \frac{m_a(T_0)}{m_a(T_{osc})} \frac{s(T_0)}{s(T_{osc})}$$

$[\text{Wantz, Shellard 0910.1066}]$
Physics case for axions and ALPs: Cold dark matter

In standard cosmology, oscillations start during radiation dominated phase. Then

\[
\frac{\rho_{a}^{(v)}(t_0)}{\rho_{\text{CDM}}}(t_0) \simeq 0.2 \sqrt{\frac{m_a(t_0)}{\text{eV}}} \sqrt{\frac{m_a(t_0)}{m_a(t_{osc})}} \left( \frac{f_a}{10^{11} \text{ GeV}} \right)^2 \langle \theta_a^2 \rangle
\]

Predictions for \( \langle \theta_a^2 \rangle \) depend on whether spontaneous symmetry breaking (SSB) of global U(1) occurred before/after inflation:

\[
\langle \theta_a^2 \rangle = \begin{cases} 
\theta_i^2 + \left( \frac{H_I}{2\pi f_a} \right)^2, & \text{if } f_a > \max \left( \frac{H_I}{2\pi}, \epsilon_{\text{eff}} E_I \right) \text{ (pre-infl. SSB)}, \\
\frac{\pi^2}{3}, & \text{if } f_a < \max \left( \frac{H_I}{2\pi}, \epsilon_{\text{eff}} E_I \right) \text{ (post-infl. SSB)}. 
\end{cases}
\]
In post-infl. SSB scenario, decay of cosmic strings and domain walls provide additional CDM axion and ALPs.

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

> In post-infl. SSB scenario, decay of cosmic strings and domain walls provide additional CDM axion and ALPs

> 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”)

[adapted by from Essig et al. 1311.0029]
Physics case for axions and ALPs: Cold dark matter

- In post-infl. SSB scenario, decay of cosmic strings and domain walls provide additional CDM axion and ALPs.

- Natural range for axion/ALP CDM: “cosmic axion window”, $10^9$ GeV $\lesssim f_A, f_a \lesssim 10^{12}$ 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

[Döbrich, Redondo 13]
Physics case for ALPs: Gamma transparency of universe

> Gamma ray spectra from distant Active Galactic Nuclei (AGN) should show an energy and distance (red-shift) dependent exponential attenuation, \( \propto \exp(-\tau(E, z)) \); \( \tau(E, z) = \int_0^z dz' \int d\epsilon' \cdots n_{\text{EBL}}(\epsilon', z') \sigma_{\gamma\gamma}(E, \epsilon', \cdots) \), due to pair production at Extragalactic Background Light (EBL).
At $\tau \gtrsim 1$, however, evidence for anomalous gamma transparency, from IACT and Fermi data [Aharonian et al. 07; Aliu et al. 08;...; Horns, Meyer 12;...; Rubtsoy, Troitsky 14]
At $\tau \gtrsim 1$, however, evidence for anomalous gamma transparency, from IACT and Fermi data [Aharonian et al. 07; Aliu et al. 08; ...; Horns,Meyer 12; ...; Rubtsov,Troitsky 14]
Physics case for ALPs: Gamma transparency of universe

Possible explanation in terms of photon <-> ALP conversions in astrophysical magnetic fields [De Angelis et al 07; Simet et al 08; Sanchez-Conde et al 09; Meyer,Horns,Raue 13]

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

Possible explanation in terms of photon <-> ALP conversions in astrophysical magnetic fields [De Angelis et al 07; Simet et al 08; Sanchez-Conde et al 09; Meyer,Horns,Raue 13]

<table>
<thead>
<tr>
<th>Name</th>
<th>$B_{0,\text{IGMF}}$ (nG)</th>
<th>$\lambda_{0,\text{IGMF}}$ (Mpc)</th>
<th>$n_{0,\text{IGMF}}$ ($\times 10^{-2}$ cm$^{-3}$)</th>
<th>$B_{0,\text{ICM}}$ (nG)</th>
<th>$\lambda_{0,\text{ICM}}$ (kpc)</th>
<th>$n_{0,\text{ICM}}$ ($\times 10^{-2}$ cm$^{-3}$)</th>
<th>$\eta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>General source</td>
<td>5</td>
<td>50</td>
<td>1</td>
<td>Only conversion in GMF, but $\rho_{\text{IGMF}} = 1/3\text{diag}(e^{-1}, e^{-1}, 1)$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Optimistic IGMF</td>
<td>5</td>
<td>50</td>
<td>1</td>
<td>Only conversion in GMF, but $\rho_{\text{IGMF}} = 1/3\text{diag}(e^{-1}, e^{-1}, 1)$</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Optimistic ICM</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
<td>...</td>
</tr>
<tr>
<td>Fiducial</td>
<td>0.01</td>
<td>10</td>
<td>1</td>
<td>1</td>
<td>10</td>
<td>2</td>
<td>1</td>
</tr>
</tbody>
</table>

Meyer,Horns,Raue 13
Physics case for ALPs: Horizontal branch star cooling

➢ Star cooling through photon-ALP conversion in stellar cores would reduce ratio of the number of stars in the horizontal and in the red giant branch of old stellar clusters.
Physics case for ALPs: Horizontal branch star cooling

- Star cooling through photon-ALP conversion in stellar cores would reduce ratio of the number of stars in the horizontal and in the red giant branch of old stellar clusters

- New analysis of sample of 39 Galactic Globular Clusters compared to prediction of state-of-the-art stellar models
  - Small non-zero axion-photon coupling improves the agreement between models and observations,
    \[ g_{a\gamma} = 0.45^{+0.12}_{-0.16} \times 10^{-10} \text{ GeV}^{-1} \]
  - Conservative upper limit,
    \[ g_{a\gamma} < 0.66 \times 10^{-10} \text{ GeV}^{-1} \]

[Ayala,Dominguez,Gianotti,Mirizzi,Straniero 14]
Hints of dark radiation $\Delta N_{\text{eff}}$ in CMB

Cosmic ALP background radiation may be generated by modulus (scalar partner of pseudoscalar ALP) decay. Spectrum peaked at around 100 eV, for modulus mass expected in IIB string compactifications, $\sim 10^6$ GeV

[Refs: Cicoli, Conlon, Quevedo 12; Higaki, Takahashi 12]

ALP conversion to photon in magnetic fields of galaxy clusters, e.g. Coma, may explain observed soft X-ray excess if

$$g_{a\gamma\gamma} \gtrsim \sqrt{0.5/\Delta N_{\text{eff}}} \times 1.4 \times 10^{-13} \text{ GeV}^{-1}$$

for $m_a \lesssim 10^{-12}$ eV

[Boyer et al., Soft excess in Coma as observed by EUVE 04]
Physics case for ALPs: Cooling of white dwarfs

> Anomalous cooling of white dwarfs (WDs) apparent in [Isern et al. 08-12]
  - luminosity function
  - period decrease of pulsating WDs G117-B15A and R548

> Required coupling to the electron

\[ \mathcal{L} \supset \frac{(g_{Ae} \partial_\mu A + g_{ae} \partial_\mu a)}{2m_e} \tilde{\epsilon} \gamma^\mu \gamma_5 e. \]

of size

\[ |g_{Ae}| \equiv |C_{Ae}| m_e / f_A \sim 10^{-13} \quad \text{and/or} \]
\[ |g_{ae}| \equiv |C_{ae}| m_e / f_a \sim 10^{-13} \]

and thus intermediate scale

\[ \frac{f_A}{C_{Ae}}, \frac{f_a}{C_{ae}} \sim 10^9 \text{ GeV}, \]

for \( m_A, m_a \lesssim \text{keV} \)
Physics case for ALPs: Summary of astro/cosmo hints

There are very-well motivated search regions for axions and ALPs:

[Dias,Machado,Nishi,AR,Vaudrevange 1403.5760]
Axions and ALPs with decay constants in the intermediate scale range

\[ 10^8 \text{ GeV} \lesssim f_A, f_a \lesssim 10^{12} \text{ GeV} \]

can be searched for in the laboratory with

- light-shining-through-a-wall: production and detection of ALPs
  
  [Anselm 85; van Bibber et al 87]

- helioscopes: detection of solar axions/ALPs
  
  [Sikivie 83]

- haloscopes: direct detection of DM axions/ALPs
  
  [Sikivie 83]
## Axion/ALP experiments worldwide

An incomplete selection of (mostly) small-scale experiments:

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Type</th>
<th>Location</th>
<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALPS II</td>
<td>Laboratory experiments, light-shining-through-a-wall</td>
<td>DESY</td>
<td>preparation</td>
</tr>
<tr>
<td>CROWS</td>
<td></td>
<td>CERN</td>
<td>finished</td>
</tr>
<tr>
<td>OSQAR</td>
<td></td>
<td>CERN</td>
<td>running</td>
</tr>
<tr>
<td>REAPR</td>
<td></td>
<td>FNAL</td>
<td>proposed</td>
</tr>
<tr>
<td>CAST</td>
<td></td>
<td>CERN</td>
<td>running</td>
</tr>
<tr>
<td>IAXO</td>
<td>Helioscopes</td>
<td>?</td>
<td>proposed</td>
</tr>
<tr>
<td>SUMICO</td>
<td></td>
<td>Tokyo</td>
<td>running</td>
</tr>
<tr>
<td>ADMX</td>
<td>Haloscope</td>
<td>Seattle, NH</td>
<td>running</td>
</tr>
<tr>
<td>WISPDMX</td>
<td></td>
<td>DESY</td>
<td>studies</td>
</tr>
</tbody>
</table>

[Lindner `14]
Light-shining-through-a-wall searches

> 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

$$P(a \leftrightarrow \gamma) = 4 \left( \frac{g_a \gamma \omega B}{m_a^4} \right)^2 \sin^2 \left( \frac{m_a^2}{4 \omega L_B} \right)$$
Light-shining-through-a-wall searches

> 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

[ Ehret et al. (ALPS I) `10 ]

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

\[ m_{\phi} \text{ [eV]} \]
Light-shining-through-a-wall searches

- Microwaves shining through a shielding
  [Hoogeveen 92; Jaeckel, AR '08; Caspers, Jaeckel, AR '09]

- CERN ResOnant Weakly interacting sub-eV particle Search (CROWS)
  [Betz et al. (CROWS) '13]
Light-shining-through-a-wall searches

- Microwaves shining through a shielding [Hoogeveen 92; Jaeckel, AR `08; Caspers, Jaeckel, AR `09]
- CERN ResOnant Weakly interacting sub-eV particle Search (CROWS) [Betz et al. (CROWS) `13]
Presently being set up: ALPS II at DESY

- 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

<table>
<thead>
<tr>
<th></th>
<th>2013</th>
<th>2014</th>
<th>2015</th>
<th>2016</th>
<th>2017</th>
<th>2018</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALPS Ila</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ilc risk assessments (Ilb)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>ALPS Ilc</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- **Installation**
- **Data runs**

Closure of the LINAC tunnel of the European XFEL project under construction at DESY.

ALPS Ilc in 2018 in HERA tunnel
ALPS II will explore new territory and probe TeV transparency region:

[Essig et al. 1311.0029]
Most sensitive until now: CERN Axion Solar Telescope (CAST)

- Superconducting LHC dipole magnet
- X-ray detectors

\[ P(\alpha \leftrightarrow \gamma) = 4 \frac{(g_\alpha \gamma B)^2}{m_\alpha^4} \sin^2 \left( \frac{m_\alpha^2}{4\omega} L_B \right) \]
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 CDR) 1401.3233]
IAXO will explore new territory, probe TeV transparency and CAB region:

adapted from [Hewett et al 12]
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: Resonant cavities

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: Dish antennas

- Oscillating axion/ALP DM in a background magnetic field carries a small electric field component
- A magnetised mirror in axion/ALP DM background radiates photons
- Simple broadband experiment: spherical dish antenna [Horns et al. 12]

\[ P_{\text{center}} \approx \langle |E_a|^2 \rangle A_{\text{dish}} \sim \chi^2 \rho_{\text{CDM}} A_{\text{dish}} \]
\[ \sim 10^{-26} \left( \frac{B}{5T} \frac{c\gamma}{2} \right)^2 \frac{A}{1\text{m}^2} \text{Watt} \]

- Pilot dish experiment at KIT in Karlsruhe presently being setup
Haloscopes: Resonant cavities and broadband searches

- ADMX and proposed broadband searches probe sizeable region:

[Diagram showing the search regions and constraints on axion mass and coupling, with references to Helioscopes (CAST) and LSW (ALPS-I).]

[Horns, Lindner, Lobanov, AR `13]
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.

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

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

- 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: Precision magnetometry

- Sensitivity of CASPEr (Cosmic Axion Spin Precession Experiment) planned to be build at Helmholtz Institute in Mainz

![Graph showing sensitivity of CASPEr](Budker et al 13)
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, 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 (V)HE gamma rays
- ALPs can explain anomalous energy loss of horizontal branch stars
- ALPs can explain soft X-ray excesses from galaxy clusters

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

- Light-shining-through-a-wall experiments
- Helioscopes
- Haloscopes
Good investment: DAX (Dow Jones AXion index) grows!

- inSPIRE: Citation of Peccei-Quinn papers or title axion (and similar)

![Graph showing the growth of DAX index from 1977 to 2013](#)