Case for Axion-Like Particles and their Terrestrial Searches.

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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)
  - Terrestrial probes of axions and ALPs

[Kim,Carosi ‘10]
Physics case for the axion: Strong CP problem

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

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

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

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

> Theta term \(\propto G_{\mu\nu}^a \tilde{G}^{a,\mu\nu} \propto E^a \cdot B^a\) 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

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

> Strong CP problem:

\[
d_n(\bar{\theta}) \sim \frac{e\bar{\theta}m_um_d}{(m_u + m_d)m_n^2} \sim 6 \times 10^{-17} \bar{\theta} \text{ e cm} \Rightarrow |\bar{\theta}| \lesssim 10^{-9}
\]
Physics case for the axion: 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,

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

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 Nambu-Goldstone field arising from the breaking of a global chiral \( U(1)_{\text{PQ}} \) symmetry featuring a \( U(1)_{\text{PQ}} \times SU(3)_C \times SU(3)_C \) anomaly. Correspondingly,

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

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

- Particle excitation of A: “Axion” [Weinberg 78; Wilczek 78]

- Mass from mixing with pion: \( m_A \sim \frac{m_\pi f_\pi}{f_A} \sim \text{meV} \times \left( \frac{10^9 \text{GeV}}{f_A} \right) \)

- Couplings, e.g. \( \mathcal{L} \ni -\frac{g_{A\gamma}}{4} A F_{\mu\nu} \tilde{F}^{\mu\nu} \), suppressed by \( f_A \), e.g. \( g_{A\gamma} \sim \frac{\alpha}{2\pi f_A} \sim 10^{-12} \text{ GeV}^{-1} \left( \frac{10^9 \text{GeV}}{f_A} \right) \)

- For large \( f_A \), ultralight and very weakly interacting [Kim 79; Shifman et al 80; Zhitnitsky 80; Dine et al 84]
Physics case for axion-like particles

Breaking of other global symmetries lead to additional axion-like particles emerging as Nambu-Goldstone bosons:

- **Majoron** from breaking of global lepton number symmetry [Chikashige et al. 78]
  - High symmetry breaking scale $f_L \simeq v_L$ explains small active neutrino mass
  $$m_\nu = -M_D M_M^{-1} M_D^T = -y_D y_M^{-1} y_D^T \frac{v^2}{v_L} = 0.06 \text{ eV} \left( \frac{10^{13} \text{ GeV}}{v_L} \right) \left( \frac{-y_D y_M^{-1} y_D^T}{10^{-2}} \right)$$

- **Familon** from breaking of family symmetry [Wilzcek 82; Berezhiani, Khlopop 90]

- Axion-like particles from string compactifications
  - Closed string axion-like particles
  - Axion-like particles from the breaking of accidental global U(1) symmetries
Physics case for ALPs: String compactifications

- 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.]
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**Theoretically favored symmetry breaking scales for axion and ALPs**

- Intermediate scale $f_I \sim \sqrt{v M_{P1}} \sim 10^{10} \text{GeV}$
- GUT scale $f_{\text{GUT}} \sim 10^{16} \text{GeV}$
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

> 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 $\rightarrow$ 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,

$$\Omega_A^{\text{P}} h^2 \approx 0.11 \left( \frac{f_A}{5 \times 10^{11} \, \text{GeV}} \right)^{1.184} F \tilde{\Theta}_i^2$$

$$= 0.11 \left( \frac{12 \, \mu\text{eV}}{m_A} \right)^{1.184} F \tilde{\Theta}_i^2,$$

> If reheating temperature after inflation is above $f_A$, initial misalignment angles take on different values in different patches of universe,

$$\Omega_A^{\text{P}} h^2 \approx 0.11 \left( \frac{40 \, \mu\text{eV}}{m_A} \right)^{1.184}$$

- Decay of cosmic strings and domain walls may provide for additional sources for axion CDM

$$\Omega_A^{\text{td}} h^2 \approx 0.11 \left( \frac{400 \, \mu\text{eV}}{m_A} \right)^{1.184}$$

[Hiramatsu et al. 12]
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,

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- Decay of cosmic strings and domain walls may provide for additional sources for axion CDM

[adapted by from Essig et al. 1311.0029]
Other bosonic WISPs, such as ALPs or Hidden Photons, are also be produced via the vacuum-realignment mechanism,

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

[Arias et al. 12]

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

[Döbrich, Redondo 13]
Physics case for axions and ALPs: Cold dark matter

- Unidentified 3.55 keV line from galaxy clusters and from Andromeda recently found [Bulbul et al. 1402.2301, Boyarski et al. 1402.4119]

- Brightness profile compatible with decaying dark matter
Physics case for axions and ALPs: Cold dark matter

> 3.55 keV line may be identified with line from two photon decay of 7.1 keV mass ALP CDM

[Higaki, Jeong, Takahashi 1402.6965; Jaeckel, Redondo, AR 1402.7335]

- For $x_\phi = \frac{\rho_\phi}{\rho_{DM}}$, required lifetime

$$\tau_\phi = \frac{64\pi}{g^2_{\phi\gamma\gamma}m^3_\phi} = x_\phi \times (4 \times 10^{27} - 4 \times 10^{28}) \text{s}$$

- Thus required coupling and scale

$$g_{\phi\gamma\gamma} \sim (3 \times 10^{-18} - 10^{-12}) \text{ GeV}^{-1}$$

$$f_\phi \sim (10^9 - 4 \times 10^{14}) \text{ GeV}$$

if one allows $x_\phi$ to be in the range

$$x_\phi \sim 10^{-10} - 1$$

adapted from [Arias et al. 12]
Gamma ray spectra from distant Active Galactic Nuclei (AGN) should show an energy and distance (red-shift) dependent exponential attenuation, \( \propto \exp(-\tau(E, z)) \); \( \tau(E, z) = \int^{z} dz' \int dE' \ldots n_{\text{EBL}}(E', z') \sigma_{\gamma\gamma}(E, E', \ldots) \), due to pair production at Extragalactic Background Light (EBL).
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, \( \propto \exp(\tau(E,z)) \); \( \tau(E,z) = \int_0^z d\epsilon' \int d\epsilon' \ldots n_{\text{EBL}}(\epsilon',z')\sigma_{\gamma\gamma}(E,\epsilon',\ldots) \), due to pair production at Extragalactic Background Light (EBL).

> Attenuation recently been observed by Fermi-LAT and H.E.S.S.
At $\tau \gtrsim 2$, however, hints for anomalous gamma transparency, from IACT and Fermi-LAT data [Aharonian et al. 07; Aliu et al. 08;...; Horns, Meyer 12;...]
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Physics case for ALPs: Gamma transparency of universe

> 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; 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: Gamma transparency of universe

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[Meyer,Horns,Raue 13]
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

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

of size

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

and thus intermediate scale

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

for \( m_A, m_a \lesssim \text{keV} \)
Physics case for ALPs: Cosmic ALP background radiation

- 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

[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 [Marsh, Conlon 13; Angus et al. 13]

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

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

[Angus et al. 13]
There are allowed regions in parameter space where an ALP can simultaneously explain the gamma ray transparency, the soft X-ray excess from Coma and be a subdominant contribution to CDM

[Dias et al. in prep.]
Physics case for axions and ALPs: Parameters of interest

> In models with several axion-like fields,

\[
\mathcal{L} = \frac{1}{2} \partial_\mu \alpha'_i \partial^\mu \alpha'_i - \frac{\alpha_s}{8\pi} \left( \sum_{i=1}^{n_{\text{ax}}} C_{i\gamma} \frac{a'_i}{f_{a'_i}} \right) G^b_{\mu\nu} \tilde{G}^{b,\mu\nu} - \frac{\alpha}{8\pi} \left( \sum_{i=1}^{n_{\text{ax}}} C_{i\gamma} \frac{a'_i}{f_{a'_i}} \right) F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{1}{2} \left( \sum_{i=1}^{n_{\text{ax}}} C_{ie} \frac{\partial_\mu a'_i}{f_{a'_i}} \right) \bar{\epsilon} \gamma^\mu \gamma_5 e
\]

the axion is in general a mixture,

\[
\frac{A}{f_A} \equiv \sum_{i=1}^{n_{\text{ax}}} C_{i\gamma} \frac{a'_i}{f_{a'_i}}
\]

> UV completions with two accidental global chiral U(1)s yield benchmark values

[Dias et al. in prep.]

<table>
<thead>
<tr>
<th>Model</th>
<th>Input values</th>
<th>Resulting low-energy parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$v_1 = f_{a'<em>1}$ [GeV] $v_2 = f</em>{a'_2}$ [GeV]</td>
<td>$f_A$ [GeV] $m_A$ [eV] $m_a$ [eV] $</td>
</tr>
<tr>
<td>A1</td>
<td>$1 \times 10^{13}$ $1 \times 10^{13}$</td>
<td>$3 \times 10^{12}$ $2 \times 10^{-6}$ $4 \times 10^{-21}$ $5 \times 10^{-17}$ $5 \times 10^{-16}$ $5 \times 10^{-17}$ $2 \times 10^{-17}$</td>
</tr>
<tr>
<td>A2</td>
<td>$1 \times 10^{10}$ $1 \times 10^{11}$</td>
<td>$0.96 \times 10^{10}$ $6 \times 10^{-4}$ $5 \times 10^{-33}$ $4 \times 10^{-13}$ $2 \times 10^{-13}$ $1 \times 10^{-15}$ $5 \times 10^{-15}$</td>
</tr>
<tr>
<td>A3</td>
<td>$1 \times 10^{13}$ $1 \times 10^{10}$</td>
<td>$3 \times 10^{9}$ $2 \times 10^{-3}$ $1 \times 10^{-28}$ $2 \times 10^{-13}$ $5 \times 10^{-16}$ $5 \times 10^{-14}$ $2 \times 10^{-17}$</td>
</tr>
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<td>$1 \times 10^{13}$ $1 \times 10^{9}$</td>
<td>$1 \times 10^{13}$ $6 \times 10^{-7}$ $2 \times 10^{-7}$ $5 \times 10^{-16}$ $1 \times 10^{-11}$ $0$ $5 \times 10^{-13}$</td>
</tr>
</tbody>
</table>
Physics case for axions and ALPs: Favored parameters

| Model | $v_1 = f_{a_1'}$ [GeV] | $v_2 = f_{a_2'}$ [GeV] | $f_A$ [GeV] | $m_A$ [eV] | $m_a$ [eV] | $|g_{A\gamma}|$ [GeV]^{-1} | $|g_{a\gamma}|$ [GeV]^{-1} | $|g_{Ae}|$ | $|g_{ae}|$ |
|-------|------------------------|------------------------|-------------|-----------|----------|------------------|------------------|-----------|-----------|
| A1    | $1 \times 10^{13}$     | $1 \times 10^{13}$     | $3 \times 10^{12}$ | $2 \times 10^{-6}$ | $4 \times 10^{-21}$ | $5 \times 10^{-17}$ | $5 \times 10^{-16}$ | $5 \times 10^{-17}$ | $2 \times 10^{-17}$ |
| A2    | $1 \times 10^{10}$     | $1 \times 10^{11}$     | $0.96 \times 10^{10}$ | $6 \times 10^{-4}$ | $5 \times 10^{-33}$ | $4 \times 10^{-13}$ | $2 \times 10^{-13}$ | $1 \times 10^{-15}$ | $5 \times 10^{-15}$ |
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| B     | $1 \times 10^{13}$     | $1 \times 10^9$        | $1 \times 10^{13}$ | $6 \times 10^{-7}$ | $2 \times 10^{-7}$ | $5 \times 10^{-16}$ | $1 \times 10^{-11}$ | $0$ | $5 \times 10^{-13}$ |

[Dias et al. in prep.]
Axions and ALPs with decay constants in the intermediate scale range

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

can be searched for in the laboratory with

- haloscopes: 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 \[\text{[Sikivie 83]}\]
Axion or ALP DM – photon conversion in microwave cavity placed in magnetic field

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

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

\[
\begin{align*}
\text{Equations of motion for a plane wave:} & \quad \begin{pmatrix} A_{\parallel} \\ a \end{pmatrix} \exp(-i(\omega t - kz)). \\
\left[ (\omega^2 - k^2) \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} + \begin{pmatrix} 0 & -g_{a\gamma}|B|\omega \\ -g_{a\gamma}|B|\omega & m_a^2 \end{pmatrix} \right] \begin{pmatrix} A_{\parallel} \\ a \end{pmatrix} &= \begin{pmatrix} 0 \\ 0 \end{pmatrix}.
\end{align*}
\]

Axion mixes with A-component PARALLEL to the external B-field

- "Dark matter" solution: \( v = \frac{k}{\omega} \); \( \omega \simeq m_a(1 + v^2/2 + ...) \)

\[
\begin{align*}
\left[ \begin{pmatrix} A_{\parallel} \\ a \end{pmatrix} \right]_{\text{DM}} \propto \begin{pmatrix} -\chi_a \\ 1 \end{pmatrix} \exp(-i(\omega t - kz)).
\end{align*}
\]

It has a small E field!

\[
\chi_a \sim \frac{g_{a\gamma}|B|}{m_a}
\]

[Redondo: talk at DESY 14 ]
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

\[ E_a = \omega_a \chi \cos(\omega_a(t + v z)). \]

\[ E_\gamma + E_a \big|_{z=z_{\text{mirror}}} = 0 \]

Radiated photon wave \[ E_\gamma = -\omega_a \chi \cos(\omega_\gamma(t - z)). \] whose frequency is \[ \omega_\gamma = \omega_a = m_a(1 + v^2/2). \]

[Redondo: talk at DESY 14]
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]

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

[Redondo: talk at DESY 14 ]
Haloscope searches: Resonant cavities and dish antennas

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

[Essig et al. 1311.0029]
Haloscope searches: Precision magnetometry

> 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]

\[
\begin{align*}
SQUID \\
\text{pickup} \\
\text{loop}
\end{align*}
\]

\[
\overrightarrow{B}_{\text{ext}}
\]

\[
\overrightarrow{E}^*
\]

- 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)

[Diagram showing sensitivity of CASPEr experiment vs. frequency and mass, with regions labeled for Static EDM, SN 1987A, ADMX, and QCD Axion.]

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

[Lewandowski et al. 1311.0029]
Helioscope searches

- Most sensitive until now: CERN Axion Solar Telescope (CAST)
  - Superconducting LHC dipole magnet
  - X-ray detectors

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

> 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]
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 (V)HE gamma rays
- ALPs may explain soft X-ray excesses from galaxy clusters
- 7.1 keV ALP may explain unidentified X-ray line from Andromeda and 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!