Terrestrial tests of the axiverse.

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Terrestrial searches for axions and axion-like particles

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

- Indirect detection of solar axions and ALPs (helioscopes)

- Direct production and detection of ALPs (light shining through walls experiments)
Axions and axion-like particles (ALPs) may be produced non-thermally via vacuum realignment in form of classical, spatially coherent field oscillations = coherent state of extremely non-relativistic dark matter (Preskill et al 83; Abbott, Sikivie 83; Dine, Fischler 83; Cadamuro et al 12)

- Axion and ALPs can contribute significantly to cold dark matter for 
  \[ f_a \gtrsim 10^9 \text{ GeV} \]
- \[ g_{a\gamma} \lesssim 10^{-12} \text{ GeV}^{-1} \], in terms of axion or ALP coupling to two photons,

\[
\mathcal{L} \supset -\frac{1}{4} \frac{\alpha}{2\pi} \frac{C_{a\gamma}}{f_a} a F_{\mu\nu} \tilde{F}^{\mu\nu}
\]

\[ = g_{a\gamma} a \mathbf{E} \cdot \mathbf{B} \]

(Cadamuro et al. 12)
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
  \[ m_a = 2\pi\nu \sim 4 \mu\text{eV} \left( \frac{\nu}{\text{GHz}} \right) \]

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

- Ongoing: ADMX (Seattle), takes decade for mass scan over two orders of magnitude
Direct detection of axion or ALP dark matter: Cavities

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

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

Ongoing pilot study for WISPDMX
Direct detection of axion or ALP dark matter: Cavities

> WISPDMX may probe mass region below ADMX:
[Horons, Jaeckel, Lindner, Lobanov, Möller, AR, Sekutowicz, Trines, Westphal]
Direct detection of axion or ALP DM: Dish Antenna

> Proposed broadband search method, based on

- radiation emitted by conducting surfaces when excited by axionic DM
- 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)
Axion DM: all nucleons have a rapidly oscillating electric dipole moment

\[ d_N \sim e \frac{m_u m_d}{(m_u + m_d)m_N^2} \theta_{\text{eff}}(t) \sim 10^{-16} \theta_{\text{eff}}(t) \text{ e cm} \]

\[ \theta_{\text{eff}}(t) \sim \frac{a(t)}{f_a} \sim \frac{\sqrt{\rho_{\text{DM}}}}{m_a f_a} \cos(m_a t) \sim \frac{\sqrt{\rho_{\text{DM}}}}{m_\pi f_\pi} \cos(m_a t) \sim 10^{-19} \cos(m_a t) \]

- Window of opportunity for \( m_a \sim m_\pi f_\pi / f_a \sim \text{MHz \ (}10^{16} \text{ GeV} \/ f_a\): 
- Molecular interferometric search for oscillating shifts of atomic energy levels due to the coupling between internal atomic fields and time varying CP-odd nuclear moments,

\[ \delta E \sim E_{\text{int}} d_N \sim 10^{-24} \text{ eV} \]

Axion dark matter 

\begin{align*}
10^8 & \quad 10^{10} & \quad 10^{12} & \quad 10^{14} & \quad 10^{16} & \quad 10^{18} \\
\text{astrophysical constraints} & \quad \text{microwave cavity (ADMX)} & \quad \text{molecular interferometry} & \quad f_a \ (\text{GeV})
\end{align*}

(Graham, Rajendran 11)
Indirect detection of solar axions and ALPs: Helioscopes

- Sun strong source of axions and ALPs
- Helioscope searches for axions and ALPs

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

- Ongoing: CAST ... CERN Axion Solar Telescope
- LoI: IAXO ... International Axion Observatory
Indirect detection of solar axions and ALPs: Helioscopes
ALPs can pass walls

Light-shining-through-walls experiments: (here ALPS (@DESY)):

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

- HERA dipole (8.4 m, 5 T)
- Primary laser: enhanced LIGO laser (1064 nm, 35 W)
- Frequency doubled: 523 nm
- 300-fold power build-up in cavity
Direct production and detection of ALPs: LSW

> **ALPS:**

- HERA dipole (8.4 m, 5 T)
- Primary laser: enhanced LIGO laser (1064 nm, 35 W)
- Frequency doubled: 523 nm
- 300-fold power build-up in cavity

> **ALPS-II (2017):**

- 12 + 12 HERA dipoles
- 5000-fold power build-up in cavity
- Cavity also on regeneration part with 40000-fold power build-up

> **Similar plans also at Fermilab (REAPR)**

> **Next-to-next generation:** sensitivity improvement by another order of magnitude in coupling
Direct production and detection of ALPs: LSW

![Graph showing direct production and detection of ALPs: LSW](image-url)
Summary and conclusions

Axiverse models that exhibit a QCD axion with an intermediate-scale decay constant $f_a \sim M_s \sim M_P/\sqrt{V} \sim (M_P m_{3/2}/W_0)^{1/2} \sim 10^{9 \div 12}$ GeV and additional even lighter axion-like particles having the same decay constant and coupling to the photon, such as they occur in the LARGE Volume Scenario of IIB string compactifications, can

- explain astrophysical anomalies (anomalous transparency of the universe for TeV photons and anomalous white dwarf energy loss)
- be tested with current technology by haloscopes, helioscopes and next-to-next generation of light-shining-through-walls experiments

Axiverse models with a QCD axion having a GUT to Planck-scale decay constant

- can not be tested by terrestrial means by currently available experimental techniques
- most promising: haloscope based on molecular interferometry, technique needs improvement by more than two orders of magnitude