The Hunt for Axions.

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Strong Case for Particles Beyond the Standard Model

> Standard Model (SM) of particle physics describes properties of known matter and forces to a great precision

[wikipedia]
Strong Case for Particles Beyond the Standard Model

> Standard Model (SM) of particle physics describes properties of known matter and forces to a great precision

> SM not a complete and fundamental theory:
  - No explanation of the origin of dark energy and dark matter (DM)

[Diagram showing percentage distribution of components in the universe at different times]

[wikipedia]
Strong Case for Particles Beyond the Standard Model

- Standard Model (SM) of particle physics describes properties of known matter and forces to a great precision

- SM not a complete and fundamental theory:
  - No explanation of the origin of dark energy and dark matter (DM)

- Plenitude of DM candidates, notably:
  - Weakly Interacting Massive Particles (WIMPs), such as neutralinos
  - Very Weakly Interacting Slim (=ultra-light) Particles (WISPs), such as axions

- Stand out because of their convincing physics case and the variety of experimental probes

[Kim, Carosi 10]
Natural Candidates for WISPs: Nambu-Goldstone Bosons

- Nambu-Goldstone boson arising from breaking of global, e.g. U(1), symmetry

- Hidden Higgs field:
  \[ H_h(x) = \frac{1}{\sqrt{2}} [v_h + h_h(x)] e^{i\alpha(x)/v_h} \]

Massive modulus, massless phase:

\[ m_{h_h} \sim v_h \quad m_\alpha = 0 \]

- Interactions with SM particles small, if scale of symmetry breaking much larger than SM Higgs vacuum expectation value,

\[ v_h \gg v = 246 \text{ GeV} \]

[Raffelt]
Natural Candidates for WISPs: Nambu-Goldstone Bosons

- Couplings to SM suppressed by powers of $f_a \sim v_h \gg v = 246 \text{ GeV}$

$$\mathcal{L} \supset -\frac{\alpha_s}{8\pi} \frac{C_{ag}}{f_a} a G_{\mu\nu}^{b,\mu\nu} - \frac{\alpha}{8\pi} \frac{C_{a\gamma}}{f_a} a F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{1}{2} \frac{C_{af}}{f_a} \partial_{\mu} a \bar{\psi}_f \gamma^{\mu} \gamma_5 \psi_f$$

- Coefficients $C_{ag}, C_{a\gamma}$ determined by loops over particles charged under hidden $U(1)$. $C_{af}$ can arise at tree or loop level.

- Global symmetry not necessarily exact: Nambu-Goldstone boson will acquire a small mass vanishing in the limit that the global hidden symmetry is exact
  - Example in SM: Pions ... pseudo Nambu-Goldstone bosons of chiral symmetry breaking in QCD ... mass vanishes for vanishing quark masses
Natural Candidates for WISPs: Nambu-Goldstone Bosons

- Often, there is more than one global symmetry and therefore more than one Nambu-Goldstone boson
  - Global lepton number symmetry: Majoron [Chikashige et al. 78; Gelmini,Roncadelli 80]
  - Global family symmetry: Familon [Wilczek 82; Berezhiani,Khlopov 90]

\[
\mathcal{L} \supset -\frac{\alpha_s}{8\pi} \frac{C'_{i q}}{f_{a'_i}} a'_i G^{b,\mu\nu}_{\mu\nu} - \frac{\alpha}{8\pi} \frac{C'_{i \gamma}}{f_{a'_i}} a'_i F_{\mu\nu} \tilde{F}^{\mu\nu} + \frac{1}{2} \frac{C'_{a'_i f}}{f_{a'_i}} \partial_{\mu} a'_i \overline{\psi}_f \gamma^\mu \gamma_5 \psi_f
\]

- The particle corresponding to the linear combination

\[
\frac{A(x)}{f_A} \equiv \frac{C'_{i q}}{f_{a'_i}} a'_i (x)
\]

is called Axion (= laundry detergent): it cleans up the strong CP problem

[Peccei,Quinn 77; Weinberg 78; Wilczek 78]

- Particle excitations of the fields orthogonal to the axion field are called Axion-Like-Particles (ALPs)

- String theory suggests a plenitude of ALPs [Witten; Arvanitaki et al., Cicoli,Goodsell,AR]
Axion/ALP Dark Matter?

- In early universe, axion/ALP frozen at random initial value
- Later, field feels pull of mass towards zero and oscillates around it
- Spatially uniform oscillating classical field = coherent state of many, extremely non-relativistic particles = cold dark matter (CDM)

\[ m_a \approx 3H \]
axion starts rolling, turns into pressureless matter.

\[ m_a < 3H \]
axion is frozen

axion number \( N_a \) is conserved

[Preskill et al 83; Abbott, Sikivie 83; Dine, Fischler 83,.....; Arias et al. 12]

[Wantz, Shellard 09]
Axion/ALP Dark Matter?

- In early universe, WISP (axion/ALP) frozen at random initial value
- Later, field feels pull of mass towards zero and oscillates around it
- Spatially uniform oscillating classical field = coherent state of many, extremely non-relativistic particles = cold dark matter (CDM)
- Energy density proportional to initial field amplitude squared,
  \[ \rho_a = n_a m_a \sim f_a^2 \]
- Axion/ALP CDM prefers:
  \[ f_a \gtrsim 10^{10-12} \text{ GeV} \]

[Preskill et al 83; Abbott,Sikivie 83; Dine,Fischler 83;..;Arias et al. 12]

adapted by from Essig et al. 1311.0029
Axion/ALP Energy Losses of Stars in Globular Clusters?

> **Red Giants** (RGs) in globular clusters mildly prefer additional energy losses due to axion/ALP emission via Bremsstrahlung \( e + Z e \rightarrow Z e + e + a \) [Viaux et al. 13]

Axion/ALP emission delays He ignition, i.e. core mass increased.
Red Giants (RGs) in globular clusters mildly prefer additional energy losses due to axion/ALP emission via Bremsstrahlung $e + Z e \rightarrow Z e + e + a$

\[
g_{ae} \equiv \frac{C_{ae} m_e}{f_a} = 1.8_{-0.6}^{+0.8} \times 10^{-13}
\]

Mild hints of anomalous energy loss of White Dwarfs (WDs) could also be explained by same parameter values

\[
g_{ae} < 4.3 \times 10^{-13} \quad (95\% \text{ CL})
\]
Axion/ALP Energy Losses of Stars in Globular Clusters?

> Horizontal Branch (HB) stars in globular clusters mildly prefer additional energy losses due to axion/ALP emission via Primakoff $\gamma + Ze \rightarrow Ze + a$

[Ayala et al. 14]
Axion/ALP Energy Losses of Stars in Globular Clusters?

- **Horizontal Branch (HB)** stars in globular clusters mildly prefer additional energy losses due to axion/ALP emission via Primakoff $\gamma + Ze \rightarrow Ze + a$ [Ayala et al. 14]

$$g_{\alpha \gamma} \equiv \frac{\alpha C_{\alpha \gamma}}{2\pi f_\alpha} = 0.45^{+0.12}_{-0.16} \times 10^{-10} \text{ GeV}^{-1}$$

$$g_{\alpha \gamma} < 0.66 \times 10^{-10} \text{ GeV}^{-1} \quad (95\% \text{ CL})$$
Axion/ALP Energy Losses of Neutron Star in Cas A?

> Neutron star in Cas A:

- Measured surface temperature over 10 years reveals unusually fast cooling rate
- Hint on extra cooling by axion/ALP due to nucleon bremsstrahlung
  \[ N + N \rightarrow N + N + a \]
- Required coupling to neutron:
  \[ g_{an} \equiv \frac{C_{an} m_n}{f_a} \sim 4 \times 10^{-10} \]

[Leinson 14]
Gamma ray spectra from distant AGNs should show an energy and redshift dependent exponential attenuation, due to pair production at Extragalactic Background Light (EBL).
Photon – ALP Conversion in Cosmic Magnetic Fields?

- Indication of anomalous gamma transparency: attenuation observed by IACT and Fermi-LAT too small [Aharonian et al. 07; de Angelis, Roncadelli et al. 07; ...; Horns, Meyer 12; ...; Rubtsov, Troitsky 14]

[Images of data plots showing gamma-ray intensity vs. energy]
Possible explanation: photon $\leftrightarrow$ ALP conversions in magnetic fields

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

[Manuel Meyer 12]
Photon – ALP Conversion in Cosmic Magnetic Fields?

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

[Diagram showing coupled regions involving ALPs and cosmic magnetic fields.]

Required photon coupling overlaps with preferred region from HBs in GCs

[Horns 15]
Photon – ALP Conversion in Cosmic Magnetic Fields?

- Photon-ALP conversion with a strength $g_{a\gamma} \sim \text{few} \times 10^{-11} \text{ GeV}^{-1}$ explains also puzzling observation of VHE photons from Flat Spectrum Radio Quasars (FSRQs) [Tavecchio, Roncadelli, Galanti, Bonnoli 12]

  - Pair production on UV photons in broad line region should prevent photons produced by the central engine to escape
Summary of Astrophysical Hints for Axion/ALPs

> Symmetry breaking scale inferred from astrophysical hints:

1. RGs + WDs: \( f_a = 3 \times 10^9 \text{GeV} \quad C_{ae} \left( \frac{2 \times 10^{-13}}{g_{ae}} \right) \)

2. n star in Cas A: \( f_a = 2 \times 10^9 \text{GeV} \quad C_{an} \left( \frac{4 \times 10^{-10}}{g_{an}} \right) \)

3. HB stars + AGN spectra: \( f_a = 2 \times 10^7 \text{GeV} \quad C_{\alpha\gamma} \left( \frac{5 \times 10^{-11} \text{GeV}^{-1}}{g_{\alpha\gamma}} \right) \)

> Astrophysical hints can be explained by

- **ALP** with \( f_a \sim 10^7 \text{GeV}, \quad m_a \lesssim 0.1 \mu\text{eV}, \quad C_{\alpha\gamma} \sim 1, \quad C_{ae} \sim C_{an} \sim 10^{-2} \)

- **Axion** with \( f_A \sim 10^9 \text{GeV}, \quad C_{An} \sim C_{A\gamma} \sim C_{Ae} \sim 1 \)

plus

- **ALP** with \( f_a \sim 10^7 \text{GeV}, \quad m_a \lesssim 0.1 \mu\text{eV}, \quad C_{\alpha\gamma} \sim 1, \quad C_{ae} \sim C_{an} \ll 10^{-2} \)

> In reach of upcoming generation of terrestrial experiments:
## Axion/ALP Experiments Worldwide

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

| Experiment   | Type                      | Location | Status      |
|--------------|---------------------------|----------|-------------|
| ALPS II      | Light-shining-through-a-wall | DESY     | preparation |
| CROWS        |                           | CERN     | finished    |
| OSQAR        |                           | CERN     | running     |
| REAPR        |                           | FNAL     | proposed    |
| CAST         | Helioscopes               | CERN     | running     |
| IAXO         |                           | ?        | proposed    |
| SUMICO       |                           | Tokyo    | running     |
| ADMX         | Halosocopes               | Seattle  | running     |
| CASPEr       |                           | Mainz    | preparation |
| QUAX         |                           | Legnaro  | preparation |

[adapted from Axel Lindner `14]
Any Light Particle Search (ALPS) at DESY (in coll. with LZH, AEI)

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

[Anselm 85; van Bibber et al. 87]
Currently best limits from LSW: **ALPS** (DESY) and **OSQAR** (CERN)
Light-shining-through-a-wall Searches

ALPS II in prepar. at DESY (in collaboration with UHH, AEI, U Mainz)

Parameter | Scaling | ALPS I | ALPS IIc | Sens. gain
---|---|---|---|---
Effective laser power $P_{\text{laser}}$ | $g_{\gamma\gamma} \propto P_{\text{laser}}^{-1/4}$ | 1 kW | 150 kW | 3.5
Rel. photon number flux $n_{\gamma}$ | $g_{\gamma\gamma} \propto n_{\gamma}^{-1/4}$ | 1 (532 nm) | 2 (1064 nm) | 1.2
Power built up in RC $P_{\text{RC}}$ | $g_{\gamma\gamma} \propto P_{\text{RC}}^{-1/4}$ | 1 | 40,000 | 14
$BL$ (before & after the wall) | $g_{\gamma\gamma} \propto (BL)^{-1}$ | 22 Tm | 468 Tm | 21
Detector efficiency $QE$ | $g_{\gamma\gamma} \propto QE^{-1/4}$ | 0.9 | 0.75 | 0.96
Detector noise $DC$ | $g_{\gamma\gamma} \propto DC^{1/8}$ | 0.0018 s$^{-1}$ | 0.000001 s$^{-1}$ | 2.6

Combined improvements

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

- Crucial test of ALP explanation of excessive HB star energy loss and AGN spectra at VHE

[Essig et al. 1311.0029]
Helioscope Searches

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

- Superconducting LHC dipole magnet
- X-ray detectors

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

- Crucial test of the axion explanation of the excessive energy losses of RGs, WDs, n star in Cas A and ALP explanation of AGN spectra at VHE
Haloscope Searches: Resonant Cavities

- Direct detection of axion/ALP dark matter!
- Axion or ALP DM – photon conversion in microwave cavity placed in magnetic field

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

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

- Direct detection of axion/ALP dark matter!
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> Best sensitivity: mass = resonance frequency \( m_a = 2\pi\nu \sim 4 \mu eV \left( \frac{\nu}{\text{GHz}} \right) \)

> Ongoing: ADMX (Seattle), exploiting high Q cavity in 8 T SC solenoid
Haloscope Searches: Resonant Cavities

> ADMX able to probe about 1.5 decades in axion/ALP mass:

adapted from [Hewett et al 12]
Haloscopes: MR Searches for Oscillating EDMs

- Axion DM gives all nucleons oscillating electric dipole moments (EDMs)
  \[ d_N \equiv g_{Ad} A(t) \sim e \frac{m_u m_d}{(m_u + m_d) m_N^2} \frac{A(t)}{f_A} \sim 10^{-16} \frac{A(t)}{f_A} e \text{ cm} \]
  \[ \frac{A(t)}{f_A} \sim \frac{\sqrt{\rho_{DM}}}{m_A f_A} \cos(m_A t) \sim \frac{\sqrt{\rho_{DM}}}{m_{\pi} f_{\pi}} \cos(m_A t) \sim 10^{-19} \cos(m_A t) \]

- EDMs cause precession of nuclear spins in a nucleon spin polarized sample in the presence of an electric field

- Resulting transverse magnetisation can be searched for exploiting magnetic resonance (MR) techniques [Budker,Graham,Ledbetter,Rajendran,Sushkov]

\[ M(t) \approx n p \mu E^* \epsilon_{sd_n} \frac{\sin\left(\frac{2 \mu B_{ext} - m_a c^2}{h} t\right)}{2 \mu B_{ext} - m_a c^2} \sin(2 \mu B_{ext} t) \]
Haloscopes: MR Searches for Oscillating EDMs

- Cosmic Axion Spin Precession Experiment (CASPER) in preparation in Mainz
  - Probes very light axion, from GUT to Planck scale SSB (anthropic axion)
  - Sensitive in a mass/symmetry breaking scale region complementary to ADMX

\[ M(t) \approx n p \mu E^* e_s d_n \left( \frac{2\mu B_{\text{ext}} - m_a c^2}{h} \right) \frac{\sin\left( \frac{2\mu B_{\text{ext}} - m_a c^2}{h} t \right)}{2\mu B_{\text{ext}} - m_a c^2} \sin(2\mu B_{\text{ext}} t) \]

| Phase  | \( n \) | \( E^* \) (V/cm) | \( p \) | \( T_2 \) (ms) | Max. \( B_{\text{ext}} \) (T) |
|--------|---------|-----------------|-------|------------|-----------------|
| Phase 1 | \( 10^{22} \) cm\(^{-3} \) | \( 3 \times 10^8 \) | \( 10^{-3} \) | 1 | 10 |
| Phase 2 | \( 10^{22} \) cm\(^{-3} \) | \( 3 \times 10^8 \) | 1 | 1 s | 20 |

\[ \mathcal{L} \equiv -\frac{i}{2} g_d a \overline{N} \sigma_{\mu\nu} \gamma_5 N F^{\mu\nu} \]
The axion/ALP nucleon coupling

\[ g_{\text{aNN}} (\partial_\mu a) \bar{N} \gamma^\mu \gamma_5 N \implies H_N \supset g_{\text{aNN}} \nabla a \cdot \vec{S}_N \]

will lead to a spin precession about the axion/ALP DM wind

Resulting magnetisation

\[ M(t) \approx np\mu \left( g_{\text{aNN}} \sqrt{2\rho_{\text{DM}} v} \right) \frac{\sin \left( (2\mu B_{\text{ext}} - m_\text{a}) t \right)}{2\mu B_{\text{ext}} - m_\text{a}} \sin (2\mu B_{\text{ext}} t) \]

[13] Graham, Rajendran
Haloscopes: MR Searches for the Axion/ALP Wind

> Cosmic Axion Spin Precession Experiment (CASPER) in preparation in Mainz

- Sensitivity does not reach axion prediction

\[
M(t) \approx n p \mu \left( g_{\text{aNN}} \sqrt{2 \rho_{DM} v} \right) \frac{\sin \left( \frac{(2 \mu B_{\text{ext}} - m_a) t}{2 \mu B_{\text{ext}} - m_a} \right)}{\sin \left( 2 \mu B_{\text{ext}} t \right)}
\]

| Element | Density \((n)\) | Magnetic Moment \((\mu)\) | \(T_2\) | Max. B | Magnetometer Sensitivity |
|---------|----------------|-----------------|--------|--------|------------------------|
| 1. \(\text{Xe}\) | \(1.3 \times 10^{22} \frac{1}{\text{cm}^3}\) | 0.35 \(\mu_N\) | 100 s | 10 T | \(10^{-16} \frac{T}{\sqrt{\text{Hz}}}\) |
| 2. \(\text{He}\) | \(2.8 \times 10^{22} \frac{1}{\text{cm}^3}\) | 2.12 \(\mu_N\) | 100 s | 20 T | \(10^{-17} \frac{T}{\sqrt{\text{Hz}}}\) |

\[ L \supset g_{\text{aNN}} \left( \partial_\mu a \right) \bar{N} \gamma^\mu \gamma_5 N \]

[Graham, Rajendran 13]
Haloscopes: ESR/MR Searches for the Axion/ALP Wind

- The axion/ALP electron coupling
  \[ \mathcal{L} \supset g_{aee} \partial_{\mu} a (\bar{e} \gamma_5 \gamma^\mu e) \]
  will also lead to a spin precession about the axion/ALP DM wind

- Larmor frequency and thus sensitivity extended to higher masses by factor
  \[ \mu_B / \mu_N \sim m_N / m_e \sim 10^3 \]

- QUAX (QUaerere AXions) in preparation by INFN (Legnaro, Padua, Torino), Birmingham, Moscow aims to exploit magnetic resonance (MR) inside a magnetized material (Electron Spin Resonance (ESR))

[Carugno,Ruoso et al.]
Summary

> Strong physics case for axion and ALPs:
  - Axion and ALPs occur naturally as NG bosons from breaking of well motivated symm.
  - Solution of strong CP problem
  - Candidates for dark matter
  - Explanation of astrophysical hints (energy losses of stars; AGN spectra)

> Large parts in axion and ALPs parameter space can be tackled in the upcoming decade by a number of terrestrial experiments:
  - Light-shining-through-a-wall experiments (ALPS II, ...)
  - Helioscopes (IAXO, ...)
  - Haloscopes (ADMX, CASPEr, QUAX, ...)

> Stay tuned!
Late-time neutrino signal most sensitive observable

- Early neutrino burst powered by accretion, not sensitive to volume energy loss
- Late-time neutrino signal associated with neutrino diffusion. Emission of axions would steal energy from the late-time neutrino burst and shorten it

[Raffelt 14]
Late-time neutrino signal most sensitive observable

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Backup: Axion and Neutrino Signal from CC Supernovae

- **Late-time neutrino signal most sensitive observable**
  - Early neutrino burst powered by accretion, not sensitive to volume energy loss
  - Late-time neutrino signal associated with neutrino diffusion. Emission of axions would steal energy from the late-time neutrino burst and shorten it

- **Limit on energy loss due to nucleon bremsstrahlung of axions/ALPs in SN 1987 A:**
  \[
g_{aN} \equiv \frac{C_{aN} m_N}{f_a} \lesssim 5 \times 10^{-10}, \quad \text{for } m_a \lesssim \text{MeV}.
\]

- **Fundamental particle physics opportunity for neutrino telescopes if galactic core-collapse supernova is observed!**
- **Sensitive in a range of symmetry breaking scale where other experiments have difficulties!**
Recent claim: no indication of pair production anomaly in VHE AGN spectra

- But then pair production anomaly replaced by EBL anomaly

**Deconvolution of the EBL** [arXiv:1502.04166]

- Approximate EBL with sums of Gaussians
- Use O(100) spectra
- Tension with models 3-5 σ
- Tension with lower limits from galaxy counts at NIR
- Tension with Fermi-LAT estimate on EBL
- Additionally: too large $H_0$, too small $z$ for 1424+240

[Horns 15]
If \( f_a > \max \left( H_I / (2\pi), \epsilon_{\text{eff}} E_I \right) \), quantum fluctuations \( \delta \theta_a = H_I / (2\pi f_a) \) of the axion/ALP lead to isocurvature (= entropy) fluctuations in CMB, with nearly scale-invariant power spectrum \[
P_i(k) \sim \left( \frac{\Omega_a}{\Omega_{\text{DM}}} \right)^2 \left\{ \frac{H_I^2}{\pi^2 f_a^2 \langle \theta_a \rangle^2} , \text{ for } \langle \theta_a \rangle^2 \gg \left( \frac{H_I}{2\pi f_a} \right)^2 \right\} 2, \text{ for } \langle \theta_a \rangle^2 \ll \left( \frac{H_I}{2\pi f_a} \right)^2 \]

Non-observation rules out existence of axion/ALP, unless \( H_I \lesssim 10^{13} \text{ GeV} \)

Detection of \( \mathcal{P}_t / \mathcal{P}_s \equiv r = 0.20^{+0.07}_{-0.05} \) by BICEP2 would have implied \( H_I \simeq \frac{1}{4} \sqrt{A_s r \pi M_{\text{Pl}}} = 1.1 \times 10^{14} \text{ GeV} \left( \frac{r}{0.2} \right)^{1/2} \)

\( f_a > 1.8 \times 10^{13} \text{ GeV} \) strongly disfavored

[Fox et al. hep-th/0409059; Higaki et al. 1403.4186; Marsh et al. 1403.4216; Visinelli,Gondolo 1403.4594]