On the Track of Ultralight Particles.

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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

![Diagram of the Standard Model](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 satisfactory explanation for values of its many parameters.

\[
\mathcal{L}_{SM} = \frac{1}{4} W_{\mu\nu} \cdot W^{\mu\nu} - \frac{1}{4} B_{\mu\nu} B^{\mu\nu} - \frac{1}{4} G^a_{\mu\nu} G^{a\mu\nu} \\
+ \mathcal{L}_{\gamma}(i\partial_{\mu} - \frac{1}{2} g_{\mu}) \cdot (W_{\mu} - \frac{1}{2} g' Y B_\mu) L + R_{\gamma}(i\partial_{\mu} - \frac{1}{2} g' Y B_{\mu}) R \\
+ \frac{1}{2} (i\partial_{\mu} - \frac{1}{2} g_{\mu} \cdot W_{\mu} - \frac{1}{2} g' Y B_{\mu}) \phi |^2 - V(\phi) \\
+ g''(\bar{q}\gamma^\mu T_a q) C^a_{\mu} + (G_1 \bar{L}\phi R + G_2 \bar{L}\phi c R + h.c.)
\]

[CBSN]
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 satisfactory explanation for values of its many parameters
  - No explanation of the origin of dark energy and dark matter

[ wikipedia ]
> Particle candidates of dark matter should feature

- Feeble interactions with SM
- Non-relativistic momentum distribution at beginning of structure formation
- Stability on cosmological time scales
Particle candidates of dark matter should feature:

- feeble interactions with SM
- non-relativistic momentum distribution at beginning of structure formation
- stability on cosmological time scales

These features can be realised by:

- Weakly Interacting Massive Particles (WIMPs), e.g. neutralino
- very Weakly Interacting Slim (in the sense of very light) Particles (WISPs), e.g. axion

[Kim, Carosi 10]
WIMPy dark matter:

- Direct detection
- Indirect detection in cosmic rays
- Production of WIMPs at accelerators
On the Track of Dark Matter Candidates

> WIMPy dark matter:
  - Direct detection
  - Indirect detection in cosmic rays
  - Production of WIMPs at accelerators

> WISPy dark matter:
  - Direct detection
  - Indirect detection in astrophysics and cosmology
  - Production of WISPs with lasers and detection via light-shining-through-a-wall
Natural Candidates for WISPs: Nambu-Goldstone Bosons

- Nambu-Goldstone bosons arising from breaking of a global U(1) symmetry

\[ H_h(x) = \frac{1}{\sqrt{2}} [v_h + h_h(x)] e^{ia(x)}/v_h \]

- Hidden Higgs field

- Radial excitation massive, phase excitation massless:

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

- 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 particles all suppressed by $f_a \sim v_h \gg v = 246 \text{ GeV}$

$$\mathcal{L} \supset -\frac{\alpha_s}{8\pi} \frac{C_{ag}}{f_a} a G_{\mu \nu}^b \tilde{G}_{\mu \nu}^b - \frac{\alpha}{8\pi} \frac{C_{a \gamma}}{f_a} a F_{\mu \nu} \tilde{F}^{\mu \nu} + \frac{1}{2} \frac{C_{af}}{f_a} \partial_\mu a \bar{\psi}_f \gamma^{\mu} \gamma^5 \psi_f$$

> 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]
- Global family symmetry: Familon [Wilczek 82; Berezhiani, Khlopov 90]

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

The particle corresponding to the linear combination

\[
\frac{A(x)}{f_A} \equiv \frac{C^i_{i g}}{f_{a'_i}} a'_i(x)
\]

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 tends to predict a plentiude of ALPs [Arvanitaki et al., Cicoli, Goodsell, AR]
Natural Candidates for WISPs: Hidden Gauge Bosons

>- Vector bosons of a local U(1) gauge theory under which SM particles are uncharged, often called Hidden photons (HPs)

>- Gauge symmetry forbids explicit mass terms; mass generated via
  - Hidden Higgs mechanism: \( m_{\gamma'} \sim g_h v_h \)
  - Stückelberg mechanism: topological mass

>- Suppressed couplings to SM particles; e.g. kinetic mixing with the photon:
  \[
  \mathcal{L} \supset -\frac{\chi}{2} F'_{\mu\nu} F^{\mu\nu}; \quad \chi \sim \frac{e g_h}{16\pi^2} \quad \text{[Holdom 86]}
  \]

>- Examples:
  - U(1) factors from breaking of grand unified gauge group
  - Often occur in low energy effective field theories from string theory [Goodsell, AR 10]
WISPy Dark Matter

> In early universe, WISP (axion/ALP/HP) frozen at random initial value

> Later, field feels pull of mass towards zero and oscillates around it

[Raffelt]
WISPy Dark Matter

- In early universe, WISP (axion/ALP/HP) 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 of WISPy CDM proportional to initial field amplitude squared, e.g. axion/ALP CDM energy density scales as $\rho_a = n_a m_a \sim f_a^2$

$\theta_a \leq 3H$
axion is frozen

$N_a$
axion number $N_a$
is conserved

$\rho_a \approx 3H$
axion starts rolling, turns into pressureless matter.

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

[Wantz, Shollard 09]
WISPy Dark Matter

- In early universe, WISP (axion/ALP/HP) frozen at random initial value
- Later, field feels pull of mass towards zero and oscillates around it
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- Energy density of WISPy CDM proportional to initial field amplitude squared, e.g. axion/ALP CDM energy density scales as \( \rho_a = n_a m_a \sim f_a^2 \)
- Axion/ALP CDM prefers:
  \[
  f_a \sim 10^{10\div12} \text{ GeV}
  \]

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

\[ f_A [\text{GeV}] \]
\[
\begin{array}{c}
10^{14} & 10^{13} & 10^{12} & 10^{11} & 10^{10} & 1
\end{array}
\]

**postinflation PQ**
(REALIGNMENT+COsmic strings+DWs)

**preinflation PQ**
(ONLY REALIGNMENT)

\[ m_A [\text{eV}] \]
\[
\begin{array}{c}
10^{-7} & 10^{-6} & 10^{-5} & 10^{-4} & 10^{-3}
\end{array}
\]

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

[Raffelt 14]
Axion/ALP Energy Losses of Stars in Globular Clusters?

[Diagram showing stellar evolution stages: Asymptotic Giant, Red Giant, Horizontal Branch, Main-Sequence.]

Isochrones for 14 Gy, [Fe/H] = -2

[Raffelt 14]
Red Giants (RGs) in globular clusters mildly prefer additional energy losses due to axion/ALP emission via Bremsstrahlung:

\[ e + Ze \rightarrow Ze + e + a \]

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

Axion/ALP emission delays He ignition, i.e. core mass increased.
Axion/ALP Energy Losses of Stars in Globular Clusters?

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\[ e + Ze \rightarrow Ze + e + a \]

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

Conservative upper limit

\[ g_{ae} < 4.3 \times 10^{-13} \] (95% CL)

[Viaux et al. 13]

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

[Raffelt 14]

[Isern et al.]
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

\[ \gamma + Ze \rightarrow Ze + a \]

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

Axion/ALP emission reduces He burning lifetime, i.e. # in HB
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

\[ \gamma + Z e \rightarrow Z e + a \]

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

Conservative upper limit

\[ g_{a\gamma} < 0.66 \times 10^{-10} \text{ GeV}^{-1} \quad (95\% \text{ CL}) \]

[Ayala et al. 14]
Pair-production at extra-galactic background light (EBL) should make Universe non-transparent to very high energy gamma rays

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

Gamma ray spectra of Active Galactic Nuclei from Imaging Atmospheric Cherenkov Telescopes (H.E.S.S., MAGIC, ...) and FERMI do not show expected break [Aharonian et al. 07; Aliu et al. 08; Horns, Meyer 12; Rubtsov, Troitsky 14]
Explanations of anomalous transparency 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]
Photon – ALP Conversion in Cosmic Magnetic Fields?

> Explanation of anomalous transparency 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]
Symmetry breaking scale inferred from astrophysical hints:

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

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

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

Astrophysical hints can be explained by

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

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


\[ \text{ALP with } f_a \sim 10^7 \text{ GeV, } m_a \lesssim 0.1 \mu\text{eV, } C_{a\gamma} \sim 1, \ C_{ae} \sim C_{an} \sim 10^{-2} \]

\[ \text{Axion with } f_A \sim 10^9 \text{ GeV, } C_{An} \sim C_{A\gamma} \sim C_{Ae} \sim 1 \]

In reach of upcoming generation of terrestrial experiments:
WISP Experiments Worldwide

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

<table>
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<th>Experiment</th>
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<td>CROWS</td>
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<td>?</td>
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<td>SUMICO</td>
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<td>FUNK</td>
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<td>KIT</td>
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[adapted from Lindner `14]
Light-shining-through-a-wall Searches

Any Light Particle Search I (ALPS I) at DESY (in coll. with LZH, AEI)

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

\[
P(\alpha \leftrightarrow \gamma) = 4 \frac{(g_\alpha \gamma \omega B)^2}{m_\alpha^4} \sin^2 \left( \frac{m_\alpha^2}{4\omega L_B} \right)
\]
Light-shining-through-a-wall Searches

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

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

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

Latest Results of the OSQAR Photon Regeneration Experiment for Axion-Like Particle Search

Rafik Ballou\textsuperscript{1,2}, Guy Deferne\textsuperscript{3}, Lionel Duvillaret\textsuperscript{4}, Michael Finger, Jr.\textsuperscript{5}, Miroslav Finger\textsuperscript{5}, Lucie Flekova\textsuperscript{5}, Jan Hosek\textsuperscript{6}, Tomas Husek\textsuperscript{5}, Vladimir Jary\textsuperscript{6}, Remy Jost\textsuperscript{1,8}, Miroslav Kraľ\textsuperscript{6}, Stepan Kuč\textsuperscript{6}, Karolina Macuchova\textsuperscript{6}, Krzysztof A. Meissner\textsuperscript{10}, Jérôme Morville\textsuperscript{11,12}, Pierre Pugnat\textsuperscript{13,14}, Daniele Romanini\textsuperscript{7,8}, Matthias Schott\textsuperscript{15}, Andrzej Siemko\textsuperscript{3}, Miloslav Shunecka\textsuperscript{5}, Miroslav Sulc\textsuperscript{6}, Guy Vitrant\textsuperscript{4}, Christoph Weinsheimer\textsuperscript{15}, Josef Zicha\textsuperscript{6}

> With two LHC dipoles OSQAR at CERN surpassed ALPS I sensitivity
> **ALPS II** at DESY (in collaboration with UHH, AEI, U Mainz)

- 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>
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<tr>
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<th>2013</th>
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<td>Ilc risk assessments (IIb)</td>
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<td>ALPS IIc</td>
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</table>

- **installation**
- **data runs**

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

ALPS IIc in 2018 in HERA tunnel
Light-shining-through-a-wall Searches

> Crucial test of ALP explanation of excessive HB star energy loss and anomalous gamma ray transparency of Universe

[Essig et al. 1311.0029]
Helioscope Searches

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

- Superconducting LHC dipole magnet
- X-ray detectors

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

- Crucial test of the axion explanation of the excessive energy losses of RGs, WDs, n star in Cas A

adapted from [Hewett et al 12]
Haloscope Searches: Resonant Cavities

- Direct detection of axion/ALP dark matter!
- Axion or ALP DM – photon conversion in microwave cavity placed in magnetic field [Sikivie 83]

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

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

- 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
- A magnetised mirror in axion/ALP DM background radiates photons
- Simple broadband experiment: spherical dish antenna

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

[Horns; Jaeckel, Lindner, Lobanov, Redondo, AR 12]
Haloscope Searches: Dish Antennas

- Dish antenna can also search for Hidden Photon dark matter (need no B)
  
  [Horns; Jaeckel, Lindner, Lobanov, Redondo, AR 12]

- Pilot dish experiment FUNK (Finding U(1)s of a Novel Kind) at KIT:

[Döbrich, Daumiller, Engel, Kowalski, Lindner, Redondo, Roth 12]
ADMX and proposed broadband (dish antenna, stellarators) searches probe sizeable region in axion/ALP dark matter parameter space:

[Figures and text about axion/ALP searches and parameter space exploration.]

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

> Strong physics case for axion and other WISPs:
  - 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; cosmic gamma transparency)

> 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

> Stay tuned!
Good Investment: DAX (Dow Jones Axion Index) Grows!

> inSPIRE: Citation of Peccei-Quinn papers or title axion (and similar)
Backup: 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]
Backup: Light-shining-through-a-wall Searches

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  [Betz et al. (CROWS) '13]
Resonant cavities also sensitive to Hidden Photon Dark Matter:

[Horns, Lindner, Lobanov, AR 14]
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, \[ m_a \sim m_\pi f_\pi / f_a \sim \text{MHz} \left(10^{16} \text{ GeV} / f_a\right) \]
Sensitivity of CASPEr (Cosmic Axion Spin Precession Experiment) planned to be built at Helmholtz Institute in Mainz

[Budker et al 13]