Andreas Ringwald (DESY)
Bethe Colloquium
Physikalisches Institut der Universität Bonn
Bonn, D, 16 April 2015

The Hunt for Axions and Other WISPs
Strong Case for Particles Beyond the Standard Model

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

![Pie charts comparing composition of the universe 13.7 billion years ago and today.](chart_image)

13.7 BILLION YEARS AGO
(Universe 380,000 years old)

TODAY
- Dark Energy: 68.3%
- Dark Matter: 26.8%
- Atoms: 4.9%
- Neutrinos: 10%
- Photons: 15%
- Atoms: 12%
Particle candidates of dark matter should feature feeble interactions with SM non-relativistic momentum distribution at beginning of structure formation and stability on cosmological timescales.
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. Well-motivated candidates realising these features: 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
On the Track of Dark Matter Candidates

WIMP:

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

**WIMP**:
- Direct detection
- Indirect detection in cosmic rays
- Production of WIMPs at accelerators

**WISP**:
- Direct detection
- Indirect detection in astrophysics and cosmology
- Production of WISPs with lasers and detection via light-shining-through-a-wall

Axion Helioscope (Sikivie 1983)
Axion-Photon-Oscillation
Nambu-Goldstone boson arising from breaking of global, e.g. U(1), symmetry

Hidden Higgs field:

Massive modulus, massless phase:

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

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

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

\[ v_h \gg v = 246 \text{ GeV} \]
Natural Candidates for WISPs: Nambu-Goldstone Bosons

Couplings to SM suppressed by powers of

Coefficients determined by loops over particles charged under hidden \(U(1)\).

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]

The particle corresponding to the linear combination 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].

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

\[
A(x) = \frac{C'_{i g}}{f_{a'_i}} a'_i(x)
\]

A ( ALP )

\[
\text{P , Q 77; W 78; W 78}
\]
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:
- Stückelberg mechanism: topological mass

Suppressed couplings to SM particles; e.g. kinetic mixing with the photon:

\[ m_{\gamma'} \sim g_h v_h \]

Examples:

- U(1) factors from breaking of grand unified gauge group
- Often occur in low energy effective field theories from string theory

\[ m_{\gamma'} \sim \frac{e g_h}{16\pi^2} \]

\[ \mathcal{L} \supset -\frac{\chi}{2} F'_{\mu\nu} F^{\mu\nu}; \quad \chi \sim \frac{e g_h}{16\pi^2} \]
Axion/ALP Dark Matter?

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

\[ \theta_a \equiv \alpha / f_a \in [-\pi, \pi] \]

\[ m_a < 3H \]

axion is frozen and the number \( N_a \) is conserved.

\[ m_a \approx 3H \]

axion starts rolling, turns into pressureless matter.

\[ \frac{m_a}{m_\gamma} \]

\[ 3H / m_\gamma \]

\[ 1 / T \text{ (Gev}^{-1}) \]

\[ \theta_a \]

\[ N_a \]
Axion/ALP Dark Matter?

In the early universe, axion/ALP frozen at its initial value. Later, the field feels a pull 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.

Axion/ALP CDM prefers:

\[ f_A \text{[GeV]} \]
\[ m_A \text{[eV]} \]

(realignment+cosmic strings+DWs)

postinflation PQ

(preinflation PQ

(only realignment)

\[ m_A \text{[eV]} \]

\[ f_A \text{[GeV]} \]
Axion/ALPs and Inflation

If axion/ALP present during inflation, induced quantum fluctuations imply lower bound on initial angle, and thus lower bound on lead to isocurvature (= entropy) fluctuations in CMB, with nearly scale-invariant power spectrum.

Non-observation rules out existence of axion/ALP, unless [Wilczek, Turner `91; Fox et al. hep-th/0409059; Beltran et al. hep-ph/0606107; Hertzberg et al. 0807.1726; ...]

\[ \theta_a^2 \gtrsim (H_I/(2\pi f_a))^2 \]

\[ R_a \equiv \frac{\rho_a}{\rho_{DM}} \]

\[ H_I \lesssim 10^{13} \text{ GeV} \]

W, T 91; F, /0409059; B, /0606107; H 0807.1726; ...
HP Dark Matter and Inflation

Also produced from primordial non-zero initial value

Lower bound from induced quantum fluctuations

\[ R_{\gamma'} \equiv \frac{\rho_{\gamma'}}{\rho_{DM}} \gtrsim \left( \frac{m_{\gamma'}}{6 \times 10^{-6} \text{ eV}} \right)^{1/2} \left( \frac{H_I}{10^{14} \text{ GeV}} \right)^2 \]
Axion/ALP Energy Losses of Stars in Globular Clusters?

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

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

Raffelt 14

T H A O WISP, B C , B , 16 A 2015 18
Axion/ALP energy losses of stars in globular clusters are considered. Red Giants (RGs) in globular clusters mildly prefer additional energy losses due to axion/ALP emission via Bremsstrahlung. This process delays He ignition, effectively increasing the core mass. The equation $e + Ze \rightarrow Ze + e + a$ is also mentioned.
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. Mild hints of anomalous energy loss of White Dwarfs (WDs) could also be explained by the same parameter values.

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

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

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

\[ M_{I,TRGB} \]

\[ g_{ae} \times 10^{13} \]

\[ R \quad 14 \]

\[ \text{Theoretical} \]

\[ \text{Observational} \]
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

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

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

\[ \text{H} \quad \text{B} \]

\[ \text{A} \quad \text{HB} \]

$\text{A} \quad \text{WISP}, \text{B} \quad \text{C} \quad \text{B} \quad \text{16 A} \quad \text{2015} \quad \text{21}$
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 effect. 

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

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

Required coupling to neutron:

\[ g_{an} \equiv \frac{C_{an} m_n}{f_a} \sim 4 \times 10^{-10} \]
Gamma ray spectra from distant AGNs should show an energy and redshift dependent exponential attenuation, due to pair production at Extragalactic Background Light (EBL).
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

Horns, Meyer 12
Possible explanation: photon <-> ALP conversions in magnetic fields

- De Angelis et al. 2007
- Simet et al. 2008
- Sanchez-Conde et al. 2009
- Meyer, Horns, Raue 2013

Manuel Meyer 2012
Possible explanation: photon <-> ALP conversions in magnetic fields

\[ \text{De Angelis et al. 07; Simet et al. 08; Sanchez-Conde et al. 09; Meyer, Horns, Raue 13} \]

Required photon coupling overlaps with preferred region from HBs in GCs

\[ \text{Carosi et al. 15} \]

Axion Coupling $|g_{a\gamma}|$ (GeV$^{-1}$) vs. Axion Mass $m_a$ (eV)

- Excluded By HB Stars
- SN1987a no burst
- HESS
- HB Stars Favored
- Soft x-rays
- Transparency
- KSVZ
- DFSZ
Summary of Astrophysical Hints for Axion/ALPs

1. RG + WD: \( f_a = 3 \times 10^9 \text{ GeV} \)
   \[ C_{ae} \left( \frac{2 \times 10^{-13}}{g_{ae}} \right) \]

2. C A: \( f_a = 2 \times 10^9 \text{ GeV} \)
   \[ C_{an} \left( \frac{4 \times 10^{-10}}{g_{an}} \right) \]

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

Astrophysical hints can be explained by:
- ALP
- Axion
- ALP

In reach of upcoming generation of terrestrial experiments:
- \( f_a \sim 10^7 \text{ GeV} \), \( m_a \lesssim 0.1 \mu\text{eV} \), \( C_{a\gamma} \sim 1 \), \( C_{ae} \sim C_{an} \sim 10^{-2} \)
- \( f_A \sim 10^9 \text{ GeV} \), \( C_{An} \sim C_{A\gamma} \sim C_{Ae} \sim 1 \)

\[ \text{ALP} \]
\( f_a \sim 10^7 \text{ GeV} \), \( m_a \lesssim 0.1 \mu\text{eV} \), \( C_{a\gamma} \sim 1 \), \( C_{ae} \sim C_{an} \ll 10^{-2} \)
### WISP 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>Light-shining-through-a-wall</td>
<td>DESY</td>
<td>preparation</td>
</tr>
<tr>
<td>CROWS</td>
<td>CERN</td>
<td>running</td>
<td></td>
</tr>
<tr>
<td>OSQAR</td>
<td>CERN</td>
<td>running</td>
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<tr>
<td>REAPR</td>
<td>FNAL</td>
<td>proposed</td>
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</tr>
<tr>
<td>CAST</td>
<td>Helioscopes</td>
<td>CERN</td>
<td>running</td>
</tr>
<tr>
<td>IAXO</td>
<td></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>Haloscopes</td>
<td>Seattle</td>
<td>running</td>
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<tr>
<td>CASPE</td>
<td></td>
<td>Mainz</td>
<td>preparation</td>
</tr>
<tr>
<td>FUNK</td>
<td></td>
<td>KIT</td>
<td>running</td>
</tr>
<tr>
<td>WISPDMX</td>
<td></td>
<td>UHH</td>
<td>running</td>
</tr>
</tbody>
</table>
Light-shining-through-a-wall Searches

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

[Anselm 85; van Bibber et al. 87]
Light-shining-through-a-wall Searches

Currently best limits from LSW:
- ALPS (DESY)
- OSQAR (CERN)

![Graph showing limits on Axion coupling vs. Axion mass](image)
Light-shining-through-a-wall Searches

ALPS II

DESY (in collaboration with UHH, AEI, U Mainz)

Parameter | Scaling | ALPS I | ALPS IIa | 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 | | | | | 3082

ALPS IIa

2013 2014 2015 2016 2017 2018

Ilc risk assessments

ALPS IIc

installation data runs
Crucial test of ALP explanation of excessive HB star energy loss and AGN spectra at VHE

[Essig et al. 1311.0029]
Dig into unexplored HP parameter space also of interest for HP DM:

Essig et al. 1311.0029
Helioscope Searches

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

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

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

\[
m_a = 2\pi\nu \sim 4 \mu\text{eV} \left(\frac{\nu}{\text{GHz}}\right)
\]
Haloscope Searches: Resonant Cavities

Direct detection of axion/ALP dark matter

Axion or ALP DM – photon conversion in microwave cavity placed in magnetic field

Best sensitivity: mass = resonance frequency

Ongoing:
- ADMX (Seattle), exploiting high Q cavity in 8 T SC solenoid

\[ m_a = 2\pi \nu \sim 4 \ \mu\text{eV} \left( \frac{\nu}{\text{GHz}} \right) \]
Haloscope Searches: Resonant cavities

Pilot study: WISPDMX at UHH, exploiting high Q HERA p acceleration cavity and H1 solenoid (1.1 T); search starts at 208 MHz towards higher frequencies

[Horns,Lindner,Lobanov,AR 14]
Andreas Ringwald

The Hunt for Axions and Other WISPs, Bethe Colloquium, Bonn, 16 April 2015

Haloscope Searches: Resonant Cavities

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

[Horns, Lindner, Lobanov, AR 14]
Resonant cavities also sensitive to (kinetically mixed) HP dark matter: [Horns, Lindner, Lobanov, AR 14]
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

$$P_{\text{center}} \sim \langle |E_a|^2 \rangle A_{\text{dish}} \sim \chi^2 \rho_{\text{CDM}} A_{\text{dish}}$$

$$\sim 10^{-26} \left( \frac{B}{5\, \text{T}} \frac{c_{\gamma}}{2} \right)^2 \frac{A}{1\, \text{m}^2} \text{Watt}$$
Dish antennas can also search for hidden photon dark matter. Pilot dish experiment FUNK (Finding U(1)s of a Novel Kind) at KIT:

Horns, Jaeckel, Lindner, Lobanov, Redondo, AR 12

Döbrich, Daumiller, Engel, Kowalski, Lindner, Redondo, Roth 12

[Graph showing the exclusion limits for dark matter particles, with regions labeled for Sun, Xenon, Haloscopes, 300K FET, 15K HEMT, PMT, and Cold HP Dark Matter.]
Haloscopes: Resonant Cavities And Broadband Searches

ADMX and proposed broadband (dish antenna, stellarators) searches probe sizeable region in axion/ALP dark matter parameter space:

\[ \text{Horns, Lindner, Lobanov, AR `13} \]
Axion DM gives all nucleons oscillating electric dipole moments (EDMs)

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

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

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

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

B, G, L, R, S

SQUID pickup loop

\[ \vec{B}_{ext} \]

\[ \vec{E}^* \]
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

Sensitive in a mass/symmetry breaking scale region complementary to ADMX

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

<table>
<thead>
<tr>
<th>n</th>
<th>$E^*$</th>
<th>$p$</th>
<th>$T_2$</th>
<th>Max $B_{ext}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Phase 1</td>
<td>$10^{22}$ cm$^{-3}$</td>
<td>$3 \times 10^8$ V/cm</td>
<td>$10^{-3}$</td>
<td>1 ms</td>
</tr>
<tr>
<td>Phase 2</td>
<td>$10^{22}$ cm$^{-3}$</td>
<td>$3 \times 10^8$ V/cm</td>
<td>1</td>
<td>1 s</td>
</tr>
</tbody>
</table>

$$\mathcal{L} \equiv -\frac{i}{2} q_d a \bar{N} \sigma_{\mu\nu} \gamma_5 N F^{\mu\nu}$$
The axion/ALP nucleon coupling will lead to a spin precession about the axion/ALP DM wind. Resulting magnetisation

\[ M(t) \approx np\mu \left( g_{aNN} \sqrt{2\rho_{DM}v} \right) \frac{\sin \left( (2\mu B_{ext} - m_a) t \right)}{2\mu B_{ext} - m_a} \sin (2\mu B_{ext}t) \]
Haloscopes: MR Searches for the Axion/ALP Wind

CASPER (CASPE) in preparation in Mainz

Sensitivity does not reach axion prediction [Graham, Rajendran 13]

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

<table>
<thead>
<tr>
<th>Element</th>
<th>Density (n)</th>
<th>Magnetic Moment (μ)</th>
<th>T_2</th>
<th>Max. B</th>
<th>Magnetometer Sensitivity</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Xe</td>
<td>1.3 × 10^{22} 1 cm^{-3}</td>
<td>0.35 ( \mu_N )</td>
<td>100 s</td>
<td>10 T</td>
<td>10^{-16} \frac{T}{\sqrt{Hz}}</td>
</tr>
<tr>
<td>2. (^3\text{He})</td>
<td>2.8 × 10^{22} 1 cm^{-3}</td>
<td>2.12 ( \mu_N )</td>
<td>100 s</td>
<td>20 T</td>
<td>10^{-17} \frac{T}{\sqrt{Hz}}</td>
</tr>
</tbody>
</table>

\[ \mathcal{L} \supset g_{aNN} \left( \partial_{\mu} a \right) \bar{N} \gamma^\mu \gamma^5 N \]
Summary

- Strong physics case for 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; 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, FUNK, WISPDMX, ...)

Stay tuned!
Deconvolution of the EBL [arXiv:1502.04166]

- Approximate EBL with sums of Gaussians
- Use $O(100)$ spectra
- Tension with models 3-5 $\sigma$
- 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
4D --

ALP

KK 10D

# ALP
PQ 10D;

PQ

NGB

W 84; C 06; A 09;
A .10; C , G , AR 12

, PQ

, PQ

L , S 86; C .09; D .14

[Backup: Axion/ALPs from String Compactification]

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, in the heterotic string case; typically lower, the intermediate scale, 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]

$10^{16}$ GeV

$10^{10}$ GeV, IIB

$10^{10}$ GeV

$10^{16}$ GeV,

$10^{10}$ GeV