Light-shining-through-walls

Axions at the crossroads: QCD, dark matter, astrophysics

Trento, November 20-24, 2017
Outline

> Motivation for shining light through walls in the laboratory

> Basic considerations for optical LSW experiments

> Status of ALPS II at DESY

> Going beyond ALPS II

> Developments at DESY on experimental WISP physics
The dark sector could be complex with several constituents.

Dark matter does not need to consist of only one particle species.

To understand dark matter, any insight into the dark sector would be extremely helpful.

Are there bright spots for dark sector searches?
Axions could explain the CP conservation of QCD and the vanishing EDM of the neutron:

- WISPs may explain dark matter:
  - Axion, axion-like particles (ALPs), hidden photons, …
Stellar developments:

> Extra energy loss beyond SM expectations is indicated by stellar developments.

> Such losses can be explained consistently by the emission of axions coupling to photons and electrons.


Anomalous transparency of the universe to TeV photons:

- TeV photons might not be absorbed in the intergalactic space due to $\gamma+\gamma \rightarrow e^+e^-$ scattering as predicted by QED.
- This could be explained by axion-like particles.

TeV photons in the universe might convert in magnetic fields to ALPs via their two-photon coupling.

Such ALPs might convert back to photons in the vicinity of earth.
Anomalous transparency of the universe to TeV photons:

> TeV photons might not be absorbed in the intergalactic space due to $\gamma + \gamma \rightarrow e^+e^-$ scattering as predicted by QED.

> This could be explained by axion-like particles.
An experimentalist’s motivation for WISP searches (3)

Anomalous transparency of the universe to TeV photons:

- TeV photons might not be absorbed in the intergalactic space due to $\gamma+\gamma \rightarrow e^+e^-$ scattering as predicted by QED.

- This could be explained by axion-like particles.

A very similar axion-photon coupling as derived from stellar developments is required!


ALPs to explain an unexpected high transparency of the universe for TeV photons:

Axion / ALP hot spots

- LSW (ALPS-I)
- Helioscopes (CAST)
- YMCE
- Solar ν
- HB
- Telescopes
- ALPS-II
- RAAPR
- AXO
- AXion
- AXion CDM
- ALP CDM
- Dush Antenna
- ADMX-HF
- ADMX
- Intermediate string scale
- EBL
- X-ray

Axion-like particle mass

Two-photon-coupling
Axion / ALP hot spots

Three main regions of interest:

> **Axion-like particles:**
  TeV transparency, stellar developments

> **QCD axions:**
  CP, stellar developments, (dark matter)

> **QCD axions:**
  CP, dark matter
WISP searches exploiting photon couplings

> Purely laboratory experiments ("light-shining-through-walls")
  optical photons,

> Helioscopes
  (WISPs emitted by the sun),
  X-rays,

> Haloscopes
  (looking for dark matter constituents),
  microwaves.
WISP searches exploiting photon couplings

- Purely laboratory experiments ("light-shining-through-walls")
  optical photons,

- Helioscopes
  (WISPs emitted by the sun),
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- Haloscopes
  (looking for dark matter constituents),
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Axion / ALP hot spots

Three main regions of interest:

> **Axion-like particles:**
  TeV transparency, stellar developments

> **QCD axions:**
  CP, stellar developments, (dark matter)

> **QCD axions:**
  CP, dark matter
### Pros and cons for LSW in the laboratory

<table>
<thead>
<tr>
<th>ALP parameter</th>
<th>LSW (laboratory)</th>
<th>Helioscopes</th>
<th>Dark matter searches</th>
</tr>
</thead>
<tbody>
<tr>
<td>Parity and spin</td>
<td>yes</td>
<td>perhaps</td>
<td>yes</td>
</tr>
<tr>
<td>Coupling $g_{\text{a}y}$</td>
<td>yes</td>
<td>no</td>
<td>no</td>
</tr>
<tr>
<td>Coupling · flux (does not apply)</td>
<td>(does not apply)</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>Mass</td>
<td>perhaps</td>
<td>perhaps</td>
<td>yes</td>
</tr>
<tr>
<td>Rely on astrophysical assumptions</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
</tr>
<tr>
<td>QCD axion</td>
<td>no</td>
<td>yes</td>
<td>yes</td>
</tr>
</tbody>
</table>

LSW in the laboratory is very well suited to look for axion-like particles motivated by astrophysical anomalies and to open up the window to the hidden sector.
Outline

- Motivation for shining light through walls in the laboratory
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- Going beyond ALPS II
- Developments at DESY on experimental WISP physics
Basics of light-shining-through-walls

Physics motivation: axion-like particles

> Unknown territory beyond CAST.

> Explore $g_{a\gamma\gamma} \approx \text{few } 10^{-11}\text{GeV}^{-1}$ as motivated by
  
  ▪ anomalous transparency of the universe to TeV $\gamma$,
  
  ▪ stellar evolutions.

Crucial ingredients:

> Strong dipole magnets from particle accelerators.

> Mode matched optical resonators on both sides of the wall.

> Large magnet aperture to allow for long setups.

> Single photon detectors.
Optical resonators

A confocal cavity:

- longest resonator for a given aperture,
- largest beamspot in the center and hence lowest power density on central mirror, therefore highest circulating power in the resonator before the wall.
Confocal cavities

Using:
- $L$: length of the optical system, length of each resonator $L/2$.
- $\lambda$: wavelength of light

- Beam waist: $(\omega_0)^2 = (L \cdot \lambda) / 2\pi$

- Beam profile development:
  $\omega^2(z) = (\omega_0)^2 \cdot (1 + (z/z_R)^2)$,
  $z_R = \pi(\omega_0)^2 / \lambda$
  $\omega(L/2) = \sqrt{2} \cdot \omega_0$

- Clear aperture required for a cavity with a power built-up $\approx 100,000$:
  $r_5 = 2.5 \cdot \omega(z)$

https://en.wikipedia.org/wiki/Gaussian_beam
### LSW: magnet options

<table>
<thead>
<tr>
<th>Aperture [mm]</th>
<th>Safety margin [mm]</th>
<th>Eff. aperture [mm]</th>
<th>$\omega$ (L/2) [mm]</th>
<th>$\omega_0$ [mm]</th>
<th>$\lambda$ [nm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>40 (LHC)</td>
<td>10</td>
<td>30</td>
<td>6.0</td>
<td>4.2</td>
<td>1064</td>
</tr>
<tr>
<td>50 (HERA, straight)</td>
<td>10</td>
<td>40</td>
<td>8.0</td>
<td>5.7</td>
<td>1064</td>
</tr>
<tr>
<td>100 (FCC)</td>
<td>10</td>
<td>90</td>
<td>18.0</td>
<td>12.7</td>
<td>1064</td>
</tr>
</tbody>
</table>

> $\lambda = 1064$ nm is assumed following LIGO experiences: mirror coatings for this wavelength can stand high power densities for long times.
**LSW: magnet options**

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<tr>
<th>Aperture [mm]</th>
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<th>( \omega ) (L/2) [mm]</th>
<th>( \omega_0 ) [mm]</th>
<th>( \lambda ) [nm]</th>
<th>L [m]</th>
<th>Maximal power [kW]</th>
<th>Magnetic length, one string [m]</th>
<th>B·L [Tm]</th>
<th>Sensitivity ( g_{ay} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>40 (LHC)</td>
<td>10</td>
<td>30</td>
<td>6.0</td>
<td>4.2</td>
<td>1064</td>
<td>106</td>
<td>280</td>
<td>43</td>
<td>390</td>
<td>0.8</td>
</tr>
<tr>
<td>50 (HERA, straight)</td>
<td>10</td>
<td>40</td>
<td>8.0</td>
<td>5.7</td>
<td>1064</td>
<td>189</td>
<td>500</td>
<td>81</td>
<td>430</td>
<td>1</td>
</tr>
<tr>
<td>100 (FCC)</td>
<td>10</td>
<td>90</td>
<td>18.0</td>
<td>12.7</td>
<td>1064</td>
<td>957</td>
<td>2500</td>
<td>426</td>
<td>5540</td>
<td>19</td>
</tr>
</tbody>
</table>

> \( \lambda = 1064 \) nm is assumed following LIGO experiences: mirror coatings for this wavelength can stand high power densities for long times.

> For the maximal power assume a damage threshold of 500 kW/cm\(^2\).

> For the magnetic length

  ▪ subtract 10 m for the optical system outside the magnets and
  ▪ assume a “filling factor” for the magnetic field of 90%.
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DESY: Any-Light-Particle-Search I and II

ALPS I:
approved 2007, concluded 2010, most sensitive WISP search experiment in the lab (surpassed by OSQAR with two LHC dipoles in 2014).

ALPS II:
proposed 2011, TDR finished and evaluated in 2012. Decision by the directorate: continue with the preparatory phase towards ALPS II.

2017:
Construction phase has started.
ALPS II collaboration and schedule

Goal: start data taking in the HERA tunnel in 2020.

HERA hall North
(former H1 experiment at HERA)
ALPS II main components: magnets

- HERA proton accelerator dipoles.
- 5.3 T on 8.8 m.
- 4 K two-phase He cooling.
- Beamtube diameter 55 mm.
- Bent, horizontal aperture ≈35 mm.
- ALPS II will use 10+10 dipoles.

Challenge:

- The dipoles are to be straightened to increase the horizontal aperture to about 45 mm. Otherwise the optical cavities will not reach the specs.
ALPS II main components: magnets

> The straightening is done with “brute force”.

> A new suspension system for the cold mass has been developed.

> Five dipoles have been straightened by now, all with success. Quench currents well above the operation current of 5,700 A.

> “Mass production” has started.

<table>
<thead>
<tr>
<th>Magnet</th>
<th>HERA quench</th>
<th>ALPS (straight) quench</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>BR120</td>
<td>6292 A</td>
<td>5729 A</td>
<td>ALPS I magnet, not to be used for ALPS IIc</td>
</tr>
<tr>
<td>BRP115</td>
<td>5779 A</td>
<td>6199 A</td>
<td>Signal fault, not to be used for ALPS IIc</td>
</tr>
<tr>
<td>BRP212</td>
<td>6499 A</td>
<td>6499 A</td>
<td></td>
</tr>
<tr>
<td>BL020</td>
<td>6300 A</td>
<td>6283 A</td>
<td></td>
</tr>
<tr>
<td>BRP030</td>
<td>6367 A</td>
<td>6126 A</td>
<td></td>
</tr>
</tbody>
</table>
ALPS II main components: optics

- Mode-matched optical resonators before (“PC”) and behind (“RC”) the wall.
- Relative angle between PC and RC less than 0.5 μrad.
- Each about 100 m long, need to compensate seismic noise.
- Power built-up PC: 5,000: 150 kW circulating power.
- Power built-up RC: 40,000: length relative to light wavelength stabilized to 0.5 pm.
ALPS II main components: optics

- Production cavity, infrared
- Wall
- Regeneration cavity
ALPS II main components: optics

The optics is developed and tested in a 20 m long dedicated lab “ALPS IIa“. ALPS IIa shall allow to search for hidden photons (no magnets required).
## ALPS II main components: optics status summary

<table>
<thead>
<tr>
<th>Requirement</th>
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<th>Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>PC circulating power</td>
<td>150 kW</td>
<td>50 kW</td>
</tr>
<tr>
<td>RC power buildup factor</td>
<td>40,000</td>
<td>23,000</td>
</tr>
<tr>
<td>CBB mirror alignment</td>
<td>&lt; 5 μrad</td>
<td>&lt; 1 μrad</td>
</tr>
<tr>
<td>Spatial overlap</td>
<td>&gt; 95%</td>
<td>work ongoing</td>
</tr>
<tr>
<td>RC length stabilization</td>
<td>&lt; 0.5 pm</td>
<td>&lt; 0.3 pm</td>
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**Characterization of optical systems for the ALPS II experiment**

AARON D. SPECTOR,1,2 JAN H. PÖLD,2 ROBIN BÄHRE,3,4 AXEL LINDNER,4 AND BENNO WILKE 3,4

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2Deutsches Elektronen-Synchrotron (DESY), Notkestraße 85, D-22607 Hamburg, Germany
3Max Planck Institute for Gravitational Physics (Albert Einstein Institute), Golmstrasse 38 D-30167 Hannover, Germany
4Institute for Gravitational Physics of the Leibniz Universität Hannover, Callinstrasse 38, D-30167 Hannover, Germany

<table>
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Probably caused by micro-roughness of the mirror substrates.
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</table>

- **Status**
  - 50 kW
  - 23,000
  - < 1 µrad
  - work ongoing
  - < 0.3 pm

> Length lock with a piezo actuator, no seismic isolation!
Length lock of the regeneration cavity

Piezo ceramic actuator attached to a 2 inch mirror.

- First resonance a 4.9 kHz.
- Stabilizes length to 0.3 pm.

ALPS II requirements reached without seismic isolation!
An unforeseen challenge: effective point of reflection

The regeneration cavity is locked by frequency doubled light from the production cavity.

1064 nm (IR) light and 532 nm (green) are effectively reflected at a different coating depths.

This difference has to stay constant to 0.5 pm!
An unforeseen challenge: effective point of reflection

First measurement of the effective point of reflection difference between 1064 and 532 nm:

> Present mirror coatings might not meet specifications.

> A new coating stack has been developed and will likely solve this issue. New mirrors are being ordered.
ALPS II main components: detectors

DESY:

- Transition edge sensor (TES) operated at 80 mK.

\[
\Delta T \approx 100 \, \mu K
\]

\[
\Delta R \approx 1 \, \Omega
\]

\[
\Delta I \approx 70 \, nA
\]
ALPS II main components: detectors

DESY:

- Transition edge sensor (TES) operated at 80 mK.

25 x 25 $\mu$m$^2$
DESY:

- Transition edge sensor (TES) operated at 80 mK.
- Single 1064 nm photon detection demonstrated:
  - 5% energy resolution
  - $10^{-4}$ counts/s intrinsic background
- R&D will resume with a new cryostat in May 2018.

University of Florida:

- Heterodyne detection scheme.
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https://arxiv.org/abs/1710.04209
ALPS II data taking could start in 2020.

Two very different detector concepts will be available to confirm a detection.

At present we are optimistic to reach (or come close) to our specs.

Most likely the performance will be “budget limited”.

We should know in late 2018 how one could further improve if the available budget increases from $O(1 \text{ M}\mathbb{E})$ to $O(10 \text{ M}\mathbb{E})$.

ALPS II could show the path to “ultimate optics and detector concepts” for laser driven LSW experiments.

But new magnets are required for further jumps in sensitivity!
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Ingredients for an “ALPS III” experiment

An “ALPS III” sketch:

- Magnetic field strength: 13 T ("FCC")
- Magnetic length: 426 m
- Light wavelength: 1064 nm ("standard")
- Circulating light power: 2.5 MW
  Photons against the wall: $1.4 \cdot 10^{25} \text{ s}^{-1}$
- Power built-up behind the wall: $10^5$
- Detector sensitivity: $10^{-4} \text{ s}^{-1}$ ("demonstrated")
Ingredients for an “ALPS III” experiment

An “ALPS III” sketch:

<table>
<thead>
<tr>
<th>Ingredient</th>
<th>Value</th>
<th>Gain/ALPS II</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnetic field strength:</td>
<td>13 T</td>
<td>2.5</td>
</tr>
<tr>
<td>Magnetic length:</td>
<td>426 m</td>
<td>4.8</td>
</tr>
<tr>
<td>Light wavelength:</td>
<td>1064 nm</td>
<td></td>
</tr>
<tr>
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<td>2.5 MW</td>
<td>2.0</td>
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<td></td>
</tr>
<tr>
<td>Power built-up behind the wall:</td>
<td>$10^5$</td>
<td>1.3</td>
</tr>
<tr>
<td>Detector sensitivity:</td>
<td>$10^{-4}$ s$^{-1}$</td>
<td>1.0</td>
</tr>
</tbody>
</table>

**Improving the sensitivity for $g_{a\gamma}$ compared to ALPS II by $2.5 \cdot 4.8 \cdot 2.0 \cdot 1.3 \cdot 1.0 = 30$**
Light-shining-through walls

> ALPS II is on its way to get two optics and detector schemes working.

> ALPS II aims for data taking in 2020.

> The “ALPS know-how” combined with dipole magnets under development at CERN (“FCC”) could facilitate a future “ALPS III” experiment.
New Experiment for aXion-like parTicle search

NEXT / STAX

- Microwaves at \( \approx 30 \) GHz (118 \( \mu \)eV)
- Cavity in front of the wall with 100 kW \( \cdot 10^4 \) circulating power: \( 10^{31} \) photons/s!
- Regeneration cavity: \( 10^4 \)
- Single photon detector (TES), no background in two months.
- \( B \cdot L = 15T \cdot 0.5m = 7.5 \) Tm or even \( 11T \cdot 1.5m \) (LHC)
The “ultimate” LSW experiment could use microwaves instead of optical photons.

It would even surpass ALPS III.

Lot’s of R&D required.

Compare CROWS (2013):

- 1.8 GHz, 50 W
- Sens: $10^{-24}$W ($\approx$1 photon/s)
- $B \cdot L = 2.9T \cdot 0.12m$

P. Spagnolo, https://indico.cern.ch/event/644287/contributions/2758461/
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Formal founding of the collaboration at a meeting 03-04 July 2017 at DESY.

DESY has offered to host IAXO and babyIAXO.

babyIAXO could start data taking in 2021.
International Axion Observatory IAXO (see Javi’s talk)

- Formal founding of the collaboration at a meeting 03-04 July 2017 at DESY.
- DESY has offered to host IAXO and babyIAXO.
- babyIAXO could start data taking in 2021.
MAgnetized Disc and Mirror Axion eXperiment MADMAX

➢ Direct search for axion dark matter (and other WISPy dark matter).

➢ 8 Institutes from 3 countries.

➢ Formal collaboration founding 20 October 2017 at DESY.

➢ DESY has offered to host MADMAX next to ALPS II.
Direct search for axion dark matter (and other WISPy dark matter).

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Prime goal: axion dark matter between 40 and 200 μeV
MAGnetized Disc and Mirror Axion eXperiment MADMAX

- Direct search for axion dark matter (and other WISPy dark matter).
- 8 Institutes from 3 countries.
- Formal collaboration founding 20 October 2017 at DESY.
- DESY has offered to host MADMAX next to ALPS II.
- Prime goal: axion dark matter between 40 and 200 μeV
- Prototype ready in 2021?
MADMAX magnet studies are ongoing:

- Length: 2 m  
- \(B^2 \cdot A: 100 \, T^2 m^2\)

- \textit{racetrack}  
- \textit{cos theta}  
- \textit{canted cos theta}  
- \textit{block dipole}

- European innovation partnership: MPI Munich, Babcock Noell, CEA Saclay

- Results by the end of 2018.
Summary (the final one)

Light-shining-through walls

> ALPS II is progressing well towards data taking in 2020.
  > The optics development is going well, construction in the HERA tunnel has started.
  > The ALPS II magnet string will be exploited with two very different detection schemes.

> Going significantly beyond ALPS II requires new dipole magnets and/or R&D on microwave options.

DESY is getting more active in experimental WISP physics beyond ALPS II:

> Direct dark matter search with MADMAX.

> Searching for solar axions with IAXO.