Axion dark matter searches

Yannis K. Semertzidis, IBS/CAPP & KAIST

✓ This decade belongs to axion dark matter experiments!

The question to answer:

Are axions a significant part of the local dark matter?
The Strong CP-problem, Axion parameters, Dark Matter
Strong CP-problem and neutron EDM

The QCD Lagrangian contains a theta-term violating both P-parity and T-time reversal symmetries.

\[ L_{QCD, \bar{\theta}} = \bar{\theta} \frac{g^2}{32\pi^2} G^a_{\mu \nu} \tilde{G}^{a\mu\nu} \]
Strong CP-problem and neutron EDM

\[ L_{QCD,\bar{\theta}} = \bar{\theta} \frac{g^2}{32\pi^2} G^{a}_{\mu\nu} \tilde{G}^{a\mu\nu} \]

Dimensional analysis (naïve) estimation of the neutron EDM:

\[ d_n(\bar{\theta}) \sim \bar{\theta} \frac{e}{m_n} \frac{m_*}{\Lambda_{QCD}} \sim \bar{\theta} \cdot (6 \times 10^{-17}) \text{e} \cdot \text{cm}, \quad m_* = \frac{m_u m_d}{m_u + m_d} \]

Exp.: \( d_n < 3 \times 10^{-26} \text{e} \cdot \text{cm} \rightarrow \bar{\theta} < 10^{-10} \)

In simple terms: the theory of strong interactions demands a large neutron EDM. Experiments show it is at least \( \sim 9-10 \) orders of magnitude less! WHY?
Strong CP-problem

- Peccei-Quinn: $\theta_{\text{QCD}}$ is a dynamical variable (1977), $a(x)/f_a$. It goes to zero naturally.

$$L_{QCD,\bar{\theta}} = \left( \bar{\theta} - \frac{a(x)}{f_a} \right) \frac{g^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{a\mu\nu}$$

The Pool-Table Analogy with Axion Physics, Pierre Sikivie
Physics Today 49(12), 22 (1996); http://dx.doi.org/10.1063/1.881573
Strong CP-problem

- Peccei-Quinn: $\theta_{\text{QCD}}$ is a dynamical variable (1977), $a(x)/f_a$. It goes to zero naturally

- Wilczek and Weinberg: axion particle (1977)

- J.E. Kim: Hadronic axions (1979)

- Axions: pseudoscalars,
  light cousins of neutral pions

$$m_a \approx 6 \times 10^{-6} \text{ eV} \quad \frac{10^{12} \text{ GeV}}{f_a}$$
Axion parameters range

G. Raffelt, Space Science Reviews 100: 153-158, 2002
Axion coupling vs. axion mass

ALPs: Axion Like Particles

Axions here solve the Strong CP-problem
Axion Dark matter

- Dark matter: $0.3-0.5 \text{ GeV/cm}^3$

- Axions in the $1-300\mu\text{eV}$ range: $10^{12}-10^{14}/\text{cm}^3$, classical system.

- Lifetime $\sim 7 \times 10^{44} \text{s} (100\mu\text{eV} / m_a)^5$

- Cold Dark Matter ($v/c \sim 10^{-3}$), Kinetic energy $\sim 10^{-6} m_a$, very narrow line in spectrum.
Axion Dark matter

- Velocity range: $<10^{-3}c$ (bound in galaxies)
- Mass range: $>10^{-22}$eV (size of galaxies)
- Coherence length (De Broglie wavelength):

$$l_{DB} \approx 1\text{m} \times \left(\frac{1\text{meV}}{m_a}\right)$$
Axion Couplings

- **Gauge fields:**
  - Electromagnetic fields
    \[ L_{\text{int}} = -\frac{g_{a\gamma}}{4} a F^{\mu\nu} \tilde{F}_{\mu\nu} = g_{a\gamma} a E \cdot B \]
  - Gluon Fields (Oscillating EDM,...)

- **Fermions (coupling with axion field gradient, pseudomagnetic field)**
  \[ L_{\text{int}} = \frac{\partial}{\partial \mu} a \bar{\Psi} f \gamma^\mu \gamma_5 \Psi_f \]
Major Axion activities

Map showing locations of ADMX, HAYSTAC, DESY, CAST, IBS/CAPP, and UWA.

- ADMX: United States (Florida)
- HAYSTAC: Florida
- DESY: Europe
- CAST: Europe
- IBS/CAPP
- UWA: Australia
>>100 participants, 12th Patras Workshop on AXIONs, WIMPs, and WISPs, Jeju Island/Korea, 20-24 June, 2016.
>>100 participants, 13th Patras Workshop on AXIONs, WIMPs, and WISPs, Thessaloniki, Greece, 15-19 May, 2017.
>150 participants, 14th Patras Workshop on AXIONs, WIMPs, and WISPs, DESY/Hamburg, Germany, 18-22 June, 2018.
Major activities

- ADMX (UW, microwave cavity)
- HAYSTAC (Yale, microwave cavity)
- IBS/CAPP (CULTASK, multiple microwave cavities)
- ORGAN (UWA, high frequency)
- KLASH (KLOE magnet in Frascati, microwave cavity)
- MADMAX (DESY, dielectric interfaces)
- ALPs (DESY, coupled FP resonators)
- CAST-CAPP (CERN, rectangular cavities-TE modes)
- ABRACADABRA (MIT, toroidal)
- Dark Matter RADIO (Looking for collaborators w/ large magnet…)}
Major activities

- CASPEn electric (Boston Univ.)
- CASPEn axion-wind (MAINZ)
- Oscillating neutron-EDM (PSI)
- Axion-EDM (JEDI at Juelich)
Major activities

- GNOME (Axion domain walls, stars; International network)

- ARIADNE (Axion-mediated long-range forces; No dark matter needed)
Axion detection method

<table>
<thead>
<tr>
<th>Detection method</th>
<th>$g_{\gamma \gamma}$</th>
<th>$g_{\gamma e}$</th>
<th>$g_{\gamma N}$</th>
<th>$g_{A \gamma n}$</th>
<th>$g_{\gamma \gamma e}$</th>
<th>$g_{\gamma \gamma N}$</th>
<th>$g_{e \gamma N}$</th>
<th>$g_{N \bar{N}}$</th>
<th>Model dependency</th>
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<td>Polarization experiments</td>
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<td>no</td>
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<tr>
<td>Spin-dependent 5th force</td>
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<td></td>
<td>×</td>
<td>×</td>
<td>×</td>
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<td></td>
<td>×</td>
<td>×</td>
<td>×</td>
<td></td>
<td>Sun</td>
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<td>Primakoff-Bragg in crystals</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td>Sun*</td>
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<td>DM</td>
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<tr>
<td>Pick up coil &amp; LC circuit</td>
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<td></td>
<td></td>
<td>DM</td>
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<tr>
<td>Dish antenna &amp; dielectric</td>
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<td>DM</td>
</tr>
<tr>
<td>DM-induced EDM (NMR)</td>
<td></td>
<td>×</td>
<td>×</td>
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<td></td>
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<td>DM</td>
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<tr>
<td>Spin precession in cavity</td>
<td>×</td>
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<td>DM</td>
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<td>Atomic transitions</td>
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<td>DM</td>
</tr>
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</table>

Table 3: List of the axion detection methods discussed in the review, with indication of the axion couplings (or product of couplings) that they are sensitive to, as well as whether they rely on astrophysical (axions/ALPs are produced by the Sun) or cosmological (the dark matter is made of axions/ALPs) assumptions. *Also “DM” when searching for ALP DM signals, see section 6.2

Nice overview: Irastorza, Redondo 1801.08127v2
# Figure of merit in various experiments


Table 3. Figure-of-merit (FOM) for various fundamental-physics experiments. $L$, $A$ and $V$ are the characteristic length, transverse area and volume of the magnetic-field region. The last column lists the sections of this paper where the corresponding experiments are discussed.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>FOM</th>
<th>Examples</th>
<th>Section</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vacuum birefringence</td>
<td>$B^2 L$</td>
<td>BMV, PVLAS, OVAL</td>
<td>2.1</td>
</tr>
<tr>
<td>Light shining through wall</td>
<td>$B^4 L^4$</td>
<td>ALPS, OSQAR, ...</td>
<td>2.2.1</td>
</tr>
<tr>
<td>Helioscope</td>
<td>$B^2 L^2 A = B^2 VL$</td>
<td>CAST, IAXO</td>
<td>2.2.2</td>
</tr>
<tr>
<td>Haloscope (Primakoff)</td>
<td>$B^2 V$</td>
<td>ADMX, HAYSTAC, ORGAN, CULTASK ...</td>
<td>2.2.3</td>
</tr>
<tr>
<td>Haloscope (other)</td>
<td>None of the above</td>
<td>CASPEr, QUAX, ...</td>
<td>2.2.3</td>
</tr>
</tbody>
</table>
Measure nothing but frequency!
Axion (Higgslet) dark matter: Imprint on the vacuum since soon after the Big-Bang!

Animation by Kristian Themann
Axion dark matter is partially converted to a very weak flickering Electric (E) field in the presence of a strong magnetic field (B).

DC magnetic field: Mixing electric field with axion field

Animation by Kristian Themann

J. Hong, J.E. Kim, S. Nam, YkS hep-ph: 1403.1576
P. Sikivie’s method: Axions convert into microwave photons in the presence of a DC magnetic field (Primakov effect)

\[ L_{a\gamma\gamma} = g_\gamma \frac{\alpha}{\pi} \frac{a}{f_a} \vec{E} \cdot \vec{B} \]
Need to tune the cavity over a vast frequency range

Figure 14: Conceptual arrangement of an axion haloscope. If $m_a$ is within $1/Q$ of the resonant frequency of the cavity, the axion will show as a narrow peak in the power spectrum extracted from the cavity.
The conversion power on resonance

\[ P = \left( \frac{\alpha g_\gamma}{\pi f_a} \right)^2 V B_0^2 \rho_a C m_a^{-1} Q_L \]

\[ = 2 \cdot 10^{-22} \text{ Watt} \left( \frac{V}{500 \text{ liter}} \right) \left( \frac{B_0}{7 \text{ Tesla}} \right)^2 \left( \frac{C}{0.4} \right) \]

\[ \left( \frac{g_\gamma}{0.36} \right)^2 \left( \frac{\rho_a}{5 \cdot 10^{-25} \text{ gr/cm}^3} \right) \left( \frac{m_a c^2}{h \text{ GHz}} \right) \left( \frac{Q_L}{10^5} \right) \]

The axion to photon conversion power is very small.
If you don’t know the axion mass need to tune

Scanning rate:

\[
\frac{df}{dt} = \frac{f}{Q} \frac{1}{t} \approx \frac{1 \text{ GHz}}{\text{year}} \left( g_{a\gamma\gamma} 10^{15} \text{GeV} \right)^4 \left( \frac{5 \text{ GHz}}{f} \right)^2 \left( \frac{4}{\text{SNR}} \right)^2 \left( \frac{0.25 \text{ K}}{T} \right)^2
\]

\[
\left( \frac{B}{25T} \right)^4 \left( \frac{c}{0.6} \right)^2 \left( \frac{V}{5l} \right)^2 \left( \frac{Q}{10^5} \right)
\]

\[T = T_N + T_{\text{ph}}\]
SQUID Amplifier Noise (ADMX)

Have we known the axion mass we could tell whether it’s the dark-matter by integrating ~1 day!

10^{-26} \text{W}
Axion dark matter search

- The axion mass is unknown, like any number in a phone book.
  The way we look for it:

- Once it’s discovered, anyone will be able to dial in… and talk to it.
The first-generation axion-dark-matter experiment
Rochester Brookhaven Fermilab, at BNL – 1980’s


First PhD Thesis
Joe Rogers (1957-2004)
RBF axion dark matter search

- The RBF-dark matter axion group, circa 1990
- Support from BNL
- Questions often asked: existence of DM and axions!
Axion dark detection mechanism

- Sikivie invented a method to detect the “invisible” axions utilizing the inverse Primakoff effect

\[ R_a \rightarrow \gamma = \left( \frac{\varepsilon_0 c^2}{\hbar^2} \right) g_{a\gamma\gamma} \omega^{-1} Q B_0^2 G_f^2. \]
ADMX, longest in the game

ADMX: Recent results at the DFSZ frontier

University of Washington

G. Carosi, N. Wollett,
Livermore

A.S. Chou, A. Sonnenschein, and W. Wester
FNAL

C. Boutan and N. Oblath
PNNL

John Clarke, S. O’Kelley, Karl van Bibber
UC Berkeley

Leanne Duffy
Los Alamos

Richard Bradley
NRAO

Ed Daw
Sheffield

Nicole Crisosto, Jeff Hoskins, J. Gleason,
R. Jois, I. Stern, Jihee Yang,
University of Florida

ADMX is the Axion Dark Matter eXperiment
Axion Dark Matter eXperiment

The ADMX-dark matter axion group, 2012
ADMX results

ADMX “G2” Dark Matter Search: Find Dark Matter Axions

Collaborating Institutions:
UW, UFL, LLNL
FNAL, UCB, PNNL
LANL, NRAO, WU, Sheffield

The ADMX collaboration gratefully acknowledges support from the US Dept. of Energy, High Energy Physics DE-SC0011665 & DE-SC0010280 & DE-AC52-07NA27344

Also support from LLNL and PNNL LDRD programs and R&D support the Heising-Simons institute

ADMX collaboration meeting, April 2018
The full ADMX receiver

\[ P_{\text{sig}} \propto (B^2 V Q_{\text{cav}})(g^2 m_a \Omega_a) \sim 10^{-23} \text{ W} \]

\[ s/n = \frac{P_{\text{sig}}}{k T_{\text{sys}}} \sqrt{\frac{t}{\Delta \nu}} \]
Axion Dark Matter eXperiment

- Cryogenics (0.1K)
- Superconducting magnet (>7.5 T)
- Large volume cavity (140l)
- Low noise amplifiers
  - From 12K to 1K
  - Currently SQUID and JPA (<1K)
ADMX results

ADMX Exclusion Limits 2017

We didn’t find an axion over this narrow range. More importantly, we could have. This is the first exploration into the plausible DFSZ coupling in the prime mass range for Dark Matter. A discovery could come at any time.
IBS/CAPP at Munji Campus, KAIST, January 2017.
CAPP Experimental Hall (LVP)
# CULTASK Refrigerators and Magnets

## Refrigerators

<table>
<thead>
<tr>
<th>Vendor</th>
<th>Model</th>
<th>$T_B$ (mK)</th>
<th>Cooling power</th>
<th>Installation</th>
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<tr>
<td>BlueFors (BF3)</td>
<td>LD400</td>
<td>10</td>
<td>$18 \mu W@20\text{mK}$ $580\mu W@100\text{mK}$</td>
<td>2016</td>
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<td>BlueFors (BF4)</td>
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<td>10</td>
<td>$18\mu W@20$ $580\mu W@100$</td>
<td>2016</td>
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<tr>
<td>Janis</td>
<td>HE3</td>
<td>300</td>
<td>$25\mu W@300\text{mK}$</td>
<td>2017</td>
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<td>BlueFors (BF5)</td>
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<td>10</td>
<td>$18\mu W@20\text{mK}$ $580\mu W@100\text{K}$</td>
<td>2017</td>
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<tr>
<td>BlueFors (BF6)</td>
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<td>10</td>
<td>$18\mu W@20\text{mK}$ $580\mu W@100\text{K}$</td>
<td>2017</td>
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<tr>
<td>Leiden</td>
<td>DRS1000</td>
<td>100</td>
<td>$1\text{mW }@100\text{mK}$</td>
<td>2018</td>
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<td>Oxford</td>
<td>Kelvin</td>
<td>&lt;30</td>
<td>$400 @120\text{mK}$</td>
<td>2017</td>
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## Magnets

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<td>3.5</td>
<td>HTS</td>
<td>SUNAM</td>
<td>2016</td>
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<tr>
<td>18T</td>
<td>7</td>
<td>HTS</td>
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<td>2017</td>
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<td>9T</td>
<td>12</td>
<td>NbTi</td>
<td>Cryo-Magnetics</td>
<td>2017</td>
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<tr>
<td>8T</td>
<td>12</td>
<td>NbTi</td>
<td>AMI</td>
<td>2016</td>
</tr>
<tr>
<td>8T</td>
<td>16.5</td>
<td>NbTi</td>
<td>AMI</td>
<td>2017</td>
</tr>
<tr>
<td>25T</td>
<td>10</td>
<td>HTS</td>
<td>BNL/CAPP</td>
<td>2020</td>
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<tr>
<td>12T</td>
<td>32</td>
<td>Nb$_3$Sn</td>
<td>Oxford</td>
<td>2020</td>
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</tbody>
</table>

Woohyun Chung’s slide
CAPP’s base plan

- Microwave cavities 0.7-20 GHz, using 25T/10cm and 12T/32cm magnets
- Combine the two magnets to obtain 37T
- Phase-lock two or more axion dark matter exps.
- Open resonators R&D for higher frequency
- GNOME
- Wide band axion-mass network...
CAPP’s base plan

- Delivery of 25T/10cm and 12T/32cm magnets in 2020 (funding limited).

- In the meantime, we are getting ready for it:
  - Quantum noise limited SQUID-amplifiers
  - Cryo-expertise, reach lowest physical temperature (down to <50mK)
  - Demonstrate efficient high-frequency, high-volume operation
  - Efficient DAQ
  - Prepare systems for large magnets
Potential shown based on single cavities
Possible to extend to >10GHz
Fig. 13. Current and projected limits on the axion-photon coupling constants from Primakoff-haloscope experiments under the assumption that dark matter is dominated by a single-species of axions or ALPs. This overview plot was created with ALPlot (https://alplot.physik.uni-mainz.de).
Haloscope axion searches

\[ \text{FOM} = B^4 V^2 Q/T^2 \]

<table>
<thead>
<tr>
<th>Experiment</th>
<th>References</th>
<th>Status</th>
<th>$B$ (T)</th>
<th>$V$ (m$^3$)</th>
<th>$B^2V$ (T$^2$m$^3$)</th>
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<th>Axion/ALP mass range ($\mu$eV)</th>
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<td>Grenoble</td>
<td>[98]</td>
<td>proposal</td>
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<td>0.49/0.05/0.0029/</td>
<td>13-0.01</td>
<td>yes/no</td>
<td>1.3-200</td>
</tr>
</tbody>
</table>

Table 7. Present and future haloscopes based on the Primakoff production of microwave photons by dark-matter axions/ALPs. In this case, $V$ refers to the volume within microwave cavities placed into magnetic field. After CAPP runs the 12 T and the 25 T magnets, they plan to combine them and reach 37 T within the volume of the 25 T magnet, with a significant boost in the sensitivity of the axion/ALP search.
Haloscopes using spins!
Resonance: \[ 2\mu B_{\text{ext}} = \omega \]
Larmor frequency = axion mass $\Rightarrow$ resonant enhancement

SQUID measures resulting transverse magnetization

Example materials: liquid $^{129}$Xe, ferroelectric PbTiO$_3$
The experimental reach of CASPer

**phase II:**
- optically enhanced spin polarization
- 5 cm sample size,
- 14T magnet, homogeneity 100 ppm
- tuned SQUID circuit?

**phase III:**
- hyperpolarization by optical pumping
- 10 cm sample size,
- 14T magnet, homogeneity 10 ppm
- tuned SQUID circuit?

---

**CASPer-now at BU:**
- thermal spin polarization,
- 0.5 cm sample size,
- 9T magnet, homogeneity 1000 ppm
- broadband SQUID detection

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[Phys. Rev. X 4, 021030 (2014)]

Slide by Alex Suskov (adapted)
Solar Axions


Fig. 9. The axion-helioscope concept. Axions are produced in the sun and travel towards the earth. In the presence of a transverse magnetic field in the haloscope (corresponding to the blue photon in the figure), the axions are converted into x-ray photons and detected. The energy spectrum of the x-ray photons corresponds to that of the axions produced in the sun.

<table>
<thead>
<tr>
<th>Experiment</th>
<th>References</th>
<th>Status</th>
<th>$B$ (T)</th>
<th>$L$ (m)</th>
<th>$A$ (cm$^2$)</th>
<th>Focusing</th>
<th>$g_{a\gamma\gamma}$ ($10^{-10}$ GeV$^{-1}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brookhaven</td>
<td>[80]</td>
<td>past</td>
<td>2.2</td>
<td>1.8</td>
<td>130</td>
<td>no</td>
<td>36</td>
</tr>
<tr>
<td>SUMICO</td>
<td>[81, 82]</td>
<td>past</td>
<td>4</td>
<td>2.5</td>
<td>18</td>
<td>no</td>
<td>6</td>
</tr>
<tr>
<td>CAST</td>
<td>[83, 84, 85, 86, 87]</td>
<td>ongoing</td>
<td>9</td>
<td>9.3</td>
<td>30</td>
<td>yes</td>
<td>0.66</td>
</tr>
<tr>
<td>TASTE</td>
<td>[79]</td>
<td>in design</td>
<td>3.5</td>
<td>12</td>
<td>$2.8 \times 10^3$</td>
<td>yes</td>
<td>0.2</td>
</tr>
<tr>
<td>BabyIAXO</td>
<td>[88]</td>
<td>in design</td>
<td>$\sim 2.5$</td>
<td>10</td>
<td>$2.8 \times 10^3$</td>
<td>yes</td>
<td>0.2</td>
</tr>
<tr>
<td>IAXO</td>
<td>[89, 74]</td>
<td>in design</td>
<td>$\sim 2.5$</td>
<td>22</td>
<td>$2.3 \times 10^4$</td>
<td>yes</td>
<td>0.04</td>
</tr>
</tbody>
</table>
Figure 9: Solar axion flux spectra at Earth by different production mechanisms. On the left, the most generic situation in which only the Primakoff conversion of plasma photons into axions is assumed. On the right the spectrum originating from processes involving electrons, bremsstrahlung, Compton and axio-recombination \[323,395\]. The illustrative values of the coupling constants chosen are \(g_{a\gamma} = 10^{-12} \text{ GeV}^{-1}\) and \(g_{ae} = 10^{-13}\). Plots from \[480\].
Solar Axions

FOM = $B^2l^2A = B^2Vl^{1.08127v^2}$
Fig. 9. The axion-helioscope concept. Axions are produced in the sun and travel towards the earth. In the presence of a transverse magnetic field in the haloscope (corresponding to the blue photon in the figure), the axions are converted into x-ray photons and detected. The energy spectrum of the x-ray photons corresponds to that of the axions produced in the sun.

CAST: LHC prototype magnet
Fig. 9. The axion-helioscope concept. Axions are field in the helioscope (corresponding to the blue spectrum of the x-ray photons) corresponds to

Fig. 10. General view of the IAXO design whose key part is a 22 m long eight-coil toroidal magnet enclosed in a 25 m long cryostat. Figure from [74].
CAST and planned axion Helioscopes
For sufficiently small axion mass
Light shining through walls

<table>
<thead>
<tr>
<th>Experiment</th>
<th>status</th>
<th>$B$ (T)</th>
<th>$L$ (m)</th>
<th>Input power (W)</th>
<th>$\beta_P$</th>
<th>$\beta_R$</th>
<th>$g\alpha\gamma$ [GeV$^{-1}$]</th>
</tr>
</thead>
<tbody>
<tr>
<td>ALPS-I [433]</td>
<td>completed</td>
<td>5</td>
<td>4.3</td>
<td>4</td>
<td>300</td>
<td>1</td>
<td>$5 \times 10^{-8}$</td>
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<tr>
<td>CROWS [435]</td>
<td>completed</td>
<td>3</td>
<td>0.15</td>
<td>50</td>
<td>$10^4$</td>
<td>$10^4$</td>
<td>$9.9 \times 10^{-8}$ (*)</td>
</tr>
<tr>
<td>OSQAR [434]</td>
<td>ongoing</td>
<td>9</td>
<td>14.3</td>
<td>18.5</td>
<td>-</td>
<td>-</td>
<td>$3.5 \times 10^{-8}$</td>
</tr>
<tr>
<td>ALPS-II [436]</td>
<td>in preparation</td>
<td>5</td>
<td>100</td>
<td>30</td>
<td>5000</td>
<td>40000</td>
<td>$2 \times 10^{-11}$</td>
</tr>
<tr>
<td>ALPS-III [437]</td>
<td>concept</td>
<td>13</td>
<td>426</td>
<td>200</td>
<td>12500</td>
<td>$10^5$</td>
<td>$10^{-12}$</td>
</tr>
<tr>
<td>STAX1 [438]</td>
<td>concept</td>
<td>15</td>
<td>0.5</td>
<td>$10^5$</td>
<td>$10^4$</td>
<td>-</td>
<td>$5 \times 10^{-11}$</td>
</tr>
<tr>
<td>STAX2 [438]</td>
<td>concept</td>
<td>15</td>
<td>0.5</td>
<td>$10^6$</td>
<td>$10^4$</td>
<td>$10^4$</td>
<td>$3 \times 10^{-12}$</td>
</tr>
</tbody>
</table>

Table 4: List of the most competitive recent LSW results, as well as the prospects for ALPS-II, together with future possible projects, with some key experimental parameters. The last column represents the sensitivity achieved (or expected) in terms of an upper limit on $g\alpha\gamma$ for low $m_\alpha$. For microwave LSW (CROWS and STAX) the quality factors $Q$ are listed. * The limit is better for specific $m_\alpha$ values, see Figure 6.
ALPS II at DESY, Start data taking 2020

ALPS II Optical System
A unique set of challenges

Two 100m optical resonators
- 30 W amplified NPRO input laser
- PC: 150 kW circulating power
- RC: 120,000 finesse

Challenges
- Maintenance of dual resonance
- Maintenance of spatial overlap
- Light tightness 1 photon / 2 weeks
Axion dark matter: open resonators, MADMAX

Dielectrics for high frequency-short wavelength

Dielectrics to suppress negative E-field

Reverse direction of B-field

Figure 19: The geometric factor of an ideal 1D cavity in a homogeneous $B$-field (green arrows) cancels between crests and valleys of a high mode (left). The cancellation can be avoided by placing high-$n$ dielectrics –grey regions– in the valleys (centre) or by alternating the polarity of the external $B_e$ field to track the mode variations (right). This case can be done by introducing wire planes with suitable currents [563].
MADMAX (dark matter)
- Site in HERA hall north being prepared
- Magnet studies by Bilfinger-Noell and CEA Saclay, aim for magnet decision in late 2018

MADMAX collaboration
- Founded at DESY in 2017
Experimental approaches: Effect of Dielectric

Mixing of axion with photon in extrenal B-field
→ Sources oscillating E-field
At surfaces with transition of $\epsilon$: Discontinuity of E-field
→ Emission of photons

\[ \left( \frac{P}{A} \right)_{\text{mirror}} \sim 2 \cdot 10^{-27} \frac{W}{m^2} \left( \frac{B_{||}}{10 T} \right)^2 \left( g_{\gamma \gamma} m_a \right)^2 \]

D. Horns, J. Jaeckel, A. Lindner, A. Lobanov, J. Redondo and A. Ringwald

B. Majorovits
Axion dark matter: MADMAX

Figure 21: Left: sketch of the dielectric haloscope experiment. Photons in the $B_e$ field are emitted from the dielectric surfaces and reflected in the leftmost mirror and other surfaces to be measured coherently by a receiver, from [585]. Right: Adjusting the distances between the layers, the frequency dependence of the boosted sensitivity can be adjusted to different bandwidths, from [590].

Figure 22: The concept of the MADMAX experiment, see text for details. From [590].
MAgnetized Disc and Mirror Axion eXperiment

Mirror

~2m

10 T dipole magnet

Horn antenna (+ receiver)

80 adjustable dielectric discs
Ø: ~1m

Parabolic Mirror

Separate cryogenic volume
Actively planned axion exps.
Optical range with photonic crystals

J. Huang, Perimeter Institute
1803.11455

Axion DM

\[ 8g^2 B^2 \frac{\rho_{DM}}{m_0^2} AN^2 \left( \frac{n_1^2-n_2^2}{n_1^4-n_2^4} \right) \]

1 week run time

- Axion-photon coupling \( g_{a\gamma\gamma} a E \cdot B \) requires background magnetic field

- Existing constraints stronger; need larger target / better detectors

Sub-component of DM
Summary

- Axion-dark-matter efforts are becoming very exciting
- A discovery can be announced at any moment (depending on the frequency number!)
- Within the next five to ten years we may very well know whether axions are 100% of the dark matter...
Extra Slides
De Broglie wavelength > 1 km, whole ring within axion-field coherence
The right machine for the resonance method!

- 184 m circumference
- Protons and Deuterons
- Polarized or un-polarized
- $p$: 295 MeV/c - 3,65 GeV/c
- Stochastic and electron cooling
- 2 e⁻ cooler: 100 keV and 2 MeV
- Typ. amount of stored particles: $10^{10}$
- Internal experiments and 3 external beam lines
- H⁻ stripping injection
A new road to axion dark matter detection?

Béla Majorovits (MPI für Physik) for the MADMAX collaboration

- Axions and ALPs as DM candidates
- The axion detection method
- Dielectric haloscope
- MADMAX status and plans
Collaboration forming at DESY, Hamburg

8 Institutes from France, Germany, Spain
Site: DESY Hamburg, hall north
Strawman: Single cavity

- Single cylinder, 8 T field; change size to resonate at search frequency
  \[ P = 130 \, \text{yW} \left( \frac{1 \, \text{GHz}}{f} \right)^{2.67} \]

- Volume decreases as \( f^{-3} \), the \( Q \) decreases as \( f^{-2/3} \) while the mass increases as \( f \)

- Length as well as diameter changes because the cavity cannot get too long
  - The longer the cavity, the more TE/TEM modes there are
  - Typically: \( L \sim 4.4r \)
Strawman 2: Single cavity

- Power and scan rate decrease as frequency goes up
- Just the opposite of what we want.
THE KLASH PROPOSAL

- KLASH - KLoe magnet for Axions Search
- Proposal of a large Haloscope
- Search of galactic axions in the mass range 0.3-1 μeV
- Large volume RF Cavity (35 m³)
- Moderate magnetic field (0.6 T)
- Copper rf cavity Q ~ 600,000
- T 4.2 K

\[ P_{\text{sig}} = \left( \frac{g^2 \alpha^2 \hbar^3 c^3 \rho_a}{\pi^2 A^4} \right) \times \left( \frac{\beta}{1 + \beta \omega_c} \frac{1}{\mu_0} B_0^2 V C_{mnl} Q_L \right) \]

\[ \text{SNR} = \frac{P_{\text{sig}}}{k_B T_{\text{sys}}} \sqrt{\frac{\tau}{\Delta
\nu_a}} \]

<table>
<thead>
<tr>
<th>Experiment</th>
<th>( \omega B^2 V Q ) (rad T²m³/s) ( \times 10^{15} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>The KLASH</td>
<td>1</td>
</tr>
<tr>
<td>ADMX</td>
<td>4</td>
</tr>
<tr>
<td>HAYSTAC</td>
<td>0.5</td>
</tr>
</tbody>
</table>
**BRASS:** Broadband Radiometric Axion/ALP Searches

\[ \nu = 10 \text{ GHz} \quad 100 \text{ GHz} \quad 1 \text{ THz} \]

**BRASS:**
- Full range
- Phase 1
- Phase 2
- Phase 2

No axion DM

**SMASH**

**Accion:**
- KSVZ

**DefSZ**

Astrophysical hints:

\[ 20 \mu \text{eV} \quad 100 \mu \text{eV} \quad 1000 \mu \text{eV} \quad 8000 \mu \text{eV} \]

D. Horns\textsuperscript{1}, P. Freire\textsuperscript{2}, E. Garutti\textsuperscript{1}, A. Jacob\textsuperscript{3}, M. Kramer\textsuperscript{1}, A.P. Lobanov\textsuperscript{1,2}, K. Menten\textsuperscript{2}, J. Liske\textsuperscript{4}, L.H. Nguyen\textsuperscript{1}, A. Ringwald\textsuperscript{4}, G. Sigl\textsuperscript{4}, J.A. Zensus\textsuperscript{2}

1 – University of Hamburg. 2 – Max-Planck Institute for Radioastronomy, Bonn. 3 – Hamburg University of Technology. 4 – Deutsches Elektronen Synchrotron (DESY).
# Superconducting materials

<table>
<thead>
<tr>
<th>Material Name</th>
<th>Class</th>
<th>Critical Temperature (K)</th>
<th>Critical Field $B_{c2}$</th>
<th>Critical Field@2.2 K</th>
<th>Geometry</th>
</tr>
</thead>
<tbody>
<tr>
<td>NbTi</td>
<td>LTS</td>
<td>9.8</td>
<td>9.5 T @ 4.2 K</td>
<td>11.5 T</td>
<td>Multi-filamentary</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>round &amp; rectangular wire</td>
</tr>
<tr>
<td>Nb$_3$Sn</td>
<td>LTS</td>
<td>18.1</td>
<td>20 T @ 4.2 K</td>
<td>23 T</td>
<td>Multi-filamentary round wire</td>
</tr>
<tr>
<td>MgB$_2$</td>
<td>MTS</td>
<td>39</td>
<td>5–10 T @ 4.2 K</td>
<td>N/A</td>
<td>Multi-filamentary round wire</td>
</tr>
<tr>
<td>Bi–2212</td>
<td>HTS</td>
<td>90–110</td>
<td>40 T @ 4.2 K</td>
<td>N/A</td>
<td>Multi-filamentary round wire</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>10 T @ 12 K</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Bi–2213</td>
<td>HTS</td>
<td>90–110</td>
<td>40 T @ 4.2 K</td>
<td>N/A</td>
<td>Tape</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>8 T @ 20 K</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>4 T @ 65 K</td>
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<tr>
<td>YBCO</td>
<td>HTS</td>
<td>92–135</td>
<td>45 T @ 4.2 K</td>
<td>N/A</td>
<td>Tape</td>
</tr>
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<td></td>
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<td></td>
<td>12 T @ 20 K</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>8 T @ 65 K</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 8. Superconducting materials. LTS, MTS, and HTS stand for low-, medium-, and high-temperature superconductors. N/A means that these materials are typically not used below 4.2 K. They can operate at lower temperatures but without particular advantage.
Superconducting materials

Fig. 22. Solenoid magnets for NMR as a representative example of the progress in magnet technology. NHMFL: National High Magnetic Field Laboratory, Tallahassee, Florida.
Superconducting materials

Fig. 14. Projected sensitivity of various stages of the Dark Matter radio (DM radio) experiment to axion-photon coupling. The inset at the lower right shows an emblem of the experiment accurately capturing some of the essential features. Figure courtesy DM radio collaboration.
18 T no insulation magnet

18 T magnet

Bore size 70 mm

476 mm

341.6 mm

25 T magnet

Bore size 100 mm

$B^2V = 0.6 T^2 m^3$

$B^2V = 1.7 T^2 m^3$

1st coil for 25 T magnet 1/28

44 double pancake coils
Axion mass target and technique

Microwave cavities

Open resonators

Monopole-Dipole Interactions, No dark matter assumed (ARIADNE)
Figure 24: Left: limits on $g_{a\gamma n}$ and prospects for CASPEr-Electric. Right: Limits on $g_{aN}$ and prospects of CASPEr “wind” experiments. From [600].
WHAT ARE AXIONS?

- New scalar field with global $U(1)$ symmetry!

\[ \mathcal{L}_{\text{CPV}} = \frac{\theta g^2}{32\pi^2} G \tilde{G} - \frac{a}{f_a} g^2 G \tilde{G} \]

- Couples to SM gauge fields (via fermions)
- Dynamically erases QCD CP-violation

- Mass through pion mixing