IAXO at Snowmass: Prospects for the International Axion Observatory

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Michael Pivovaroff
On behalf of the IAXO collaboration

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Overview

- **Solar Axion Searches**
- **The International Axion Observatory (IAXO)**
  - Magnet
  - X-ray optics
  - Low-background detectors
  - Prototype testing
- **IAXO Science Reach**
  - Sensitivity prospects
  - Collaboration and schedule
- **Conclusions**

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Towards a new generation axion helioscope

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Irastorza et al. JCAP 06 (2011) 013
Axion phase space

\[ g_{a\gamma} [\text{GeV}^{-1}] \]

- **Laser experiments (ALPS)**
- **Helioscopes (CAST)**
- **Microwave cavities (ADMX+RBF+UF)**

\[ m_a [\text{eV}] \]
Axion phase space

- Laser experiments (ALPS)
- Helioscopes (CAST)
- Microwave cavities (ADMX+RBF+UF)
- HB stars
- KSVZ
- HDM limit

$g_{a\gamma}$ [GeV$^{-1}$]

$m_a$ [eV]
Axion phase space
Axion phase space

$g_{a\gamma}$ [GeV$^{-1}$]

$10^{-6}$

$10^{-8}$

$10^{-10}$

$10^{-12}$

$10^{-14}$

$10^{-16}$

$10^{-8}$

$10^{-7}$

$10^{-6}$

$10^{-5}$

$10^{-4}$

$10^{-3}$

$10^{-2}$

$10^{-1}$

$10^{0}$

$10^{1}$

$m_a$ [eV]

laser experiments (ALPS)

helioscopes (CAST)

HB stars

microwave cavities (ADMX+RBF+UF)

KSVZ

HDM limit

classical CDM [vac. mis. + defects]

1987a limit
Axion phase space

- Laser experiments (ALPS)
- Helioscopes (CAST)
- Microwave cavities (ADMX + RBF + UF)
- Mixed-axion CDM
- Classical CDM [vac. mis. + defects]
- KSVZ
- 1987a limit
- HDM limit

$g_{\alpha\gamma}$ [GeV$^{-1}$]

$m_a$ [eV]
Axion phase space

\( g_{\alpha\gamma} \) [GeV\(^{-1}\)]

\( m_a \) [eV]

- Laser experiments (ALPS)
- Helioscopes (CAST)
- Microwave cavities (ADMX+RBF+UF)
- HB stars
- Mixed-axion CDM
- Classical CDM [vac. mis. + defects]
- Anthropic CDM

1987a limit

HDM limit
Axion phase space

- Laser experiments (ALPS)
- Helioscopes (CAST)
- Microwave cavities (ADMX+RBF+UF)
- HB stars
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- KSVZ
- HDM limit
- 1987a limit

$g_{a\gamma}$ [GeV$^{-1}$]

$m_a$ [eV]
Axion phase space

- Laser experiments (ALPS)
- Helioscopes (CAST)
- Microwave cavities (ADMX+RBF+UF)
- ANP CDM
- ALP CDM
- HB stars
- Mixed-axion CDM
- Classical CDM
- KSVZ

- HDM limit
- 1987a limit

- Hint, astrophysics ALPs
- Anthropic CDM
- Classical CDM [vac. mis. + defects]
- Hint, WD cooling

$g_{\alpha} \gamma \left[ \text{GeV}^{-1} \right]$ vs $m_a \left[ \text{eV} \right]$
IAXO – 4th generation helioscope

- 1st generation: Brookhaven Experiment
- 2nd generation: Tokyo Helioscope
- 3rd generation: CAST

IAXO = 4th generation axion helioscope

- CAST is established as a reference result in experimental axion physics
- IAXO builds on CAST innovations to improve the helioscope technique...
  - Based on the more than a decade CAST experience
  - Technologies have high maturity [TRL ≥ 6] – no fundamental challenges nor high-risk R&D required
- No other technique can realistically improve grasp over a wide mass range for γ–a coupling
IAXO – How to improve sensitivity

\[ g_a^4 \propto b^{1/2} \varepsilon^{-1} \times s^{1/2} \varepsilon_0^{-1} \times (BL)^{-2} A^{-1} \times t^{-1/2} \]

- **detectors**
  - \( b = \) background
  - \( \varepsilon = \) efficiency

- **optics**
  - \( s = \) spot size
  - \( \varepsilon_0 = \) efficiency

- **magnet**
  - \( B = \) magnetic field
  - \( L = \) magnet length
  - \( A = \) cross-sectional area

- **exposure**
  - \( t = \) time

\( s = \) spot size
\( \varepsilon_0 = \) efficiency
\( B = \) magnetic field
\( L = \) magnet length
\( A = \) cross-sectional area
IAXO – How to improve sensitivity (2)

- To improve sensitivity, compared to CAST, we define a figure of merit, $f$, that accounts for improvements in sub-systems

$$f \equiv f_M \times f_{DO} \times f_T \propto g_{a\gamma}^4$$

- Achieving one order of magnitude better sensitivity than CAST requires

$$g_{a\gamma}^{\text{IAXO}} < \frac{g_{a\gamma}^{\text{CAST}}}{10} \quad \Rightarrow \quad \frac{f_{\text{IAXO}}}{f_{\text{CAST}}} > 10000$$
### IAXO – How to improve sensitivity (3)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Units</th>
<th>CAST-I</th>
<th>IAXO nominal</th>
<th>IAXO enhanced</th>
</tr>
</thead>
<tbody>
<tr>
<td>$B$</td>
<td>T</td>
<td>9</td>
<td>2.5</td>
<td>2.5</td>
</tr>
<tr>
<td>$L$</td>
<td>m</td>
<td>9.26</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>$A$</td>
<td>m²</td>
<td>$2 \times 0.0015$</td>
<td>2.3</td>
<td>2.3</td>
</tr>
<tr>
<td>$f_M$</td>
<td></td>
<td>1</td>
<td>300</td>
<td>300</td>
</tr>
<tr>
<td>$b$</td>
<td>$10^{-5}/(\text{keV cm}^2 \text{ s})$</td>
<td>~4</td>
<td>$5 \times 10^{-3}$</td>
<td>$1 \times 10^{-3}$</td>
</tr>
<tr>
<td>$\varepsilon_d$</td>
<td></td>
<td>0.5–0.9</td>
<td>0.7</td>
<td>0.8</td>
</tr>
<tr>
<td>$\varepsilon_o$</td>
<td></td>
<td>0.3</td>
<td>0.5</td>
<td>0.7</td>
</tr>
<tr>
<td>$s$</td>
<td>cm²</td>
<td>0.15</td>
<td>$8 \times 0.2$</td>
<td>$8 \times 0.15$</td>
</tr>
<tr>
<td>$f_D$</td>
<td></td>
<td>1</td>
<td>17</td>
<td>60</td>
</tr>
<tr>
<td>$\varepsilon_t$</td>
<td></td>
<td>0.12</td>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>$t$</td>
<td>year</td>
<td>~1</td>
<td>3</td>
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<tr>
<td>$f_T$</td>
<td></td>
<td>1</td>
<td>3.5</td>
<td>3.5</td>
</tr>
<tr>
<td>$f$</td>
<td></td>
<td>1</td>
<td>$2 \times 10^4$</td>
<td>$6 \times 10^4$</td>
</tr>
</tbody>
</table>
Magnet for IAXO

- CAST has pushed the limits of "recycling", by using one of the best existing magnets (LHC test magnet)
- Only way to markedly improve reach is to build a new magnet for axions
- Significant modeling and design work completed

- Optimal design is a toroidal configuration (similar to ATLAS):
  - Much bigger bores than CAST — 60 cm versus 5 cm
  - Relatively light (no iron yoke)
  - Bores at room temperature
- Incorporate operational principles of a detector magnet with the performance required for axion physics

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
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<tbody>
<tr>
<td>Toroid radius</td>
<td>4.1 m</td>
</tr>
<tr>
<td>Bore diameter</td>
<td>600 mm</td>
</tr>
<tr>
<td>Number of bores</td>
<td>8</td>
</tr>
<tr>
<td>Cryostat diameter</td>
<td>5.2 m</td>
</tr>
<tr>
<td>Cryostat length</td>
<td>25 m</td>
</tr>
<tr>
<td>Peak field</td>
<td>5.4 T</td>
</tr>
<tr>
<td>Stored Energy</td>
<td>500 MJ</td>
</tr>
<tr>
<td>Total mass</td>
<td>≈ 250 Tons</td>
</tr>
</tbody>
</table>

Shilon et al. arXiv:1212.4633v1
Magnet for IAXO (2)

Fig. 4. Cross section of the conceptual design of the two double pancake winding pack and the coil casing (top) and the conductor with a 40 strands NbTi Rutherford cable embedded in a high purity Al stabilizer (bottom).

Shilon et al. arXiv:1212.4633v1
Magnet for IAXO (3)

- Keystone Box
- Keystone Plate
- Coil Casing
- Coil
- Thermal Shield
- Support Feet
- Vessel
Maturing design for IAXO

Shilon et al. arXiv:1212.4633v1
IAXO conventional facilities

- Cryostat
- Flexible Lines
- Telescopes
- Services
- Inclination System
- Support Frame
- Rotating Disk
- Rotation System
X-ray optics

- X-ray astrophysics community has invested heavily in the development of reflective x-ray optics:
  - 40+ years of telescopes in space
  - Excellent imaging capabilities

- Innovations include:
  - Nested designs (e.g., Wolter telescopes)
  - Low-cost substrates
  - Highly reflective coatings

- IAXO optics requirements:
  - Exquisite imaging not needed for solar studies
  - Optics aperture matched to magnet bore size
    → IAXO requires dedicated but cost-effective optics
  - Good throughput (30–50% integrated reflectivity)
X-ray optics (2)

- Thermally-formed glass substrates optics
  - Successfully used for NASA’s *NuSTAR*
  - Leverage of existing infrastructure
    → Minimize costs & risks
  - Allows for optimization of the reflective coating (multilayers or thin metal films)

- *NuSTAR* launched 13 June 2012
  - Specialized tooling for mirror production and telescope-assembly now available
  - Hardware can be easily configured to tailor dimensions of optics

- Many institutes from *NuSTAR* optics team [Columbia U, DTU Space, LLNL] in IAXO

W Craig et al., *Proc SPIE*, 8147, (2011)
X-ray optics (3)

- Telescopes = 8
- Layers per telescope = 123
- Mirrors per telescope ≈ 2200
- Focal length = 5 m
- Coatings = W/B₄C multilayers
- Pass band = 1–10 keV
- Half-power diameter = 60 arcsec
Low-background detectors

- **Goal**
  - Micromegas detectors with at least $10^{-7}$ cts/(keV×cm$^2$×s)
  - May be possible to reach $10^{-8}$ cts/(keV×cm$^2$×s)

- **Work ongoing**
  - Experimental tests with current micromegas detectors at CERN, Saclay & Zaragoza
  - Underground setup at Canfranc
  - Simulation works to build up a background model
  - Design a new detector with improvements implemented
Low-background detectors (2)

- Latest Micromegas background improved by 20×
  - Shielding & radiopure materials
  - New fabrication methods (microbulk readouts)
  - More powerful post-processing methods

- Tests in controlled conditions underground at Canfranc:
  - Better shielding coverage
  - Thicker shielding

History of background improvement of Micromegas detectors at CAST

Graph showing background reduction over time with nominal values at CAST.

- Backgrounds around ~10^-7 cts/keV/s/cm^2 with improved shielding ~ 30× better than CAST

Underground testing of new configurations
Low-background detectors (3)

As implemented in CAST [2013]
Pathfinder detector+optics for IAXO

- Small x-ray optics
  - Fabricated purposely using thermally-formed glass substrates (NuSTAR-like)

- Micromegas low background detector:
  - Apply lessons learned from R&D: compactness, better shielding, radiopurity,…
  - Aim for background of $10^{-7}$ cts/(keV×cm$^2$×s) or lower

- Collaboration of key groups: Saclay, Zaragoza, LLNL, DTU, Columbia

  - Installation at CAST in 2014
  - Tests of techniques and instrumentation; gain operational knowledge for IAXO
IAXO sensitivity prospects

- **Hadronic axion models**
  - Improvements of $8-30\times$ in $g_{a\gamma}$ ($4\times10^3 - 1\times10^6$ in signal strength)
  - QCD axions at masses of $\sim1$ meV seem out of reach even for an improved axion helioscope **but …**

- **Non-hadronic axion models** provide extra axion emission from the Sun through axion-electron Compton and bremsstrahlung processes

IAXO could improve current CAST sensitivity to non-hadronic axions by about **3 orders of magnitude**
IAXO sensitivity prospects (2)

Astrophysical hints for ALPs

Exploration of very extended QCD axion region

IAXO complements ADMX
Collaboration status and schedule

- Collaboration formed and growing
  - 100 physicists, 20 institutions, 15 countries
- Conceptual design report in preparation; LOI solicited by CERN and **submitted August 2013**
- 4\textsuperscript{th} gen helioscope supported in 2011 ASPERA roadmap

- Socializing IAXO with DOE/SC/HEP and communities of interest (dark matter, particle astrophysics, …)
- Budget [ROM] = $60−110M (dependent on cost models)
  - $30M magnet
  - $10M CF
  - $16M optics
  - $6M detectors

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<table>
<thead>
<tr>
<th>Yr 1</th>
<th>Yr 2</th>
<th>Yr 3</th>
<th>Yr 4</th>
<th>Yr 5</th>
<th>Yr 6</th>
<th>Yr 7</th>
<th>Yr 8</th>
<th>Yr 9</th>
<th>Yr 10</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Phase I</strong></td>
<td><strong>Phase II</strong></td>
<td><strong>Phase III</strong></td>
<td><strong>Phase IV</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reduce risk</td>
<td>Construction</td>
<td>Commission</td>
<td>Science observations:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Prototype: optics, detector, magnet</td>
<td>Build: conventional facilities, magnet, optics detectors</td>
<td>Integrate elements, calibrate, test operations</td>
<td>Solar searches, Extragalactic? Microwave cavities?</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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**does not include labor**
Conclusions

- **CAST** is at the forefront of experimental axion physics
  - CAST PRL2004 most cited experimental paper in axion physics
  - Expertise gathered in magnet, optics, low background detectors, gas systems
  - No other technique can realistically improve on CAST sensitivity over a wide mass range.

- **IAXO** is a proposed 4th generation axion helioscope
  - Good prospects to improve CAST by 1–1.5 orders of magnitude in sensitivity
  - Conceptual design effort is underway and will be completed in 2013
  - Together IAXO and haloscopes (ADMX) could explore a large part of the QCD axion model region in the next decade
  - Potential for other physics (White Dwarfs, ALPs,...)
Additional physics potential

- More specific ALP or WISP (weakly interacting slim particle) models could be searched for at the low energy frontier of particle physics:
  - Paraphotons / hidden photons
  - Chameleons
  - Non-standard scenarios of axion production

- Axions will also have more subtle implications on other astrophysical objects:
  - Neutron stars
  - SNe
  - Red Giants in Globular Clusters

- If equipped with microwave cavities, dark matter halo axions could be searched for, extending the sensitivity to lower masses.
  - under study → Baker et al. (PRD 85 035018 [2012])

- IAXO is a true “axion facility” open to the community

- Groups are invited to contribute and enrich the science program of IAXO