Present and Future of axion searches: the International AXion Observatory IAXO

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Origin of Mass 2014 – Odense, Denmark – May 18th, 2014
Outline

- Axion motivation:
  - Strong CP problem
  - Axions as CDM
  - Solar axions

- Previous helioscopes & CAST

- IAXO Conceptual Design
  - Magnet
  - Optics
  - Detectors

- IAXO physics potential

- Status of project. Requests to CERN. Next steps

- Conclusions

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**Letter of Intent to the CERN SPSC**

**The International Axion Observatory**

IAXO

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W. Wester$^{37}$, C. S. Yildiz$^{3}$, K. Zioutas$^{38}$

IAXO Letter of Intent: CERN-SPSC-2013-022

90 signatures / 38 institutions

IAXO Conceptual Design: JINST 9 (2014)

T05002 (arXiv:1401.3233)
**Axion: introduced to solve the strong CP problem**

In QCD, nothing prevents from adding a term like that to the lagrangian:

\[ \mathcal{L}_{CP} = \theta \frac{\alpha_s}{8\pi} G \tilde{G} \]

This term is **CP violating**.

From non-observation of neutron electric dipole moment:

- Why so small?
- High fine-tuning required for this to work in the SM

\[ |\theta| < 0.7 \times 10^{-11} \]
AXION theory motivation

- **Peccei-Quinn solution** to the strong CP problem
  - New U(1) symmetry introduced in the SM:
    - Peccei Quinn symmetry of scale $f_a$
  - The AXION appears as the **Nambu-Goldstone boson** of the spontaneous breaking of the PQ symmetry

"Axion lagrangian"
\[
\mathcal{L}_a = \frac{1}{2} (\partial_\mu a)^2 - \frac{\alpha_s}{8\pi f_a} aG\tilde{G}
\]

θ absorbed in the definition of a

\[\theta = \alpha f_a\] relaxes to zero…
CP conservation is preserved “dynamically”
THE AXION

- The PQ scenario solves the strong CP-problem. But a most interesting consequence is the appearance of this new particle, the axion.
  (Weinberg, Wilcek)

- **Basic properties:**
  - Pseudoscalar particle
  - Neutral
  - Gets very small mass through mixing with pions
  - Stable (for practical purposes).
  - Phenomenology driven by the PQ scale $f_a$.
    (couplings inversely proportional to $f_a$)

\[
L_a = \frac{1}{2} (\partial_\mu a)^2 - \frac{\alpha_s}{8\pi f_a} a G \tilde{G}
\]

\[
m_a \sim 0.6 \text{ eV} \frac{10^7 \text{GeV}}{f_a}
\]
AXION phenomenology

- **Axion-photon coupling** present in every model.

\[ \mathcal{L}_{a\gamma} = g_{a\gamma}(E \cdot B) a \]

\[ g_{a\gamma} = \frac{\alpha_s}{2\pi f_a} \left( \frac{E}{N} - 1.92 \right) \]

- **Axion-photon conversion** in the presence of an electromagnetic field (Primakoff effect)

This is probably the most relevant of axion properties. Most axion detection strategies are based on the axion-photon coupling
Beyond axions

Hidden photons
/ paraphotons

ALPS

AXIONS

Chamaleons

Minicharged particles

WISPs (Weakly interacting Slim Particle)

- Diverse theory motivation
  - Higher scale symm. breaking
  - String theory
  - DM / DE candidates
  - Astrophysical hints

- Generic Axion-like particles (ALPs) parameter space
AXION as Dark Matter?

- Can not be baryonic
- Can not be relativistic (CDM)
- Can not be standard (neutrinos)
- Need to go **beyond the SM**

Galactic scale

Cosmological scale

“Dark energy”
\~68.3%

Baryonic
\(< 5\%

Visible
\(< 1\%

non baryonic

Dark Matter
\~26.8 \%

Can not be baryonic

Can not be relativistic (CDM)

Can not be standard (neutrinos)

Need to go **beyond the SM**

SUSY

PQWW

WI MPs

AXIONS
AXION as Dark Matter?

- **Axions are produced** in the early Universe by a number of processes:
  - Axion realignment
  - Decay of axion strings
  - Decay of axion walls

- Axion mass giving the right CDM density? Depends on cosmological assumptions:
  - "classical window" $\sim 10^{-5} - 10^{-3}$ eV
  - "anthropic window" $\sim$ much lower masses possible
  - Other $\rightarrow$ subdominant CDM / non-standard scenarios

- **Thermal production**

- Axion masses $m_a > \sim 0.9$ eV gives densities too much in excess to be compatible with latest CMB data

Axion DM after BICEP2

- Quite an impact… (a few preprints)
  - Marsh et al. arXiv:1403.4216
  - L. Visinelli, P. Gondolo arXiv:1403.4594
  - Chun. arXiv:1404.4284

among others…

In summary:

if “high inflation scale” interpretation of BICEP2 results is right… “classical window” (high mass) scenario is favored.
Axions in Astrophysics

- **Axions are produced at the core of stars**, like the Sun, by Primakoff conversion of the plasma photons.
  - Axions drain energy from stars and may alter their lifetime. Limits are derived to the axion properties.

- **Axion decay** $a \rightarrow \gamma \gamma$ may produce gamma lines in the emission from certain places (i.e. galactic center).

**Astrophysical hints for axions/ ALPs**

- Anomalous gamma transparency of the Universe (observation of gamma rays from distant sources) $\rightarrow$ very light ALPs
- Anomalous cooling of white dwarfs
  - Favors few meV axions

See PDG and references therein
Axion motivation in a nutshell

- Most compelling solution to the **Strong CP problem** of the SM

- Axion-like particles (ALPs) **predicted by many extensions** of the SM (e.g. string theory)

- Axions, like WIMPs, may **solve the DM problem for free**. (i.e. not *ad hoc* solution to DM)

- **Astrophysical hints** for axion/ALPs?
  - Transparency of the Universe to UHE gammas
  - White dwarfs anomalous cooling → point to few meV axions

- Relevant axion/ALP parameter space at **reach of current and near-future experiments**

- Still too little experimental efforts devoted to axions when compared e.g. to WIMPs... (not justified...)

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Mass2014, Odense, May 2014

Igor G. Irastorza / Universidad de Zaragoza
Detecting axions

- Relic Axions
  - Axions that are part of galactic dark matter halo:
    - Axion Haloscopes
      - ADMX in US

- Solar Axions
  - Emitted by the solar core.
    - Crystal detectors
    - Axion Helioscopes
      - CAST @ CERN
      - IAXO

- Axions in the lab
  - “Light shining through wall” experiments
  - Vacuum birrefringence experiments
    - ALPS-II @ DESY
    - OSQAR @ CERN
Solar Axions

- Solar axions produced by photon-to-axion conversion of the solar plasma photons in the solar core

- **Solar axion flux** [van Bibber PRD 39 (89)]
  [CAST JCAP 04(2007)010]

\[
\frac{d\Phi_a}{dE} = 6.02 \times 10^{10} \text{ cm}^{-2} \text{ s}^{-1} \text{ keV}^{-1} \ g_{10}^2 E^{2.481} e^{-E/1.205}.
\]

\[
g_{10} = g_{\gamma\gamma}/10^{-10} \text{ GeV}^{-1}
\]

**Solar physics + Primakoff effect**

Only one unknown parameter \( g_{\gamma\gamma} \)
Axion Helioscope principle

- Axion helioscope [Sikivie, PRL 51 (83)]

Axion photon conversion

\[ P_{a\gamma} = 2.6 \times 10^{-17} \left( \frac{B}{10 \text{ T}} \right)^2 \left( \frac{L}{10 \text{ m}} \right)^2 \left( g_{a\gamma} \times 10^{10} \text{ GeV} \right)^2 \mathcal{F} \]
Axion Helioscopes

- Previous helioscopes:
  - First implementation at Brookhaven (just few hours of data) [Lazarus et at. PRL 69 (92)]
  - TOKYO Helioscope (SUMICO): 2.3 m long 4 T magnet

- Presently running:
  - CERN Axion Solar Telescope (CAST)
CAST experiment @ CERN

- Decommissioned LHC test magnet (L=10m, B=9 T)
- Moving platform ±8°V ±40°H (to allow up to 50 days / year of alignment)
- 4 magnet bores to look for X rays
- 3 X rays detector prototypes being used.
- X ray Focusing System to increase signal/noise ratio.
CAST at work
Axion parameter space

Astrophysical hints for ALPs

CDM
"anthropic window"

CDM
"classical window"
Vaxuum mis. + defects

mixed CDM

White Dwarfs

Axions as HDM

JCAP06(2012)013

WISPy CDM

Mass2014, Odense, May 2014
IAXO – Concept


Solar axion flux

MAGNET COIL

MAGNET COIL

L

X-ray optics

X-ray detectors

Shielding

No technological challenge (build on CAST experience)

- New dedicated superconducting magnet, built for IAXO (improve >300 B²L²A f.o.m wrt CAST)
- Extensive (cost-effective) use of x-ray focalization over ~m² area.
- Low background detectors (lower 1-2 order of magnitude CAST levels)

Sensitivity goal: >4 orders of magnitude improvement in signal-to-noise ratio wrt CAST. (>1 order of magnitude in sensitivity of $g_{a\gamma}$)

\[
g_{a\gamma}^4 \propto \frac{b^{1/2} \epsilon^{-1}}{\text{detectors}} \times \frac{a^{1/2} \epsilon_o^{-1}}{\text{optics}} \times \frac{(BL)^{-2} A^{-1}}{\text{magnet}} \times t^{-1/2} \times \text{exposure}
\]
IAXO – Conceptual Design

- Large toroidal 8-coil magnet $L = \sim 20$ m
- 8 bores: 600 mm diameter each
- 8 x-ray optics + 8 detection systems
- Rotating platform with services
IAXO magnet

TOROIDAL CONFIGURATION specifically built for axion physics

Each conversion bore (between coils) 600 mm diameter

Cryostat Cold mass

Magnetic length 20 m Total cryostat length 25 m

Bores go through cryostat
IAXO magnet concept presented in:
• IEEE Trans. Appl. Supercond. 23 (ASC 2012)

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<th>Property</th>
<th>Value</th>
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<td>Overall length (m)</td>
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<td>Outer diameter (m)</td>
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<td>Cold Mass (tons)</td>
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<td>Overall size (mm$^2$)</td>
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<td>at 4.5 K (W)</td>
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<tr>
<td>at 60-80 K (W)</td>
<td>$\sim 1.6$</td>
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IAXO x-ray optics

- X-rays are focused by means of grazing angle reflection (usually 2)
- Many techniques developed in the x-ray astronomy field. But usually costly due to exquisite imaging requirements
IAXO x-ray optics

- Each bore equipped with an x-ray optics
- Exquisite imaging not required
- BUT need cost-effective way to build 8 (+1 spare) optics of 600 mm diameter each
IAXO x-ray optics

• Technique of choice for IAXO: optics made of slumped glass substrates coated to enhance reflectivity in the energy regions for axions
• Same technique successfully used in NuSTAR mission, recently launched

• The specialized tooling to shape the substrates and assemble the optics is now available
• Hardware can be easily configured to make optics with a variety of designs and sizes
• Key institutions in NuSTAR optics: LLNL, U. Columbia, DTU Denmark. All in IAXO !
IAXO x-ray optics

Telescopes: 8
N. Layers (or shells) per telescope: 123
Segments per telescope: 2172
Geometric area of glass per telescope: 0.38 m²
Focal length: 5.0 m
Inner radius: 50 mm
Outer Radius: 300 mm
Minimum graze angle: 2.63 mrad
Maximum graze angle: 15.0 mrad
Coatings: W/B₁₄C multilayers
Pass band: 1—10 keV
IAXO Nominal, 50% EEF (HPD): 0.29 mrad
IAXO Enhanced, 50% EEF (HPD): 0.23 mrad
IAXO Nominal, 80% EEF: 0.58 mrad
IAXO Enhanced, 90% EEF: 0.58 mrad
FOV: 2.9 mrad

Optimal focal length ~5 m
IAXO low background detectors

- 8 detector systems
- Small gas chamber with Micromegas readouts for low-background x-ray detection
- Shielding
IAXO low background detectors

- Small Micromegas-TPC chambers:
  - Shielding
  - Radiopure components
  - Offline discrimination

- Goal background level for IAXO:
  - $10^{-7} - 10^{-8} \text{ c keV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$

- Already demonstrated:
  - $\sim 8 \times 10^{-7} \text{ c keV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$
    (in CAST 2013 result)
  - $10^{-7} \text{ c keV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$
    (underground at LSC)

- Active program of development. Clear roadmap for improvement.

See arXiv:1310.3391

History of background improvement of Micromegas detectors at CAST
IAXO low background detectors
Optics+detector pathfinder system in CAST

- IAXO optics+detector joint system
  - Newly designed MM detector (following IAXO CDR)
  - New x-ray optics fabricated following technique proposed for IAXO (but much smaller, adapted to CAST bore)

- It will take data in CAST in 2014
  - First time low background + focusing in the same system
  - Very important operative experience for IAXO

Detector installed at CAST this year. New optics coming beginning of 2014
IAXO sensitivity prospects

IAXO in the high mass end, and future phases of ADMX in the low mass end will explore large part of the QCD axion model region in the next decade.

IAXO in the high mass end, and future phases of ADMX in the low mass end will explore large part of the QCD axion model region in the next decade.

Much larger QCD axion region explored

Astrophysical hints for ALPs
Additional IAXO physics cases

- IAXO sensitivity to BCA solar axion with values of $g_{ae}$ of relevance
- 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
  - Chamaleons
  - Non-standard scenarios of axion production
- Microwave LSW setup
- Use of microwave cavities or dish antennas, dark matter halo axions could be searched for → next slide
- IAXO as “generic axion/ALP facility”
Detecting DM axions: “haloscopes”

- Resonant cavities (Sikivie, 1983)
  - Primakoff conversion inside a “tunable” resonant cavity
  - Energy of photon = $m_a c^2 + O(\beta^2)$

$P_0 = g_{a\gamma}^2 V B^2 C \frac{\rho_a}{m_a} Q$

- Axion DM field
  - Non-relativistic
  - Frequency $\leftrightarrow$ axion mass

- Cavity dimensions smaller than de Broglie wavelength of axions

- If cavity tuned to the axion frequency, conversion is “boosted” by resonant factor (Q quality factor)
Haloscopes - AMDX

- Leading experiment: ADMX @ U. Washington
  - Many years of R&D
  - high Q cavity (1 m x 60 cm Ø)
  - 8 T superconducting solenoid
  - Low noise receivers based on SQUIDs
  - Sensitivity to few µeV proven
  - New program ADMX-HF to go to higher frequencies
Axion DM detection – new ideas

• Recent papers proposing new detection schemes. Very active field!

  – Directional effect in long thin cavities: JCAP 1210 (2012) 022
  – Dish antenna: JCAP 1304 (2013) 016
  – Active resonators: arXiv:1403.6720
  – Cavity with wires: arXiv:1403.3121 (also old Sikivie paper)
Detecting DM axions with IAXO?

• All ideas have in common: big magnets needed

- Large spherical mirror
- Long thin cavities in dipole magnets

References:
IAXO-DM configurations?

- Prospects under study. Very motivated (encouraged by CERN SPSC)
- Needed new know-how (cavities, low noise microwave detectors...)
- Various possible arrangements in IAXO. Profit the huge magnetic volume available:
  1. Single large cavity tuned to low masses
  2. Thin long cavities tuned to mid-high masses. Possibility for directionality. Add several coherently?
  3. Dish antenna focusing photons to the center. Not tuned. Broadband search. Competitive at higher masses?
**Additional IAXO physics cases**

direct detection or relic axions/ALPs

- Promising as further pathways for IAXO beyond the helioscope baseline
- First indications that IAXO could improve or complement current limits at various axion/ALP mass ranges...
- **Caution**: preliminary studies still going on. Important know-how to be consolidated. Precise implementation in IAXO under study.

**Tentative future prospects**

Beyond current helioscope
## IAXO timeline

- **~18 months -> TDR + preparatory activities**
- **~3.5 years construction**
- **~2.5 years integration + commissioning**

### Table

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<td>Build assembly machines</td>
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<td>Procure mandrels &amp; ovens</td>
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</tr>
<tr>
<td>Construction (incl. spares)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Installation &amp; commissioning</td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

Mass2014, Odense, May 2014

Igor G. Irastorza / Universidad de Zaragoza
# IAXO costs

<table>
<thead>
<tr>
<th>Item</th>
<th>Cost (MCHF)</th>
<th>Subtotals (MCHF)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Magnet</strong></td>
<td></td>
<td>31.3</td>
</tr>
<tr>
<td>Eight coils based assembled toroid</td>
<td>28</td>
<td></td>
</tr>
<tr>
<td>Magnet services</td>
<td>3.3</td>
<td></td>
</tr>
<tr>
<td><strong>Optics</strong></td>
<td></td>
<td>16.0</td>
</tr>
<tr>
<td>Prototype Optic: Design, Fabrication, Calibration, Analysis</td>
<td>1.0</td>
<td></td>
</tr>
<tr>
<td>IAXO telescopes (8 + 1 spare)</td>
<td>8.0</td>
<td></td>
</tr>
<tr>
<td>Calibration</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>Integration and alignment</td>
<td>5.0</td>
<td></td>
</tr>
<tr>
<td><strong>Detectors</strong></td>
<td></td>
<td>5.8</td>
</tr>
<tr>
<td>Shielding &amp; mechanics</td>
<td>2.1</td>
<td></td>
</tr>
<tr>
<td>Readouts, DAQ electronics &amp; computing</td>
<td>0.8</td>
<td></td>
</tr>
<tr>
<td>Calibration systems</td>
<td>1.5</td>
<td></td>
</tr>
<tr>
<td>Gas &amp; vacuum</td>
<td>1.4</td>
<td></td>
</tr>
<tr>
<td>Dome, base, services building and integration</td>
<td>3.7</td>
<td></td>
</tr>
<tr>
<td><strong>Sum</strong></td>
<td></td>
<td><strong>56.8</strong></td>
</tr>
</tbody>
</table>

Table 5: Estimated costs of the IAXO setup: magnet, optics and detectors. It does not include laboratory engineering, as well as maintenance & operation and physics exploitation of the experiment.
IAXO in astroparticle roadmaps

- **ASPERA/APPEC Roadmap** acknowledges axion physics, CAST, and recommends progress towards IAXO.

  "...A CAST follow-up is discussed as part of CERN’s physics landscape (new magnets, new cryogenic and X-ray devices). The Science Advisory Committee **supports** R&D on this follow up, as well as smaller ongoing activities on the search for axions and axion-like particles."

  C. Spiering, ESPP Krakow

- Important community input in the **European Strategy for Particle Physics**
- Presence in the Briefing Book of the ESPP, which reflects also APPEC roadmap recommendations.
- **ESPP recomends CERN to follow APPEC recomendations.**
- Important effort in relation with US roadmapping (Snowmass, and P5 process). **Snowmass reports speak very favourably of axion physics and IAXO.**
IAXO status of project

- **2011**: First studies concluded *(JCAP 1106:013,2011)*
- **2013**: Conceptual Design finished *(arXiv:1401.3233)*.
  - Most activity carried out up to now ancillary to other group’s projects (e.g. CAST)
- **August 2013**: Letter of Intent submitted to the CERN SPSC
  - LoI: [CERN-SPSC-2013-022]
  - Presentation in the open session in October 2013:
- **January 2014**: Positive recommendations from SPSC.

- **2014**: Transition phase: In order to continue with TDR & preparatory activities, formal endorsement & resources needed.
  - Some IAXO preparatory activity already going on as part of CAST near term program.
  - Preparation of a MoU to carry out TDR work.
CERN SPSC recommendations

SPSC Draft minutes [Jan 2014]

The Committee recognises the physics motivation of an International Axion Observatory as described in the Letter of Intent SPSC-I-242, and considers that the proposed setup makes appropriate use of state-of-the-art technologies i.e. magnets, x-ray optics and low-background detectors.

The Committee encourages the collaboration to take the next steps towards a Technical Design Report.

The Committee recommends that, in the process of preparing the TDR, the possibility to extend the physics reach with additional detectors compared to the baseline goal should be investigated. The collaboration should be further strengthened.

Considering the required funding, the SPSC recommends that the R&D for the TDR should be pursuit within an MOU involving all interested parties.
Next steps

• Start works towards a Technical Design Report. As part of such:
  – Construction of a demonstration coil **IAXO-T0**
  – Construction of a prototype x-ray optics **IAXO-X0**
  – Construction of a prototype low background detector setup **IAXO-D0**
  – Complete pathfinder project detector+optic at CAST
  – Coordination activities. Update physics case. Site. Tracking platform. Gas system. Software
  – Feasibility studies for “IAXO-DM” options.

• TDR completion is a ~2-4 MEUR effort.

• Memorandum of Understanding in preparation among interested parties

• Search for new interested partners (in view of construction phase – magnet is the issue)
Conclusions

• Axion searches $\rightarrow$ strong physics case.
• Increase experimental effort in different directions: solar axions, relic axions, axions in the lab.
• In particular, solar axions $\rightarrow$ CAST has been a very important milestone in axion research during the last decade
  – 1st CAST limits most cited exp. axion paper
  – Largest effort/collaboration in axion physics so far
• IAXO, a forth generation axion helioscope, natural and timely large-scale step to come now. It can probe deep into unexplored axion+ALP parameter space.
  – But also several additional physics cases. Possibility to host relic axion searches in the future. Studying actively this possibility
• LoI to CERN recently proposed. Positive recommendation from SPSC. MoU to start TDR under preparation.
• IAXO could become next large project & a “generic axion facility” with discovery potential in the next decade.