Searches for axions and ALPs with helioscopes

Igor G. Irastorza (Universidad de Zaragoza)
Open Symposium – Update of the European Strategy for Particle Physics
Granada, 14 May 2019

Based mainly on input to ESPP:
#27 The International Axion Observatory (IAXO): case, status and plans.
but also
#112 A European Strategy Towards Finding Axions and Other WISPs
#42 The Physics Beyond Colliders Study at CERN
#60 PBC technology subgroup report
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
  - Stellar anomalous cooling $\rightarrow g_{a\gamma} \sim \text{few } 10^{-11} \text{ GeV}^{-1}/m_a$
  - $\sim \text{few } \text{meV}$
- Relevant axion/ALP parameter space at **reach of current and near-future experiments**
Axion/ALP searches motivation

“Focuses of interest” in the ALP parameter space

Theory
Astrophysics
Cosmology

IAXO addresses partially all of them

meV+ QCD axion region exclusive target of IAXO
# Detection of axions

<table>
<thead>
<tr>
<th>Source</th>
<th>Experiments</th>
<th>Model &amp; Cosmology dependency</th>
<th>Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Relic axions</td>
<td>ADMX, HAYSTAC, CASPER, CULTASK, CAST-CAPP, MADMAX, ORGAN, RADES, QUAX, AXIOMA, ABRA, DM-Radio, …</td>
<td>High</td>
<td>New ideas emerging, Active R&amp;D going on,…</td>
</tr>
<tr>
<td>Lab axions</td>
<td>ALPS, JURA, OSQAR, CROWS, ARIADNE,…</td>
<td>Very low</td>
<td>Ready for large scale experiment</td>
</tr>
<tr>
<td>Solar axions</td>
<td>SUMICO, CAST, (Baby)IAXO</td>
<td>Low</td>
<td>Ready for large scale experiment</td>
</tr>
</tbody>
</table>
Solar Axions

- Primakoff conversion of solar plasma photons \(\rightarrow\) generic prediction of most axion models
- In addition, \(g_{ae}\)-mediated axions (model dependent)

**Diagram:**
- Non-hadronic “ABC” Solar axion flux at Earth
  - *JCAP 1312 008* (only if axion couples to electron)
- Standard Primakoff spectrum

**Graph:**
- Differential solar axion flux (10^9 cm^{-2} s^{-1} keV^{-1})
  - Primakoff \(\times 50\)
  - Non hadronic

ESSP Granada, 14-May-2019
Igor G. Irastorza
Axion helioscopes

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

Current state-of-the-art:
CERN Axion Solar Telescope (CAST)

First helioscope using low background techniques & x-ray focusing
Latest CAST limit

X-ray optics specifically built for axions

Low background Micromegas

IAXO pathfinder system at CAST:
 x-ray focusing + low background detector combined in same system
 Small-scale version of IAXO baseline detection lines

$g_{ay} < 0.66 \times 10^{-10} \text{ GeV}^{-1}$ at 95% CL

New CAST limit on the axion-photon interaction

CAST Collaboration

Hypothetical low-mass particles, such as axions, provide a compelling explanation for the dark matter in the universe. Such particles are expected to emerge abundantly from the hot interior of stars. To test this prediction, the CERN Axion Solar Telescope was directed towards the Sun. In the strong magnetic field of the Sun, axions are converted into photons, which can be detected by x-ray detectors. In the 2013-2015 run, thanks to the X-ray optics specifically built for axions and the low background Micromegas detector, the CAST Collaboration has achieved a new limit on the axion-photon coupling constant:

$g_{ay} < 0.66 \times 10^{-10} \text{ GeV}^{-1}$ at 95% CL

ESSP Granada, 14-May-2019

Igor G. Irastorza
IAXO pathfinder system in CAST

Test MM detector + slumped-glass x-ray optics together

Detector: JCAP12 (2015)

Background spectrum

• Best SNR of any previous detector
• 290 tracking hour acquired (6.5 months operation)
• 3 counts observed in RoI (1 expected)

ESSP Granada, 14-May-2019
Igor G. Irastorza
An enhanced axion helioscope

IAXO is conceived as a large-scale, but realistic, enhanced axion helioscope

>10^4 better SNR than CAST

Sensitive to $g_{ag} \sim x20$ lower than CAST

Enhanced axion helioscope: 
*JCAP 1106:013, 2011*
IAXO – Conceptual Design

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

BabyIAXO

- **Prototype:** Intermediate experimental stage before IAXO
  - Two bores of dimensions similar to final IAXO bores → detection lines representative of final ones.
  - Magnet will test design options of final IAXO magnet
  - Test & improve all systems. Risk mitigation for full IAXO

- **Physics:** will also produce relevant physics outcome
  (~100 times larger FOM than CAST)

~100x CAST SNR

ESSP Granada, 14-May-2019

Igor G. Irastorza
(Baby)IAXO @ DESY

- BabyIAXO under review by DESY PRC

- DESY in a ideal host for IAXO. Existing expertise/capabilities nicely complements those of collaboration.

- DESY “axion program” under consideration, ideal environment for BabyIAXO and IAXO

- Important connection with CERN (magnet expertise)
Collaboration & timeline

- Large collaboration with needed experience
  17 institutions from Germany, Spain, US, France, Russia, Italy, Croatia, S. Africa, CERN.

- Know-how portfolio encompassing all needed expertise
  Involvement of large institutes like DESY (site), CERN (magnet)

- Realistic timeline leading to BabyIAXO commissioning by 2023
BabyIAXO & IAXO physics reach

IAXO will fully explore ALP models invoked to solve the “transparency hint”

BabyIAXO & IAXO prospects:
Following current LoI designs

IAXO+: enhanced scenario with x10 (x4) higher FOM (MFOM) with respect to LoI

... as well as a large fraction of the axion & ALP models invoked in the “stellar cooling anomaly”
But for this the $g_{ae}$ is particularly interesting

MFOM = Magnet FOM

ESSP Granada, 14-May-2019
Igor G. Irastorza
IAXO & stellar cooling hints

- IAXO can detect “ABC” solar axions (i.e. non-hadronic, $g_{ae}$-mediated)
- Boost in sensitivity for models featuring $g_{ae}$-coupling.
- Will probe QCD axion models invoked to solve all stellar cooling anomalies
IAXO & axion cosmology

- Axion post-inflation mass window overlaps with astro window
  - Uncertainty in topological defect decay is large (Gorghetto et al 2018)
  - NDW>1 models (Saikawa, Ringwald 2016)

- Also:
  - If axions only subdominant DM component, axion mass moves to higher values.
  - "ALP miracle" (ALP inflation + DM) models @ 0.01 to 1 eV
  - EDGES anomaly interpretation with DM axions at 0.01-1 eV range

- IAXO will probe interesting DM axion & ALP models
Post-discovery physics

- A positive signal in BabyIAXO will be seen >100x stronger in IAXO
- With sufficient statistics and precision detectors IAXO can determine axion model parameters:
- IAXO collaboration is developing high-precision (“post-discovery”) detectors (e.g. MMCs or TES)
IAXO will probe…

- Large generic unexplored ALP space
  - down to $g_{aY} \sim \text{few } 10^{-12} \text{ GeV}^{-1}$
  - down to $g_{ae} \sim \text{few } 10^{-13}$

- **QCD axion models** in the meV to eV mass band.
- Astrophysically hinted regions
- Cosmologically interesting regions

- All this, independent of the axion-as-DM hypothesis.
- No other competing technique. **IAXO is unique in the axion experimental landscape and very complementary.**
- **BabyIAXO** relevant intermediate physics potential
Conclusions

- Helioscopes have a unique and complementary physics case in the “axion experimental landscape”.

- Realistic path to physics in a few years:
  - BabyIAXO is well on track” for implementation at DESY (in-depth review of project will take place next week!)
  - The IAXO collaboration encompasses the needed know-hows and has already secured a substantial fraction of the resources.
  - The project relies on the 15+ year experience with CAST + CERN expertise in large SC magnets.
  - DESY in a ideal host for IAXO. Expertise/capabilities complementary to collaboration. IAXO part of the DESY “axion program” under consideration.
Backup slides
IAXO & stellar cooling

• Multiple stellar anomalies (HB, RG, WD, NS,..). Overall $3\sigma$ effect.

- IAXO will explore most of the relevant models (especially with IAXO+)
- Only experiment with such capability

Region of QCD axion models that solve the stellar anomaly

M. Giannotti et al.
JCAP 1710 (2017) 010
arXiv:1708.02111
IAXO and CERN

[from PBC technology subgroup meetings]

• IAXO crucially relies on CERN’s expertise on large-scale superconducting detector magnets. Both BabyIAXO and IAXO detector magnets are systems of a scale for which CERN’s expertise and infrastructure is almost unique.

• The collaboration expects support and significant participation of CERN, in particular, but not exclusively, with knowledge and expert personnel to the Technical Design Report of magnets and related infrastructure, as well as the technical follow-up during construction, testing and commissioning, first of BabyIAXO and then for IAXO.

• CAST is still active at CERN hosting a number of small-scale prototypes for testing novel concepts or performing R&D. There is potential in further using CAST infrastructure for providing feedback during the preparatory phase of IAXO, for example, to improve the insight on detector backgrounds.
Axions: theory motivation

• Axion: introduced to solve the strong CP problem

• In QCD, nothing prevents from introducing a term like:

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

This term is CP violating.

\[ \theta = \bar{\theta} + \arg \det M . \]

From non-observation of neutron electric dipole moment:

\[ |\theta| < 1.3 \times 10^{-10} \]

• Why so small?

• High fine-tuning required for this to work in the SM
Axions: 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

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

- $\theta$ absorbed in the definition of $a$

- $\theta = a f_a$ 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 $f_a$)

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

\[
m_A = 5.70(7) \mu eV \left( \frac{10^{12} \text{GeV}}{f_A} \right)
\]
Axion phenomenology

- Some phenomenology depends on the "axion model", e.g.
  - KSVZ axions are "hadronic axions" (no coupling with leptons at tree level)
  - DFSZ axions couple to electrons

### Gluon coupling

\[
\frac{\alpha_s}{8\pi f_a} a G \tilde{G}
\]

**generic**

### Mass

\[
m_A = 5.70(7) \mu\text{eV} \times \left(\frac{10^{12}\text{GeV}}{f_A}\right)
\]

**generic**

### Photon coupling

\[
g_{a\gamma\gamma}(E \cdot B)a
\]

**generic but value model dependent**

### Fermion couplings

**Electron coupling**

**Nucleon coupling**

...
Axion phenomenology

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

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

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

- **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

- Many extensions of SM predict axion-like particles
  - Higher scale symmetry breaking

![Diagram of particle physics concepts]

**Generic ALPs parameter space**

![Graph showing particle interactions and mass spectra]

String theory predicts a plenitude of ALPs
Cosmological axions: axion realignment

As the Universe cools down below $T_{QCD}$, space is filled with low energy axion field fluctuations → act as cold dark matter

Their density depends on the initial value of $<a_{phys}>$ (“misalignment angle”) which:

- Unique (but unknown) for all visible Universe in pre-inflation models
- Effectively averaged away in post-inflation models $\langle \theta_{a}^2 \rangle = \pi^2 / 3$
Cosmological axions: topological defects

But inflation may "wipe out" topological defects… Did inflation happen before or after the creation of defects (PQ transition) ?

*pre-inflation or post-inflation scenarios*

Computation of axion DM density from defect decay is complicated (→ big uncertainty)
Astrophysical hints for axions
Axion/ALP searches motivation

“Focuses of interest” in the ALP parameter space

Theory
Astrophysics
Cosmology

Generic ALP DM models
Cosmological axions

Axion realignment
(initial misalignment angle?)

But also... topological defects
(inflation can wipe them out if it happens afterwards)

Note: thermal production of axions (as neutrinos) gives hot DM (upper limit $m_a \sim 1$ eV)
Axion DM density vs axion mass

• **Axions are good DM candidates** → for which $m_a$ do we get $\Omega_a \sim \Omega_{DM}$?
  - **Pre-inflation models** → only misalignment contribution, but initial angle unknown → very large $m_a$ range possible (even very low $m_a$ values with anthropic tuning)
  - **Post-inflation models** → misalignment becomes more predictive as initial angle gets averaged. BUT, topological defects are now important (source of uncertainty).

• **In any case, for** $\Omega_a < \Omega_{DM}$ → $m_a$ increases as $m_a \sim \Omega_a^{-1}$
• **Note:** thermal production of axions (as neutrinos) gives hot DM (upper limit $m_a \sim 1$ eV)
Astrophysical hints for axions

- Gama ray telescopes like MAGIC or HESS observe HE photons from very distant sources...

\[ g_{\alpha\gamma} \sim 10^{-12} - 10^{-10} \, \text{GeV}^{-1} \]
\[ m_a \lesssim 10^{-10^{-7}} \, \text{eV} \]
Astrophysical hints for axions

- Most stellar systems seem to cool down faster than expected.
- Presence of axions/ALPs offer a good joint explanation (Giannotti et al. JCAP05(2016)057 [arXiv:1512.08108])
- Parameters at reach of IAXO

\[
\begin{align*}
\Delta L/L_{\text{st}} &\quad g_{\alpha\gamma} \\
\text{HB} &\quad Ayala et. al. (2014), Straniero (proc. of XI Patras Workshop) \\
\text{RG} &\quad Viaux et. al. (2013), Arceo-Daz et. al. (2015) \\
\text{WDLF (M_{\text{bol}} \sim 9)} &\quad Bertolami (2014) \\
\text{PG 1351} &\quad Corsico et. al., (2014, 2015) \\
\text{R 548} &\quad Corsico et. al., (2012) \\
\text{G117-B15A} &\quad Kepler et. al., (1991) + many others \\
\text{NS} &\quad Shternin et. al. (2011)
\end{align*}
\]
Sources of axions

Natural sources

<table>
<thead>
<tr>
<th>Dark matter</th>
<th>Dark radiation</th>
<th>Stellar</th>
</tr>
</thead>
<tbody>
<tr>
<td>DM(m_a = 10^{-4}\text{eV})</td>
<td>DR(T_d = 1\text{GeV})</td>
<td>Sun</td>
</tr>
<tr>
<td>DR(\Delta N_{\text{eff}} = 0.1)</td>
<td>Betelgeuse</td>
<td>DSAB</td>
</tr>
</tbody>
</table>

Laboratory sources

- Photon-ALP conversion in strong magnetic fields (axion-photon coupling)
- ALP fields from macroscopic bodies (fermionic couplings)
Most detection strategies rely on the axion-photon conversion

**Axion detection strategies**

<table>
<thead>
<tr>
<th>Detection method</th>
<th>$g_{a\gamma}$</th>
<th>$g_{ae}$</th>
<th>$g_{aN}$</th>
<th>$g_{A\gamma N}$</th>
<th>$g_{a\gamma g_{ae}}$</th>
<th>$g_{a\gamma g_{aN}}$</th>
<th>$g_{ae}g_{aN}$</th>
<th>$g_{N\bar{N}}$</th>
<th>Model dependency</th>
</tr>
</thead>
<tbody>
<tr>
<td>Light shining through wall</td>
<td>×</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>no</td>
</tr>
<tr>
<td>Polarization experiments</td>
<td>×</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>no</td>
</tr>
<tr>
<td>Spin-dependent 5th force</td>
<td>×</td>
<td>×</td>
<td></td>
<td></td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>no</td>
</tr>
<tr>
<td>Helioscopes</td>
<td>×</td>
<td></td>
<td></td>
<td>×</td>
<td>×</td>
<td></td>
<td></td>
<td></td>
<td>Sun</td>
</tr>
<tr>
<td>Primakoff-Bragg in crystals</td>
<td>×</td>
<td></td>
<td></td>
<td>×</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>Sun</td>
</tr>
<tr>
<td>Underground ion. detectors</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td></td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td>Sun*</td>
</tr>
<tr>
<td>Haloscopes</td>
<td>×</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>DM</td>
</tr>
<tr>
<td>Pick up coil &amp; LC circuit</td>
<td>×</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>DM</td>
</tr>
<tr>
<td>Dish antenna &amp; dielectric</td>
<td>×</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>DM</td>
</tr>
<tr>
<td>DM-induced EDM (NMR)</td>
<td>×</td>
<td>×</td>
<td>×</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>DM</td>
</tr>
<tr>
<td>Spin precession in cavity</td>
<td>×</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>DM</td>
</tr>
<tr>
<td>Atomic transitions</td>
<td>×</td>
<td>×</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>DM</td>
</tr>
</tbody>
</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
\[ \mathcal{L}_{\text{ALP-int.}} = -\frac{g_{\alpha \gamma}}{4} F_{\mu \nu} \tilde{F}^{\mu \nu} a - a \sum_f g_{af} i \bar{f} \gamma^5 f - a F_{\mu \nu} \sum_f \frac{\bar{g}_{\alpha \gamma f}}{2} i \bar{f} \sigma^{\mu \nu} \gamma^5 f + \ldots \]

\[ -\frac{\bar{g}_{\alpha \gamma}}{4} F_{\mu \nu} F^{\mu \nu} a - a \sum_f \bar{g}_{af} \bar{f} \bar{f} \]

\[ g_{Af} \equiv \frac{C_{Af} m_f}{f_A} = 1.75 \times 10^{-13} C_{Af} \frac{m_f}{\text{GeV}} \frac{m_A}{\mu\text{eV}}, \]

\[ g_{A\gamma} \equiv \frac{\alpha}{2\pi} \frac{C_{A\gamma}}{f_A} = 2.0 \times 10^{-16} C_{A\gamma} \frac{m_A}{\mu\text{eV}} \text{GeV}^{-1}, \]

\[ \bar{g}_{A\gamma n} \equiv \frac{C_{A\gamma n}}{m_n f_A} = 6.4 \times 10^{-16} \frac{m_A}{\mu\text{eV}} \text{GeV}^{-2}, \]
“Common coil” configuration chosen
- **Minimal risk**: conservative design choices
- **Cost-effective**: Best use of existing infrastructure (tooling) at CERN
- **Prototyping** character: winding layout very close to that of IAXO toroidal design.
BabyIAXO optics

- 2 detection lines in BabyIAXO
- Optics:
  - IAXO Custom segmented-glass optics and flight spare XMM optics from ESA
  - Prototyping + physics considerations
  - Risk reduction for final IAXO segmented-glass optics
  - XMM optics specs very close to IAXO optics design
  - ESA preliminary support to the use of XMM optics in BabyIAXO (2 XMM optics exist)
BabyIAXO detectors

- **Detectors (baseline option):**
  - 2 “microbulk” Micromegas detectors
  - “Discovery detectors” (priority to low background)
  - Experience in CAST
  - Low background capability, radiopurity, shielding.

- **Beyond baseline:**
  - “high precision” detectors (post-discovery?)
  - Better threshold & resolution
  - 2 low-background Micromegas setups
  - R&D in several technologies: GridPix, MMCs, TES, NTD, SSD.
BabyIAXO platform & infrastructure

• Existing CTA MST mount matches BabyIAXO specs remarkably well

• HERA South hall: perfect site for BabyIAXO
BabyIAXO: beyond baseline

• Baseline program is realistic and low-risk. No pending R&D.

• After that, the BabyIAXO infrastructure would be available for further activities “beyond-baseline”
• New detectors with improved performance to: 1) extended physics runs or 2) preparatory tests for IAXO (in the event of a discovery, high-precision detectors)
• Implementation of “haloscope” schemes inside the BabyIAXO magnet (RF cavities or other resonant structures)
• Assist the final IAXO program with ancillary actions.
• Definition of “beyond-baseline” BabyIAXO program will depend on future R&D results.
IAXO collaboration

17 institutions from Germany, Spain, US, France, Russia, Italy, Croatia, S. Africa, CERN.
Know-how portfolio nicely encompasses IAXO needs:

- Likely to grow in the future, more groups showing interest...
- Work Breakdown Structure being defined.
# BabyIAXO (& IAXO) timeline

<table>
<thead>
<tr>
<th></th>
<th>2019</th>
<th>2020</th>
<th>2021</th>
<th>2022</th>
<th>2023</th>
<th>2024</th>
<th>2025</th>
<th>2026</th>
<th>2027</th>
<th>2028</th>
<th>2029+</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Design</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Construction</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Commissioning</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Vacuum phase</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Upgrade to gas</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Gas phase</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Beyond-baseline</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>IAXO</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Design</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Construction</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

**Tentative**

ESSP Granada, 14-May-2019

Igor G. Irastorza
IAXO magnet & optics

IAXO magnet
- Superconducting “detector” magnet.
- Toroidal geometry (8 coils)
- Based on ATLAS toroid technical solutions.
- CERN+CEA expertise
- 8 bores / 20 m long / 60 cm Ø per bore

IAXO telescopes
- Slumped glass technology with multilayers
- Cost-effective to cover large areas
- Similar to NuSTAR optics
- Focal length ~5 m
- 60-70% efficiency
- LLNL+UC+DTU + MIT + INAF

Baseline developed at:
IAXO low background MM detectors

- Goal background level for IAXO:
  - $10^{-7} - 10^{-8}$ c keV$^{-1}$ cm$^{-2}$ s$^{-1}$
- Already demonstrated:
  - $\sim 8 \times 10^{-7}$ c keV$^{-1}$ cm$^{-2}$ s$^{-1}$
    (in CAST 2014 result)
  - $10^{-7}$ c keV$^{-1}$ cm$^{-2}$ s$^{-1}$
    (underground at LSC)

- Active program of development.
- IAXO-D0 test-platform to explore background sources and improve levels
GridPix detectors (U. Bonn):
- Micromegas on top of a CMOS chip (Timepix)
- Very low threshold (tens of eV)
- Tested in CAST

Typical X-ray event
Single e- visible

MMC detectors (U. Heidelberg):
- Extremely low threshold and energy resolution (~eV scale)
- Low background capabilities under study

Also:
- Transition Edge Sensors (TES)
- Silicon Drift Detectors (SDD)
Other types of helioscope

• Instead of magnetic field, one can use the electromagnetic field of crystals…

• « Primakoff-Bragg » effect

• WIMP-like experiments provide limit to axions: SOLAX, COSME, DAMA, EDELWEISS, CDMS, etc…

• Characteristical temporal pattern:
Other types of helioscope

- «TPC in a magnetic field»: conversion and absorption happening in the gas
- Competitive only for high axion mass ~0.1-10 eV
- No coherence, but large volume can compensate. Also no preferred direction, so no tracking needed

Galán et al, arXiv:1508.03006

ESSP Granada, 14-May-2019
Igor G. Irastorza
Axion helioscopes

Axion helioscope concept
P. Sikivie, 1983
(use of buffer gas)

\[ P_{a\gamma} = 2.6 \times 10^{-17} \left( \frac{B}{10 \text{T}} \right)^2 \left( \frac{L}{10 \text{ m}} \right)^2 \left( g_{a\gamma} \times 10^{10} \text{ GeV} \right)^2 \Phi \]
Buffer gas for higher masses

Coherence condition ($qL \ll 1$) is recovered for a narrow mass range around $m_\gamma$

\[ |q| = \frac{m_a^2 - m_\gamma^2}{2E} \]

$N_e$: number of electrons/cm$^3$
$r$: gas density (g/cm$^3$)
IAXO magnet

TOROIDAL CONFIGURATION specifically built for axion physics

Each conversion bore (between coils) 600 mm diameter

Magnetic length 20 m Total cryostat length 25 m

Cryostat

Cold mass

Bores go through cryostat

Cryostat Cold mass

Inclination System

Support Frame

Flexible Lines

Rotating Disk

Rotation System

Services

Telescopes

Cryostat
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 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 available
- Hardware can be easily configured to make optics with a variety of designs and sizes
IAXO x-ray optics

Telescopes

\( N \), Layers (or shells) per telescope

Segments per telescope

Geometric area of glass per telescope

Focal length

Inner radius

Outer Radius

Minimum graze angle

Maximum graze angle

Coatings

Pass band

IAXO Nominal, 50% EEF (HPD)

IAXO Enhanced, 50% EEF (HPD)

IAXO Nominal, 80% EEF

IAXO Enhanced, 90% EEF

FOV

8

123

2172

0.38 m²

5.0 m

50 mm

300 mm

2.63 mrad

15.0 mrad

W/B₄C multilayers

1–10 keV

0.29 mrad

0.23 mrad

0.58 mrad

0.58 mrad

2.9 mrad

Optimal focal length \( \approx 5 \) m

IAXO optics conceptual design

IAXO low background detectors

- 8 detector systems
- Baseline: small Micromegas-TPC chambers:
  - Shielding
  - Radiopure components
  - Offline discrimination
IAXO technologies – Baseline

IAXO detectors
- Micromegas gaseous detectors
- Radiopure components + shielding
- Discrimination from event topology in gas
- Long trajectory in CAST
- Zaragoza + CEA + Bonn + others expertise

Ingrid detectors
- Better threshold
- U. Bonn

MMC (Magnetic Metallic Calorimeters)
- TES (Transition Edge Sensors)
- Very good E resolution & threshold
- Heidelberg + CEA + CNSMS

Low noise CCDs

Solar axion spectroscopy:
Axion-electron ABC spectrum
Axion mass determination

Optics+detector IAXO pathfinder system
(in operation in CAST during 2014-5)

Calibration photons (source 14 m away) focused onto the Micromegas
Additional physics cases

- Use of (Baby)IAXO large magnetic volume for axion DM setups.
- Various possible arrangements in IAXO. Leverage 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? → e.g. RADES R&D
  3. Pick-up coils for very low mass detection

RADES concept: array of small cavities interconnected with irises:

Installed successfully in CAST last year, and first engineering run took place Nov-Dec 2017
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.

sensitivity prospects to be considered tentative
RADES

Haloscope FOM:

\[ \mathcal{F} \sim g_{a\gamma}^4 m_a^2 B^4 V^2 T^{-2} C^2 Q \]

- RADES concept: array of small cavities interconnected with irises:
  - No need to phase match externally
  - Clear prescription to optimize coupling to axion:
  - Robust and flexible scaling up
  - Preference for long aspect-ratio: CAST (and IAXO) magnets
  - Problem: how to tune.

- First RADES cavity with 5 subcavities, non-tunable (f = 8.5 GHz; \( m_a = 34.75 \ \mu\text{eV} \))

\[ V \text{ is usually linked with } m_a \ (V \sim 1/m_a^3) \] how to go to much higher \( V \) and higher \( m_a \)?
Installed successfully in CAST last year, and first engineering run took place Nov-Dec 2017
Sensitivity to (optimistically coupled) QCD axions with this very simple setup. Only a factor of a few away from KSVZ. [But at a fixed $m_a$ value]

Challenge for next runs:
- Larger cavities
- Tuning
IAXO physics case grows…

Distinguishing axion models with IAXO
Jaeckel et al. arXiv:1811.09278

“Weighing” the solar axion
Dafni et al. arXiv:1811.09278

Axion-DM explanation of EDGES 21 cm observation
Houston et al. arXiv:1812.03931
• **Summary of current status and future prospects...**

• A diverse experimental landscape has emerged with potential to cover a substantial fraction of parameter space

• **Caution**: many of these prospects still rely on a prior successful R&D phase

• **Caution**: Green areas rely on axion as DM hypothesis...