Axion helioscopes update: the status of CAST & IAXO

T. Dafni[1] & F.J. Iguaz[2]
On behalf of CAST & IAXO collaborations
TIPP 2014 Conference- 5th June 2014

Universidad Zaragoza 1542
(1) tdafni@unizar.es   (2) iguaz@unizar.es

Work partially supported by Juan de la Cierva program

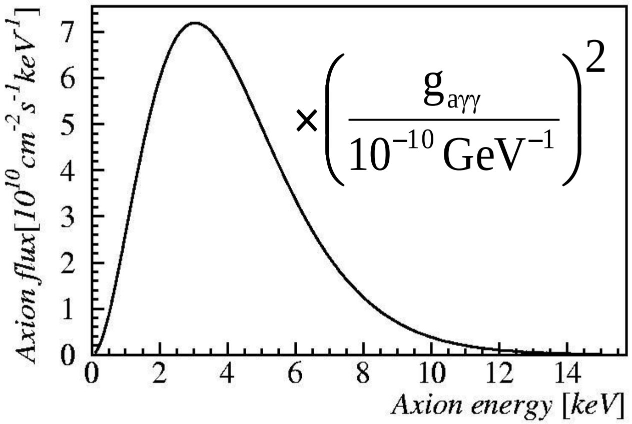
Outline

- Axion physics.
- The CAST experiment: description & results.
- The future IAXO experiment: description & status.
- Summary

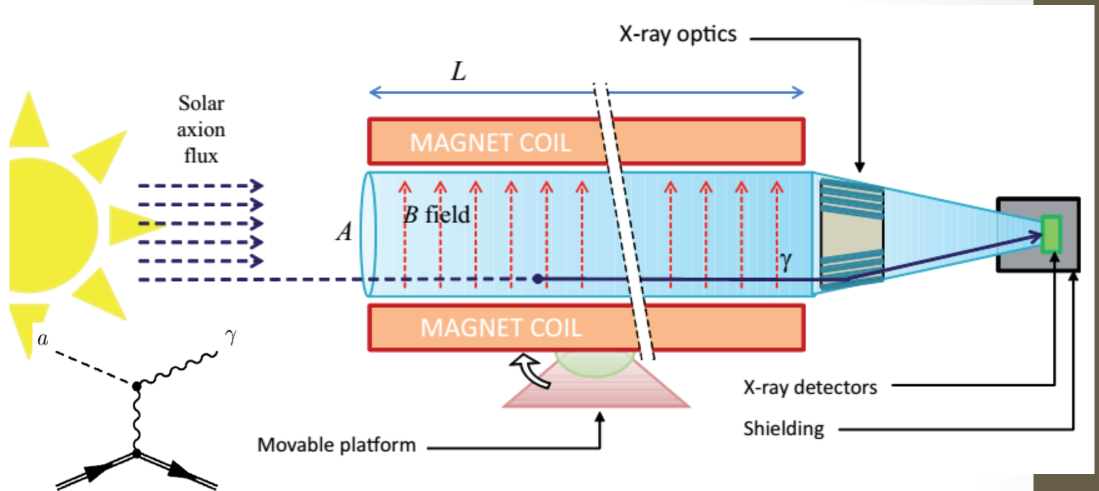
Axions

- Axions are the most elegant solution to the Strong CP problem (why QCD does not seem to break the CP symmetry):
  - Pseudoscalar particles, neutral, practically stable.
- Candidates for both cold and hot dark matter.
- Axion-like particles (ALPs) are predicted by many extensions of the Standard Model
- Relevant axion/Axion-Like Particles parameter space at reach of current and near-future experiments
- New theory scenarios: string theory predicts axions/ALPs with detectable parameters
- Astrophysical hints for axion/ALPs?
  - transparency of the Universe to UHE gammas
  - white dwarf cooling anomaly $\rightarrow$ point to few meV axions

Axion detection by an helioscope



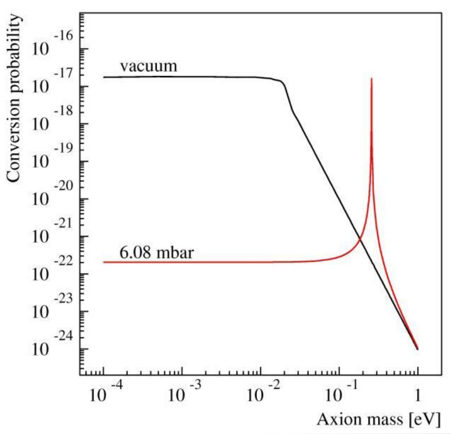
Serpico & Raffelt, JCAP04 (2007) 010



Production: *Primakoff effect.*
Thermal photons interacting with solar nuclei produce axions.

Detection: *inverse Primakoff* (Sikivie 1983)
Axions in a magnetic field convert to photons.
Expected x-ray excess when the magnet points to the Sun.

- Conversion probability depends on medium.
- In vacuum coherence is lost for $m_a > 0.02$ eV.
- In the presence of a buffer gas, the coherence can be restored for a narrow mass range.



CAST: CERN Axion Solar Telescope

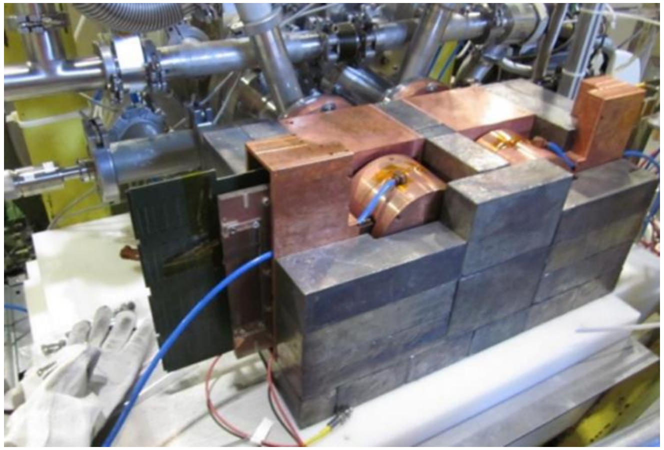
Description of CAST:

- Decommissioned prototype LHC dipole magnet. Length = 9.3 m. Field = 9 T.
- Range of movement: 80º horizontally and ± 8º vertically.
- Solar tracking possible during sunrise and sunset (2 x 1.5 h per day).

Detectors in 2010-2:

- Sunrise: x-ray focusing device + CCD / Micromegas.
- Sunset: 2 Micromegas detectors.

CAST detectors



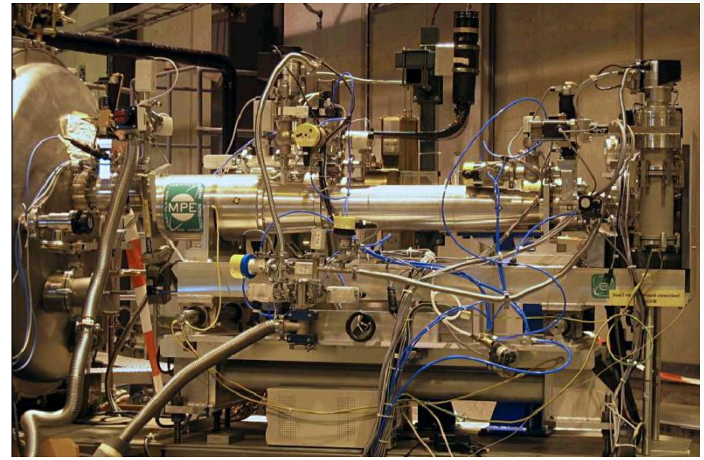
CAST-Micromegas at Sunset

Micromegas microbulk detectors

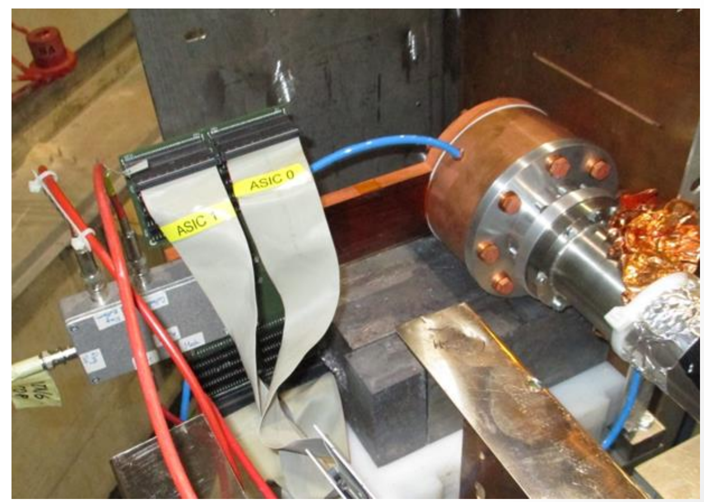
- High power to discriminate x-rays.
- Low intrinsic radiopurity.
- Shielding techniques applied.
- **JINST 9 (2014) P01001.**

X-ray telescope + CCD

- Telescope: prototype of ABRIXAS mission.
- CCD: Excellent spatial & energy resolution. SN~150 due to simultaneous measurement.
- **New J. Phys. 9 (2007) 169.**



X-ray telescope + CCD



CAST-Micromegas at Sunrise

CAST Physics Program

1) CAST Phase I, Vacuum

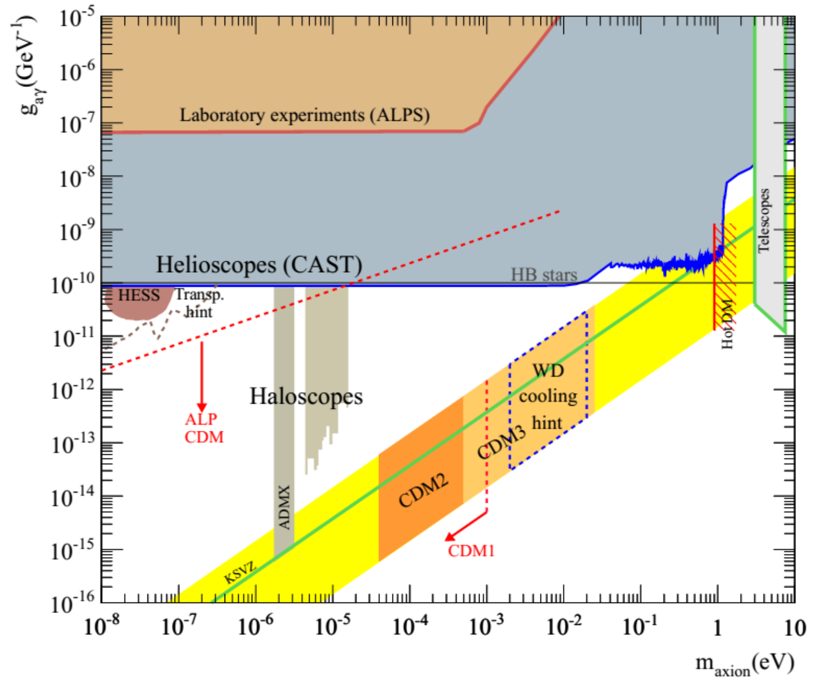
- $m_a < 0.02$ eV
- $g_{a\gamma\gamma} \lesssim$ **0.88 × 10^{-10} GeV^{-1}**
- **PRL94 (2005) 121301** & **JCAP04(2007)020.**

2) CAST Phase II, ^{4}He

- P < 13.4 mbar (1.8K), 160 steps
- 0.02 eV < m_a < 0.39 eV
- $g_{a\gamma\gamma} \lesssim$ **2.2 × 10^{-10} GeV^{-1}**
- **JCAP02 (2009) 008.**

3) CAST Phase II, ^{3}He

- P < 120 mbar (1.8K), 160 steps
- 0.39 eV < m_a < 1.17 eV
- $g_{a\gamma\gamma} \lesssim$ **3.3 × 10^{-10} GeV^{-1}**
- **PRL 107 (2011) 261302** & **PRL 112 (2014) 091302**



Parallel searches:

- HE axions: **JCAP 1003 (2010) 032**.
- 11.4 keV axions from M1 transitions: **JCAP 0912 (2009) 002**.
- LE (visible) axions: **arXiv:0809.4581**.
- Constrains on axion-electron coupling: **JCAP 1305 (2013) 010**

CAST: latest results & current activites

Latest results:

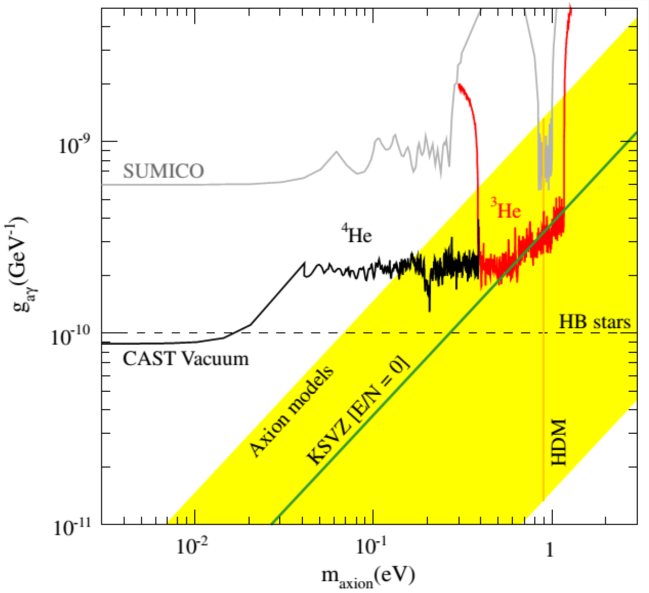
- ^{3}He phase results recently published: PRL 112 (2014) 091302 (only mM).
- Axion mass 0.64 – 1.17 eV excluded down to **~3.3 × 10^{-10} GeV^{-1}**.
- Paper on the simulation of gas dynamics inside the magnet in preparation.

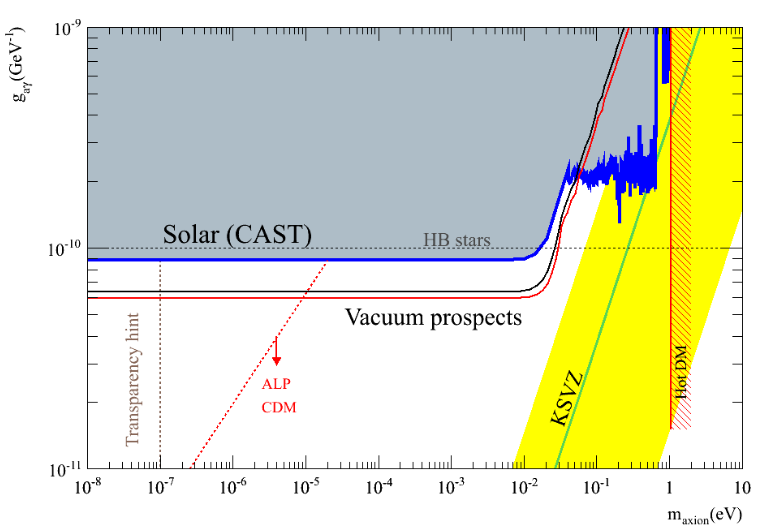
Current activities:

- Revisiting the vacuum phase with three high performance microbulk detectors.
- Seach of exotic physics (chameleons, paraphotons, low energy axions).

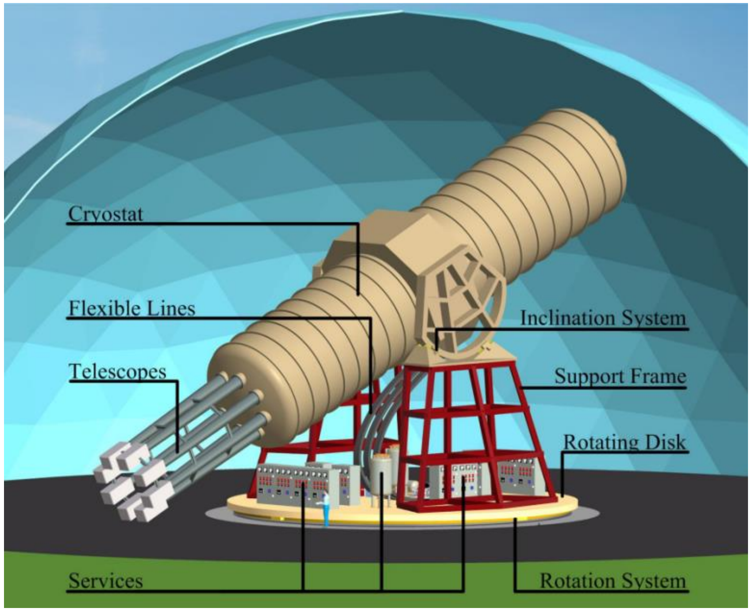
Detector updates:

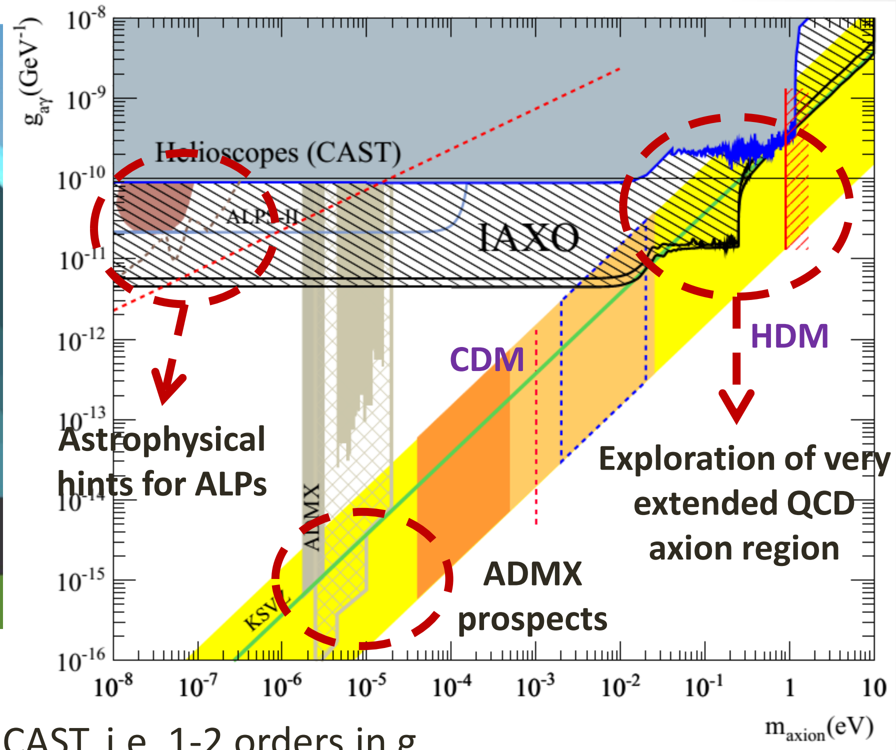
- An x-ray optics will increase the sensitivity of Sunrise detector.
- InGrid micromegas and Silicon Drift Detectors (SDD) are tested.





IAXO: International AXion Observatory

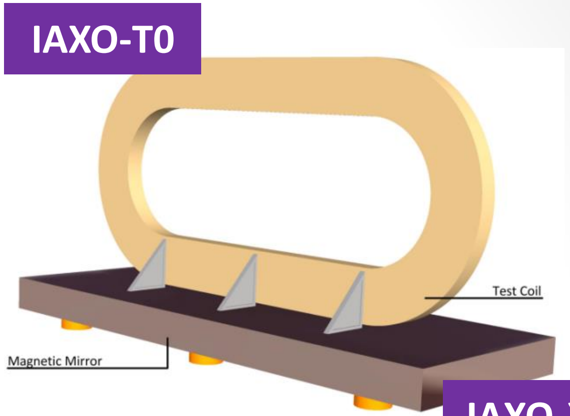


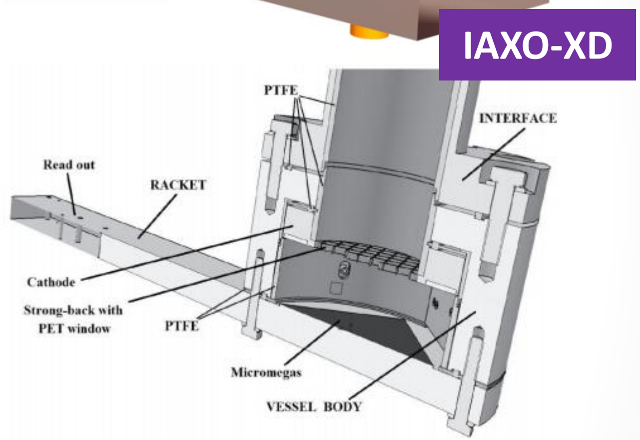


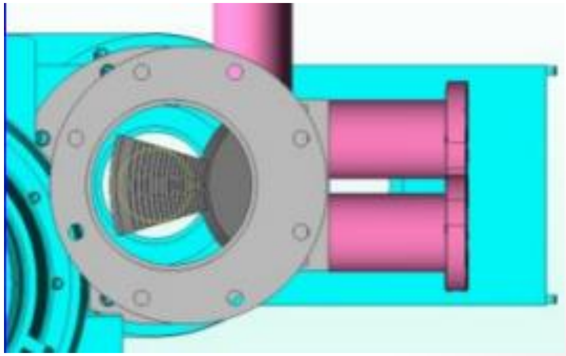
- New generation of axion helioscope.
- 4 orders of magnitude better in S/N wrt CAST, i.e. 1-2 orders in $g_{a\gamma}$.
- New features: toroidal magnet, dedicated optics, low background detectors.
- CAST & ADMX can explore a big part of the axion model region in next decade.
- Potential for new physics: white dwarfs, ALPs, low energy axions…
- Ideas under discussion to explore μeV axions (resonant cavities, antenna dishes).
- More details: IAXO-CDR (**2014 JINST 9 T05002**) & NGAH (**JCAP 06 (2011) 013**).

Status of IAXO

- 90 signatures. 38 institutions. Enlarged community interested in IAXO physics.
- In International roadmaps of Europe (**ASPERA/APPEC, ESPP**) & US (**Snowmass**).
- Conceptual Design: **2014 JINST 9 T05002**.
- Letter of Intent presented at CERN-SPSC on 22th Oct 2013: **SPSC-2013-022**.
- Positive recommendations from SPSC.
- Preparation of a MoU to carry out TDR work. Search for new interested partners.
- Several preparatory activities in parallel for the Technical Design Report (TDR):
  - **IAXO-T0**: a demonstration coil.
  - **IAXO-X0**: a prototype x-ray optics.
  - **IAXO-DO**: a low background detector.
  - **Pathfinder**: a small optics & detector at CAST. The same techniques as for IAXO.

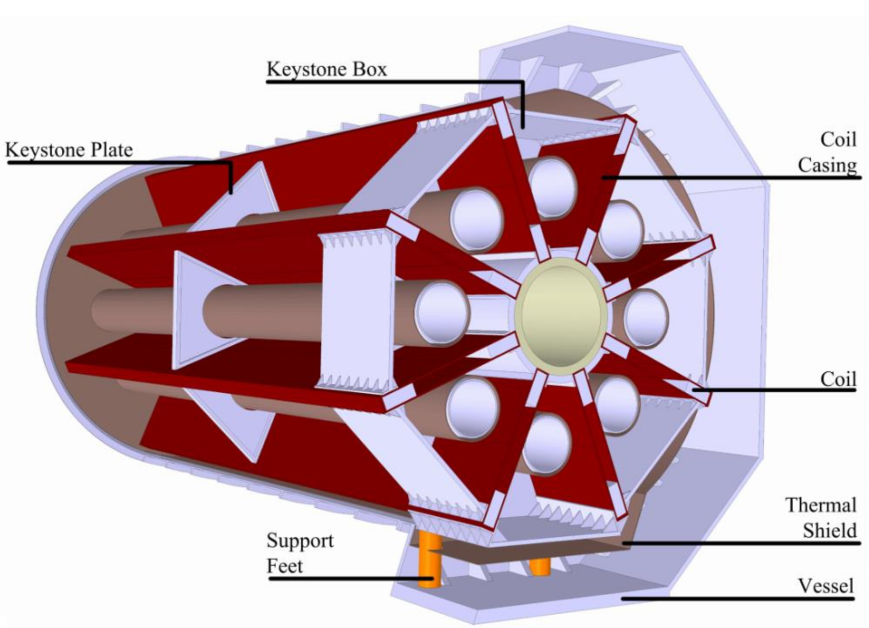


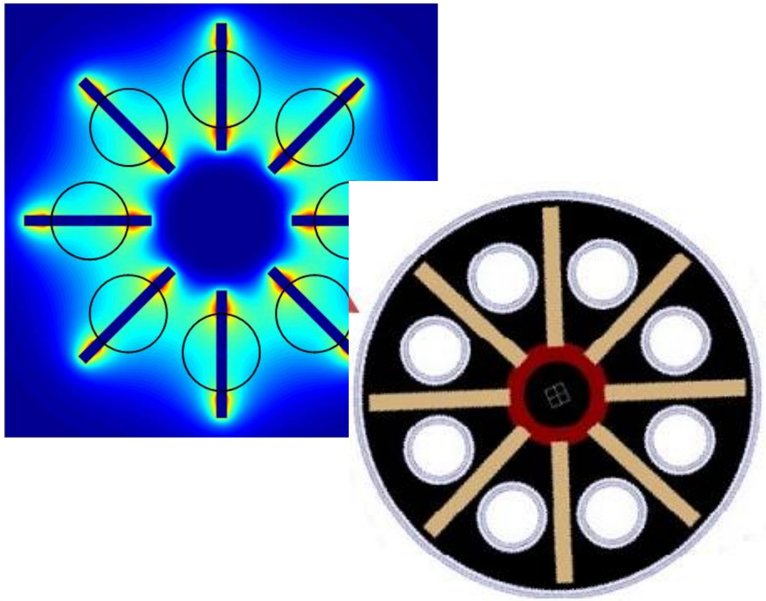




IAXO Magnet

- Large toroidal 8-coil magnet specifically built for axion physics.
- Many technical aspects studied and defined in the CDR.
- Magnetic length: 20 m.
- Bore diameter: 0.6 m.
- IAXO-T0 project to build a test coil.



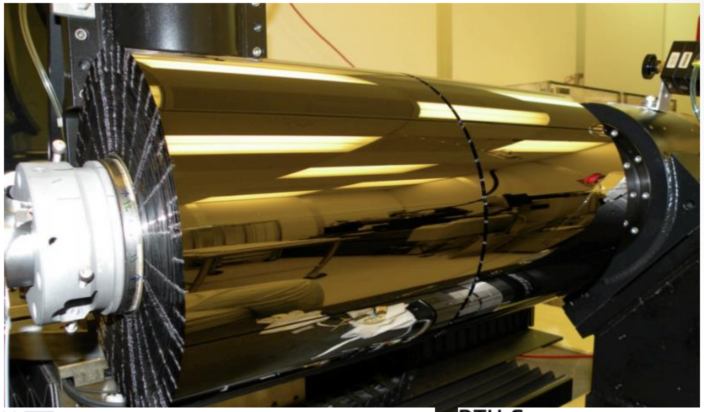


IAXO magnet concept presented in:

- IEEE Trans. Appl. Supercond. 23 (ASC 2012)
- Adv . Cryo. Eng. (CEC/ICMC 2013)
- IEEE Trans. Appl. Supercond. (MT 23)

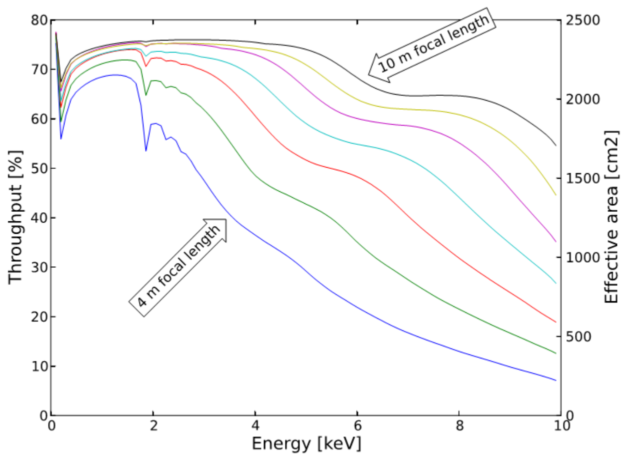
IAXO Optics

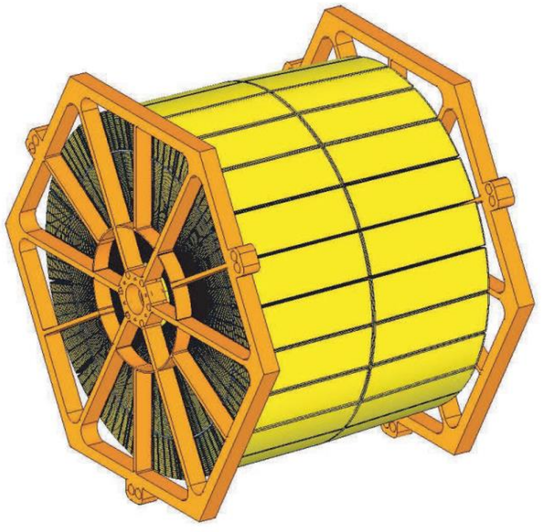
- Technique of choice: optics made of thin glass substrates coated to enhance reflectivity in the energy regions for axions. Used in NuSTAR/HEFT project.
- Optimization study to maximize the efficiency in the focussing power:
- Diameter: 600 mm. Focal length: 10 m.
- First realistic drawings made.
- New telescope for CAST in construction.



Lawrence Livermore National Laboratory

DTU Space
National Space Institute

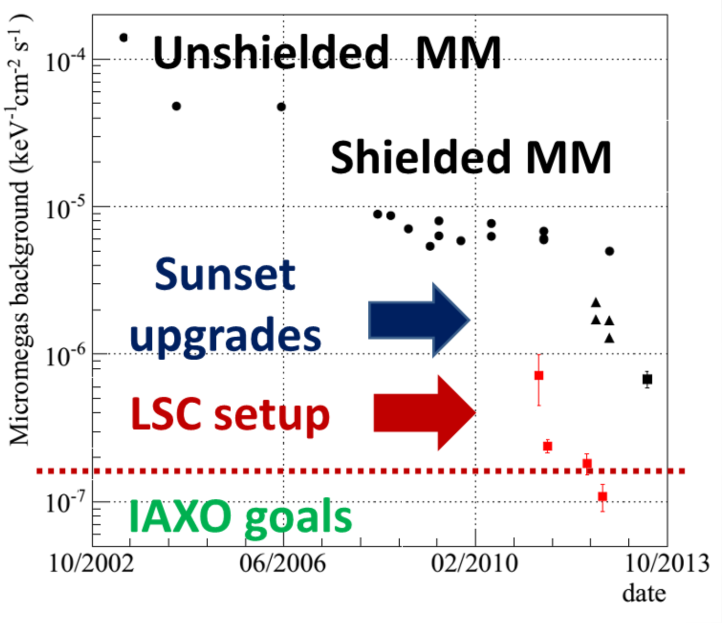




IAXO detector: Microbulk Micromegas

Why are they used in axion searches?

- High power to discriminate x-rays signals from other type of events.
- Intrinsic radiopure (***Astr . Part. 34 (2011) 354***).
- Consolidated manufacture (**JINST 5 (2010) P02001, JINST 7 (2012) P04007**).
- Shielding techniques from low background experiments can be also applied.



Status of Micromegas for IAXO

- Background levels below **10^{-6} s^{-1}keV^{-1}cm^{-2}** obtained **in CAST** for the first time.
- Levels at **10^{-7} s^{-1}keV^{-1}cm^{-2} at LSC**.
- Roadmap to reach IAXO levels, based on
  - In-situ measurements at CAST.
  - Replica at Canfranc Laboratory (LSC).
  - Geant4 simulations of CAST-MM.

Have a look at my poster on CAST-MM detectors for more details!!!

Summary

In the last 12 years, the **CAST experiment**

- has put the strictest limit on axion coupling for a wide range of masses and has gained extensive experience on Helioscope Axion Searches.
- has just published the first results of 3He phase (**PRL 112 (2014) 091302**): $\mathbf{g_{a\gamma\gamma} \lesssim 3.3 \times 10^{-10}\ GeV^{-1}}$ (95% CL) for $\mathbf{0.64\ eV < m_a < 1.17\ eV}$.
- is revisiting the vacuum phase to increase the sensitivity and explore other exotica like solar chamaleons, paraphotons, improve the LE setup.

The future is the **International Axion Observatory (IAXO)** which

- will improve on CAST results more than one order of magnitude.
- will use a dedicated magnet, large area optics and low background detectors.
- can explore a big part of axion models in next decade together with ADMX.
- has published its LoI (**SPSC-2013-022**) & CDR (**2014 JINST 9 T05002**).
- develops several activities for the TDR: test coil, optics, detectors,…

Back-up slides

Theoretical motivation for axions: the strong CP problem

CP-violation can explain in the standard model the matter-antimatter-asymmetry

CP is violated in weak interactions but not in strong ones: Neutron electric dipole moment not observed.

A possible solution is the elimination of the CP-violating term in QCD Langrangian by the introduction of an additional symmetry U(1)

$$L_a = C \frac{a}{f_a} \frac{g^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{\mu\nu}_a$$

$$m_a \simeq 0.6 \text{ eV} \frac{10^7 \text{GeV}}{f_a}$$

- New pseudo-scalar field: AXION
- First proposed by Peccei & Quinn (1977)
- Particle interpretation by Weinberg & Wilczek (1978)

Axion as Dark Matter candidate

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

  → **Non relativistic COLD AXIONS**
- Axion mass giving the right CDM density? Depends on cosmological assumptions:
  - "classical window": around 10^{-5}-10^{-3} eV
  - "anthropic window" ~ much lower masses possible
  - Other subdominant CDM / non standard scenarios

- Thermal production
  - Axion masses **ma > ~0.9 eV** gives densities too much in excess to be compatible with latest CMB.

Hannestad et al, JCAP 08 (2010) 001

→ **Relativistic HOT AXIONS**

What is the motivation of axions?

- Most compelling solution to the Strong CP problem of the SM.
- Axion-like particles (ALPs) predicted by many extensions of the Standard Model (like the string theory)
- Axions, like WIMPs, may solve the Dark Matter (DM) problem for free. (i.e. not an 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 to WIMPs.

CERN SPSC recommendations (Jan 2014)

*The Committee **recognizes 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 **encourage**s 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 r**ecommends** that the R&D for the TDR should be pursuit within **an MOU** involving all interested parties.*

IAXO in astroparticle roadmaps

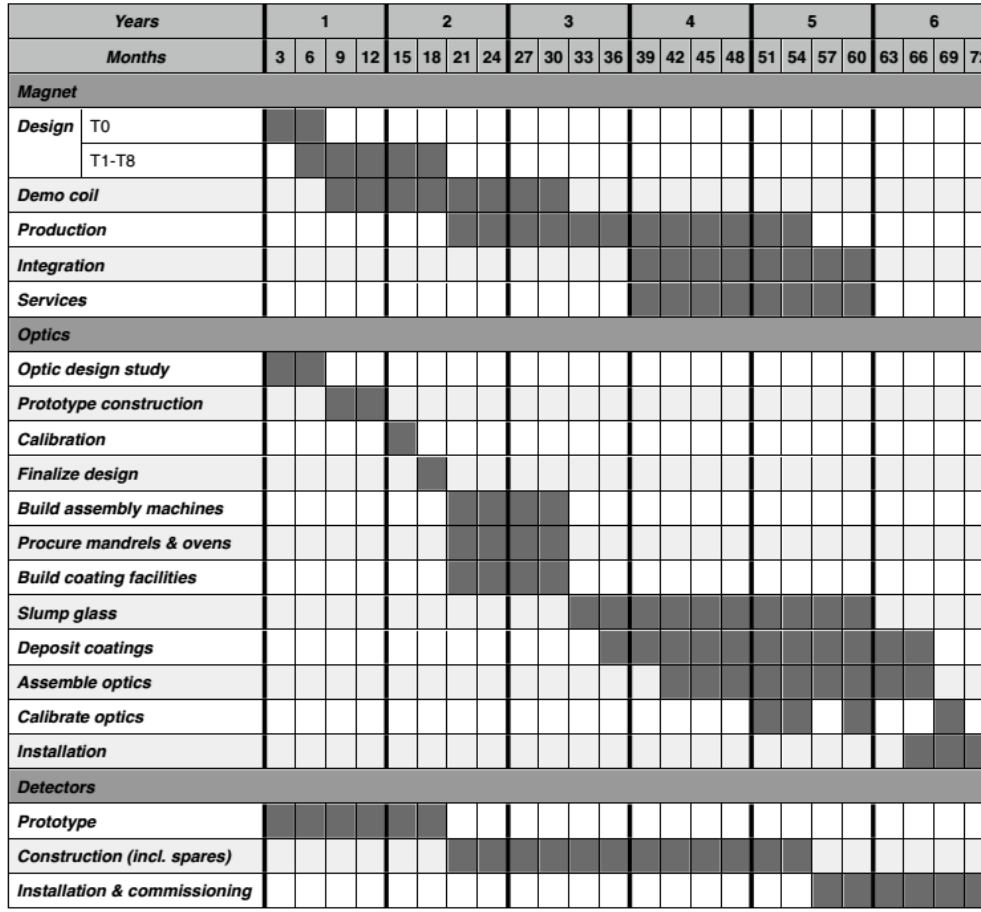
- **ASPERA/APPEC Roadmap** acknowledges axion physics, CAST, and **recommends** progress towards IAXO.

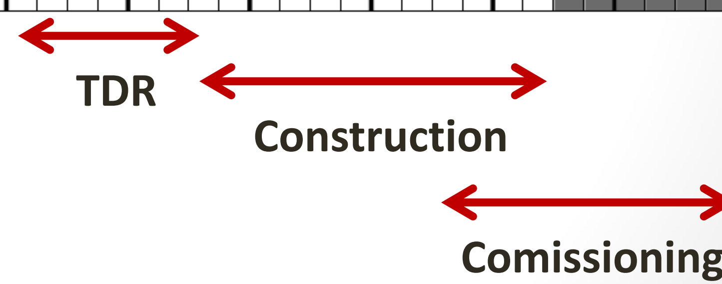
> "...A CAST follow-up is discussed as part of CERN's physics landscape (new magnets, new cryogenic and X-ray devices). The Science Advisory Committee **supports** R&D on this follow up, as well as smaller ongoing activities on the search for axions and axion-like particles."

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 recommends CERN to follow APPEC recommendations.**
- Important effort in relation with US roadmapping (Snowmass, and P5 process). **Snowmass reports speak very favorably of axion physics and IAXO.**

IAXO timeline





- TDR + preparatory activites: 1.5 years.
- Construction: 3.5 years.
- Integration & comissioning: 2.5 years.
- Total: **6 years**.

IAXO costs

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

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.

Laboratory engineering, maintenance & operation and physics exploitation not included