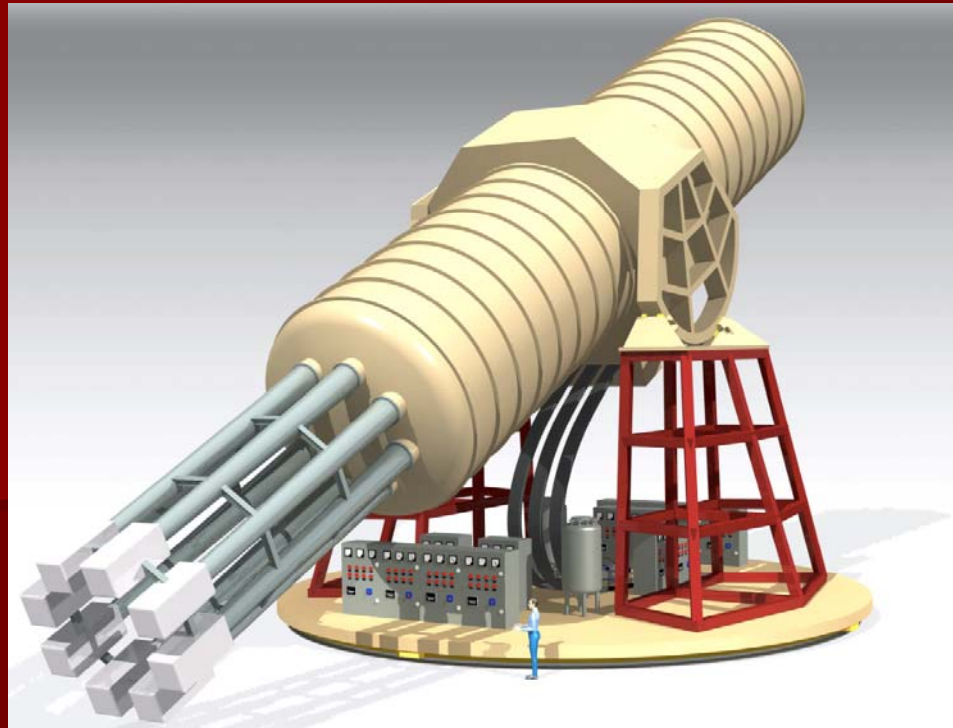


# Searches for axions with the International AXion Observatory IAXO

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Universidad de Zaragoza

*Workshop on Off-the-Beaten-Track Dark Matter  
and Astrophysical Probes of Fundamental Physics*  
Trieste, 13-17 April, 2015



# 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. Next steps
- Conclusions

Letter of Intent to the CERN SPSC  
**The International Axion Observatory**  
**IA XO**

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**IA XO Letter of Intent: CERN-SPSC-2013-022**

90 signatures / 38 institutions

**IA XO Conceptual Design: JINST 9 (2014) T05002 (arXiv:1401.3233)**

# Why axions?

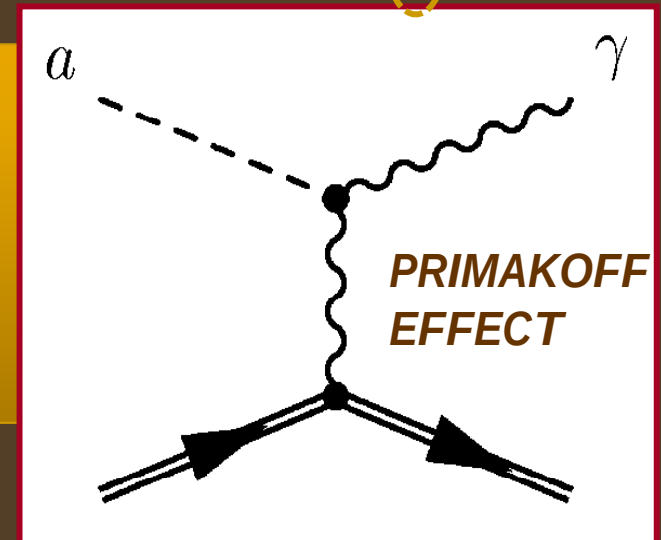
- **Strong CP problem:** why strong interactions seem not to violate CP?
  - CP violating term in QCD is not forbidden. But neutron electric dipole moment not observed
- Natural answer if Peccei-Quinn mechanism exists
  - New U(1) global symmetry  $\rightarrow$  spontaneously broken
  - Proposed in 1977

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



$$\frac{\alpha_s}{8\pi f_a} a G\tilde{G}$$

- As a result, new pseudoscalar, neutral and very light particle is predicted, the axion (Weinberg, Wilczek)
- It couples to the photon in every model



# Beyond axions

Hidden photons  
/ paraphotons

ALPS

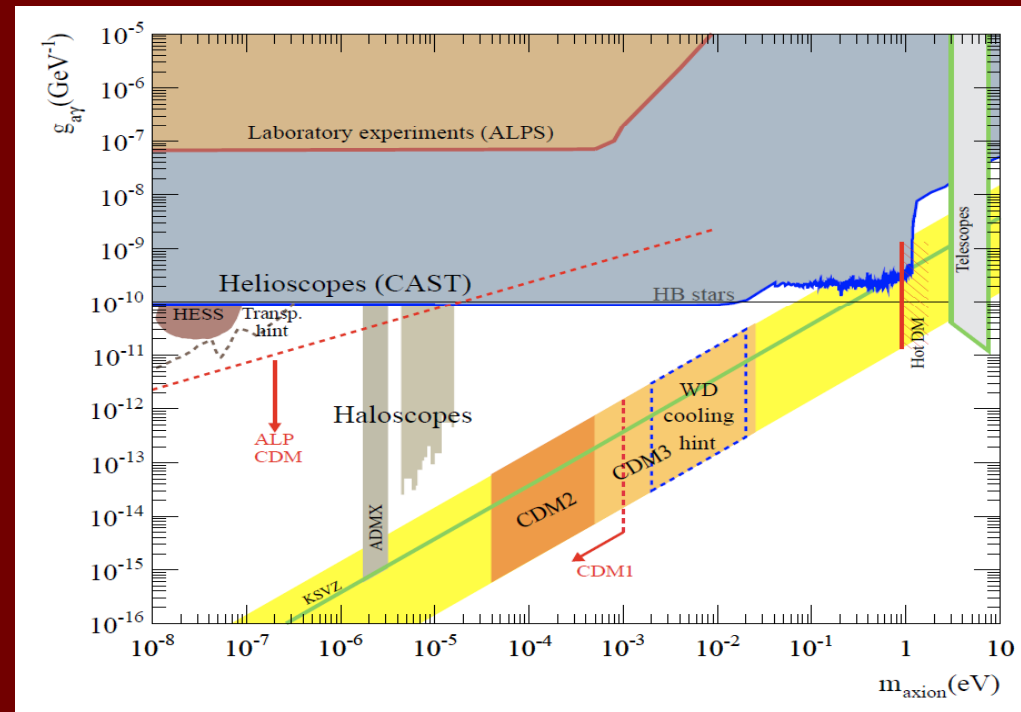
**AXIONS**

Chamaleons

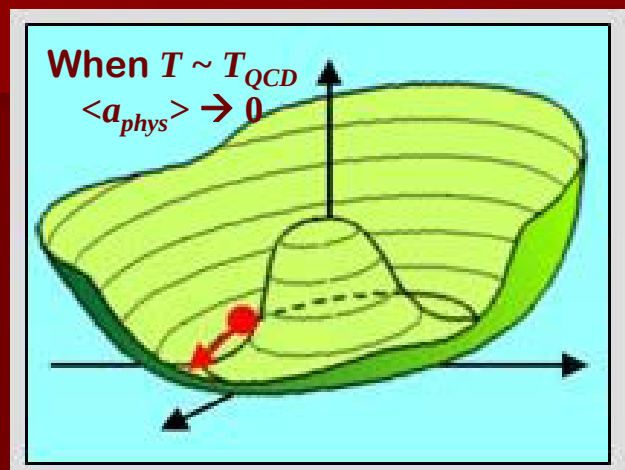
Minicharged  
particles

**WISPs** (Weakly interacting Sub-eV Particle)

- Diverse theory motivation
  - Higher scale symm. breaking
  - String theory
  - DM / DE candidates
  - Astrophysical hints
- Generic Axion-like particles (ALPs) parameter space →



# Non thermal cosmological axions



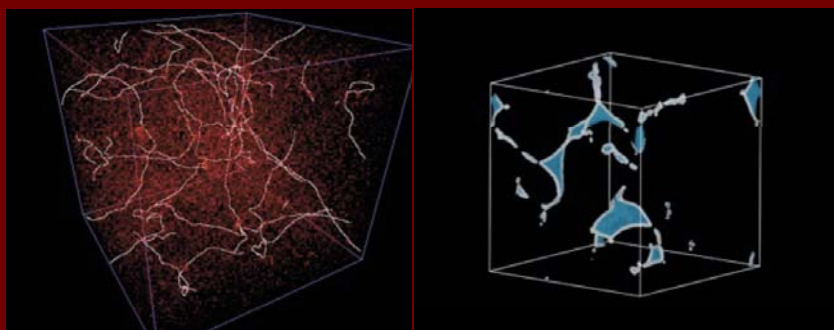
## Axion realignment

As the Universe cools down below  $T_{QCD}$ , space is filled with low energy axion field fluctuations.

Their density depends on the initial value of  $\langle a_{phys} \rangle$  (“misalignment angle”)



## But also... 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*

# Axions 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



**NON-RELATIVISTIC  
(COLD) AXIONS**

- Axion mass giving the right CDM density? Depends on cosmological assumptions:

- Post-inflation scenario (“classical window”)  $\sim 10^{-5} - 10^{-3} \text{ eV}$
- Pre-inflation scenario (“anthropic window”)  $\sim$  lower masses possible
- Higher masses  $\rightarrow$  subdominant CDM / non-standard scenarios

- **Thermal production**

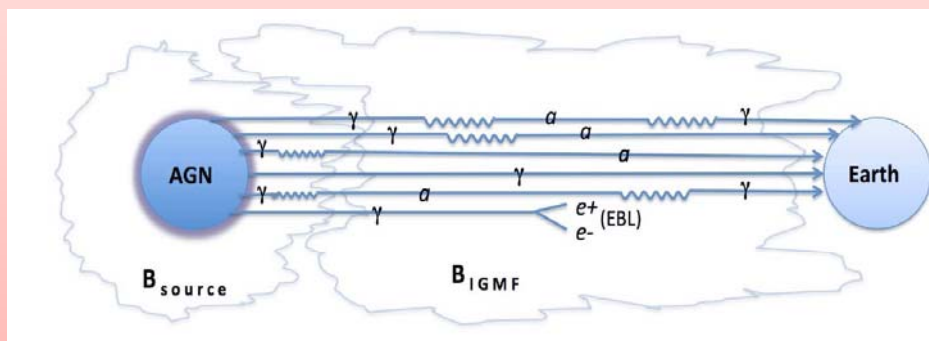


**RELATIVISTIC  
(HOT) AXIONS**

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

Hannestad et al, JCAP 08 (2010) 001 (arXiv:1004.0695)

# Astrophysical hints for axions(?)



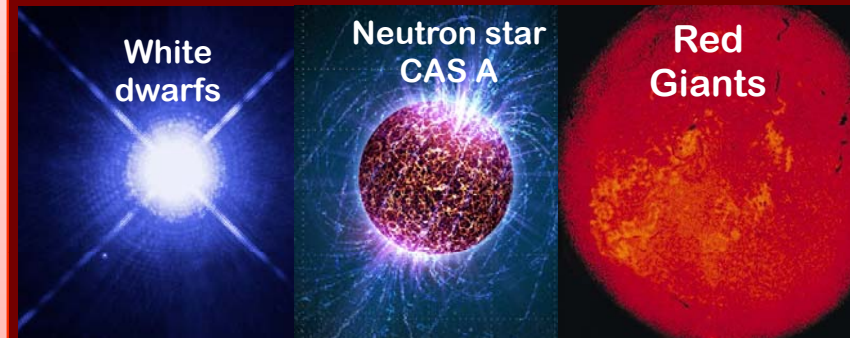
Gamma ray telescopes like MAGIC or HESS observe HE photons from very distant sources...



ALP:

$$g_{a\gamma} \sim 10^{-12} - 10^{-10} \text{ GeV}^{-1}$$

$$m_a \lesssim 10^{-(10-7)} \text{ eV}$$



However, diverse evidence of anomalous cooling has been observed in a number of stars...

Complex situation, but generally compatible with QCD axions with masses at the 10 meV scale...

# 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 effort devoted to axions when compared e.g. to WIMPs... (not justified...)

# 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.

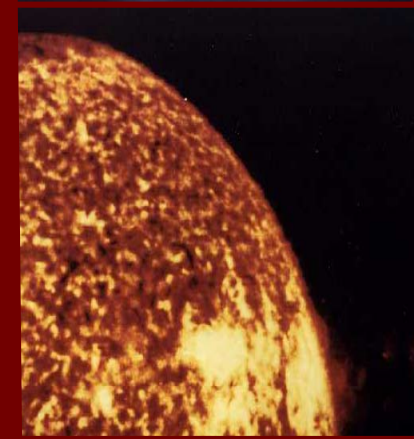
- Crystal detectors
- Axion Helioscopes

CAST @ CERN  
→ IAXO

## ■ Axions in the lab

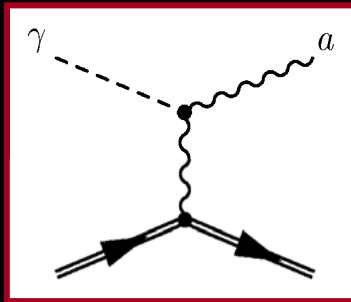
- “Light shining through wall” experiments
- Vacuum birefringence experiments

ALPS-II @ DESY  
OSQAR @ CERN



# Solar Axions

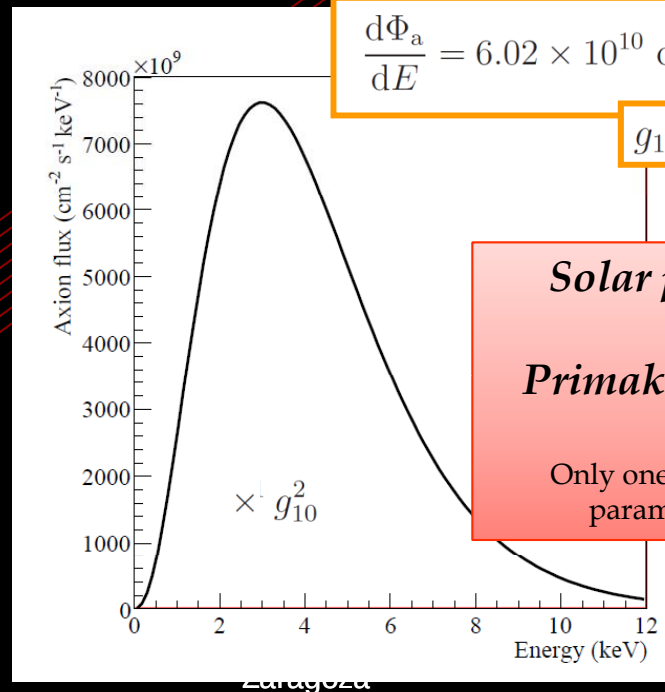
- Solar axions produced by photon-to-axion conversion of the solar plasma photons in the solar core



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

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

$$g_{10} = g_{a\gamma}/10^{-10} \text{ GeV}^{-1}$$

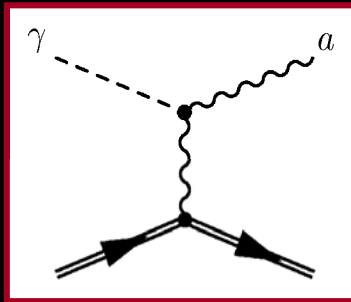


**Solar physics**  
+  
**Primakoff effect**

Only one unknown  
parameter  $g_{a\gamma}$

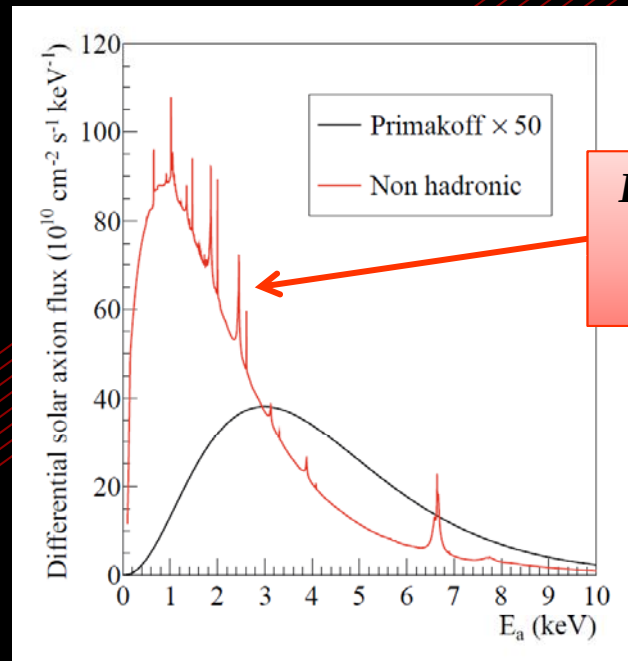
# Solar Axions

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



## ➤ “ABC” Solar axion flux

[J Redondo JCAP 1312 008]

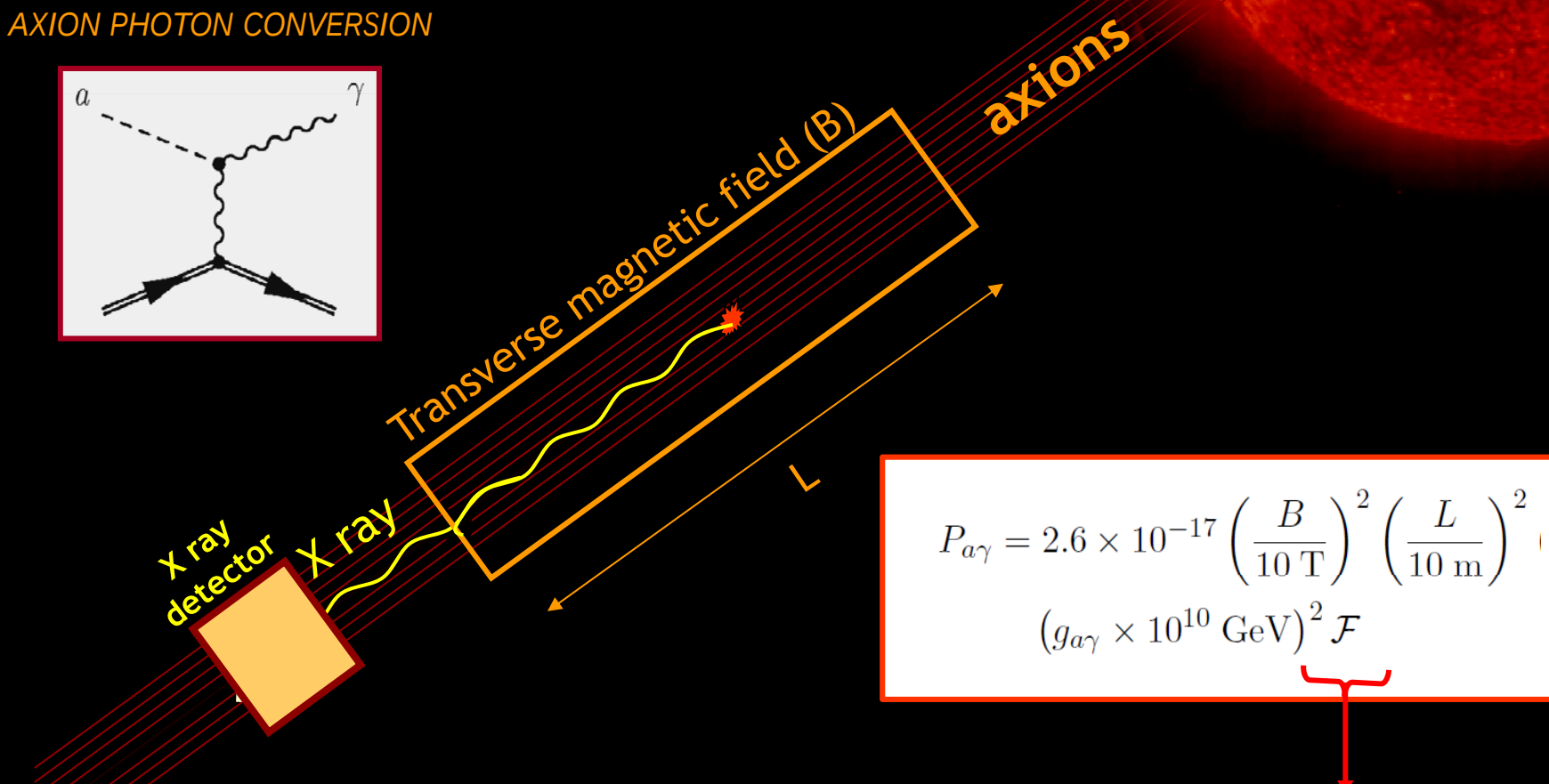
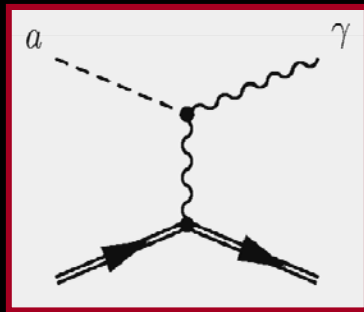


*If the axion couples with the electron ( $g_{ae}$ ) (non hadronic axion)*

# Axion Helioscope principle

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

## AXION PHOTON CONVERSION

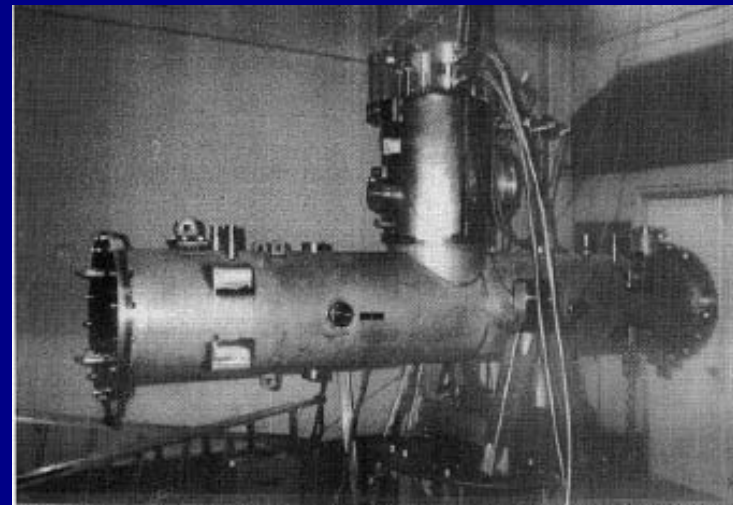
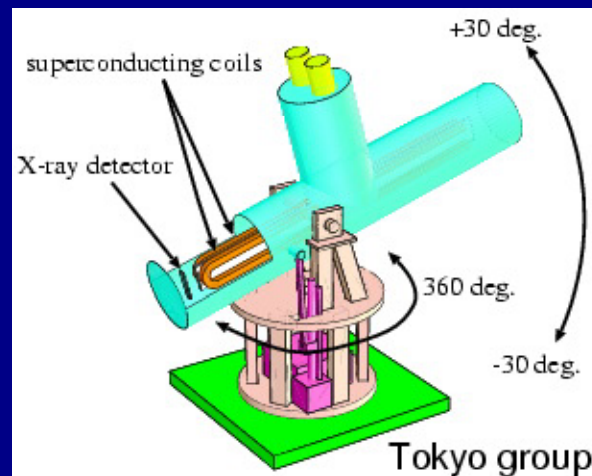


$$P_{a\gamma} = 2.6 \times 10^{-17} \left( \frac{B}{10 \text{ T}} \right)^2 \left( \frac{L}{10 \text{ m}} \right)^2 (g_{a\gamma} \times 10^{10} \text{ GeV})^2 \mathcal{F}$$

# 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

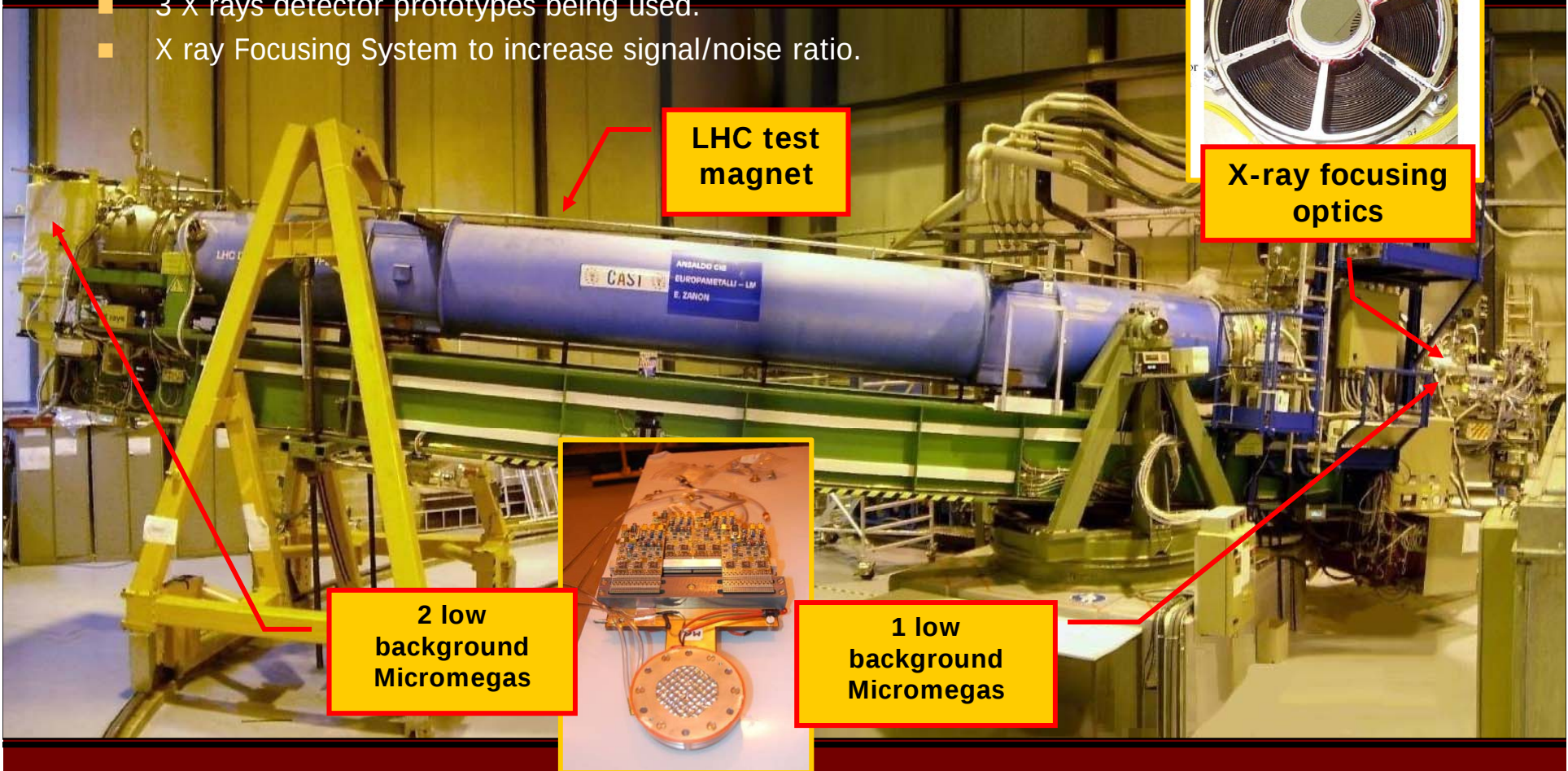


## ■ Presently running:

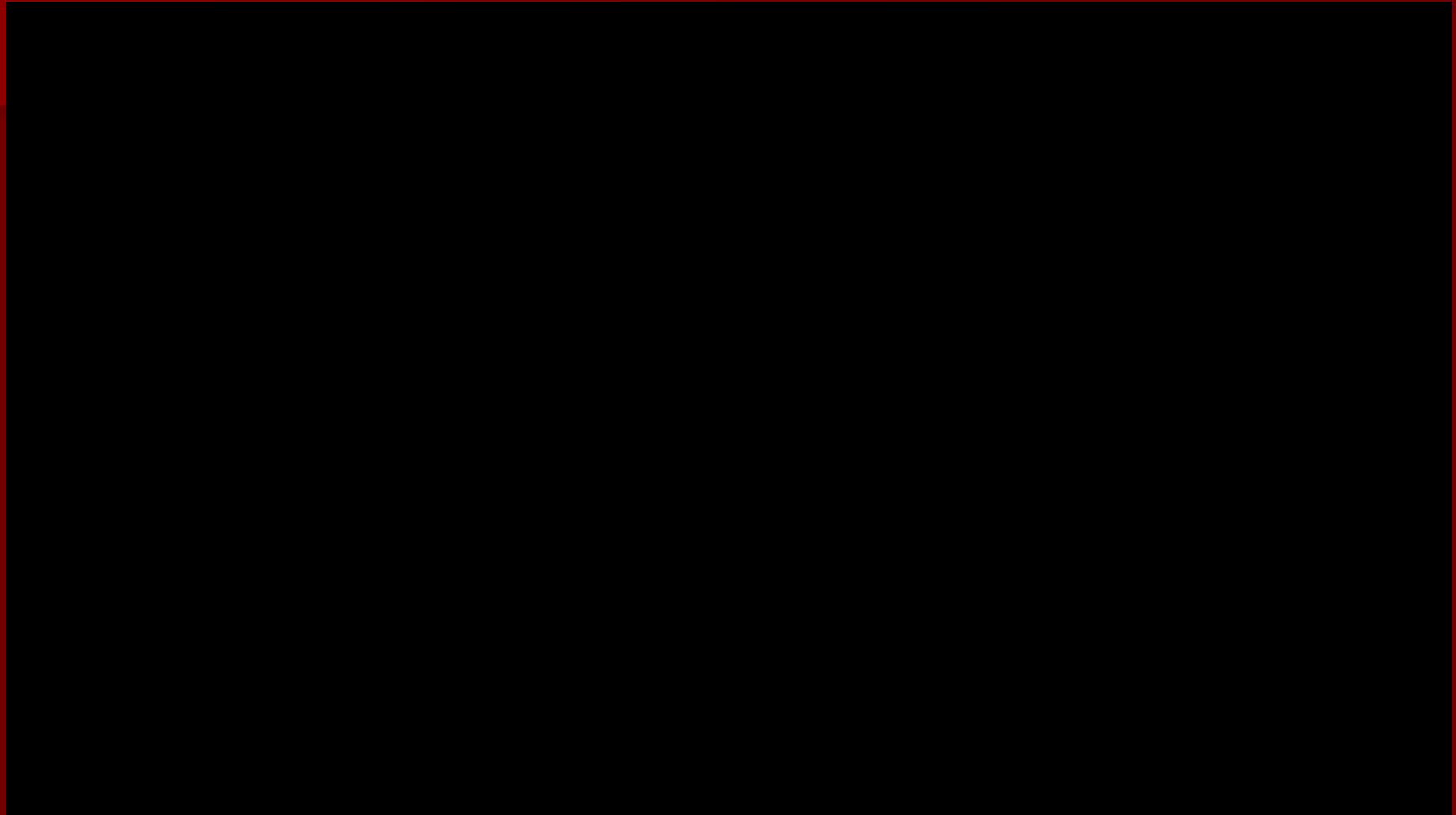
- CERN Axion Solar Telescope (**CAST**)

# CAST experiment @ CERN

- Decommissioned LHC test magnet (L=10m, B=9 T)
- Moving platform  $\pm 8^\circ V \pm 40^\circ H$  (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



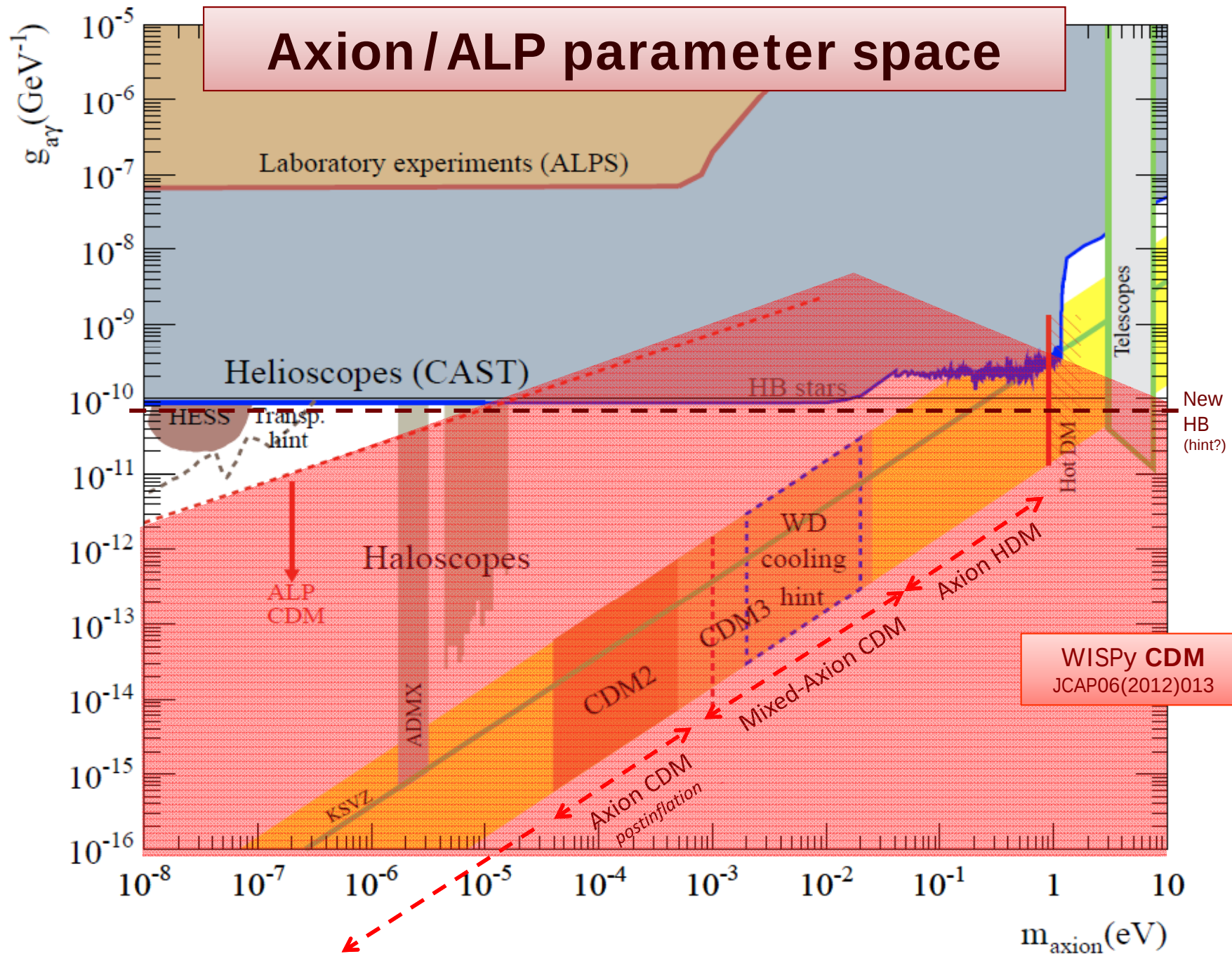
Off-the-beaten-track DM,  
Trieste, Apr2015

Igor G. Irastorza / Universidad de  
Zaragoza

Movie credit:  
Cenk Yildiz

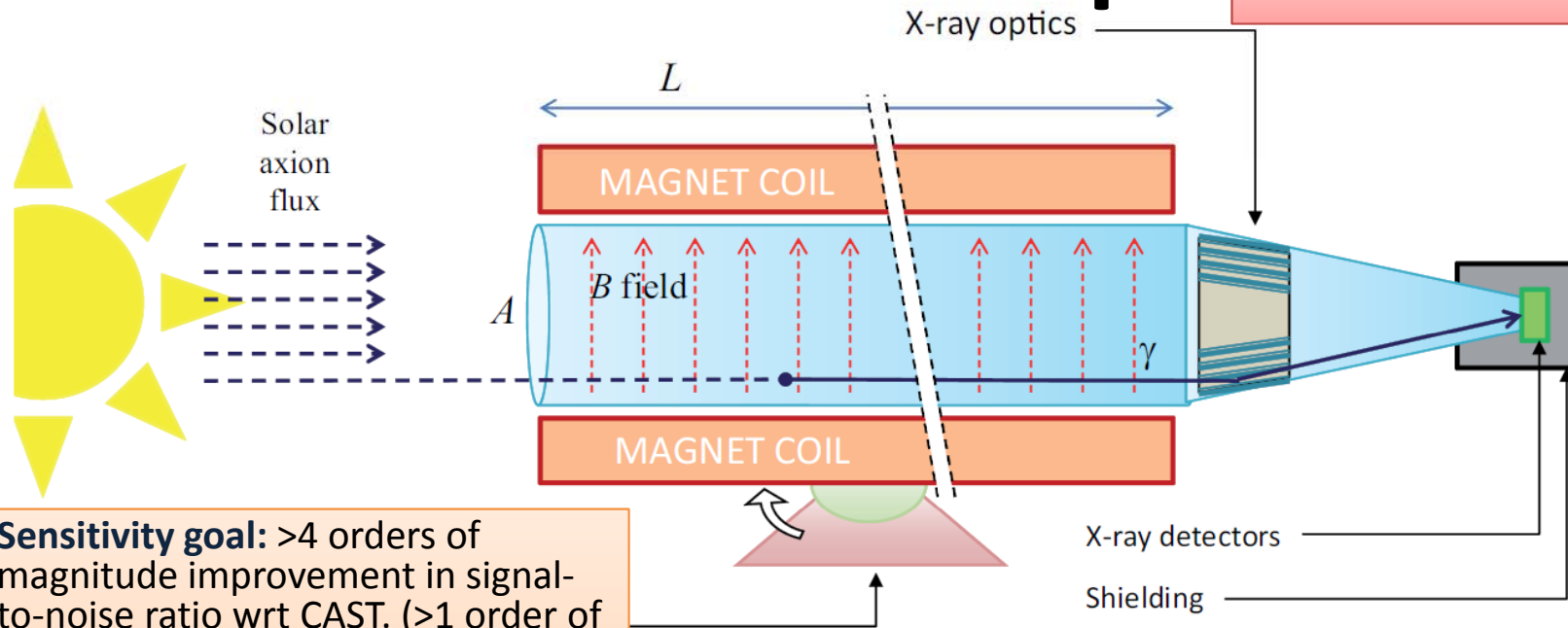
15

# Axion / ALP parameter space



# IAXO – Concept

Enhanced axion helioscope:  
JCAP 1106:013,2011



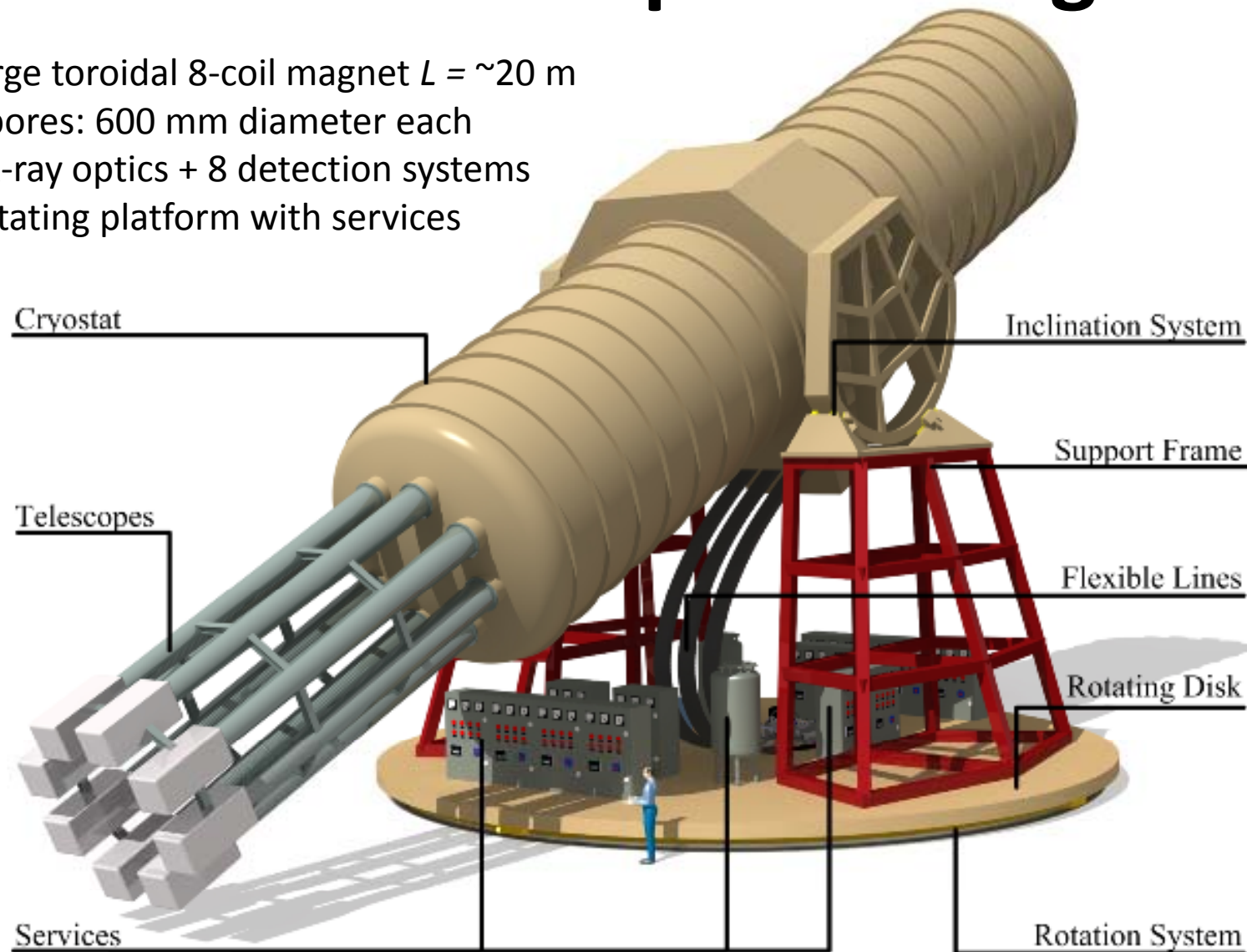
- **Sensitivity goal:** >4 orders of magnitude improvement in signal-to-noise ratio wrt CAST. (>1 order of magnitude in sensitivity of  $g_{a\gamma}$ )

$$g_{a\gamma}^4 \propto \underbrace{b^{1/2} \epsilon^{-1}}_{\text{detectors}} \times \underbrace{a^{1/2} \epsilon_o^{-1}}_{\text{optics}} \times \underbrace{(BL)^{-2} A^{-1}}_{\text{magnet}} \times \underbrace{t^{-1/2}}_{\text{exposure}}$$

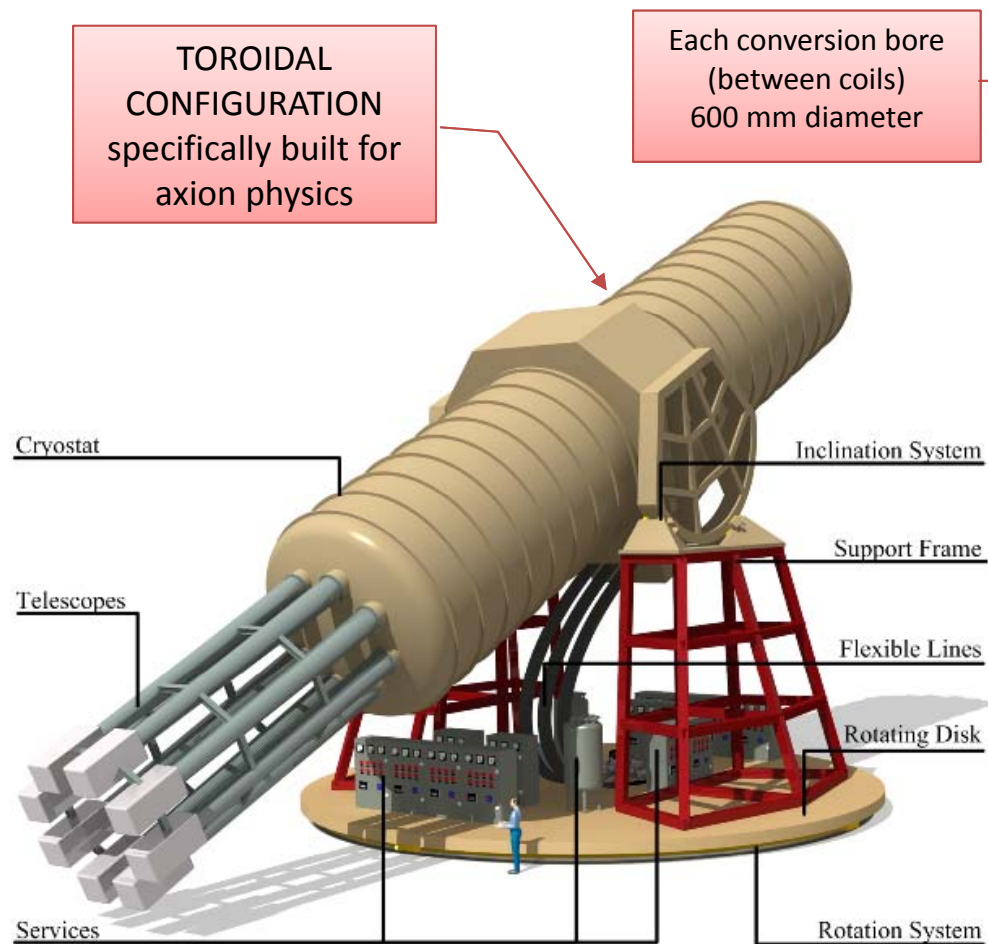
- No technological challenge (build on CAST experience)
  - New dedicated **superconducting magnet**, built for IAXO (improve >300  $B^2 L^2 A$  f.o.m wrt CAST)
  - Extensive (cost-effective) use **x-ray focalization** over  $\sim m^2$  area.
  - **Low background detectors** (lower 1-2 order of magnitude CAST levels)

# IAXO – Conceptual Design

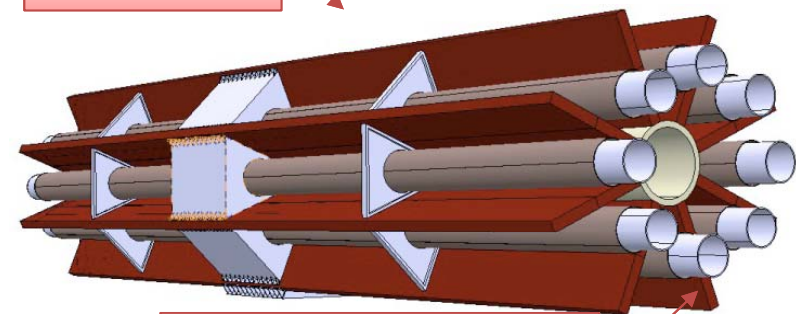
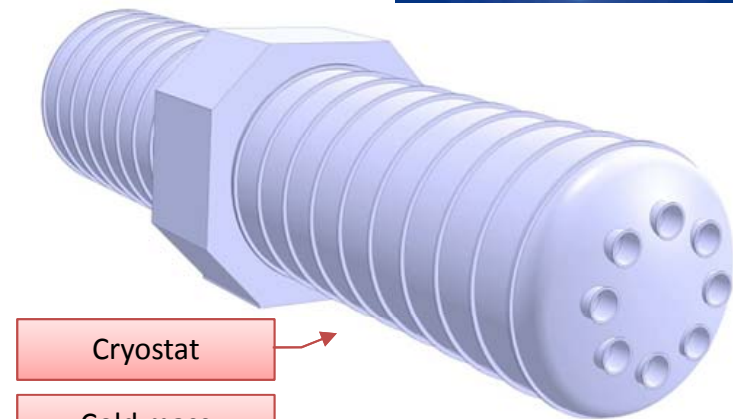
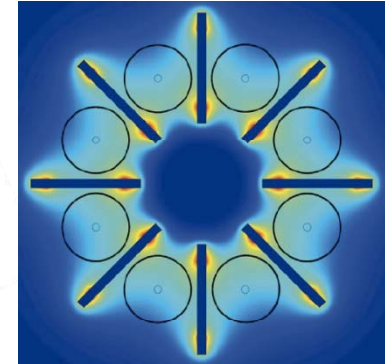
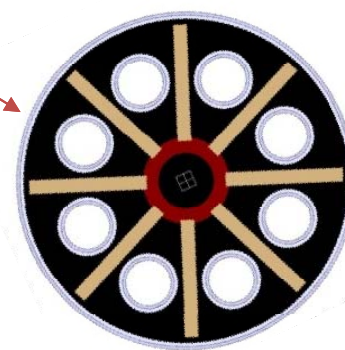
- Large toroidal 8-coil magnet  $L = \sim 20$  m
- 8 bores: 600 mm diameter each
- 8 x-ray optics + 8 detection systems
- Rotating platform with services



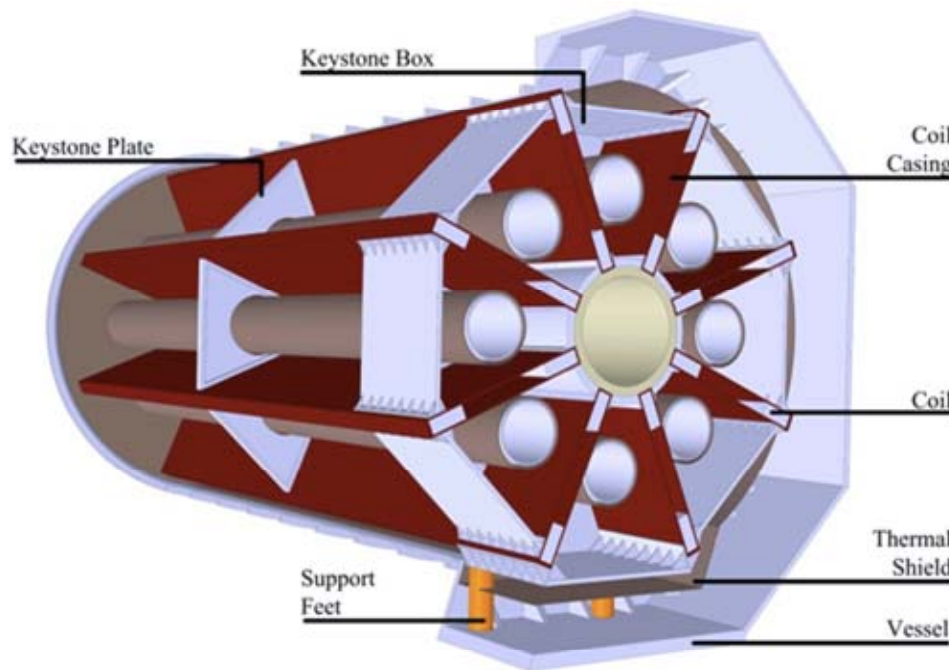
# IAXO magnet



Magnetic length 20 m Total cryostat length 25 m



# IAXO magnet



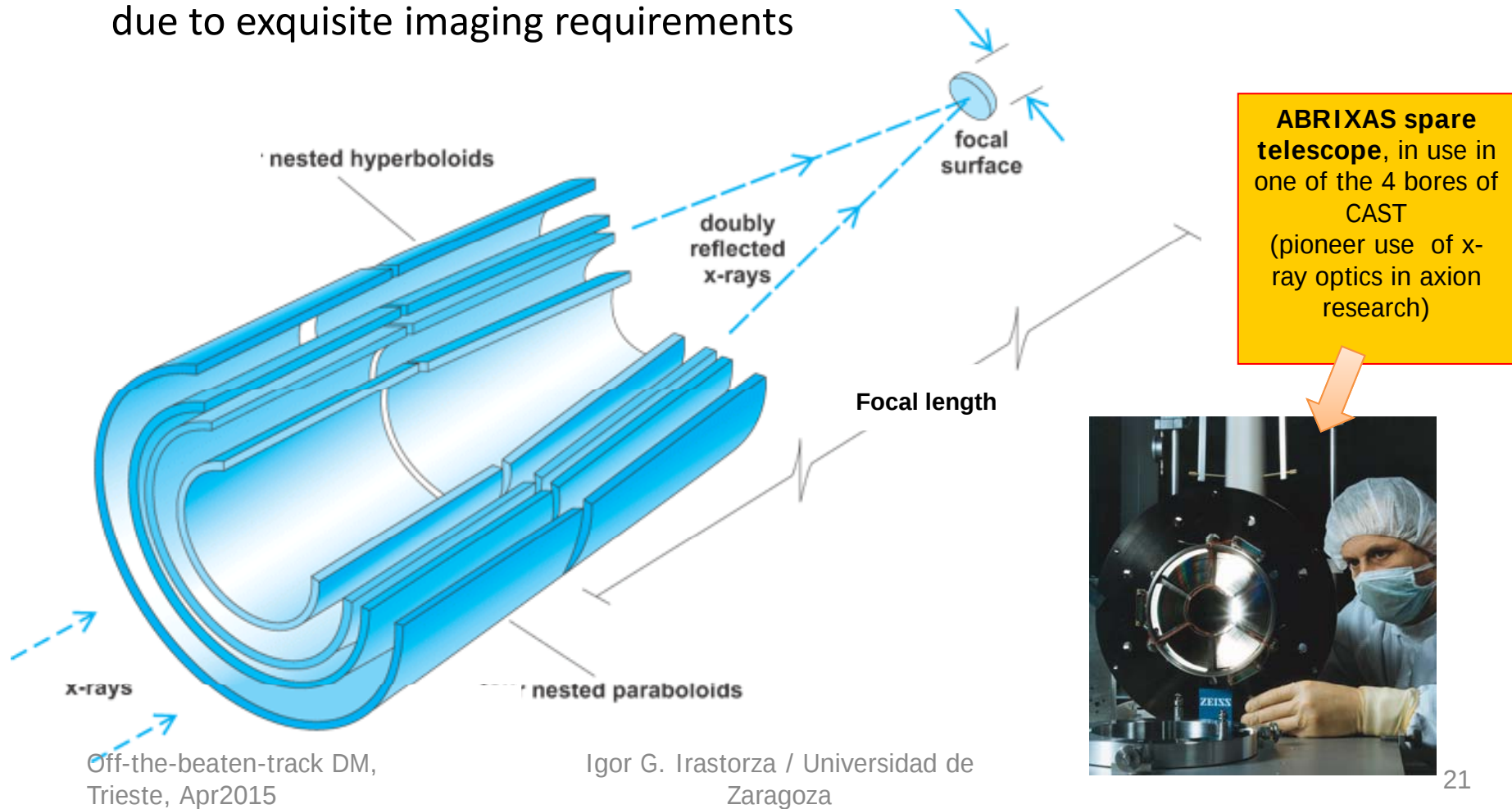
## IAXO magnet concept presented in:

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

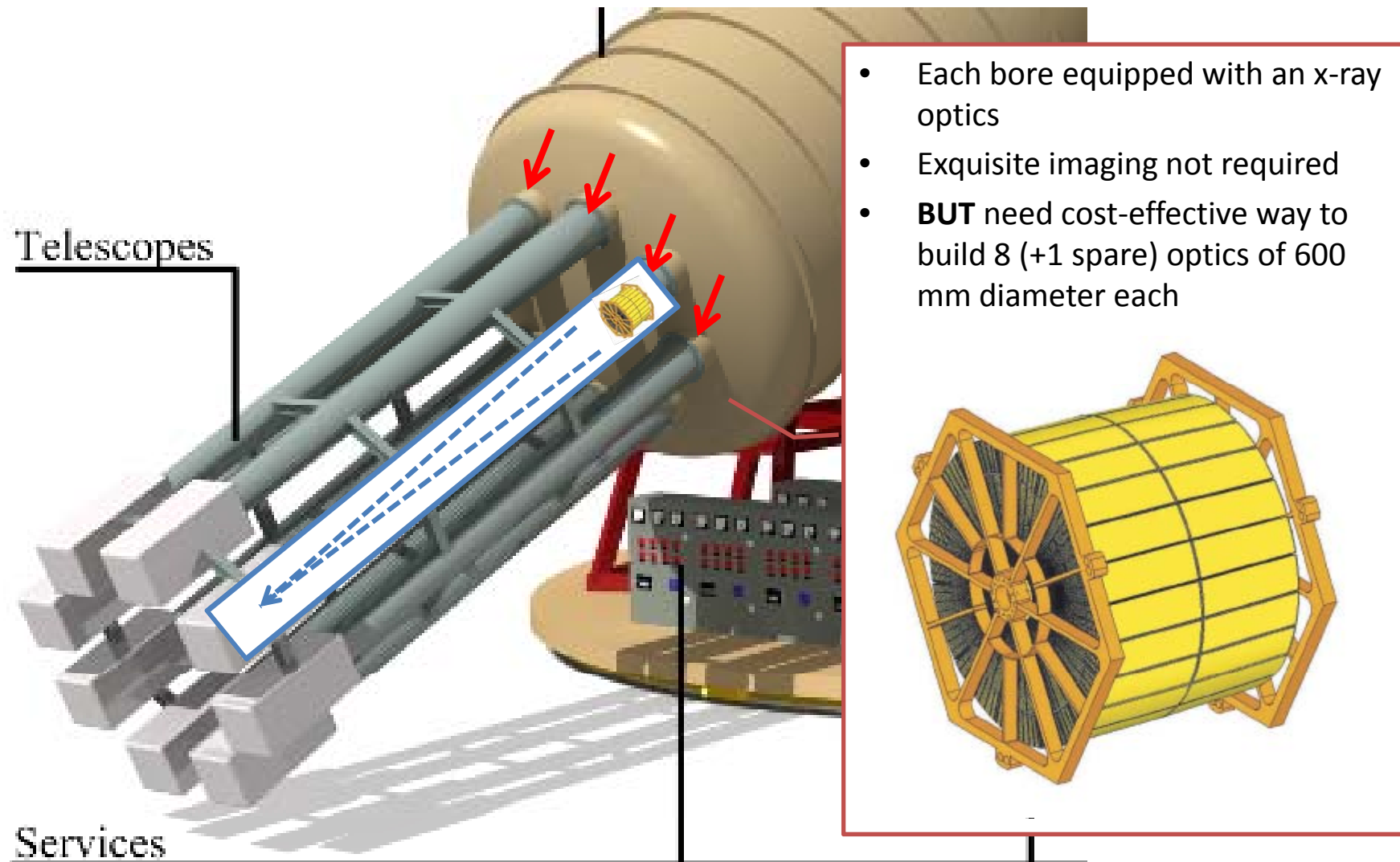
| Property                    | Value                               |        |
|-----------------------------|-------------------------------------|--------|
| <b>Cryostat dimensions:</b> | Overall length (m)                  | 25     |
|                             | Outer diameter (m)                  | 5.2    |
|                             | Cryostat volume (m <sup>3</sup> )   | ~ 530  |
| <b>Toroid size:</b>         | Inner radius, $R_{in}$ (m)          | 1.0    |
|                             | Outer radius, $R_{out}$ (m)         | 2.0    |
|                             | Inner axial length (m)              | 21.0   |
|                             | Outer axial length (m)              | 21.8   |
| <b>Mass:</b>                | Conductor (tons)                    | 65     |
|                             | Cold Mass (tons)                    | 130    |
|                             | Cryostat (tons)                     | 35     |
|                             | Total assembly (tons)               | ~ 250  |
| <b>Coils:</b>               | Number of racetrack coils           | 8      |
|                             | Winding pack width (mm)             | 384    |
|                             | Winding pack height (mm)            | 144    |
|                             | Turns/coil                          | 180    |
|                             | Nominal current, $I_{op}$ (kA)      | 12.0   |
|                             | Stored energy, $E$ (MJ)             | 500    |
|                             | Inductance (H)                      | 6.9    |
|                             | Peak magnetic field, $B_p$ (T)      | 5.4    |
|                             | Average field in the bores (T)      | 2.5    |
|                             | Overall size (mm <sup>2</sup> )     | 35 × 8 |
| <b>Conductor:</b>           | Number of strands                   | 40     |
|                             | Strand diameter (mm)                | 1.3    |
|                             | Critical current @ 5 T, $I_c$ (kA)  | 58     |
|                             | Operating temperature, $T_{op}$ (K) | 4.5    |
|                             | Operational margin                  | 40%    |
|                             | Temperature margin @ 5.4 T (K)      | 1.9    |
| <b>Heat Load:</b>           | at 4.5 K (W)                        | ~150   |
|                             | at 60-80 K (kW)                     | ~1.6   |

# 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



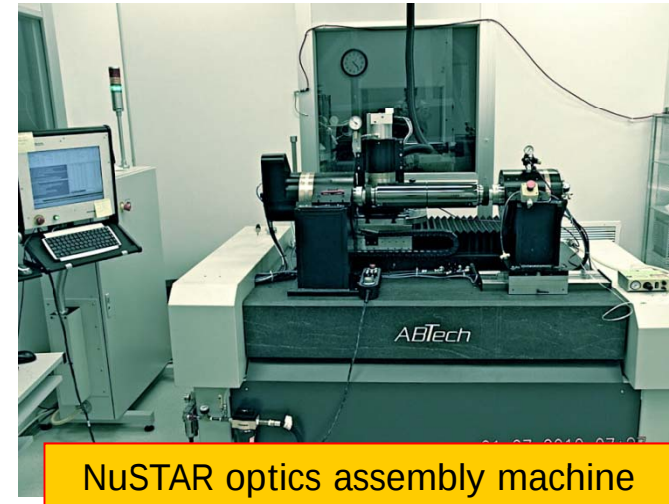
Services

Off-the-beaten-track DM,  
Trieste, Apr2015

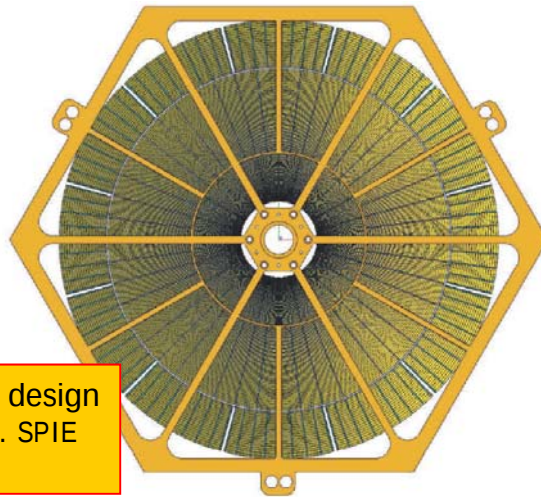
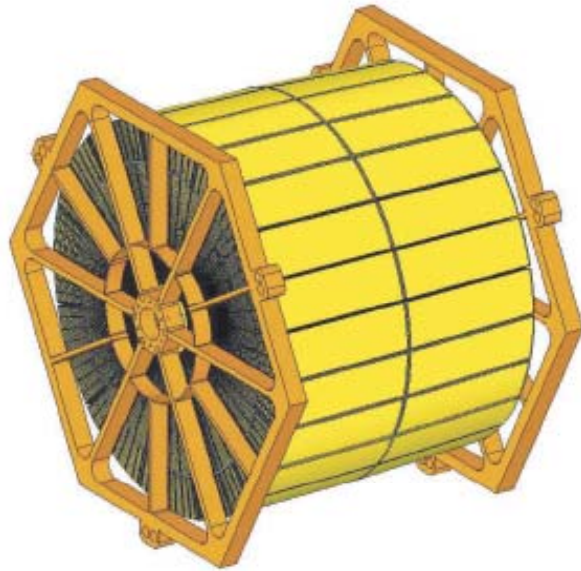
Igor G. Irastorza / Universidad de  
Zaragoza

# IAXO x-ray optics

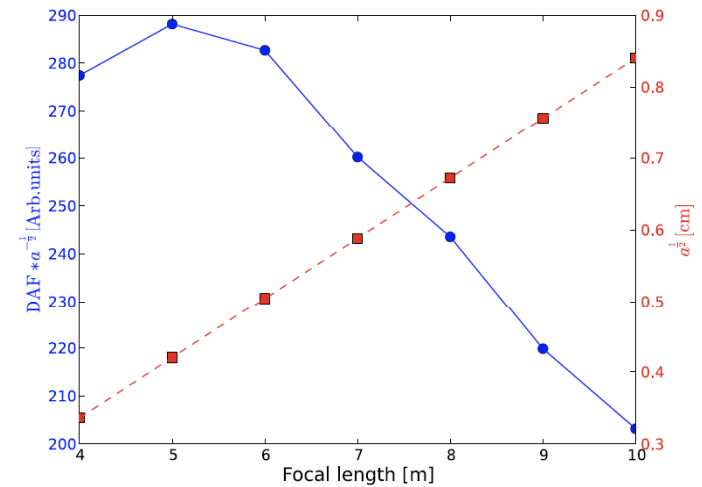
- Technique of choice for IAXO: optics made of slumped glass substrates coated to enhance reflectivity in the energy regions for axions
- Same technique successfully used in NuSTAR mission, recently launched
- The specialized tooling to shape the substrates and assemble the optics is now available
- 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



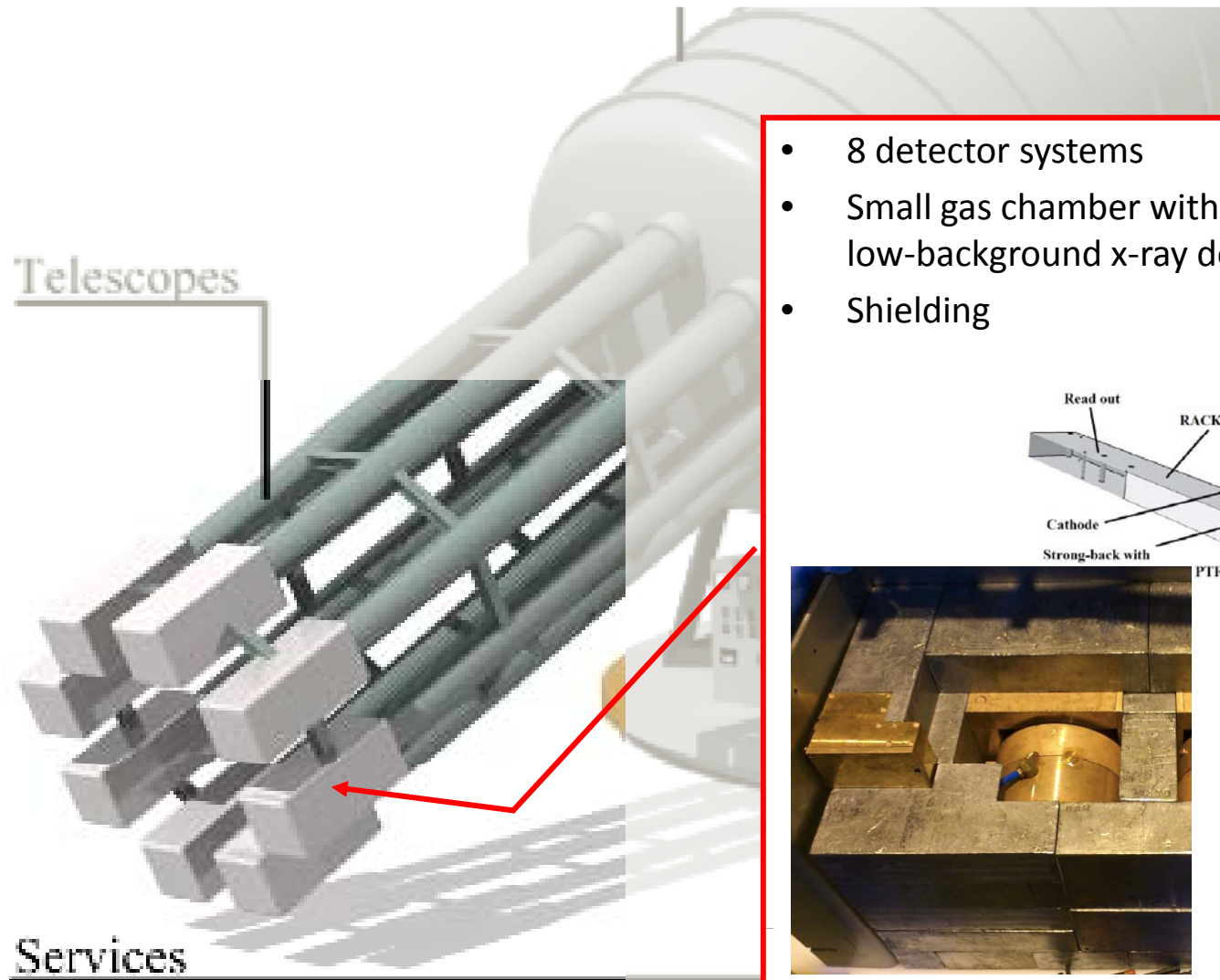
IAXO optics conceptual design  
AC Jakobsen et al, Proc. SPIE  
8861 (2013)



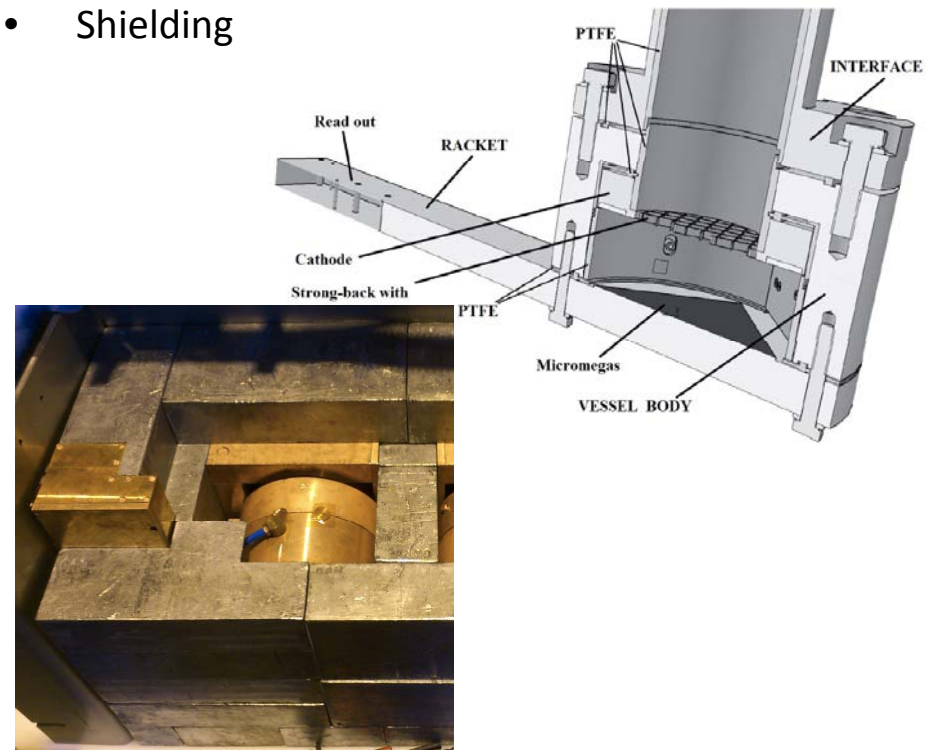
Optimal focal length  $\sim 5$  m

|                                        |                                |
|----------------------------------------|--------------------------------|
| Telescopes                             | 8                              |
| $N$ , Layers (or shells) per telescope | 123                            |
| Segments per telescope                 | 2172                           |
| Geometric area of glass per telescope  | 0.38 m <sup>2</sup>            |
| 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/B <sub>4</sub> C 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                       |

# 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 2014 result)
- $10^{-7} \text{ c keV}^{-1} \text{ cm}^{-2} \text{ s}^{-1}$   
(underground at LSC)

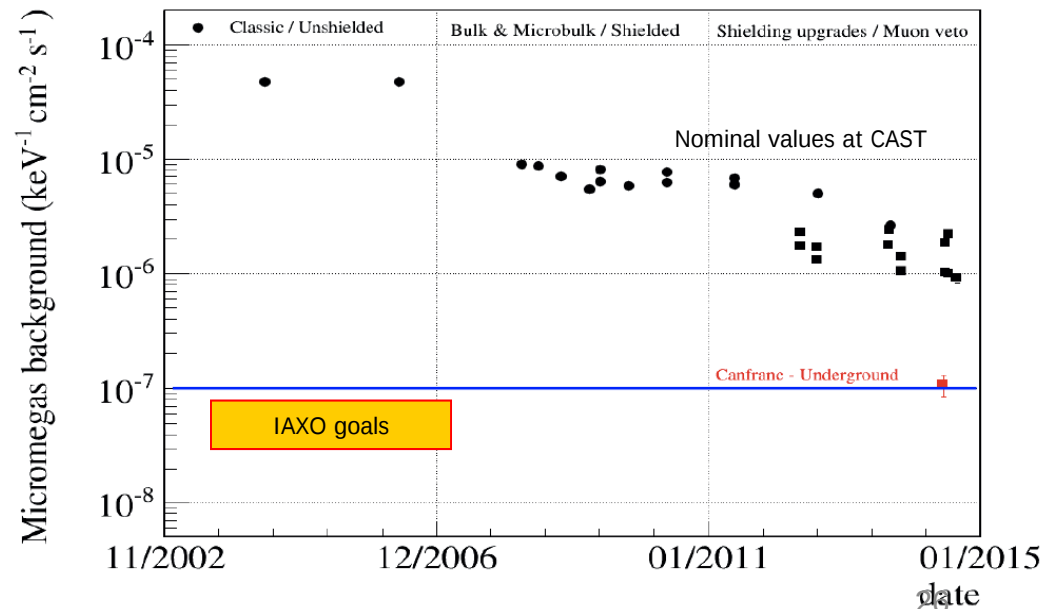
- Active program of development.  
Clear roadmap for improvement.

See [arXiv:1310.3391](https://arxiv.org/abs/1310.3391)

Off-the-beaten-track DM,  
Trieste, Apr2015



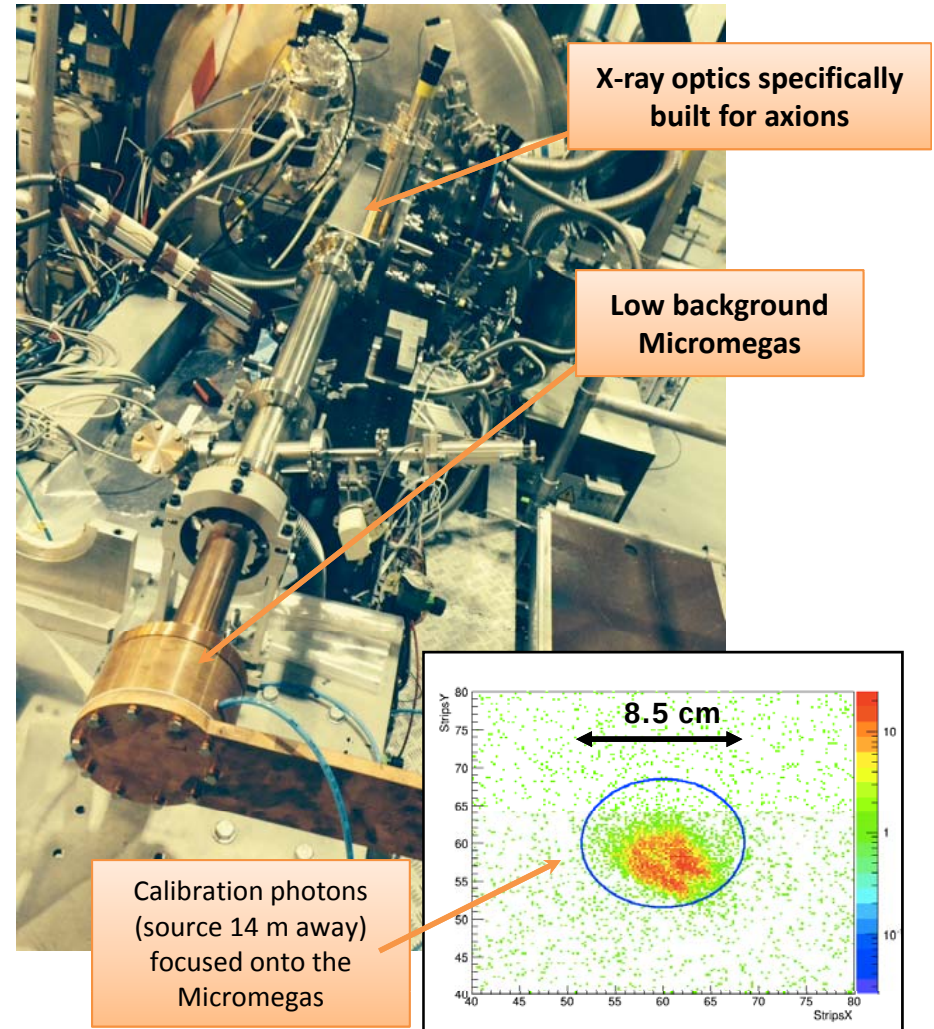
History of background improvement of  
Micromegas detectors at CAST



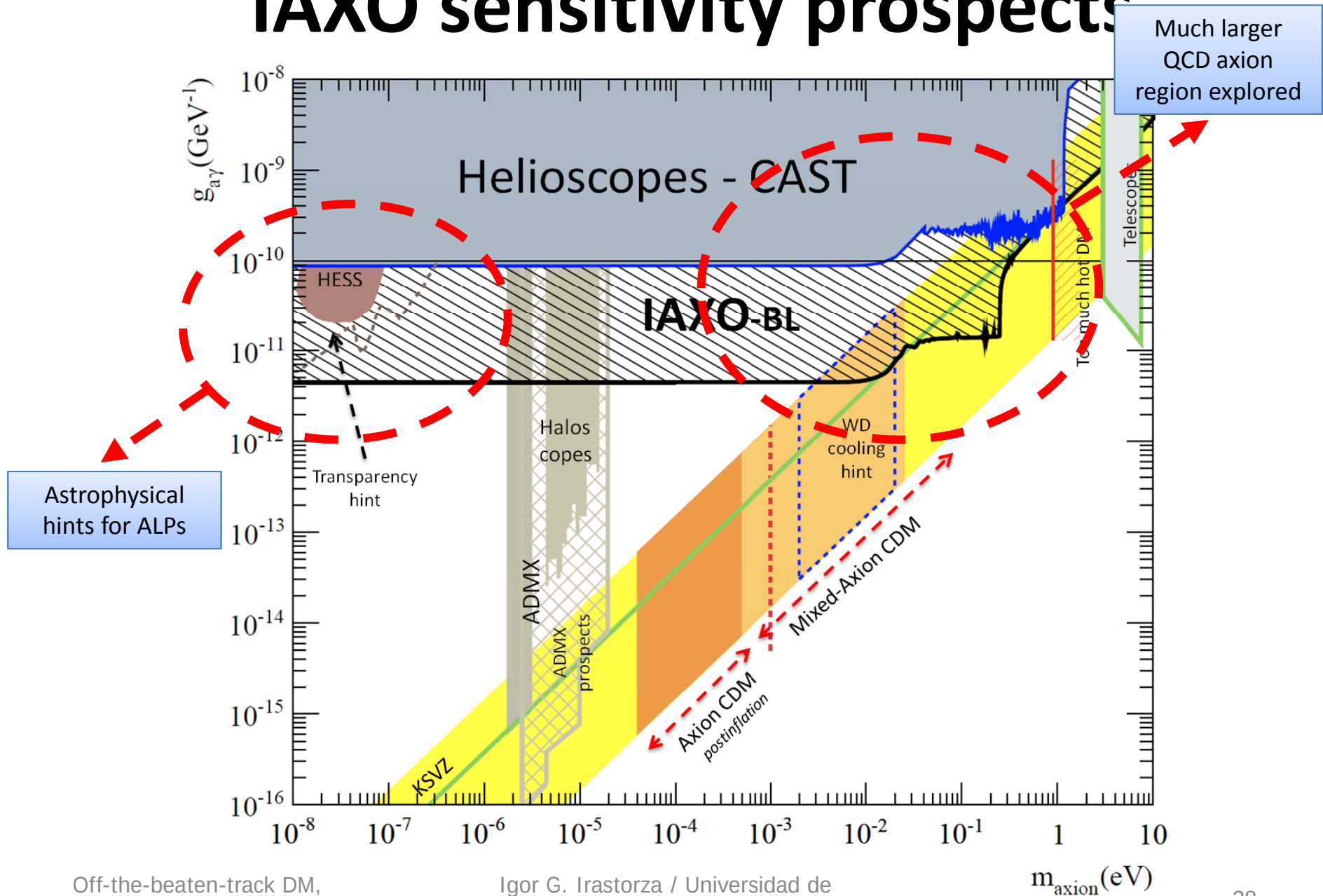
# IAXO low background detectors

## 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)
  - First time low background + focusing in the same system
  - Very important operative experience for IAXO
- Installed & commissioned successfully in CAST last september. Now taking data (**Bck: 0.21 c/month of data taking in the focal spot !!!**)

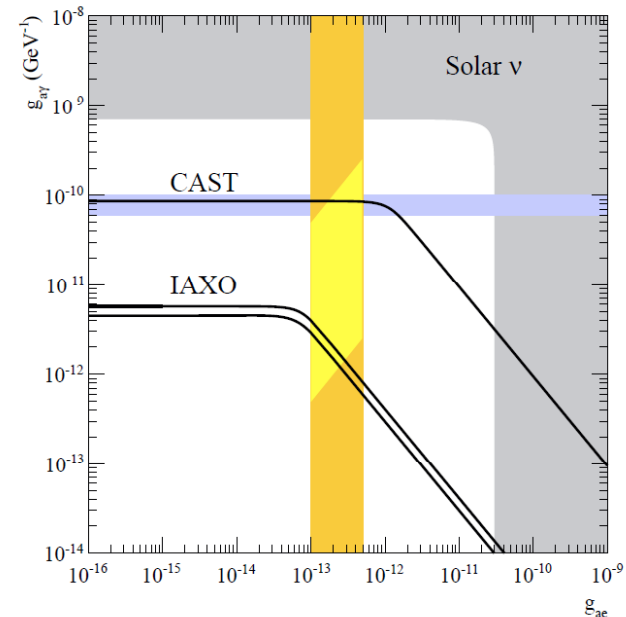


# IAXO sensitivity prospects

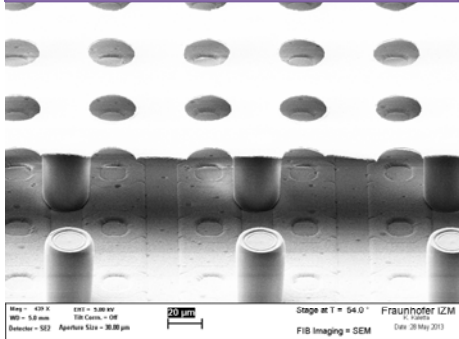


# Additional IAXO physics cases

- Detection of “ABC”-produced solar axions (with relevant  $g_{ae}$  values)
- More specific WISPs models at the **low energy frontier** of particle physics:
  - Paraphotons / hidden photons
  - Chamaleons
  - Non-standard scenarios of axion production
- Possible addition technologies to push E thresholds down:

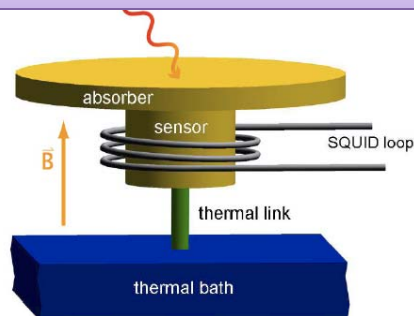


GridPix/Ingrid detectors



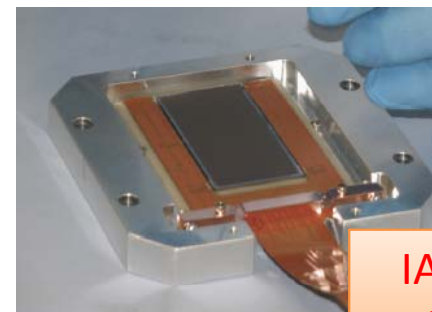
Off-the-beaten-track DM,  
Trieste, Apr2015

Magnetic Metallic Calorimeter (MMC)



Igor G. Irastorza / Universidad de  
Zaragoza

Low-noise CCDs

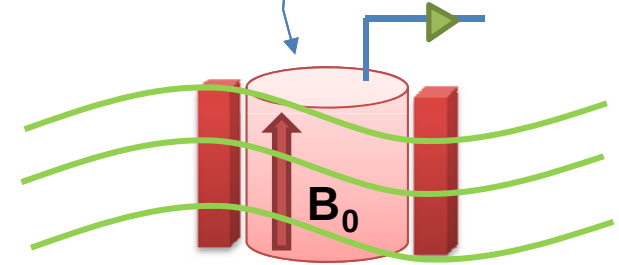


IAXO as “generic  
axion/ALP facility”

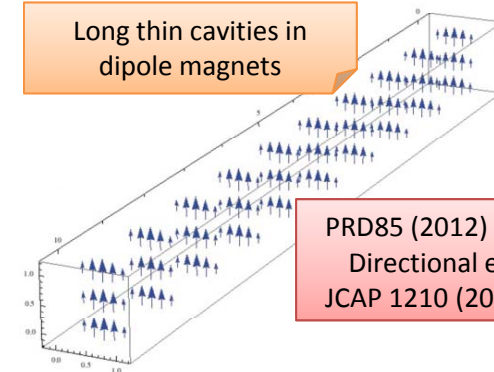
# IAXO-DM configurations?

- ADMX leader haloscope at  $m_a \sim 1\text{-}10 \mu\text{eV}$ . Big motivation to explore higher masses.
- Many new ideas being put forward. R&D needed. Common point: large magnets needed.
- 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?

**Haloscope concept:**  
DM axions convert into  
MW photons inside  
cavity resonant to  $m_a$

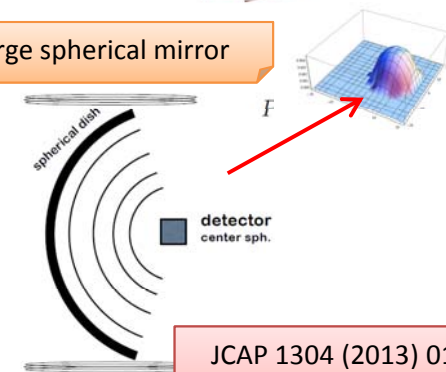


Long thin cavities in  
dipole magnets



PRD85 (2012) 035018  
Directional effect:  
JCAP 1210 (2012) 022

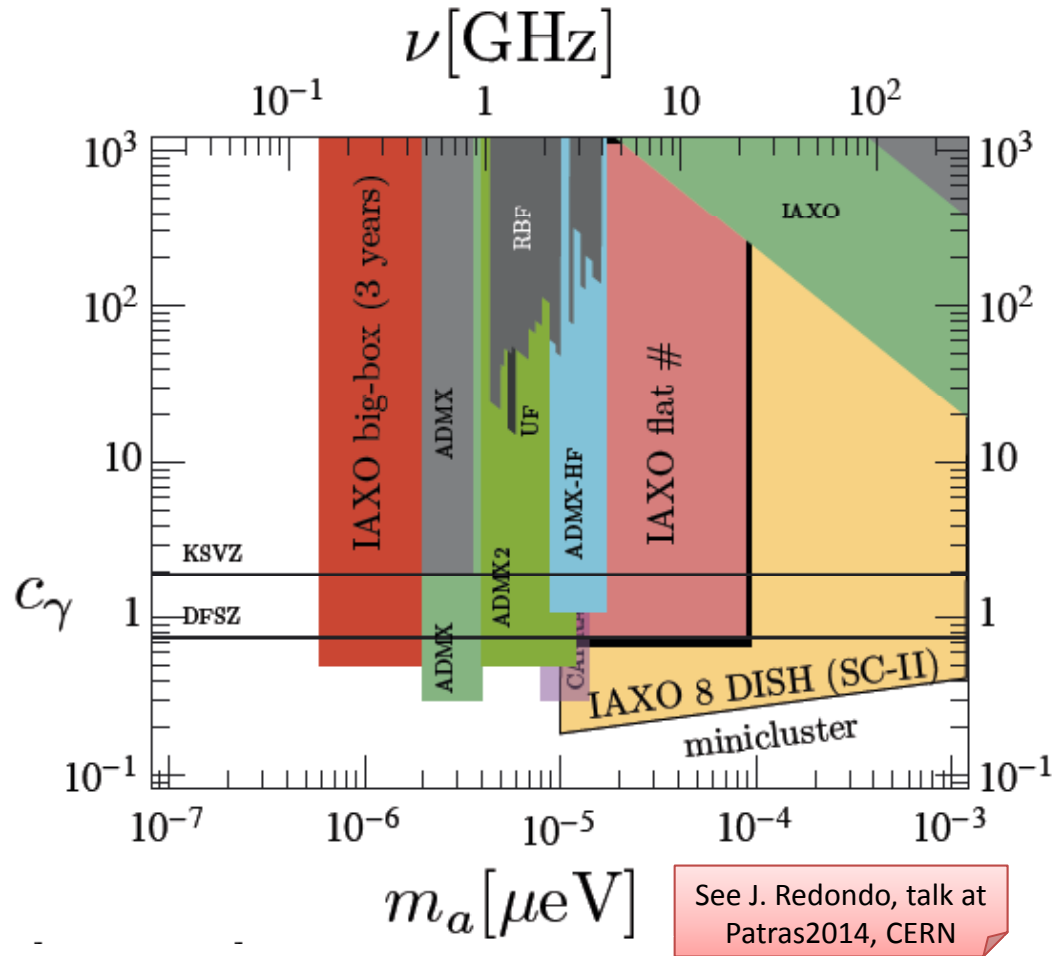
Large spherical mirror



JCAP 1304 (2013) 016  
Directional effect:  
arXiv:1307.7181

# 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**

# 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 pursued within an MOU involving all interested parties.

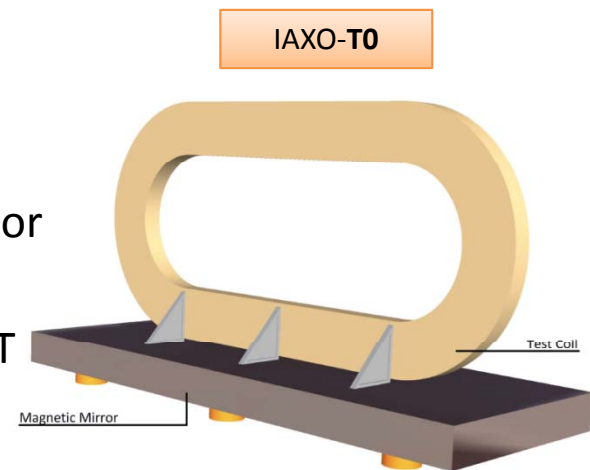
This was endorsed by the Research Board in March 2014

Minutes of the 206th CERN Research Board held on March 2014:

<https://cds.cern.ch/record/1695812/files/M-207.pdf>

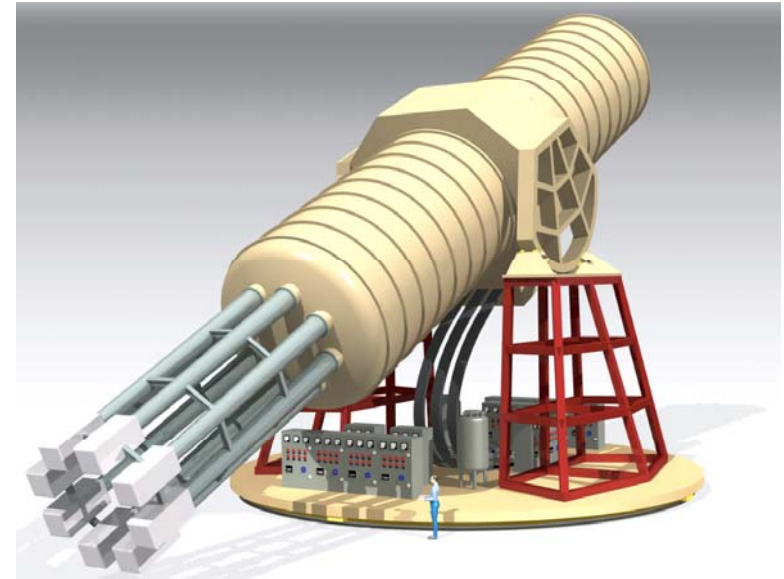
# Next steps

- 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
  - Feasibility studies for “IAXO-DM” options.
- Memorandum of Understanding in preparation among interested parties.
- Site studies
- Search for new interested partners



# Conclusions

- Increasing interest for axions:
  - Physics case, theory, cosmology, astrophysics
- Increasing experimental effort
  - CAST at CERN
- Field in a **transition**: from small experiments to Big Science?
- **IAXO proposal** is timely, ambitious, large impact in the axion landscape & discovery potential
- IAXO as a generic multi-experiment “axion facility”
- First steps after the positive recommendation from CERN SPSC.
- New partners welcome.



**Announcement: next Patras workshop in Zaragoza→**

# 11th Patras Workshop on Axions, WIMPs and WISPs

**22-26 June 2015**

**University of Zaragoza, Spain**

## Scientific Programme

- The physics case for WIMPs, Axions, WISPs
- Searches for Hidden Sector Photons
- Direct and indirect searches for Dark Matter
- Direct laboratory searches for Axions, WISPs
- Signals from astrophysical sources
- Review of collider experiments
- New theoretical developments
- Scalar Dark Energy, theory and experiment

## Organizing committee:

I. G. Irastorza (Chair, U Zaragoza), V. Anastassopoulos (Patras),  
L. Baudis (U Zurich), J. Jaeckel (U Heidelberg), A. Lindner (DESY),  
A. Ringwald (DESY), M. Schumann (AEC Bern), K. Zioutas (U Patras & CERN)

## Local organizing committee:

I. G. Irastorza (chair), J. M. Carmona, S. Cebrián, T. Dafni,  
D. González-Díaz, F. J. Iguaz, G. Luzón, J. Redondo, J. A. Villar

Contact: [axionwimp2015@gmail.com](mailto:axionwimp2015@gmail.com)

**<http://axion-wimp.desy.de>**

## Important dates:

01 April 2015 Deadline of abstract submission  
20 April 2015 Announcement of decisions on  
submitted contributions  
01 May 2015 Deadline of early registration  
15 June 2015 Deadline of late registration

Sponsors: AEC Bern, CERN, DESY, European Research Council, U Patras, U Zaragoza & U Zurich

