Searches for axions with the

International AXion Observatory IAXO

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Universidad de Zaragoza

XLIII International Meeting on Fundamental Physics
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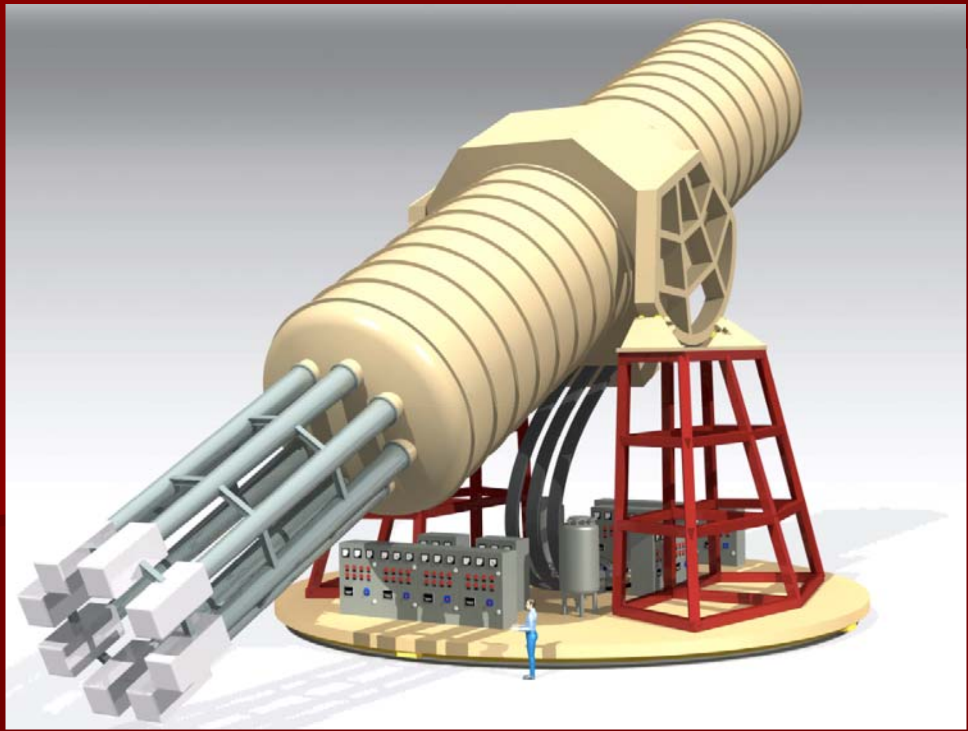

Outline

- 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
IAXO

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IAXO Letter of Intent: CERN-SPSC-2013-022
90 signatures / 38 institutions
IAXO Conceptual Design: JINST 9 (2014) T05002 (arXiv:1401.3233)

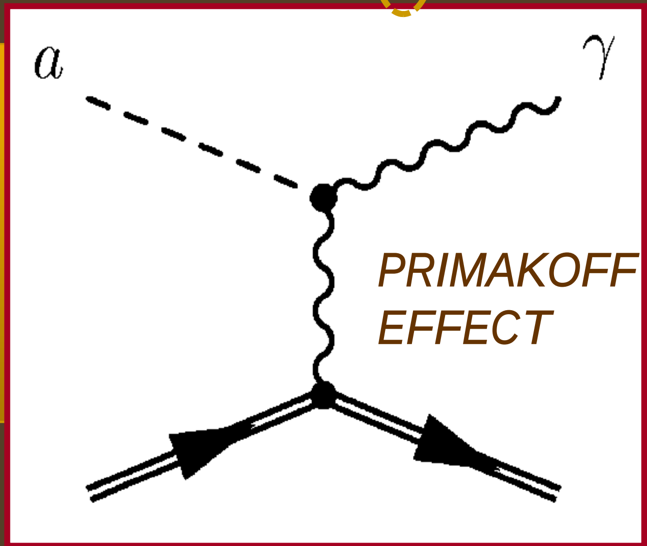
Why axions?

- **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 → 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**

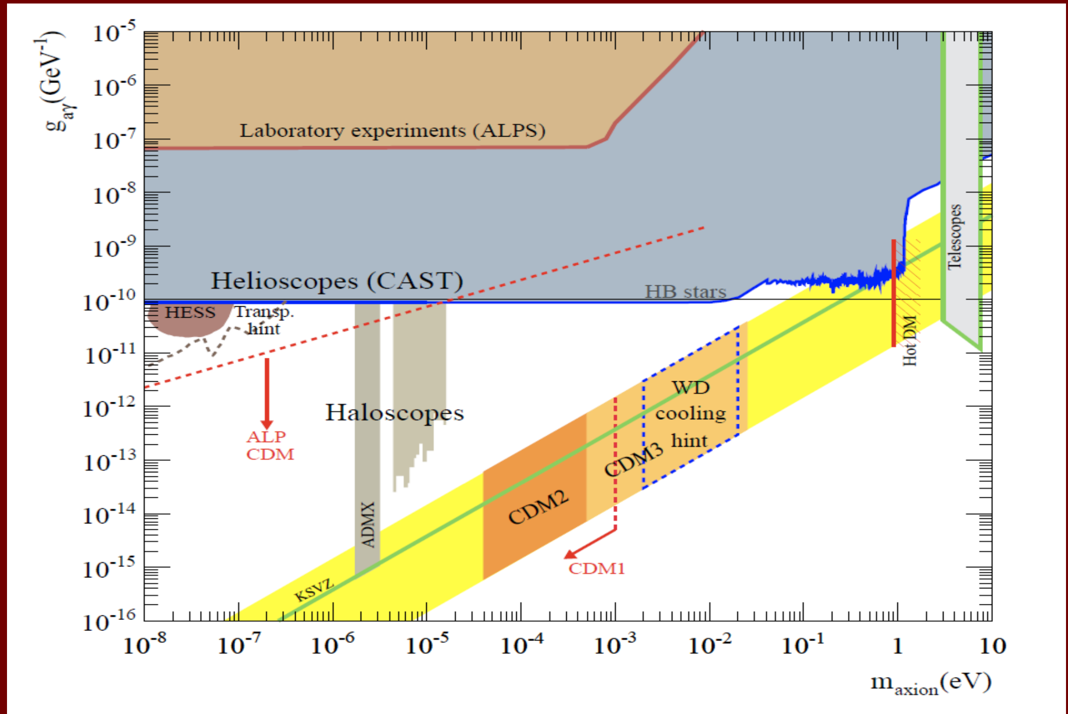


Beyond axions

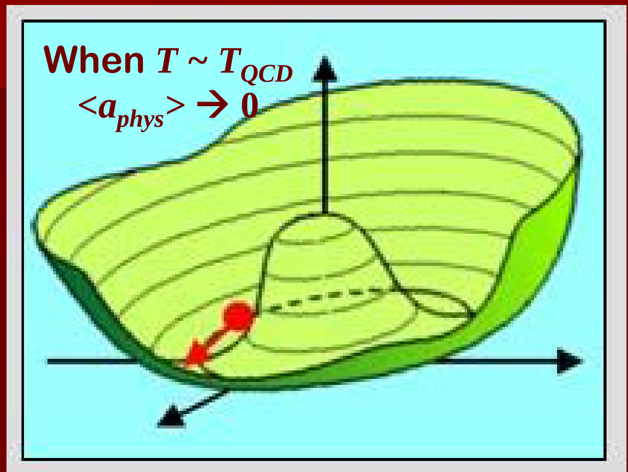
Hidden photons / paraphotons ALPS **AXIONS** Chamaleons Minicharged particles

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



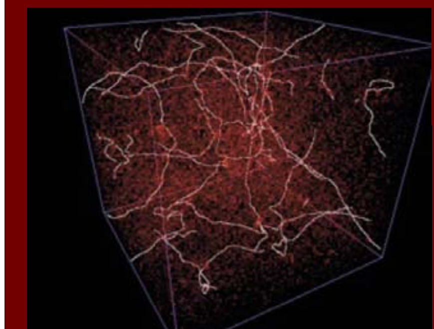
Axion realignment

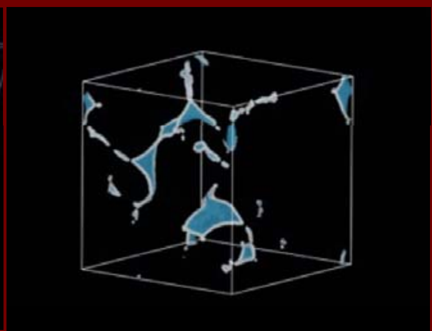
As the Universe cools down below T_{QCD}, space is filled with low energy axion field fluctuations.

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?

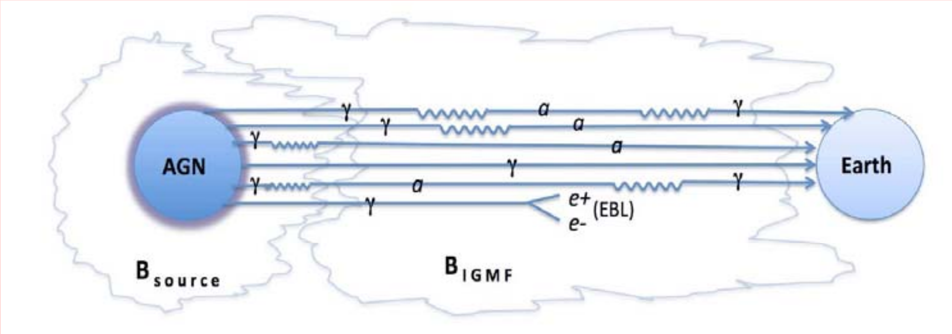
- **Axions are produced** in the early Universe by a number of processes:
  - Axion realignment
  - Decay of axion strings
  - Decay of axion walls

  } → **NON-RELATIVISTIC (COLD) AXIONS**

  - Axion mass giving the right CDM density? Depends on cosmological assumptions:
    - Post-inflation scenario ("classical window") **$\sim 10^{-5} – 10^{-3}$ eV**
    - Pre-inflation scenario ("anthropic window") ~ lower masses possible
    - Higher masses→ subdominant CDM / non-standard scenarios
  - Thermal production → **RELATIVISTIC (HOT) AXIONS**
- Axion masses ma > ~0.9 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(?)

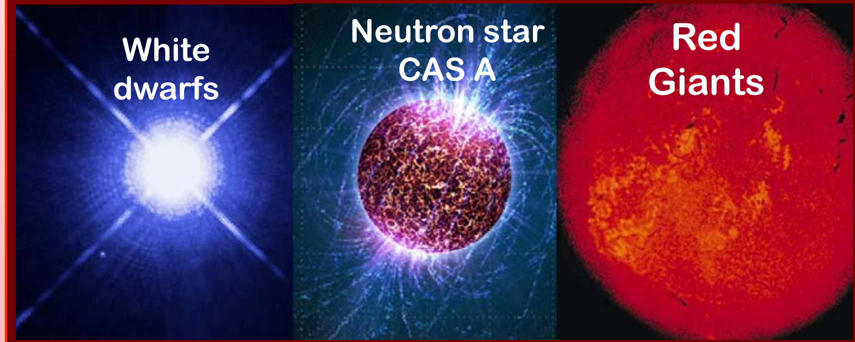


Gama ray telescopes like MAGIC or HESS observe HE photons from very distant sources...

ALP:

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

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



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

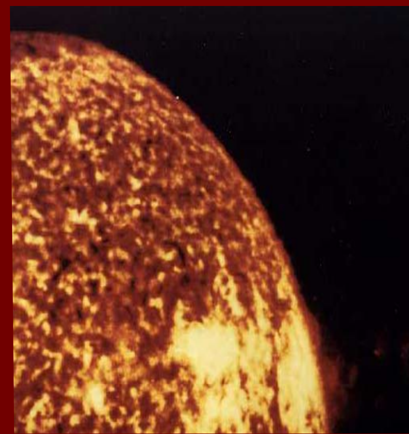
ADMX in US

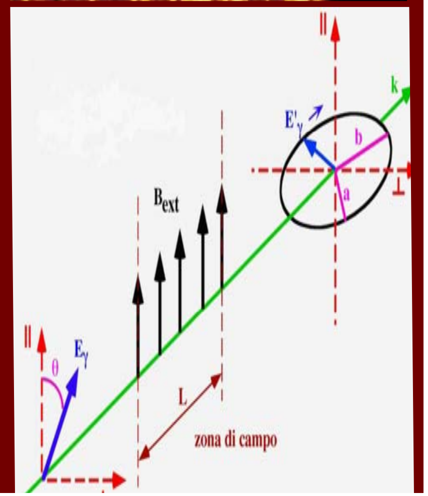
- Solar Axions
  - Emitted by the solar core.
    - Crystal detectors
    - Axion Helioscopes

CAST @ CERN
→ IAXO

- Axions in the lab
    - “Light shinning through wall” experiments
    - Vacuum birrefringence experiments

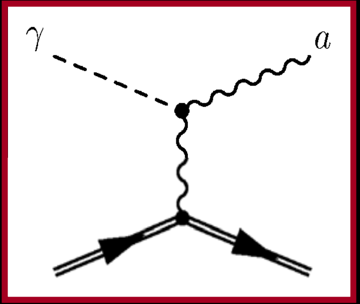
ALPS-I I @ DESY
OSQAR @ CERN

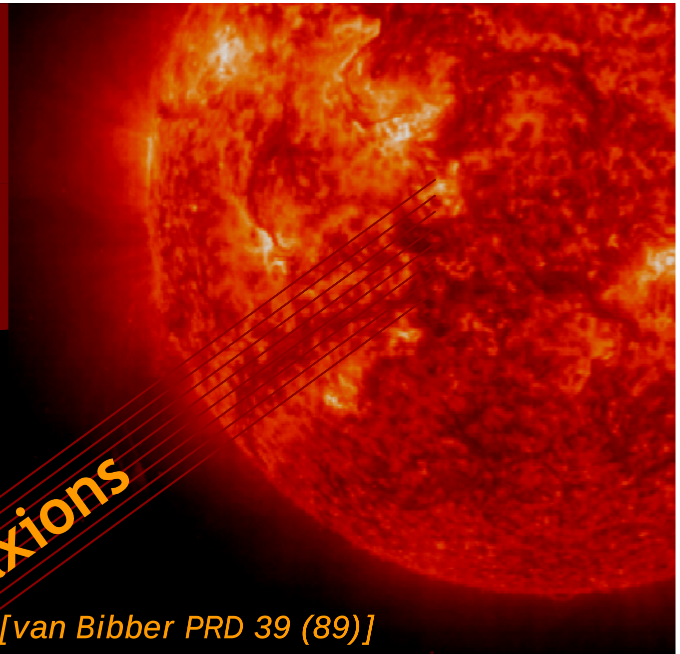




Solar Axions

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

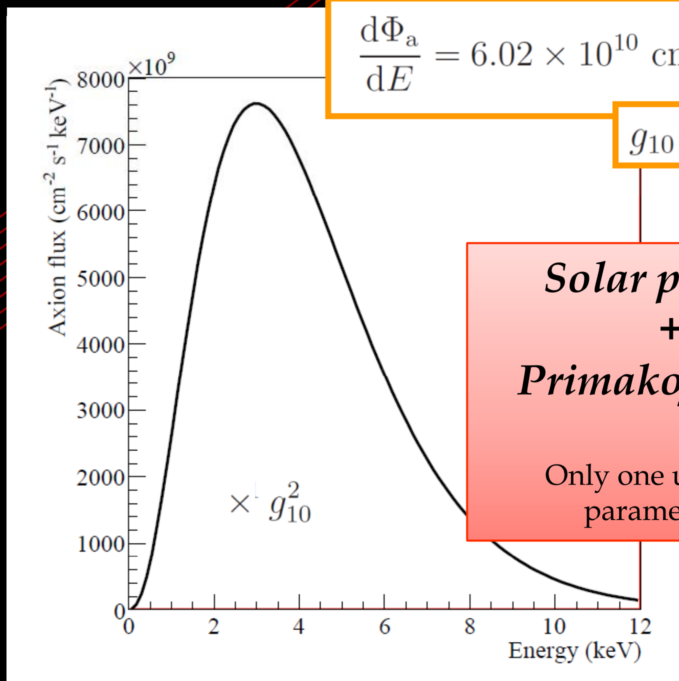




➢ *Solar axion flux* *[van Bibber PRD 39 (89)]* *[CAST JCAP 04(2007)010]*

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

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



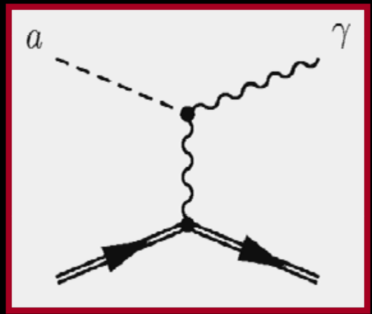
Solar physics
+
Primakoff effect

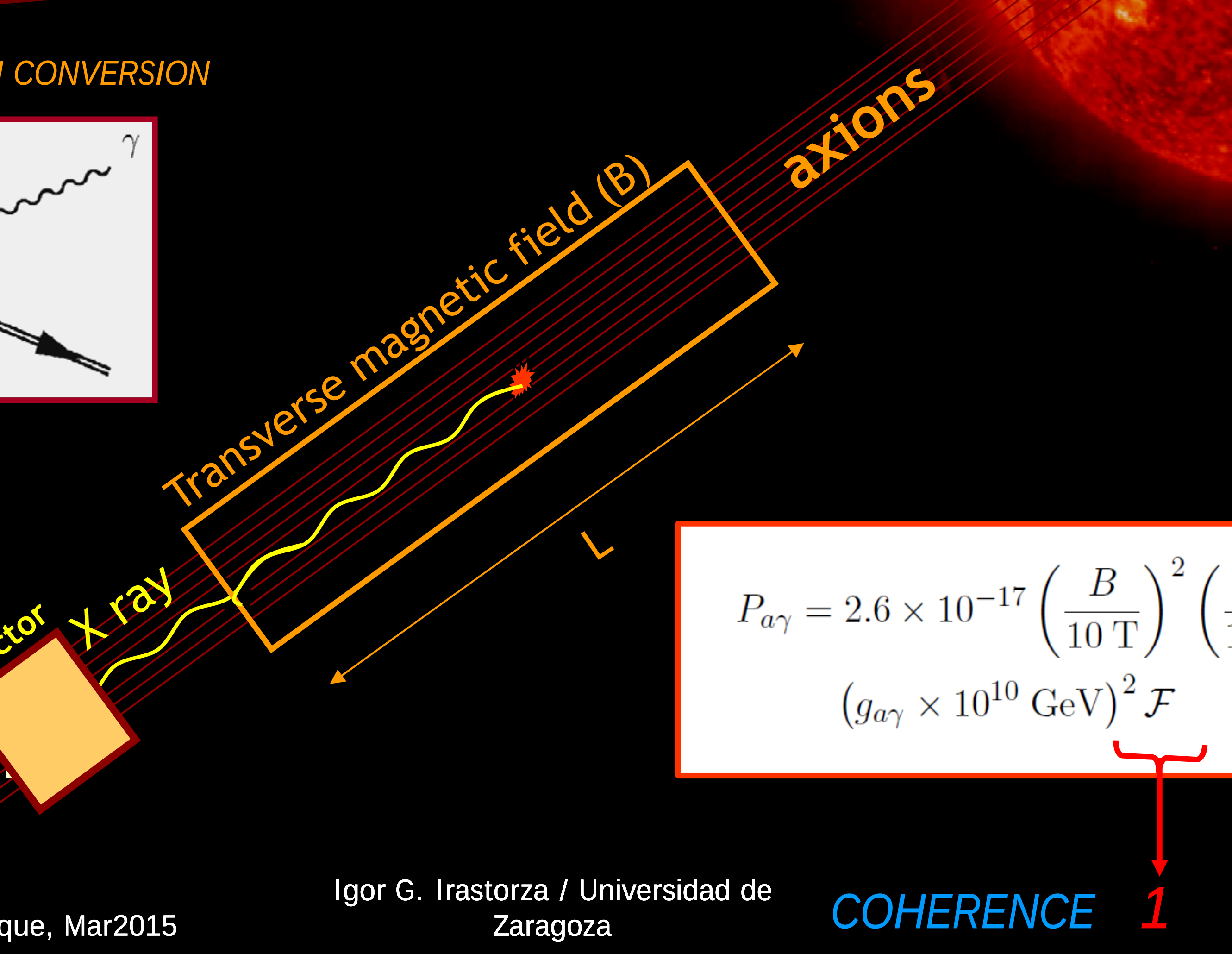
Only one unknown parameter $g_{a\gamma}$

Axion Helioscope principle

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

AXION PHOTON CONVERSION



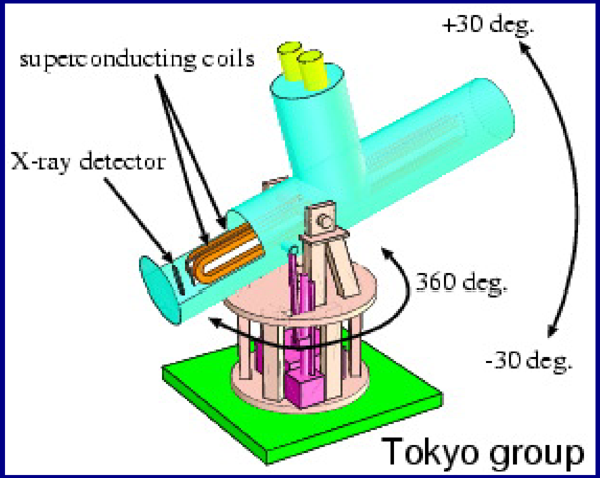


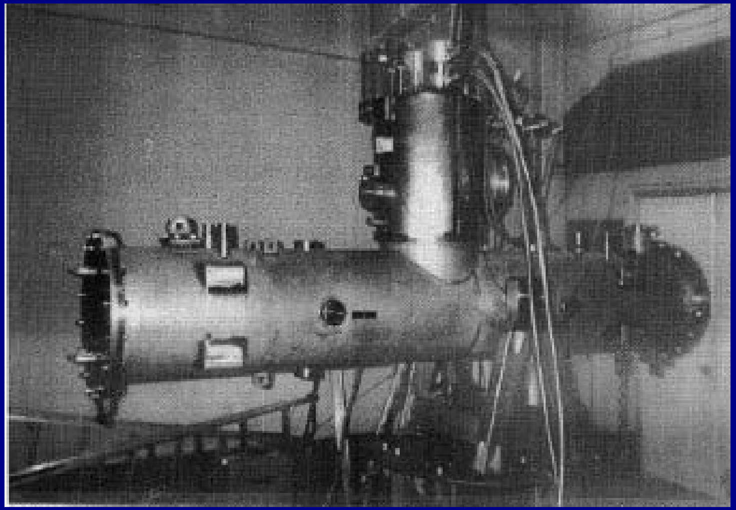
$$P_{a\gamma} = 2.6 \times 10^{-17} \left(\frac{B}{10\ \mathrm{T}}\right)^2 \left(\frac{L}{10\ \mathrm{m}}\right)^2 \left(g_{a\gamma} \times 10^{10}\ \mathrm{GeV}\right)^2 \mathcal{F}$$

COHERENCE 1

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

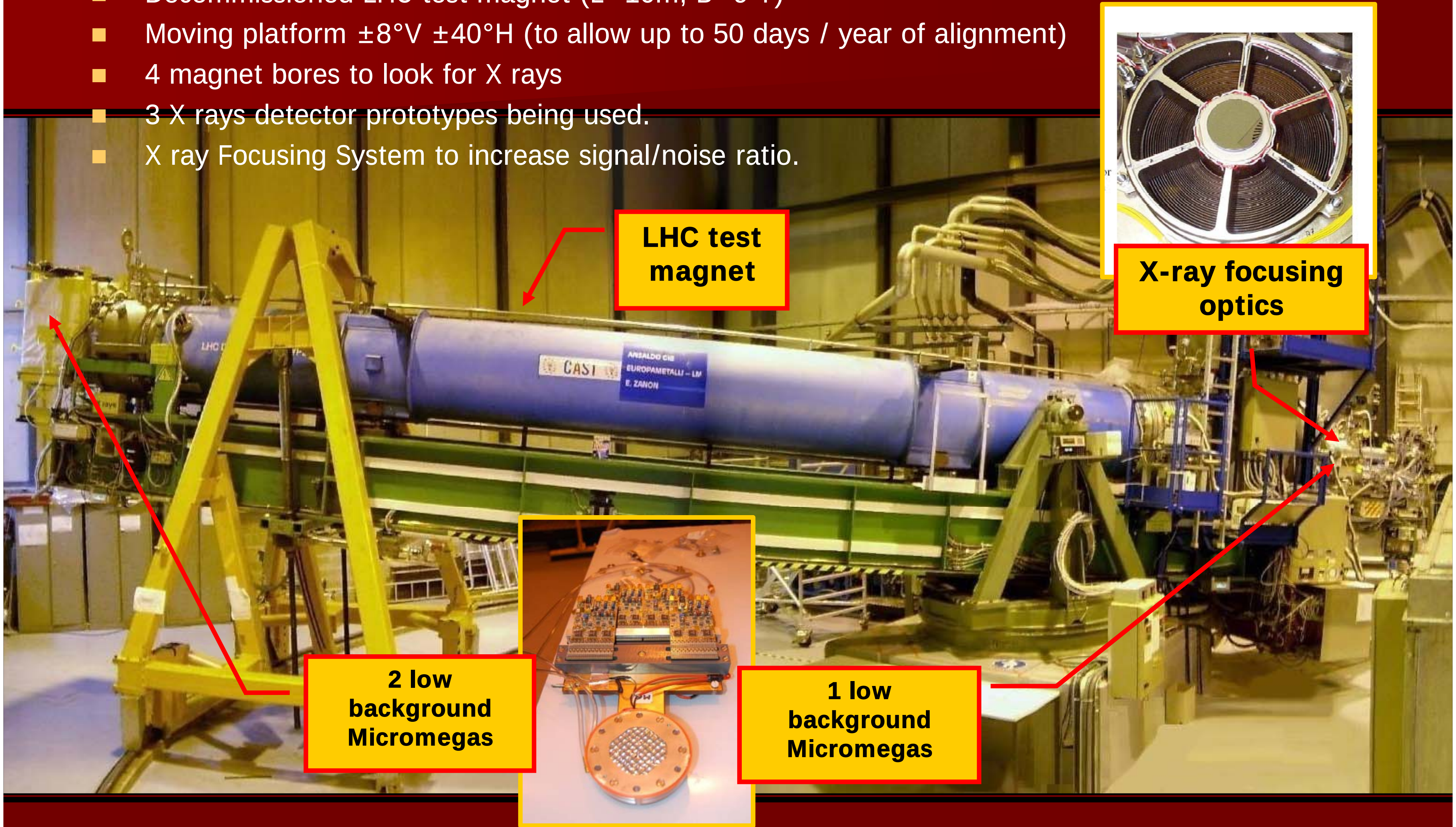




- Presently running:
  - CERN Axion Solar Telescope (**CAST**)

CAST experiment @ CERN

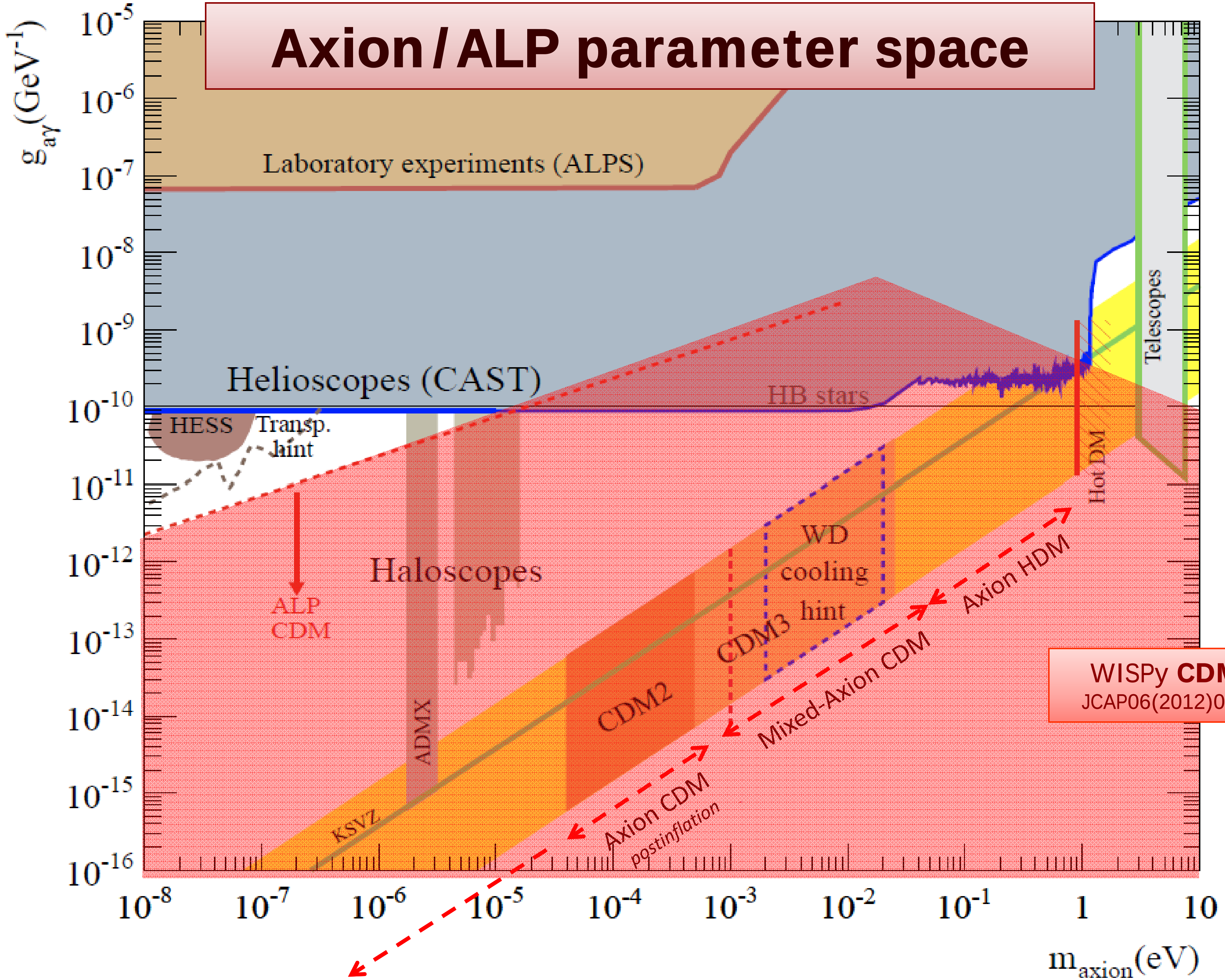
- Decommissioned LHC test magnet (L=10m, B=9 T)
- Moving platform ±8°V ±40°H (to allow up to 50 days / year of alignment)
- 4 magnet bores to look for X rays
- 3 X rays detector prototypes being used.
- X ray Focusing System to increase signal/noise ratio.



CAST at work

Movie credit:
Cenk Yildiz

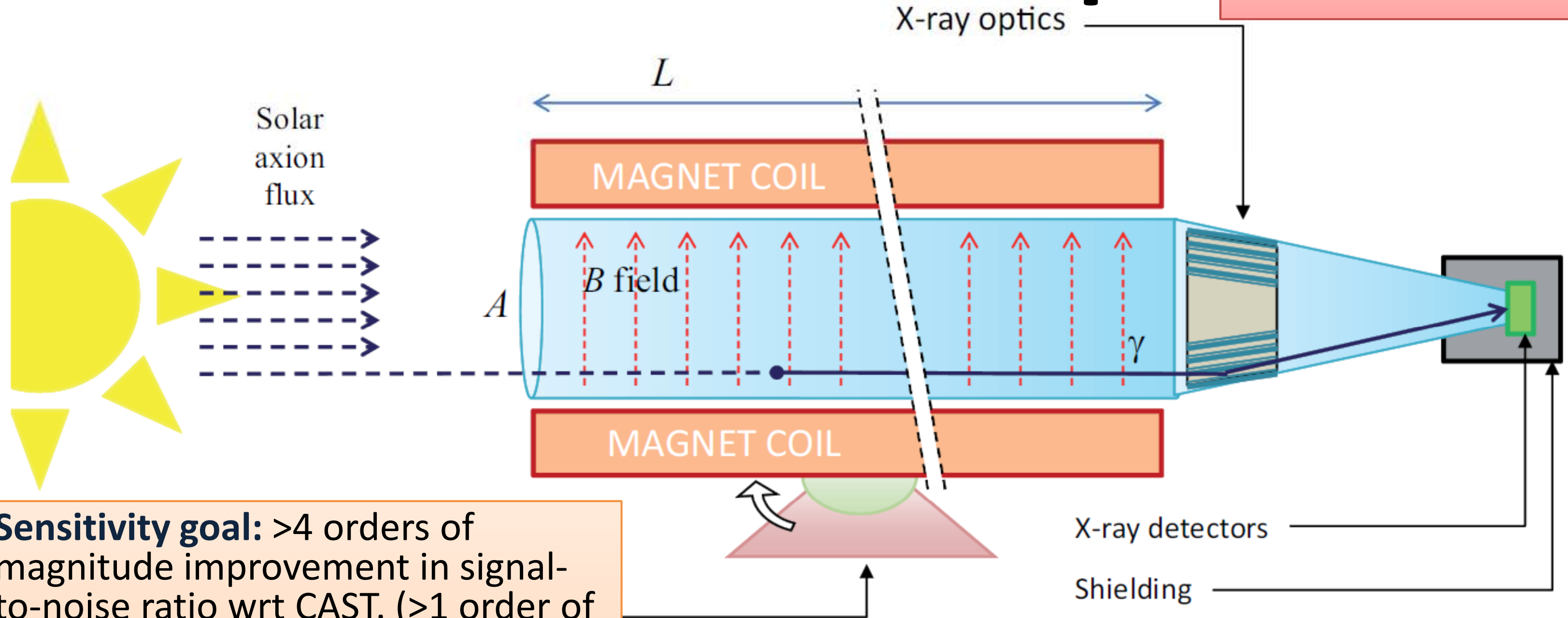
Axion / ALP parameter space



WISPy **CDM**
JCAP06(2012)013

IAXO – Concept

Enhanced axion helioscope:
JCAP 1106:013,2011



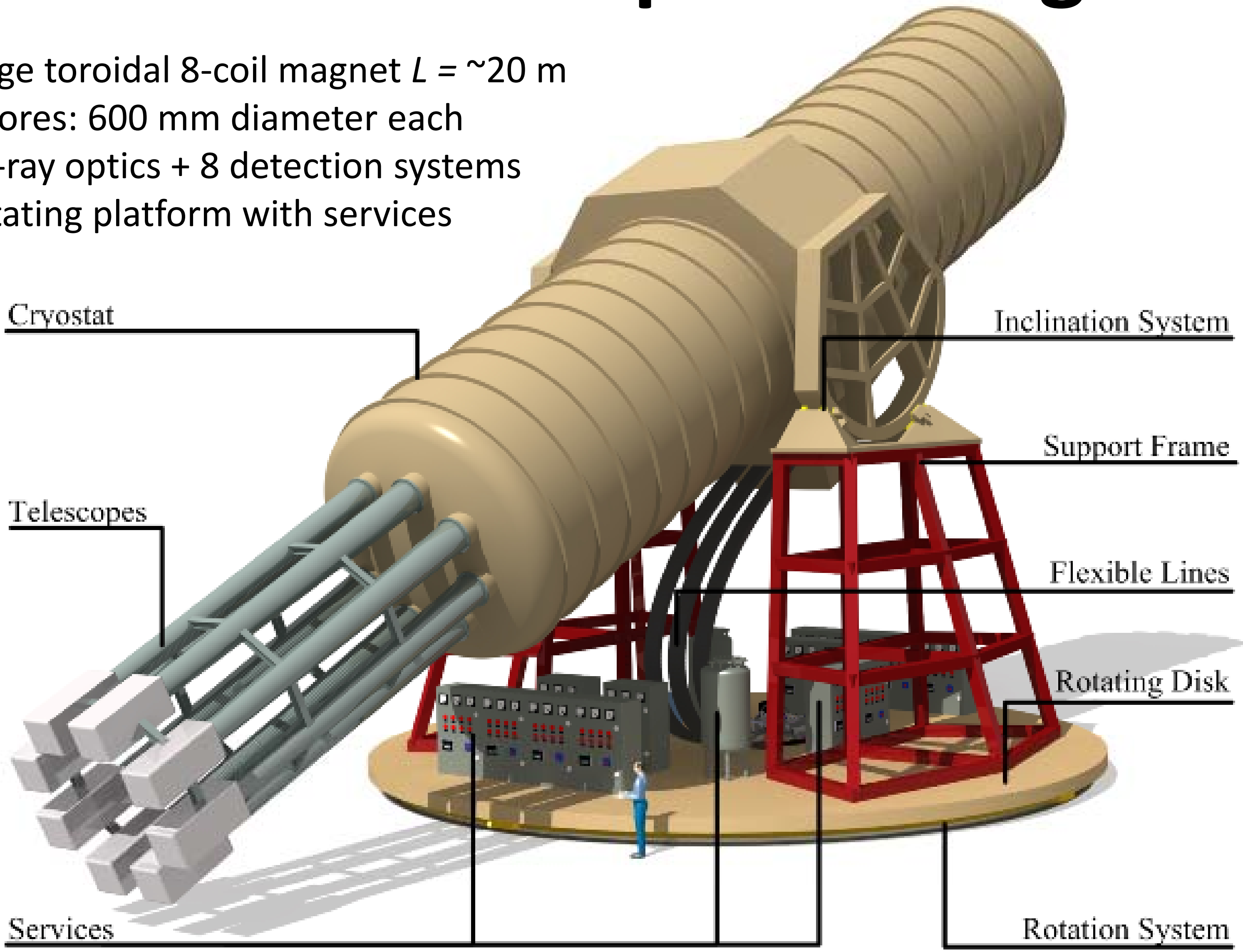
- **Sensitivity goal:** >4 orders of magnitude improvement in signal-to-noise ratio wrt CAST. (>1 order of magnitude in sensitivity of $g_{a\gamma}$)

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

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

IAXO – Conceptual Design

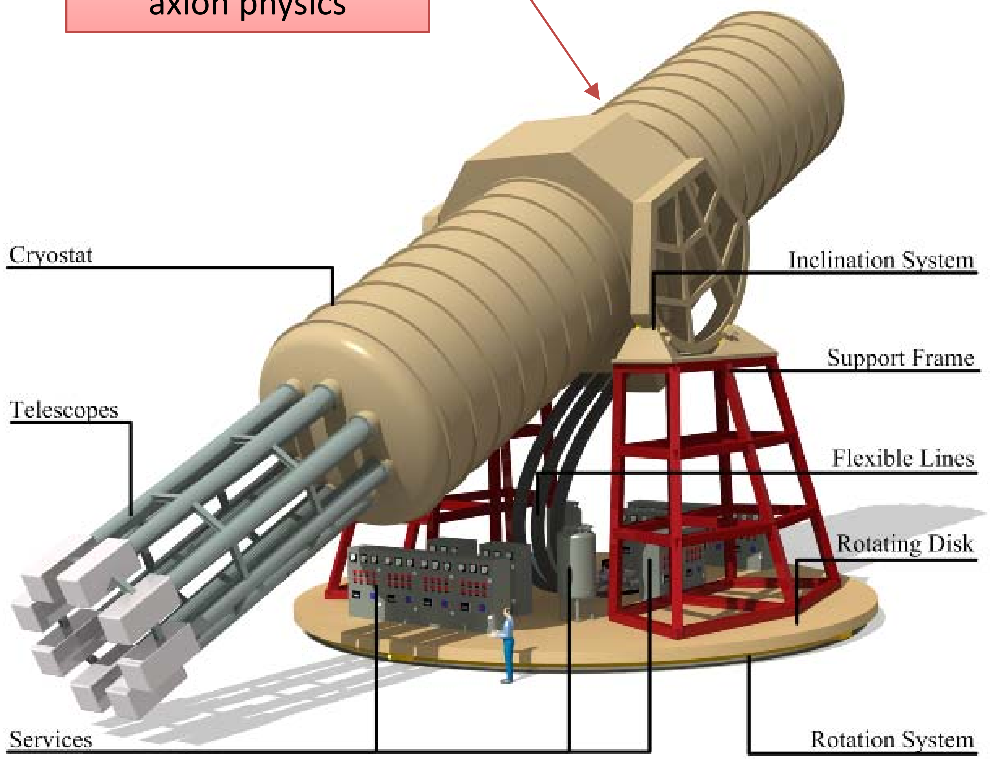
- Large toroidal 8-coil magnet *L* = ~20 m
- 8 bores: 600 mm diameter each
- 8 x-ray optics + 8 detection systems
- Rotating platform with services

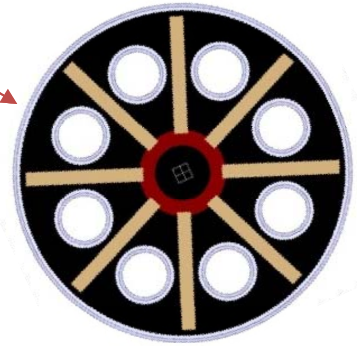


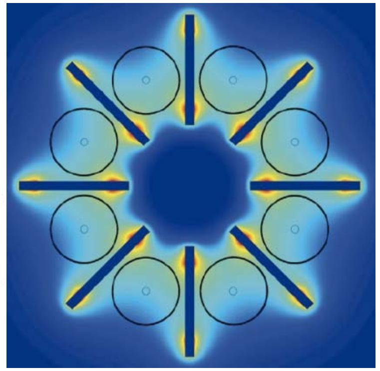
IAXO magnet

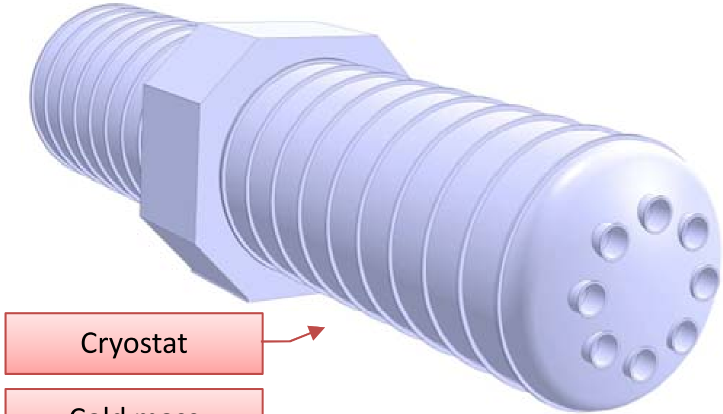
TOROIDAL CONFIGURATION specifically built for axion physics

Each conversion bore (between coils) 600 mm diameter



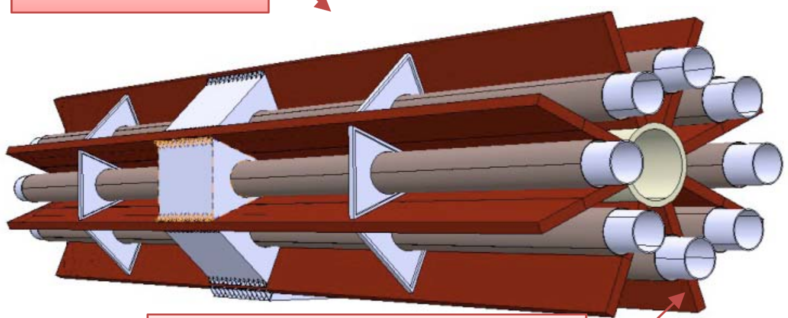






Cryostat

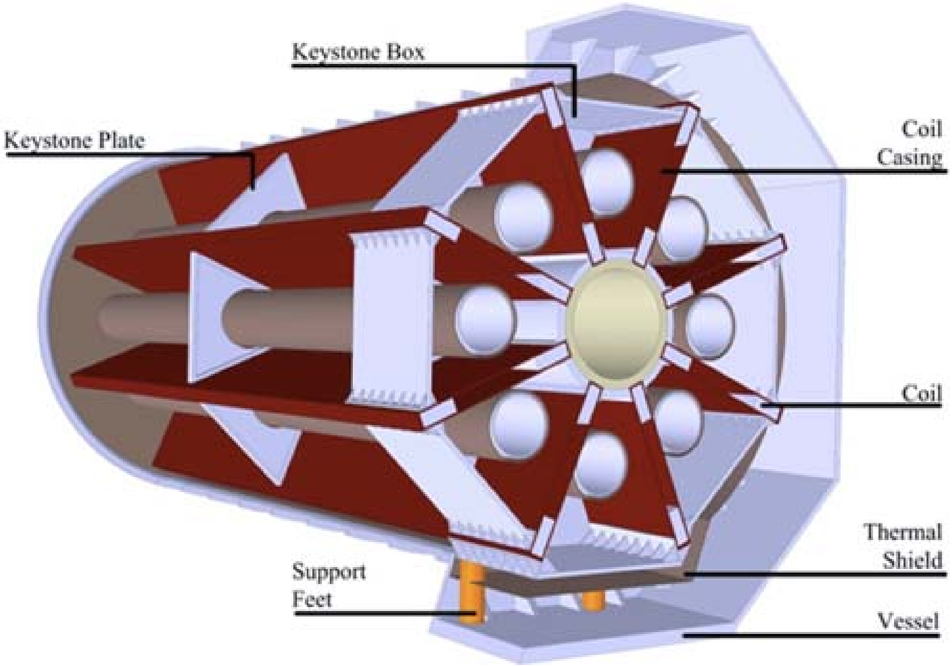
Cold mass



Bores go through cryostat

Magnetic length 20 m Total cryostat length 25 m

IAXO magnet

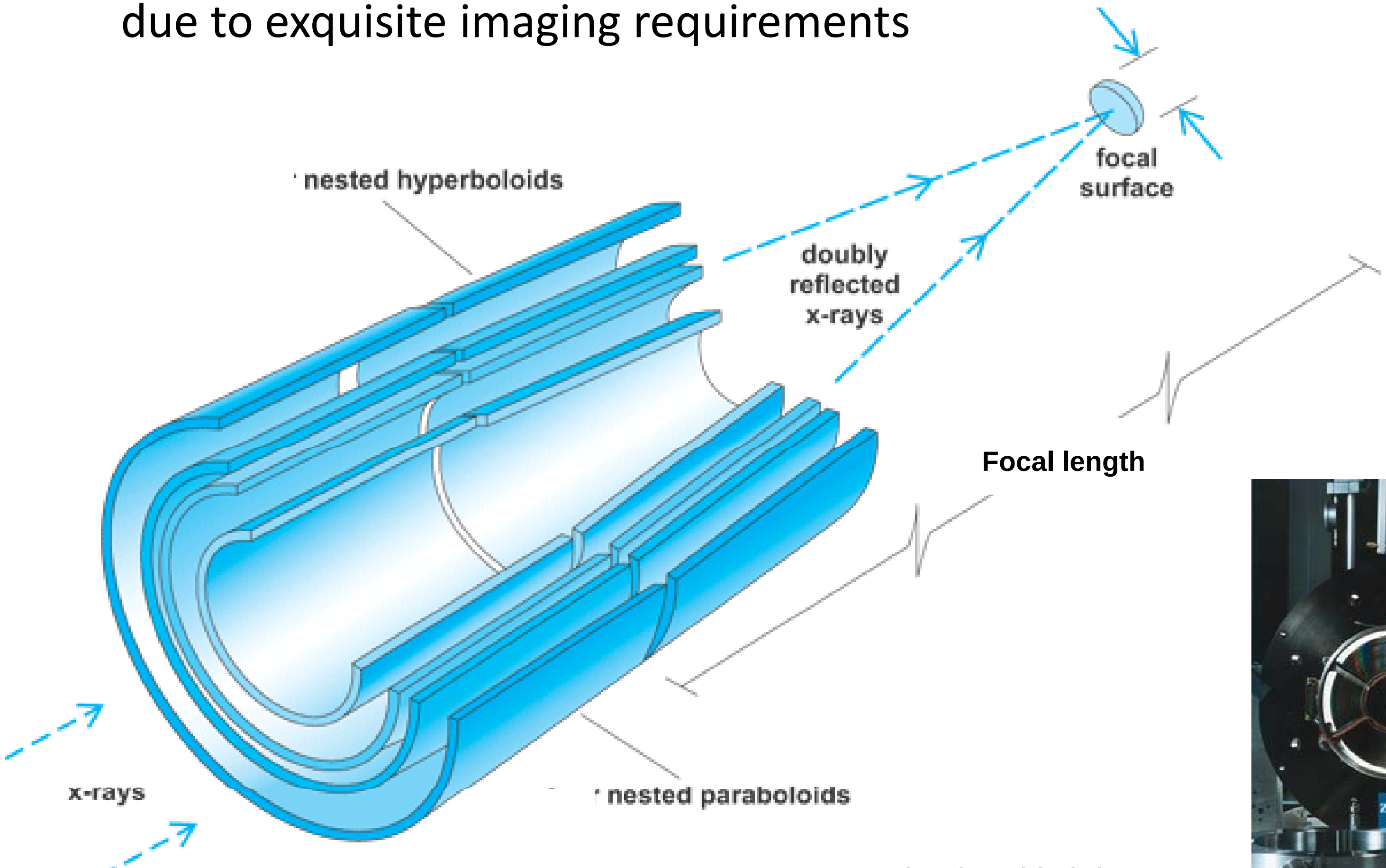


IAXO magnet concept presented in:
- IEEE Trans. Appl. Supercond. 23 (ASC 2012)
- Adv. Cryo. Eng. (CEC/ICMC 2013)
- IEEE Trans. Appl. Supercond. (MT 23)

Property		*Value*
Cryostat dimensions:	Overall length (m)	25
	Outer diameter (m)	5.2
	Cryostat volume (m^3)	~ 530
Toroid size:	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
Mass:	Conductor (tons)	65
	Cold Mass (tons)	130
	Cryostat (tons)	35
	Total assembly (tons)	~ 250
Coils:	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
Conductor:	Overall size (mm^2)	35 × 8
	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
Heat Load:	at 4.5 K (W)	~150
	at 60-80 K (kW)	~1.6

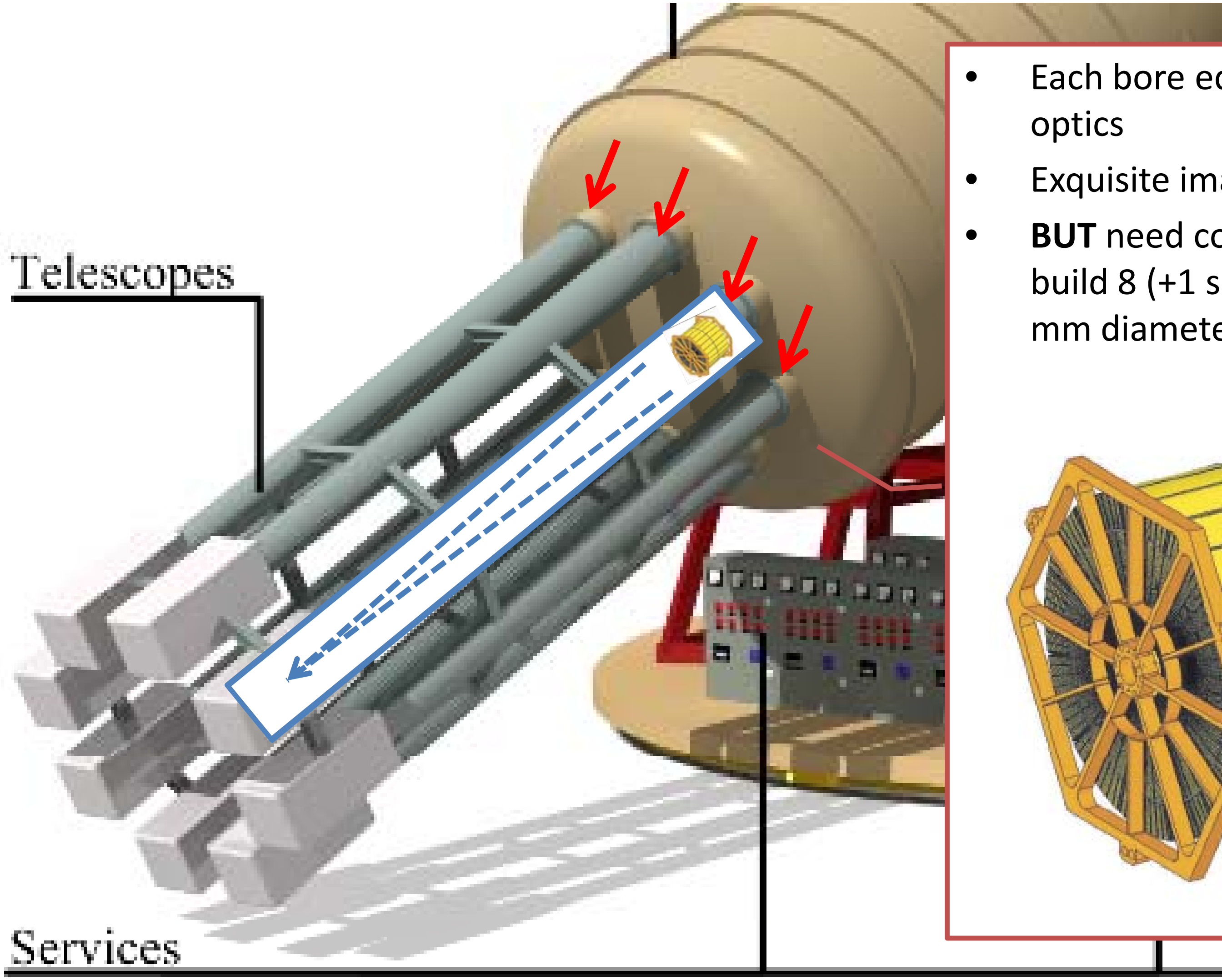
IAXO x-ray optics

- 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

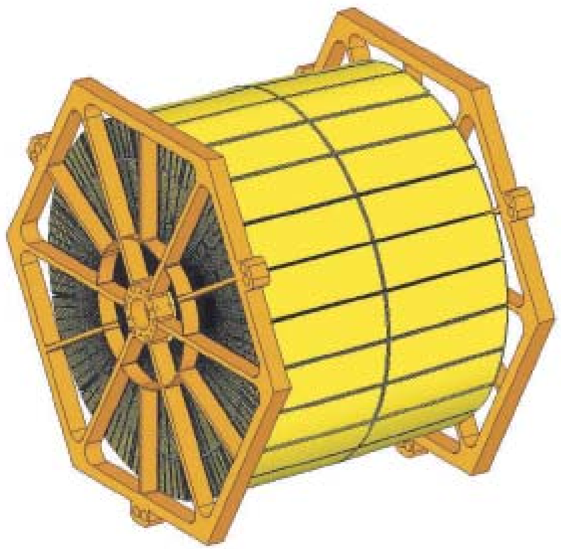


ABRIXAS spare telescope, in use in one of the 4 bores of CAST
(pioneer use of x-ray optics in axion research)

IAXO x-ray optics



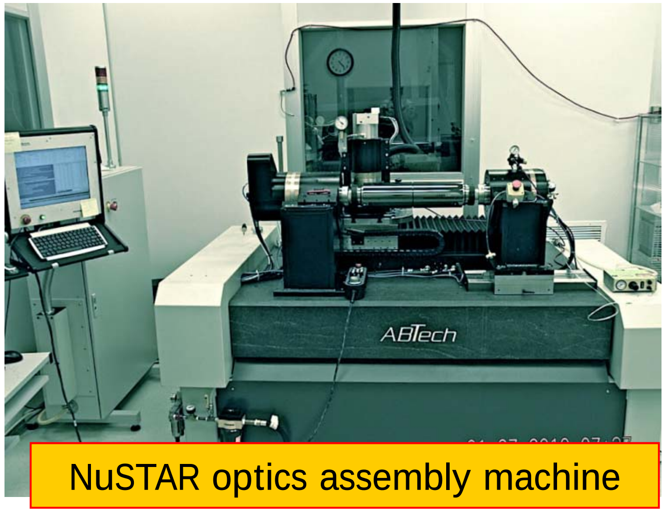
- Each bore equipped with an x-ray optics
- Exquisite imaging not required
- **BUT** need cost-effective way to build 8 (+1 spare) optics of 600 mm diameter each



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

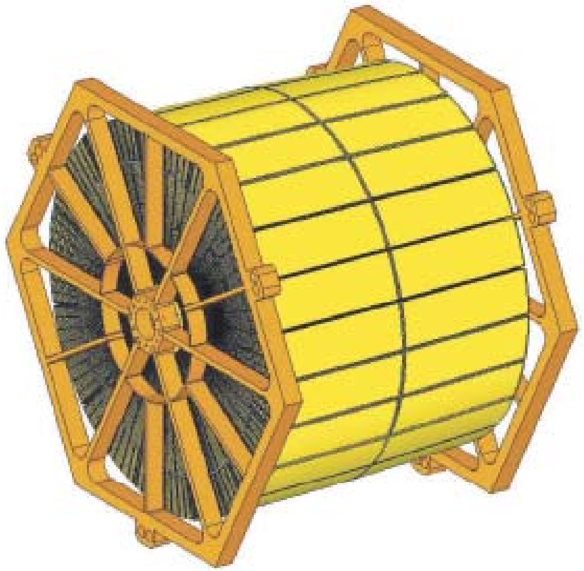
- The specialized tooling to shape the substrates and assemble the optics is now available
- Hardware can be easily configured to make optics with a variety of designs and sizes
- Key institutions in NuSTAR optics: LLNL, U. Columbia, DTU Denmark. All in IAXO !

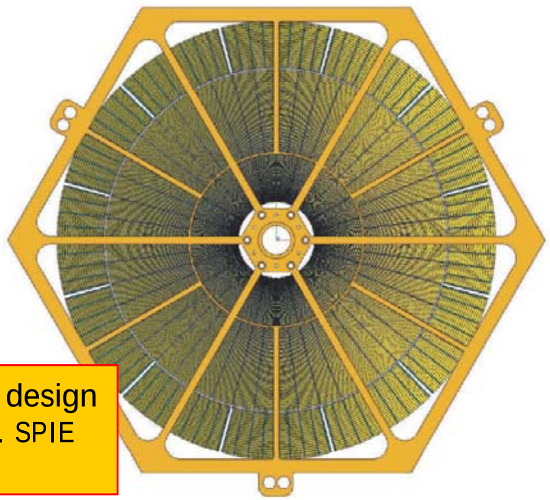


NuSTAR optics assembly machine

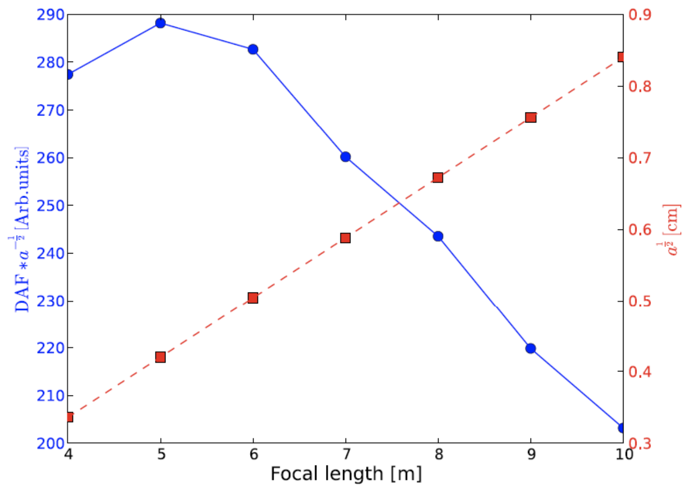
NuSTAR telescope
~400 mm Ø

IAXO x-ray optics





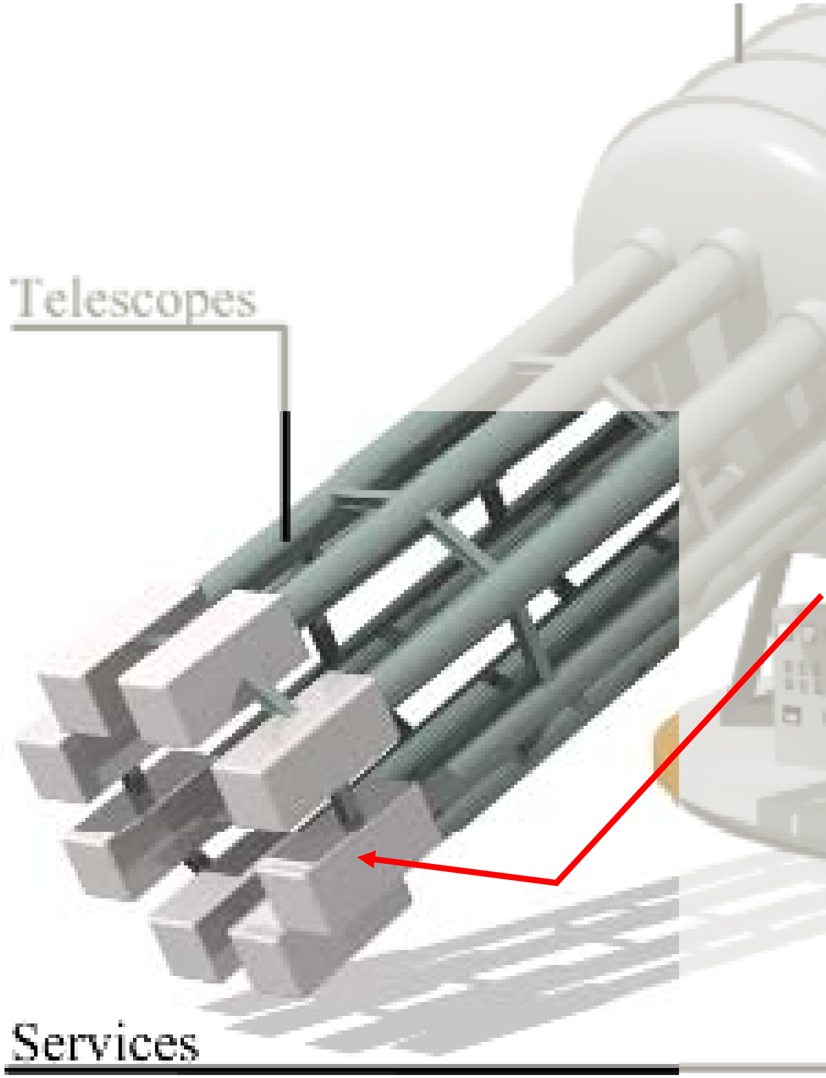
IAXO optics conceptual design
AC Jakobsen et al, Proc. SPIE 8861 (2013)



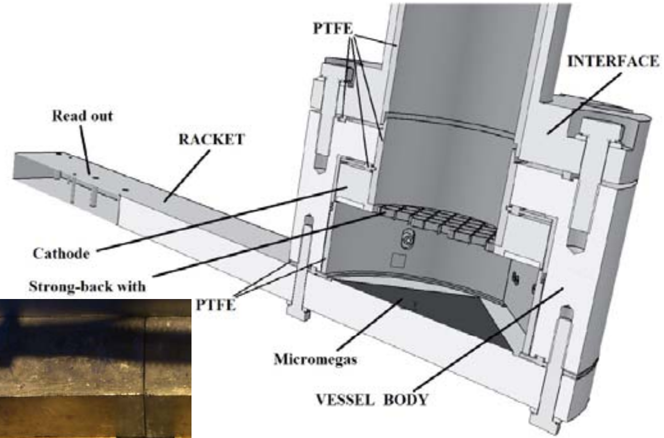
Optimal focal length ~5 m

Telescopes	8
N, Layers (or shells) per telescope	123
Segments per telescope	2172
Geometric area of glass per telescope	0.38 m^2
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_4C 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



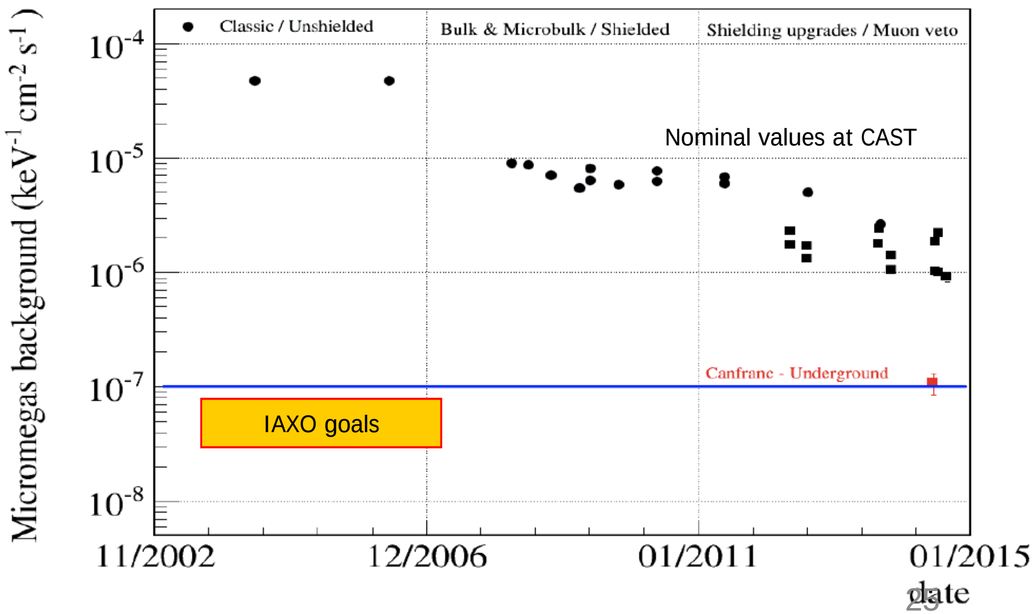
IAXO low background detectors

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

- Goal background level for IAXO:
  - **10^{-7} – 10^{-8} c keV^{-1} cm^{-2} s^{-1}**
- Already demonstrated:
  - ~8×10^{-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. Clear roadmap for improvement.

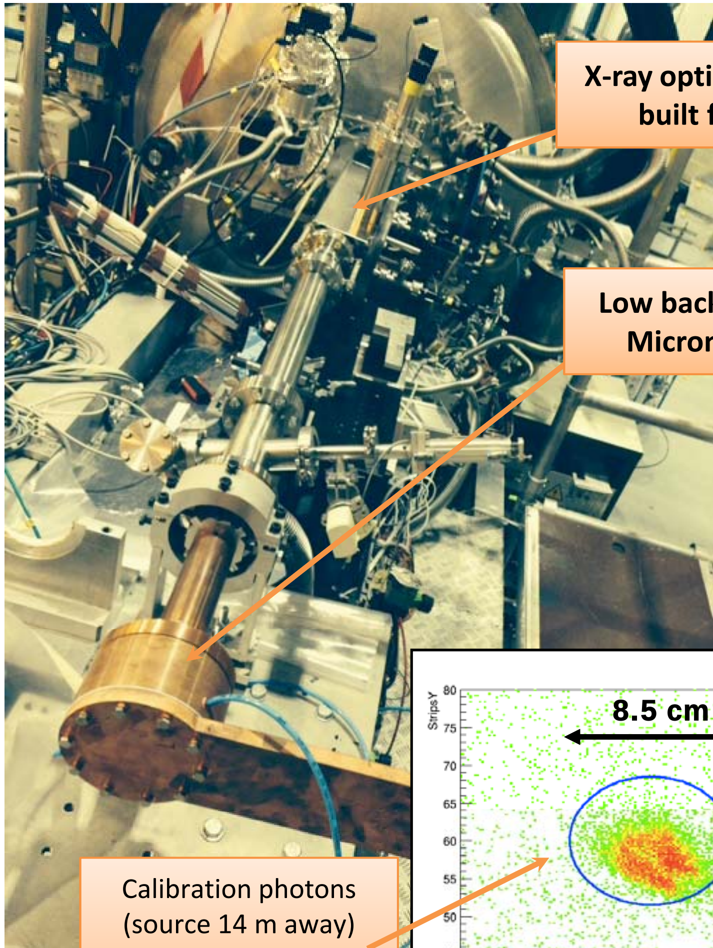
See arXiv:1310.3391

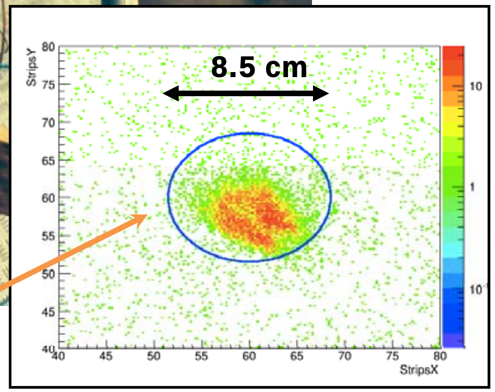
History of background improvement of Micromegas detectors at CAST



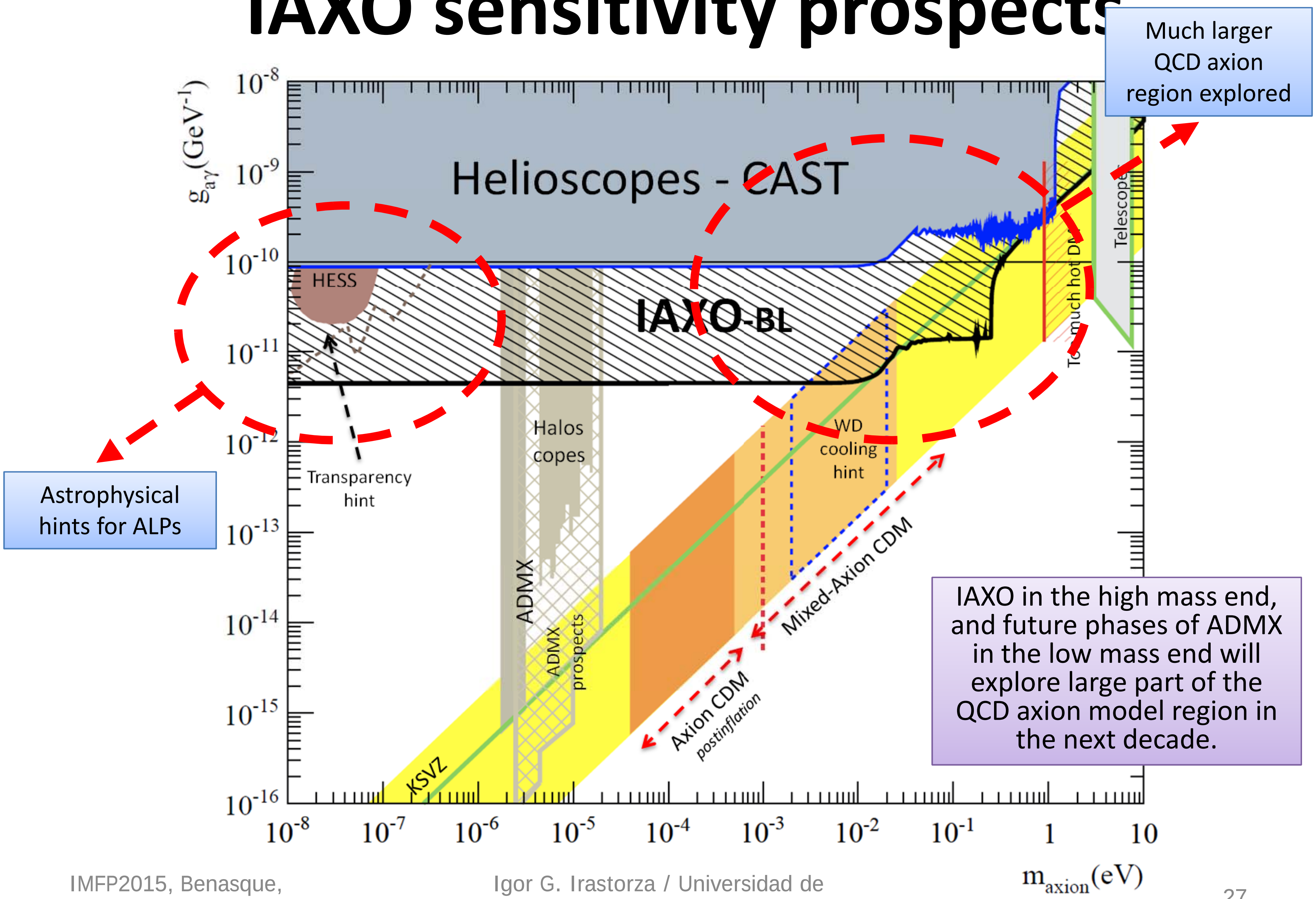
IAXO low background detectors
Optics+detector pathfinder system in CAST

- **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)
  - 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



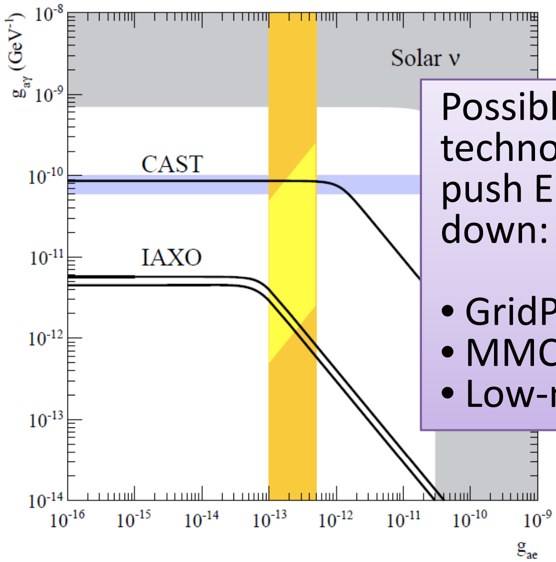


IAXO sensitivity prospects



Additional IAXO physics cases

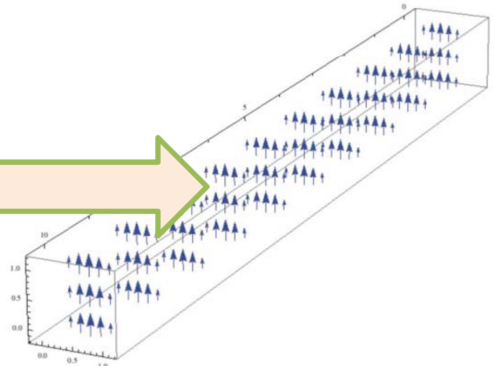
- Detection of “BCA”-produced solar axions (with relevant g_{ae} values)
- More specific WISPs models at the **low energy frontier** of particle physics:
  - Paraphotons / hidden photons
  - Chamaleons
  - Non-standard scenarios of axion production
- Microwave LSW setup



Possible additional technologies to push E thresholds down:

- GridPix
- MMC
- Low-noise CCDs

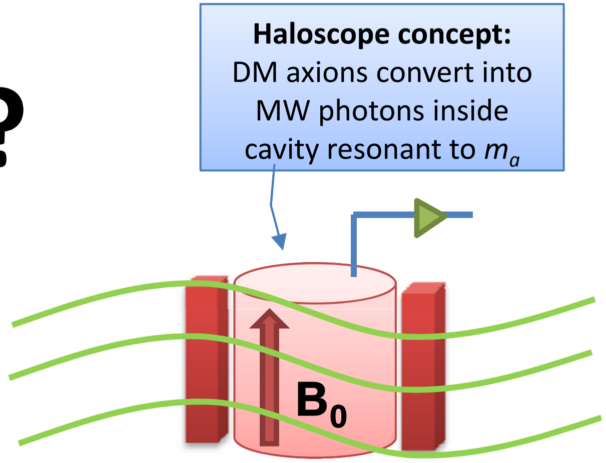
- Use of microwave cavities or dish antennas, **DM** axion searches

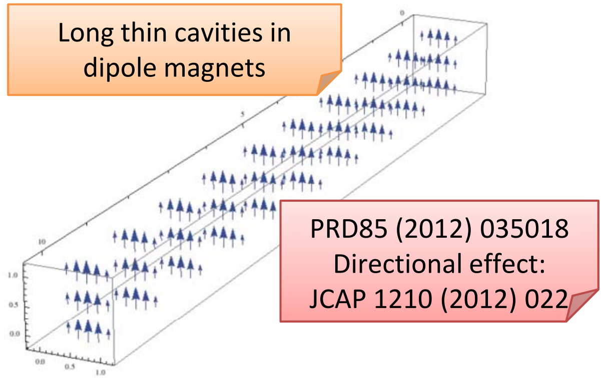


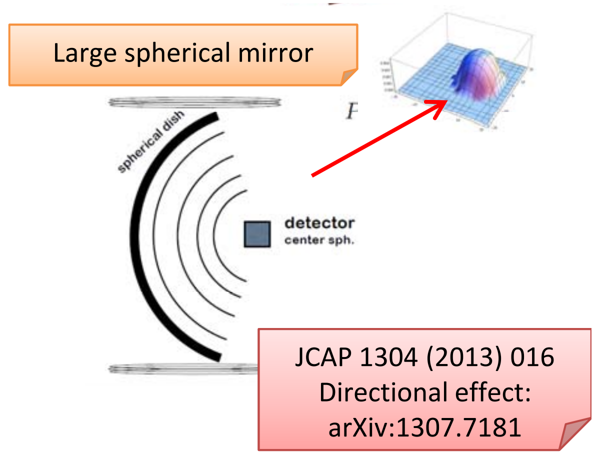
IAXO as “generic axion/ALP facility”

IAXO-DM configurations?

- ADMX leader halosocope at m_a~1-10 μeV. 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?

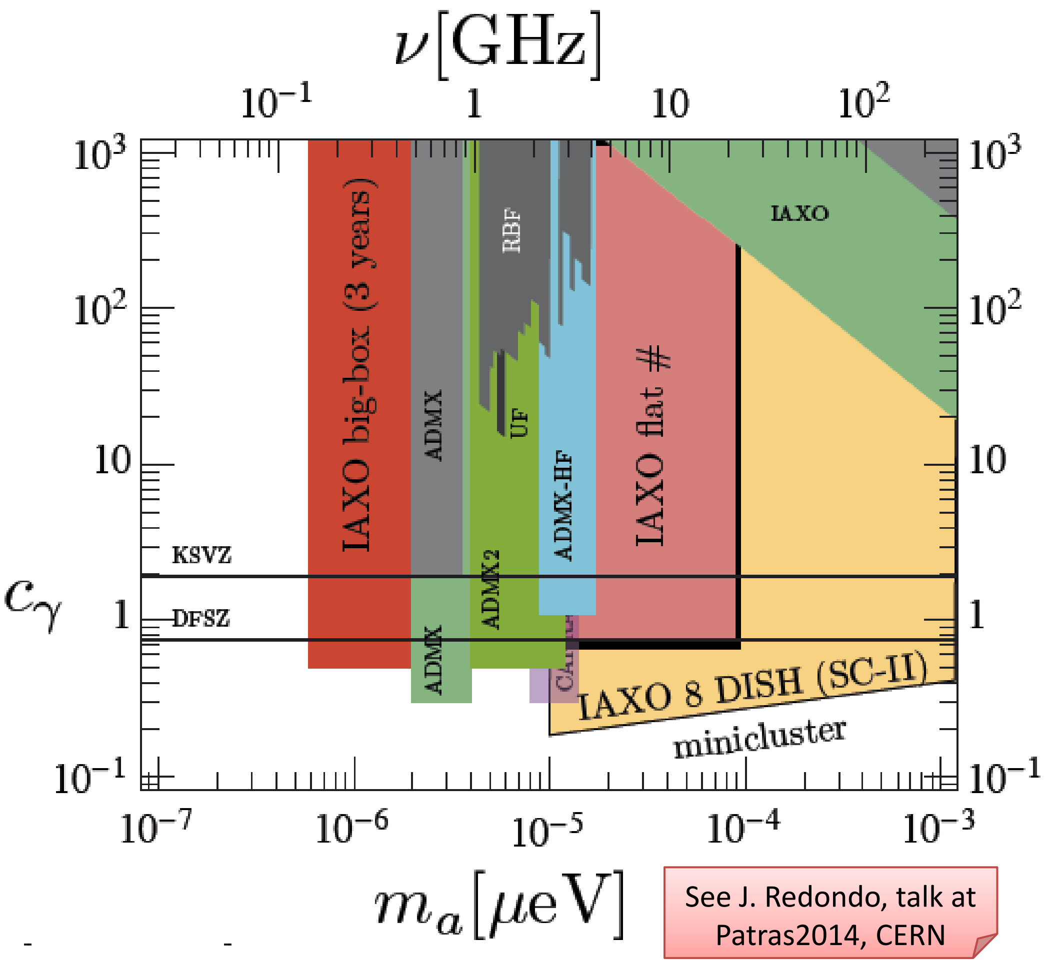






Additional IAXO physics cases

direct detection or relic axions/ALPs



See J. Redondo, talk at Patras2014, CERN

- 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

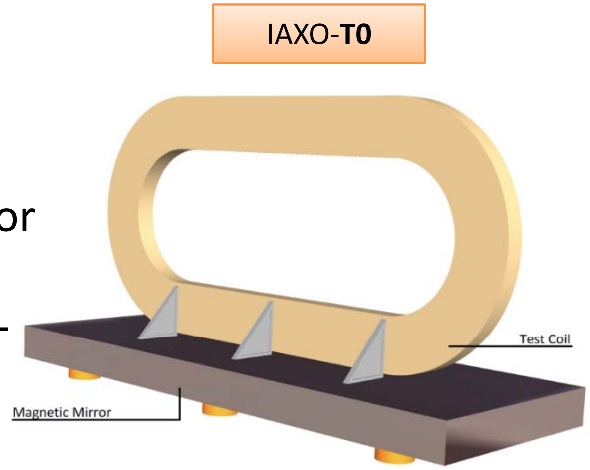
SPSC Draft minutes [Jan 2014]
The Committee **recognises** the physics motivation of an International Axion Observatory as described in the Letter of Intent SPSC-I-242, and considers that the proposed setup makes appropriate use of state-of-the-art technologies i.e. magnets, x-ray optics and low-background 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 pursuit within an MOU involving all interested parties.

This was endorsed by the Research Board in March2014

Minutes of the 206th CERN Research Board held on March2014:
https://cds.cern.ch/record/1695812/files/M-207.pdf

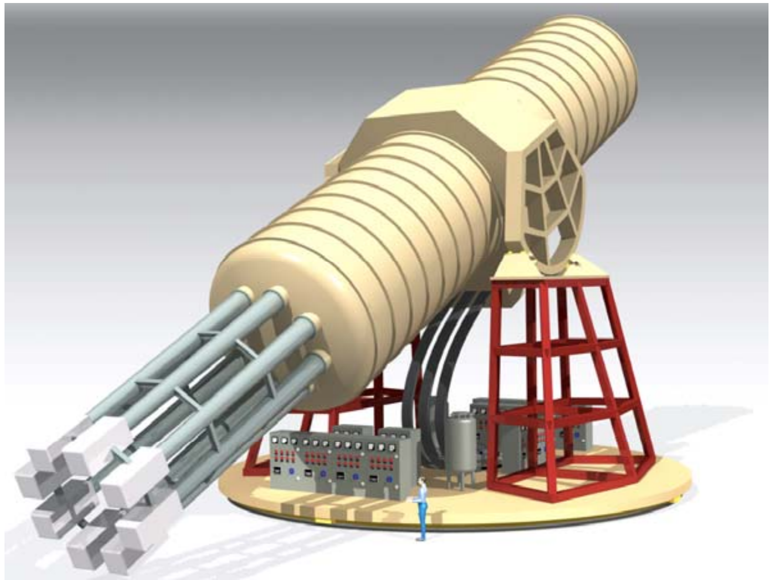
Next steps

- Start works towards a Technical Design Report. As part of such:
  - Construction of a demostration 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
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
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