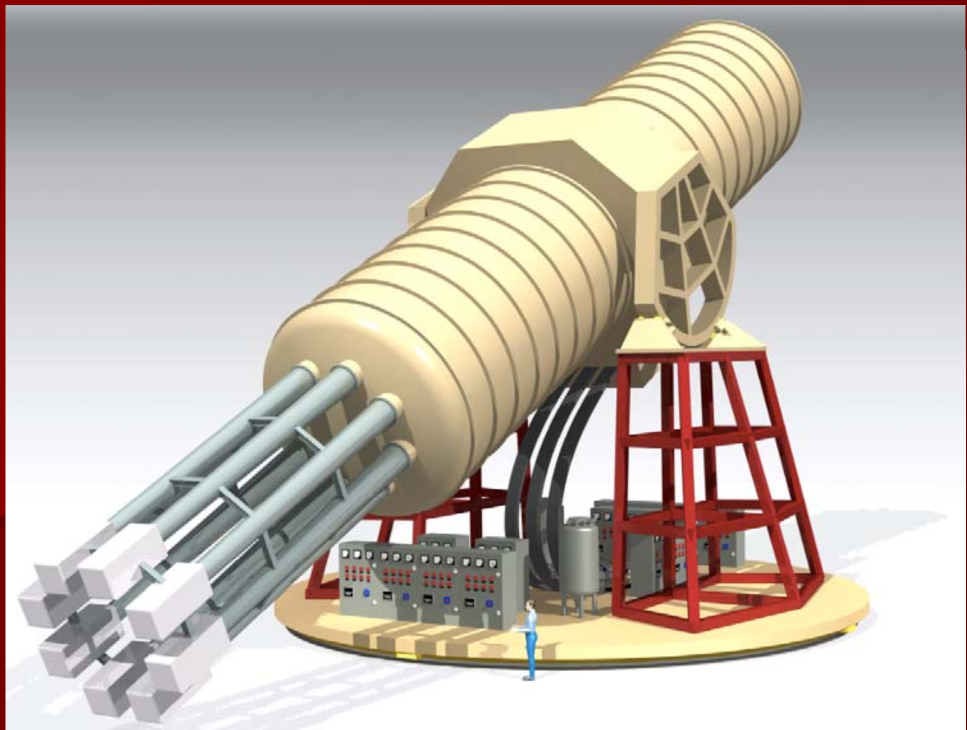
From CAST to IAXO

(International AXion Observatory)

towards a new generation axion helioscope

Igor G Irastorza
Universidad de Zaragoza

ISOLDE Seminar – CERN – April 9th, 2014



Outline

- Axion motivation:
  - Strong CP problem
  - Axions as CDM
  - Solar axions
- Previous helioscopes & CAST
- IAXO Conceptual Design
  - Magnet
  - Optics
  - Detectors
- IAXO physics potential
- Status of project. Requests to CERN. Next steps
- Conclusions

Letter of Intent to the CERN SPSC

The International Axion Observatory
IAXO

E. Armengaud[1], F. T. Avignone[2], M. Betz[3], P. Brax[4], P. Brun[1], G. Cantatore[5], J. M. Carmona[6], G. P. Carosi[7], F. Caspers[3], S. Caspi[8], S. A. Cetin[9], D. Chelouche[10], F. E. Christensen[11], A. Dael[1], T. Dafni[6], M. Davenport[3], A.V. Derbin[12], K. Desch[13], A. Diago[6], B. Döbrich[14], I. Dratchnev[12], A. Dudarev[3], C. Eleftheriadis[15], G. Fanourakis[16], E. Ferrer-Ribas[1], J. Galán[1], J. A. García[6], J. G. Garza[6], T. Geralis[16], B. Gimeno[17], I. Giomataris[1], S. Gninenko[18], H. Gómez[6], D. González-Díaz[6], E. Guendelman[19], C. J. Hailey[20], T. Hiramatsu[21], D. H. H. Hoffmann[22], D. Horns[23], F. J. Iguaz[6], I. G. Irastorza[6,*], J. Isern[24], K. Imai[25], A. C. Jakobsen[11], J. Jaeckel[26], K. Jakovčić[27], J. Kaminski[13], M. Kawasaki[28], M. Karuza[29], M. Krčmar[27], K. Kousouris[3], C. Krieger[13], B. Lakić[27], O. Limousin[1], A. Lindner[14], A. Liolios[15], G. Luzón[6], S. Matsuki[30], V. N. Muratova[12], C. Nones[1], I. Ortega[6], T. Papaevangelou[1], M. J. Pivovaroff[7], G. Raffelt[31], J. Redondo[31], A. Ringwald[14], S. Russenschuck[3], J. Ruz[7], K. Saikawa[32], I. Savvidis[15], T. Sekiguchi[28], Y. K. Semertzidis[33], I. Shilon[3], P. Sikivie[34], H. Silva[3], H. ten Kate[3], A. Tomas[6], S. Troitsky[18], T. Vafeiadis[3], K. van Bibber[35], P. Vedrine[1], J. A. Villar[6], J. K. Vogel[7], L. Walckiers[3], A. Weltman[36], W. Wester[37], S. C. Yildiz[9], K. Zioutas[38]

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

AXION theory motivation

- Axion: introduced to solve the **strong CP problem**

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

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

This term is **CP violating**.

$$\theta = \bar{\theta} + \arg\det M$$

2 contributions of very different origin...

From non-observation of neutron electric dipole moment:

$$|\theta| < 0.7 \times 10^{-11}$$

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

AXION theory motivation

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

"Axion lagrangian"

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

θ absorbed in the definition of a

$\theta = a/f_a$ relaxes to zero...

CP conservation is preserved "dinamically"

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)

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

- **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)

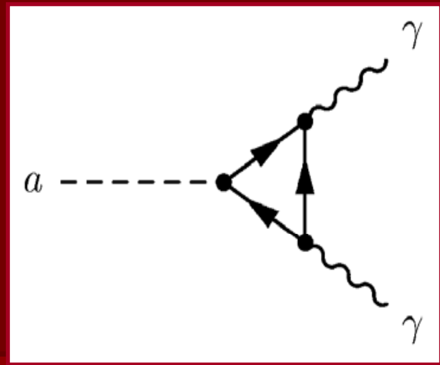
$$m_a \simeq 0.6 \text{ eV} \frac{10^7 \text{GeV}}{f_a}$$

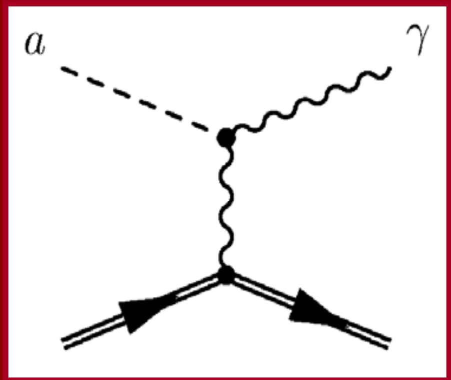
AXION phenomenology

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

$$\mathcal{L}_{a\gamma} = g_{a\gamma\gamma}(\mathbf{E}\cdot\mathbf{B})a$$

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





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

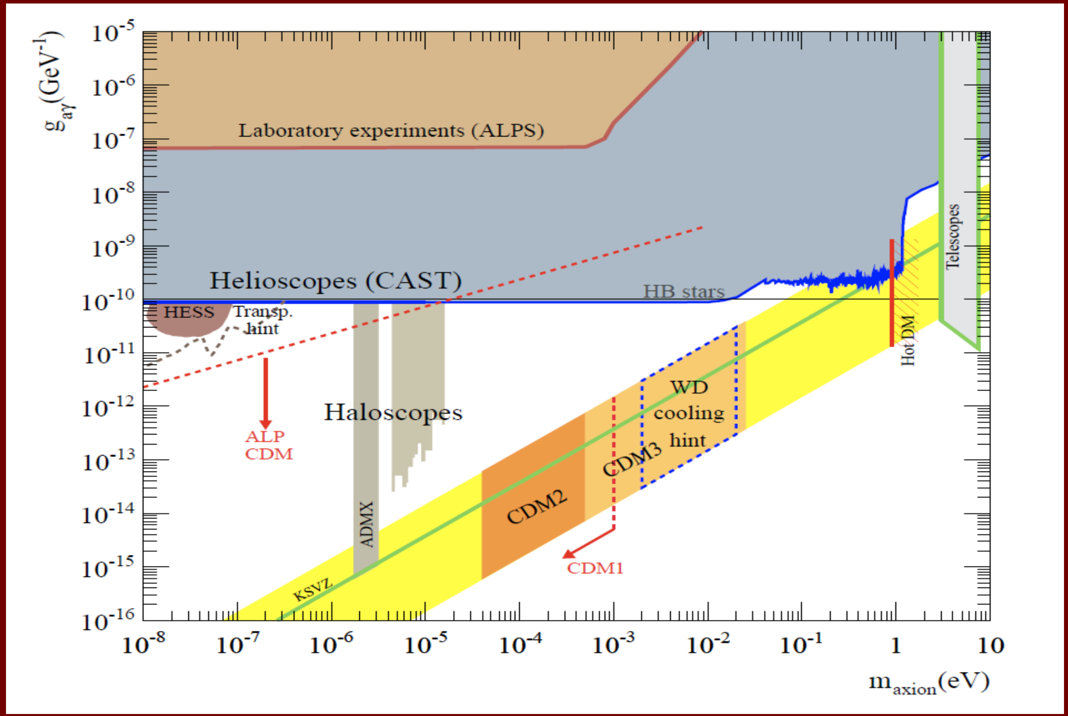
This is probably the most relevant of axion properties.
Most axion detection strategies are based on the axion-photon coupling

Beyond axions

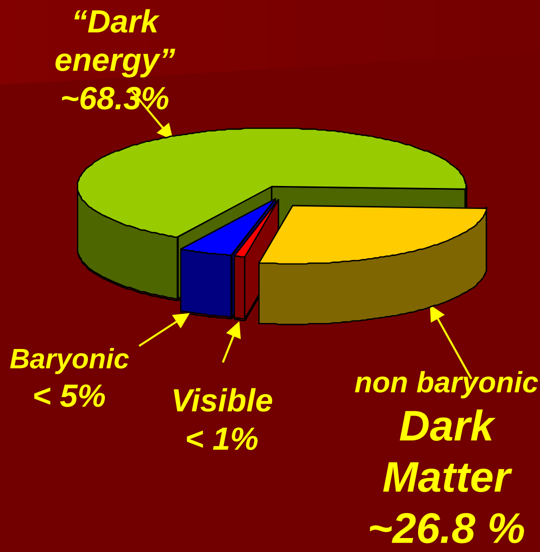
Hidden photons / paraphotons | ALPS | **AXIONS** | Chamaleons | Minicharged particles

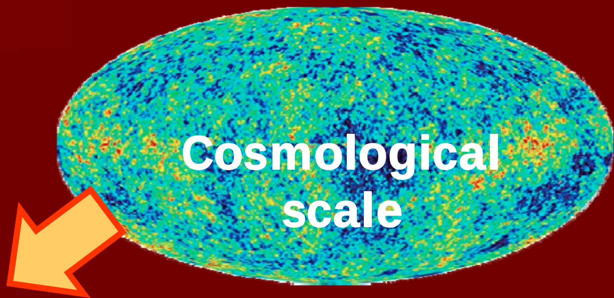
WISPs (Weakly interacting Slim Particle)

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

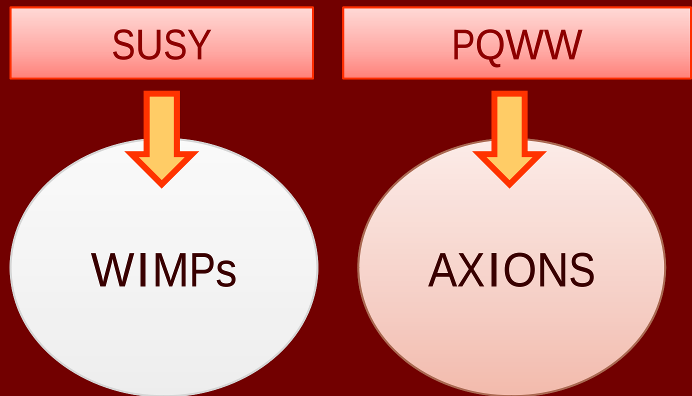


AXION as Dark Matter?





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



AXION as Dark Matter?

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

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

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

  → **RELATIVISTIC (HOT) AXIONS**

- Axion mases 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)

Axions in Astrophysics

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

See PDG
and references therein

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

Astrophysical hints for axions/ALPs

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

Axion motivation in a nutshell

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

- Axion-like particles (ALPs) **predicted by many extensions** of the SM (e.g. string theory)
- Axions, like WIMPs, may **solve the DM problem** *for free*. (i.e. not *ad hoc* solution to DM)
- **Astrophysical hints** for axion/ALPs?
  - Transparency of the Universe to UHE gammas
  - White dwarfs anomalous cooling → point to few meV axions

- Relevant axion/ALP parameter space at **reach of current and near-future experiments**
- Still too little experimental efforts devoted to axions when compared e.g. to WIMPs... (not justified...)

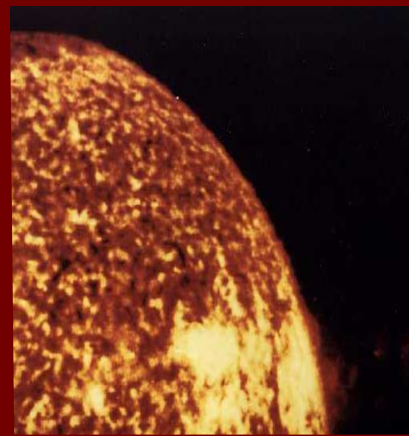
Detecting axions

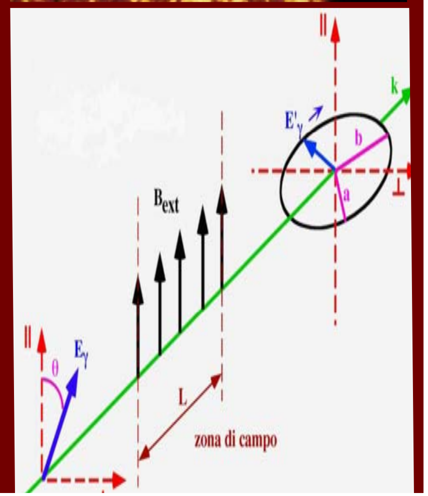
- Relic Axions
  - Axions that are part of galactic dark matter halo:
    - Axion Haloscopes **ADMX in US**

- 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

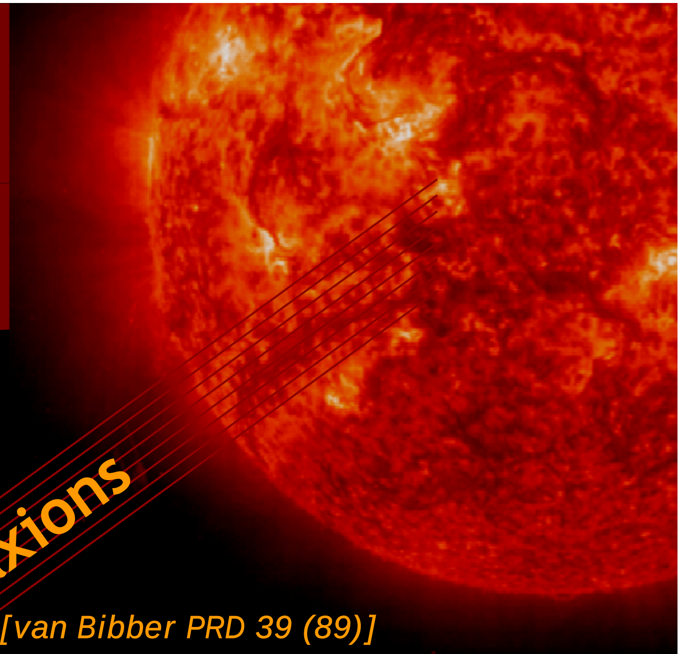
ALPS-II @ DESY
OSQAR @ CERN

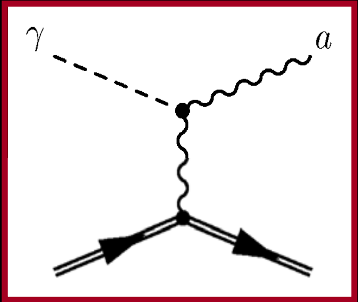




Solar Axions

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

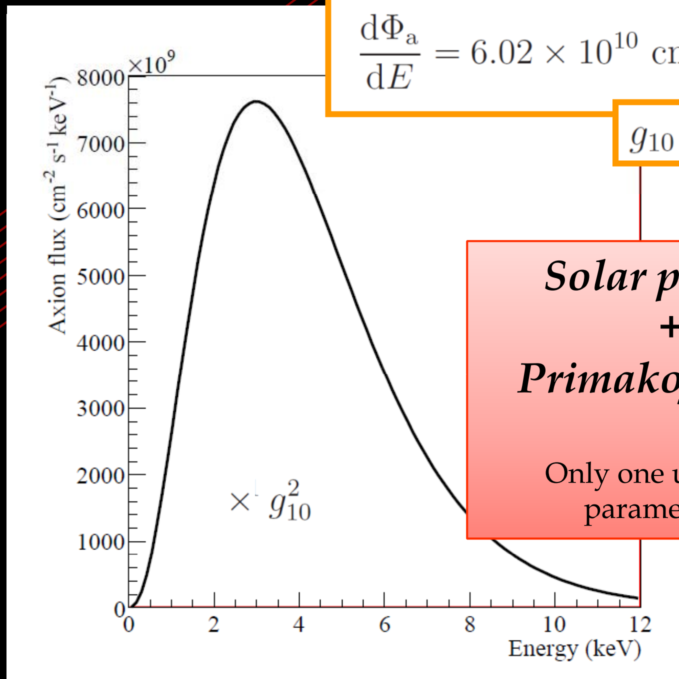




- *Solar axion flux* [van Bibber PRD 39 (89)] [CAST JCAP 04(2007)010]

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

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



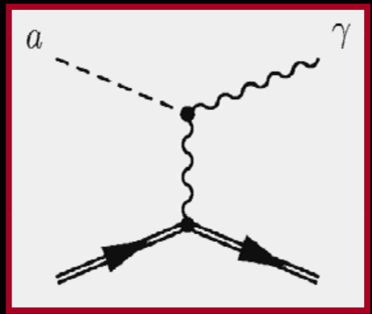
Solar physics
+
Primakoff effect

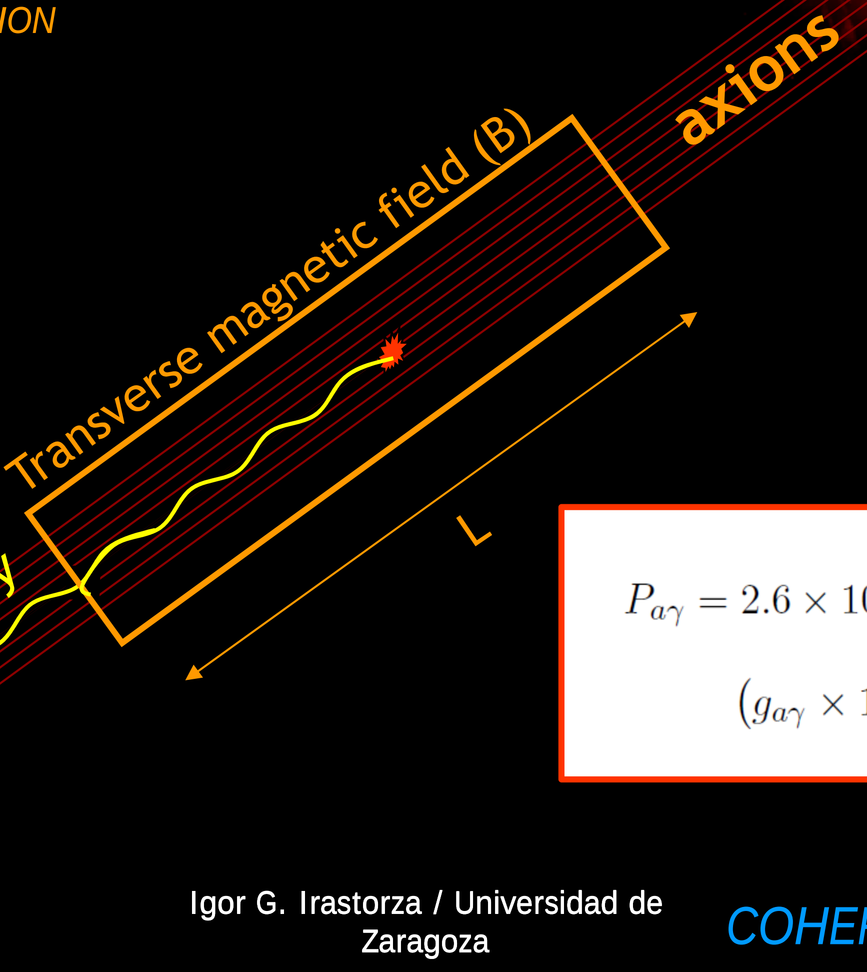
Only one unknown parameter $g_{a\gamma}$

Axion Helioscope principle

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

AXION PHOTON CONVERSION



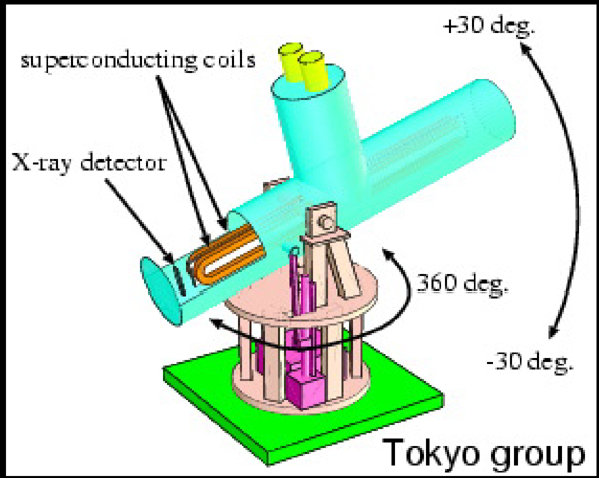


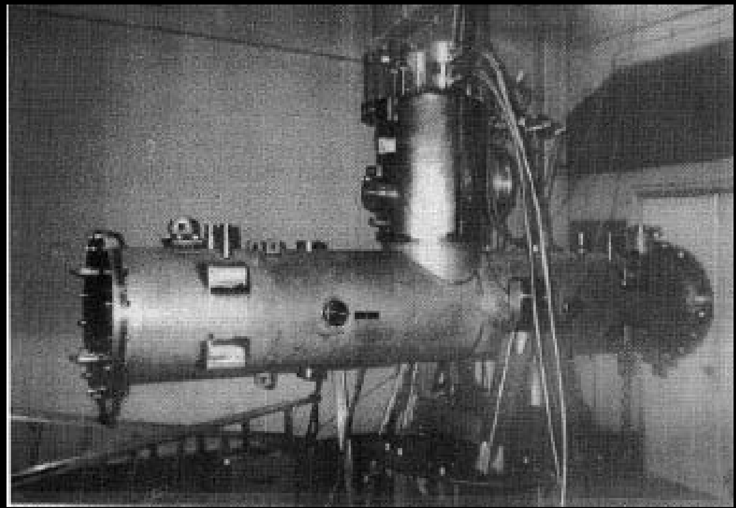
$$P_{a\gamma} = 2.6 \times 10^{-17} \left(\frac{B}{10\ \mathrm{T}}\right)^2 \left(\frac{L}{10\ \mathrm{m}}\right)^2 \left(g_{a\gamma} \times 10^{10}\ \mathrm{GeV}\right)^2 \mathcal{F}$$

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

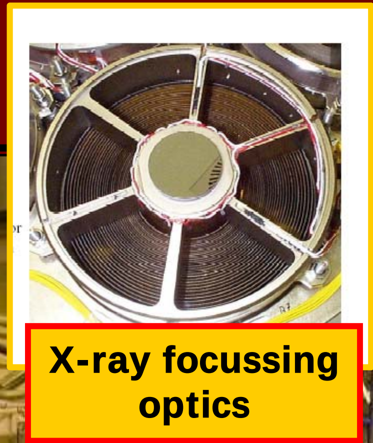


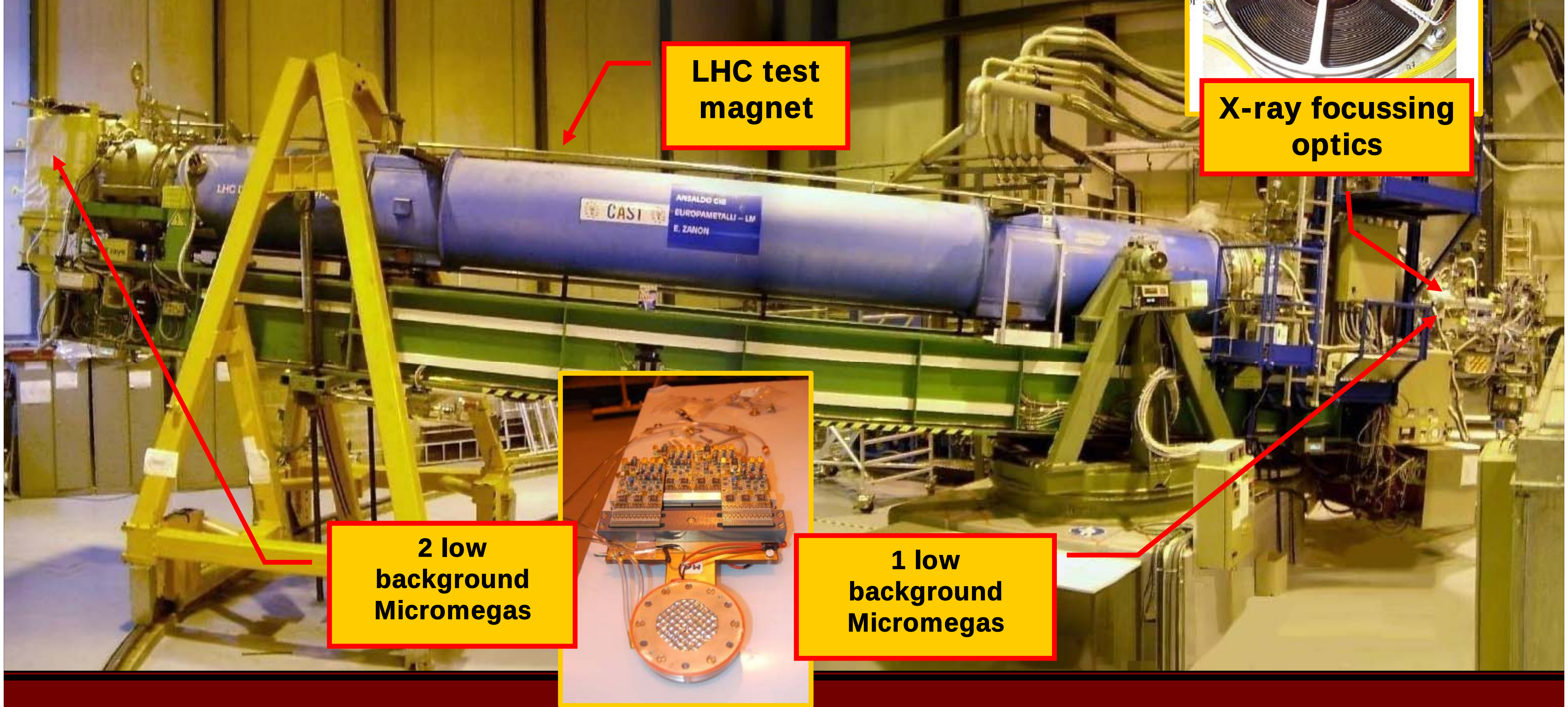


- Presently running:
  - CERN Axion Solar Telescope (**CAST**)

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.

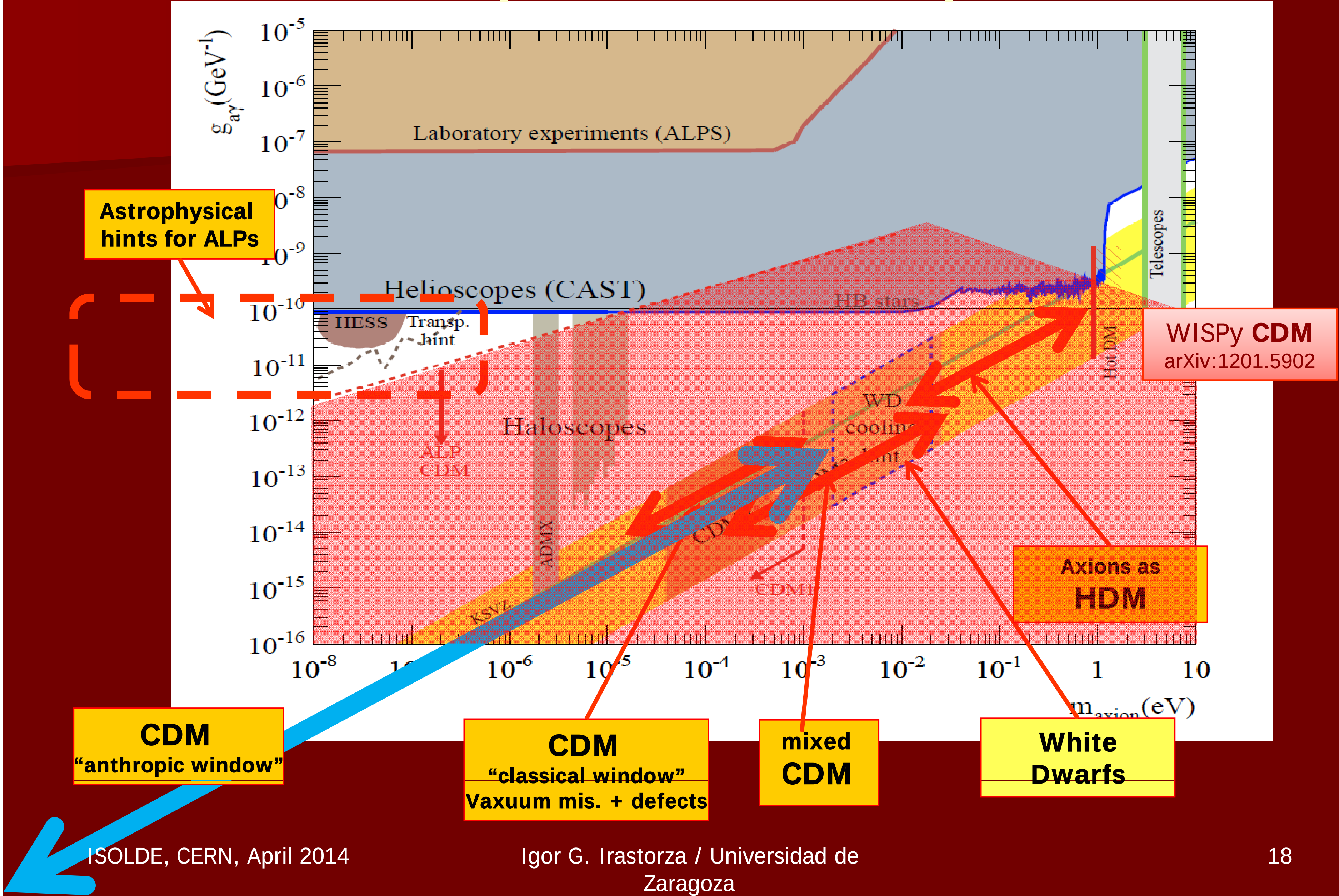




CAST at work

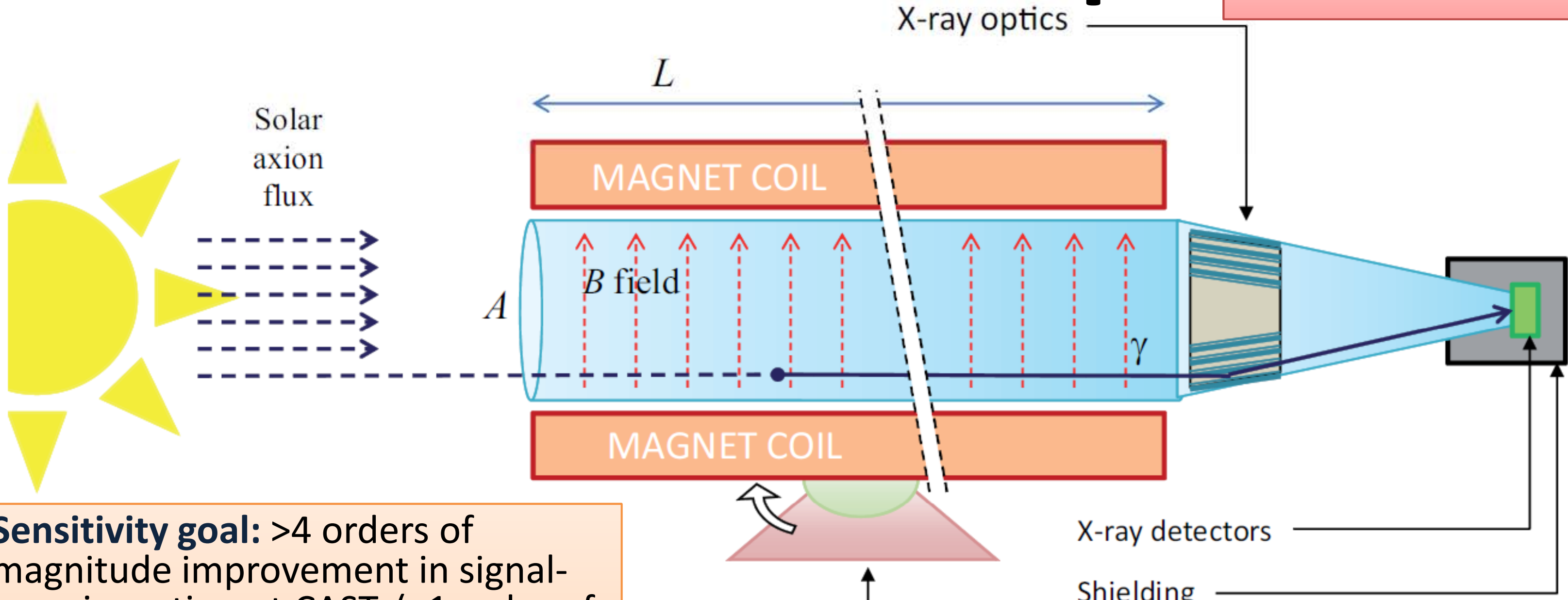
Movie credit:
Cenk Yildiz

Axion parameter space



IAXO – Concept

Enhanced axion helioscope:
JCAP 1106:013,2011



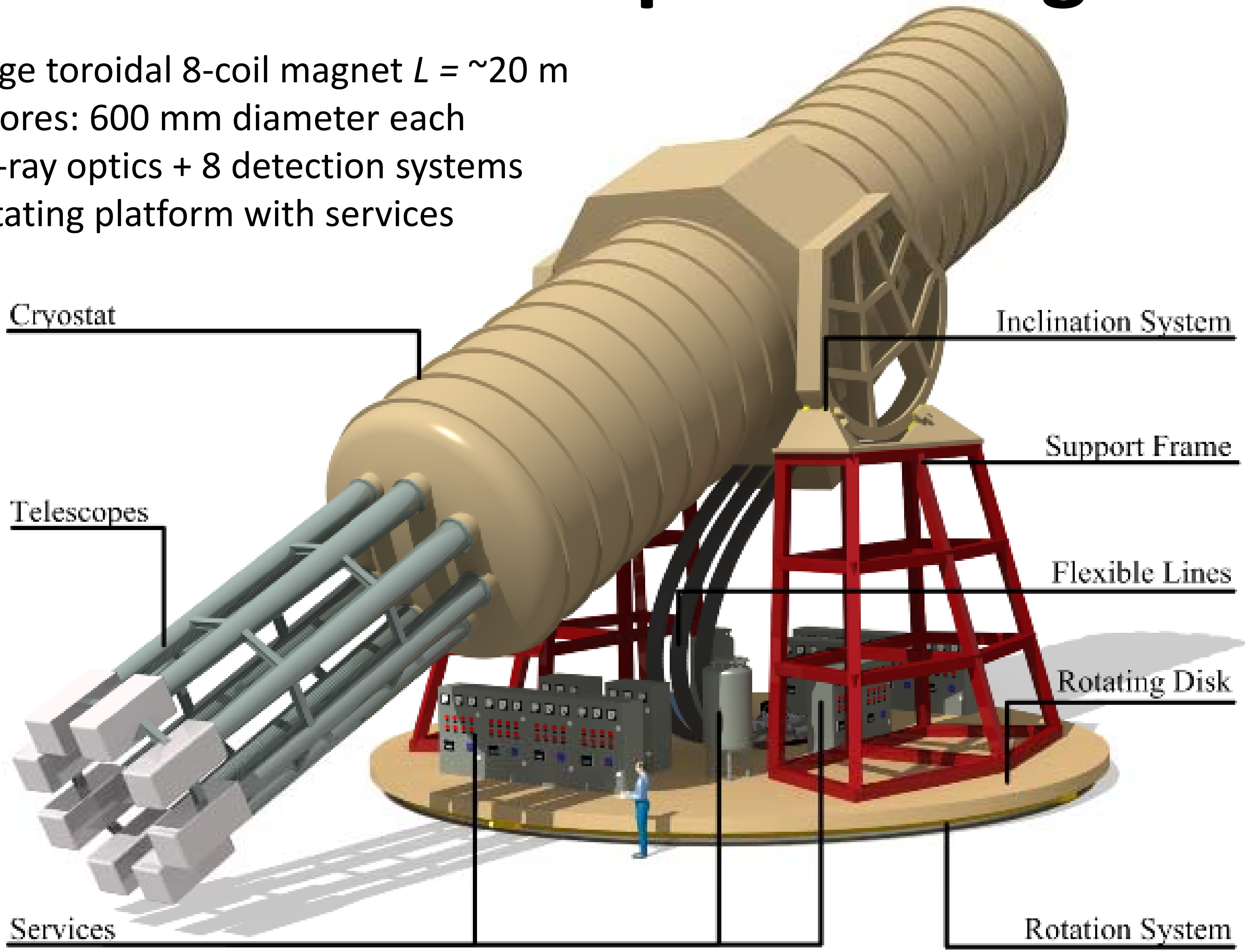
- **Sensitivity goal:** >4 orders of magnitude improvement in signal-to-noise ratio wrt CAST. (>1 order of magnitude in sensitivity of $g_{a\gamma}$)

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

- No technological challenge (build on CAST experience)
  - New dedicated **superconducting magnet,** built for IAXO (improve >300 B^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

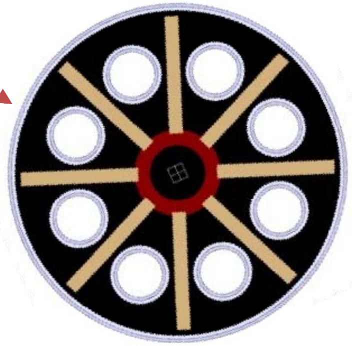
- Large toroidal 8-coil magnet *L* = ~20 m
- 8 bores: 600 mm diameter each
- 8 x-ray optics + 8 detection systems
- Rotating platform with services

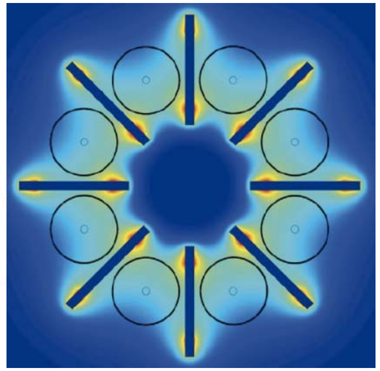


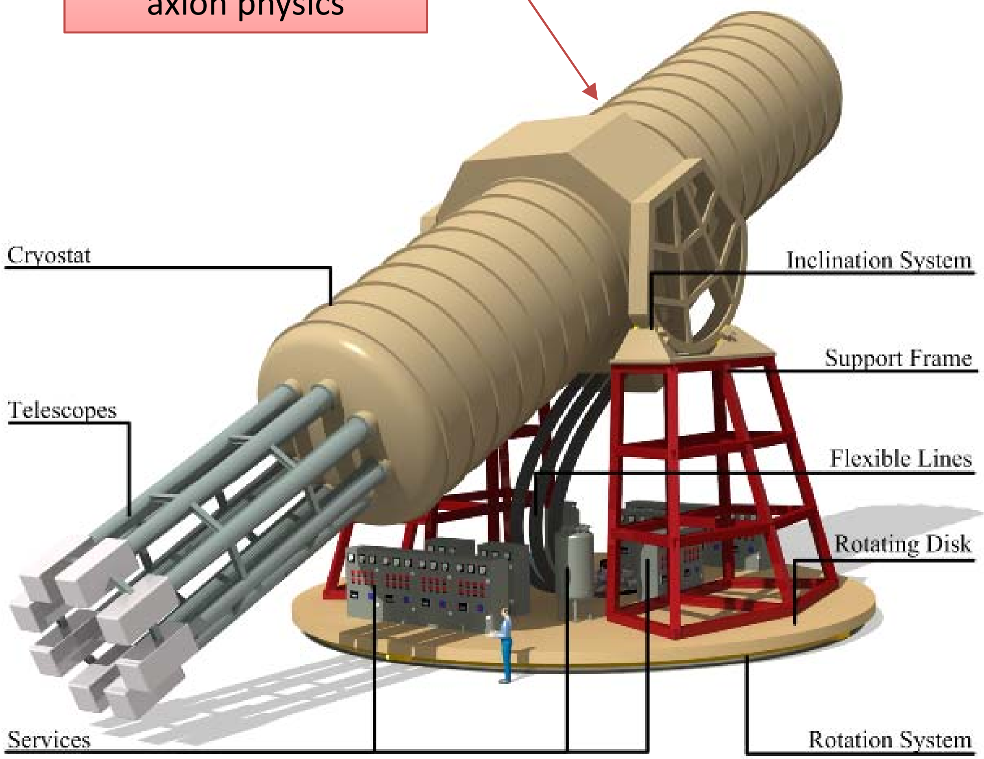
IAXO magnet

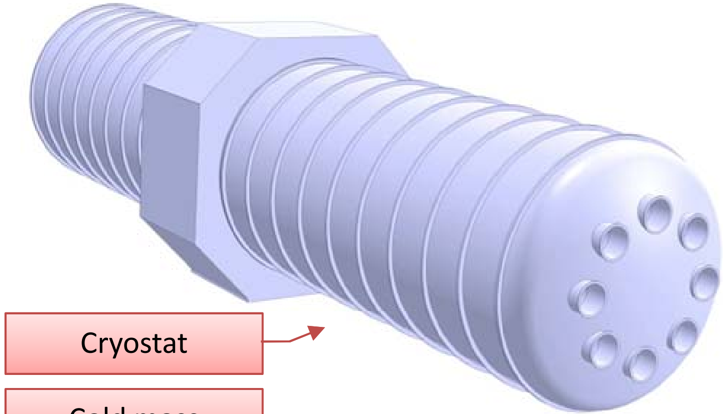
TOROIDAL CONFIGURATION specifically built for axion physics

Each conversion bore (between coils) 600 mm diameter



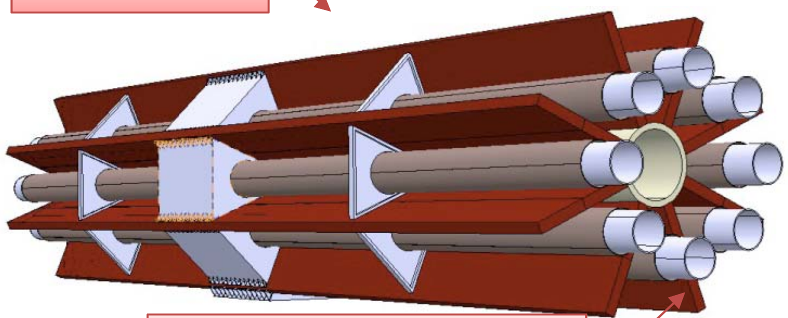






Cryostat

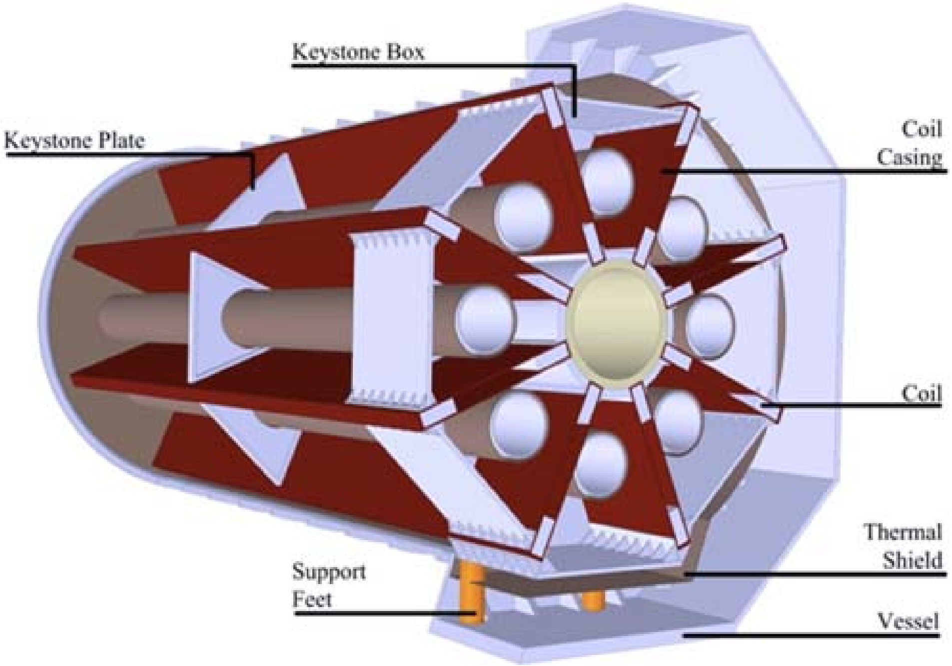
Cold mass



Bores go through cryostat

Magnetic length 20 m Total cryostat length 25 m

IAXO magnet

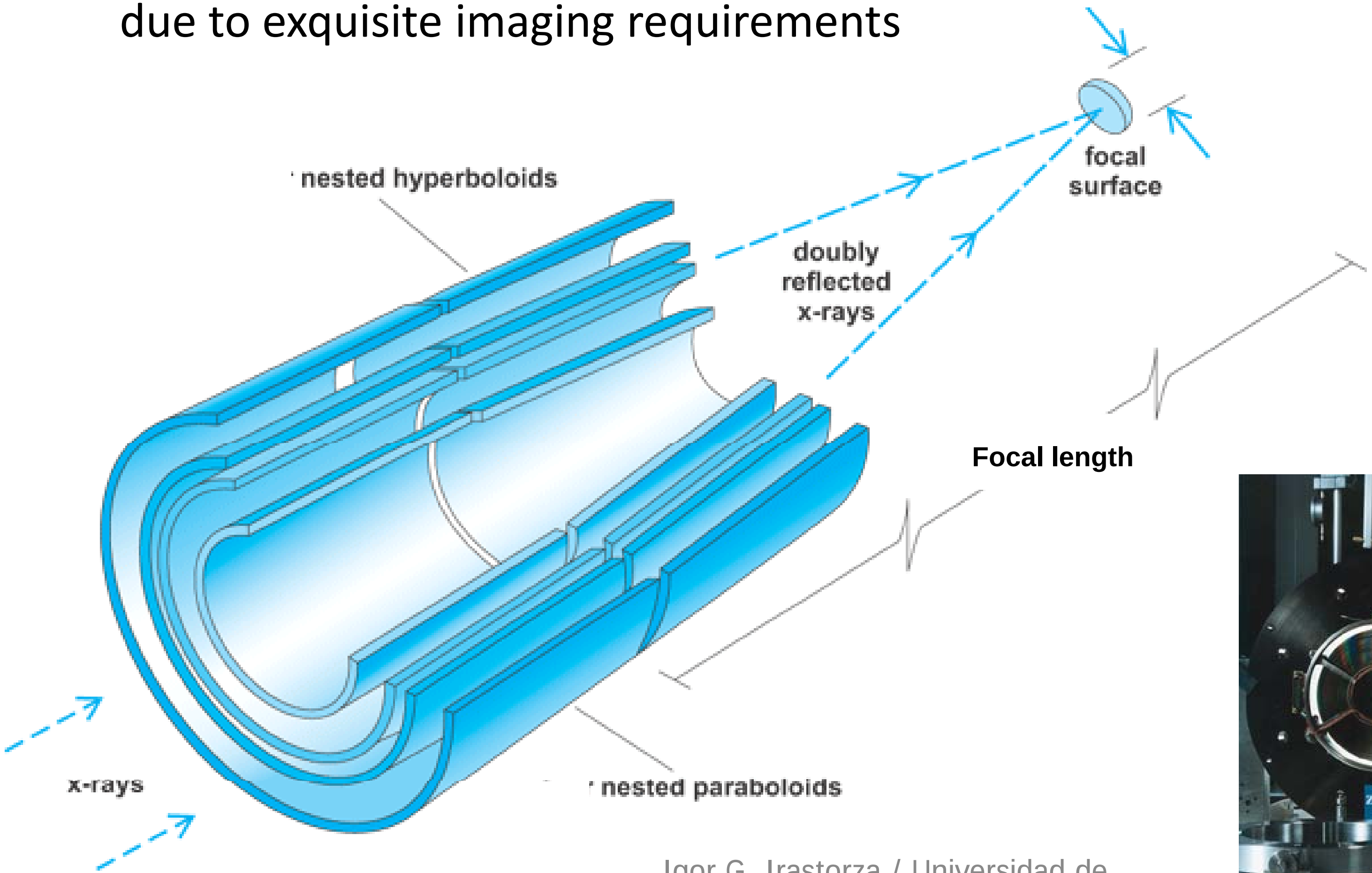


Property		*Value*
Cryostat dimensions:	Overall length (m)	25
	Outer diameter (m)	5.2
	Cryostat volume (m^3)	$\sim$ 530
Toroid size:	Inner radius, R_{in} (m)	1.0
	Outer radius, R_{out} (m)	2.0
	Inner axial length (m)	21.0
	Outer axial length (m)	21.8
Mass:	Conductor (tons)	65
	Cold Mass (tons)	130
	Cryostat (tons)	35
	Total assembly (tons)	$\sim$ 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 $\times$ 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)	$\sim$150
	at 60-80 K (kW)	$\sim$1.6

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

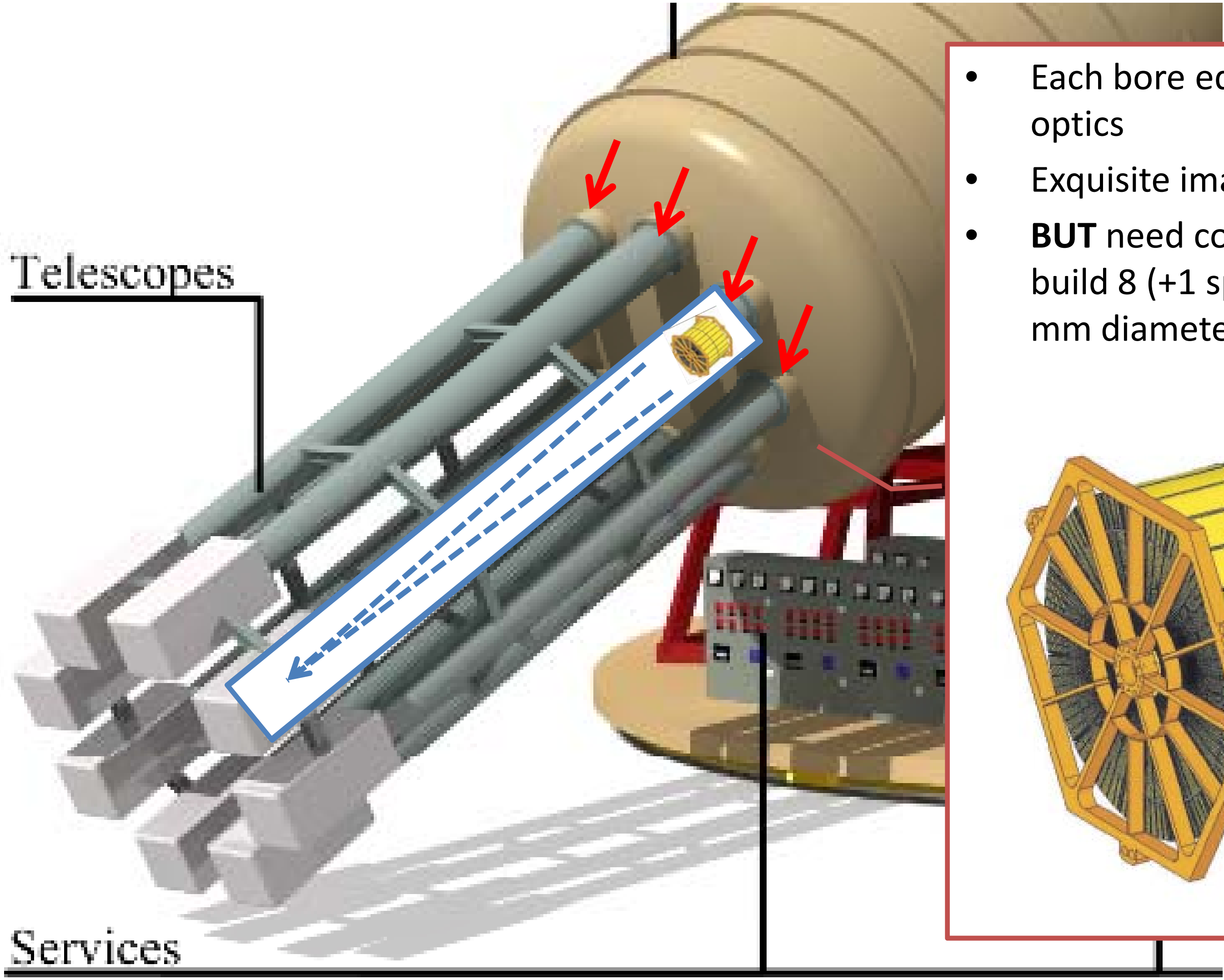
IAXO x-ray optics

- 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

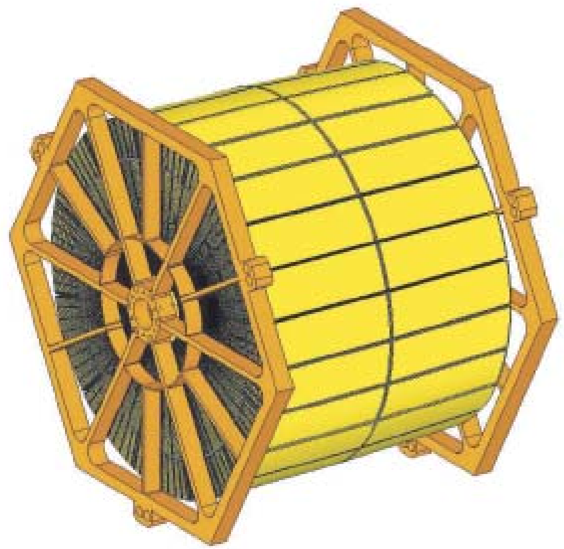


ABRIXAS spare telescope, in use in one of the 4 bores of CAST
(pioneer use of x-ray optics in axion research)

IAXO x-ray optics



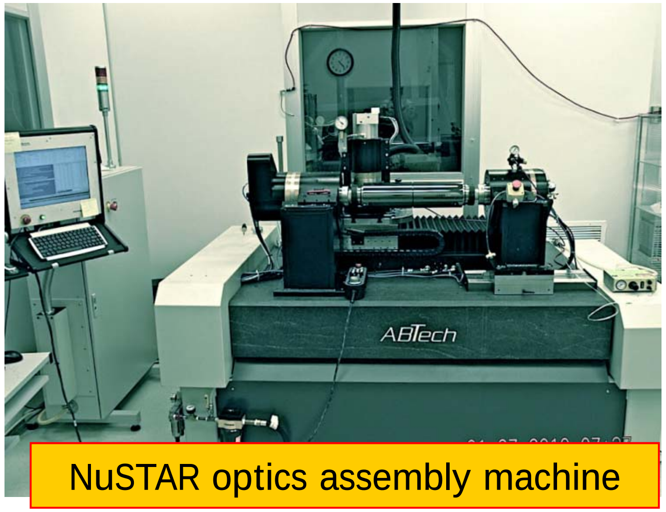
- Each bore equipped with an x-ray optics
- Exquisite imaging not required
- **BUT** need cost-effective way to build 8 (+1 spare) optics of 600 mm diameter each



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

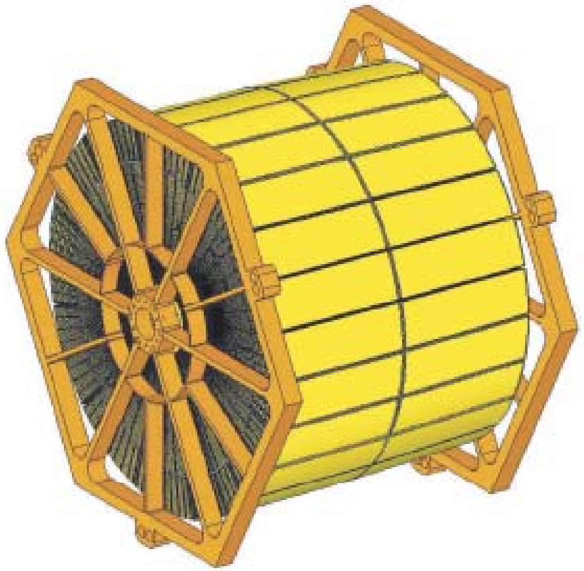
- The specialized tooling to shape the substrates and assemble the optics is now available
- Hardware can be easily configured to make optics with a variety of designs and sizes
- Key institutions in NuSTAR optics: LLNL, U. Columbia, DTU Denmark. All in IAXO !

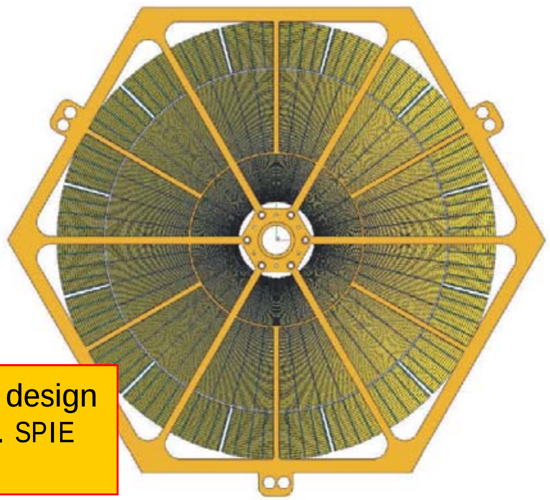


NuSTAR optics assembly machine

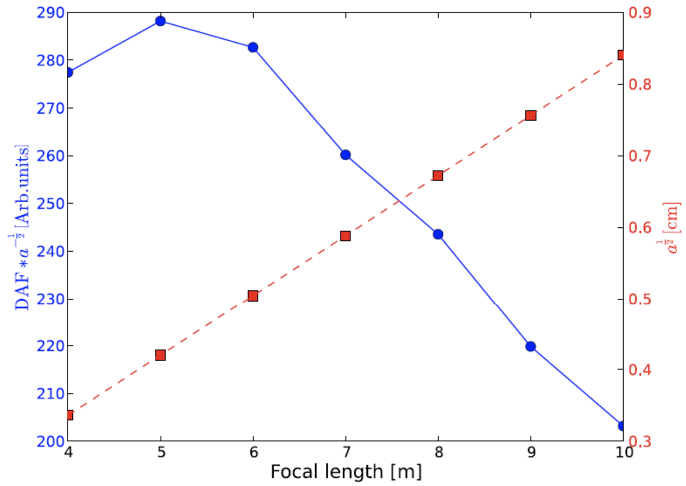
NuSTAR telescope
~400 cm Ø

IAXO x-ray optics





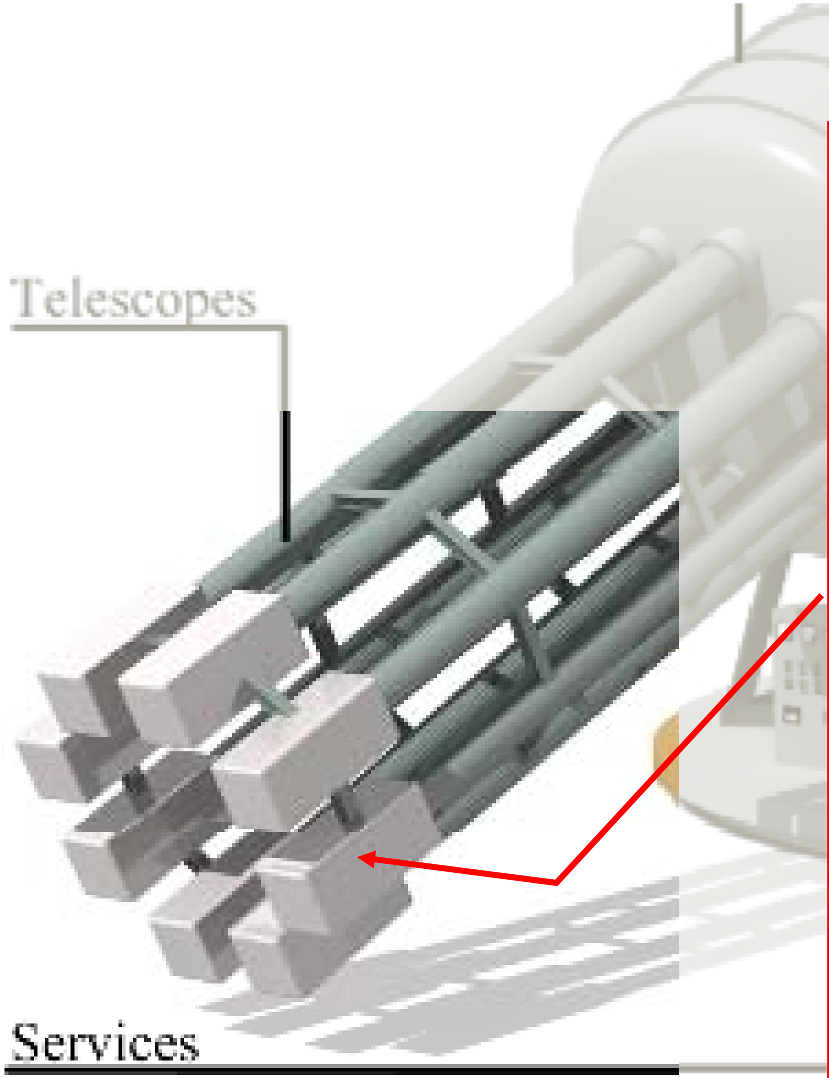
IAXO optics conceptual design
AC Jakobsen et al, Proc. SPIE 8861 (2013)



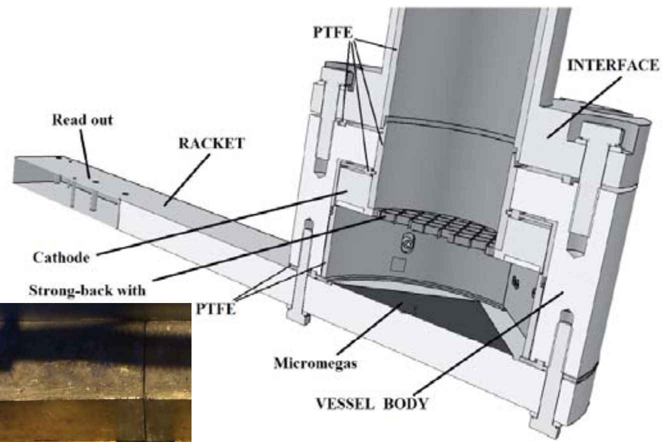
Optimal focal length ~5 m

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



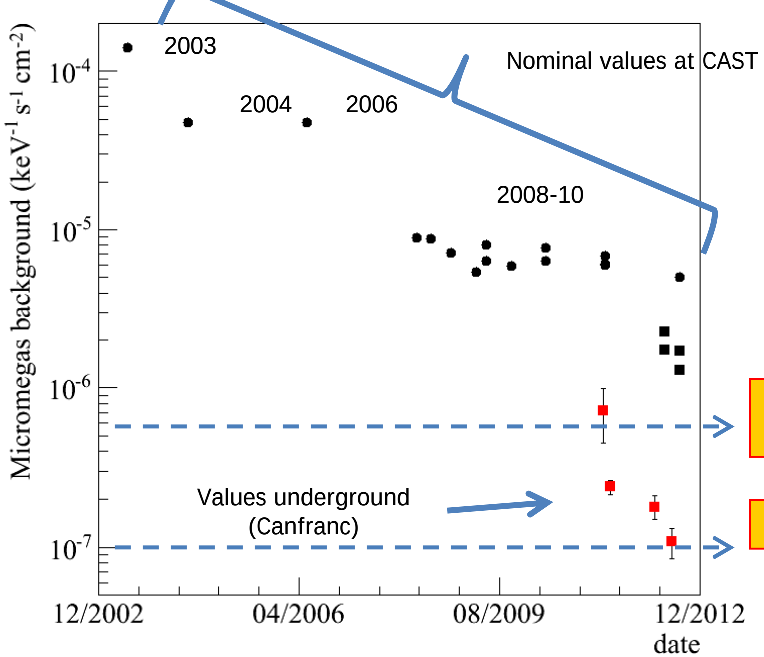
- 8 detector systems
- Small gas chamber with Micromegas readouts for low-background x-ray detection
- Shielding



IAXO low background detectors

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

History of background improvement of Micromegas detectors at CAST



Latest CAST SSMM 2013 levels

IAXO goals

- 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 2013 result)
  - 10^{-7} c keV^{-1} cm^{-2} s^{-1} (underground at LSC)
- Active program of development. Clear roadmap for improvement.

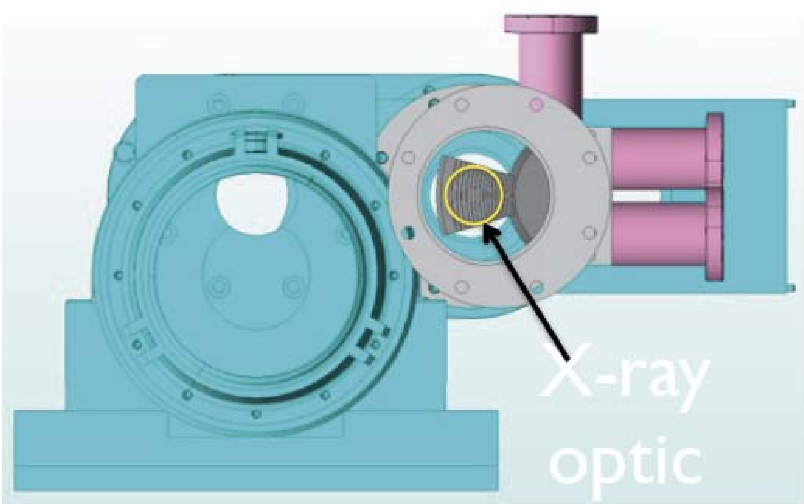
See arXiv:1310.3391

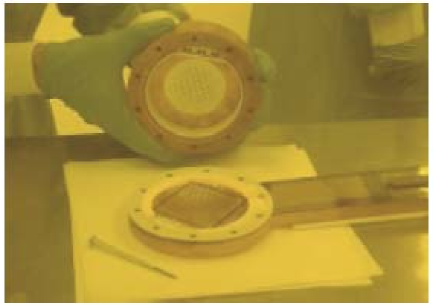
IAXO low background detectors

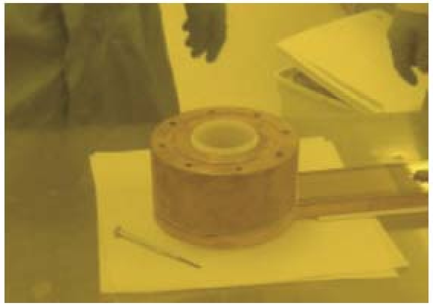
Optics+detector pathfinder system in CAST

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

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

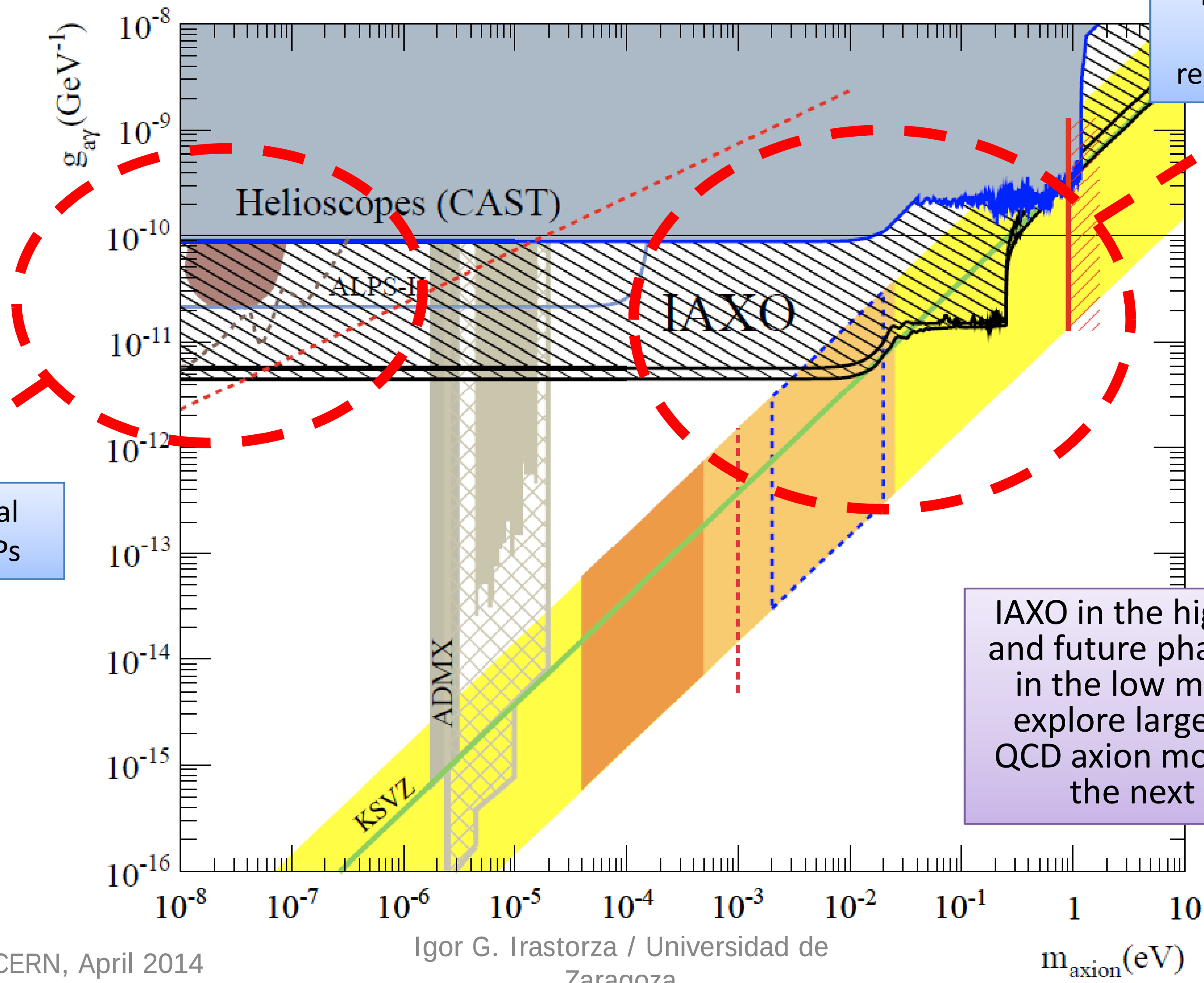






Detector installed at CAST this year. New optics coming beginning of 2014

IAXO sensitivity prospects



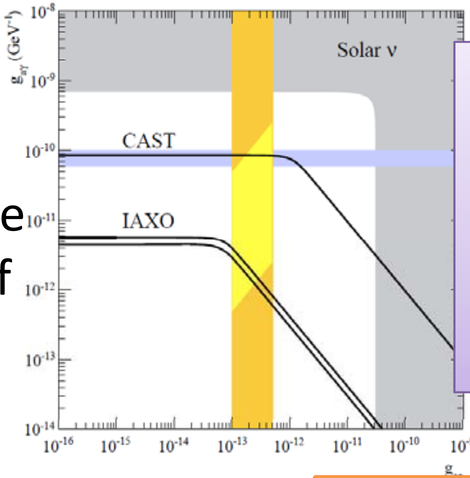
Much larger QCD axion region explored

Astrophysical hints for ALPs

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

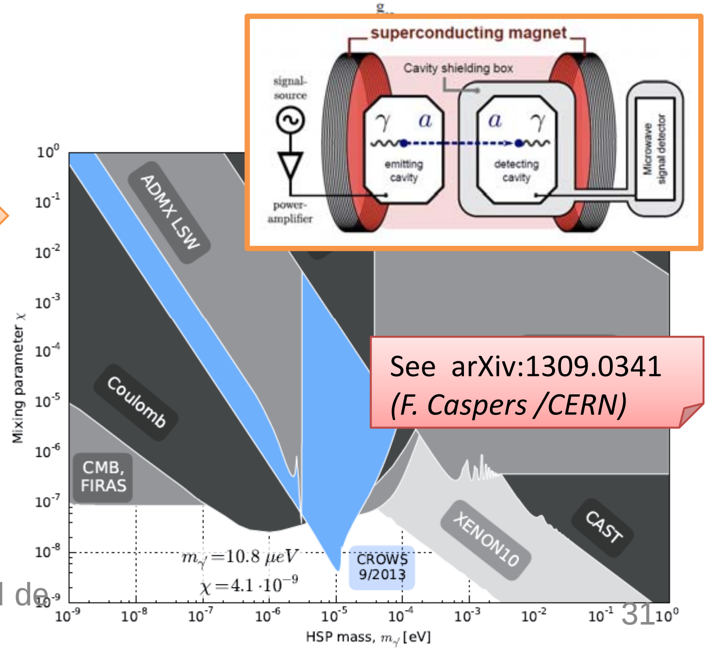
Additional IAXO physics cases

- IAXO sensitivty to BCA solar axion with values of g_{ae} of relevance
- More specific ALP or WISP (weakly interacting slim particle) models. could be searched for at the **low energy frontier** of particle physics:
  - Paraphotons / hidden photons
  - Chamaleons
  - Non-standard scenarios of axion production
- Microwave LSW setup
- Use of microwave cavities or dish antennas, **dark matter** halo axions could be searched for → next slide
- **IAXO as "generic axion/ALP facility"**



Possible additional technologies to push E thresholds down:

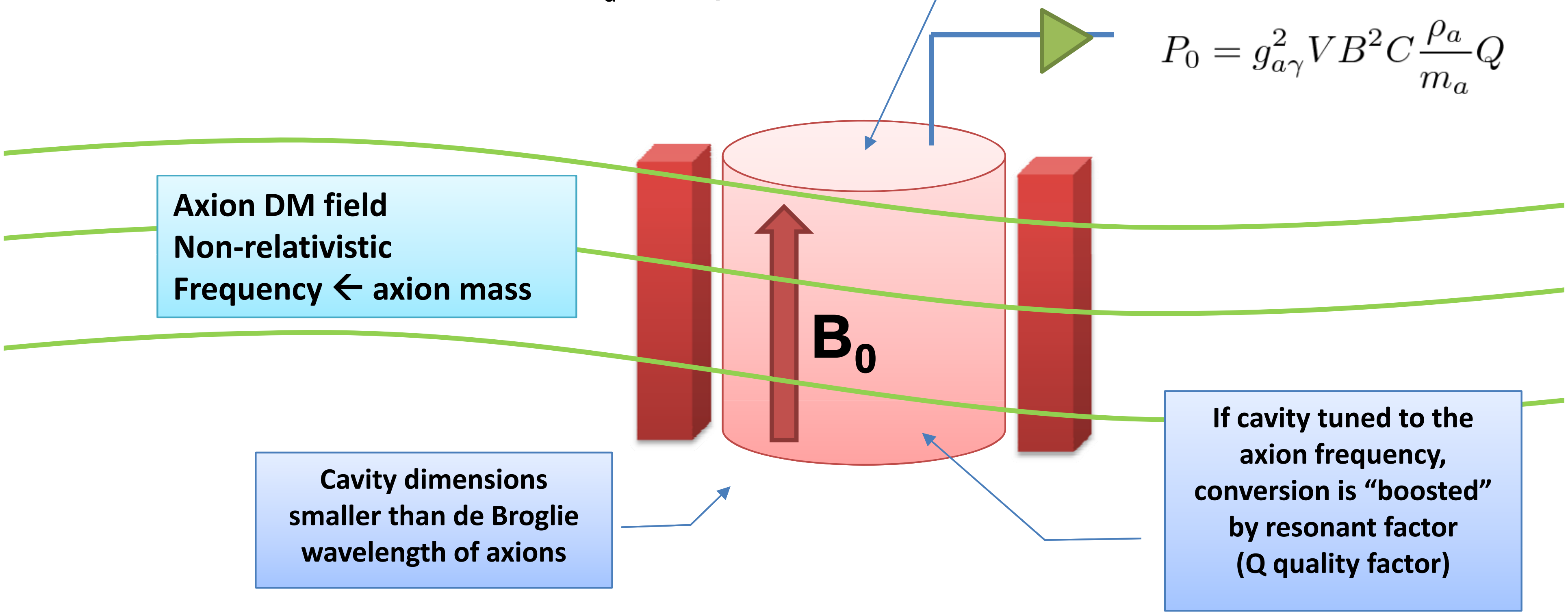
- GridPix
- TES
- Low-noise CCDs



See arXiv:1309.0341
(F. Caspers /CERN)

Detecting DM axions: "haloscopes"

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



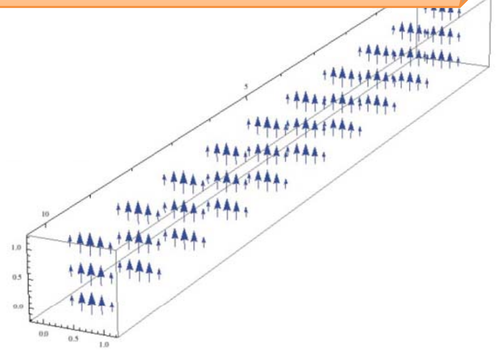
$$P_0 = g_{a\gamma}^2 V B^2 C \frac{\rho_a}{m_a} Q$$

Detecting DM axions with IAXO?

- Haloscopes good for μeV range (ADMX)
- Beyond haloscopes. New ideas recently being proposed…

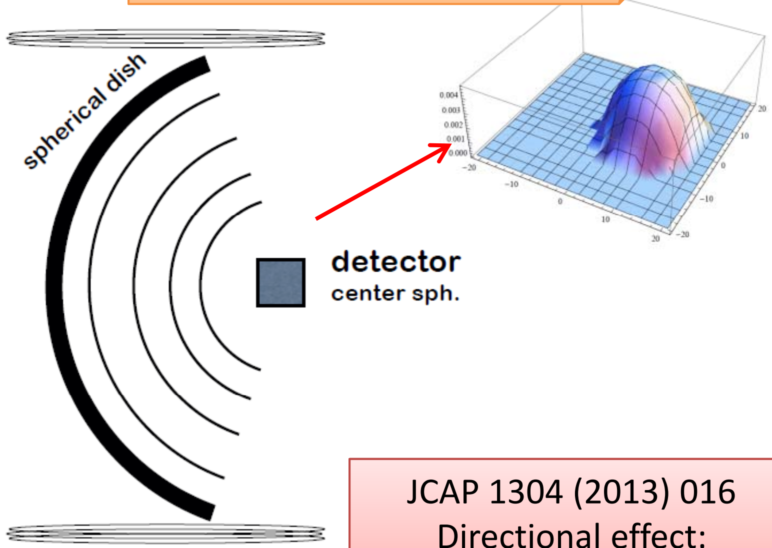
  (big magnets needed anyway...)

Long thin cavities in dipole magnets



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

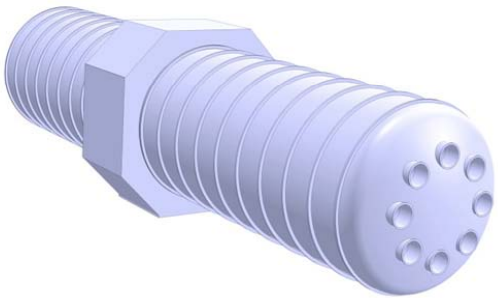
Large spherical mirror

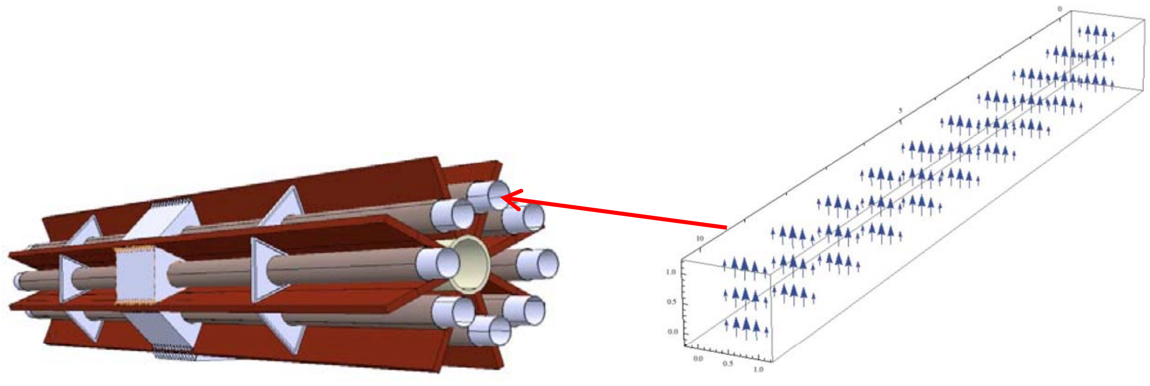


JCAP 1304 (2013) 016
Directional effect:
arXiv:1307.7181

IAXO-DM configurations?

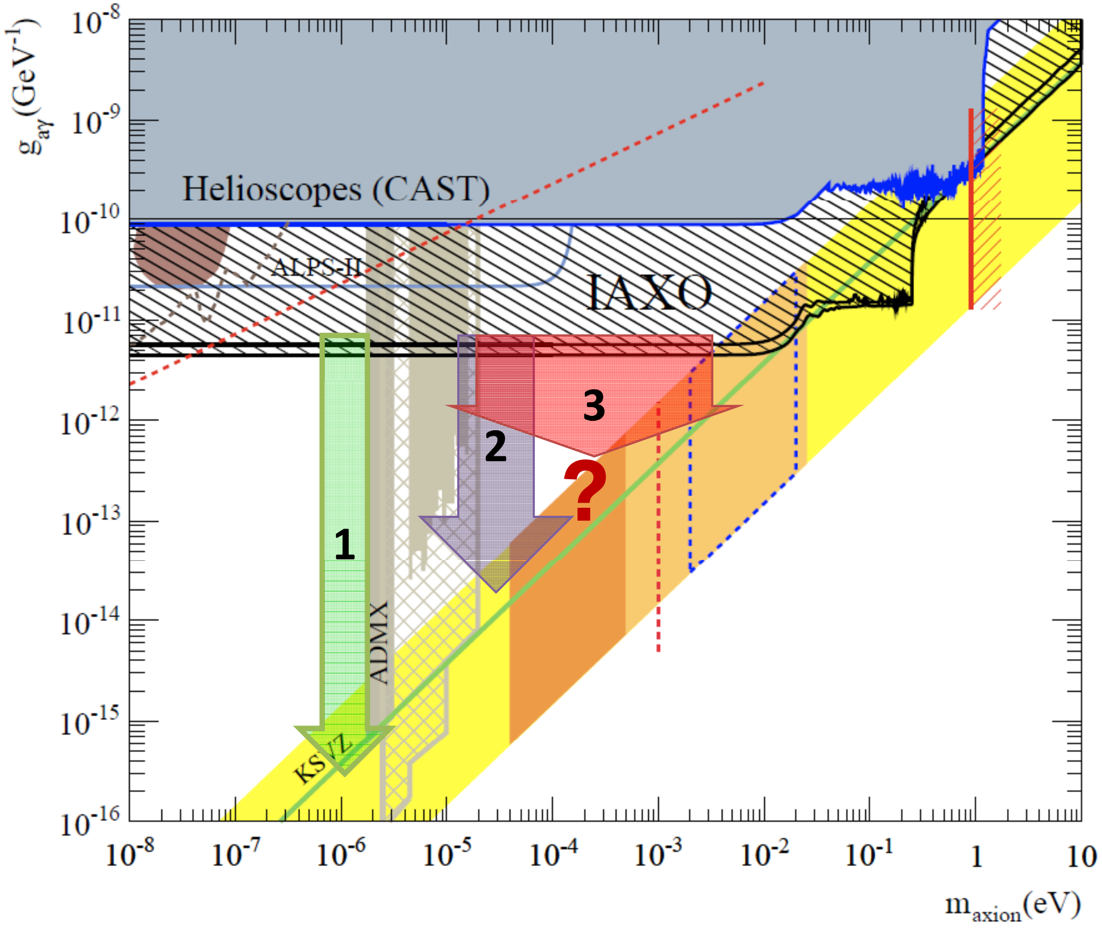
- Prospects under study. Very motivated (encouraged by CERN SPSC)
- Needed new know-how (cavities, low noise microwave detectors…)
- Various possible arrangements in IAXO. Profit the huge magnetic volume available:
  1. Single large cavity tuned to low masses
  2. Thin long cavities tuned to mid-high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





Additional IAXO physics cases

direct detection or relic axions/ALPs

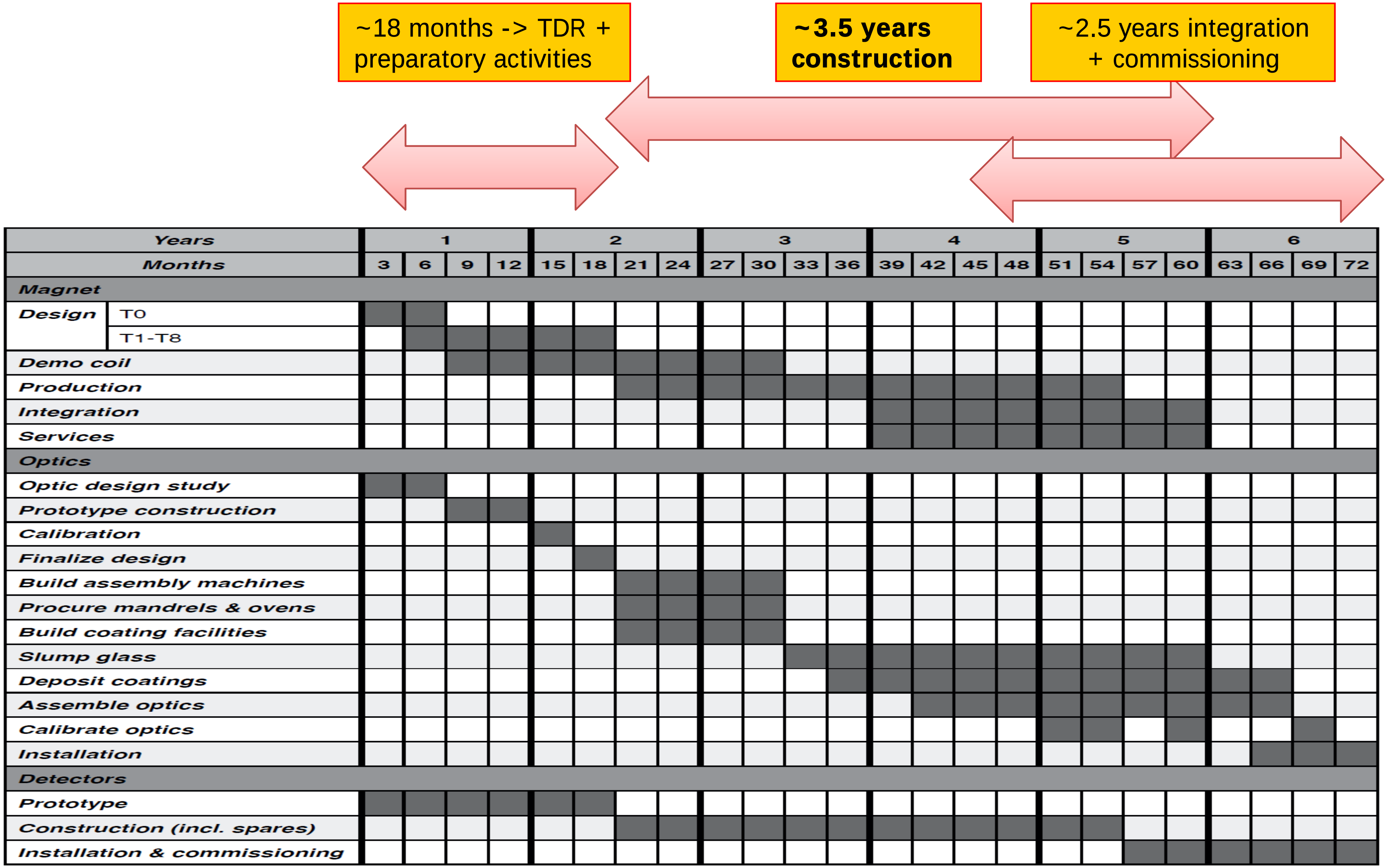


- Promising as further pathways for IAXO beyond the helioscope baseline
- First indications that IAXO could improve or complement current limits at various axion/ALP mass ranges…
- **Caution**: preliminary studies still going on. Important know-how to be consolidated. Precise implementation in IAXO under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

Tentative future prospects

Beyond current LoI scope

IAXO timeline



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**

IAXO in astroparticle roadmaps

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

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

C. Spiering, ESPP Krakow

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

IAXO status of project

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

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

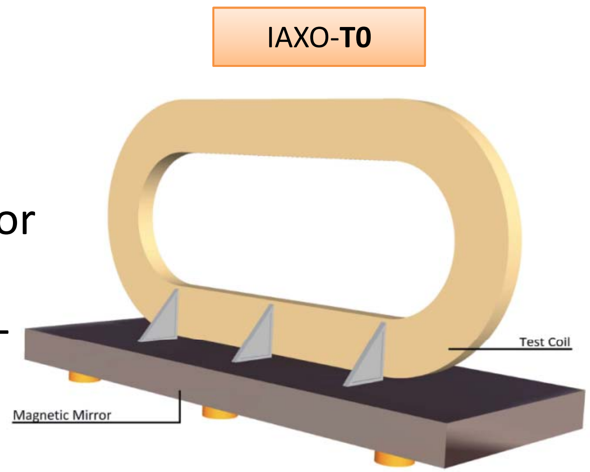
CERN SPSC recommendations

SPSC Draft minutes [Jan 2014]

The Committee **recognises** the physics motivation of an International Axion Observatory as described in the Letter of Intent SPSC-I-242, and considers that the proposed setup makes appropriate use of state-of-the-art technologies i.e. magnets, x-ray optics and low-background detectors.
The Committee **encourages** the collaboration to take the next steps towards a **Technical Design Report**.
The Committee recommends that, in the process of preparing the TDR, the possibility to **extend the physics reach** with additional detectors compared to the baseline goal should be investigated. The collaboration should be further strengthened.
Considering the required funding, the SPSC **recommends** that the R&D for the TDR should be pursuit within an MOU involving all interested parties.

Next steps

- Start works towards a Technical Design Report. As part of such:
  - Construction of a 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
  - Coordination activities. Update physics case. Site. Tracking platform. Gas system. Software
  - Feasibility studies for "IAXO-DM" options.
- TDR completion is a ~2-4 MEUR effort.
- Memorandum of Understanding in preparation among interested parties
- Search for new interested partners (in view of construction phase – magnet is the issue)



Conclusions

- CAST has been a very important milestone in axion research during the last decade
  - 1st CAST limits most cited exp. axion paper
  - Largest effort/collaboration in axion physics so far
- **IAXO, a forth generation axion helioscope**, natural and timely large-scale step to come now.
- A clear high level baseline physics case. IAXO can **probe deep into unexplored** axion+ALP parameter space.
  - But also several additional physics cases. Possibility to host relic axion searches in the future. Studying actively this possibility
- No technological challenge. All enabling technologies exist
- Investment effort at the level of Next Generation DM experiments under consideration in the astropaticle community
- LoI to CERN recently proposed. Positive answer from SPSC. MoU to start TDR under preparation.
- IAXO could become next large project & a “generic axion facility” **with discovery potential** in the next decade.