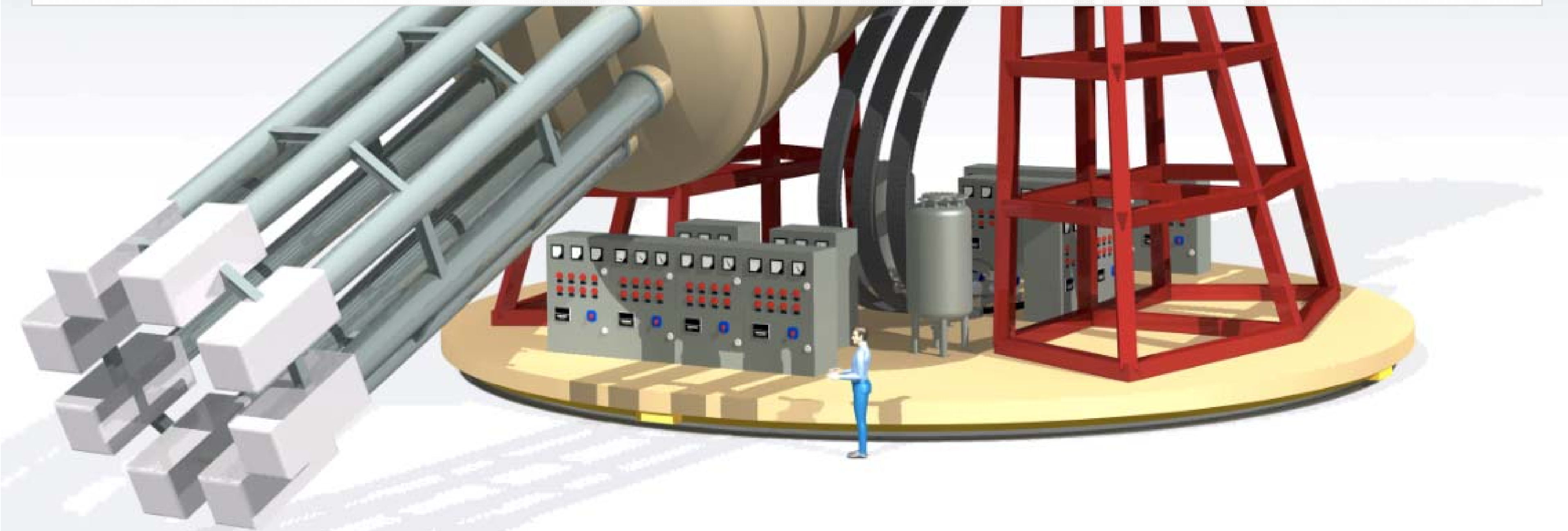
Physics case, prospects and status of the International AXion Observatory IAXO

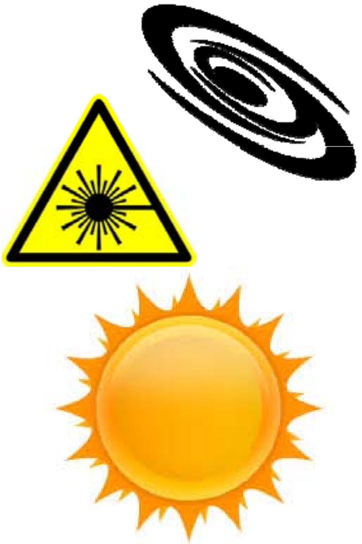
Igor G. Irastorza
Universidad de Zaragoza
IPPP, Durham, 14th Apr 2016



Why to search for axions?

- 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
  - Anomalous cooling of different types of star
- Relevant axion/ALP parameter space at **reach of current and near-future experiments**
- Still too little experimental effort devoted to axions when compared to WIMPs

IAXO in the axion landscape

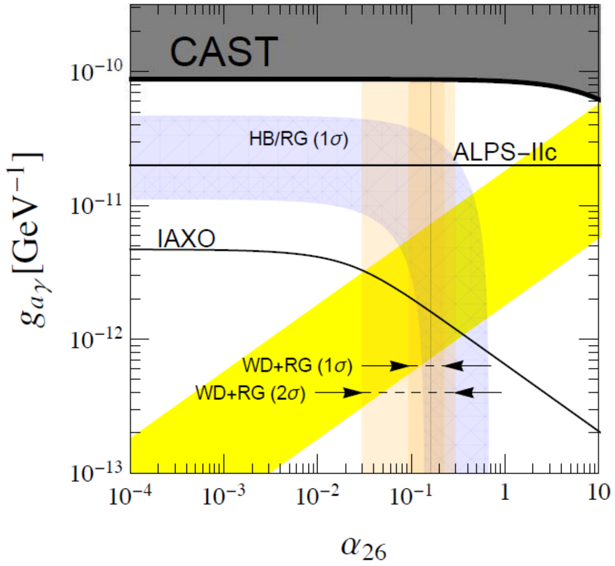


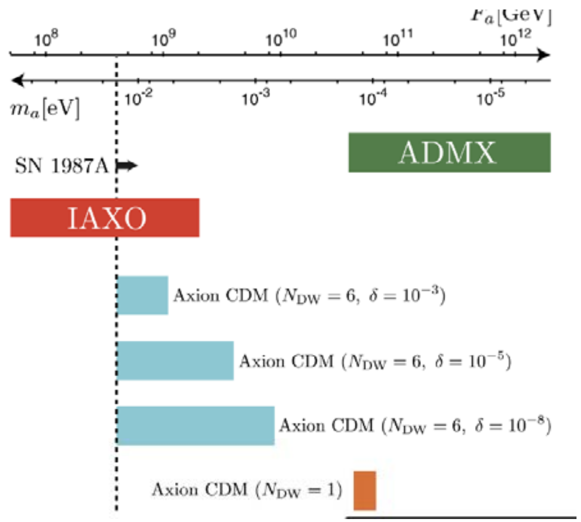
Source	Experiments	Model & Cosmology dependency	Technology
Relic axions	ADMX, ADMX-HF, Casper, CAPP, …	High	New ideas emerging, Active R&D going on,…
Lab axions	ALPS, OSQAR, fifth force exps,…	Very low	
Solar axions	SUMICO, CAST, IAXO	Low	Ready for large scale experiment

- Helioscopes → do not rely on the axion being the dominant DM component. Solar axion emission robust prediction
- Helioscopes → No R&D needed. Technology mature enough for a large scale experiment (IAXO)
- Large complementarity with other detection strategies

The multi-meV axion

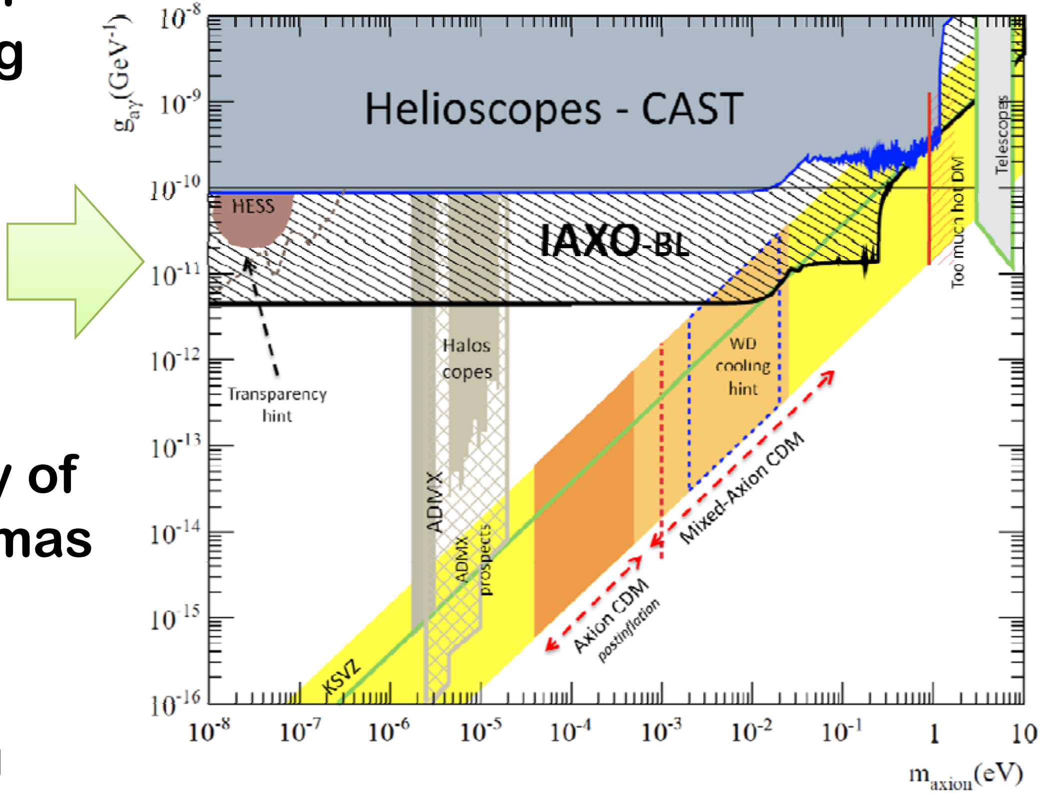
- Is compatible with all current axion bounds.
- Is invoked in several anomalous stellar cooling scenarios
  - Gianotti et al. arXiv:1512.08108
- Can be the cold DM in some models
  - with NDW>1 and bias term to break the discrete symmetry (Kawasaki et al. PRD91 (2015), Ringwald et al. arXiv:1512.06436)
  - or it can be a subdominant DM component
- Very hard to detect (→ IAXO!)
- SN axion background
  - Raffelt et al. PRD84 (11)





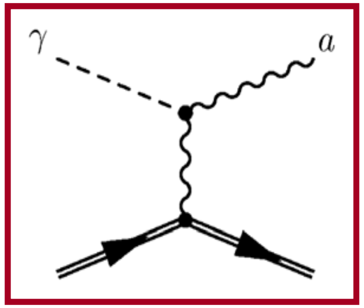
An ALP with $g_{a\gamma}$~ 10^{-11-12} GeV^{-1}

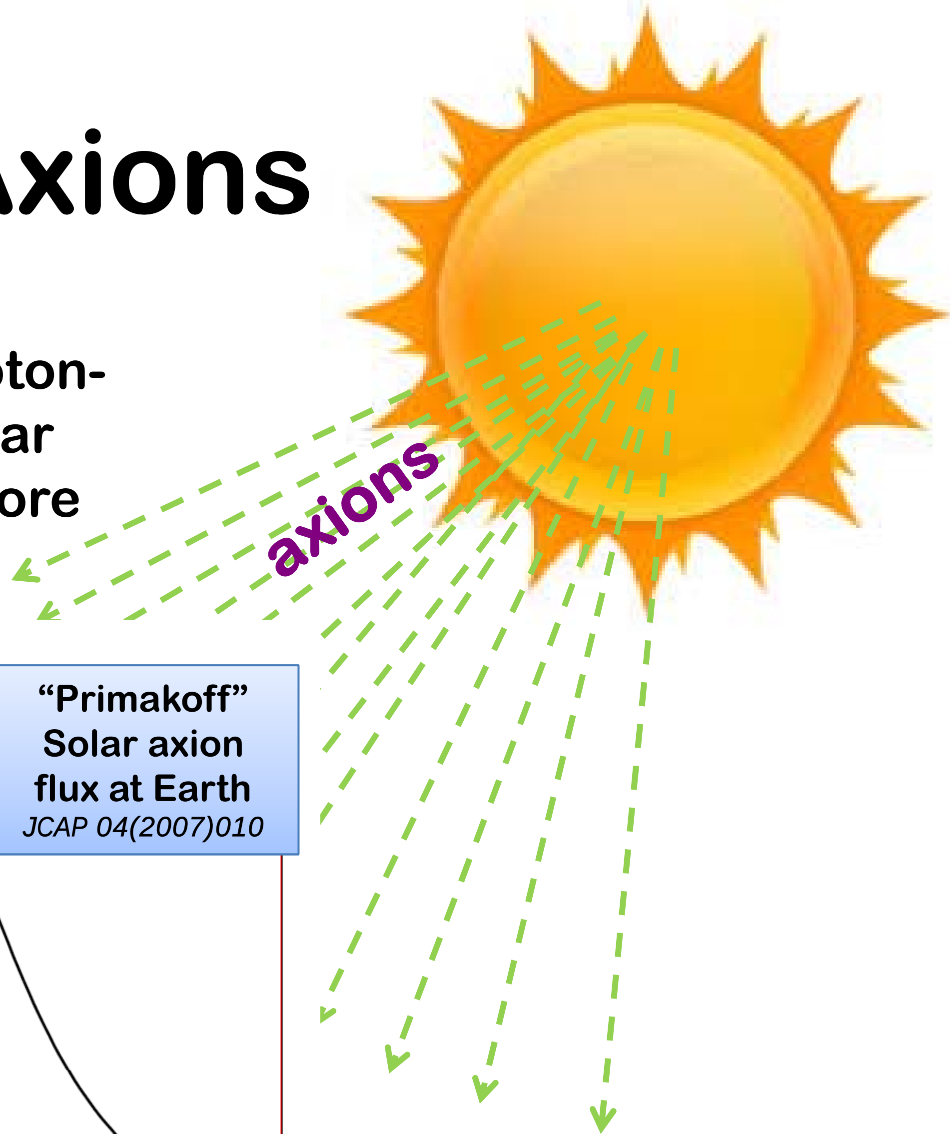
- **Well beyond current upper bounds on the $g_{a\gamma}$ coupling** (CAST & HB stars ~ 10^{-10} GeV^{-1})
- **String theory ALPs**
- **Invoked to explain the anomanlous transparency of the Universe to UHE gammas**
- **Could explain some anomalous stellar cooling observations**

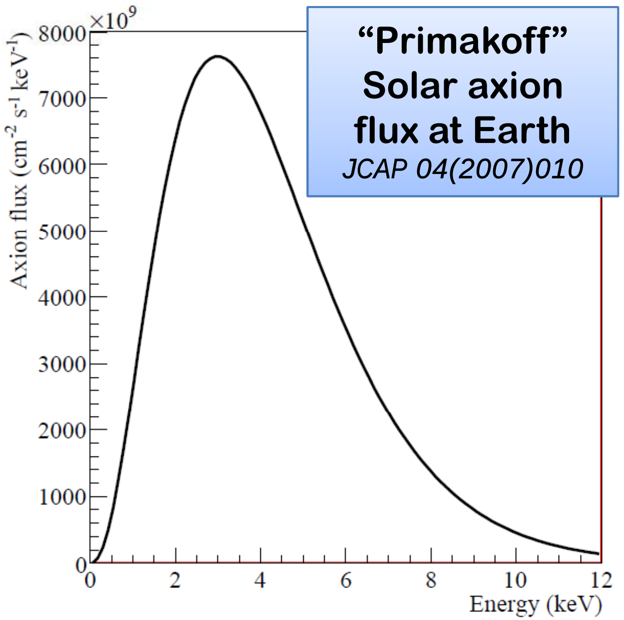


Solar Axions

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







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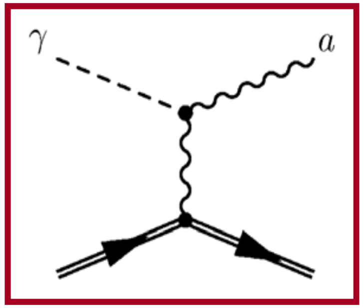
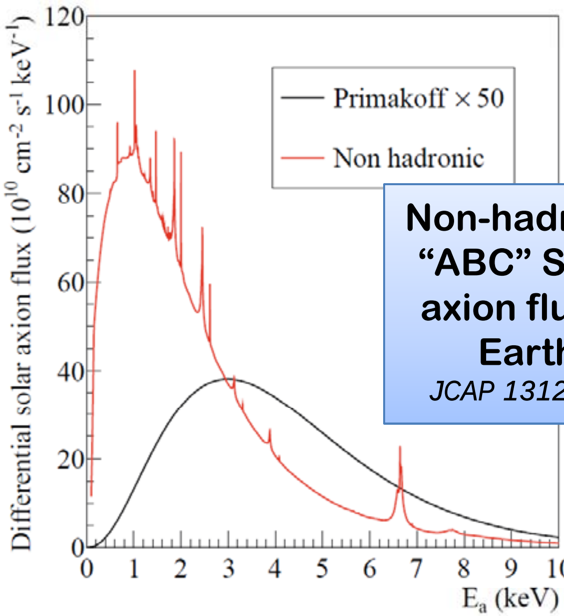
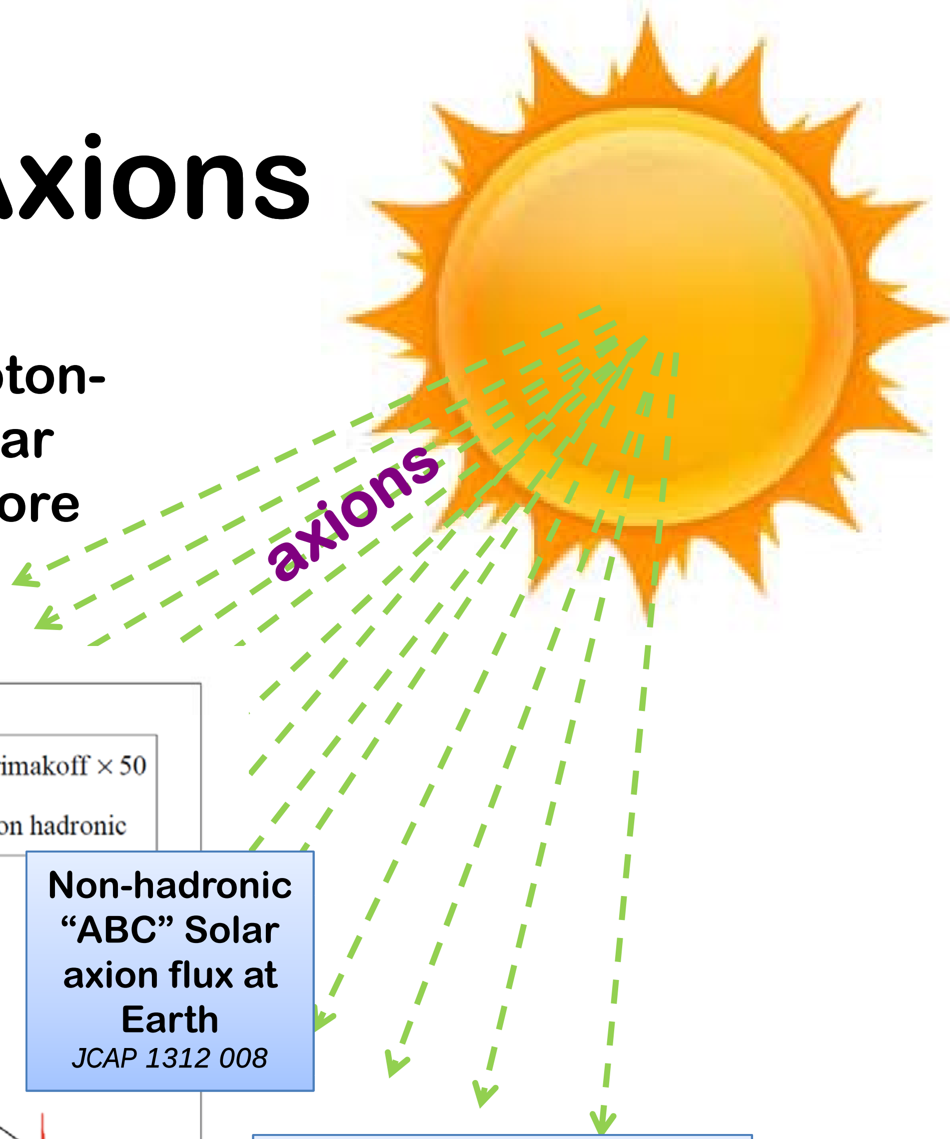






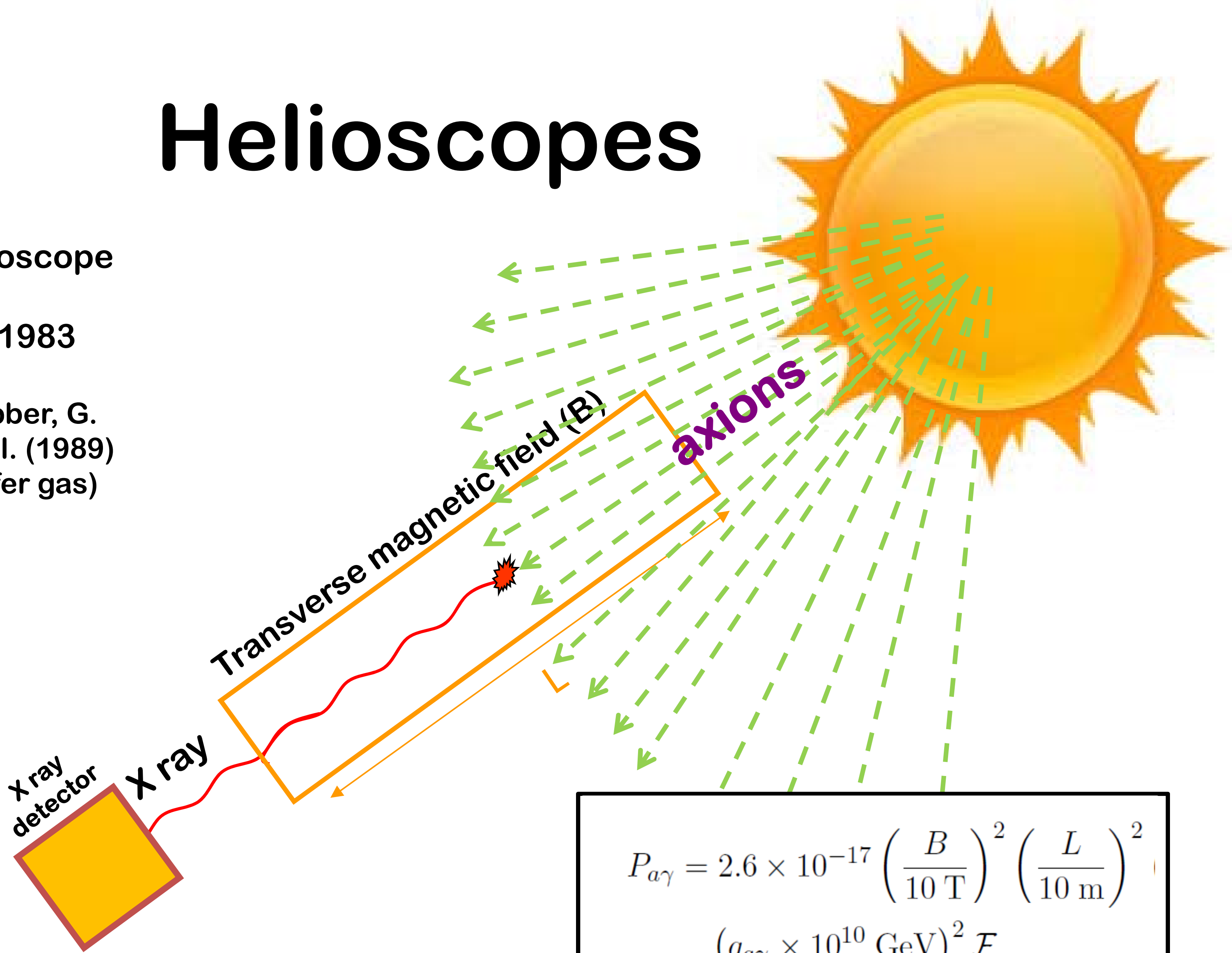
Non-hadronic "ABC" Solar axion flux at Earth
JCAP 1312 008

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

Helioscopes

Axion helioscope concept
P. Sikivie, 1983

+ K. van Bibber, G. Raffelt, et al. (1989) (use of buffer gas)



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

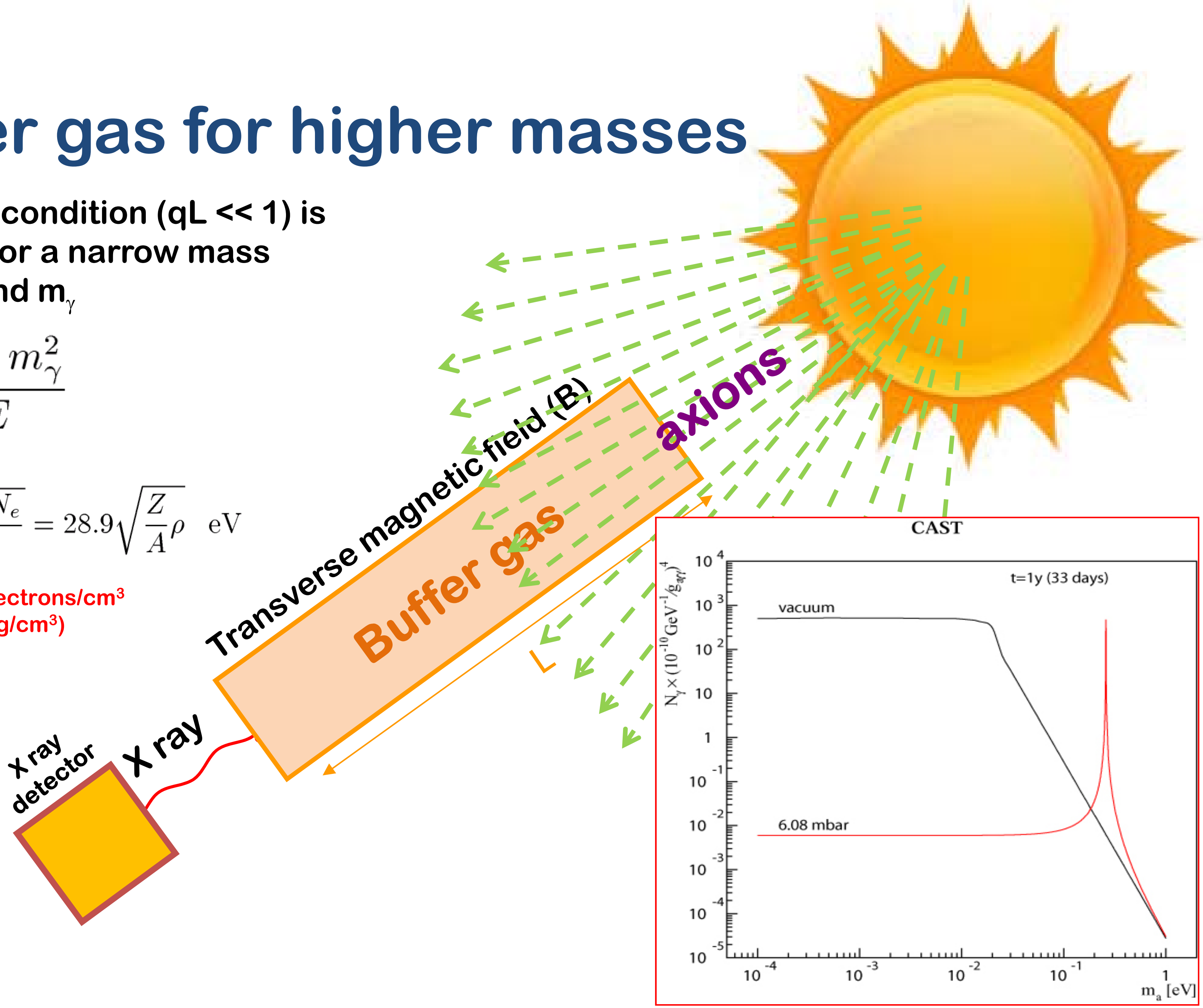
Buffer gas for higher masses

Coherence condition (qL << 1) is recovered for a narrow mass range around m_γ

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

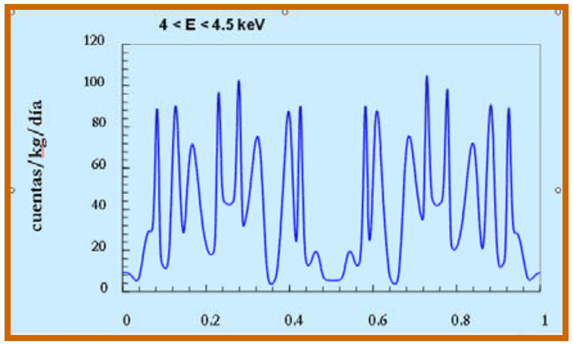
$$m_\gamma \approx \sqrt{\frac{4\pi\alpha N_e}{m_e}} = 28.9\sqrt{\frac{Z}{A}\rho} \quad \text{eV}$$

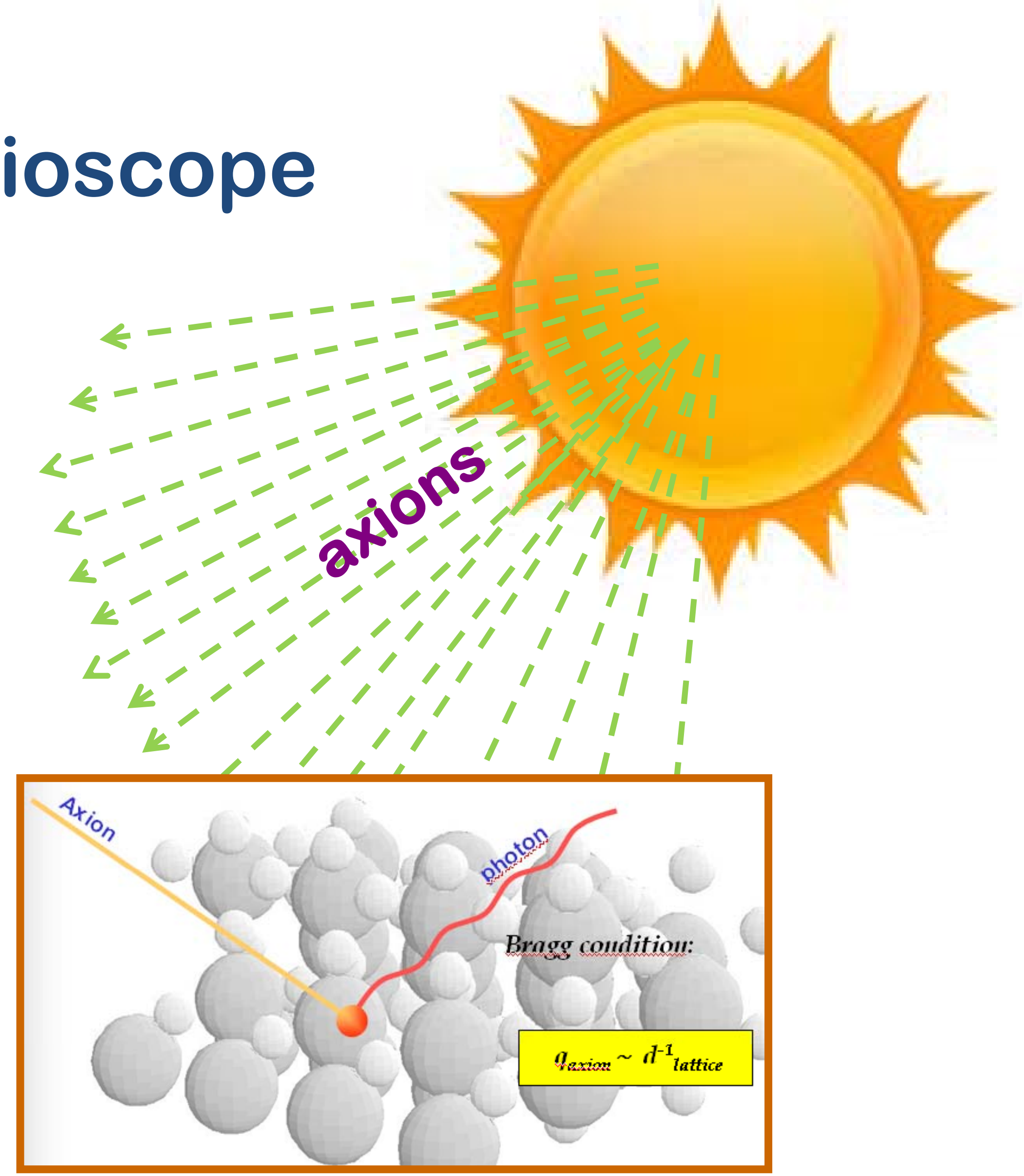
N_e: number of electrons/cm^3
r: gas density (g/cm^3)



Other types of helioscope

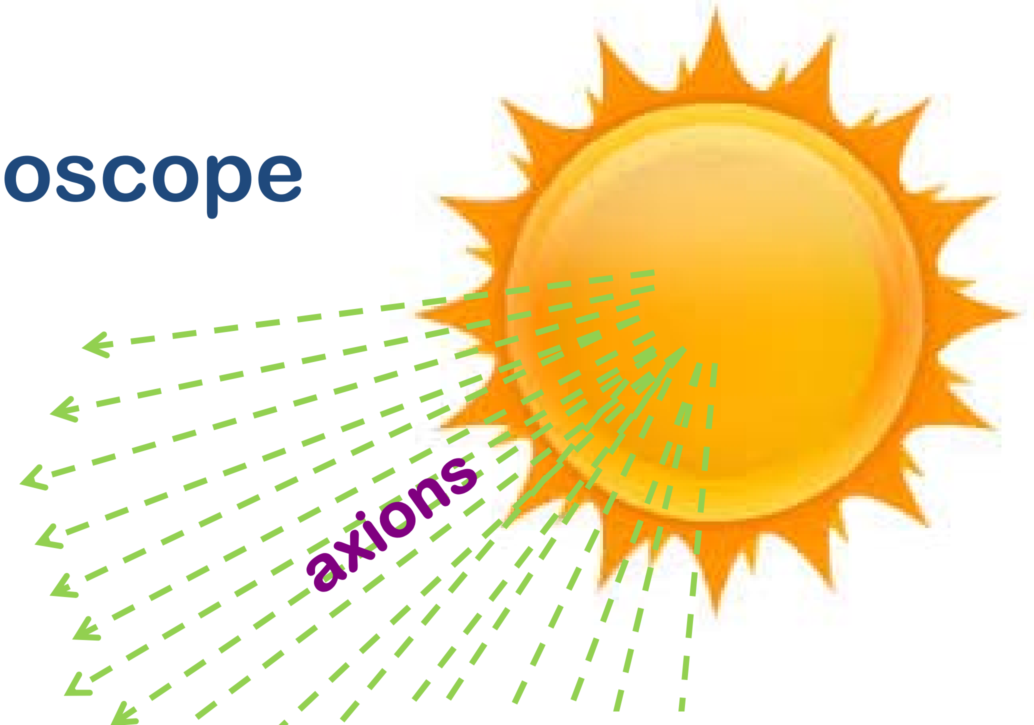
- Instead of magnetic field, one can use the electromagnetic field of crystals…
- « Primakoff-Bragg » effect
- WIMP-like experiments provide limit to axions: SOLAX, COSME, DAMA, EDELWEISS, CDMS, etc…
- Characteristic temporal pattern:

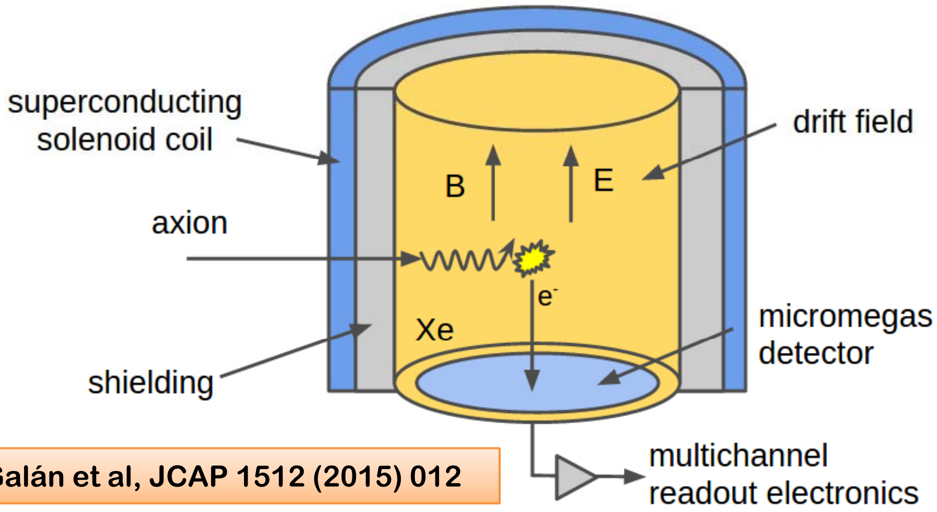




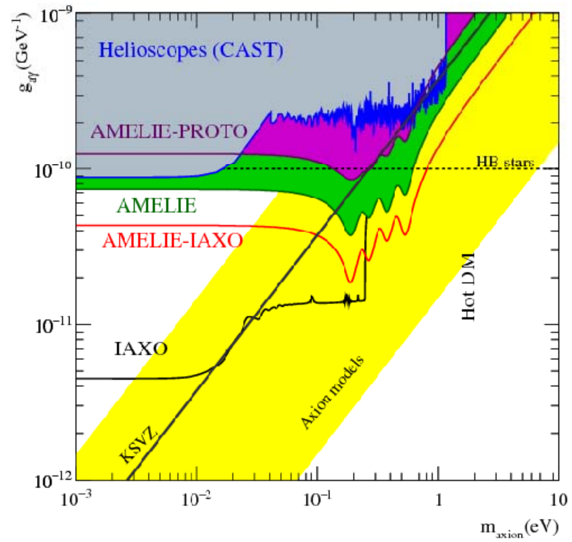
Other types of helioscope

- « TPC in a magnetic field »: conversion and absorption happening in the gas
- Competitive only for high axion mass
- Old idea recently studied



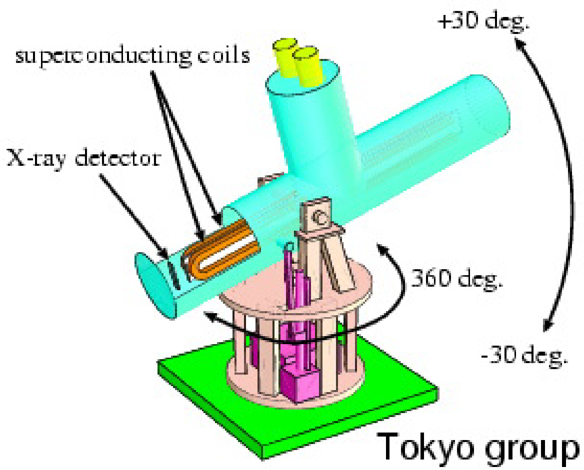


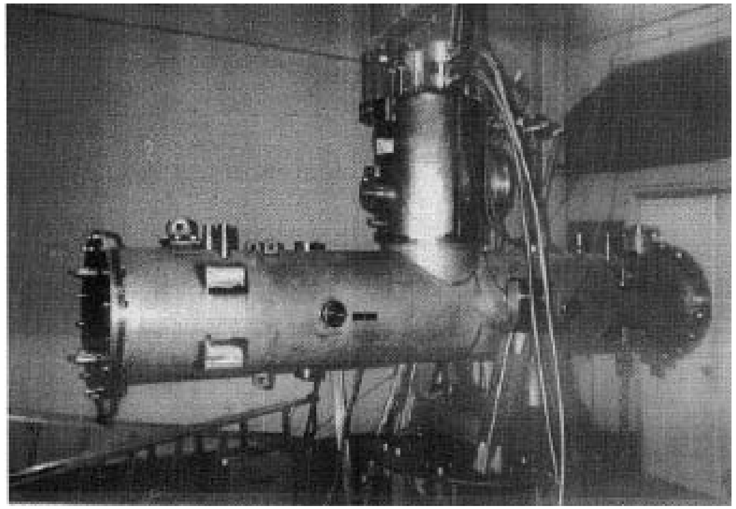
Galán et al, JCAP 1512 (2015) 012



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

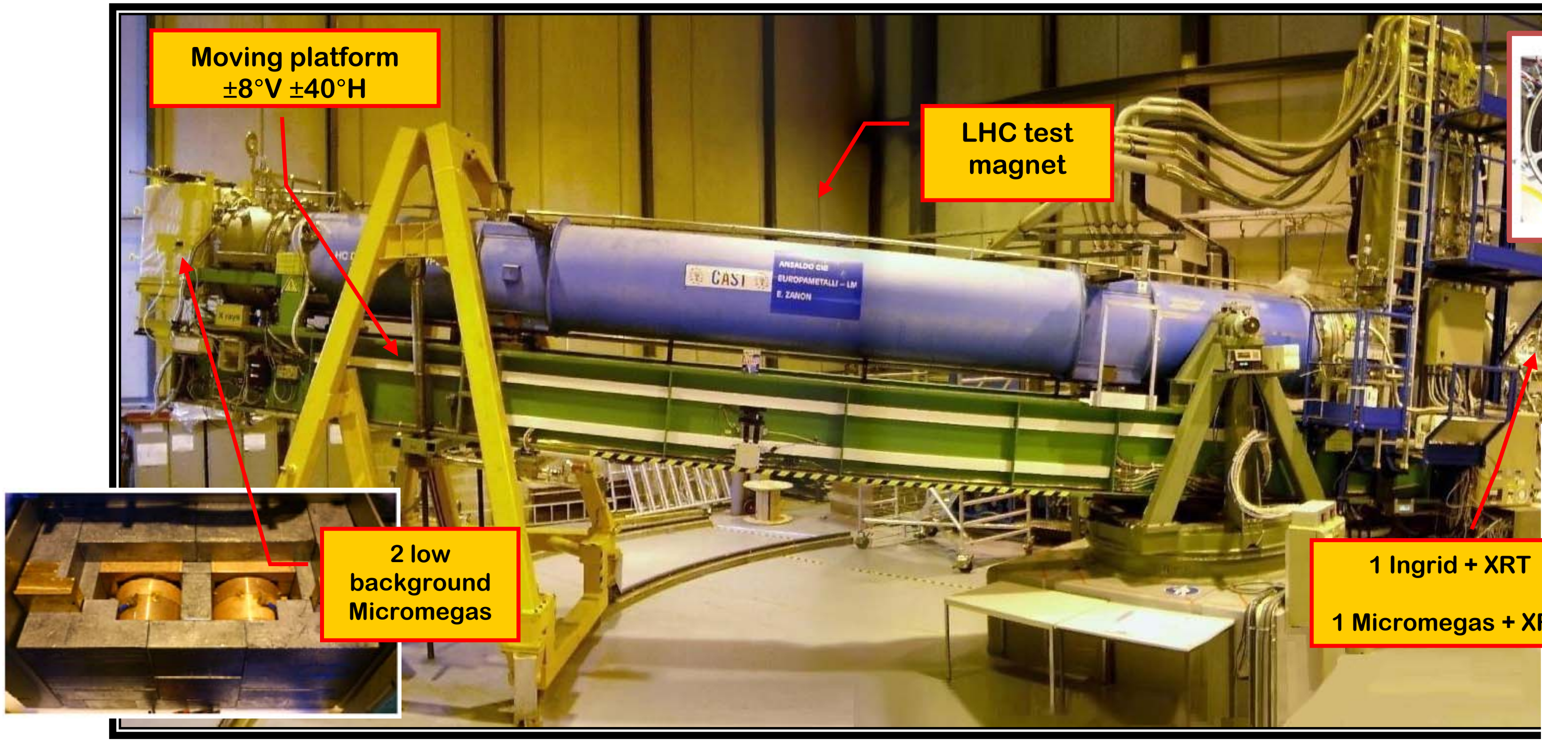


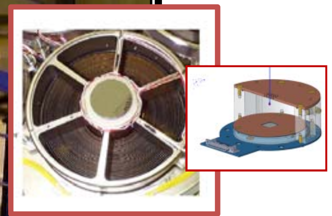


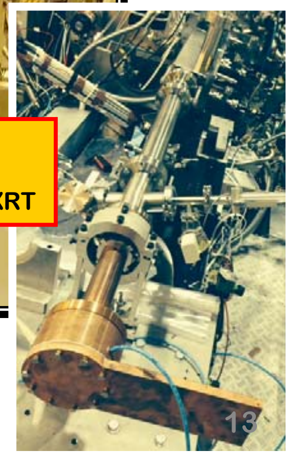
- **Presently running:**
  - CERN Axion Solar Telescope (CAST)

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
- 2 X ray telescopes to increase signal/noise ratio.







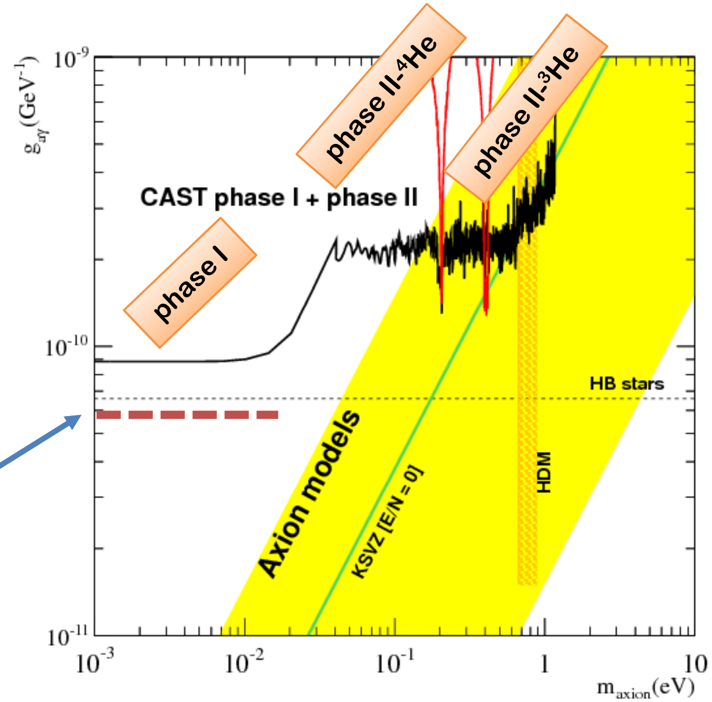
CAST at work (movie)

Movie credit:

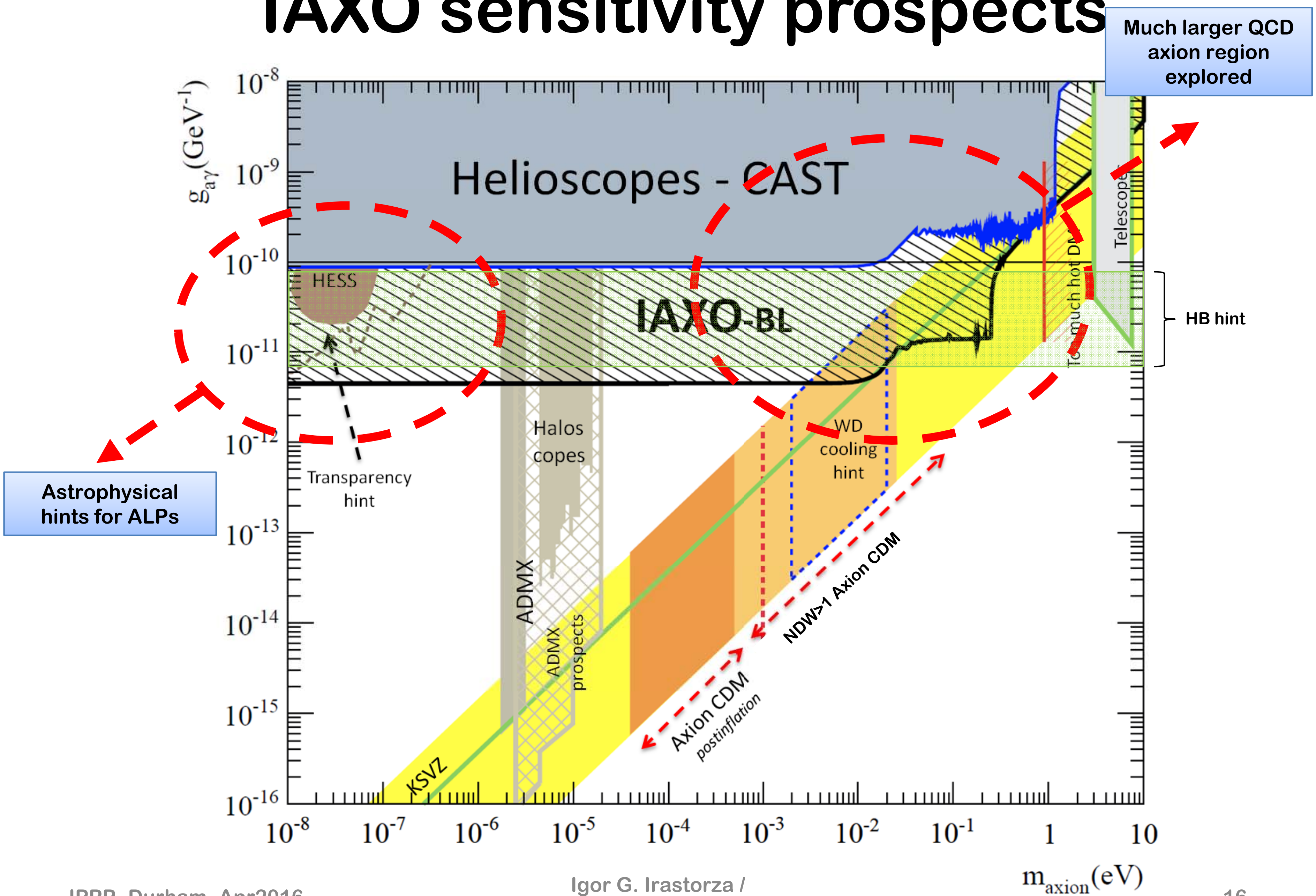
Cenk Yildiz

CAST results (solar axions)

2003 – 2004	CAST phase I • vacuum in the magnet bores
2006	CAST phase II - ^{4}He Run • axion masses explored up to 0.39 eV (160 P-steps)
2007	^{3}He Gas system implementation
2008 - 2011	CAST phase II - ^{3}He Run • axion masses explored up to 1.17 eV • bridging the dark matter limit
2012	•Revisit 4He Run with improved detecors
2013-2015	•Revisit vacuum phase with improved detectors •New data in the pipeline. •Analysis ongoing…

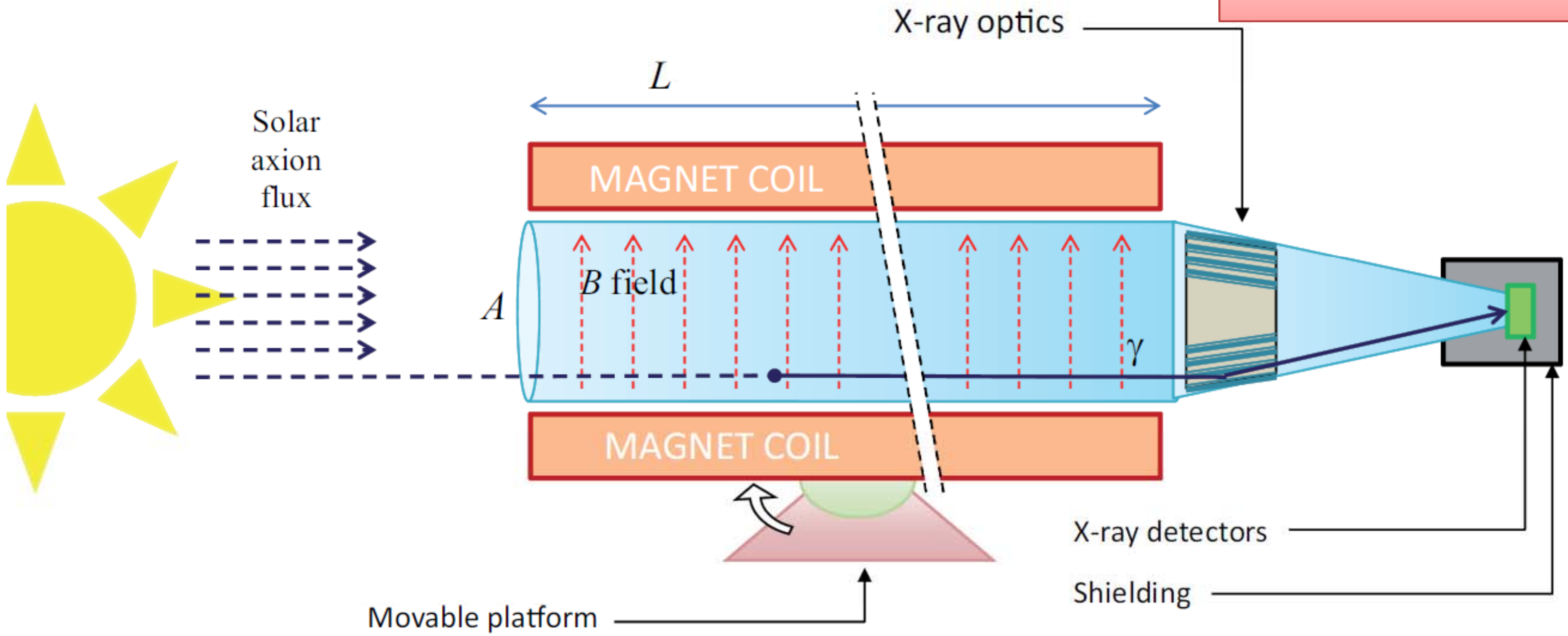


IAXO sensitivity prospects



IAXO – Concept

Enhanced axion helioscope:
JCAP 1106:013,2011

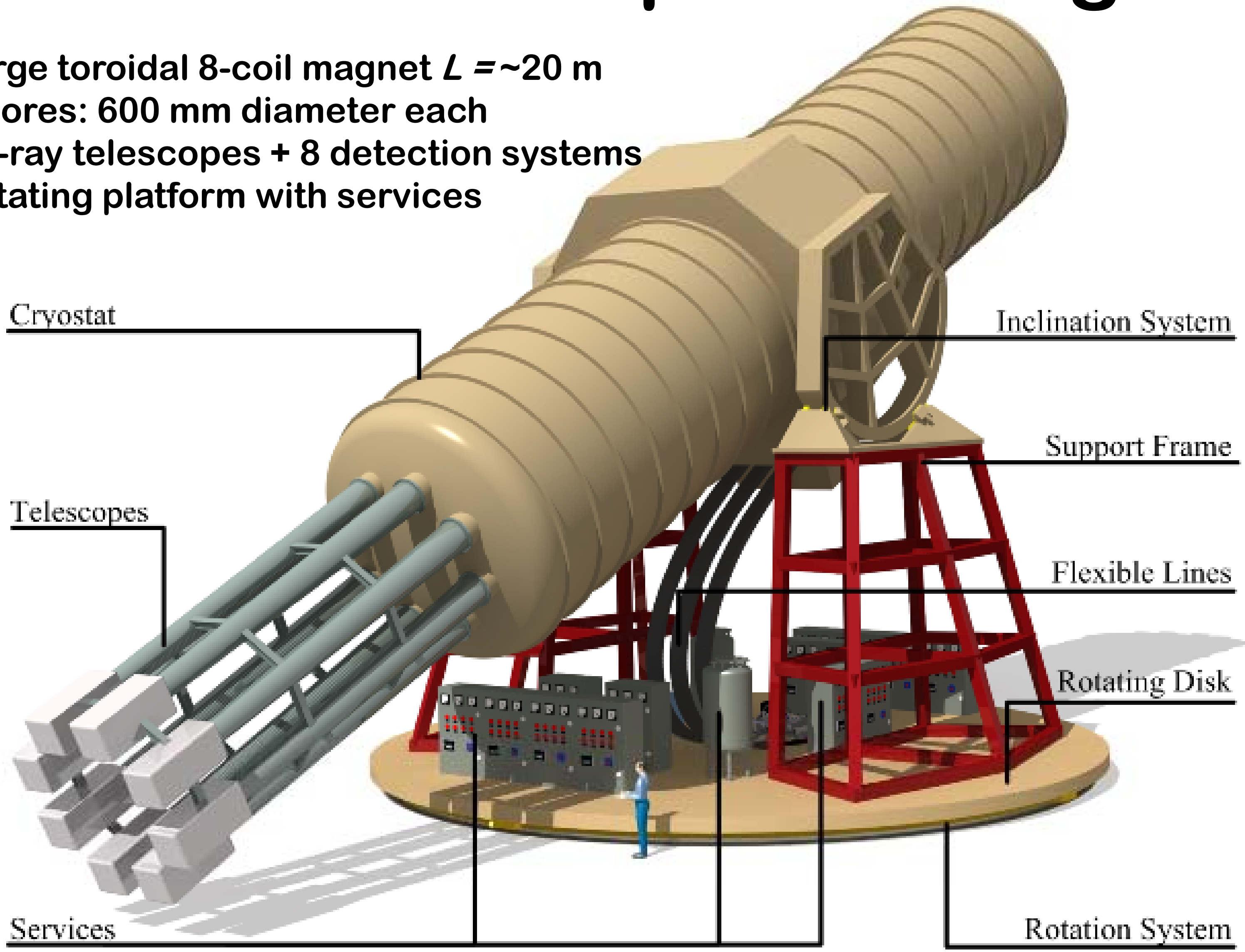


$$g_{a\gamma}^4 \propto \underbrace{b^{1/2}\epsilon_d^{-1}}_{\text{detectors}} \times \underbrace{a^{1/2}\epsilon_o^{-1}}_{\text{optics}} \times \underbrace{(BL)^{-2}A^{-1}}_{\text{magnet}} \times \underbrace{t^{-1/2}}_{\text{exposure}}$$

4+ orders of magnitude better SNR that CAST **(JCAP 1106:013)**

IAXO – Conceptual Design

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

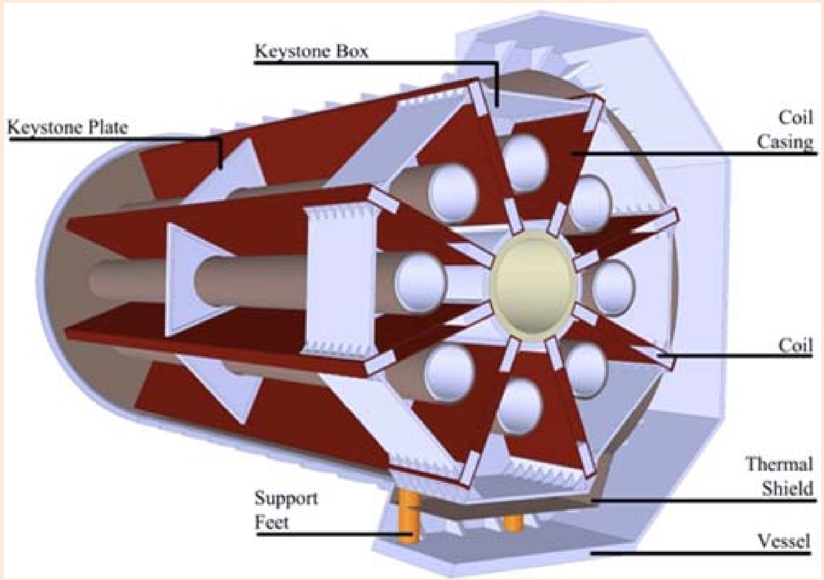


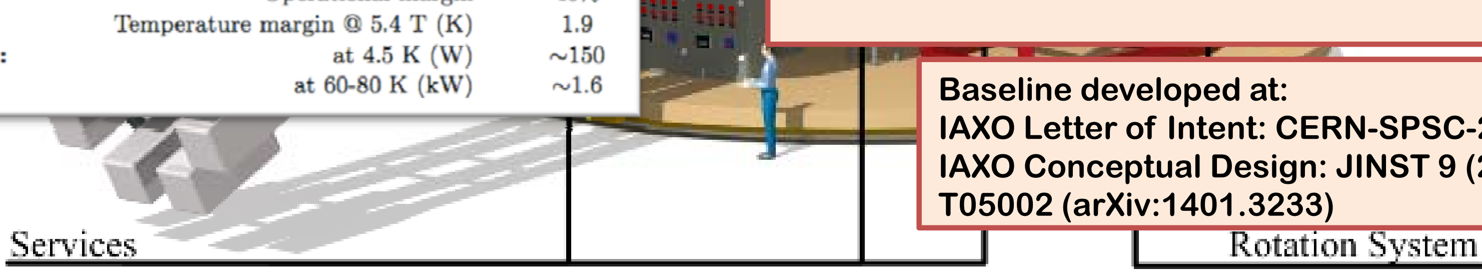
IAXO technologies – Baseline

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 magnet

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



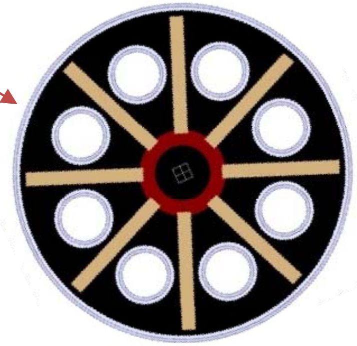


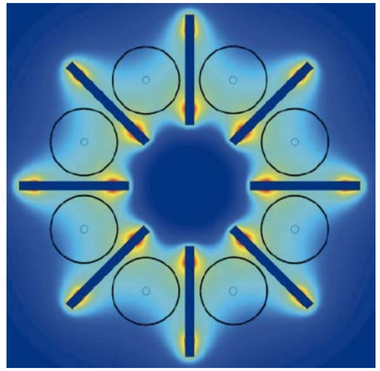
Baseline developed at:
IAXO Letter of Intent: CERN-SPSC-2013-022
IAXO Conceptual Design: JINST 9 (2014) T05002 (arXiv:1401.3233)

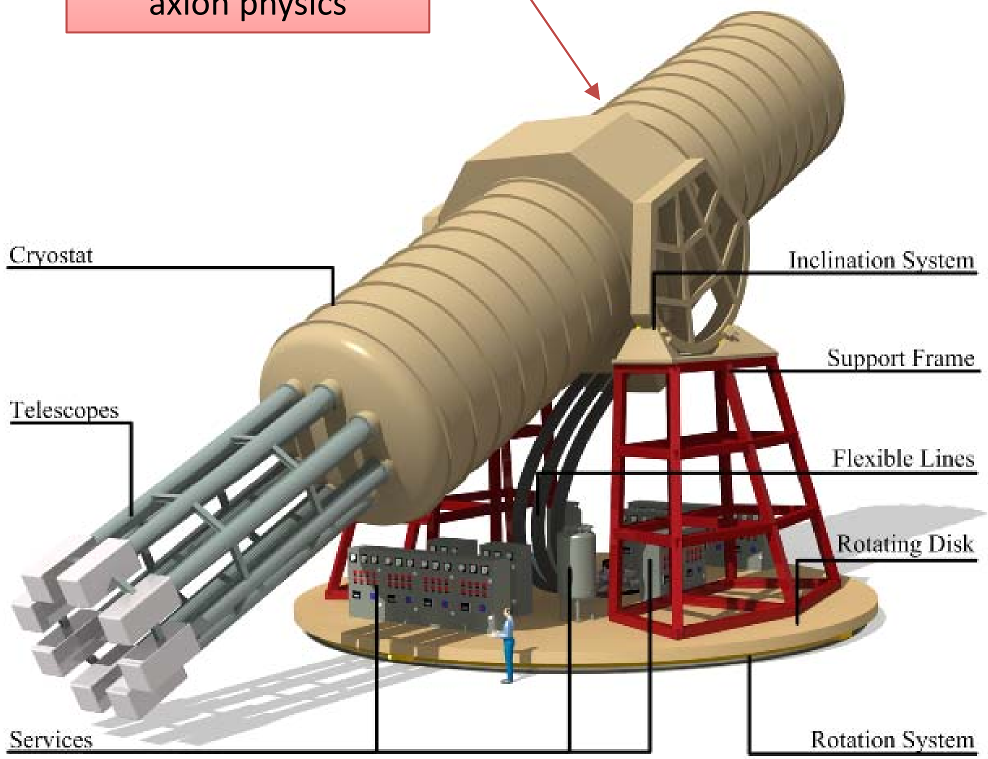
IAXO magnet

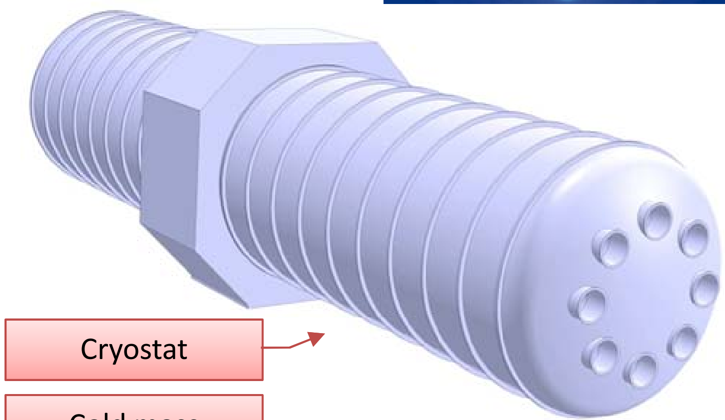
TOROIDAL CONFIGURATION specifically built for axion physics

Each conversion bore (between coils) 600 mm diameter



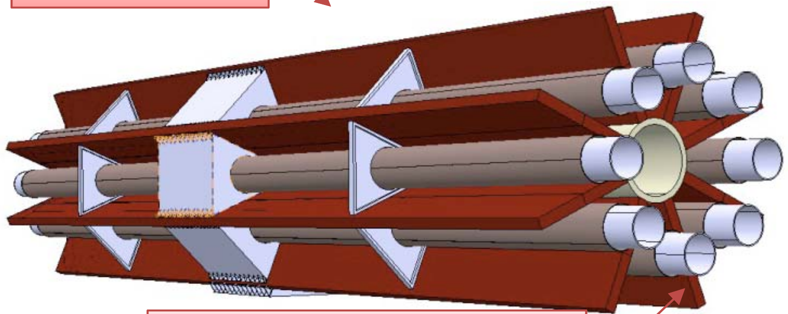






Cryostat

Cold mass

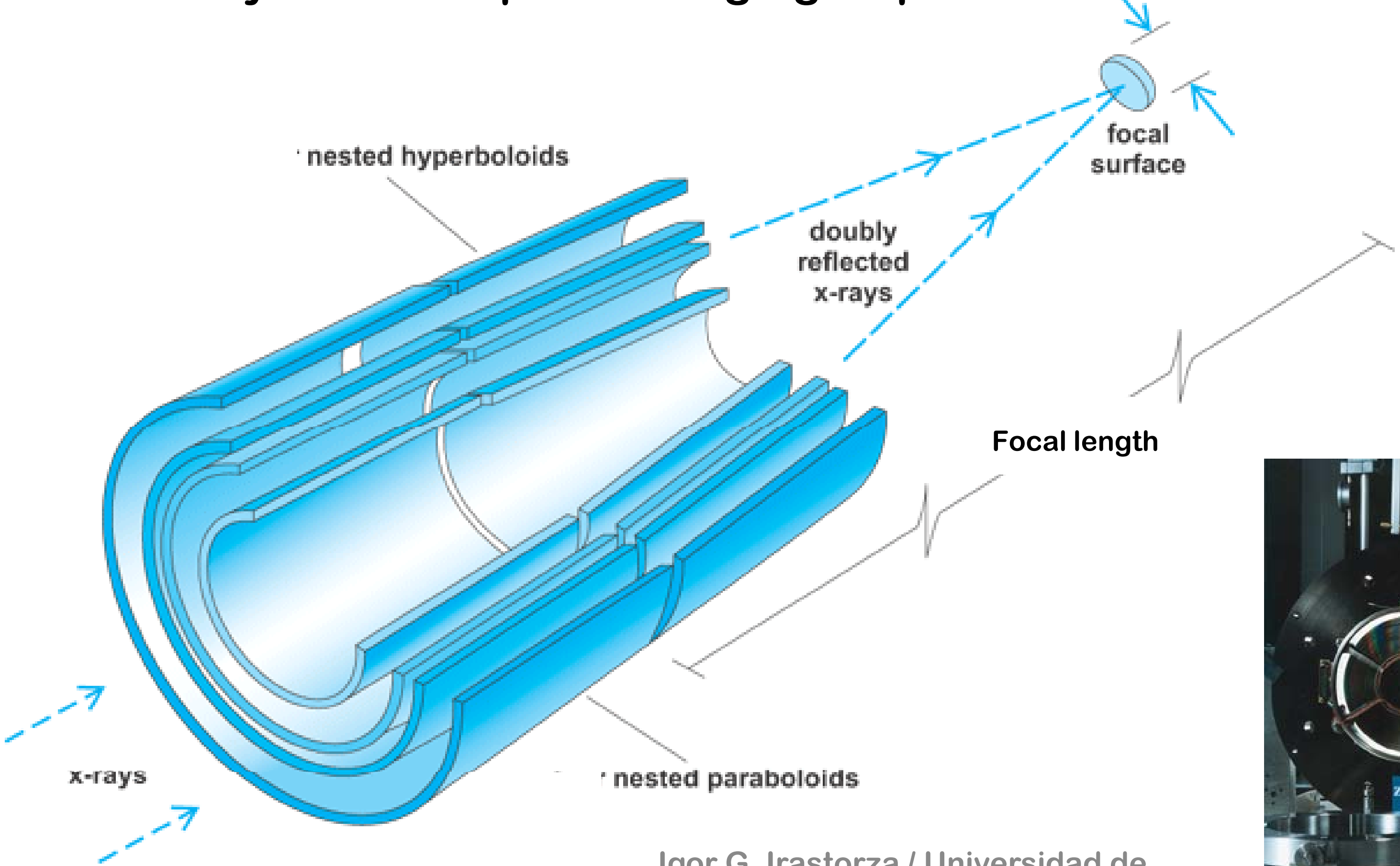


Bores go through cryostat

Magnetic length 20 m Total cryostat length 25 m

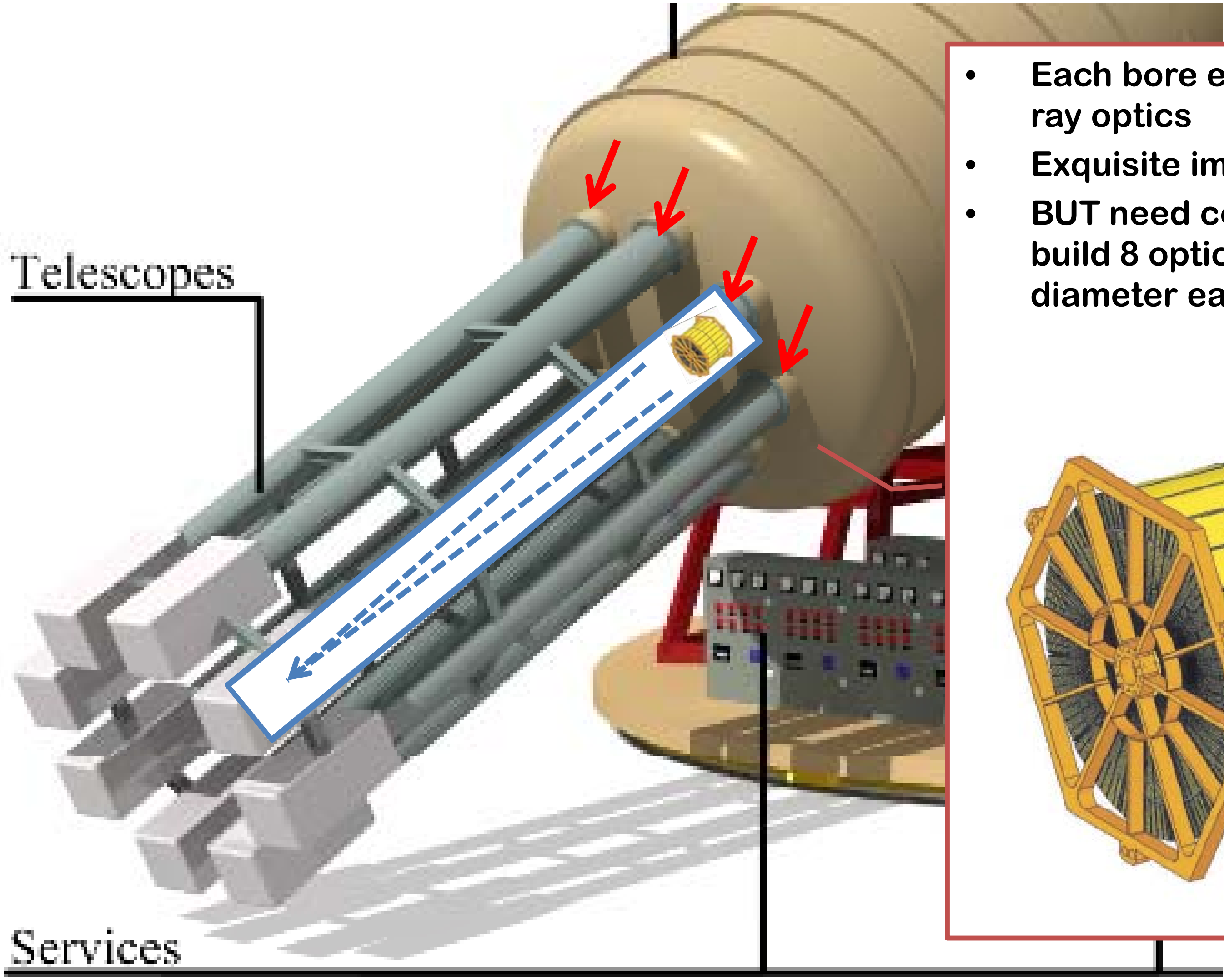
IAXO x-ray optics

- 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

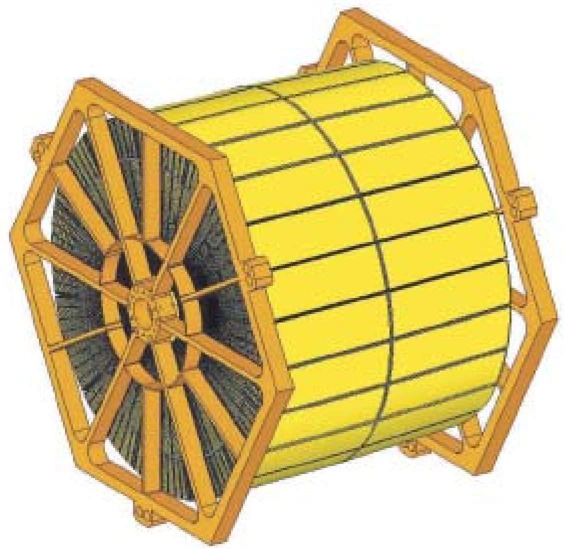


ABRIXAS spare telescope, in use in one of the 4 bores of CAST (pioneer use of x-ray optics in axion research)

IAXO x-ray optics

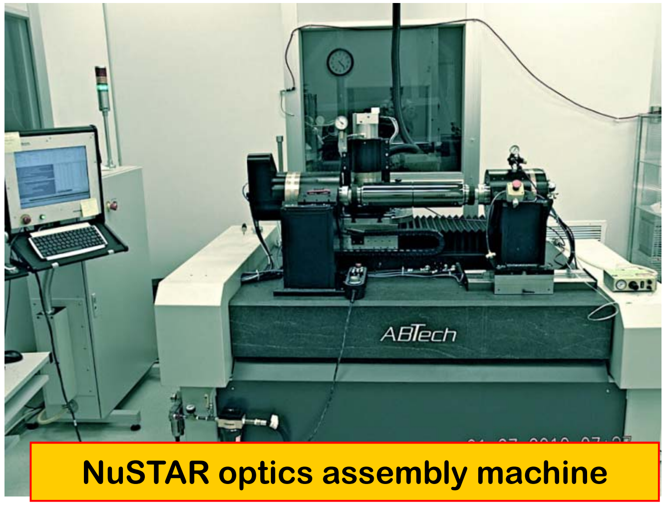


- Each bore equipped with an x-ray optics
- Exquisite imaging not required
- BUT need cost-effective way to build 8 optics of 600 mm diameter each.



IAXO x-ray optics

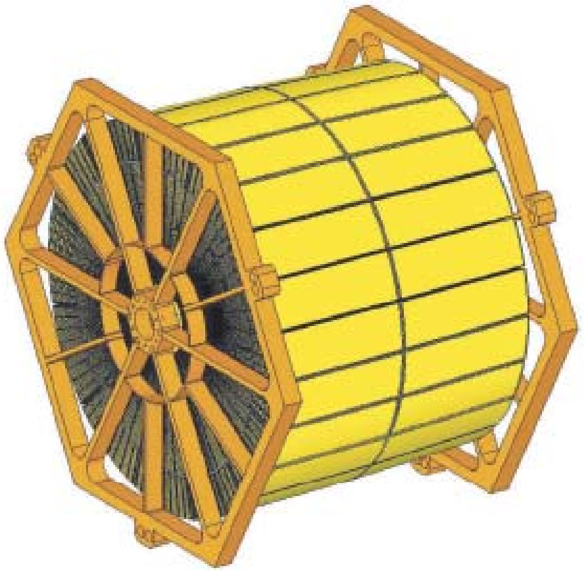
- Technique of choice for IAXO: optics made of slumped glass substrates coated to enhance reflectivity in the energy regions for axions.
- Same technique successfully used in NuSTAR mission, recently launched
- The specialized tooling to shape the substrates and assemble the optics is now available
-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

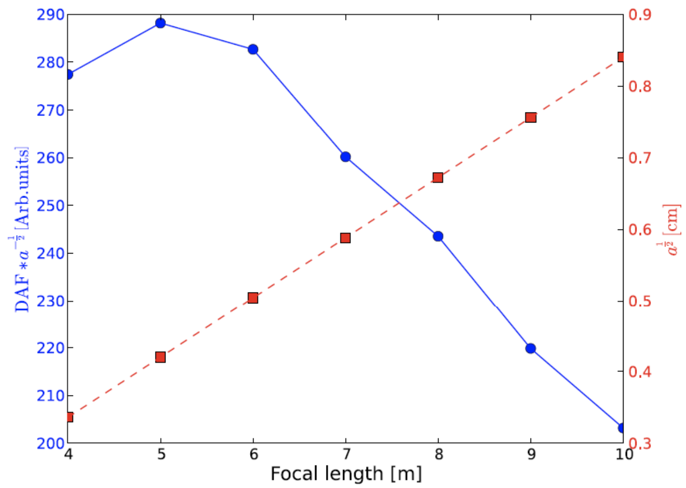


NuSTAR optics assembly machine

NuSTAR telescope ~400 mm Ø

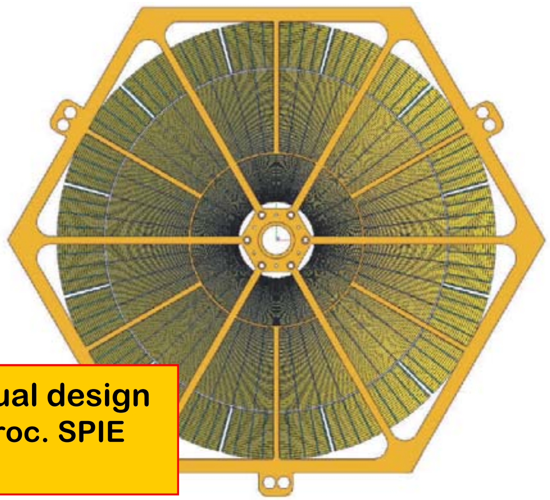
IAXO x-ray optics





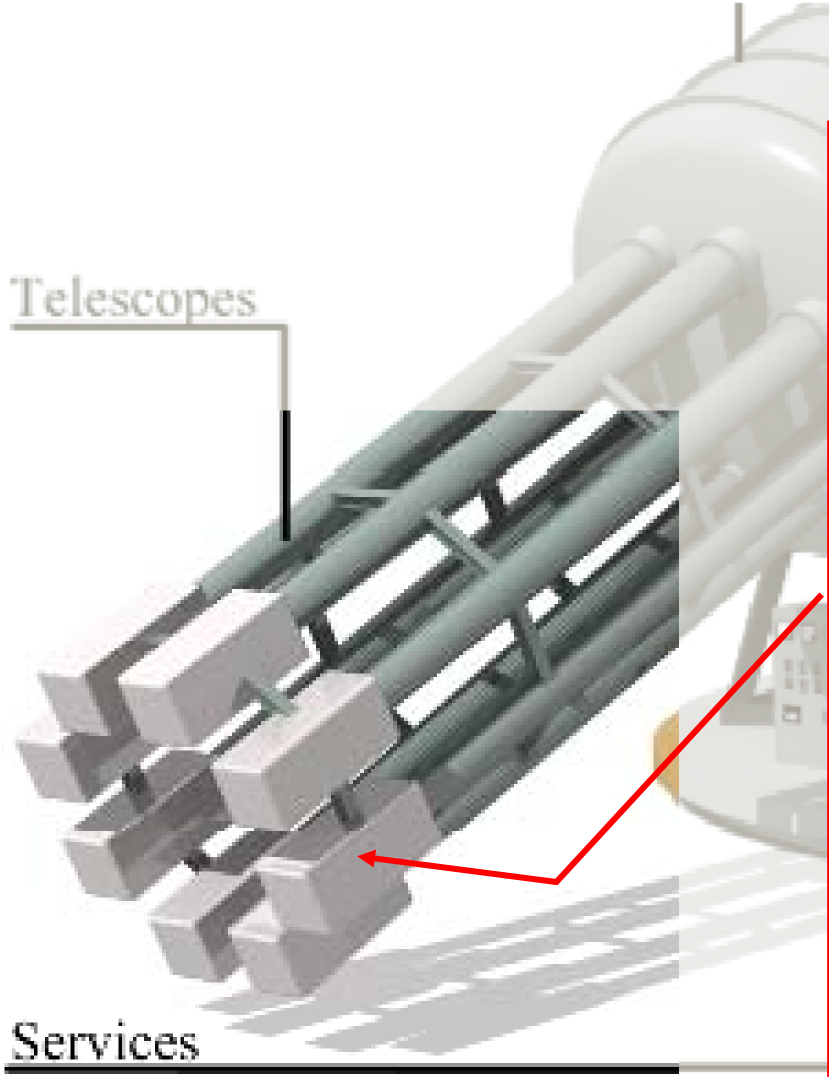
Optimal focal length ~5 m

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

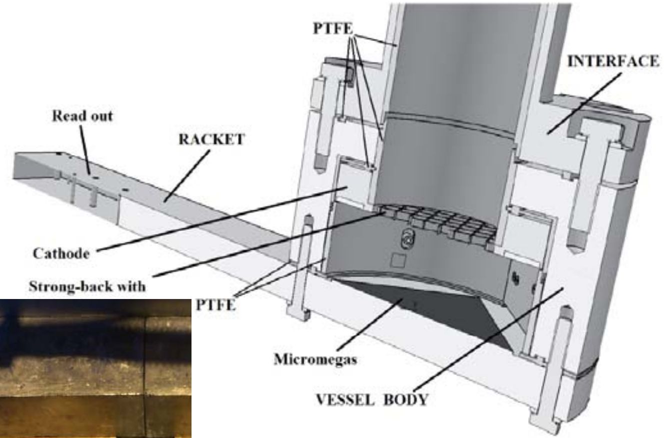


IAXO optics conceptual design
AC Jakobsen et al, Proc. SPIE 8861 (2013)

IAXO low background detectors



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

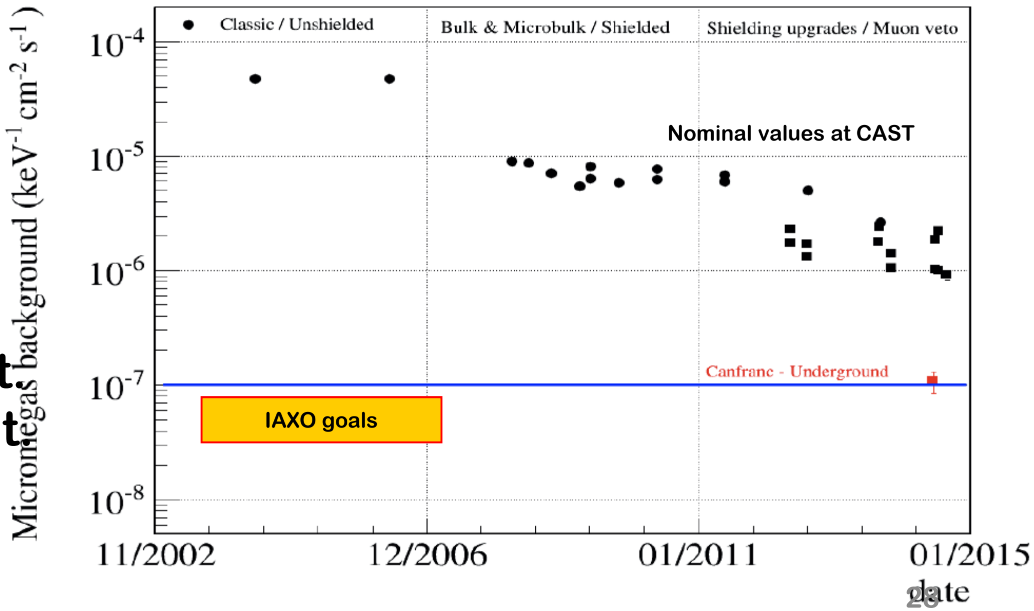


IAXO low background MM detectors

- 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:
  - ~$8{\times}10^{-7}$ c keV^{-1} cm^{-2} s^{-1} (in CAST 2014 result)
  - 10^{-7} c keV^{-1} cm^{-2} s^{-1} (underground at LSC)
- Active program of development. Clear roadmap for improvement

History of background improvement of Micromegas detectors at CAST

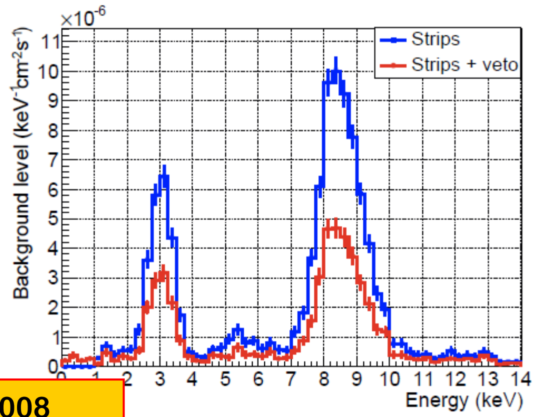


See arXiv:1310.3391

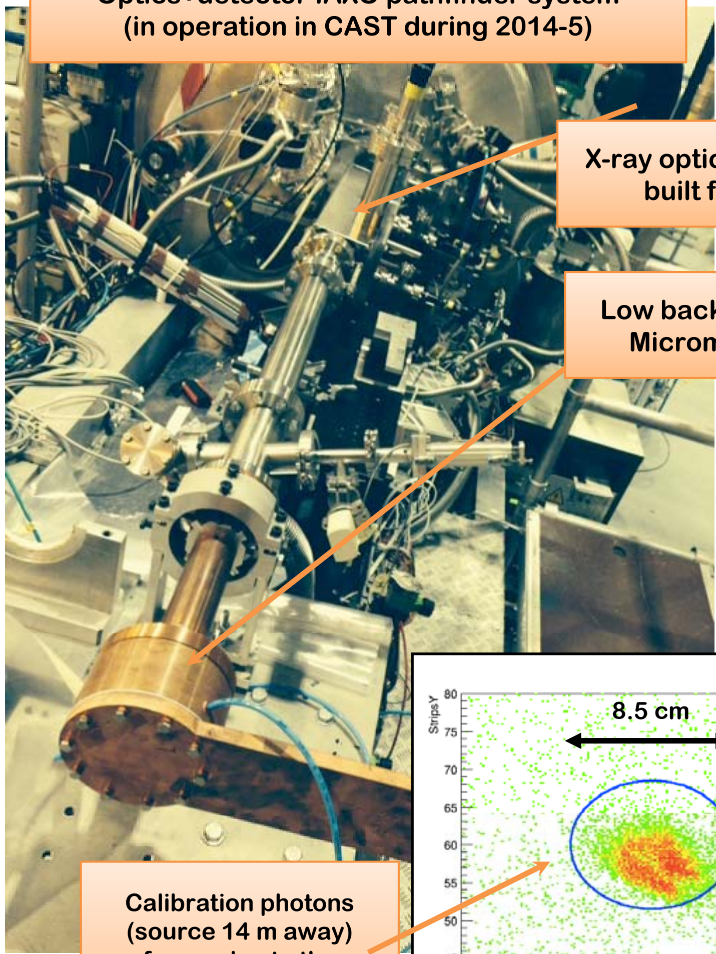
IAXO low background detectors

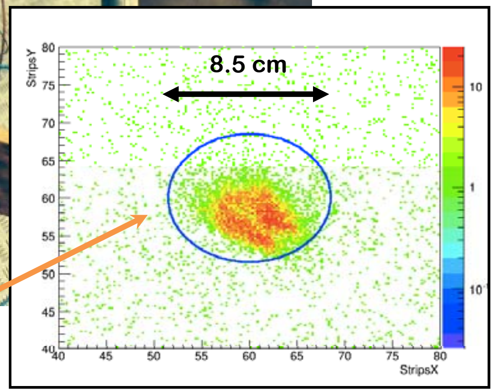
Optics+detector pathfinder system in CAST

- IAXO optics+detector joint system
  - First time x-ray optics built specifically “for axions”.
  - First time low background + focusing in the same system
  - Installed & operated in CAST 2014-15



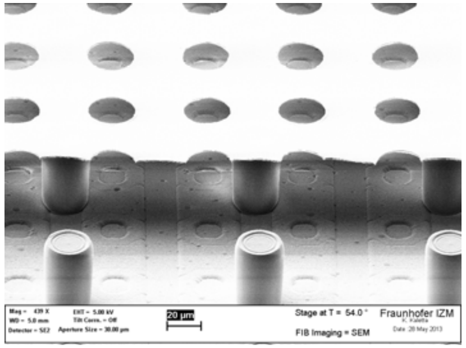
JCAP12 (2015) 008
JCAP01 (2016) 034



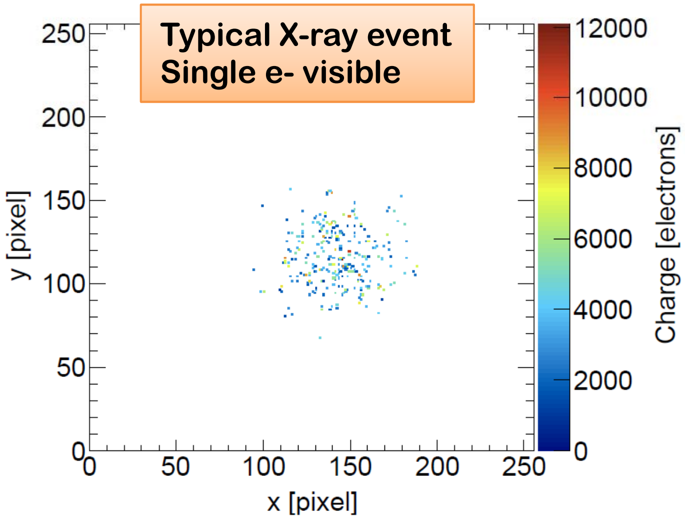


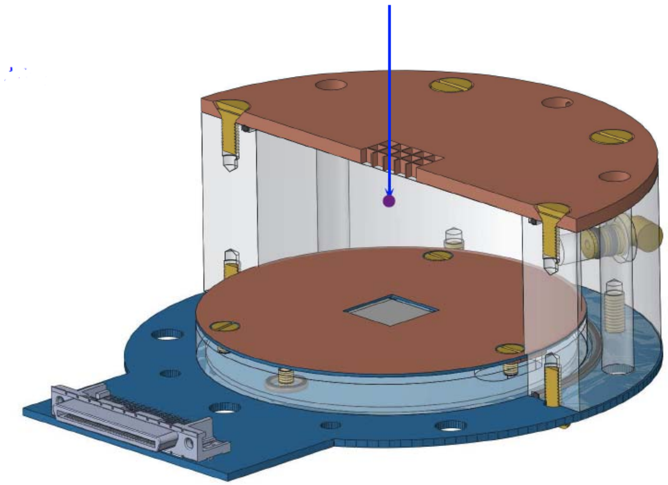
Additional detector technologies

Ingrid detectors (U. Bonn):



- Micromegas on top of a CMOS chip (Timepix)
- Very low threshold (tens of eV)
- Tested in CAST

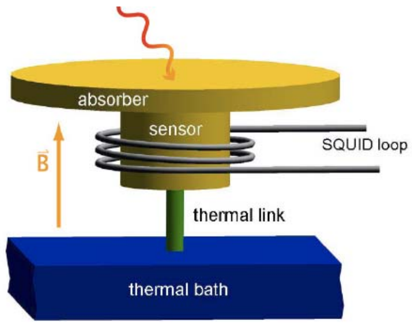


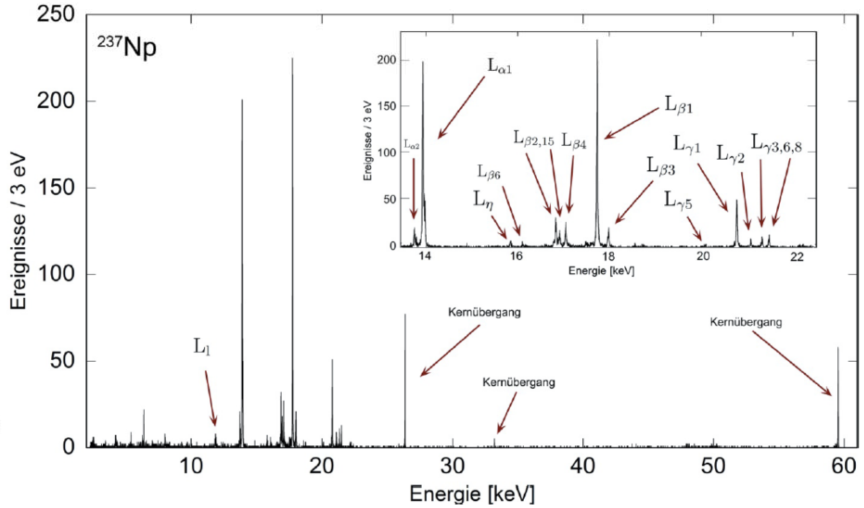


Additional detector technologies

MMC detectors (U. Heidelberg):

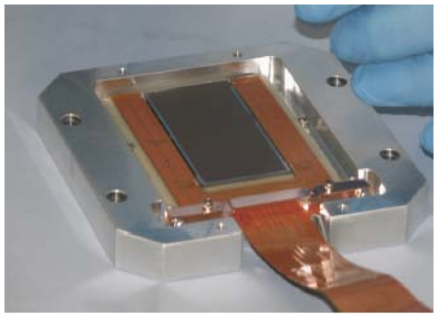
- Extremely low threshold and energy resolution (~eV scale)
- Low background capabilities under study





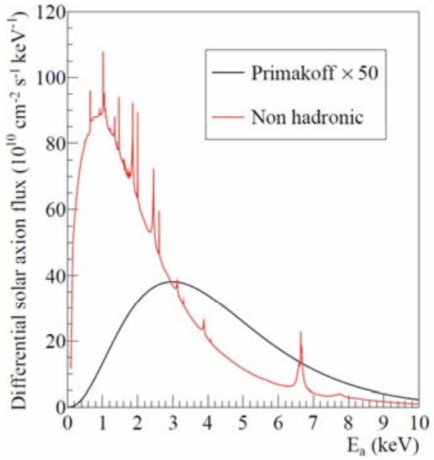
Low noise CCDs

- Developed for low mass WIMP experiments (DAMIC)



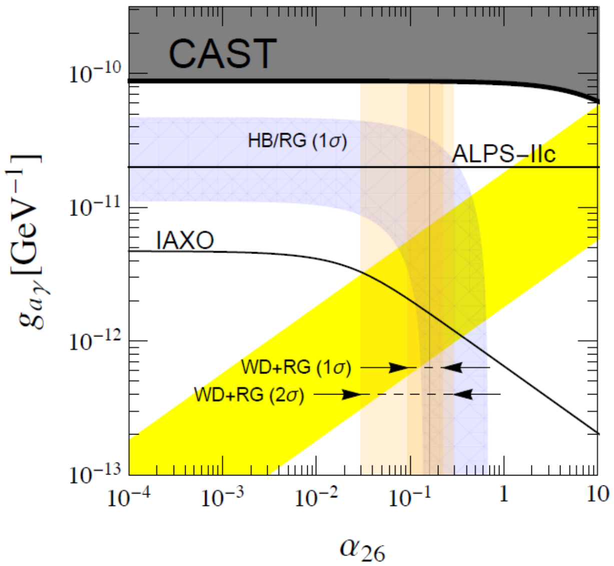
Additional IAXO physics cases

- **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
  - Chameleons
  - Non-standard scenarios of axion production



And more…

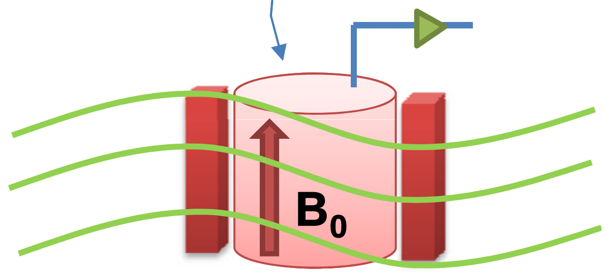
- **Dark Matter Axions (→ use of IAXO magnet with cavities / RF antennas)**
- **ALPs from Dark Radiation**
- **ALPs from nearby Supernova (connection with SNEWS) → MeV photon detector at the other end**
- **More ideas?**



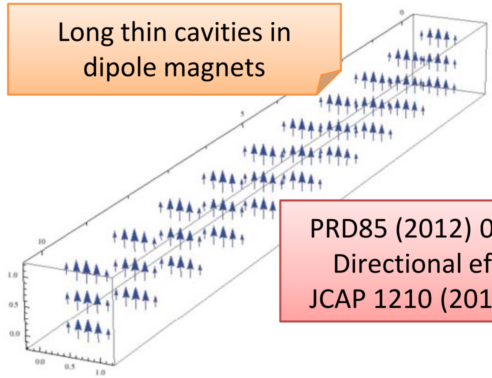
IAXO-DM configurations?

- **ADMX has proved halosocope concept competitive at m_a~1-10 μeV. Big motivation to explore higher masses.**
- **Many new ideas being put forward. R&D needed.**
- **Various possible arrangements in IAXO. Leverage the huge magnetic volume available:**
  1. **Single large cavity tuned to low masses**
  2. **Thin long cavities tuned to mid-high masses. Possibility for directionality. Add several coherently?**
  3. **Dish antenna focusing photons to the center. Not tuned. Broadband search. Competitive at higher masses?**
- **Initial stages of exploring and developing concepts.**

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

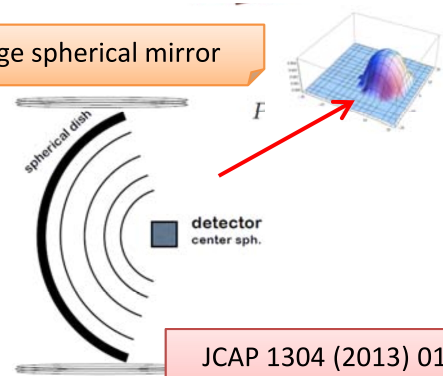


Long thin cavities in dipole magnets



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

Large spherical mirror



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

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.**

- **2014-15: 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: IAXO pathfinder system (Micromegas + telescope) installed in CAST in 2014
  - 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.

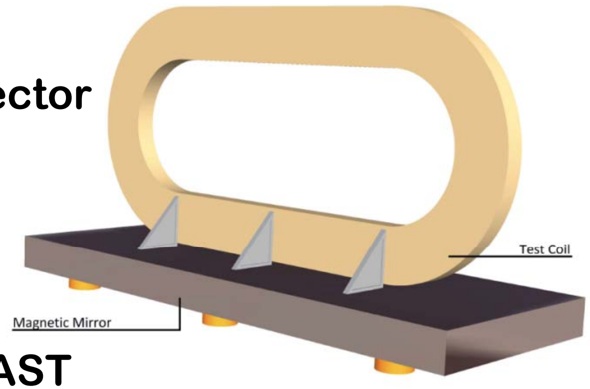
This was endorsed by the Research Board in March2014

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

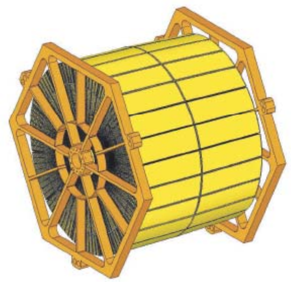
Near term plans (time scale ~2 years)

- Complete a **Technical Design Report**. Activities include:
  - 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**
  - Potential construction of additional detector prototypes to perform validation of alternative detector technologies
  - Complete pathfinder project detector+optic at CAST
  - Feasibility studies for "IAXO-DM" options.
- Memorandum of Understanding in preparation among interested parties.
- Site studies
- Build strong community around project
- Search for new interested partners

IAXO-**T0**



IAXO-**X0**



Mid term plans (+4 years)
towards IAXO construction

- **Site:**
  - CERN is Plan A, but alternatives under consideration: it may affect funding strategies. Some preliminary interest from a number of institutions.
- **Magnet:**
  - Magnet construction → main resources challenge
  - Plan A: Form international consortium, coordinated by CERN (+CEA?) to collectively support the magnet construction, by means of inkind contributions to the effort.
  - Plan B: Large investment by host institution (IAXO being hosted outside CERN)
- **X-ray optics:**
  - Construction efforts distributed among groups pushing x-ray technologies for IAXO: US (LLNL, UC, MIT) + Europe (DTU, INAF-Milano)
- **Detectors:**
  - Efforts distributed among groups pushing each detector technology (actual decisions taken after TDR):
    - Micromegas: Zaragoza, CEA
    - Ingrid: Bonn
    - CCD: FNAL?, LPNHE?
    - MMCs/TES: Heidelberg, Orsay, CEA

IAXO costs

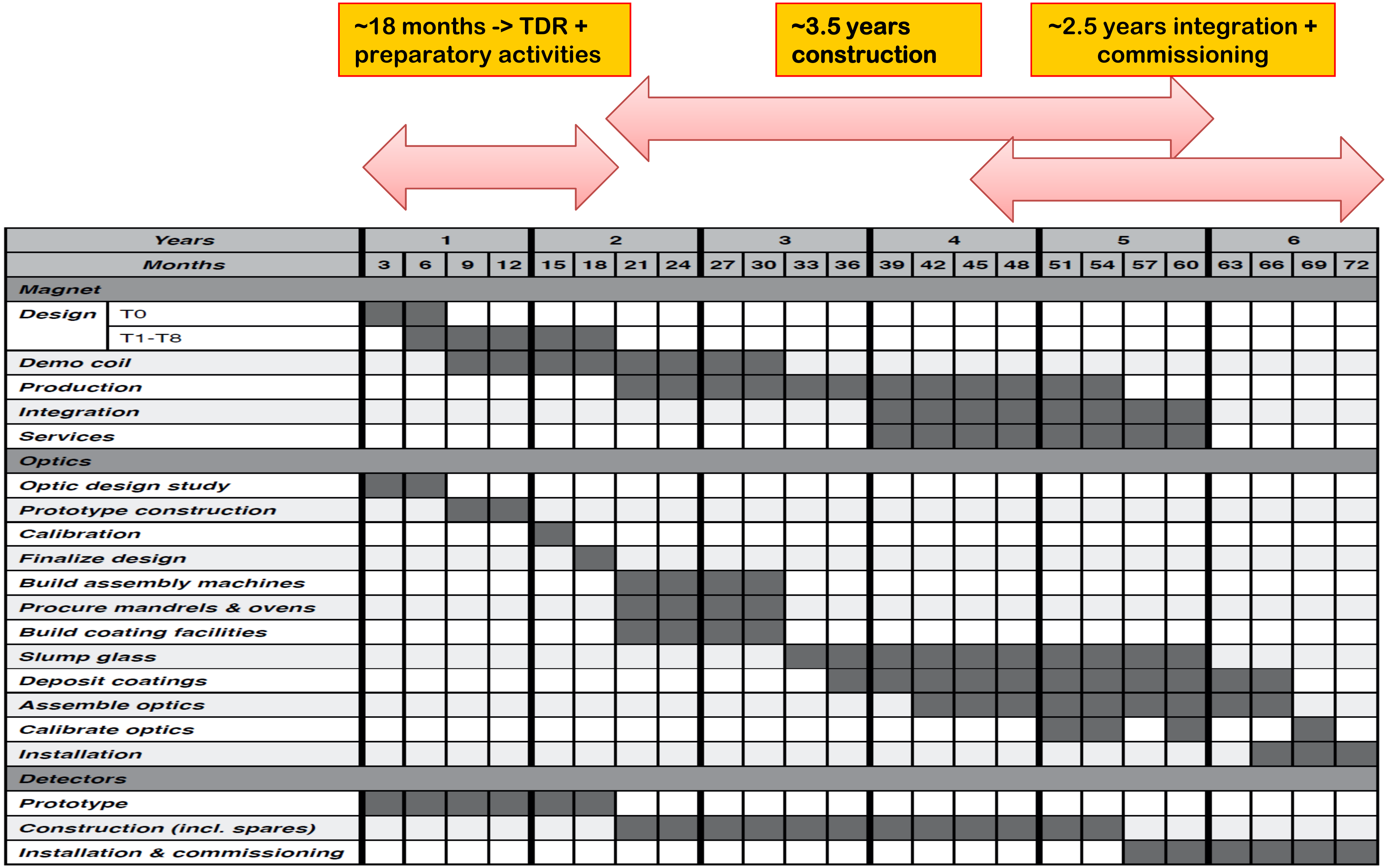
Item	Cost (MCHF)	Subtotals (MCHF)
Magnet		31.3
Eight coils based assembled toroid	28	
Magnet services	3.3	
Optics		16.0
Prototype Optic: Design, Fabrication, Calibration, Analysis	1.0	
IAXO telescopes (8 + 1 spare)	8.0	
Calibration	2.0	
Integration and alignment	5.0	
Detectors		5.8
Shielding & mechanics	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.

Comments/caveats:

- **Costs are for construction, and do not include operations and science support**
- **Costs based on initial estimates that need to be confirmed at TDR**
- **Labor for engineering, maintenance & operations not included**
- **Estimates do not include contingencies**

IAXO timeline



IAXO proto-collaboration

	Institution [potential contributions]	
Europe	CERN [magnet] CEA-Saclay (France) [magnet, detectors, dm-studies] Zaragoza (Spain) [detectors] RBI (Croatia) [physics] DESY (Germany) Bonn (Germany) [detectors (Ingrid)] Heidelberg (Germany) [detectors (MMC)] LPNHE (France) [detectors]	DTU (Denmark) [optics] Mainz (Germany) [detectors, magnet] MPI(Germany) [theory] St. Petersburg (Russia) INR-Moscow (Russia) U.Valencia (Spain) [dm-studies] INAF-Milano, Italy [optics] INFN, Italy [physics,+…] … +Interest in physics by a number of other European groups
US	LLNL [optics] Columbia [optics] MIT [optics] LANL [physics] S. Carolina [eng. support? electronics?] FNAL [detectors, magnet?]	U. Barry [physics] U. Florida [physics] Stony Brook [physics] Princeton [detector* depleted Ar] (possibly) U. Maryland (*)

Black: formal activity ongoing & IAXO TDR funding already secured or to be secured.
Red: interested community & informal (inkind) activities ongoing + formal support under discussion
Orange: interested community & potential contributions identified if support secured

Conclusions

- **Increasing interest for axions:**
  - **Physics case, theory, cosmology, astrophysics**
- **Increasing experimental effort worldwide**
  - **Still modest compared e.g. with WIMPs**
- **Field in a transition: from small experiments to Big Science?**
- **IAXO will probe deep into unexplored axion+ALP parameter. IAXO is timely, ambitious, with discovery potential**
- **IAXO as a generic "axion/ALP facility"**
- **First steps after the positive recommendation from CERN SPSC.**
- **Need consolidate community. New partners welcome.**