IAXO International AXion Observatory
Letter of Intent to CERN SPSC

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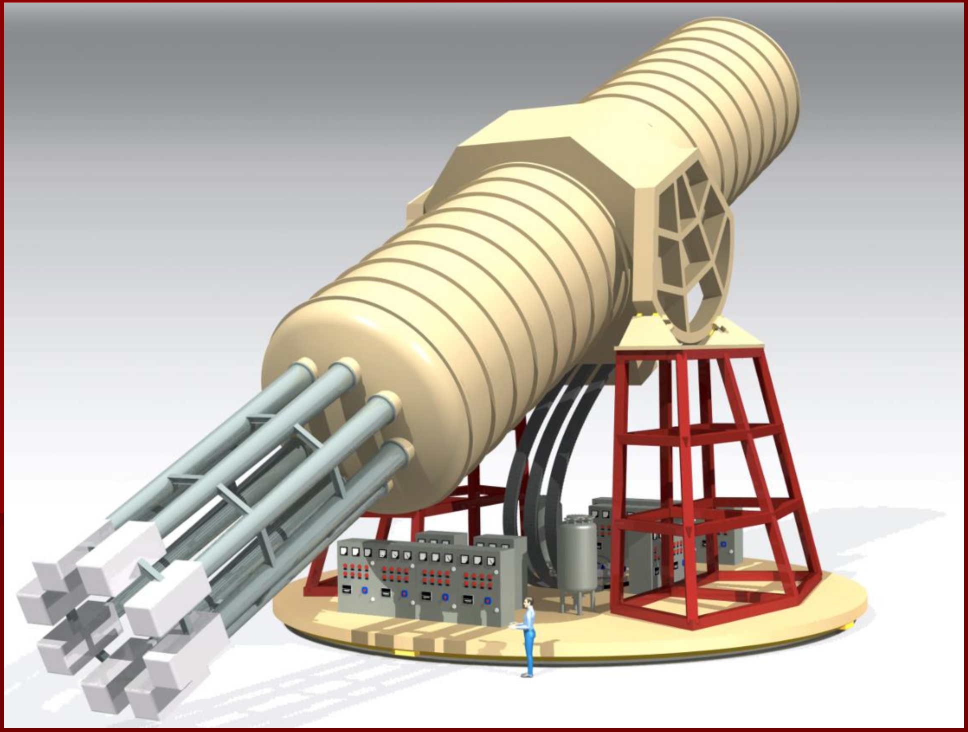
On behalf of the IAXO collaboration

Open session of the 111th SPS Committee Meeting – October 22nd 2013 – CERN



Outline

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

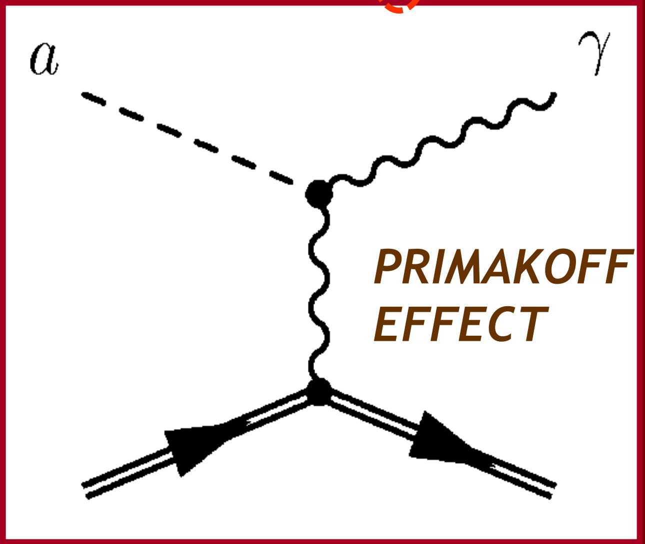
Why axions? (since 1977)

- **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

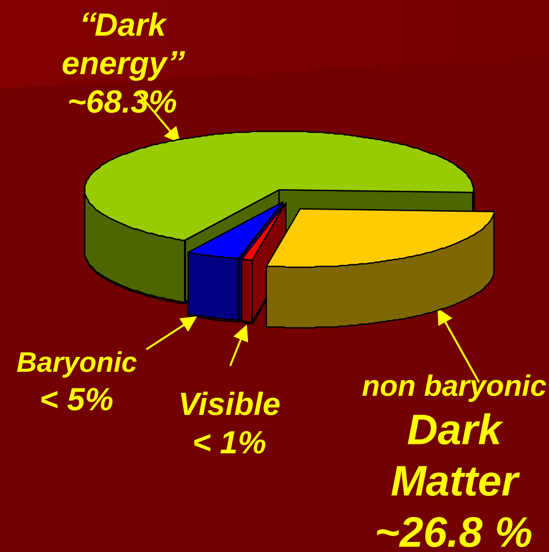
$$\mathcal{L}_{CP} = \theta \frac{\alpha_s}{8\pi} G\tilde{G}$$

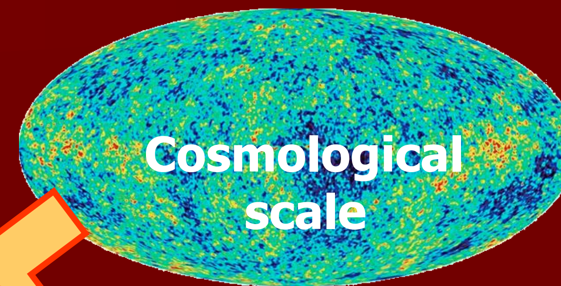
$$\frac{\alpha_s}{8\pi f_a} a G\tilde{G}$$

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

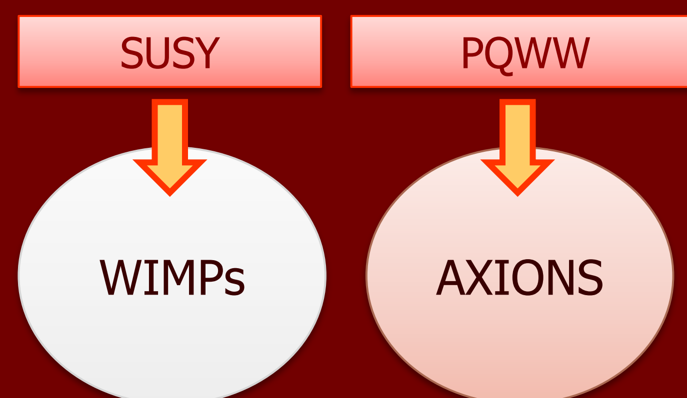


AXION as Dark Matter?





- 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 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)

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**

Detecting axions

- Relic Axions
  - Axions that are part of galactic dark matter halo:
    - Axion Haloscopes

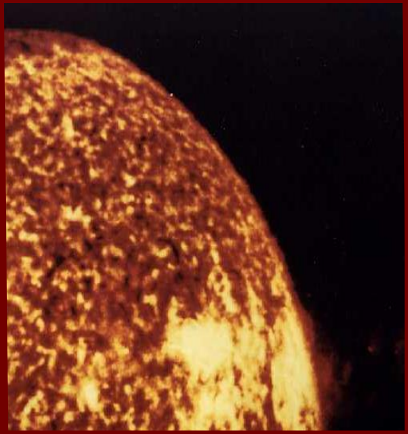
ADMX in US

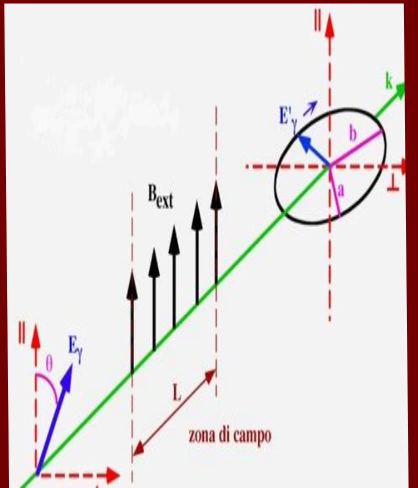
- Solar Axions
  - Emitted by the solar core
    - Crystal detectors
    - Axion Helioscopes

CAST @ CERN
→ IAXO

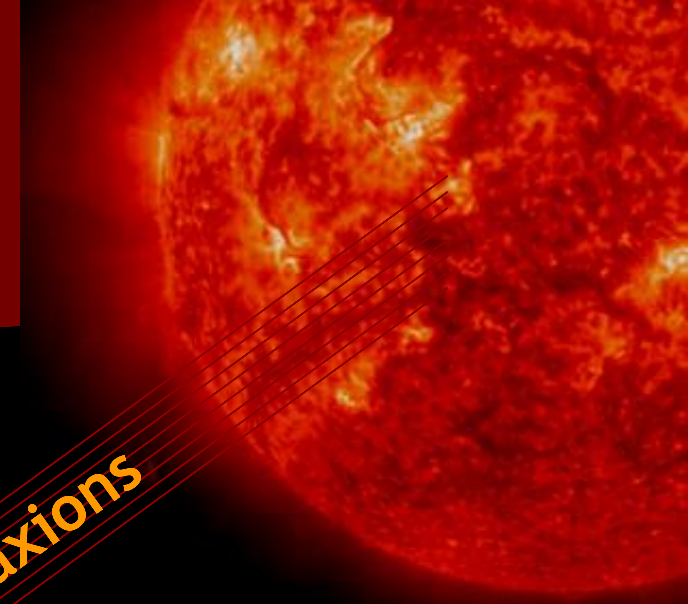
- Axions in the lab
    - “Light shinning through wall” experiments
    - Vacuum birrefringence experiments

ALPS-II @ DESY
OSQAR @ CERN

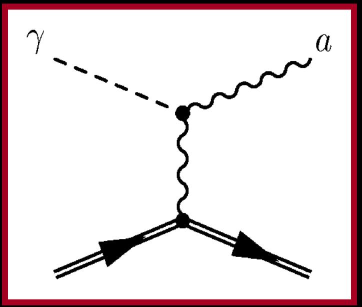




Solar Axions



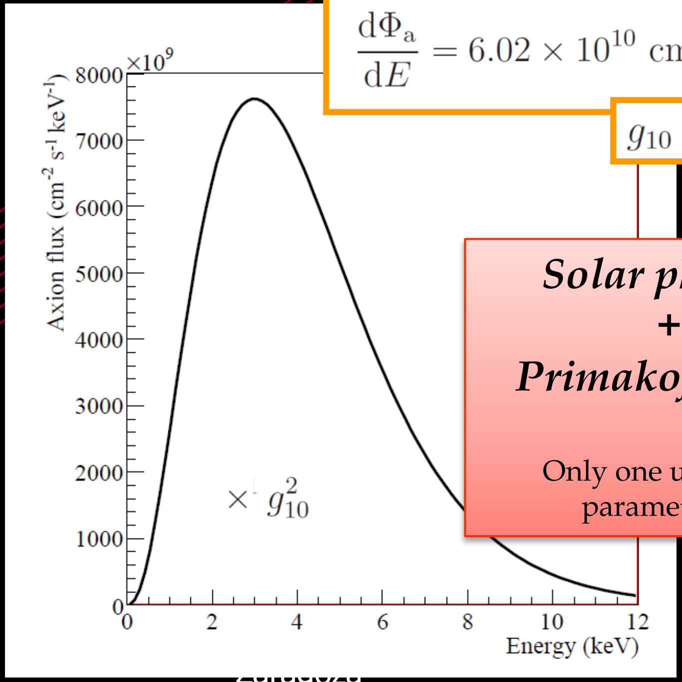
- Solar axions produced by photon-to-axion conversion of the solar plasma photons in the solar core



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

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

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



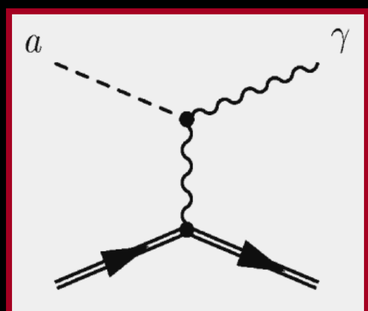
Solar physics* + *Primakoff effect

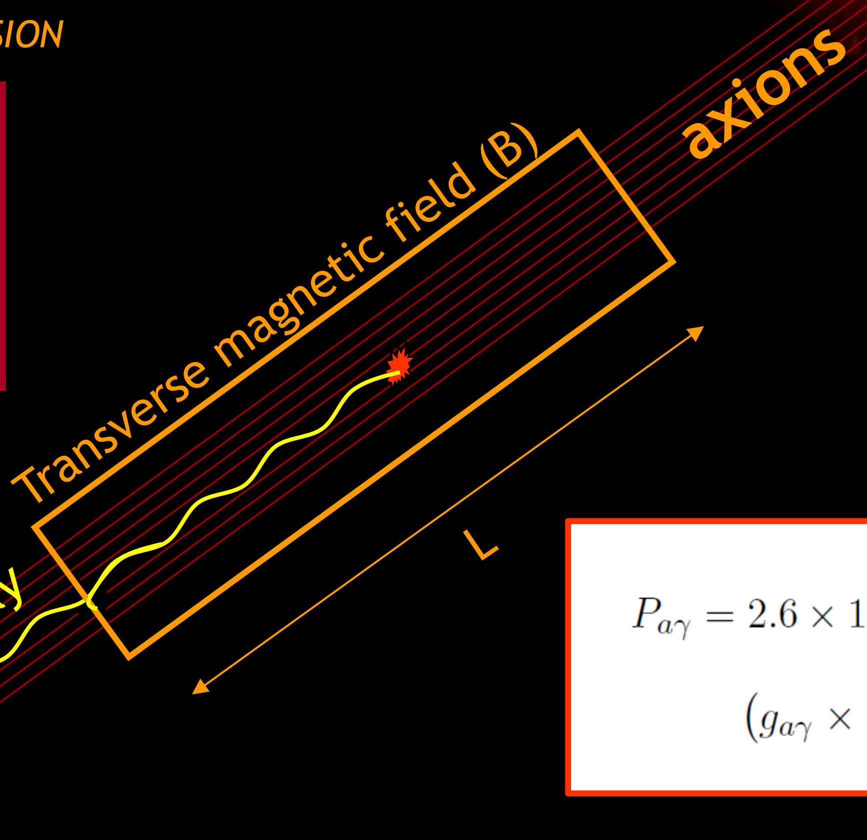
Only one unknown parameter $g_{a\gamma}$

Axion Helioscope principle

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

AXION PHOTON CONVERSION



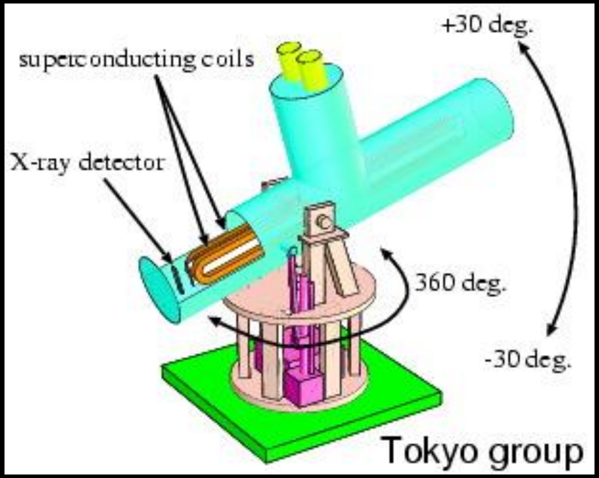


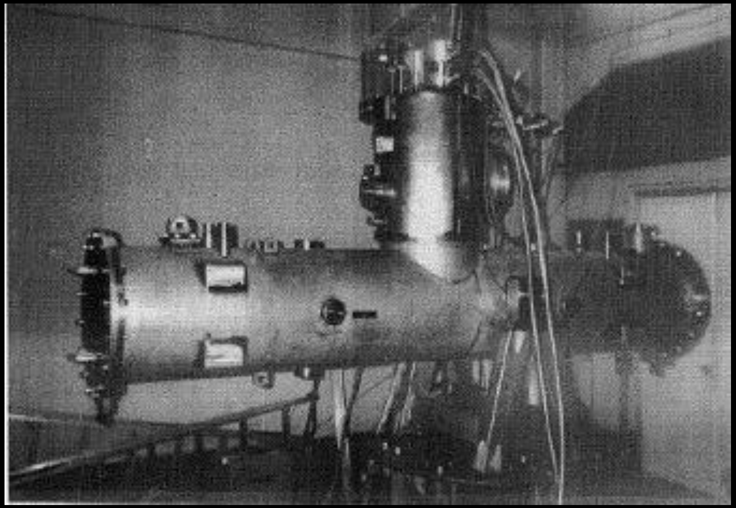
$$P_{a\gamma} = 2.6 \times 10^{-17} \left(\frac{B}{10\ \mathrm{T}}\right)^2 \left(\frac{L}{10\ \mathrm{m}}\right)^2 (g_{a\gamma} \times 10^{10}\ \mathrm{GeV})^2 \mathcal{F}$$

COHERENCE $\mathcal{F} \rightarrow$ *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

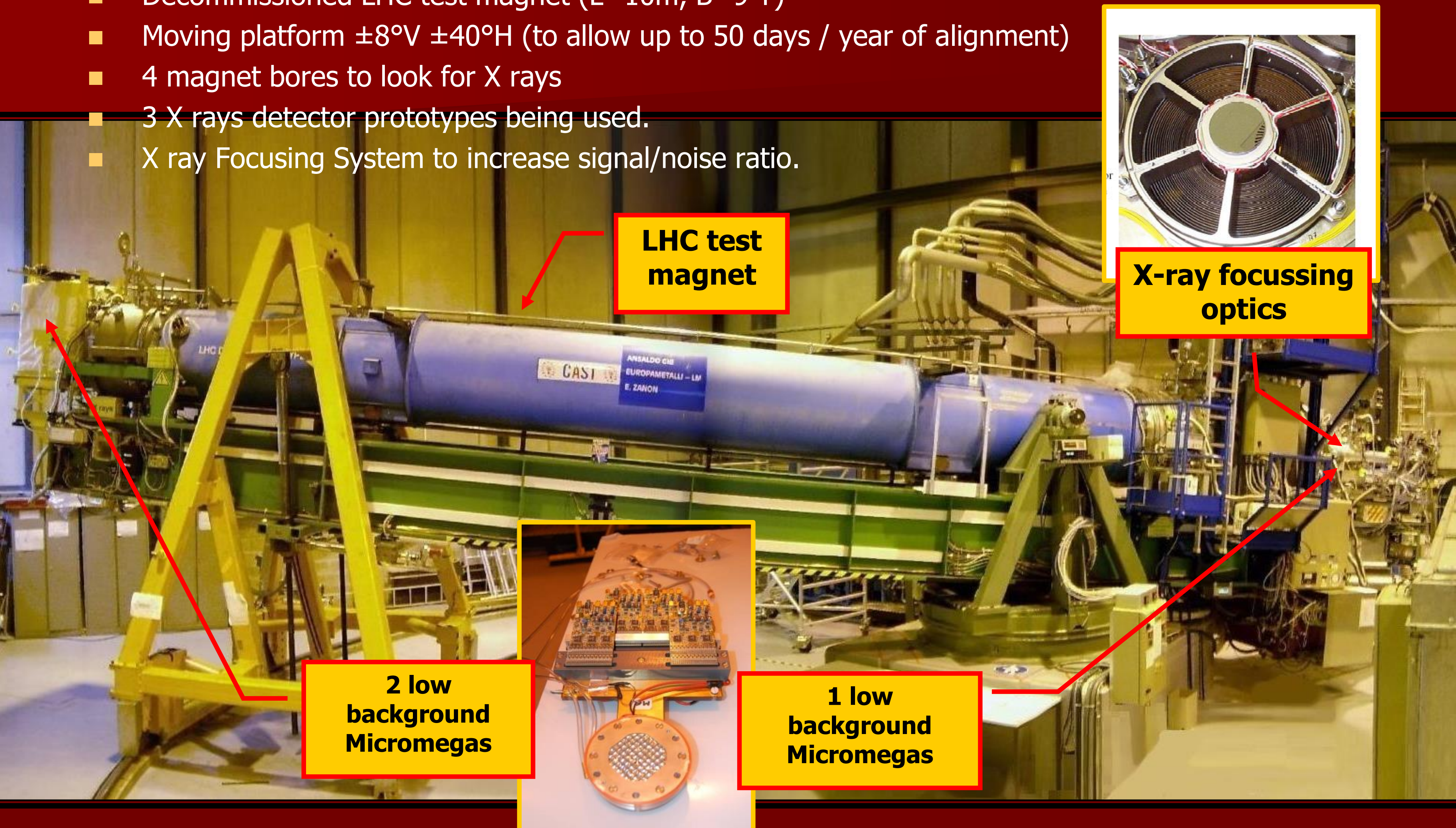




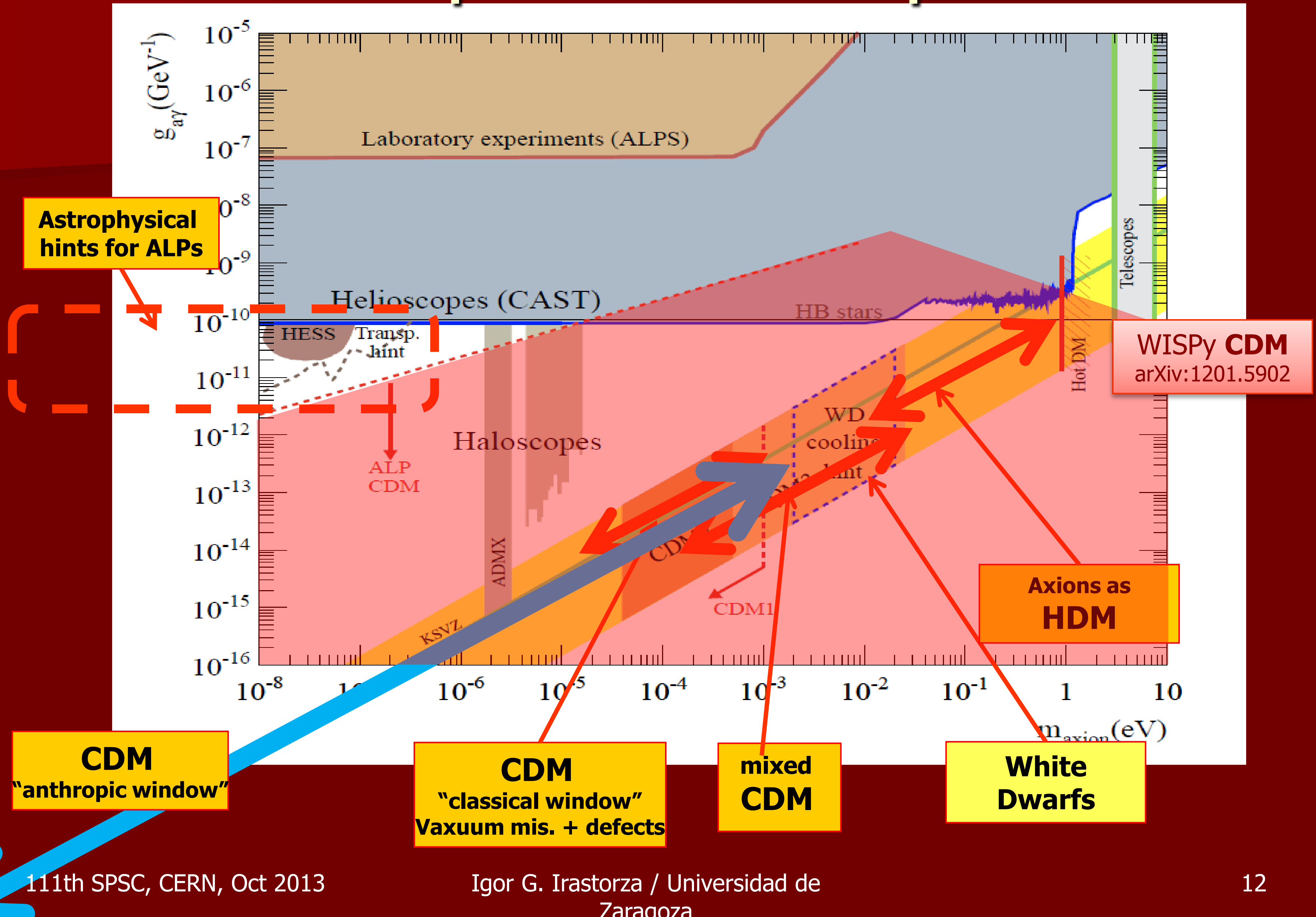
- Presently running:
  - CERN Axion Solar Telescope (**CAST**)

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.

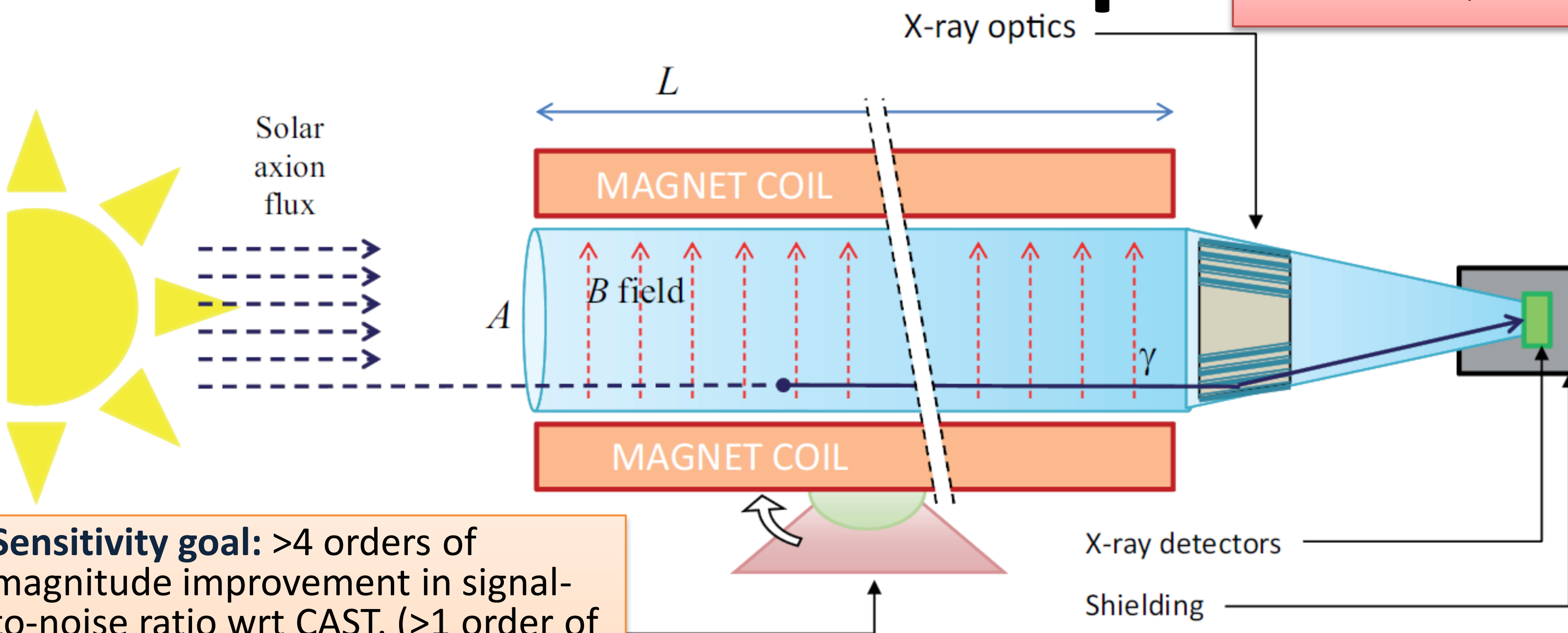


Axion parameter space



IAXO – Concept

Enhanced axion helioscope: *JCAP 1106:013,2011*



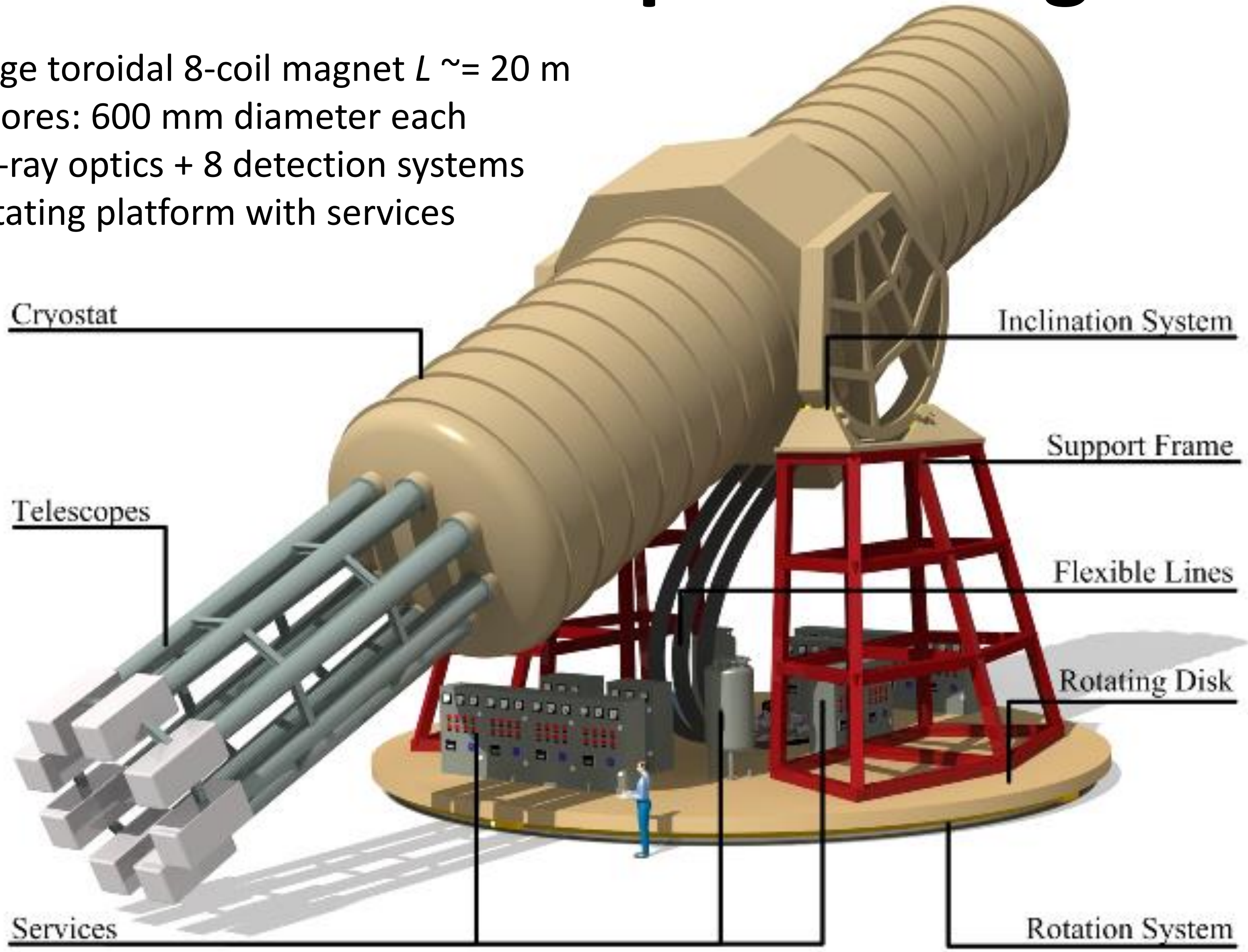
- **Sensitivity goal:** >4 orders of magnitude improvement in signal-to-noise ratio wrt CAST. (>1 order of magnitude in sensitivity of $g_{a\gamma}$)

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

- 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 of **x-ray focalization** over ~m^2 area
  - **Low background detectors** (lower 1-2 order of magnitude CAST levels)

IAXO – Conceptual Design

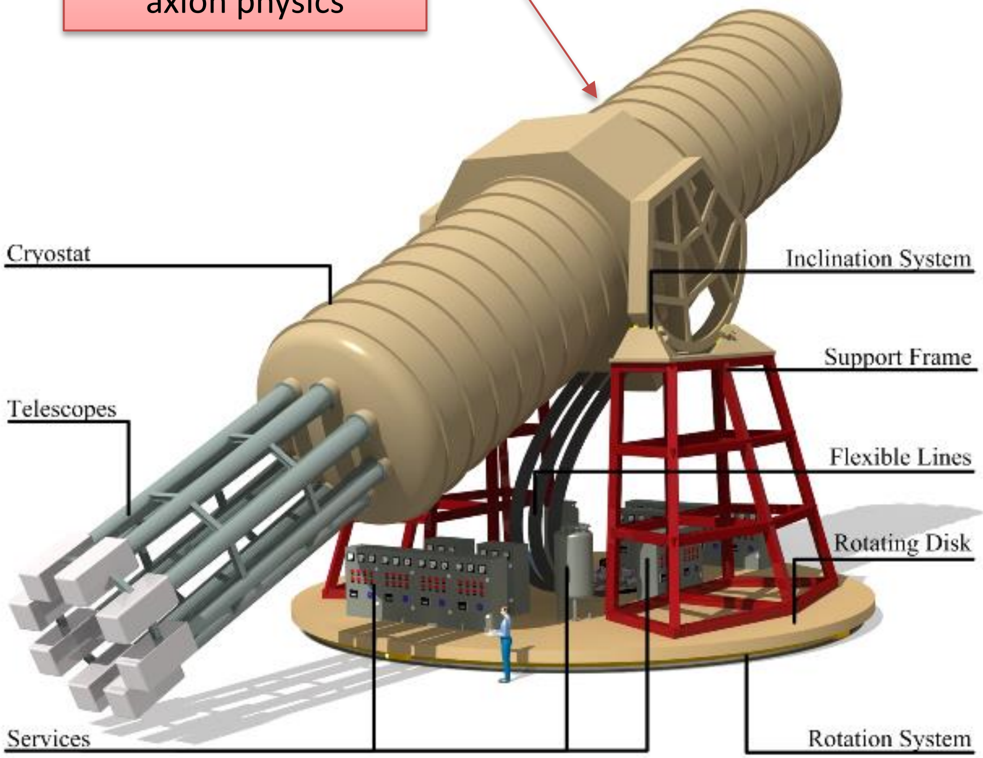
- Large toroidal 8-coil magnet *L* ~= 20 m
- 8 bores: 600 mm diameter each
- 8 x-ray optics + 8 detection systems
- Rotating platform with services

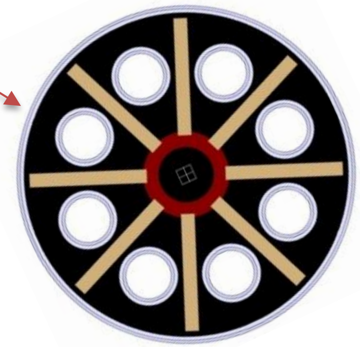


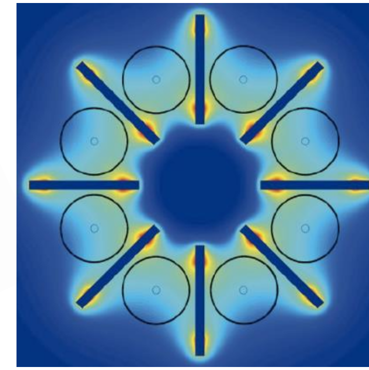
IAXO magnet

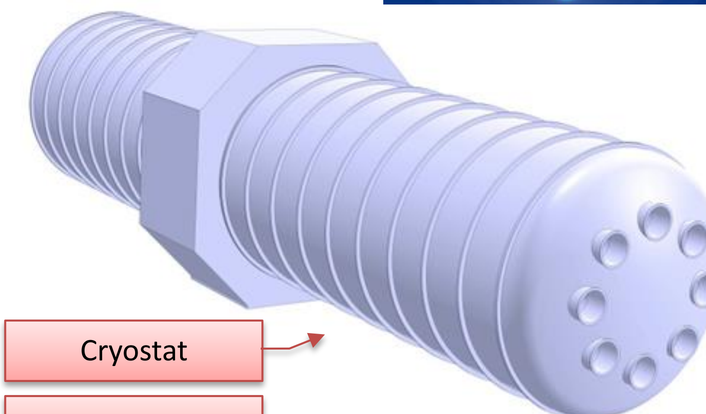
TOROIDAL CONFIGURATION specifically built for axion physics

Each conversion bore (between coils) 600 mm diameter



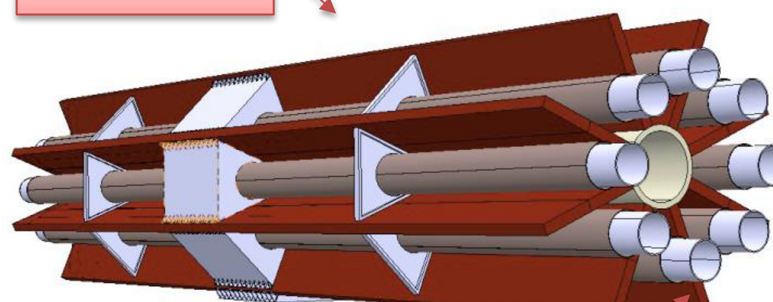






Cryostat

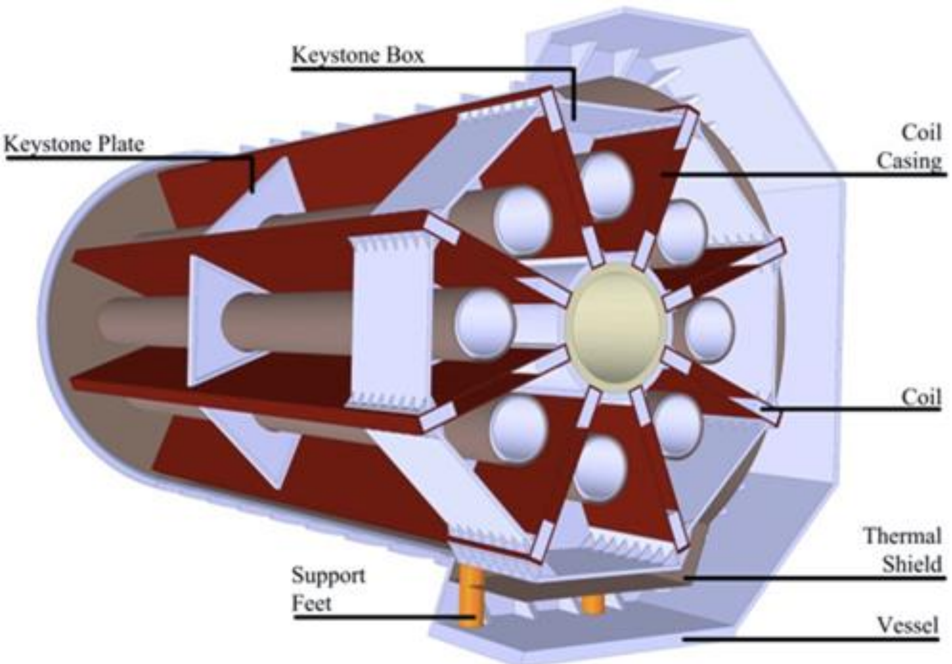
Cold mass



Bores go through cryostat

Magnetic length 20 m Total cryostat length 25 m

IAXO magnet

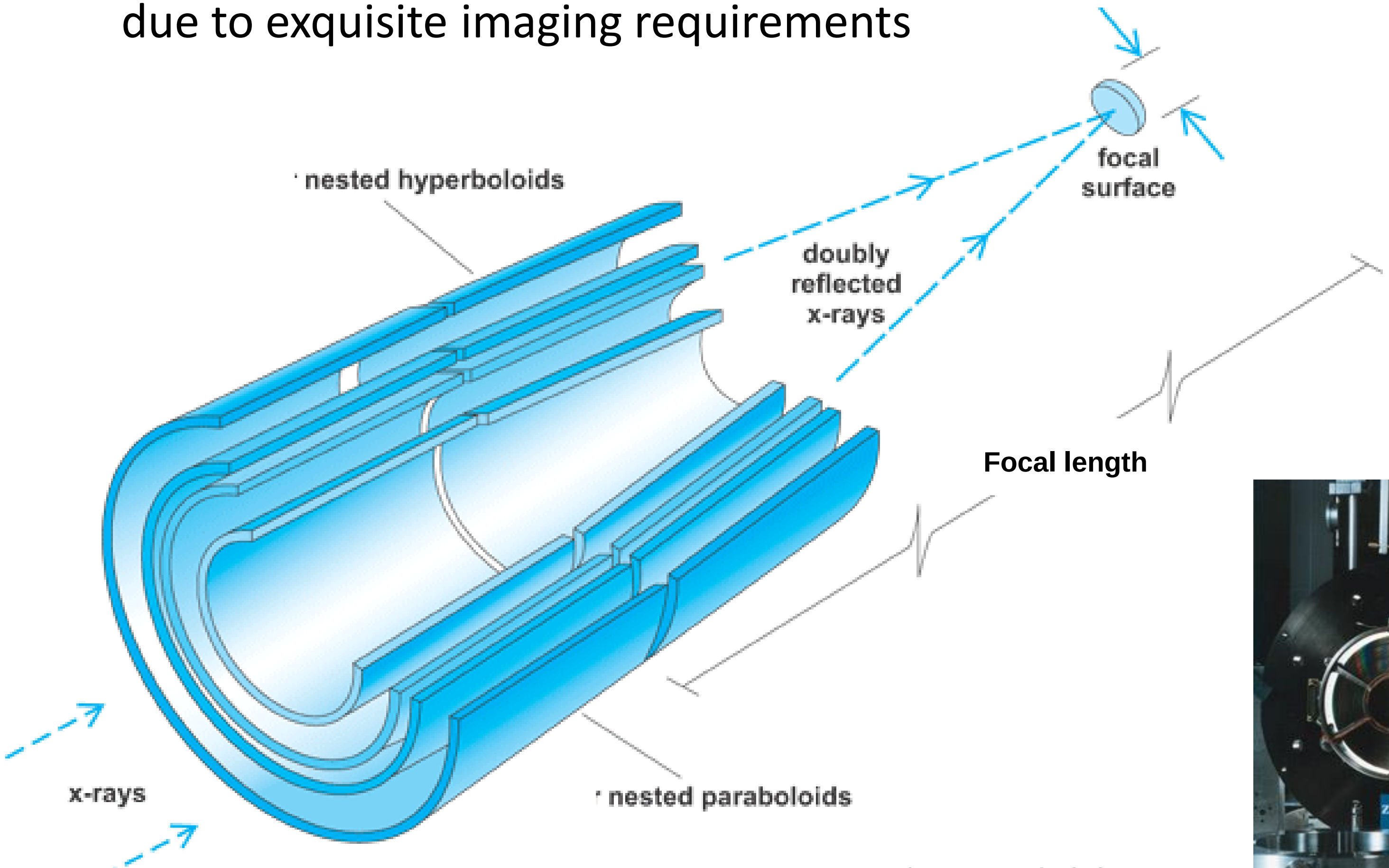


Property		*Value*
Cryostat dimensions:	Overall length (m)	25
	Outer diameter (m)	5.2
	Cryostat volume (m^3)	$\sim$ 530
Toroid size:	Inner radius, R_{in} (m)	1.0
	Outer radius, R_{out} (m)	2.0
	Inner axial length (m)	21.0
	Outer axial length (m)	21.8
Mass:	Conductor (tons)	65
	Cold Mass (tons)	130
	Cryostat (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 × 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 concept presented in:
- IEEE Trans. Appl. Supercond. 23 (ASC 2012)
- Adv. Cryo. Eng. (CEC/ICMC 2013)
- IEEE Trans. Appl. Supercond. (MT 23)

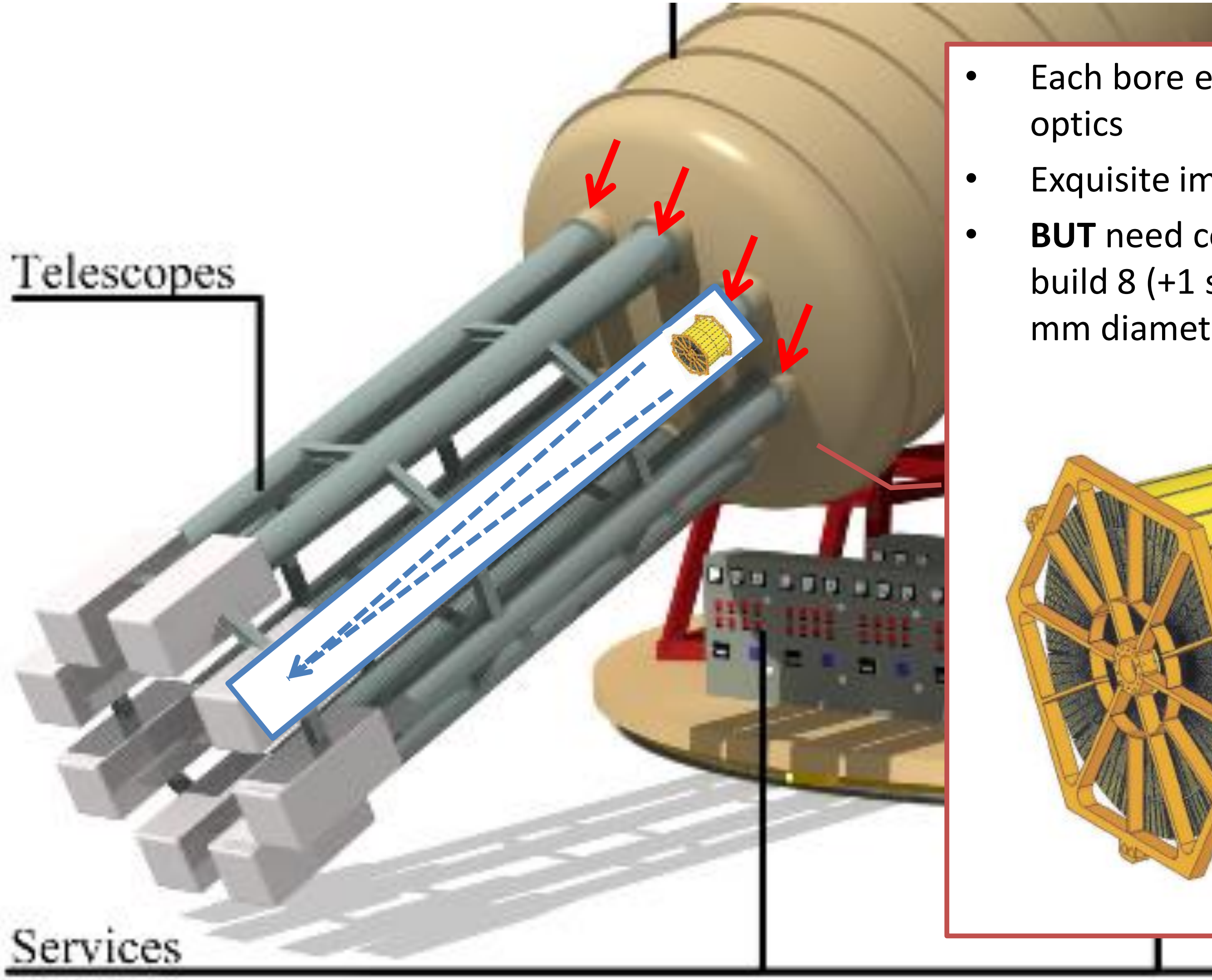
IAXO x-ray optics

- 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

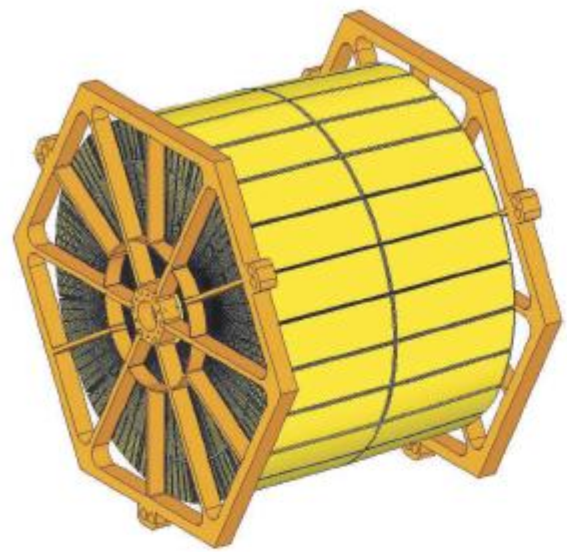


ABRIXAS spare telescope, in use in one of the 4 bores of CAST (pioneer use of x-ray optics in axion research)

IAXO x-ray optics



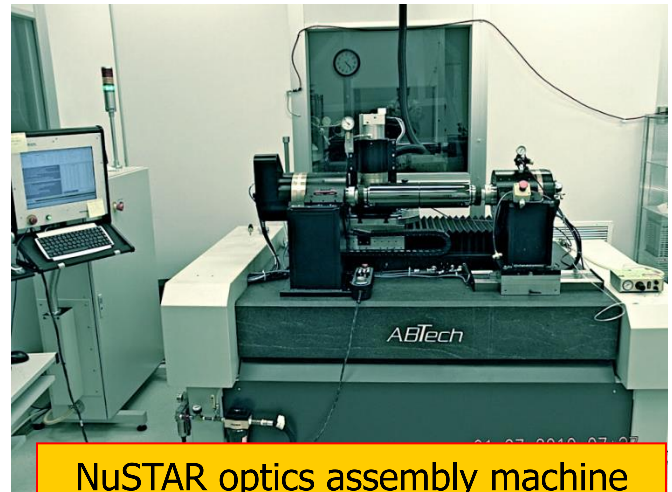
- Each bore equipped with an x-ray optics
- Exquisite imaging not required
- **BUT** need cost-effective way to build 8 (+1 spare) optics of 600 mm diameter each



IAXO x-ray optics

- Technique of choice for IAXO: optics made of thin glass substrates coated to enhance reflectivity in the energy regions for axions
- Same technique successfully used in NuSTAR mission, recently launched

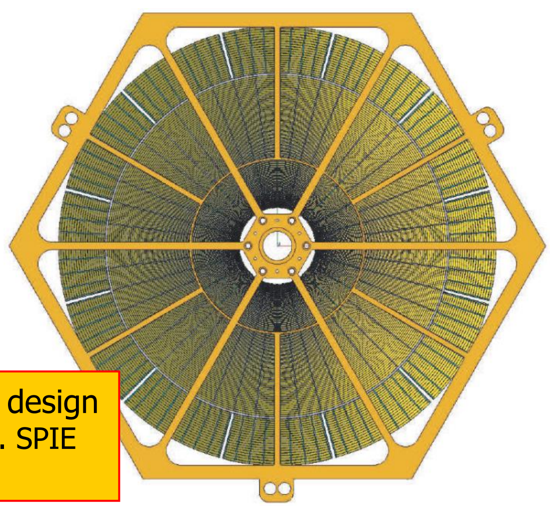
- The specialized tooling to shape the substrates and assemble the optics is now available
- Hardware can be easily configured to make optics with a variety of designs and sizes
- Key institutions in NuSTAR optics: LLNL, U. Columbia, DTU Denmark. All in IAXO !



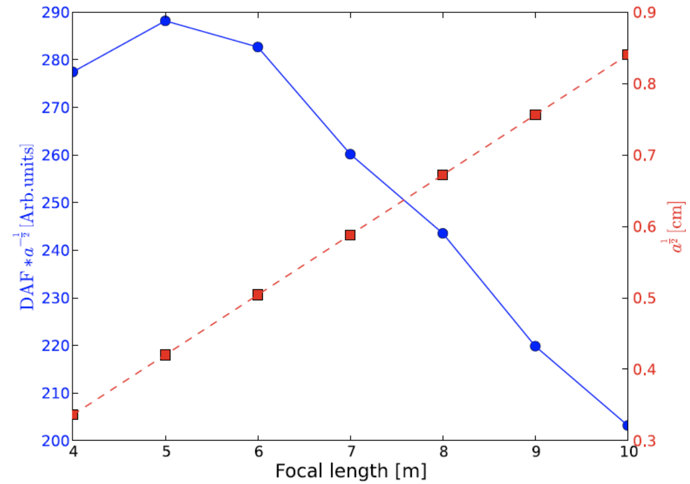
NuSTAR optics assembly machine

NuSTAR telescope
~400 cm Ø

IAXO x-ray optics



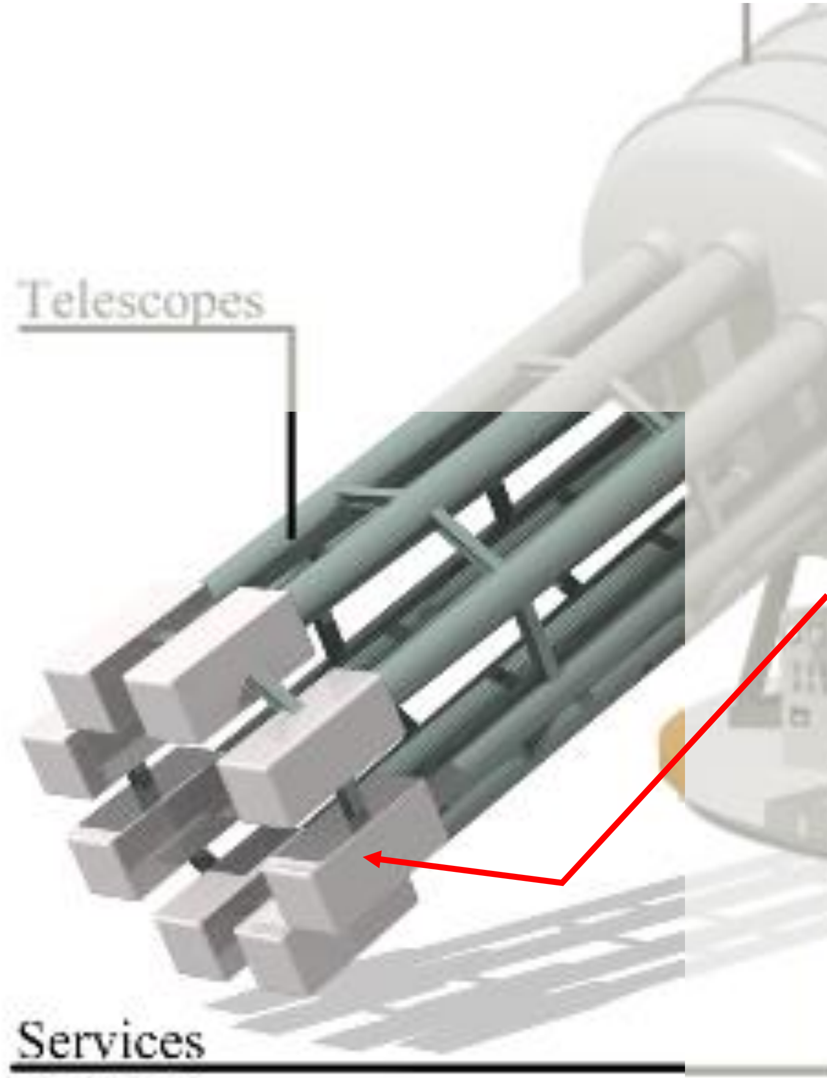
IAXO optics conceptual design
AC Jakobsen et al, Proc. SPIE 8861 (2013)



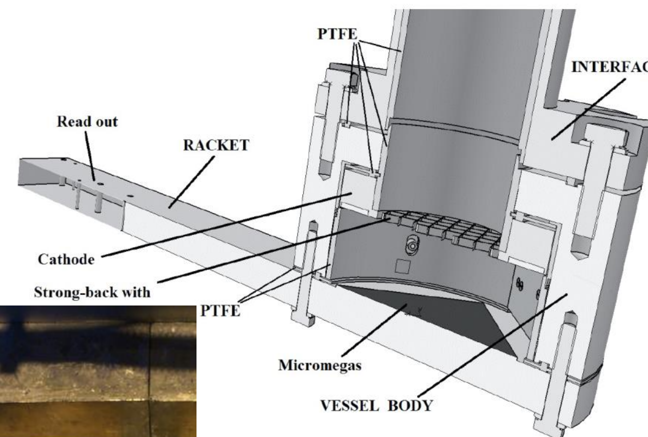
Optimal focal length ~5 m

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



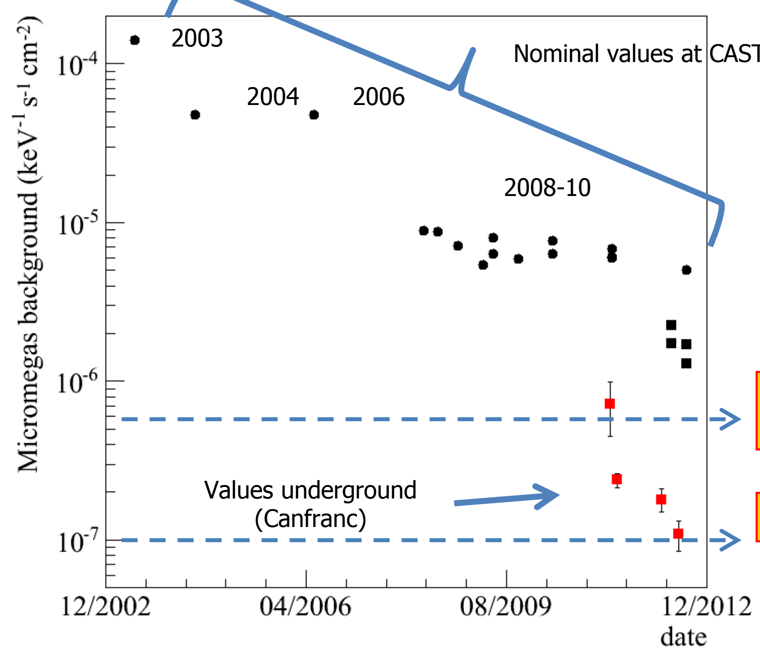
IAXO low background detectors

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

- Goal background level for IAXO:
  - **$10^{-7} – 10^{-8}$ c keV^{-1} cm^{-2} s^{-1}**
- Already demonstrated:
  - 6×10^{-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

History of background improvement of Micromegas detectors at CAST



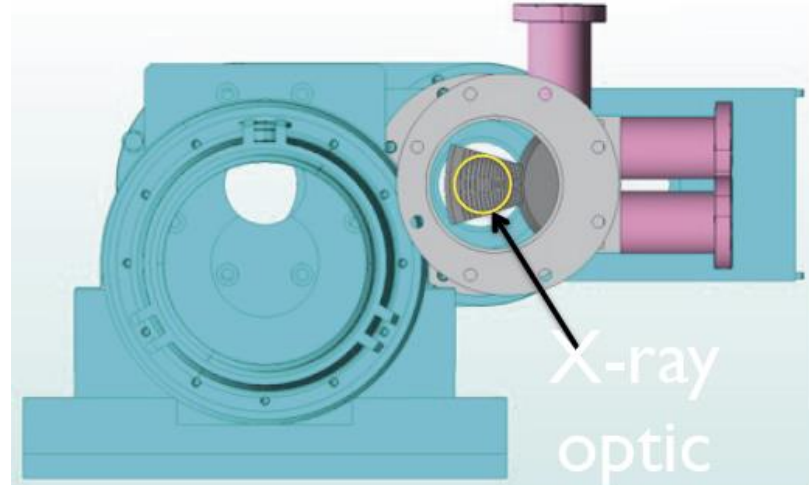
Latest CAST SSMM 2013 levels

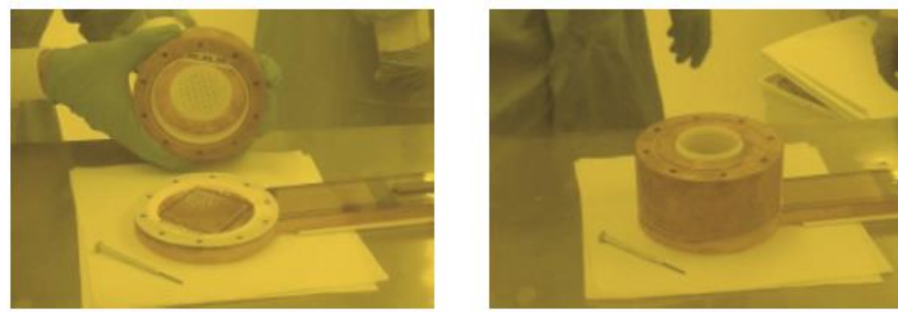
IAXO goals

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)

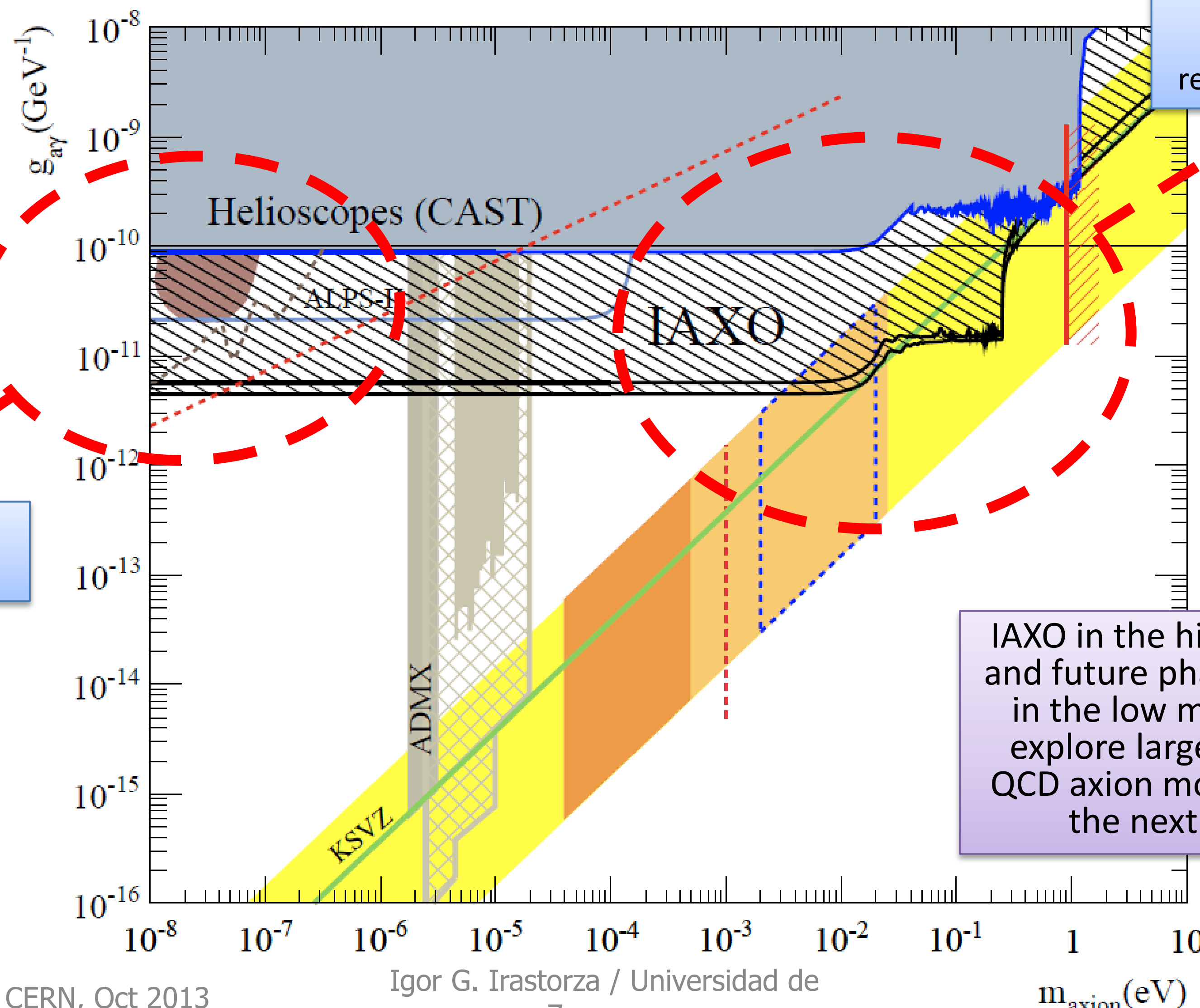
- **It will take data in CAST in 2014**
  - First time low background + focusing in the same system
  - Very important operative experience for IAXO





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

IAXO sensitivity prospects



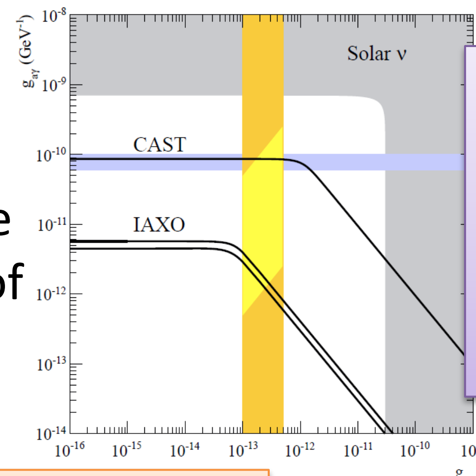
Much larger QCD axion region explored

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

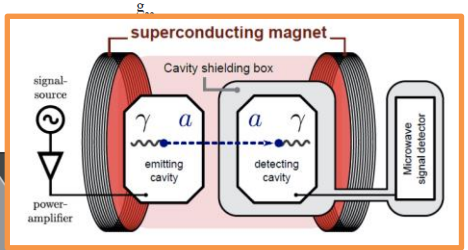
- IAXO sensitivty to BCA solar axion with values of g_{ae} of relevance
- More specific ALP or WISP (weakly interacting slim particle) models could be searched for at the **low energy frontier** of particle physics:
  - Paraphotons / hidden photons
  - Chamaleons
  - Non-standard scenarios of axion production
- 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"**

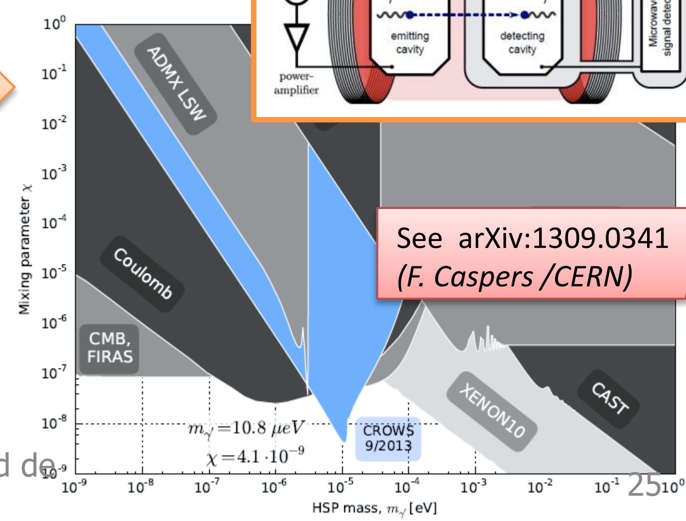


Possible additional technologies to push E thresholds down:

- GridPix
- TES
- Low-noise CCDs

See CAST talk before!



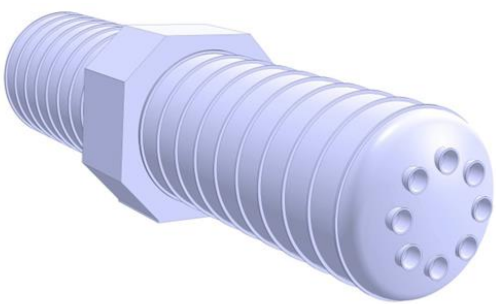


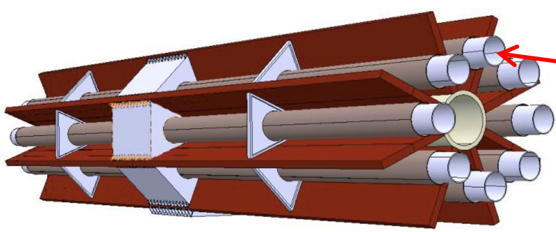
See arXiv:1309.0341 *(F. Caspers /CERN)*

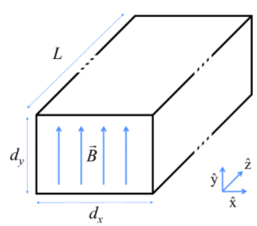
Additional IAXO physics cases

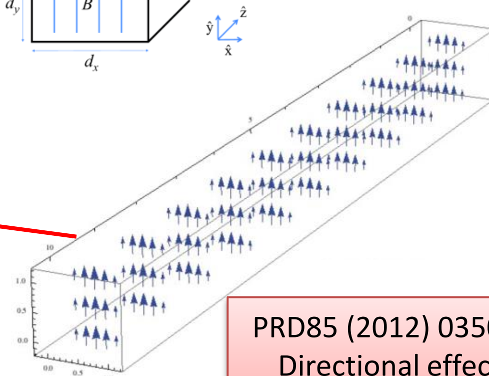
direct detection of relic axions/ALPs

- Highly motivated
- Big technical challenge, but new ideas under discussion:
- Various possible arrangements (under study)
  1. Single large cavity tuned to low masses
  2. Thin long cavities tuned to mid-high masses (directionality)
  3. Dish antenna focusing photons to the center. Not tuned. Broadband search.

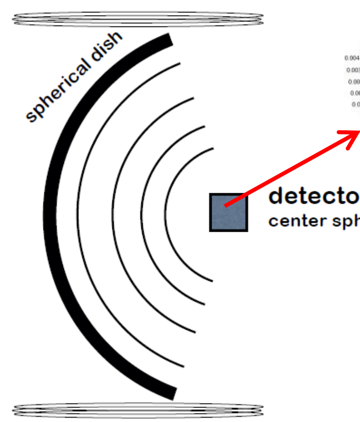


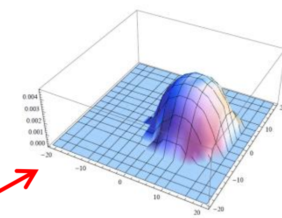






PRD85 (2012) 035018
Directional effect:
JCAP 1210 (2012) 022

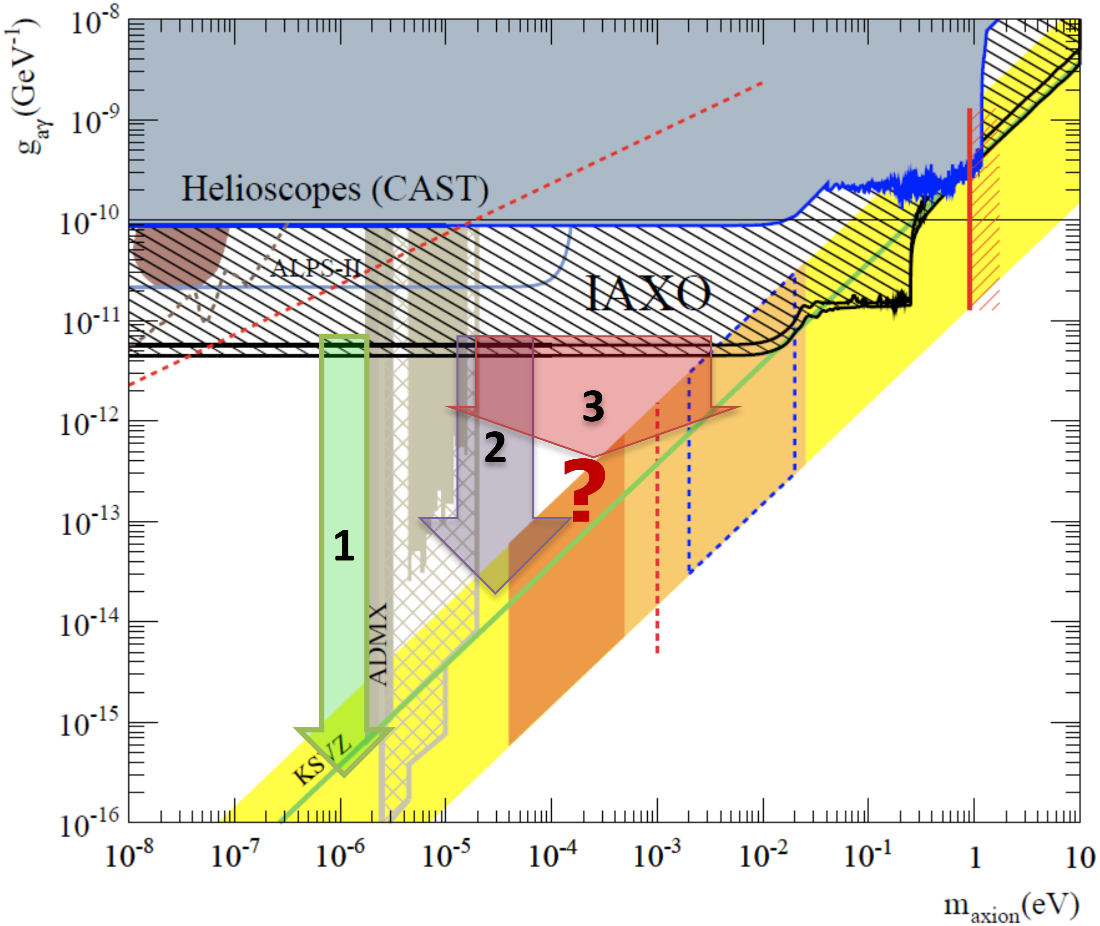




JCAP 1304 (2013) 016
Directional effect:
arXiv:1307.7181

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.

Tentative future prospects

Beyond current LoI scope

IAXO timeline

~18 months -> TDR + preparatory activities

~3.5 years construction

~2.5 years integration + commissioning

Years		1				2				3				4				5				6			
Months		3	6	9	12	15	18	21	24	27	30	33	36	39	42	45	48	51	54	57	60	63	66	69	72
Magnet																									
Design	T0	■	■																						
	T1-T8		■	■	■	■	■																		
Demo coil				■	■	■	■	■	■	■	■														
Production								■	■	■	■	■	■	■	■	■	■	■	■						
Integration														■	■	■	■	■	■	■	■				
Services														■	■	■	■	■	■	■	■				
Optics																									
Optic design study		■	■																						
Prototype construction				■	■																				
Calibration						■																			
Finalize design							■																		
Build assembly machines								■	■	■	■														
Procure mandrels & ovens								■	■	■	■														
Build coating facilities								■	■	■	■														
Slump glass												■	■	■	■	■	■	■	■	■	■				
Deposit coatings													■	■	■	■	■	■	■	■	■	■	■		
Assemble optics															■	■	■	■	■	■	■	■	■		
Calibrate optics																		■	■		■			■	
Installation																							■	■	■
Detectors																									
Prototype		■	■	■	■	■	■																		
Construction (incl. spares)								■	■	■	■	■	■	■	■	■	■	■	■						
Installation & commissioning																				■	■	■	■	■	■

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 LoI authorlist

Letter of Intent to the CERN SPSC

The International Axion Observatory
IAXO

90 signatures
38 institutions

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Expertise

Needed know-how well covered:

- Axion theory & phenomenolgy
- Axion Cosmology & Astrophysics
- Axion detection phenomenology
- X-ray detectors
- Low background techniques
- X-ray optics
- Superconducting magnets and technology

Group	(*)	Axion theory and phenomenology	Axion cosmology and astrophysics	Axion detection phenomenology	X-ray detectors	Low background techniques	X-ray optics	SC magnets and technology
South Carolina (US)	2	x		x				
CERN (Switzerland)	3			x				x
IPHT CEA/Saclay (France)	4	x	x					
IRFU CEA/Saclay (France)	1		x	x	x			x
U. Trieste (Italy)	5			x	x			
U. Zaragoza (Spain)	6			x	x	x		
LLNL (US)	7			x			x	
LBNL (US)	8			x				x
Dogus U. (Turkey)	9			x				
U. Haifa (Israel)	10		x					
DTU-Space (Denmark)	11						x	
St. Petersburg NPI (Russia)	12	x		x				
U. Bonn (Germany)	13				x			
DESY Hamburg (Germany)	14	x		x		x	x	x
U. Thessaloniki (Greece)	15			x				
RCLTMS Kyoto U. (Japan)	30			x				
NCSR Demokritos (Greece)	16			x	x			
U. Valencia (Spain)	17							
INR Moscow (Russia)	18	x		x				
Ben Gurion U. (Israel)	19	x						
Columbia Astrophysics Lab (US)	20						x	
Kyoto U. (Japan)	21	x	x					
TU-Darmstadt (Germany)	22			x	x			
ICE Barcelona (Spain)	24		x					
JAEA (Japan)	25			x				
U. Hamburg (Germany)	23		x					
U. Heidelberg (Germany)	26	x						
RBI Zagreb (Croatia)	27	x		x				
U. Tokyo (Japan)	28		x	x				
U. Rijeka (Croatia)	29			x	x			
MPI Munich (Germany)	31	x	x					
Tokyo I.T. (Japan)	32		x	x				
BNL (US)	33			x				
U. Florida (US)	34	x	x					
Berkeley (US)	35			x				x
Cape Town U. (South Africa)	36	x						
FNAL (US)	37			x	x			x
U. Patras (Greece)	38	x		x				

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 to participate in US roadmapping (Snowmass, and P5 process)
  - IAXO present e.g. in Intensity Frontier, Vistas on Axions workshop, recent Snowmass meetings,...

IAXO status of project

- Conceptual Design finished.
- Most activity carried out up to now ancillary to other group's projects (e.g. CAST)
- Some IAXO preparatory activity already going on as part of CAST near term program.
- Transition phase: In order to continue with TDR & preparatory activities, formal endorsement & resources needed.
- CERN SPSC endorsement is a very important first step.

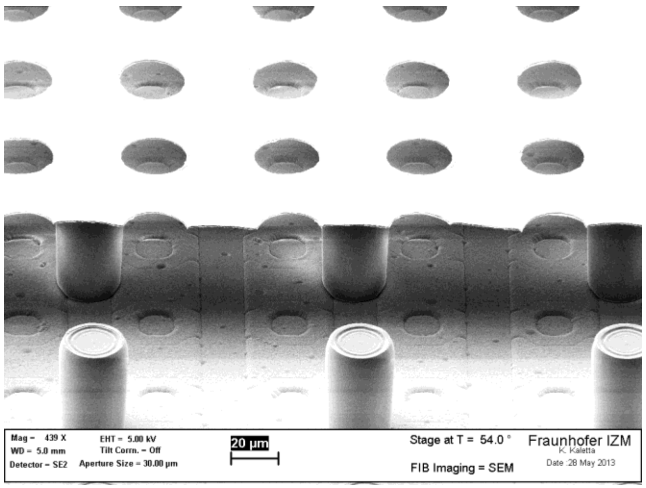
- **Requests to SPSC/CERN management**
  - Formal endorsement of project at CERN. Next steps: TDR, prototyping.
  - Local resources for magnet group & tech. coordination (Magnet TDR + T0 construction)
  - Help with project internationalization.

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 fourth generation axion helioscope**, natural and timely large-scale step to come now.
  - A great opportunity for CERN, and the axion community
- A clear high level baseline physics case. IAXO can probe deep into unexplored axion+ALP parameter space. **Discovery potential**
  - But also several additional physics cases: **IAXO as a “generic axion facility”**
  - 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
- Request CERN support to advance as quick as possible to the forthcoming steps (TDR + prototyping activities)

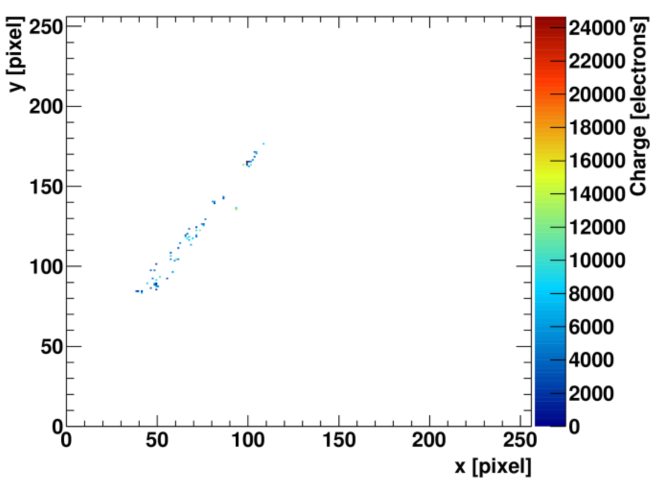
Backup slides…

InGrid Detectors

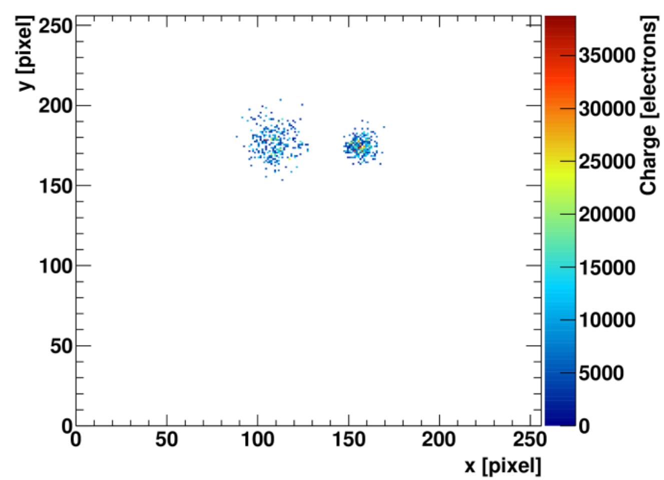


- Micromegas built on top of a CMOS ASIC
- Bump bond pads of the ASIC are used as charge collection pads
- Mesh made of thin aluminum foil
- One hole per readout pixel
  → well aligned
  → each primary electron can be seen as one hit on a pixel

Cosmic ray track



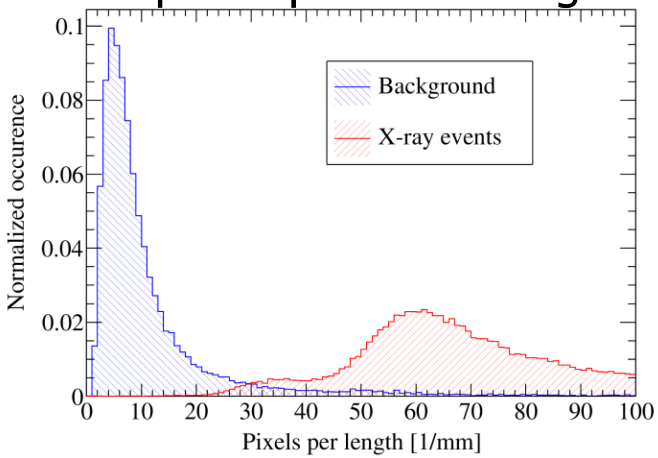
2 X-ray photons of a ^{55}Fe source



Background Suppression

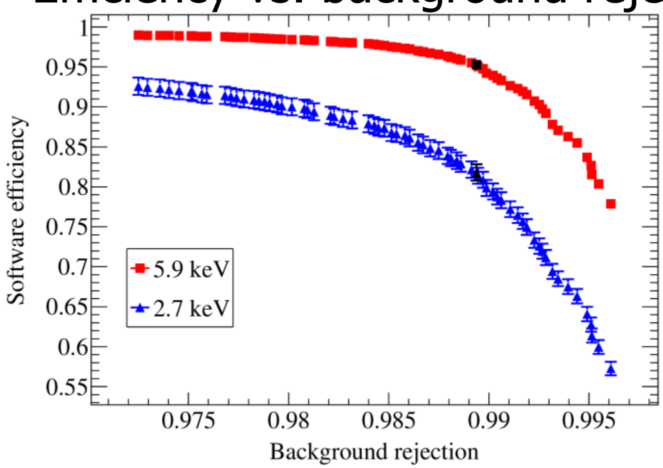
Detailed desciption in: C. Krieger, J. Kaminski and K. Desch, *InGrid-based X-ray detector for low background searches*, NIM A729 (2013) 905–909

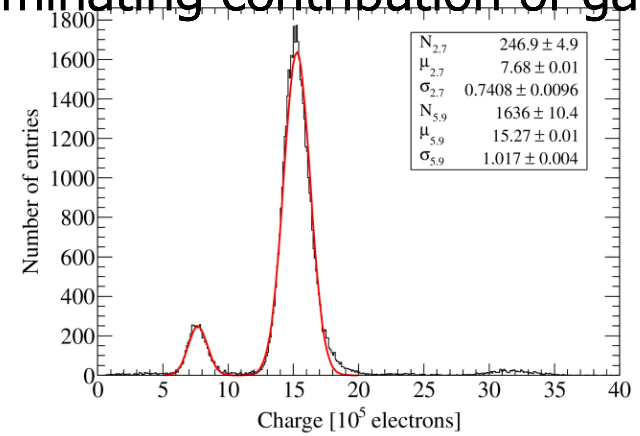
pixels per track length



- Knowledge of individual primary electrons gives detailed information on signal shape
- Different event shape variables can be used to distinguish background events (tracks) from signal events (photons)
- First likelihood ratio-based analysis reached a background suppression of 120
- Threshold of detector is dominated by transmission of entrance window
- Good energy resolution with pixel counting eliminating contribution of gas amplification

Efficiency vs. background rejection





Spectrum of a ^{55}Fe source