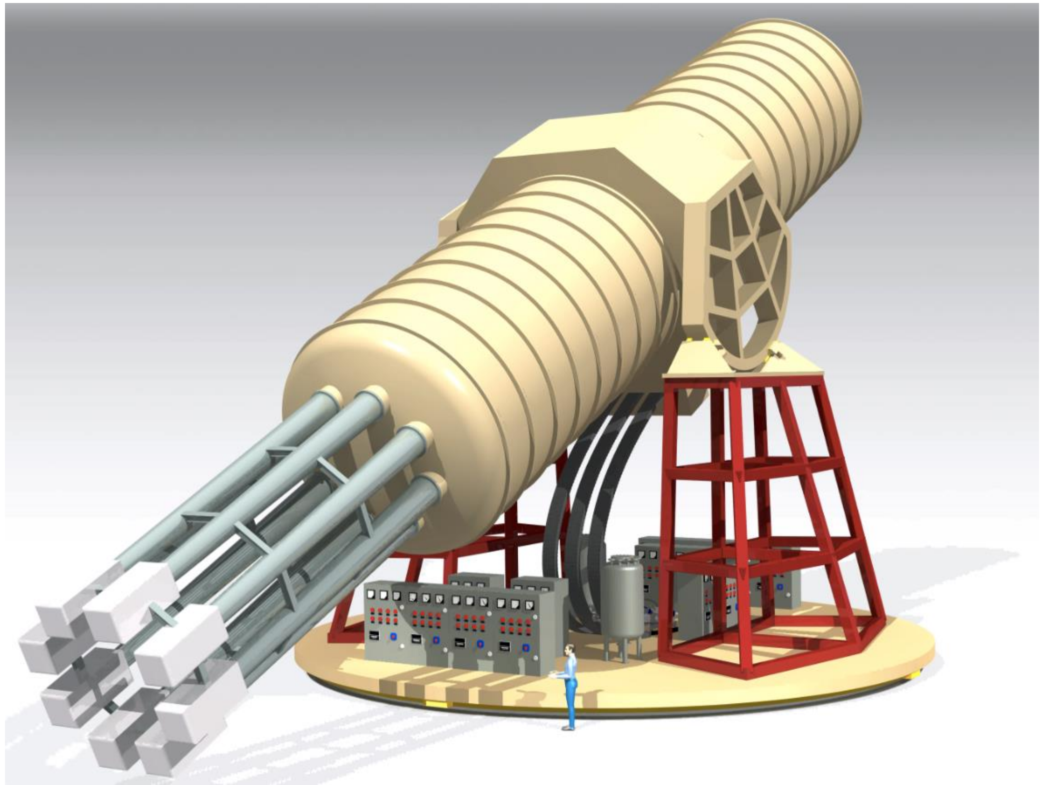
Axion search with the International Axion Observatory



Esther Ferrer Ribas

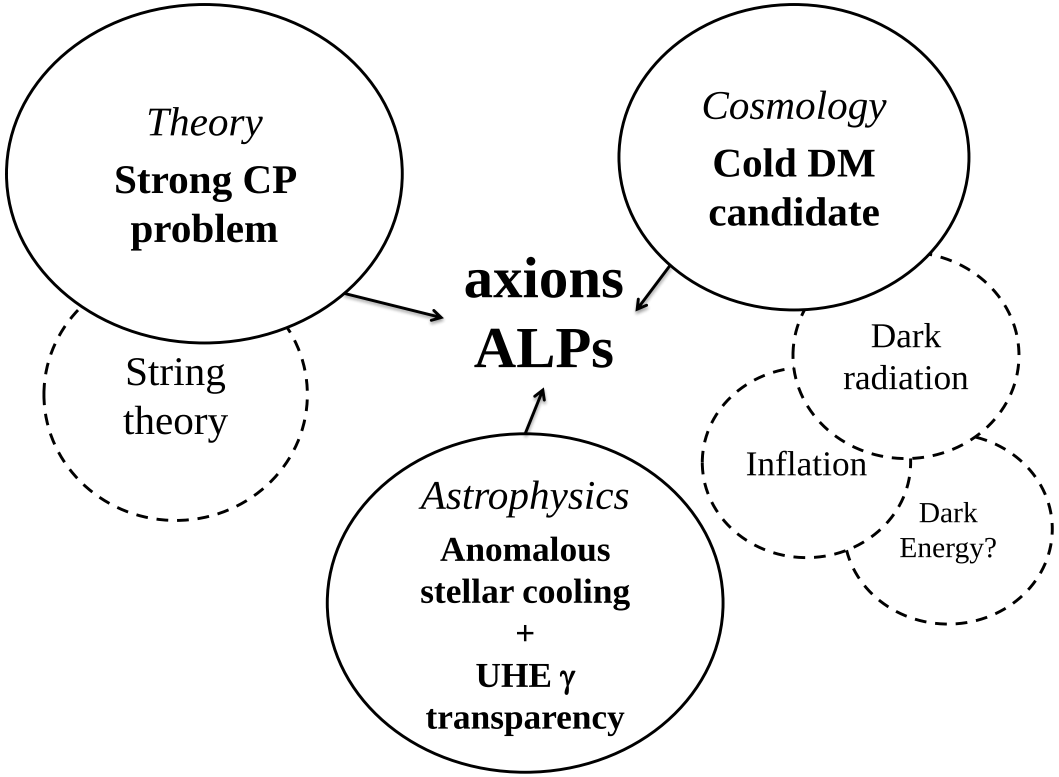
3eme Journée Matière Sombre France et Physique Souterraine,

IPNL, Lyon, 23 Novembre 2018

Irfu - CEA Saclay
Institut de recherche
sur les lois fondamentales
de l'Univers

International AXion Observatory (IAXO) motivation

- Baseline search: **solar axions**
- Why are we looking for axions?
  - Most elegant solution to explain the apparent symmetry between matter and anti-matter in the strong interactions (CP violation);
  - Predicted by SM extensions, neutral, very light, low interacting cross-section;
  - Dark matter candidates;
  - Astrophysical hints for axion/ALPs?
    - Transparency of the Universe to UHE gammas;
    - Anomalous cooling of different types of stars;
  - Relevant axion/ALP parameter space at reach of current and near-future experiments;
  - Still too little experimental effort devoted to axions when compared to WIMP.



I. G. Irastorza & J. Redondo, PNPP2018 (arXiv:1801.08127)
New experimental approaches in the search for axion-like particles

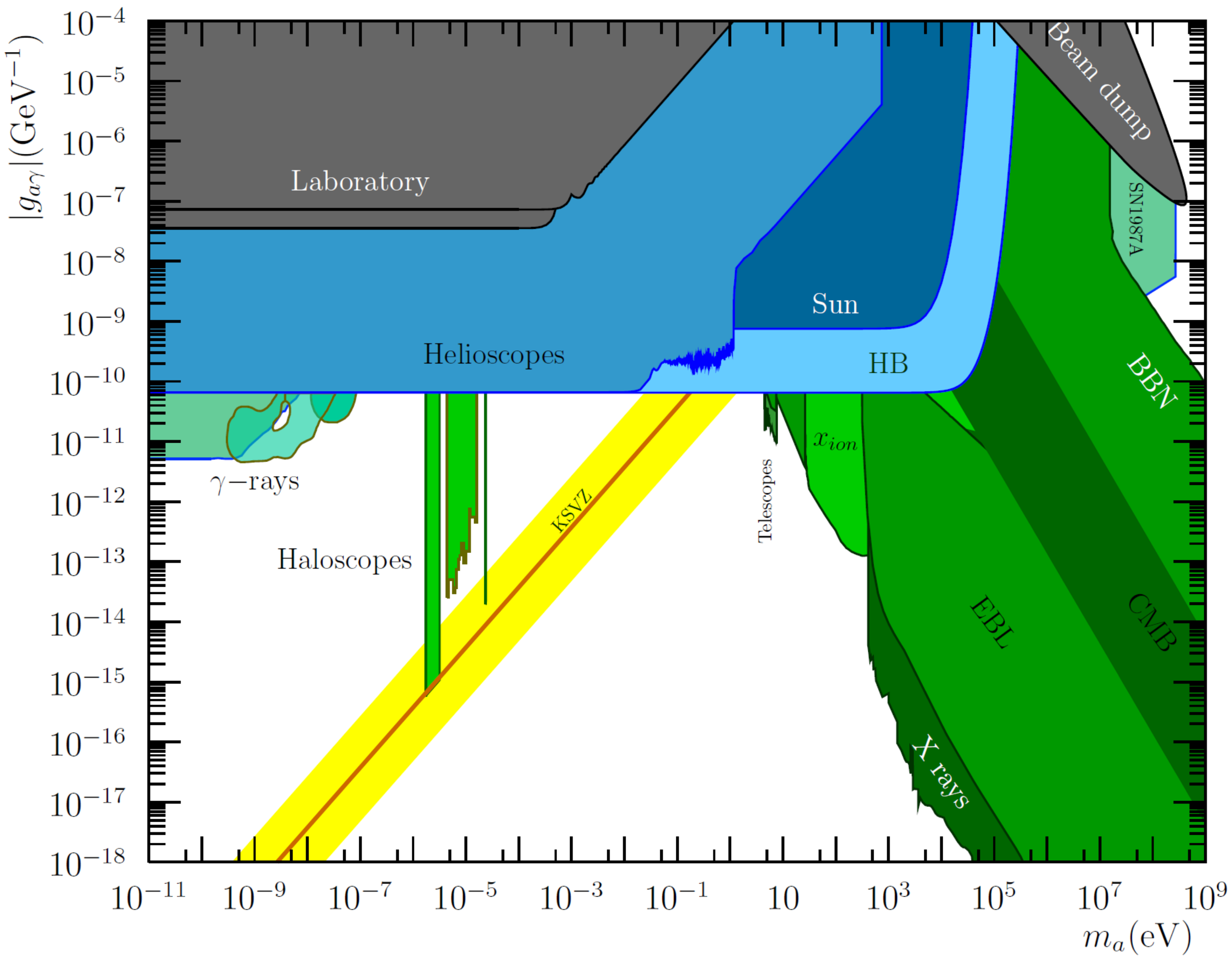
IAXO motivation

"Focuses of interest" in the ALP parameter space

Theory
Astrophysics
Cosmology

IAXO addresses partially all of them

meV+ QCD axion region exclusive target of IAXO



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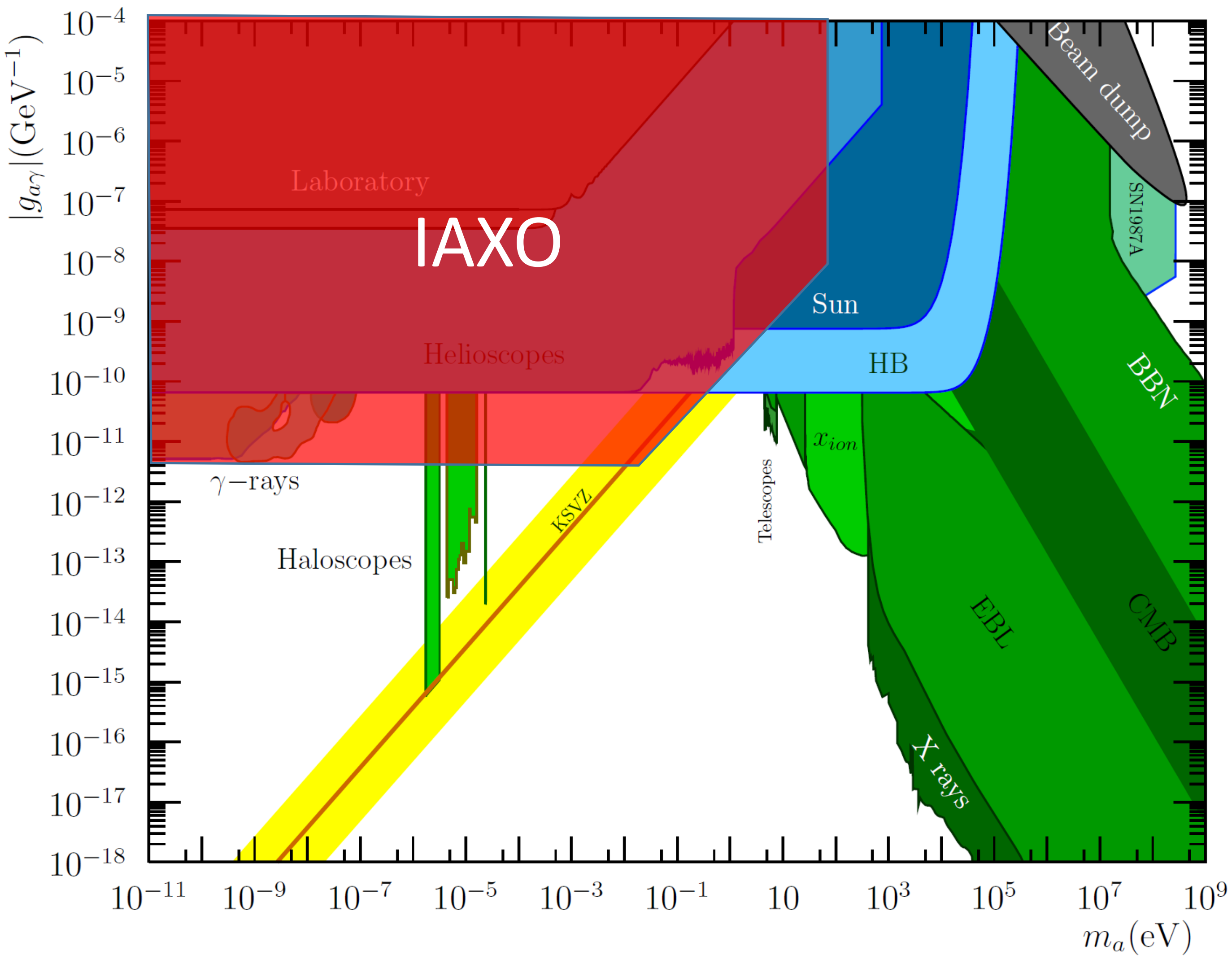
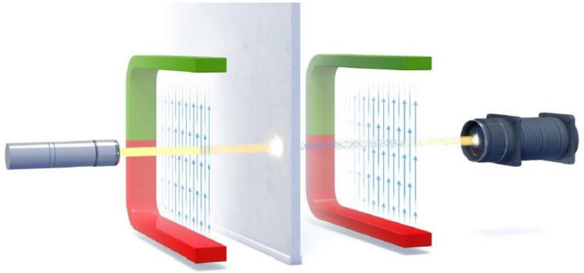


Search strategies

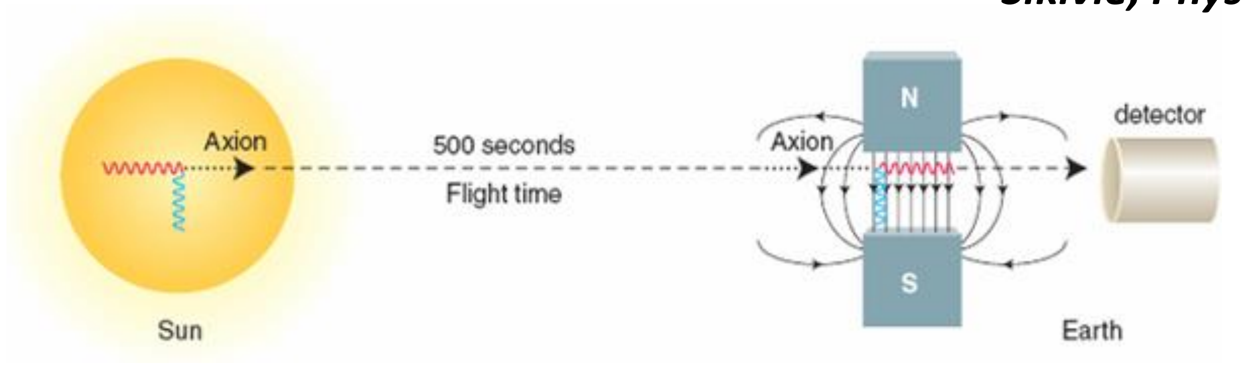
Axions couple to photons in the presence of a magnetic field in all models.

- Relic Axions
  - Axions that are part of galactic dark matter halo:
    - Axion Haloscopes **(ADMX, MADMAX…)**
- Solar Axions
  - Emitted by the solar core.
    - Axion Helioscopes **(SUMICO, CAST, Baby-IAXO, IAXO)**
- Axions in the laboratory
    - “Light shinning through wall” experiments **(ALPS, OSQAR….)**



Helioscope Physics

Sikivie, Phys. Rev. Lett 51 (1983)

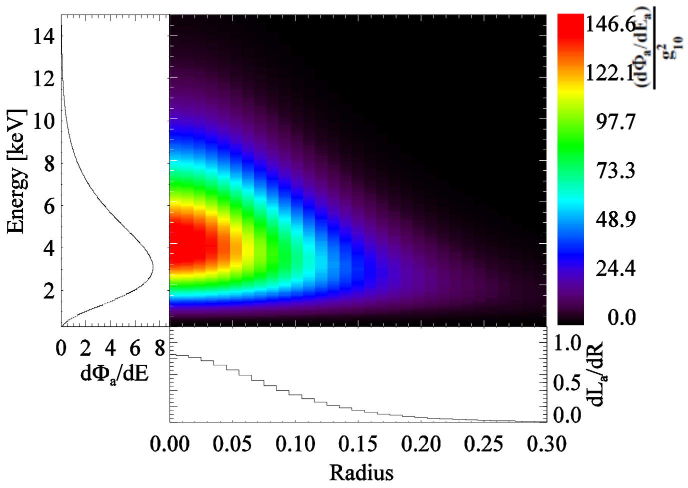


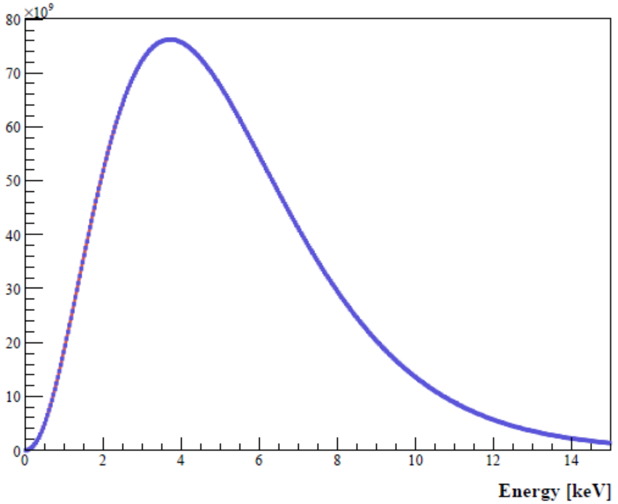
Production in the Sun

Conversion of thermal photons into axions via Primakoff effect in the solar core

Detection in the helioscope

Conversion of axions into photons via the inverse Primakoff effect in a strong magnetic field





Expected number of photons:

$$N_\gamma = \Phi_a \cdot A \cdot P_{a\rightarrow\gamma}$$

$$P_{a\rightarrow\gamma} = 1.7\times10^{-17}\left(\frac{B\cdot L}{9.0T\cdot 9.3m}\right)^2\left(\frac{g_{a\gamma}}{10^{-10}\,GeV^{-1}}\right)^2$$

$\approx$ 0.3 evts/hour

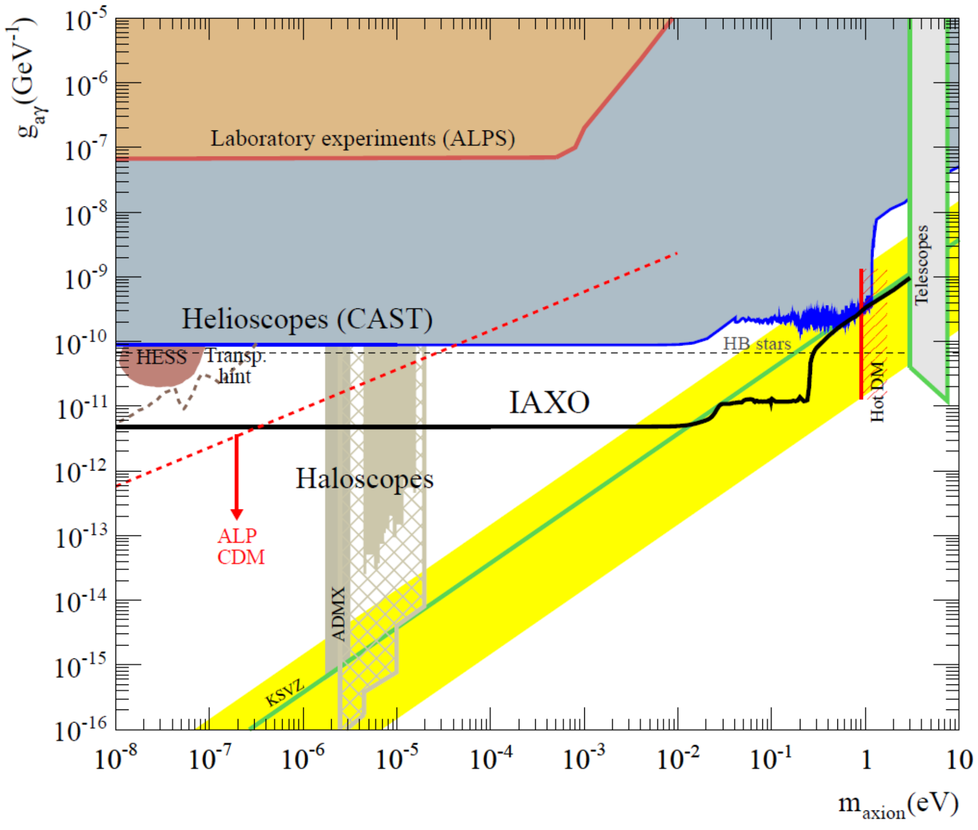
with $g_{a\gamma} = 10^{-10}$ GeV^{-1} and A = 14 cm^2

CAST: CERN Axion Solar Telescope

LHC dipôle : L = 9 m, B = 9 T

Rotating platform to follow the sun

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 hot dark matter limit
2012	•Revisit 4He Run with improved detectors
2013-2015	•Revisit vacuum phase with improved detectors •**Final QCD axion results**



The axion has not been observed➔ limit on the coupling constant

Best world-wide limit for a wide range of masses

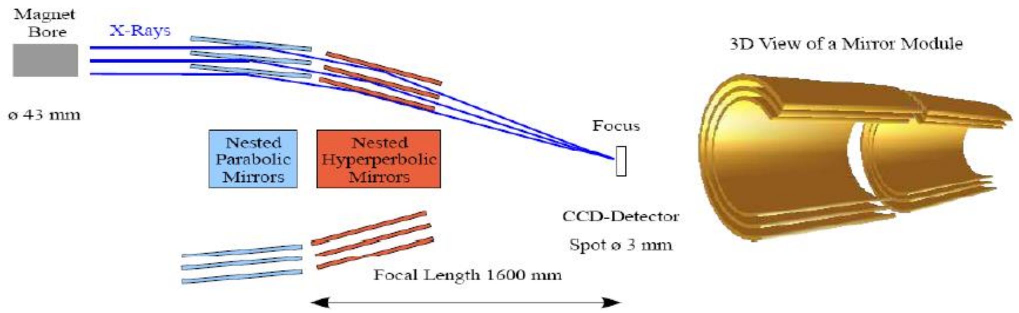
CAST Coll., JCAP 0704(2007) 010, CAST Coll., PRL (2005) 94, 121301

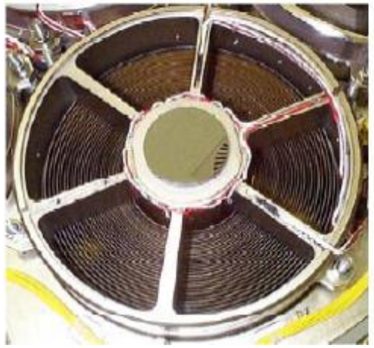
CAST Coll., JCAP 0902 (2009) 008, CAST Coll, PRL (2011) 107 261302

CAST Coll., Phys. Rev. D92 (2015) no2, 021101CAST Coll, Nature Physics (2017) doi:10.1038/nphys4109

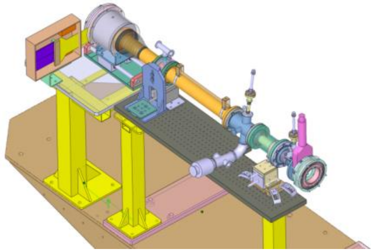
Originalities of CAST

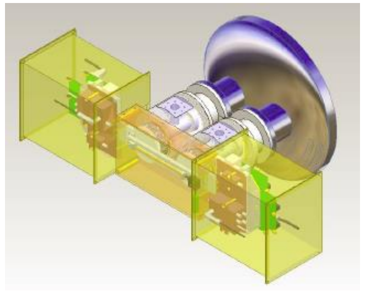
- Use of X-ray telescope ➔ increase S/B noise➔ sensitivity improved by a factor 150 by focusing a ø43 mm x-ray beam to ø3mm

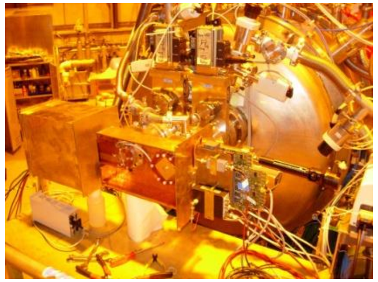




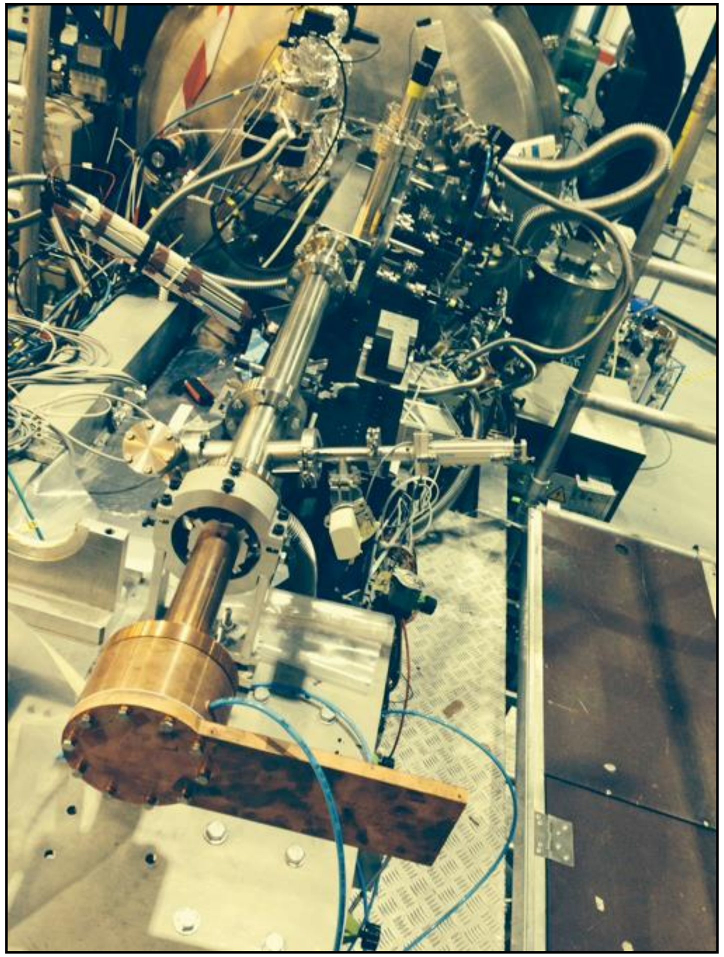
- Low background techniques➔ shieldings, low radioactive materials, simulation and modeling of backgrounds….







CAST Coll, Nature Physics (2017)



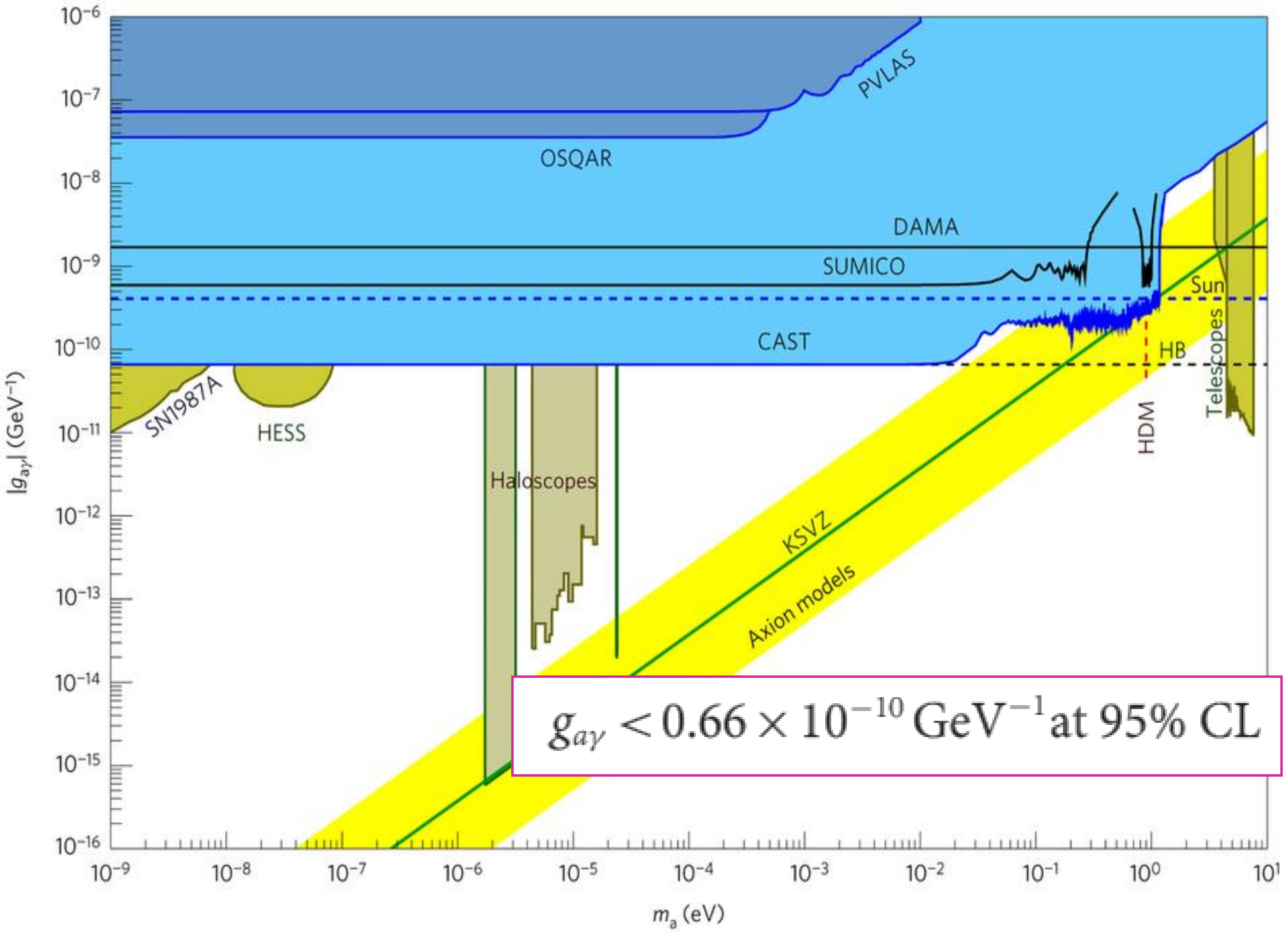
IAXO pathfinder system at CAST:
x-ray focusing + low background detector combined in same system
Small-scale version of IAXO baseline detection lines

nature physics
ARTICLES
PUBLISHED ONLINE: 1 MAY 2017 | DOI: 10.1038/NPHYS4109
OPEN

New CAST limit on the axion–photon interaction

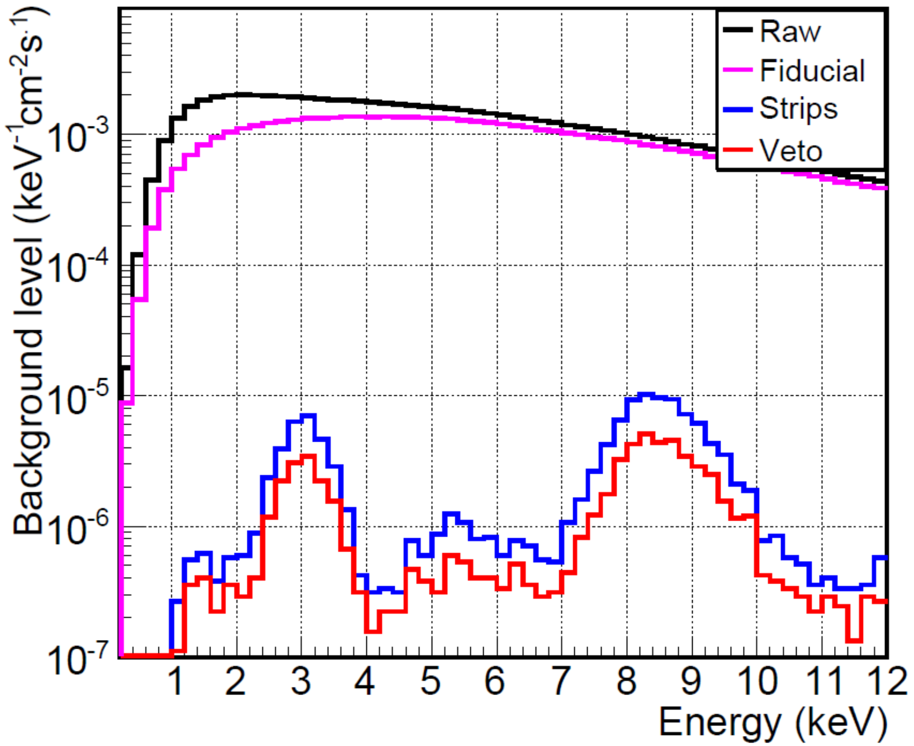
CAST Collaboration†

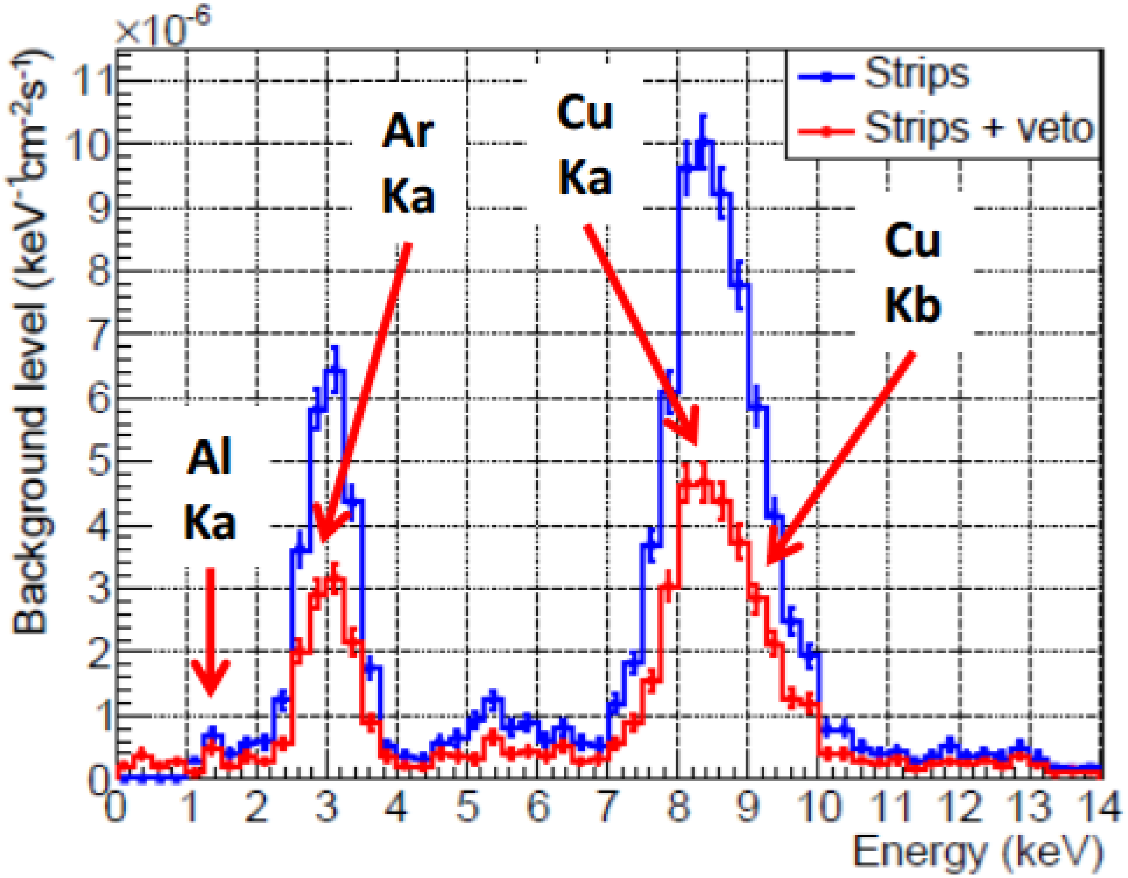
Hypothetical low-mass particles, such as axions, provide a compelling explanation for the dark matter in the universe. Such particles are expected to emerge abundantly from the hot interior of stars. To test this prediction, the CERN Axion Solar Telescope (CAST) uses a 9 T refurbished Large Hadron Collider test magnet directed towards the Sun. In the strong magnetic field, solar axions can be converted to X-ray photons which can be recorded by X-ray detectors. In the 2013–2015 run, thanks to low-background detectors and a new X-ray telescope, the signal-to-noise ratio was increased by about a factor of three. Here, we report the best limit on the axion–photon coupling strength (0.66 x 10^{-10} GeV^{-1} at 95% confidence level) set by CAST, which now reaches similar levels to the most restrictive astrophysical bounds.



$$g_{a\gamma} < 0.66 \times 10^{-10}\,\mathrm{GeV}^{-1} \text{at 95\% CL}$$

IAXO pathfinder system in CAST



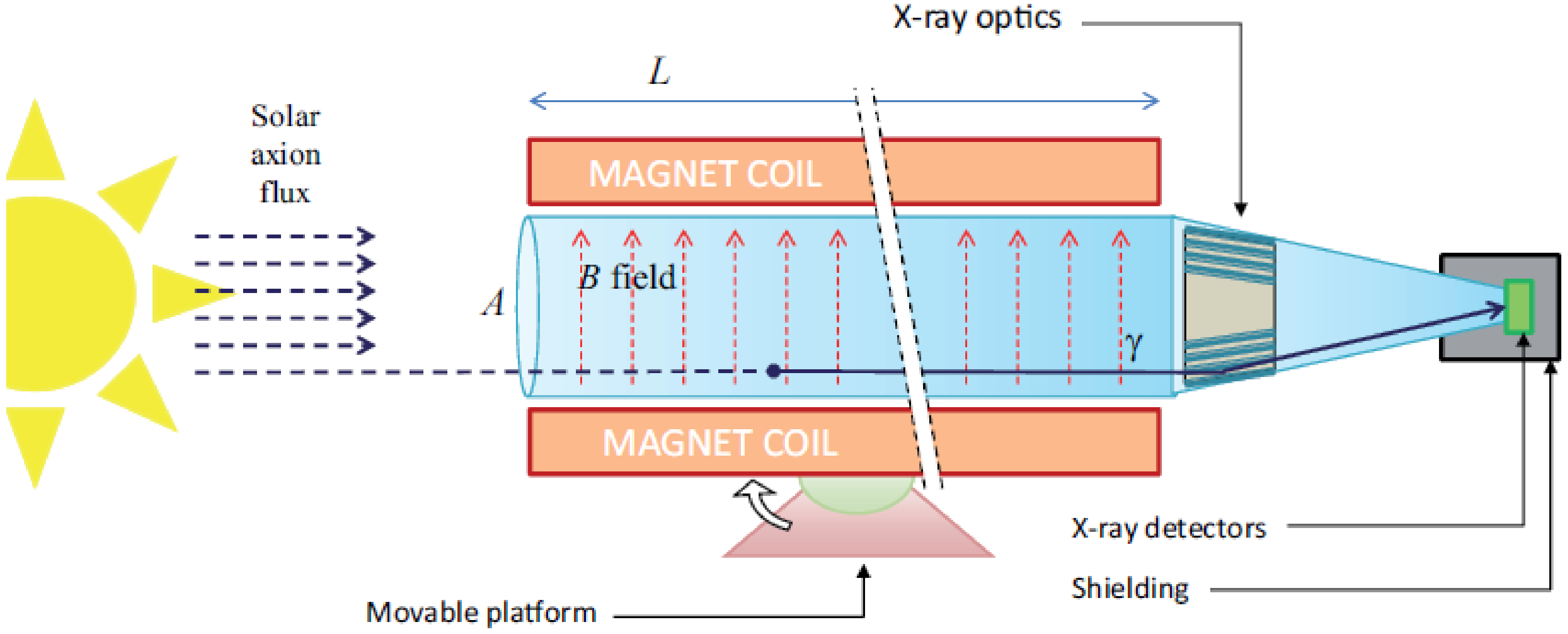


Use of shieldings
Passive and active vetos
archeological lead, inner Cu, N_2 flushing

Offline discrimination + Background simulation

Best SNR of any previous detector
290 tracking hour acquired (6.5 months operation)

IAXO concept



Goal: in terms of signal to background ratio 4-5 orders of magnitude more sensitive than CAST, which means sensitivity to axion-photon couplings down to a few $\times 10^{-12}$ GeV^{-1}

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

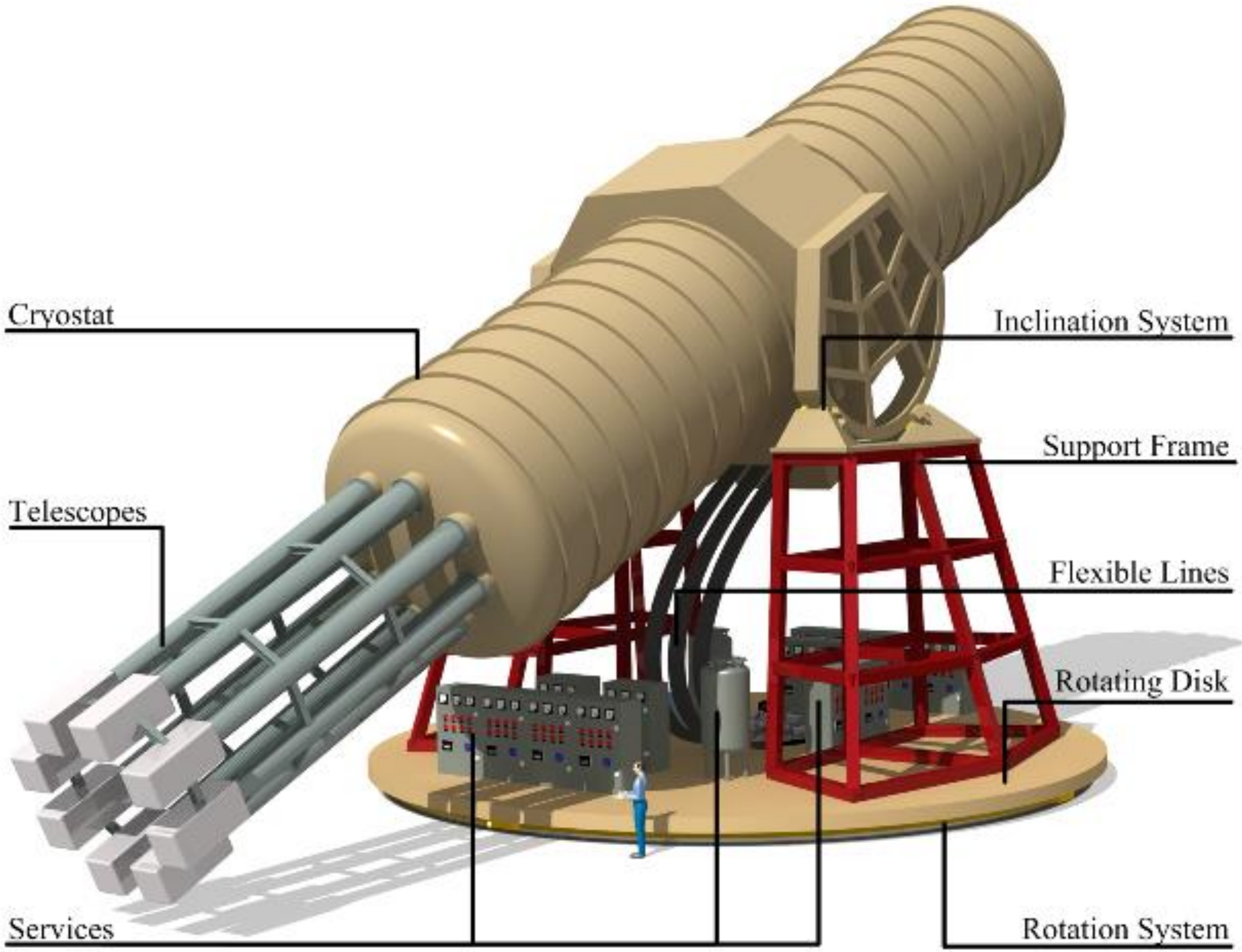
No technology challenge (built on CAST experience)

- ✓New dedicated superconducting magnet
- ✓Use of X-ray focalisation over ~m^2 area
- ✓Low background detectors (improve bck by 1-2 orders of magnitude)

IAXO Conceptual Design

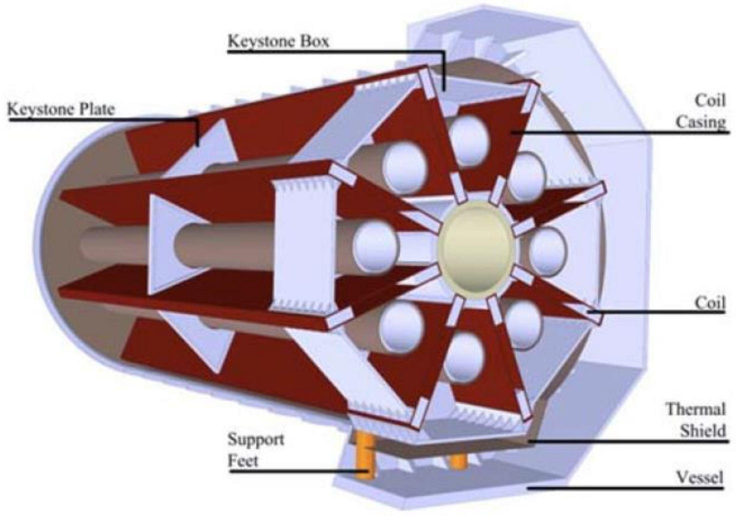
- Large toroidal 8-coil magnet *L* = ~20 m
- 8 bores: 600 mm diameter each
- 8 x-ray telescopes + 8 detection systems
- Rotating platform with services

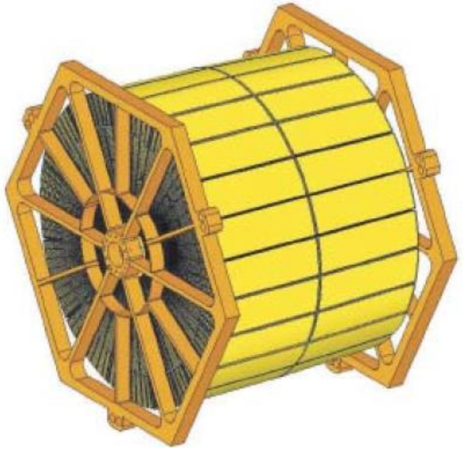
I. Irastorza et al., JCAP 06 (2011) 013
E. Armengaud et al., JINST 9 (2014) T05002



IAXO magnet and optics

Baseline : Use approach NASA's NUSTAR satellite





Optimised configuration: TOROIDAL with 8 bores
20 m long, 5 m diameter and a peak field of 5.4 T

Shilon et al. IEEE T. Ap. SupCond 23:4500604 (2013)
Shilon et al. AIP Conf. Proc. 1573:1574 (2014)
Shilon et al. IEEE T. Ap. SupCond 24:4500104 (2014)

Each bore equipped with an X-ray optics
8 systems of 600 mm diameter each

Specifications:

- Refined imaging not needed
- Need to cover large area (cost-effective)
- Good throughput (0.3-0.5)
- Small focal point (~1 cm^2)

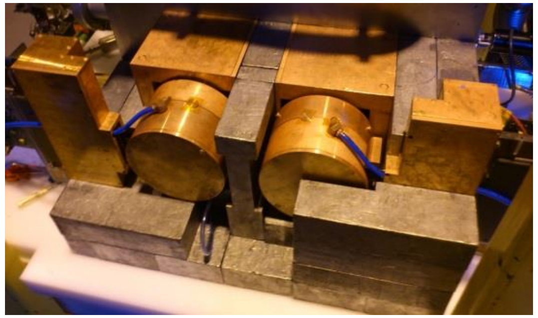
Jakobsen et al. Proc SPIE 8861:886113 (2013)

IAXO low background detectors

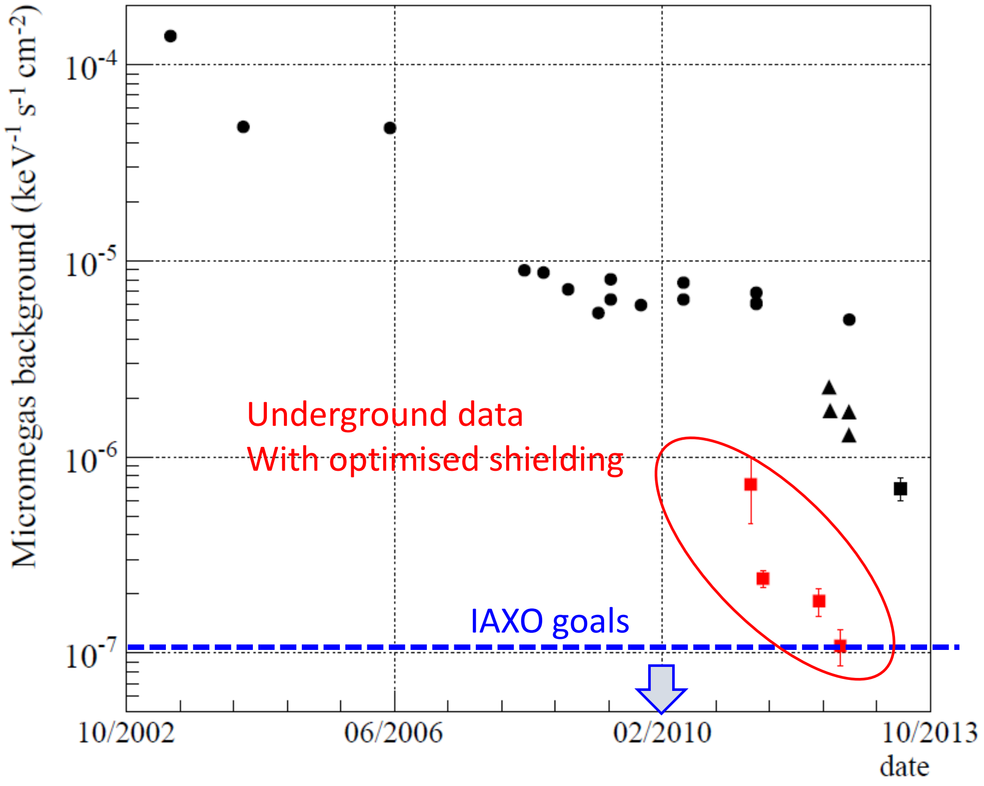
Baseline: Micromegas detectors

Goal: below 10^{-7} c/keV/s/cm^2

Key elements:
•Radiopure components
•Shielding
•Offline discrimination



IAXO Pathfinder system at CAST 2014-2015:
last generation of Microbulk detectors + optimised shielding + Xray telescope IAXO pathfinder ➔ CASTMM 2014 : 0.85 x 10^{-6} c/keV/s/cm^2



S. Aune et al., JINST 9 (2014) 9 P01001
F. Aznar et al., JCAP 12 (2015) 9 008

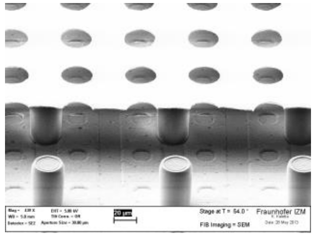
Additional X-ray detectors

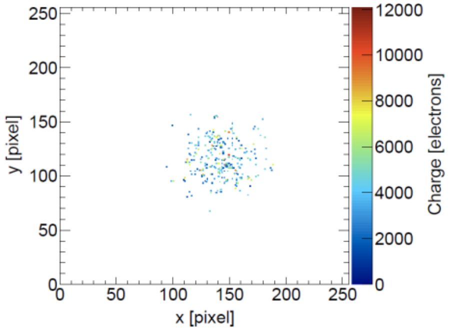
GridPix detectors (U. Bonn):

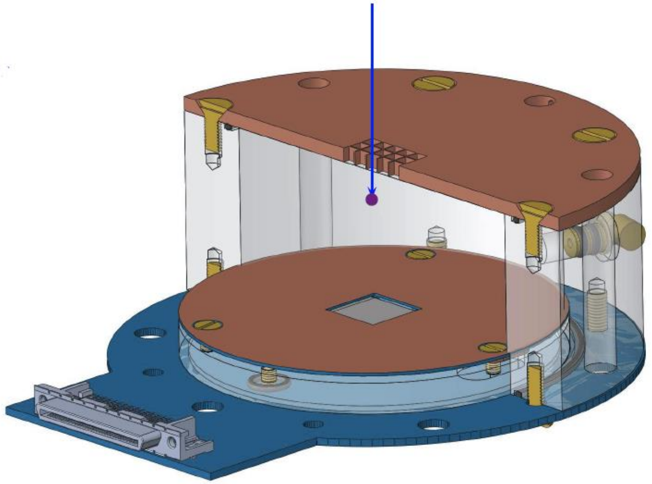
- Micromegas on top of a CMOS chip (Timepix)
- Very low threshold (tens of eV)
- Tested in CAST

C. Krieger et al. Nucl.Instrum.Meth. A867 (2017) 101-107

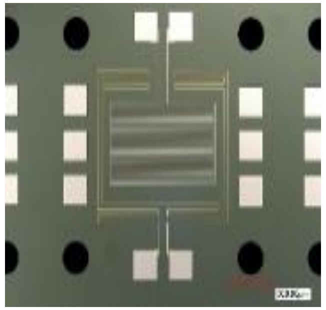
C. Krieger et al. Nucl.Instrum.Meth. A893 (2018) 26-34



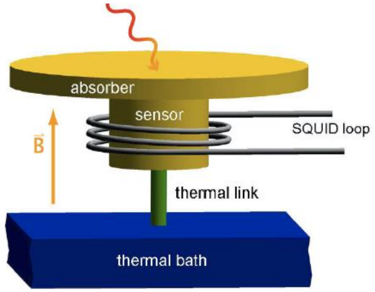




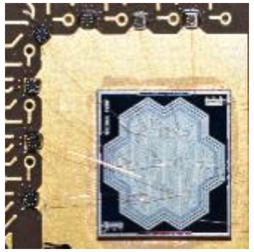
TES



MMC



SDD

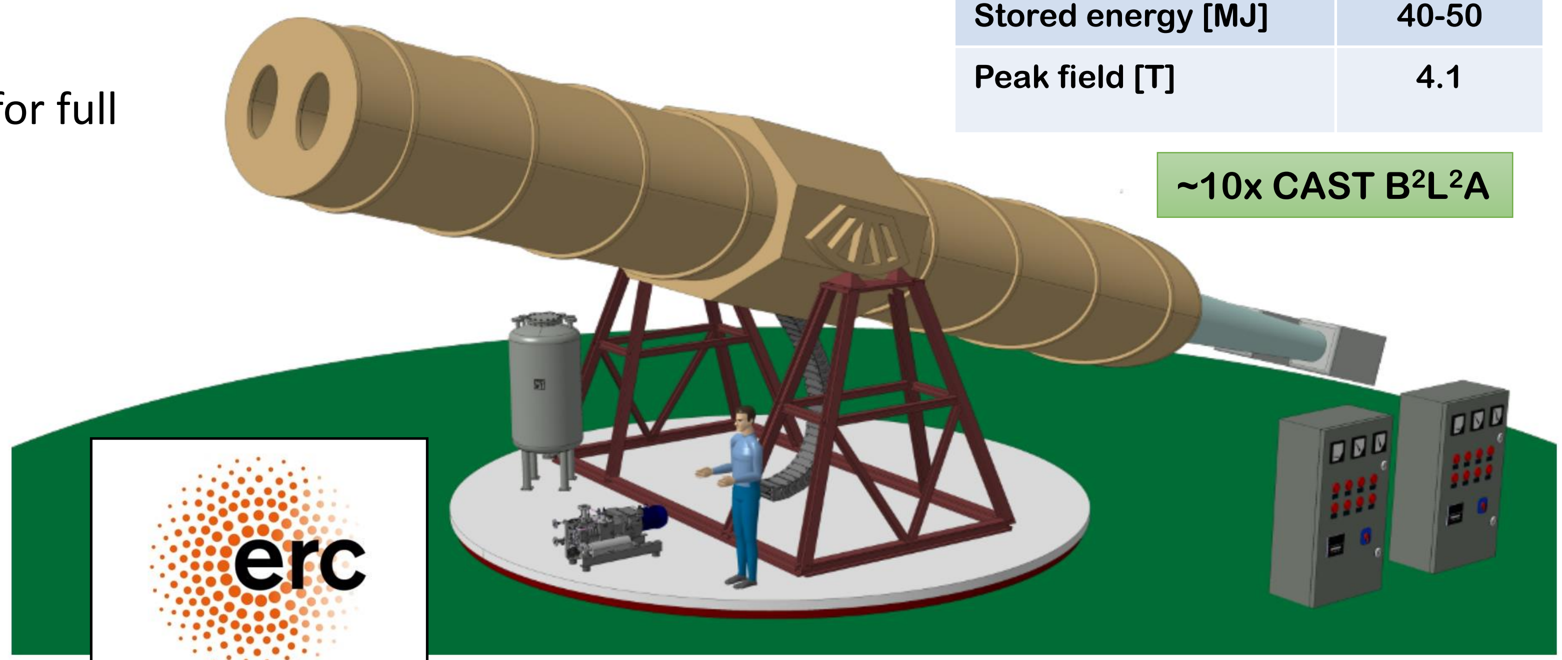


BabyIAXO

- Intermediate experimental stage before IAXO
- Two bores of dimensions similar to final IAXO bores → detection lines representative of final ones.
- Test & improve all systems. Risk mitigation for full IAXO
- Will produce relevant physics
- Move earlier to "experiment mode"
- Magnet Technical Design ongoing at CERN

Free bore [m]	2 x 0.7
Magnetic length [m]	10
Field in bore [T]	~2-3
Stored energy [MJ]	40-50
Peak field [T]	4.1

~10x CAST B^2L^2A

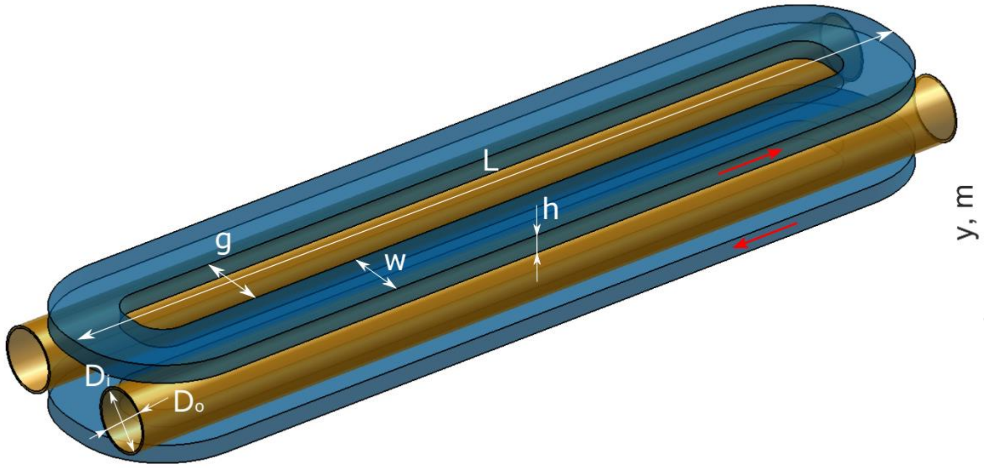


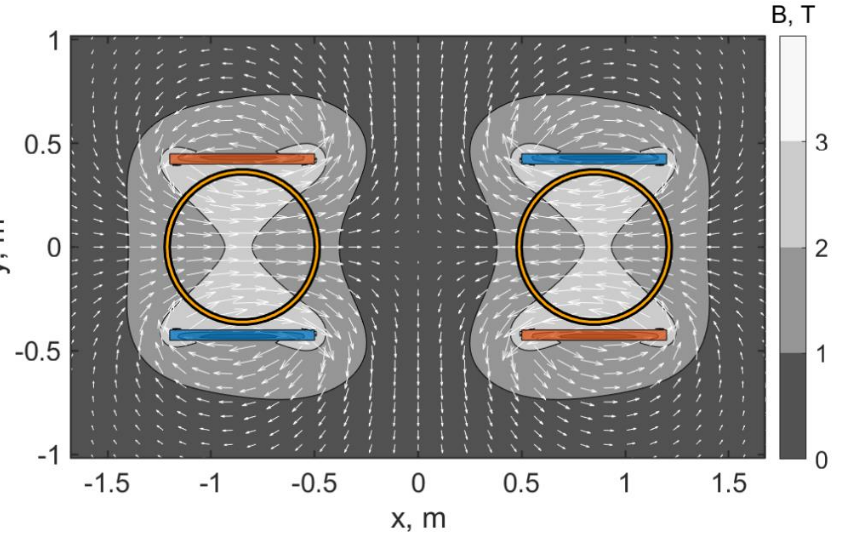
European Research Council
Established by the European Commission

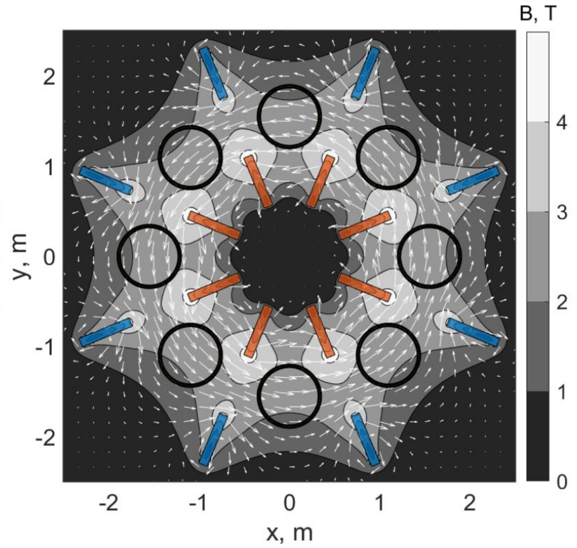
ERC-AvG 2017 IAXO+

BabyIAXO magnet

- “Common coil” configuration chosen
  - Minimal construction risk: move to construction asap
  - Cost-effective: Best use of existing infrastructure (tooling) at CERN
  - Winding layout very close to current IAXO toroidal design.



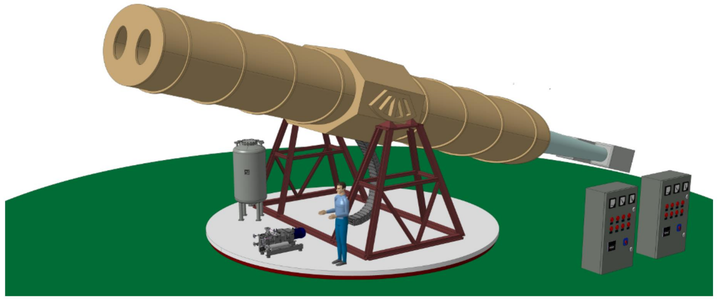




BabyIAXO optics & detectors

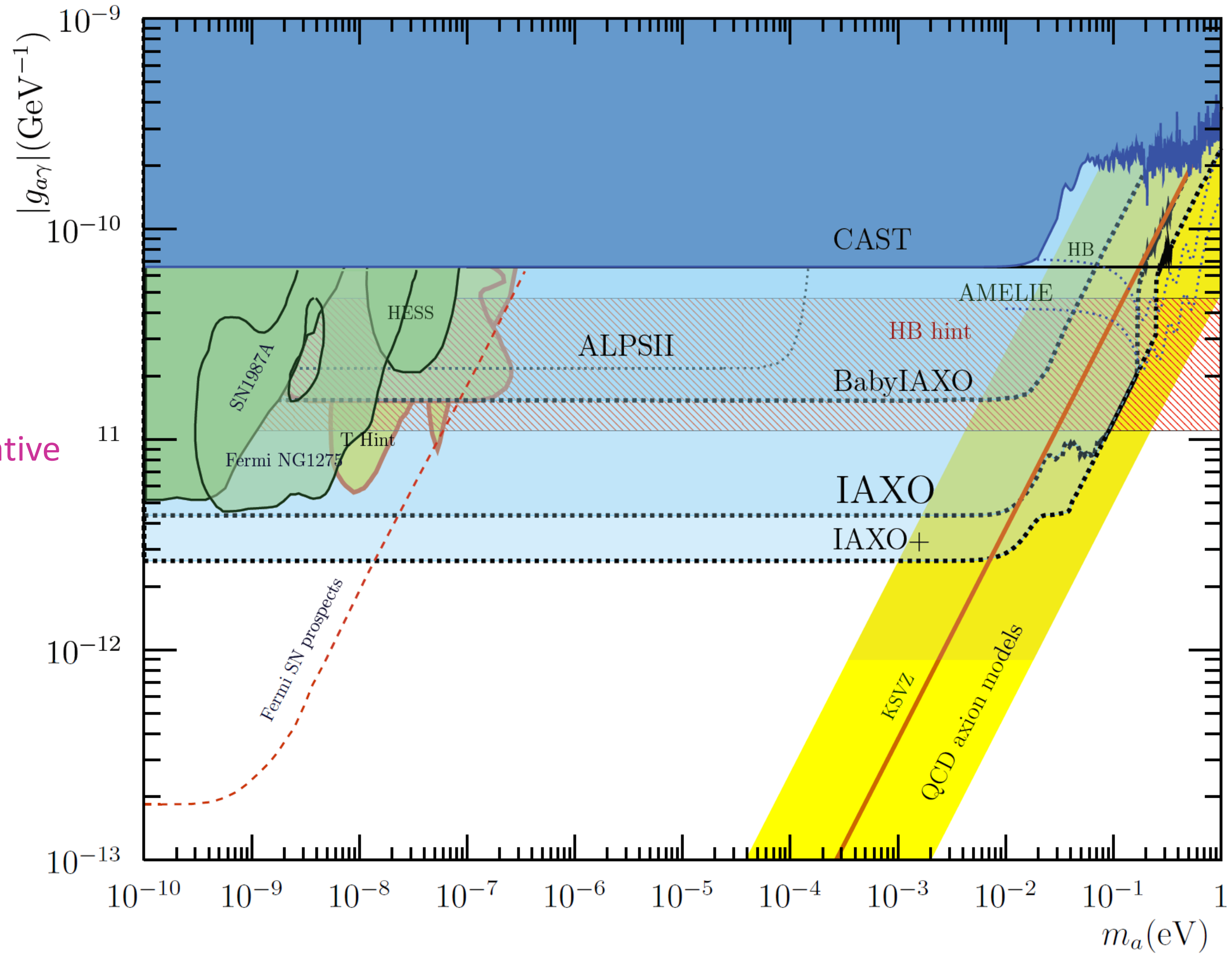
- Optics:
  - Baseline option: Segmented-glass and flight spare XMM optics from ESA
  - Minimal risk to the project
    - Risk reduction for final IAXO segmented-glass optics
    - XMM optics specs very close to IAXO optics design

- Detectors:
  - Baseline option: 2 Micromegas setups
  - In addition: a R&D generic platform to improve and tests all other detection technologies



BabyIAXO & IAXO physics reach

BabyIAXO prospects: 10xMFOM + optics and detector from conservative scenario of LoI

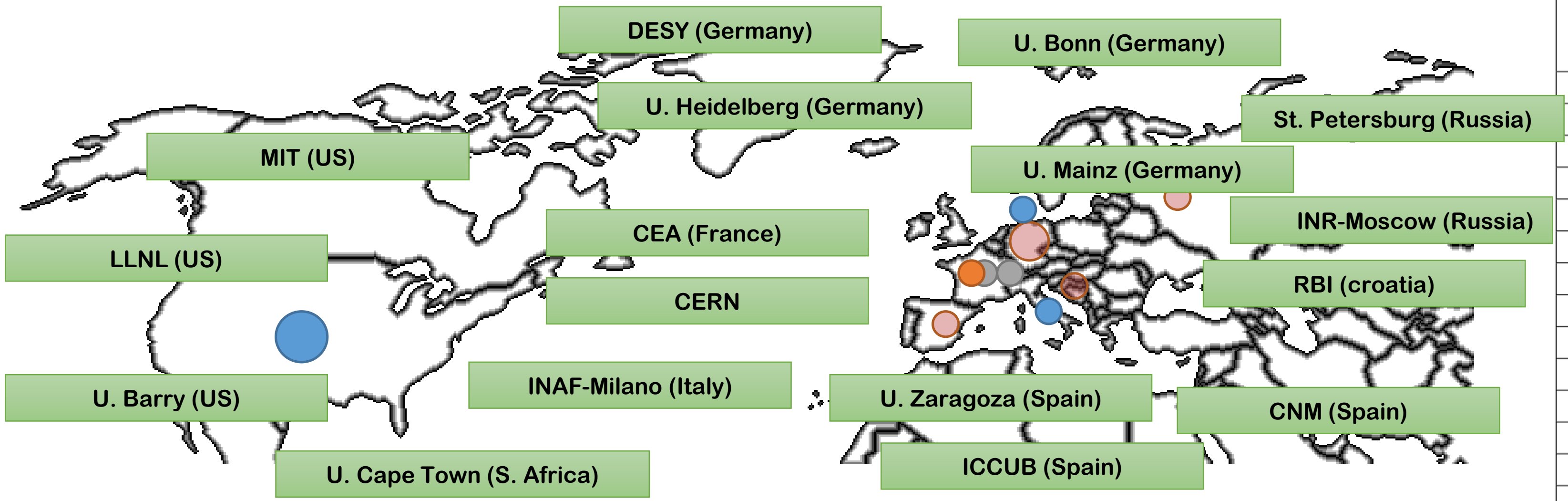


IAXO+: enhanced scenario with x10 (x4) higher FOM (MFOM) with respect LoI

MFOM = Magnet FOM

IAXO Collaboration

17 institutions from Germany, Spain, US, France, Russia, Croatia, S. Africa, CERN.
Know-how portfolio nicely emcompasses IAXO needs:



Institution	Superconducting magnets	X-ray optics	Detector & electronics	Axion phenomenology	Low background techniques	General infrastructures & engineering
Barry U. (USA)				x		
Irfu/CEA-Saclay (France)	x		x	x	x	x
U. Cape Town (S. Africa)				x		
ICCUB Barcelona (Spain)			x			
LLNL (USA)		x		x		
St. Petersburg NPI (Russia)				x		
Heidelberg U. (Germany)			x		x	
U. of Zaragoza (Spain)			x	x	x	
MIT (USA)		x				
INR Moscow (Russia)	x			x		
RBI Zagreb (Croatia)				x		
U. Bonn (Germany)			x			
CNM-IMB Barcelona (Spain)			x			
JGU Mainz (Germany)			x			
INAF - Brera (Italy)		x				
DESY (Germany)				x	x	x
CERN (Switzerland)	x					x

IAXO status of project

2011: First studies Irastorza et al. JCAP (2011) 1106:013.

CERN SPSC reviewed positively physics program of IAXO in 2014.

IAXO progress is being followed by “Physics Beyond Colliders” process at CERN (to provide feedback for the European Strategy Part Phys)

Collaboration formally established in july 2017 at collaboration meeting at DESY:

17 institutions to sign IAXO bylaws

Management structure defined and operative.

Near term goal defined for the collaboration: **BabyIAXO.**

Review process with DESY PRC for BabyIAXO started October 2018. Goal: making BabyIAXO an approved DESY project

Full intermediate experiment with relevant physics potential

Solid plans towards BabyIAXO. First physics could come in 3-4 years.

Discussion started towards an MoU, detailed cost sharing and timetable.

DESY is very interested in hosting IAXO

Conclusions and next steps

Axion searches→ strong physics case

Increasing experimental effort in the different axion searches strategies: solar axions, relic axions, laboratory axions…

CAST has been a very important milestone in axion research during the last decade

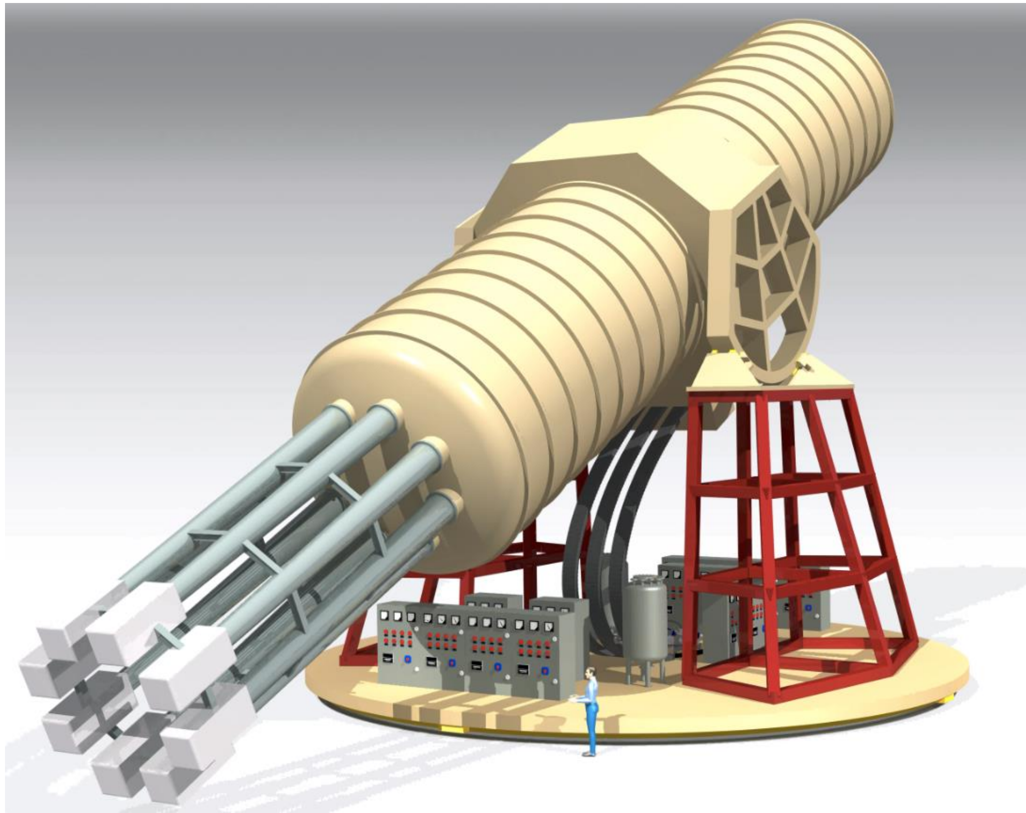
IAXO can probe deep into unexplored axion-ALP parameter space

IAXO could become next large project & a **generic axion facility with discovery potential in the next decade**

Need to continue with TDR & preparatory activities, formal endorsement & resources finding

BabyIAXO → new concept that can

- Enhance final FOM of experiment
- Catalize near-term activities in the collaboration towards an intermediate experiment with relevant physics outcome
- Host: DESY



Exciting work in front us: join us!

Letter of Intent to the DESY PRC

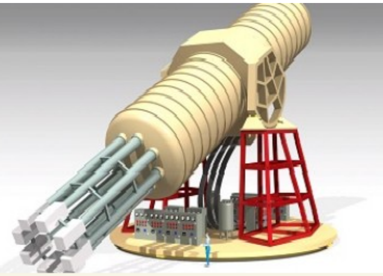
BabyIAXO: a first stage of the International Axion Observatory IAXO

E. Armengaud[1], D. Attie[1], S. Basso[2], P. Brun[1], N. Bykovskiy[3], J. M. Carmona[4], J. F. Castel[4], S. Cebrián[4], M. Civitani[2], C. Cogollos[5], D. Costa[5], T. Dafni[4], A.V. Derbin[6], M.A. Descalle[7], K. Desch[8], B. Döbrich[3], I. Dratchnev[6], A. Dudarev[3], E. Ferrer-Ribas[1], J. Galán[1], G. Galanti[2], D. Gascón[5], L. Gastaldo[9], L. Garrido[5], C. Germani[5], G. Ghisellini[2], M. Giannotti[10], I. Giomataris[1], S. Gninenko[11], N. Golubev[11], R. Graciani[5], I. G. Irastorza[4,*], K. Jakovčić[12], J. Kaminski[8], M. Krčmar[12], C. Krieger[8], B. Lakić[12], T. Lasserre[1], P. Laurent[1], I. Lomskaya[6], E. Unzhakov[6], O. Limousin[1], A. Lindner[13], G. Luzón[4], F. Mescia[5], J. Miralda-Escudé[5], H. Mirallas[4], V. N. Muratova[6], X.F. Navick[1], C. Nones[1], A. Notari[5], A. Nozik[11], A. Núñez[4], A. Ortiz de Solórzano[4], V. Pantuev[11], T. Papaevangelou[1], G. Pareschi[2], E. Picatoste[5], M. J. Pivovaroff[7], K. Perez[14], J. Redondo[4], A. Ringwald[13], J. Ruz[7], E. Ruiz-Chóliz[4], J. Salvadó[5], T. Schiffer[8], S. Schmidt[8], U. Schneekloth[13], M. Schott[15], H. Silva[3], G. Tagliaferri[2], F. Tavecchio[2], H. ten Kate[3], I. Tkackev[11], S. Troitsky[11], P. Vedrine[1], J. K. Vogel[7], A. Weltman[16].

http://iaxo.web.cern.ch/iaxo/

IAXO

The International Axion Observatory



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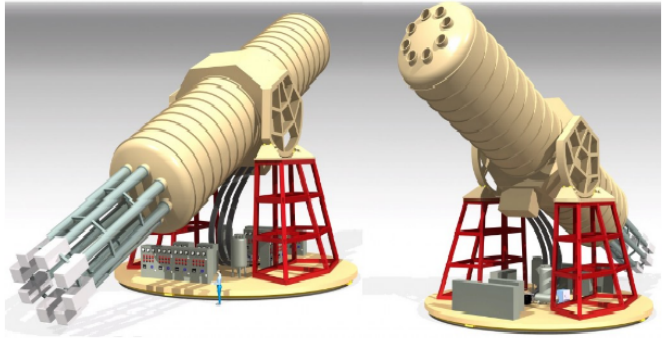
Home

Welcome to the home page of the IAXO project!

The International Axion Observatory (IAXO) is a proposed fourth generation axion helioscope. It aims at a sensitivity much improved with respect to past and current axion searches, with real discovery potential.

The conceptual design of the experiment has been finished and a Letter of Intent submitted to CERN. Recently, the SPSC has recognised the physics case of IAXO and has recommended to proceed with a Technical Design Report.



Views of the conceptual design of IAXO

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- IAXO in the CERN Courier
- SPSC recommends IAXO
- Letter of Intent to CERN submitted

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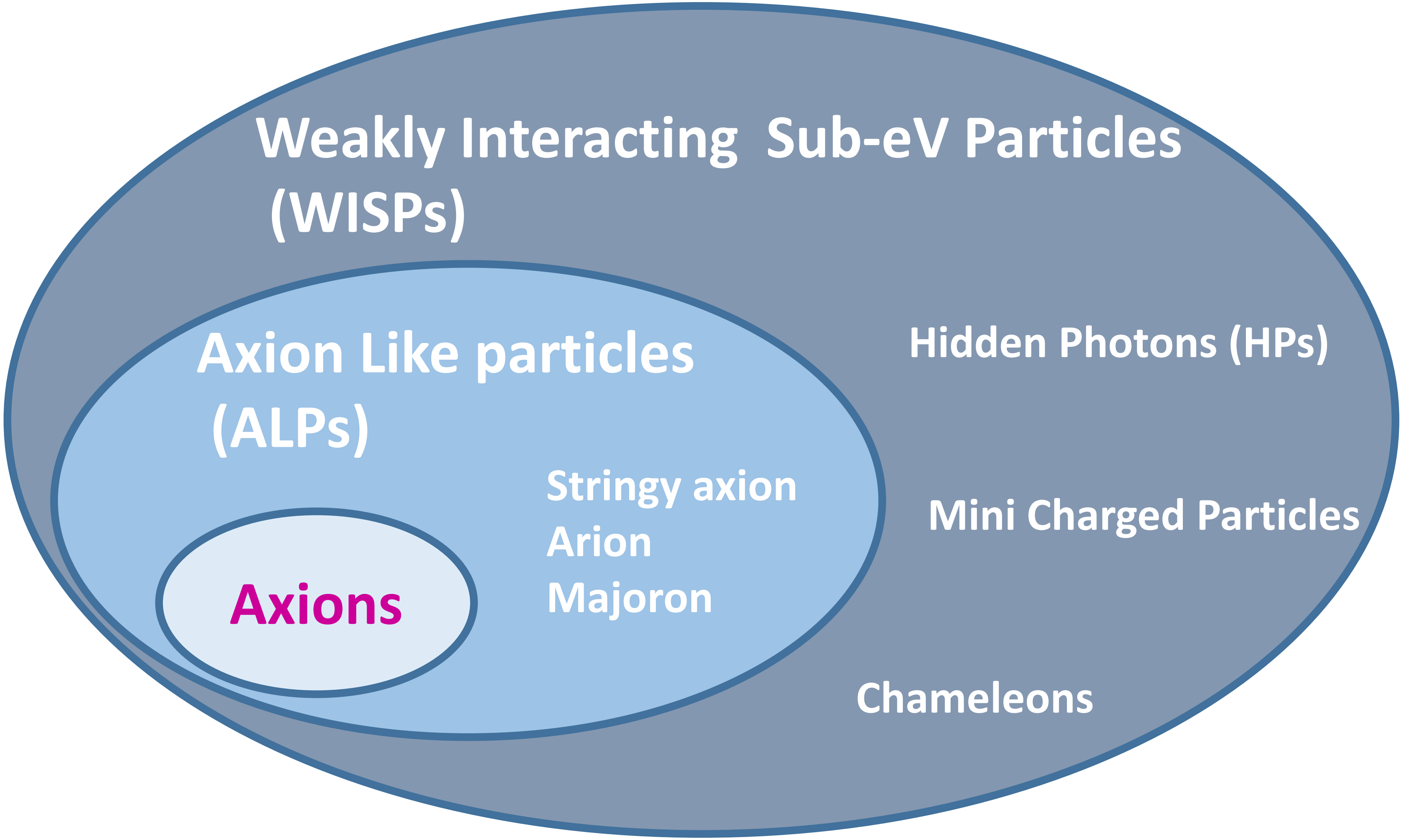
IAXO costs

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.

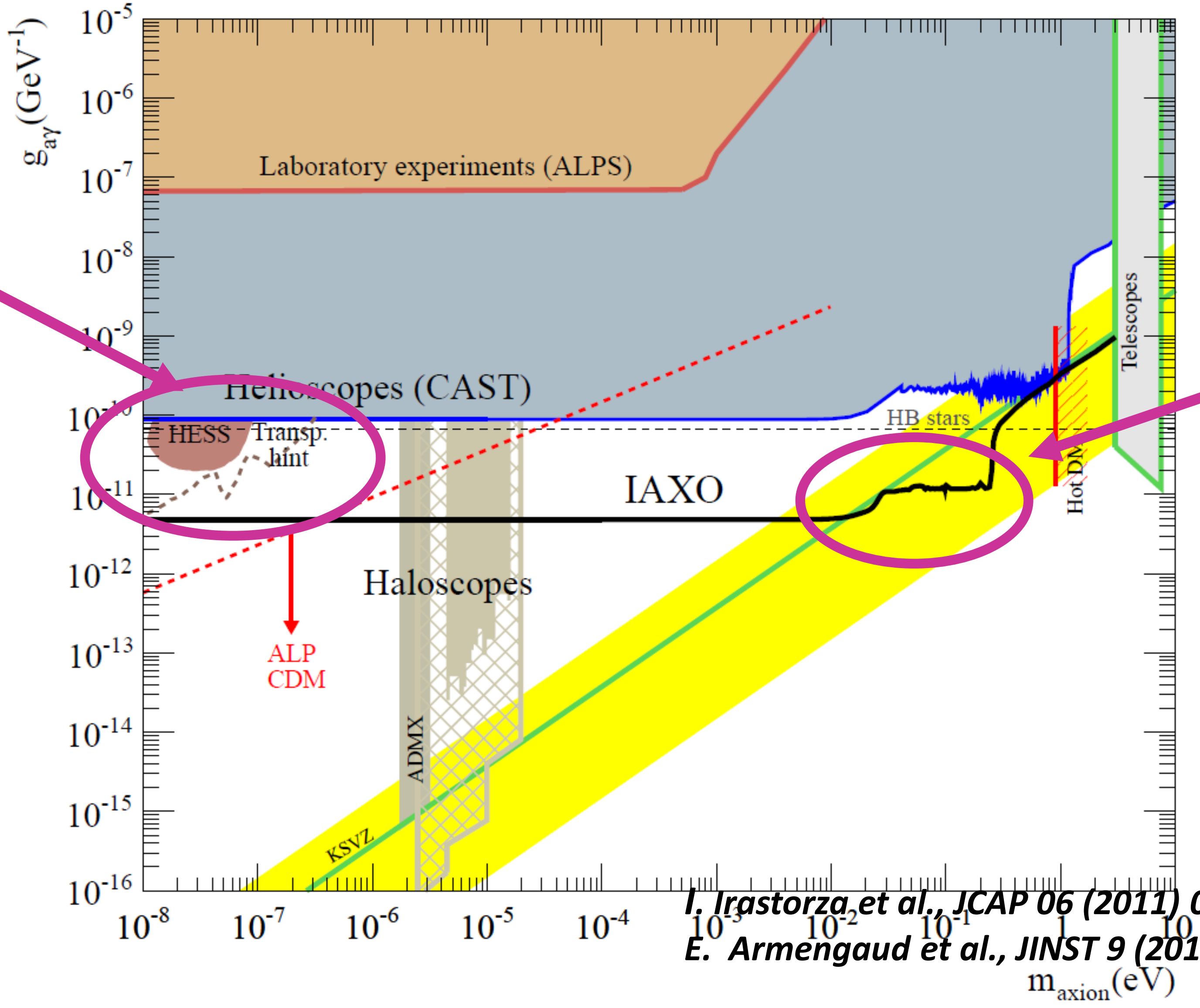
The WISPs zoo



$g_{a\gamma}$ and m_a are two independent "phenomenological" parameters

IAXO Sensitivity

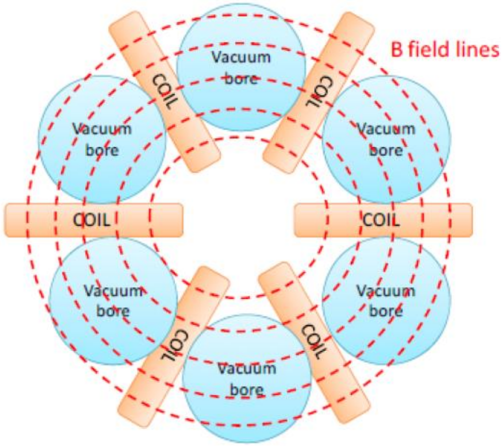
Transparency ALP hints Accesible to IAXO & ALPS-II



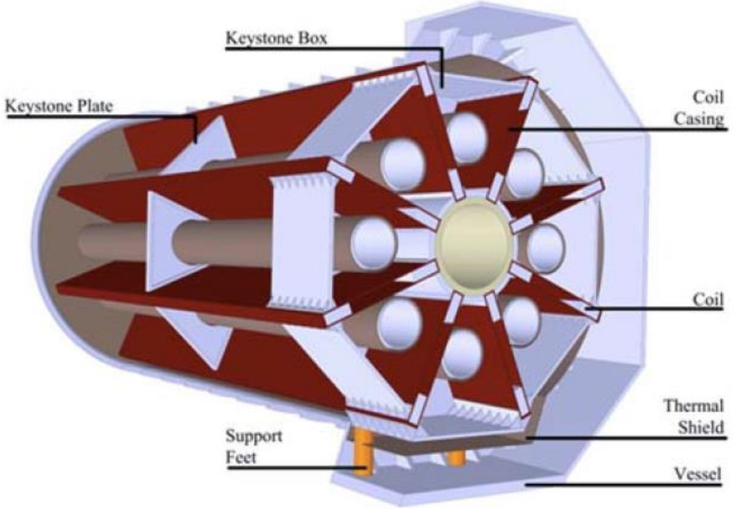
Few meV scale QCD axion & anomaly cooling hints accessible to IAXO

I. Irastorza et al., JCAP 06 (2011) 013
E. Armengaud et al., JINST 9 (2014) T05002

IAXO magnet



Shilon et al. IEEE T. Ap. SupCond 23:4500604 (2013)
Shilon et al. AIP Conf. Proc. 1573:1574 (2014)
Shilon et al. IEEE T. Ap. SupCond 24:4500104 (2014)



Optimised configuration: TOROIDAL with 8 bores
25 m long, 5 m diameter and a peak field of 5.4 T

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

(ATLAS toroid 26 m long, 20 m diameter, peak field 3.9 T)

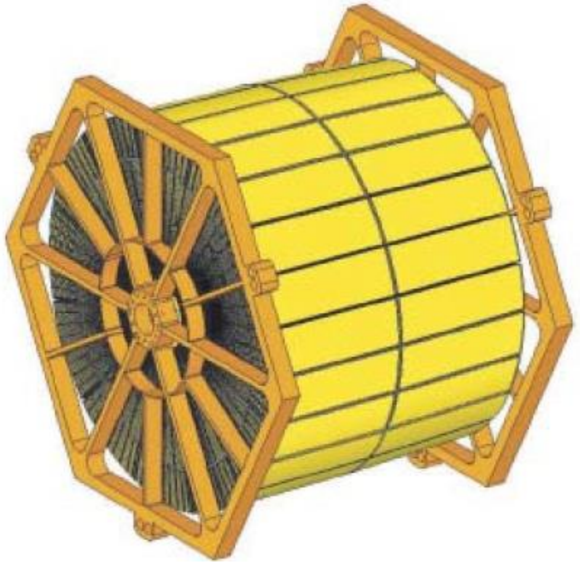
IAXO x-ray optics

Baseline : Use approach NASA's NUSTAR satellite

Each bore equipped with an X-ray optics
8 systems of 600 mm diameter each

Specifications:

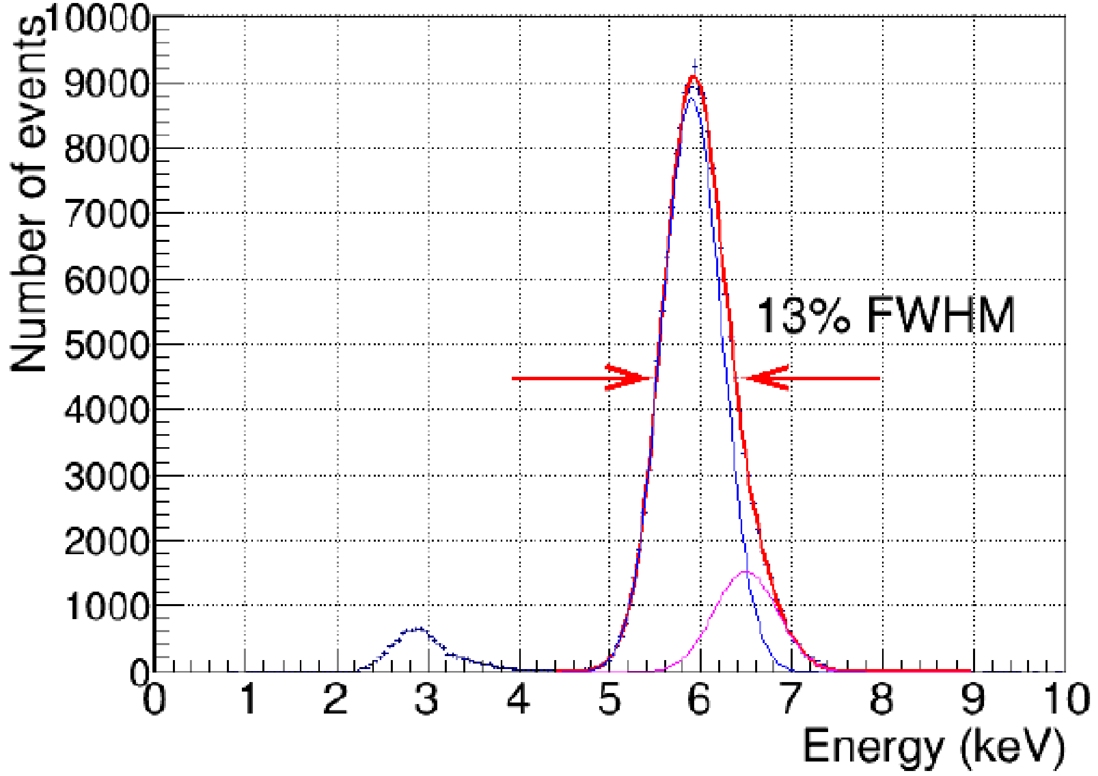
- Refined imaging not needed
- Need to cover large area (cost-effective)
- Good throughput (0.3-0.5)
- Small focal point (~1 cm^2)

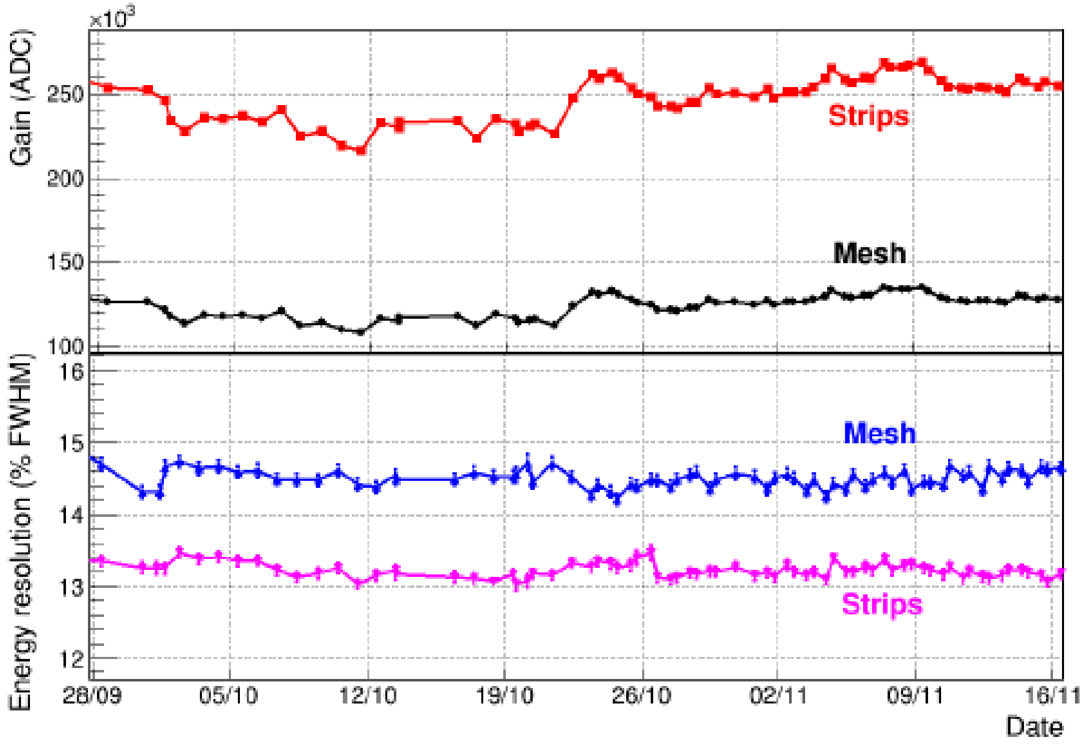


Telescopes	8
N, Layers (or shells) per telescope	123
Segments per telescope	2172
Geometric area of glass per telescope	0.38 m^2
Focal length	5.0 m
Inner radius	50 mm
Outer Radius	300 mm
Minimum graze angle	2.63 mrad
Maximum graze angle	15.0 mrad
Coatings	W/B_4C multilayers
Pass band	1 – 10 keV
IAXO Nominal, 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

Jakobsen et al. Proc SPIE 8861:886113 (2013)

Detector installed in 2014: performance

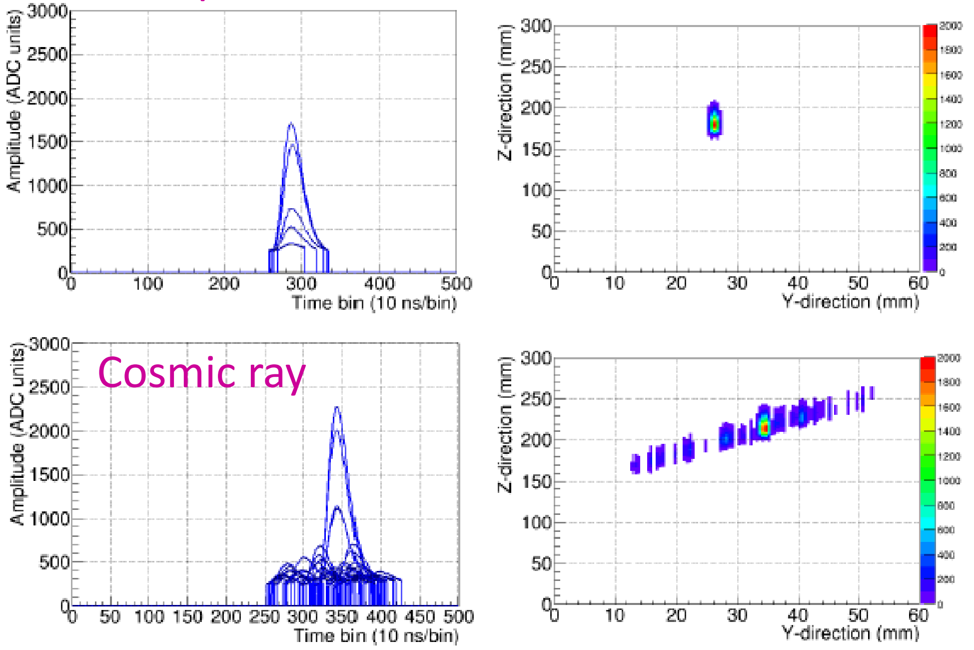




Excellent energy resolution

Excellent stability

6 keV photon


Amplitude (ADC units)
Time bin (10 ns/bin)
Z-direction (mm)
Y-direction (mm)
Cosmic ray
Amplitude (ADC units)
Time bin (10 ns/bin)
Z-direction (mm)
Y-direction (mm)