STATUS OF BABYIAXO

Elisa Ruiz-Chóliz

Johannes Gutenberg University – Mainz
On behalf of the IAXO Collaboration

16th Patras Workshop on Axions, WIMPs and WISPs
17 June 2021

The International Axion Observatory

JOHANNES GUTENBERG UNIVERSITÄT MAINZ

Axions and axion-like particles (ALPs)

Axions and beyond

ALPs predicted as pseudo-NG bosons by many extensions of the SM

ALPs and axions couple to photons, but ALPs m_A and $g_{A\gamma}$ are not correlated: big parameter space

Weakly Interacting Slim Particles (WISPs) → cold and hot Dark Matter (DM) candidates!

Motivations

Predicted by extensions of the SM and string theory

Not an *ad hoc* solution to DM

Invoked to solve astrophysical observations

Astrophysical hints

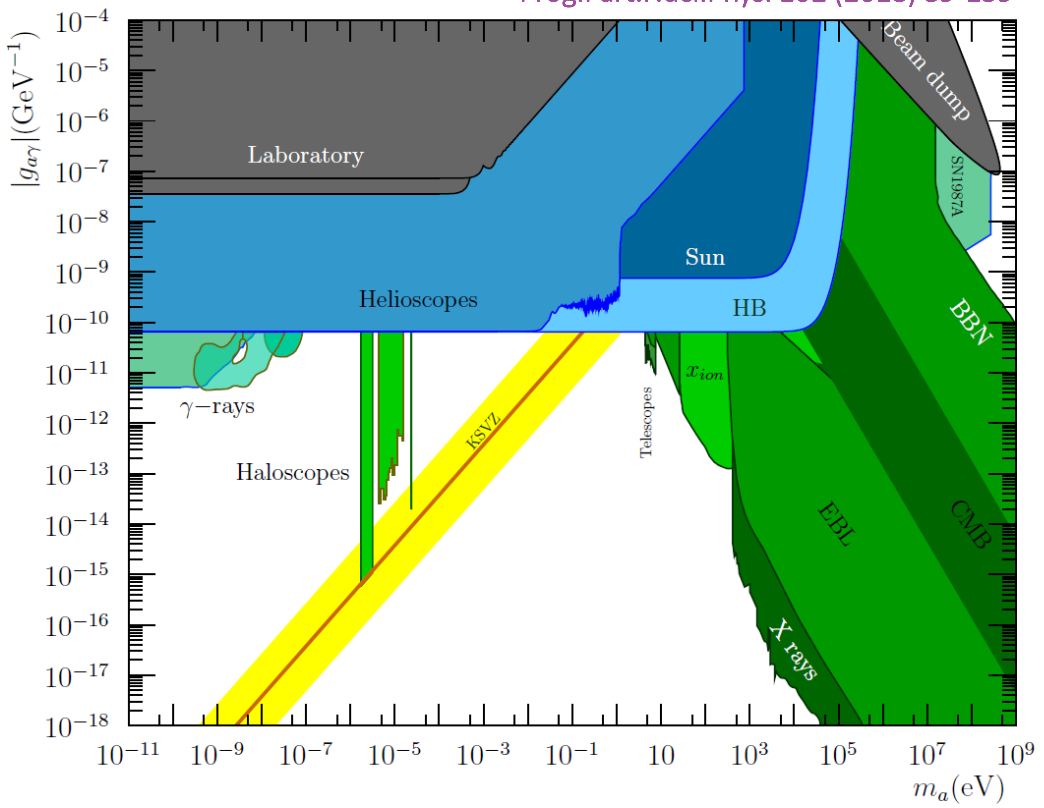
- Intergalactic transparency to VHE photons

  Axion-photon conversion allows VHE travel longer distances

- Anomalous cooling of different stellar objects

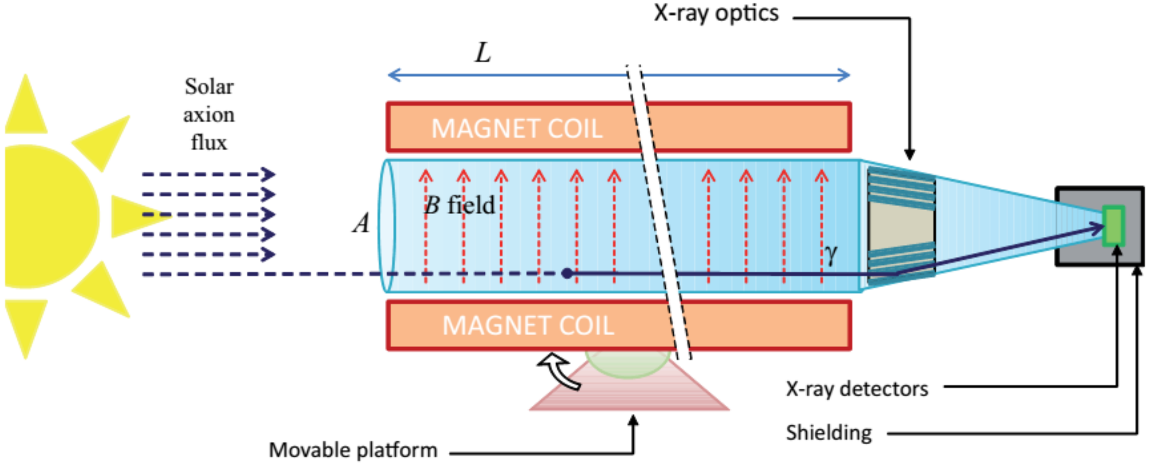
  Axion emission adds an undetected cooling mechanism

Prog.Part.Nucl.Phys. 102 (2018) 89-159



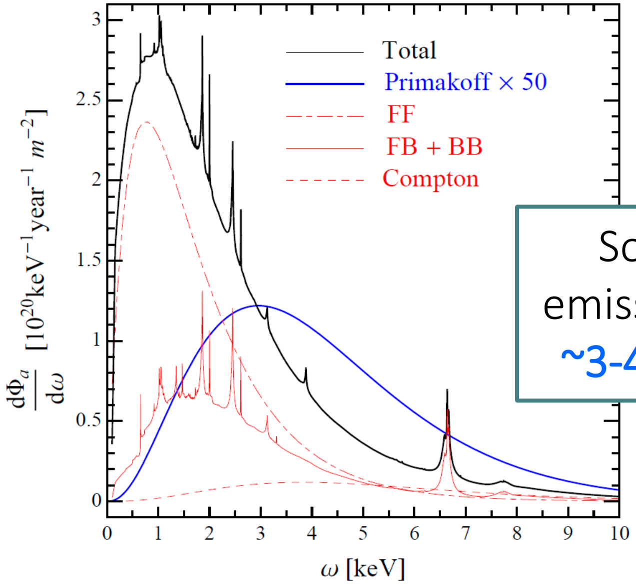
Helioscope technique

Physical principle:



- Production: **Primakoff effect (a-γ coupling)**
  Thermal photons interacting with solar nuclei produce Axions
- Detection: **Inverse Primakoff** (Sikivie 1983)
  Axion interacting with a very strong magnetic field converts to a photon

JCAP12(2013)008



Solar axion emission spectra
~3-4 keV x-rays

Enhanced layout description:

- A powerful and large dedicated magnet
- X-ray focusing optics optimized for axion spectrum
- Ultra-low background x-rays detectors

magnet, optics

Figure of Merit (FoM): $g_{a\gamma}^4 \sim B^2 L^2 A \cdot \varepsilon_d b^{-1/2} \cdot \varepsilon_o \alpha^{-1/2} \cdot \varepsilon_t^{-1/2} t^{-1/2}$

JCAP 1106:013,2011

detectors, time

State of the art: CAST

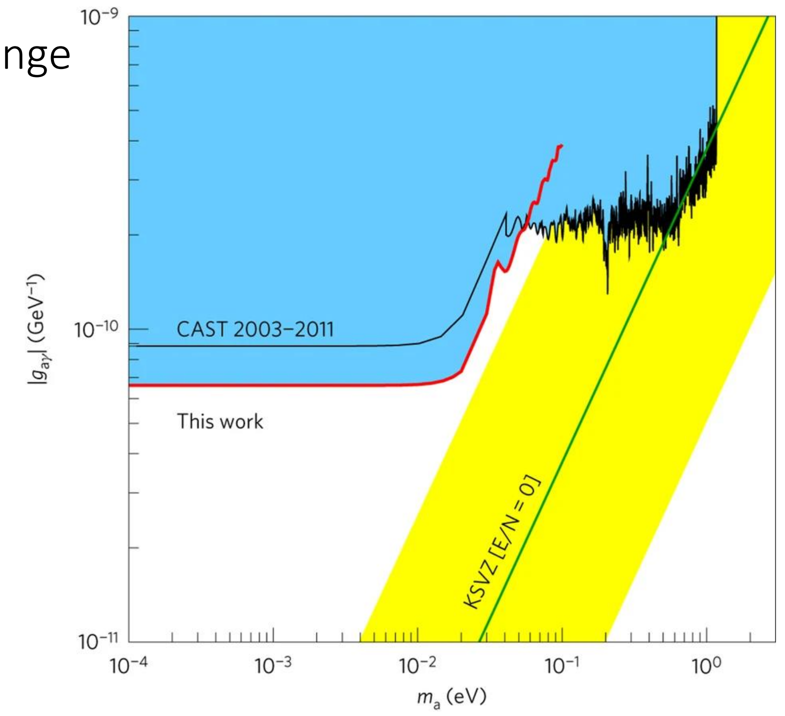
CERN Axion Solar Telescope

A powerful axion helioscope → more than 18 years of experience
Decommissioned prototype LHC dipole magnet → Length = 9.3 m; Magnetic field = 9 T
Solar tracking possible during sunrise and sunset (2 x 1.5 h per day)

2013-2015: IAXO pathfinder

Sunrise detector: x-ray focusing optics + Micromegas (IAXO Pathfinder)
Best experimental limit on axion-photon coupling over broad axion mass range

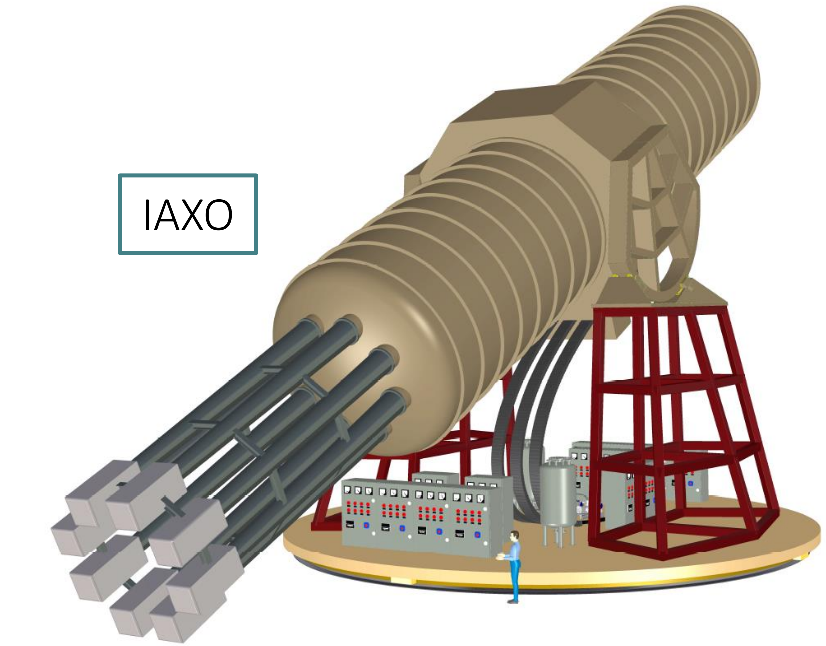
$|g_{a\gamma}| < 0.66 \times 10^{-10}$ [GeV^{-1}] (95% C.L.) [NPHYS4109]



IAXO and BabyIAXO

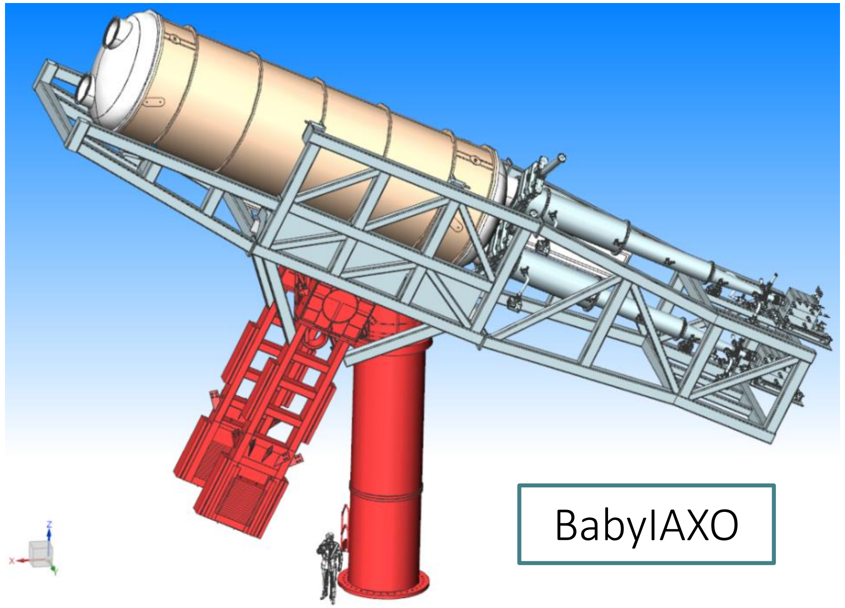
International AXion Observatory

- Next generation enhanced helioscope for solar axions
- Mature and state-of-the-art technology
- Purpose-built large-scale magnet
  - >300 times larger FoM than CAST magnet
  - Toroid geometry
  - 8 conversion bores of 60 cm Ø, ~20 m long
- 8 detection systems (XRT+detectors)
  - Scaled-up versions based on experience in CAST
  - Optics based on slumped-glass technique used in NuStar
  - Low-background techniques for detectors
- ~50% Sun-tracking time



BabyIAXO [JHEP05(2021)137]

- Technological prototype of IAXO (to be hosted at **DESY**)
- Relevant physical outcome (FoM ~100 times larger than CAST)
- Improvement of the IAXO baseline experimental parameters
- Collaboration growth and consolidation



Sensitivity and physics potential

Expected sensitivity to solar axions

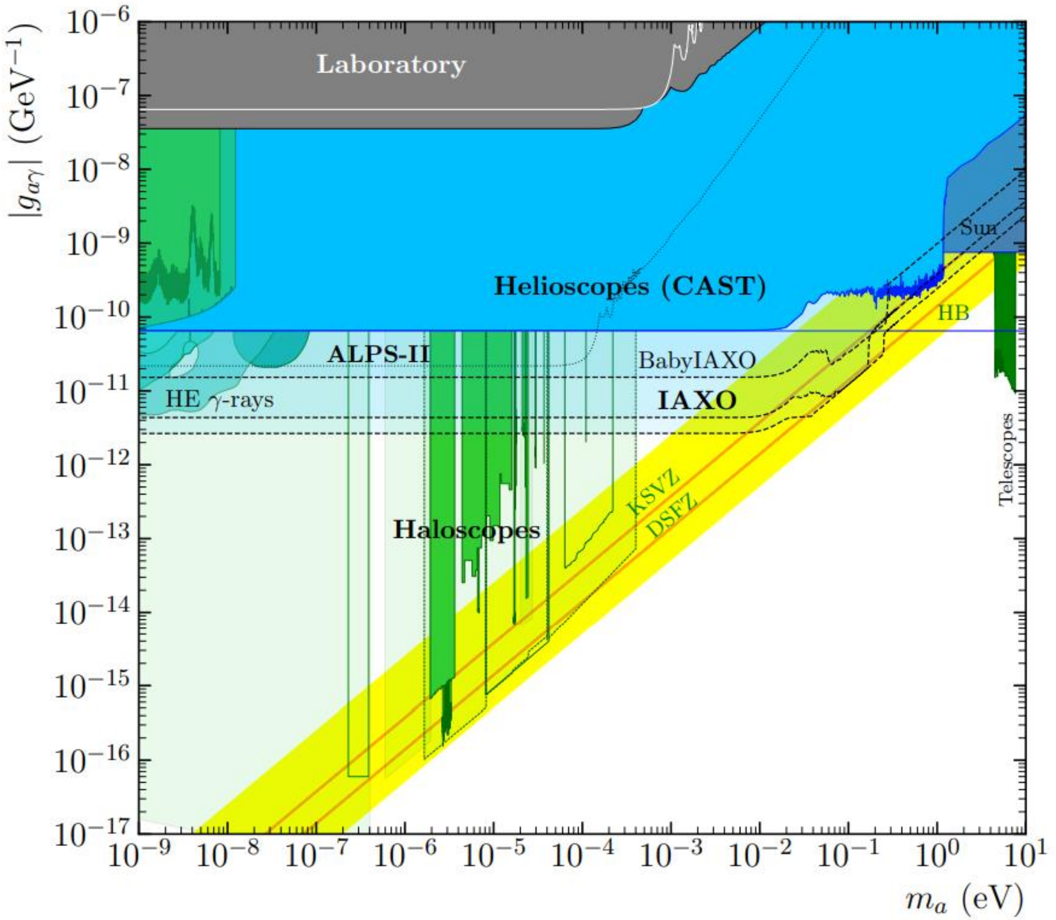
	BabyIAXO (~3y exposure)	IAXO (~6y exposure)
$\lvert g_{a\gamma}\rvert$ [GeV^{-1}]	~1.5x10^{-11} → $m_a \leq 0.02$ eV	~5x10^{-12} → $m_a \leq 0.01$ eV ~10^{-11} → $m_a \sim 0.01\text{-}0.25$ eV
$\lvert g_{ae}g_{a\gamma}\rvert$ [GeV^{-1}]		<2.5x10^{-25} → $m_a \leq 0.01$ eV
Signal-to-noise CAST improvement	10^2	$10^4 - 10^5$

Physics potential [JCAP 06 (2019) 047]

VHE photons and anomalous cooling hints

QCD axions

CDM, and more exotic physics (relic axions, dark radiation, inflation)



BabyIAXO Magnet

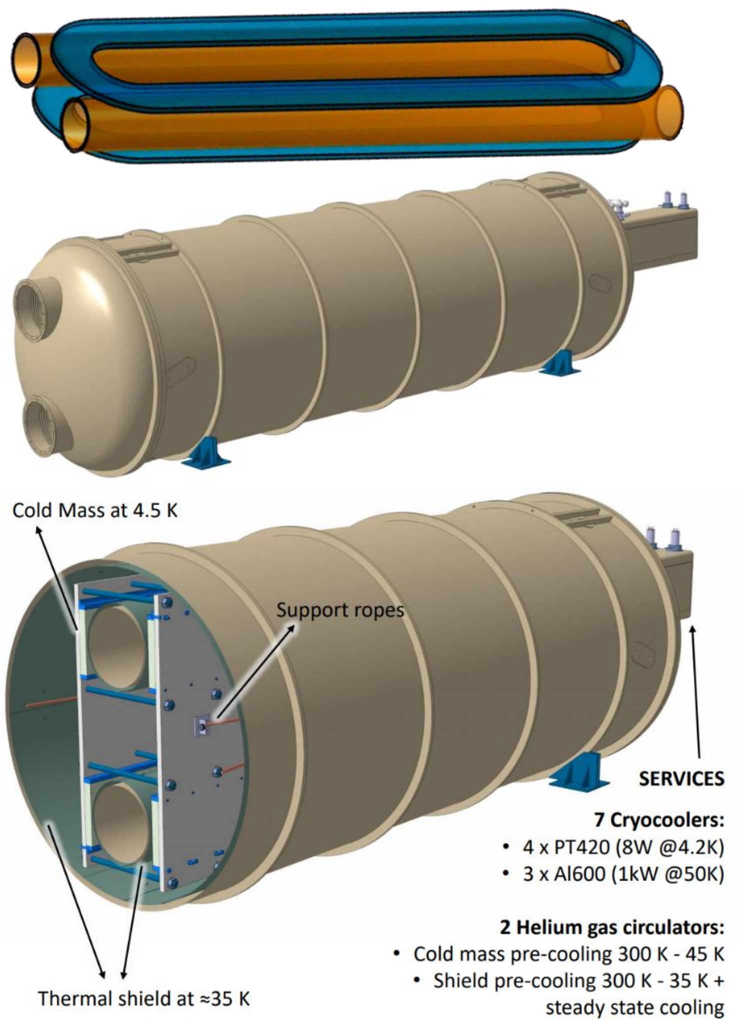
$$f_M = B^2 L^2 A$$

Design

- 2 flat racetrack coils: 10m long; 12 strands of NbTi/Cu
- 2 bores: 0.7m diameter; vacuum & buffer gas
- Optimized layout: maximum magnetic field at bores
- Minimal risk: conservative design choices
  - Cost effective : Best use of existing infrastructure and experience at CERN
  - Prototyping approach: very close layout to that of IAXO toroidal design

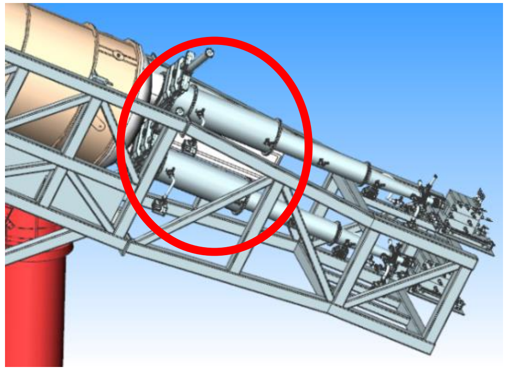
Status

- Technical in-depth review of magnet design (by DESY PRC) successfully passed last year.
- Design adapted to use of an existing SC cable offered in-kind to IAXO by INR Moscow . Currently qualifying the cable for use in BabyIAXO
- Quotations being received for magnet subsystems. Almost ready to start placing orders (cryostat, cold mass,…).
- CERN contribution for BabyIAXO magnet construction



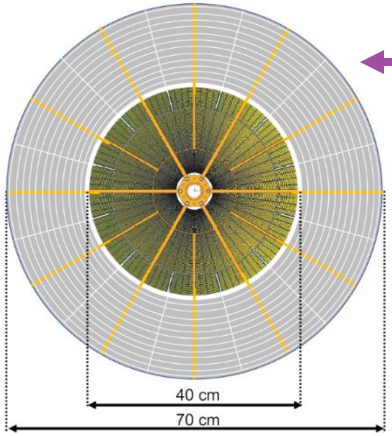
BabyIAXO X-ray optics

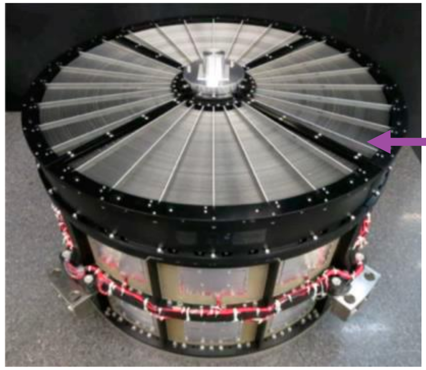
$$f_O = \epsilon_o \alpha^{-1/2}$$



Optics technology

- Multilayer-coated segmented-glass Wolter-I optics
- Signal from the 0.7 m diameter bore focused to 0.2cm^2 area
- Mature technology based on NASA's NuSTAR telescopes



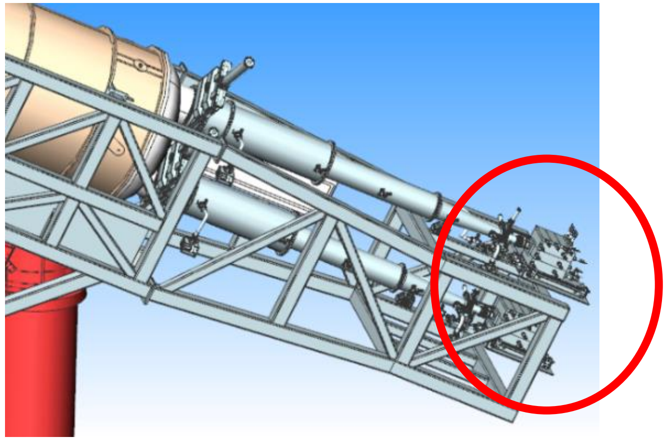


2 detection lines in BabyIAXO

- Custom hot & cold-slumped segmented glass
  - Two techniques at the same telescope to increase the diameter and cover the bore
  - Being commissioned for BabyIAXO
  - Inner part Al-foil or segmented glass optic (NASA/LLNL/DTU/MIT/Columbia)
  - Outer part cold-slumped Willow-glass technology (INAF/DTU)
- ESA's XMM flight spare
  - Already available and compatible with BabyIAXO design
  - List for ESA operational requirements and loan agreement in preparation

BabyIAXO detectors requirements

$$f_D = \epsilon_d b^{-1/2}$$



IAXO as an observatory

- Multiple and diverse detectors working at the same time

Technical requirements:

- High detection efficiency in RoI (0-10 keV)
- Very low background in RoI: < 10^{-7} counts keV^{-1} cm^{-2} s^{-1}
  - Use of shielding (active and pasive)
  - Radiopurity
  - Advanced event discrimination strategies

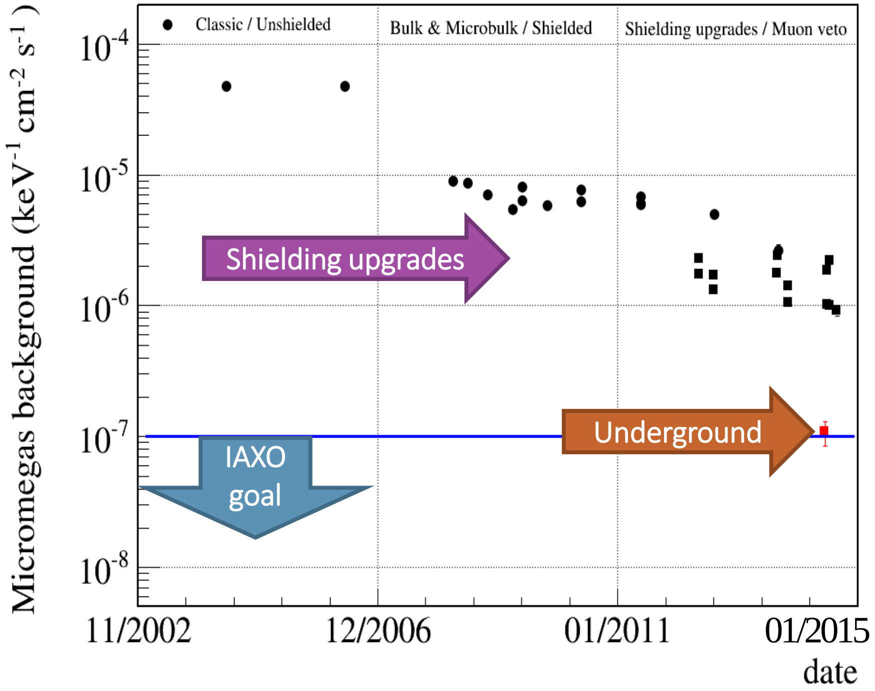
Baseline detector technology:

- Time Projection Chambers (TPC) based on the Micromegas technology after the experience of the CAST experiment.

Alternative technologies under study

- Gridpix, Metallic Magnetic Calorimeters (MMC), Transition Edge Sensors (TES) and Silicon Drift Detectors (SDD)

State of the art: IAXO pathfinder - CAST



Background achieved at CAST

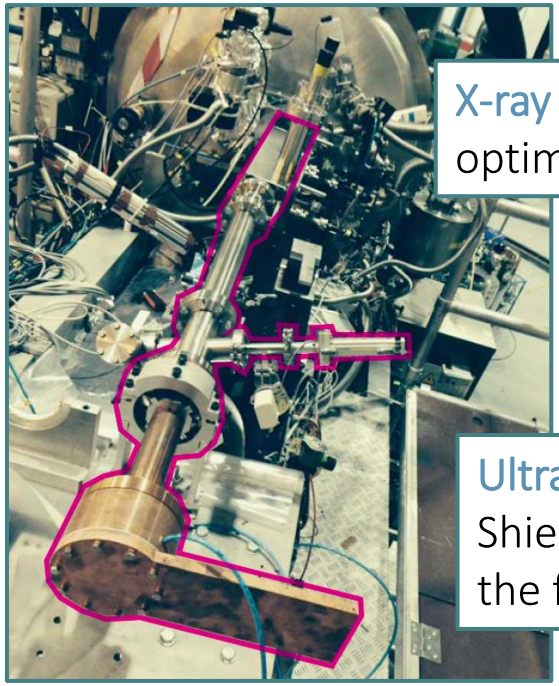
(1.0 ± 0.2) x 10^{-6} counts keV^{-1} cm^{-2} s^{-1}

Background in LSC (underground)

~ 10^{-7} counts keV^{-1} cm^{-2} s^{-1}

IAXO goal

10^{-7}-10^{-8} counts keV^{-1} cm^{-2} s^{-1}



X-ray optics (Wolter I x-ray telescope)
optimized for axion spectrum

Ultra-low background detectors
Shielded Microbulk Micromegas at the focal point

Performance and results [JCAP12(2015)008; JCAP01(2016)034; NPHYS4149]

8 months of data-taking → Best signal-to-noise ratio in CAST

Background level:

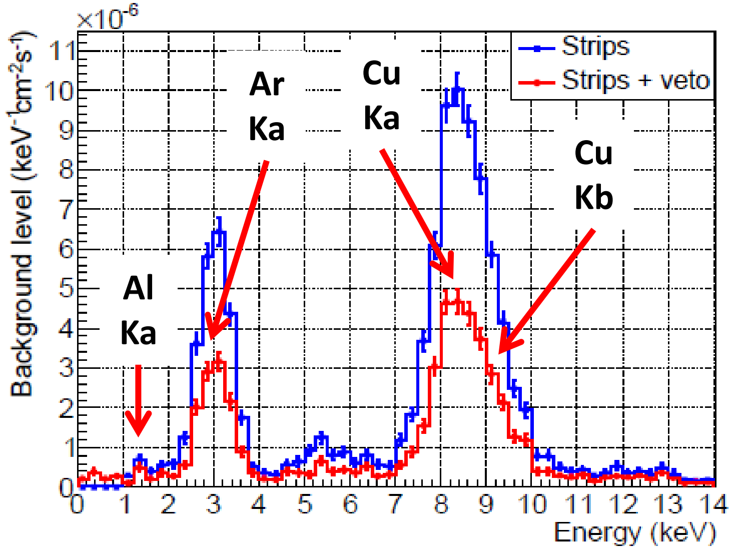
(1.0 ± 0.2) x 10^{-6} counts keV^{-1}cm^{-2}s^{-1} for [2,7] keV & all detector area

Micromegas background source understanding

Detector's figure of merit: $f_D = \epsilon_a b^{-1/2}$

Background contribution	Reduction technique
Cosmic muons and neutrons ~ $1\text{x}10^{-6}$ nfu	- Active vetos (scintillators+PMT/SiPM) - Capture sheets (cadmium)
External gamma radiation ~ $1.5\text{x}10^{-6}$ nfu	- Passive shielding (lead)
Internal radiation from materials (natural and cosmogenic) ~ $5\text{x}10^{-8}$ nfu	- Radiopure materials (mainly copper) - Internal shielding
Radiation from target gas (Ar) ~ $1\text{x}10^{-8}$ nfu	- Other gas mixtures (Xe)

* *nfu = normalized flux units = counts keV^{-1} cm^{-2} s^{-1}*



Micromegas spectrum dominated by

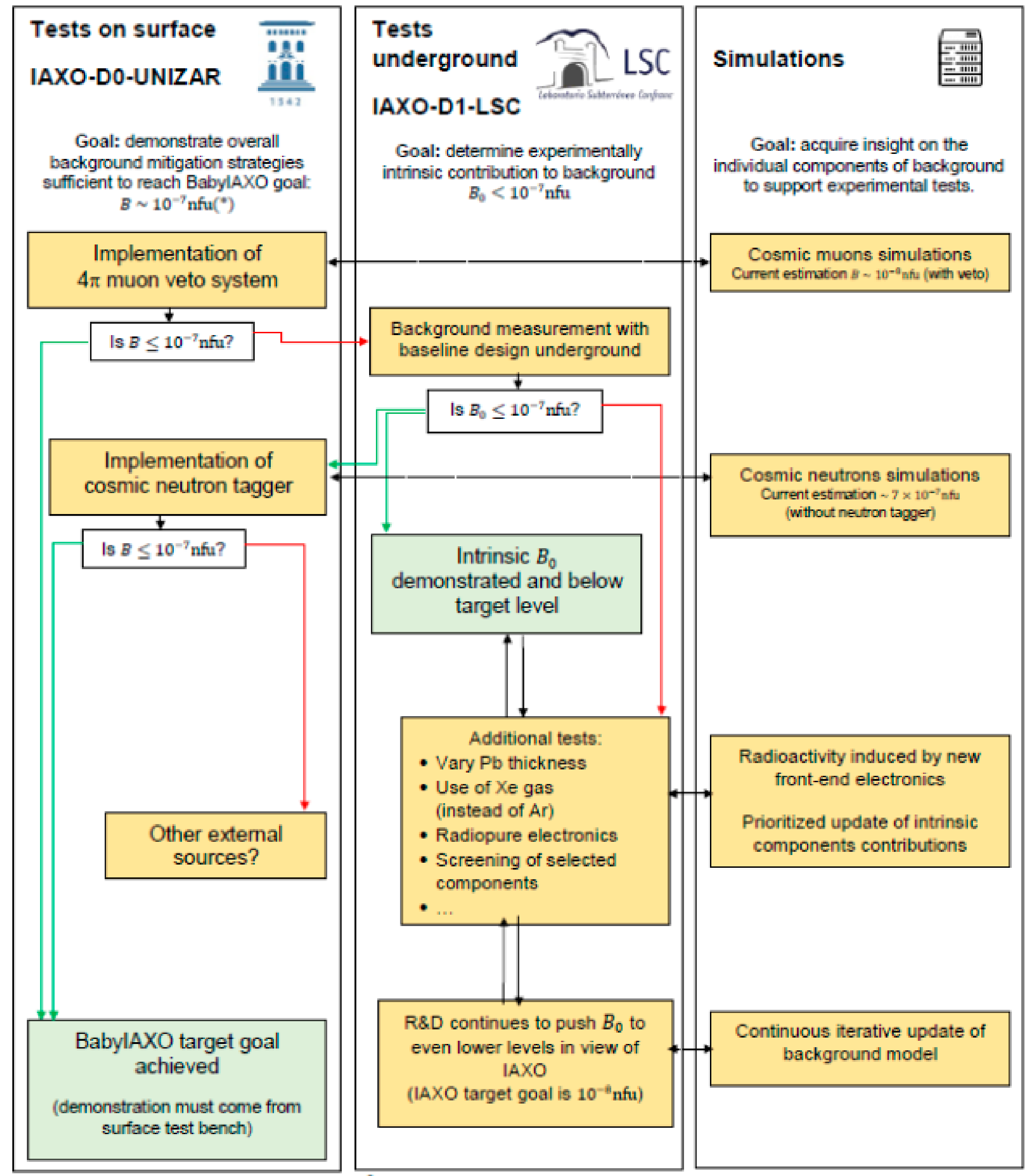
- **Cu fluorescence** at 8 keV
- **Ar fluorescence** at 3 keV

from cosmic induced events

Other background reduction techniques:

- Topological information from the detector and electronics (AGET)
- Offline discrimination analysis (**REST software**)

Background demonstration



(*) nfu = normalized flux units = counts/keV/cm^2/s

Roadmap to demonstrate BabyIAXO target levels

Combination surface and underground measurements, simulations and experimental improvements

Tests at surface:

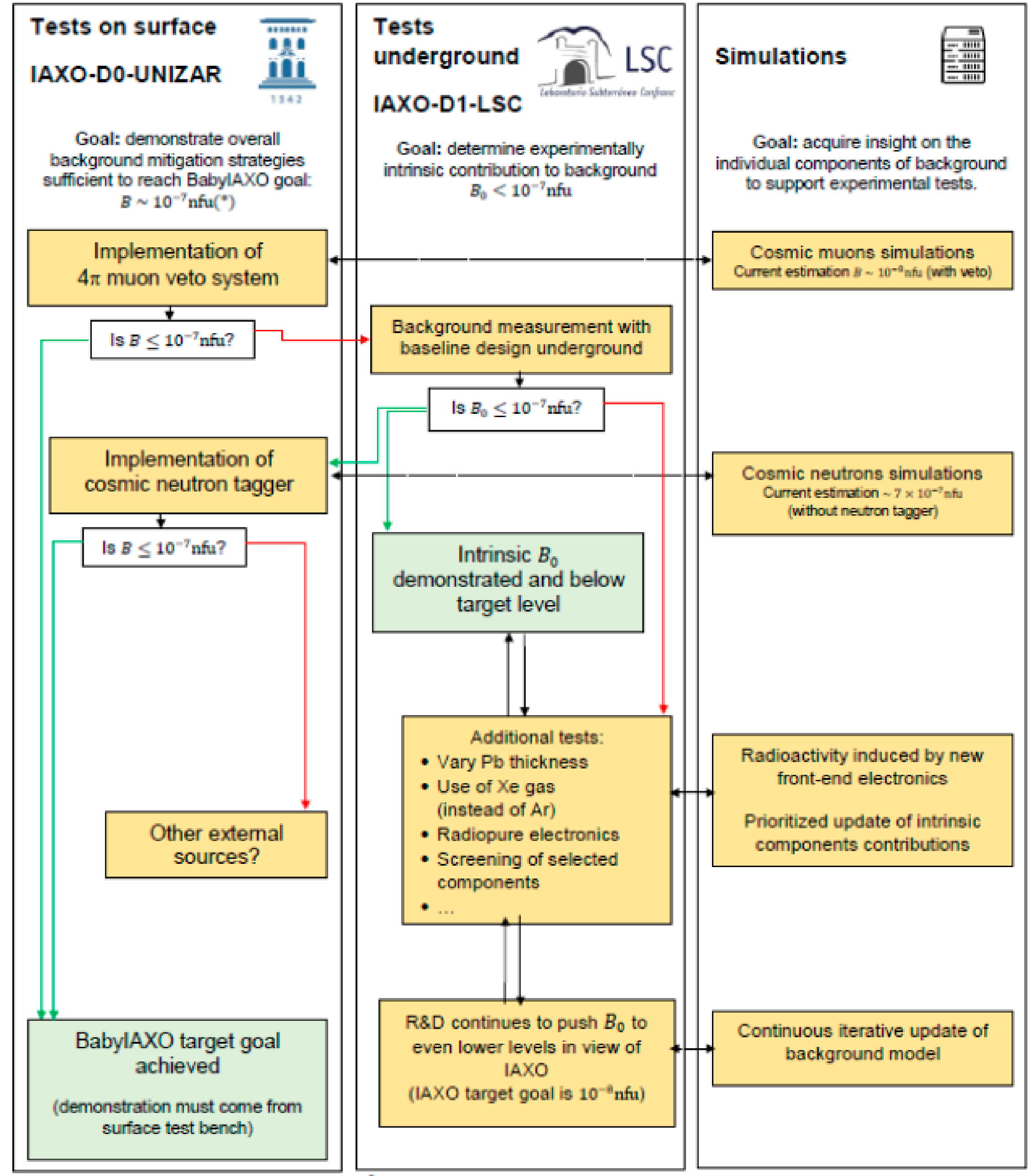
- Demonstrate overall background reduction strategy ($B \sim 1 \times 10^{-7}$ nfu)

Tests underground:

- Determine intrinsic radioactivity (internal or inner shielding components) of the detector ($B_0 < 1 \times 10^{-7}$ nfu)

Simulations:

- Insight on individual components of the background to support experimental tests



(*) nfu = normalized flux units = counts/keV/cm²/s

Current status

Tests at surface UNIZAR with IAXO-D0

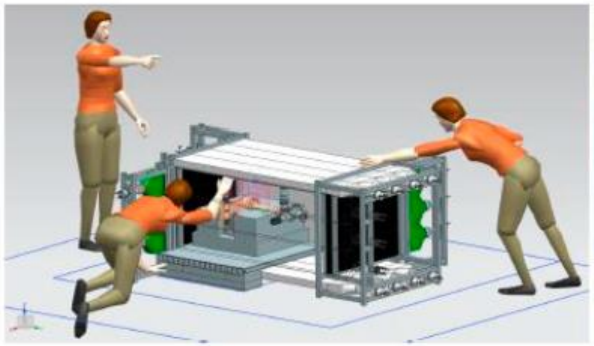
- Implementation of 4π muon veto.

Tests at underground with IAXO-D1

- Determine part of intrinsic and cosmic induced events

Simulations

- Background might be limited by cosmic neutrons
- Hypothesis to be confirmed by IAXO-D0/IAXO-D1
- Cosmic neutron tagger is being designed and will be implemented in IAXO-D0.

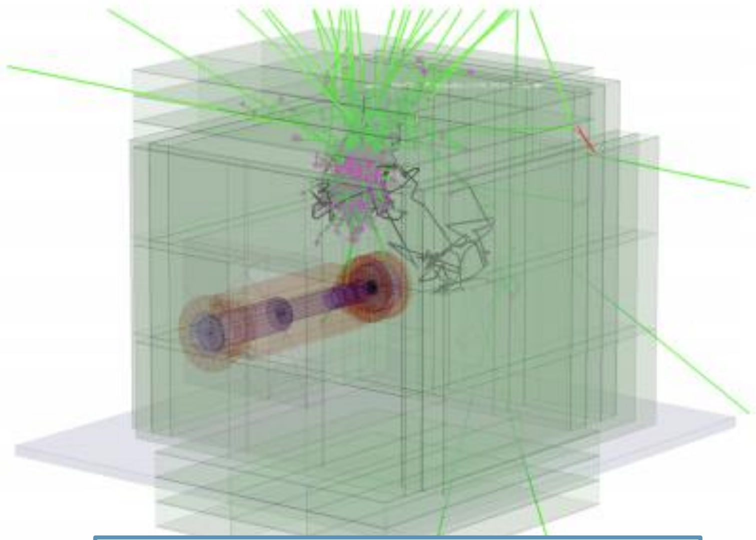


REST for Physics

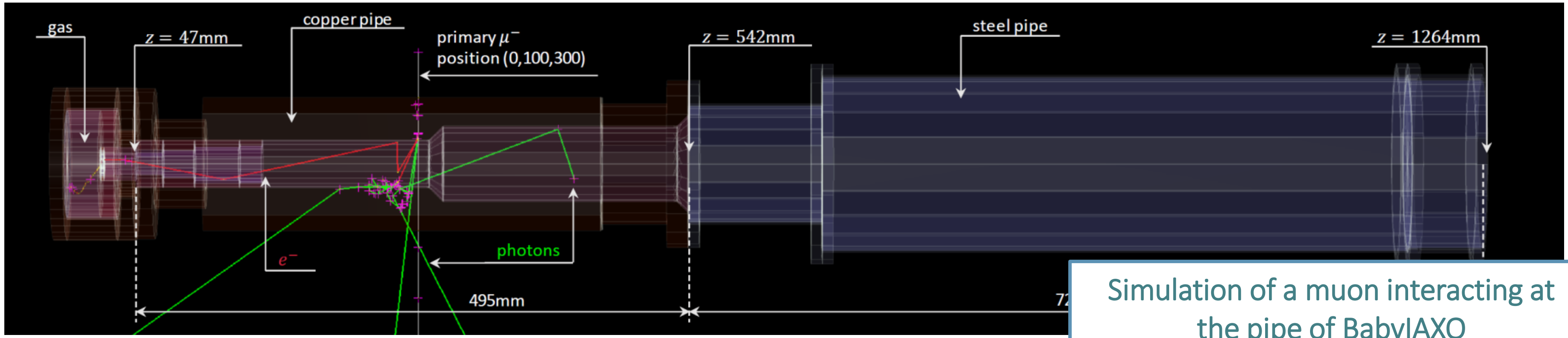
Software development: REST (Rare Event Searches with TPCs)

- Collaborative framework
- C++, ROOT, GEANT4, magboltz…
- https://github.com/rest-for-physics

- Background simulations (detectors and electronics)
- Data analysis routines
- Axion signal calculation for IAXO and BabyIAXO
- Slow control for BabyIAXO



Simulation of a cosmic neutron interacting at the shielding



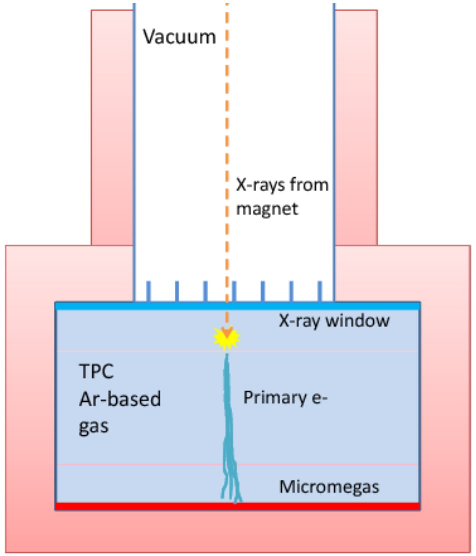
Simulation of a muon interacting at the pipe of BabyIAXO

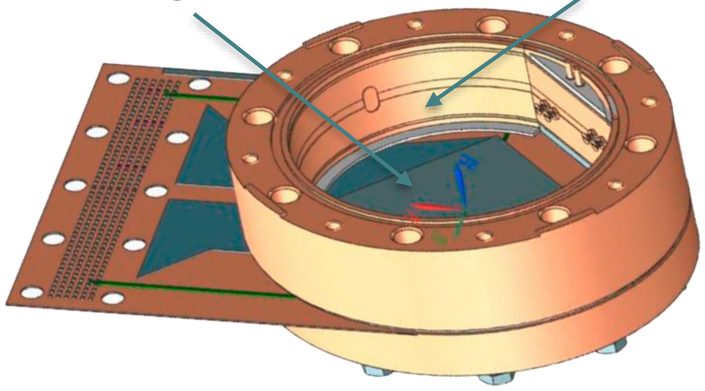
BabyIAXO baseline detector

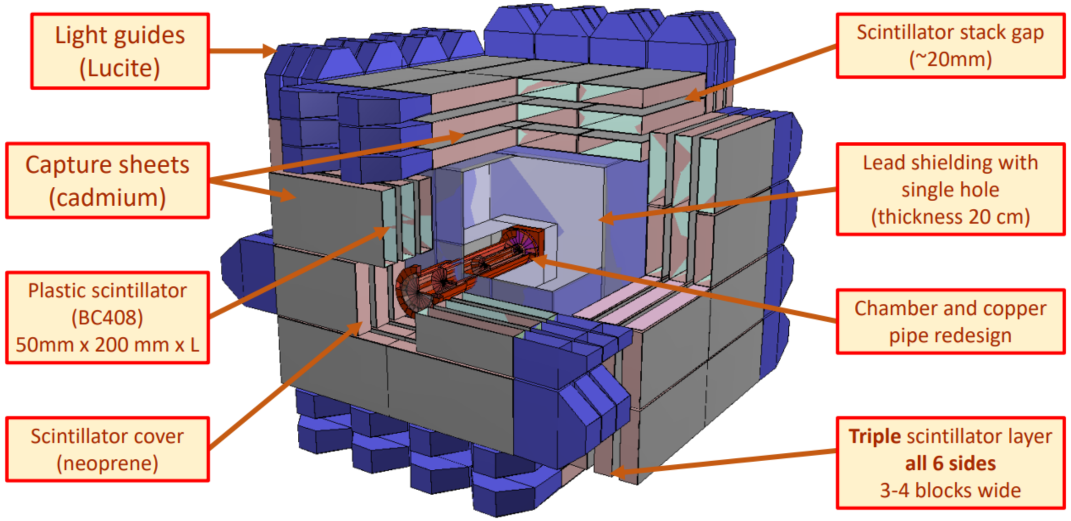
$$f_D = \epsilon_d b^{-1/2}$$

Baseline technology: Microbulk Micromegas

- Gaseous detector
  - Gas chamber with electric field
  - Primary e- from ionization drift towards the readout
  - Amplification region → detectable signals
- Suitable for axion detection
  - Readout with high granularity
  - Good energy and position resolution
  - Low energy threshold
  - Very radiopure (low background)
  - Performance tested in CAST [JCAP12(2015)008, NPHYS4109]
- State
  - New detector design: reduced drift
  - New electronics design: radiopure front end cards
  - Optimized lead shielding and 4π active muon veto
  - Neutron tagger system







Other BabyIAXO detectors under study

$f_D = \epsilon_d b^{-1/2}$

Other technologies under study

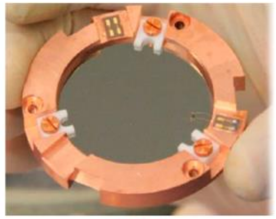
- IAXO as a generic infrastructure for axions and ALPs physics
- and R&D of alternative detectors with different properties
  - Excellent energy resolution, energy threshold, high efficiency and ultra-pure materials
  - Improve the energy threshold → investigation of fine structures in the axion spectrum

Post-discovery scenario

- If positive signal, low threshold + good energy resolution → possibility to determine m_a and g_{ae}
- Minimization of systematics effects and reinforcement of the claim significance

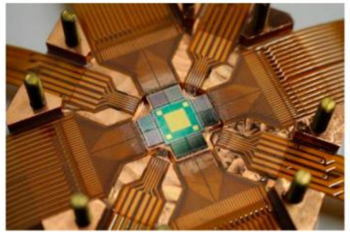
Status

- Design and material optimization ongoing in all fronts
- Background studies with different shielding configurations

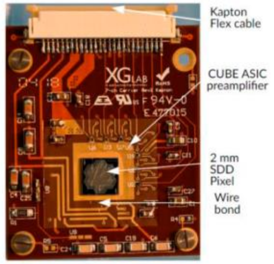


Transition Edge Sensors (TES)

Gridpix



Metallic Magnetic Calorimeter (MMC)



Silicon Drift Detectors (SDD)

Project tentative timeline

		2019	2020	2021	2022	2023	2024	2025	2026	2027	2028	2029+
BabyIAXO	Design											
	Construction											
	Commissioning											
BabyIAXO Data taking	Vacuum phase											
	Upgrade to gas											
	Gas phase											
	Beyond-baseline											
IAXO	Design											
	Construction					Tentative						

The IAXO Collaboration

...officially since 2017!

Full members: Kirchhoff Institute for Physics, Heidelberg U. (Germany) | IRFU-CEA (France) | CAPA-UNIZAR (Spain) | INAF-Brera (Italy) | CERN (Switzerland) | ICCUB-Barcelona (Spain) | Petersburg Nuclear Physics Institute (Russia) | Siegen University (Germany) | Barry University (USA) | Institute of Nuclear Research, Moscow (Russia) | University of Bonn (Germany) | DESY (Germany) | Johannes Gutenberg University - Mainz (Germany) | MIT (USA) | LLNL (USA) | University of Cape Town (S.Africa) | Moscow Institute of Physics and Technology (Russia) | Max Planck Institute for Physics, Munich (Germany) | CEFCA-Teruel (Spain) | (1 more in process to join + several expression of interest)

Associate members: DTU (Denmark) | U.Columbia (USA) | SOLEIL (France) | IJCLab (France) | LIST-CEA (France)

Summary

Thank you for your attention!

Axions and ALPs

- Hypothetical particles very well motivated by new physics
- Candidates to the DM

IAXO and babyIAXO

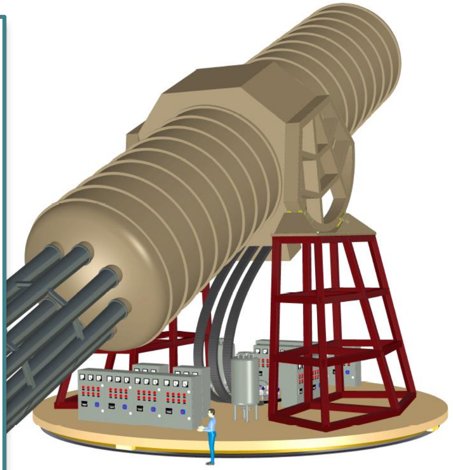
- Enhanced helioscopes
- To search for axions from the Sun with competitive sensitivity

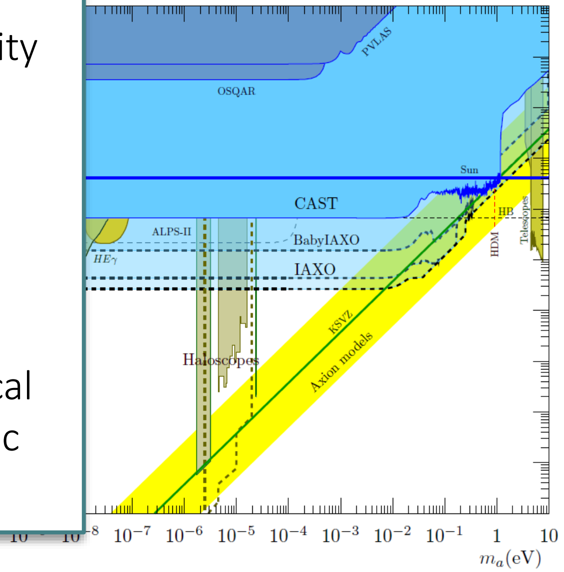
  BabyIAXO ~ 10^{-11} $|g_{a\gamma}|$ [GeV^{-1}]

  IAXO ~ 10^{-12} $|g_{a\gamma}|$ [GeV^{-1}]

Physics potential

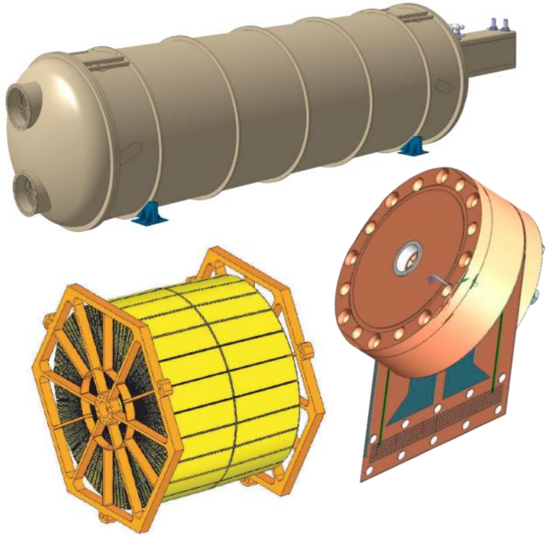
- QCD axions, ALPs, astrophysical hints, dark matter, more exotic physics...

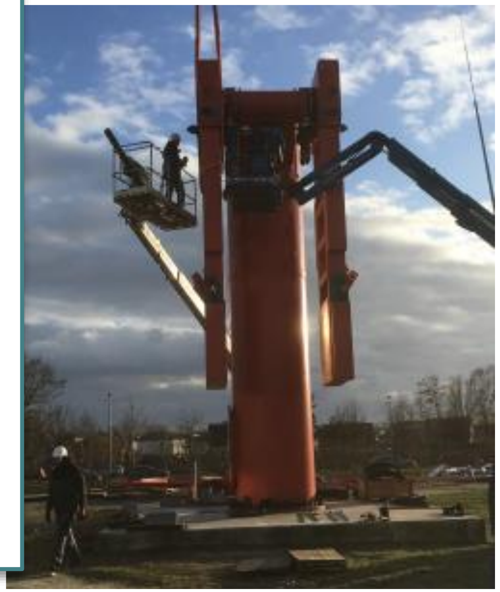




BabyIAXO status

- Magnet
  - SC cable being qualified
  - Almost ready to place orders
  - CERN backed
- Optics
  - Hybrid optics multilayer deposition tests and characterization to be published
  - ESA agreement in preparation
- Detectors
  - Baseline: background demonstration strategy on surface, underground and simulations
  - Other technologies: optimization and background studies
- To be hosted at DESY
- First physics ~ 2024





Back-up Slides

Axions

What are they?

Hypothetical pseudoscalar, neutral and very light elementary particle

Postulated by Weinberg and Wilczek from the Peccei-Quinn theory in 1978

Where do they come from?

Elegant solution to the Strong CP problem:

CP problem

CP violating term in QCD is not forbidden…
but CP violation → neutron electric dipole moment has **never** been observed!

→

Peccei-Quinn solution

Extension of the SM → new $U(1)_{PQ}$ symmetry spontaneously broken at hig scale f_a
→ new massive pseudo-NG boson: axion!

What are their properties?

Determined by the symmetry breaking scale f_a → Mass: $m_a \propto \frac{1}{f_a}$; Coupling constant: $g_{ai} \propto \frac{1}{f_a}$

- Natural couplings: gluons and photons
- Model-dependent couplings: fermions
  - DSFZ models: normal quarks and leptons carry PC charge
  - KSVZ models: new heavy quark that carry PQ charge

Experimental searches for axions and ALPs

Based on Primakoff effect: Axion-to-photon conversion in magnetic fields

Detection technique	Helioscopes	Haloscopes	Light Shining Through Walls (LSTW)
Source	**Solar Axions** Emitted by the solar core	**Relic Axions** Axions that are part of galactic dark matter halo	**Axions produced in the laboratory**
Concept	Magnet pointing to the Sun to allow axion-photon conversion inside (~keV)	Axion-photon conversion in a magnetic field inside of resonant cavities (matching resonant frequency)	Photon-axion-photon conversion in two different magnetic fields in the laboratory
Pros	- Based only on well known solar physics → less model dependent - Mature technology, scalable	- Tunable resonant frequencies → different m_a - QCD axions at reach	- Based only on axion-photon coupling → not model dependent
Cons	- Coherence limited by magnet length (buffer gas!)	- Higly dependent on axions being the DM of the universe	- Sensitivity penalized due to double axion-photon conversion

Parameter	Units	BabyIAXO	IAXO	IAXO+
B	T	$\sim$2	$\sim$2.5	$\sim$3.5
L	m	10	20	22
A	m^2	0.77	2.3	3.9
f_M	T^2m^4	$\sim$230	$\sim$6000	$\sim$24000
b	$keV^{-1}\,cm^{-2}\,s^{-1}$	1×10^{-7}	10^{-8}	10^{-9}
ϵ_d		0.7	0.8	0.8
ϵ_o		0.35	0.7	0.7
a	cm^2	2×0.3	8×0.15	8×0.15
ϵ_t		0.5	0.5	0.5
t	year	1.5	3	5

Table 1. Indicative values of the relevant experimental parameters representative of BabyIAXO as well as IAXO. The parameters listed are the magnet cross-sectional area A, length L and magnetic field strength B, the magnet figure of merit $f_M = B^2L^2A$, the detector normalized background b and efficiency ϵ_d in the energy range of interest, the optics focusing efficiency or throughput ϵ_o and focal spot area a, as well as the tracking efficiency ϵ_t (i.e. the fraction of the time pointing to the sun) and the effetive exposure time. We refer to [21] for a detailed explanation and justification of these values.

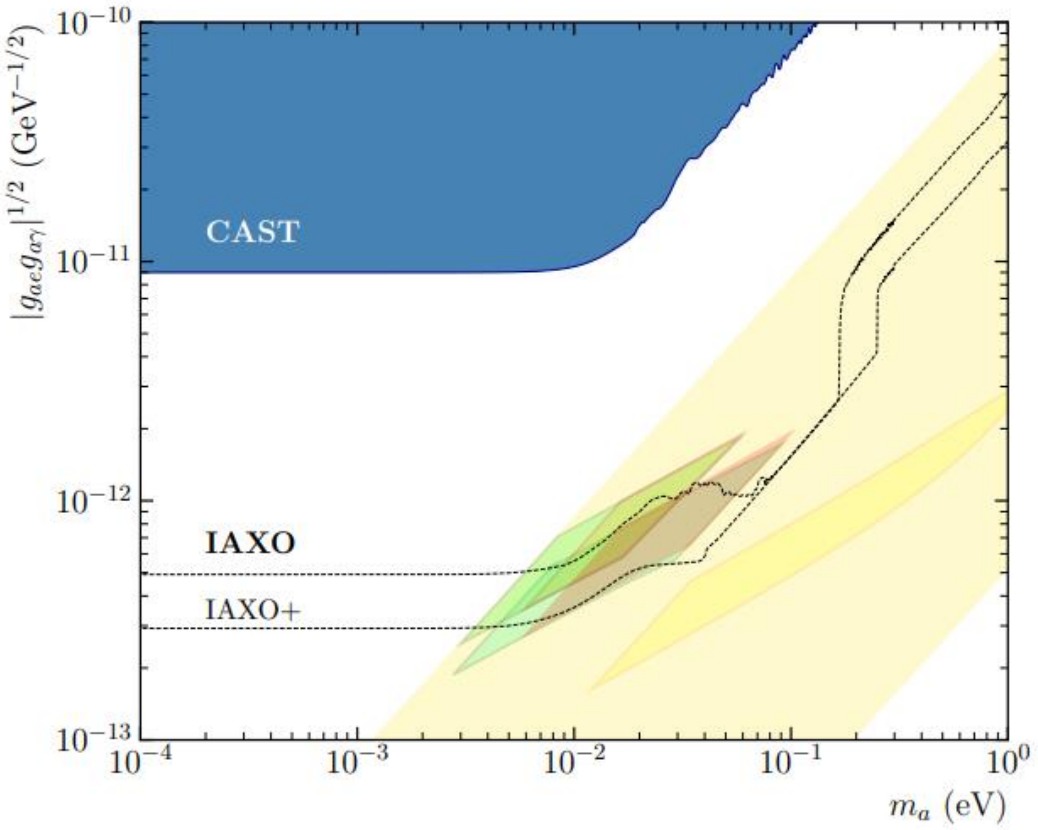
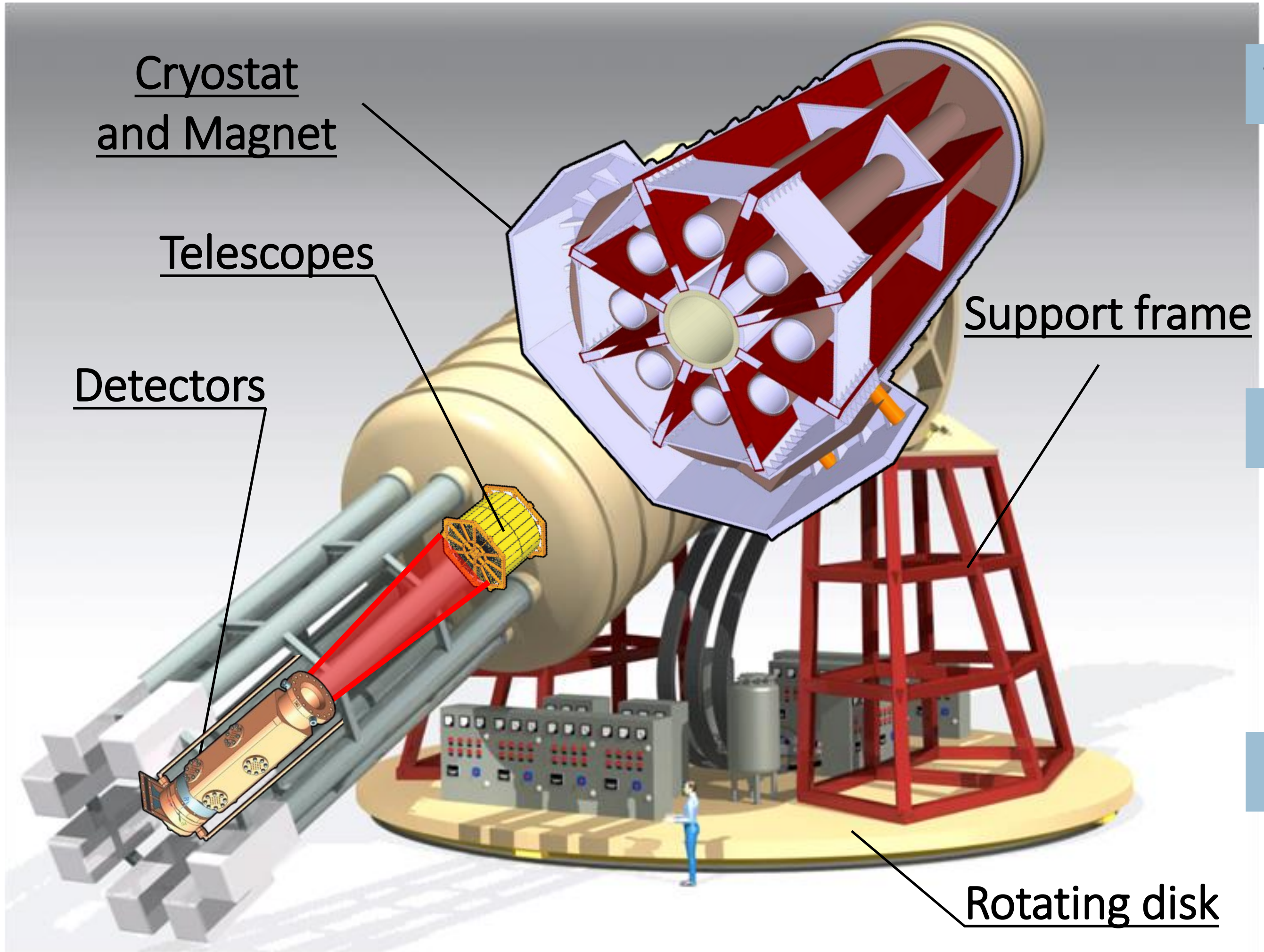


Figure 3. Sensitivity plot of IAXO to BCA (g_{ae}-mediated) solar axions, in the ($|g_{ae}g_{a\gamma}|^{1/2}$-$m_a$) parameter space. The yellow band corresponds to the QCD axion models and the diamond-shaped color regions correspond to particular QCD axion models that are able to fit all the anomalous stellar cooling observations, following [23].

International AXion Observatory (IAXO)

CERN-SPSC-2013-022; SPSC-I-242; JINST 9 (2014) T05002

IAXO - A 4th generation axion helioscope



Toroidal 8-coil NbTi magnet

$$f_M = B^2 L^2 A$$

- Magnetic field: 2.5T
- Magnet length: 20m
- Total aperture: 2.3m^2
- Rotating platform → 12h tracking

$$f_t = (\epsilon_t t)^{1/2}$$

8 x-ray Wolter I telescopes

$$f_O = \epsilon_o \alpha^{-1/2}$$

- Thin glass substrates
- Reflective coatings for axions range
- Focal length: 5m
- Spot area: 0.2cm^2

$$f_D = \epsilon_d b^{-1/2}$$

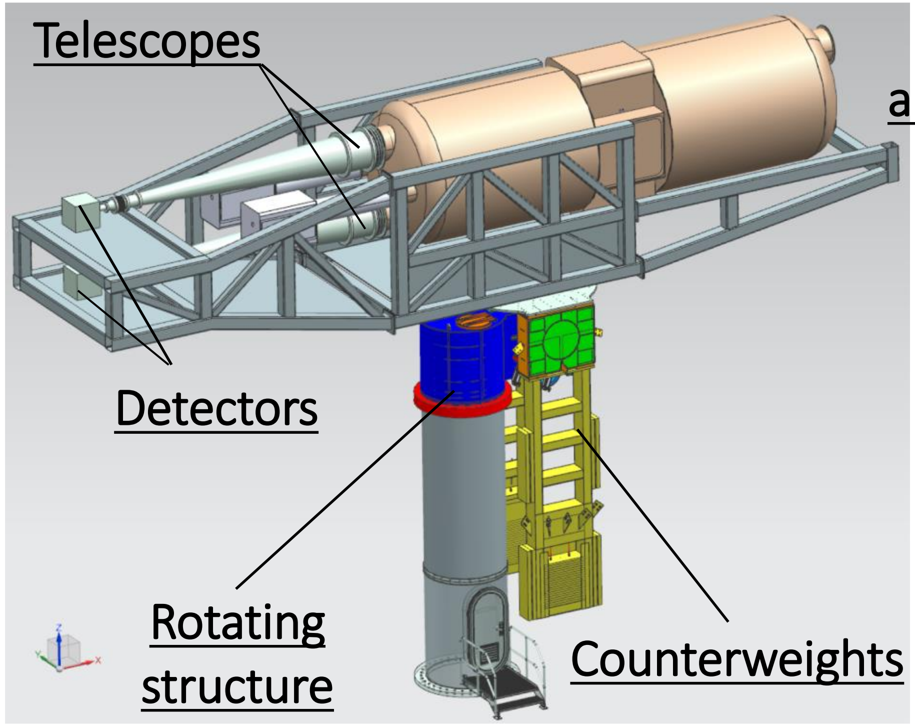
8 ultra-low background x-ray detectors

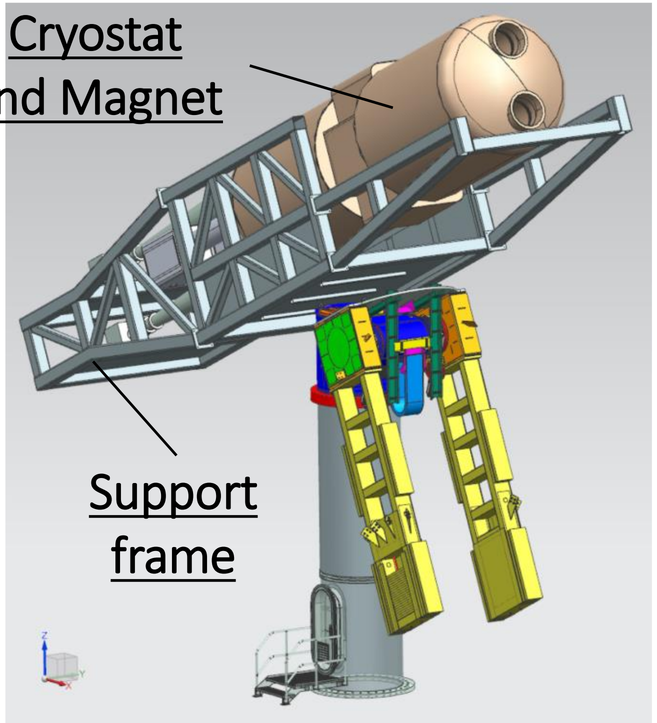
- Radiopure microbulk Micromegas
- Background: 10^{-7}-10^{-8} counts keV^{-1} cm^{-2} s^{-1}

BabyIAXO at DESY

First step: Baby IAXO

- Technological prototype of IAXO
- Relevant physical outcome
- Improvement of the baseline experimental parameters
  → IAXO enhancement
- Collaboration growth and consolidation

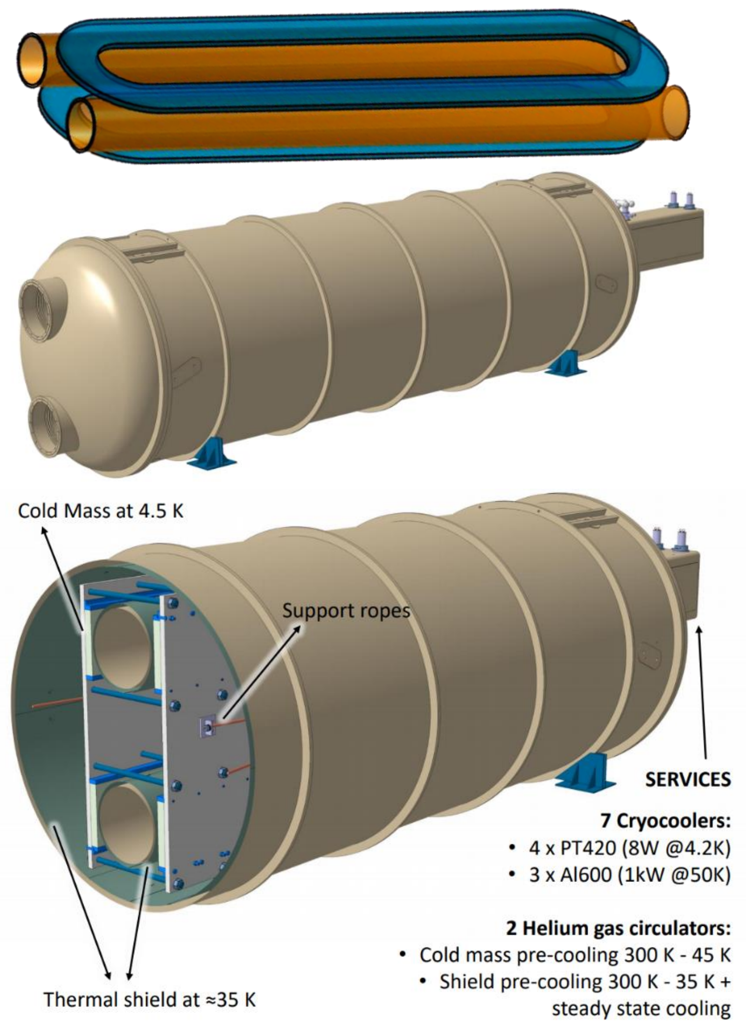




Magnet

$$f_M = B^2 L^2 A$$

Design: 2 coil and 2 bore NbTi/Cu magnet



Common coil design

- Simple and cost-efficient
- 2 flat racetrack coils
  - 10m long
  - 12 strands of NbTi/Cu (coextruded with Al)

Bores

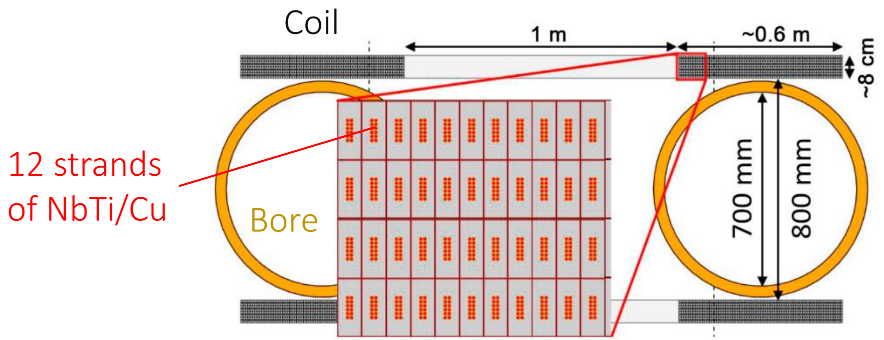
- Vacuum and buffer gas
- 2 bores
  - 0.7m diameter
  - 10m long

Cryostat

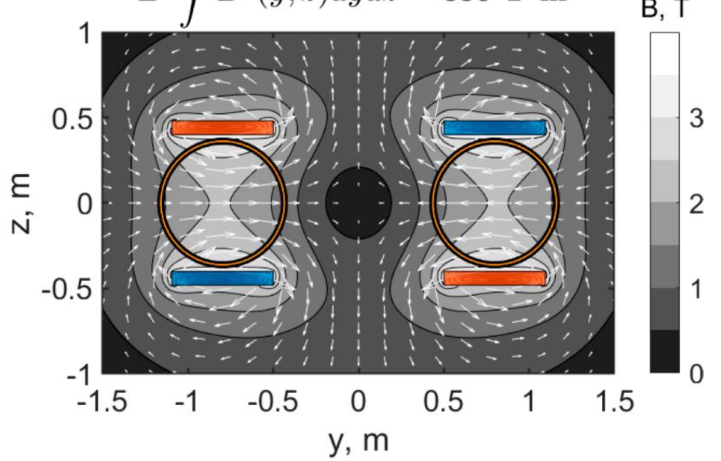
- Al5083-O alloy
- Thermal shield ~35K
- Dry cooling system with cryocoolers

Layout and magnetic field

Optimized layout: **maximum magnetic field** at bores

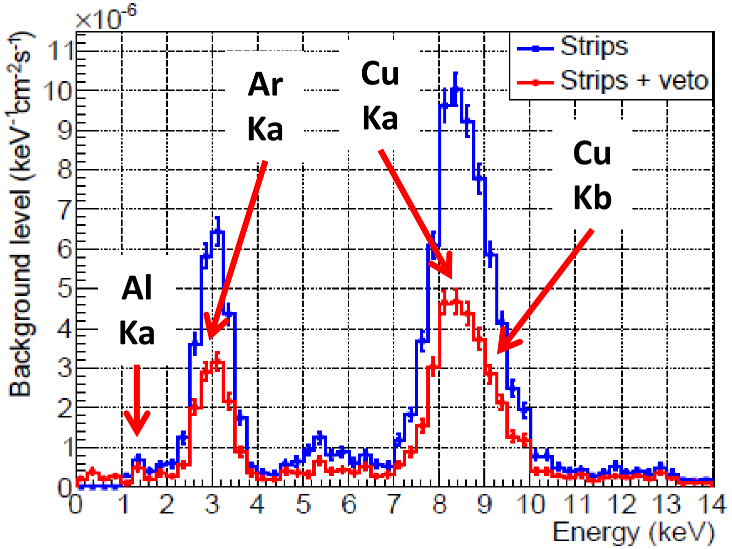


$$L^2 \int B^2(y,z)dydz = 330\ \mathrm{T^2m^4}$$



IAXO pathfinder performance

JCAP12 (2015) 008; NPHYS4149 !!!



Best background level

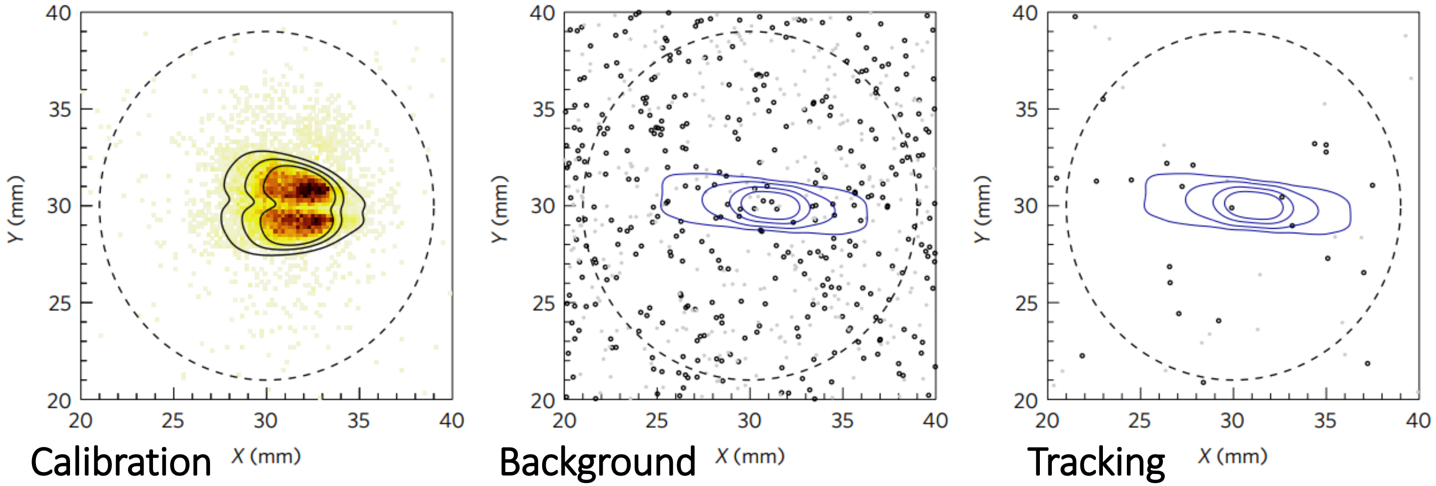
at the RoI [2,7] keV & all detector area

Strips + veto: (1.0 ± 0.2) x 10^{-6} counts $keV^{-1}cm^{-2}s^{-1}$

Spectrum dominated by

- Cu escape peak at 8 keV
- Ar fluorescence line at 3 keV

2D hitmap of events

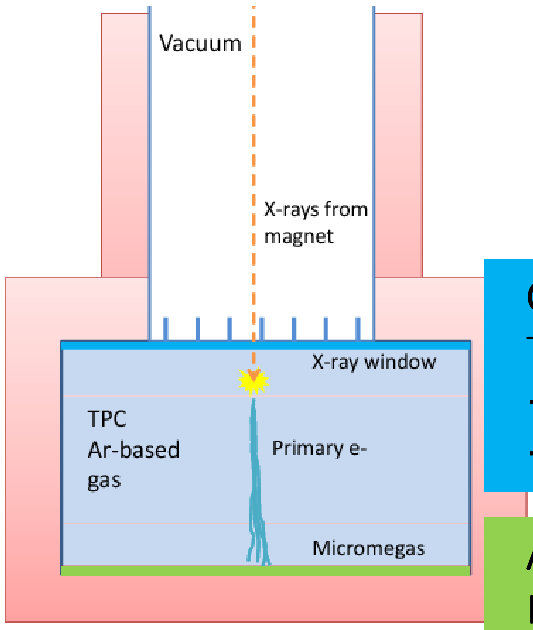


- ● Muon veto coincidences
- ○ Final counts
- — (99%) 95%, 85% and 68% signal-encircling regions (simulations)

Micromegas detection principle

Time projection chamber (TPC)

Step 1: Conversion region



Cathode:
Thin x-ray window
→ Gas tight
→ x-ray transparent

Anode:
Micromegas readout

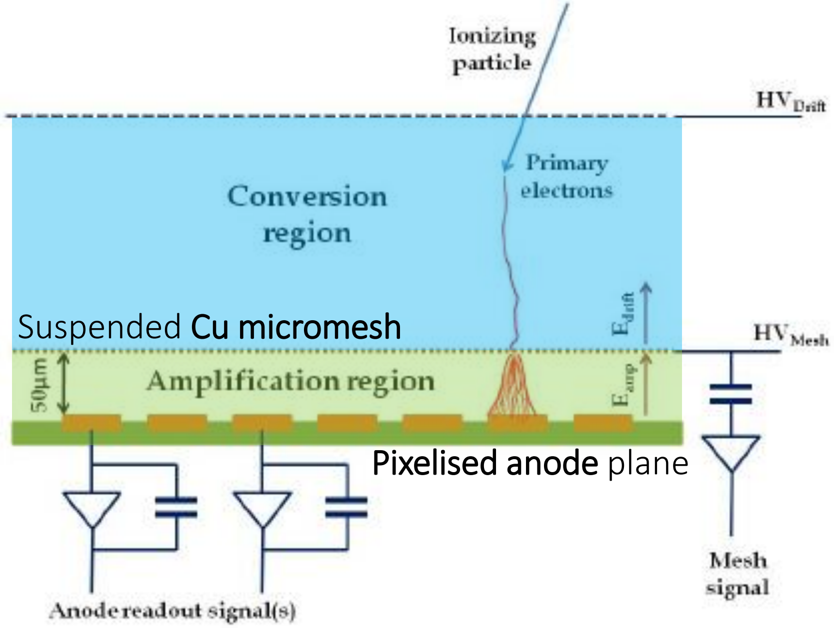
TPC working principle:

1. Ionizing radiation creates primary charges
2. Primary charges drift towards the anode
   → enter the amplification region

+

Micromegas Readout

Step 2: Amplification region



Micromegas working principle:

1. Primary e^- go through mesh holes
2. Trigger an e^- avalanche in the gap
   → detectable signals at mesh and anode