Solar Axion Searches with BabyIAXO

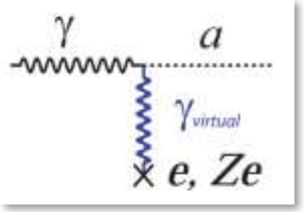
Ana Quintana García on behalf of the IAXO Collaboration

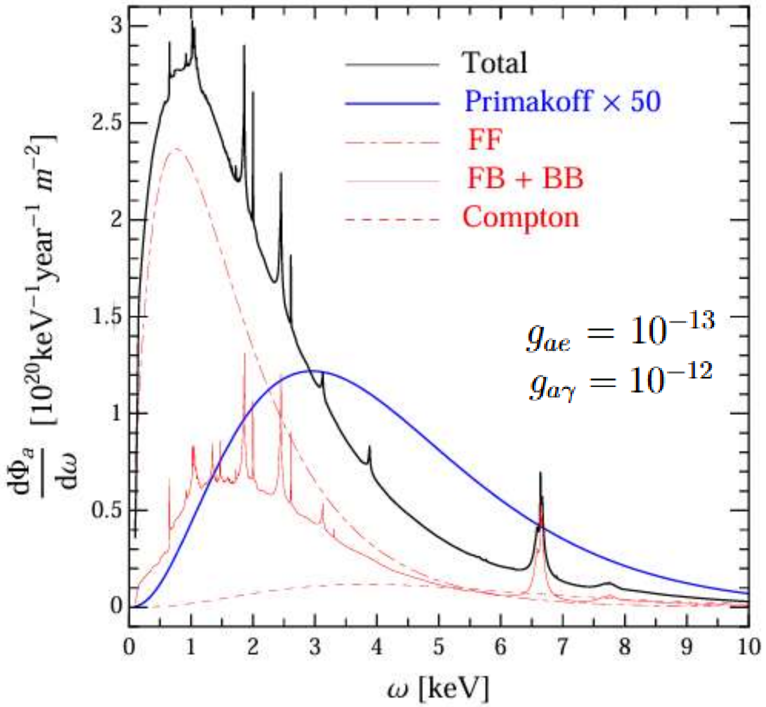
16th International Workshop on the Identification of Dark Matter 2026
Zaragoza-Spain, 2th June 2026

Contents

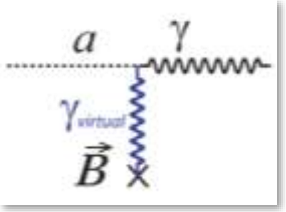
- Solar axions and helioscopes
- Next generation: BabyIAXO and IAXO
- BabyIAXO subsystems
- X-ray detectors for (Baby)IAXO
  - Microbulk Micromegas

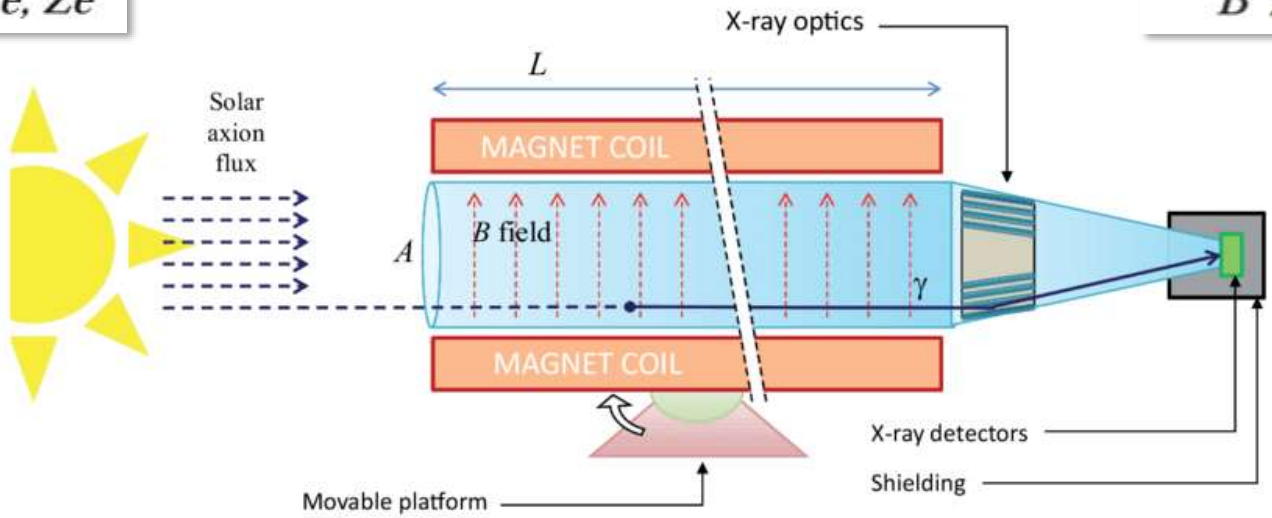
Production: stars produce axions from thermal photons via Primakoff effect





Detection: conversion of axions into photons in the presence of a magnetic field



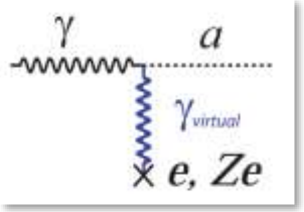


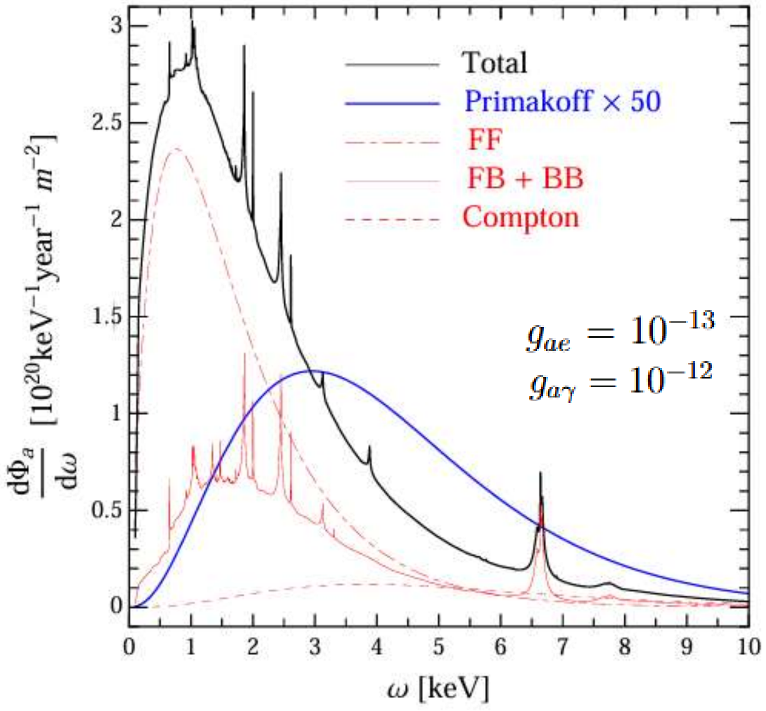
Expected X-ray excess when the magnet points to the Sun

Figure of Merit (FOM)

$$FOM \sim f_{Magnet} \times f_{Detector} \times f_{Optics} \times f_{Exposure}$$

Production: stars produce axions from thermal photons via Primakoff effect





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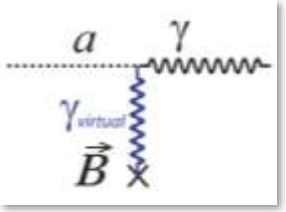
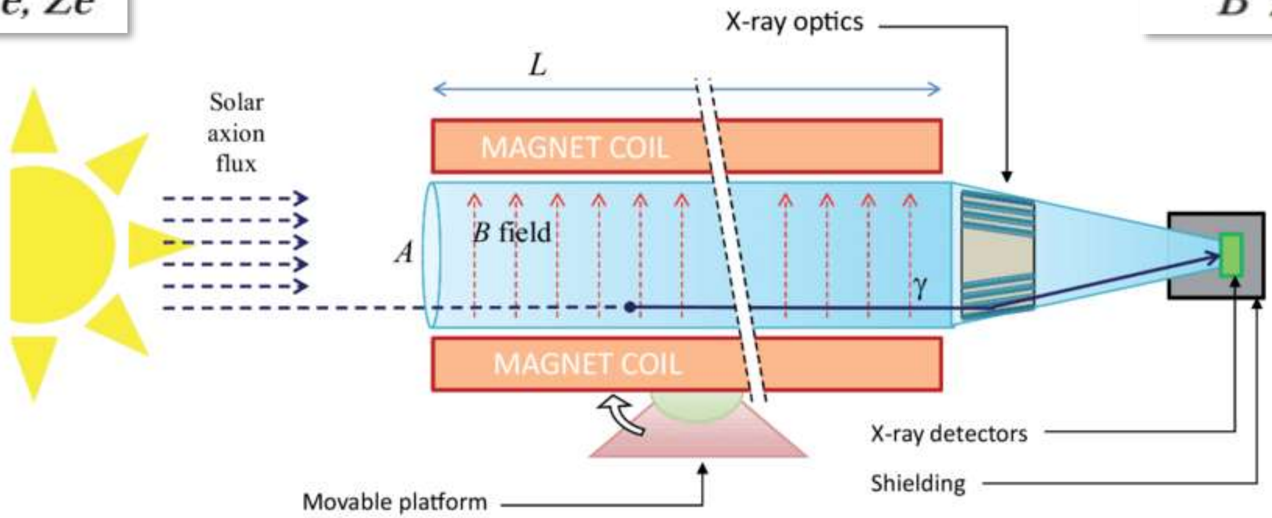




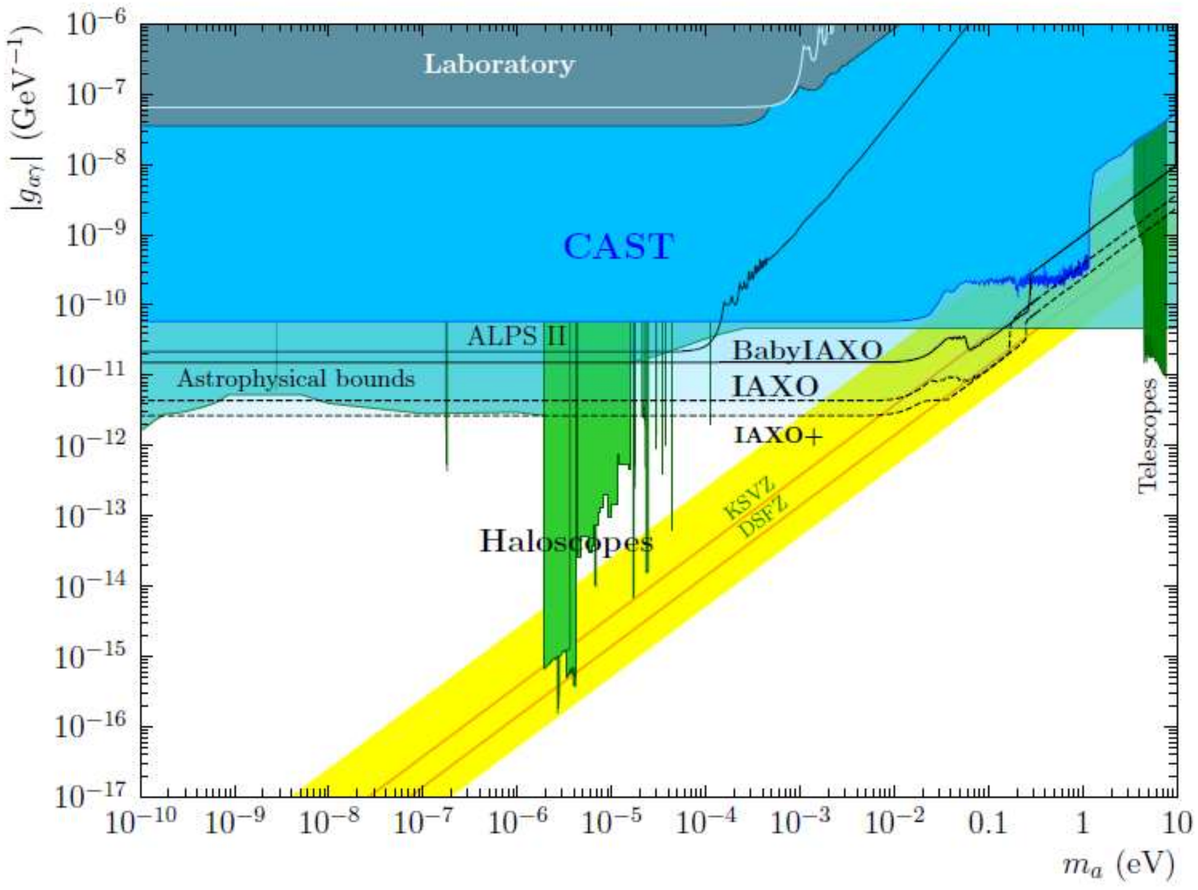
Expected X-ray excess when the magnet points to the Sun

Figure of Merit (FOM)

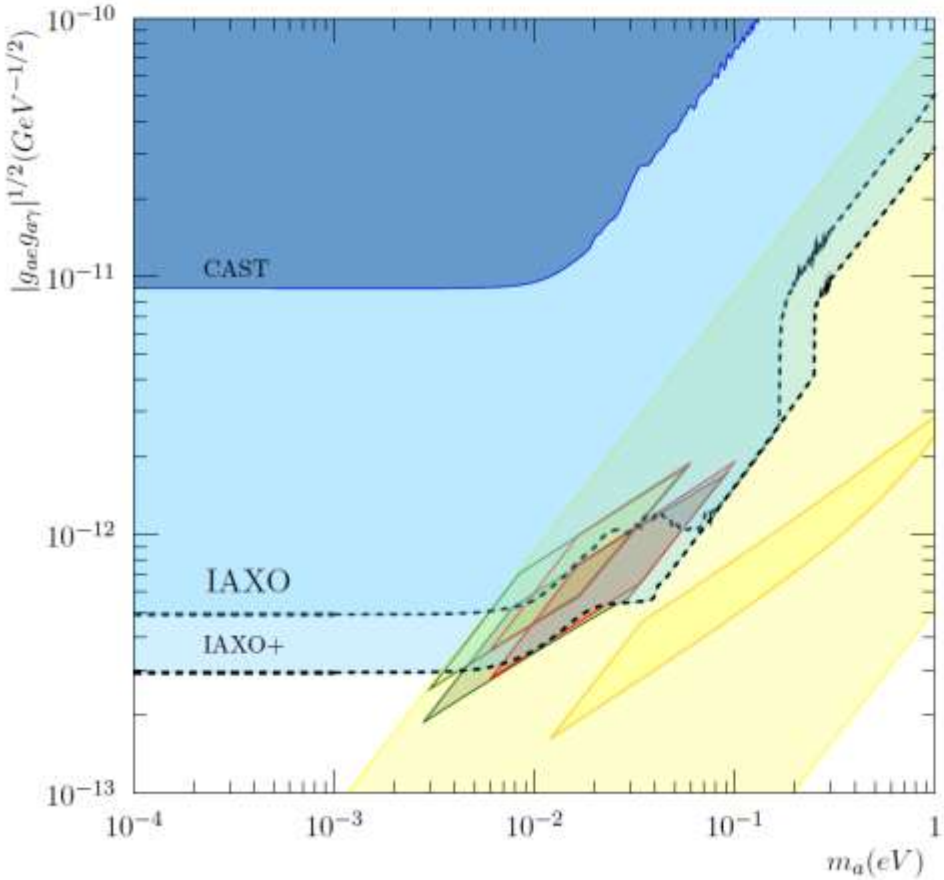
	Magnet		Detector		Optics		Exposure
$g_{a\gamma}^{-4} \sim$	$B^2 L^2 A$	$\times$	$\varepsilon_d b^{-1/2}$	$\times$	$\varepsilon_0 \alpha^{-1/2}$	$\times$	$\varepsilon_t^{1/2} t^{1/2}$

https://github.com/iaxo/axion-limits

Solar axion photon flux



Solar axion electron flux



State of the art: CAST

Next generation: (Baby)IAXO

(Baby)IAXO: a generic axion (ALP) facility

- Beyond Pimakoff axions (ALPs): $g_{a\gamma} - m_a$

Non-primakoff solar axions
g_{ae} g_{aN}

10.1088/1475-7516/2025/07/075

Axions from close-by supernovae

DM axions: Haloscope setups

10.1088/1475-7516/2019/06/047

Other WISPs: hidden (dark) photons, chameleons …
And also high-frequency GW!

Post-discovery “precision” physics (solar B and T, axion mass and model)

CAST specifications

CERN Axion Solar Telescope

- The most sensitive helioscope so far
- Operation period 2003-2021

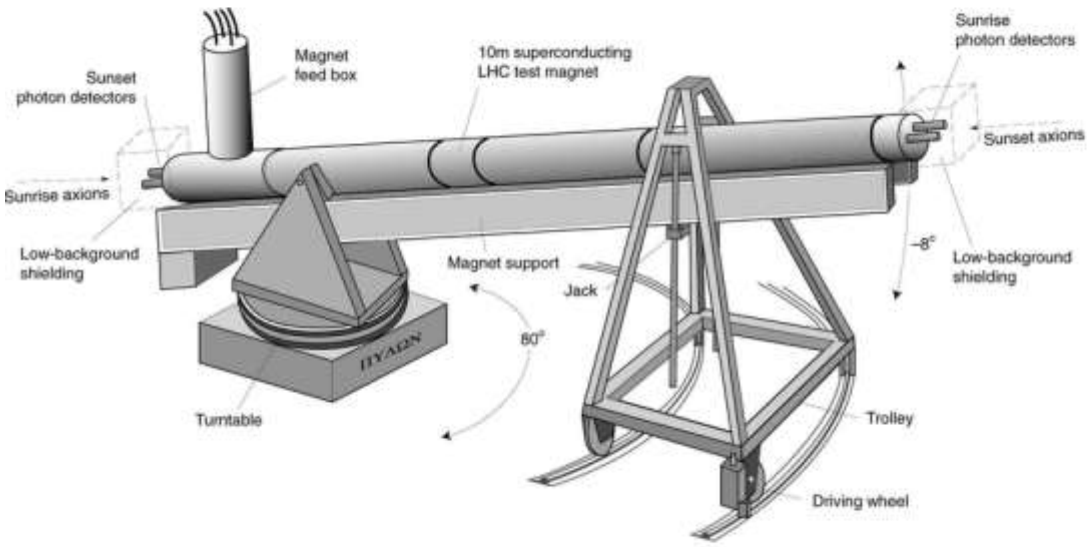
❖ Tracking system:
  - Solar tracking 3h per day (ε = **0.12**)

❖ Magnet:
  - Decommissioned prototype **LHC dipole**
  - **L = 10 m, B = 9 T, A = 15 cm^2**

❖ Optics:
  - Focusing optics at sunset detectors
  - IAXO pathfinder: NuSTAR telescope

❖ Detectors:
  - $\sim$ 1-2 $\times$ 10^{-6} counts/(keV cm^2 s)
  - Best results with **Microbulk Micromegas**

$g_{a\gamma} < 5.7 \times 10^{-11}$ **GeV^{-1} for** $m_a < 0.02$ **eV (95% C.L.)**

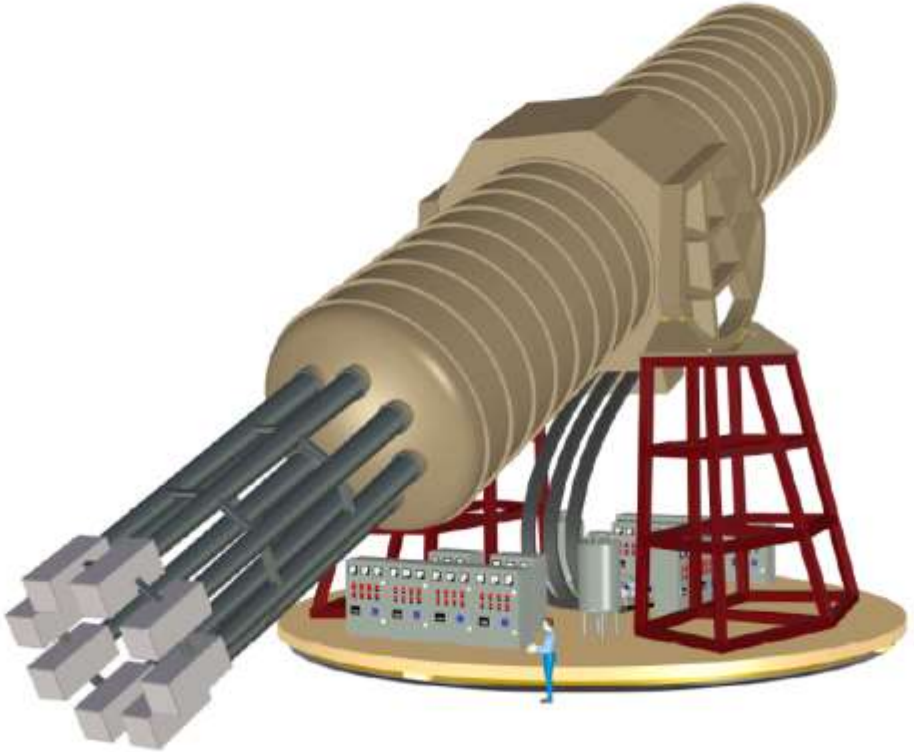


[Phys. Rev. Lett 133.22 (2024): 221005.]

International AXion Observatory

- Next generation: Enhanced helioscope

- Tracking system:
  - Solar tracking 12h per day (**ε = 0.5**)
- Magnet:
  - Toroidal with **8** coils
  - **L = 20 m, B = 3.5 T, A = 70-80 cm Ø**
- Optics:
  - X-ray telescope from NuSTAR mission
- Detectors:
  - High efficiency and resolution in RoI [0-10]keV
  - Bkg requirement: 10^{-8} counts/(keV cm^2 s)
  - Baseline: **Microbulk Micromegas**
  - Other technologies: GridPix, SDD, MMC, TES



10.1088/1748-0221/9/05/T05002

FOM 10^4 that of CAST **sensitivity to $g_{a\gamma}$ factor 10 that of CAST**

Intermediate state to International AXion Observatory

- Tracking system:
  - Solar tracking 12h per day (ε = **0.5**)
  - Based on CTA
- Magnet:
  - Common-coil, 2 bores
  - L = 11 m, B = 2-2.5 T, A = 70 cm Ø
- Optics:
  - XMM XRT
  - Custom made (NuSTAR based)
- Detectors:
  - High efficiency and resolution in RoI [0-10]keV
  - Bkg requirement: 10^{-7} counts/(keV cm^2 s)
  - Baseline: Microbulk Micromegas
  - Other technologies: GridPix, SDD, MMC, TES

FOM factor 100 better than CAST

10.1007/JHEP05(2021)137

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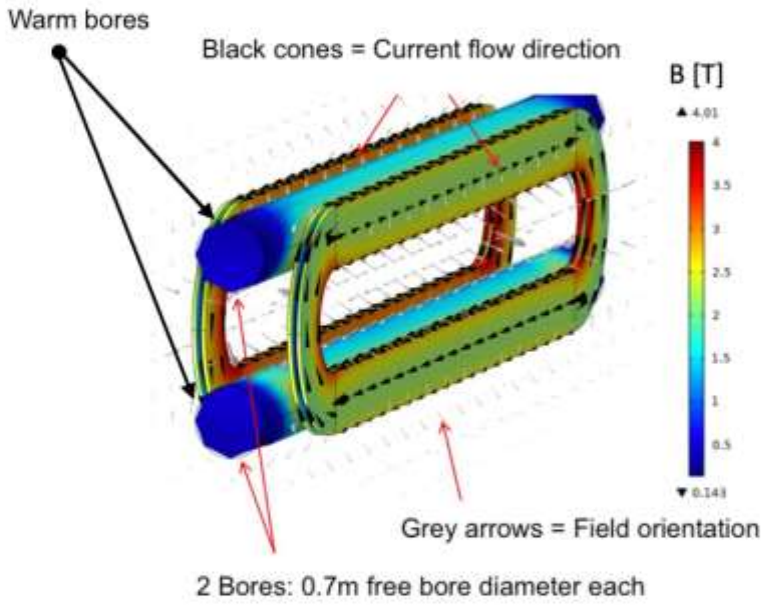

$f_M = 290$ T^{2}m^4 (×14 f_M of CAST)

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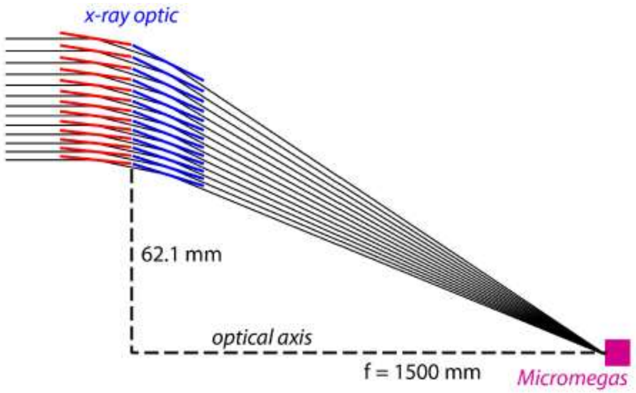


NuSTAR based XRT

- Mirrors in 124 nested layers
- $a \sim 0.2$ cm^2
- 10 layer prototype tested

XMM XRT

- Spare XRT from XMM-Newton mission
- $a \sim 0.3 - 0.7$ cm^2

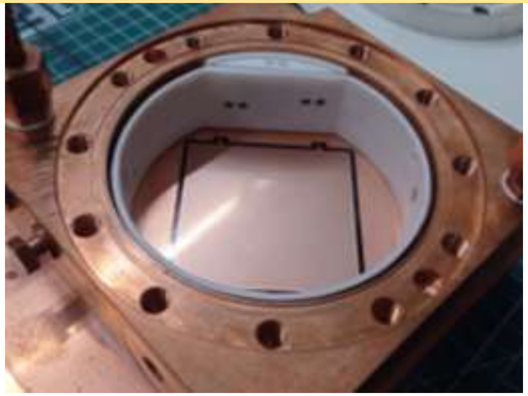
BabyIAXO specifications: low-background detectors

Intermediate state to International AXion Observatory

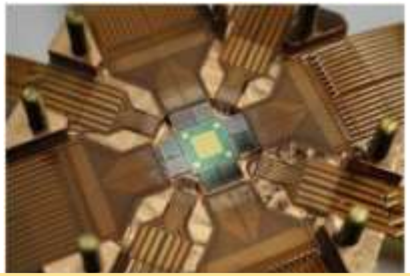
- Tracking system:
  - Solar tracking 12h per day (ε = **0.5**)
  - Based on CTA
- Magnet:
  - Common-coil, **2** bores
  - **L = 11 m, B = 2-2.5 T, A = 70** cm Ø
- Optics:
  - XMM XRT
  - Custom made (NuSTAR based)
- Detectors:
  - High efficiency and resolution in RoI [0-10]keV
  - Bkg requirement: **10^{-7} counts/(keV cm^2 s)**
  - Ideally:
    - Good energy resolution
    - Low energy threshold

GridPix TPC

Microbulk Micromegas TPC



SDD: Silicon Drift Detectors



MMC: Metallic Magnetic Calorimeters

TES: Transition Edge Sensors

Intermediate state to International AXion Observatory

- Tracking system:
  - Solar tracking 12h per day (ε = **0.5**)
  - Based on CTA
- Magnet:
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- Detectors:
  - High efficiency and resolution in RoI [0-10]keV
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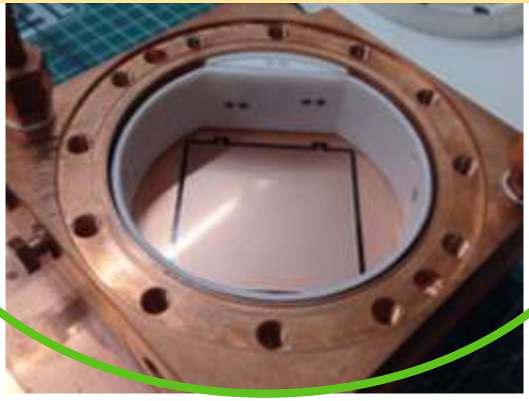
GridPix TPC

Microbulk Micromegas TPC



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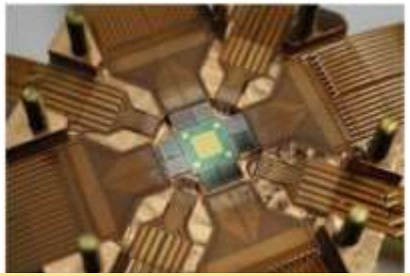

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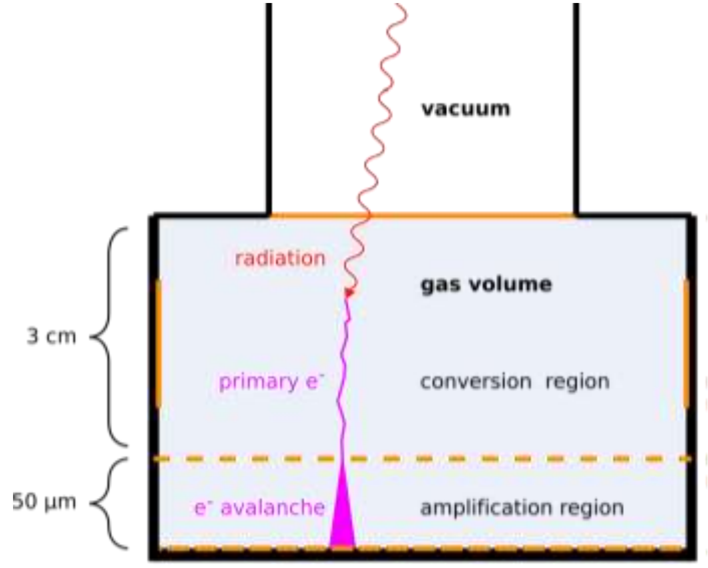
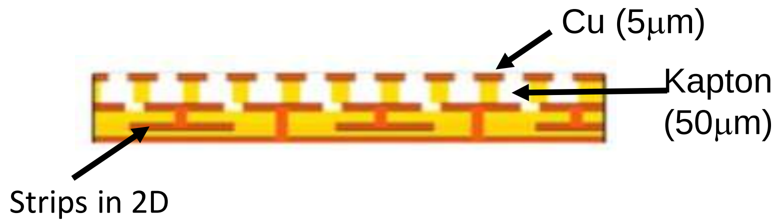
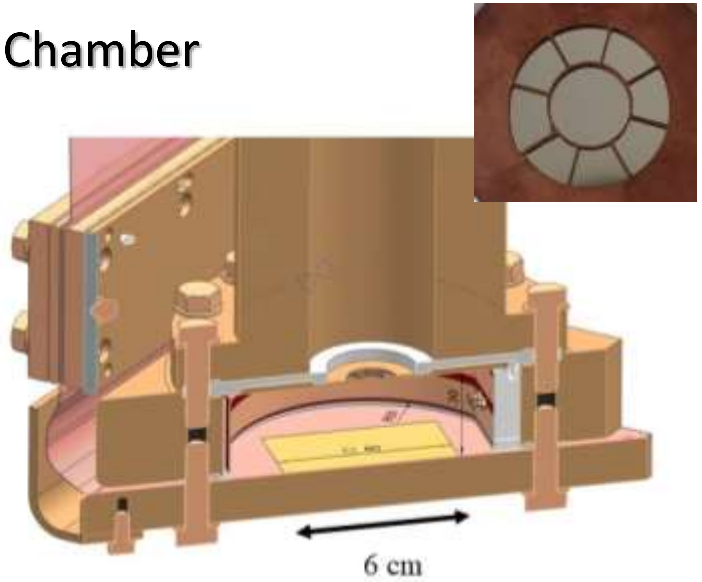
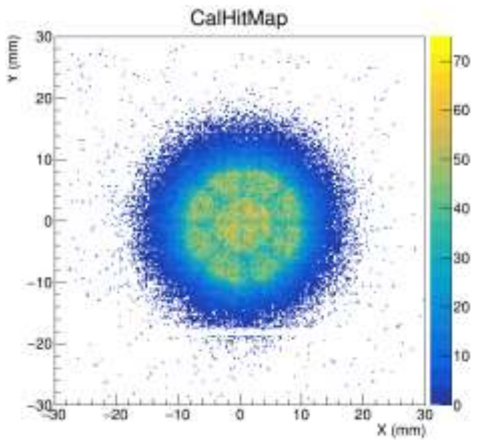


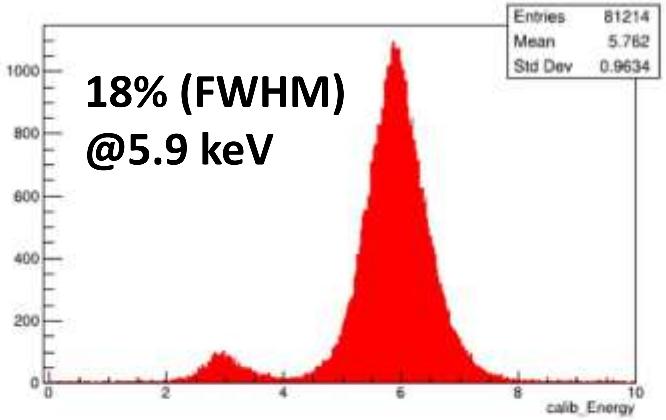
- 3 cm drift distance **Gaseous Time Projection Chamber**
- **Microbulk Micromegas readout**
  - 50 µm amplification gap
  - 120 x 120 strips (6 x 6 cm^2)





- ✓ Very homogeneous amplification gap, uniform gain
- ✓ Microbulk: intrinsically radiopure
- ✓ Good energy resolution: ~ 10 – 20 % FWHM
- ✓ Good spatial resolution: ~ 100 µm
- ✓ Pixelized readout gives topological information



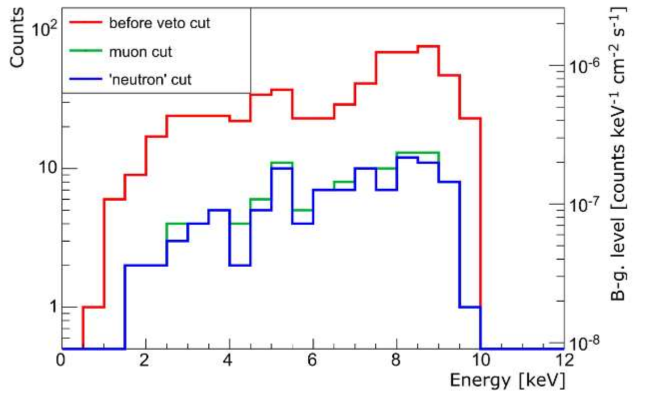


State of the art on ultra-low background techniques: IAXO-D1

- IAXO pathfinder (CAST)
- Muon cut: veto system
- Neutron cut: multilayer veto

Background in [2-7] keV, r < 1 cm

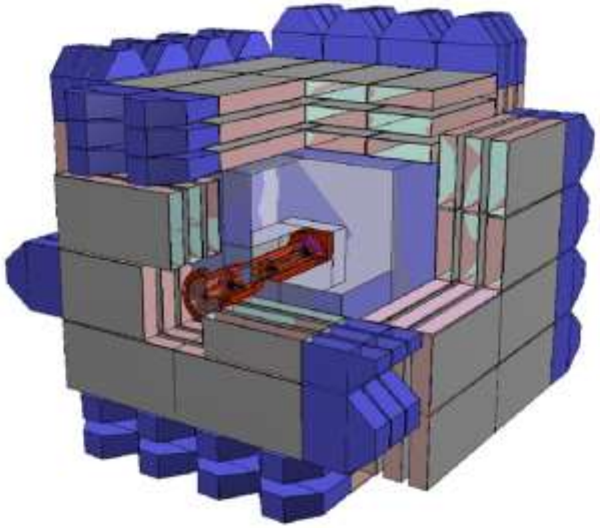
(8.6 ± 1.2) x 10^{-7} counts/keV·cm^2·s

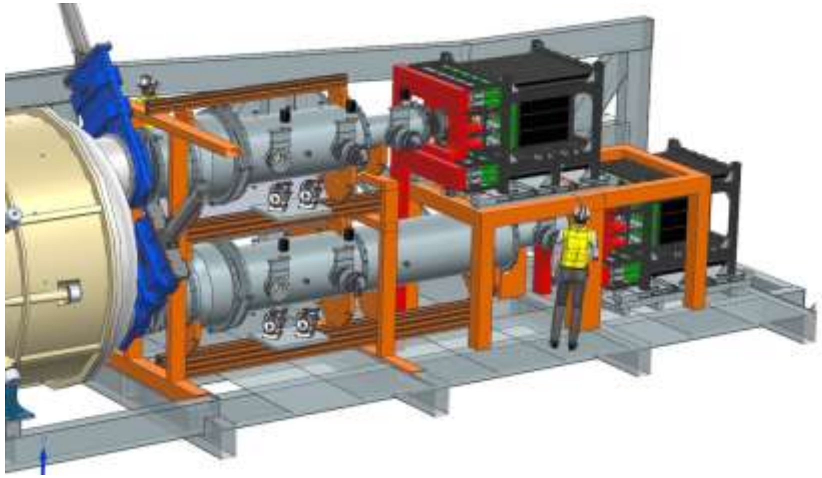


[Frontiers in Physics 12 (2024): 1384415.]

- Radiopurity
- Shielding
  - Radiopure copper: 2.5 cm
  - Passive: 20 cm of lead
  - Active: veto system (plastic scintillators) for cosmic rays induce events.
- Event discrimination strategies
  - Micromegas: event topology
  - Veto system: multiplicity

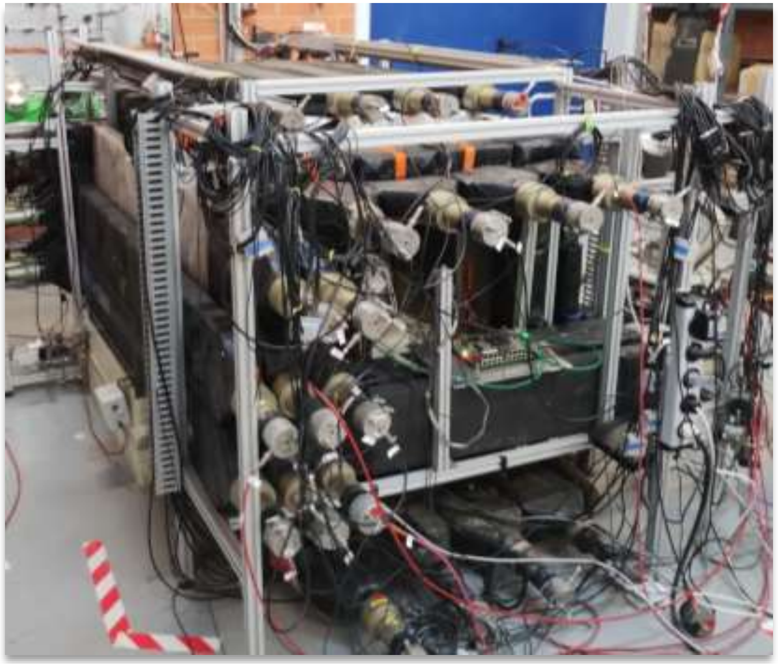
REST-for-Physics





BabyIAXO: MM protypes and performance

@Zaragoza



- On surface
- Effect of multi-layer veto system to tag cosmogenic neutrons (in addition to muons)

@CEA-Saclay / @DESY

- On surface
- Used for spatial resolution study
- Background measurement on experimental site (w. different shieldings)

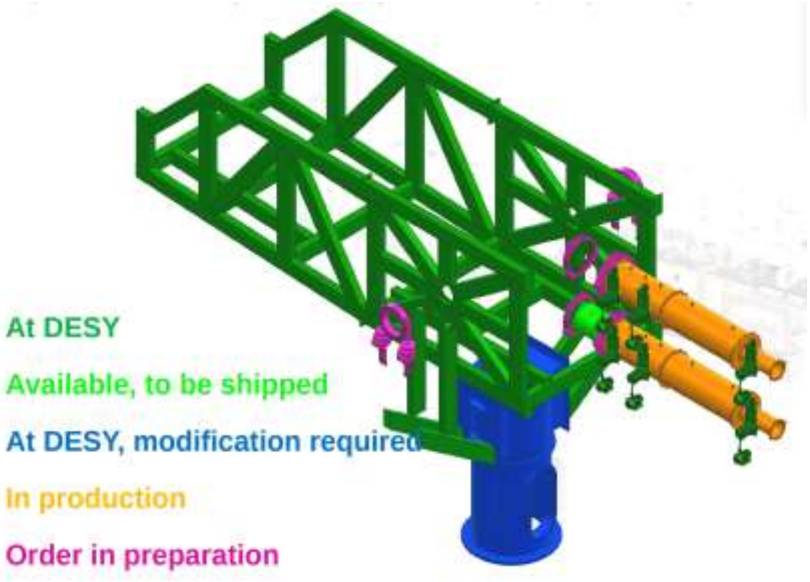
@LSC

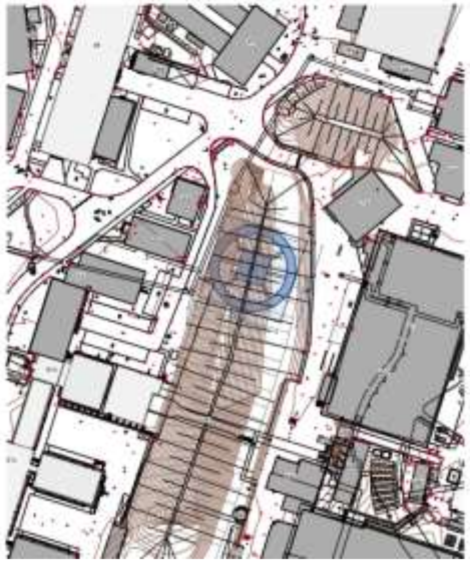
- Underground
- Intrinsic detector background
- Test of different gas mixtures
- $\sim$ 1-2 $\times$ 10^{-7} c/(keV cm^2 s)

- BabyIAXO is under construction at DESY, Hamburg.
  - Towards a magnet-less commissioning before 2028: Dark Photons physics run.

- Two detector systems mM + optics to be ready.
  - With on-going R&D: reducing Rn sources and optimise the active shielding.

- BabyIAXO will have competitive results on solar axions and could explore more physics cases





Current BabyIAXO timeline:
- **2026**: Site activation
- **2027**: *magnetless*-commissioning
- **2028**: dark photon run
- **2029**: magnet installation
- **2030+**: commissioning + axion runs

Thank you for your attention!

Acknowledgments

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In particular, we acknowledge support from:

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Y UNIVERSIDADES

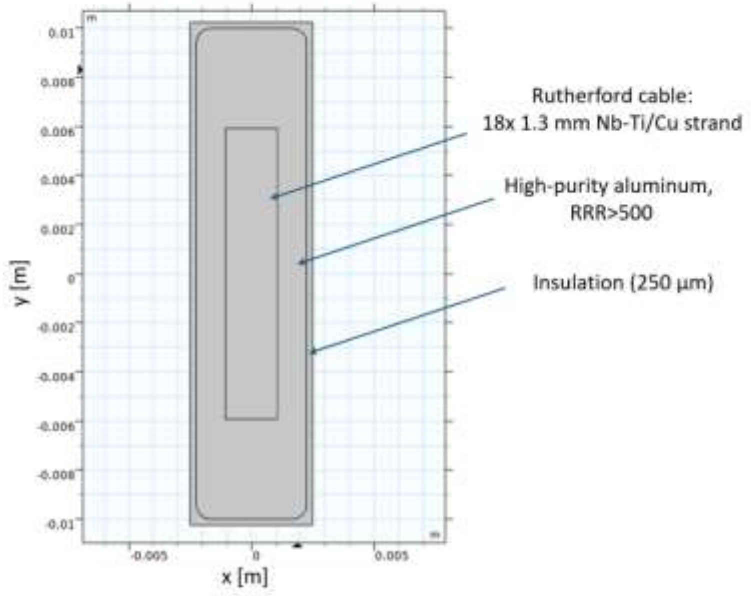
Plan de
Recuperación,
Transformación
y Resiliencia

BACKUP SLIDES

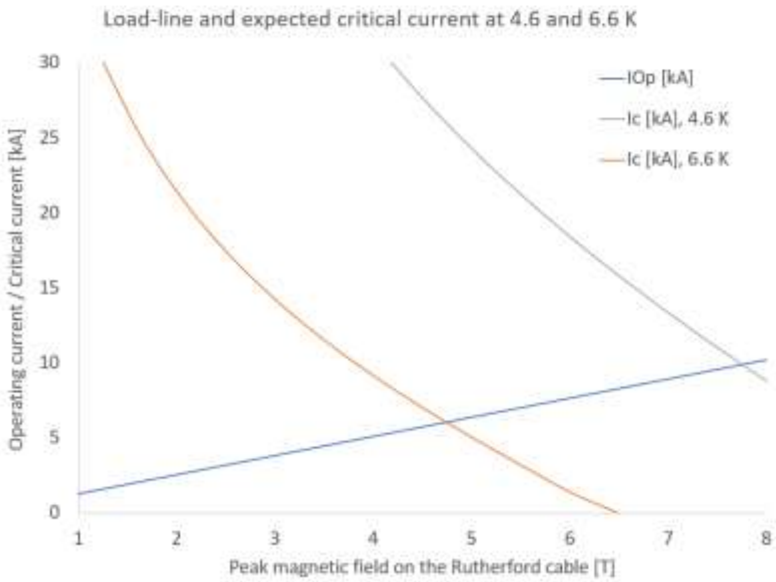
FOM of CAST, BabyIAXO, IAXO and IAXO+

Parameter	Units	CAST	BabyIAXO	IAXO	IAXO+ (enhanced)
B	T	9	~ 2	~ 2.5	~ 3.5
L	m	9.26	11	20	22
A	m^2	0.003	0.77	2.3	3.9
f_M^*		1	~ 14	~ 300	~ 1000
b	$\frac{\text{counts}}{\text{keV cm}^2\text{ s}}$	1×10^{-6}	1×10^{-7}	$\sim 10^{-8}$	$\sim 10^{-9}$
ϵ_d		~ 0.6	0.7	0.8	0.8
ϵ_o		0.3	0.35	0.7	0.7
a	cm^2	0.15	2×0.3	8×0.15	8×0.15
f_{DO}^*		1	~ 2	11	35
ϵ_t		0.12	0.5	0.5	0.5
t	year	1	1.5	3	5
f_T^*		1	2.5	3.5	4.5
f^*		1	~ 70	$\sim 10^4$	$\sim 10^5$

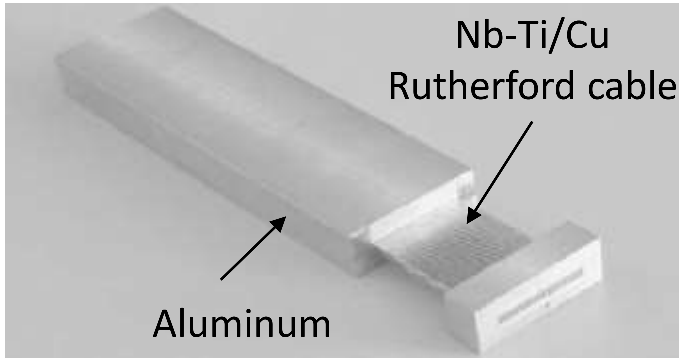
BabyIAXO: Superconducting Magnet



Conductor geometry



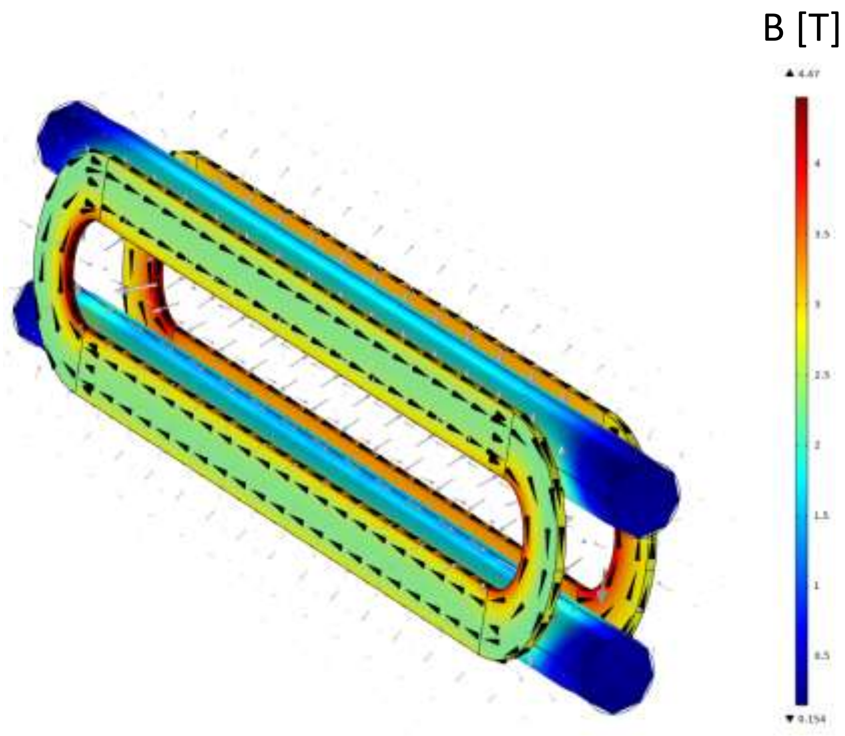
Magnet operating load line



Example of an aluminum-stabilized Nb-Ti/Cu conductor (pull-out sample for CMS)

- Metric for the useful magnetic field component: the so-called Magnet-Figure-of-Merit.
- When powered at the operating current of 6 kA, the coils generate 2.1 T in the warm bores on average.
- **Resulting Magnet-Figure-of-Merit at 6 kA: 290 T^2m^4.**

BabyIAXO: Superconducting Magnet



Magnet 3D coil geometry, current direction, and resulting magnetic field (homogeneous current density approximation)

Parameter	Value
Operating current [kA]	6.0
Free bore diameter	0.7
Transverse magnetic field during operation [T]	2.1
Stored magnetic energy [MJ]	56
Inductance [H]	3.1
Cold mass weight [tons]	38
Energy density [kJ/kg]	1.5
Overall coil conductor length [km]	22
Conductor length per pancake [km]	2.5
Peak magnetic field magnitude on the Rutherford cable [T]	4.7

Overview of various parameters

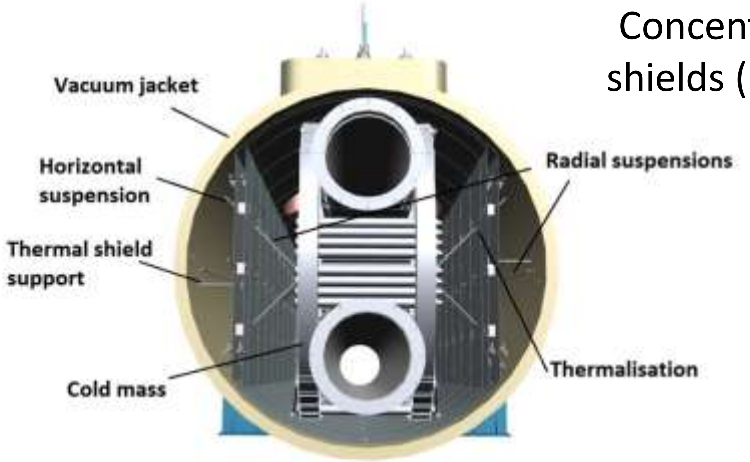
- 22 km of aluminum-stabilized conductor is needed.
- Stored magnetic energy of 56 MJ at the operating current of 6.0 kA.

Integrated cryogenics:
- Using cryo-coolers integrated into the magnet vacuum vessel itself, rather than an external cryogenic plant.

Multiple elements to be cooled:
- Cold mass at T < 5 K → Cooled with liquid helium from phase separator via thermosiphon (gravity-driven circulation)

- Two concentric thermal shields, to mitigate low cooling budget at 4.5 K:
  - 25 K thermal shield → Cryocooler + helium-gas cooling, circulated with cryo-fan.
  - 50 K thermal shield, intercepting most of the thermal radiation from room temperature → Cryocoolers + helium-gas cooling, circulated with cryo-fan.

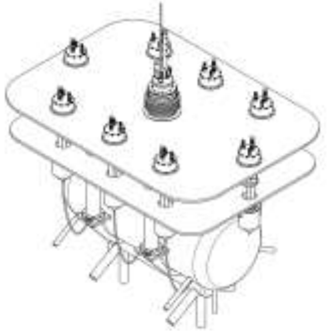
Concentric thermal shields (25 and 50 K)

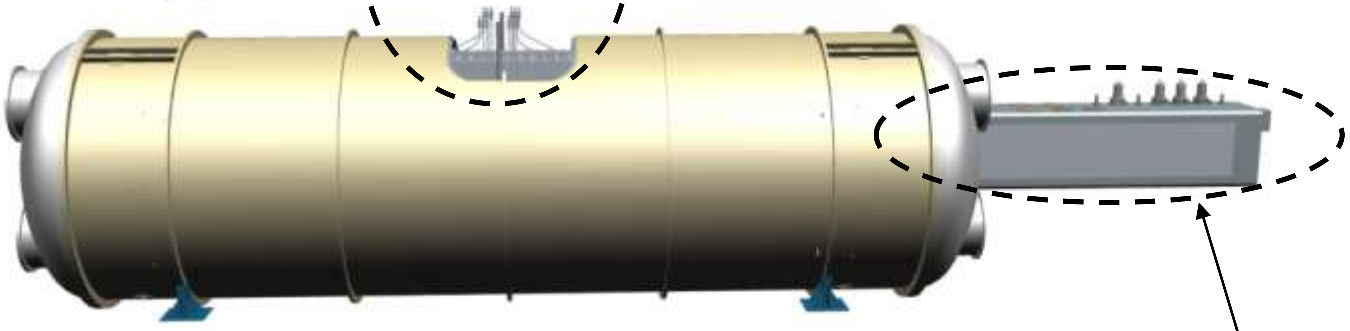


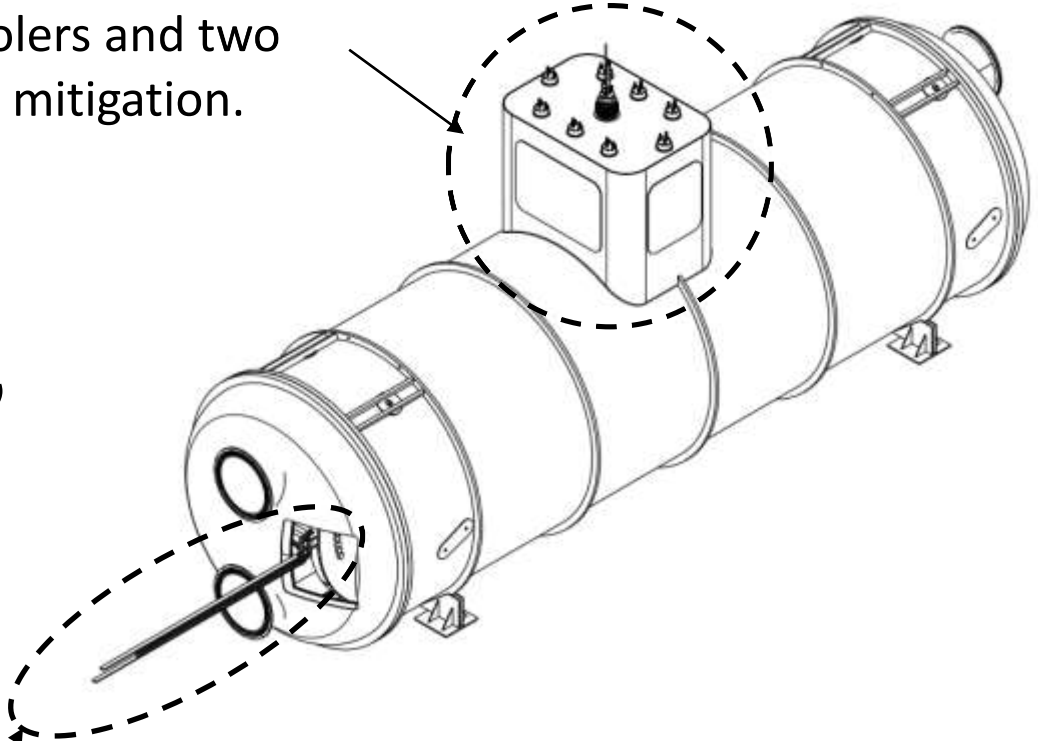
Cold mass, concentric thermal shields and coil suspension

BabyIAXO: Magnet cryogenics

Cryogenics turret, featuring six two-stage PT425 cryocoolers and two spare slots for risk mitigation.



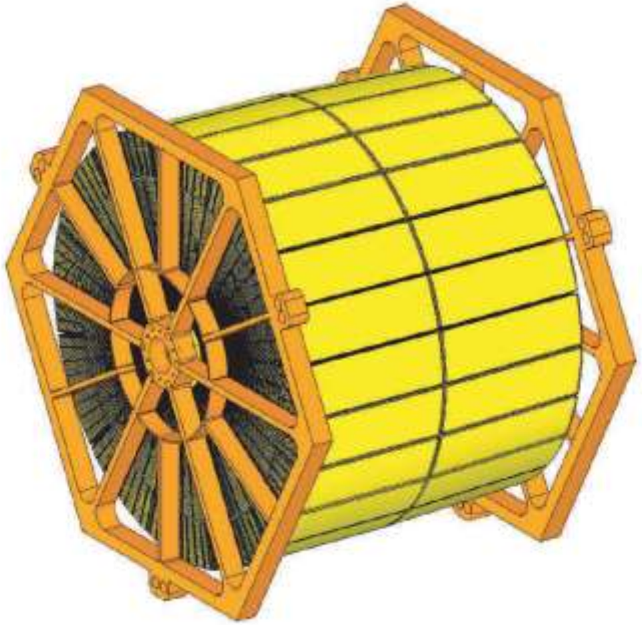


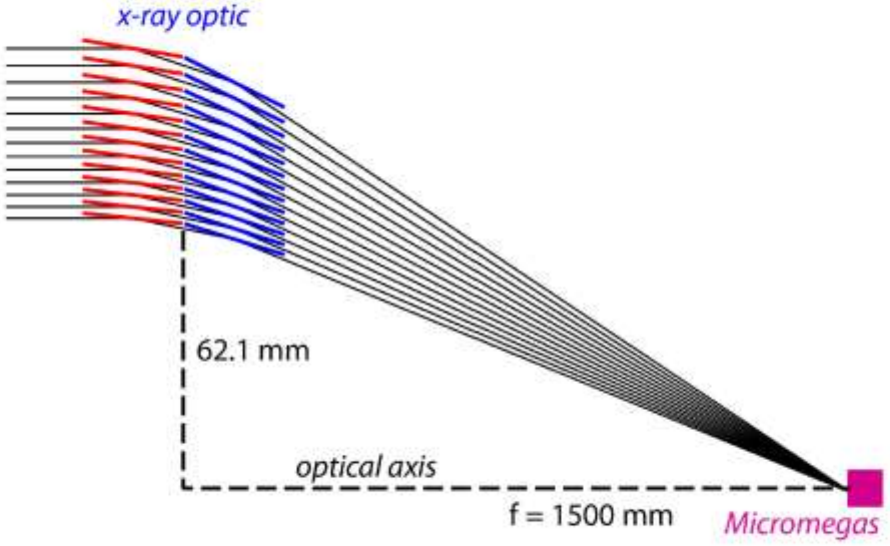


Two main cryogenic elements:

- Cryogenics turret, providing thermosiphon liquid helium cooling (4.5 K).
- Service box, providing gaseous helium cooling (25 and 50 K).

Service box, featuring three Al-600 cryocoolers, one Al630 cryocooler, three cryo-fans for helium gas circulation, and spare slot for additional cryo-cooler, as well as HTS-based current leads and vacuum pumps.





- Need to cover bore aperture.
- Reflecting in mirrors with small grazing angle.

NuSTAR based XRT

- Mirrors in 124 nested layers
- Inner region: hot-slumped, multilayer-coated glass (as NuSTAR).
- Outer region explores cold-slumped glass techniques.
- $a \sim 0.2\ \text{cm}^2$
- 10 layer prototype tested.

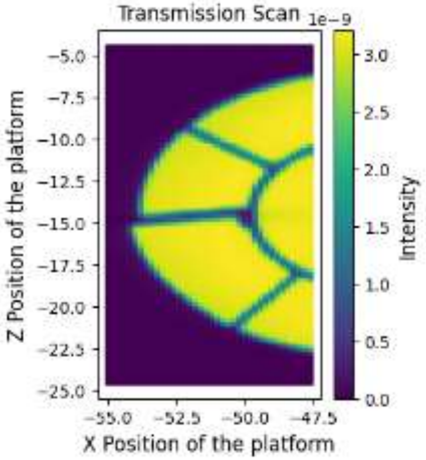
XMM XRT

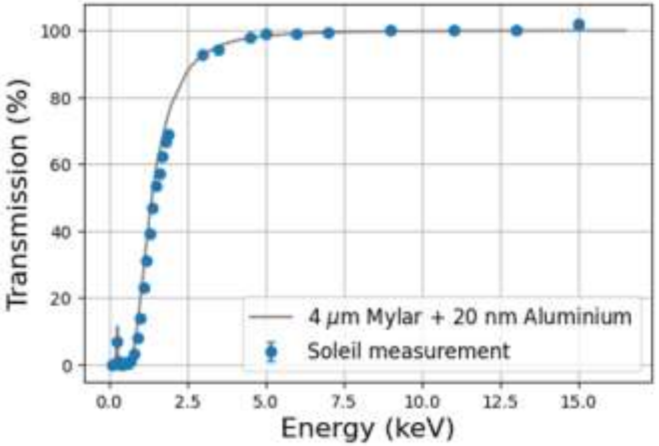
- Spare XRT from XMM-Newton mission (ESA).
- Fulfils BabyIAXO requirements.
- $a \sim 0.3 - 0.7\ \text{cm}^2$
- Recalibrated @PANTER.

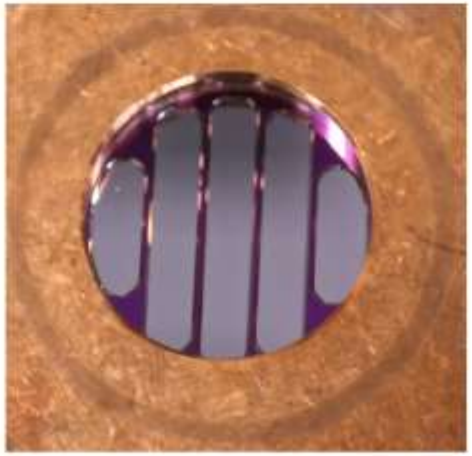
BabyIAXO: Vacuum beanlines

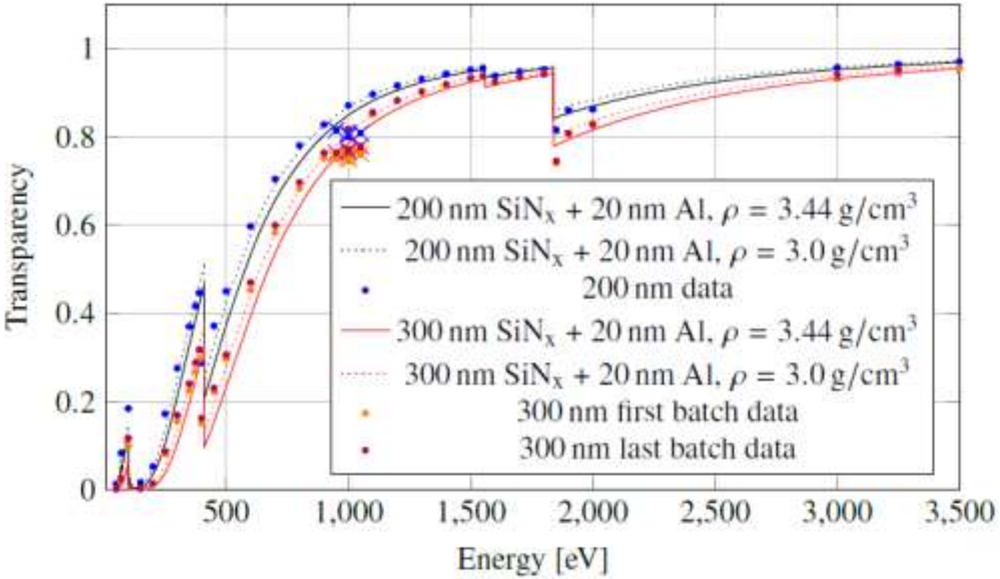
Large vacuum beamlines just finished

- X-ray transmission window for the Microbulk Micromegas: 4μm aluminised mylar (measured at SOLEIL).
- **Ultra-thin silicon nitride windows**: Lower energy threshold and 80% transparency at 1keV (BCA flux peak).



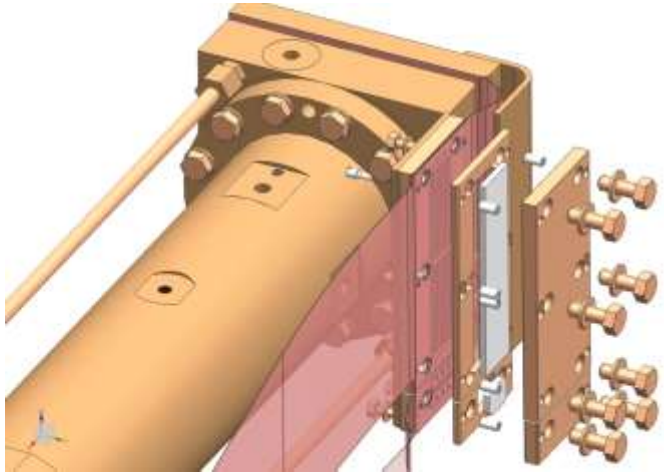






arXiv:2605.12234

Electronics



- BabyIAXO Micromegas electronics based on the a AGET chip (ASIC for Generic Electronic system for TPCs)
- The 64-channel ASIC performs the amplification, detection and analog storage of the shaped detector signal before its digitization by an external 12-bit ADC
- Large flexibility in sampling frequency (100 MHz max.)
- Peaking time (16 values from 50 ns to 1 /ls)
- Gain (4 ranges from 120 fC to 10 pC per channel)
- Resolution < 850 e- (Gain: 120 fC; Peaking Time: 200 ns; Cdetector < 30 pF)

FEMINOS: digital board to read out a front-end card equipped with AGET chips

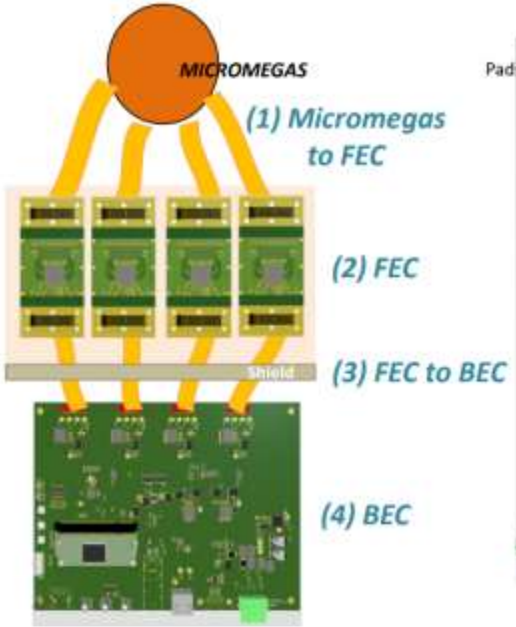
Front End Card AGET

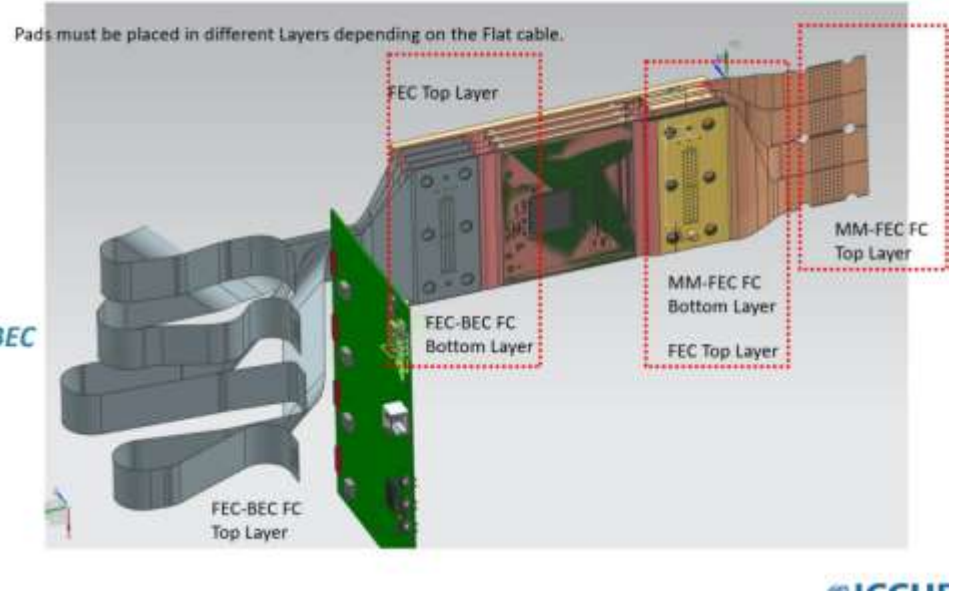
FEMINOS

AGET: S. Anvar et al., AGET, the get front-end asic, for the readout of the time projection chambers used in nuclear physic experiments, IEEE Nucl. Sci. Symp. Conf. Rec. (2011)
FEMINOS: Anvar et al., "The readout electronics and data acquisition system of the MINOS vertex tracker," 2014 19th IEEE-NPSS Real Time Conference, Nara, Japan, 2014, pp. 1-5, doi: 10.1109/RTC.2014.7097530.

Electronics(future)

- Readout noise as low as possible for low energy threshold
- New architecture of the existing system in order to improve the electronic noise: approach the front end cards (FEC) to the detector and improve the radiopurity of the components
- Optimization of the FEC locations to study the electronics effect on the background of the detector





Being tested now

Data analysis:

Rare Event Searches Toolkit software

REST-for-Physics v2.3

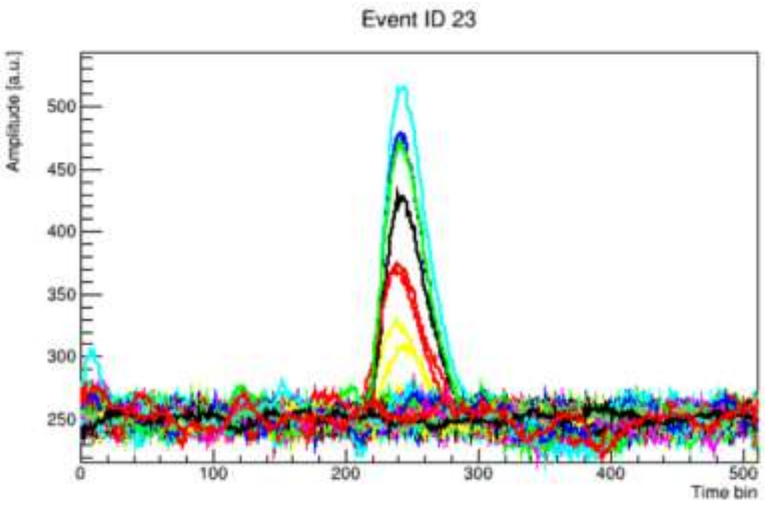
Rare Event Searches ToolKit for Physics

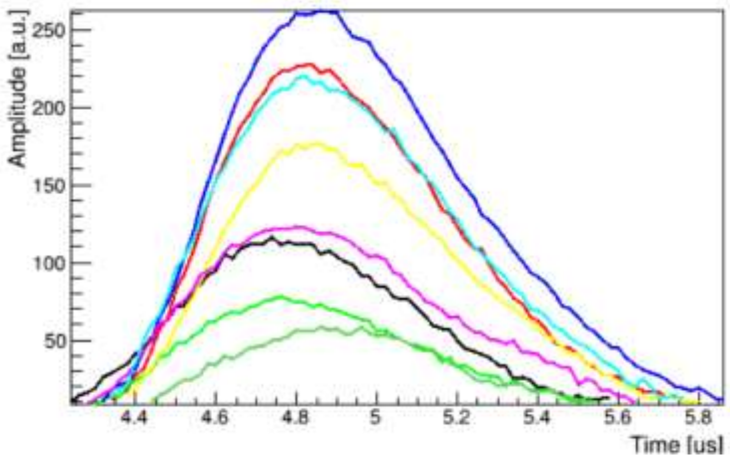
https://inspirehep.net/literature/1921138

TRestRawSignal → TRestDetectorSignal →

Gas mixture:

XeNeISO





Data analysis:

REST-for-Physics v2.3

Rare Event Searches ToolKit for Physics

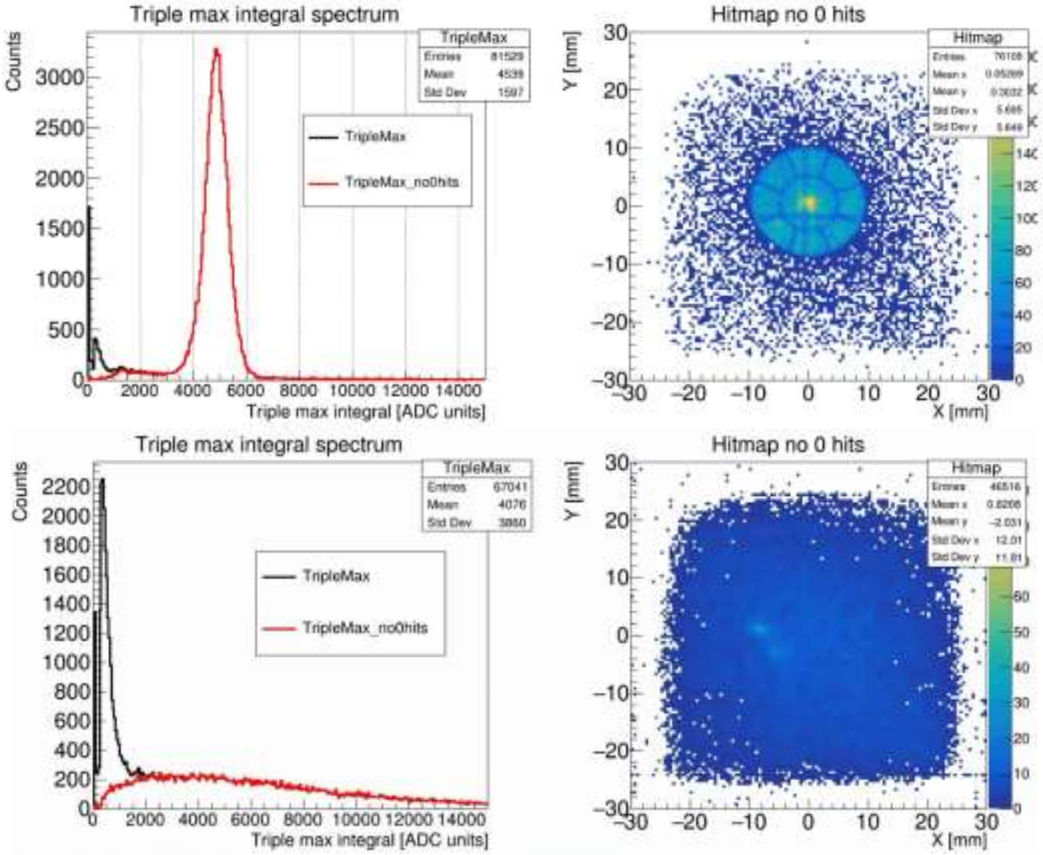
https://inspirehep.net/literature/1921138

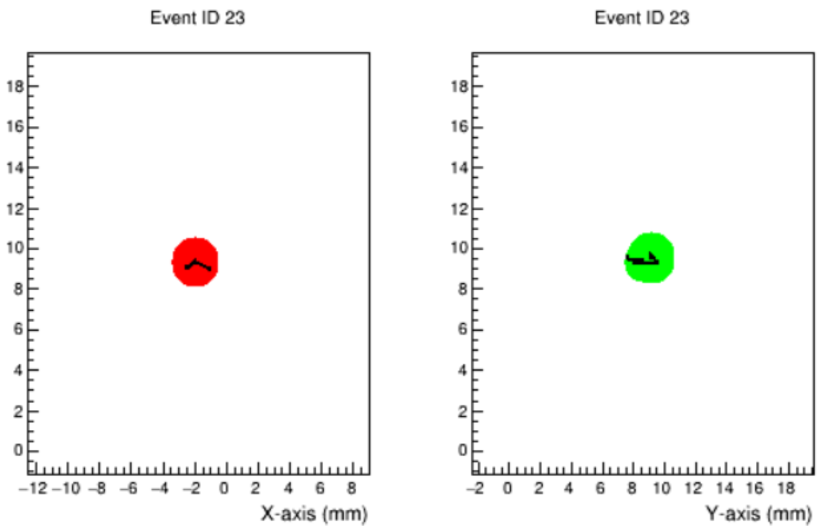
TRestDetectorHits

TRestTrackEvent

Calibration

Background





Goals

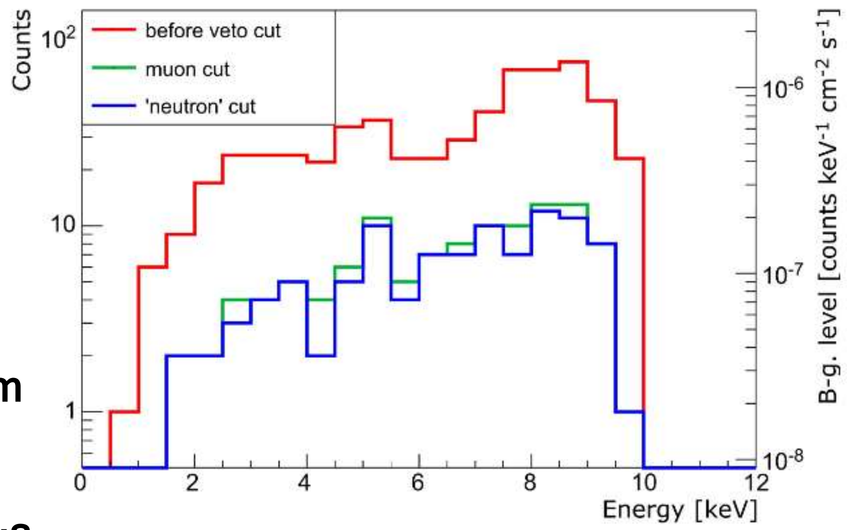
- Study of the effect of multi-layer veto system to tag cosmogenic neutrons (in addition to muons)
- Optimization of background discrimination techniques

Experience from previous prototype (IAXO-D0)

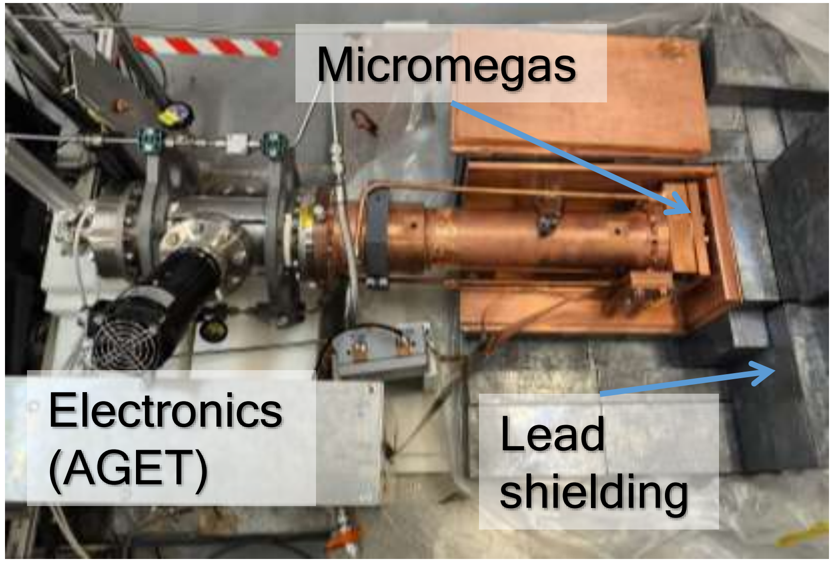
- CAST microbulk MM
- 48.5%Xe-48.5%Ne-2.3%Iso
- Neutron cut: high multiplicity in veto system

Background in [2-7] keV, r < 1 cm after 51 days:

(8.6 ± 1.2) x 10^{-7} counts/keV·cm^2·s

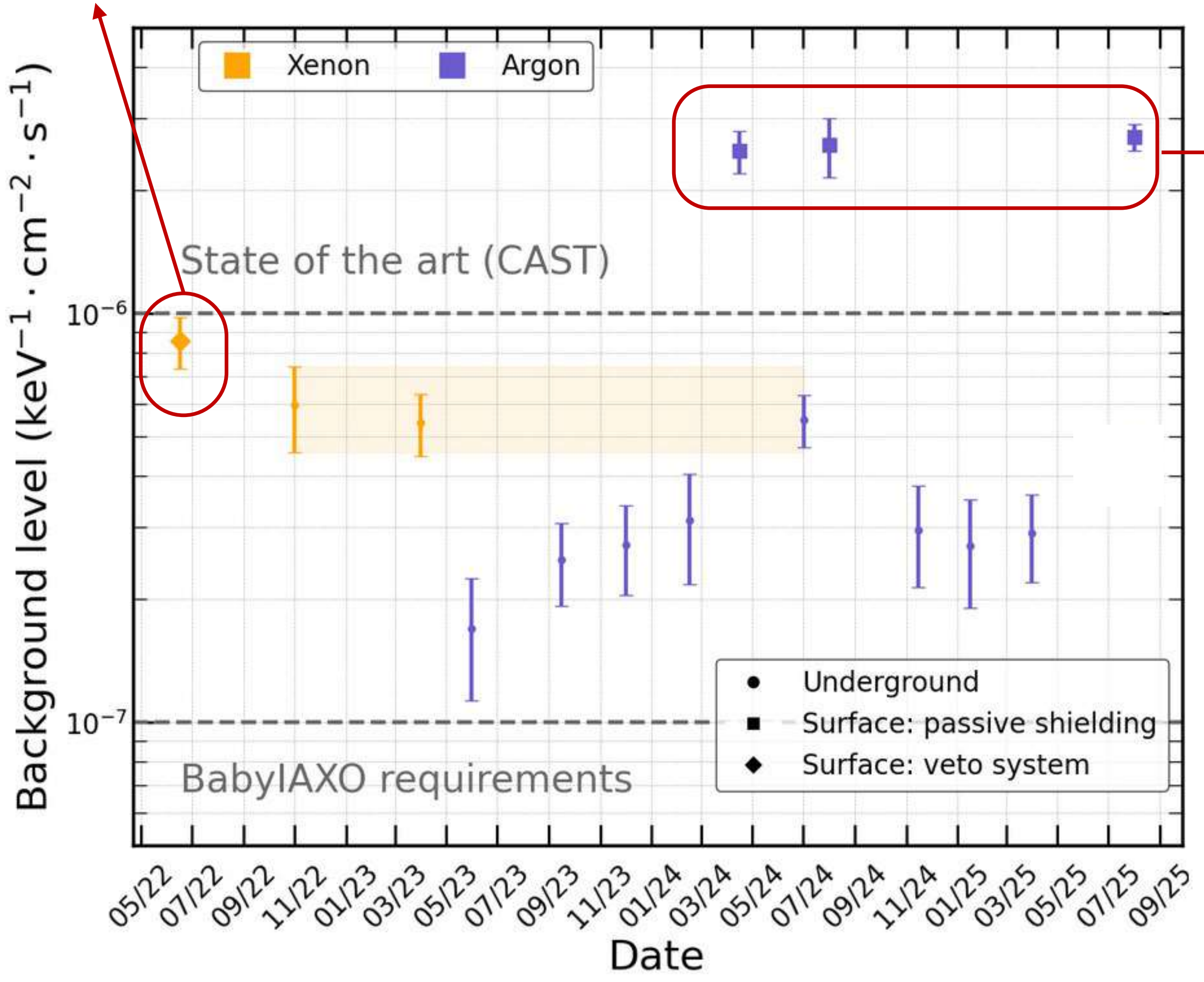


Frontiers in Physics 12 (2024): 1384415.



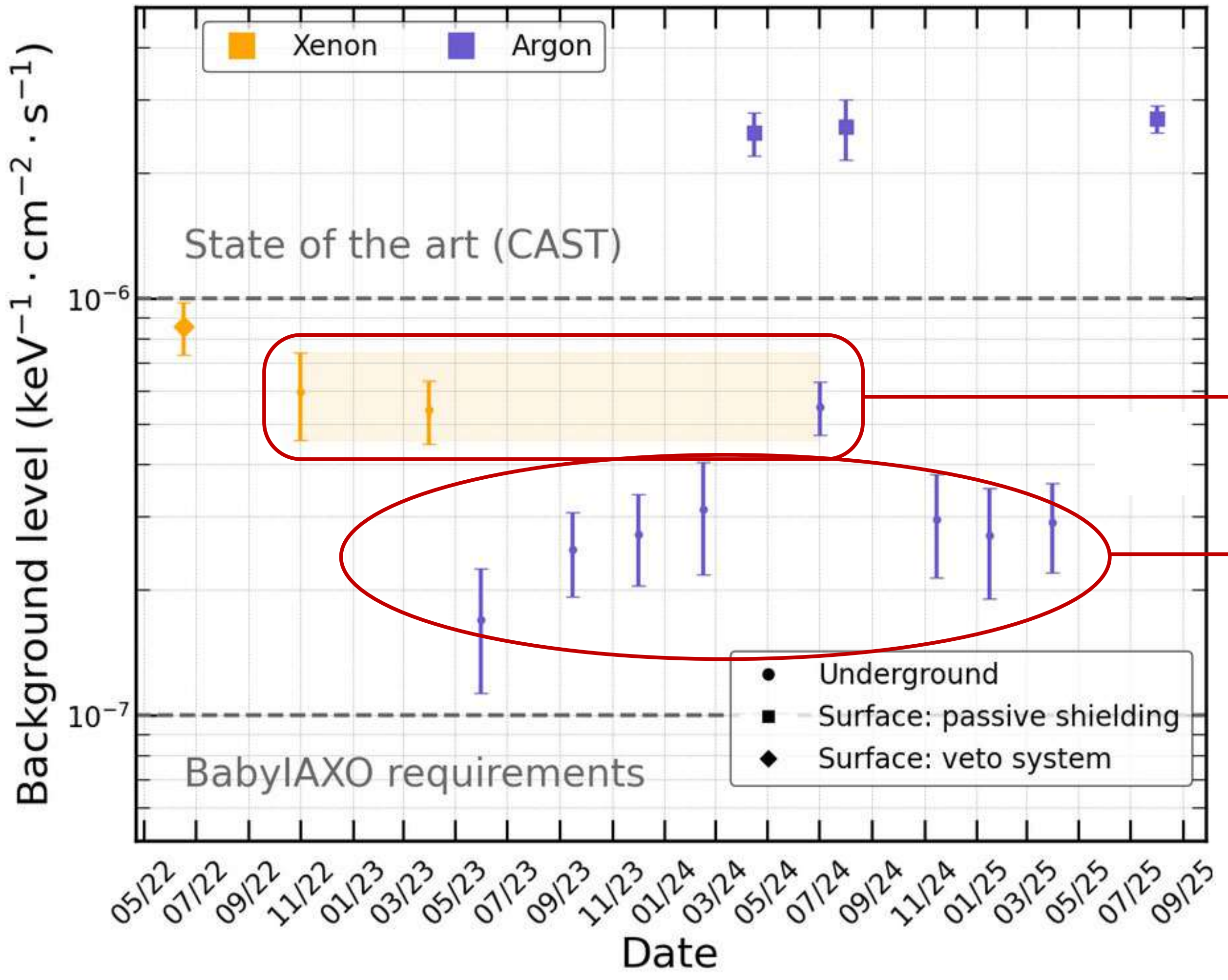
BabyIAXO: MM current background level

IAXO-D0



Need for a veto system

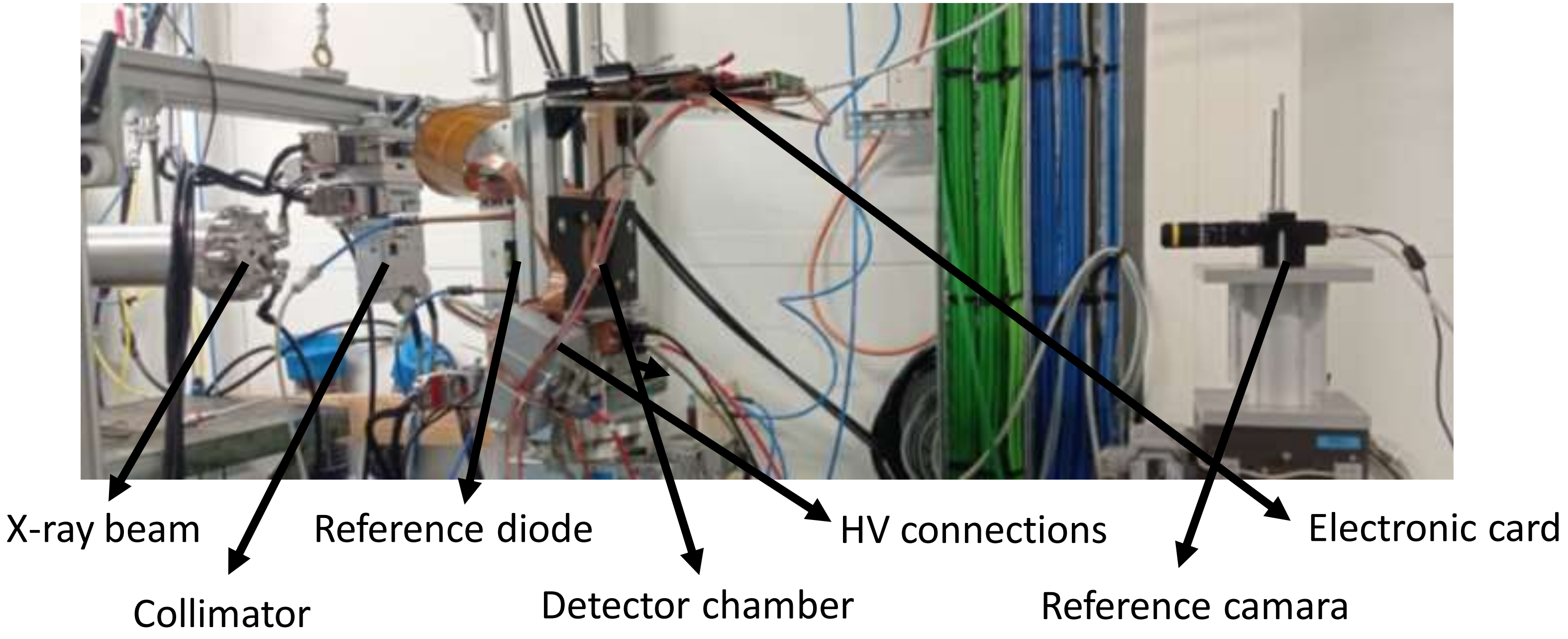
BabyIAXO: MM current background level

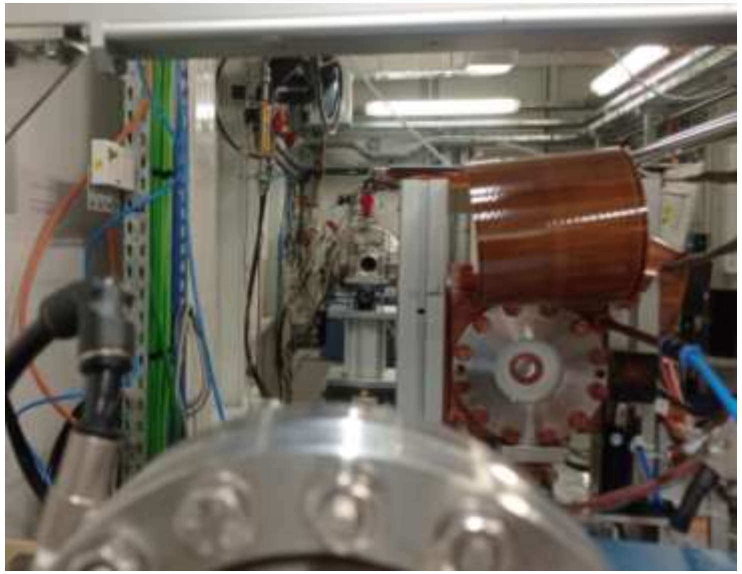


Recirculation:
Rn emanation from purifiers

Open loop

IAXO-D1-Saclay test at SOLEIL



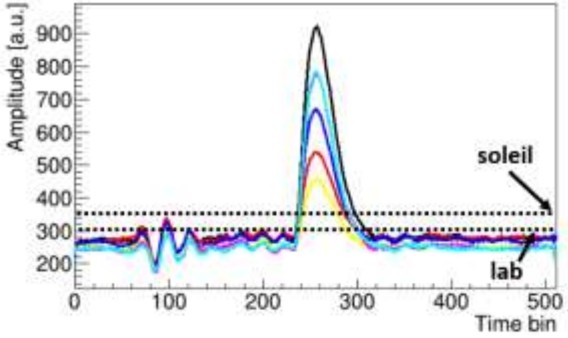


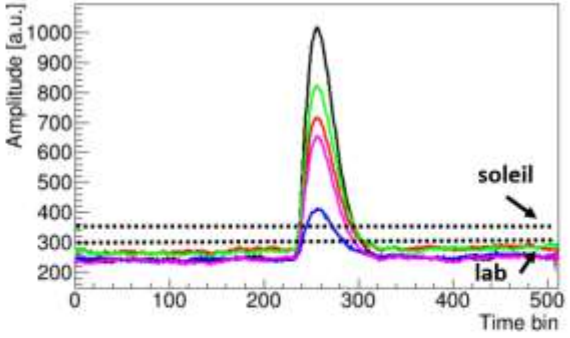
Goals of SOLEIL test:

- Spatial resolution of the IAXO-D1 Microbulk.
- Total efficiency of the detector.

Measurements made:

- Position scan for different beam sizes @6keV.
- Drift field scan (50/60 - 400 V/cm) for different energies (5 – 10 keV) with a beam size of 0.09×0.09 mm^2.
- Energy scan (4.5 – 10 keV) @100 V/cm.





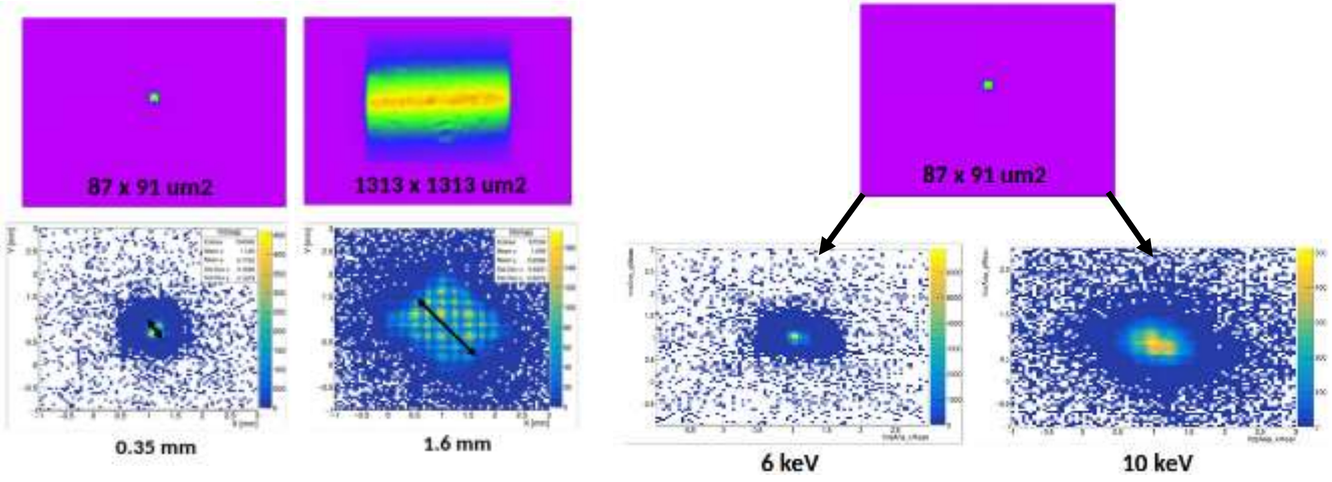
The results are limited by:

- Noise we had during the data taking – high electronic threshold.
- Maximum flux allowed by the AGET electronics – only hit channel were saved.

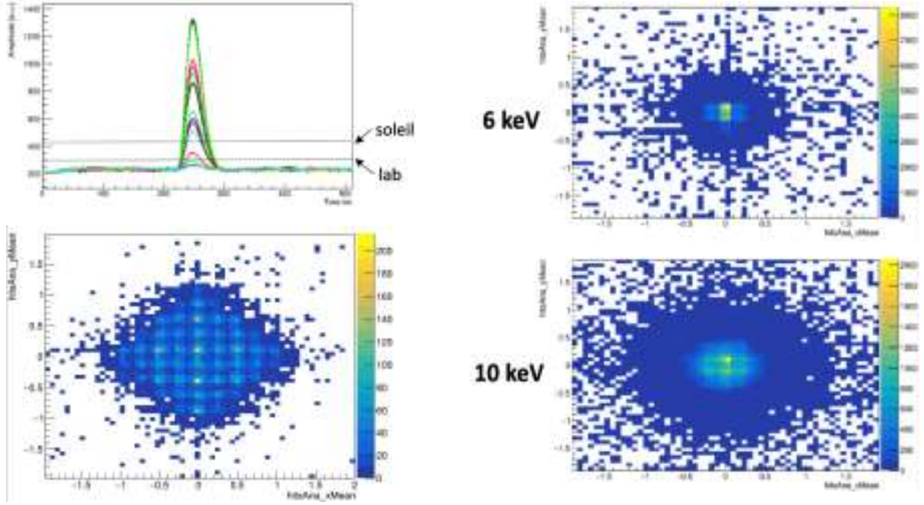
This affects #hits

IAXO-D1-Saclay test at SOLEIL

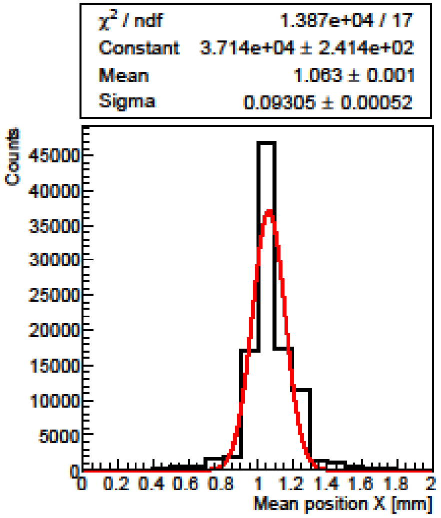
Soleil data

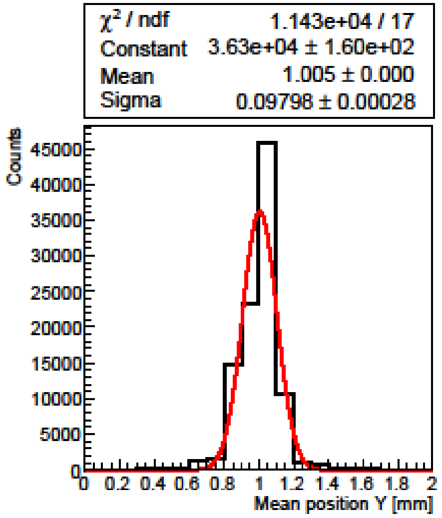


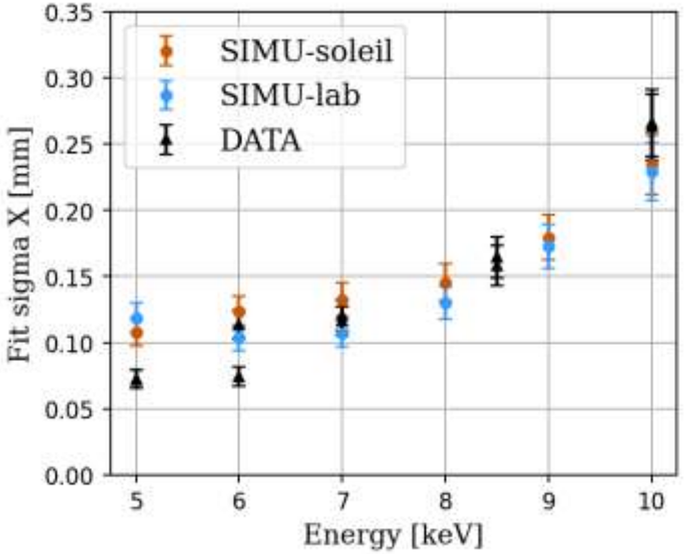
Simulation with Soleil conditions

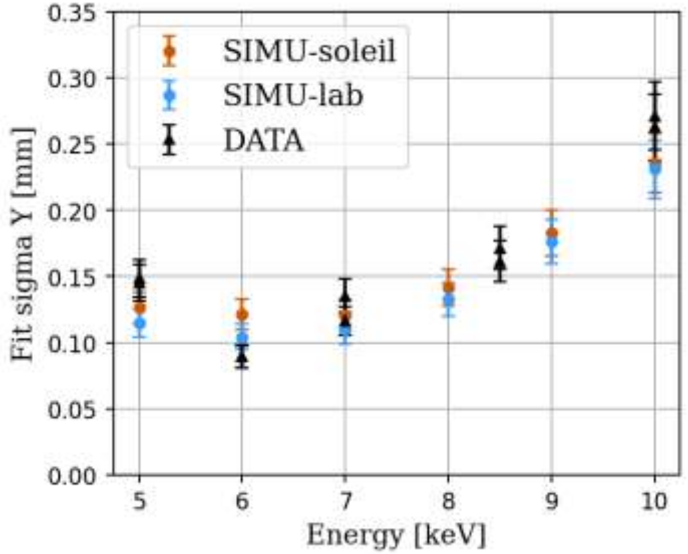


SPATIAL RESOLUTION:



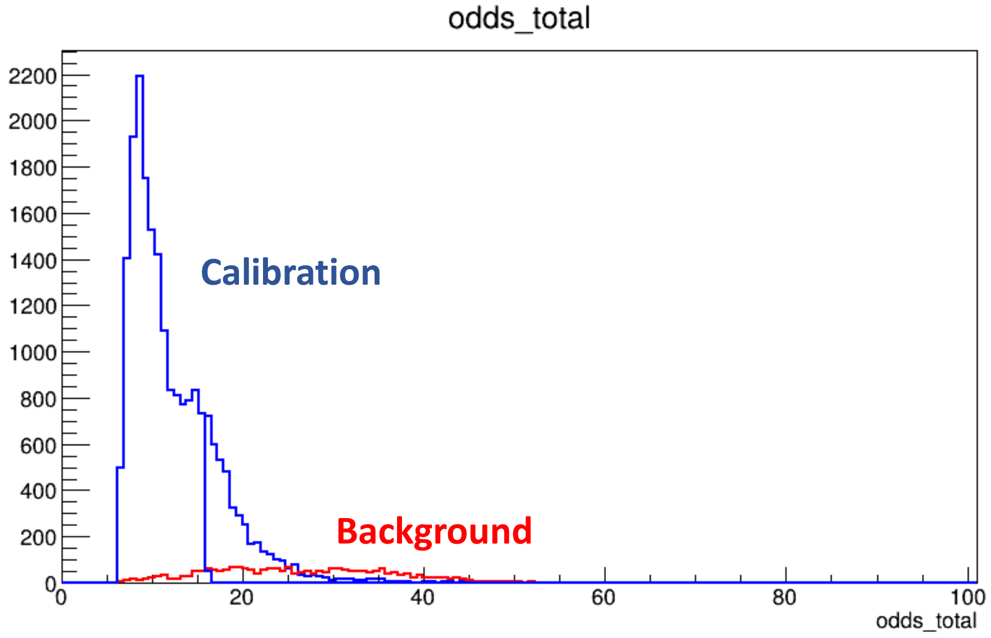






Bkg rejection: LogOdds

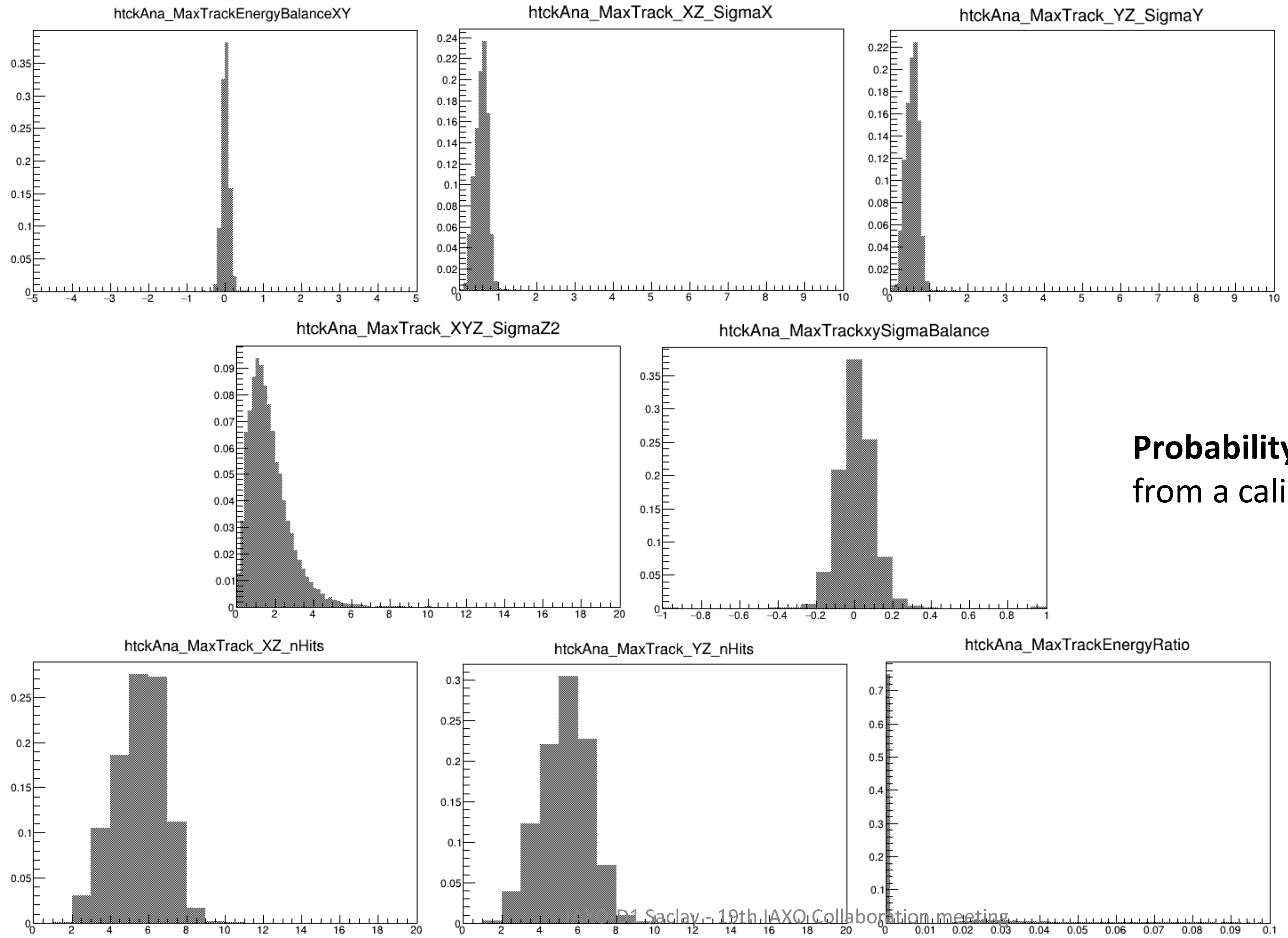
- **The log-odds distribution** (from JuanAn analysis) **is computed for a set of given observables for calibration and background events.**
- **The software efficiency for the calibration events is fixed at 80% (@ 5.9 keV).**



List of observables (track analysis level):

- MaxTrack_SigmaZ -> dispersion of the event in the Z axis
- MaxTrackEnergyBalanceXY -> energy deposited on the X strips vs. Y strips
- MaxTrack_XZ_nHits -> multiplicity in X (strips hit)
- MaxTrack_YZ_nHits -> multiplicity in Y (strips hit)
- MaxTrackEnergyRatio -> energy ratio of the biggest track/cluster
- MaxTrack_XZ_SigmaX -> dispersion of the event in the X axis
- MaxTrack_YZ_SigmaY -> dispersion of the event in the Y axis
- MaxTrackxySigmaBalance -> dispersion in X vs. dispersion in Y

$$-log(\Pi) = -\sum_i \log(O_i(x_i)) = -\sum_i \log\left(\frac{P_i(x_i)}{1-P_i(x_i)}\right) = -\sum_i \log(P_i(x_i)) + \sum_i \log(1-P_i(x_i))$$



Probability distributions P(x)
from a calibration run