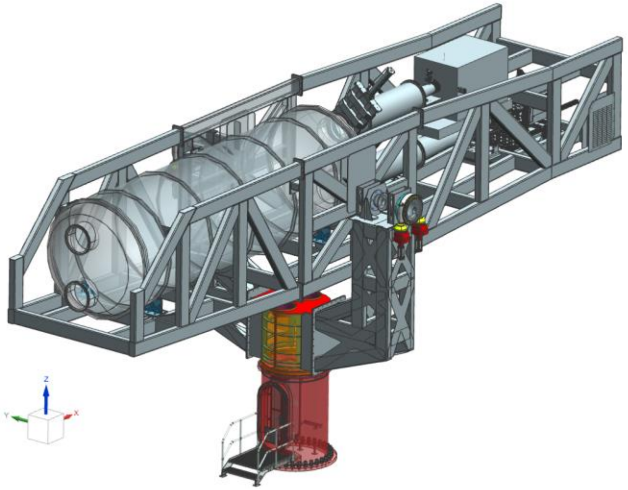
Irfu

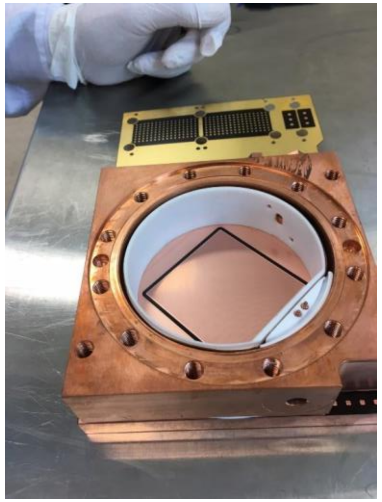
The 7th International Conference on Micro Pattern Gaseous Detectors 2022
December 11-16, 2022
Weizmann Institute of Science, Rehovot, Israel

Ultra-low background Micromegas detectors for BabyIAXO solar axion search

Esther Ferrer Ribas (IRFU/CEA/Saclay)
on behalf of the IAXO collaboration

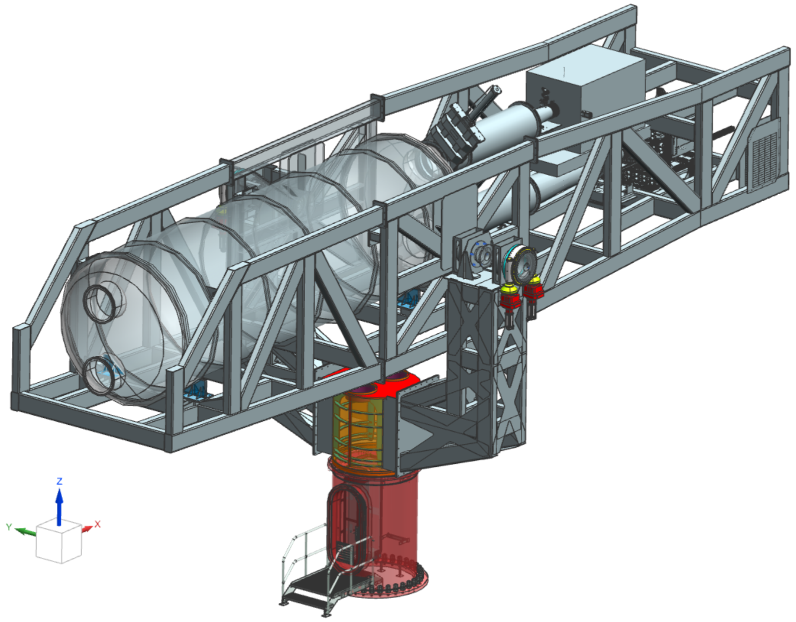
15th December 2022





Plan

- Motivations, strategies, IAXO
  - Axions in a nutshell
  - Solar axion search: the helioscope technique
  - CAST/IAXO/BabyIAXO
- Detector development:
  - State of the art
  - Requirements and strategy
  - Developments on the baseline technology: Micromegas

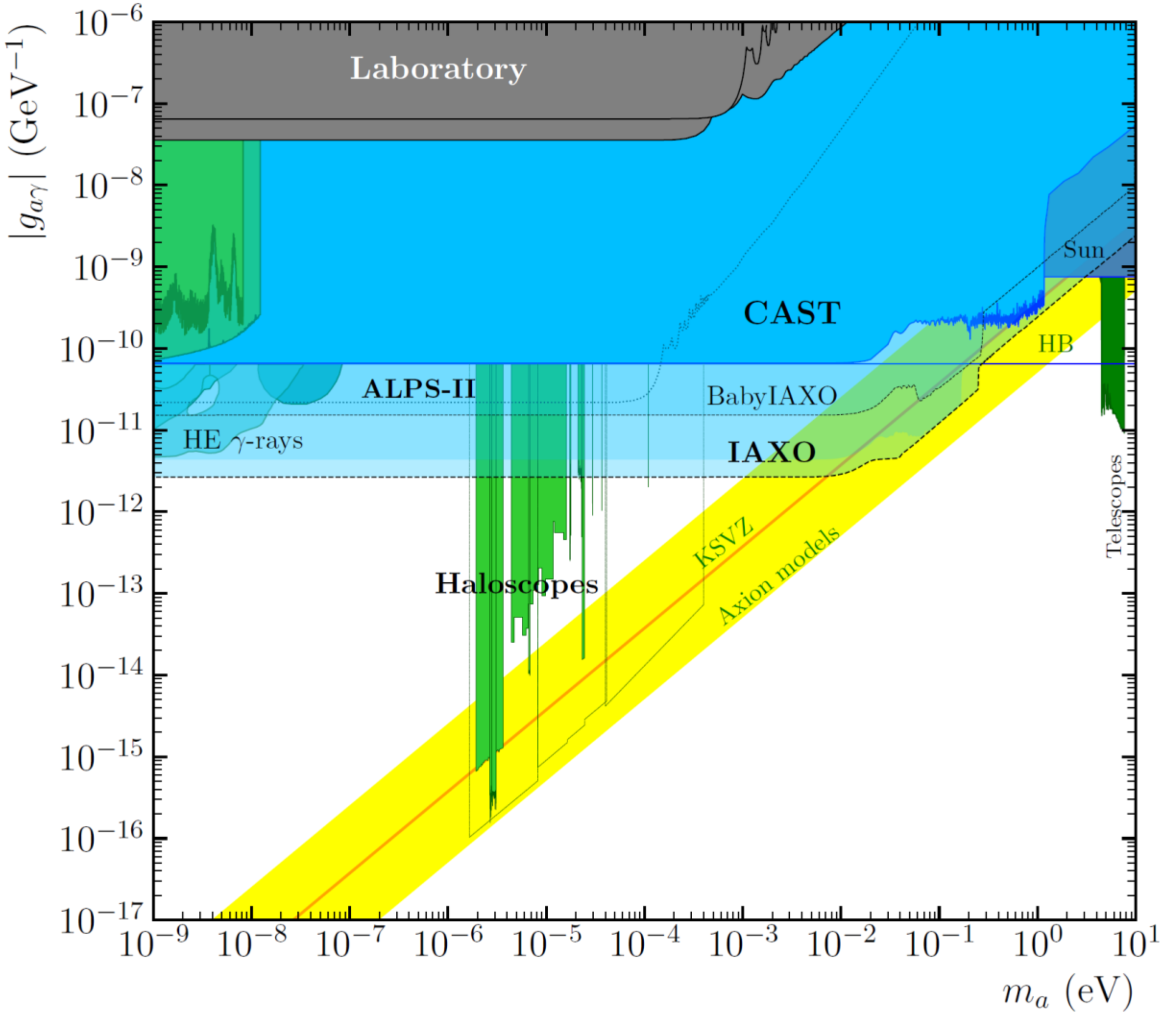


Axion motivation

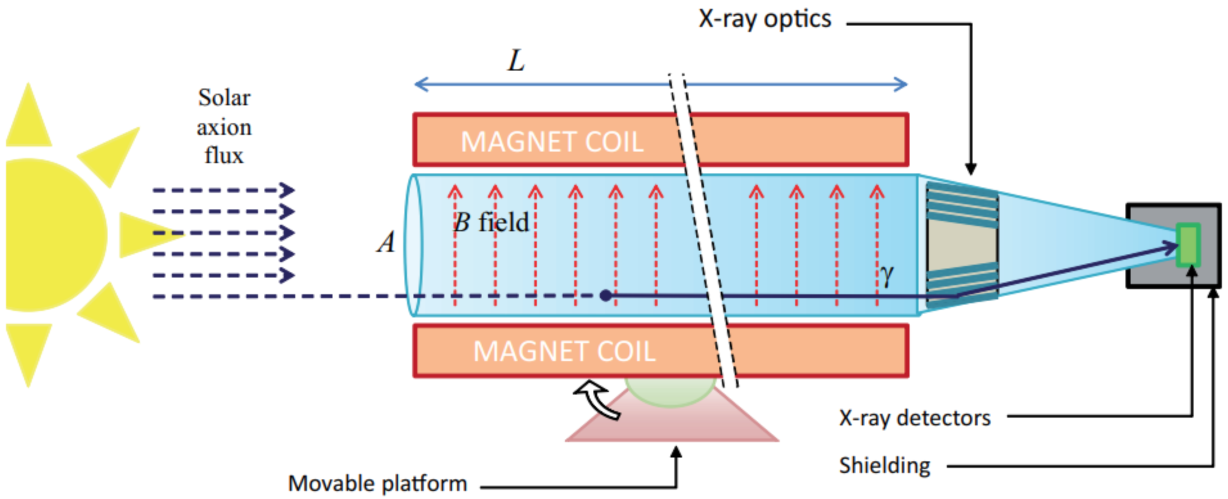
- Most compelling solution to the **Strong CP problem** of the SM

- 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
  - Stellar anomalous cooling → $g_{a\gamma}$ ~ few 10^{-11} GeV^{-1} / m_a ~few meV ?

- Relevant axion/ALP parameter space at **reach of current and near-future experiments**
- Experimental efforts growing fast but still small

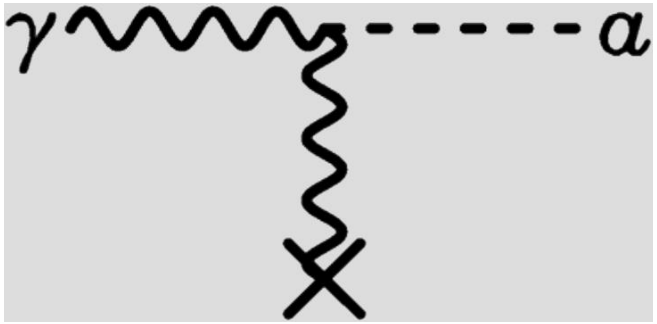


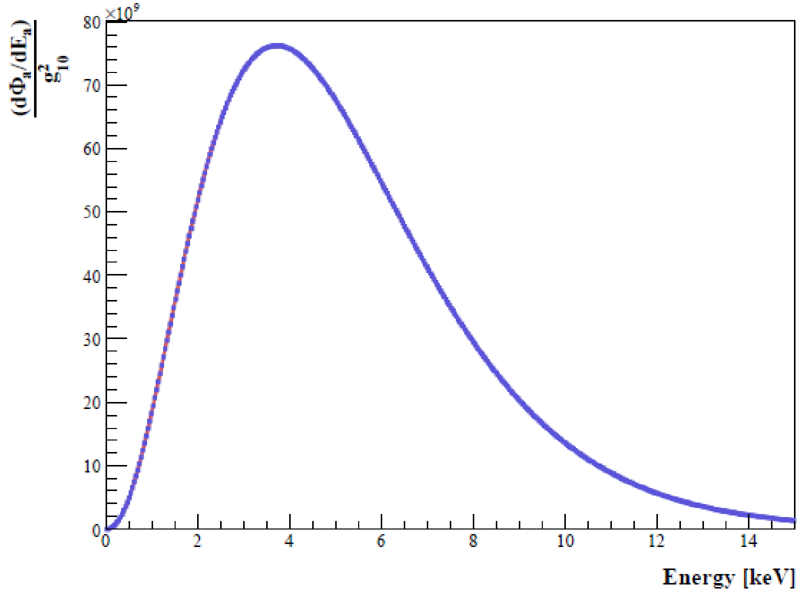
Axion helioscopes



Production

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

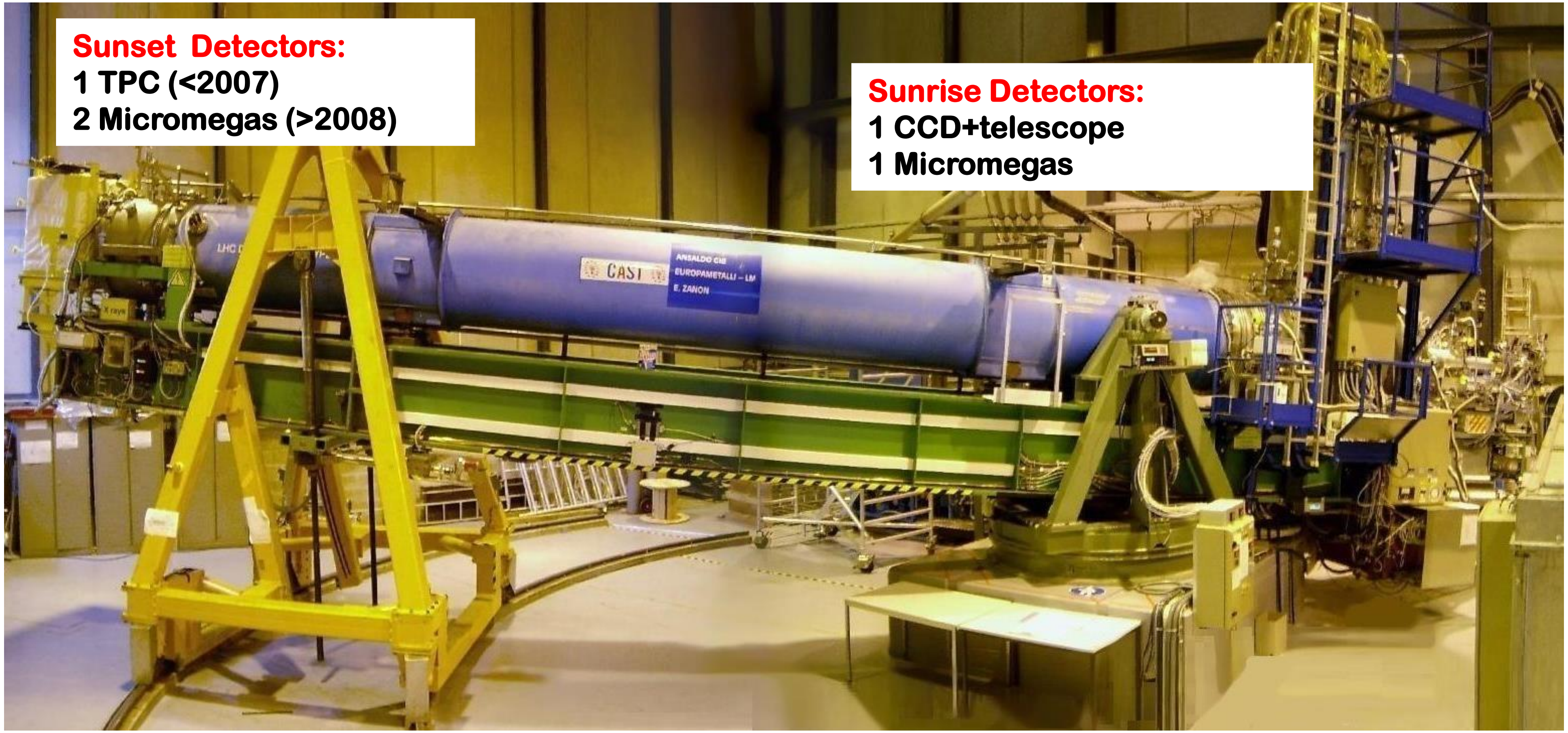




Detection

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

CAST: CERN Axion Solar Telescope



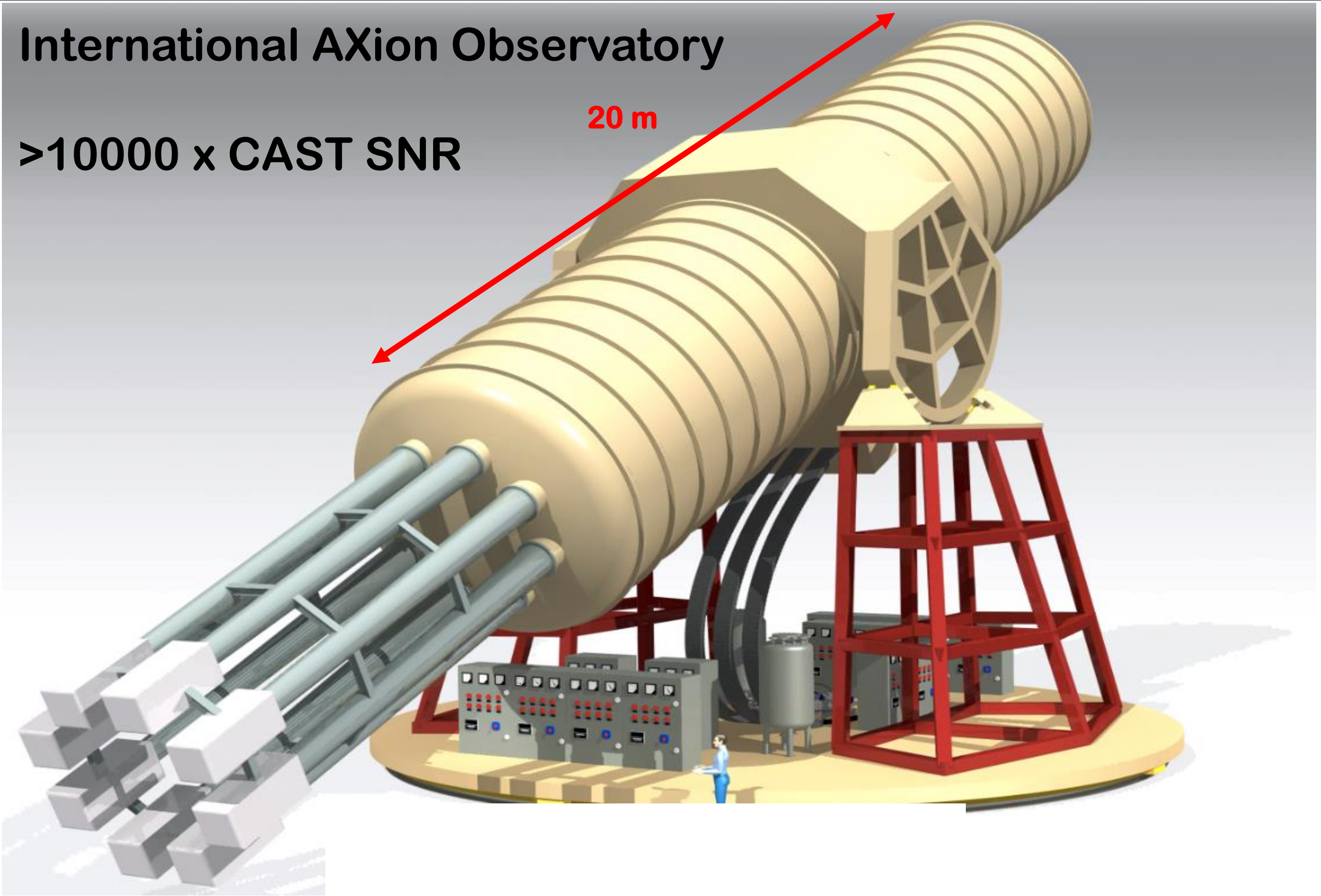
Sunset Detectors:
1 TPC (<2007)
2 Micromegas (>2008)

Sunrise Detectors:
1 CCD+telescope
1 Micromegas

LHC dipole : L = 9.3 m, B = 9 T
Rotating platform : vertical movement 16°
horizontal movement 100°
Solar « Tracking » ~3 h/day, background data rest of the day
4 X-rays detectors

Signal: excess of X-rays while pointing at the Sun

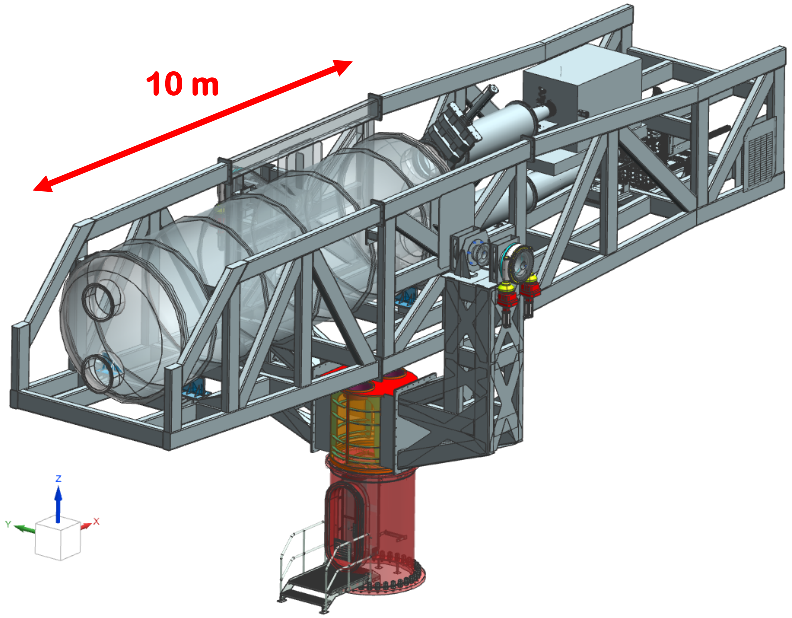
Next generation: IAXO/BabyIAXO



Armengaud et al. JINST105002 (2014)

BabyIAXO

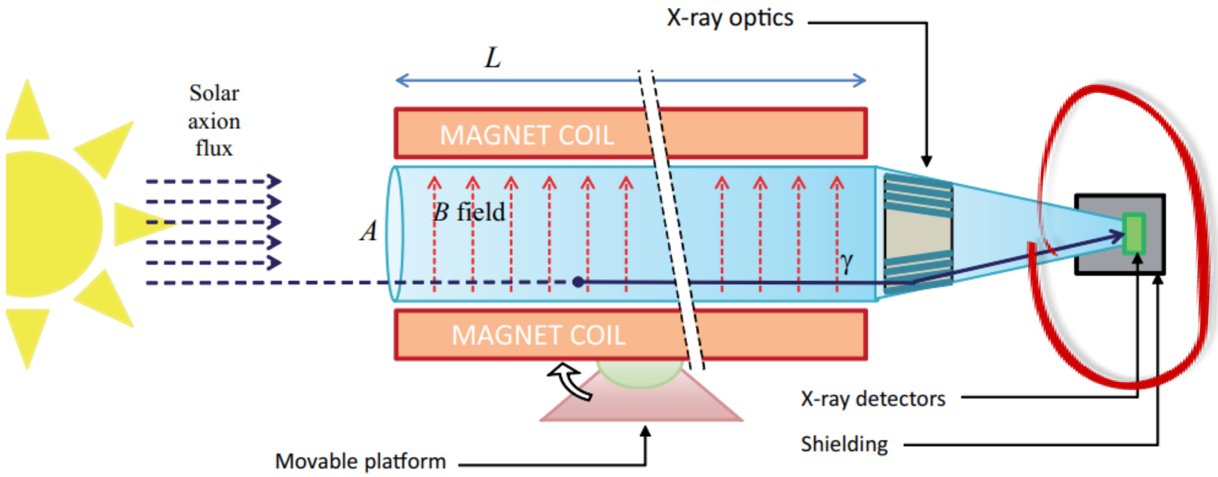
>100 x CAST SNR



BabyIAXO CDR: JHEP 05 (2021) 137

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

Detector requirements

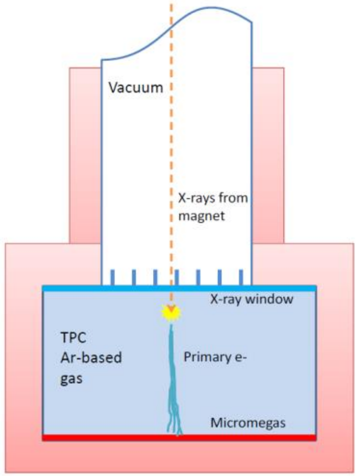


- **High detection efficiency in the RoI [1-10 keV]**

- **Very low background < 10 keV**: 10^{-7} c/keV/cm^2/s ➔ *less than 1 event per 6 months of data taking!*
  - ➔ use of shielding
  - ➔ 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 *(talk J. Kaminski),* Metallic Magnetic Calorimeters (MMC), Neutron Transmutation Doped sensors (NTD), Transition Edge Sensors (TES) and Silicon Drift Detectors (SDD)

State of the art: CAST MM detector



Microbulk produced at CERN workshop

Amplification gap: 50 µm

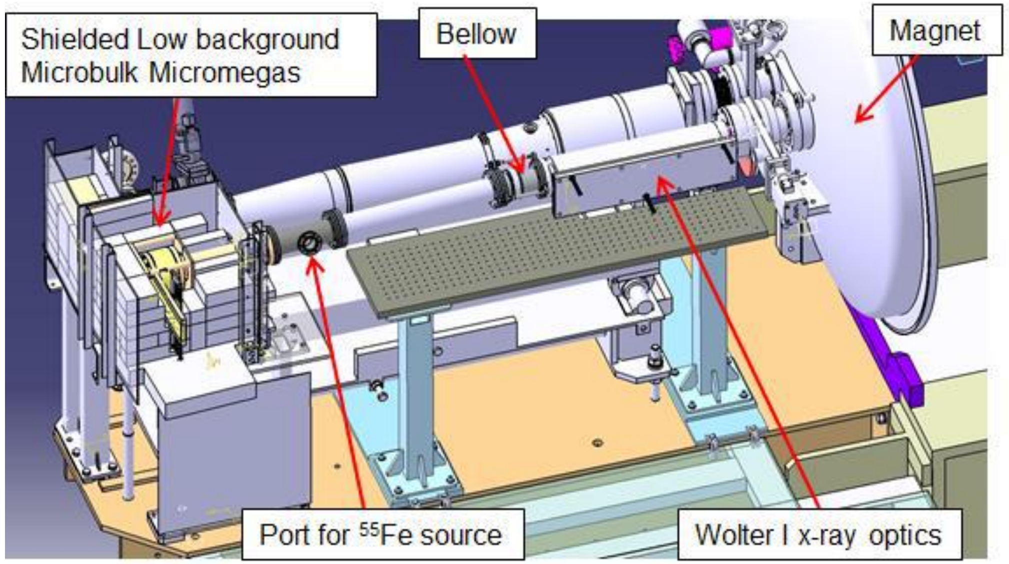
Conversion region: 3 cm

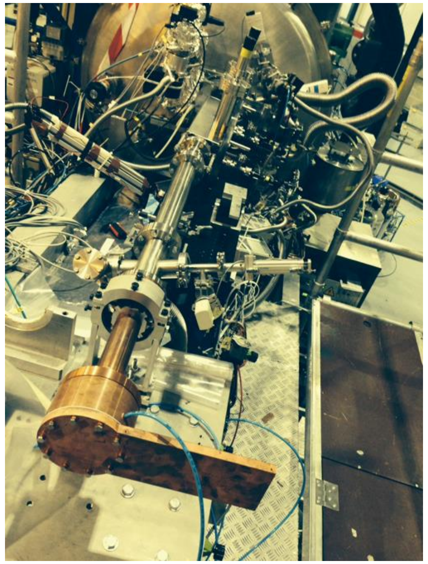
Active area: 6x6 cm^2 (120x120 strips)

Gas: Ar+2%C_2H_{10} at 1.4 bar

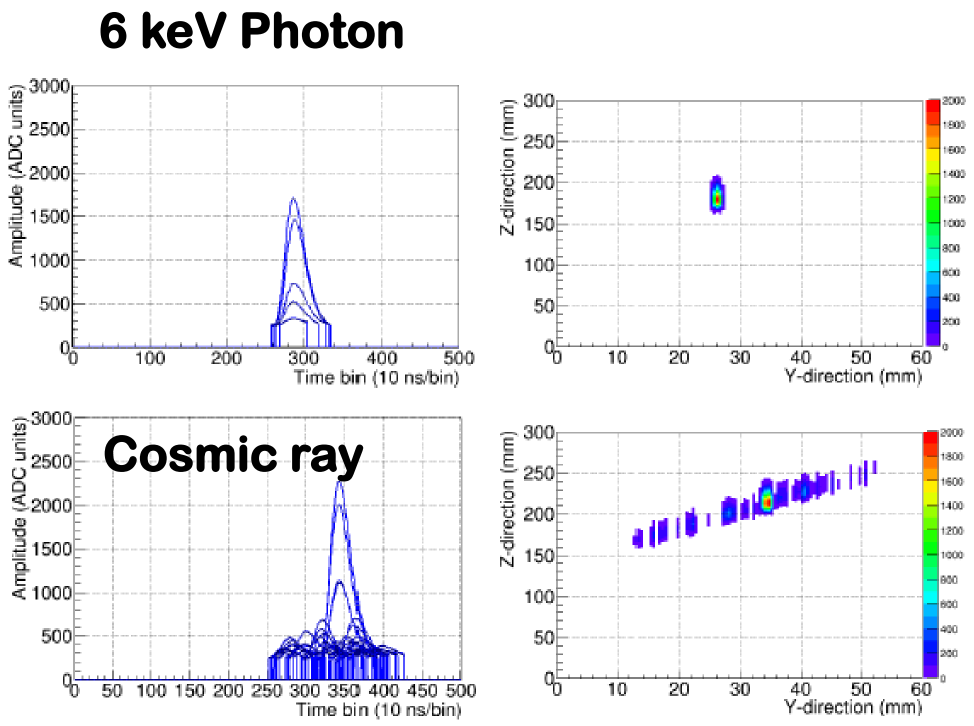
X-ray window: 4 µm aluminised mylar

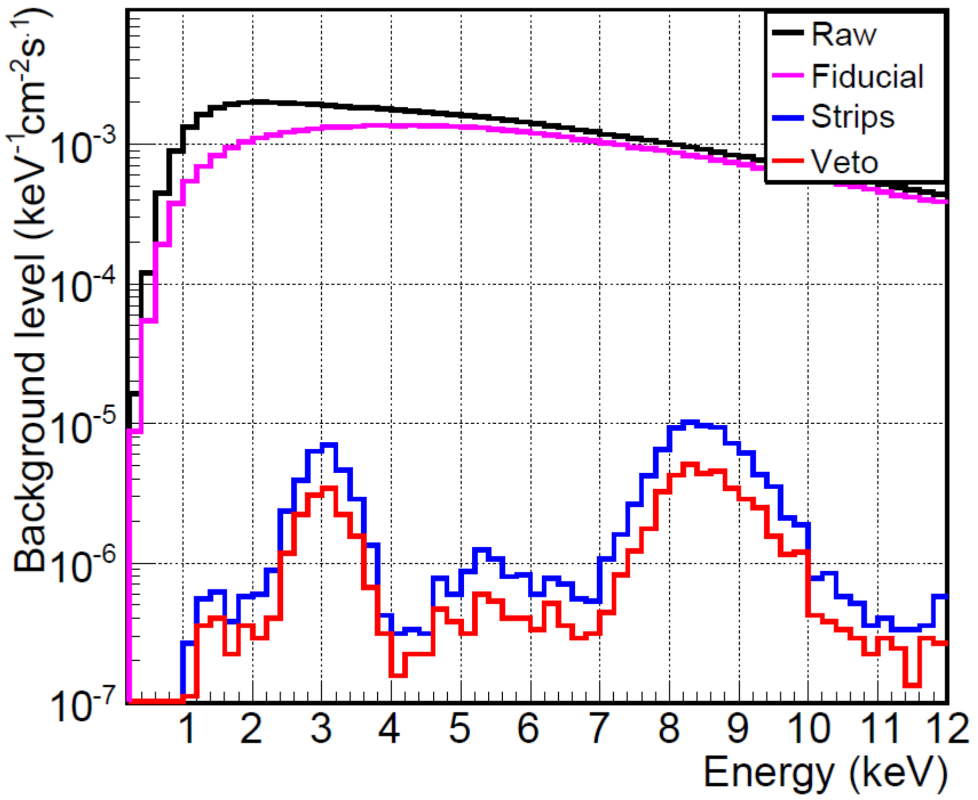
AGET-based readout electronics





Exploiting event topology





S. Aune et al., JINST 9 (2014) 9 P01001
F. Aznar et al., JCAP 12 (2015) 9 008
I.G. Irastorza et al., JCAP 01 (2016) 034

State of the art

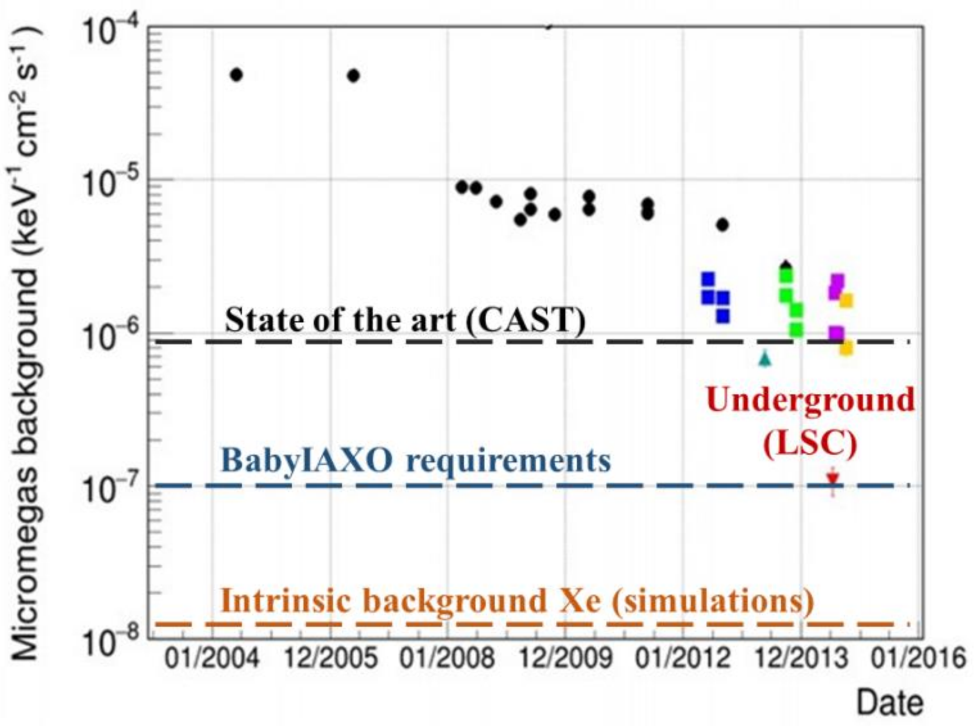
Experimental results :

At surface:

- CAST data taking in the IAXO pathfinder system: 10^{-6} c/keV/cm²/s
- Starting point to go to BabyIAXO target level

At underground:

- Old tests with a CAST replica detector at the LSC: 10^{-7} c/keV/cm²/s
  - Level representative of intrinsic limitation of the current design



Main contributions of background

Cosmic rays

- Muons
- Gammas
- Neutrons

Contamination/radiogenic activation (vessel, shieldingn electronics)

Environnemental: gammas, neutrons…

Gas (^{39}Ar)

State of the art

Experimental results :

At surface:

- CAST data taking in the IAXO pathfinder system: 10^{-6} c/keV/cm²/s
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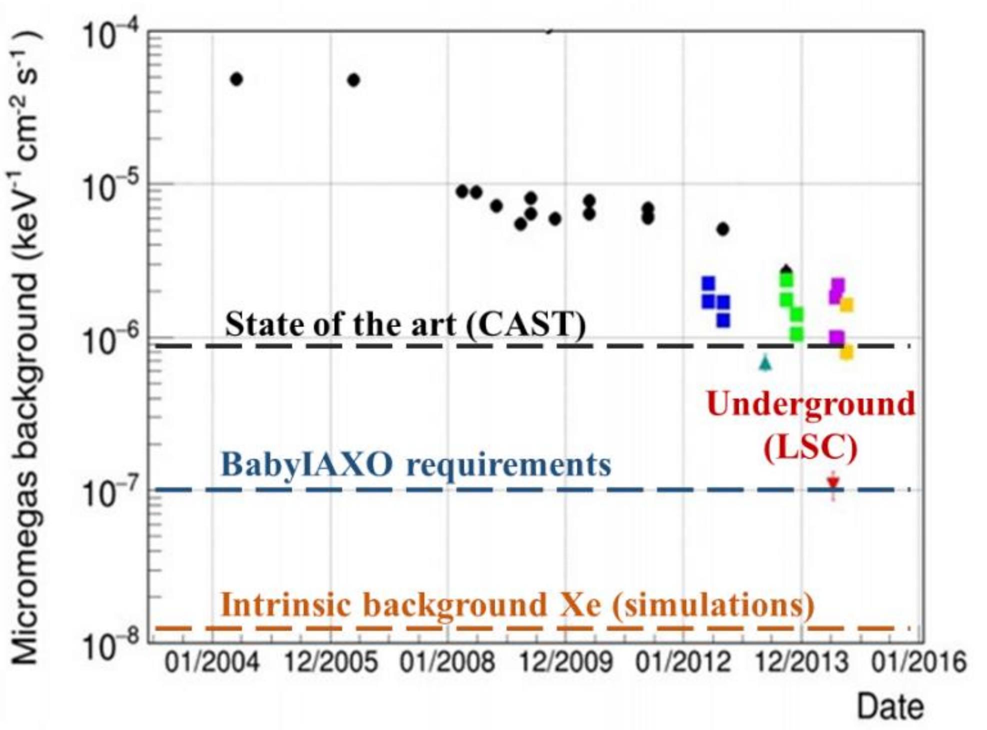


Main contributions of background

Cosmic rays

- Muons ➔ 4 pi coverage muon vetos (scintillators)
- Gammas ➔ low (negligeable) background
- Neutrons ➔difficult/ neutron tagging system under development

Contamination/radioganic activation (vessel, shieldingn electronics)➔ radiopurity

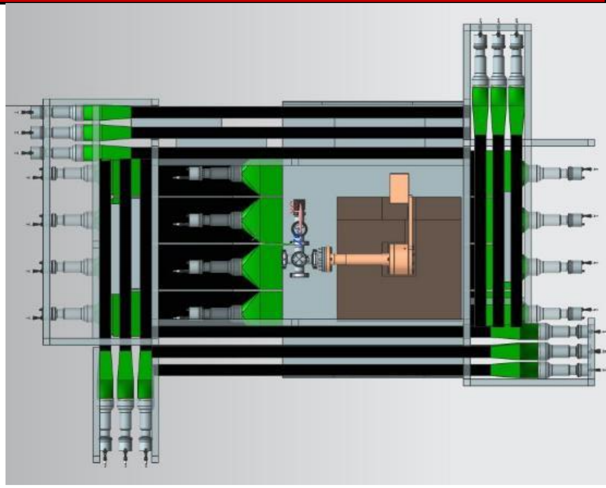
Environmental: gammas, neutrons…➔shielding

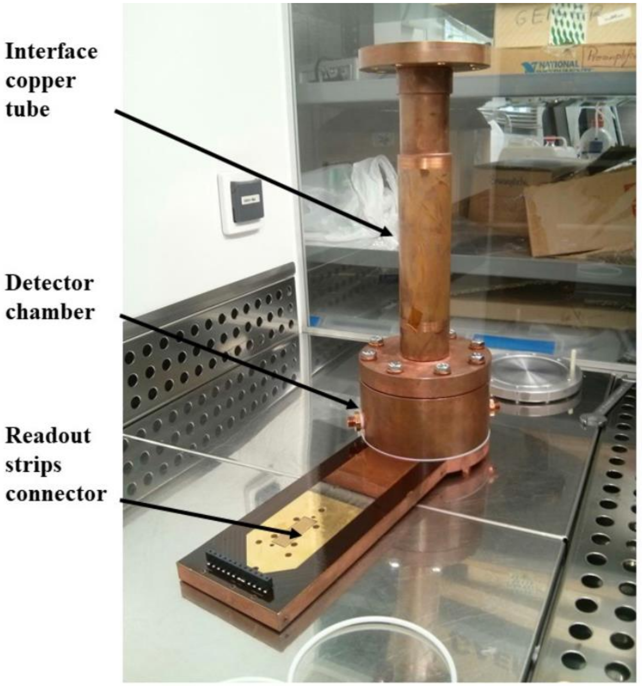
Gas (^{39}Ar) ➔Use of other mixtures (Xe based)

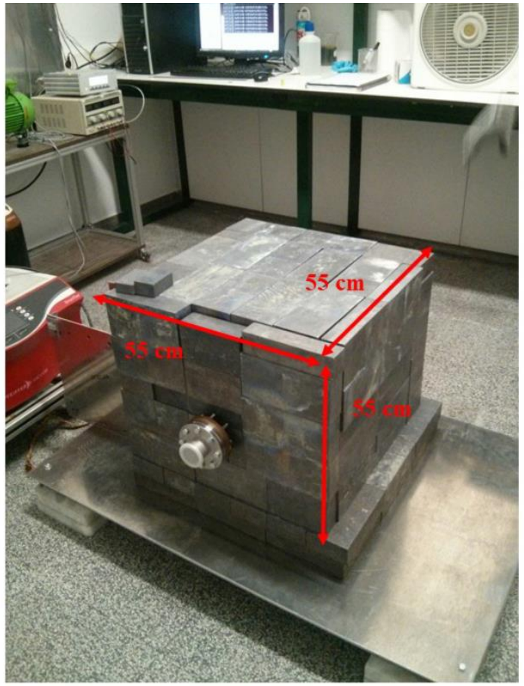
Tests at Unizar with IAXO-D0

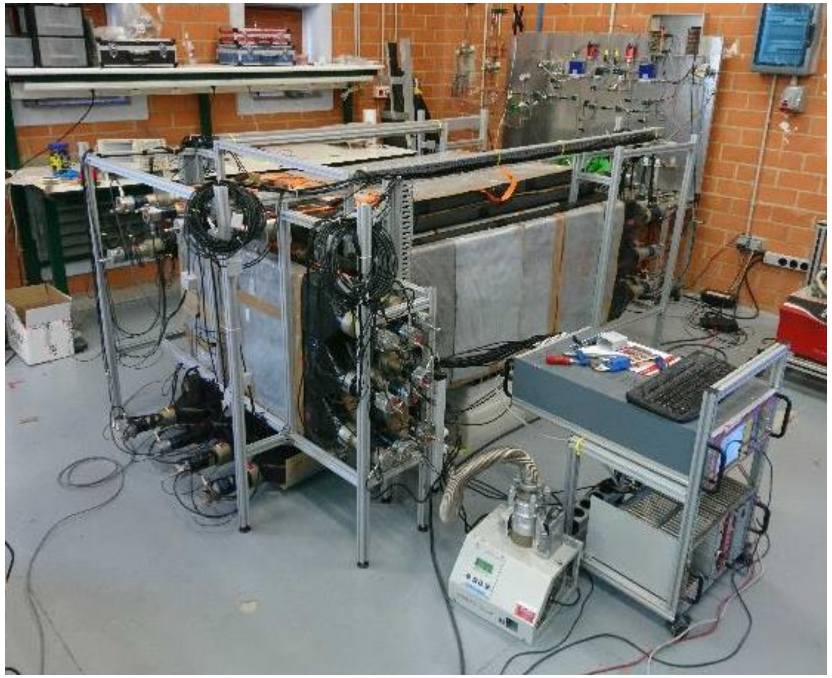
- Gas mixture: 48.85 % Xe + 48.85 % Ne + 2.3 % Isobutane

- Detector equipped with 57 veto panels
- 4 π coverage with 3 veto layers
- Cadmium sheets placed between the veto layers
- Vetos calibrated with cosmic muons





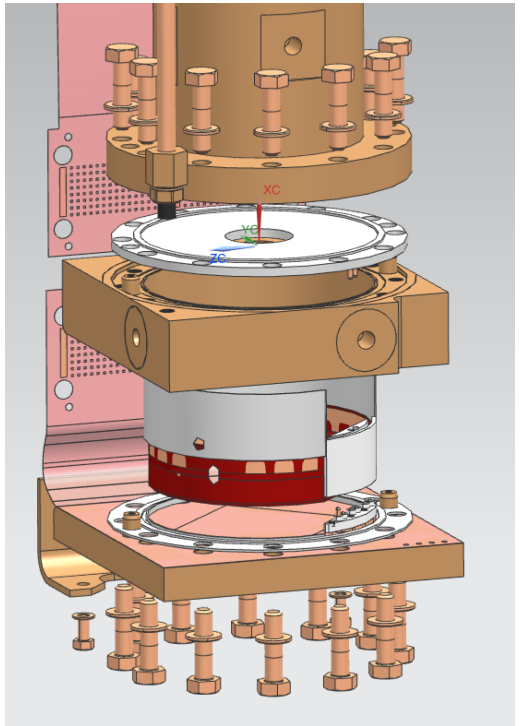


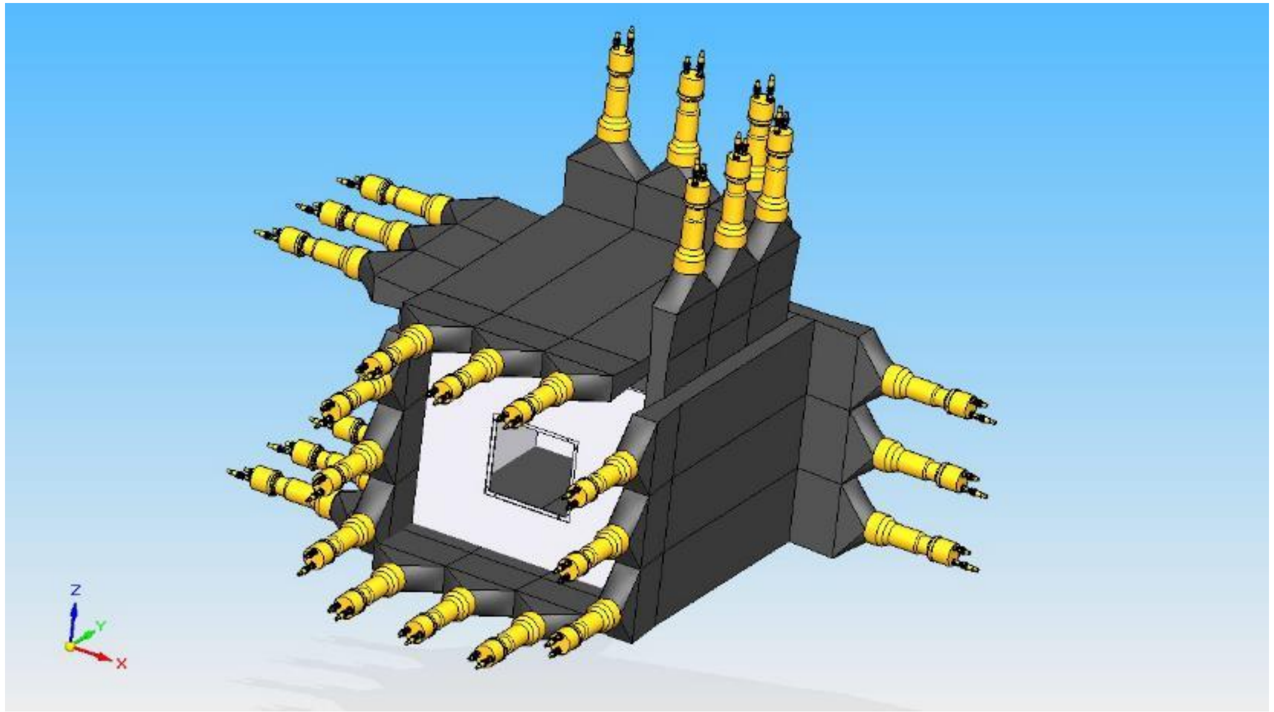


New prototype: IAXO-D1

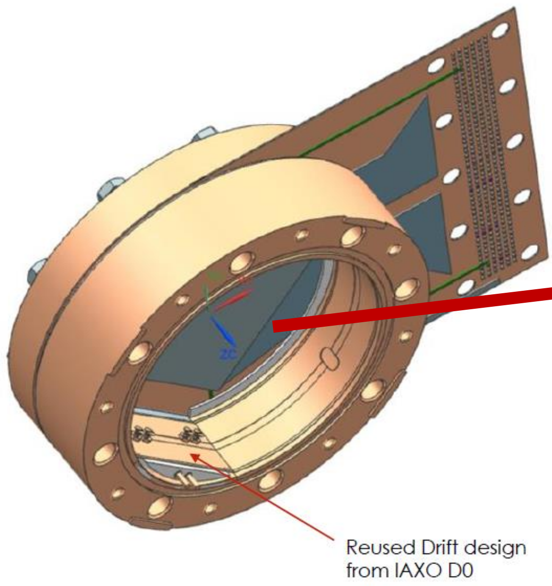
Improve the background level of a new, optimized Micromegas detector by 1 order of magnitude :

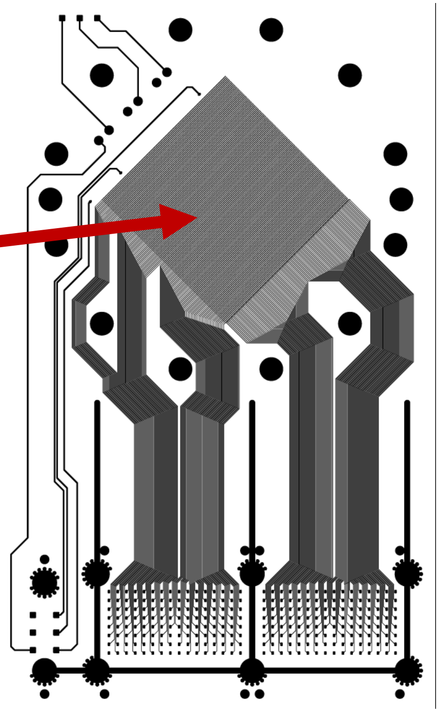
- **New detector design & operation with Xenon gas**
- **Optimized shielding with active veto**
- **New radiopure electronics**
- **Improved particle identification capabilities**

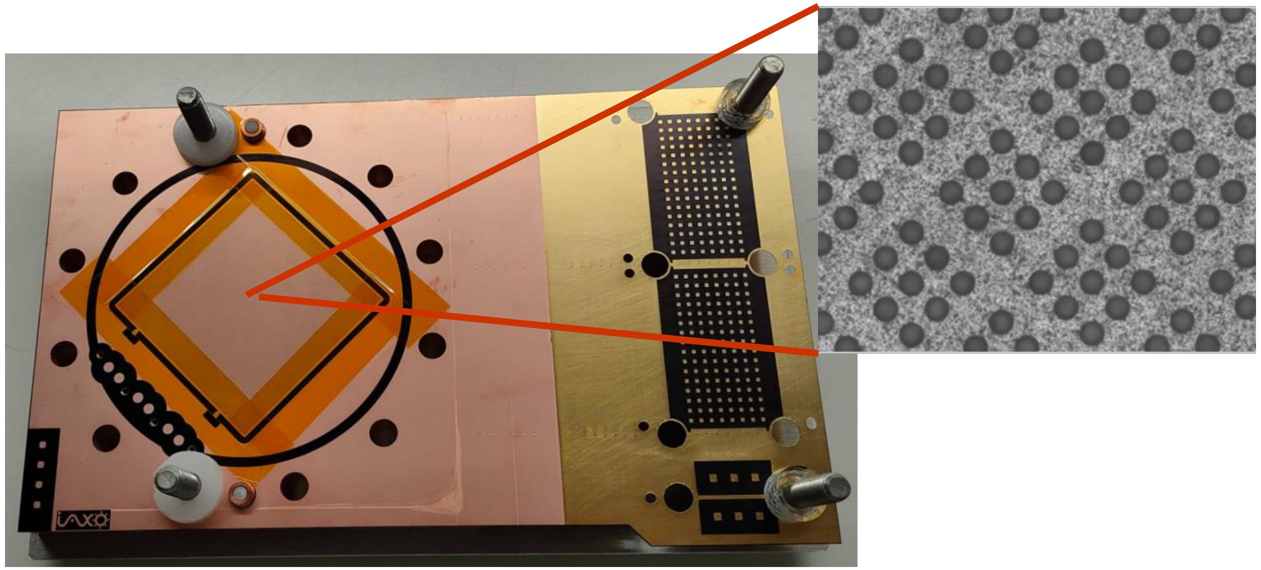


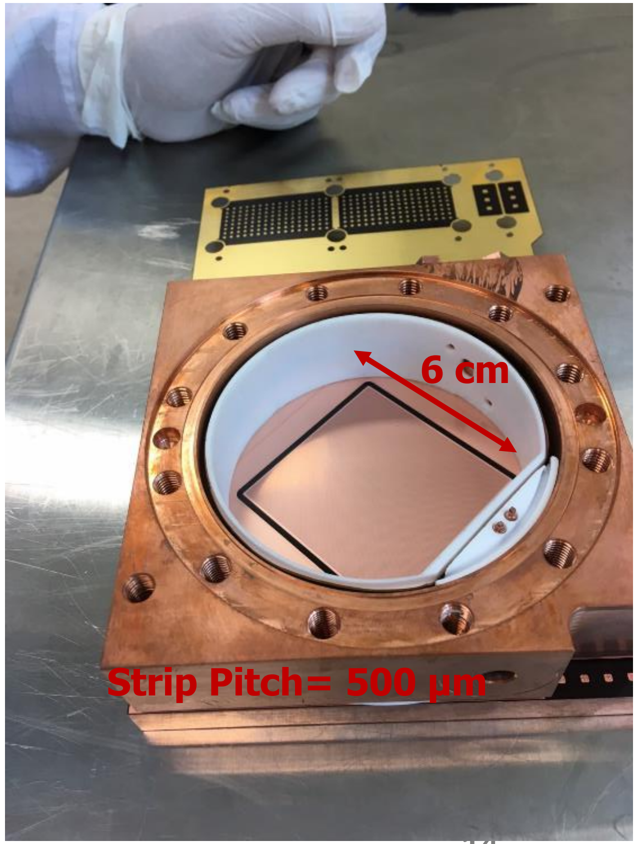


New design: IAXO-D1

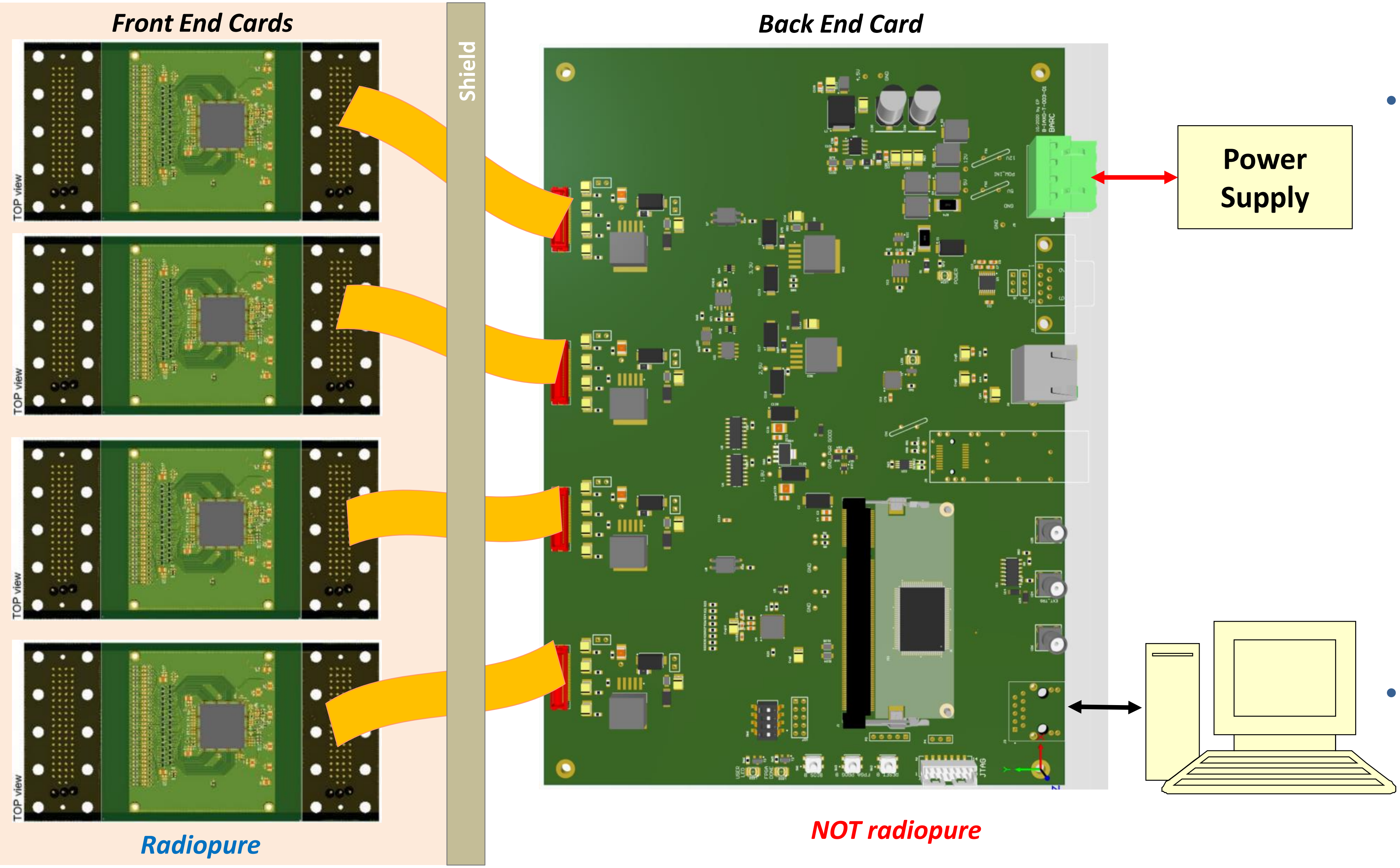






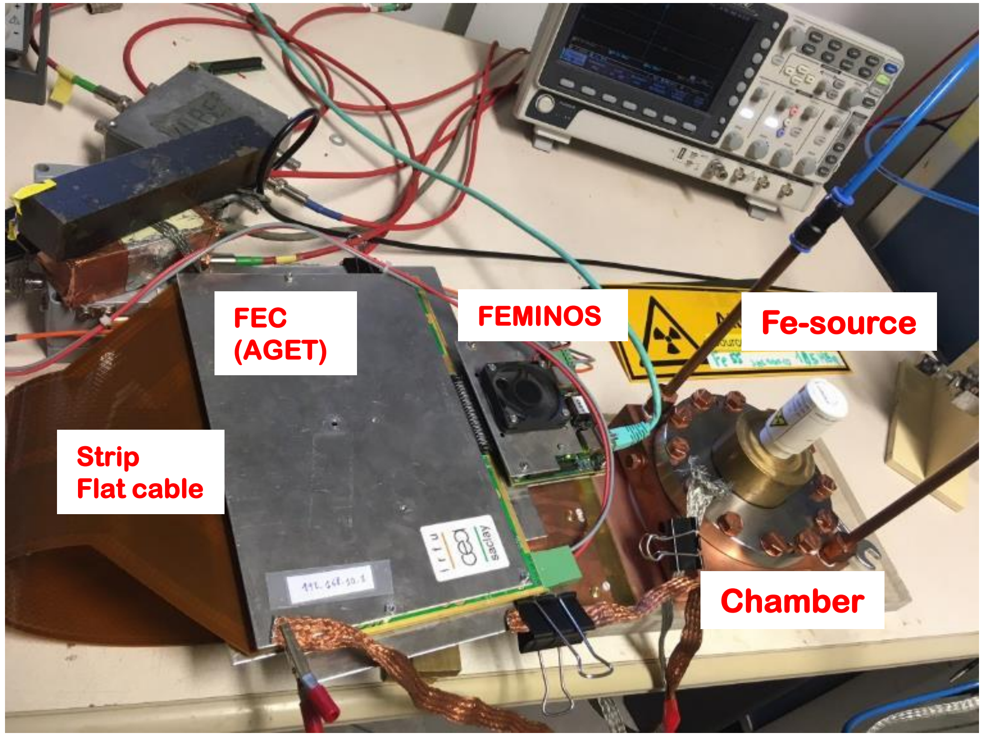


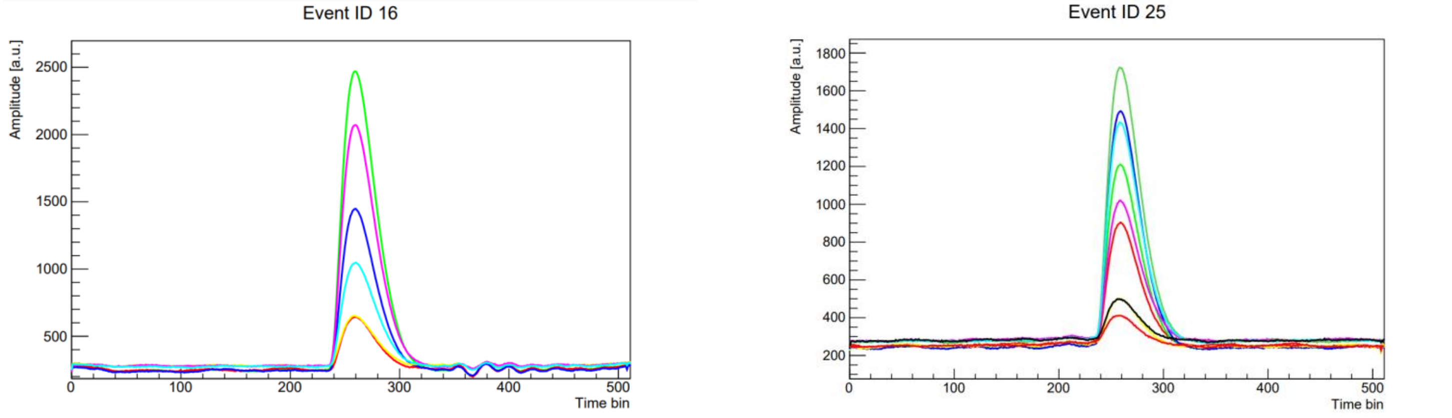
IAXO-D1: Radiopure electronics

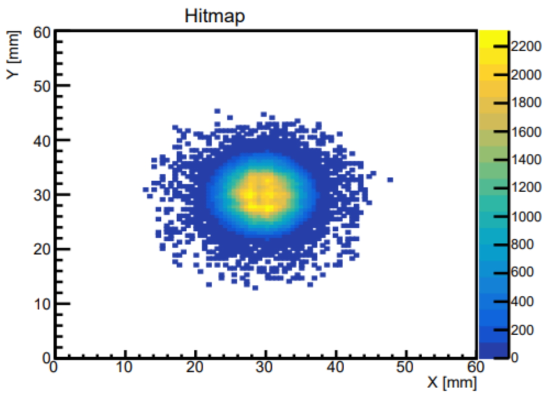


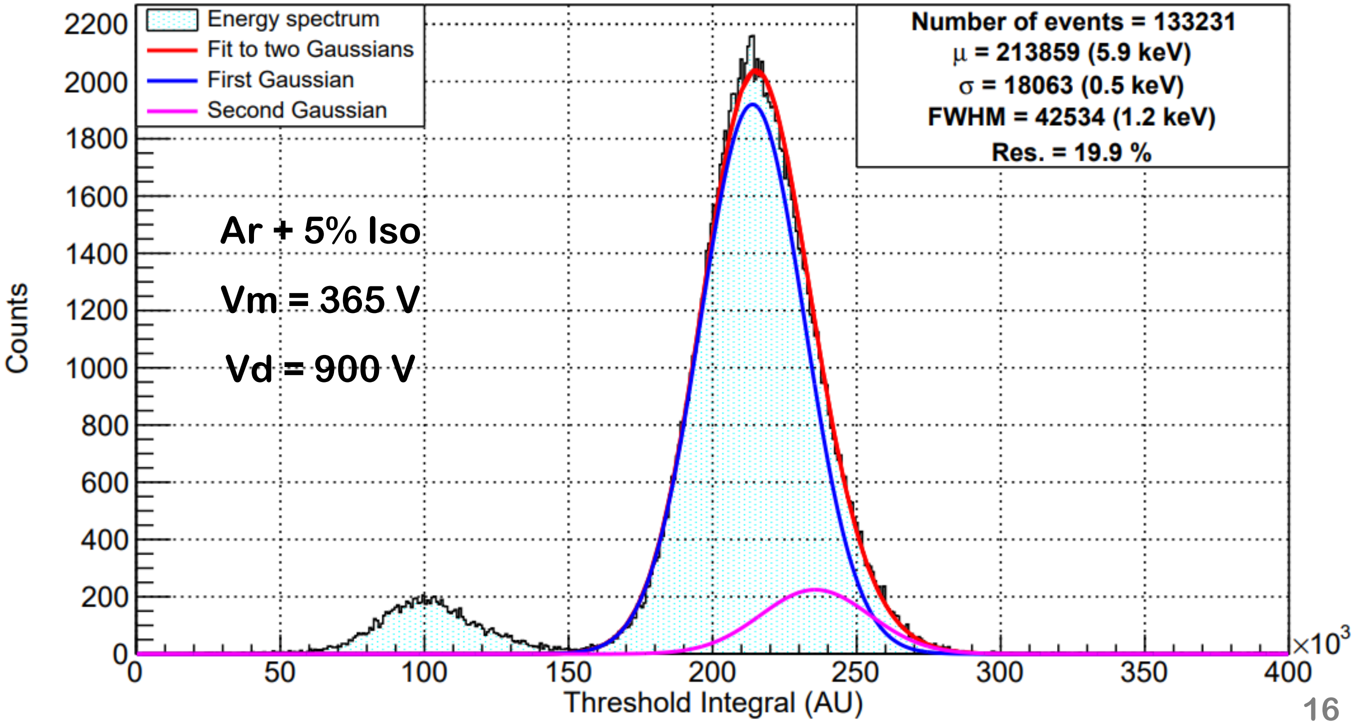
- **Electronics partition**
  - Based on the ARC (newer FEC-Feminos) cards (Saclay)
  - Move sensitive, AGET, in Front End Card (FEC) as close as possible to the detector to optimize S/N
  - Back End Card (BEC), with FPGA+ADC, separated tens of cm by extra shielding
- **Redesign of the cards**
  - Different partition
  - Component selection and validation

IAXO-D1 first characterisations









IAXO-D1in Underground laboratory of Canfranc

LSC 800 m deep under Mount Tobazo in the Spanish side of the Aragon Pyrenees. Rock filters cosmic radiation

Data-taking started on October 18th 2022

Conclusions

BabyIAXO detector requirements are very challenging. Micromegas is the baseline technology.

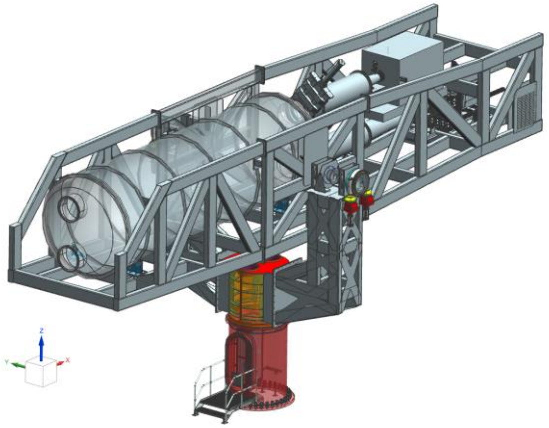
IAXO-D1 is an optimised prototype:

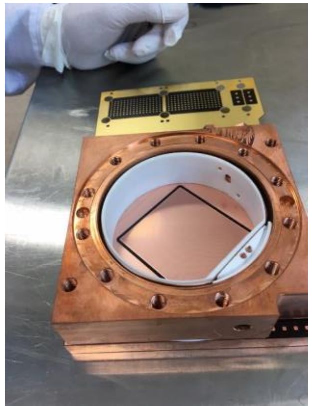
- **low radioactive materials**
- **optimised shielding and muon veto**
- **radiopure electronics.**

Several prototypes have been built and have started operation in Saclay, Zaragoza and Canfranc.

BabyIAXO has been approved at DESY (Hambourg). Construction phase just started.

Commissioning of first systems (platform, optics, detectors) by 2024.





THANKS!

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) | University of Mainz (Germany) | University of Columbia (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) | MPE/PANTER (Germany)

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

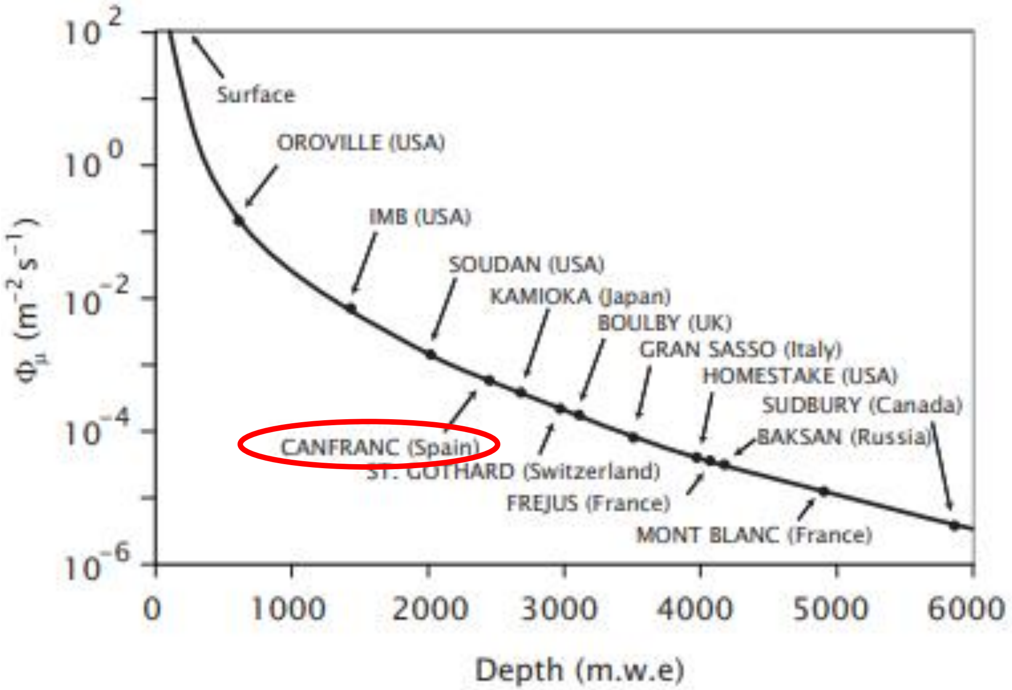
Backup slides

Detection of axions

Large complementarity among categories

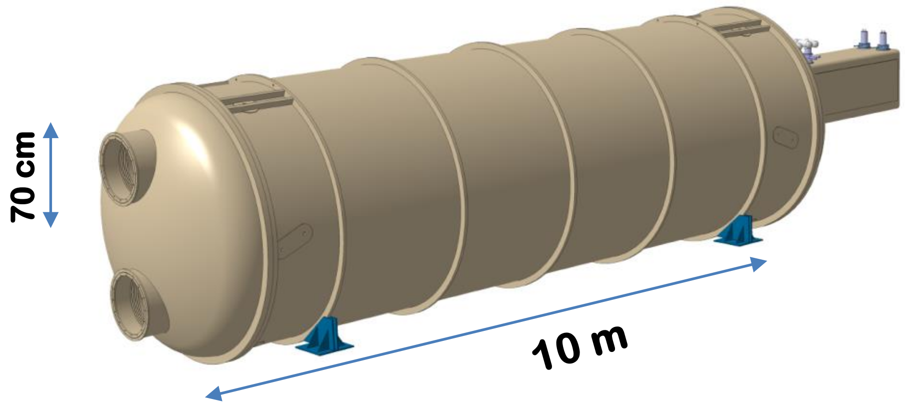
Source	Experiments	Model & Cosmology dependency	Technology
Relic axions 	ADMX, HAYSTAC, CASPEr, CULTASK, CAST-CAPP, MADMAX, ORGAN, RADES, G-LEAD, …	High	New ideas emerging, Active R&D going on,…
Lab axions 	ALPS, OSQAR, CROWS, ARIADNE,…	Very low	
Solar axions 	SUMICO, CAST, (Baby)IAXO	Low	Ready for large scale experiment

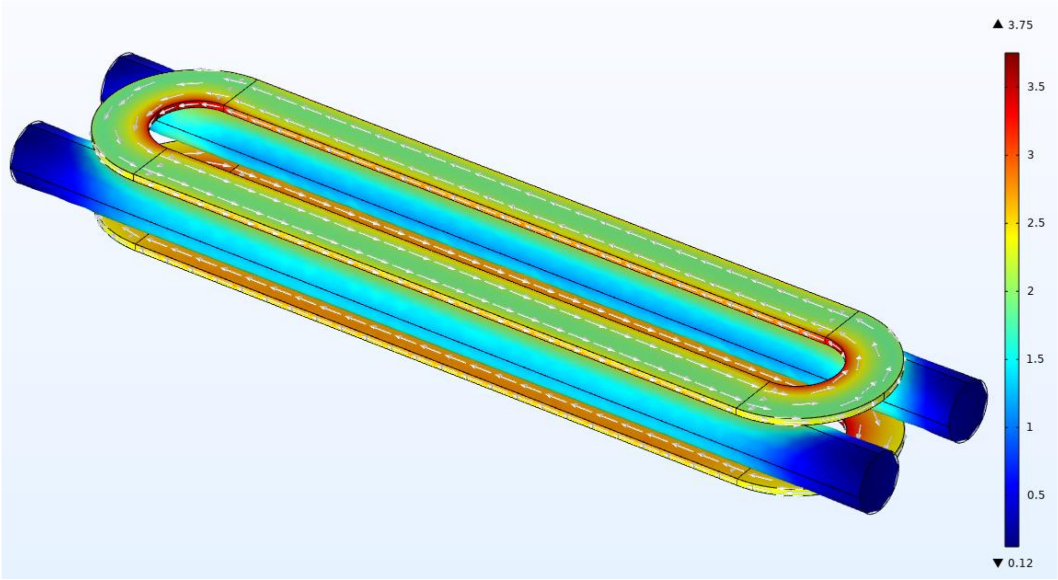
Underground Laboratory of Canfranc



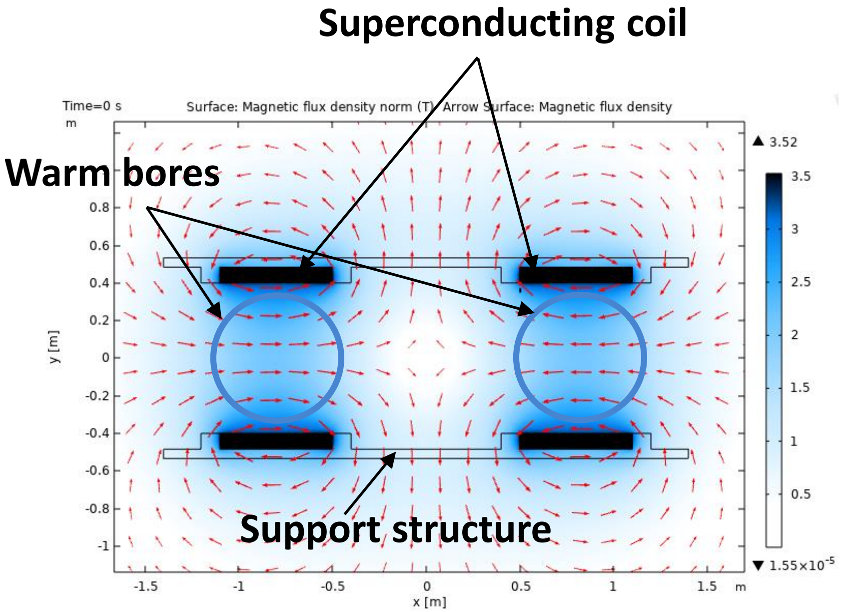
BabyIAXO Magnet

- **Common-coil superconducting dipole with a coil length of 10 meters**
- **Produces a transverse magnetic field over two 11-meter-long bores with a free diameter of 0.7 m**
- **To be operated at T ≤ 5 K featuring Nb-Ti-based superconducting coils with about 2 T in the bore**





Common-coil dipole, with counter-flowing current in two superconducting race-track coils



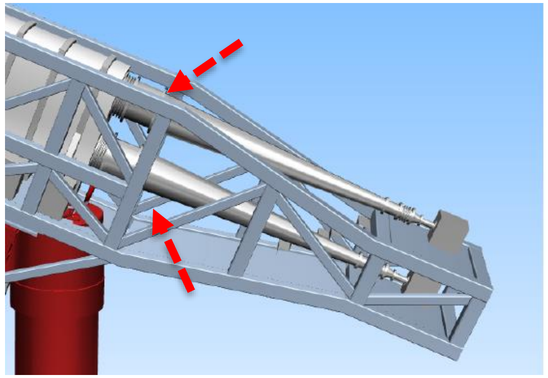
Cross-section of magnet with magnetic field

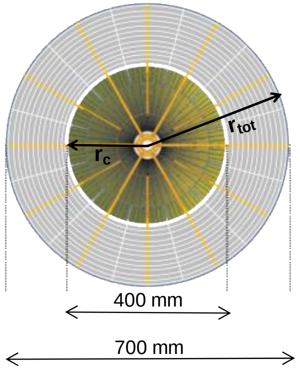
BabyIAXO Optics

2 detection lines in BabyIAXO:

Hybrid approach for custom BabyIAXO optic

- Inner part Al-foil or segmented glass optic (NASA/LLNL/DTU/MIT/Columbia)
- Outer part cold-slumped Willow-glass technology (INAF/DTU)
- First multilayer deposition tests and characterization with NuSTAR flight glass and Willow glass completed
- Design of support structure and vessel to hold, co-align and calibrate both under way as collaborative effort between all optics institutions (MIT)



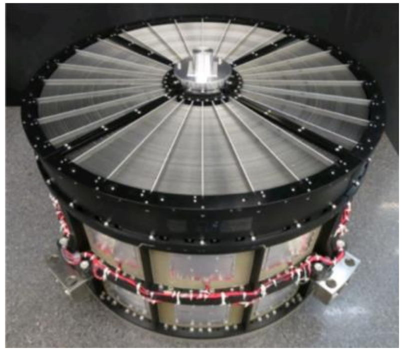


XMM Flight Spare XRT

- Engineering model for DESY, Actual optic currently at PANTER (Munich)

→ First collection of technical drawings at DESY, shipment is being arranged

- List for ESA operational requirements and loan agreement in preparation



Micromegas radiopurity measurements

Contents lists available at ScienceDirect

Astroparticle Physics

journal homepage: www.elsevier.com/locate/astropart

Radiopurity of micromegas readout planes

S. Cebrián [a], T. Dafni [a], E. Ferrer-Ribas [b], J. Galán [a], I. Giomataris [b], H. Gómez [a,*], F.J. Iguaz [a,1], I.G. Irastorza [a], G. Luzón [a], R. de Oliveira [c], A. Rodríguez [a], L. Seguí [a], A. Tomás [a], J.A. Villar [a]

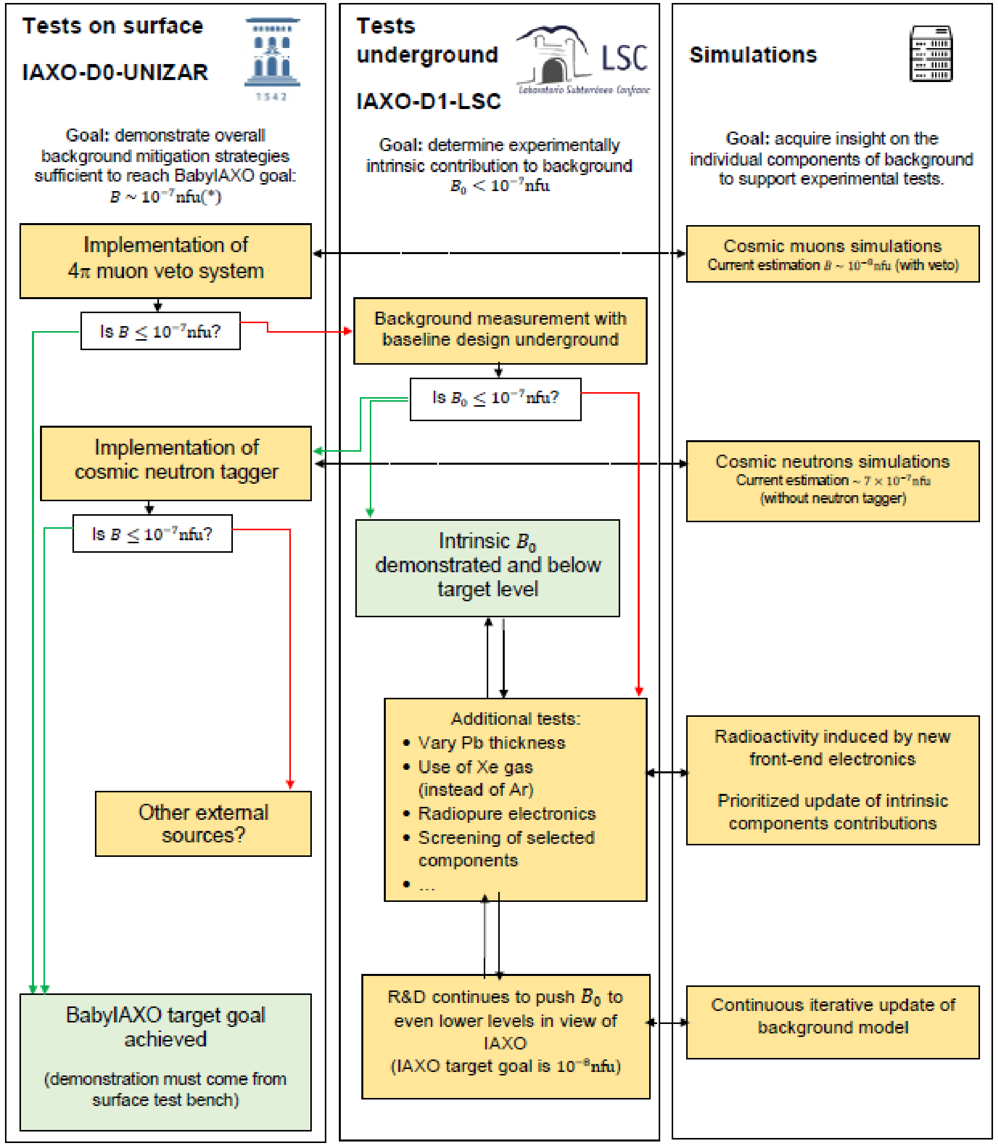
[a] Laboratorio de Física Nuclear y Astropartículas, Universidad de Zaragoza, 50009 Zaragoza, Spain
[b] CEA, IRFU, Centre d'etudes de Saclay, 91191 Gif-sur-Yvette, France
[c] European Organization for Nuclear Research (CERN), CH-1211 Genève, Switzerland

Table 2
Radioactivity levels (in µBq/cm^2) measured for a Micromegas without mesh, a *microbulk*-Micromegas, a kapton–copper raw material foil, a copper–kapton–copper raw material foil and those in a PMT used in XENON experiment, taken from [30].

Sample	^{232}Th	^{235}U	^{238}U	^{40}K	^{60}Co
Micromegas without mesh	4.6 ± 1.6	<6.2	<40.3	<46.5	<3.1[a]
Microbulk-Micromegas	<9.3	<13.9	26.3 ± 13.9	57.3 ± 24.8	<3.1[a]
Kapton–copper foil	<4.6[a]	<3.1[a]	<10.8	<7.7[a]	<1.6[a]
Copper–kapton–copper foil	<4.6[a]	<3.1[a]	<10.8	<7.7[a]	<1.6[a]
Hamamatsu R8520-06 PMT [30]	27.9 ± 9.3	–	<37.2	1705.0 ± 310.0	93.0 ± 15.5

[a] Level obtained from the minimum detectable activity (MDA) of the detector [31].

Proposed Strategy



(*) 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 strategy

Tests at underground (Canfranc Laboratory):
Determine intrinsic radioactivity (internal or inner shielding components) of the detector

Simulations:
Insight on individual components of the background to support experimental tests

AGET CHIP

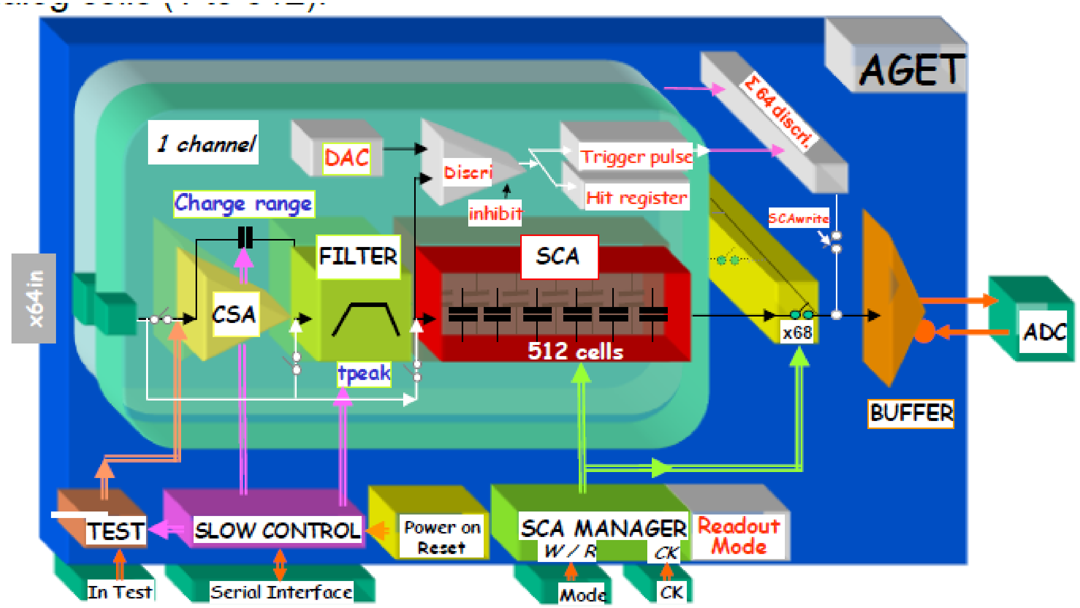


Fig. 2: Block diagram of the AGET chip.

Parameter	Value
Polarity of detector signal	Negative or Positive
Number of channels	72
External Preamplifier	Yes; access to the filter or SCA input
Charge measurement	
Input dynamic range	120 fC; 1 pC; 10 pC
Gain	Adjustable/(channel)
Output dynamic range	2V p-p
I.N.L	< 2%
Resolution	< 850 e- (Charge range: 120fC; Peaking Time: 200ns; Cinchannel. < 30pF)
Sampling	
Peaking time value	50 ns to 1 µs (16 values)
Number of SCA Time bins	511
Sampling Frequency	1 MHz to 100 MHz
Time resolution	
Jitter	60 ps rms
Skew	< 700 ps rms
Trigger	
Discriminator solution	L.E.D
Trigger Output/Multiplicity	OR of the 72 hit channel registers; Width = 2xTSCAckread
Dynamic range	5% of input charge range
I.N.L	< 5%
Threshold value	4-bit DAC/channel + (3-bit + polarity bit) common DAC
Minimum threshold value	≥ noise
Readout	
Readout frequency	20 MHz to 25 MHz
Channel Readout mode	Hit channel; specific channels; all channels
SCA Readout mode	511 cells; 256 cells; 128 cells
Test	
calibration	1 channel / 72; external test capacitor
test	1 channel / 72; internal test capacitor (1/charge range)
functional	1, few or 76 channels; internal test capacitor/channel
Counting rate	< 1 kHz
Power consumption	< 10 mW / channel

Table 1: The synthesis of the AGET requirements.

IAXO neutron tagging

- Neutron multiply via ineslastic processes. Most of them (~85%) take place on the shielding.
- Secondary neutrons can leave axion-like on detector
- Secondary neutrons can be themalized and captured in Cd Layers to allow detection
- Neutrons are produced instantaneously but they take significant time to be themalised/captured
- Use timing and multiplicity information to tag these events