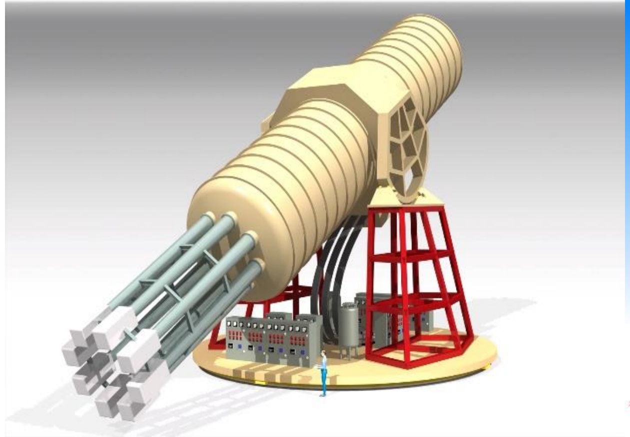
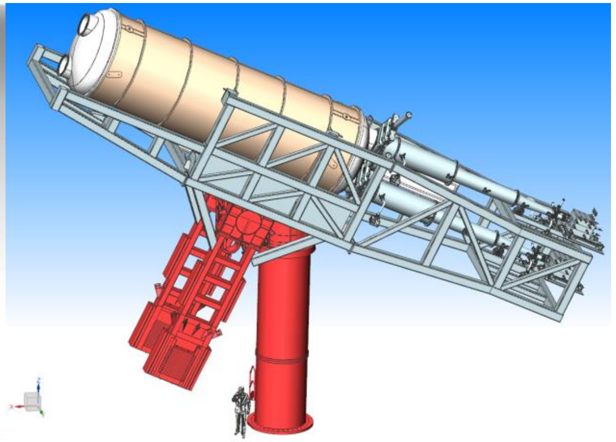
IAXO: International AXion Observatory

Esther Ferrer Ribas (IRFU/CEA)

13th Terascale Detector Workshop, 8th March 2021



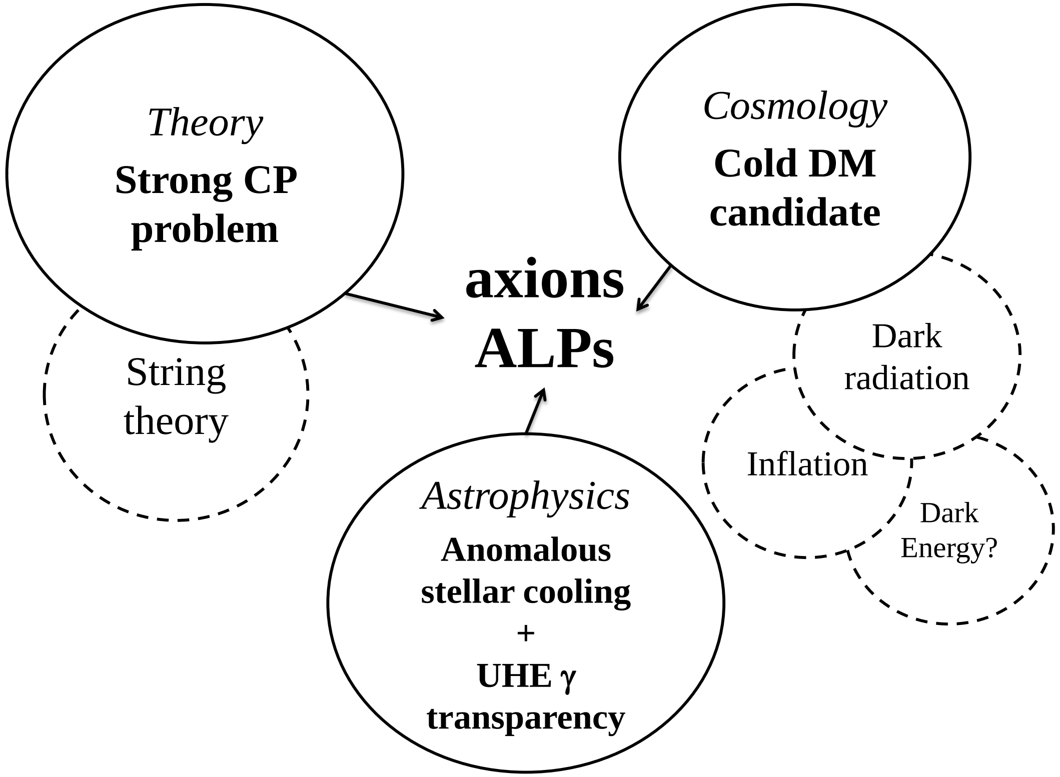


Plan

- **Motivations, strategies, IAXO**
  - Axions in a nutshell
  - Experimental strategies for axion search
  - IAXO/BabyIAXO
- **Detector development:**
  - State of the art
  - Requirements, strategy, on going developments

Axions in a nutshell

- **Most compelling solution to the Strong CP problem of the SM**
- **Axion-like particles (ALPs) predicted by many extensions of the SM (e.g. string theory)**
- **Axions, like WIMPs, may solve the DM problem *for free*. (i.e. not *ad hoc* solution to DM)**
- **Astrophysical hints for axion/ALPs?**
  - Transparency of the Universe to UHE gammas
  - Stellar anomalous cooling → $g_{a\gamma}$ ~ few 10^{-11} GeV^{-1} / m_a ~few meV ?

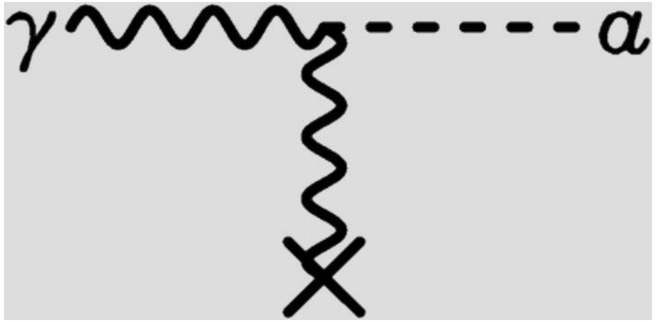


- **Relevant axion/ALP parameter space at reach of current and near-future experiments**
- **Experimental efforts growing fast but still small**

Axions

- Hypothetical particle
- Introduced in 1977 by Roberto Peccei and Helen Quinn
- Pratically stable
- Very low mass
- Very low cross-section
- Coupling to photons

$$m_a \simeq 0.6\ \mathrm{eV}\,\frac{10^7\,\mathrm{GeV}}{f_a}$$



$$L_{a\gamma} = g_{a\gamma}(\vec{E}\cdot\vec{B})a$$

$$g_{a\gamma} \propto 1/\,f_a$$

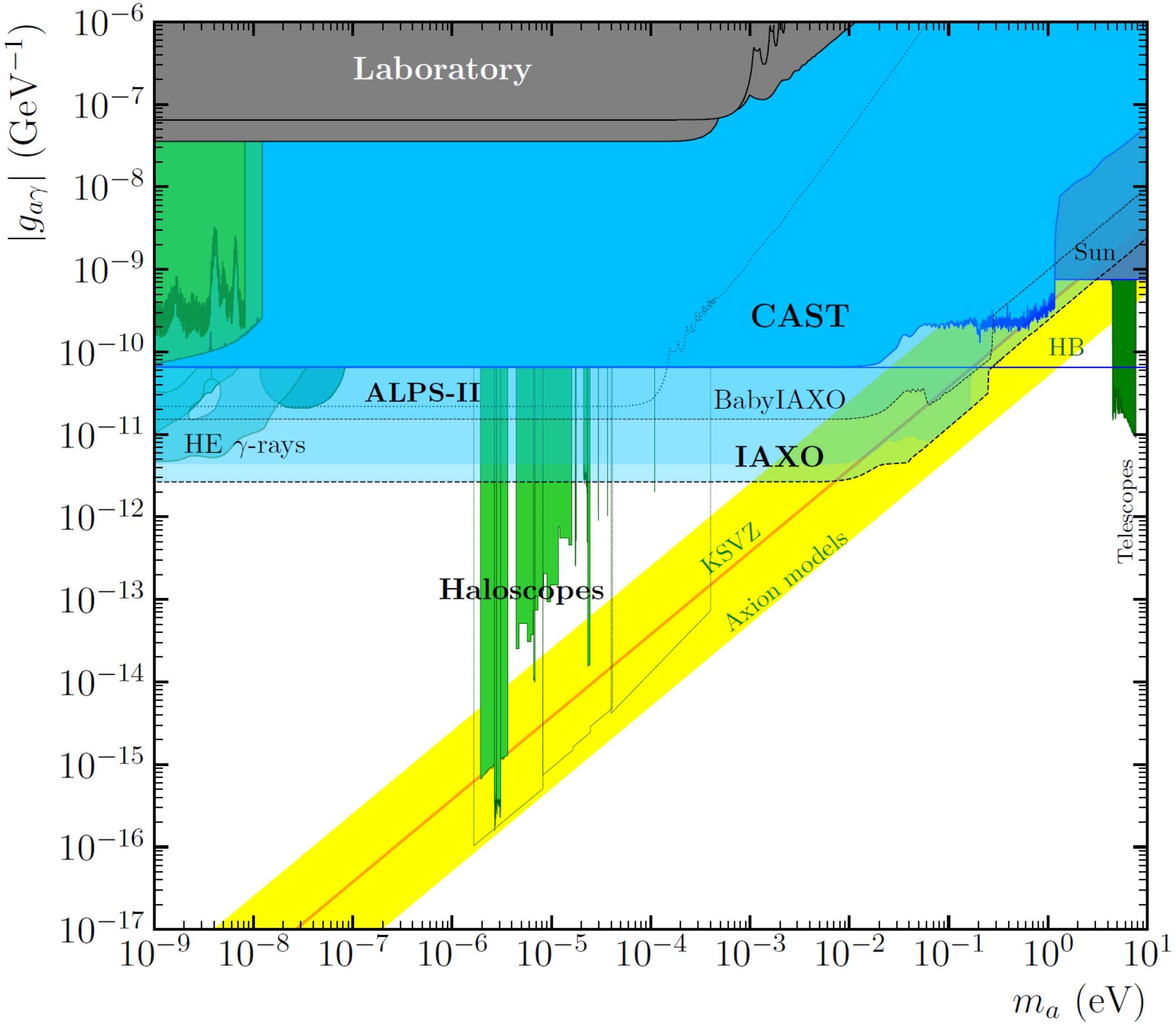
$$g_{a\gamma} \propto m_a$$

Detection of axions

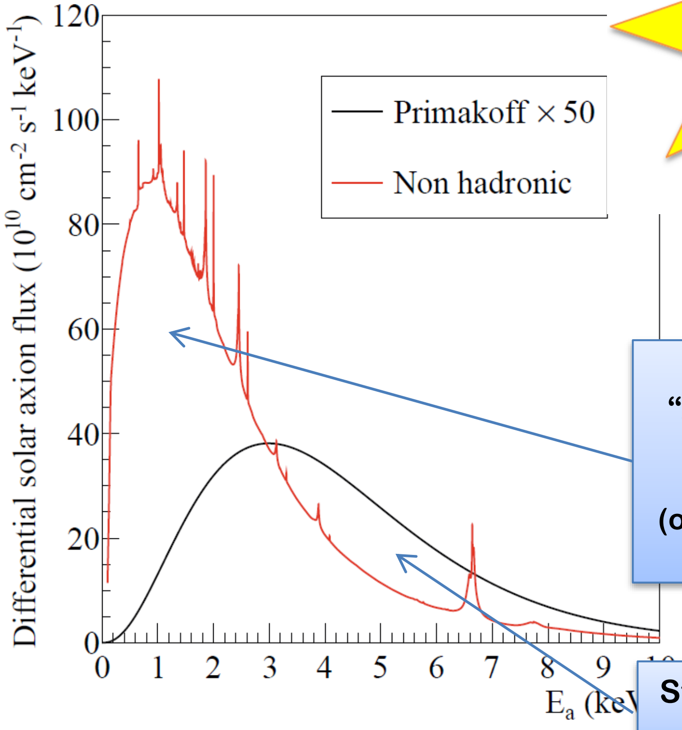
Large complementarity among categories

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

Experimental, astrophysical, cosmological bounds

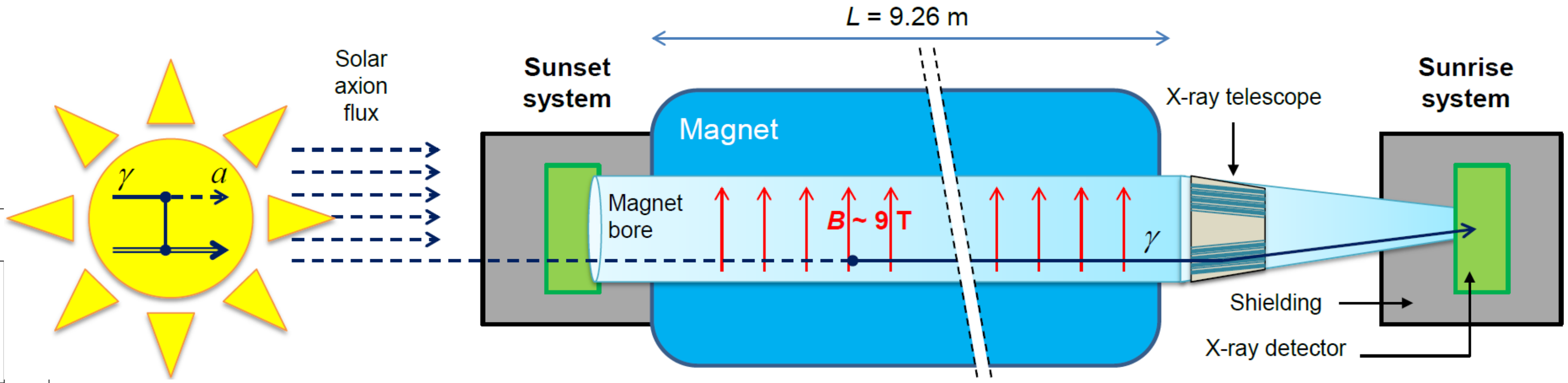


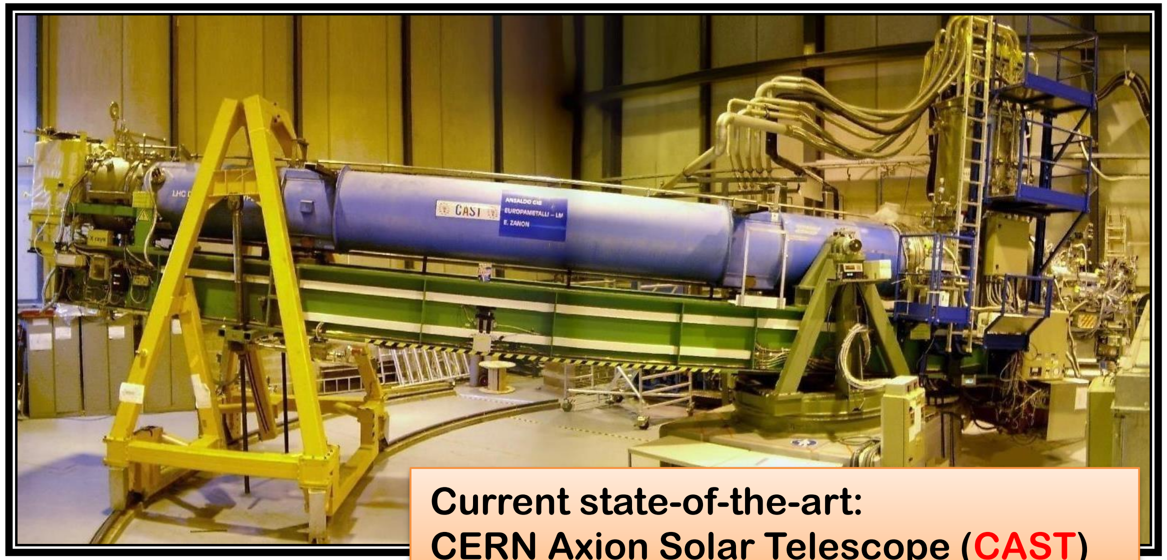
Axion helioscopes



Non-hadronic "ABC" Solar axion flux at Earth
JCAP 1312 008
(only if axion couples to electron)

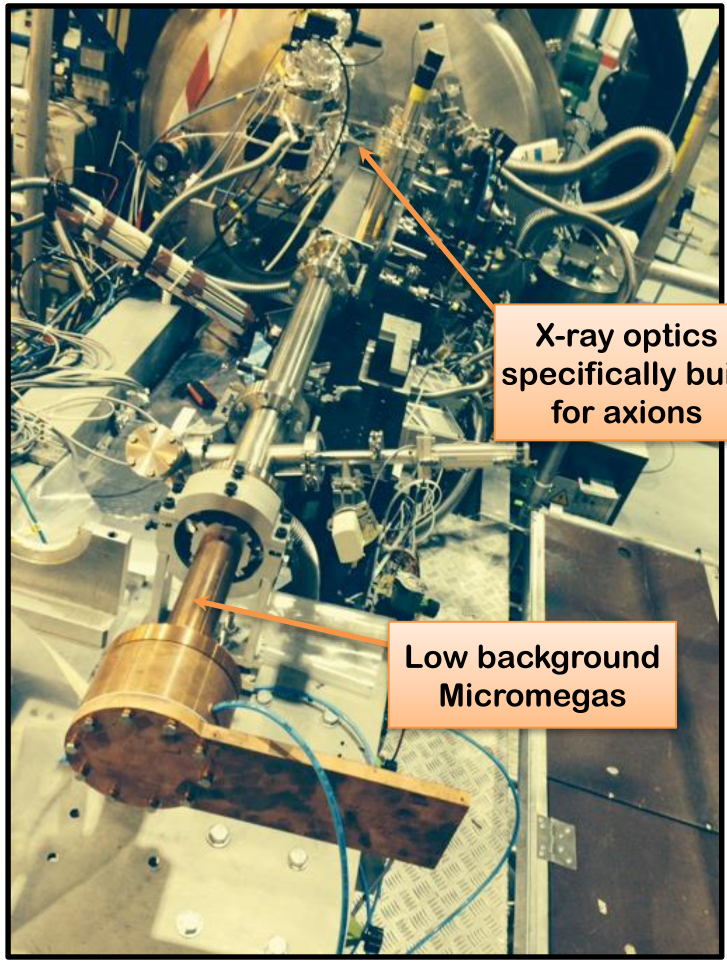
Standard Primakoff spectrum





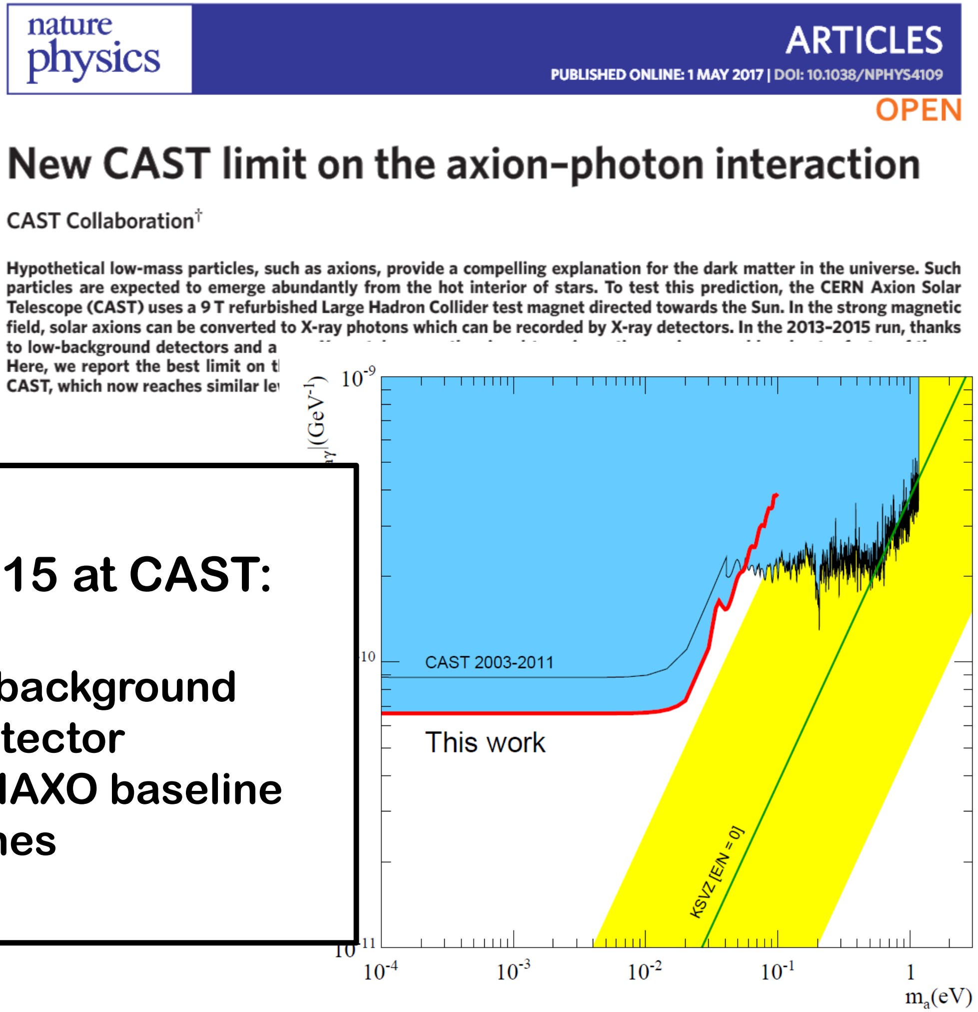
Current state-of-the-art:
CERN Axion Solar Telescope (CAST)

IAXO pathfinder at CAST



Data taking 2013-2015 at CAST:

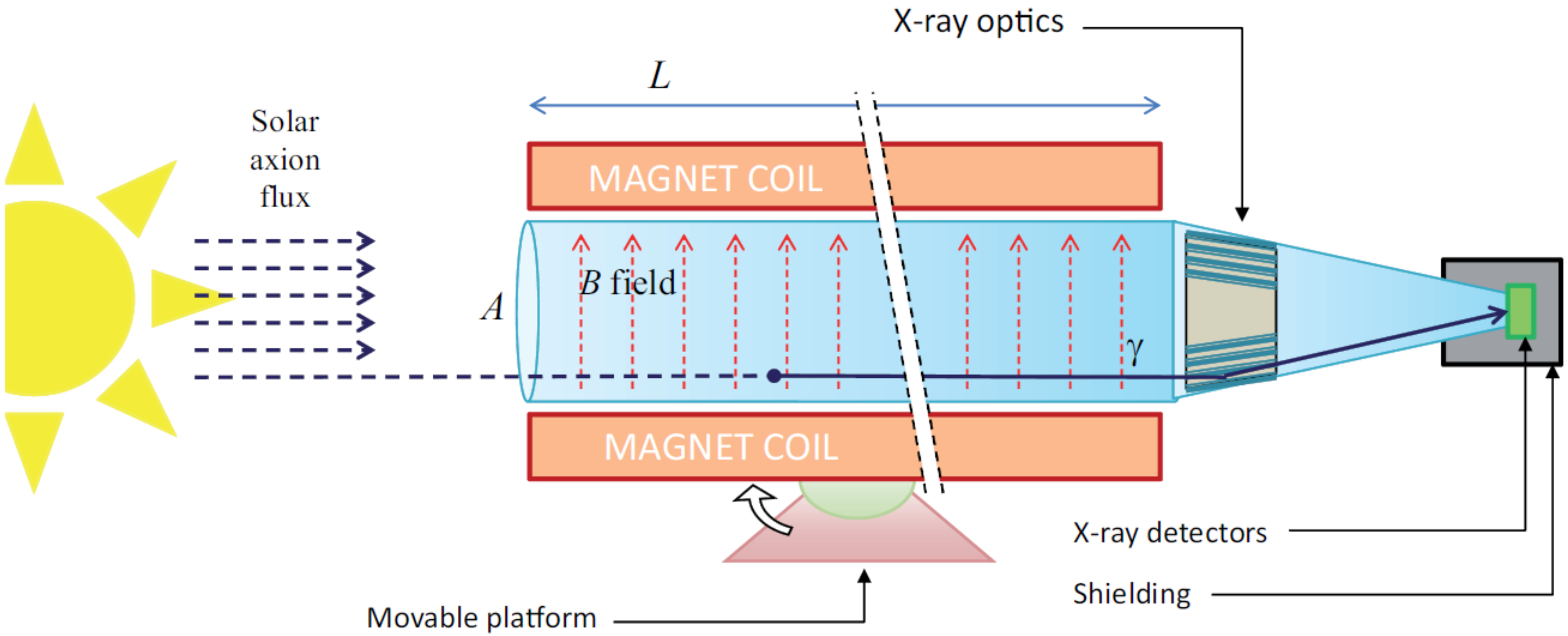
x-ray focusing + low background Micromegas detector
Small-scale version of IAXO baseline detection lines



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

CAST experiment: 4 gaseous MPGD detectors (3 Miromegas + Gridpix)

An enhanced axion helioscope



IAXO is conceived as a large-scale, but realistic, enhanced axion helioscope

$>10^4$ better SNR than CAST

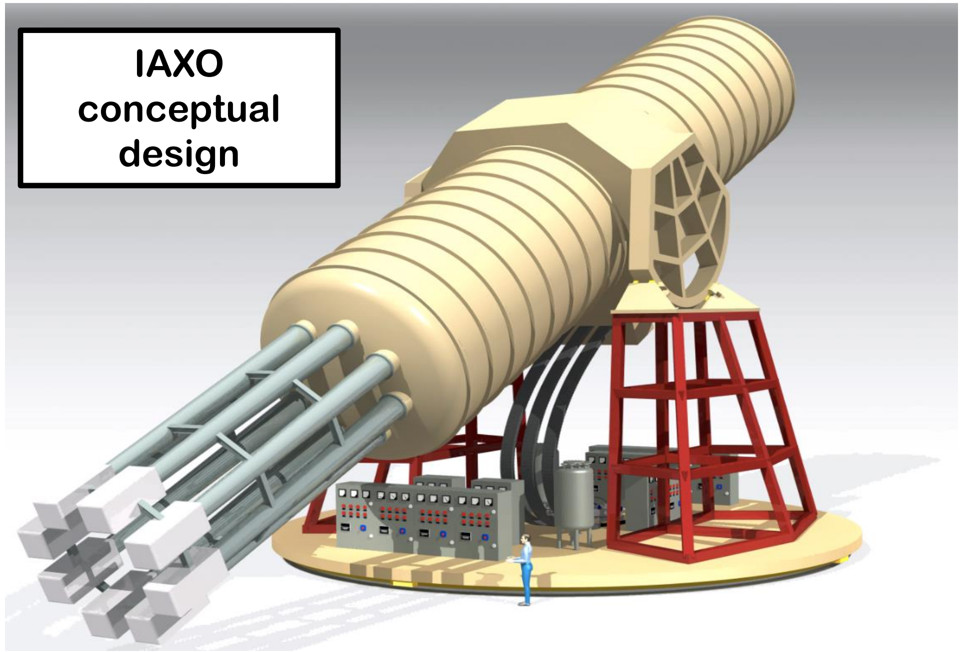
Sensitive to g_{ag} ~ x20 lower than CAST

Enhanced axion helioscope:
JCAP 1106:013,2011

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

IAXO experiment summary

- Next generation "axion helioscope" after CAST
- Purpose-built large-scale magnet
  - >300 times larger B^2L^2A than CAST magnet
  - Toroid geometry
  - 8 conversion bores of 60 cm Ø, ~20 m long
- Detection systems (XRT+detectors)
  - Scaled-up versions based on experience in CAST
  - Low-background techniques for detectors
  - Optics based on slumped-glass technique used in NuStar
- ~50% Sun-tracking time

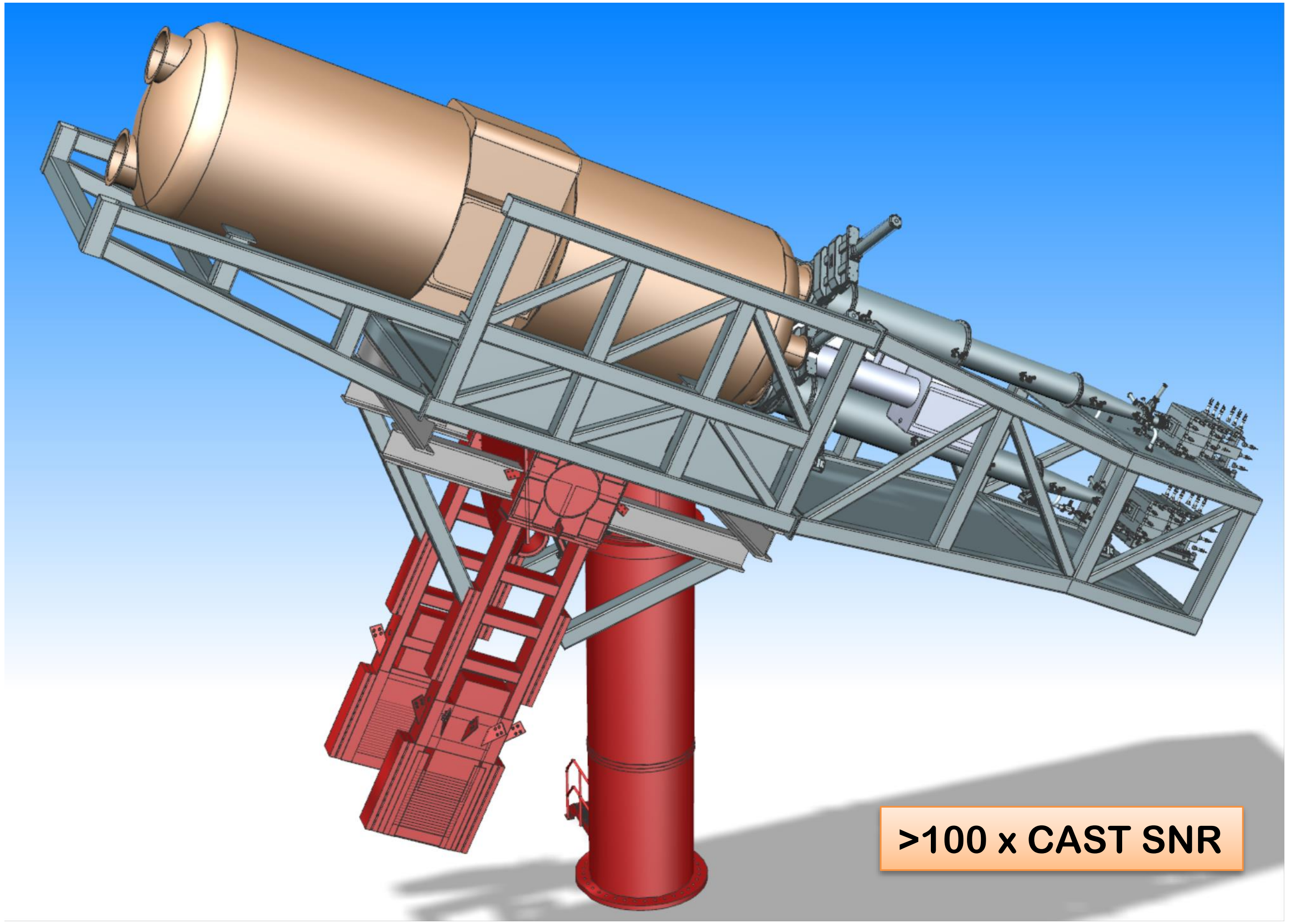


BabyIAXO

- **Prototype:** Intermediate experimental stage before IAXO
  - Two bores of dimensions similar to final IAXO bores → detection lines representative of final ones.
  - Magnet will test design options of final IAXO magnet
  - Test & improve all systems. Risk mitigation for full IAXO
- **Physics:** will also produce relevant physics outcome

  (~100 times larger FOM than CAST)

BabyIAXO CDR:
arXiv:2010.12076

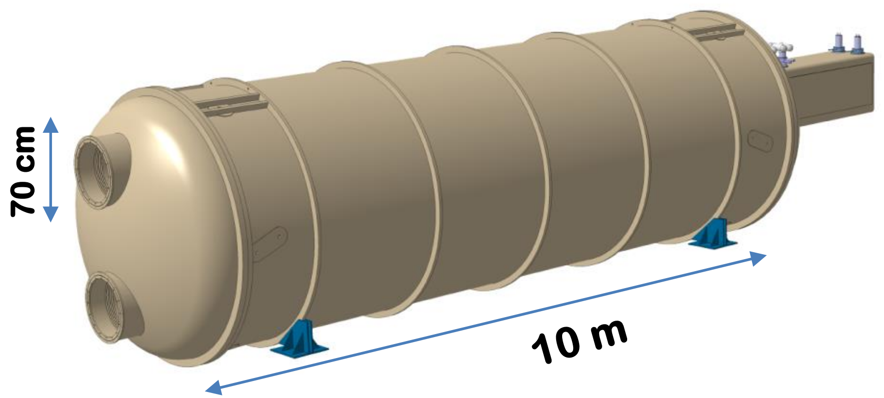


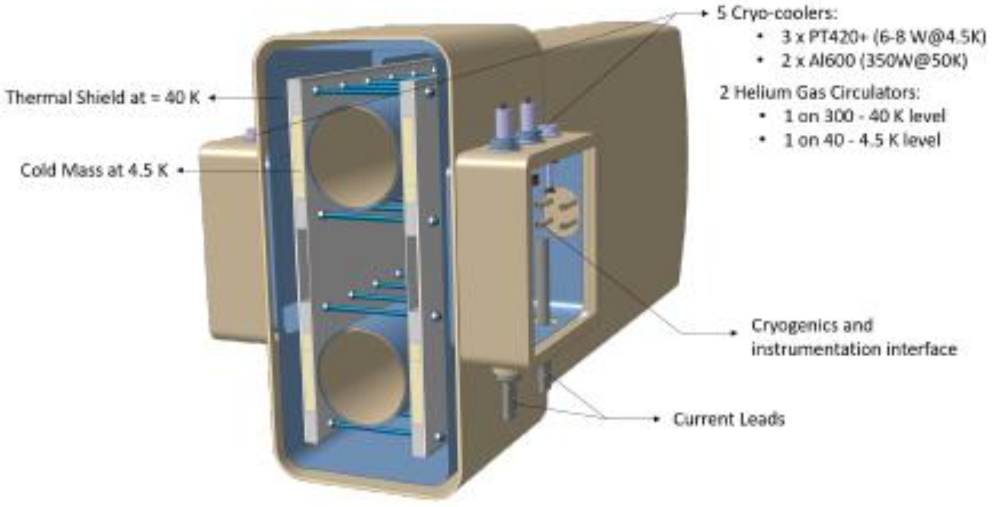
BabyIAXO Magnet

- **Minimal risk:** conservative design choices
  - **Cost-effective**: Best use of existing infrastructure and experience at CERN
  - **Prototyping** character: winding layout very close to that of IAXO toroidal design.

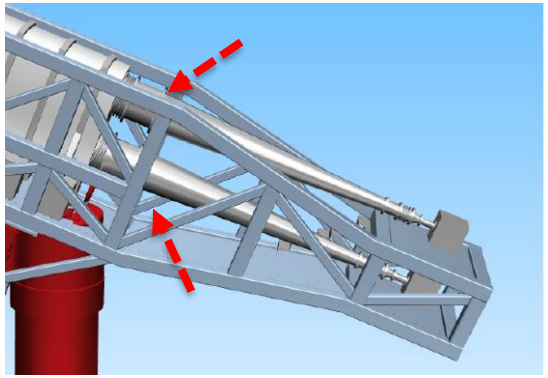
- **Technical in-depth review** of magnet design (by DESY PRC) successfully passed last November.
  - Design adapted to the use of a existing SC cable offered **inkind to IAXO by INR-Moscow**. Currently qualifying the cable for use in BabyIAXO.

- Quotations being received for magnet subsystems. Almost ready to start placing orders (cryostat, cold-mass,…).





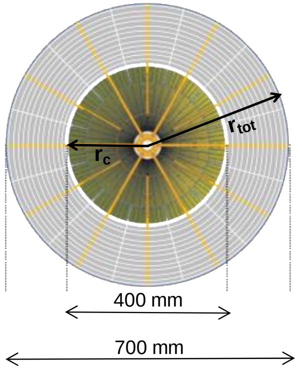
BabyIAXO Optics



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 → publication in preparation
- Design of support structure and vessel to hold, co-align and calibrate both under way as collaborative effort between all optics institutions (MIT)

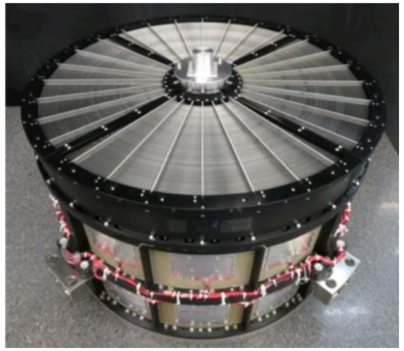


XMM Flight Spare XRT

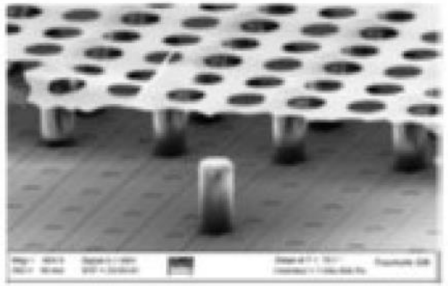
- Engineering model for DESY, Actual optic currently at PANTER (Munich)

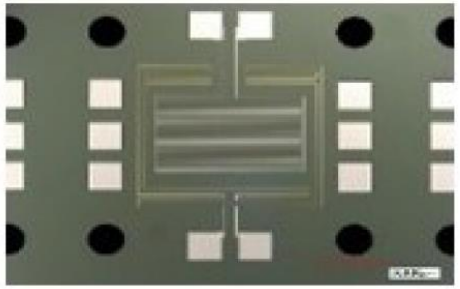
→ First collection of technical drawings at DESY, shipment is being arranged

- List for ESA operational requirements and loan agreement in preparation

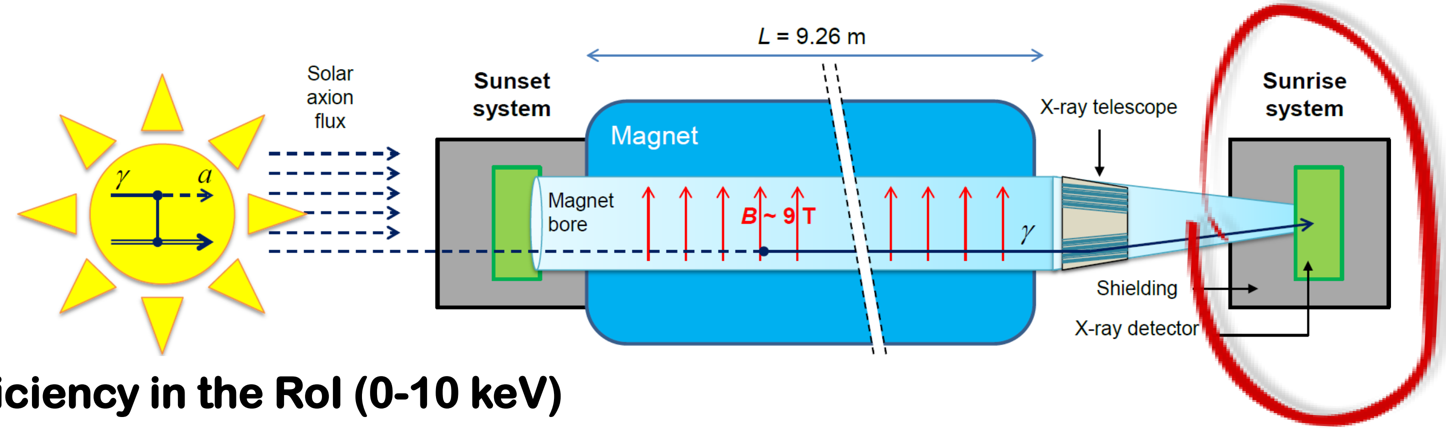


Detector development




Detector requirements



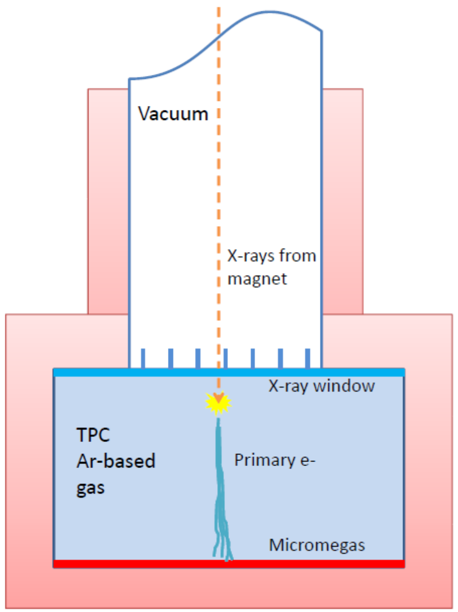
- **High detection efficiency in the RoI (0-10 keV)**

- **Very low background < 10 keV**: 10^{-7} c/keV/cm^2/s
  - ➔ use of shielding
  - ➔ radiopurity
  - ➔ advanced event discrimination strategies

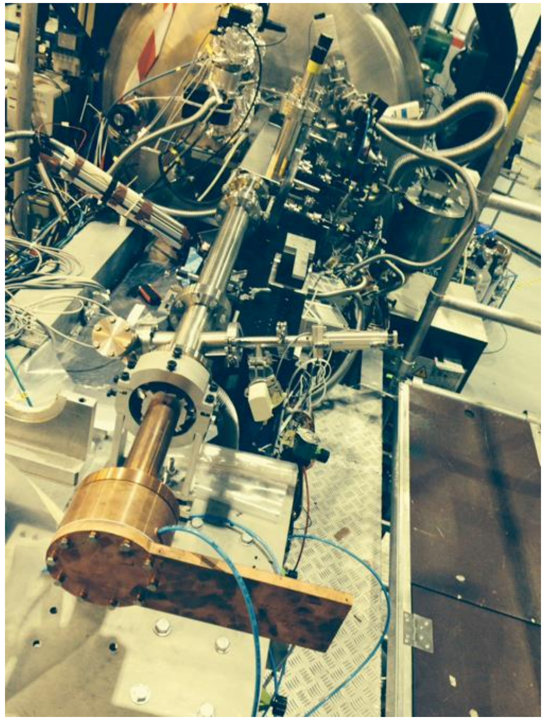
- **Baseline detector technology**: Time Projection Chambers (TPC) based on the **Micromegas technology** after the experience of the CAST experiment.
- **Alternative technologies under study**: Gridpix, Metallic Magnetic Calorimeters (MMC), Neutron Transmutation Doped sensors (NTD), Transition Edge Sensors (TES) and Silicon Drift Detectors (SDD)

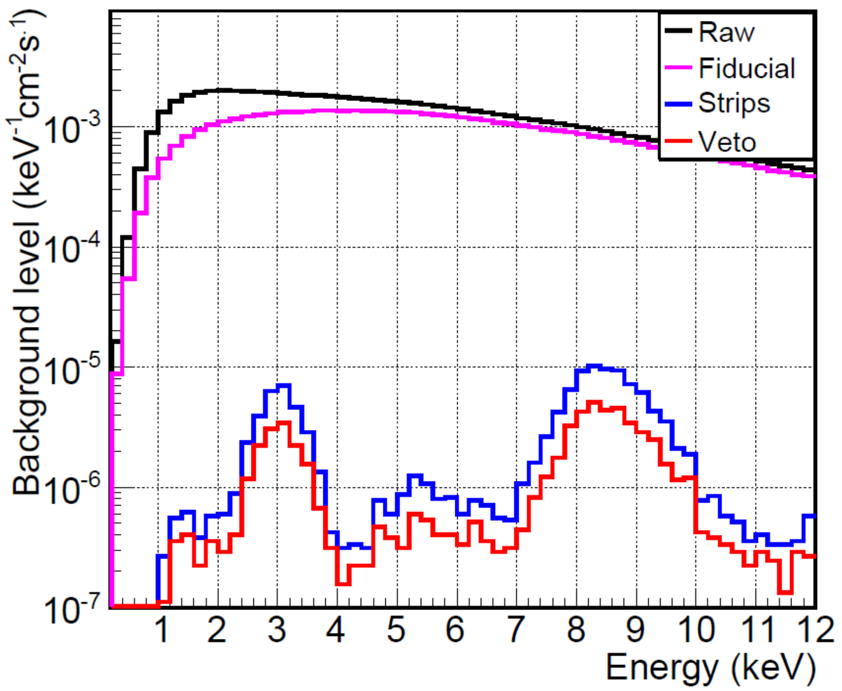
State Of the Art (I)

Principle of Micromegas



IAXO pathfinder at CAST 2014-2015

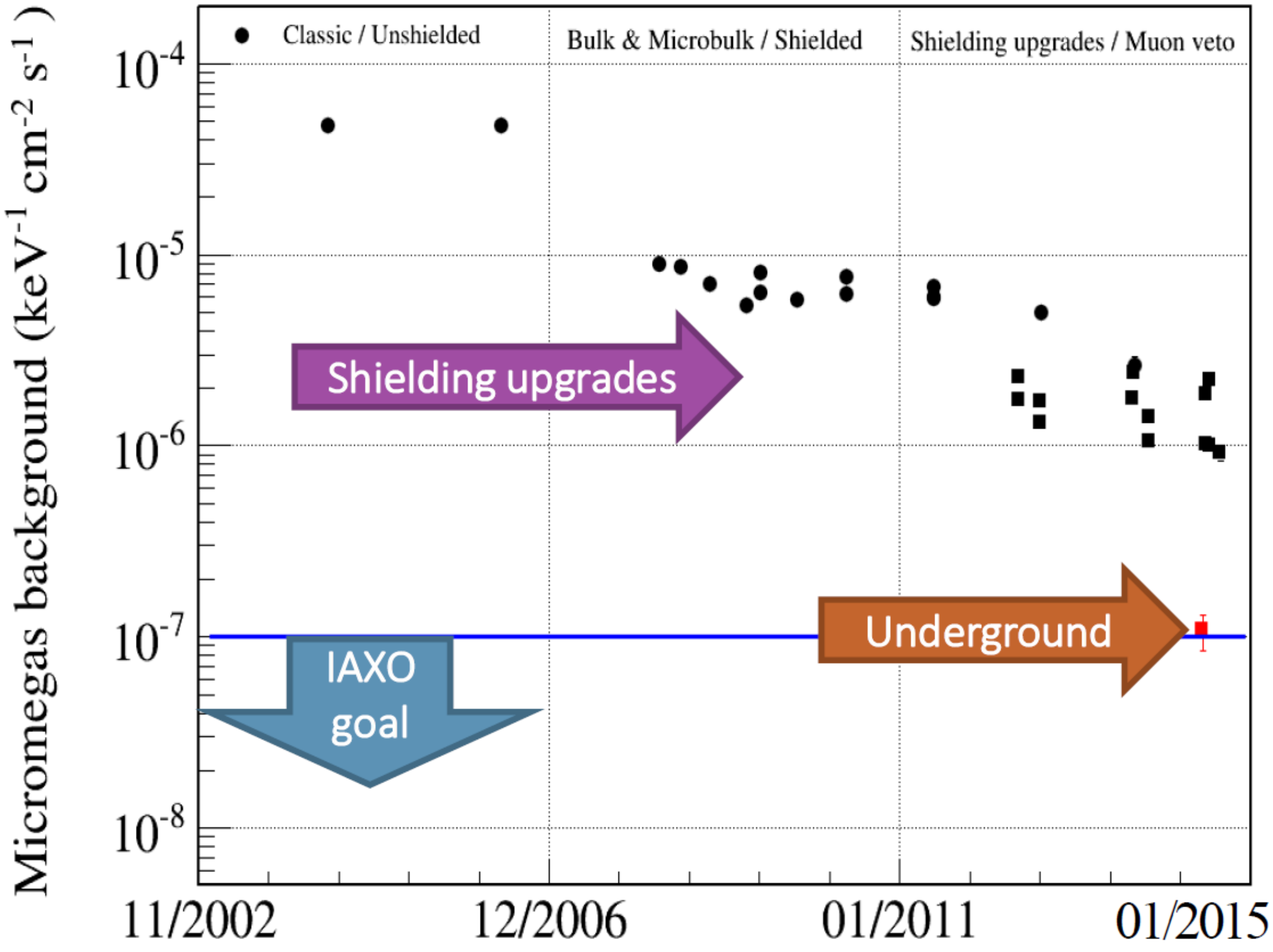




S. Aune et al., JINST 9 (2014) 9 P01001
F. Aznar et al., JCAP 12 (2015) 9 008
I.G. Irastorza et al., JCAP 01 (2016) 034

X-ray telescope + low background detector
Small-scale version of IAXO baseline detection lines

State Of the Art (II)



Achieved result 2013-2015 CAST data taking in the IAXO pathfinder system:

10^{-6} c/keV/cm^2/s (~0.2 c/h)

Old tests (2014) with a CAST replica detector at the LSC:

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

Current efforts focused to reduce cosmic-induced background

Understanding background sources

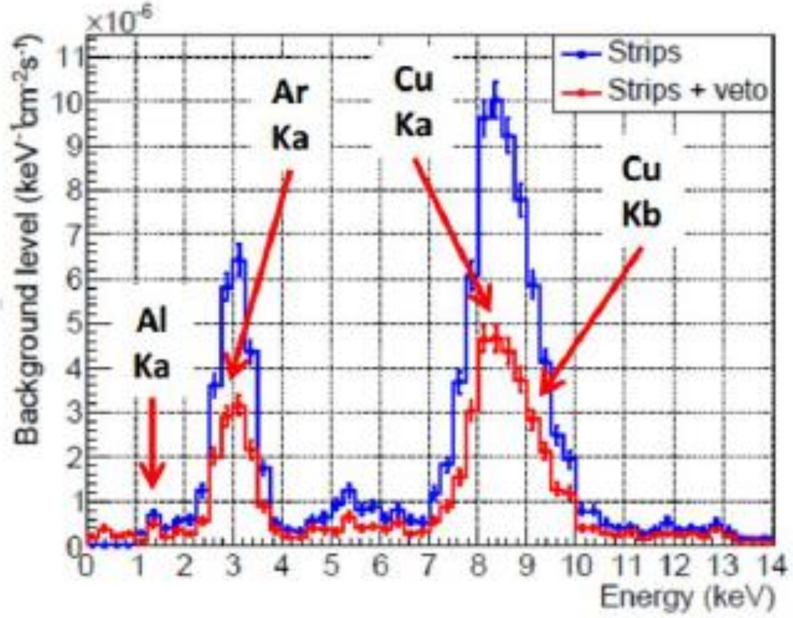
Experimental results :

At surface:

- CAST data taking in the IAXO pathfinder system: 10^{-6} c/keV/cm^2/s
- Starting point to go to BabyIAXO target level
- Effect of the muon veto 50% of the background in the RoI

At underground:

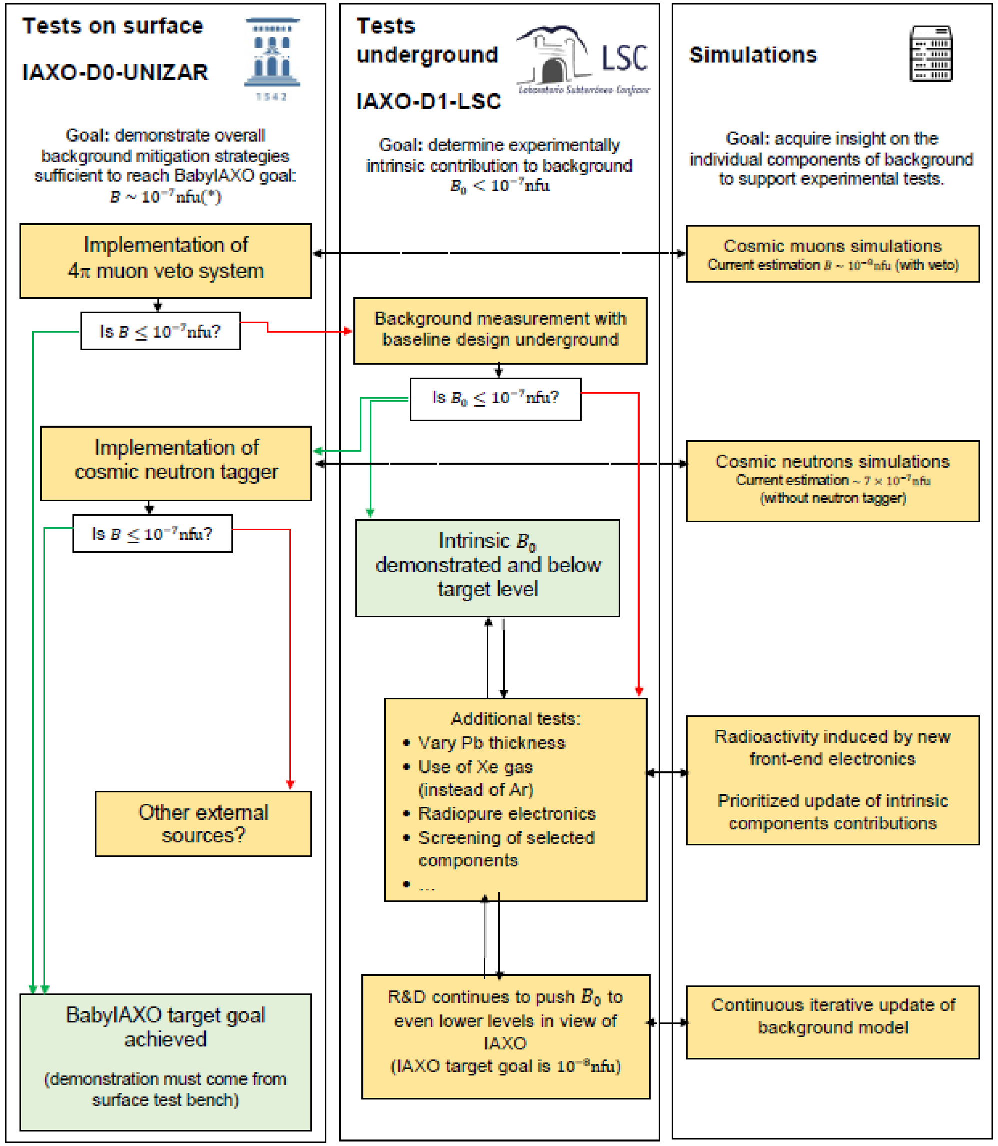
- Old tests with a CAST replica detector at the LSC: 10^{-7} c/keV/cm^2/s
  - Level representative of intrinsic limitation of the current design
  - CAST result dominated by cosmic related events



Simulation results :

- Main background at CAST : cosmic induced events related to X-rays fluorescence
- Achieved result is compatible with simulations indicating that the intrinsic background is 5×10^{-8} c/keV/cm^2/s
- Most of the intrinsic background from ^{39}Ar
- External components (neutrons or high energy gammas) seem to be negligible

Proposed Strategy (I)



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

Roadmap to demonstrate BabyIAXO target levels

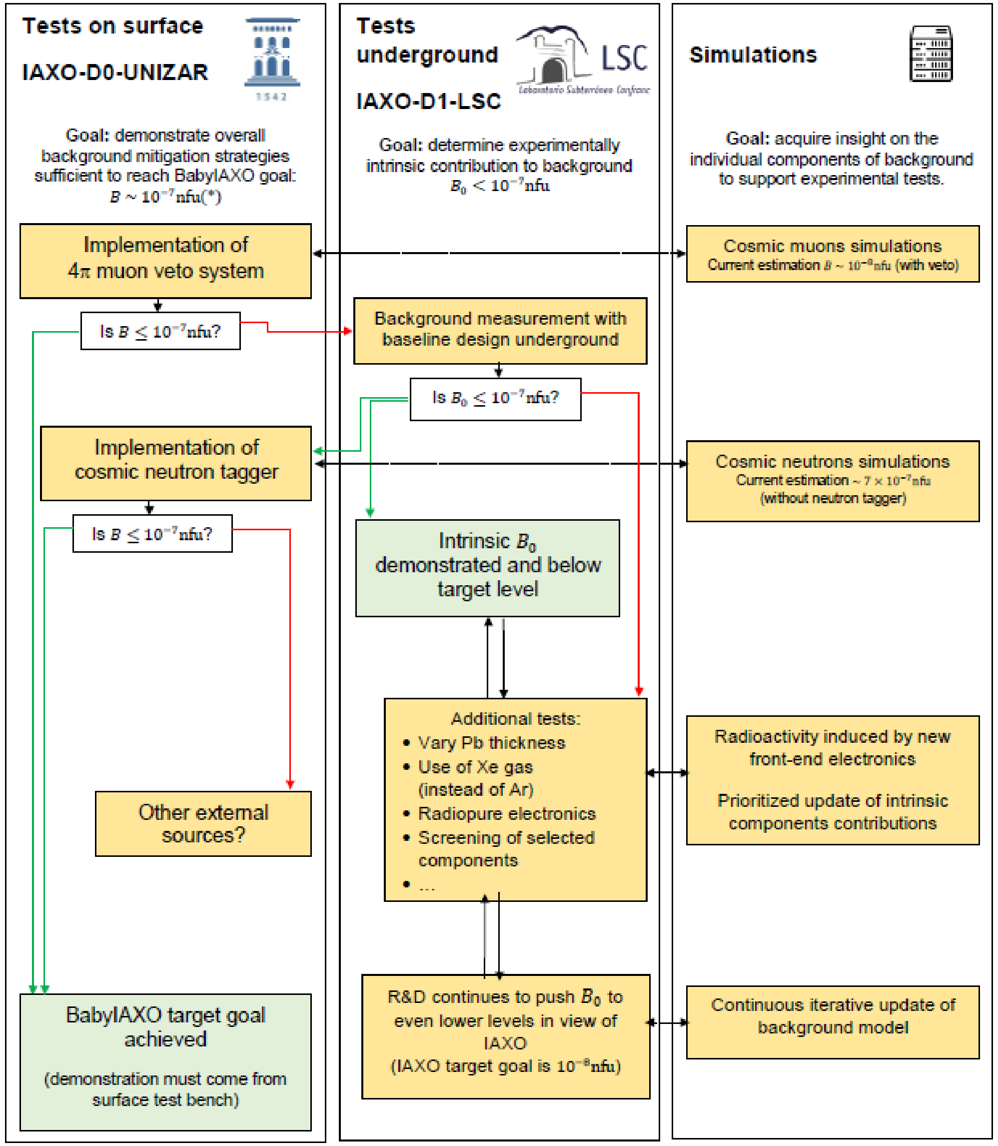
Combination surface and underground measurements, simulations and experimental improvements

Tests at surface:
Demonstrate overall background strategy

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

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

Proposed Strategy (II)



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

Tests at surface UNIZAR with IAXO-D0

Implementation of 4pi muon veto.
Enough to obtain 10^{-7} c/keV/cm^2/s?

Tests at underground with IAXO-D1

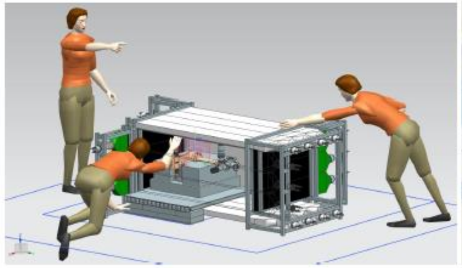
Determine part of intrinsic and cosmic induced events

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.

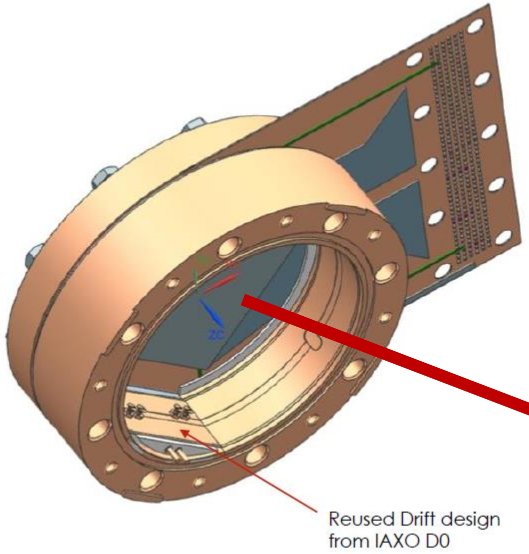


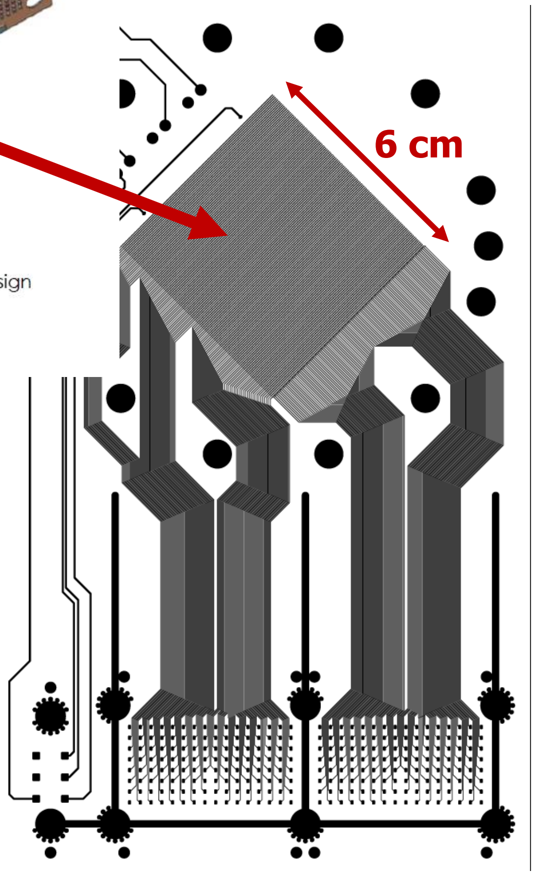
Micromegas new Design

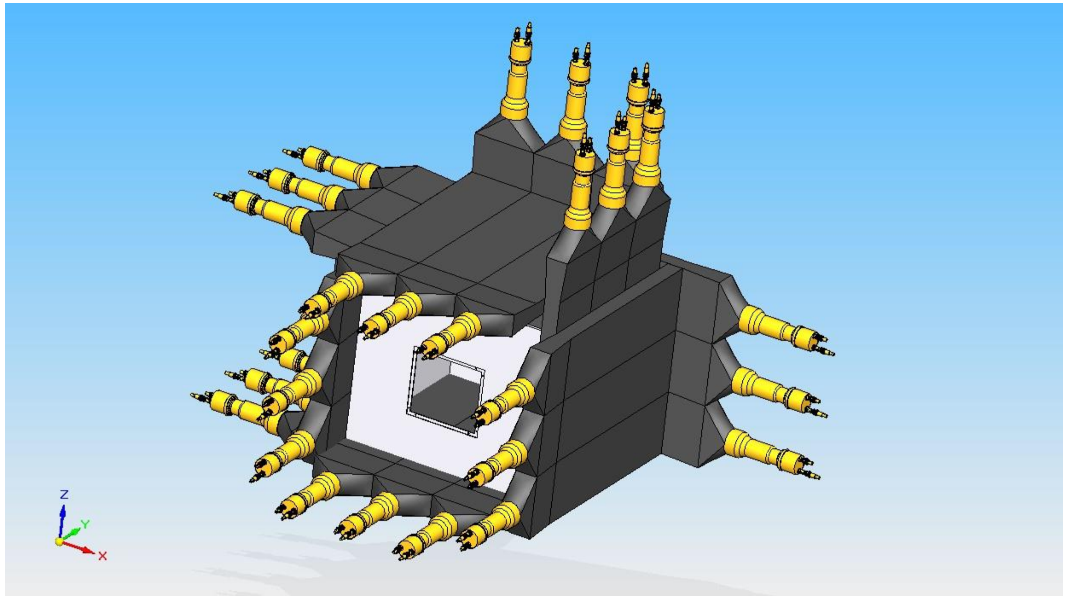
New detector design based on the CAST IAXO pathfinder

New electronics: approach the front end cards to the detector and improve the radiopurity of the components

Optimised lead shielding and 4pi actif muon veto







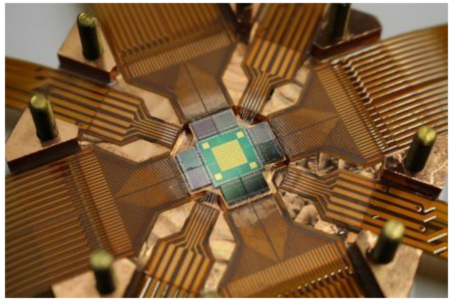
Alternative detector technologies

- Gridpix, Metallic Magnetic Calorimeters (MMC), Neutron Transmutation Doped sensors (NTD), Transition Edge Sensors (TES) and Silicon Drift Detectors (SDD)
- Excellent energy resolution, energy threshold, high efficiency and ultra-pure materials
- Improve the energy threshold ➔ investigation of fine structures in the axion spectrum

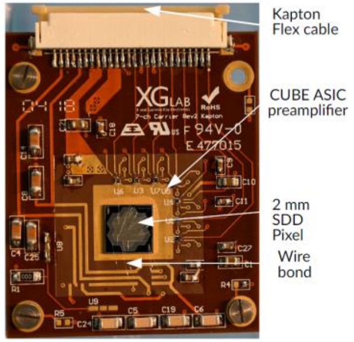
- Post-discovery scenario: If positive signal, low threshold + good energy resolution➔ possibility to determine m_a and g_{ae}
- Minimization of systematics effects and reinforcement of the claim significance

- At present :

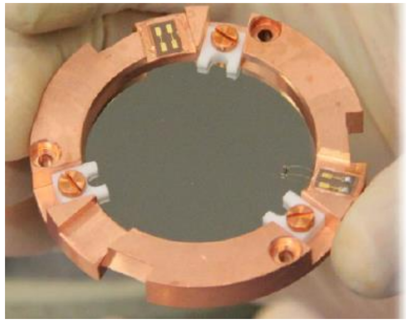
  Design and material optimization ongoing in all fronts
  Background studies with different shielding configurations



MMC



SDD



TES

Gridpix

Project tentative timeline

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

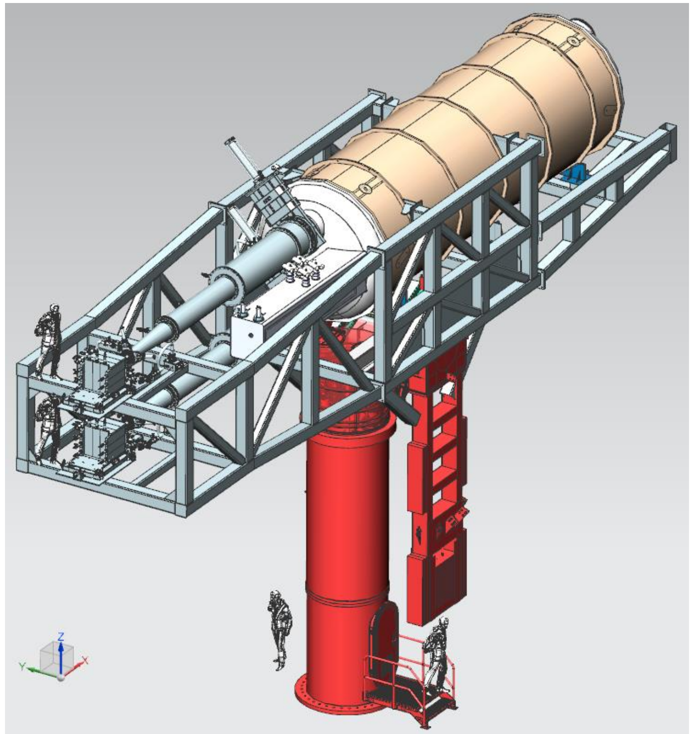
Conclusions

IAXO has a unique physics case in the "axion experimental landscape". A discovery is possible, even already at the BabyIAXO stage.

Micromegas detectors baseline for BabyIAXO.

Beyond baseline: GridPix, MMC, TES, NTD, SDD. High precision detectors with better threshold and energy resolution.

Active program of development and clear roadmap for the detectors of BabyIAXO.



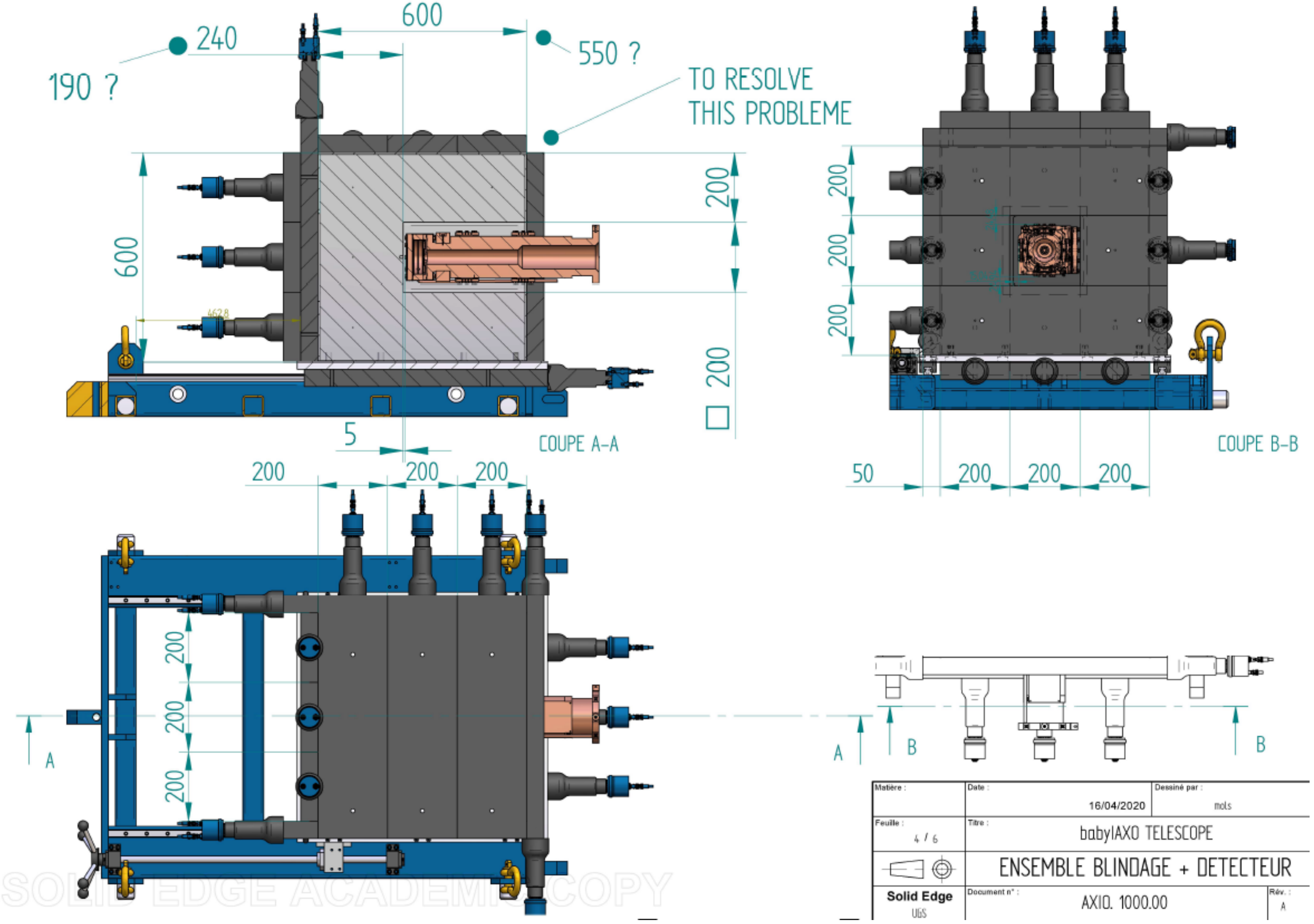
THANK YOU!

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) | 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)

Backup slides

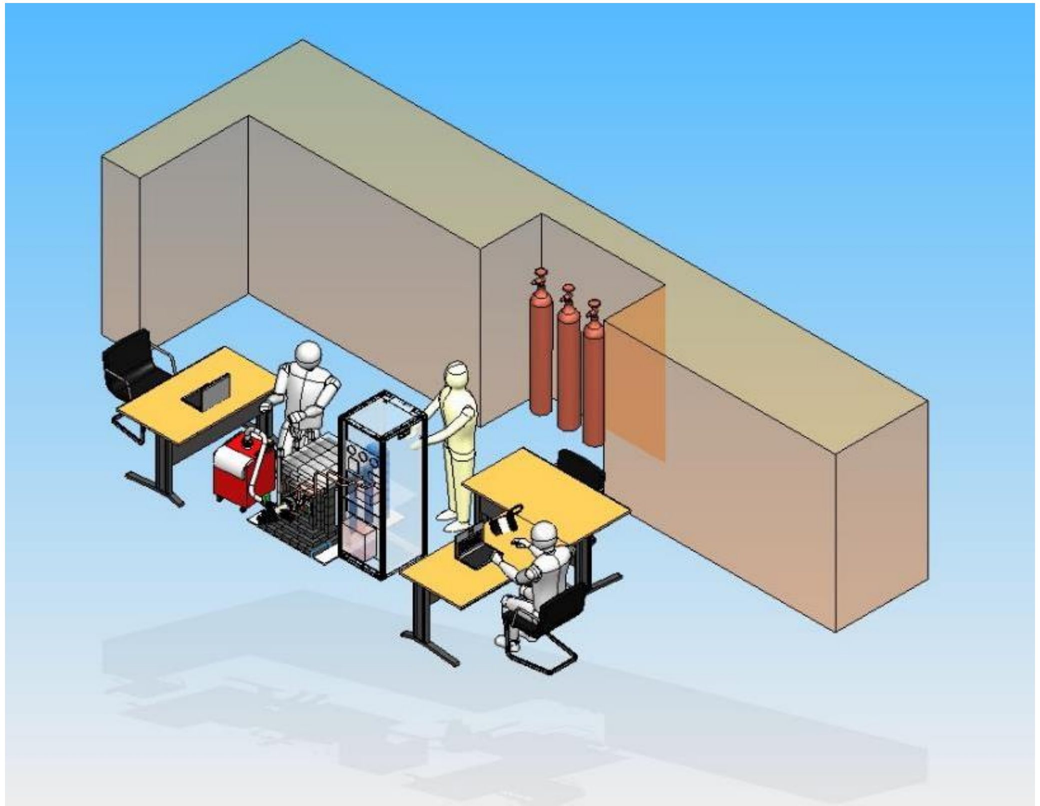
Shielding design

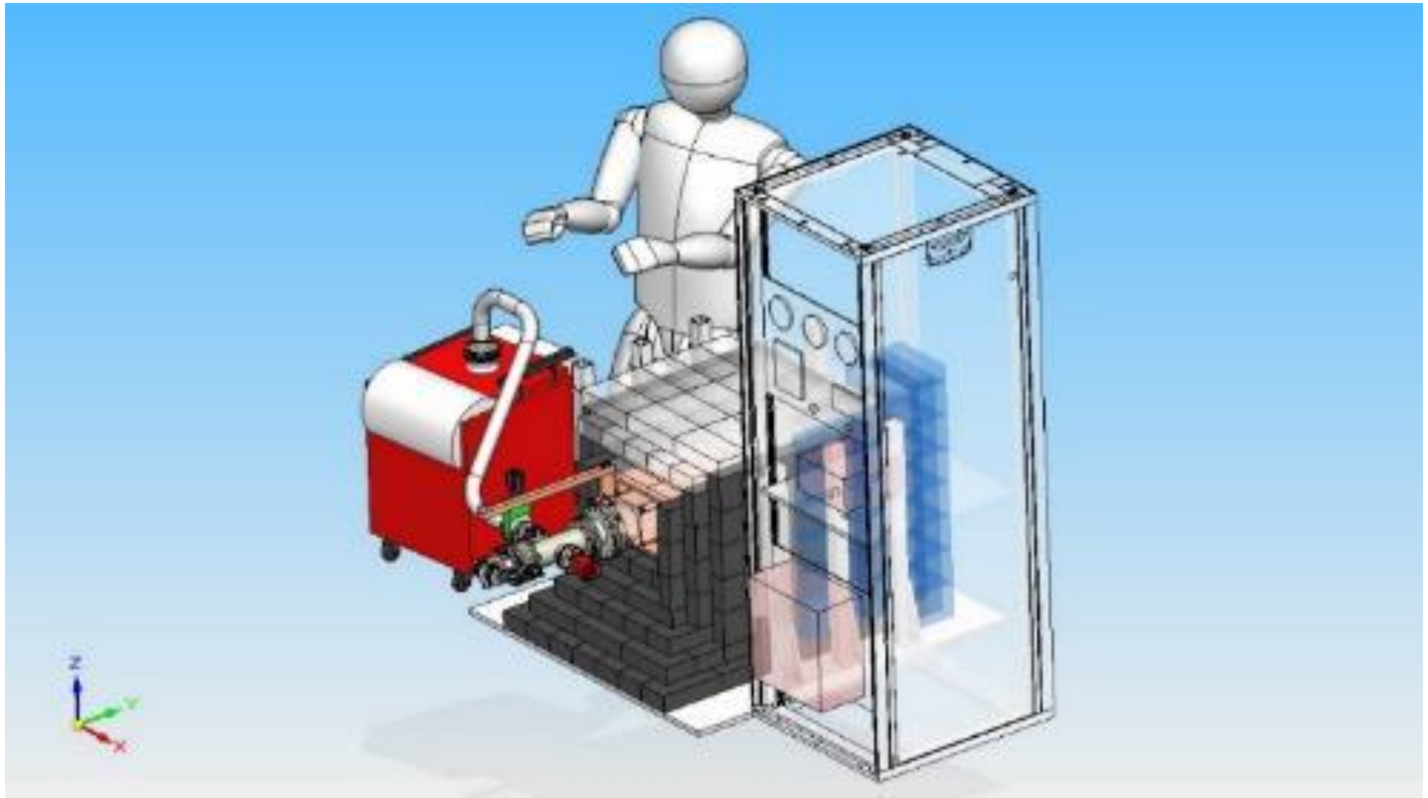


Lead shielding: 20 cm thickness

JP Mols + EFR + University Zaragoza

Detector platform at Canfranc

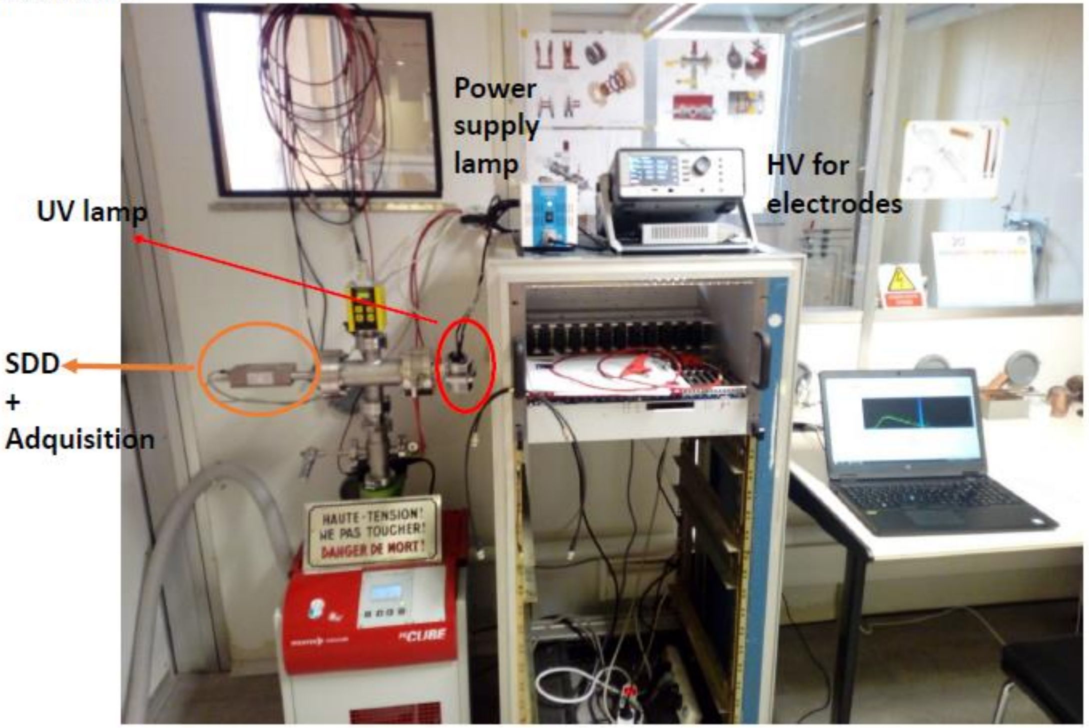




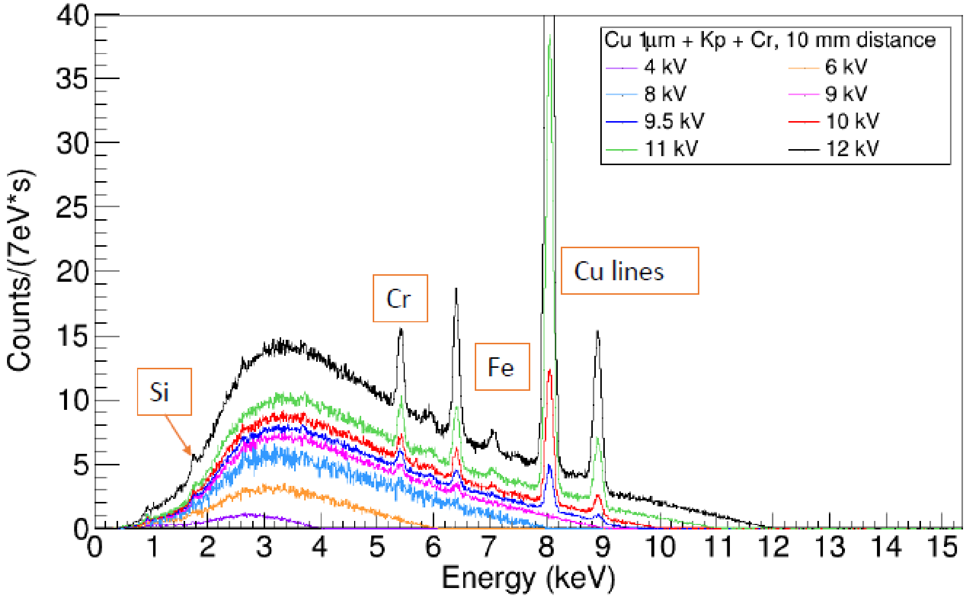
JP Mols + EFR + University Zaragoza

Calibration systems

- **Prototype for laboratory tests**: Design finished and ordered
- Installation



- **Prototype for laboratory tests**: Design finished and ordered
- Installation
- First measurements with 1 μm Copper (+ 12.5 μm Kapton + Cr [nm])

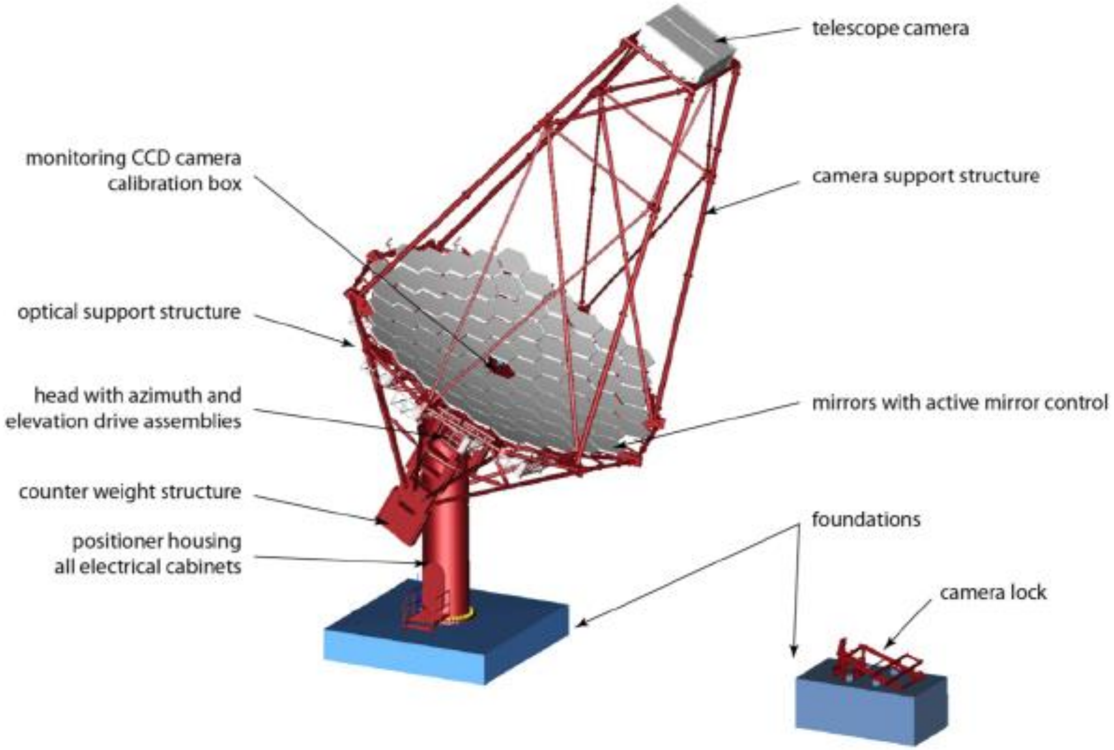


L Segui + T Papaevangelou + JP Mols

BabyIAXO Structure and drive system

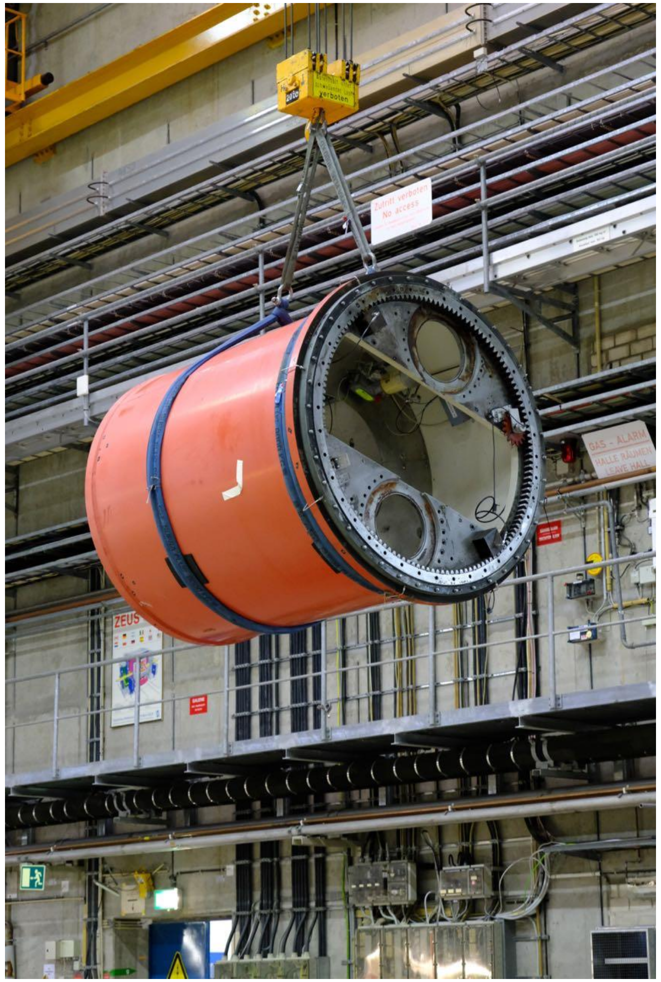
Recycling of the tower and positionning system of the Medium Size Telescope (MST) for CTA

	BabyIAXO			CTA MST
Technical Data				
	Magnet length	11 m	Diameter	12 m
	Total length	21 m	Focal length	16 m
	Weight of magnet	35 t	optical system	53.6 t
	Load on drive system	71.6 t		53.6 t
Requirements on drive system				
	Movement in altitude	±25°		−2° to 95°
	Movement in azimuth	360°		360° (540°)
	Speed of movement			
	- normal tracking	speed of Sun		speed of stars
	- fast movement			<90 s
	Pointing precision			
	- during tracking	<0.01°		<0.1°
	- RMS post-calibration			<7″ (<0.002°)



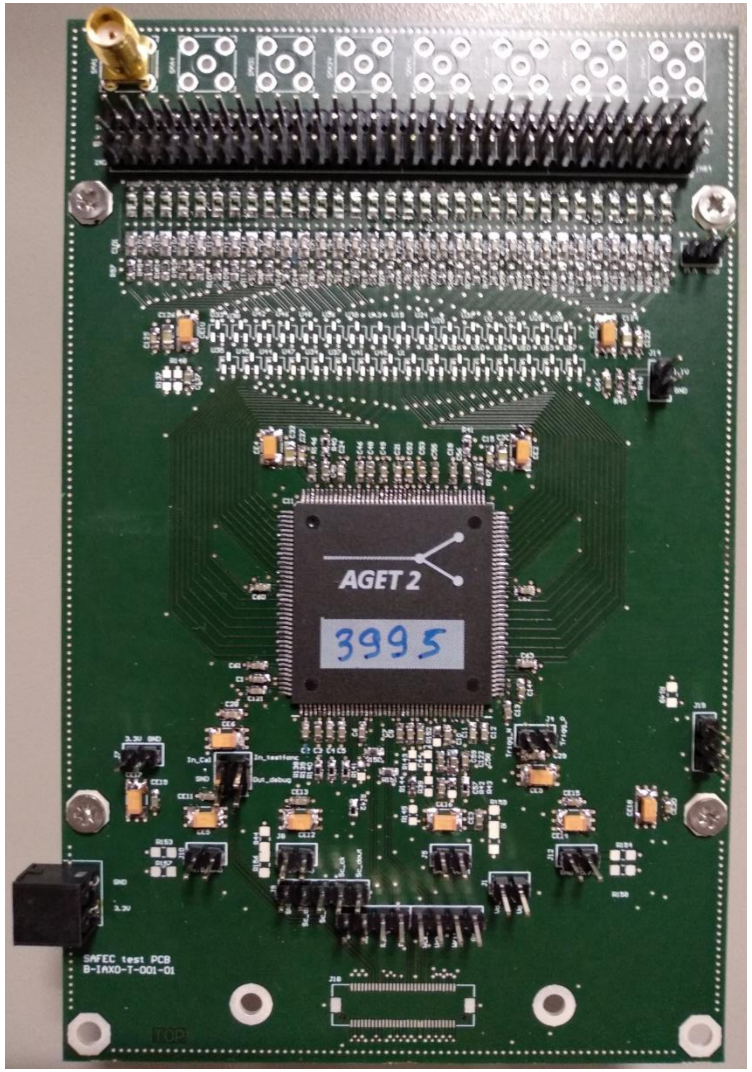
BabyIAXO Structure and drive system

Tower dismounted and shipped from Berlin to DESY (Hambourg) where BabyIAXO will take place



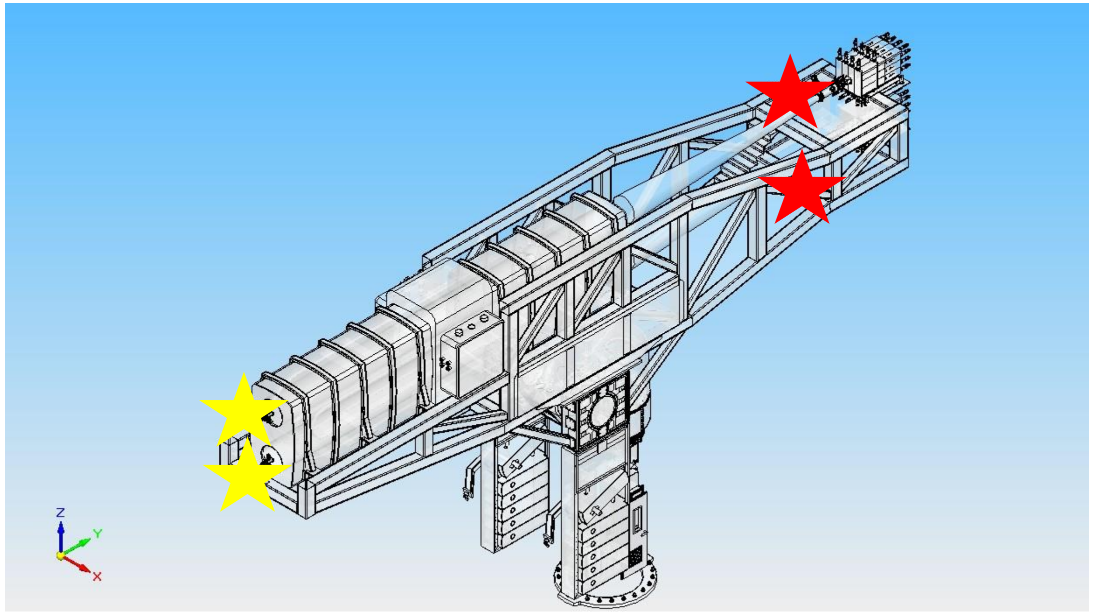
FEC for functionality tests (not radiopure)

- **VFE prototype zero step:**
  - **Check functionality**
    - **Easy access to all signals**
  - **Check distance to ADC**
  - **Not radiopure**
    - **Standard PCB prototype is cheaper and faster to produce**
    - **No face-to-face connectors**
  - **Requires a BEC or a controller to generate all signals to configure the ASIC.**
    - **General purpose PCB with FPGA at lab.**



Calibration systems

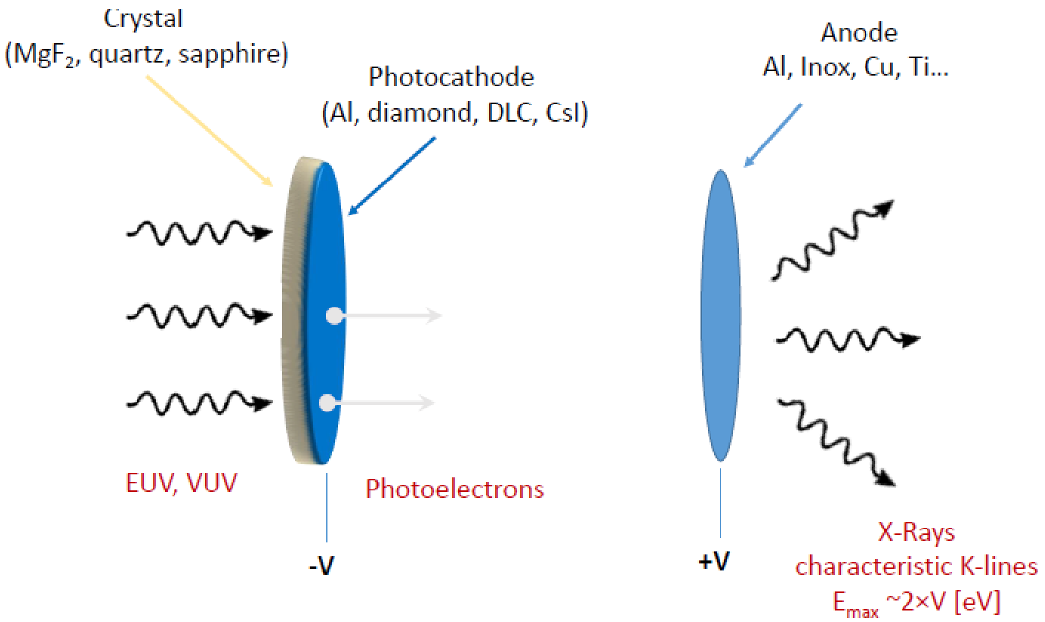
Need to calibrate and monitor « telescope + detector » and « detector » : 4 calibrators



L Segui + T Papaevangelou + JP Mols

Use of a novel generator conceived at CEA

- **Radiopure**
- **Compatible with vaccuum**



Original idea by Ioannis Giomataris
Development team: Francesca Belloni, Jean-Philippe Mols, Laura Segui, Thomas Papaevangelou
e-Print: arXiv:2002.08328 [physics.ins-det]

Sensitivity

$$g_{a\gamma}^4 \propto \underbrace{b^{1/2}\epsilon^{-1}}_{\text{detectors}} \times \underbrace{a^{1/2}\epsilon_o^{-1}}_{\text{optics}}$$

$$\times \underbrace{(BL)^{-2}A^{-1}}_{\text{magnet}} \times \underbrace{t^{-1/2}}_{\text{exposure}}$$

$$f_D = \frac{\epsilon}{\sqrt{b}}$$

		IAXO Detector Figure of Merit		
	Energy Threshold (eV)	ε (%)	b (keV^{-1}cm^{-2} s^{-1})	$f_D = \frac{\varepsilon}{\sqrt{b}}$
Micromegas	1000	~70% (2-8 keV) (2016) ? (2022)	1×10^{-6} (2016) ? (2022)	700 (2016) ? (2022)
TES	50	>95%	1×10^{-6}	950
MMC	30	>99%	1×10^{-5} (2018) ? (2022)	300 (2018) ? (2022)
SDD	500	>99%	1×10^{-2} (2019) ? (2022)	10 (2019) ? (2022)

Table 1: *Detail of the current efficiency, background rate and Figure of Merit for the four technologies selected for DALPS, including a preliminary estimation for the TES [35], MMC and SDD technologies.*

+ GridPix

DESY endorses BabyIAXO

- **Outcome of PRC of May:**

General remarks

At the 87th meeting of the PRC, a dedicated review panel evaluated the case for the realisation of the babyIAXO experiment – as a precursor for IAXO – at DESY. The chair of the panel reported to the PRC about the outcome of the review. A written report will follow in due time. The PRC welcomes very much the proposal to host the babyIAXO experiment at DESY. Besides its role as a precursor experiment, babyIAXO will already be able to explore new and very relevant parameter space for axion like particles and has therefore a strong physics case of its own. The installation of babyIAXO at DESY would add significantly to the international visibility of the axion program at DESY. PRC encourages the babyIAXO collaboration to continue their preparations for the realization of this experiment. PRC encourages DESY to take all necessary steps to host babyIAXO and in particular to help in consolidating the collaboration with CERN on the construction of the babyIAXO magnet.

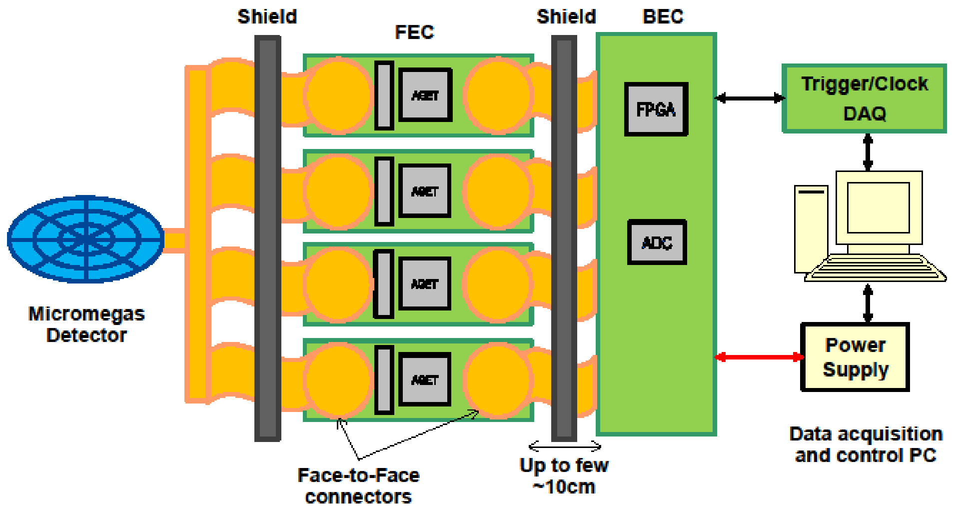
- **Also last November:**

BabyIAXO

PRC congratulates the BabyIAXO experiment for the very successful evaluation in the spring PRC meeting, and for their very swift and complete reaction to the recommendations issued there.

Electronics

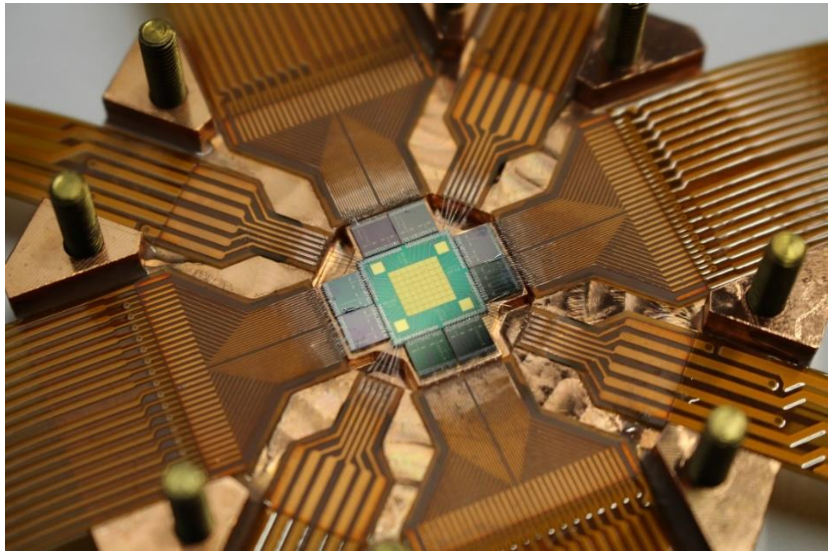
- **Readout noise as low as possible for low energy threshold**
- **Ideally radiopure electronics**
- **AGET chip currently has been used in CAST with autotrigger capabilities**



- 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
- Simulation to study the electronics effect on the detector: optimisation of the FEC location

D Calvet + University of Barcelona

Metallic Magnetic Calorimeters (MMC)



- **Production at U Heidelberg**
- **Optimized for BabyIAXO**
- **Design finished**
- **Background evaluation with the cryostat of LNHB in Building 546**

Status of project

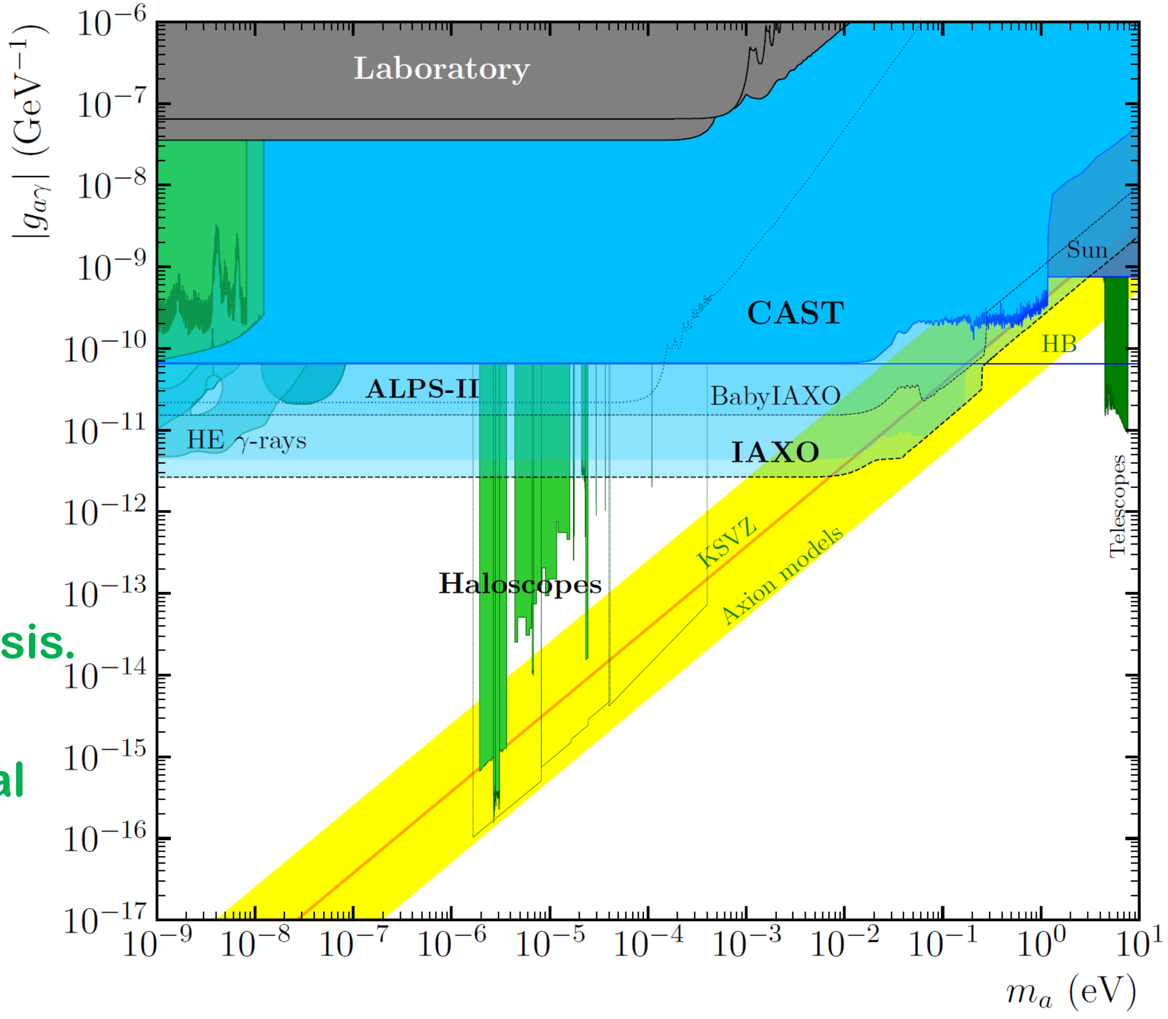
- Formal BabyIAXO proposal to DESY last year approved.
  - Site for BabyIAXO chosen: one of underground HERA halls
- Construction costs mostly secured (critical point passed):
  - ERC, but also ANR, BMBF, AEI, LLNL LDRD, etc…
  - DESY fully committed: 3.1 M€ “host investment” approved by council
  - Ongoing conversations with CERN, regarding magnet construction
  - Very important in-kind contributions secured: SC cable from INR, platform from DESY (refurbished CTA mount)
- Construction phase just started. Expected commissioning by 2023

- Outcome from ESPP very positive for axions. Search for axions explicitly mentioned (and even the DESY axion program mentioned in the deliberation document)

IAXO physics case

IAXO will probe

- Large generic unexplored ALP space
  - down to $g_{a\gamma}$ ~ few 10^{-12} GeV^{-1}
- QCD axion models in the meV to eV mass band.
- Astrophysically hinted regions
  - ALP region invoked to solve the transparency anomaly
  - axion region invoked to solve the stellar cooling anomaly
- Cosmologically interesting regions
  - viable QCD axion DM models,
  - ALP DM+inflation models
  - EDGES anomaly
- All this, independent of the axion-as-DM hypothesis.
- No other competing technique. IAXO unique.
- BabyIAXO relevant intermediate physics potential



Review of Physics potential of IAXO
arXiv:1904.09155

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.