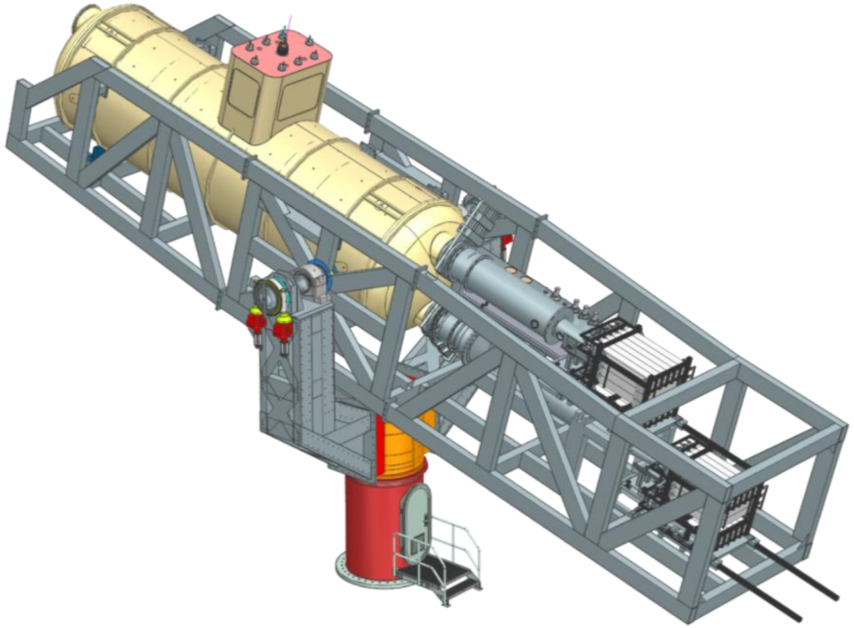
AstroParticle Symposium
Université Paris-Saclay

The IAXO and BabyIAXO experiments
Status, detector developments and future plans

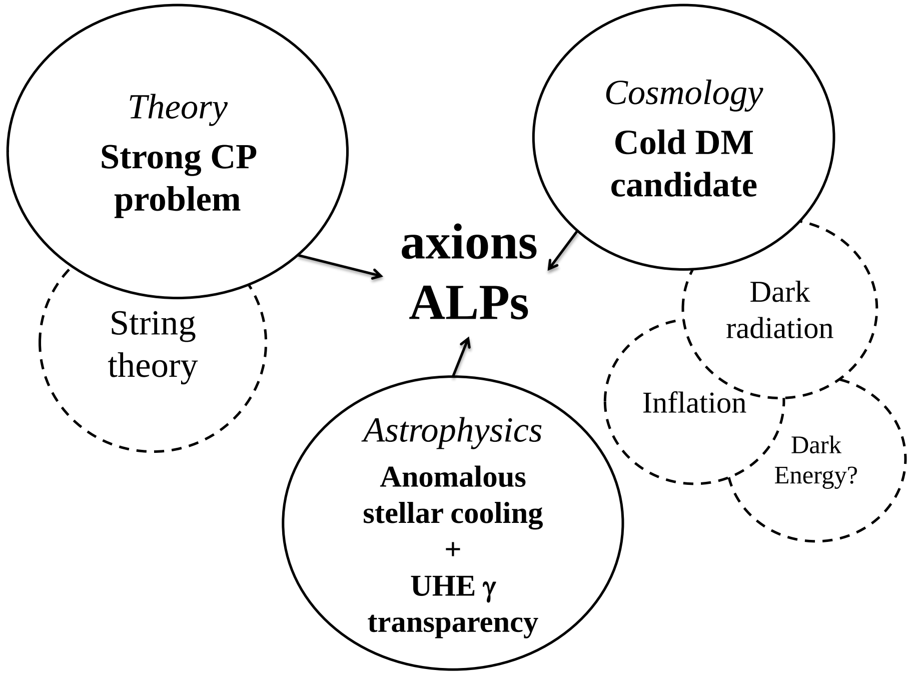


Esther Ferrer Ribas (IRFU/CEA)

6th November 2025

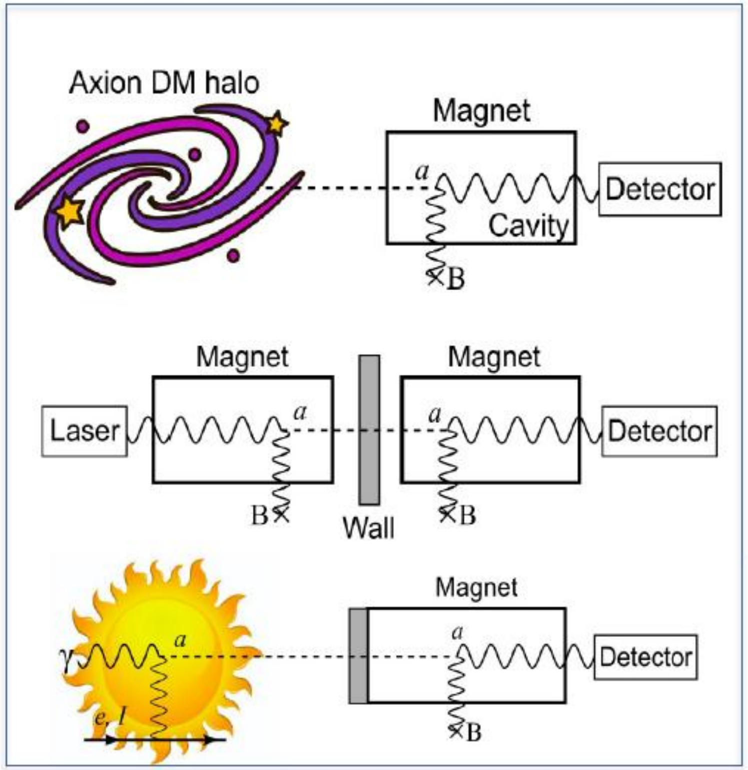
Axions in a nut shell

- 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_{ag} ~ 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



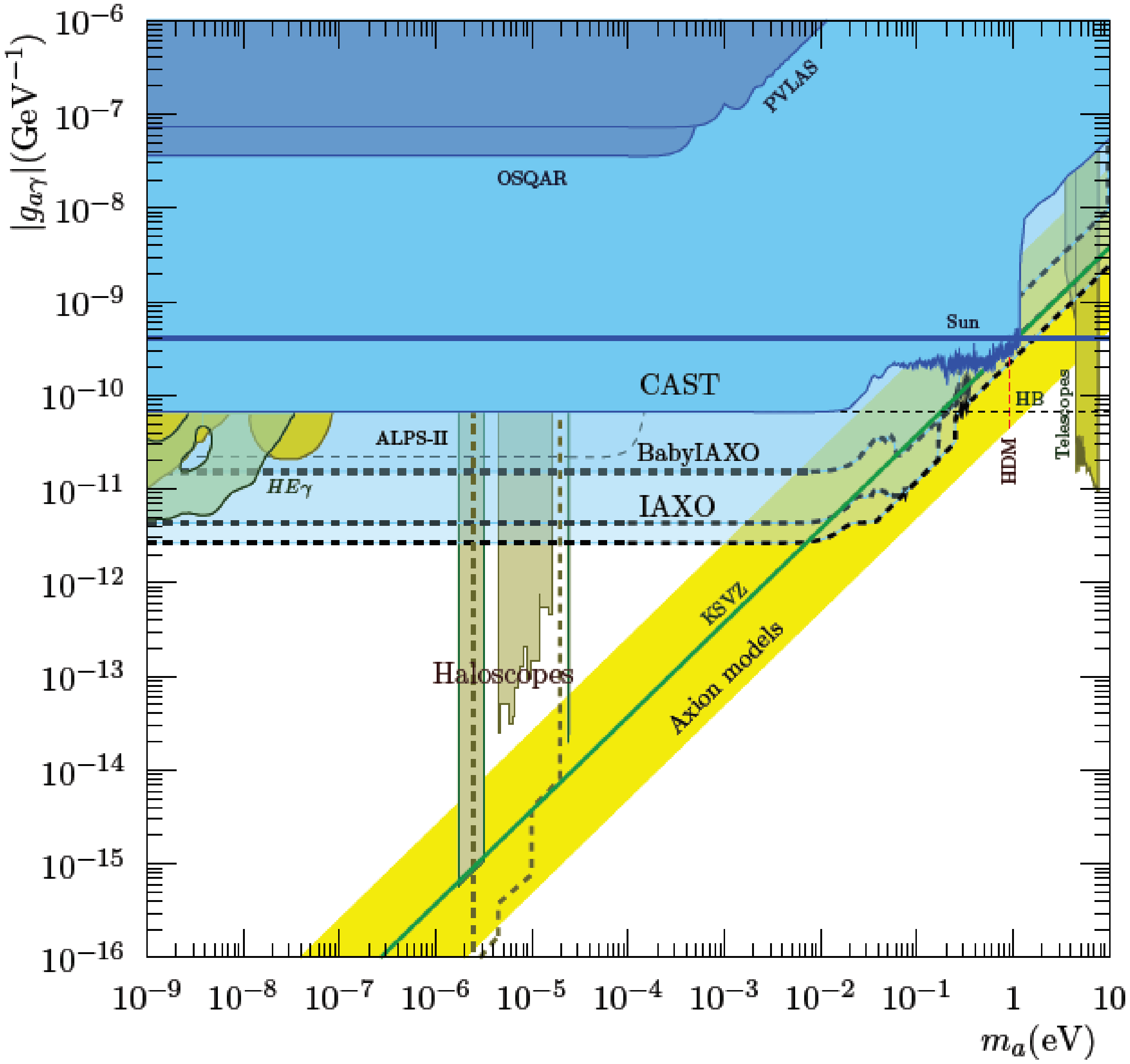
Detection of axions

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



Large complementary between the different approaches

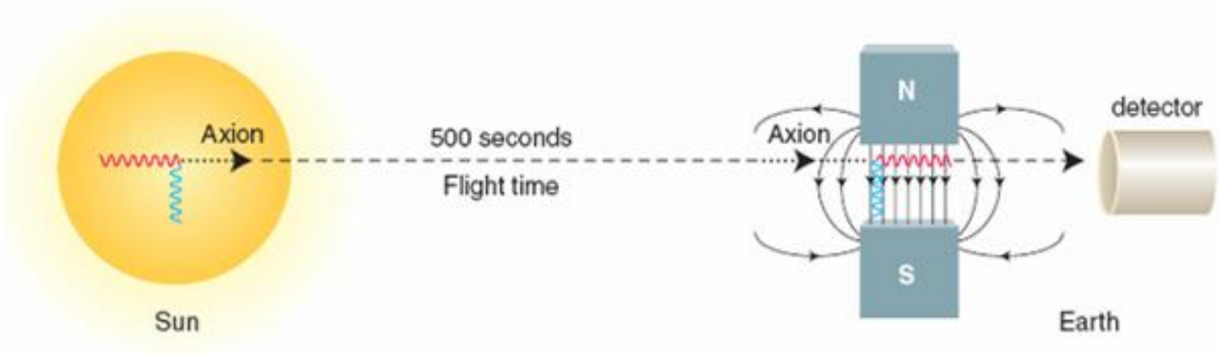
Parameter space

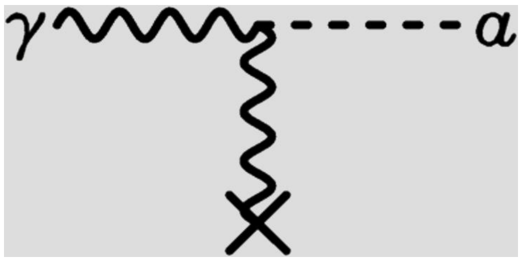


Armengaud et al. JCAP (2019) 06 047

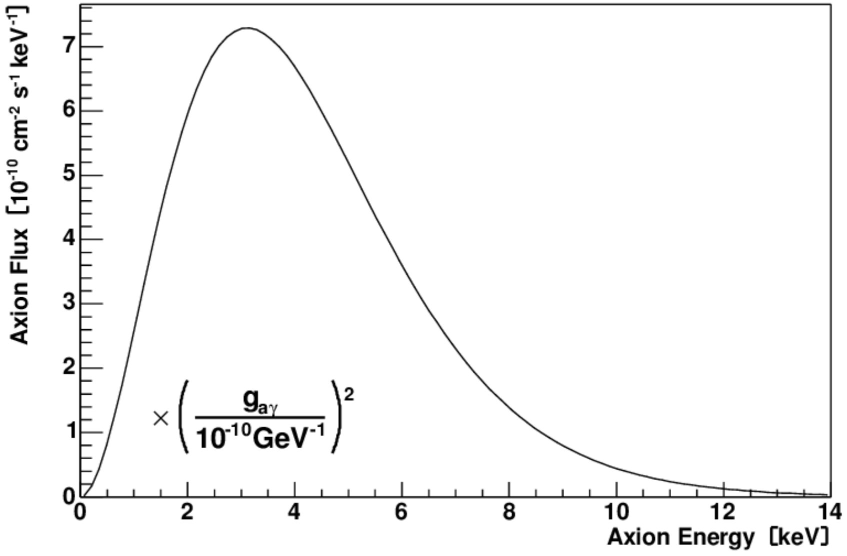
SOLAR AXIONS

Photons (keV) in solar core can be converted into axions in the presence of a strong electromagnetic field via the **Primakoff Effect**





$$\boxed{\frac{d\Phi_a}{dE} = 6.02 \times 10^{10} \left(\frac{g_{a\gamma}}{10^{-10}\mathrm{GeV}^{-1}}\right)^2 E^{2.481} e^{-E/1.205} \frac{1}{\mathrm{cm}^2\ \mathrm{s\ keV}}}$$



Van Bibber et al. Phys. Rev D39:2089 (1989)
CAST JCAO 04 (2007)010

SOLAR HELIOSCOPES

1st generation: Brookhaven (a few hours of data):
1.8 m, 2.2 T

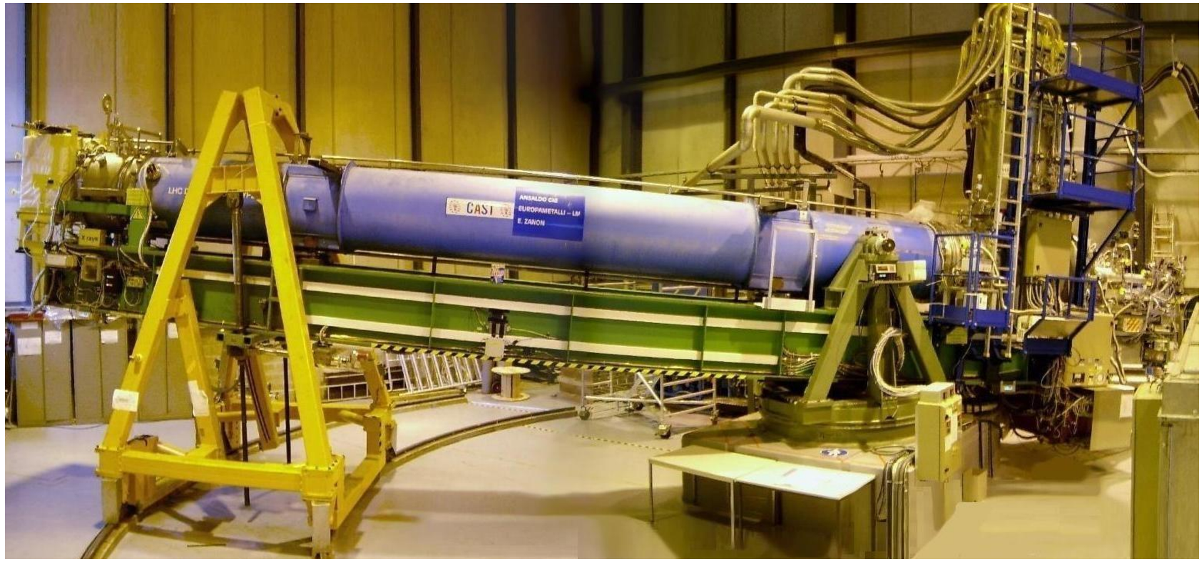
Lazarus et al. PRL 69 (92)

2nd Generation: Tokyo Helioscope (SUMICO):
2.3 m long 4 T

Inoue et al. Phys.Lett.B668:93-97,2008.

3rd Generation: CAST (CERN Axion Solar Telescope):
10 m long, 9 T 2002-2022

Nature Phys. 13 (2017) 584-590
JHEP 2021 75, (2021)
Nature Commun. 13 (2022) 1, 6180
Phys.Rev.Lett. 133 (2024) 22, 221005



CAST

Decommissioned LHC dipole magent (L= 10 m, 9 T)

X-ray focussing and using low background techniques for detection: active and passive shieldings, low background materials, discrimination techniques

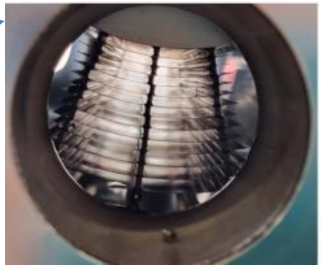
Solar tracking possible suring sunrise and sunset (2x 1.5 h per day)

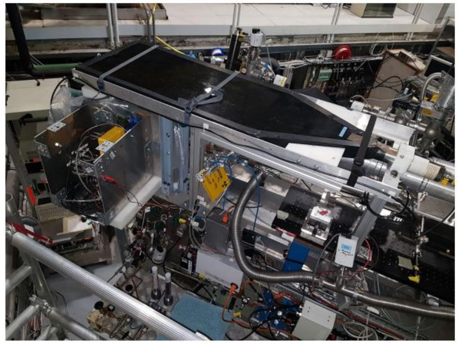
Phases

- Phase I, vacuum: 2003-2004
- Phase II, buffer gas: 2006-12
- Improved vacuum run I: 2013-15
- Improved vacuum run II: 2019-21 (with improved detectors performances, Neon)

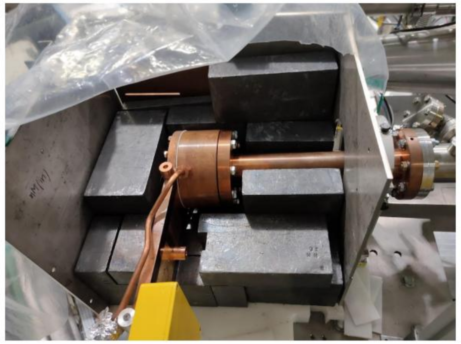
Cavities RADES + CAPP

X-rays optics



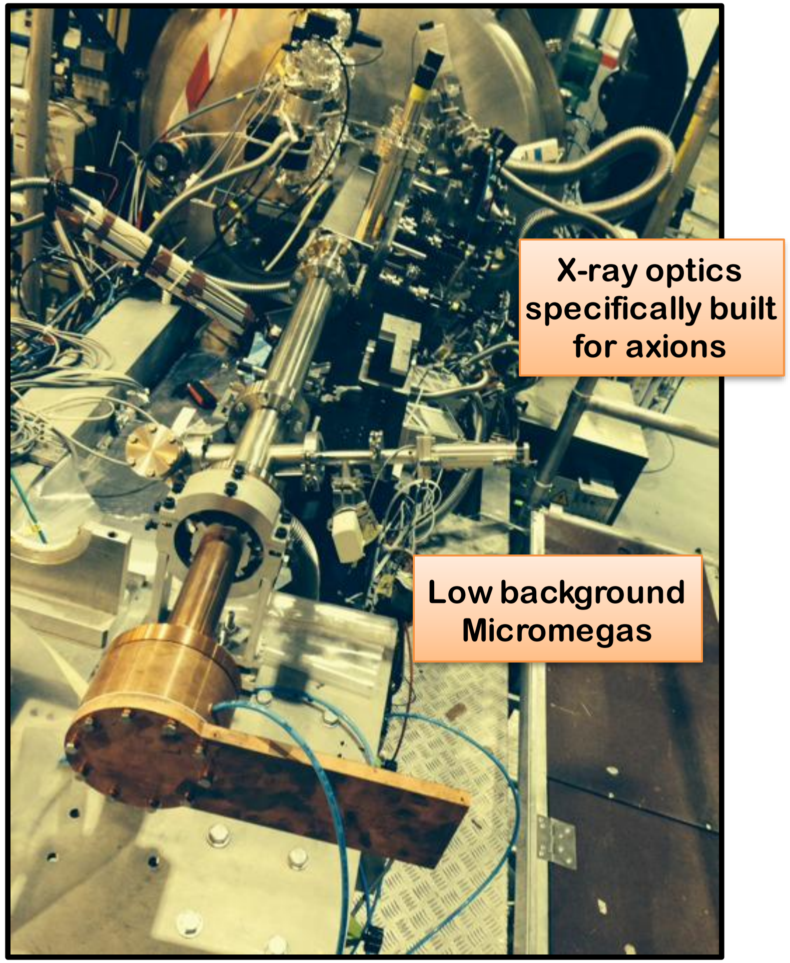


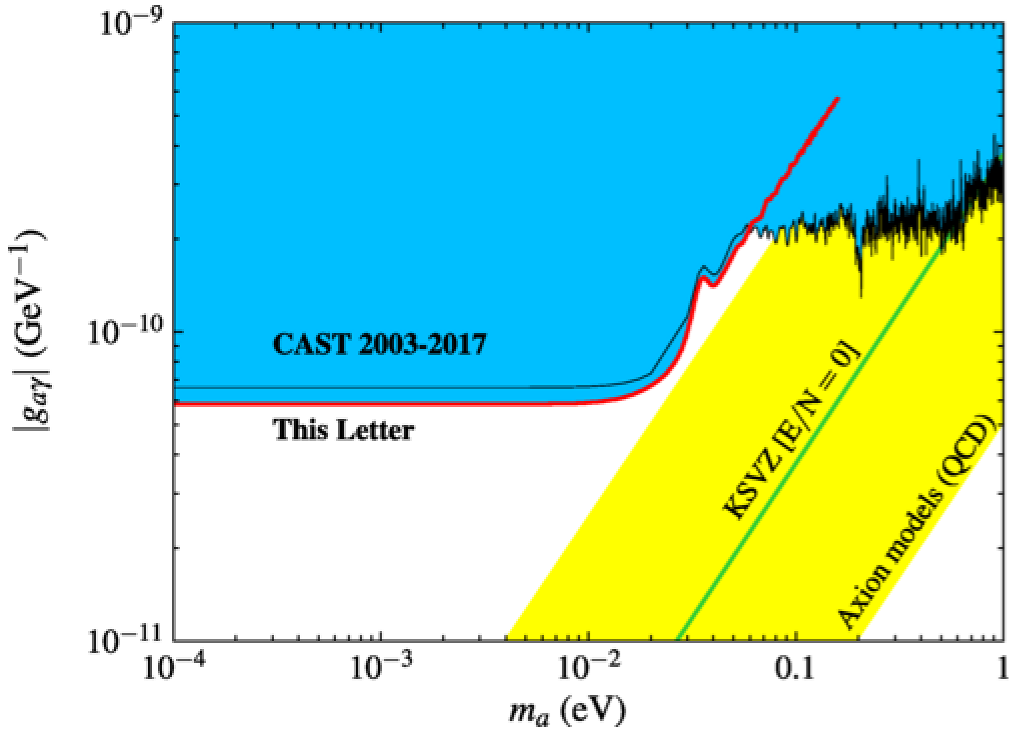
Muon veto



Passive shielding

CAST



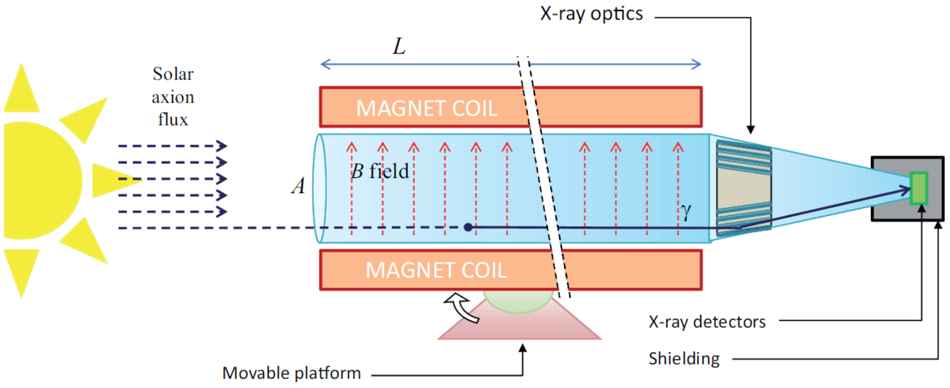


Phys. Rev. Lett. 133, 221005

$g_{a\gamma} < 5.8 \times 10^{-11}$ GeV^{-1} at 95% CL.

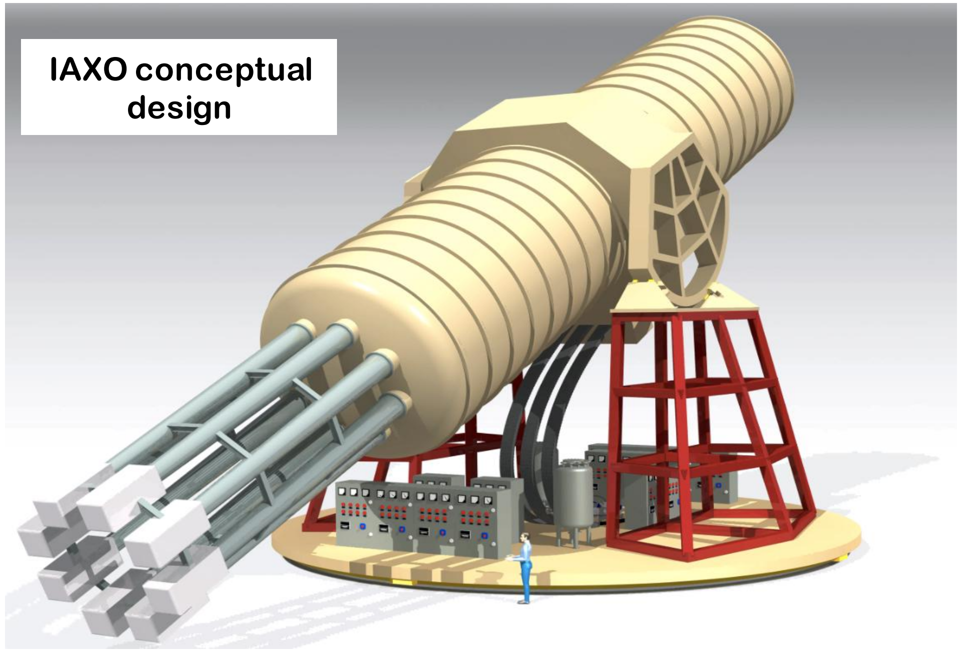
X-ray focusing + low background Micromegas detector
Small-scale version of IAXO baseline detection lines

International Axion Observatory



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

- 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



>10^4 better SNR than CAST

Sensitive to g_{ag} ~ x20 lower than CAST

Armengaud et al, 2014 JINST 9 T05002

125 scientists from 21 full member institutes + 5 associate institutions

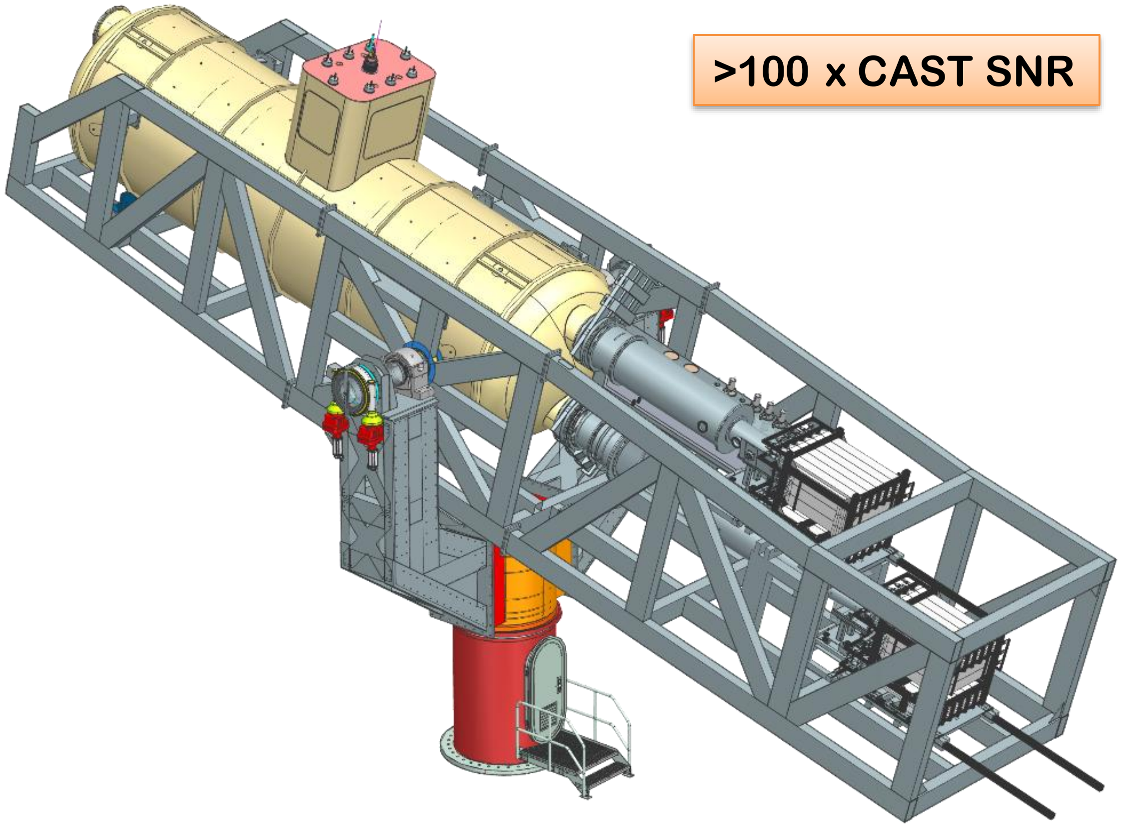
Full members: Kirchoff Institute for Physics, Heildelberg U. (Germany) | IRFU-CEA (France) | CAPA-UNIZAR (Spain) | CERN (Switzerland) | INAF-Brera (Italy) | ICCUB-Barcelona (Spain) | Siegen University (Germany) | Barry University (USA) | CEFCA-Teruel (Spain) | University of Bonn (Germany) | MIT (USA) | LLNL (USA) | University of Cape Town (S. Africa) | MPP Munich (Germany) | U. Polytechnical of Cartegena (Spain) | Technical University Munich (TUM) (Germany) | University of Hamburg (Germany) | MPE/PANTER (Germany)

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

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

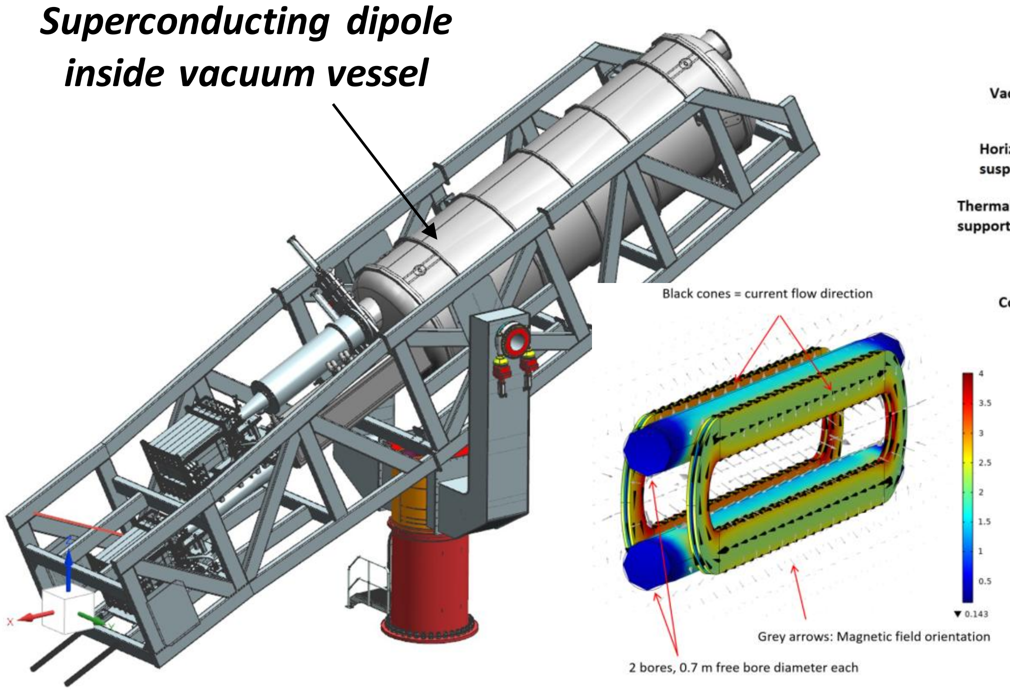
  (~100 times larger FOM than CAST)

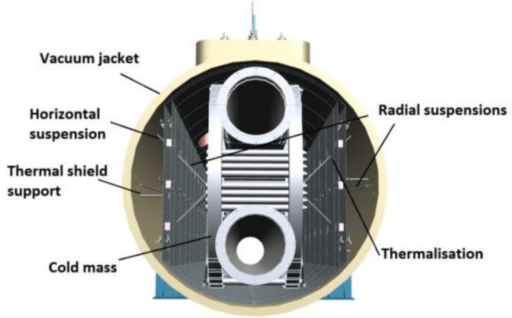


>100 x CAST SNR

Abeln et al. JEHP 05 (2021) 137

BabyIAXO magnet





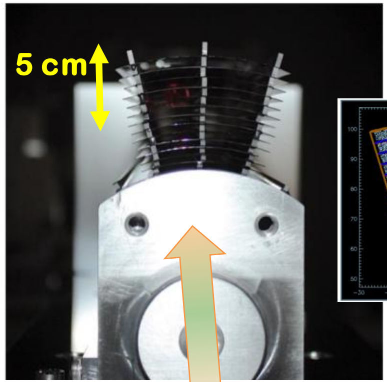
Parameter	Value
Operating current [kA]	6.0
Free bore diameter	0.7
Transverse magnetic field during operation [T]	2.1
Stored magnetic energy [MJ]	56
Inductance [H]	3.1
Cold mass weight (preliminary) [tons]	38
Energy density (preliminary) [kJ/kg]	1.5
Overall coil conductor length [km]	22
Conductor length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

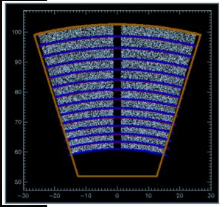
- ~2 T of transverse magnetic field over a free bore volume of about 8 m^3, i.e. the combined free bore volume of 120 LHC dipoles
- "Standard" Aluminum-stabilized Nb-Ti/Cu conductor: Nb-Ti/Cu Rutherford cable cladded with high-purity aluminum.

BabyIAXO optics

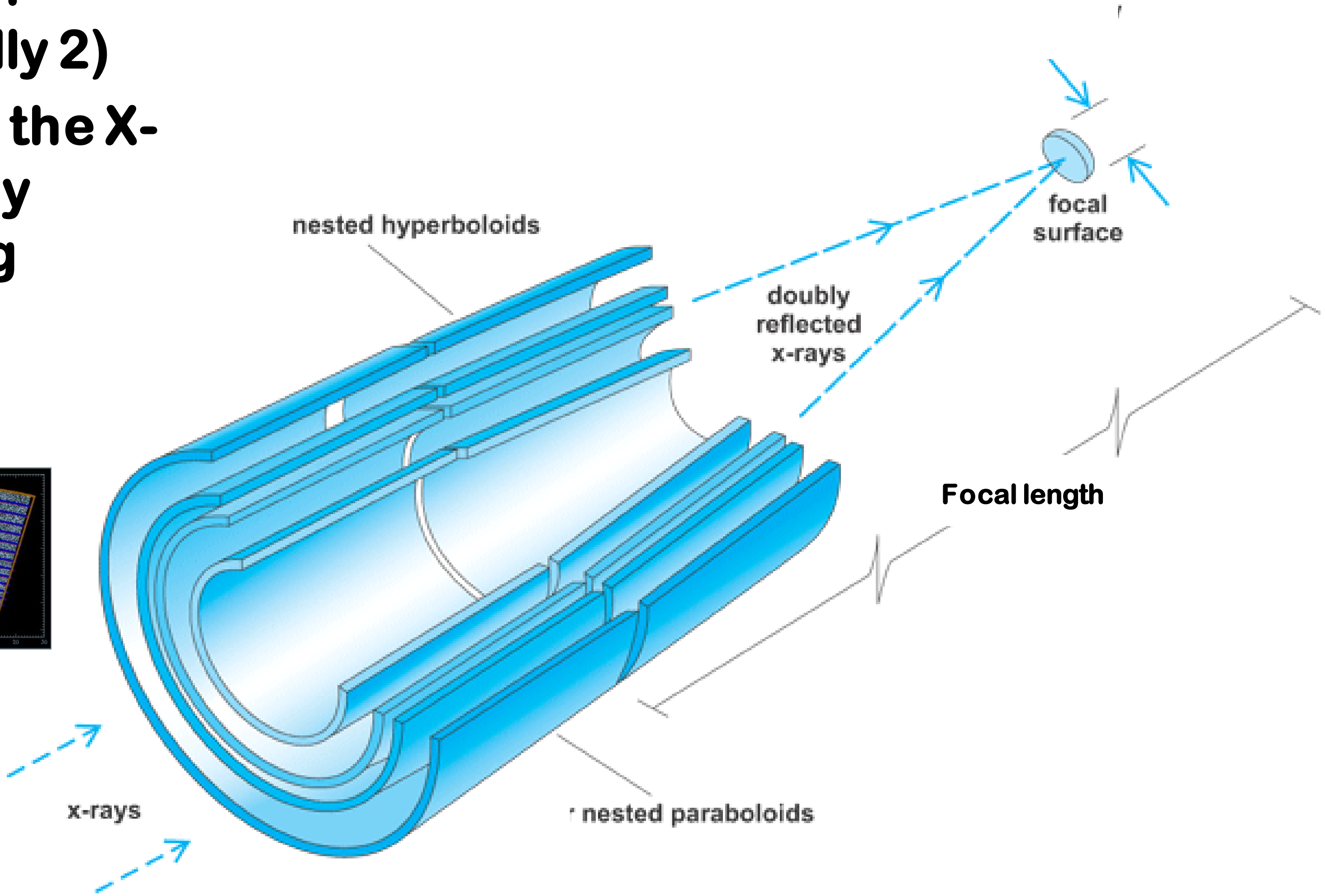
- X-rays are focused by means of grazing angle reflection (usually 2)
- Many techniques developed in the X-ray astronomy field. But usually costly due to exquisite imaging requirements

ABRIXAS spare telescope, used in one of the 4 bores of CAST (pioneer use of x-ray optics in axion research)





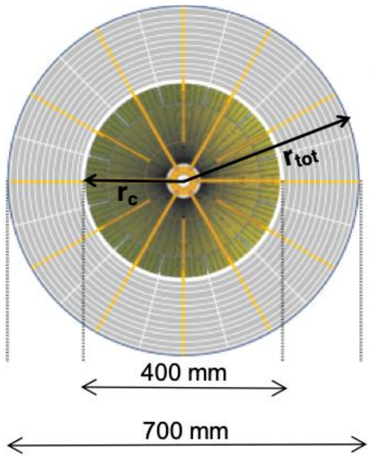
First X-ray optics specifically built for axions in CAST (LLNL)



BabyIAXO optics

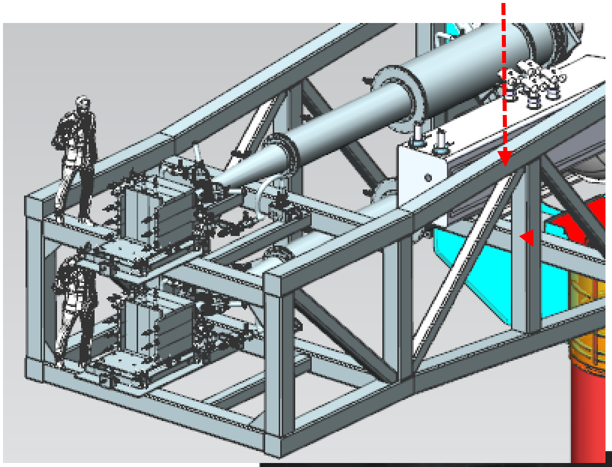
Columbia, INAF, DTU, LLNL, TUDo, MPE-Panter, NASA(*), ESA(*)

2 detection lines in BabyIAXO with different solutions:



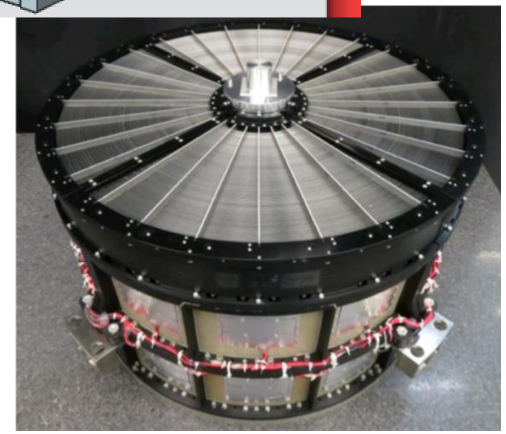
Hybrid approach for custom BabyIAXO optic

- Inner part Al-foil or segmented glass optic
- Outer part cold-slumped Willow-glass technology
- Fabrication of actual parts already started!
- Design of support structure and vessel to hold, co-align and calibrate both underway



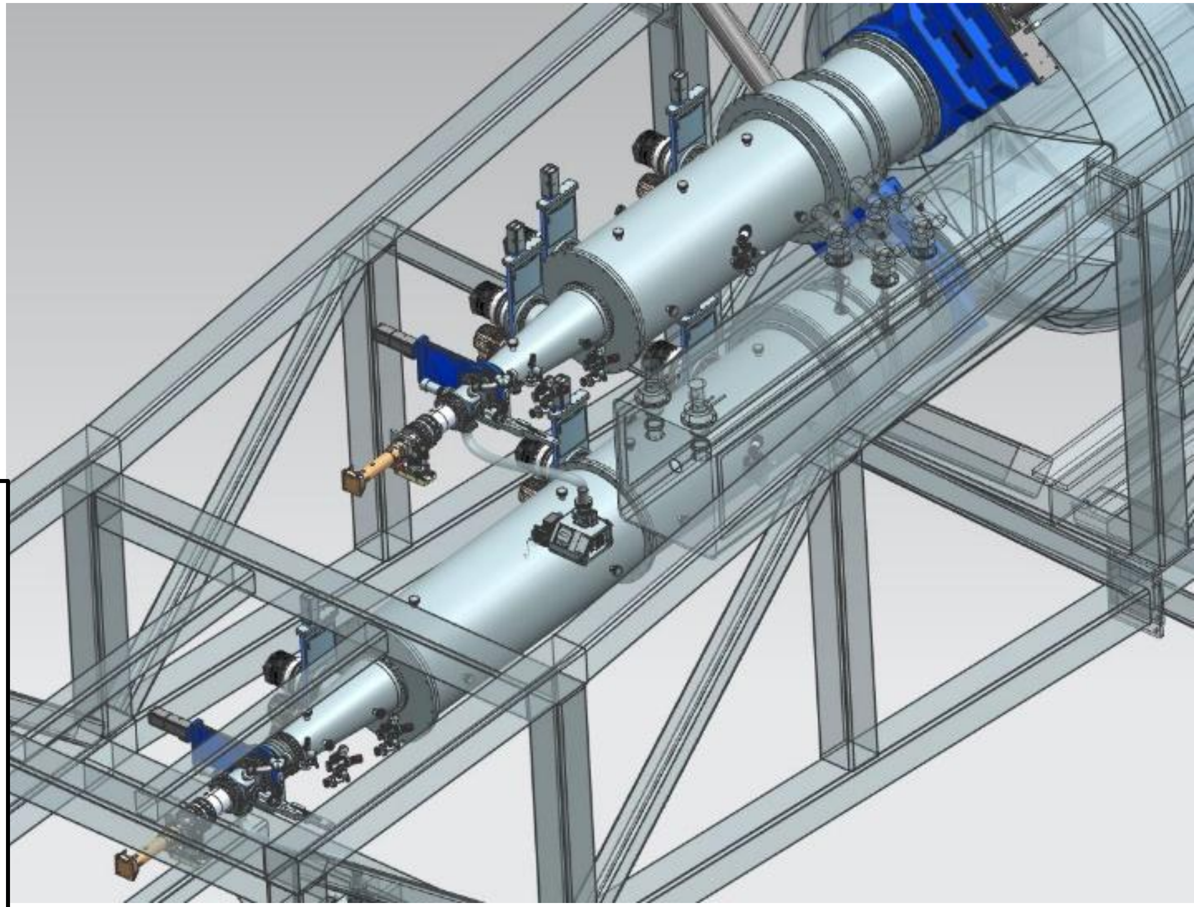
XMM Flight Spare XRT

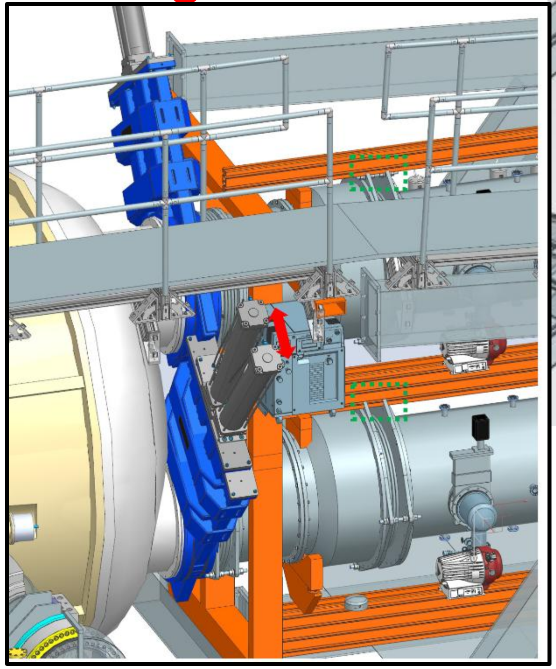
- Property of ESA, loan agreement with IAXO.
- Actual optic currently at PANTER (MPE). To be recalibrated at PANTER in 2026, then to be sent to DESY.
- Vessel to host it in the BabyIAXO detection line being designed.



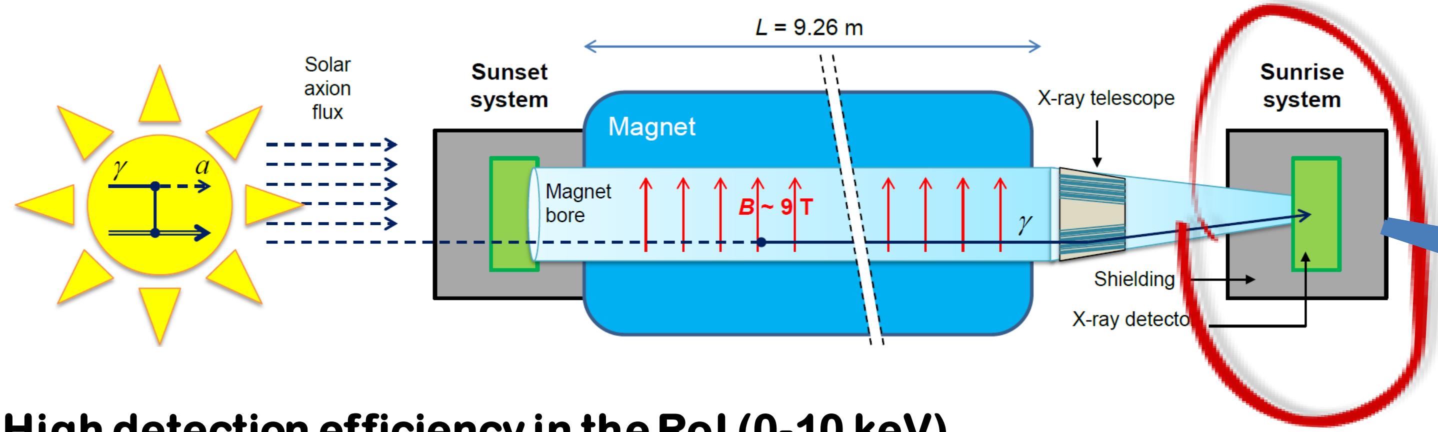
BabyIAXO beamlines

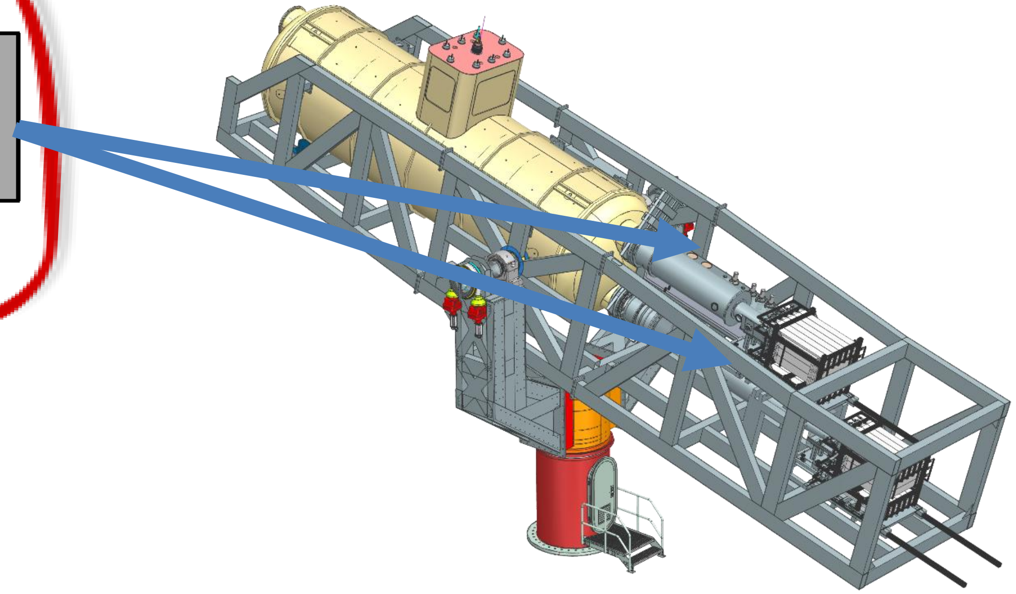
- Experimental Setup Interfaces: Finalized.
- Beamline Sectors: Fabrication ongoing.
  - Expected delivery Nov. 2025
- Vacuum Bellow Design: Completed.
  - Purchase in preparation (U. Zaragoza)
- Surrounding Structure: Designed
- Vacuum equipment (pumps, valves,…): already purchased and at DESY





BabyIAXO detectors





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

Very low background < 10 keV: 10^{-7} c/keV/cm^2/s :
less than 1 event per 6 months of data taking!

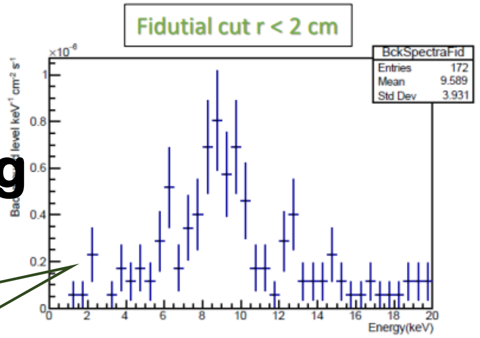
➔ use of shielding
➔ radiopurity
➔ advanced event discrimination strategies

ANR-19-CE31 0024

Baseline detector technology: Time Projection Chambers (TPC) based on the **Micromegas technology** after the experience of the CAST experiment.

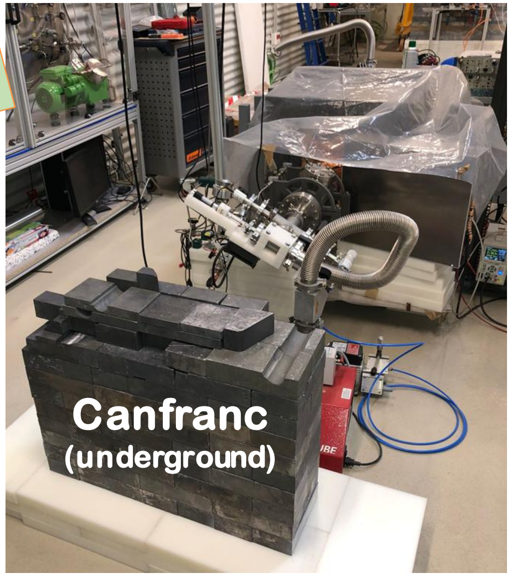
BabyIAXO Micromegas prototypes

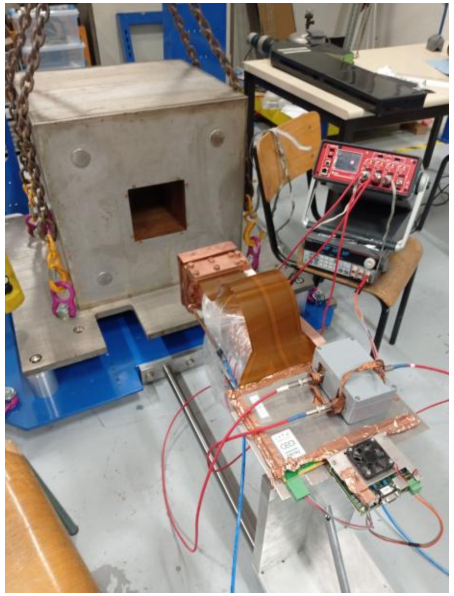
- **BabyIAXO target background recently demonstrated in underground location**
  - **Now working on reproducing same result on surface**



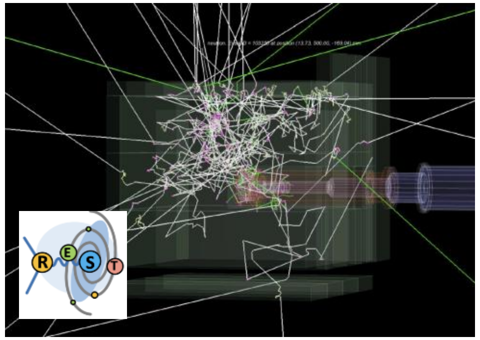
~1 count/month background in the RoI!

[2 – 7] keV 32 counts:
(1.84 ± 0.33) x 10^{-7} c·keV^{-1}·cm^{-2}·s^{-1}

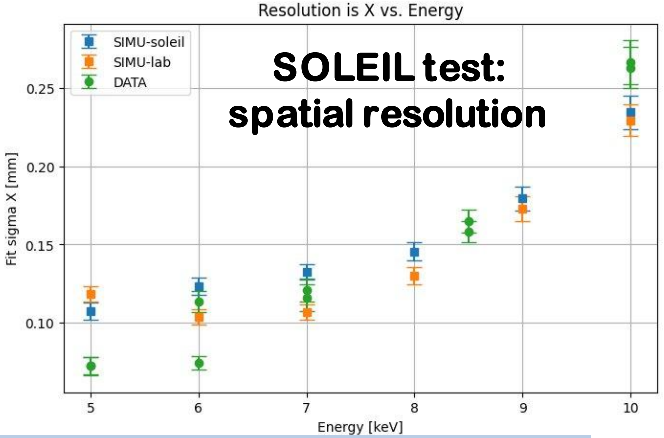




Simulation studies (neutron event)



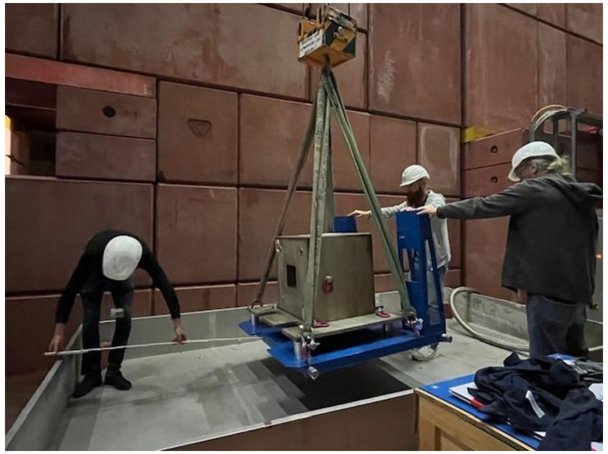
System on suface to test active shielding concepts (cosmic neutron tagging)

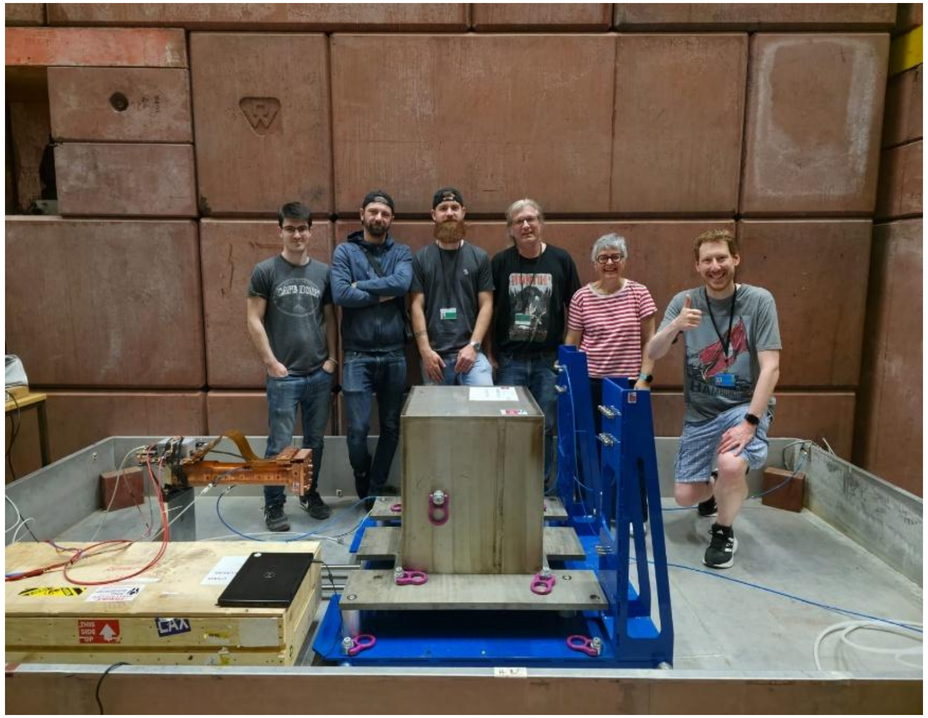


e-Print: 2509.08138 [physics.ins-det]

First Micromegas prototype @ DESY

Transport from Saclay to DESY in June 2025



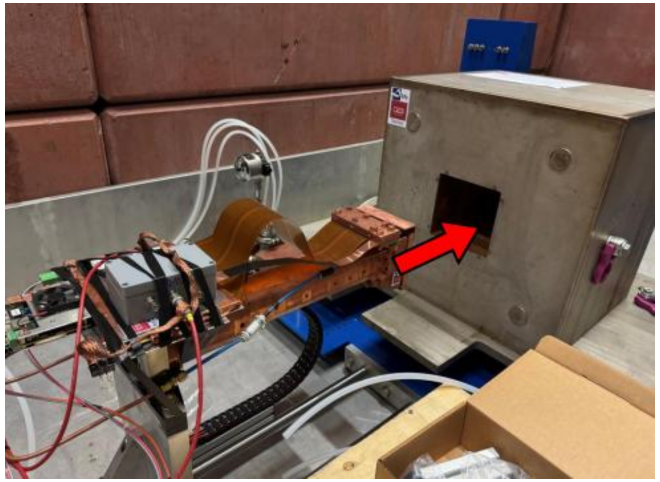


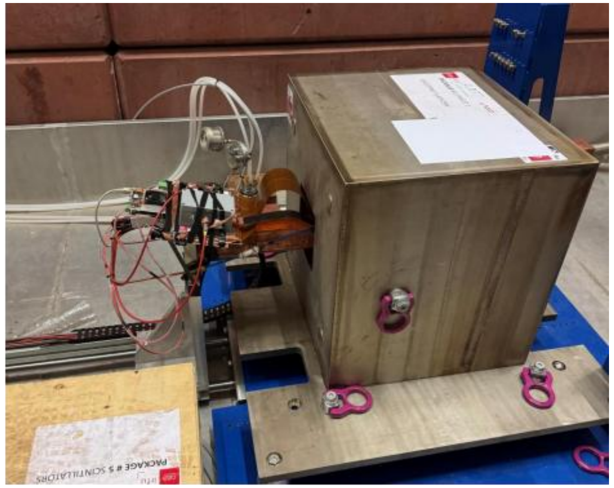
ANR-19-CE31 0024

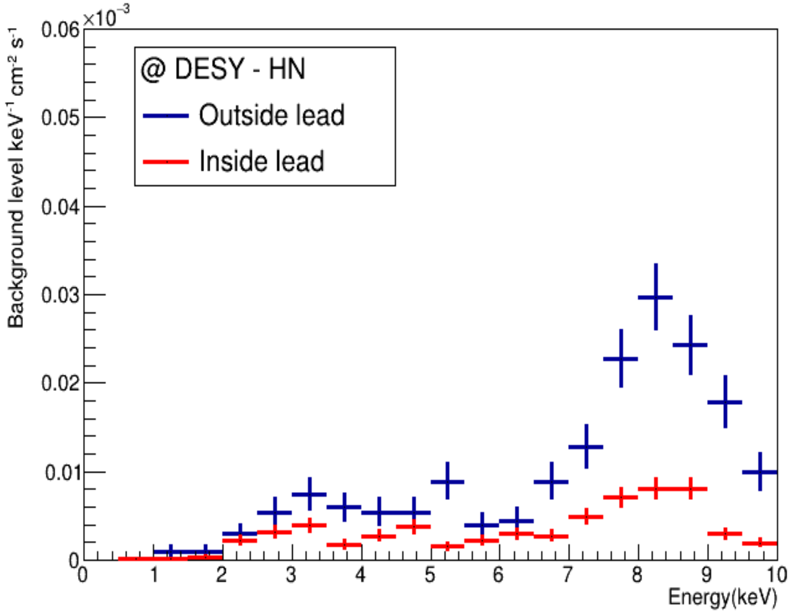
First Micromegas prototype @ DESY

- **Compatible data takings in the two sites**
- **Next steps:**
  - **Muon/neutron veto**
  - **Radiopure electronics**

$\times10^{-6}$ c/(keV cm^2 s)	DESY – HN w lead	CEA –Saclay w lead
[2-7] keV R < 1cm	2.7 ± 0.2	2.5 ± 0.3
[1-10] keV R < 1cm	3.36 ± 0.19	3.6 ± 0.3







Complementary detector technologies

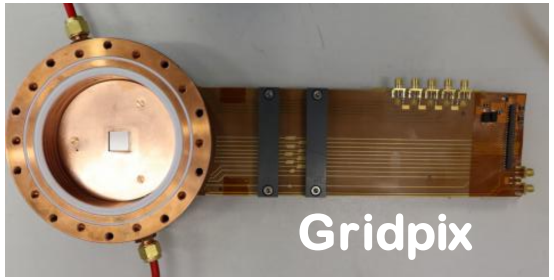
Beyond baseline, "high precision" detectors : **Gridpix, Metallic Magnetic Calorimeters (MMC), Transition Edge Sensors (TES) and Silicon Drift Detectors (SDD)**

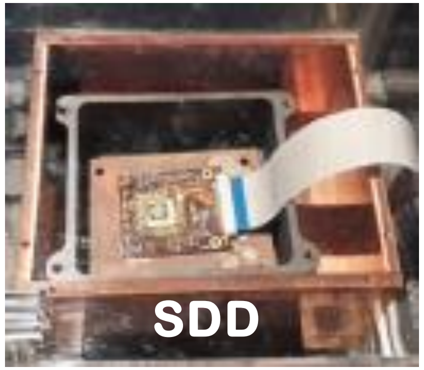
- Better threshold & energy resolution
- Design and material optimization ongoing in all fronts
- Background studies with different shielding configurations

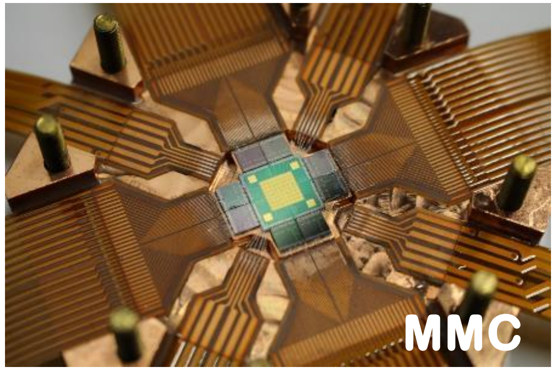
Post-discovery scenario: If positive signal, low threshold + good energy resolution→ possibility to determine m_a and g_{ae}

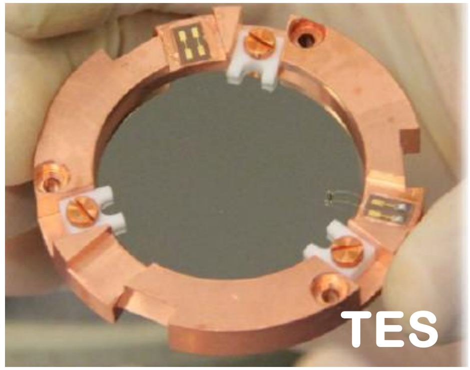
Phys. Rev. D 99, 035037

Minimization of systematics effects and reinforcement of the claim significance









BabyIAXO construction at DESY

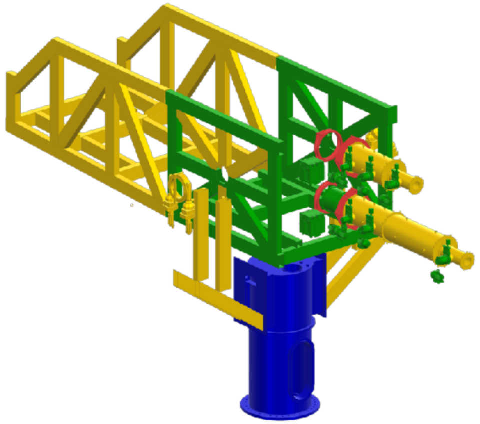
- **Site**: HERA South Hall, former ZEUS detector hall: 43 x 25m. On-surface site also under consideration
- **Support and Drive System**: Reusing (parts of) CTA MST Prototype (Berlin)
- **Technical coordination and project office** very active, WBS, PBS, …

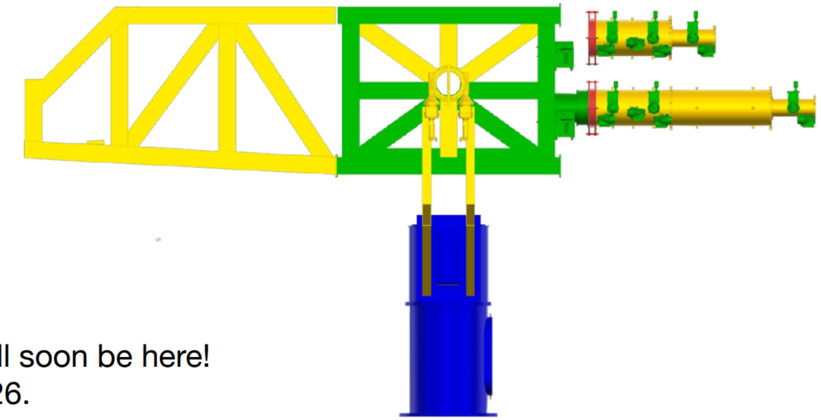
BabyIAXO under construction at DESY

Status of Components

- Available or on campus
- On campus, needs to be modified
- Ordered
- In preparation to be ordered

From David Reuther!





- Many parts are either already in DESY, or will soon be here!
  - Rest of the steel will be ordered early 2026.
  - Recently purchased elevation drive
- Design of most SDS and frame mechanical part already exist!

Current BabyIAXO timeline:

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

BabyIAXO: beyond solar axions

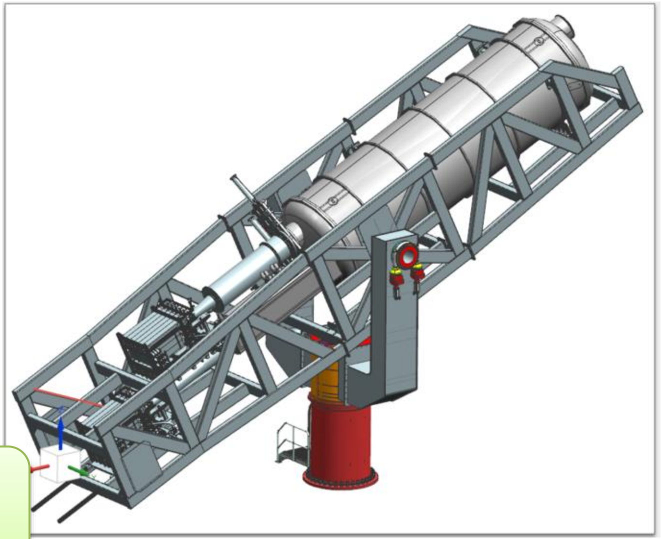
BabyIAXO as a generic axion(-like) facility

- BabyIAXO constitutes a great infrastructure that can be used to target other physics goals beyond Primakoff solar axions:

Other (non-Primakoff) solar axion production mechanisms

Axions from SN

post-Discovery “precision” physics



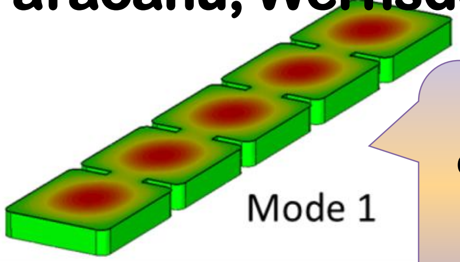
Dark Matter axions: haloscope setups inside the BabyIAXO bores

Other WISPs: hidden (dark) photons, chameleons, …

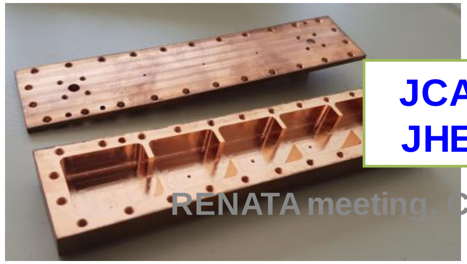
RADES (Relic Axion Detector Experimental Setup)

- **Exploratory project emerged at a later stage of CAST: use of “helioscope” magnets for “haloscope” searches**
- **Creation and build-up “axion haloscope” community in Europe**
- **Strong boost by ERC-StG (B. Döbrich) in 2018**
- **Now ultra-cryogenic setup being built at MPP-Munich**
- **DarkQuantum ERC-SyG started 2024 (Irastorza, Kontos, Paraoanu, Wernsdorfer)**

Various R&D and physics results

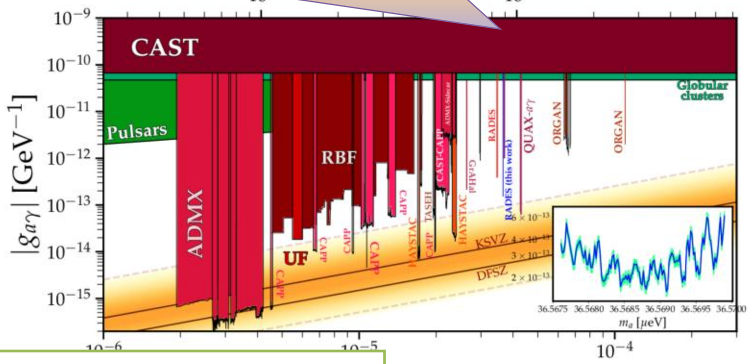


New geometry concepts to scale in V but keeping high resonant *f*



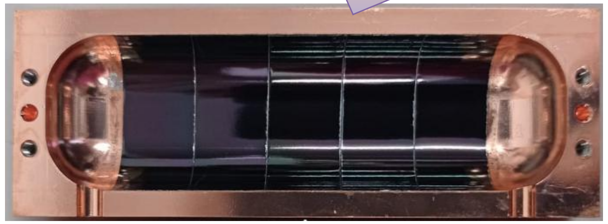
JCAP 05 (2018) 040
JHEP 07 (2020) 084

Physics result at single *f* point in CAST and in SM18 magnets



JHEP 21 (2020) 075
JHEP 04 (2025) 113

Inner HTS coatings to improve Q factor



IEEE Trans. Appl. Supercond. 32 (2022) 45

CONCLUSIONS

IAXO has a unique physics case in the "axion experimental landscape". A discovery is possible, already at the BabyIAXO stage (expected commissioning~2030)

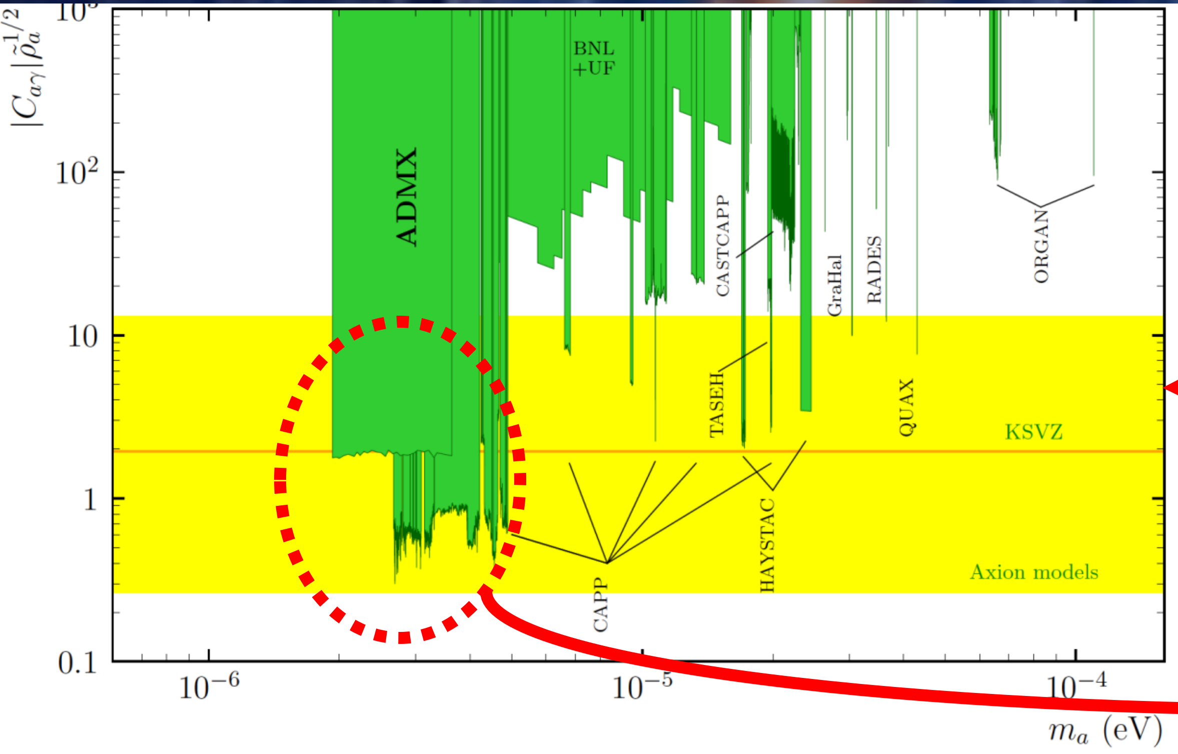
BabyIAXO is under construction at DESY: support drive system, vacuum lines, the first Micromegas detector is on site

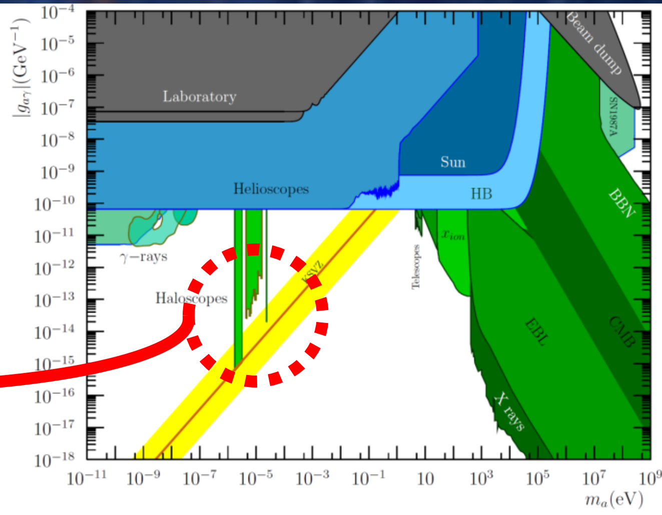
Active detector development: discovery and energy resolution detectors

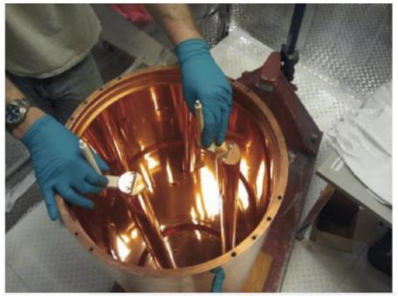
BabyIAXO constitutes a great infrastructure that can be used to target other physics goals beyond Primakoff solar axions

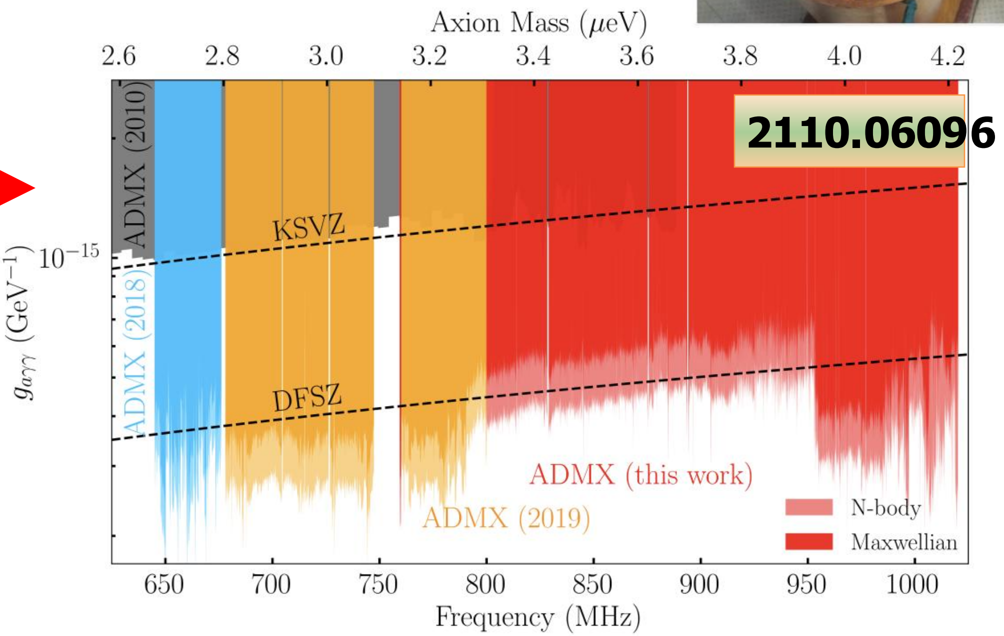
BACK UP

Haloscopes current results









- **AMDX** @ U. Washington, "prototype" axion haloscope
- Many years of R&D, progressively exploring the **few μeV** region
- What about higher (or lower) masses?

DarKQuantum: enhancing RADES

- **Built on RADES plans. Add "quantum" ingredient.**
  - **Establish link with key experts and bring them to the axion field.**
- **Well defined roadmap of technical and physics outcome (→ impact)**
  - **Low frequency search in RADES @BabyIAXO**
  - **High frequency search in RADES @LSC**