BABYIAXO, AN EXPERIMENT TO LOOK AT AXIONS FROM THE SUN

LOUIS HELARY (DESY)

DMLAB@PARIS MEETING - OCTOBER 21ST 2026

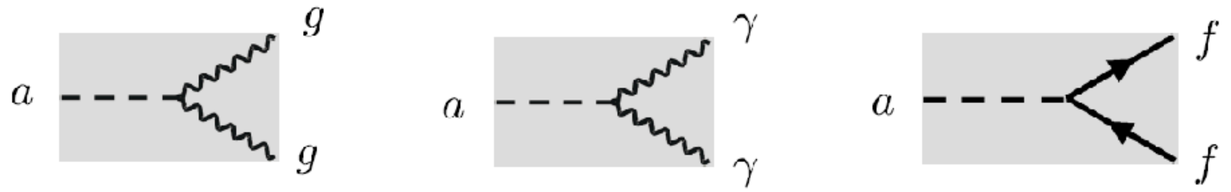
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

Some context

AXIONS AND AXION LIKE PARTICLES

- Axions originally introduced in the 70s to solve the strong CP problems.
  - Pseudo-scalar particles.
  - Couple to:
    To gluons ($g_a g$), photons ($g_a \gamma$), fermions ($g_a f$).

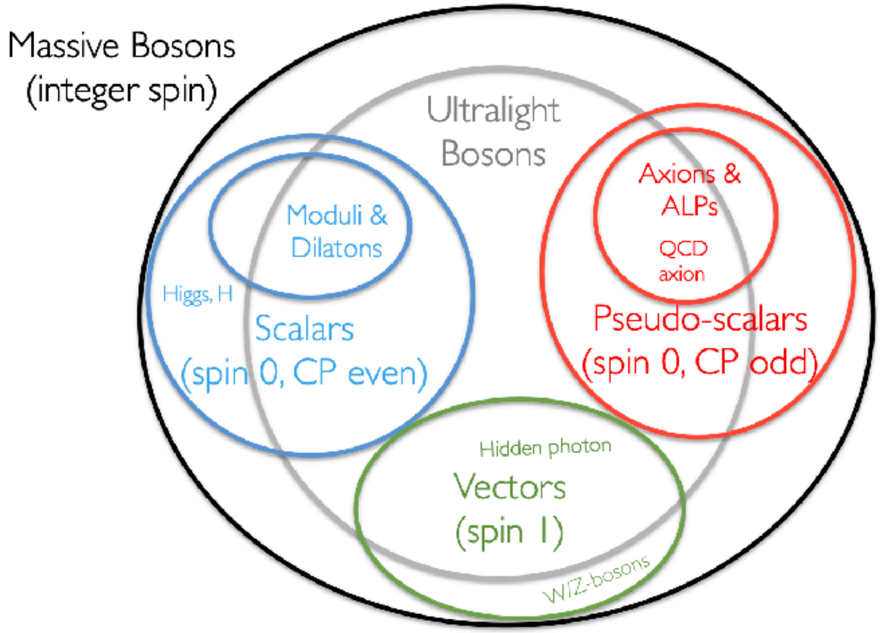
$$\mathcal{L} \supset -\frac{\alpha_s}{8\pi}\frac{C_{ag}}{f_a}\, a\, G^b_{\mu\nu}\tilde{G}^{b,\mu\nu} - \frac{\alpha}{8\pi}\frac{C_{a\gamma}}{f_a}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{1}{2}\frac{C_{af}}{f_a}\partial_\mu a\, \overline{\psi}_f \gamma^\mu \gamma_5 \psi_f$$



  - Coupling and masses expected to be small:
    - Long lived particles.

- Axion-like particles (ALPs):
  - In many BSM theories (string theory, hidden sectors, extra dimensions, etc) particles similar to axions appear.
  - Mass and coupling are independent parameters and can be much larger (GeV)/lighter(neV) or more/less coupled.

- Since Axions or ALPS are long lived particles, constitute a good candidate to dark matter.

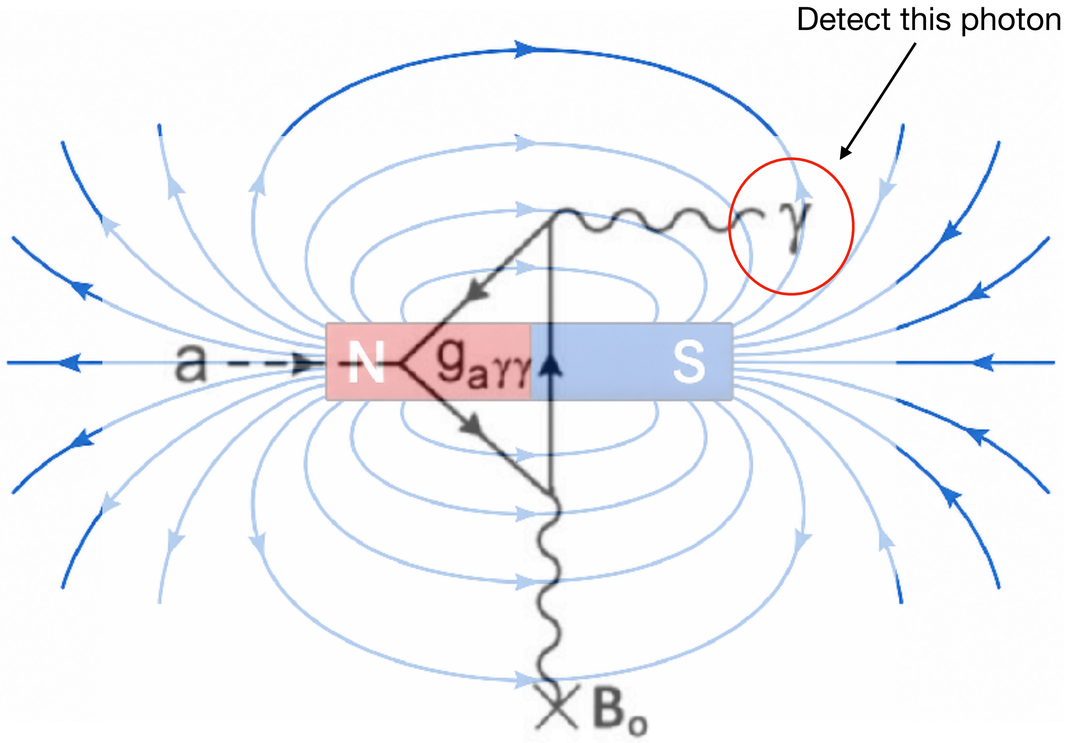


Axion dark matter: What is it and why now?

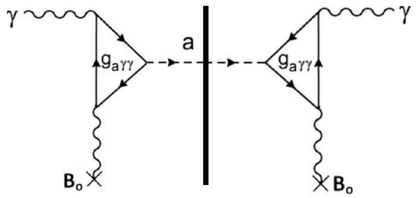
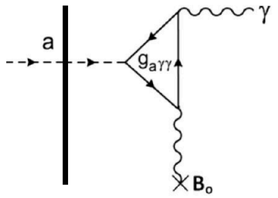
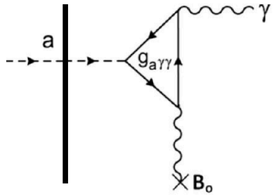


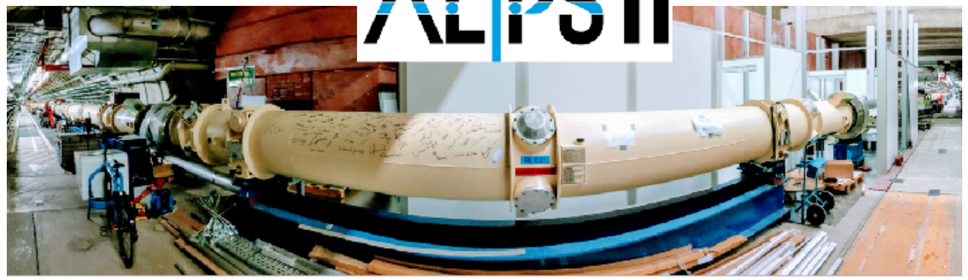
HOW TO DETECT AN AXION-LIKE PARTICLE?

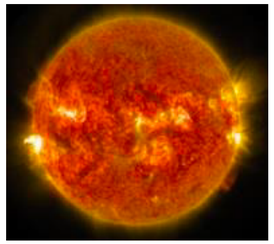
- ALPs are very light and weakly interacting particles, so how to detect them?
  - Use coupling to (virtual) photons by immersing the axion field in a large magnetic field!
    - Allow the conversion of the axion to a real photon which can then be detected!
      - Basis of axion helioscope and haloscope searches.

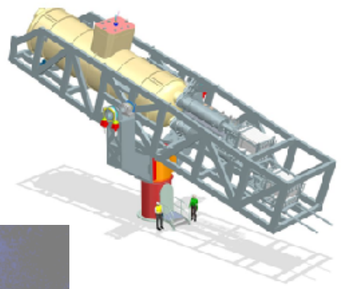


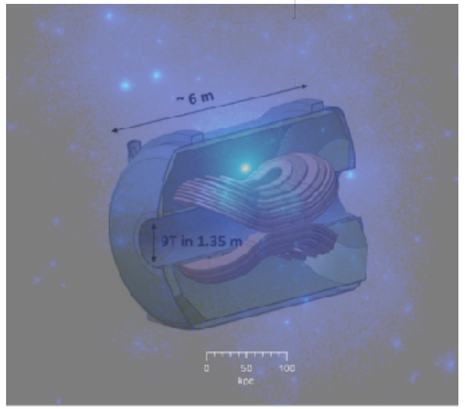
EXPERIMENTAL APPROACHES - LIGHT-SHINING-THROUGH-WALLS EXPERIMENTS

	Source	Detection	Model & Cosmology Dependency	Photon Energy Experiments
Light-shining-through-wall experiments	 Axions produced in the lab		**Independent** “lab-created” axions	Microwave or Optical OSQAR, CROWS, ALPS, **ALPS II,** STAX
Helioscopes	 Solar axions		**Low - medium** Depending on solar production channel	X-Ray SUMICO, CAST, **(Baby)IAXO**
Haloscopes			**High** Axions = cold dark matter constituents	Microwave ADMX, CAST-CAPP, CASPEr, RADES, **MADMAX**,…





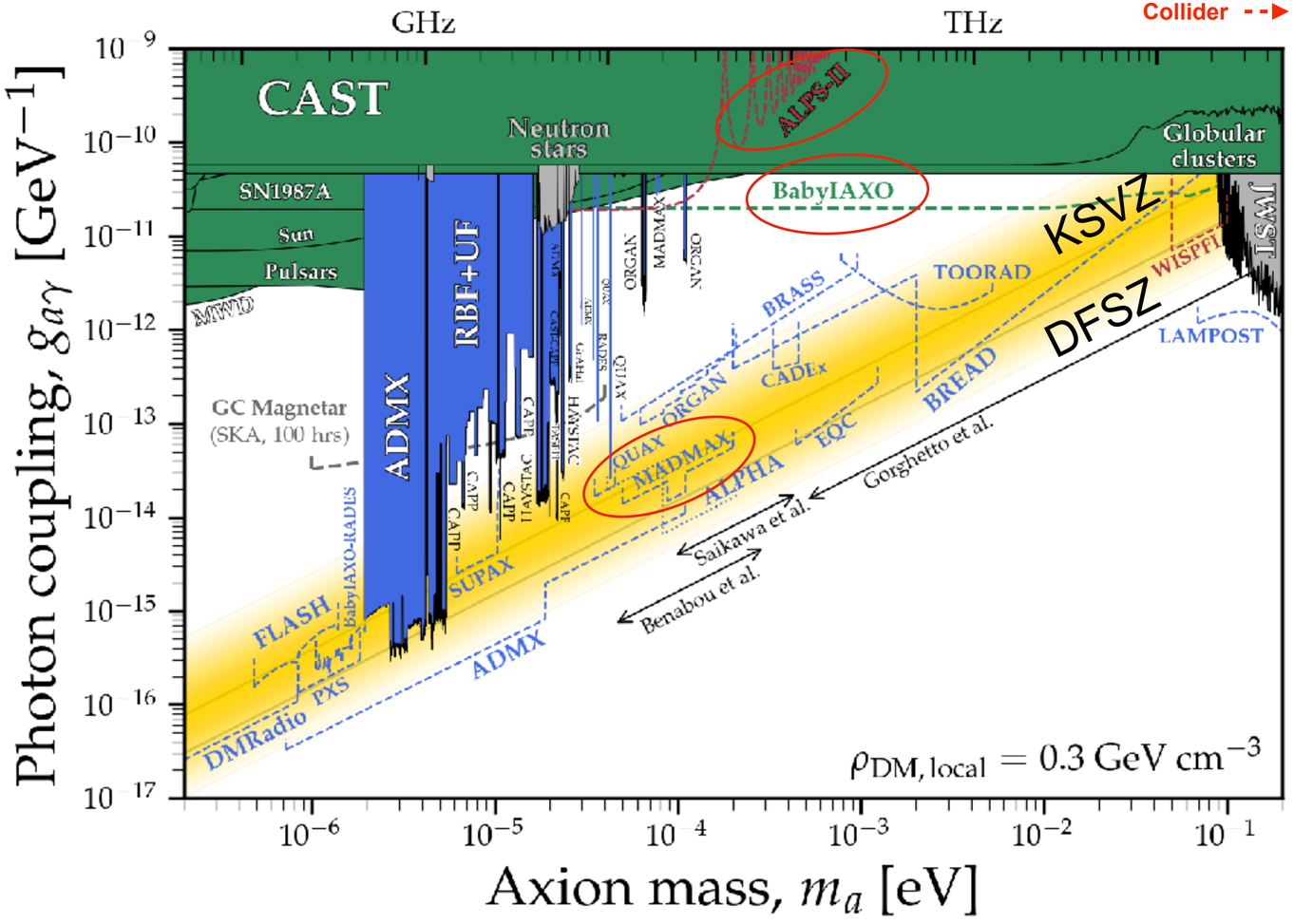






AXION PARAMETER LANDSCAPE

- Limit plot usually shown in plane $g_{a\gamma}$ - m_a.
- QCD axion lies in the yellow band
  - KSVZ: axions couple to BSM quarks only
  - DFSZ: axions couple to fermions
- Collider typically sensitive to higher masses.
- Significant part of the spectrum covered by current or future experiment in DESY.



ALPS2

IAXO

MadMAX

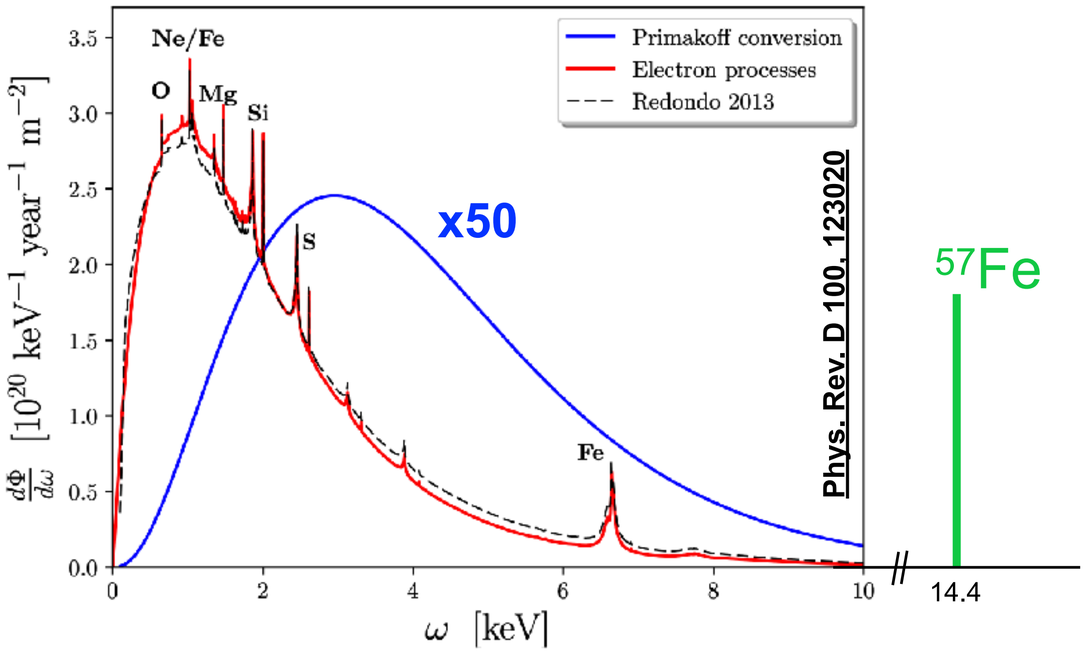
Ciaran O'Hare axion limits

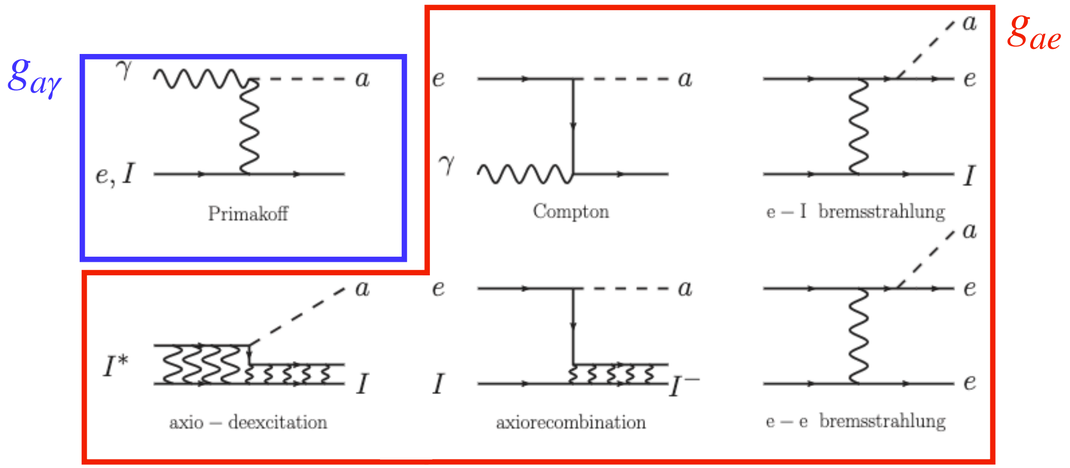
The helioscope concepts and experiments

AXIONS PRODUCTION IN THE SUN

- Sun core constitutes a good laboratory to study axions.
  - Main production mechanism:
    - Primakoff effect from thermal photons ($g_{a\gamma}$).
      - Generic prediction.
    - Axion-electron coupling (g_{ae}).
      - Model dependent.
  - Also contributing but subdominant:
    - Axion-neutron coupling (g_{aN}).
    - Photon conversion in solar magnetic field, …
      - Model dependent.

Differential axion flux at earth

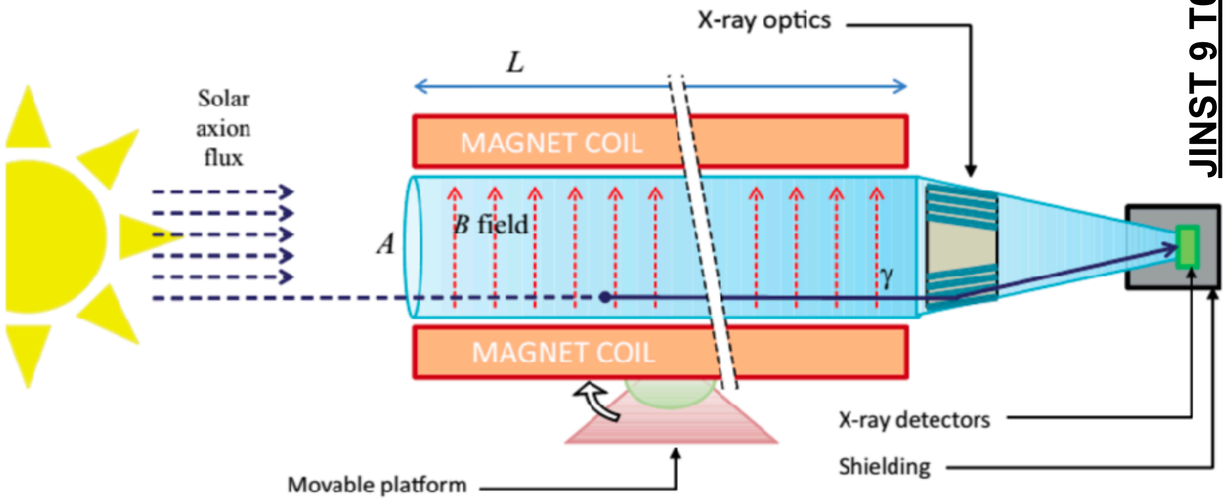




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DETECTING AXIONS FROM THE SUN

- Helioscope idea:
  - Using large dipole magnet pointed to the sun core, try to detect excess of X-ray photons coming from the reconversion of axions!
  - Experiment sensitivity can be characterised by its figure of merit (FOM).
    - Proportional to $g_{a\gamma}^{-4}$, product of 4 terms describing performance of:
      - Exposure
      - Magnet
      - X-ray optics
      - X-ray detectors



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$$g_{a\gamma}^{-4} \propto \underbrace{t^{-1/2}}_{\text{Exposure}} \times \underbrace{(BL)^{-2}A^{-1}}_{\text{Magnet}} \times \underbrace{a^{1/2}\epsilon_0^{-1}}_{\text{Optics}} \times \underbrace{b^{1/2}\epsilon^{-1}}_{\text{Detectors}}$$

CERN AXION SOLAR TELESCOPE (CAST)

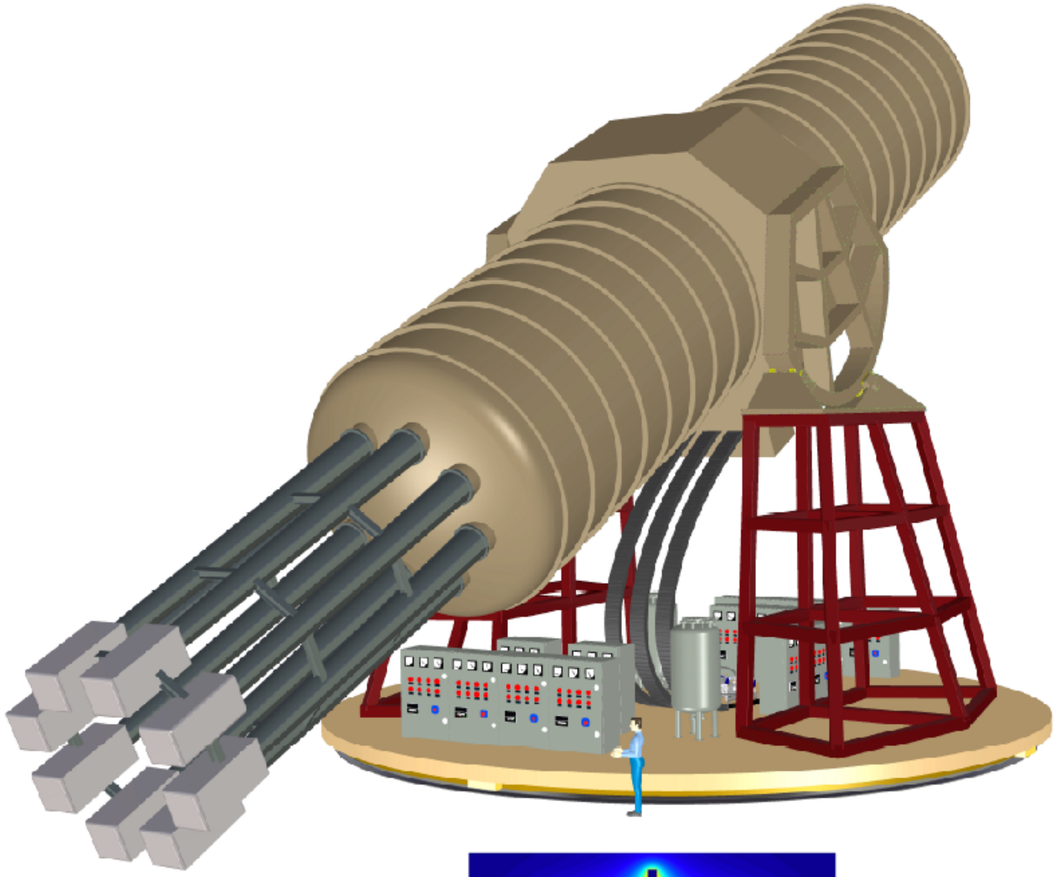
- CAST was operated at CERN from 2003-2021.
  - Exposure:
    - Tracking system allowed 3h sun tracking per day: sunrise-sunset.
  - Magnet:
    - Decommissioned straight LHC prototype.
    - L=10m, B=9T, A=2x4.3cm Ø bore.
  - Optics:
    - Focusing optics at sunset detectors (IAXO pathfinder optics reused from NuStar telescope).
  - Detectors:
    - Micromegas achieved $1-2\times10^{-6}$ counts/$(keV\,.\,cm^2\,.\,s)$
- Best limit set so far with this technique!
  - $g_{a\gamma}$<5.7 x 10^{-11} GeV^{-1} for m_a<0.02 eV



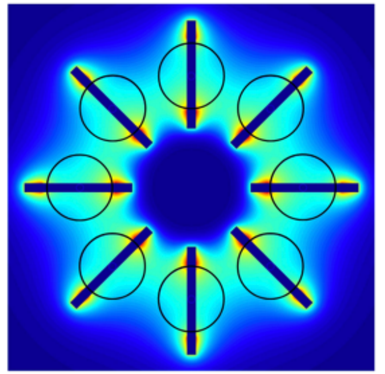
PRL.133.221005

INTERNATIONAL AXION OBSERVATORY (IAXO)

- IAXO CDR was released in 2014.
  - Exposure:
    - 12 hours solar tracking + 12 hours off-sun for background measurements per day.
  - Magnet:
    - Superconducting toroid model after ATLAS toroid.
    - L=20m, B=3T, A=8x60cm Ø beamline.
  - Optics:
    - Dedicated X-ray optics with ~0.2 cm^2 focal spots.
  - Detectors:
    - 8 detection lines available for detector technologies.
    - Detector requirement 1×10^{-8} counts/$(keV\,.\,cm^2\,.\,s)$
    - Baseline: Microbulk Micromegas
- FOM (sensitivity): **~10.000x CAST**



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BABY IAXO

- Baby IAXO was first presented in 2017 as an intermediate step toward IAXO.
- Since then the project has gone through a lot of changes.
- Baby IAXO CDR was released in 2020.
- FOM (sensitivity): **~100x CAST**



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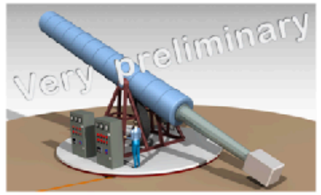
mini-IAXO (aka babyIAXO)

- **Goal: full intermediate experimental stage**
  - Test magnet design at relevant scale (only 1 bore full diameter)
  - Test bench for optics + detector
  - Will deliver relevant physics (at intermediate level). Under work

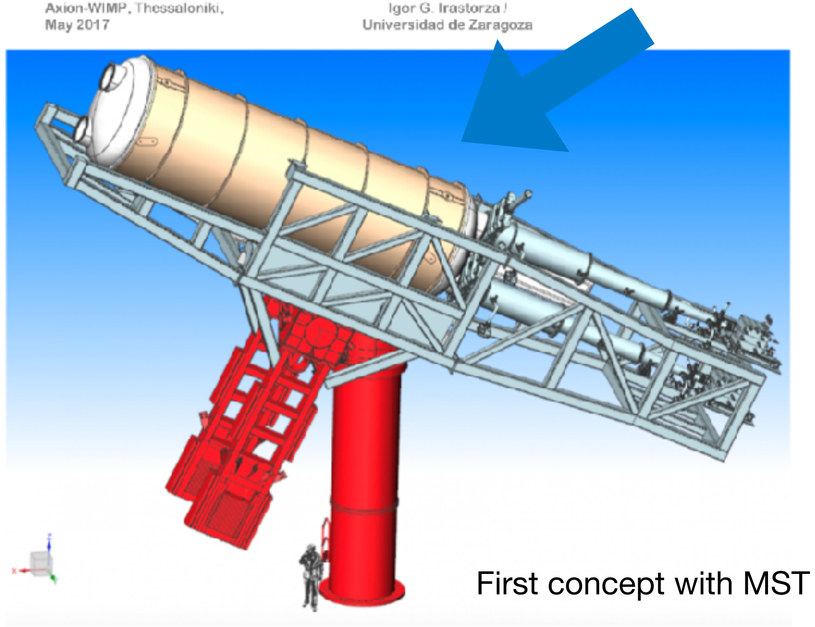
Detailed conceptual design under preparation:

Presumably:
1-bore magnet with relevant dimensions.
1 optics+detector system of specs close to final ones.

- Will better mobilize community into experimental activity & increase interest
- Better (more staged) access to funding
- Detail concept and effect on near-term planning under intense study at the moment in the collaboration.



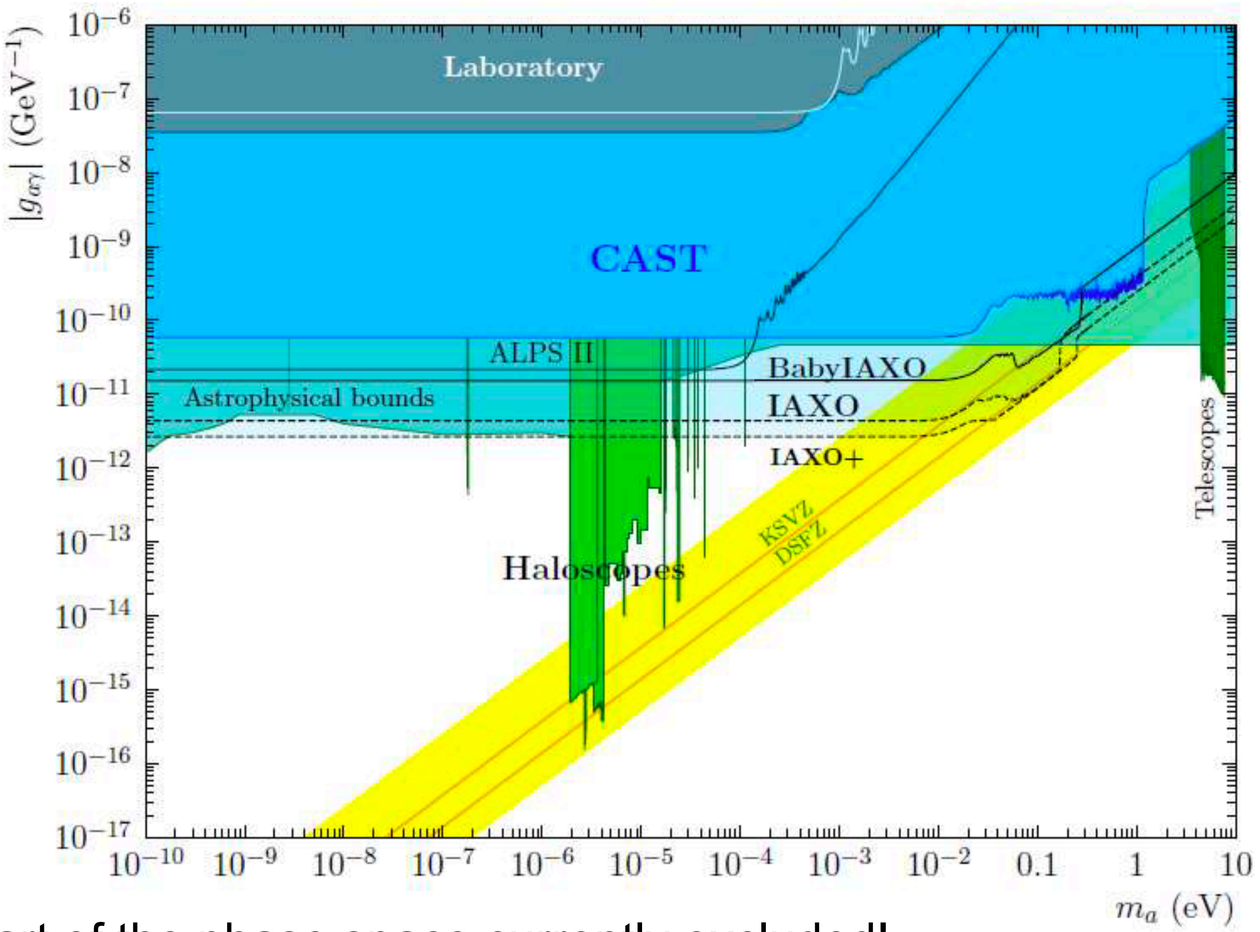
Axion-WIMP, Thessaloniki, May 2017 — Igor G. Irastorza / Universidad de Zaragoza — 14



First concept with MST

HELIOSCOPE LIMITS AND PROSPECTS

Solar axion photon flux



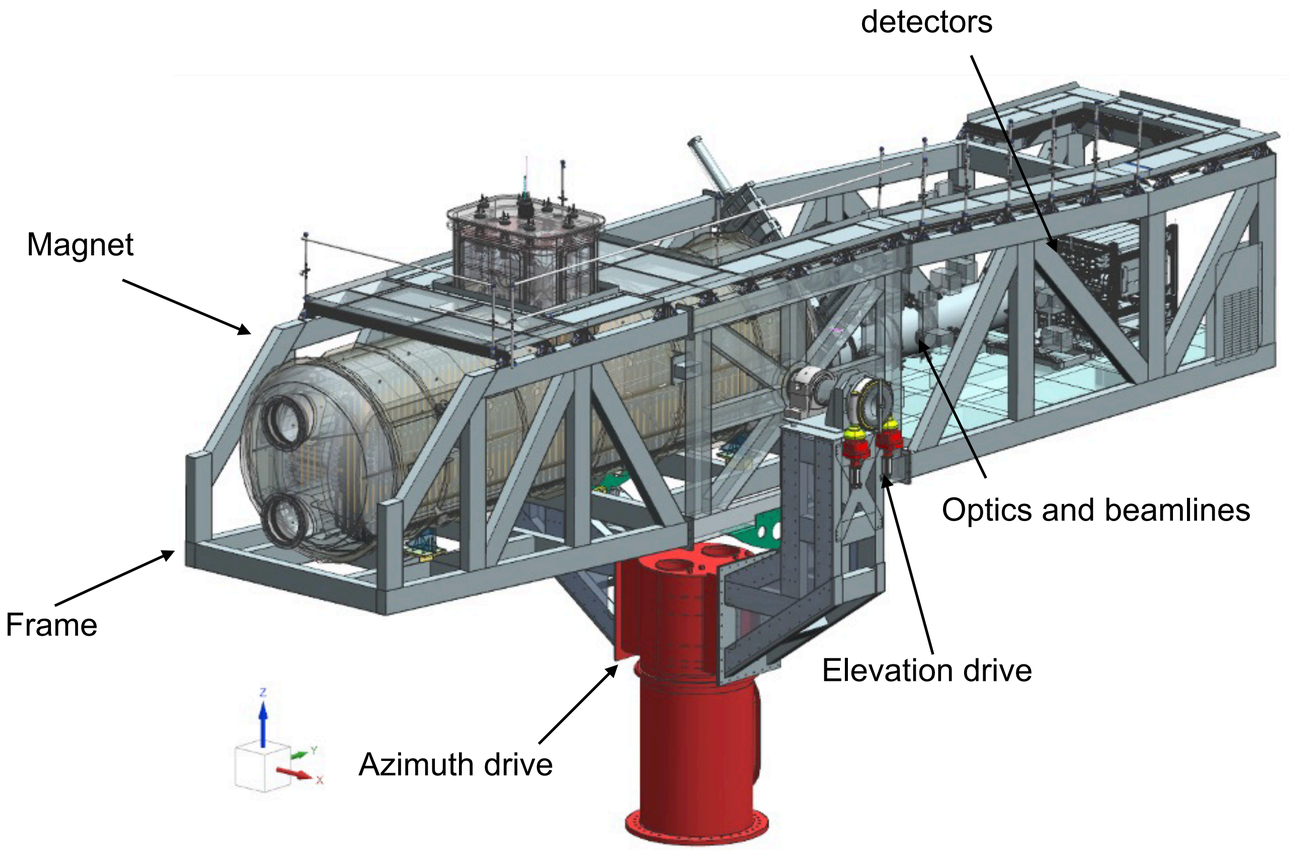
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- CAST probed a large part of the phase space currently excluded!
  - Even touching the QCD axions band.
- Baby IAXO on its own will allow to probe the QCD axions in the [10^{-3},10^{-1}] eV range and update limits wrt CAST!
- Let's look into more details of BabyIAXO!

Baby IAXO

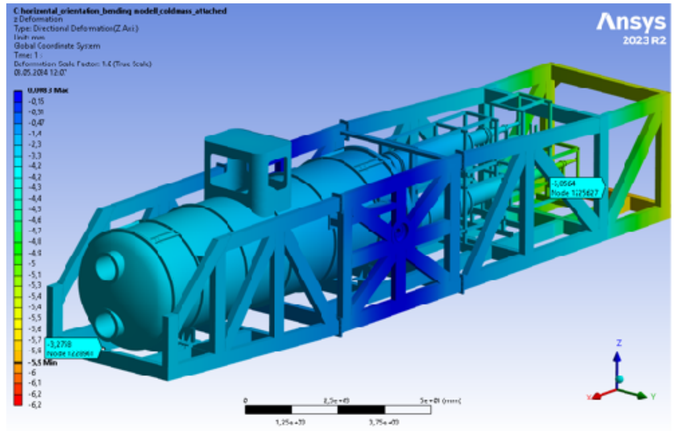
Experiment composed of following systems:

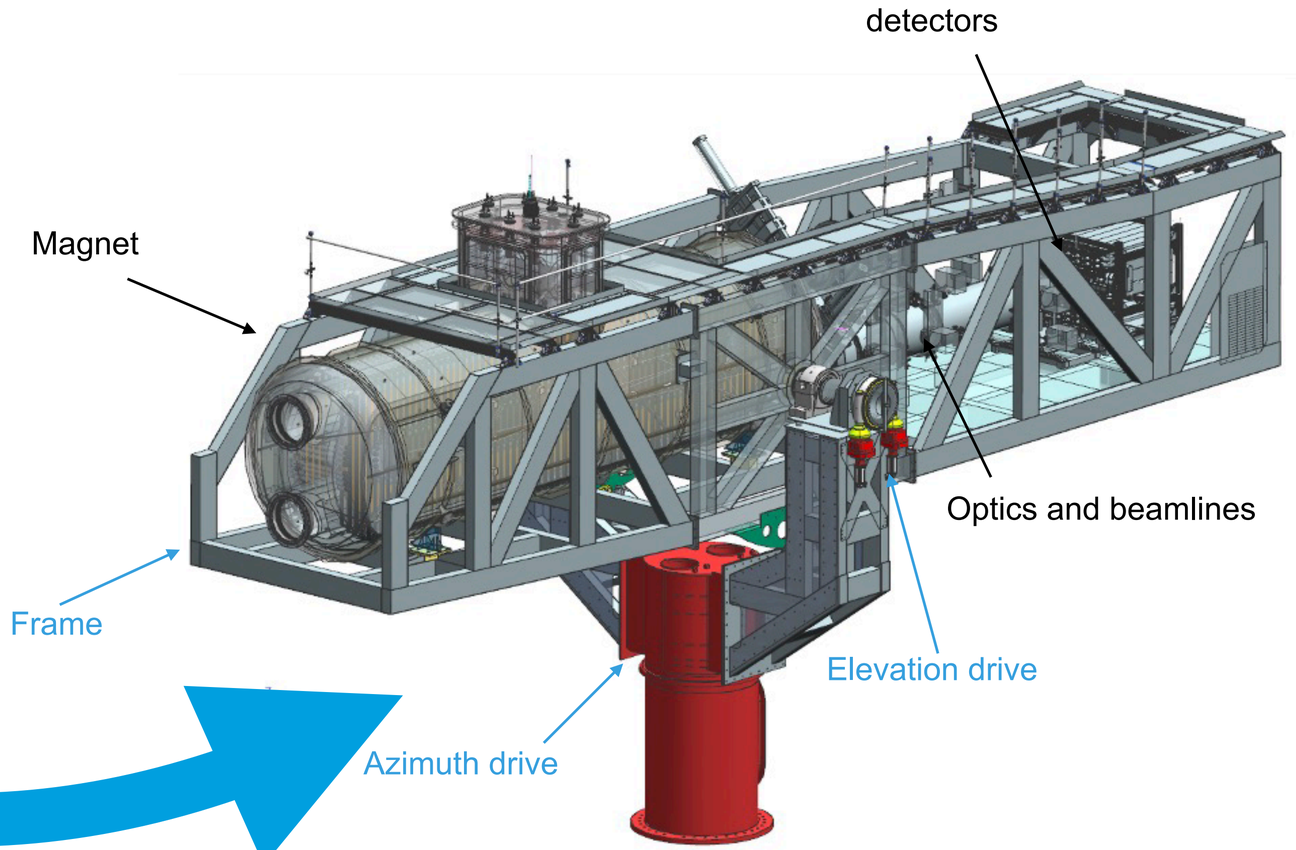
- Structure and Drive (elevation, azimuth, frame)
- Magnet
- Vacuum beamlines
- X-ray Optics
- X-ray Detectors
- And more…



BABY IAXO - STRUCTURE AND DRIVE SYSTEM

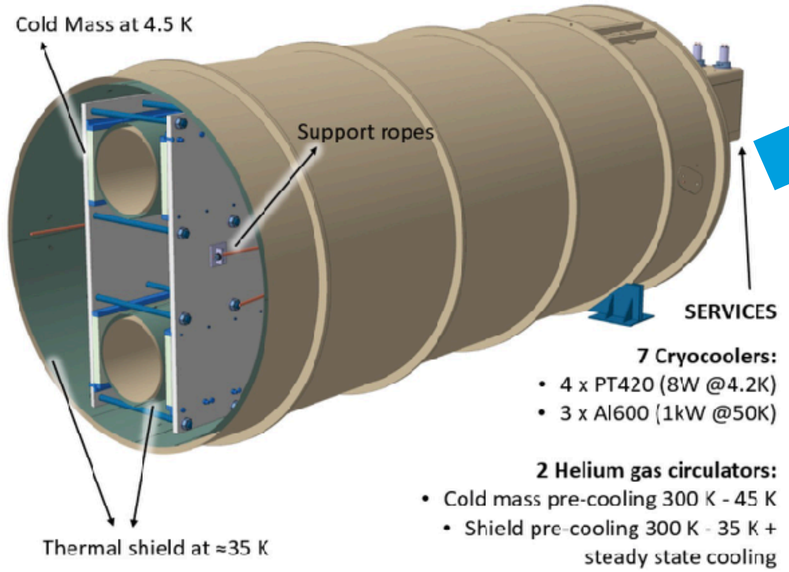






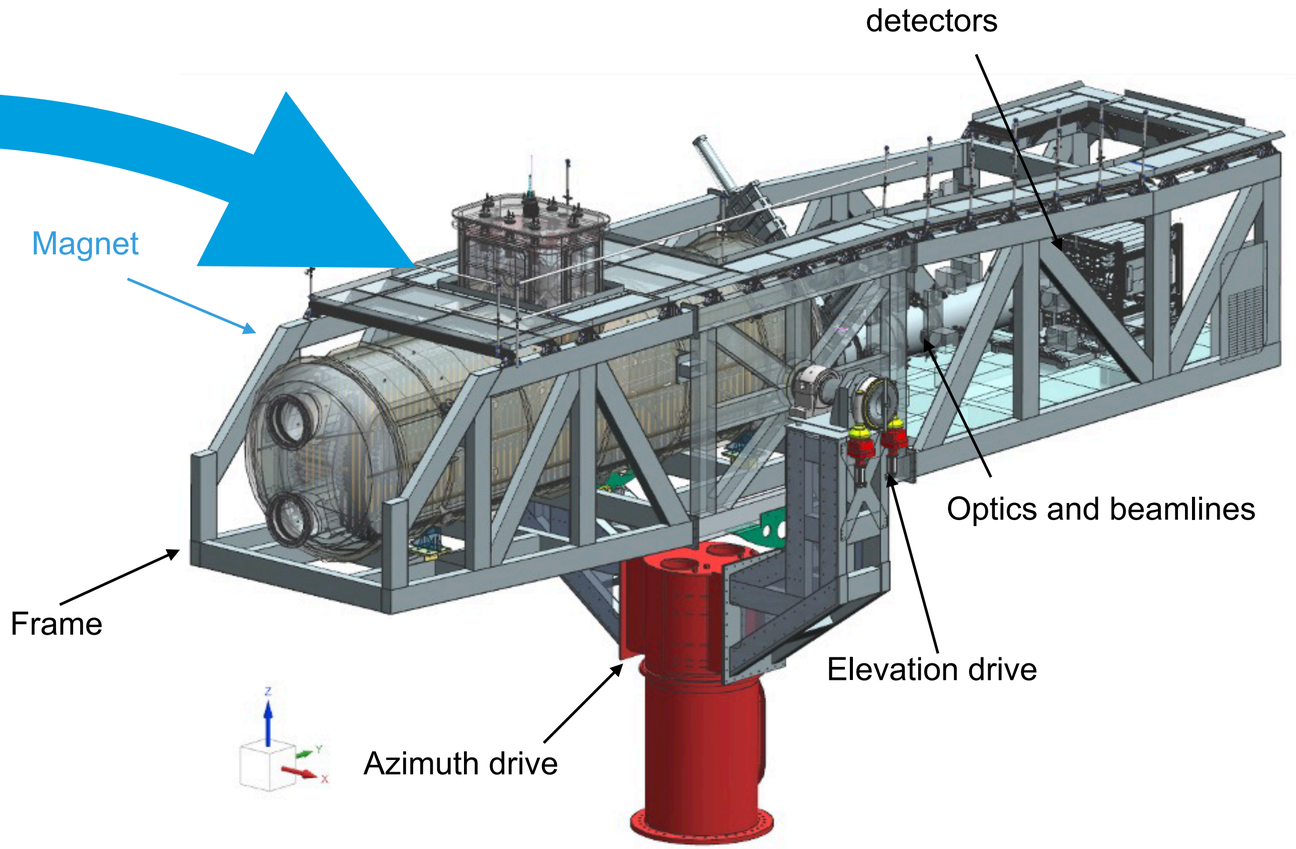
- Reusing parts of CTA/MST prototype installed in Adlershof and developed by DESY Zeuthen
  - Duty cycle at least 50%
  - Pointing precision < 0.01°
  - Frame: 21 meter length
  - Rotation: 360° azimuth, ± 25° elevation
  - Moving mass of about 110t
  - Design fully done in DESY!

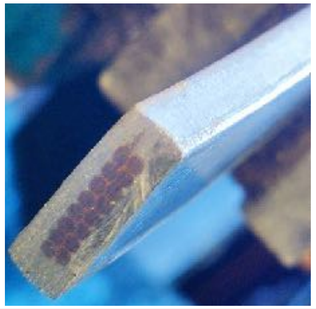
BABY IAXO - MAGNET SYSTEM

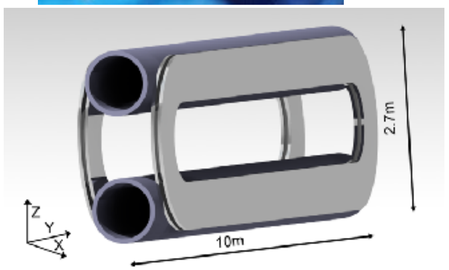


7 Cryocoolers:
- 4 x PT420 (8W @4.2K)
- 3 x AL600 (1kW @50K)

2 Helium gas circulators:
- Cold mass pre-cooling 300 K - 45 K
- Shield pre-cooling 300 K - 35 K + steady state cooling



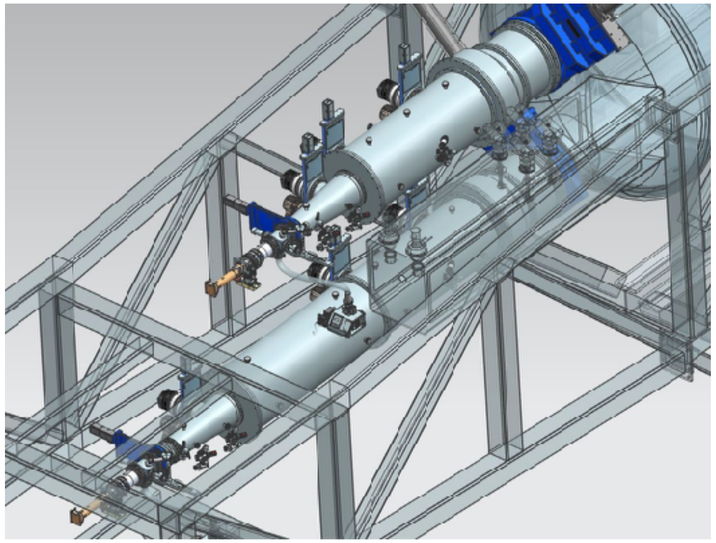




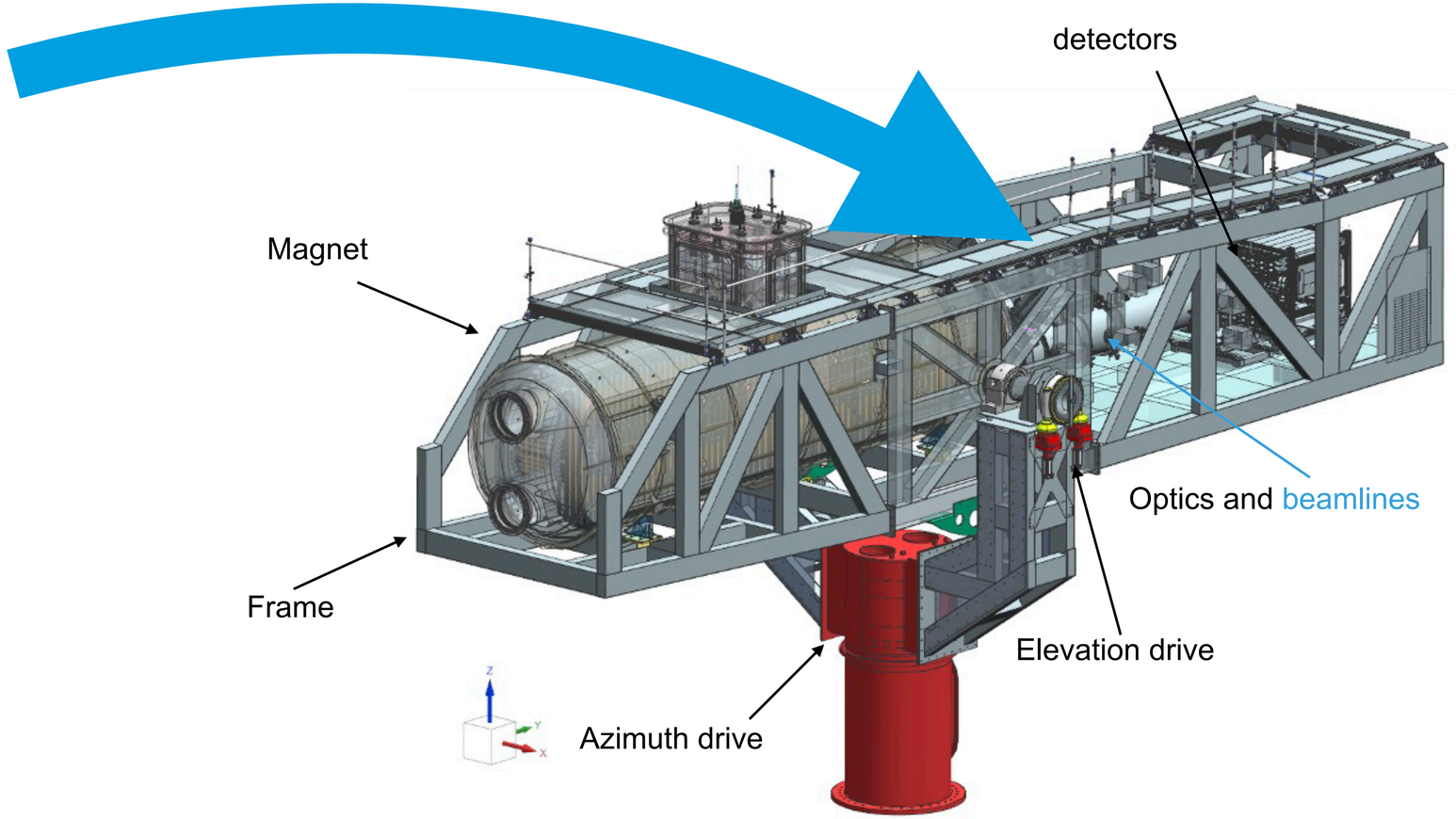


- Common coil racetrack design, with innovative cryocooler concept
- 10m long, and about 50t
- Can reach ~2T in 2 bores of 70cm ⌀.
- (volume~120 LHC dipoles)
- Design work from CERN & DESY with support from ELYTT company
- Credible path to purchase full cable is now established and could proceed very soon!

BABY IAXO - VACUUM AND GAS SYSTEM



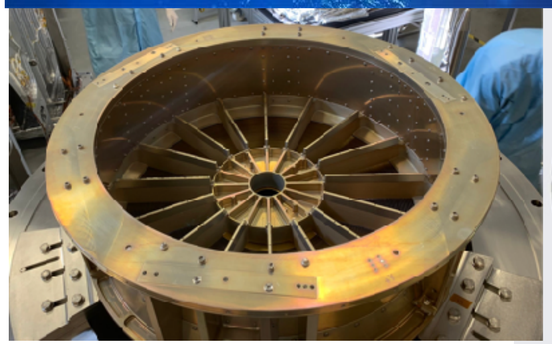


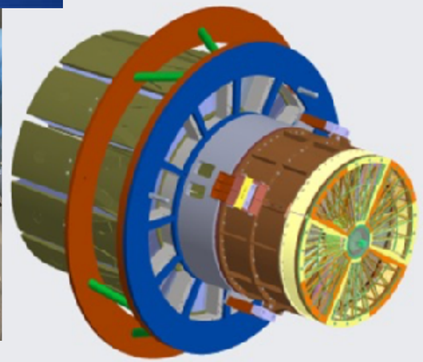


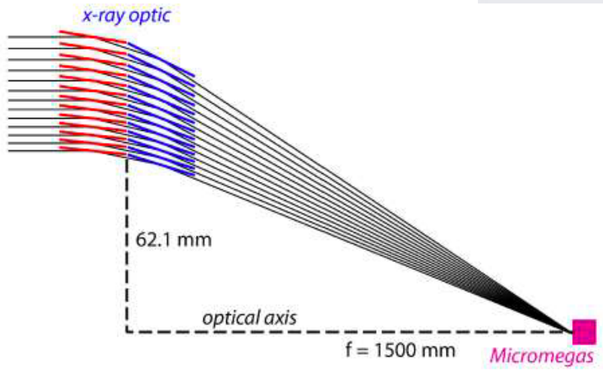
- Vacuum line to connect to magnet bore and guide photons to detectors
  - Beam-lines, pumps, most vacuum equipments already in DESY since 2025!
  - University of Zaragoza, DESY, CEA Saclay, University of Bonn, Technical University Dortmund

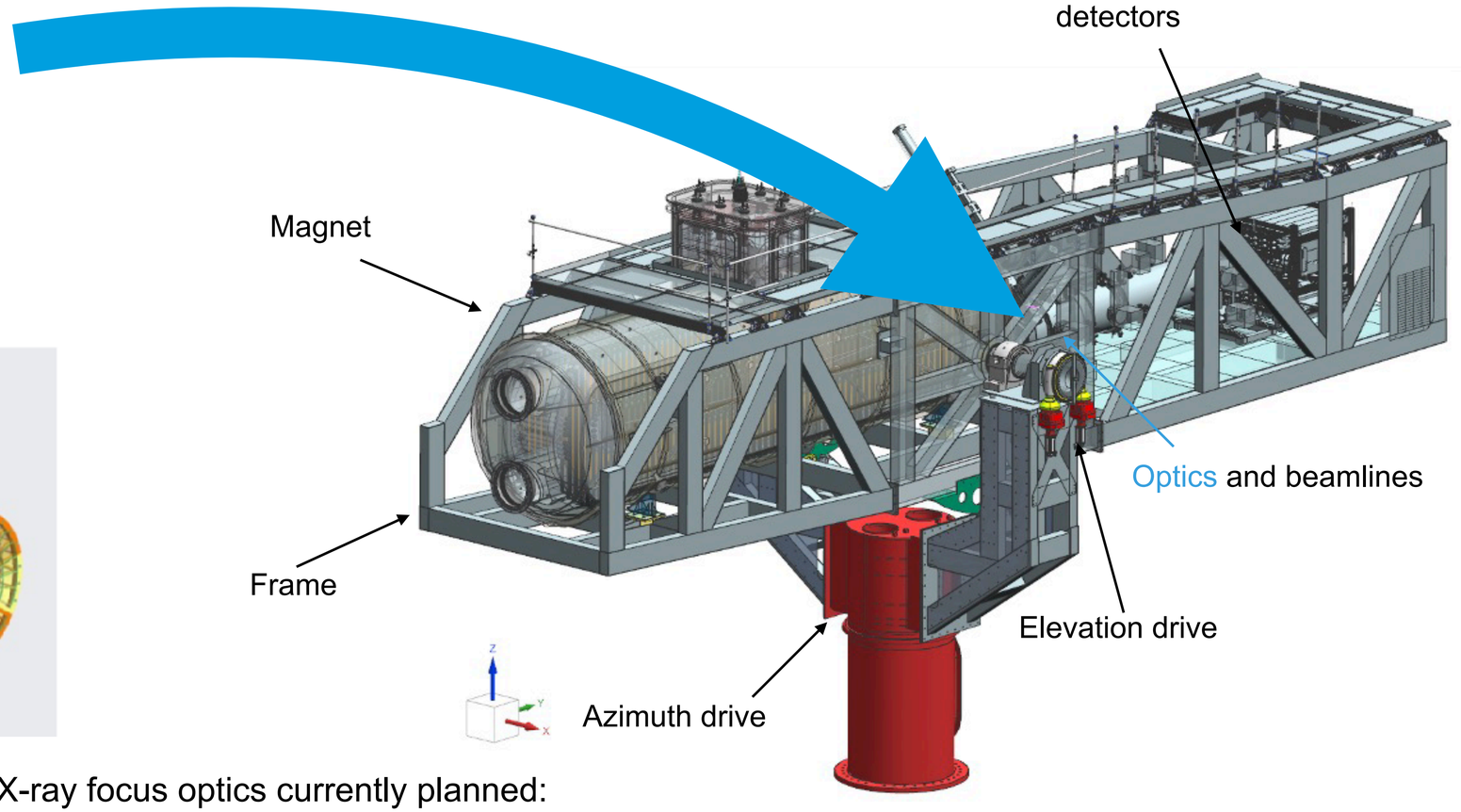
BABY IAXO - X-RAY OPTICS







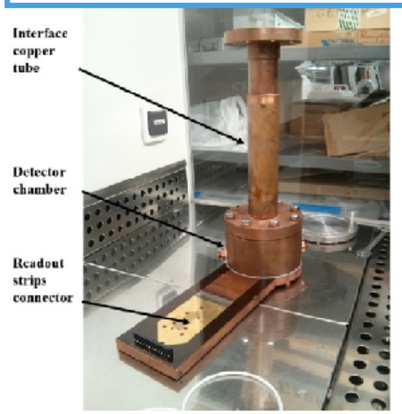




- X-ray focus optics currently planned:
  - Recycle a flight spare from ESA XMM Newton (MPI PANTER)
    - a~0.5cm^2
  - Custom-made hybrid optics (INAF/Columbia/DTU) based on NuSTAR XRT
    - 124 nested layers.
    - a~0.2cm^2
  - Newer concept possible with NASA!

BABY IAXO - X-RAY DETECTORS

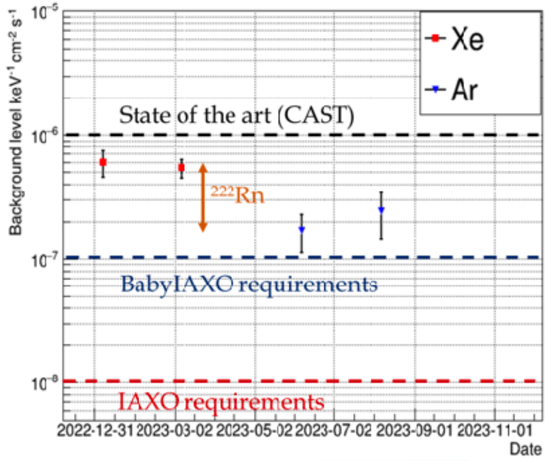
"Discovery technology" σ_E~1-10 keV

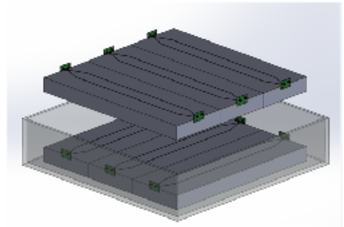


Microbulk Micromegas TPC (U. Zaragoza & CEA Saclay)



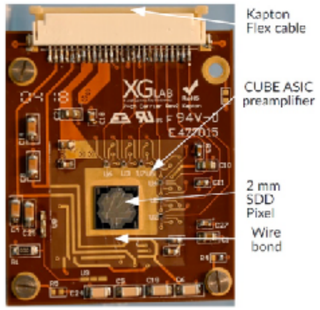
GridPix TPC (U. Bonn)



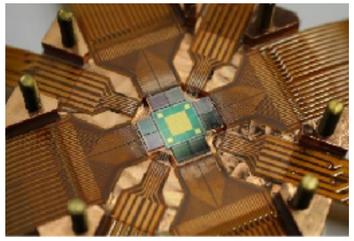


Cosmic veto R&D (U. Mainz and U. Bonn)

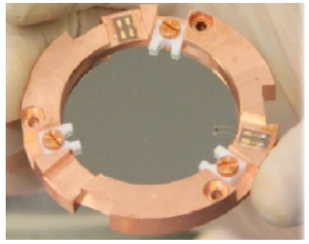
"Energy-resolving technologies" σ_E~100 eV



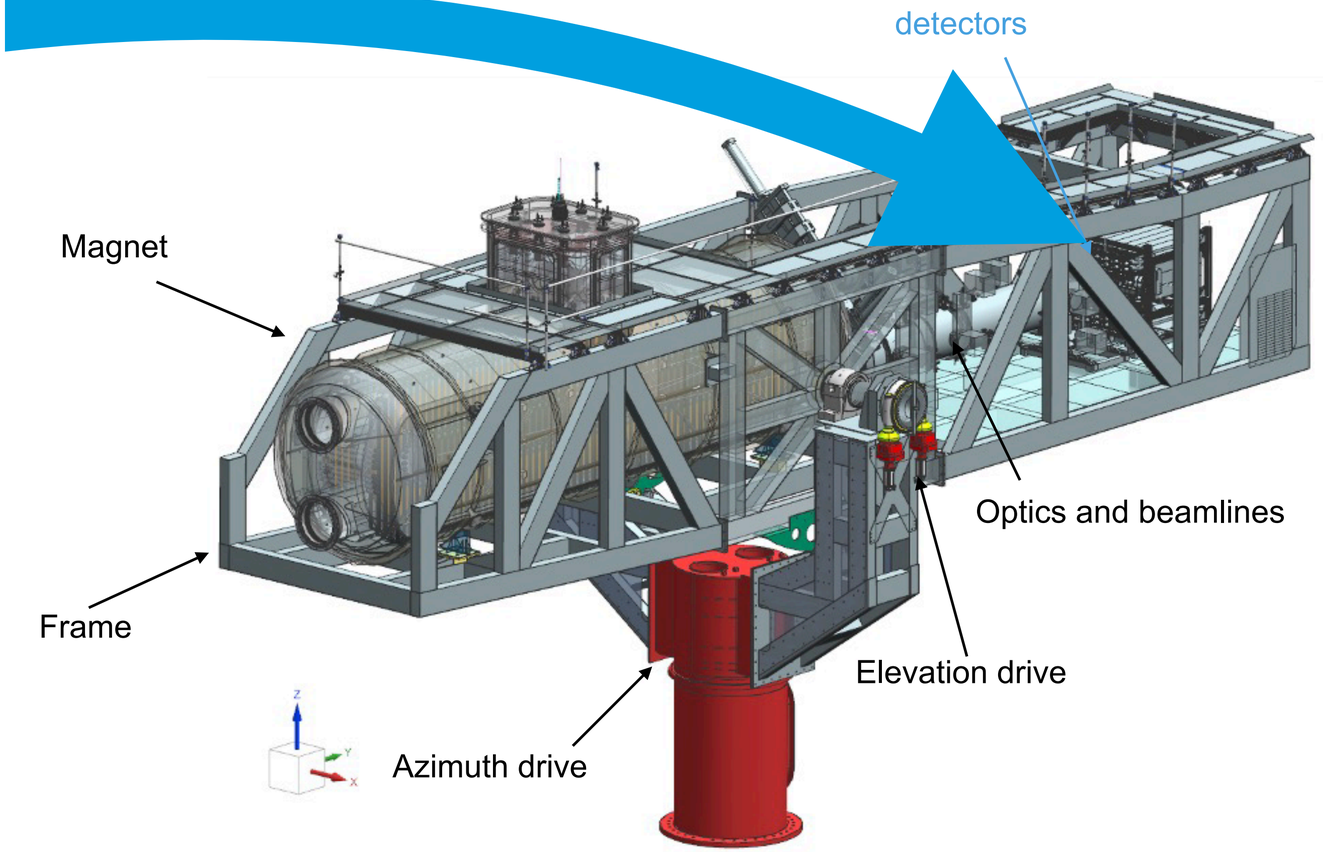
SDD: Silicon Drift Detectors (MPIK Heidelberg)



MMC: Metallic Magnetic Calorimeters (U. Heidelberg & CEA Saclay)



TES: Transition Edge Sensors (U. Zaragoza + INMA-ICMAB CSIC+ IJCLab)

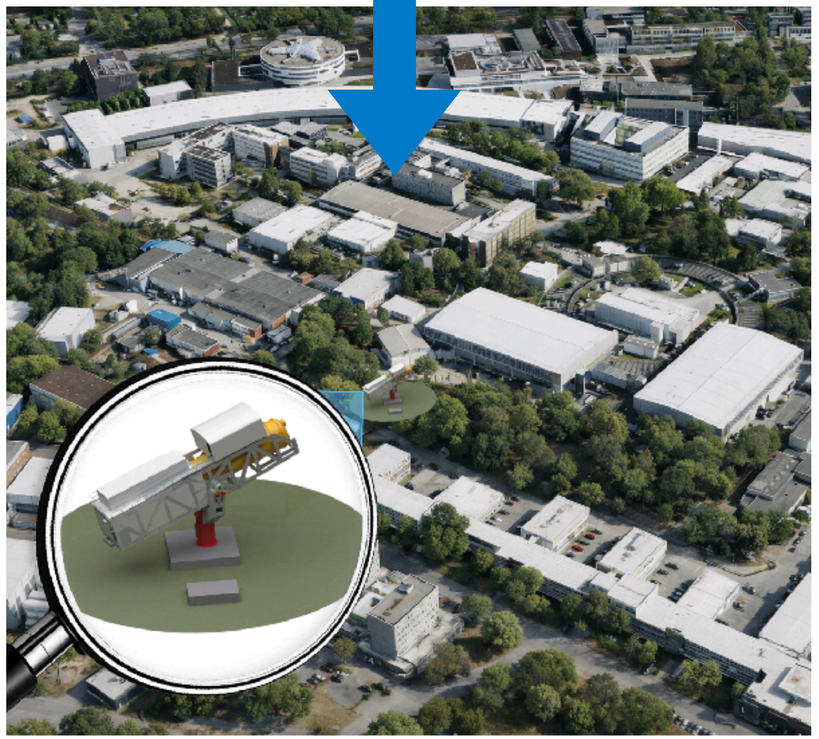


- Various detector systems developed to reach: 1×10^{-7} counts/$(keV\,.\,cm^2\,.\,s)$
- About 1 background event per month!
- Baseline using Micromegas detector with cosmic veto!
  - 1 Micromegas has been in DESY since Spring 2025!

BABY IAXO - NEWS - SITE

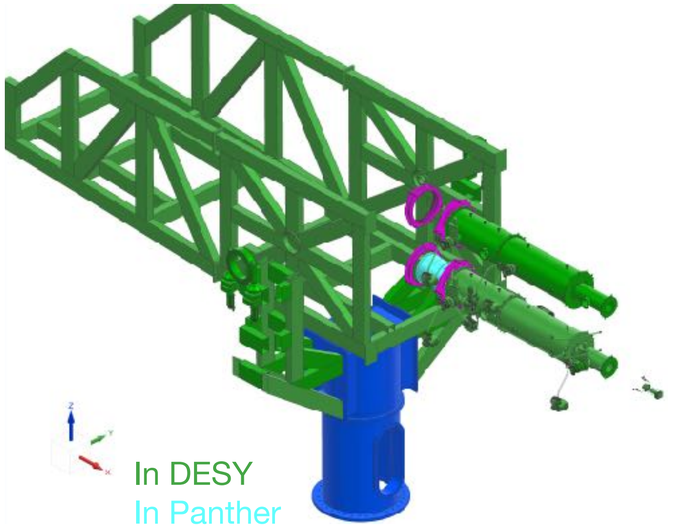
- Baby IAXO originally designed for installation in HERA South hall.
  - Now seek to install the experiment on-surface in DESY.
    - Ease preparation, survey, pointing, alignment, etc.
    - Local housing on support frame for sensitive equipments.
  - Site stability has been checked by external company installation in principle possible in this site.
    - Further detailed study with statics company pending.
  - Decision accepted by IAXO collaboration in September.
    - Statics calculation of frame and SDS shows no problem expected.
    - Whenever possible reuse part of the CTA-MST site design.



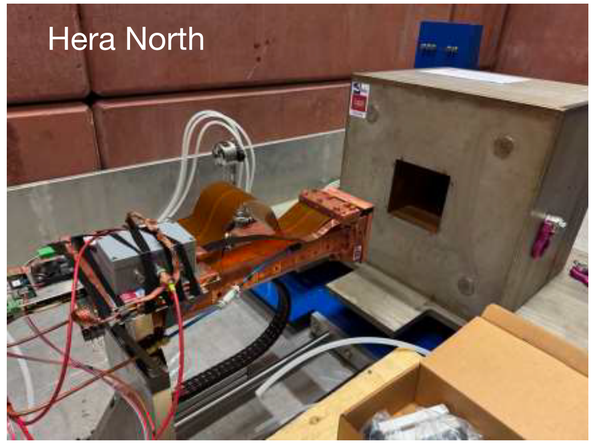


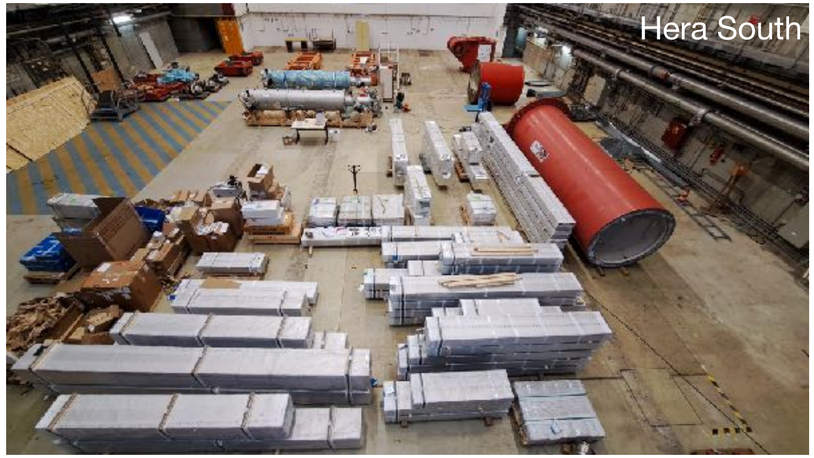
BABY IAXO - COMPONENTS AND TIMELINE

- Most of the experiment funding is secured.
  - A large part of the equipments that will be used in the experiment is already sitting in DESY.
- Current timeline envision installation for the next few years, followed by first physics results.
  - Site and positionner will be installed and commissioned.
  - Magnet to be constructed in parallel.
  - First axion results could be expected in the early 2030s
  - Data taking to last at least 10 years.



BabyIAXO Timeline:
- **2026-2027: Site activation**
- **2027-2028: Magnetless-commissioning**
- **2028-2029: Dark photon run**
- **2029-2030: Magnet installation**
- **2030+: BabyIAXO commissioning, physics runs**





THE IAXO COLLABORATION - WORLD'S LARGEST AXION COLLABORATION

The International Axion Observatory (IAXO): case, status and plans. Input to the European Strategy for Particle Physics

A. Arcusa,[1] S. Ahycune,[2] K. Altenmüller,[3] I. Antolín,[3,4] S. Basso,[5] P. Brun,[6] V. Burwitz,[7] F. R. Candón,[3] J. F. Castel,[3] S. Cebrián,[3] D. Chouhan,[8] R. Della Ceca,[5] M. Cervera-Cortés,[9] M. M. Civitani,[5] C. Cogollos,[10] E. Costa,[11] V. Cotroneo,[5] T. Dafní,[3] K. Desch,[8] M. C. Díaz-Martín,[9] A. Díaz-Morcillo,[12] D. Díez-Ibáñez,[3] C. Diez Pardos,[13] M. Dinter,[14] B. Döbrich,[10] A. Dudarev,[15] A. Ezquerro,[3] S. Fabiani,[11] E. Ferrer-Ribas,[6] F. Finelli,[16,17] I. Fleck,[13] J. Galán,[3] G. Galanti,[18] M. Galaverni,[16,17,19] J. Galindo Guarch,[1] J. A. García,[3] J. M. García-Barceló,[10] L. Gastaldo,[20] M. Giannotti,[3,21,*] A. Giganon,[6] C. Goblin,[6] N. Goyal,[22] Y. Gu,[3] L. Hagge,[14] L. Helary,[14] D. Hengstler,[20] D. Heuchel,[14] S. Hoof,[23,24] R. Iglesias-Marzoa,[9] F. J. Iguaz,[22] M. Iglesias,[3] C. Iñiguez,[9] I. G. Irastorza,[3,†] K. Jakovčić,[25] D. Käfer,[14] J. Kaminski,[8] S. Karstensen,[14] M. Law,[26] A. Lindner,[14,‡] M. Loidl,[27] C. Loiseau,[6] G. López-Alegre,[9] A. Lozano-Guerrero,[12] G. Luzón,[3] I. Manthos,[4] C. Margalejo,[3] A. Marín-Franch,[9] J. Marqués,[3] F. Marutzky,[14] C. Menneglier,[22] M. Mentink,[15] S. Mertens,[28,29] J. Miralda-Escudé,[2,30] H. Mirallas,[3] F. Muleri,[11] J. R. Navarro-Madrid,[12] X. F. Navick,[6] K. Nikolopoulos,[4,31] A. Notari,[2,32] L. Obis,[3] A. Ortiz-de-Solórzano,[3] T. O'Shea,[3] J. von Oy,[8] G. Pareschi,[5] T. Papaevangelou,[6] K. Perez,[26] O. Pérez,[3] E. Picatoste,[2] M. J. Pivovaroff,[33] J. Porrón,[3] M. J. Puyuelo,[3] A. Quintana,[3,6] J. Redondo,[3] D. Reuther,[14] A. Ringwald,[14] M. Rodrigues,[27] A. Rubini,[11] S. Rueda-Teruel,[9] F. Rueda-Teruel,[9] E. Ruiz-Chóliz,[34] J. Ruz,[3,35] J. Schaffran,[14] T. Schiffer,[8] S. Schmidt,[8] U. Schneekloth,[8] L. Schönfeld,[28,29] M. Schott,[8] L. Segui,[3] U. R. Singh,[14] P. Soffitta,[11] D. Spiga,[5] M. Stern,[25] O. Straniero,[36,37] F. Tavecchio,[5] G. Vecchi,[5] J. K. Vogel,[3,35] R. Ward,[4] A. Weltman,[38,39] C. Wiesinger,[28,29] R. Wolf,[14] J. Woo,[26] A. Yanes-Díaz,[9] and Y. Yu[26]



IAXO Collaboration Meeting @ DESY, September 2026

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

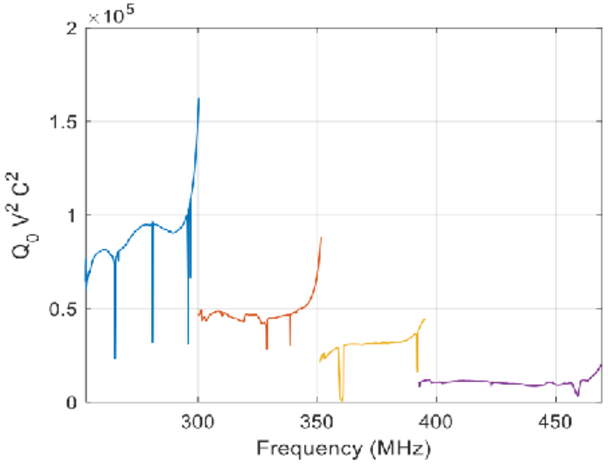
Associate members: DTU (Denmark) | U. Columbia (USA) | SOLEIL (France) | IJCLab (France) | LIST-CEA (France)

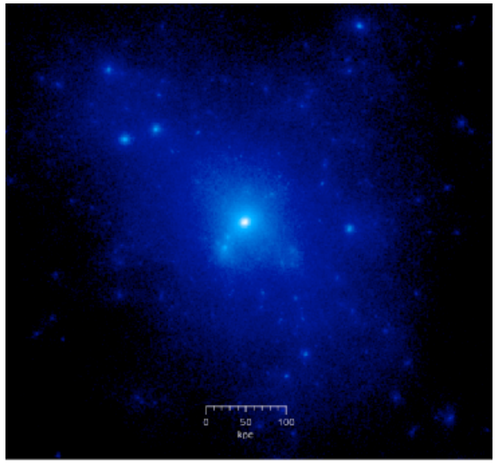
- ~125 scientists from 23 full member institutions + 5 associate institutions
- DESY has a leading contribution (Host lab, Technical Coordination, Project Engineer, Physics Coordination,…)

IAXO Collaboration

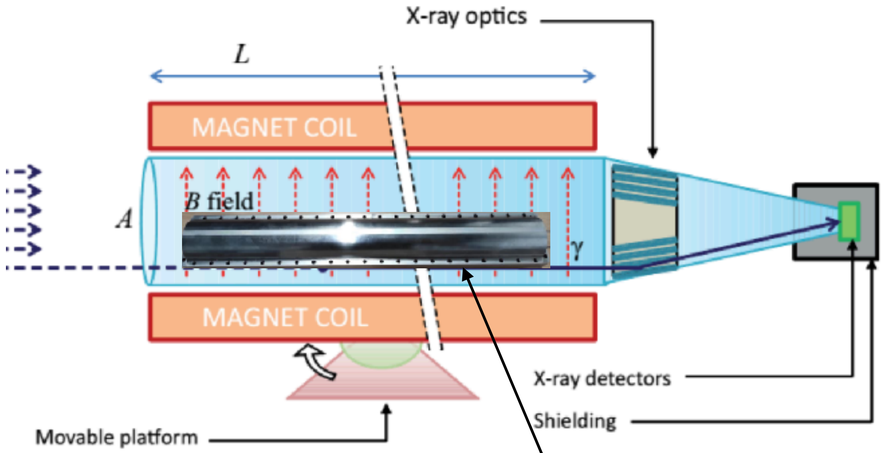
Baby IAXO - beyond baseline physics

EXTENDED DETECTION PRINCIPLE (DM HALO, SN)





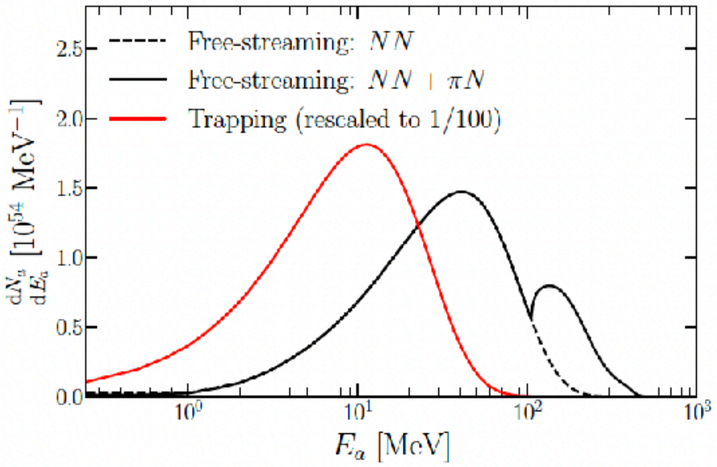
Dark Matter Halo

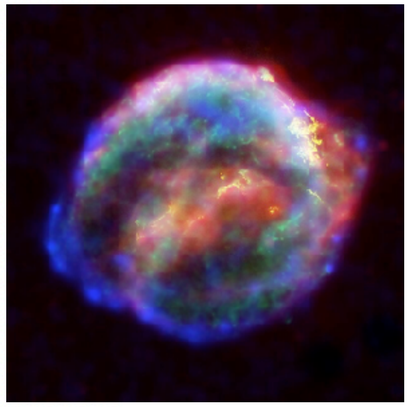


RADES (MPP, U. Zaragoza, KIT, …)

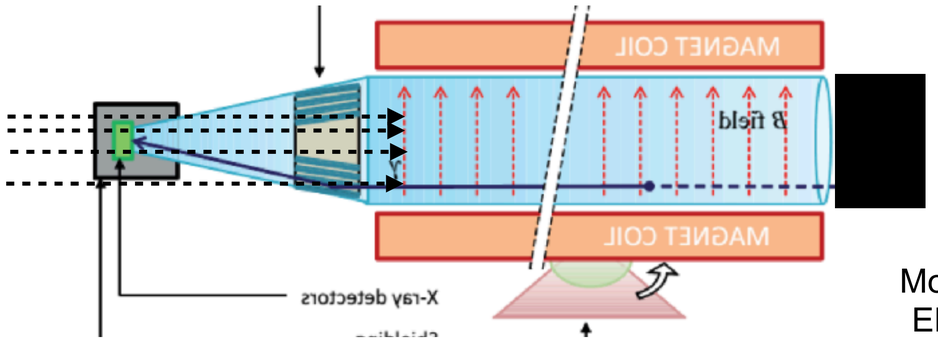
radio frequency cavity in magnetic field (MHz, GHz)

European Research Council
Established by the European Commission
Synergy Dark Quantum:
https://cordis.europa.eu/project/id/101118911





Super Nova



← γ (O(1-100)MeV) detector

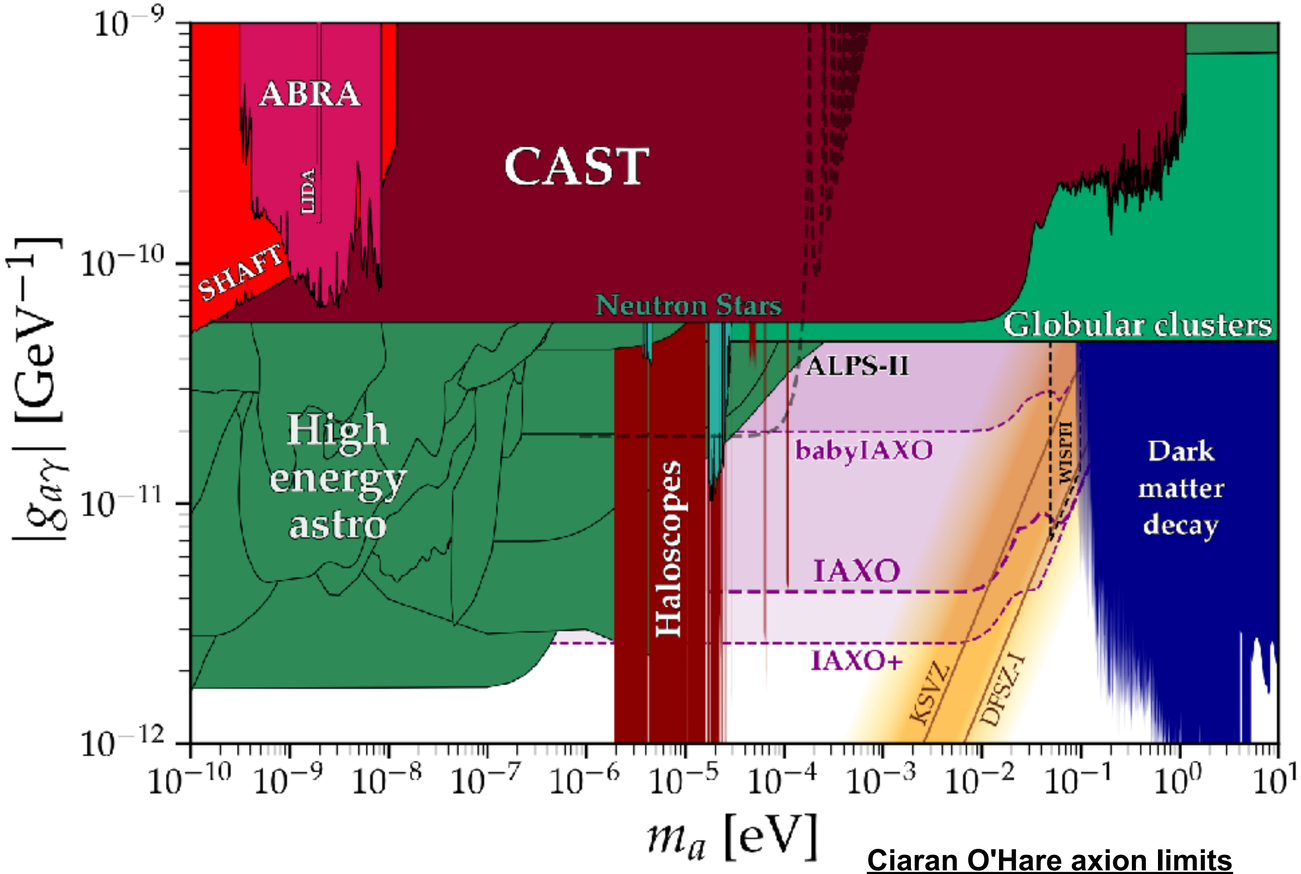
Most probably an EM calorimeter. Theoretical paper being submitted.

Conclusions

CONCLUSIONS

- Axions provide an elegant solution to
  - The strong CP problem.
  - Potential candidate to Dark Matter.
  - And more!

- Baby IAXO is well prepared to probe a significant part of the axion discovery plane!
  - Preparing the future and technologies toward the large IAXO!
  - Data-taking will also probe other scenarios:
    - Dark photons, High Frequency Gravitational Waves, Chameleons, Axion DM, etc..



Ciaran O'Hare axion limits

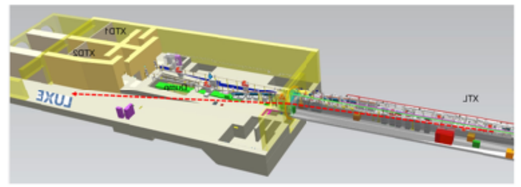
Backup

DESY on-site particle physics

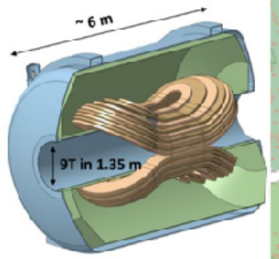
ALPS II

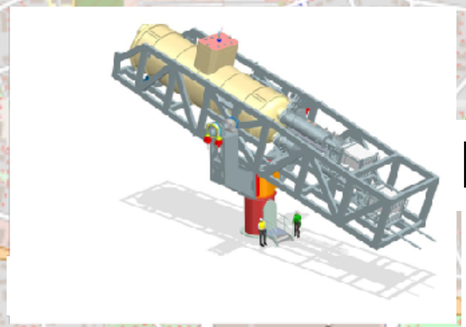


LUXE



MADMAX



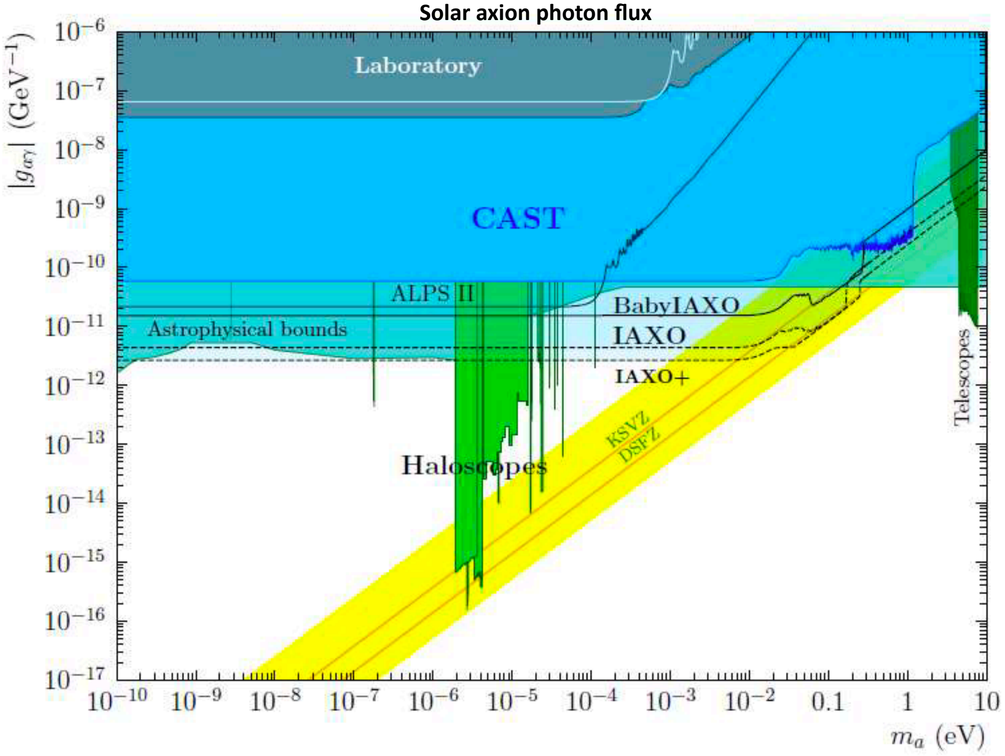


Baby IAXO

Nicely complementing remote experiments

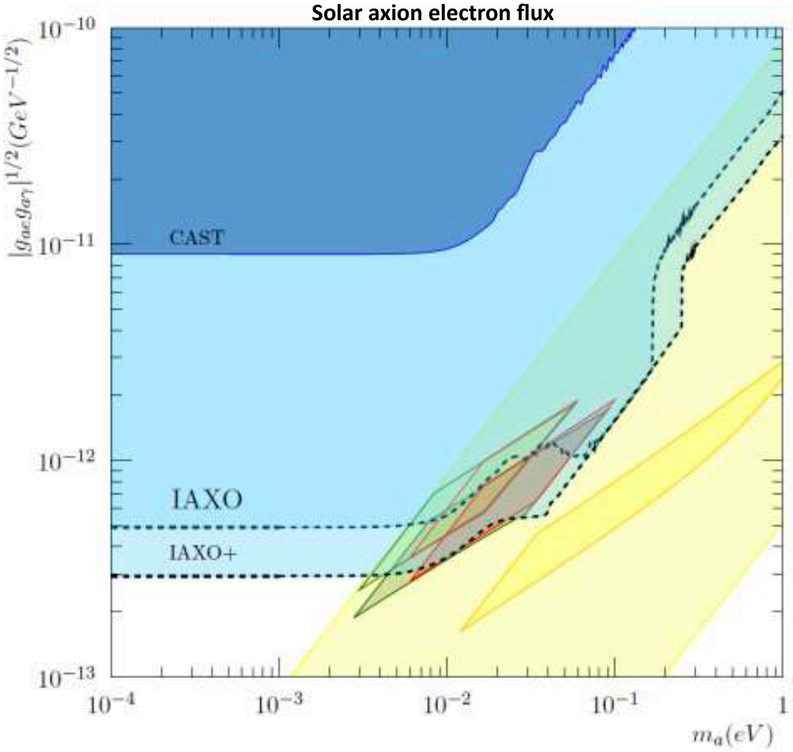
HELIOSCOPE LIMITS AND PROSPECTS

Solar axion photon flux



JHEP 05 (2021) 137

Solar axion electron flux



- CAST probed a large part of the phase space currently excluded!
  - Even touching the QCD axions band.
- Baby IAXO on its own will allow to probe the QCD axions in the [10^{-3},10^{-1}] eV range and update limits wrt CAST!
- Let's look into more details of BabyIAXO!

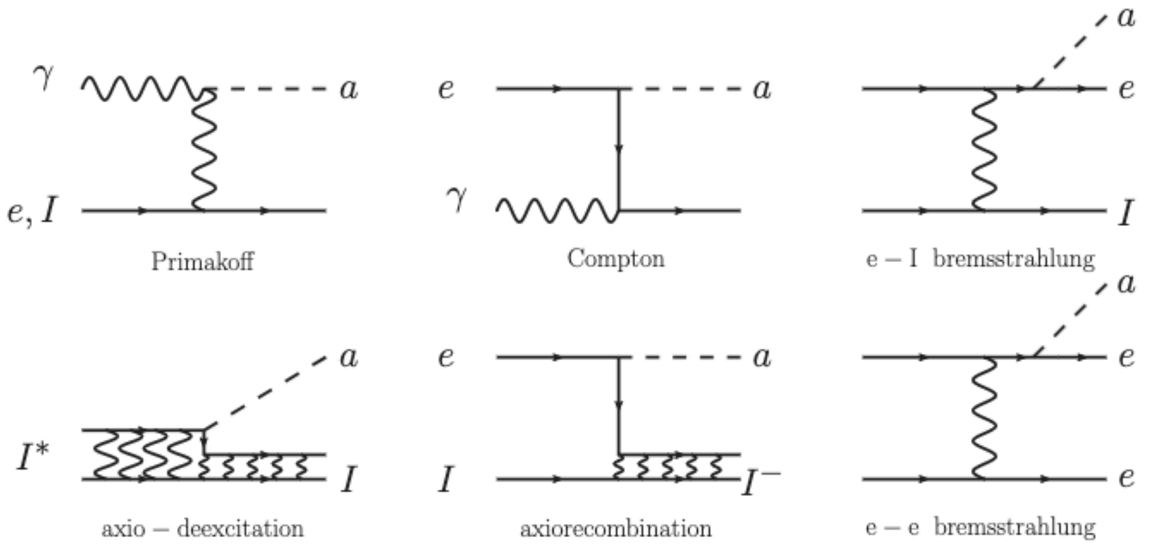


Figure 1. Feynman diagrams of the different processes responsible for axion production in the Sun. The Primakoff conversion of photons in the electromagnetic fields of the solar plasma depends on the axion-photon coupling $g_{a\gamma}$, and is present is practically every axion model. In non-hadronic models, in which axions couple with electrons at tree level, additional mechanisms of solar axion production are relevant, namely: atomic axio-recombination and axion-deexcitation, axio-Bremsstrahlung in electron-ion or electron-electron collisions and Compton scattering with emission of an axion. Collectively, the flux of solar axions from all these latter g_{ae}-mediated channels is sometimes called ABC solar axions, from the initials of the mentioned processes. In the diagrams, the letters γ, a, e and I represent a photon, axion, electron and ion respectively. Figure from ref [19].

BABY IAXO

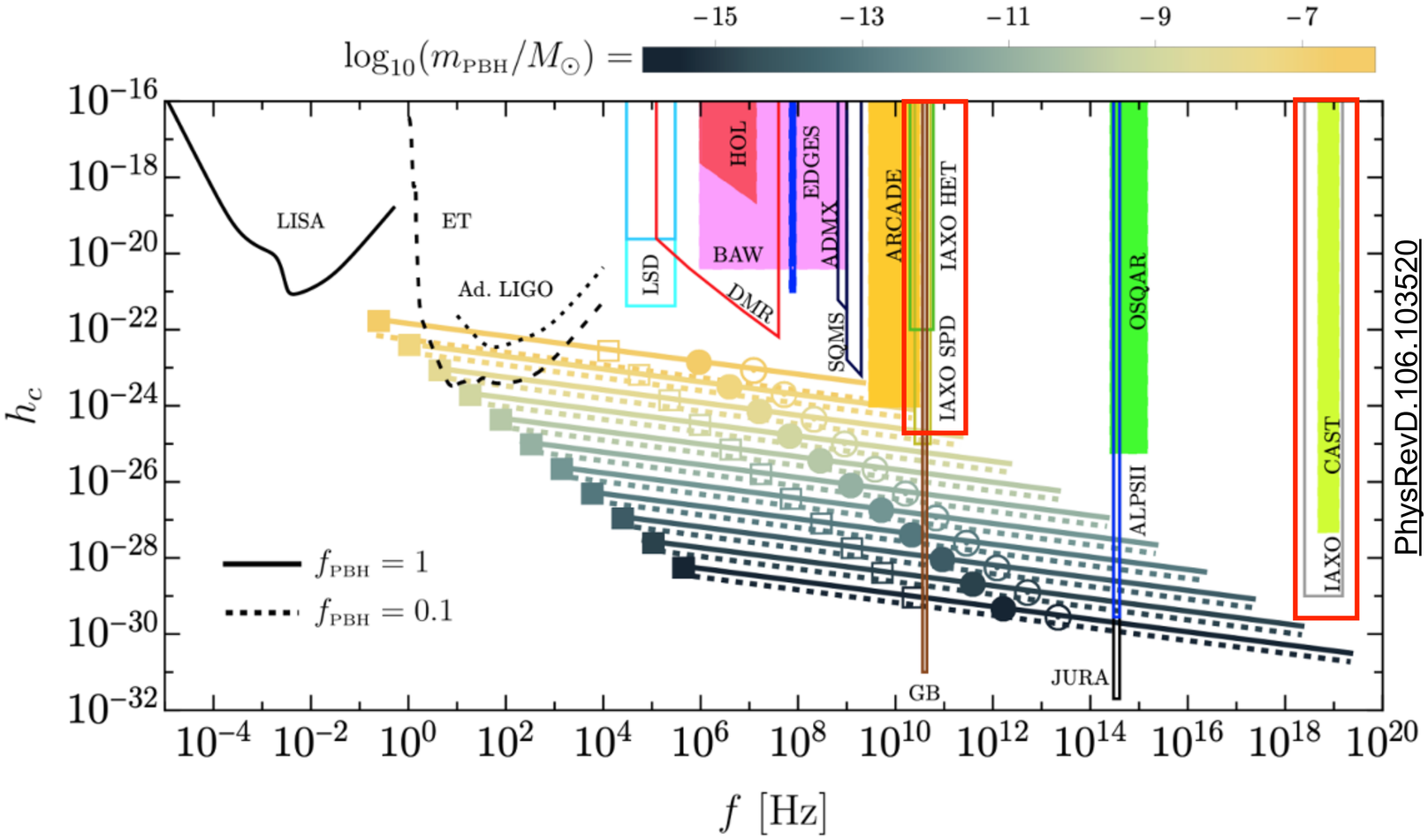
- IAXO CDR was released in 2020.
- Intermediate experiment toward the realisation of IAXO.
  - Exposure:
    - 50% solar tracking average along the year.
  - Magnet:
    - Superconducting dipole.
    - L=10m, B=2T, A=2x70cm Ø beamline.
  - Optics:
    - Spare XMM X-ray telescope.
    - Custom made from NuSTAR.
  - Detectors:
    - Detector requirement 1×10^{-7} counts/$(keV\,.\,cm^2\,.\,s)$
    - Baseline: Microbulk Micromegas
- FOM (sensitivity): **~100x CAST**



https://link.springer.com/article/10.1007/JHEP05(2021)137

High Frequency Gravitational Waves

Detection Possible with (Baby)IAXO?



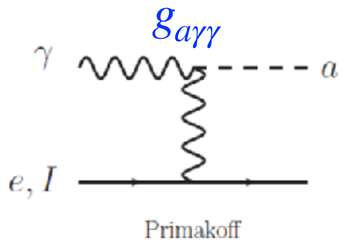
PhysRevD.106.103520

(Baby)IAXO sensitivities: PhysRevD.106.063027 + JCAP03(2021)054

- HF-gravitational waves are expected in non-standard scenarios, e.g. from primordial black hole formation
- Gravitational wave to photon conversion in a strong magnetic field (inverse Gertsenshtein effect)
  ➡ (Baby)IAXO sensitive?
- Emerging field of study, synergies?

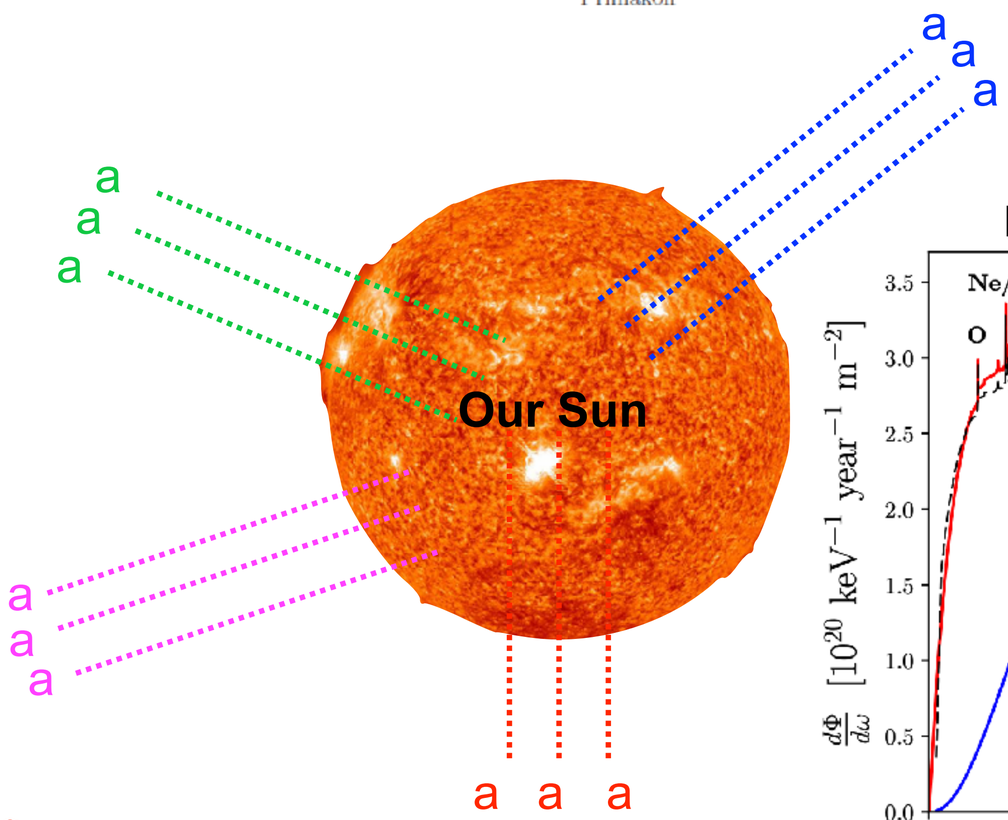
Solar Axions

Production Mechanisms

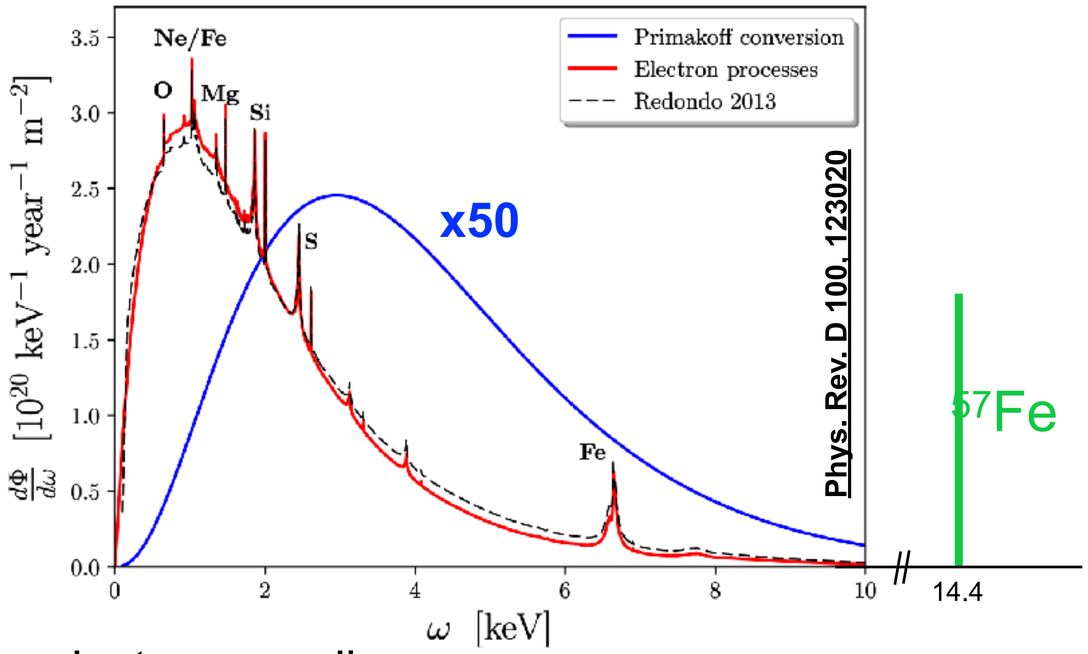


1. “Classical” Primakoff axions from solar plasma photons
   - ➡ **Generic prediction** of most axion models
   - ➡ Energy: thermal spectrum of sun

3. Solar axions from axion-nucleon coupling g_{an}
   - ➡ **Model dependent**
   - ➡ Most promising: nuclear transition ^{57}Fe (14.4 keV)



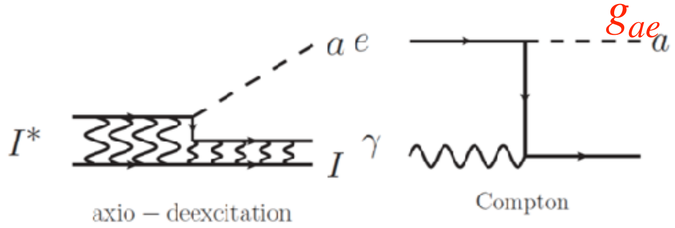
Differential axion flux at earth



4. Other channels:

Phys. Rev. D 101, 123004

Phys. Rev. D 102, 123024

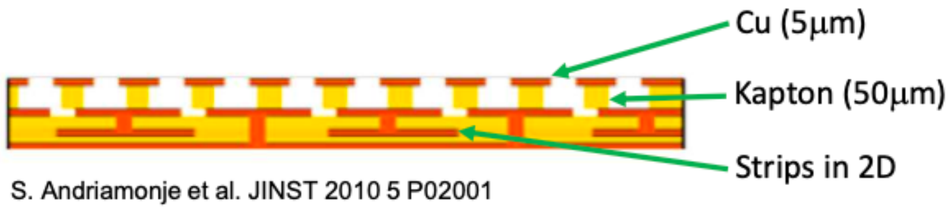


2. “ABC” solar axions from axion-electron coupling
   - ➡ **Model dependent**
   - ➡ Energy: continuous spectrum + elemental peaks

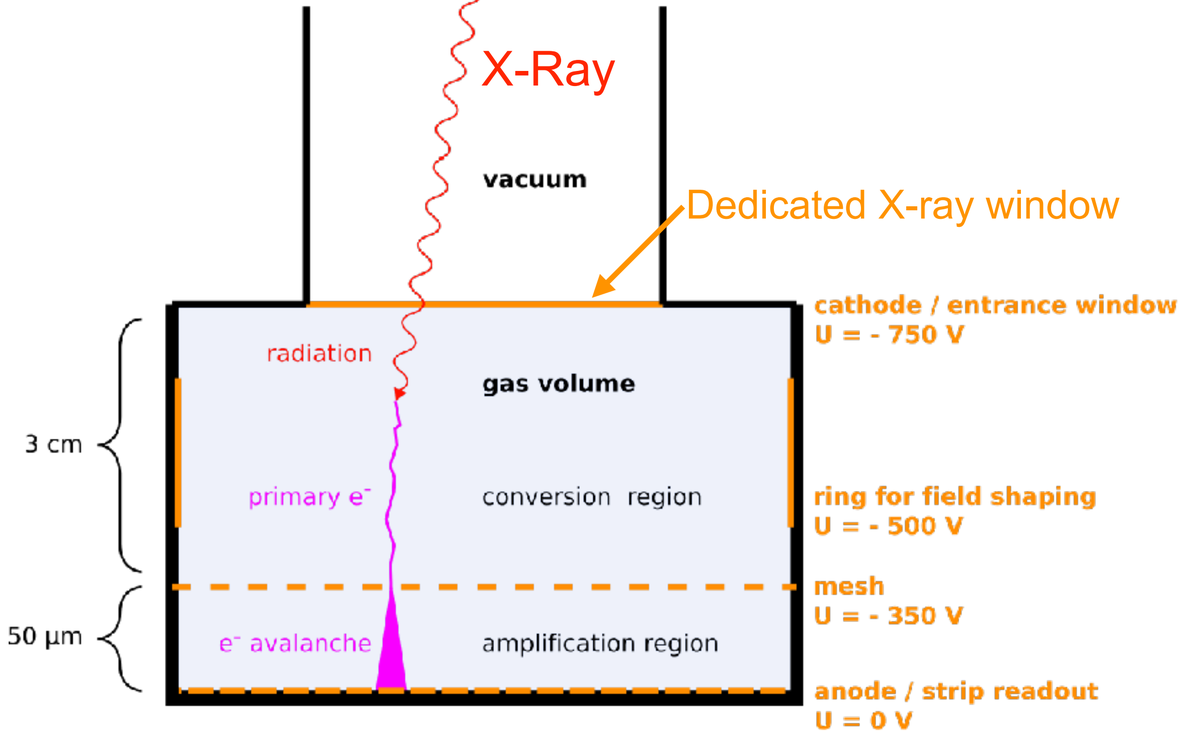
Microbulk Micromegas TPC

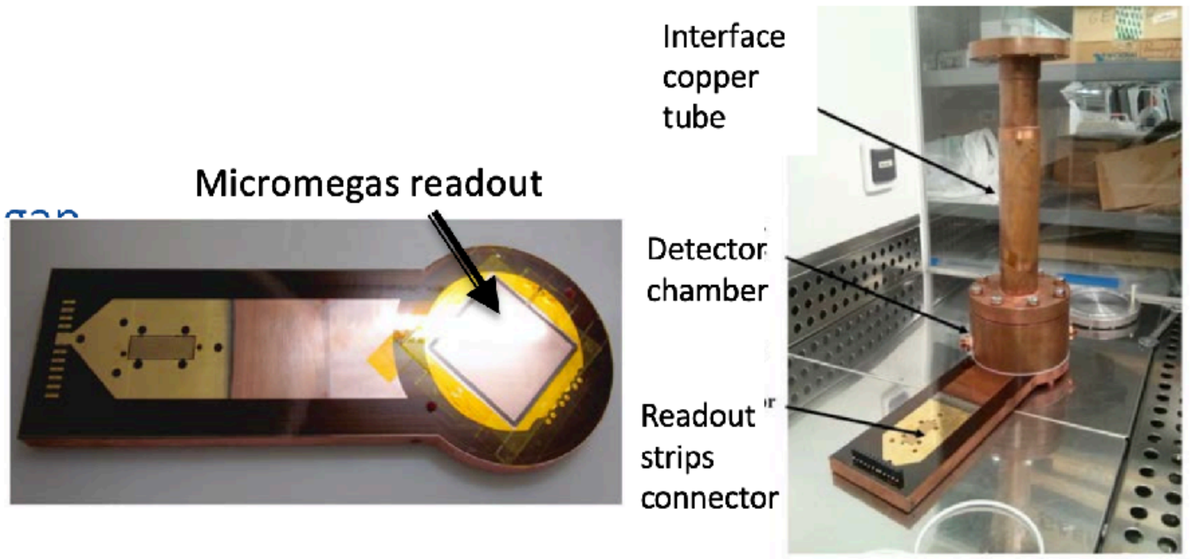
Working Principle

- Time projection chamber:
  - ➡ X-ray inducing photoelectric effect with gas atom
  - ➡ Further ionisations by primary electron and drift of secondary electrons towards amplification region
  - ➡ Electrons pass through mesh holes, gas amplification in high E-field. Signal induction in mesh and readout strips
  - ➡ Reconstruction: x, y, time (z) and charge with effective strip granularity



S. Andriamonje et al. JINST 2010 5 P02001

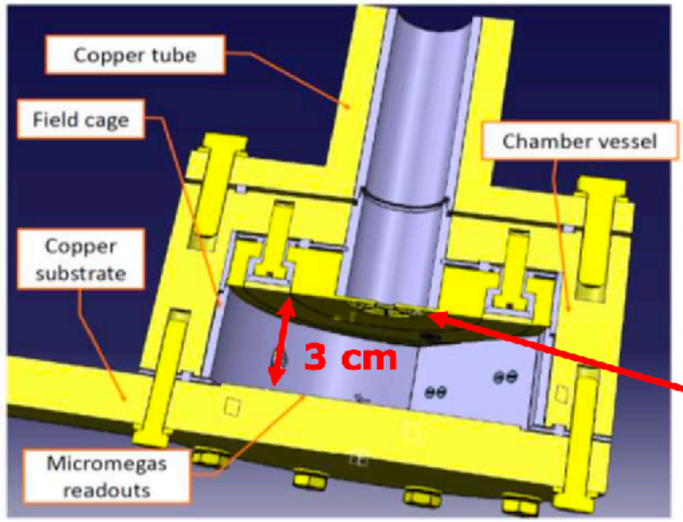


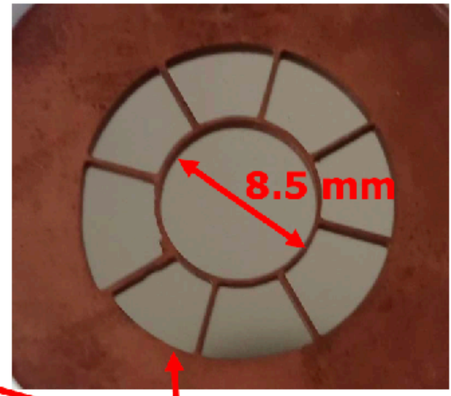


BabyIAXO MicroMegas Prototypes

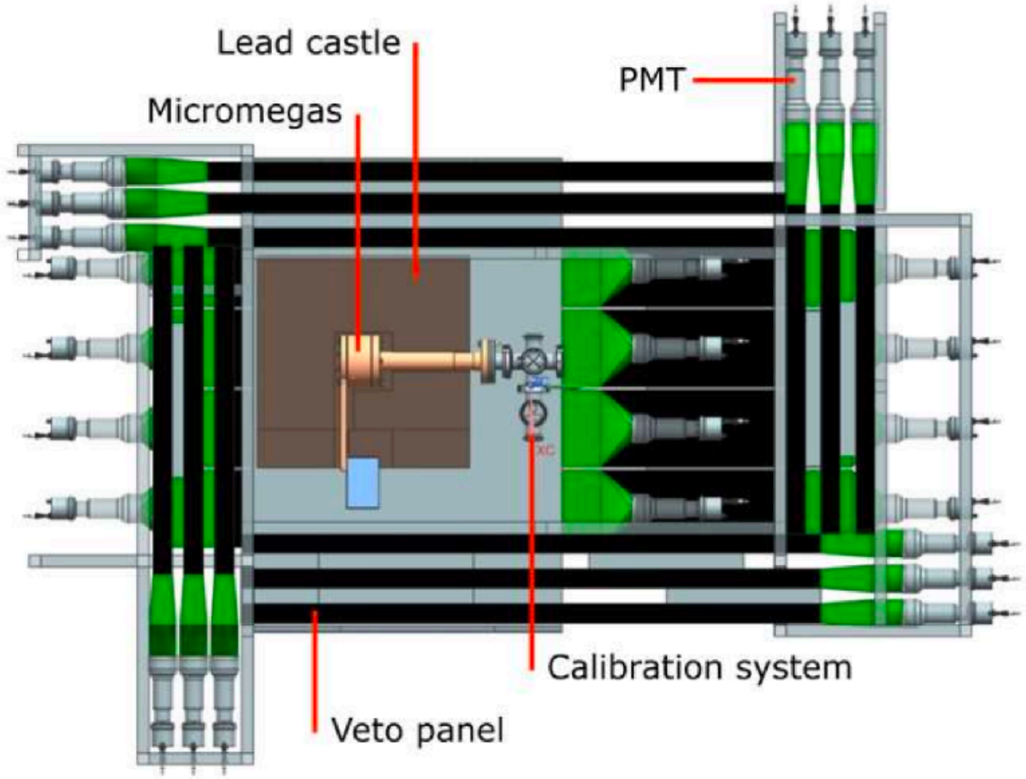
Setup Details

- Basic structure: radiopure copper
- Gas mixture: Ar (or Xe or Ne) + isobutane: 97.7/2.3
- Drift: l = 3 cm
- 50 µm amplification region, E = ~ 70kV/cm
- Micro-bulk readout: 6 x 6 cm^2 anode with 120 x 120 strips and pitch = 0.5 mm
- X-ray window with high transmissivity in ROI
- Shielding: 4π coverage with 20cm lead
- Veto: 4π coverage with 3 layers of organic scintillator + low noise PMTs



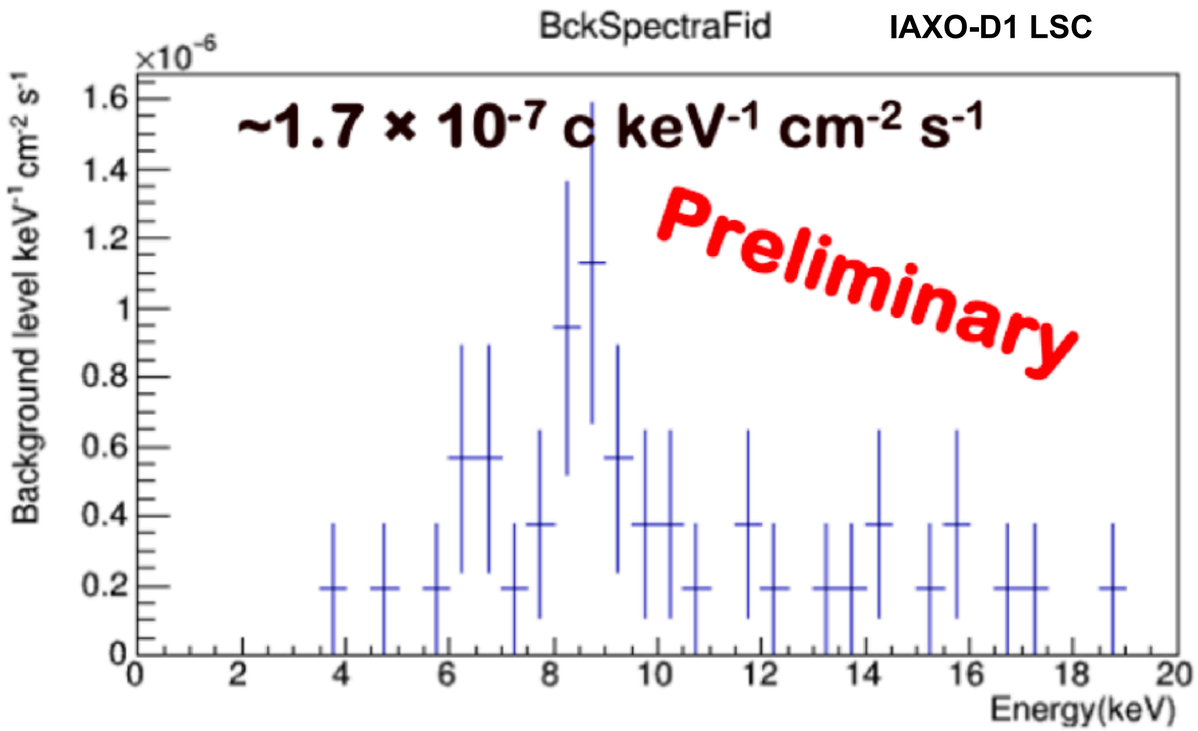


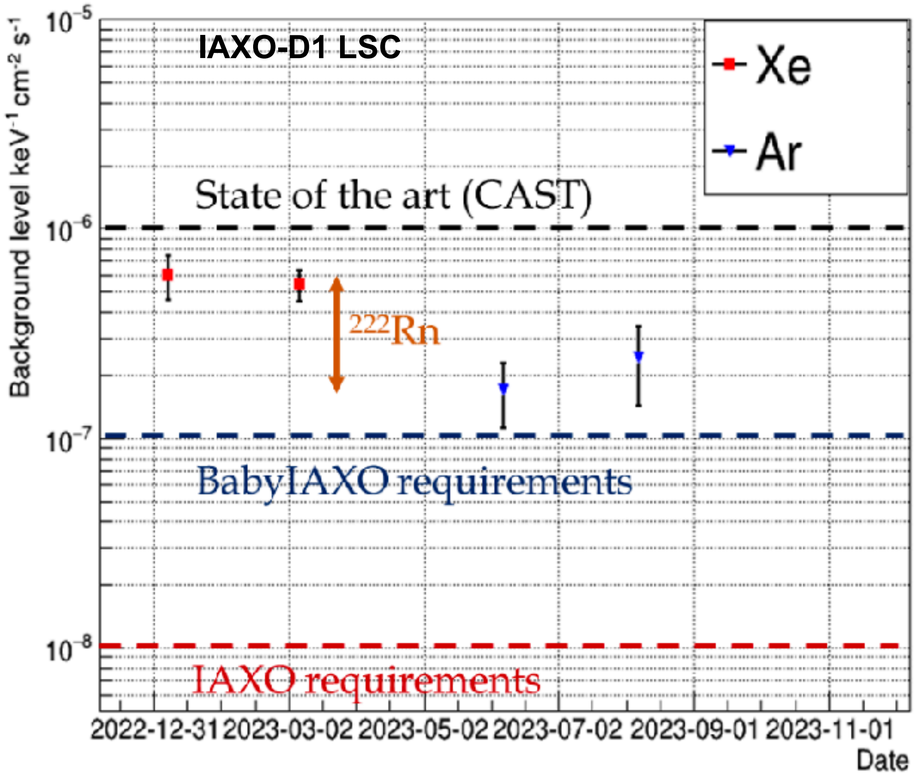
mylar window



BabyIAXO MicroMegas Prototypes Status II

Overview & R&D

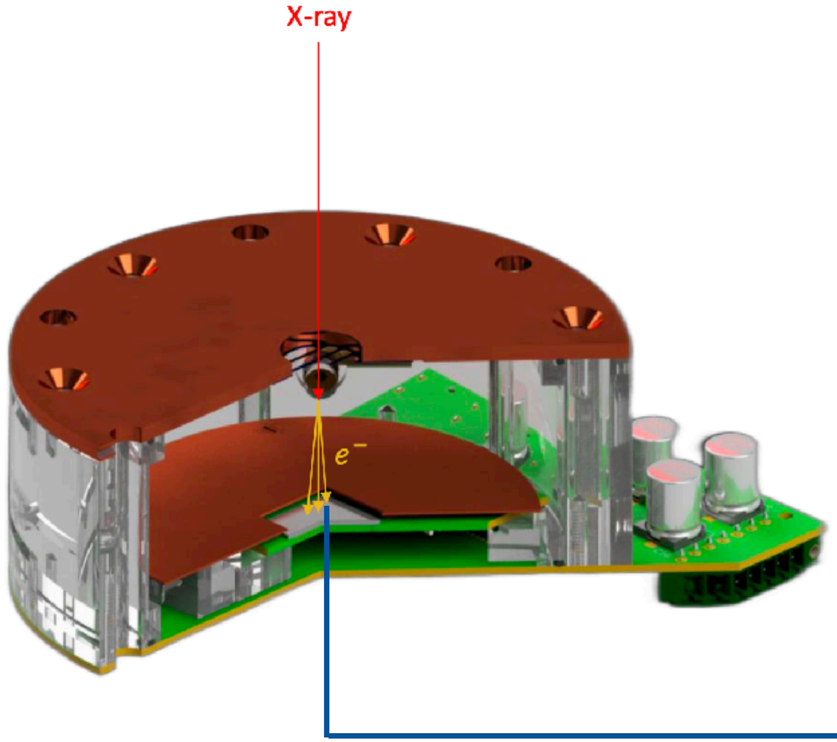




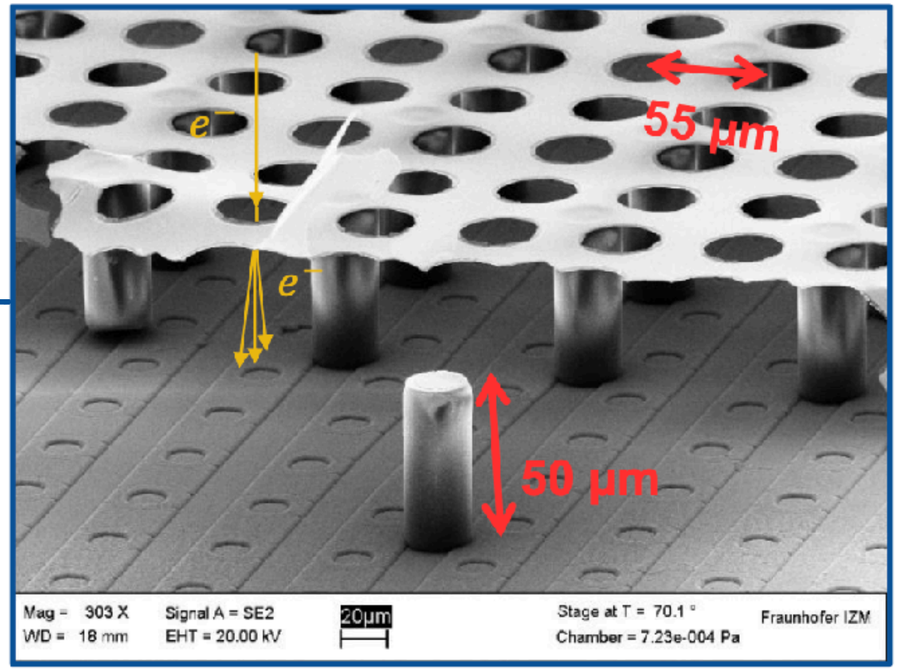
- May 2023: ~38 days of data taking with IAXO-D1 (Ar-isobutane 1% open loop) at Canfranc
  - ➡ **BKG level: ~1.7x10^{-7} counts/s/keV/cm^2 (~5 events/year/keV/cm^2)**
    - ➡ Lowest BKG level ever achieved with detector type, almost meeting BabyIAXO requirements
  - ➡ **Detection efficiency (including software cuts): ~80%**

Gridpix TPC

Working Principle



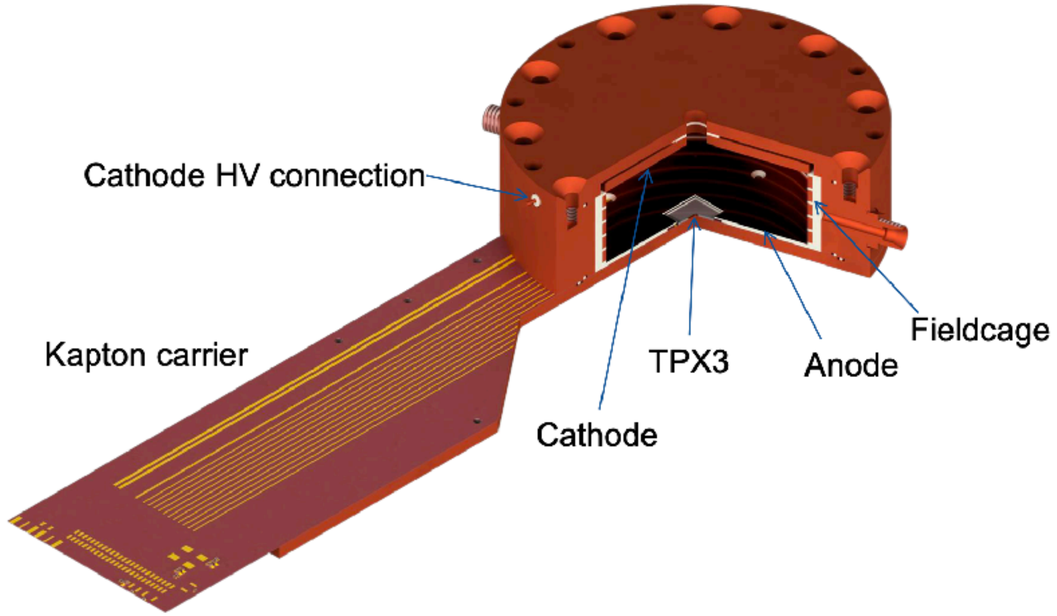
- Basically an upgraded MicroMegas TPC
  - ➡ Instead of mesh: aluminium grid with holes above pixels of **Timepix3** readout chip with 256x256 pixels on ~2 cm^2
  - ➡ Higher spatial resolution, single electron detection, lower energy threshold, better energy resolution
  - ➡ Goal: Same BKG levels as for Micromegas

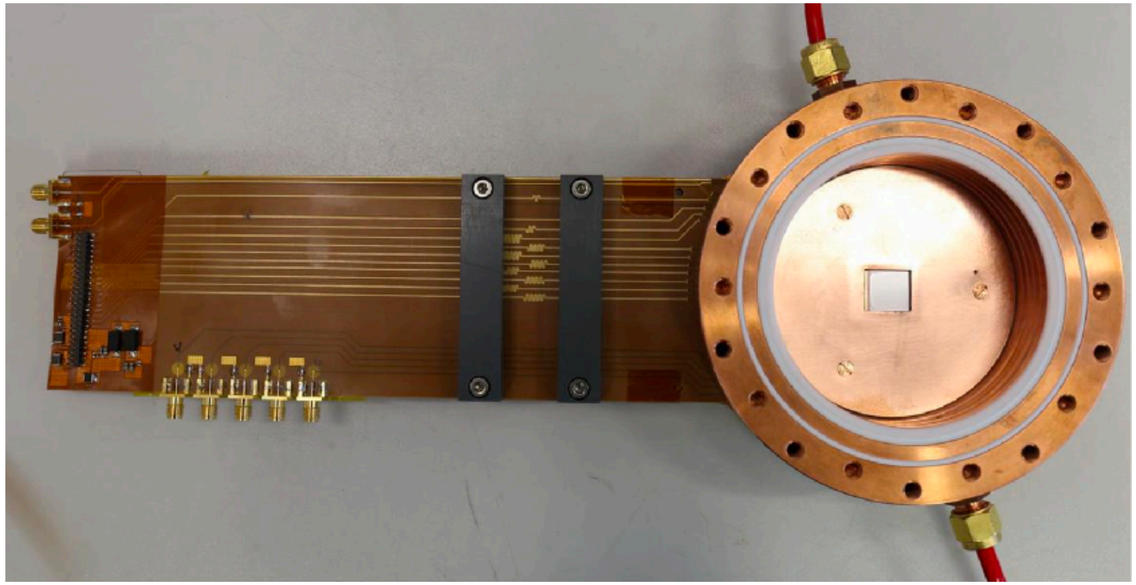


Gridpix TPC

Status

- First IAXO prototype being commissioned and optimised
  - ➡ Focus on radiopurity: material, outsourced electronics, window, cleaning
  - ➡ Calibration
  - ➡ Enabling full power of Timepix3 (granularity, timing) with software framework
  - ➡ Shielding and veto configurations



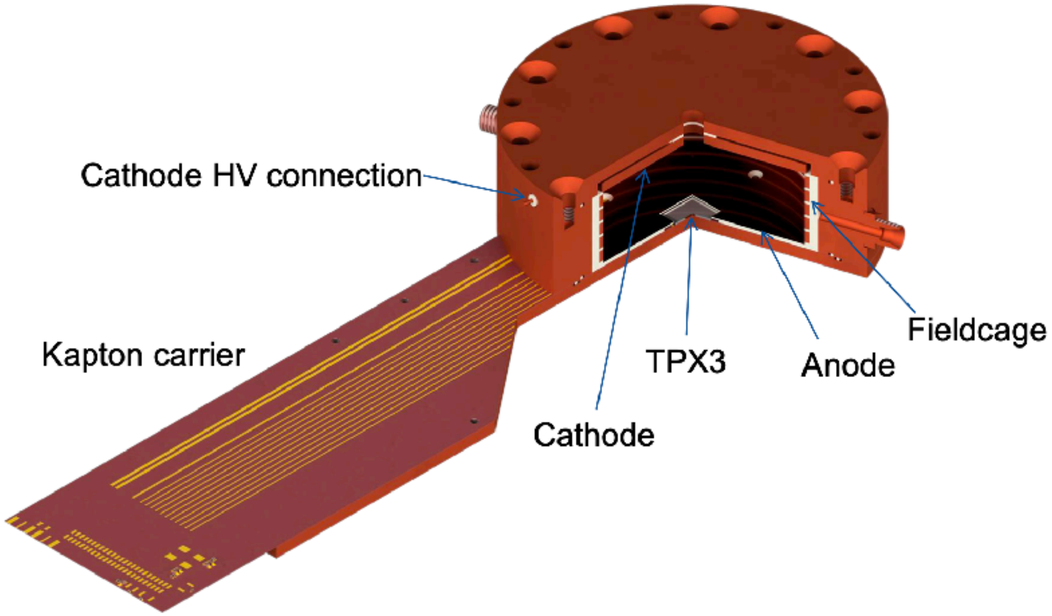


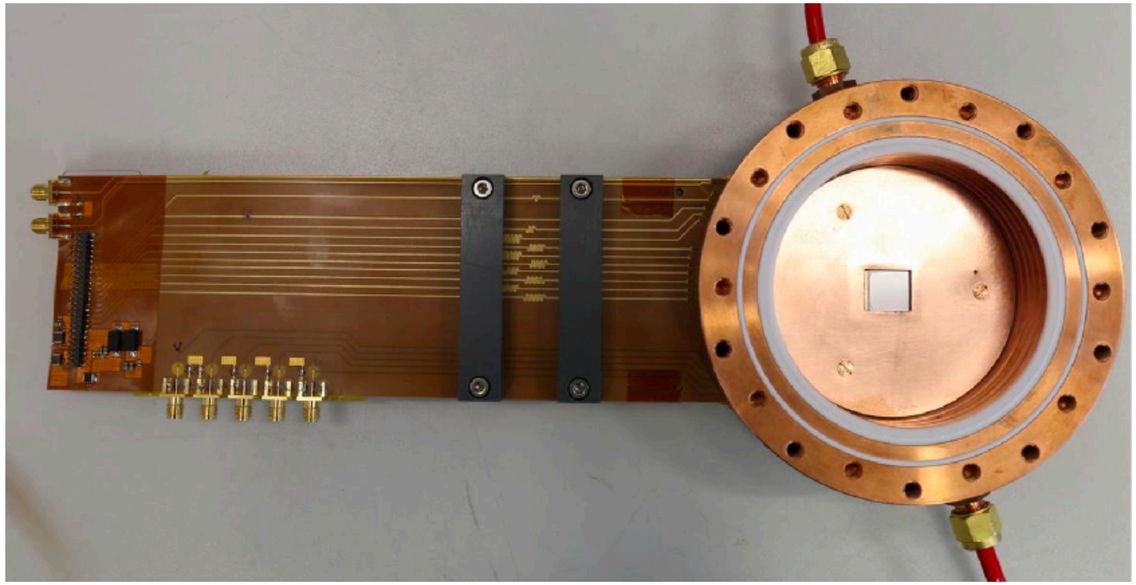
Gridpix TPC

Status

Extensive campaigns to to measure transmission vs. X-ray energy at SOLEIL SYNCHROTRON

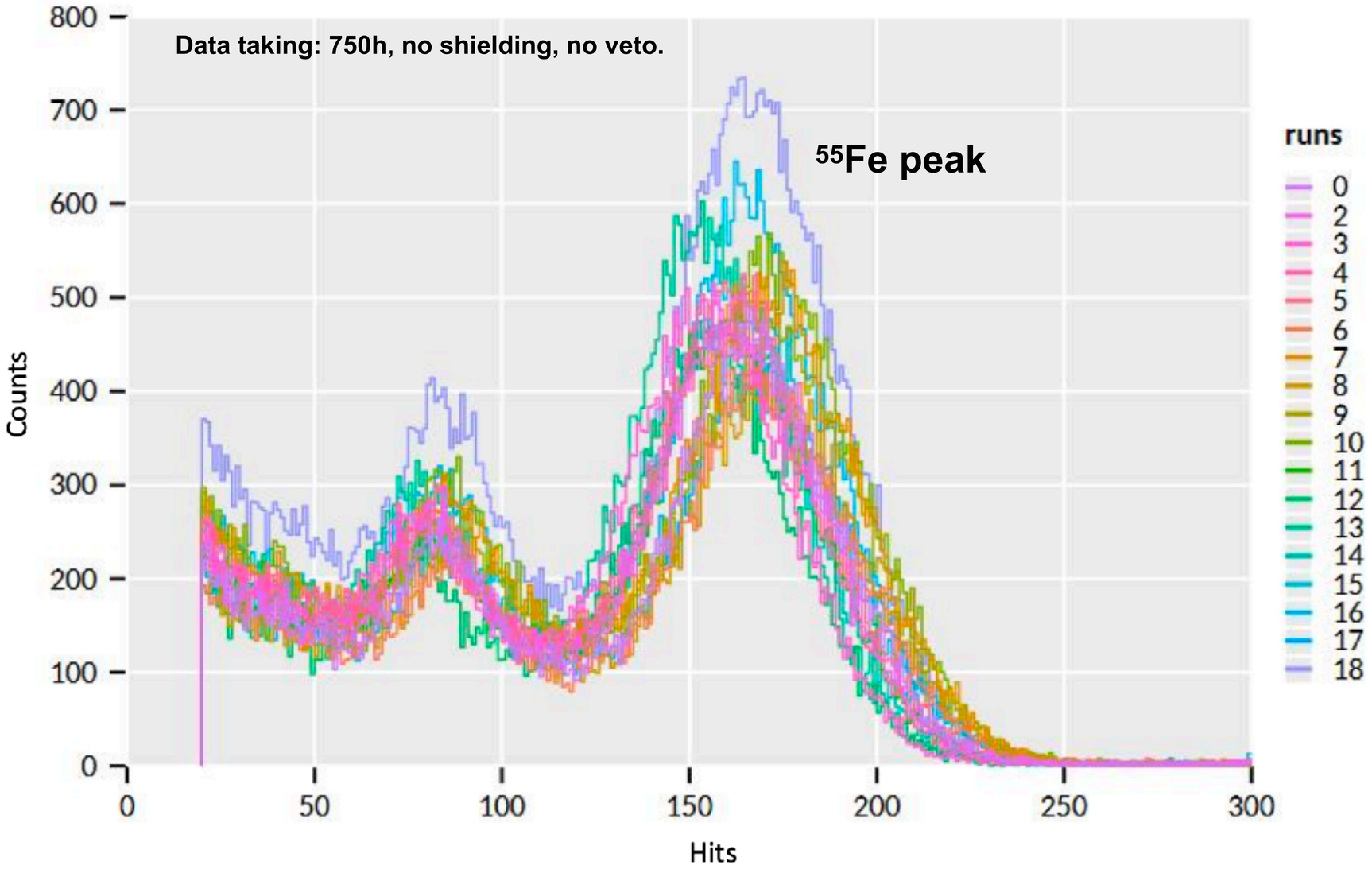
- First IAXO prototype being commissioned and optimised
  - ➡ Focus on radiopurity: material, outsourced electronics, window, cleaning
  - ➡ Calibration
  - ➡ Enabling full power of Timepix3 (granularity, timing) with software framework
  - ➡ Shielding and veto configurations





Gridpix TPC

First Calibration Spectrum

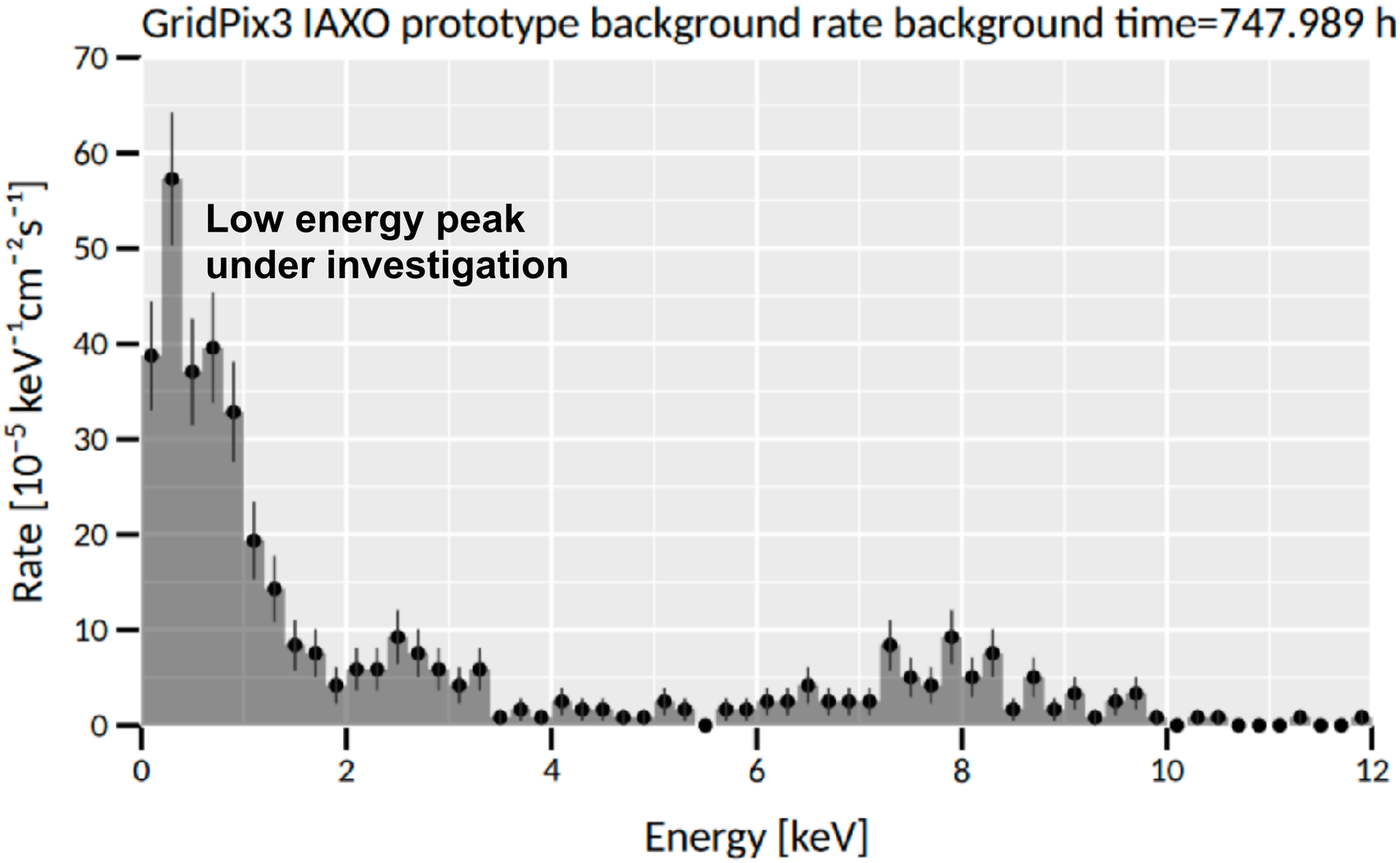


- Peak position as expected, but slightly varying over time

➡ To be investigated

Gridpix TPC

First Energy Spectrum: BKG Measurement



- No shielding, no veto, no radiopure materials
- Looks promising:

➡ ~10^{-4} counts/s/keV/cm^2· [1, 10 keV]

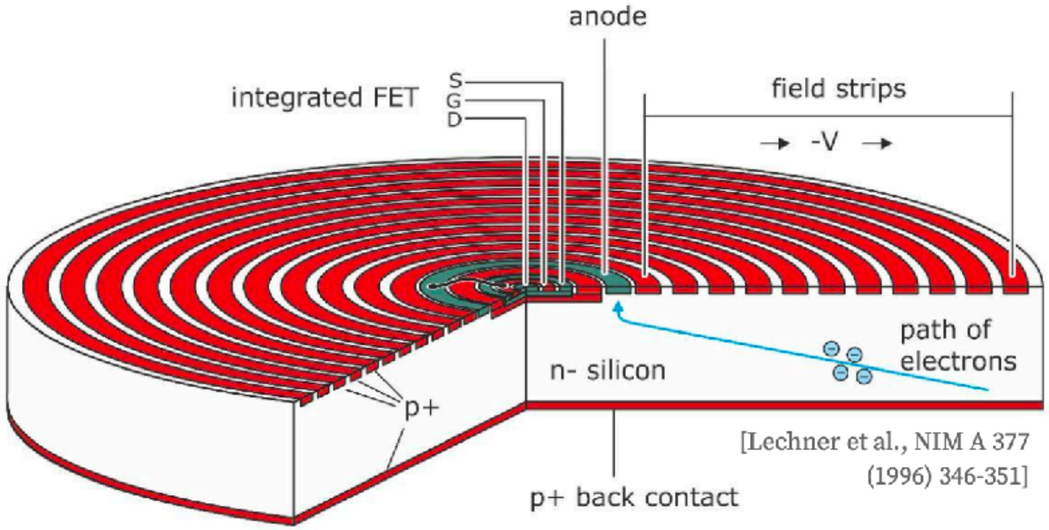
IAXO Detector Technologies

Silicon Drift Detectors

Silicon Drift Detectors (SDD)

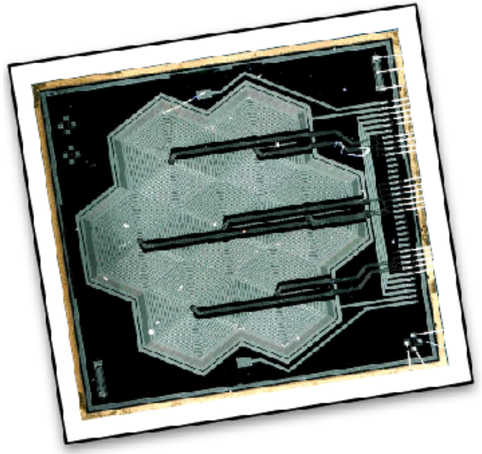
Overview and Potential

- Tiny readout anode with low capacity
  - ➡ Low energy thresholds (few 100 eV)
  - ➡ Good energy resolution (< 200 eV FWHM at 6 keV)



- Thin dead-layer (< 100 nm), **no X-ray entrance window needed!**
  - ➡ High detection efficiency in [1, 10] keV

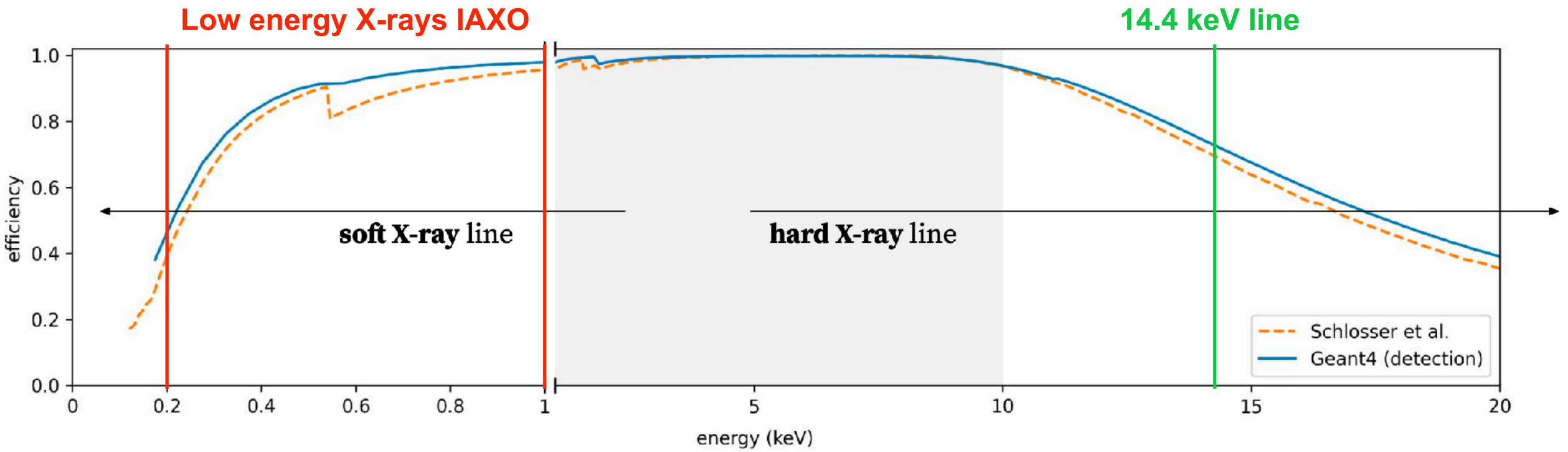
- Semiconductor-grade materials, little auxiliaries
  - ➡ Great potential for ultra-low background operations



Similar SDD's employed in Tristan@KATRIN
Tristan + IAXO -> TAXO

Silicon Drift Detectors (SDD)

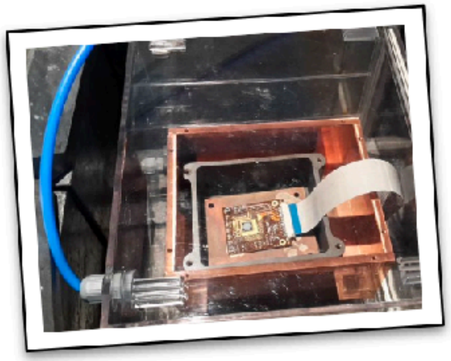
Detection Efficiency



- **Excellent detection efficiencies** quoted for TAXO SDD's in required energy range

  ➡ IAXO colleagues currently analysing X-ray data taken at SOLEIL for confirmation

TAXO *development steps*



SDD **pathfinder**

material insufficiencies, close-by electronics

→ **$(1.9 \pm 0.2) \cdot 10^{-5}$ cts/keV/cm²/s** at shallow depth

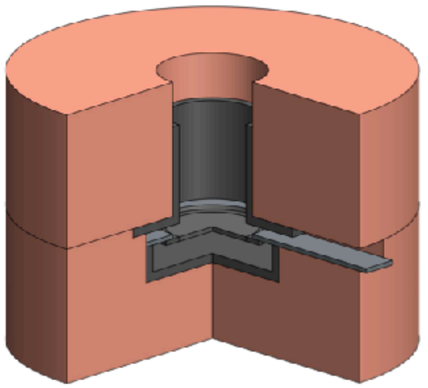
[Houdy et al., 2019]



TAXO **demonstrator**

consequent **low-background** approach, **far electronics**

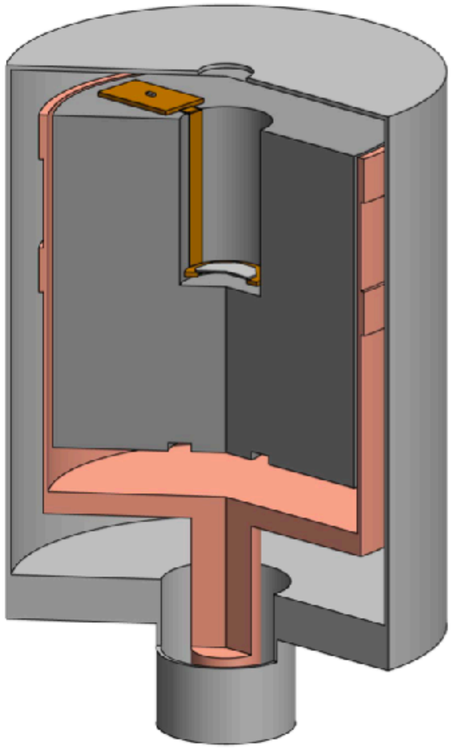
→ demonstrate **$O(10^{-7})$ cts/keV/cm²/s**



BabyTAXO

dedicated SDD production, improved **passive shield**

→ target **$< 10^{-7}$ cts/keV/cm²/s** at shallow depth



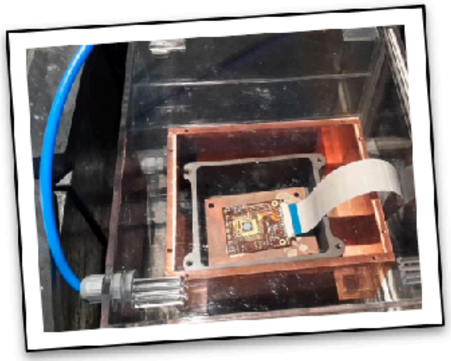
TAXO

all-semiconductor **active shield** SDD-in-HPGe detector

→ target **$< 10^{-8}$ cts/keV/cm²/s** at shallow depth

TAXO *development steps*

Ongoing R&D



SDD **pathfinder**

material insufficiencies, close-by electronics

→ **$(1.9 \pm 0.2) \cdot 10^{-5}$ cts/keV/cm²/s** at shallow depth

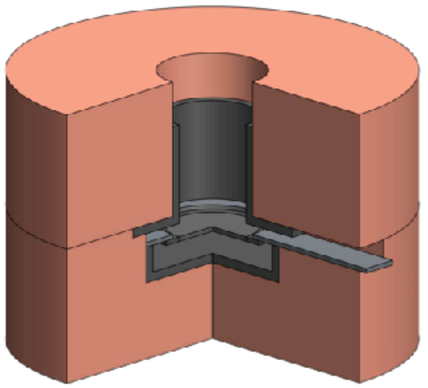
[Houdy et al., 2019]



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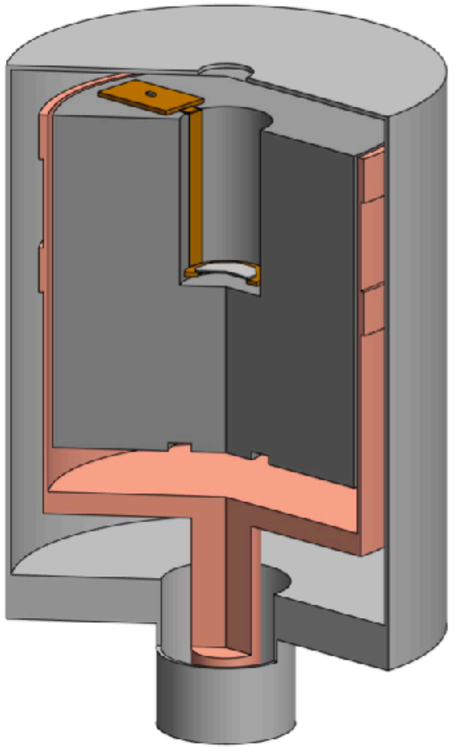
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TAXO

all-semiconductor **active shield** SDD-in-HPGe detector

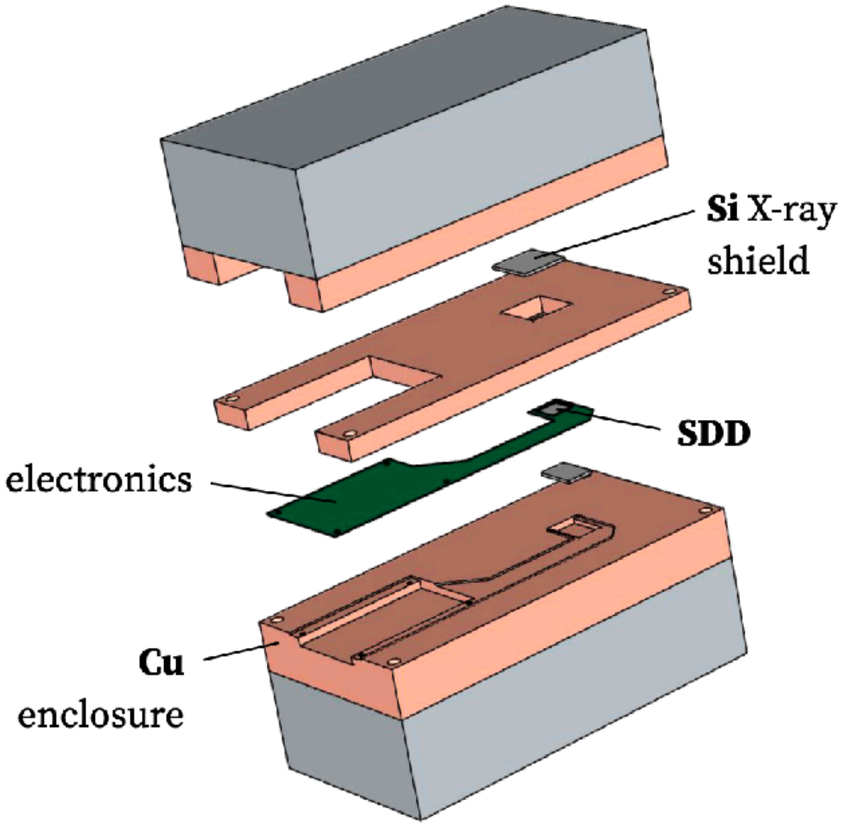
→ target **< 10^{-8} cts/keV/cm²/s** at shallow depth

TAXO Demonstrator Prototypes

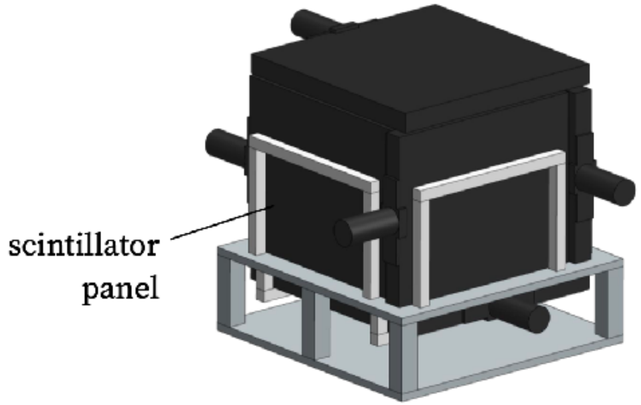
Status

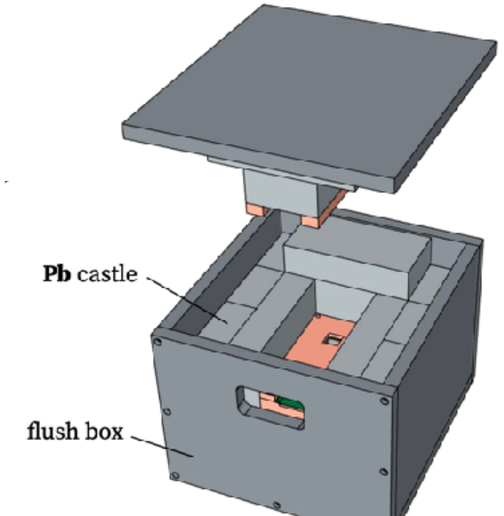
- SDD on polyimide board, far electronics
- Si X-ray shield, radiopure copper structure
- Compact Pb castle, flush box

- Two twin prototypes:
  - ➡ One operating at Canfranc underground lab
  - ➡ One operating in Munich at shallow depth with muon veto and neutron shield





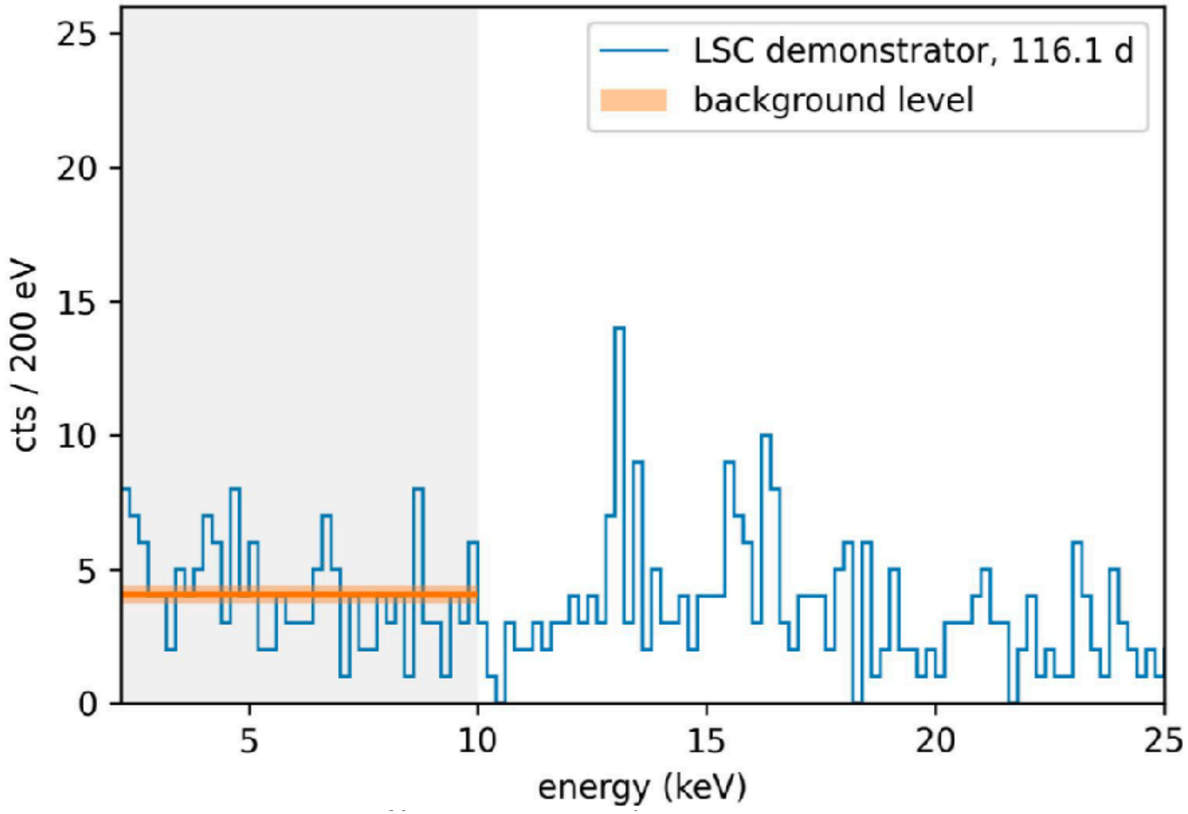


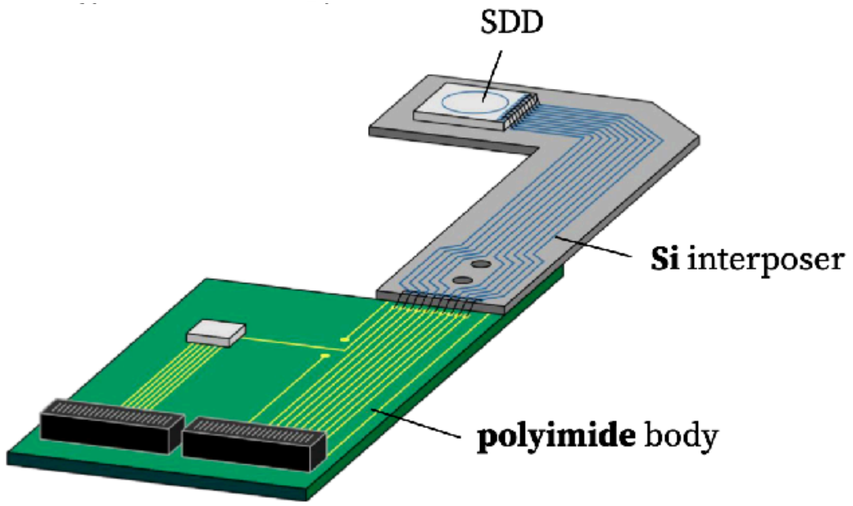


TAXO Demonstrator Prototypes

Measurements at Canfranc Underground Lab

- Noise situation suboptimal
  - ➡ 2 keV threshold, 300 eV FWHM at 10 keV
- BKG level much higher than anticipated
  - ➡ $(5.6 \pm 0.5) \cdot 10^{-6}$ cts/keV/cm^2/s in [2, 10] keV
  - ➡ Polyimide head close to SDD shows 10-100x higher activity than expected
  - ➡ Exchange with Si interposer, tests ongoing
- Meanwhile: Tests with twin setup in Munich to disentangle BKG contribution from cosmics





IAXO (Superconducting) Detector Technologies

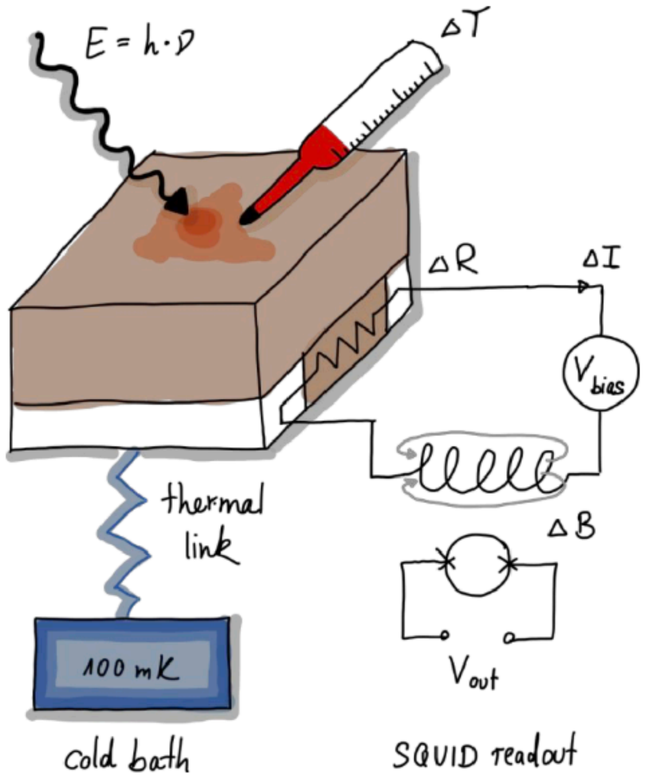
Transition Edge Sensors (TES)
&
Metallic Magnetic Calorimeters (MMC)

TES and MMC

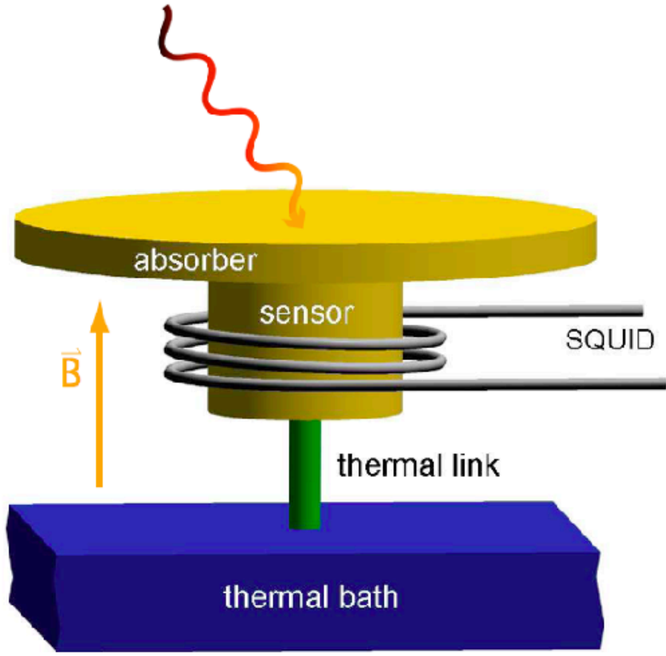
Working Principle

- Quantum sensors operating at very low temperatures (~10 mK)
  - ➡ TES: SC material e.g. NbSi
  - ➡ MMC: Paramagnetic material e.g. Au:Er
- Incoming absorbed X-ray causes ΔT

TES



MMC



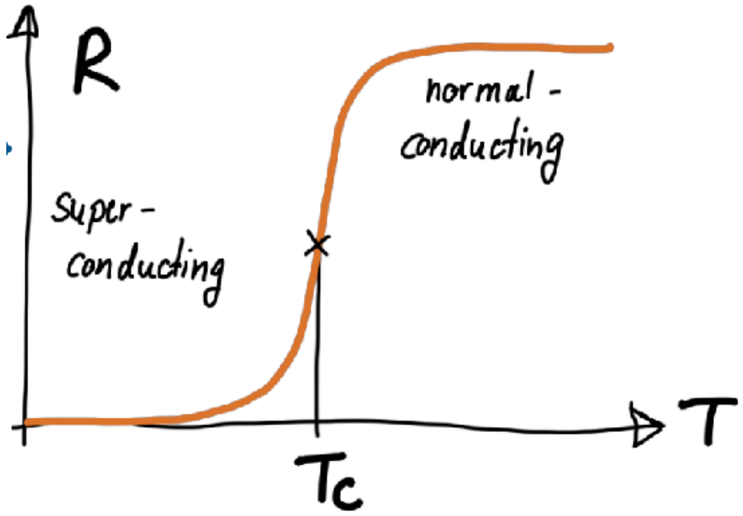
Courtesy: K.-S. Isleif

TES and MMC

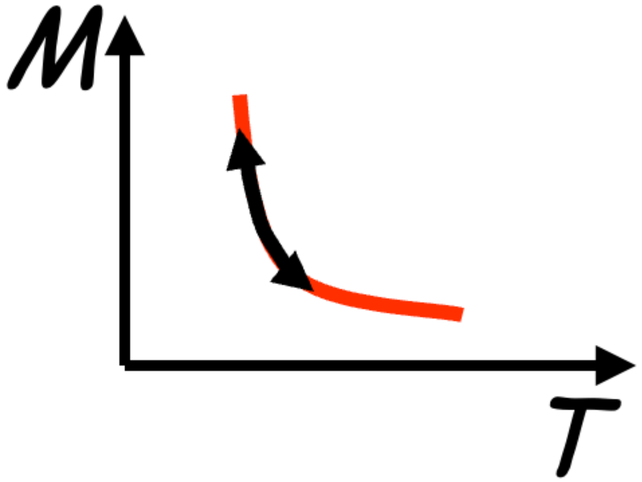
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  - ➡ TES: SC material e.g. NbSi
  - ➡ MMC: Paramagnetic material e.g. Au:Er
- Incoming absorbed X-ray causes ΔT
- ΔT causes a drastic change in ΔR (TES) or ΔM (MMC)

TES



MMC



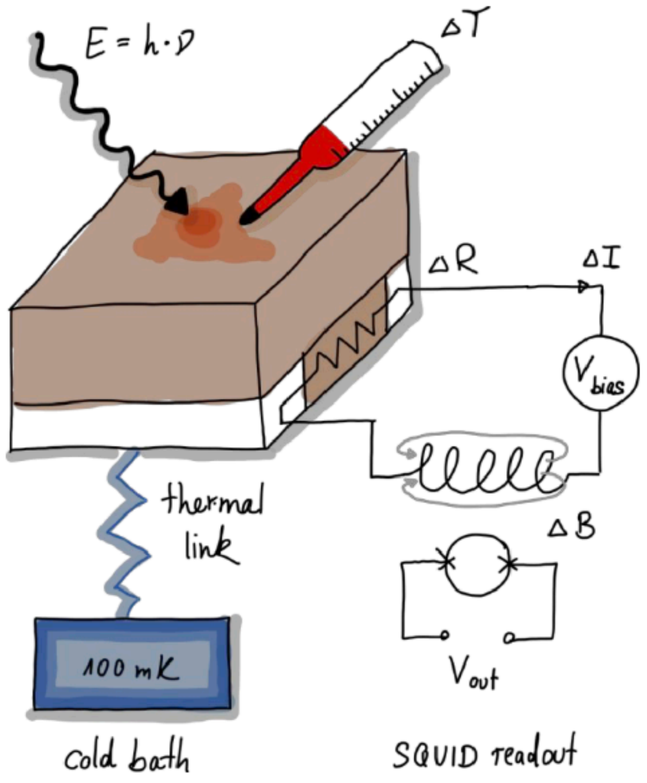
Courtesy: K.-S. Isleif

TES and MMC

Working Principle

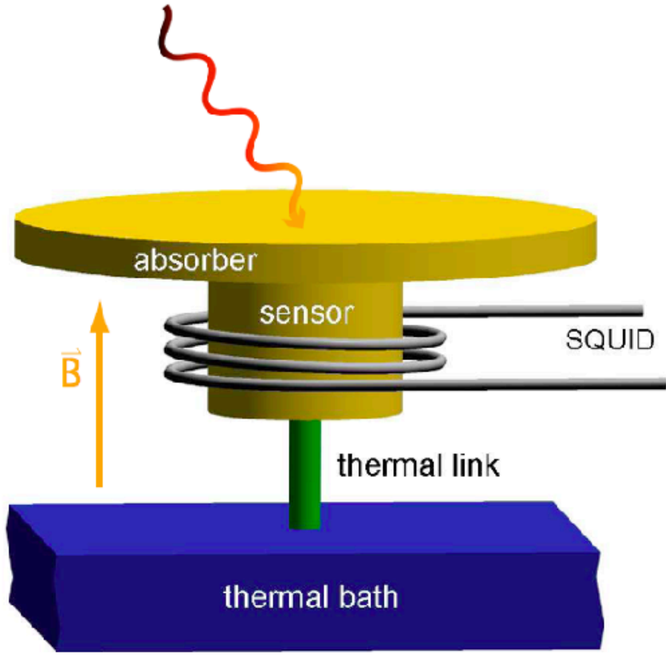
- Quantum sensors operating at very low temperatures (~10 mK)
  - ➡ TES: SC material e.g. NbSi
  - ➡ MMC: Paramagnetic material e.g. Au:Er
- Incoming absorbed X-ray causes ΔT
- ΔT causes a drastic change in ΔR (TES) or ΔM (MMC)
- Resulting in ΔB, read out by a superconducting quantum interference device (SQUID)
  - ➡ Signals

TES



Courtesy: K.-S. Isleif

MMC



TES and MMC for IAXO

Challenges

Detector challenges:

- ✅ High efficiency in energy range $0 \ldots 15\ \mathrm{keV}$
- ✅ High energy resolution
- ✅ Active area matching IAXO optics focal spot size

Setup challenges:

- ☐ Extremely low background of $10^{-8}\ \frac{\mathrm{counts}}{\mathrm{keV\ cm^2\ s}}$
- ✅ Good mechanical stability for operating while moving/vibrating
- ✅ Good magnetic shielding

Cryostat challenges:

- ✅ Reliable operation @ $20\ \mathrm{mK}$
- ☐ Tiltable to 30°

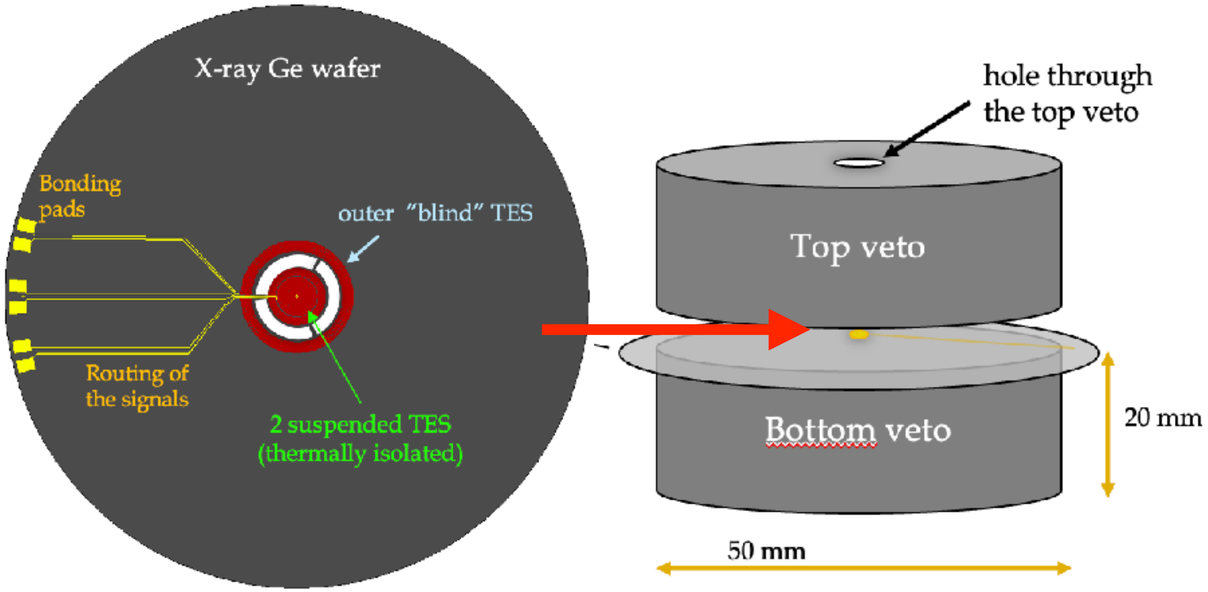
TES and MMC for IAXO

Status

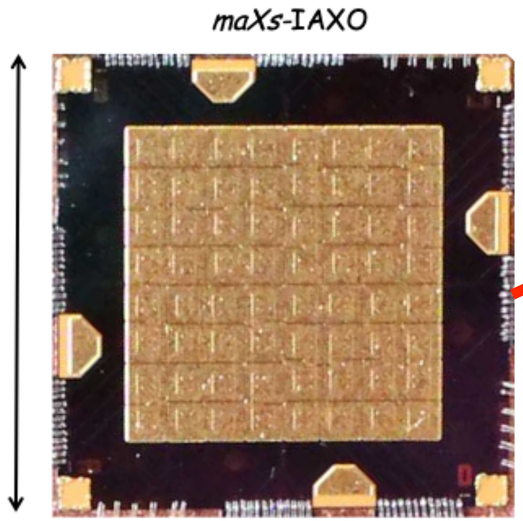
- Both technology branches actively working on R&D for IAXO prototypes

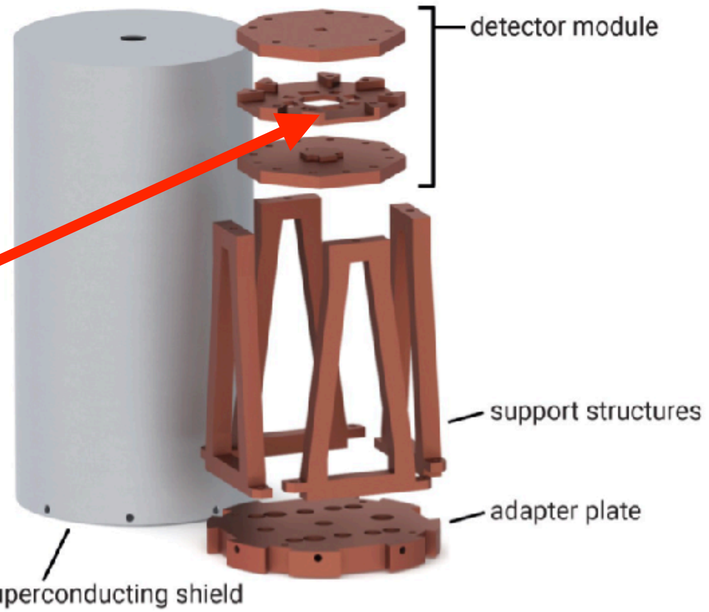
  ➡ Main challenges: Very low background levels (radiopurity and cryostat shielding/veto), energy resolution optimisation, focal-spot-size sensors, cryostat stability optimisation

TES



MMC





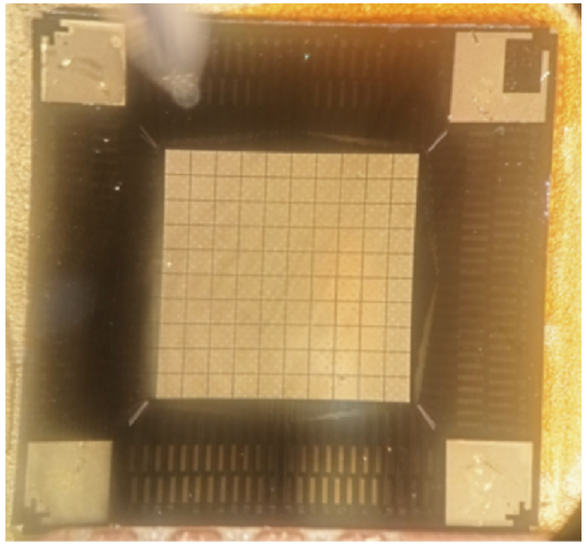
TES and MMC for IAXO

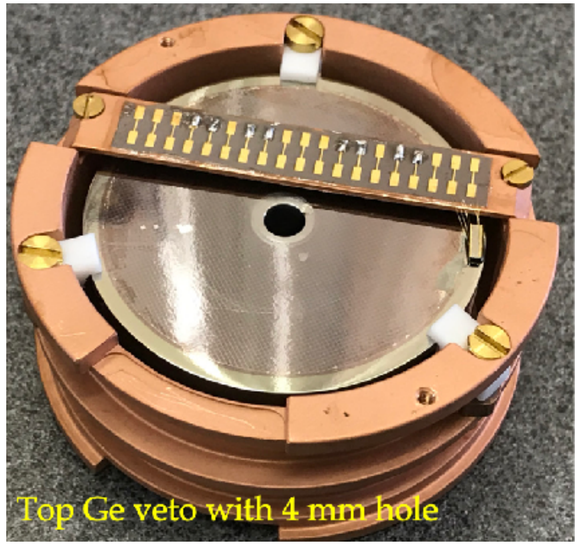
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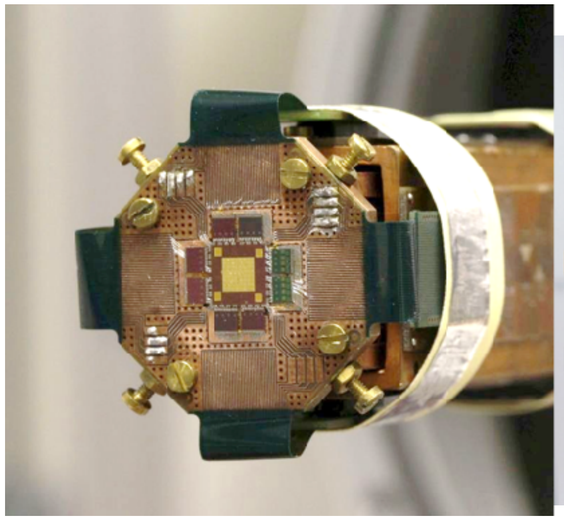
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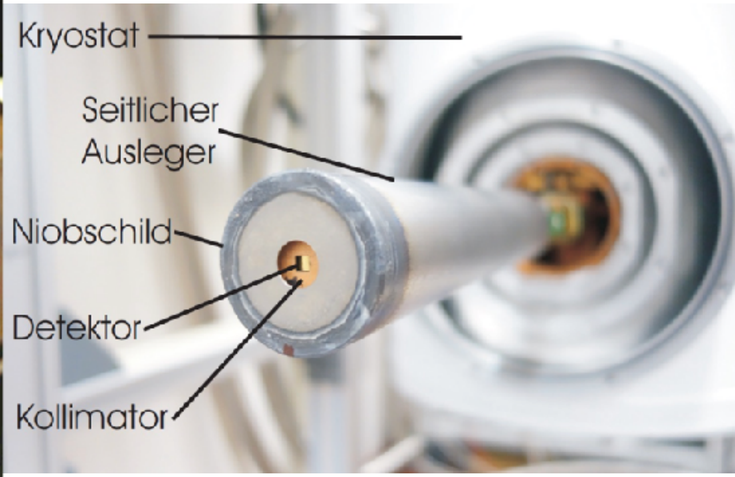
TES





MMC





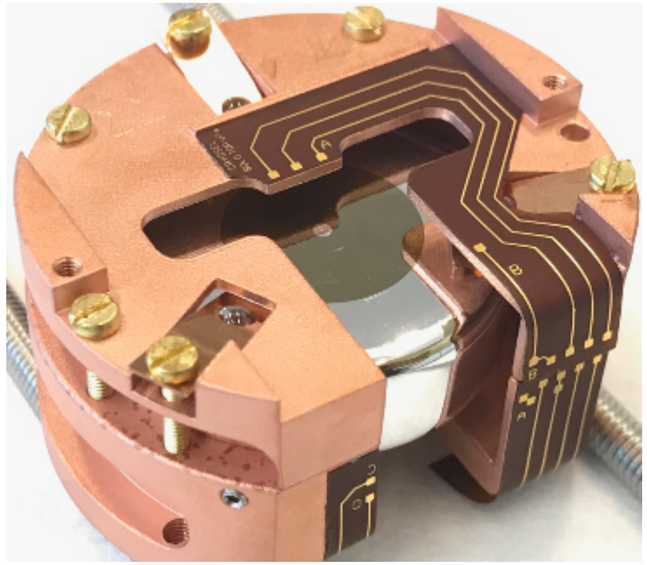
TES and MMC for IAXO

Status

- Both technology branches actively working on R&D for IAXO prototypes

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TES



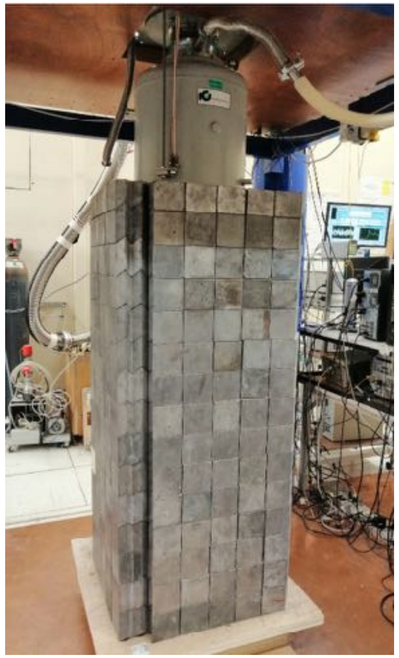
Very low energy threshold Ge veto-4π detector shell

MMC



~ 100 yrs old lead
^{210}Pb: (2.27 ± 0.69) Bq/kg

CuC2 copper

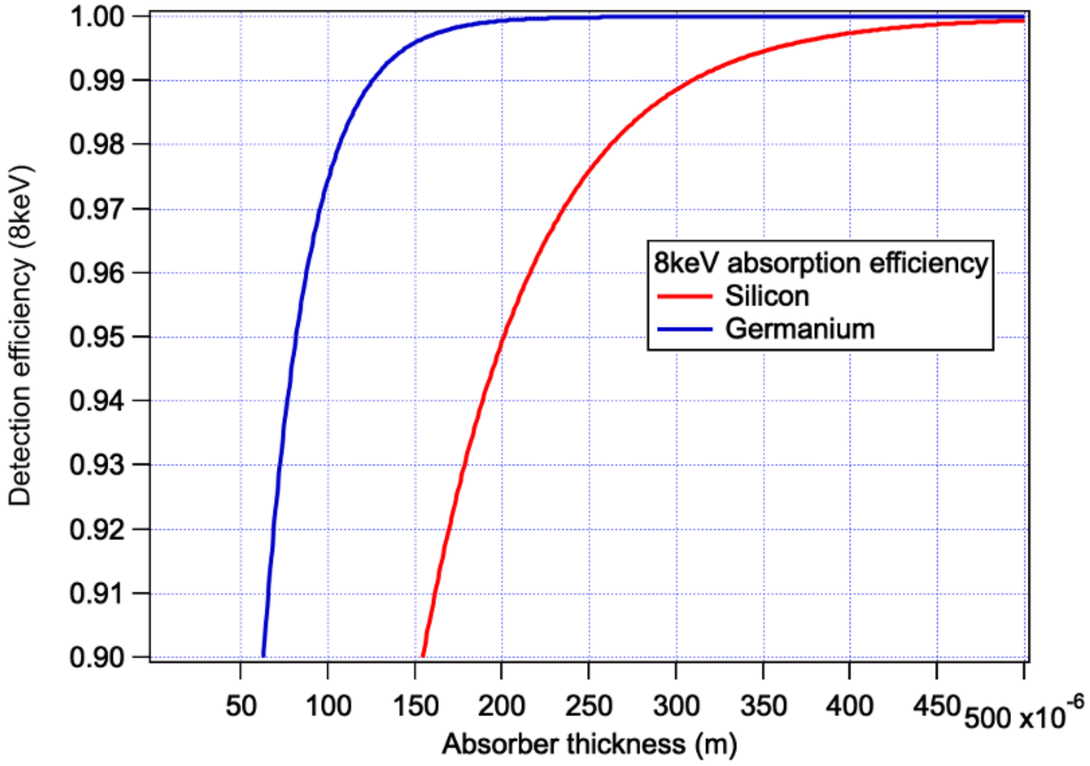


TES and MMC for IAXO

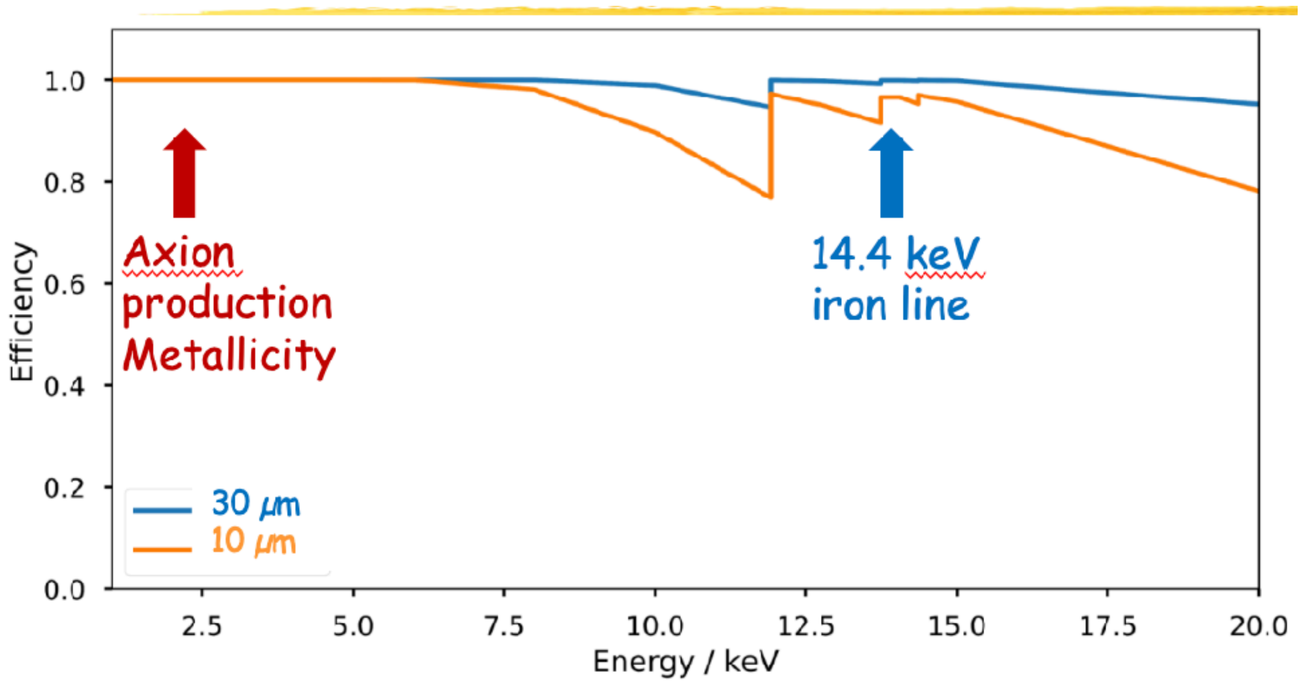
Detection Efficiency and Energy Threshold

- Excellent detection efficiencies > 99% for most of the ROI [0.1, 10] keV
- Goal for energy threshold: <200 eV

TES



MMC

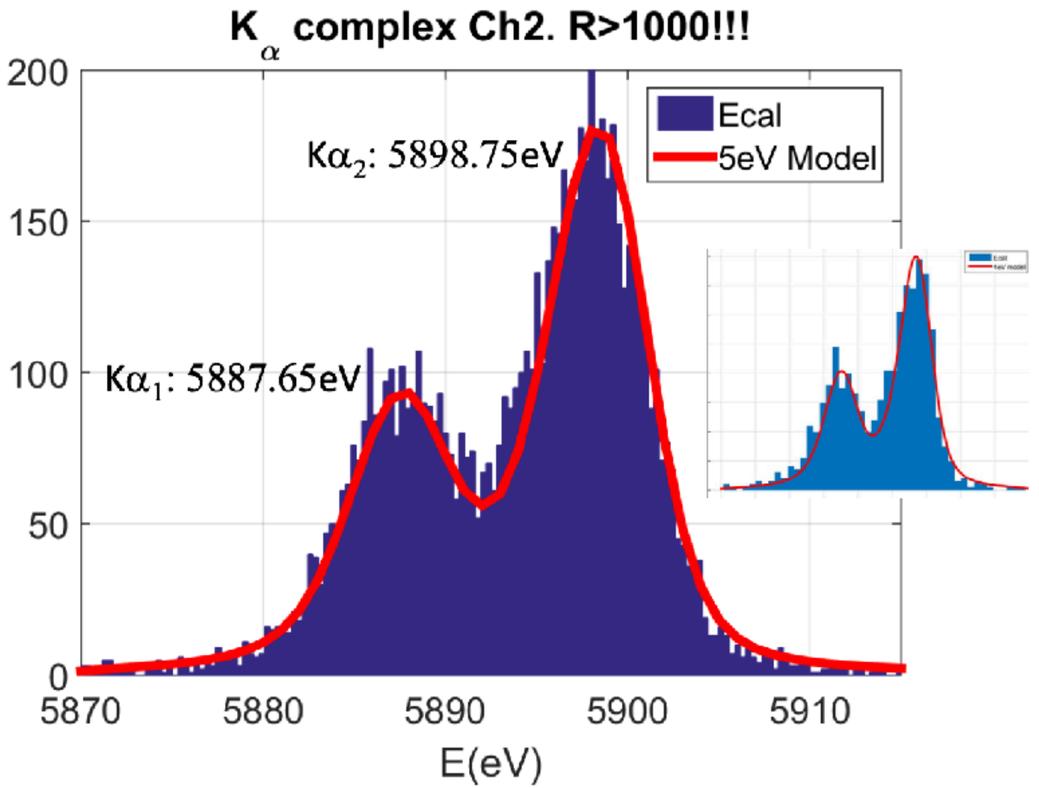


TES and MMC for IAXO

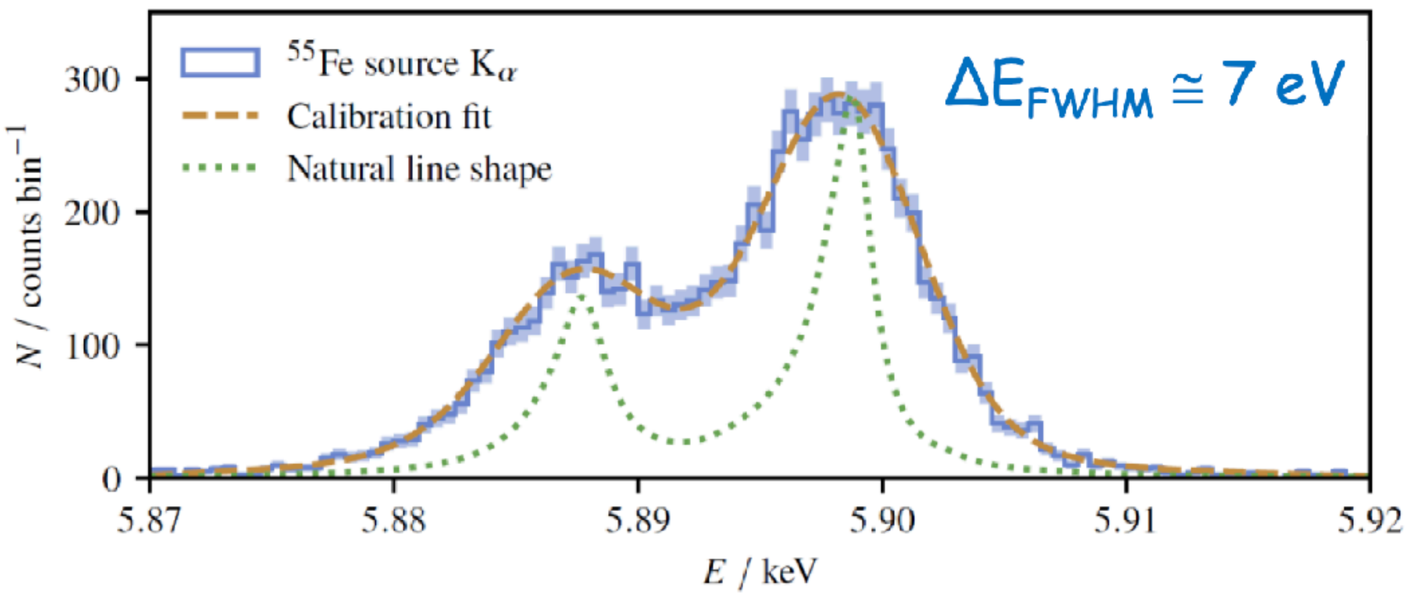
Energy Resolution

- Ultimate energy resolutions in order of per-mille, approaching natural line shapes!

TES



MMC



Optics

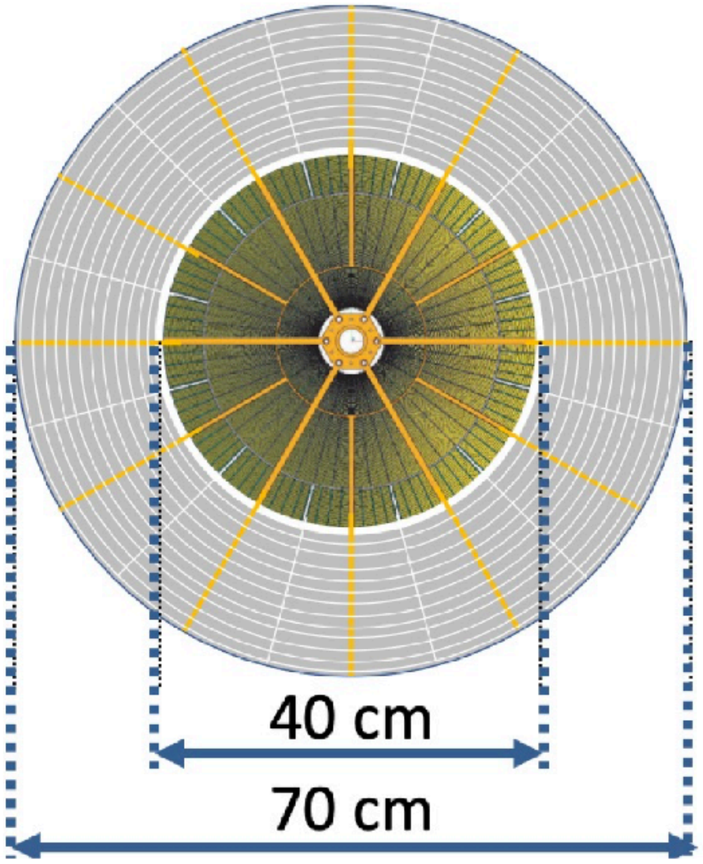
Focusing X-Rays

(Baby)IAXO needs

- Maximized throughput efficiency
  - Tuned to axion spectrum and detector response
  - Can be enhanced with multilayer coatings for ROI and low energy response
- Minimized focal spot area ($0.2\ cm^2$/ $r < 2.5\ mm$)
  - Modest spatial resolution (arcmin level)
  - Moderate focal length
- Cost effective way to build 1 to 8 highly nested, high-efficiency optics

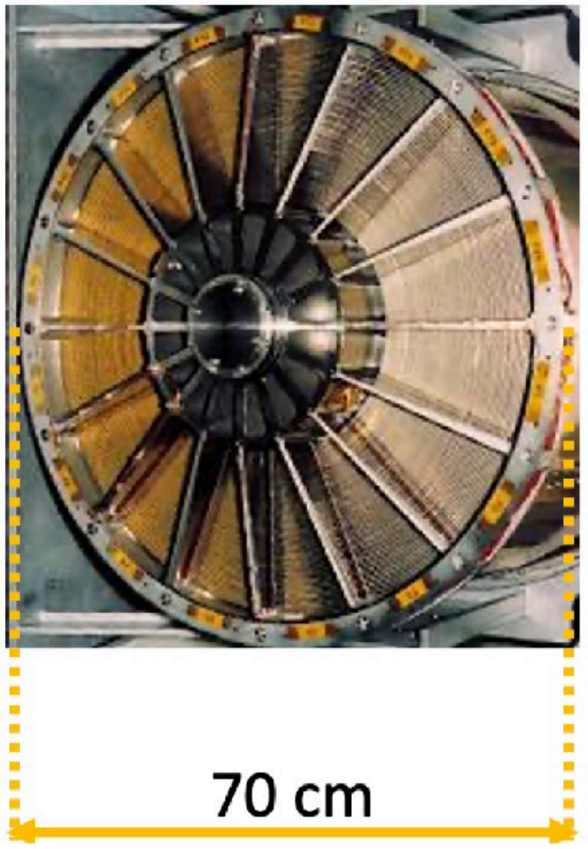
Custom optics

Hot and cold slumped glass



XMM Flight spare

Replicated optics



X-Ray Telescope I

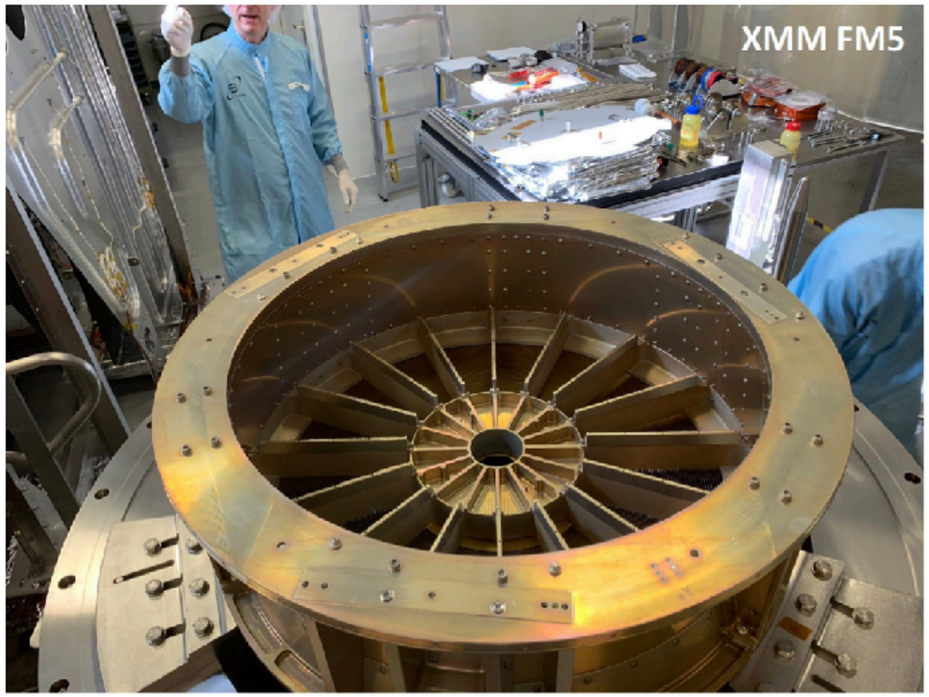
XMM Newton Flight Spare

Telescope 1: XMM

- XMM FM1 and FM5 back in storage till ready for re-calibration whenever vacuum vessel available
- Revisiting loan agreement with ESA

- To Do:
  - Loan agreement (ESA)
  - Finish simulations (INAF)
  - Vacuum Vessel
  - Calibrate at Panter

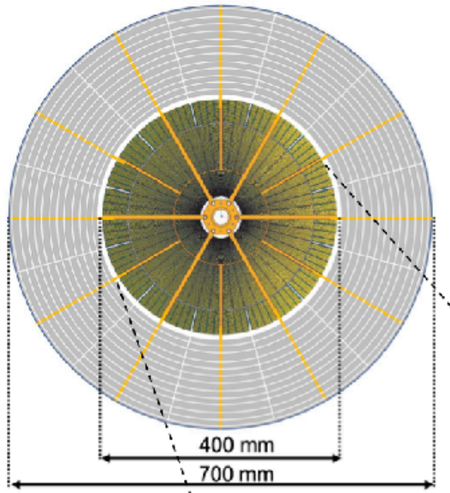
BCV progetti s.r.l.



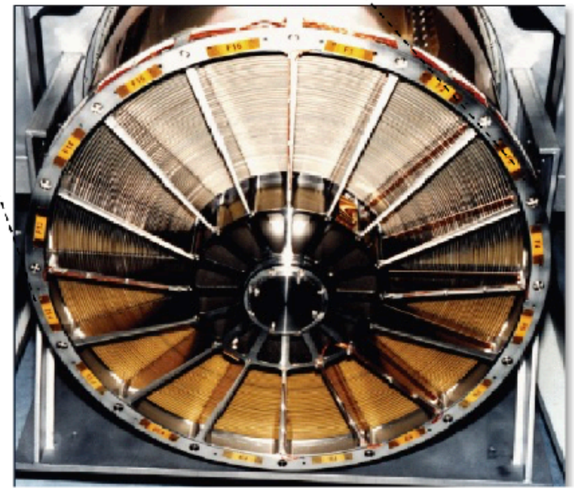
X-Ray Telescope II

Custom Optics

Telescope 2: Core (NuSTAR)



Henriksen, et al. Applied Optics 60, 22 (2021)



SPIE Vol. 7473, p.107-114 (2009)

U.S. preparing for BabyIAXO inner-core optic

- Inner-core optic utilize the same segmented glass technology as the NuSTAR satellite telescope

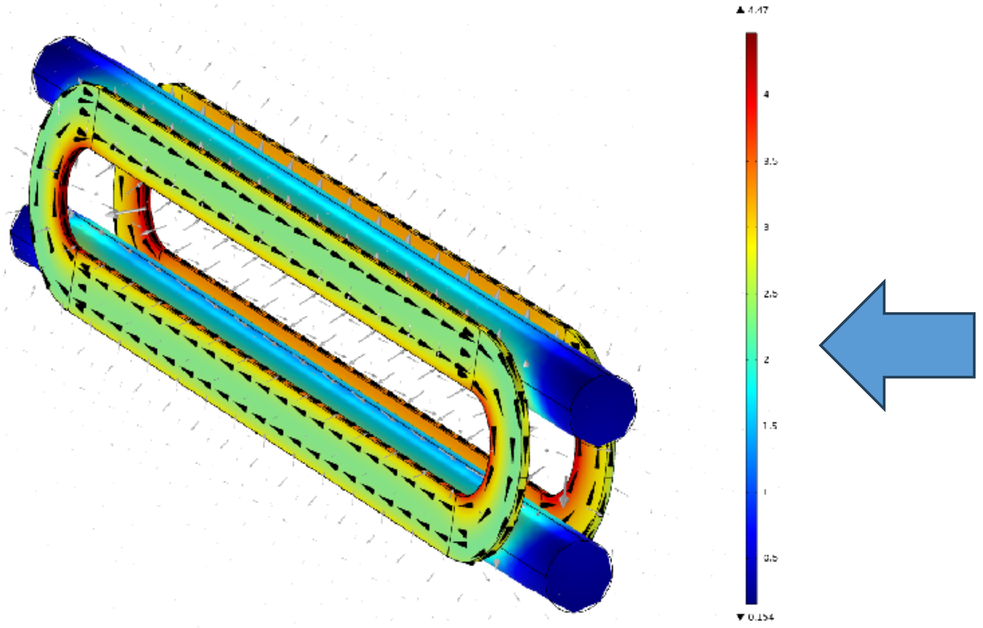
Funding status:

- **Previous MIT support** funded conceptual design of optic mounting and alignment within beamline
- **NSF proposal awarded**, June 2024-May 2027
- Funds construction of one inner-core optic
  - *Does not include* coating of glass at DTU, further engineering work for optic mounting design
- Move to **Columbia University** allows for some internal funding, access to and refurbishment of facilities that built NuSTAR, closer collaboration with technical experts on optics construction

Kerstin Perez (Columbia U.)

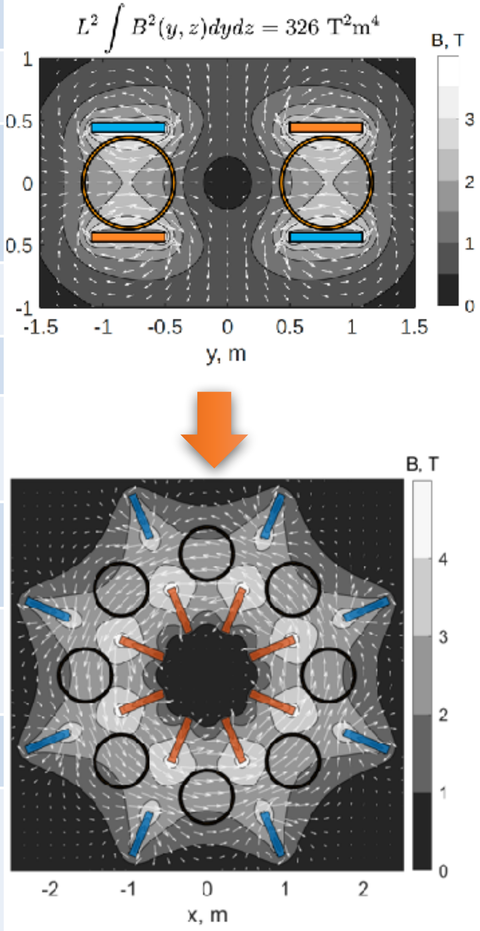
BabyIAXO magnet

- “Common coil” configuration
  - Reduce risk: known design choices as much as possible
  - Cost-effective: Best use of existing infrastructure and experience at CERN
  - Prototyping character: winding layout very close to that of IAXO toroidal design.



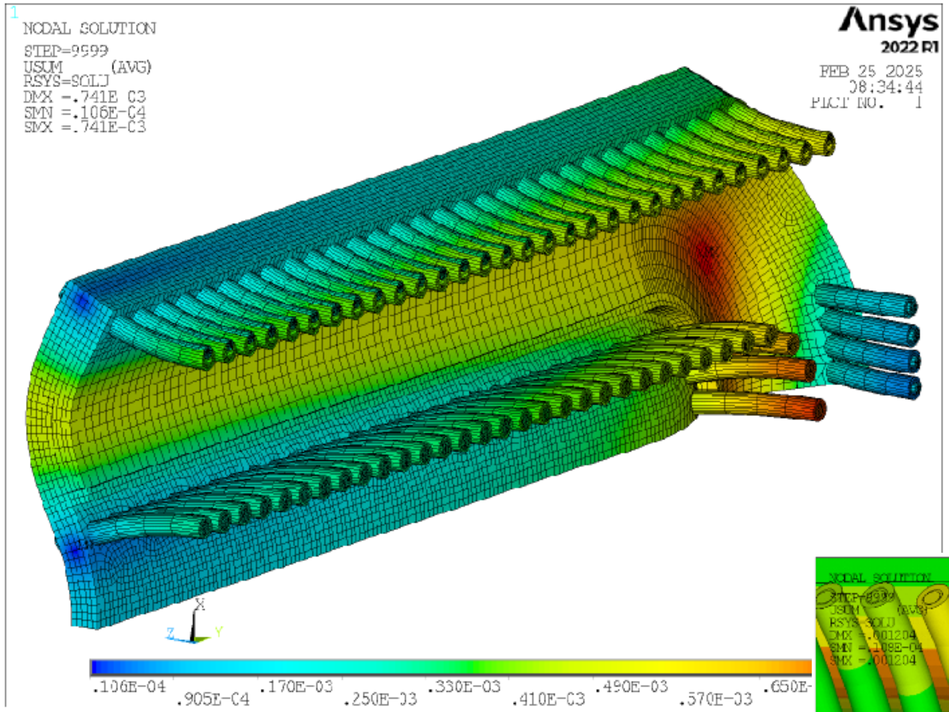
Magnet design led by CERN-EP (M. Mentink), with support from DESY, Elytt, and Zaragoza (cable)

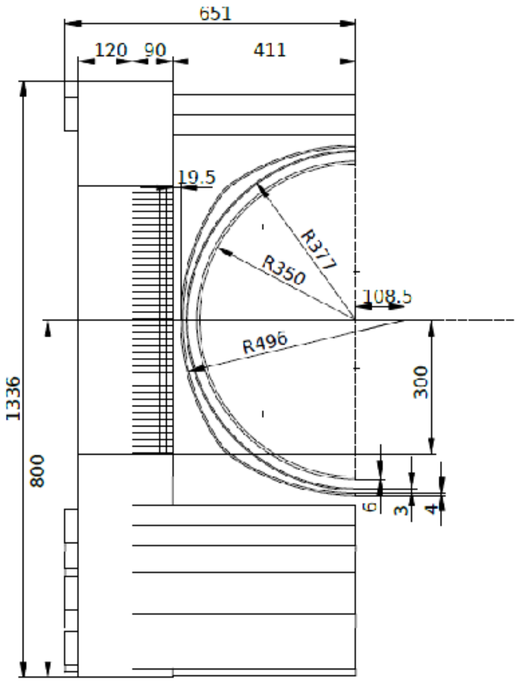
Parameter	Value
Operating current [kA]	6.0
Free bore diameter	0.7
Transverse magnetic field during operation [T]	2.1
Stored magnetic energy [MJ]	56
Inductance [H]	3.1
Cold mass weight (preliminary) [tons]	38
Energy density (preliminary) [kJ/kg]	1.5
Overall coil conductor length [km]	22
Conductor length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



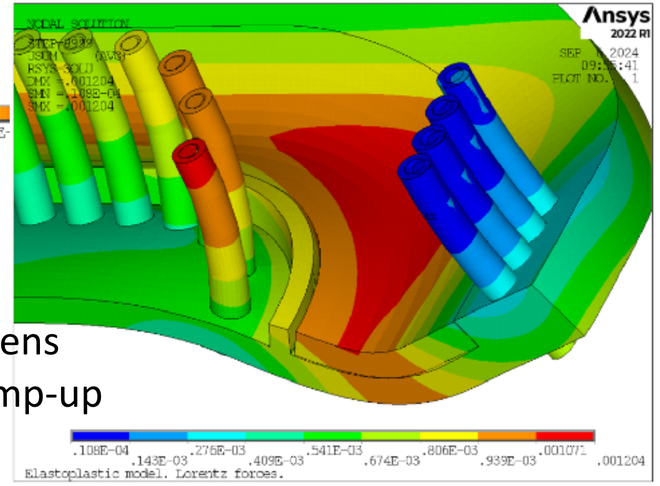
BabyIAXO magnet: cold-mass

- Al alloy support structure to hold considerable forces
- Coil bonded to structure
  - Four layers stack
  - Requirement on conductor: transverse yield strength of >50 MPa at 4K
- System of pretensioned tie rods to hold repulsion forces (also vertical ones due to mech. tolerances)
- Extensive 3D simulations to evaluate deformations/ displacements





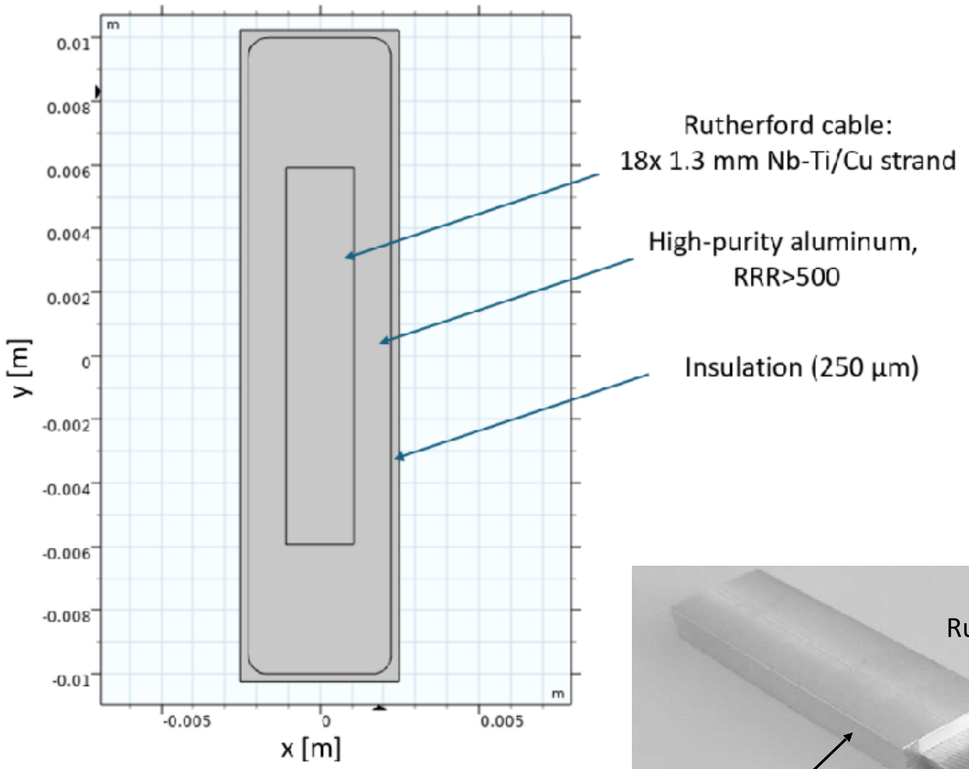
Dimensions

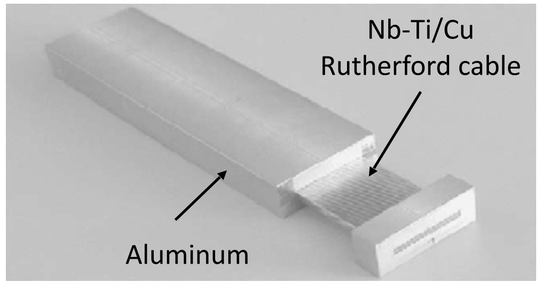


Gap opens during ramp-up

BabyIAXO magnet: conductor

Aluminum-stabilized Nb-Ti/Cu conductor:

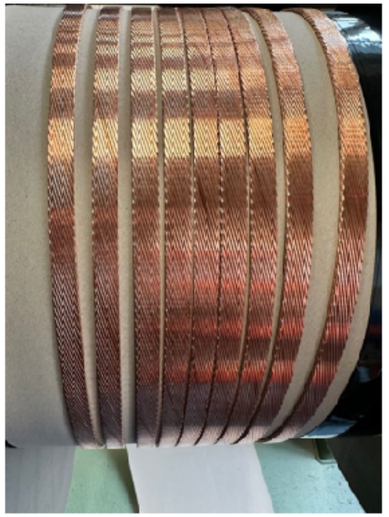




- Conventional technology but no providers in recent years! (+ Russian war) → causing delay to project
- Rutherford cable already under production
- CERN-TE support in quality control & cabling → thanks to A. Devred, T. Boutboul & J. Fleiter !
- Al co-extrusion: possible provider found in China, first trials…
- Cold-working needed to meet yield strength specs



CERN Rutherford cabling machine



NbTi Rutherford cable (NbTi RC) produced at CERN (72 m)

BabyIAXO magnet: cryogenics

- Cold mass (<5K), Cooled with liquid He from phase separator via thermosiphon (cryo turret)
- 50 K & 25 K thermal shields and HTS-based current leads, cooled with He gas circulation with cryo fan (service box).

