BabyIAXO

Prospects and Status of a New Generation Axion Helioscope

Daniel Heuchel (DESY)
for the IAXO Collaboration
daniel.heuchel@desy.de

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Dresden, 23rd March 2023

HELMHOLTZ

DESY.

Axions and ALPs

Physics Motivation and Prospects

Elegant solution to the strong CP problem

Very weakly interacting, very light, very long lived.

Dark matter candidate

Astrophysical hints:
- Universe too transparent for HE gamma-rays
- Too fast stellar cooling
- …

Relevant parameter space can be probed with current and next generation experiments

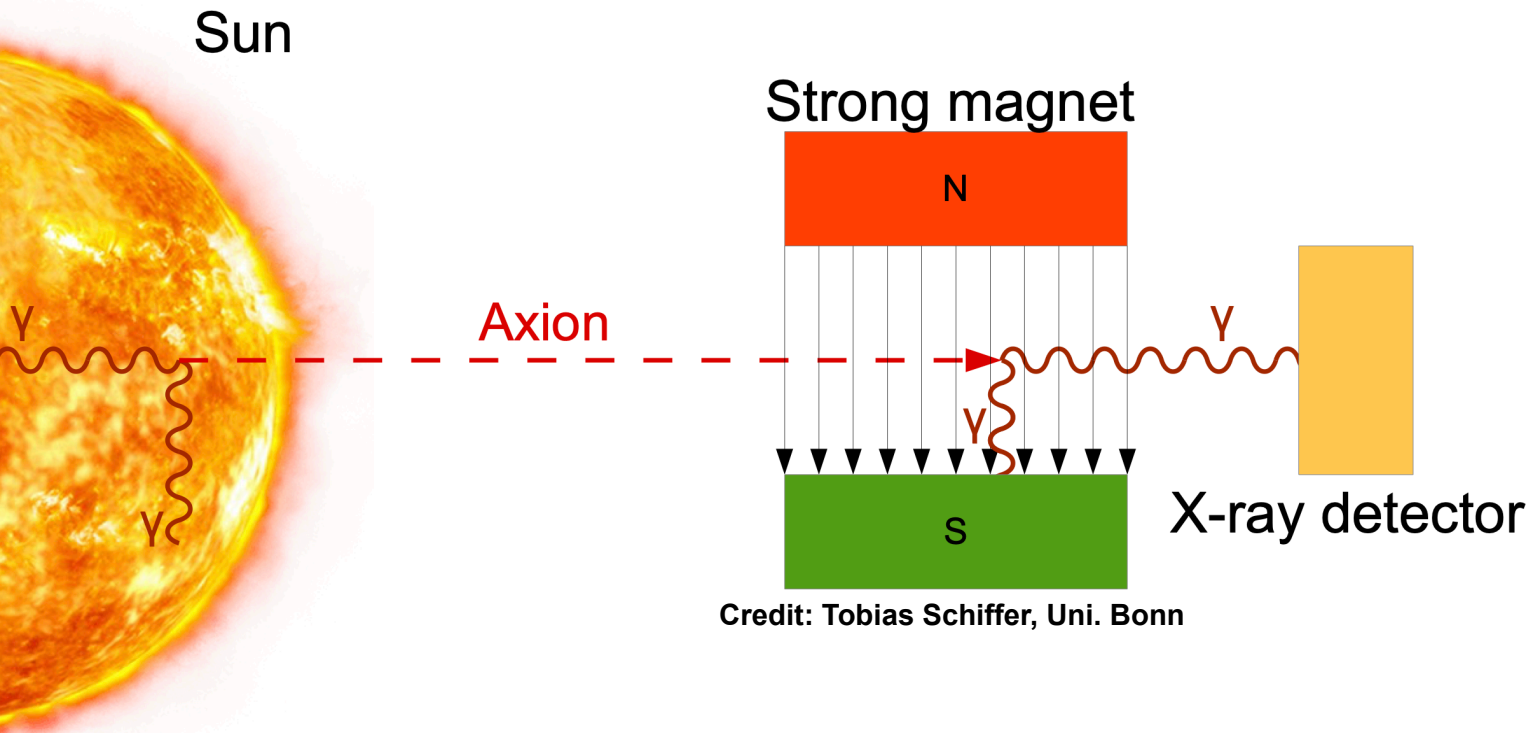
Little experimental efforts so far, but currently “trending”

More generic axion-like particles (ALPs) predicted by many theories

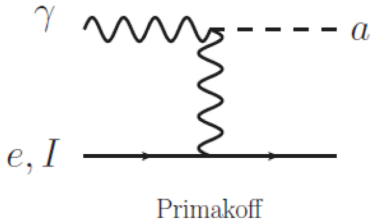
Credit: Konrad Altenmüller, Uni. Zaragoza

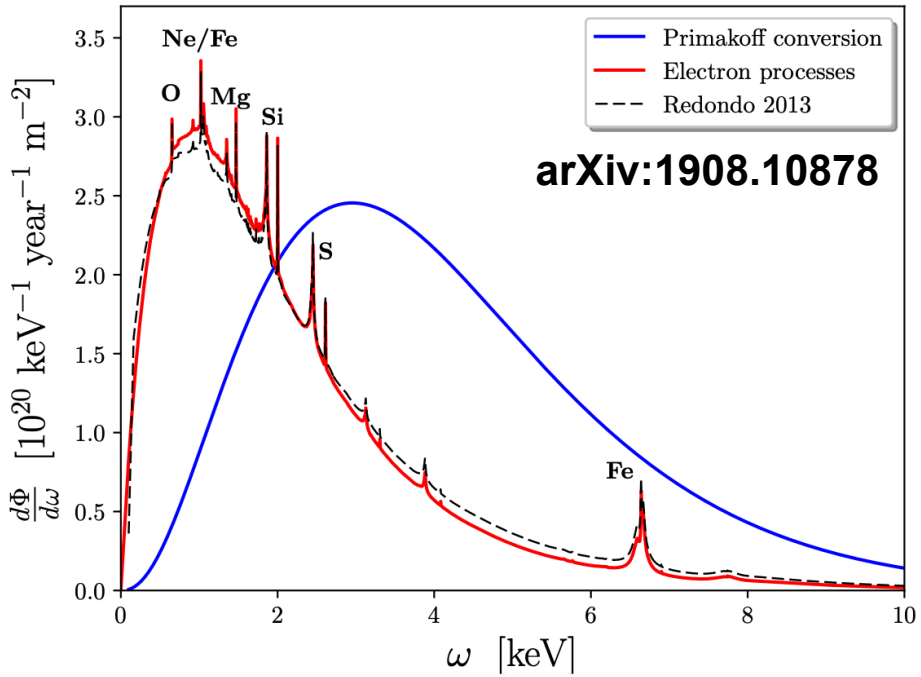
Axion Production in the Sun

And Detection Principles



Credit: Tobias Schiffer, Uni. Bonn





- Primakoff conversion of solar plasma photons within sun (generic prediction of most axion models)
- Other model-dependent productions via axion-electron coupling or axion-nucleon coupling
- Detection: axion to X-ray conversion via inverse Primakoff effect in a strong magnetic field

Helioscopes for Axion Searches

Example: CERN Axion Solar Telescope (CAST)

Helioscope axion searches:

- Axions not required to dominate DM
- Largely model-independent
- Complementary sensitivity to other experimental approaches like haloscopes or light-shining-through-wall experiments

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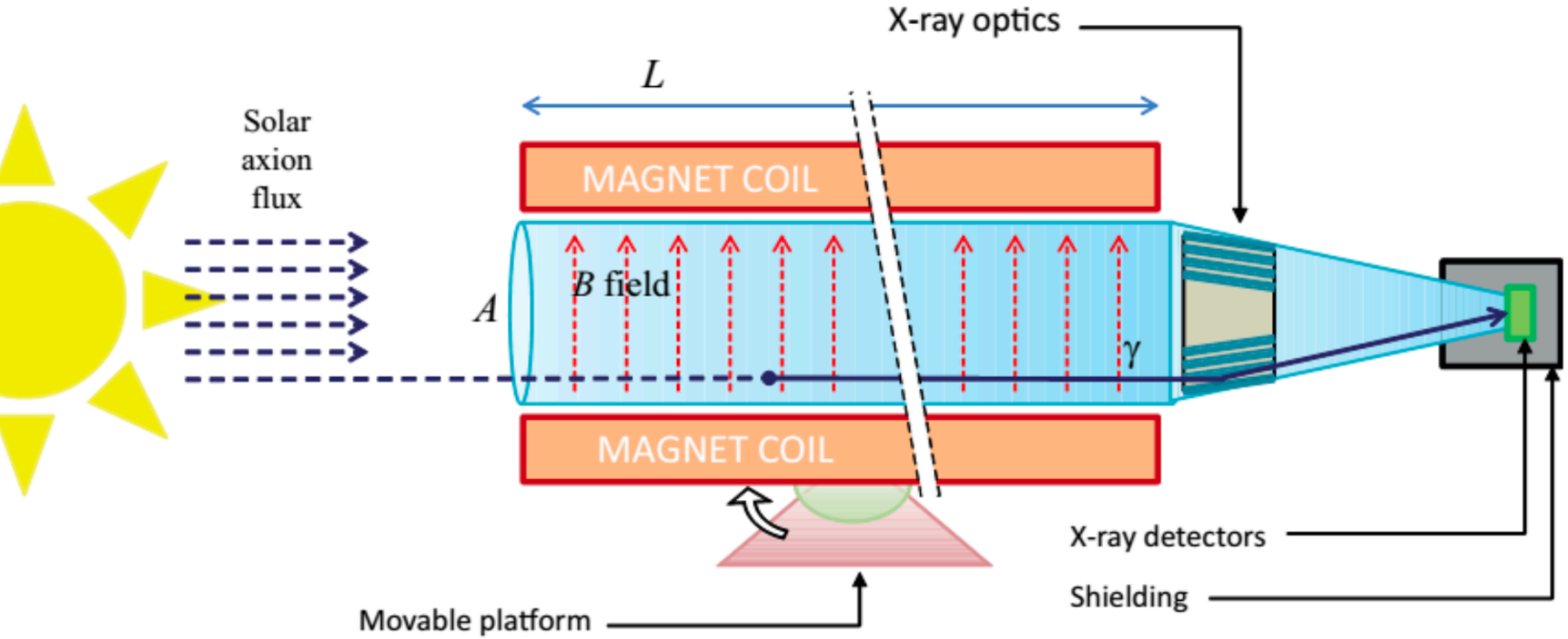

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- Structure & drive system: precise and long sun tracking capability
- Magnet: large bore and high field strength
- Optics: small focal spot and high throughput
- X-ray detectors: high efficiency, low background, low threshold

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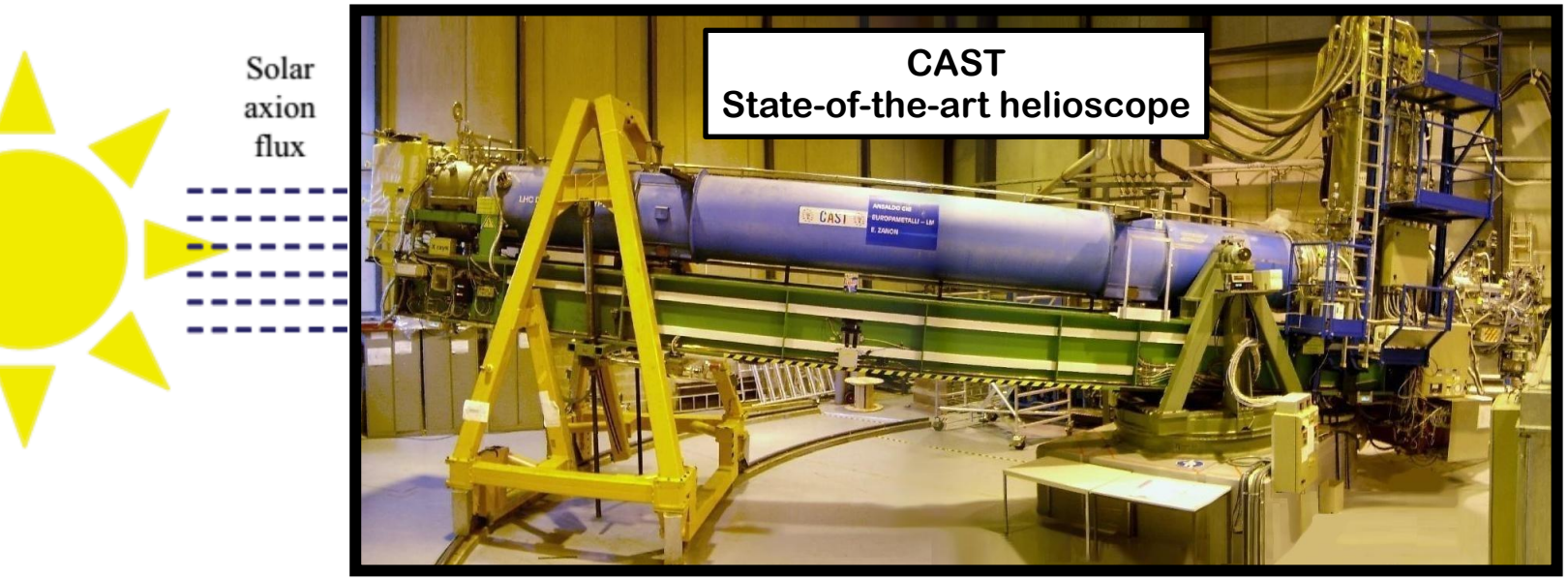


Helioscope axion searches:

- Axions not required to dominate DM
- Largely model-independent
- Complementary sensitivity to other experimental approaches like haloscopes or light-shining-through-wall experiments

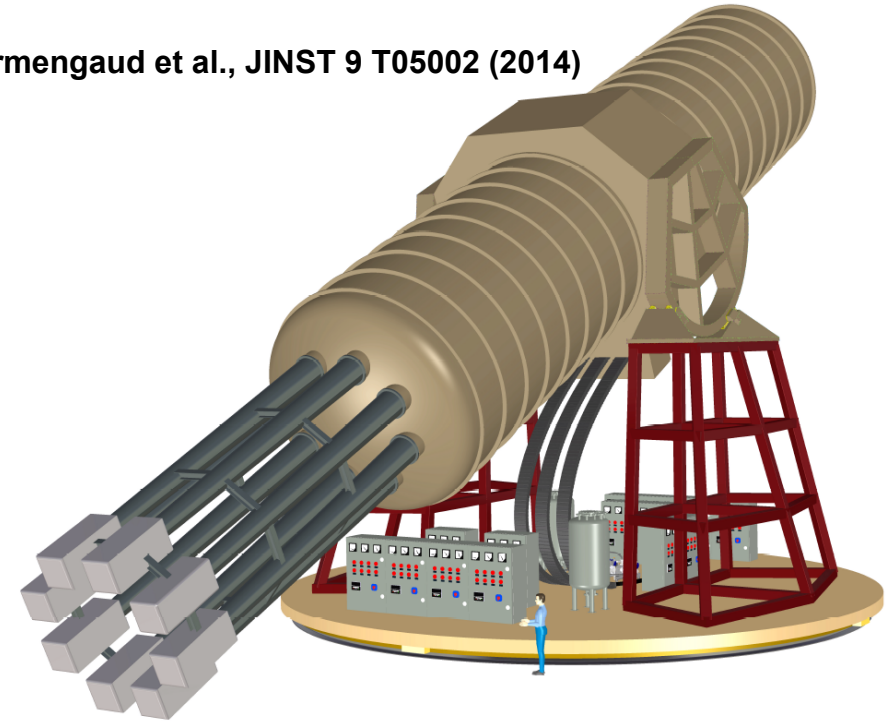
- Structure & drive system: precise and long sun tracking capability → 2 x 1.5 h per day
- Magnet: large bore and high field strength → 10 m long, 9 T
- Optics: small focal spot and high throughput
- X-ray detectors: high efficiency, low background, low threshold

→ Extensiv experiences including IAXO pathfinder phase

International AXion Observatory (IAXO) and BabyIAXO

The Next Generation Helioscopes

E. Armengaud et al., JINST 9 T05002 (2014)



- 12 h solar tracking per day
- 20 m superconducting magnet, up to 5.4 T
- 8 x 60 cm magnet bores with 8 detector lines
- X-ray optics with 0.2 cm^2 focal spots

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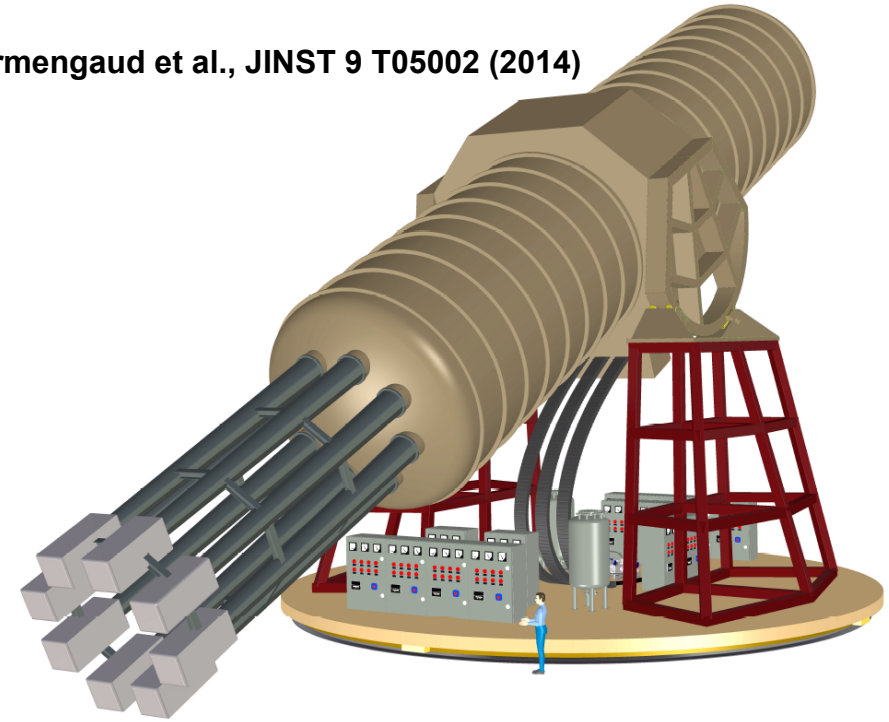

New life arises at Hera South hall at DESY, Hamburg!

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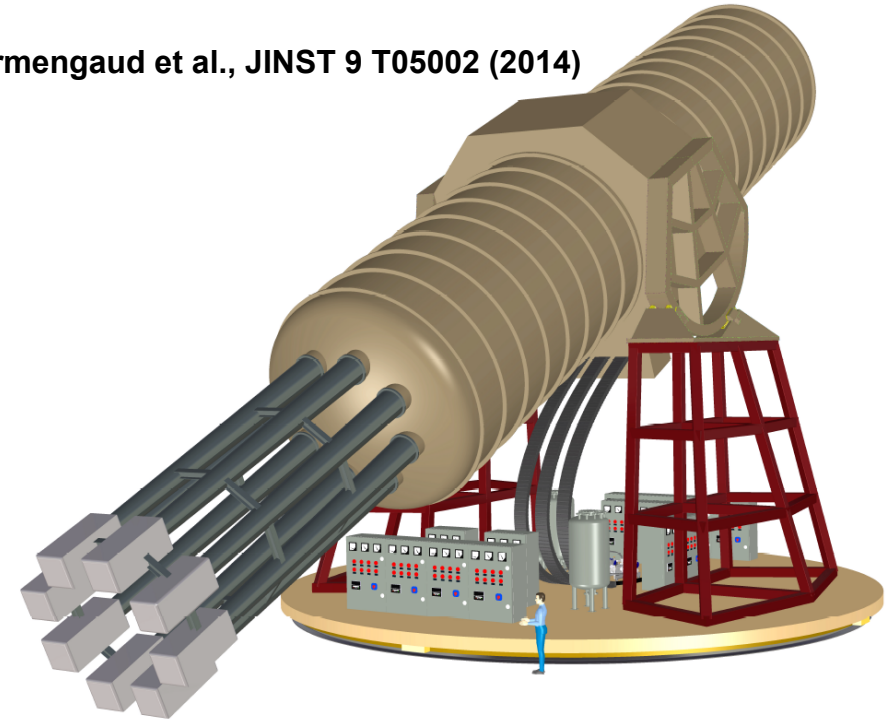


The IAXO collaboration, *J. High Energ. Phys.* 2021, 137 (2021)

- 12 h solar tracking per day
- 20 m superconducting magnet, up to 5.4 T
- 8 x 60 cm magnet bores with 8 detector lines
- X-ray optics with 0.2 cm^2 focal spots

- Technological prototype for all IAXO sub-systems
- **Fully-fledged helioscope that will deliver important physics results**

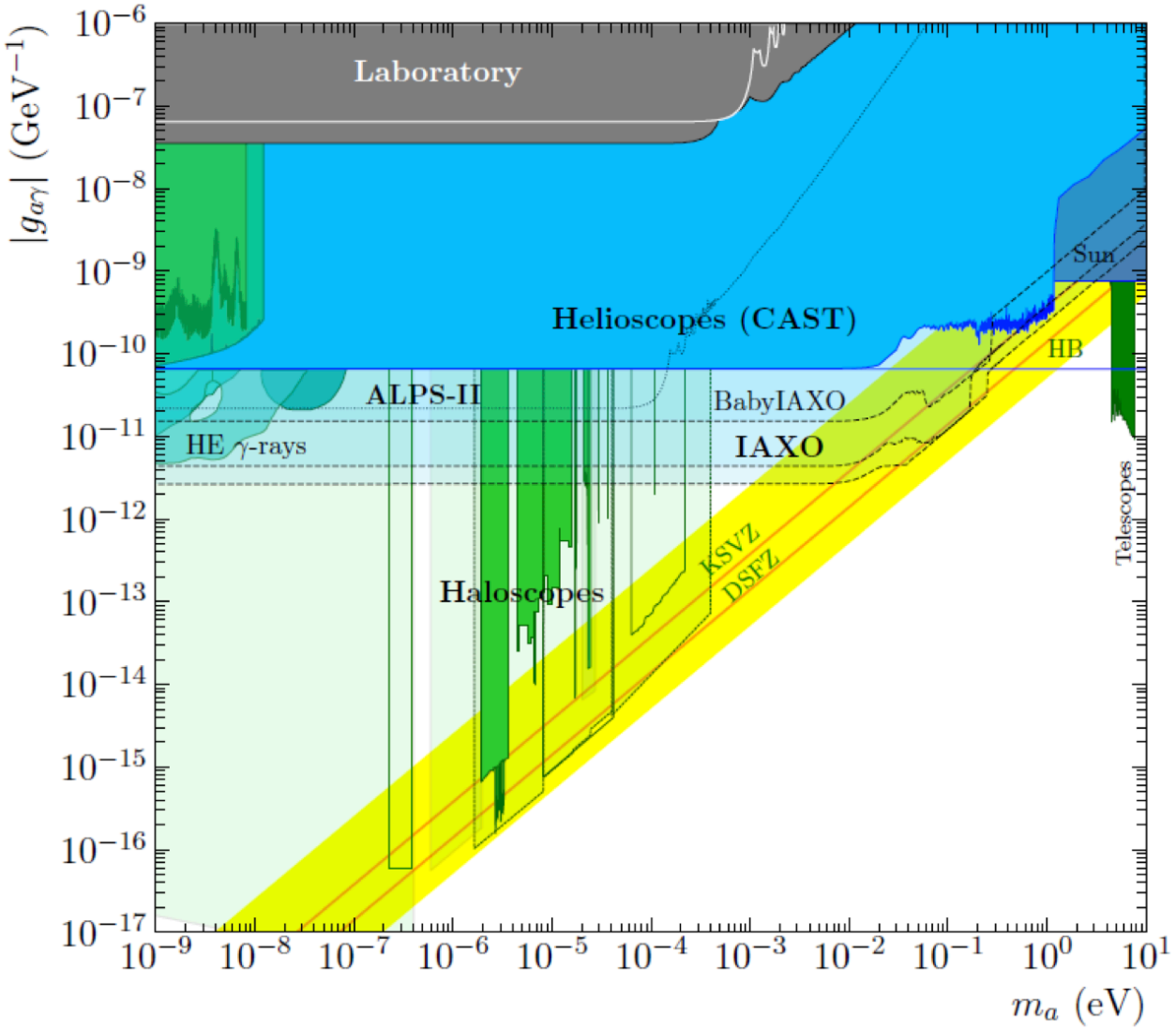
Physics Prospects of (Baby)IAXO

Axion-Photon Coupling and further Searches

- Parameter space: coupling constant to photons ($g_{a\gamma}$) vs axion mass (m_a)
  - ➡ BabyIAXO sensitive to wide range of masses and able to push sensitivity limits beyond astrophysical bounds
- Investigation of other (non-Primakoff) solar axion production mechanisms
- Axions from supernovae
- DM axions with haloscope setups in BabyIAXO magnetic bores
- …

Check out IAXO physics case paper:

E. Armengaud et al. JCAP06(2019)047

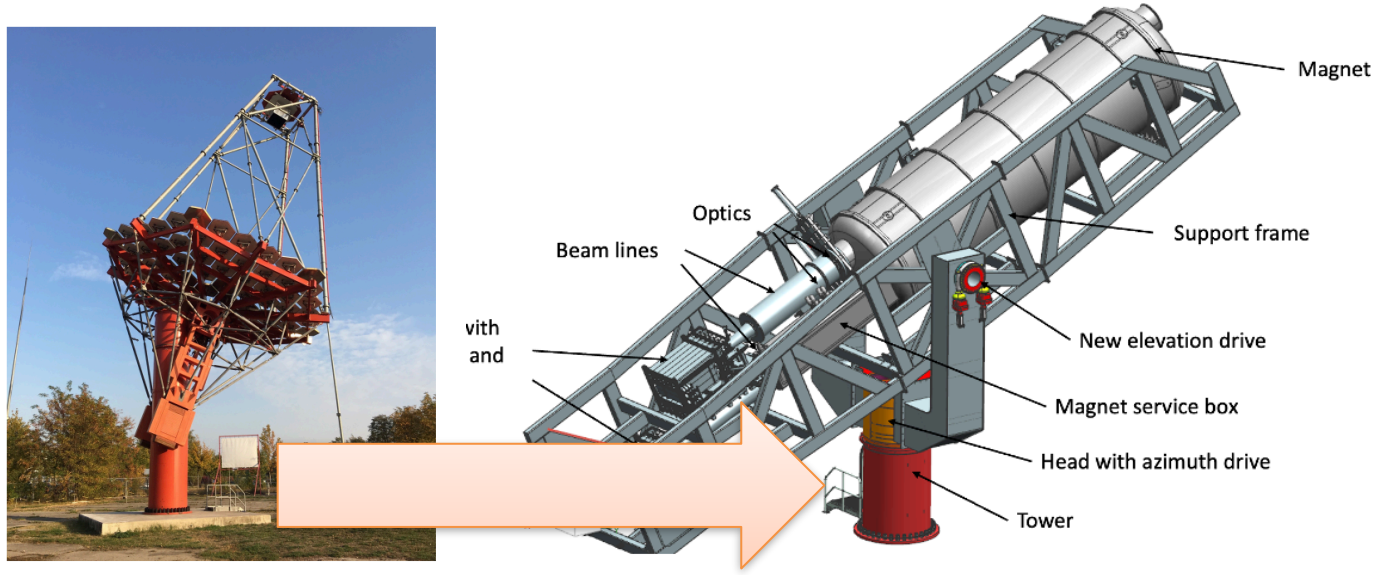


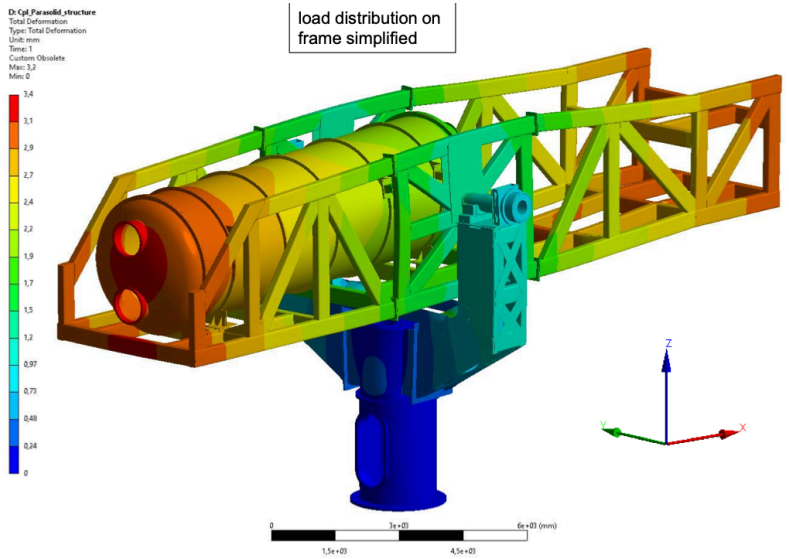
IAXO collaboration. *J. High Energ. Phys.* **2021**, 137 (2021)

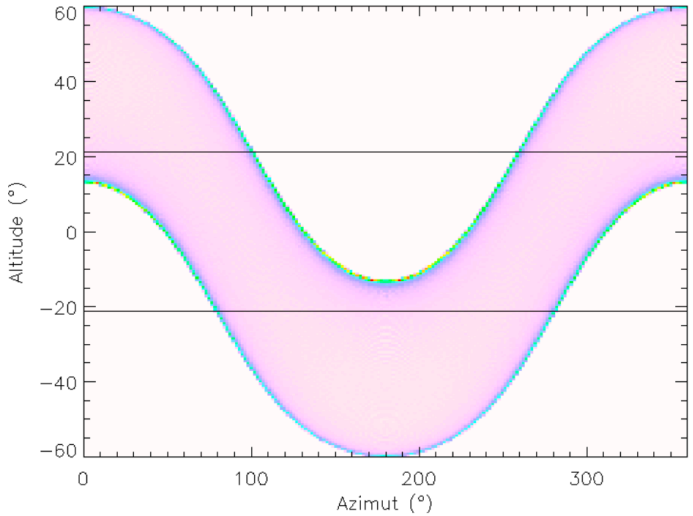
Structure & Drive System

And Internal and External Alignment

- Reusing parts of CTA/MST prototype from DESY Zeuthen
- Technical studies and coordination at DESY Hamburg
  - ➡ Extensive simulations of load distributions and deformations
  - ➡ Design almost finished
  - ➡ Rotation: 360°, Tilt: ±21.1°
  - ➡ Pointing precision < 0.01°
- BabyIAXO component alignment with photogrammetry under investigation
- BabyIAXO sun alignment model under development by telescope experts

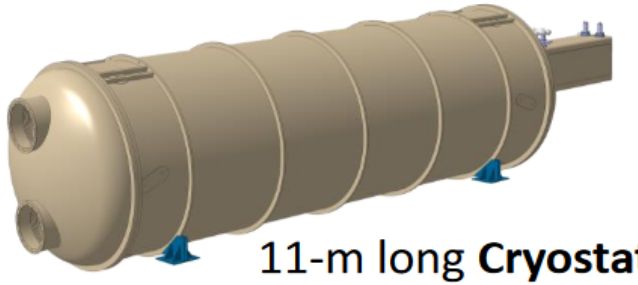




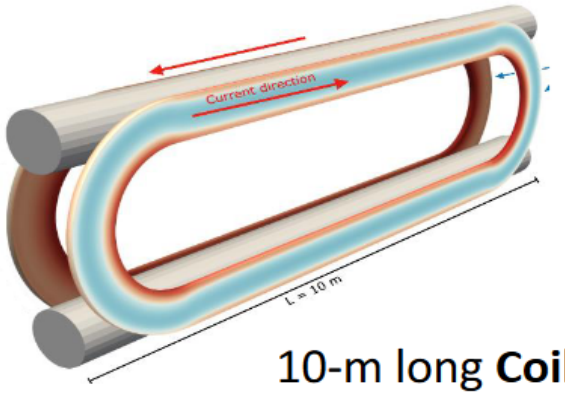


Magnet

Prospects and Challenges

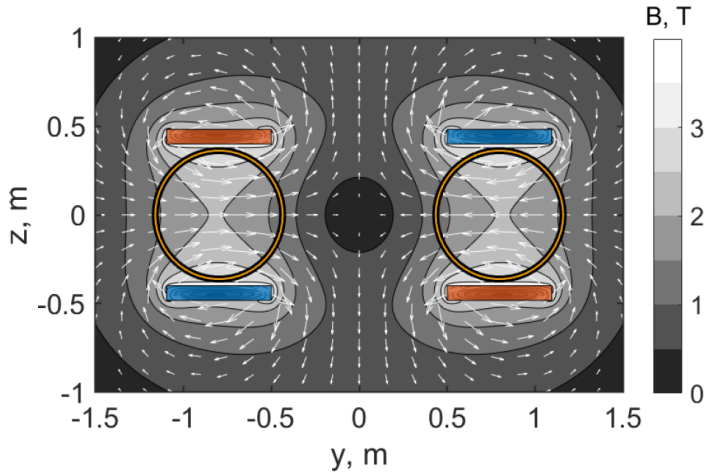


11-m long **Cryostat**



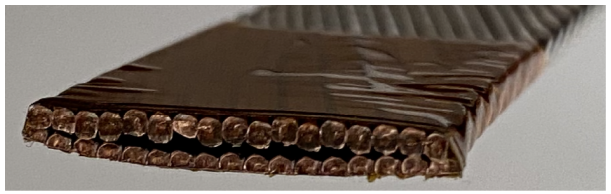
10-m long **Coils**

- Two 10 m long bores with 70 cm diameter each, magnetic field ~2-3 T
  - ➡ Common coil racetrack design with counter-flowing currents



- Ongoing adaptations due to difficulties in obtaining Al-stabilised superconducting cables
  - ➡ Potential Russian providers not available
  - ➡ Critical item, causing delays

~35 km **Superconductor**

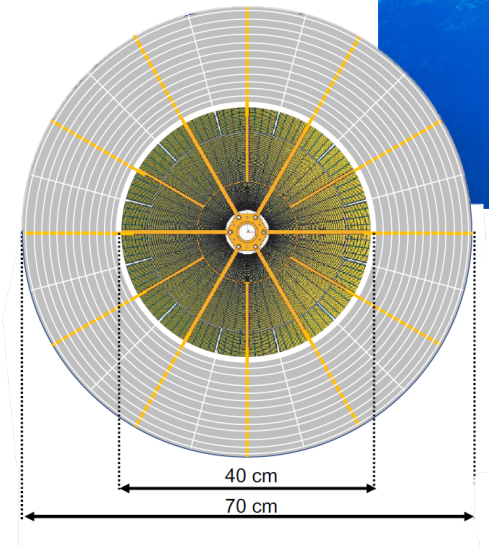


- Intense collaboration with magnet experts at CERN
  - ➡ Requests for quotations and tendering restarted recently
  - ➡ New review upcoming, conceptual design under preparation

Optics

Focusing X-Rays

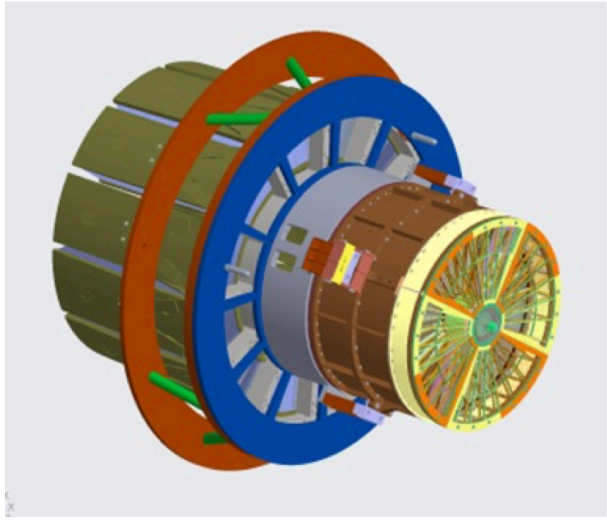
- Two different X-ray focusing optics to be used (Wolter type)



➡ XMM flight spare XRT from ESA

  ➡ Focal length: 7.5 m

  ➡ Calibration at MPE/PANTER scheduled soon



➡ Custom optics (hybrid approach for inner/outer parts)

  ➡ Focal length: 5 m

  ➡ Significant progress in coating tests, design and calibration

- Challenges: Throughput efficiency (40-60%) and focal area (r < 2.5 mm)

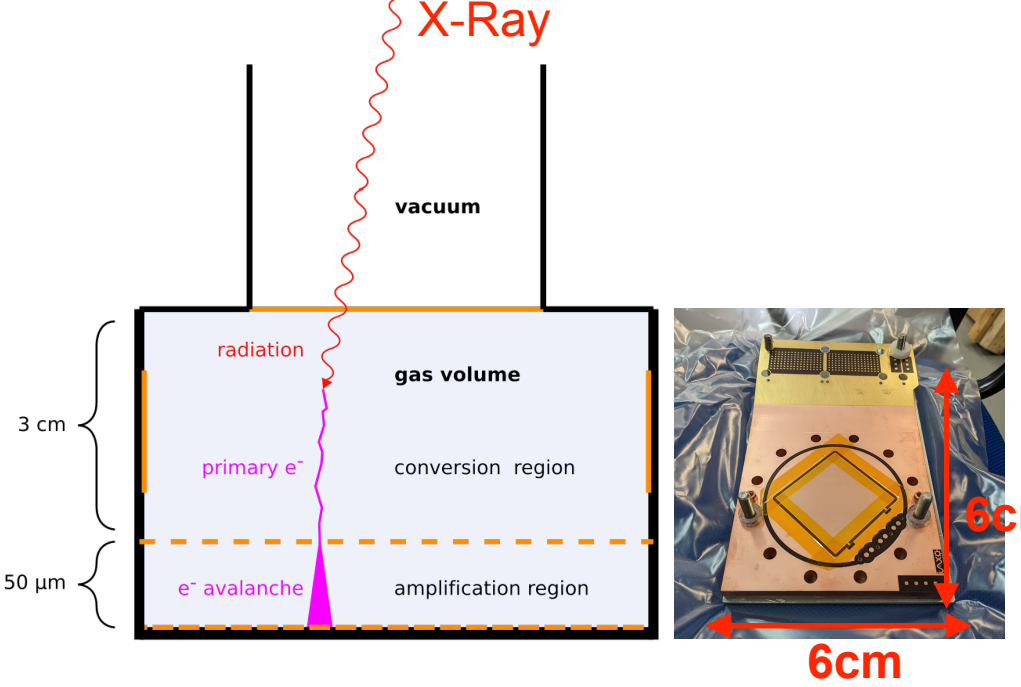
X-Ray Detectors

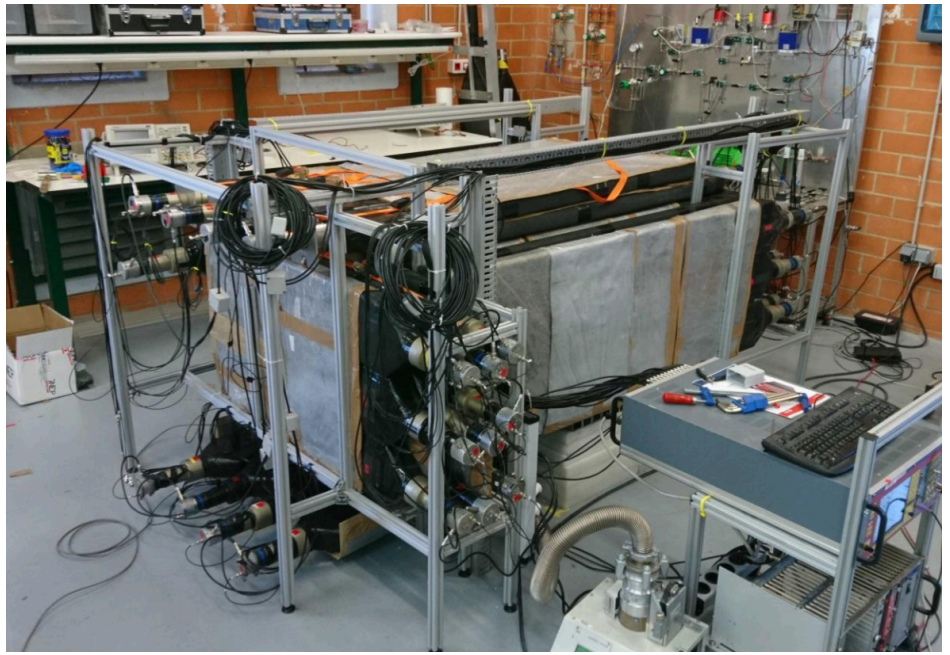
Micromegas TPC and Other Technologies

- Requirements: High detection efficiency (1-10 keV) and ultra-low background levels
- Baseline option: small gaseous micro-mesh TPCs with pixelated readout + dedicated shielding + muon veto system
  - ➡ 60-70% detection efficiency in RoI
  - ➡ Proven design, demonstrated in CAST with achieved BKG-level of < 10^{-6} counts keV^{-1} cm^{-2} s^{-1}

    ≈ 32 photon/year per keV^{-1} cm^{-2}

    Goal: ~1 photon/year per keV^{-1} cm^{-2}
  - ➡ Currently under investigation: cosmic neutron BKG
- ➡ Other technologies in R&D phase progressing well: GridPix-based TPC, silicon drift detectors, metallic magnetic calorimeters, transition edge sensors





Background Measurement & Simulation Campaigns

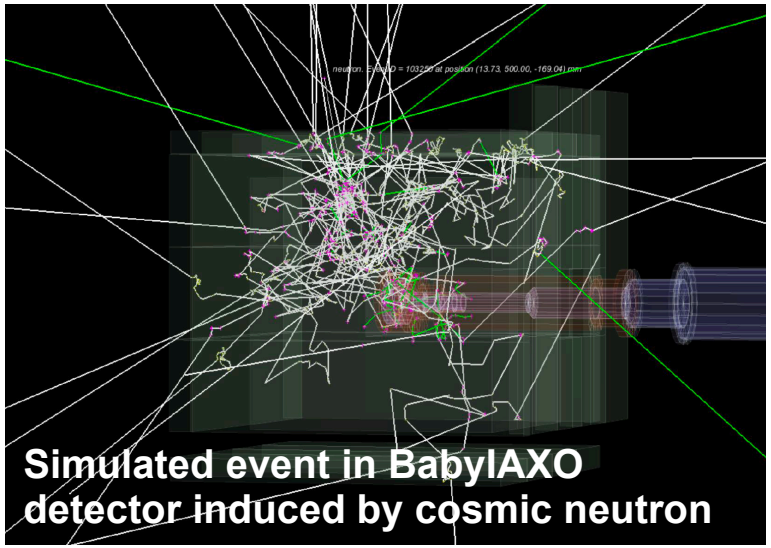
Investigating Potential Background Sources

- Extensive background measurement campaigns at underground laboratory Canfranc (LSC) ongoing
  - ➡ Intrinsic (internal) vs. cosmic BKG
- Recently first background measurements started in Hera Hall South at DESY

- Dedicated MonteCarlo Geant4 simulation campaigns with REST ongoing
  - ➡ e.g. investigate potential BKG induced by cosmic neutrons

Studies are powered by REST-for-Physics (Rare Event Searches Toolkit) Framework for data analysis and Geant4 MonteCarlo simulation.

https://github.com/rest-for-physics



Simulated event in BabyIAXO detector induced by cosmic neutron

Summary & Outlook

… and a Dream

- Helioscopes such as (Baby)IAXO can search for axions/ ALPs from the sun in a very wide mass range
- BabyIAXO is commissioned as prototype for IAXO, but will be a fully fledged helioscope with discovery potential
  - ➡ Key components: strong & large magnet, focusing X-ray optics, high-efficiency & low-BKG detectors
- Challenges in magnet construction remain, but overall good progress in all sub-systems
- Expected start of data taking: ~2028
- (Baby)IAXO might turn into a facility to search for more generic axion-related physics: axion-electron(nucleon) couplings, DM axions, dark photons, …

Thank you for your attention!

IAXO Collaboration Meeting @ DESY, Hamburg, 12-15.03.2023
~125 scientists from 22 full member institutions + 5 associate institutions.
https://iaxo.desy.de

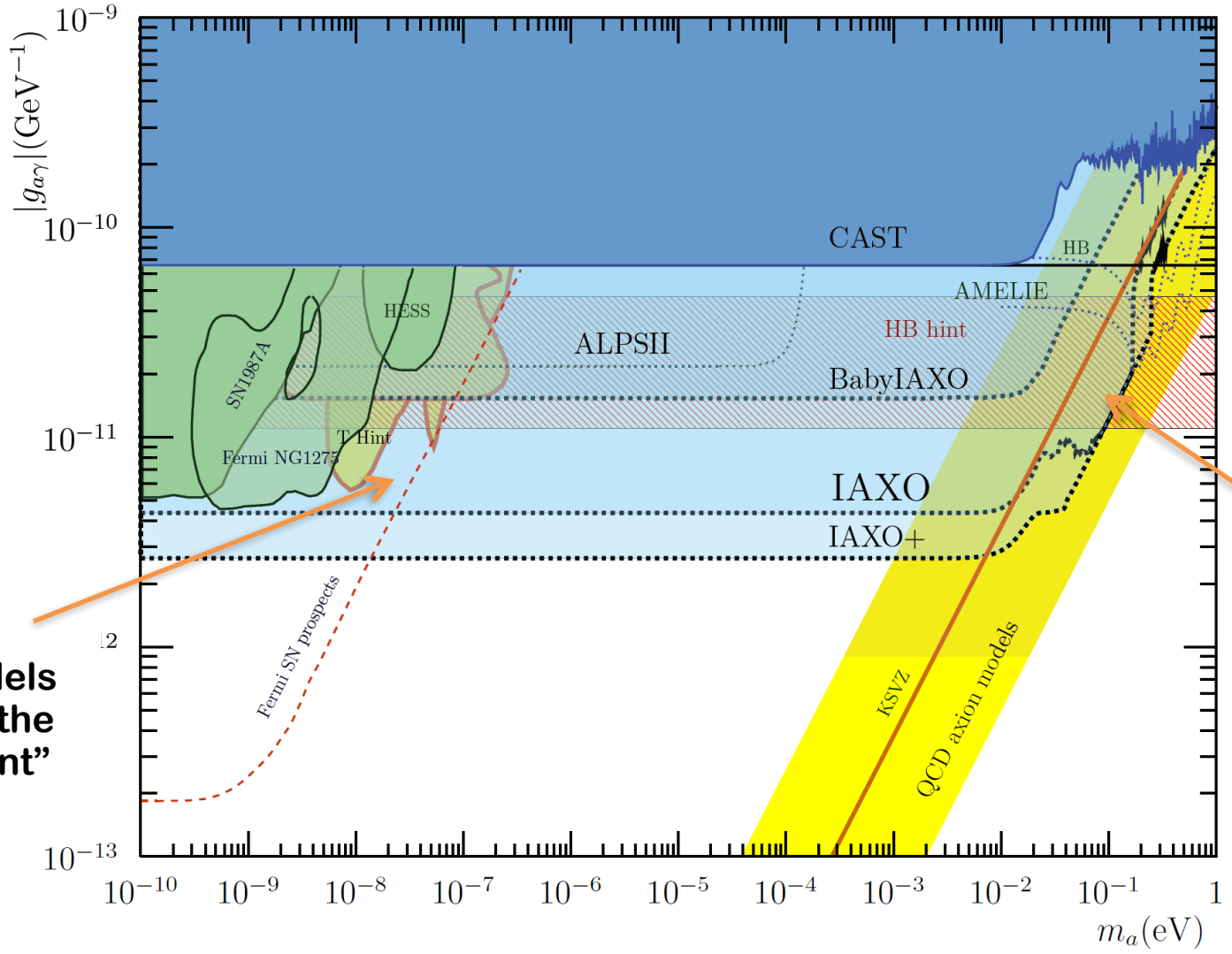
Backup

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) | Technical University Munich (TUM) (Germany) | CEFCA-Teruel (Spain) | U. Polytechnical of Cartagena (Spain) | U. of Hamburg (Germany) | MPE/PANTER (Germany) |

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

BabyIAXO & IAXO physics reach

BabyIAXO prospects: 10xMFOM + optics and detector from conservative scenario of LoI



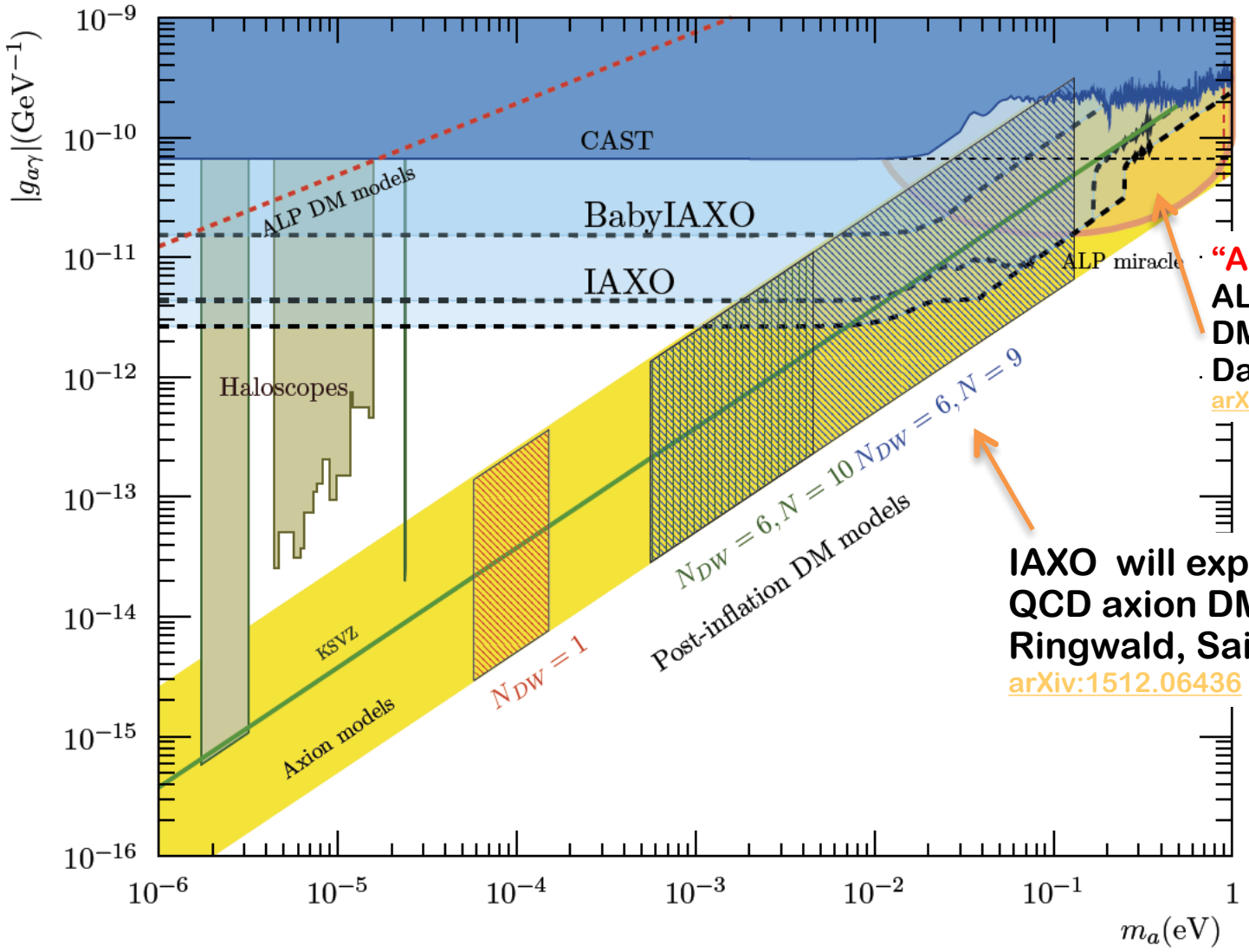
IAXO+: enhanced scenario with x10 (x4) higher FOM (MFOM) with respect LoI

IAXO will fully explore ALP models invoked to solve the "transparency hint"

… as well as a large fraction of the axion & ALP models invoked in the "stellar cooling anomaly"
But for this the g_{ae} is particularly interesting

MFOM = Magnet FOM

IAXO & meV axion cosmology



"ALP miracle" region
ALPs solving both DM & inflation
Daido et al. 2017
arXiv:1710.11107

IAXO will explore viable QCD axion DM models
Ringwald, Saikawa 2016
arXiv:1512.06436

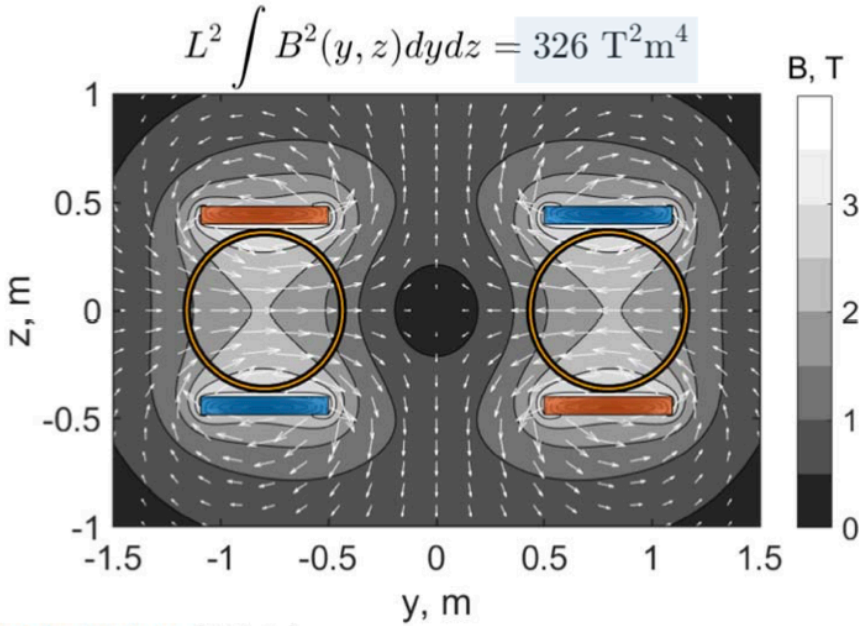
Baby-IAXO magnets (II)

- Two bores of 70 cm diameter (dimensions similar to final IAXO bores) and 10 m length
- Field in bore 2 – 3 T

  Magnetic figure of merit

  $f_M = B^2L^2A$

  About 10 times larger than in CAST



- Design of supporting structures

  Repelling force 34 MN

- Defining the electrical circuit:

  Direct drive (no risk) vs Persistent Mode Drive (R&D)

  Quench protection

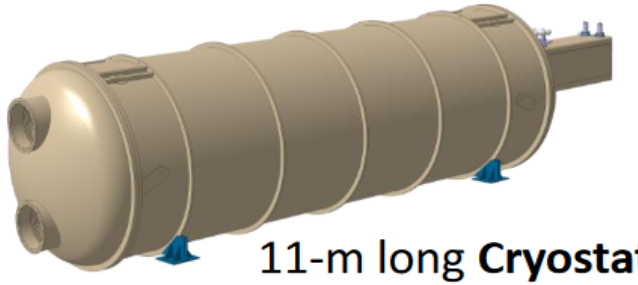
- Cryogenics:

  cryocoolers based cooling system

  evaluation of the heat load

Magnet

Prospects and Challenges



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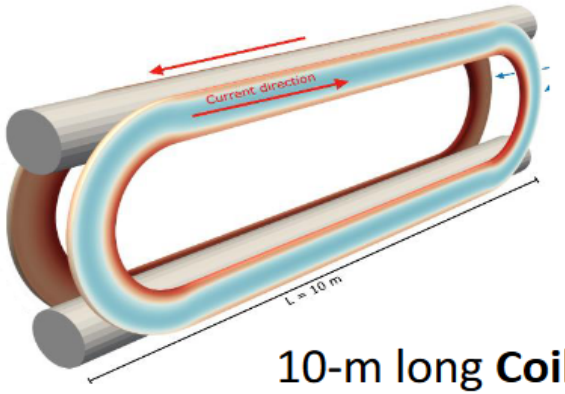

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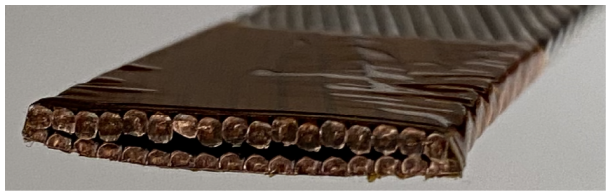
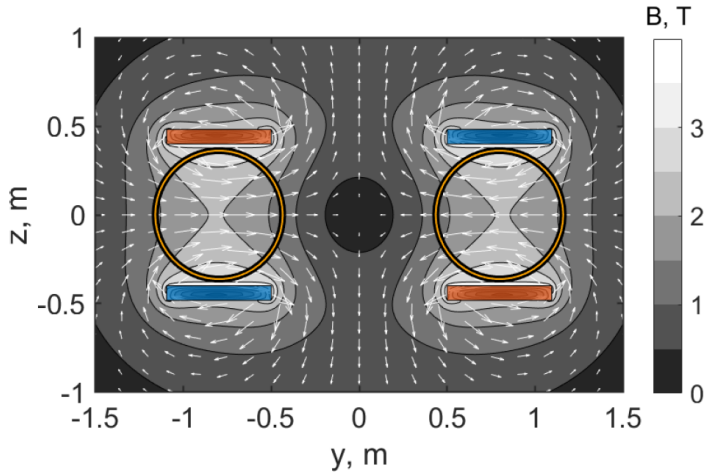


- Two 10 m long bores with 70 cm diameter each, magnetic field ~2 T
  - ➡ Common coil racetrack design with counter-flowing currents
- Dry detector magnet concept based on cryocoolers, cold mass 4.5 K



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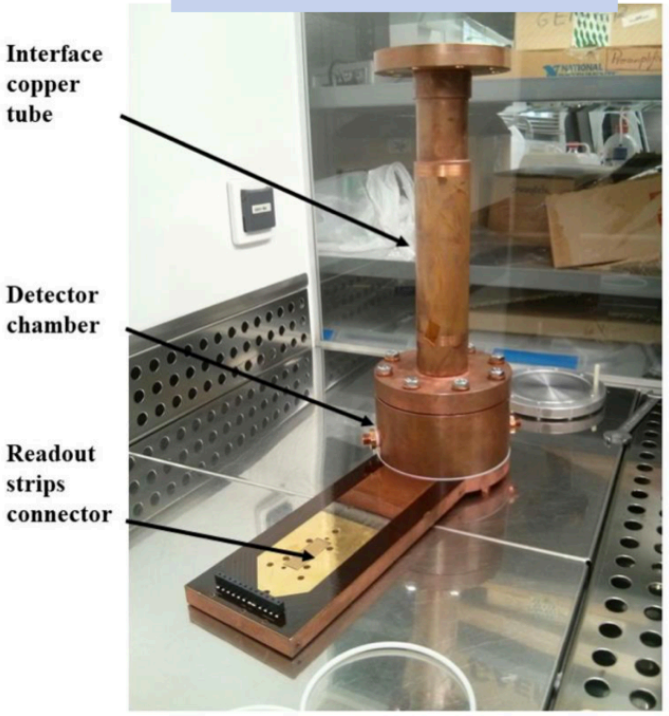
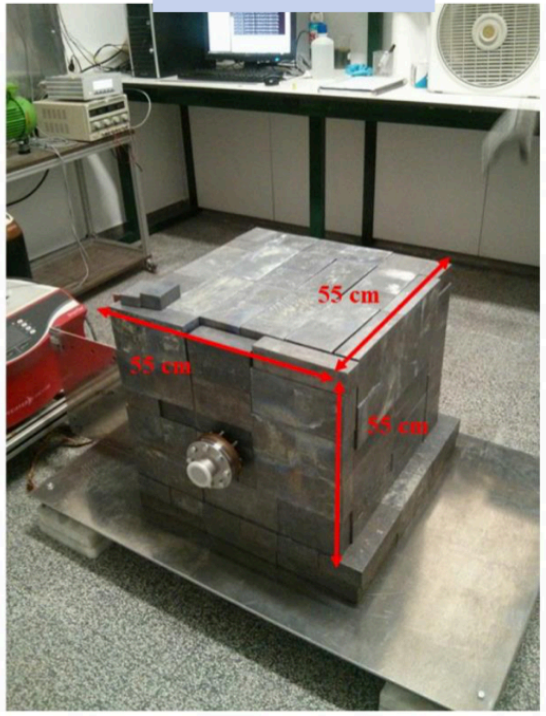
IAXO-D0: the Micromegas prototype at Unizar

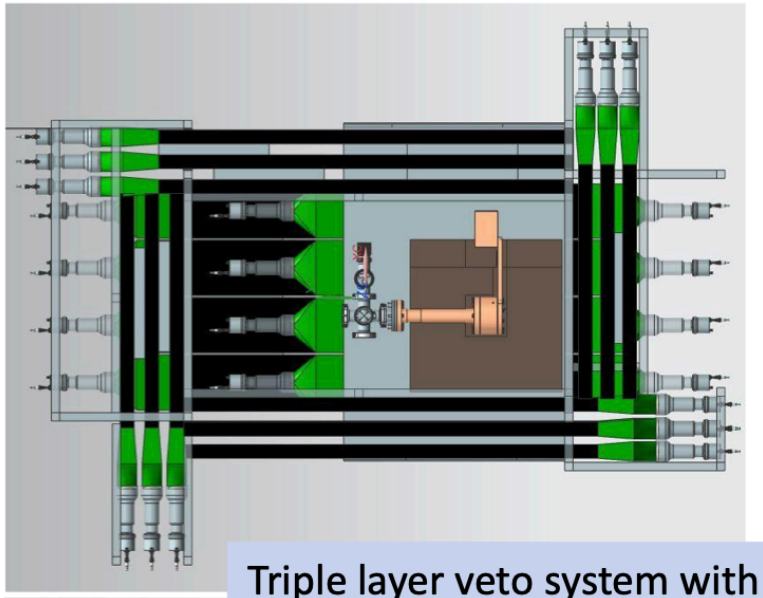
Centro de Astropartículas y Física de Altas Energías
Universidad Zaragoza

Micromegas detector



Lead castle



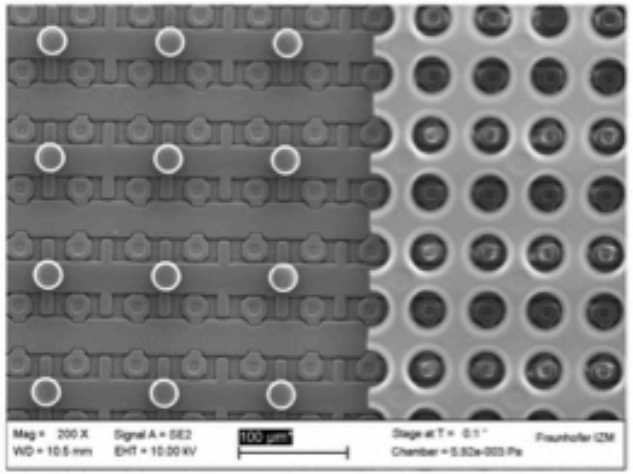


Triple layer veto system with cadmium sheets to discriminate neutron background

Prospective (Baby)IAXO X-ray detectors

GridPix

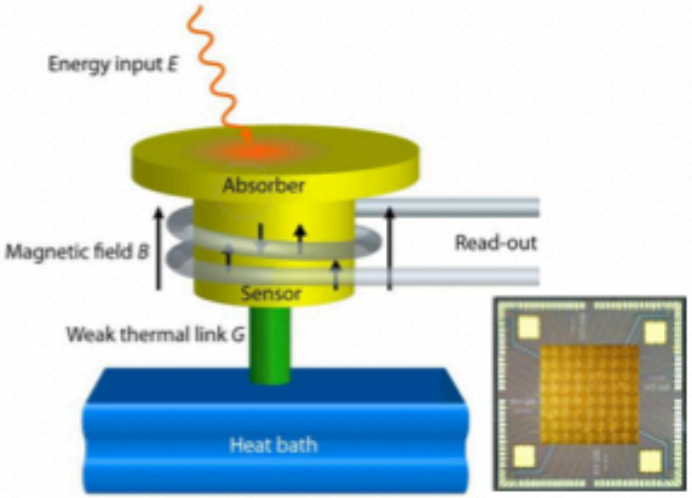
- Evolution of Micromegas detector
- CMOS chip in readout plane
- Single electron detection



Metallic magnetic calorimeters

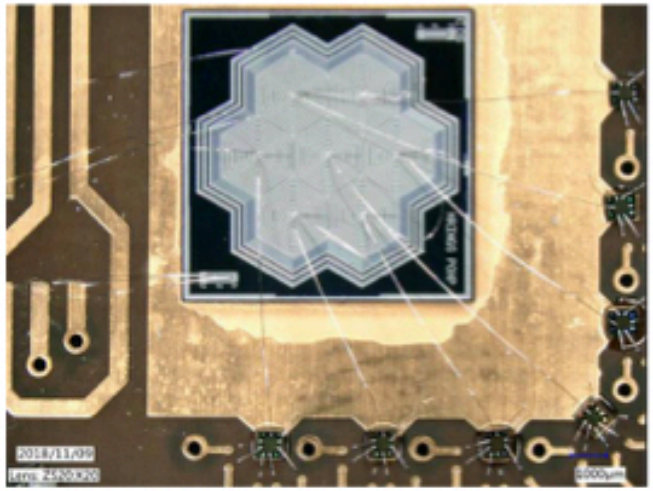
- high energy resolution ~1.6 eV fwhm
- "no" threshold from detector, but window necessary for cryostat

→ Especially useful for axion spectroscopy in case of signal



Silicon drift detectors

- Low threshold < 500 eV
- Good energy resolution ~ 130 eV fwhm
- no window necessary



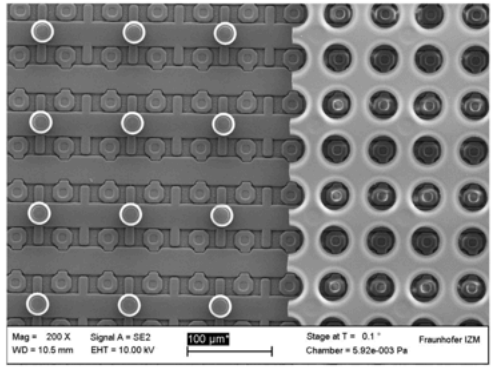
+ Transition Edge Sensors (TES) R&D

Other detectors under study

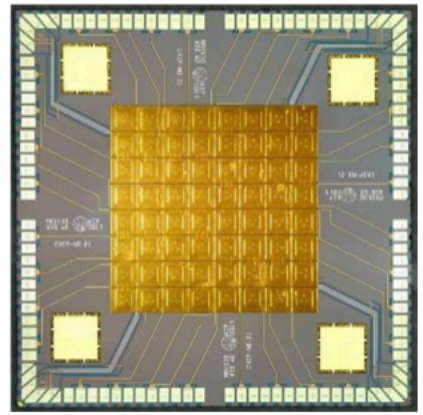
Many alternative detectors are being considered and are undergoing development for later stages of BabyIAXO data taking

- Other technologies under study
  - IAXO as a generic infrastructure for axions and ALPs physics
  - and R&D of alternative detectors with different properties
    - Excellent energy resolution, energy threshold, high efficiency and ultra-pure materials
    - Improve the energy threshold → investigation of fine structures in the axion spectrum

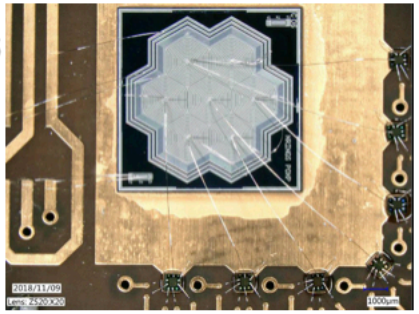
- Post-discovery scenario
  - If positive signal, low threshold + good energy resolution → possibility to determine m_a and g_{ae}
  - Minimization of systematics effects and reinforcement of the claim significance



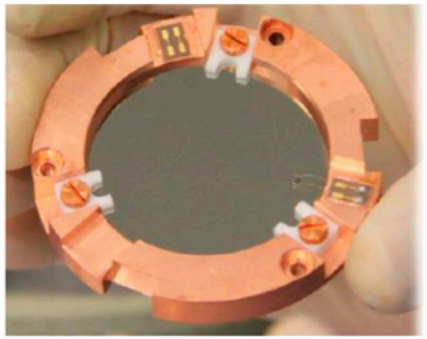
GridPix – evolution of Micromegas



Metallic magnetic calorimeters (MMC)



Silicon Drift Detectors (SDD)



Transition Edge Sensors (TES)