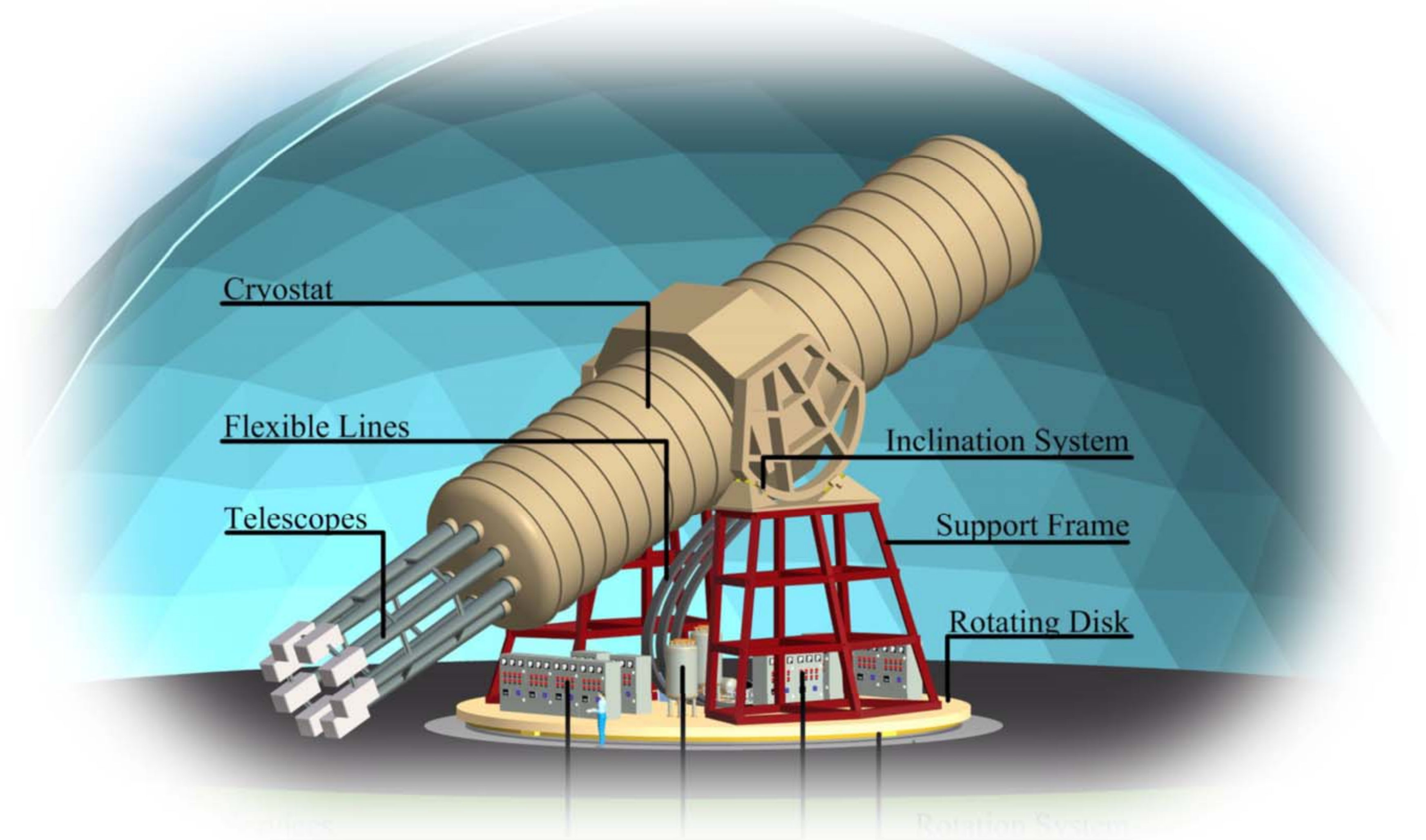
Status of Baby-IAXO

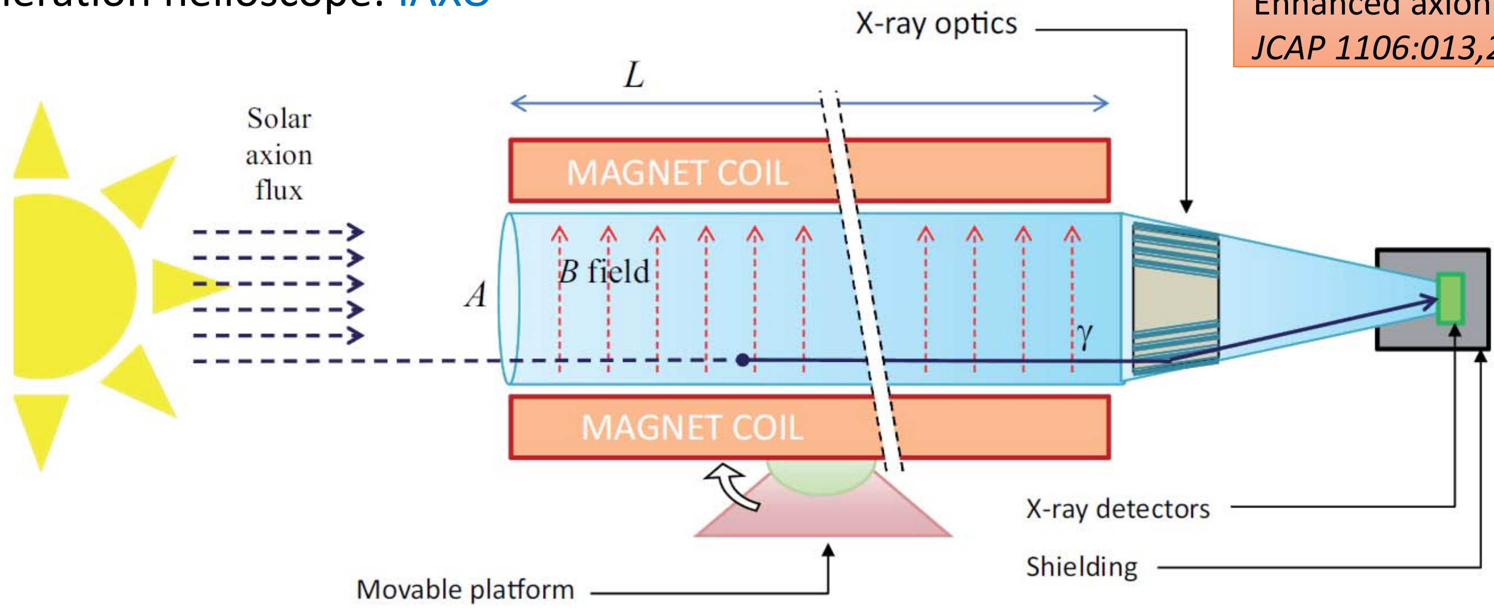


Loredana Gastaldo (Kirchhoff Institute for Physics, Heidelberg University)
on behalf of the IAXO and Baby-IAXO collaboration

Helioscopes – experiments

4th generation helioscope: IAXO

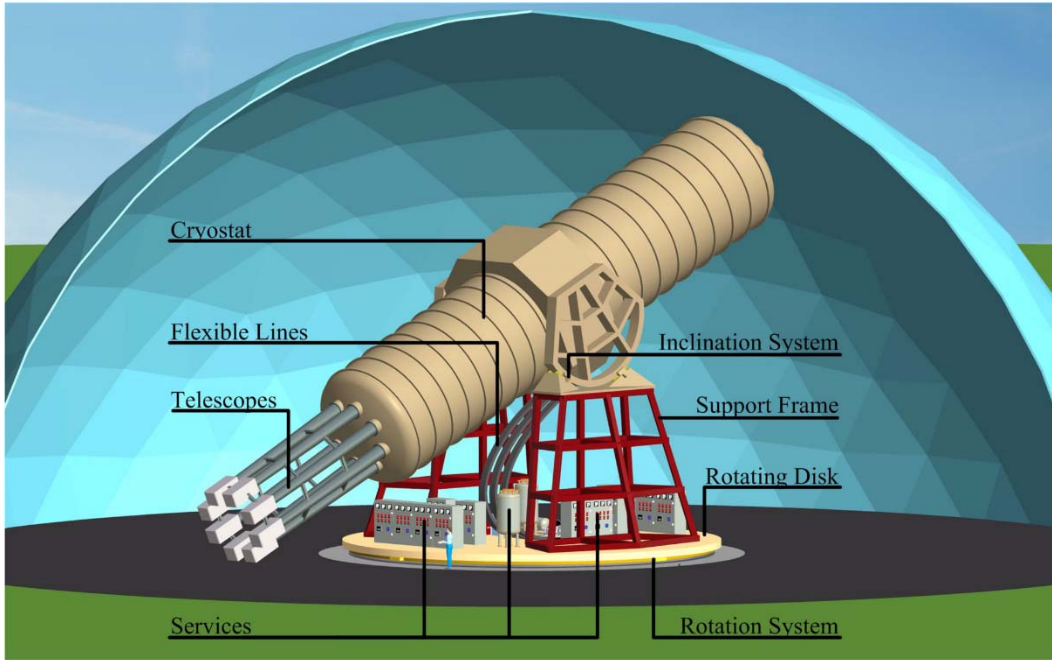
Enhanced axion helioscope:
JCAP 1106:013,2011



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

Expected improvement over CAST:
1−1.5 orders of magnitude in sensitivity to $g_{a\gamma}$ (factor of 10000-20000 in S/N)

IAXO



Enhanced axion helioscope:
JCAP 1106:013,2011

- Large toroidal 8-coil magnet
  $L \simeq 20$ m
- 8 bores: 60 cm diameter each
- 8 x-ray telescopes
- 8 detection systems
- Rotating platform with services

Ambitious project → necessary an intermediate step:

Baby-IAXO

♦ Two bores of dimensions similar to final IAXO bores

♦ Detection lines as for IAXO

→ Risk mitigation

→ Will produce relevant physics

Baby-IAXO and IAXO physics reach

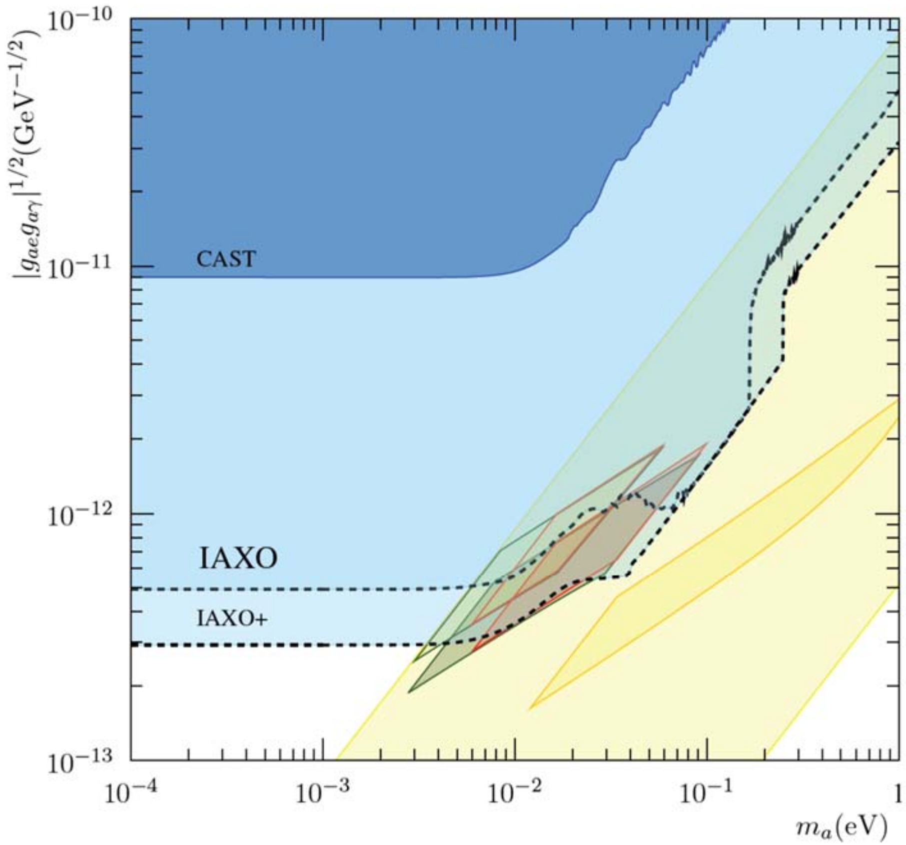
QCD axions in meV to eV mass band

Astrophysically hinted regions invoked to solve stellar cooling anomaly

Cosmologically interesting regions including ALP region astrophysically invoked to solve the transparency anomaly

Large generic unexplored ALP space

- Down to $g_{a\gamma}$ ~ few 10^{-12} GeV^{-1}
- Down to g_{ae} ~ few 10^{-13}



Baby-IAXO and IAXO physics reach

QCD axions in meV to eV mass band

Astrophysically hinted regions invoked to solve stellar cooling anomaly

Cosmologically interesting regions including ALP region astrophysically invoked to solve the transparency anomaly

Large generic unexplored ALP space

- Down to $g_{a\gamma}$ ~ few 10^{-12} GeV^{-1}
- Down to g_{ae} ~ few 10^{-13}

More can be found in:
Physics potential of the international Axion Observatory (IAXO)
The IAXO Collaboration
JCAP (2019) 06 047

Physics potential of the International Axion Observatory (IAXO)

E. Armengaud,[a] D. Attie,[a] S. Basso,[b] P. Brun,[a] N. Bykovskiy,[c] J. M. Carmona,[d] J. F. Castel,[d] S. Cebrián,[d] M. Cicoli,[e,f] M. Civitani, [b] C. Cogollos,[g] J. P. Conlon,[h] D. Costa,[g] T. Dafni,[d] R. Daido,[i] A.V. Derbin,[j] M. A. Descalle,[k] K. Desch,[l] I.S. Dratchnev,[j] B. Döbrich,[c] A. Dudarev,[c] E. Ferrer-Ribas,[a] I. Fleck,[m] J. Galán,[d] G. Galanti,[b] L. Garrido,[g] D. Gascon,[g] L. Gastaldo,[n] C. Germani,[g] G. Ghisellini,[b] M. Giannotti,[o] I. Giomataris,[a] S. Gninenko,[p] N. Golubev,[p] R. Graciani,[g] I. G. Irastorza,[d,1] K. Jakovčić,[q] J. Kaminski,[l] M. Krčmar,[q] C. Krieger,[l] B. Lakić,[q] T. Lasserre,[a] P. Laurent,[a] O. Limousin,[a] A. Lindner,[r] I. Lomskaya,[j] B. Lubsandorzhiev,[p] G. Luzón,[d] M. C. D. Marsh,[s] C. Mergalejo,[d] F. Mescia,[g] M. Meyer,[t] J. Miralda-Escudé,[g,u] H. Mirallas,[d] V. N. Muratova,[j] X. F. Navick, [a] C. Nones, [a] A. Notari,[g] A. Nozik,[p,v] A. Ortiz de Solórzano,[d] V. Pantuev,[p] T. Papaevangelou,[a] G. Pareschi,[b] K. Perez,[w] E. Picatoste,[g] M. J. Pivovaroff,[k] J. Redondo,[d,x] A. Ringwald,[r] M. Roncadelli,[y] E. Ruiz-Chóliz,[d] J. Ruz,[k] K. Saikawa,[x] J. Salvadó,[g] M. P. Samperiz,[d] T. Schiffer,[l] S. Schmidt,[l] U. Schneekloth,[r] M. Schott,[z] H. Silva,[c] G. Tagliaferri,[b] F. Takahashi,[i,aa] F. Tavecchio,[b] H. ten Kate,[c] I. Tkachev,[p] S. Troitsky,[p] E. Unzhakov,[j] P. Vedrine,[a] J. K. Vogel,[k] C. Weinsheimer,[z] A. Weltman,[ab] W. Yin.[ac,ad]

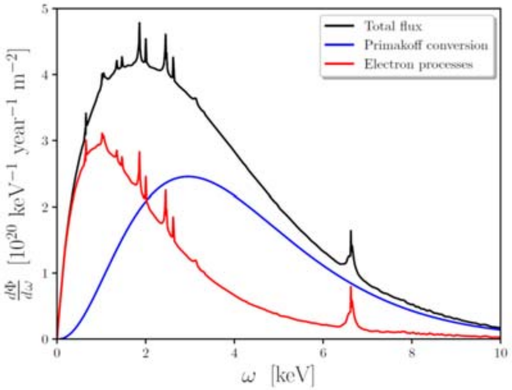
Energy resolution and threshold

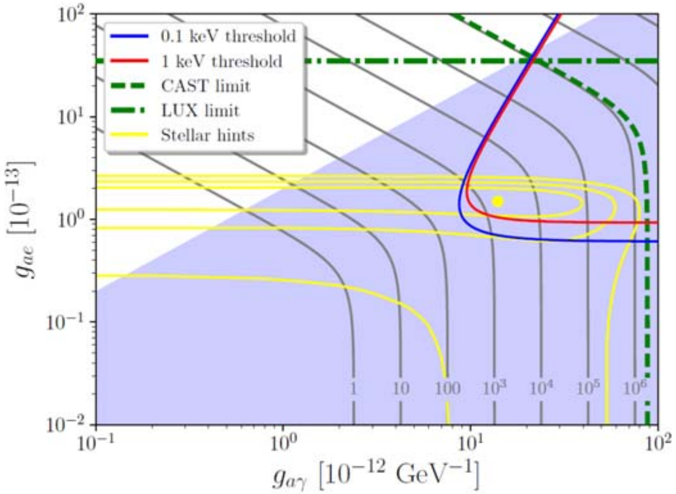
Distinguishing Axion Models with IAXO

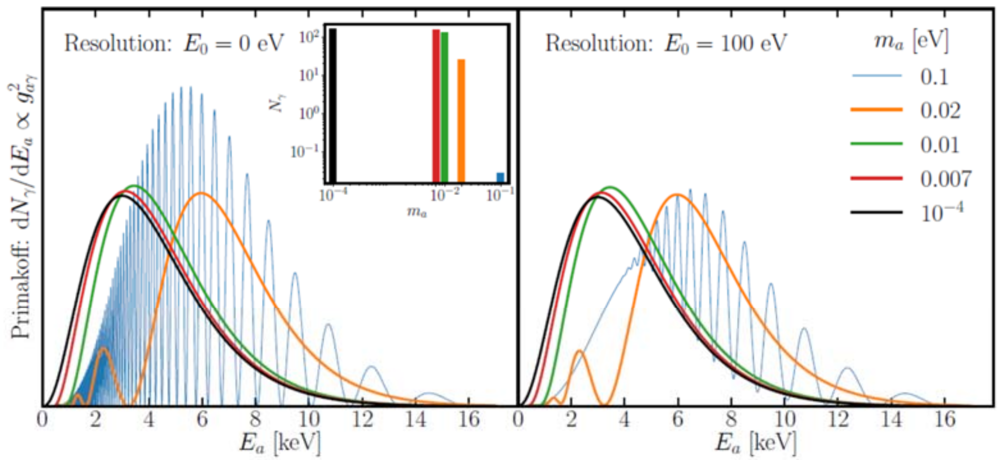
J. Jaeckel and L. J. Thormaehlen,
DOI: 10.1088/1475-7516/2019/03/039

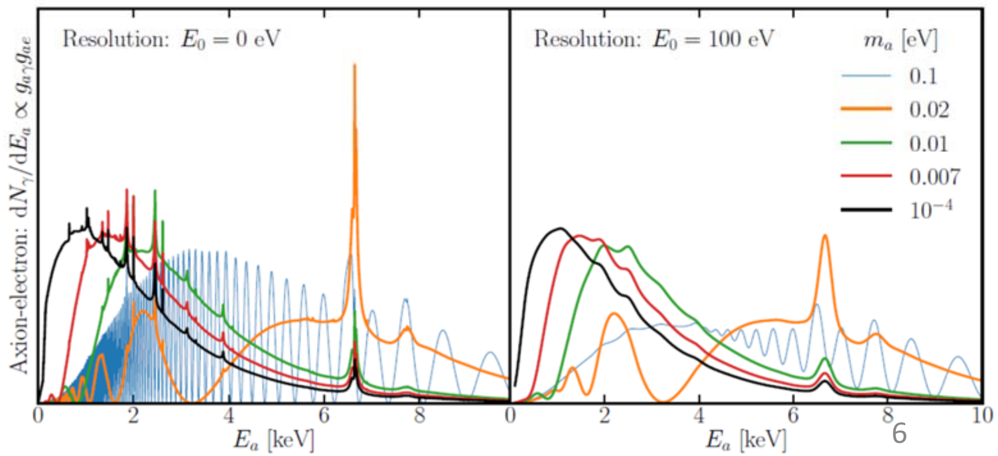
Weighing the Solar Axion

T. Dafni et al., Phys. Rev. D 99, 035037 (2019)





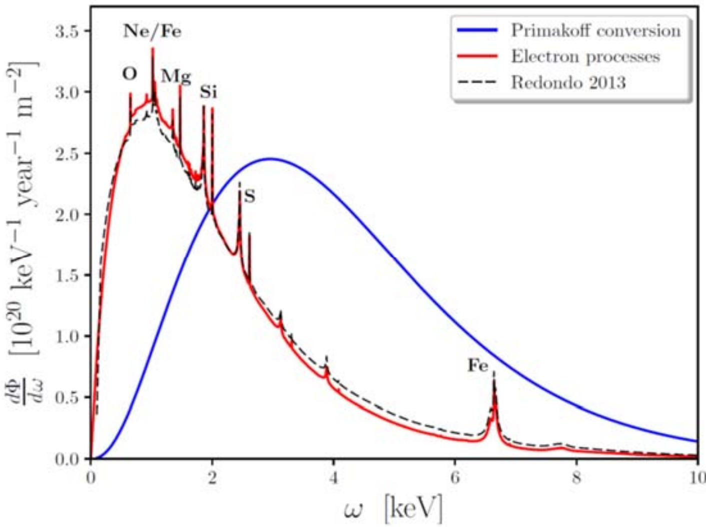




Additional Physics

Axions as a probe of solar metals

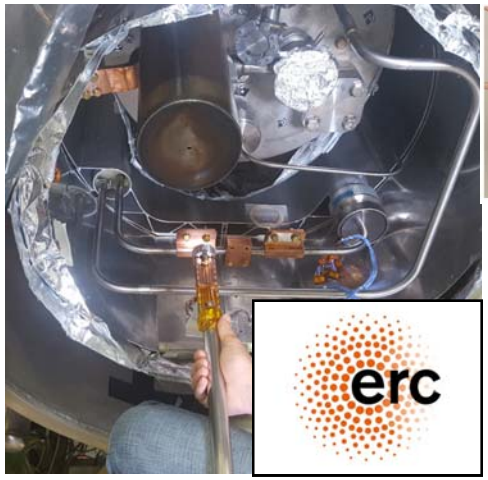
J. Jaeckel and L. J. Thormaehlen,
Arxiv 1908.10878



- the peak strength is directly related to the abundance of metal in the interior of the Sun
- peaks can tell us about the atomic states in the environment of the interior of the Sun

(Baby)IAXO magnetic volume for DM axion

- RADES R&D exploring new concept to fill large V with high-frequency cavities
- Proof-of-concept at small scale successful tested in CAST



Part of ERC-StG (2018)
B. Döbrich/CERN

DESY PRC endorsed BabyIAXO

General remarks

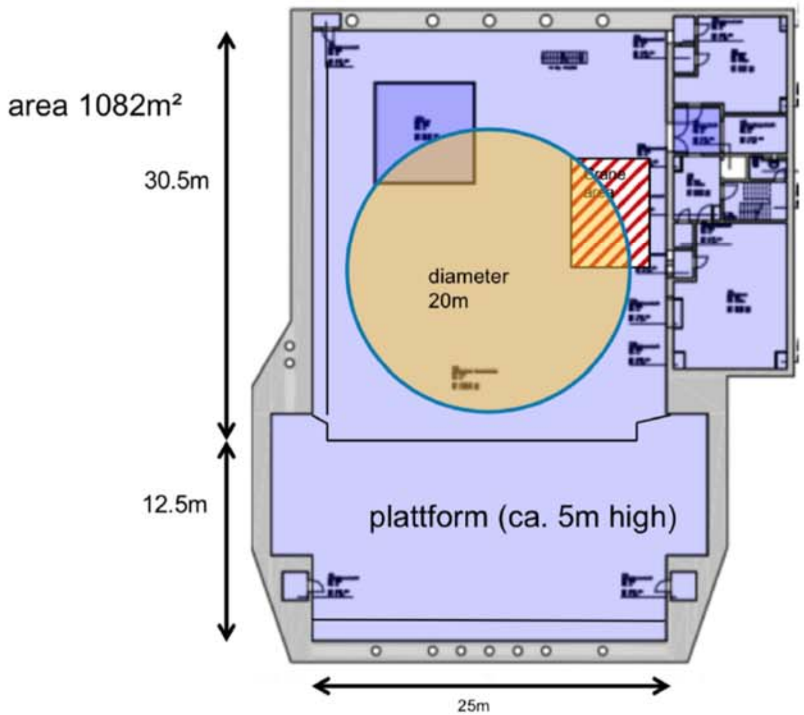
At the 87th meeting of the PRC, a dedicated review panel evaluated the case for the realisation of the babyIAXO experiment – as a precursor for IAXO – at DESY. The chair of the panel reported to the PRC about the outcome of the review. A written report will follow in due time. The PRC welcomes very much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

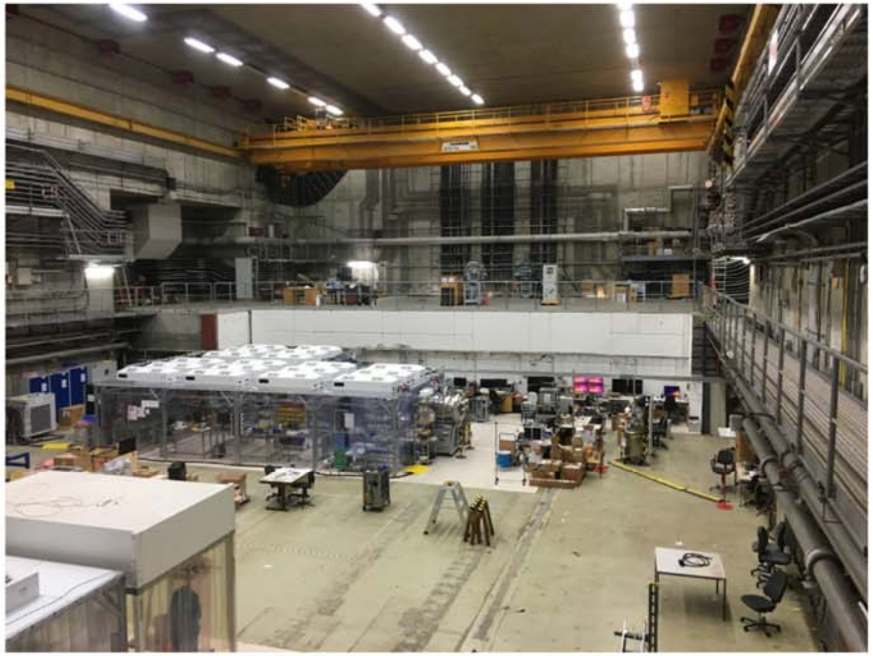
In-depth review of BabyIAXO on 20th May

- List of recommendations → preparation of a document with answers
- Biannual PRC meetings → Next 12/13 November DESY-Hamburg

Baby-IAXO @DESY (I)

Housing and Infrastructures





HERA South hall: defined site for BabyIAXO
DESY infrastructure & expertises very well suited to IAXO

Sun Allignment system: how to link local RF coordinates with astronomical coordinates.
on-going evaluation of possibilities

Baby-IAXO @DESY (II)

Drive mount & platform

- Concerns from PRC regarding suitability of CTA mount

  → Solved

  → Document from Zeuthen experts

- Plans to dismount platform and move it to DESY-Hamburg

Beschleuniger | Forschung mit Photonen | Teilchenphysik

Deutsches Elektronen-Synchrotron
Ein Forschungszentrum der Helmholtz-Gemeinschaft

DESY

BabyIAXO review
Feedback to the telescope positioner comments

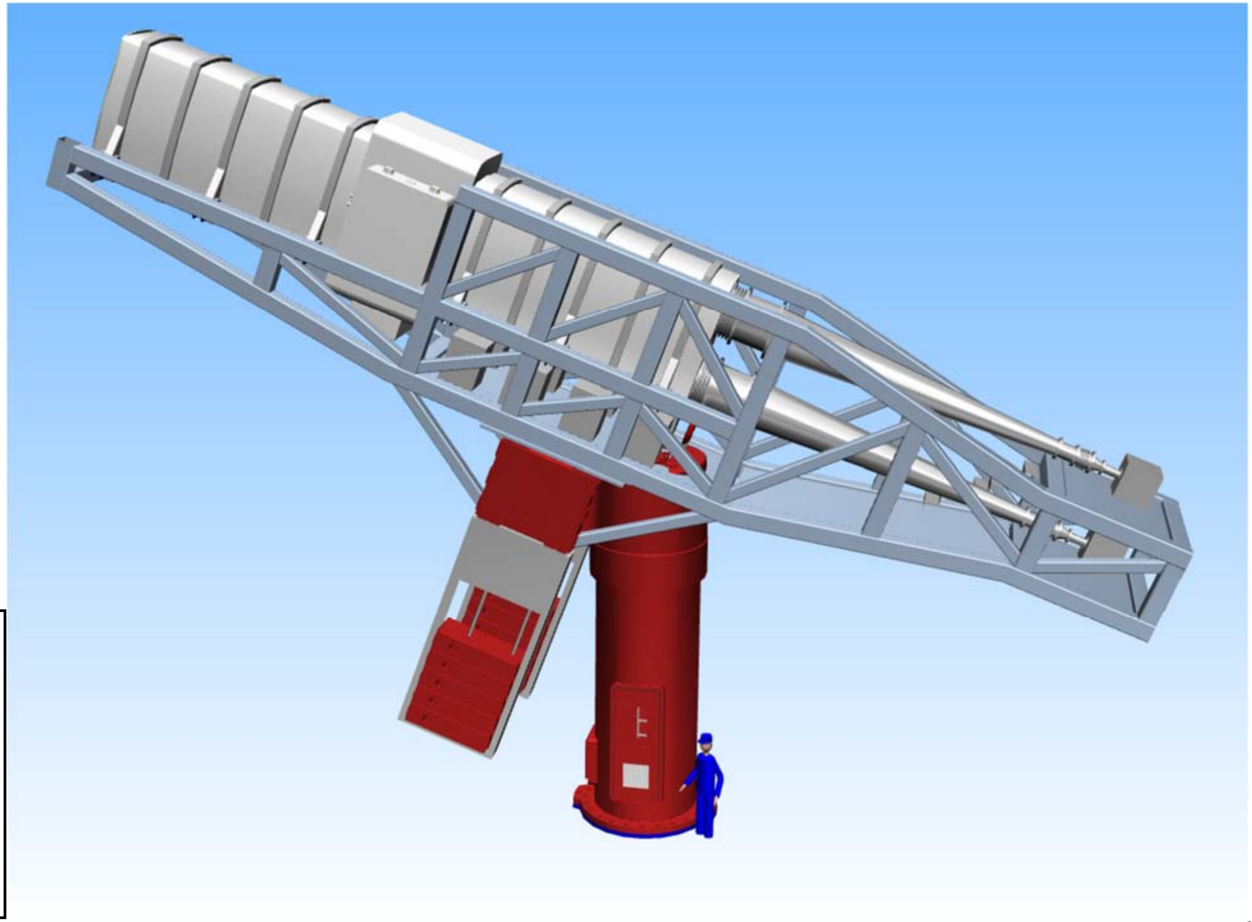
Authors: Markus Garczarczyk (DESY)
Ullrich Schwanke (Humboldt University)
Ronny Sternberger (DESY)

Date: 22.07.2019

This letter addresses the questions from the review panel and gives more detailed information about the drive system implemented at the Medium Size Telescope (MST) prototype. The MST prototype was built in 2012 in Berlin with the goal to validate the design and prepare the mass production of the telescopes for CTA. It is planned to dismount the prototype telescope in the first quarter of 2020 and re-use the positioner for the BabyIAXO experiment.

Baby-IAXO: progress in 2019

- Magnet
- Optics
- Detectors

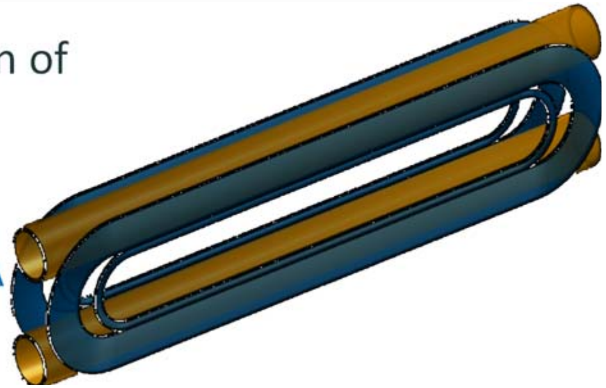


European Research Council
Established by the European Commission

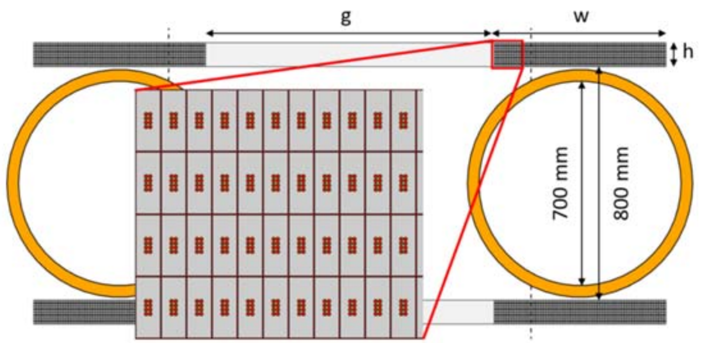
ERC-AvG 2017 IAXO+

Baby-IAXO magnets (I)

- 2-double pancake windings for Baby-IAXO as baseline design of IAXO winding
- Nominal operating current 9.8 kA
- Ultimate performance may be ≈ 20% more in current, 12 kA



Winding

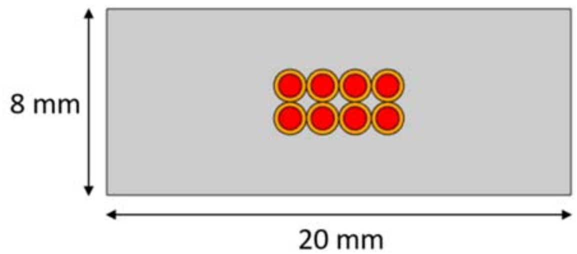


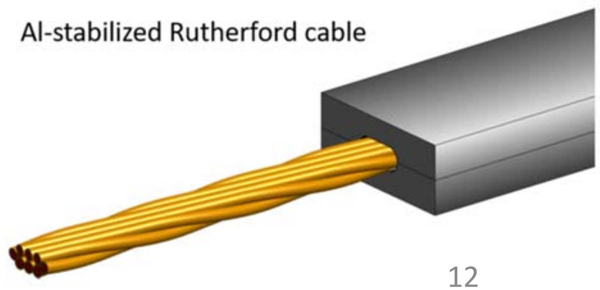
Cable:

Rutherford cable with

8 NbTi/Cu strands

(1.4 mm diameter)





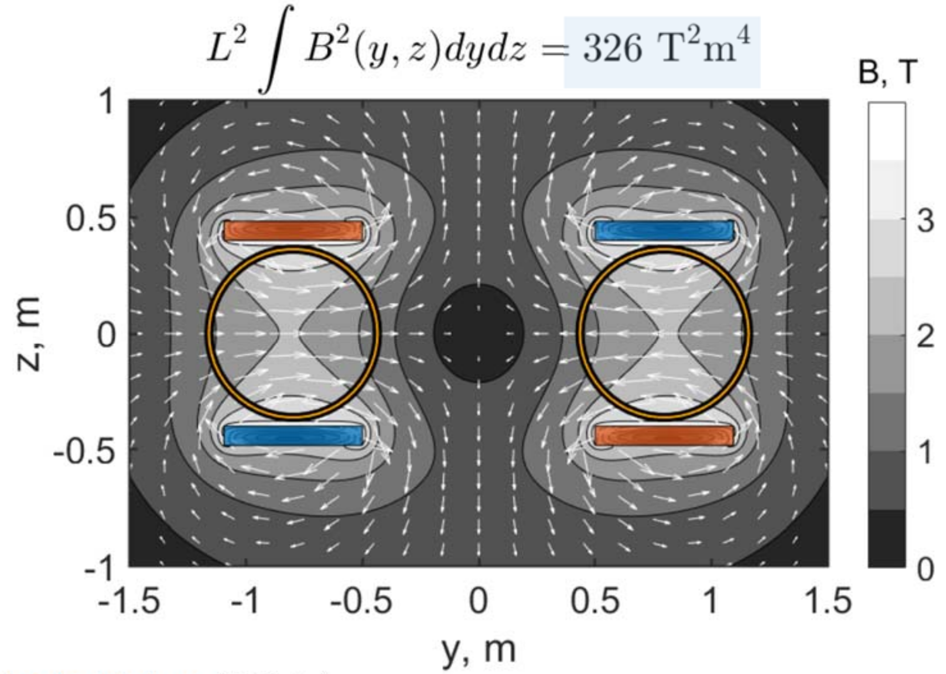
Baby-IAXO magnets (II)

- 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

  $f_M = B^2 L^2 A$

  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

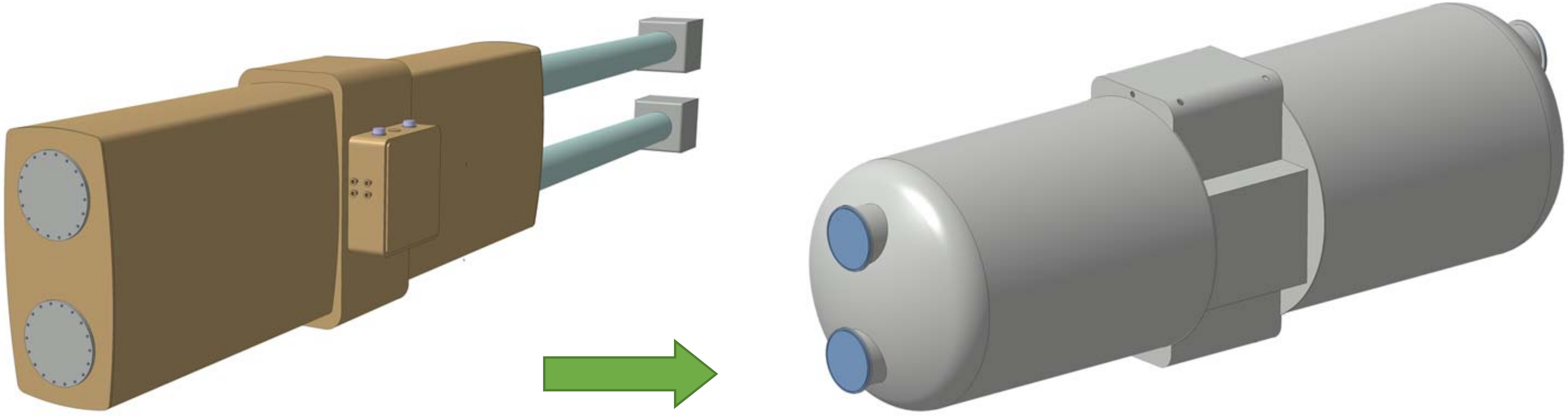
- Cryogenics:

  cryocoolers based cooling system

  evaluation of the heat load

Cryostat design → changed

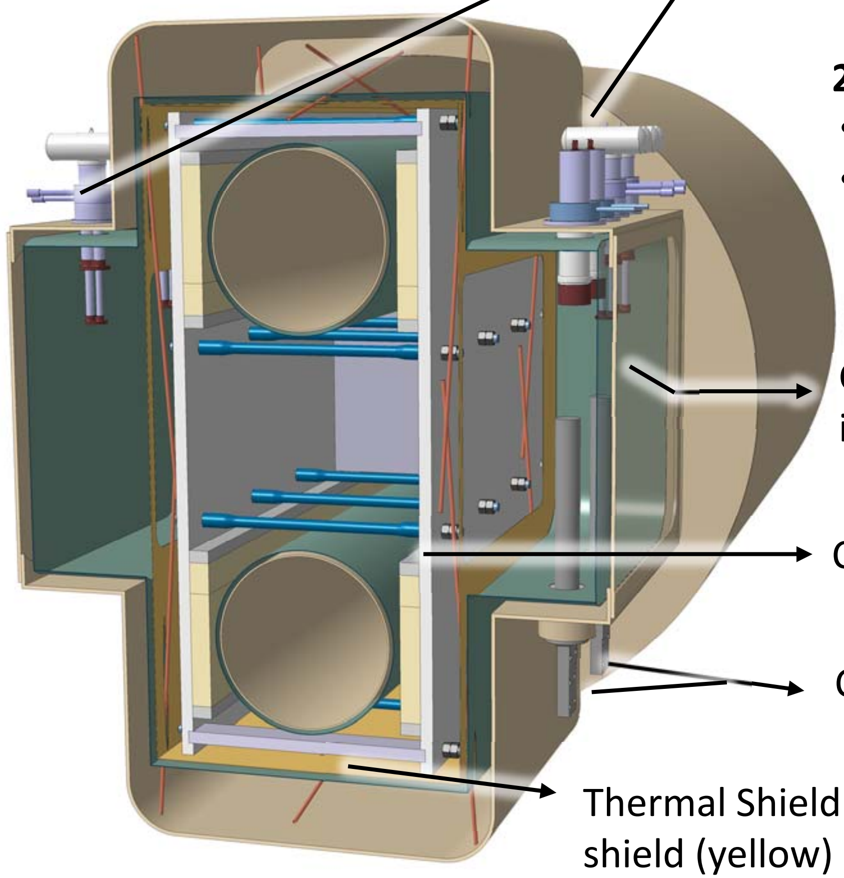
Baby-IAXO magnets (III)



- A cylindrical vessel is cheaper to manufacture
- Stainless steel is the chosen material for highest reliability of vacuum welds and seals
- Connection of cryostat to support frame is in the center post where all services arrive
- Loads transferred to the frame:
    Weight of the cold mass and thermal shield (20 t)
    Weight of the cryostat (15 t)

→ Definition of the interface between magnet, optics and detectors, as well support and services

Baby-IAXO magnets (IV)



6 Cryocoolers:
- 4 x PT420 (8-10W@4.2K)
- 2 x Al600 (700W@50K)

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

Cryogenics and instrumentation interface

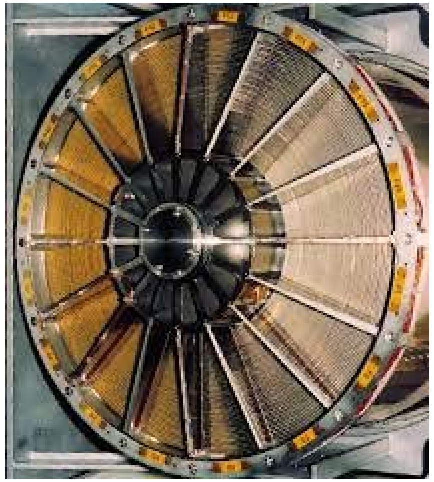
Cold Mass at 4.5 K

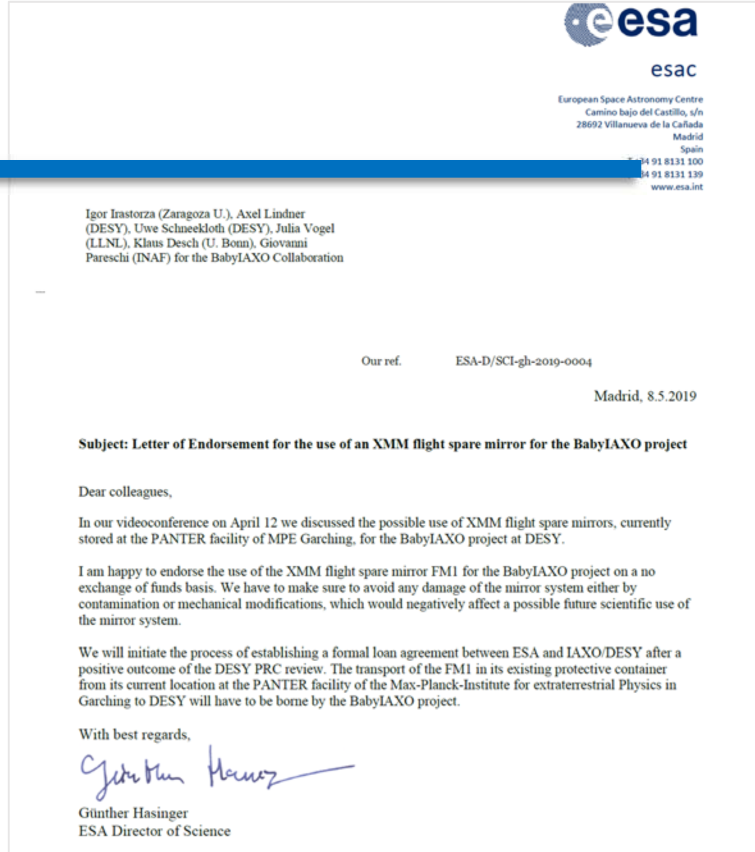
Current Leads

Thermal Shield at ≈45 K + floating shield (yellow)

Baby-IAXO Optics

ESA supports the use of a XMM optics for BabyIAXO
Letter of endorsement from G. Hasinger
(ESA Director of Science)





esa

esac

European Space Astronomy Centre
Camino bajo del Castillo, s/n
28692 Villanueva de la Cañada
Madrid
Spain
34 91 8131 100
34 91 8131 139
www.esa.int

Igor Irastorza (Zaragoza U.), Axel Lindner (DESY), Uwe Schneekloth (DESY), Julia Vogel (LLNL), Klaus Desch (U. Bonn), Giovanni Pareschi (INAF) for the BabyIAXO Collaboration

Our ref. ESA-D/SCI-gh-2019-0004

Madrid, 8.5.2019

Subject: Letter of Endorsement for the use of an XMM flight spare mirror for the BabyIAXO project

Dear colleagues,

In our videoconference on April 12 we discussed the possible use of XMM flight spare mirrors, currently stored at the PANTER facility of MPE Garching, for the BabyIAXO project at DESY.

I am happy to endorse the use of the XMM flight spare mirror FM1 for the BabyIAXO project on a no exchange of funds basis. We have to make sure to avoid any damage of the mirror system either by contamination or mechanical modifications, which would negatively affect a possible future scientific use of the mirror system.

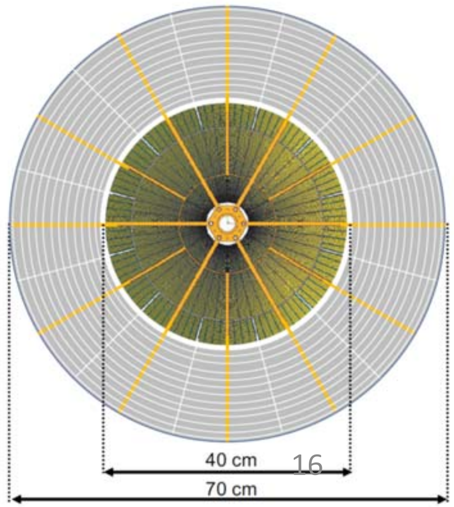
We will initiate the process of establishing a formal loan agreement between ESA and IAXO/DESY after a positive outcome of the DESY PRC review. The transport of the FM1 in its existing protective container from its current location at the PANTER facility of the Max-Planck-Institute for extraterrestrial Physics in Garching to DESY will have to be borne by the BabyIAXO project.

With best regards,

Günther Hasinger
ESA Director of Science

Progress towards definition of a roadmap to build a new Custom x-ray telescope using a segmented-glass approach

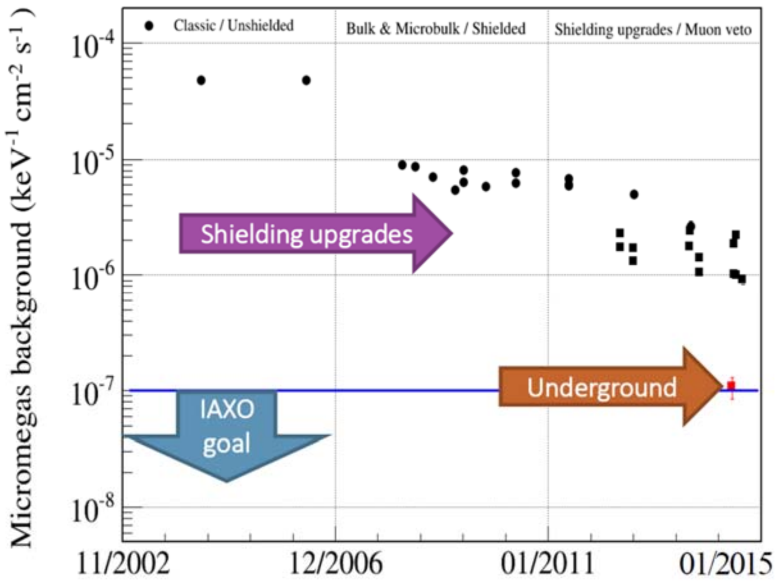
- The inner part from r =5 cm to r =20 cm will rely on the same technology as the NuSTAR telescopes (hot-slumped, multilayer-coated glass)
- The outer part from r = 20 cm r = 35 cm will be covered using cold-slumped glass (INAF – financed project)



Baby-IAXO detectors

Steady progress with the Micromegas test benches & background model:

- IAXO-D0 @ UNIZAR to be equipped with INR muon vetoes…
- IAXO pathfinder reinstalled in the CAST magnet



Intensive low-background development during the last years

The background level targeted for for BabyIAXO is at least of 10^{-7} c/keV/cm^2/s

University of Zaragoza

Baby-IAXO detectors – new technologies

GridPix, metallic Magnetic Calorimeters (MMC), NbSi Transition Edge Sensors (TES), Silicon Drift Detectors (SSD) and Neutron Transmutation Doped Ge sensors (NTD) are interesting because:

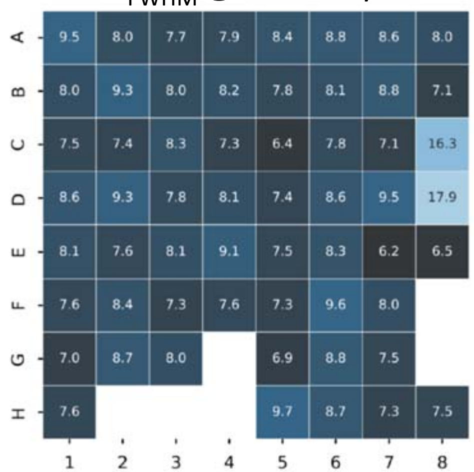
- excellent energy resolution,
- energy threshold,
- efficiency
- possibility to use ultra-pure materials

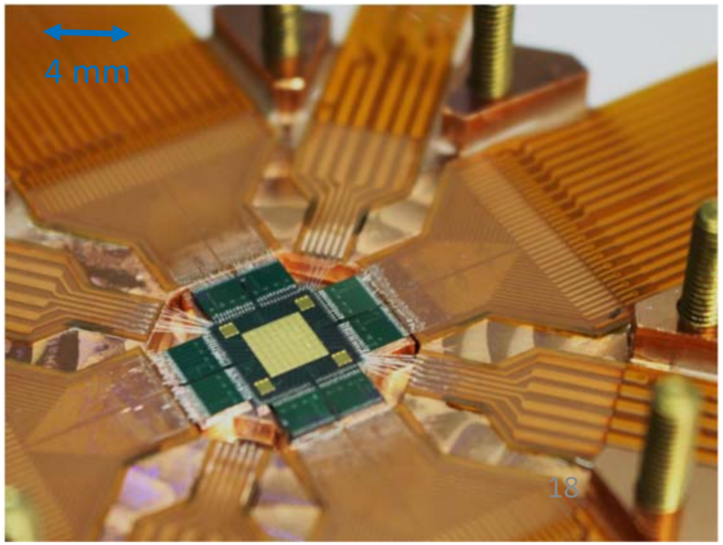
Supported by
- ANR (France) „DALPS“ proposal
- BMBF (Germany) „5H2018 - R&D Detektoren (Axionen)“ Proposal

New MMC-IAXO detector platform

- 4×4 mm^2
- 0.5 mm position resolution
- ΔE_{FWHM} @ 5.9 keV < 10 eV
- bg ~ 10^{-4} Counts/keV/cm^2/s (mainly muon induced)

ΔE_{FWHM} @ 5.9 keV / eV





Conclusions

DESY PRC endorsed IAXO

Baby-IAXO will be hosted in HERA Hall II at DESY

CTA Medium Size Telescope platform suitable for Baby-IAXO

Moved from Berlin to Hamburg in 2020

Magnet conceptual design finished

qualification of coil material and winding methods as well as mechanical stability

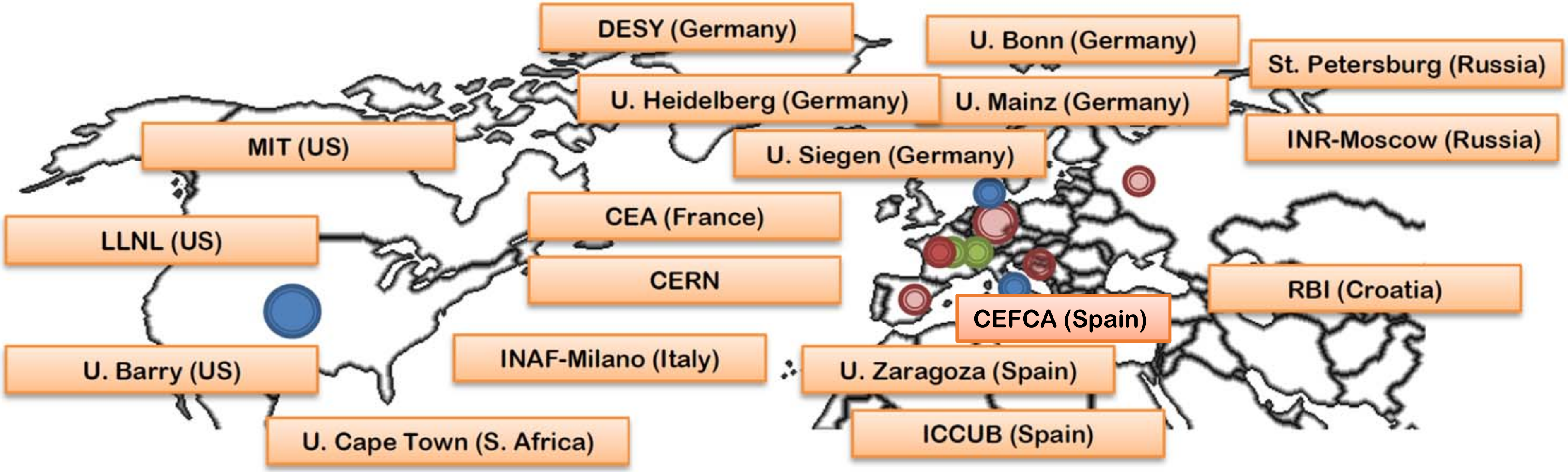
on going R&D for defining electrical circuit and cryogenics

ESA XMM optics available for Baby-IAXO and on-going R&D for a new IAXO dedicated optics

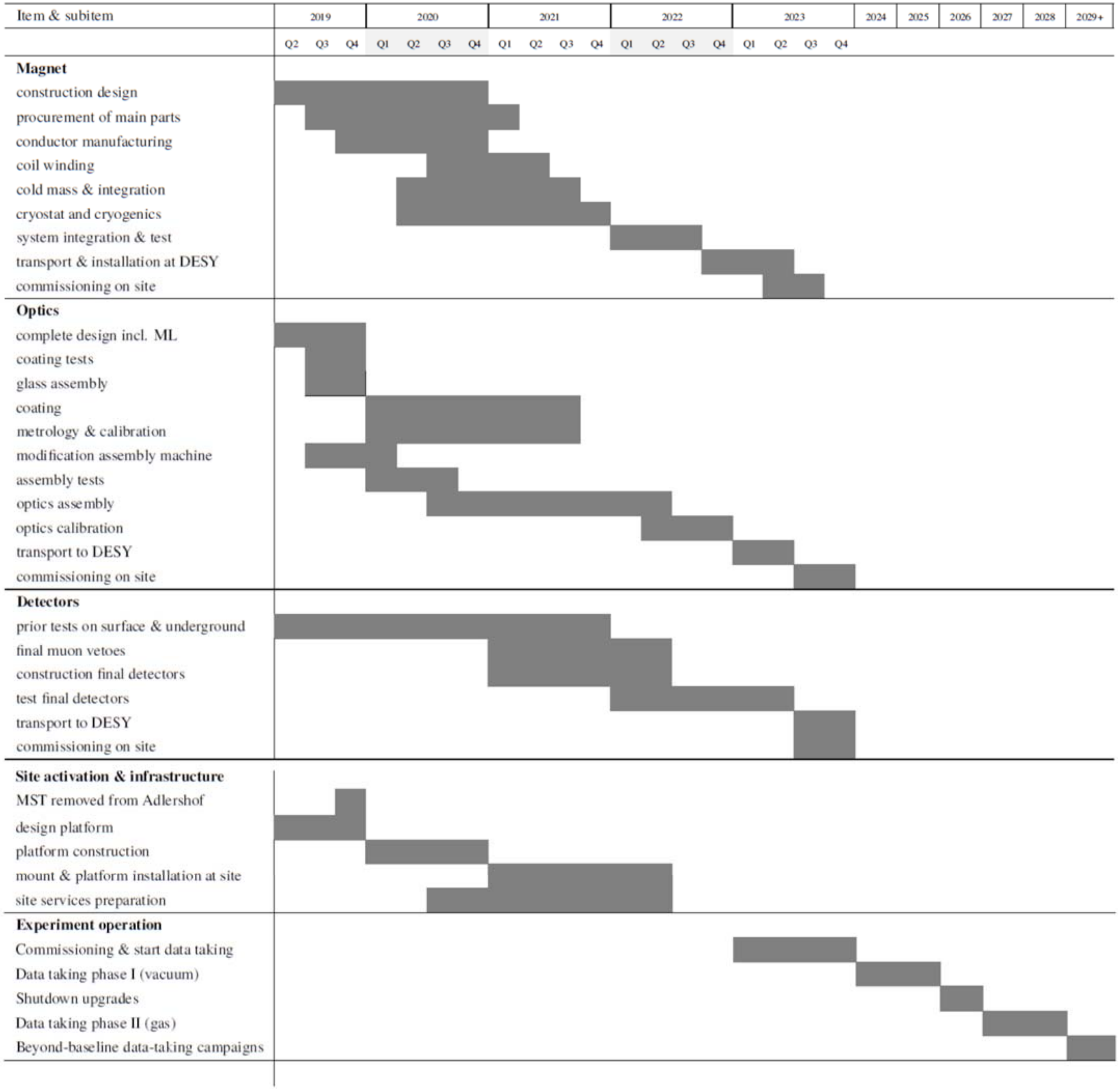
Micromegas detector are approaching the design figure of merit

New detector technologies can overcome moderate energy resolution of MM

Very exciting time for the IAXO collaboration!


DESY (Germany)
U. Bonn (Germany)
St. Petersburg (Russia)
U. Heidelberg (Germany)
U. Mainz (Germany)
MIT (US)
INR-Moscow (Russia)
U. Siegen (Germany)
CEA (France)
LLNL (US)
CERN
RBI (Croatia)
CEFCA (Spain)
U. Barry (US)
INAF-Milano (Italy)
U. Zaragoza (Spain)
U. Cape Town (S. Africa)
ICCUB (Spain)

Thank you!


Item & subitem
2019
2020
2021
2022
2023
2024
2025
2026
2027
2028
2029+
Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4 Q1 Q2 Q3 Q4
Magnet
construction design
procurement of main parts
conductor manufacturing
coil winding
cold mass & integration
cryostat and cryogenics
system integration & test
transport & installation at DESY
commissioning on site
Optics
complete design incl. ML
coating tests
glass assembly
coating
metrology & calibration
modification assembly machine
assembly tests
optics assembly
optics calibration
transport to DESY
commissioning on site
Detectors
prior tests on surface & underground
final muon vetoes
construction final detectors
test final detectors
transport to DESY
commissioning on site
Site activation & infrastructure
MST removed from Adlershof
design platform
platform construction
mount & platform installation at site
site services preparation
Experiment operation
Commissioning & start data taking
Data taking phase I (vacuum)
Shutdown upgrades
Data taking phase II (gas)
Beyond-baseline data-taking campaigns

Energy resolution and threshold

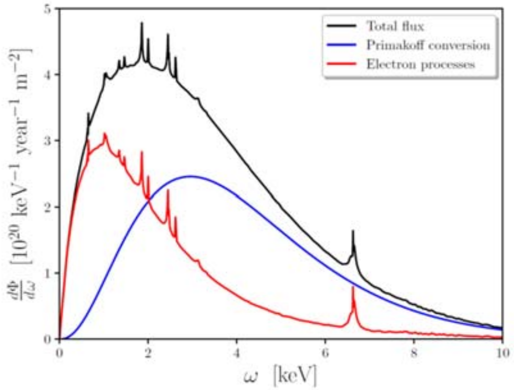
Distinguishing Axion Models with IAXO

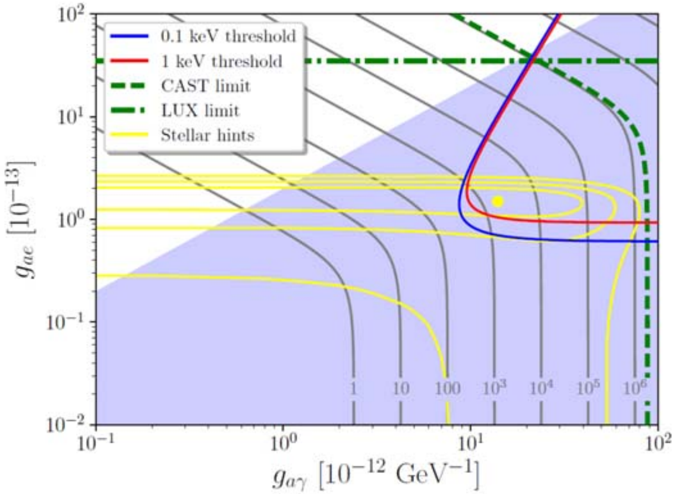
J. Jaeckel and L. J. Thormaehlen,

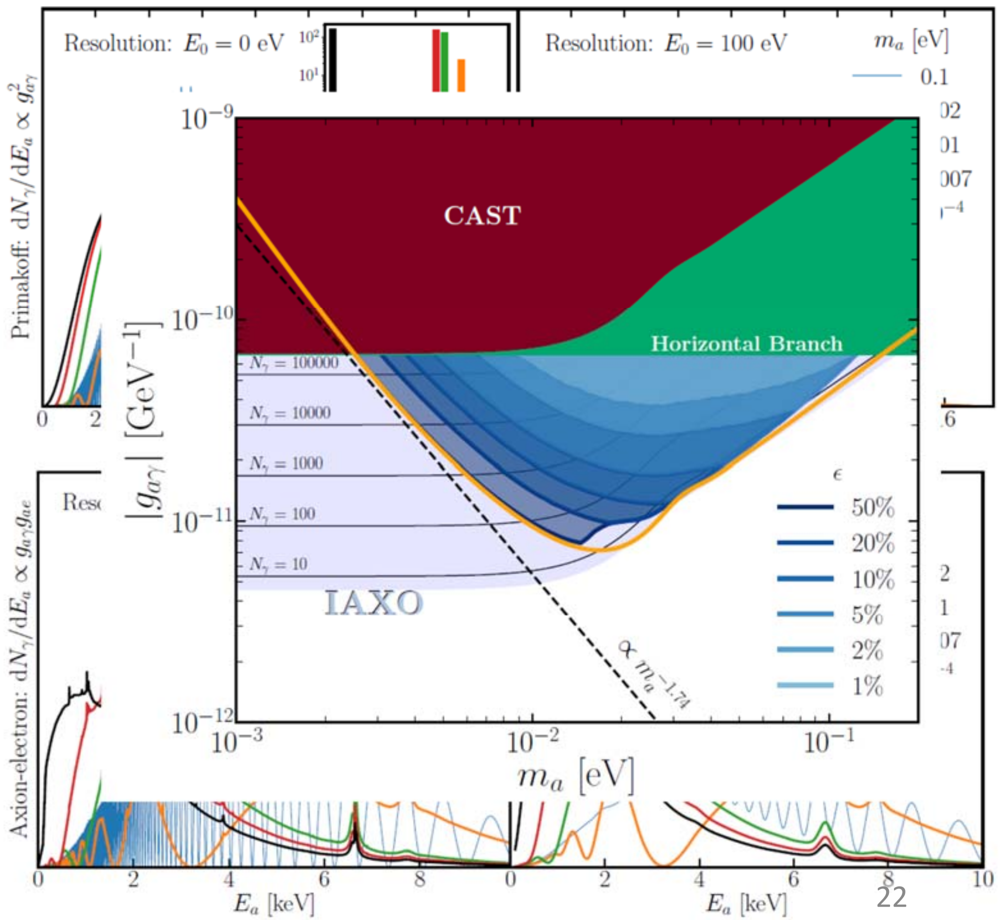
DOI: 10.1088/1475-7516/2019/03/039

Weighing the Solar Axion

T. Dafni et al., Phys. Rev. D 99, 035037 (2019)

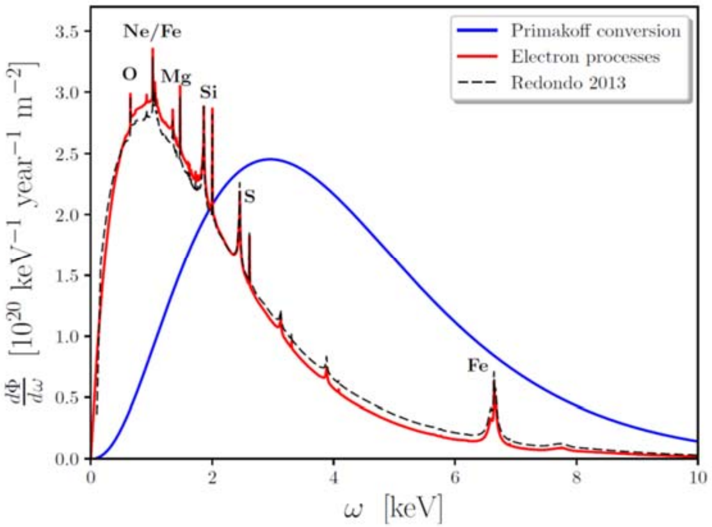


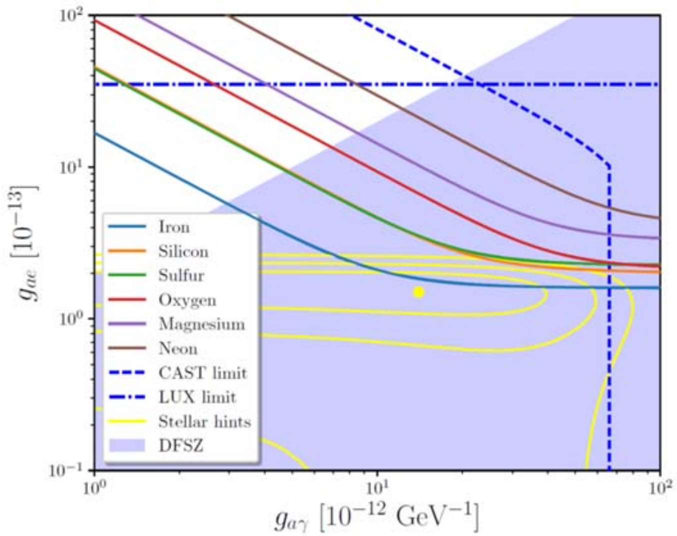




Additional Physics

Axions as a probe of solar metals
J. Jaeckel and L. J. Thormaehlen,
Arxiv 1908.10878





- the peak strength is directly related to the abundance of metal in the interior of the Sun
- peaks can tell us about the atomic states in the environment of the interior of the Sun

Helioscopes – experiments

1st generation helioscope: Brookhaven

- Short run (just a few hours of data)
  Lazarus et at. *PRL* 69 (1992) 2333

2nd generation: Tokyo Helioscope (SUMICO)

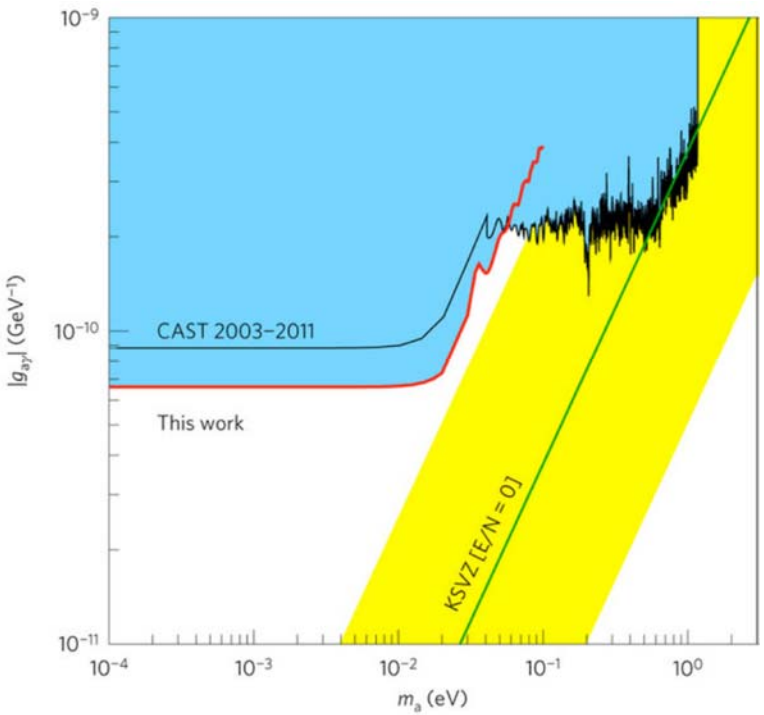
- 2.3m long, 4T magnet
  Moriyama et al., *Phys. Lett. B* 434 (1998) 147

3rd generation: CERN Axion Solar Telescope (CAST)

- Most sensitive axion helioscope to date (10m, 9T)
- Best experimental limit on axion-photon coupling over broad axion mass range

$$g_{a\gamma} < 0.66 \times 10^{-10}\ \text{GeV}^{-1}\ (95\%\ \text{C.L.})$$

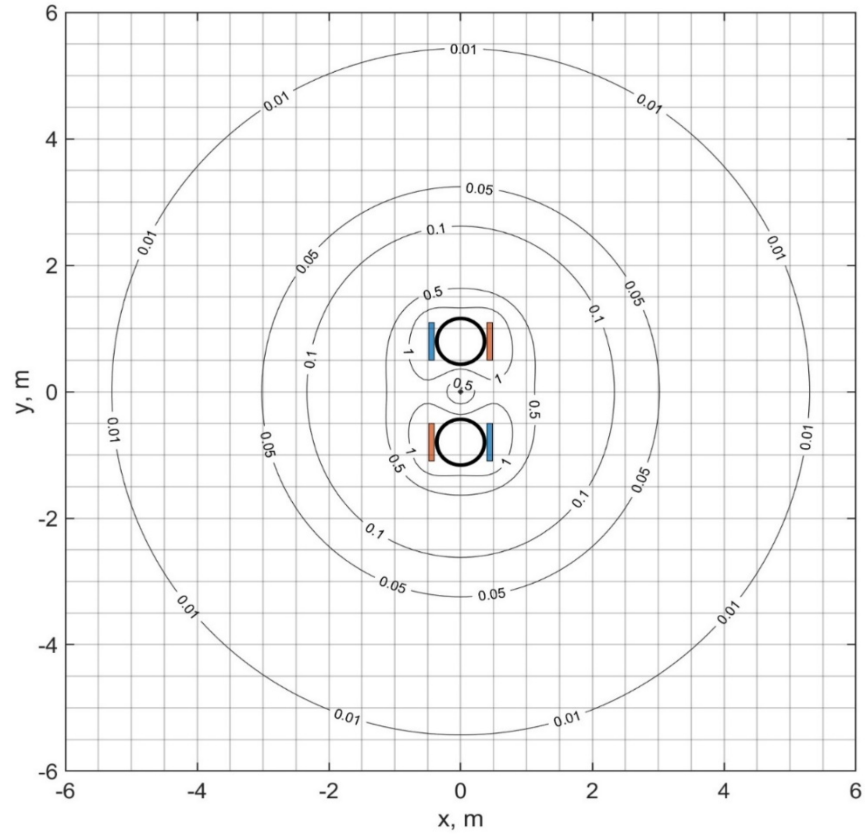
- Latest results enabled by IAXO-pathfinder: NuSTAR-like X-ray optic coupled with low background Micromegas



CAST Collaboration *Nature Phys.* 13 (2017) 584

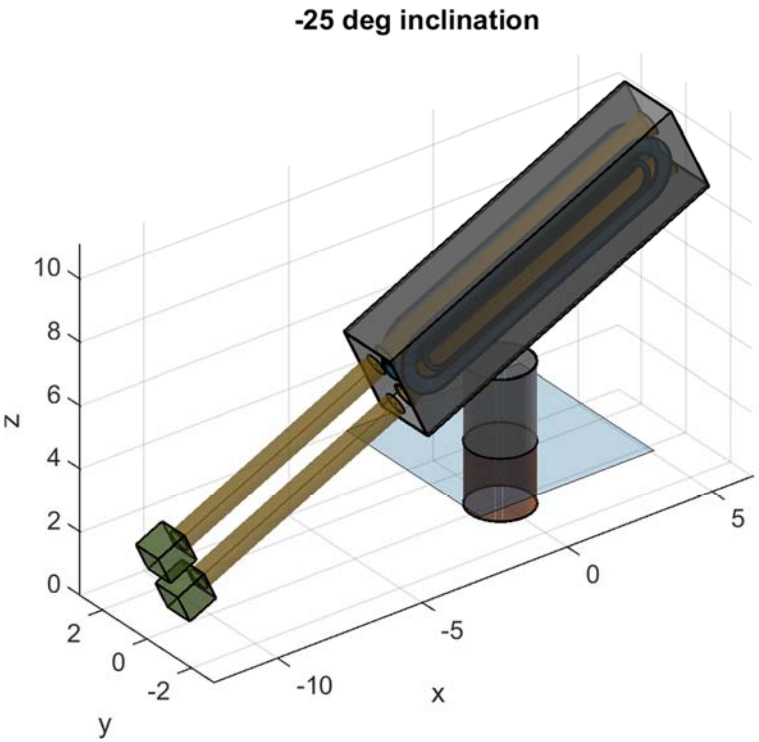
Baby-IAXO magnets – stray fields

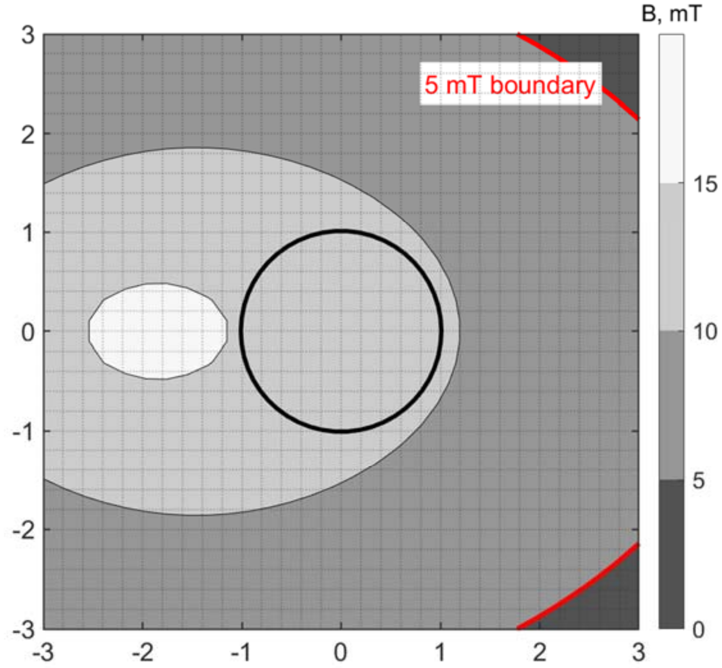
- Assuming no shielding properties of cold mass nor cryostat (non-magnetic)



Baby-IAXO magnets – stray fields

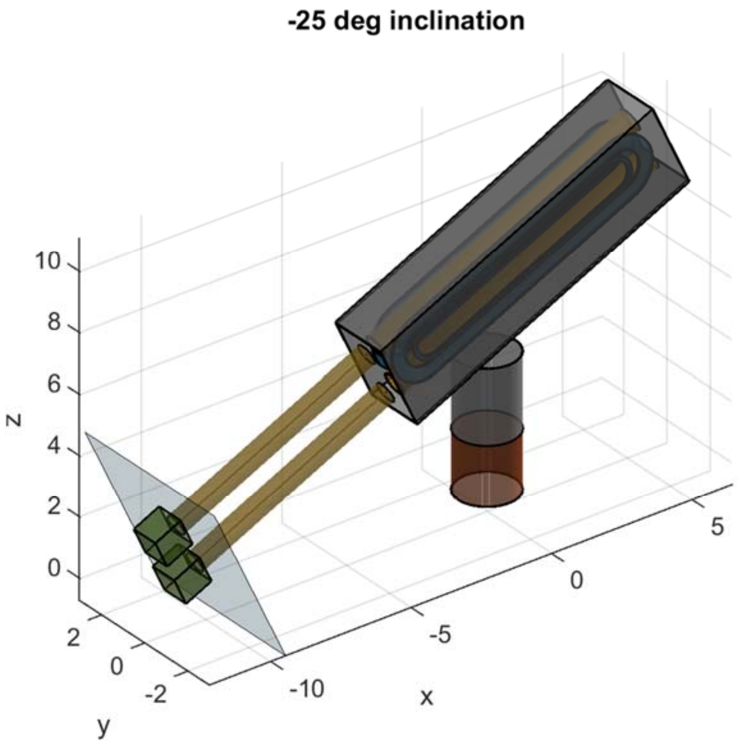
- Assuming no shielding properties
  of cold mass nor cryostat (non-magnetic)
- Plane 2 m above the floor

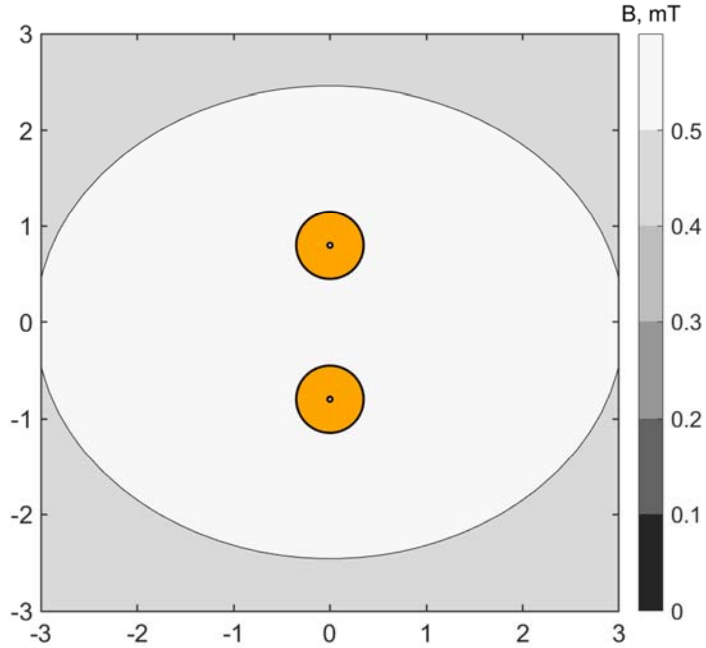




Baby-IAXO magnets – stray fields

- Assuming no shielding properties
  of cold mass nor cryostat (non-magnetic)
- Plane 2 m above the floor
- Plane at the end of optics (7.5 m away from the cryostat)





Baby-IAXO optics

The performance of an x-ray optic is characterized by three basic properties:

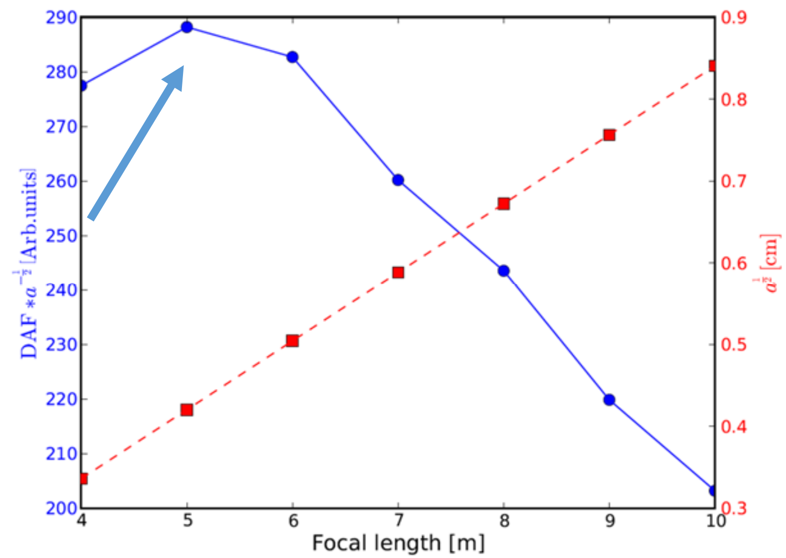
- the point spread function (PSF) determining the shape and size of the focal spot *a*
- the throughput, ε_O, which refers to the amount of incident photons properly focused by the optic
- the field-of-view (FOV) describing how the optic can focus off-axis photons properly (slightly larger than the inner 0.9 mrad of the Solar disk)

energy range E < 10 keV
pupils 60 – 70 cm diameter

grazing-incident reflective optics

Figure of merit of the optics:

$$f_O = \frac{\varepsilon_O}{\sqrt{a}}$$



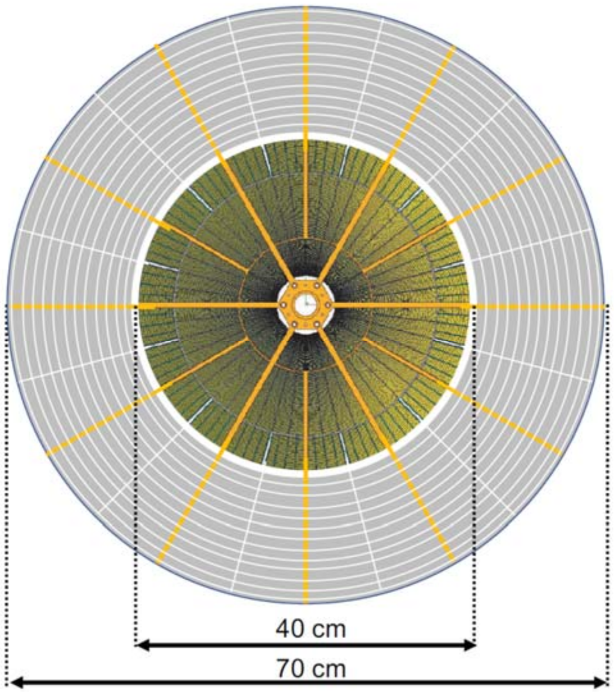
Baby-IAXO optics

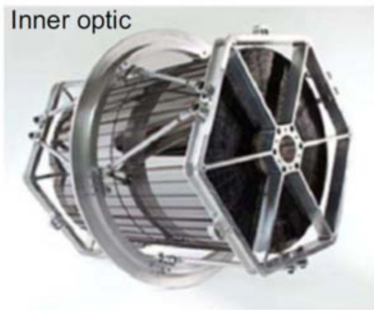
Custom x-ray telescope will use a segmented-glass approach

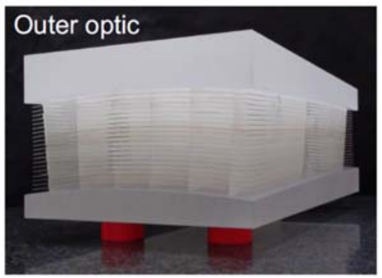
- The inner part from r =5 cm to r =20 cm will rely on the same technology as the NuSTAR telescopes (hot-slumped, multilayer-coated glass)
- The outer part from r = 20 cm r = 35 cm will be covered using cold-slumped glass and its assembly technology (INAF)

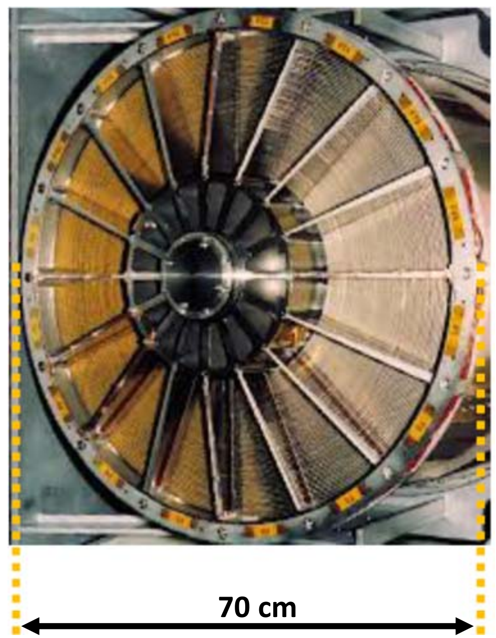
XMM x-ray telescope

specifications very close to IAXO optics design









Baby-IAXO detectors

Detector optimized for energy range below 10 keV

Important features:

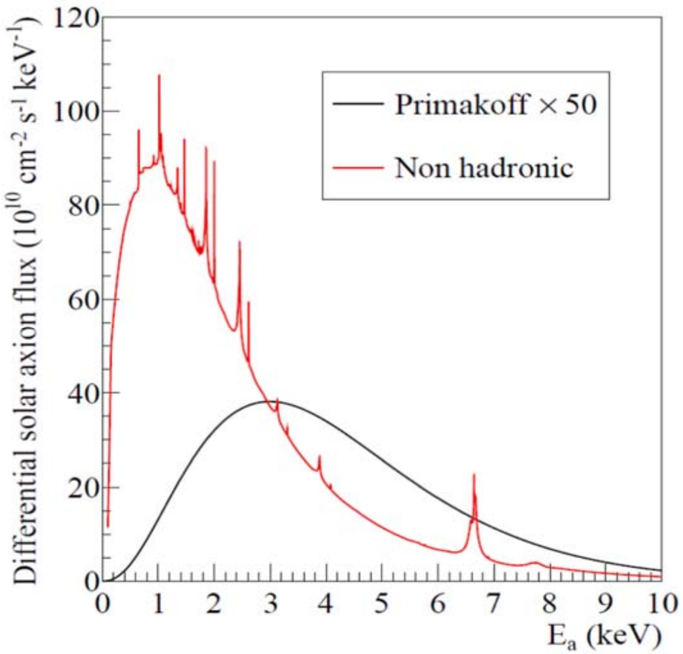
- high detection efficiency ε
- very low background *b*

but also

- position sensitivity for background reduction
- low threshold for studying axion coupling

Detector figure of merit:

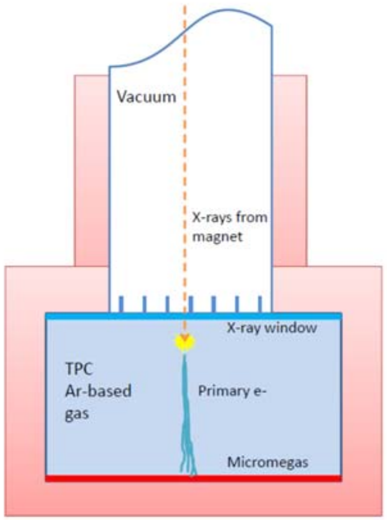
$$f_D = \frac{\varepsilon}{\sqrt{b}}$$



Baby-IAXO detectors

Baseline option: 2 Micromegas setups:

small Time Projection Chambers (TPC) with pixelated Micromegas readouts built with the microbulk technology



Successfully used in CAST

University of Zaragoza
CEA/IRFU Saclay

Baby-IAXO detectors

Baseline option: 2 Micromegas setup

Planned improvements:

conversion volume

Present: 3 cm thickness filled with 1.4 bar Argon and a small quantity of quencher as 2% isobutene (presence of ^{39}Ar)

Planned: use xenon – mixture 500 mbar of Xe plus isobutane
higher stopping power and lower intrinsic radioactivity

Baby-IAXO detectors

Baseline option: 2 Micromegas setup

Planned improvements:

conversion volume

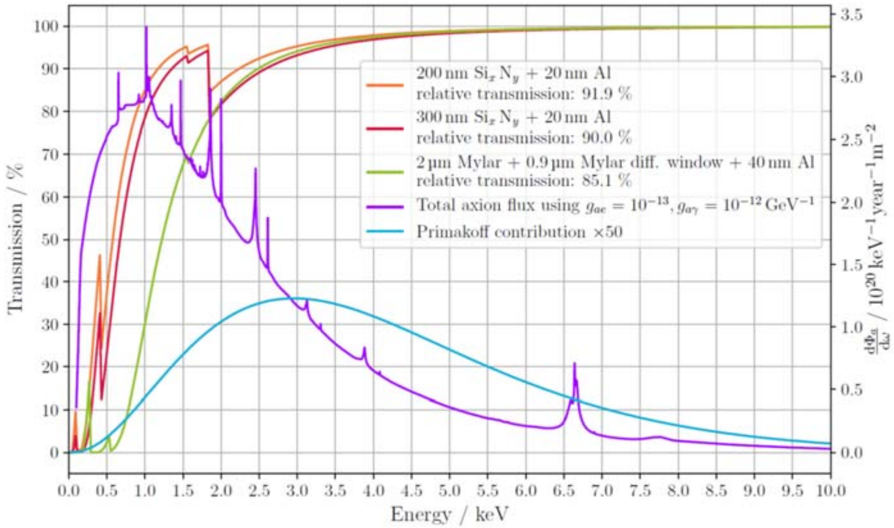
Present: 3 cm thickness filled with 1.4 bar Argon and a small quantity of quencher as 2% isobutene (presence of ^{39}Ar)

Planned: use xenon – mixture 500 mbar of Xe plus isobutane
higher stopping power and lower intrinsic radioactivity

X-ray windows

present: 2 -4 µm thick mylar foil –
transmission drops below 1.5 keV

Planned: 300 nm Si_xN_y + 20 nm Al windows
supported by silicon structures



Bonn University

Baby-IAXO detectors

Baseline option: 2 Micromegas setup

Planned improvements:

conversion volume

Present: 3 cm thickness filled with 1.4 bar Argon and a small quantity of quencher as 2% isobutene (presence of ^{39}Ar)

Planned: use xenon – mixture 500 mbar of Xe plus isobutane higher stopping power and lower intrinsic radioactivity

X-ray windows

present: 2 -4 µm thick mylar foil – transmission drops below 1.5 keV

Planned: 300 nm Si_xN_y + 20 nm Al windows supported by silicon structures

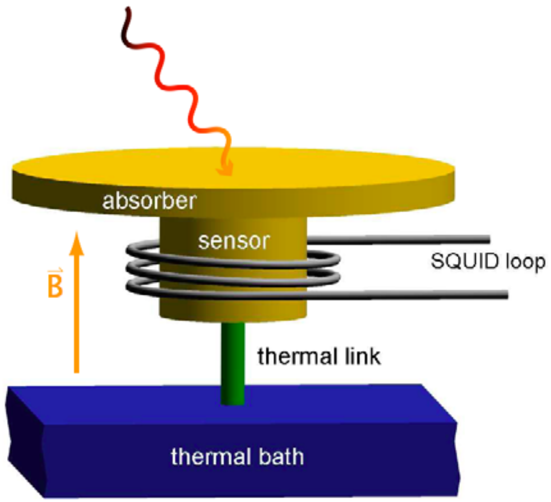
Passive and active shileding

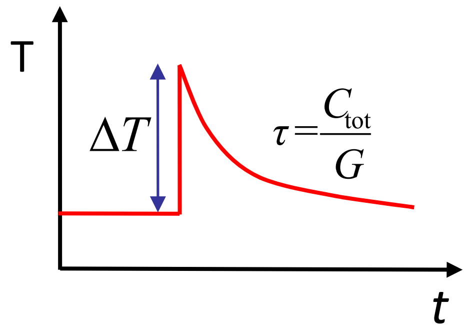
Present: 50% muon veto

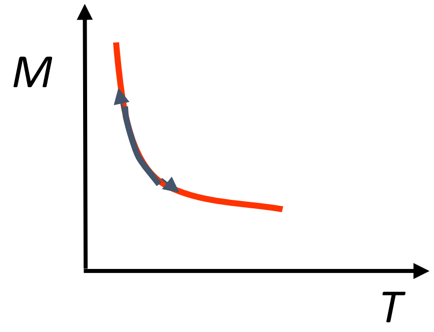
Planned: almost 4π coverage veto system

- cube of 65×65 cm^2 side plastic-scintillator muon veto system at Institute for Nuclear Research (INR) in Moscow
- alternative approach based on large bulk Micromegas detectors (100×50 cm^2) at Johannes Gutenberg University (Mainz)

Baby-IAXO detectors - MMCs







- Calorimetric principle

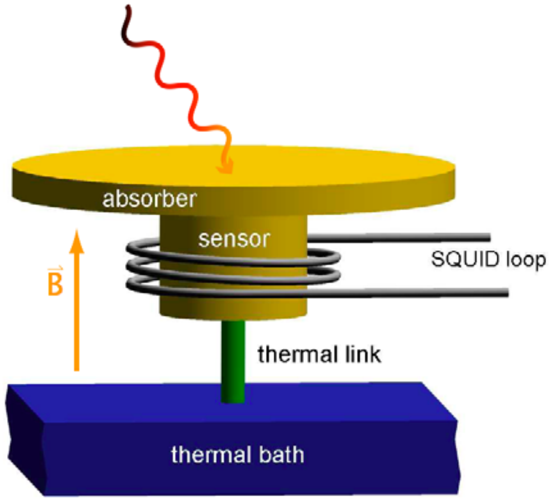
$$\Delta T \cong \frac{E}{C_{\mathrm{tot}}}$$

- Paramagnetic Au:Er sensor
  Ag:Er

$$\Delta\Phi_{\mathrm{S}} \propto \frac{\partial M}{\partial T}\Delta T \;\rightarrow\; \Delta\Phi_{\mathrm{S}} \propto \frac{\partial M}{\partial T}\,\frac{E}{C_{\mathrm{sens}}+C_{\mathrm{abs}}}$$

A. Fleischmann et al.,
AIP Conf. Proc. **1185**, 571, (2009)

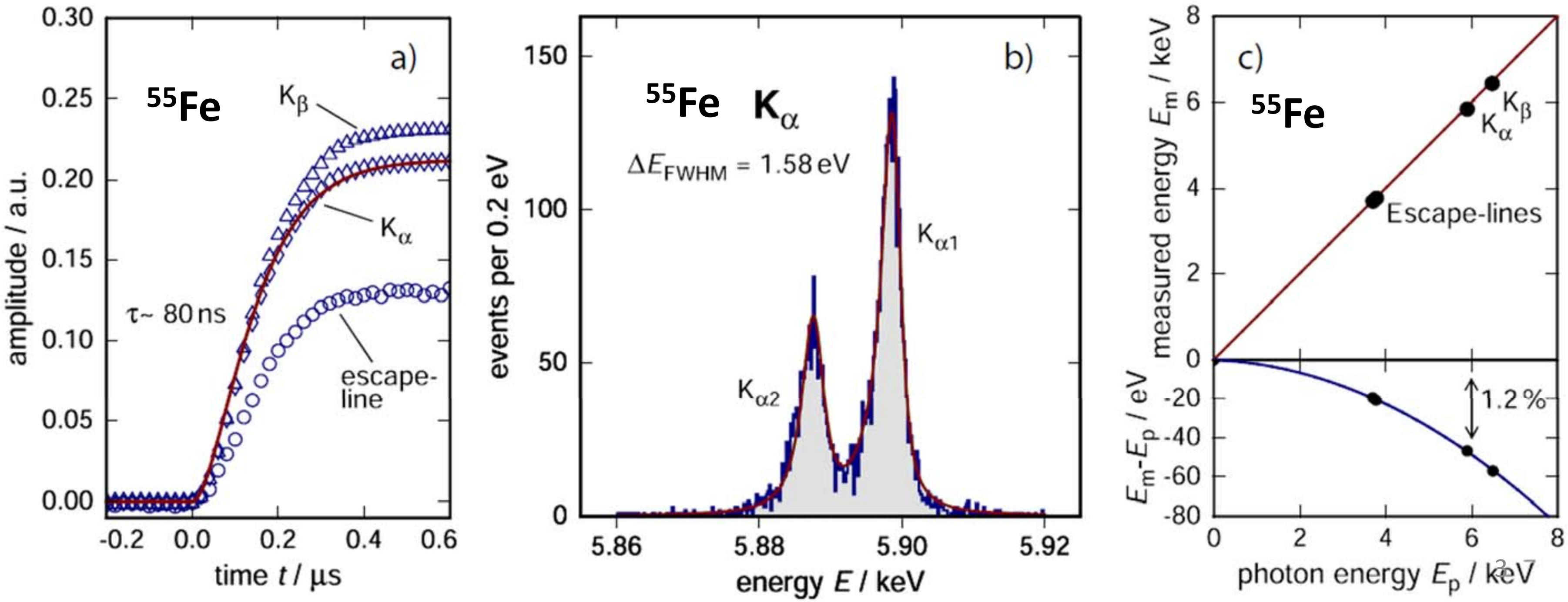
Baby-IAXO detectors - MMCs



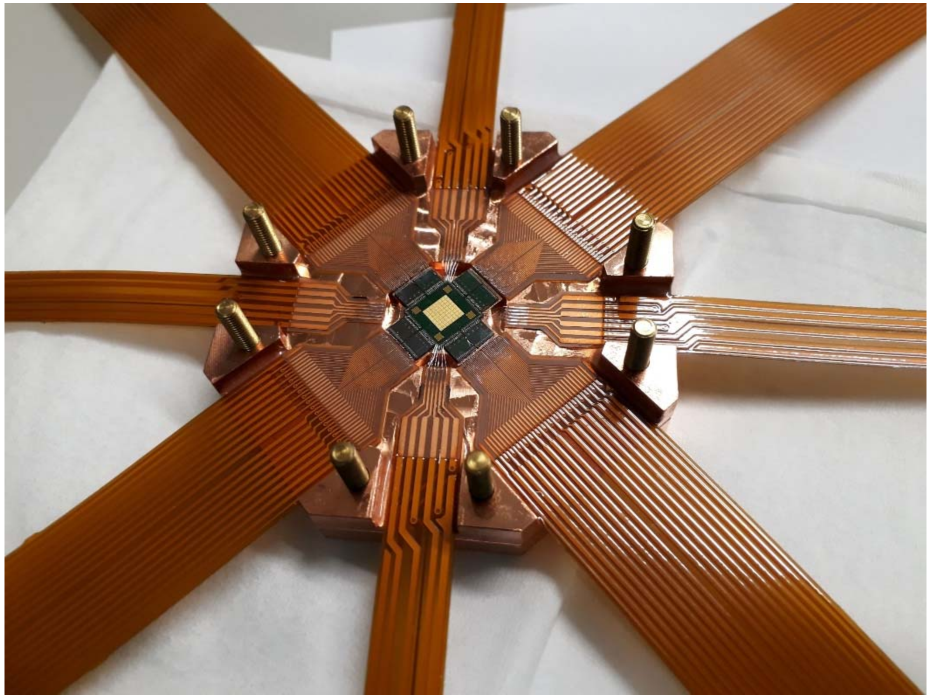
Fast risetime
→ Reduction un-resolved pile-up

Extremely good energy resolution
→Reduced smearing of resonances

Excellent linearity
→ precise definition of the energy scale



Baby-IAXO detectors - MMCs



First IAXO-MMC set-up

- 2D array – 64 pixels series maXs-20
- active area $4 \times 4\ mm^2$

Expected energy resolution: 6 eV FWHM

- Presently at 20 mK
- first test 58 pixels perfectly operating
- for 6 pixels readout problems

➢ Single pixel characterization
➢ background measurement without veto

Heidelberg University