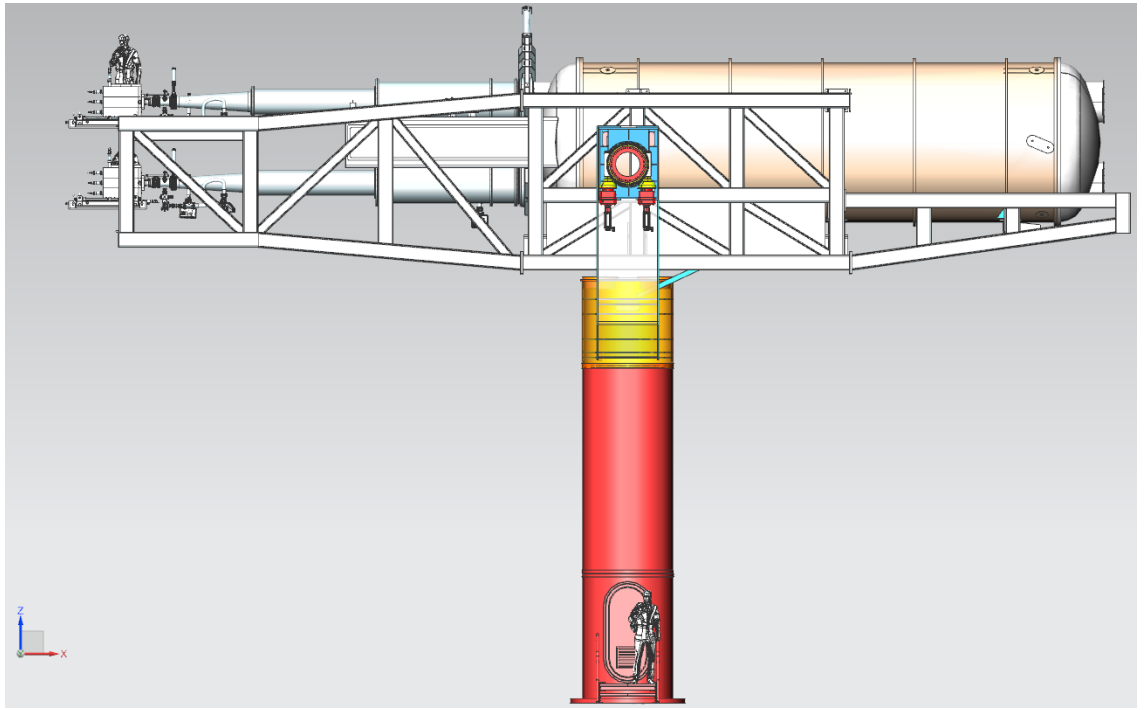
International AXion Observatory (IAXO)
Status of BabyIAXO

Igor G. Irastorza (CAPA - U. Zaragoza)
on behalf of the IAXO collaboration

Physics Beyond Colliders, CERN, March 2nd, 2021



European Research Council
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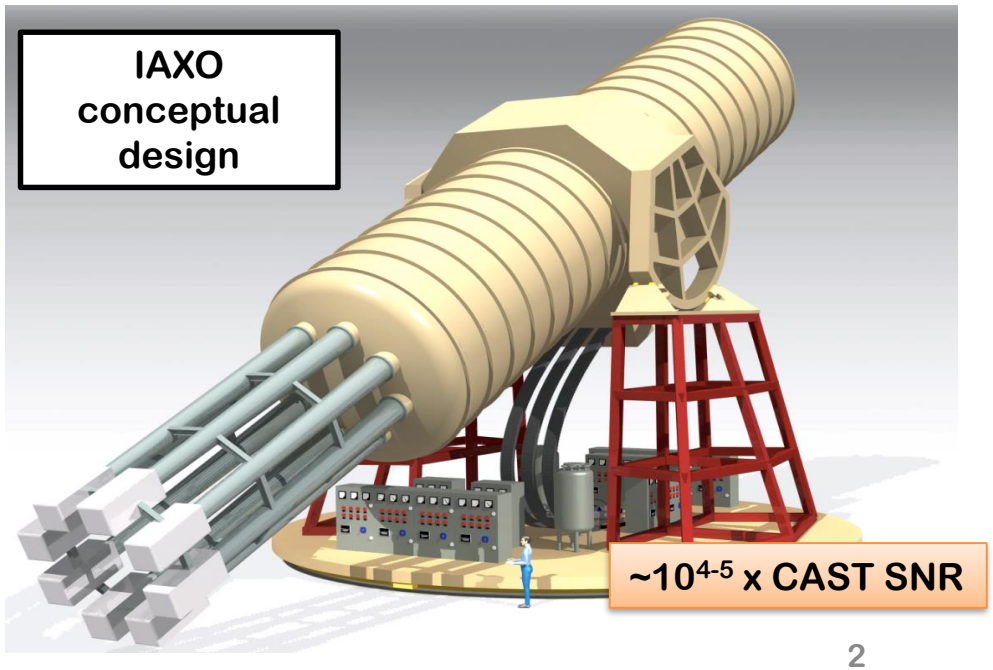
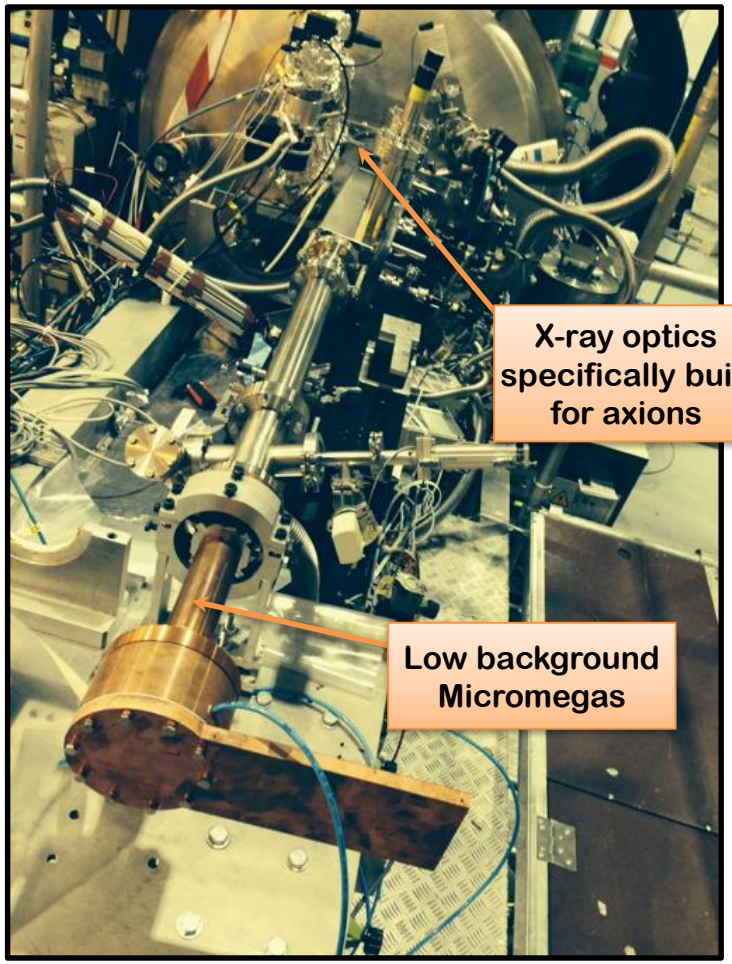
IAXO experiment summary

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

- Large magnetic volume available for additional “axion” physics (e.g. DM setups)



IAXO pathfinder at CAST



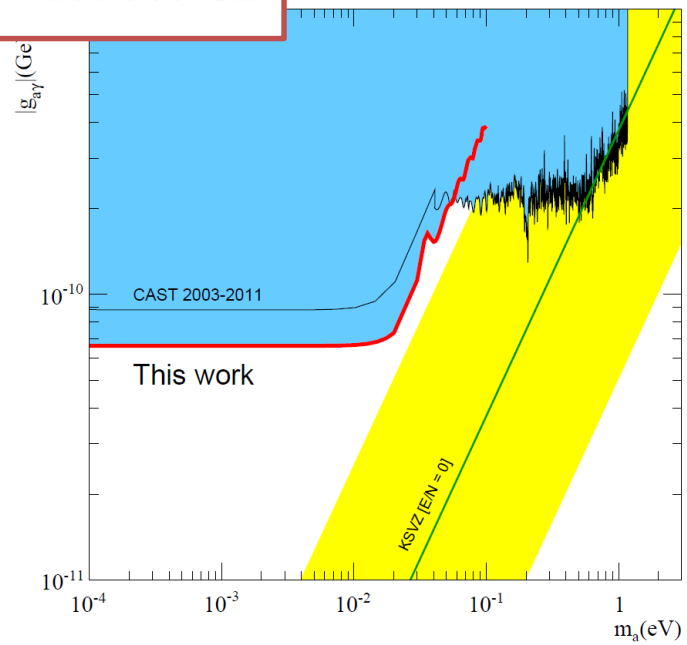
nature physics
ARTICLES
PUBLISHED ONLINE: 1 MAY 2017 | DOI: 10.1038/NPHYS4109
OPEN

New CAST limit on the axion–photon interaction

CAST Collaboration†

Hypothetical low-mass particles, such as axions, provide a compelling explanation for the dark matter in the universe. Such particles are expected to emerge abundantly from the hot interior of stars. To test this prediction, the CERN Axion Solar t directed towards the Sun. In the strong magnetic d by X-ray detectors. In the 2013–2015 run, thanks

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

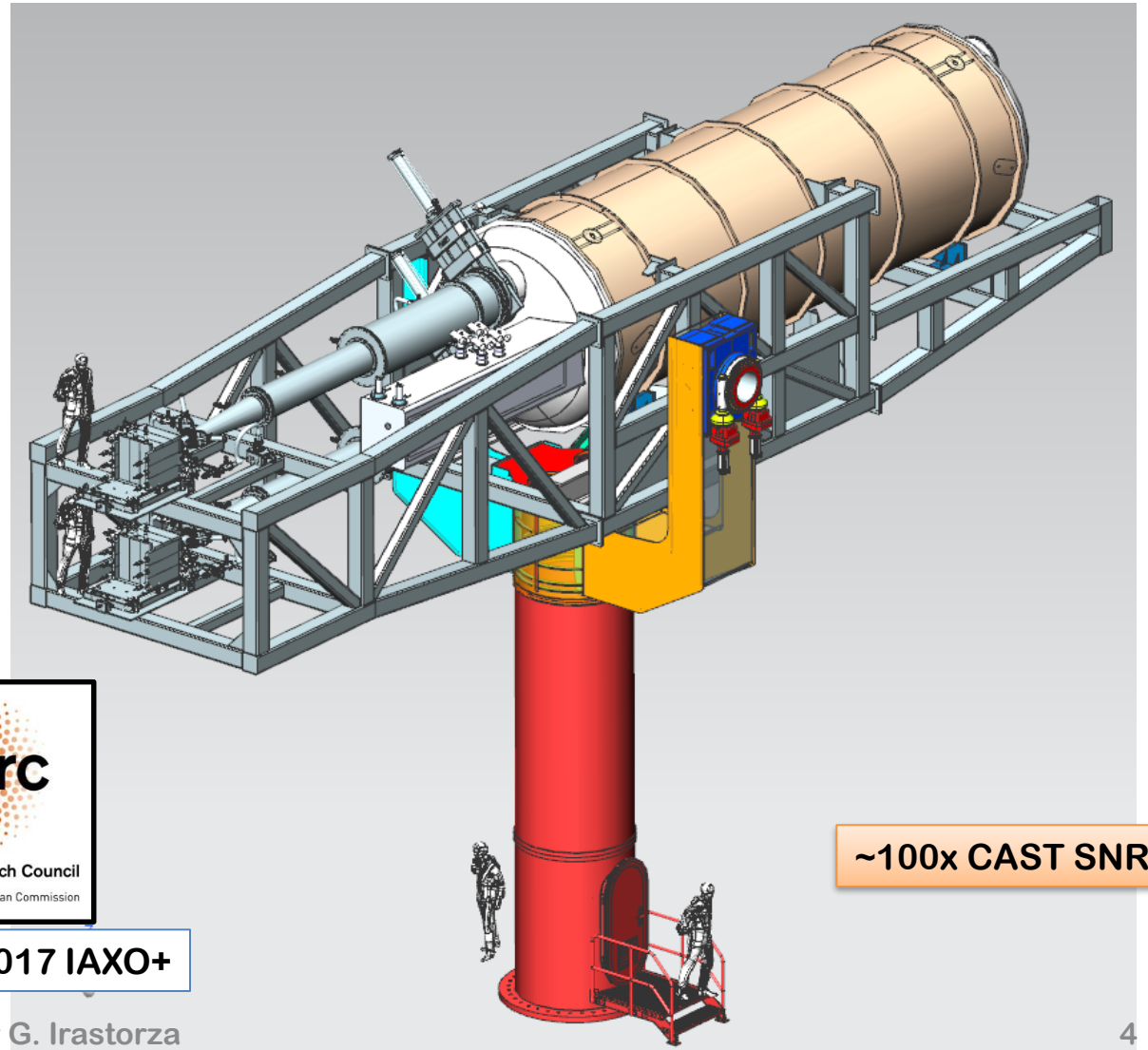


IAXO pathfinder system at CAST:
x-ray focusing + low background detector combined in same system
Small-scale version of IAXO baseline detection lines

BabyIAXO

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

  (~100 times larger FOM than CAST)



~100x CAST SNR

European Research Council
Established by the European Commission

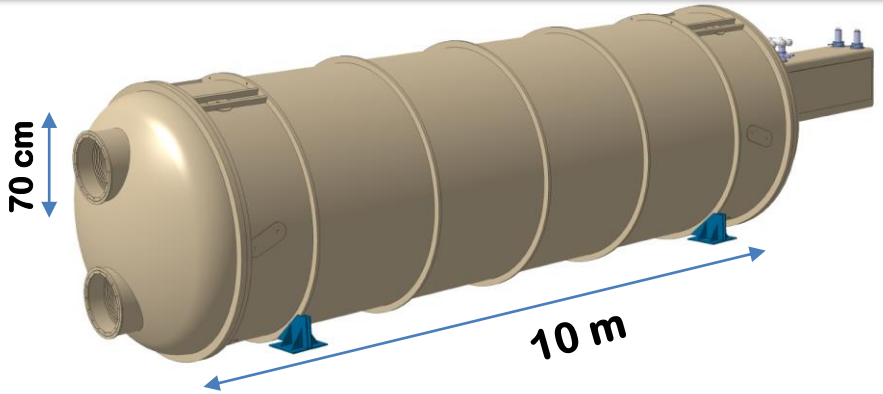
ERC-AvG 2017 IAXO+

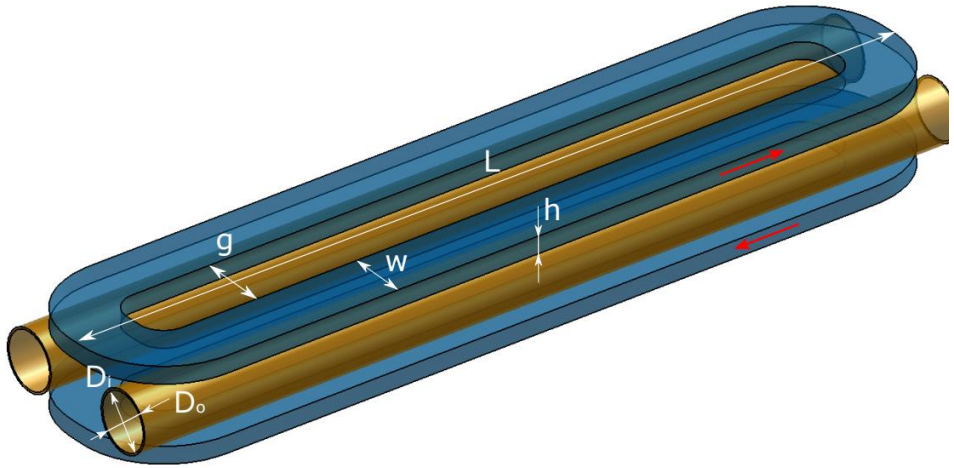
Important recent milestones

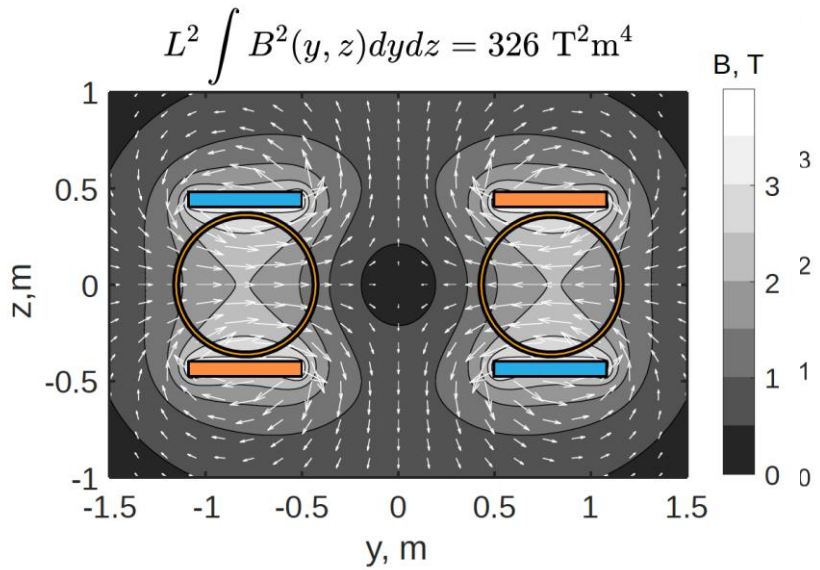
- Some history: first concept 2011, IAXO CDR (2014), BabyIAXO concept (2016), IAXO collaboration formally stablished in 2017.
- **Project aproved by DESY after LoI (2018) and full proposal (2019), being reviewed by DESY PRC since then.**
- **Funding almost secured: ERC-AdG @ UNIZAR (2018), DESY as host + many other institutions**
- **CERN crucial participation in magnet expertise: DESY-CERN MoU on magnet signed recently.**
- **Two other ERC-StG attracted for related technologies…**
- **BabyIAXO conceptual design about to get published (2010.12076)**
- **Technical design very much advanced. Magnet tendering design complete.**
- **First construction preparation steps being taken.**

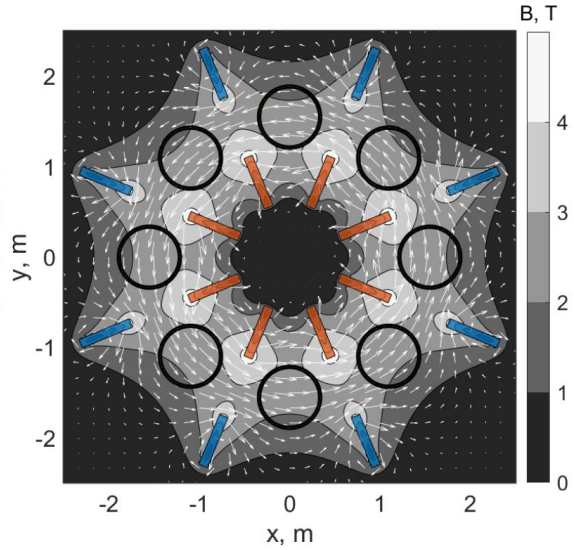
BabyIAXO magnet

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



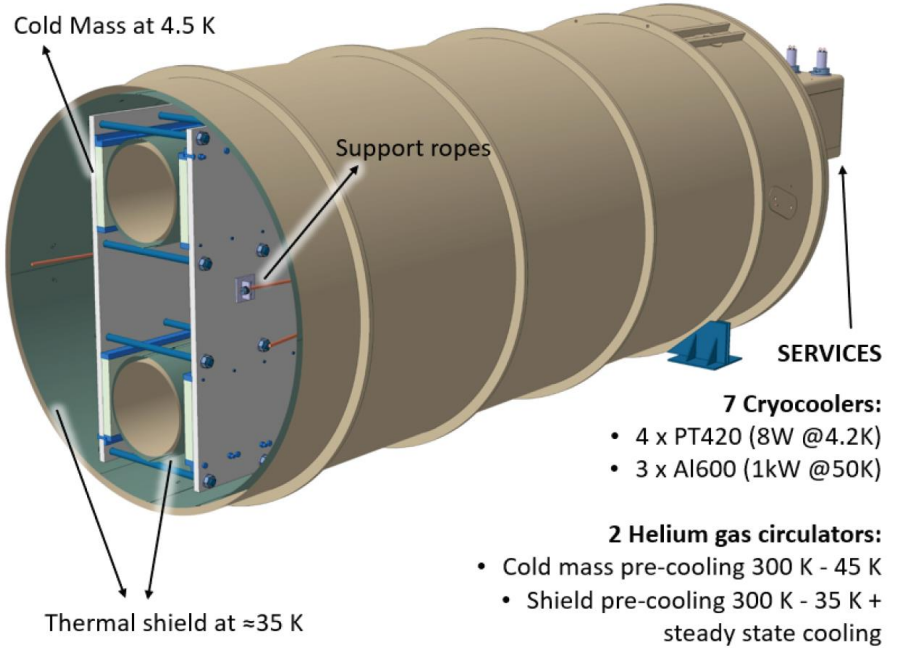


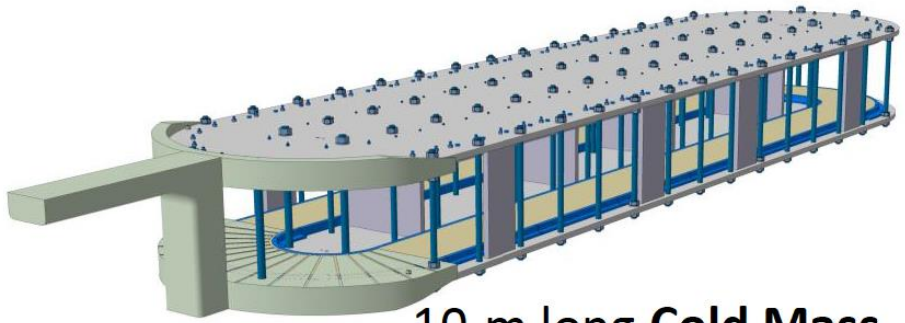




BabyIAXO magnet

- **Tendering design completed.**
  - Thanks to PBC for its support during the previous mandate!
- **Technical in-depth review of magnet design (by DESY PRC) successfully passed last November.**
  - Design adapted to the use of a existing SC cable offered inkind to IAXO by INR-Moscow. Currently qualifying the cable for use in BabyIAXO.
- **Quotations being received for magnet subsystems. Almost ready to start placing orders (cryostat, cold-mass,…).**



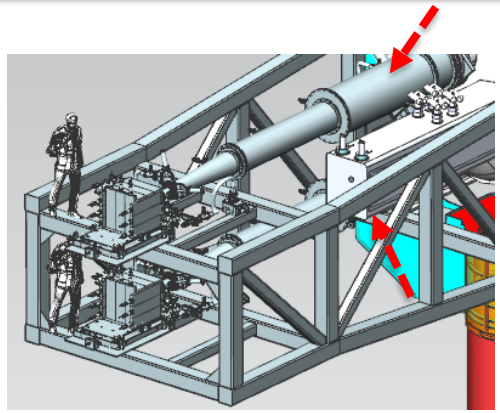


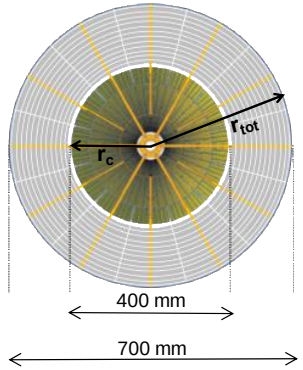
BabyIAXO optics

2 detection lines in BabyIAXO:

Hybrid approach for custom BabyIAXO optic

- Inner part Al-foil or segmented glass optic (NASA/LLNL/DTU/MIT/Columbia)
- Outer part cold-slumped Willow-glass technology (INAF/DTU)
- First multilayer deposition tests and characterization with NuSTAR flight glass and Willow glass completed → publication in preparation
- Design of support structure and vessel to hold, co-align and calibrate both under way as collaborative effort between all optics institutions (MIT)





XMM Flight Spare XRT

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

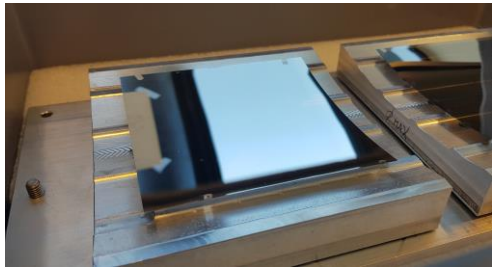
→ First collection of technical drawings at DESY, shipment is being arranged

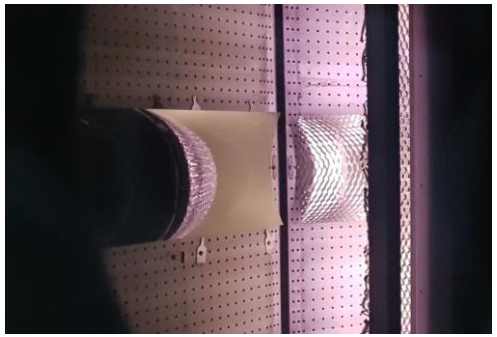
- List for ESA operational requirements and loan agreement in preparation

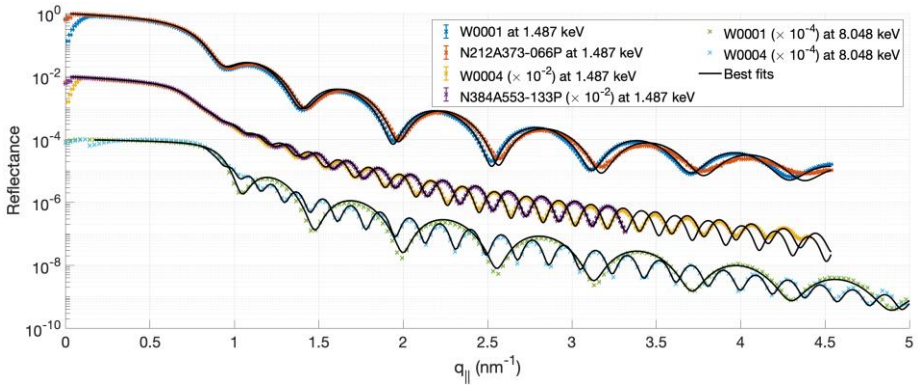
BabyIAXO optics: status

Coating development for BabyIAXO:

- Raytrace modelling ongoing together with software group
- Both NuSTAR glass and (flat) Willow glass pieces coated (DTU/INAF)
  - Metallic coating (Ir) used for first tests
- Full characterization of coated samples performed; Willow glass was measured pre- and post-bending to study stress and stability of coating (INAF)
  - Data and model agree well
  - Results indicate that bending after coating deposition is no issue for performance
- Plan is to measure all coated samples at Berkeley Natl' Laboratory's ALS when possible
- Publication of results in progress



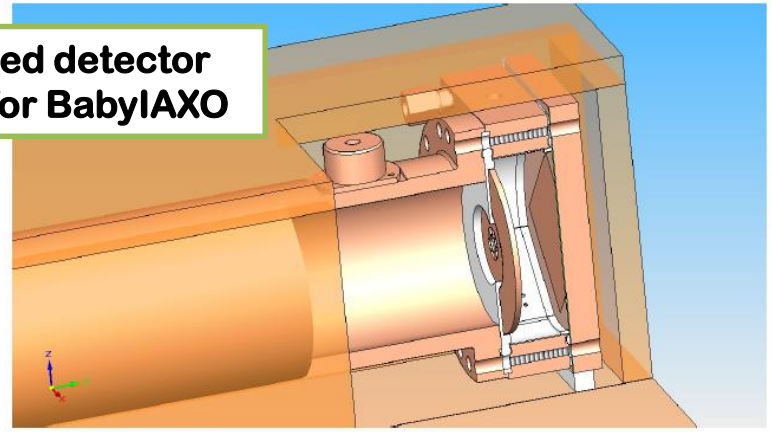




BabyIAXO detectors

- **Baseline detectors:**
  - Low background Micromegas detectors of *microbulk* type
  - "Discovery detectors" (priority to low background)
  - Experience in CAST
  - Low background capability, radiopurity, shielding.

Improved detector design for BabyIAXO



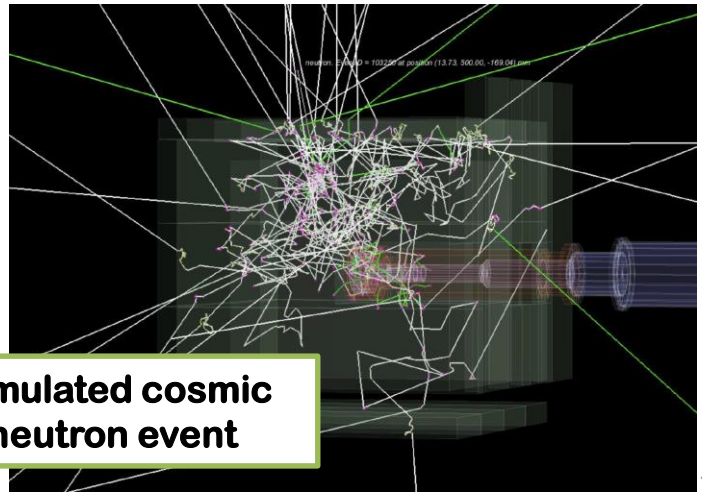
IAXO-D0 prototype in its shielding

Baseline detectors

- **Tests at surface UNIZAR with IAXO-D0.**
  - Implementation of 4π muon veto.
  - Enough to obtain 10^{-7} c/keV/cm^2/s?
- **Tests at underground planned with a second prototype IAXO-D1**
  - Determine part of intrinsic and cosmic induced events
- **Simulations**
  - Background might be limited by cosmic neutrons

- Near term goal: confirm hypothesis cosmic neutrons main limitation to lower background
- Cosmic neutron tagger is being built and will be implemented in IAXO-D0.

IAXO-D0 with muon shielding

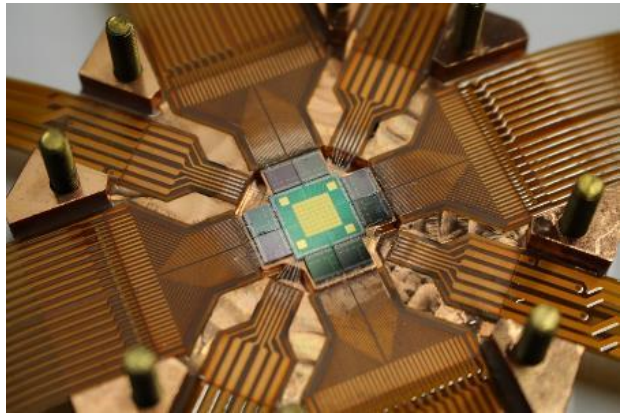


Simulated cosmic neutron event

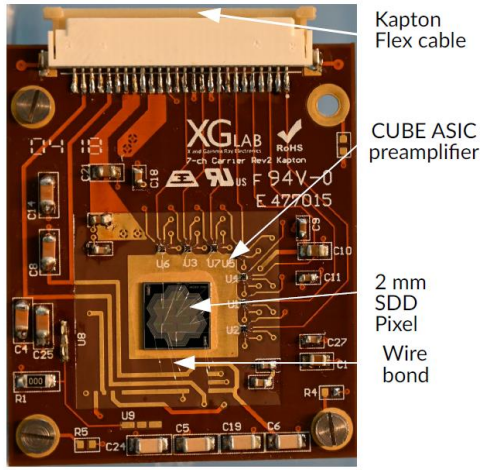
Complementary technologies

- Beyond baseline, “high precision” detectors (post-discovery?)
  - Better threshold & energy resolution
  - Design and material optimization ongoing in all fronts
  - Background studies with different shielding configurations
  - DALPS project (French ANR)

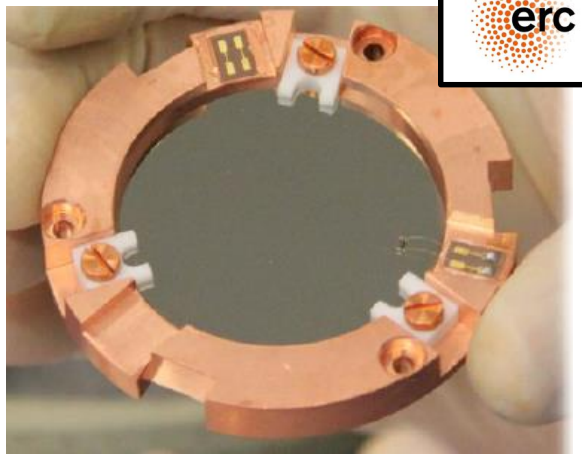
ERC-StG (2020)
M.Meyer/Hamburg



MMC: Metallic Magnetic calorimeters



SDD: Silicon Drift Detectors



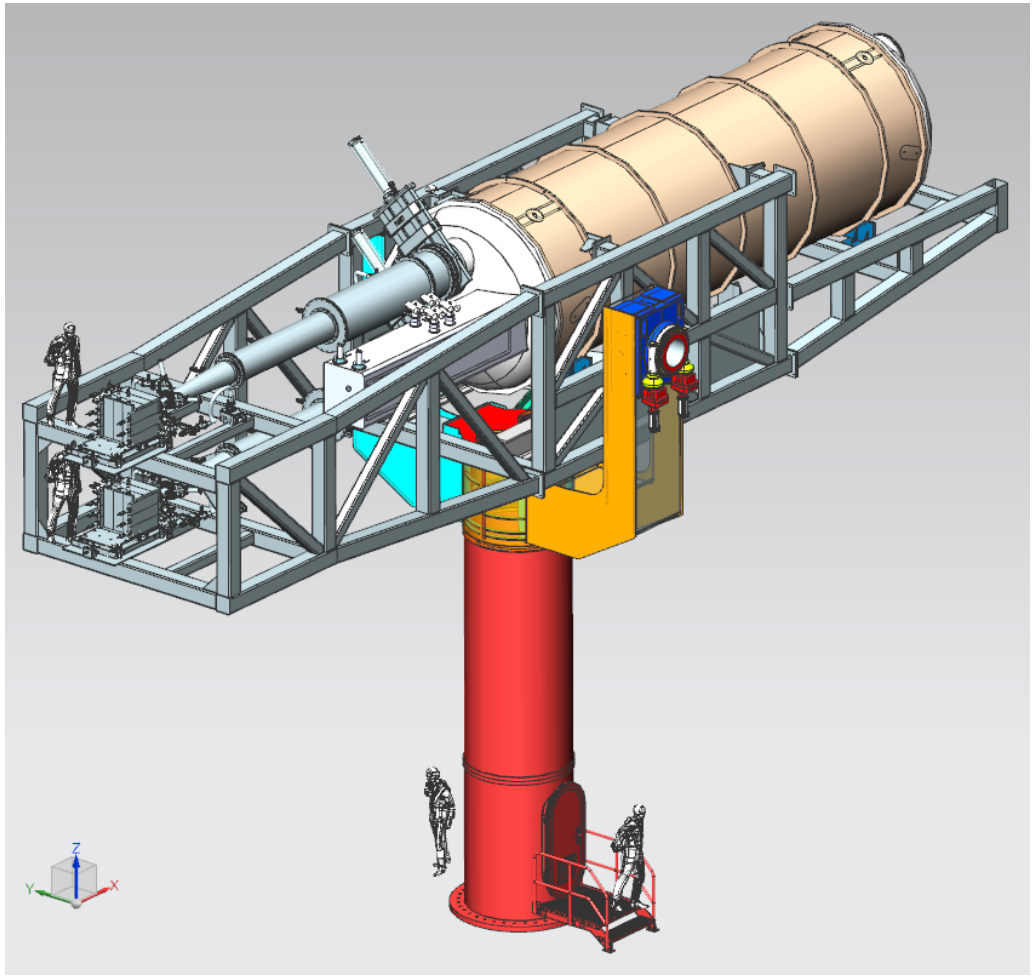
TES: Transition Edge senstors

Gridpix

Project preparation at DESY

- **Platform and drive**: advanced design.
  - Part of existing CTA MST mount will be re-used.
- **Technical coordination** very active
- **WBS** almost defined, with support from DESY Project Office.
- BabyIAXO alignment concepts defined

- **Site**: recent developments: BabyIAXO will be sited on surface



BabyIAXO: beyond baseline

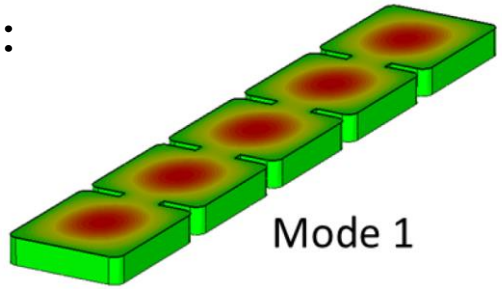
- Baseline program is realistic and low-risk. No pending R&D. After that, the BabyIAXO infrastructure would be available for further activities "beyond-baseline". For example:
  - New detectors with improved performance to: 1) extended physics runs or 2) preparatory tests for IAXO
  - Supernova axions? HE gamma detector at the other end of magnet.
  - Implementation of "haloscope" schemes inside the BabyIAXO magnet (RF cavities or other resonant structures)
  - If discovery: precision detectors may measure m_a and g_{ae}.
    - New sources of low enery solar axions being proposed in the literature
- Definition of "beyond-baseline" BabyIAXO program will depend on future R&D results.

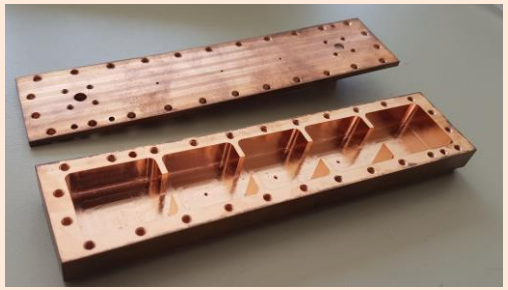
Haloscopes inside BabyIAXO

- Use of (Baby)IAXO large magnetic volume for axion DM setups.
- RADES R&D exploring new concept to fill large V with cavities.
  - Proof-of-concept at small scale successful tested in CAST
  - Technological connection with CERN

- Aim: to become the seed of a program to implement DM searches in BabyIAXO.
- Extension to very low masses: BASE-like search inside BabyIAXO?
  - (see S. Ulmer & J. Devlin talks)

RADES concept: array of small cavities interconnected with irises:





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

IAXO collaboration is growing

IAXO collaboration: 125 scientists from 19 full member institutions + 5 associate institutions.

Full members: Kirchhoff Institute for Physics, Heidelberg U. (Germany) | IRFU-CEA (France) | CAPA-UNIZAR (Spain) | INAF-Brera (Italy) | CERN (Switzerland) | ICCUB-Barcelona (Spain) | Petersburg Nuclear Physics Institute (Russia) | Siegen University (Germany) | Barry University (USA) | Institute of Nuclear Research, Moscow (Russia) | University of Bonn (Germany) | DESY (Germany) | University of Mainz (Germany) | MIT (USA) | LLNL (USA) | University of Cape Town (S. Africa) | Moscow Institute of Physics and Technology (Russia) | Max Planck Institute for Physics, Munich (Germany) | CEFCA-Teruel (Spain) | (1 more in process to join + several expression of interest)

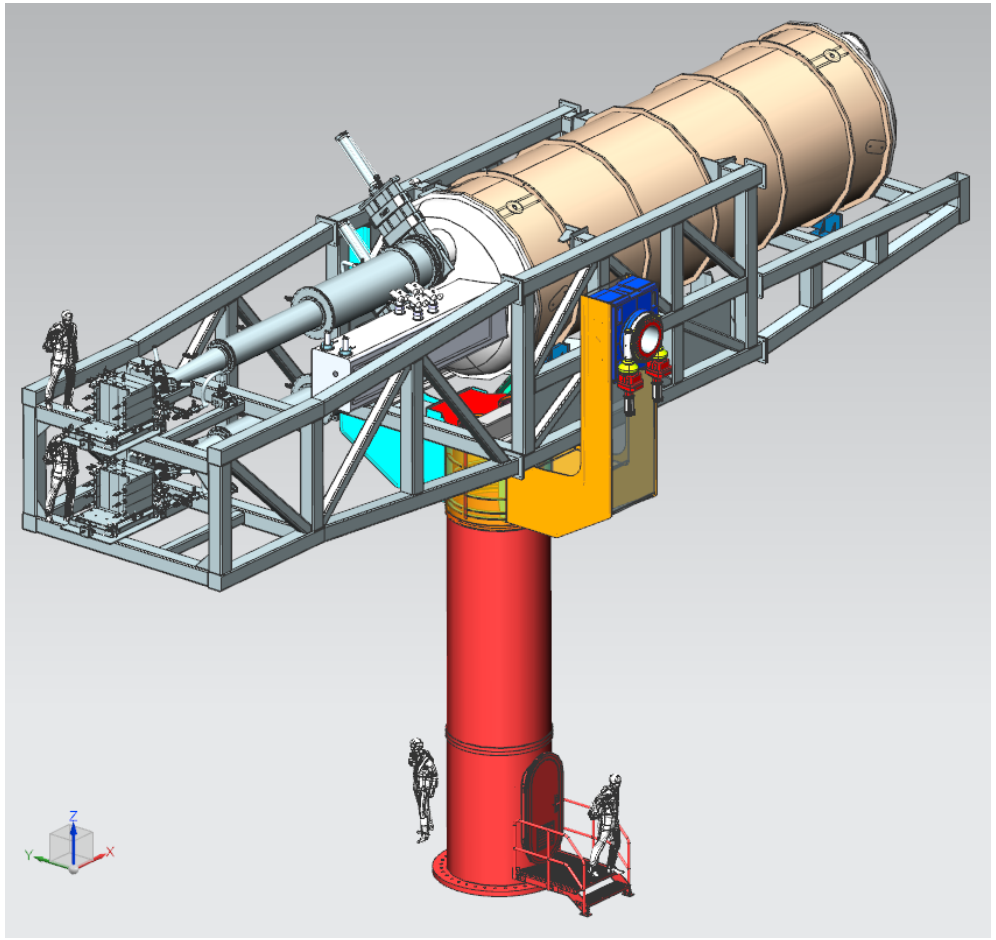
Associate members: DTU (Denmark) | U. Columbia (USA) | SOLEIL (France) | IJCLab (France) | LIST-CEA (France)

Conclusions

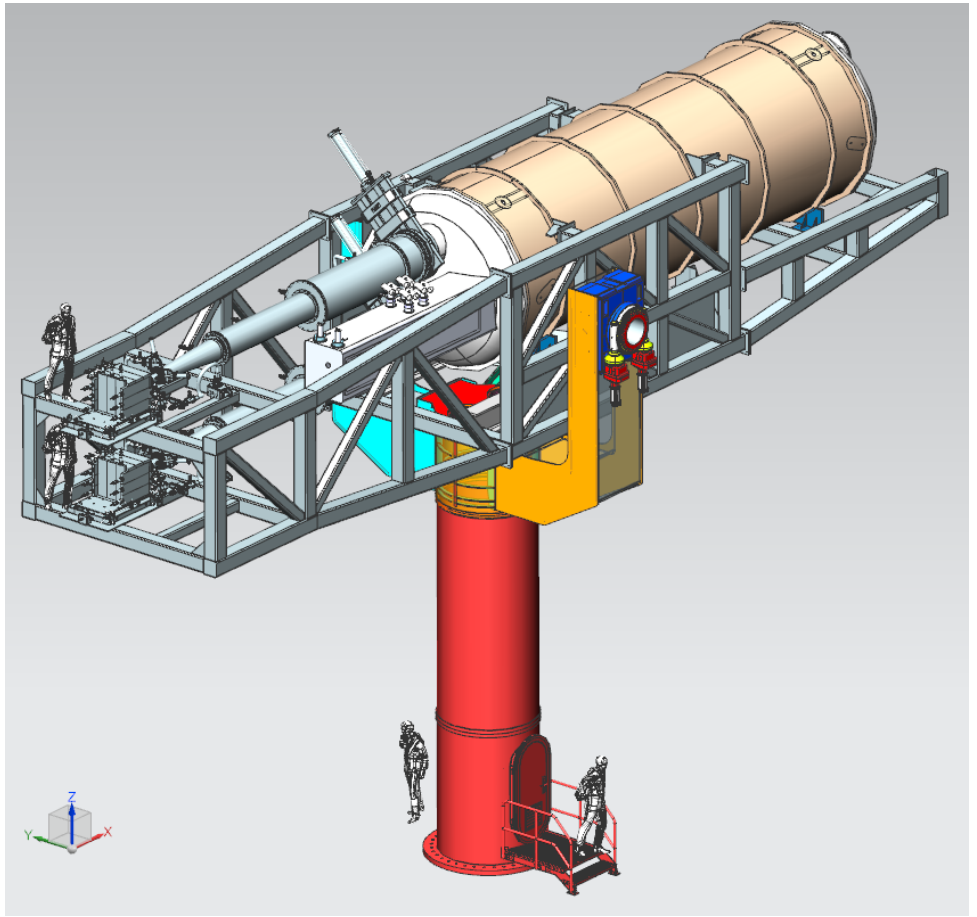
- CERN support during previous PBC period was crucial for IAXO (BabyIAXO) success:
  - Project funding almost complete.
  - Collaboration consolidated
  - Design phase almost finished. Facing BabyIAXO construction.

- We want to thank PBC for the support during the process.

- We expect further CERN/PCB support for the next steps.



- **Thank you for your attention**

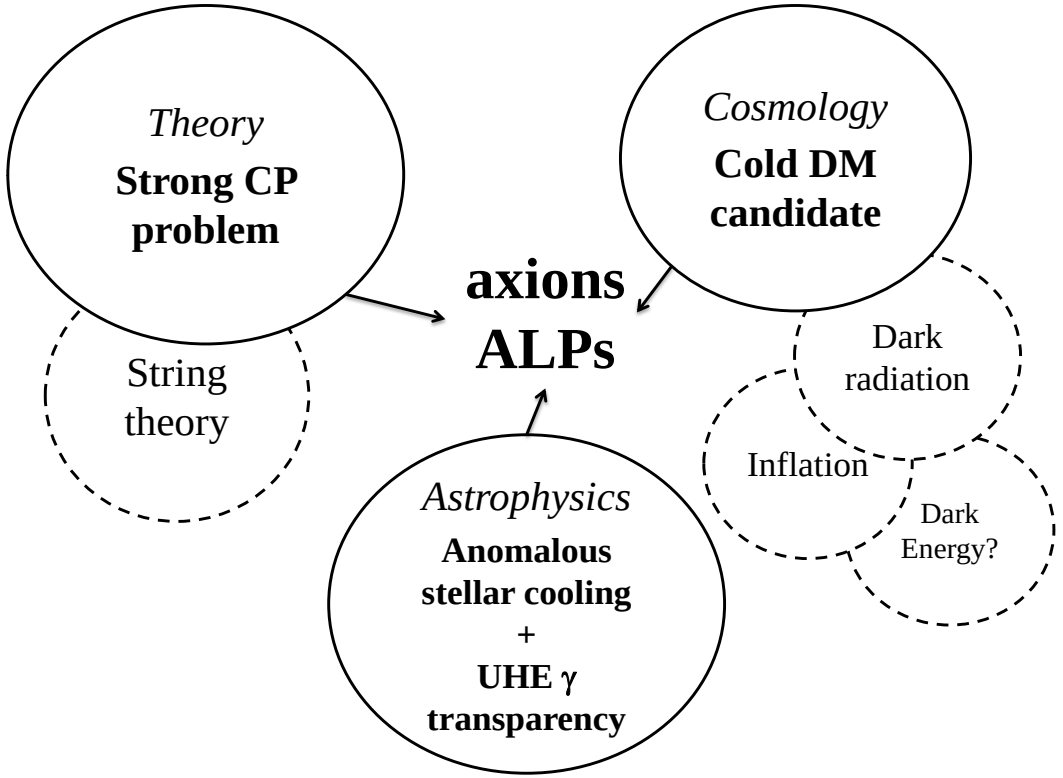


Axion motivation in a nutshell

- Most compelling solution to the **Strong CP problem** of the SM

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

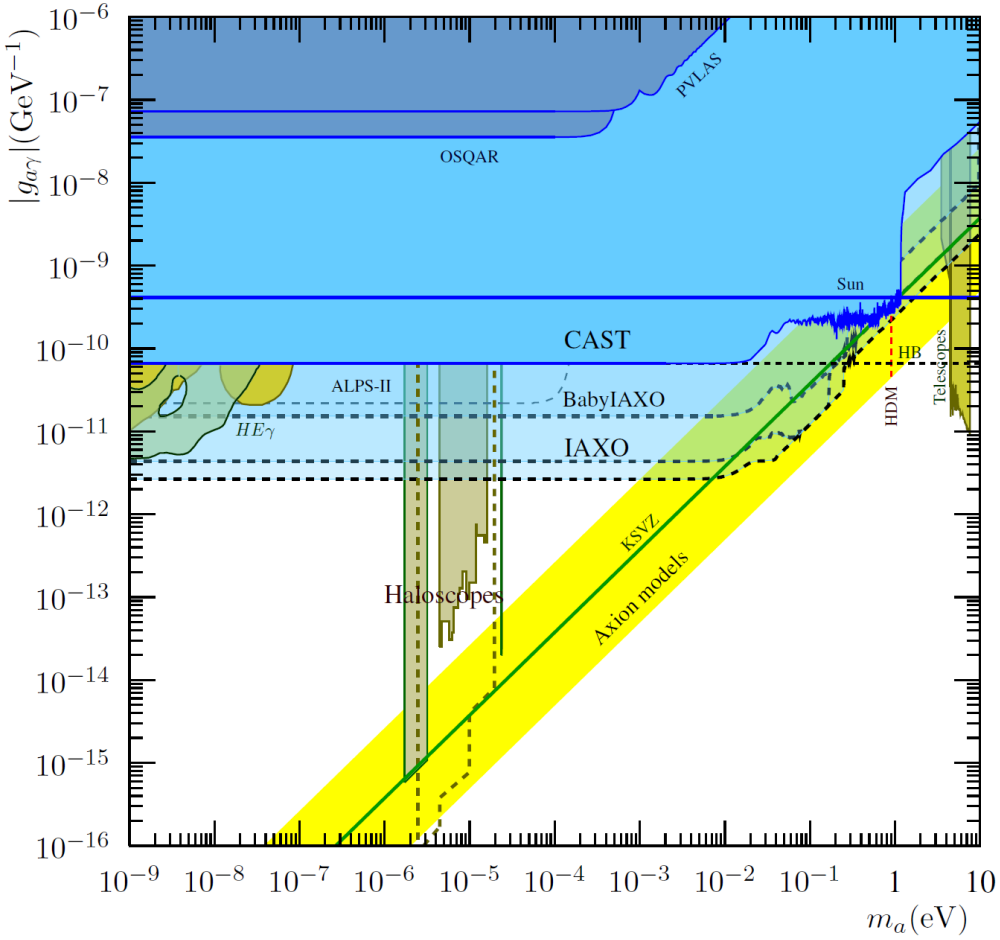
- Relevant axion/ALP parameter space at **reach of current and near-future experiments**
- Experimental efforts growing fast but still small (when compared e.g. to WIMPs…)



IAXO physics case

IAXO will probe

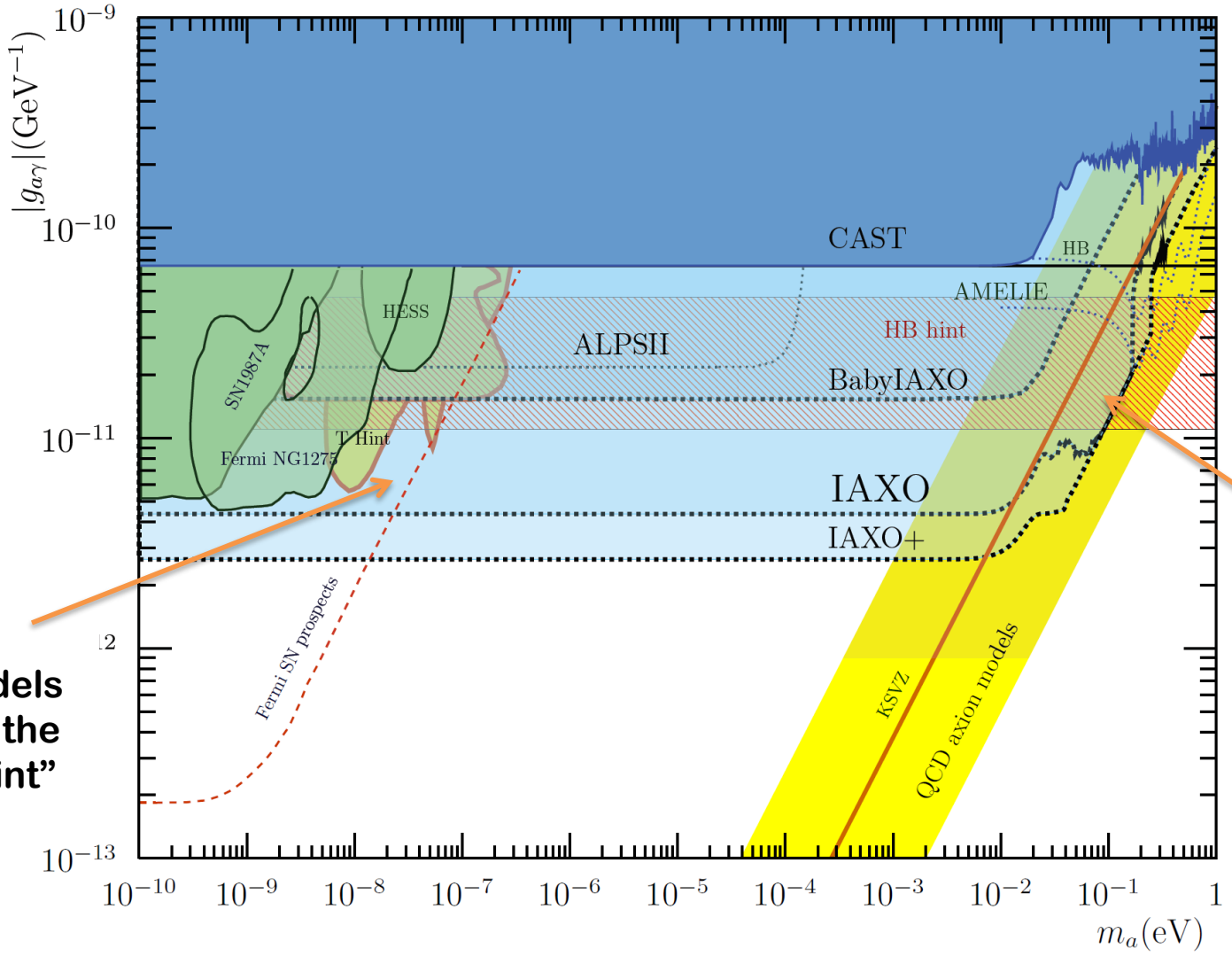
- Large generic unexplored ALP space
  - down to $g_{a\gamma}$ ~ few 10^{-12} GeV^{-1}
  - down to g_{ae} ~ few 10^{-13}
- QCD axion models in the meV to eV mass band.
- Astrophysically hinted regions
  - ALP region invoked to solve the transparency anomaly
  - axion region invoked to solve the stellar cooling anomaly
- Cosmologically interesting regions
  - viable QCD axion DM models,
  - ALP DM+inflation models
  - EDGES anomaly
- All this, independent of the axion-as-DM hypothesis.
- No other competing technique. IAXO unique.
- BabyIAXO relevant intermediate physics potential



Review of Physics potential of IAXO
JCAP (2019) 06 047 (arXiv:1904.09155)

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

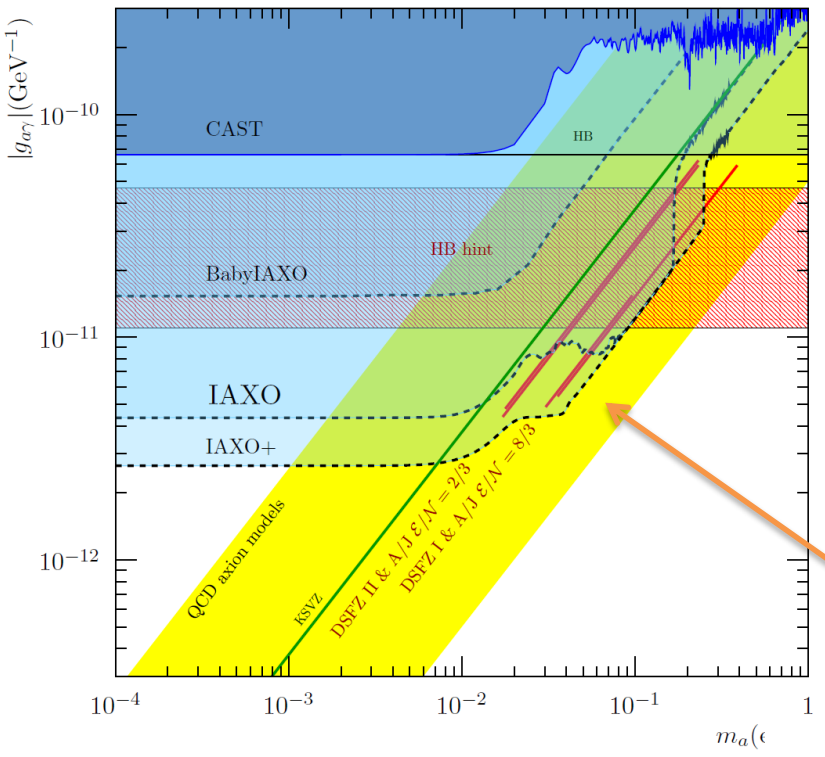
IAXO will fully explore ALP models invoked to solve the "transparency hint"

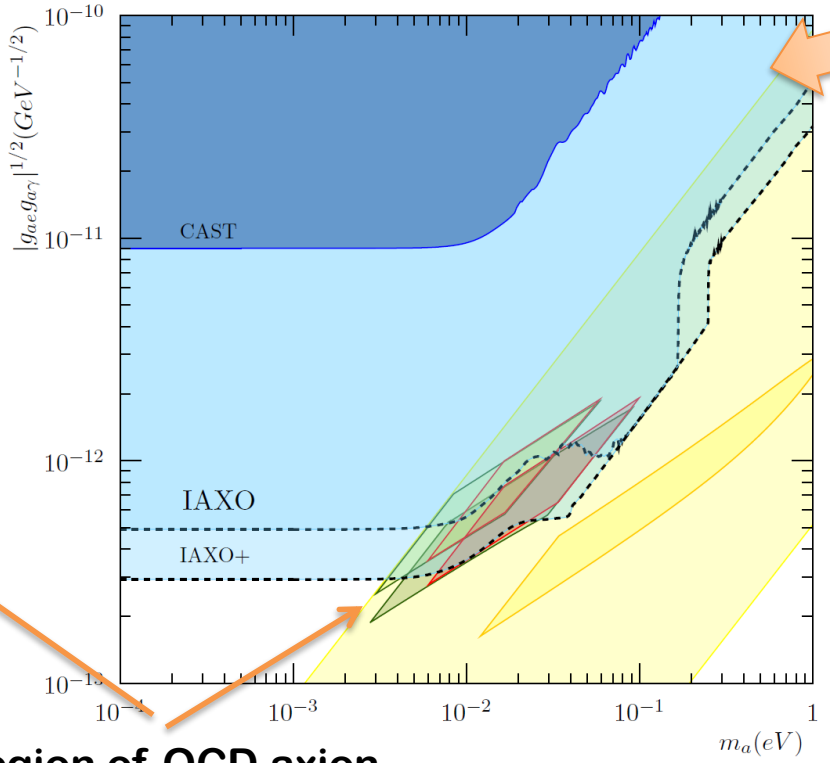
… as well as a large fraction of the axion & ALP models invoked in the "stellar cooling anomaly"
But for this the g_{ae} is particularly interesting

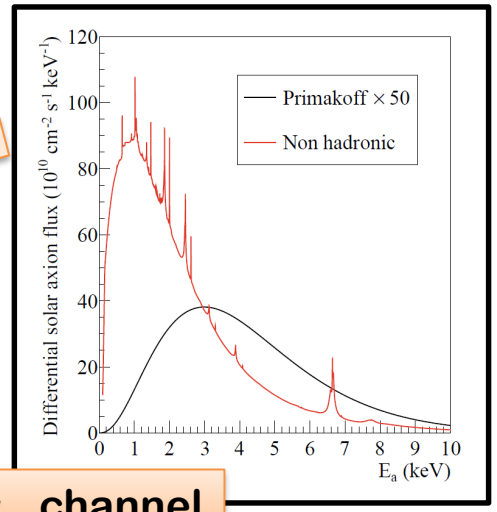
MFOM = Magnet FOM

IAXO & stellar cooling

- **Multiple stellar anomalies (HB, RG, WD, NS,..). Overall 3σ effect.**







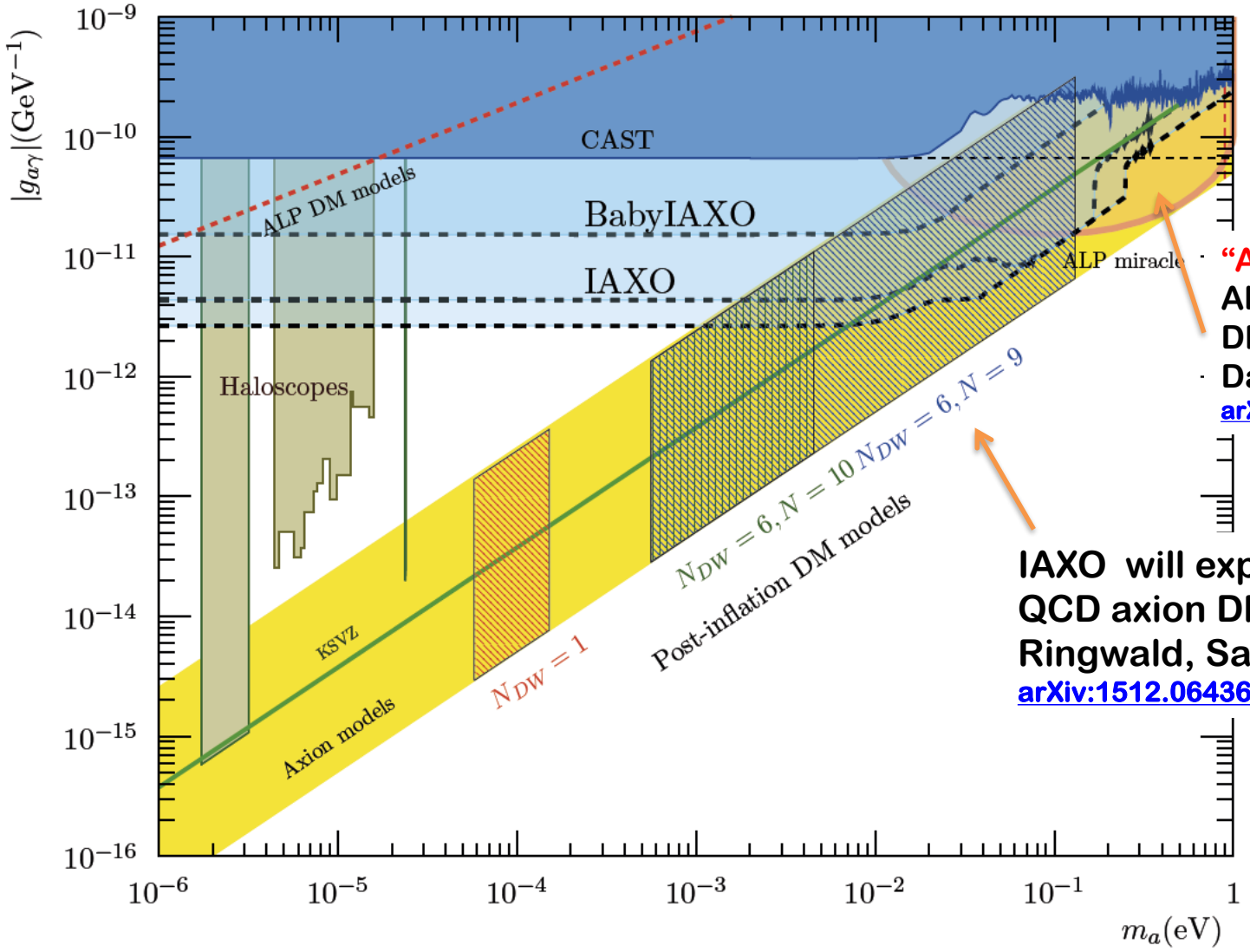
g_{ae} **channel**

Region of QCD axion models that solve the stellar anomaly

M. Giannotti et al.
JCAP 1710 (2017) 010
arXiv:1708.02111

- **IAXO will explore most of the relevant models (especially with IAXO+)**
- **Only experiment with such capability**

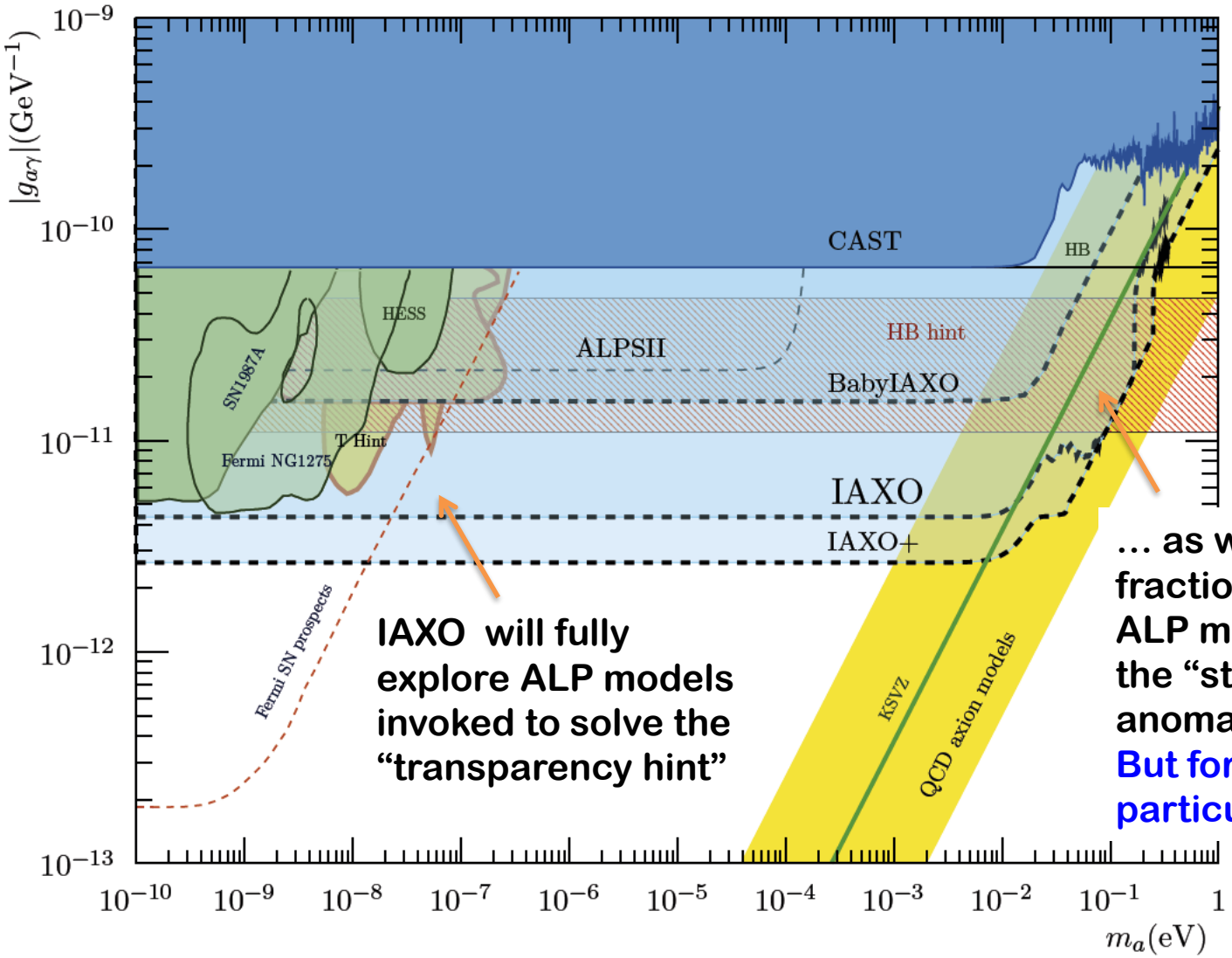
IAXO & meV axion cosmology



"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

IAXO & astrophysics hints



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

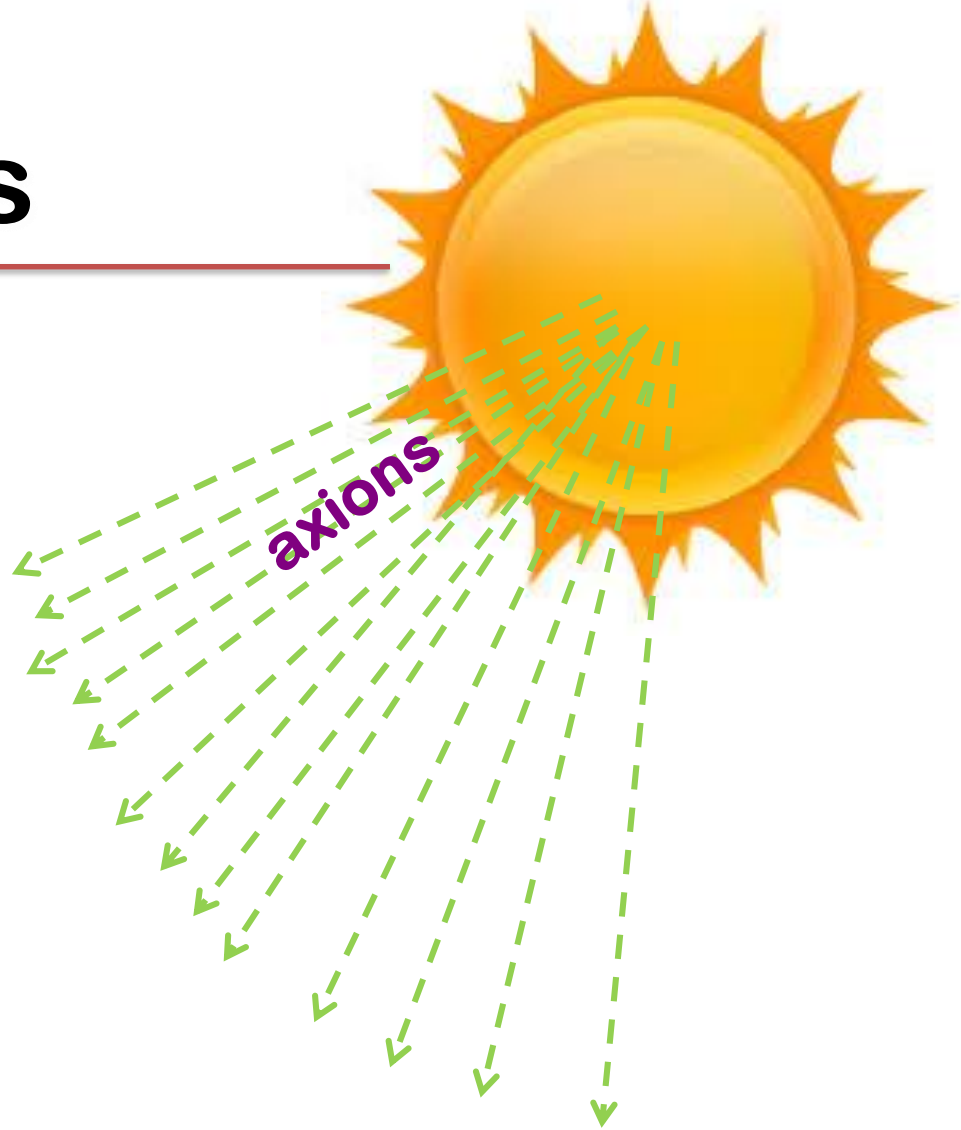
Detection of axions

Large complementarity among categories

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

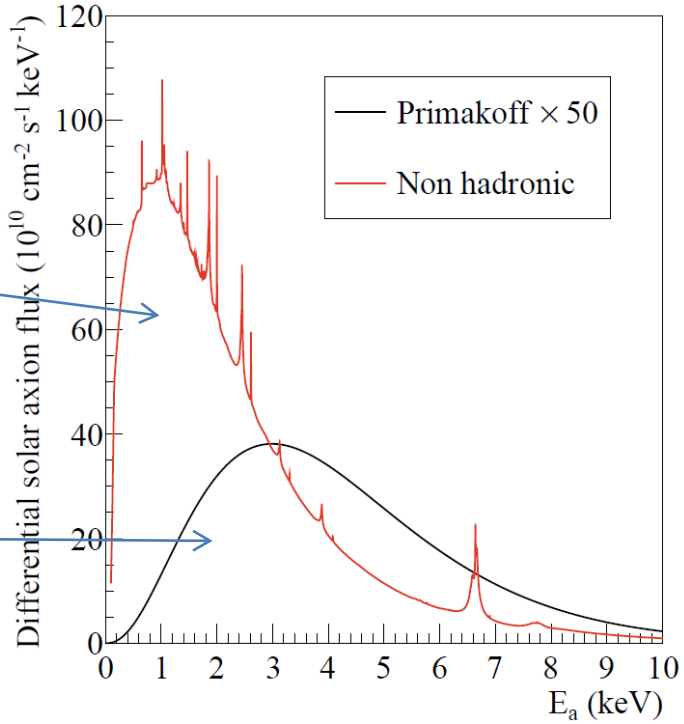
Solar Axions

- **Primakoff conversion of solar plasma photons** → generic prediction of most axion models
- In addition, g_{ae}-mediated axions (model dependent)



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

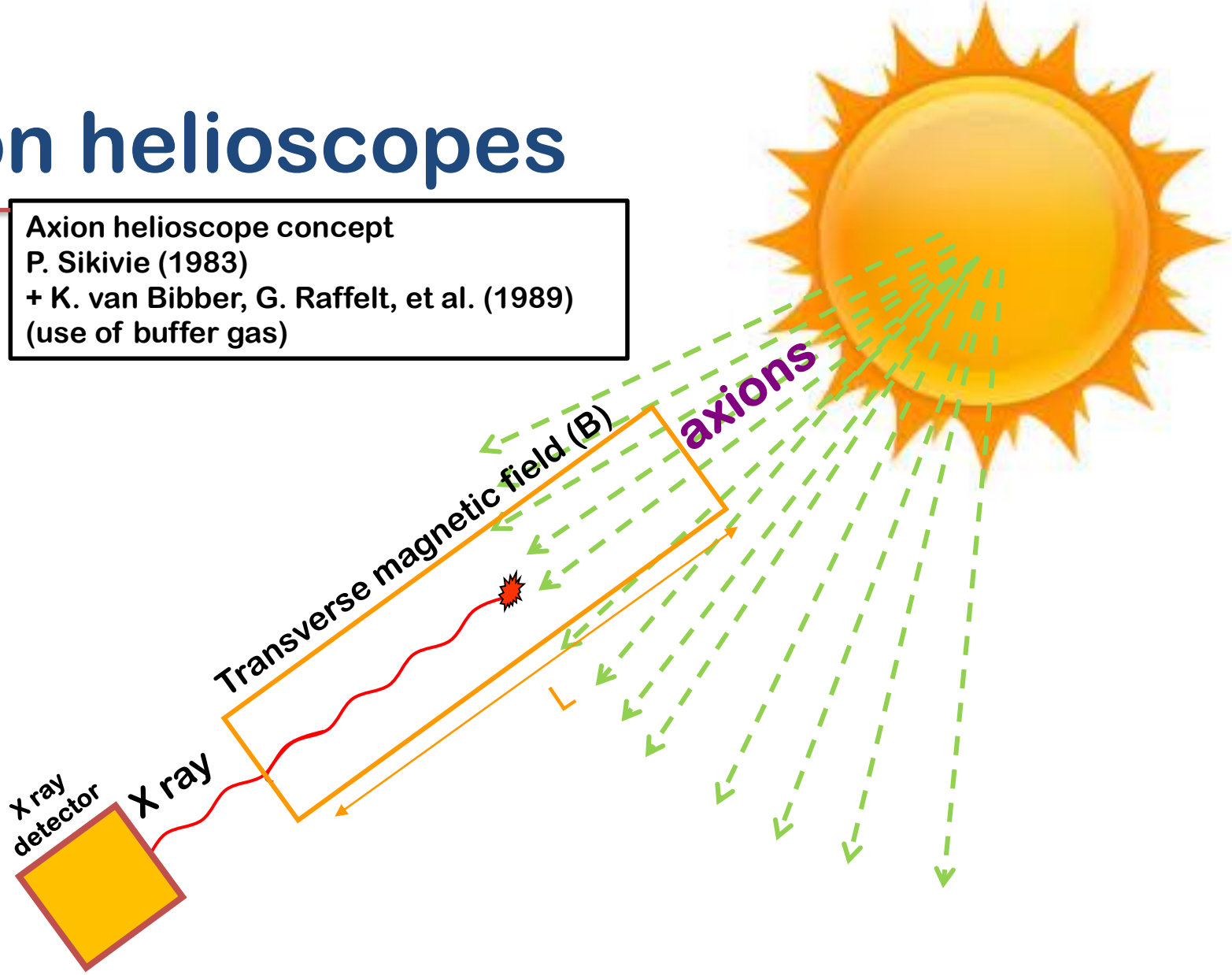
Standard Primakoff spectrum



Axion helioscopes

- **Previous helioscopes:**
  - First implementation at Brookhaven (just few hours of data) [Lazarus et at. PRL 69 (92)]
  - TOKYO Helioscope (SUMICO): 2.3 m long 4 T magnet

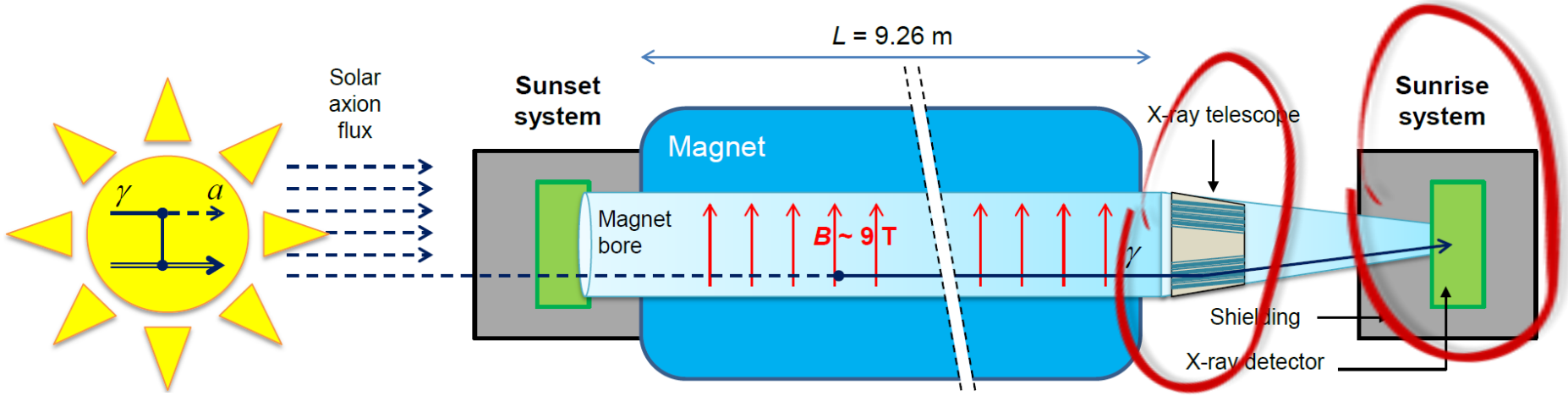
Axion helioscope concept
P. Sikivie (1983)
+ K. van Bibber, G. Raffelt, et al. (1989)
(use of buffer gas)



CAST: state-of-the-art

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

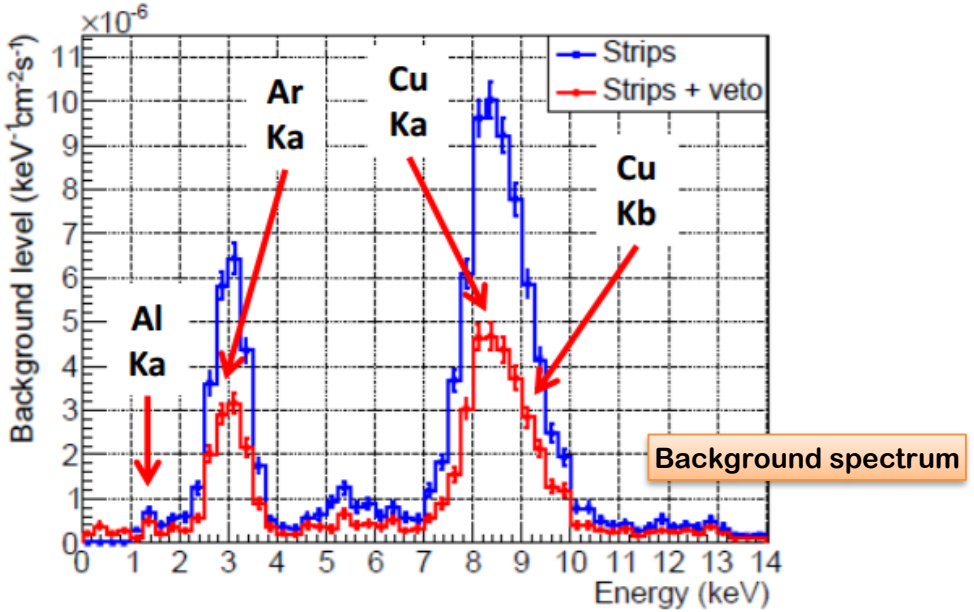
First helioscope using low background techniques & x-ray focusing



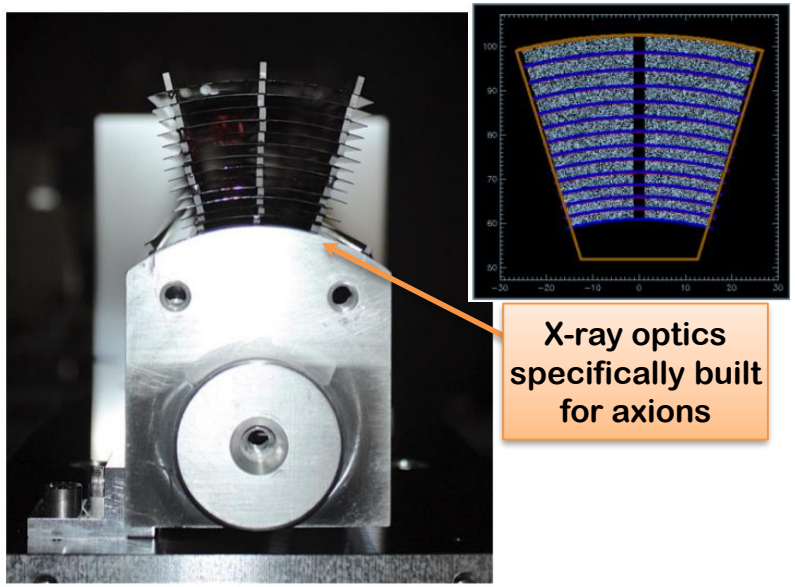
IAXO pathfinder system in CAST

Test MM detector + slumped-glass x-ray optics together

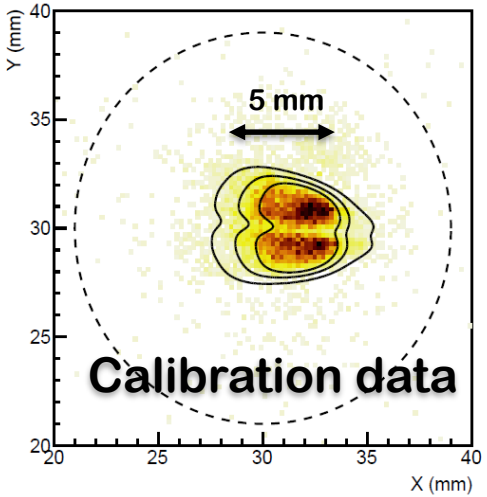
Detector: JCAP12 (2015)
Physics: Nature Phys. 13 (2017) 584-590

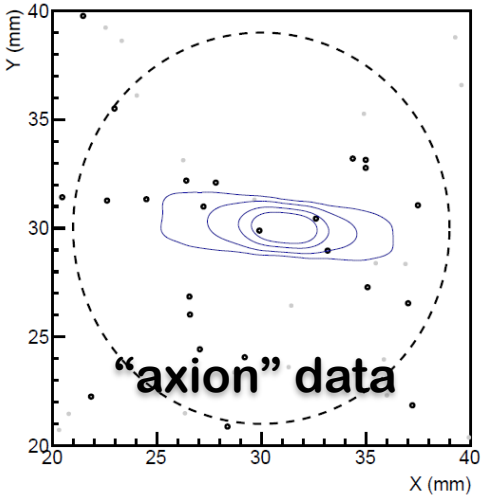


Background spectrum

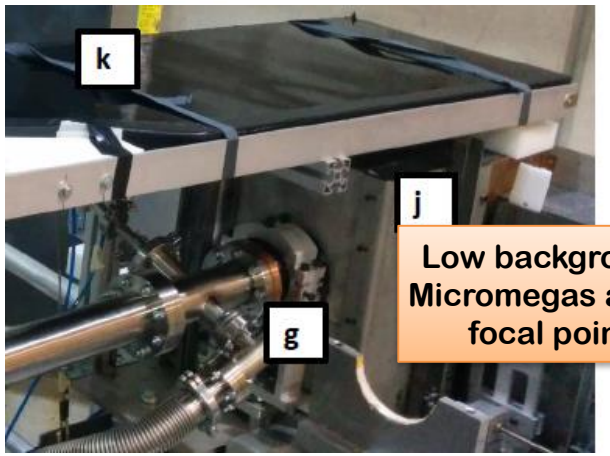


X-ray optics specifically built for axions



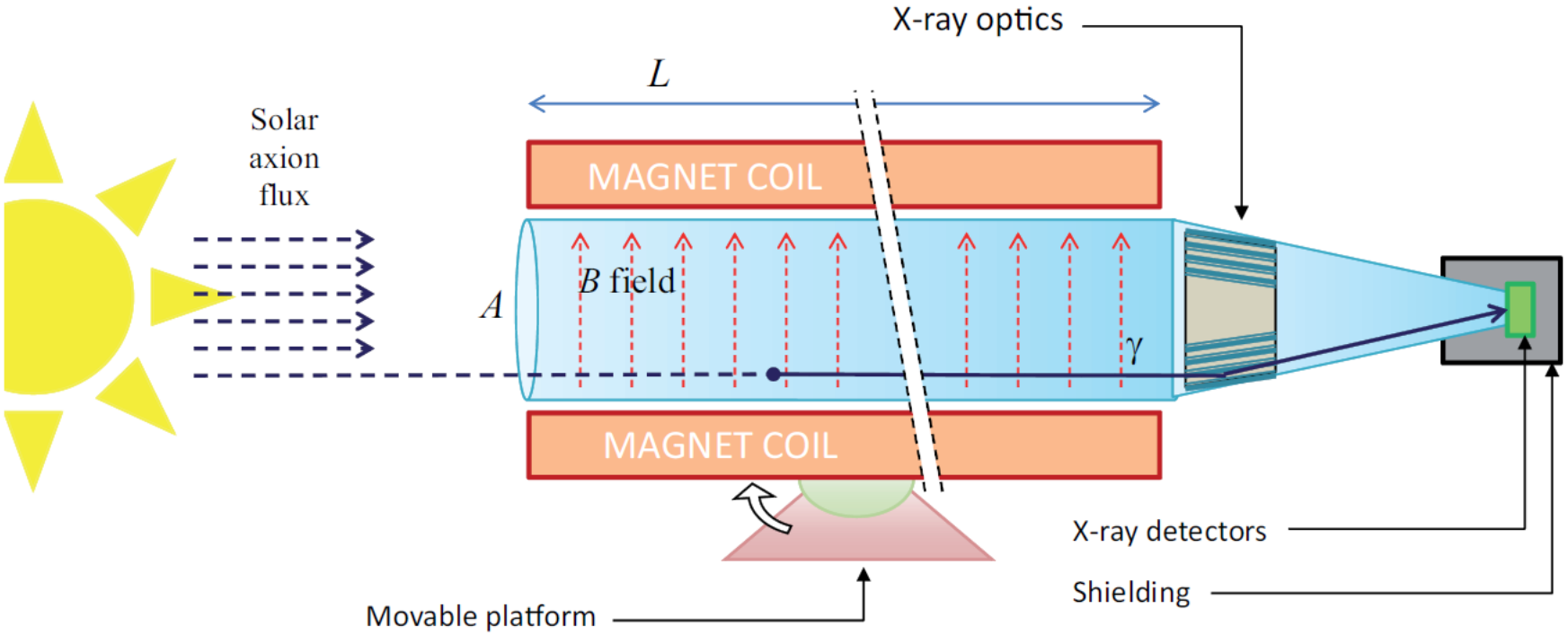


- Best SNR of any previous detector
- 290 tracking hour acquired (6.5 months operation)
- 3 counts observed in RoI (1 expected)



Low background Micromegas at the focal point

An enhanced axion helioscope



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

>10^4 better SNR than CAST

Sensitive to g_{ag} ~ x20 lower than CAST

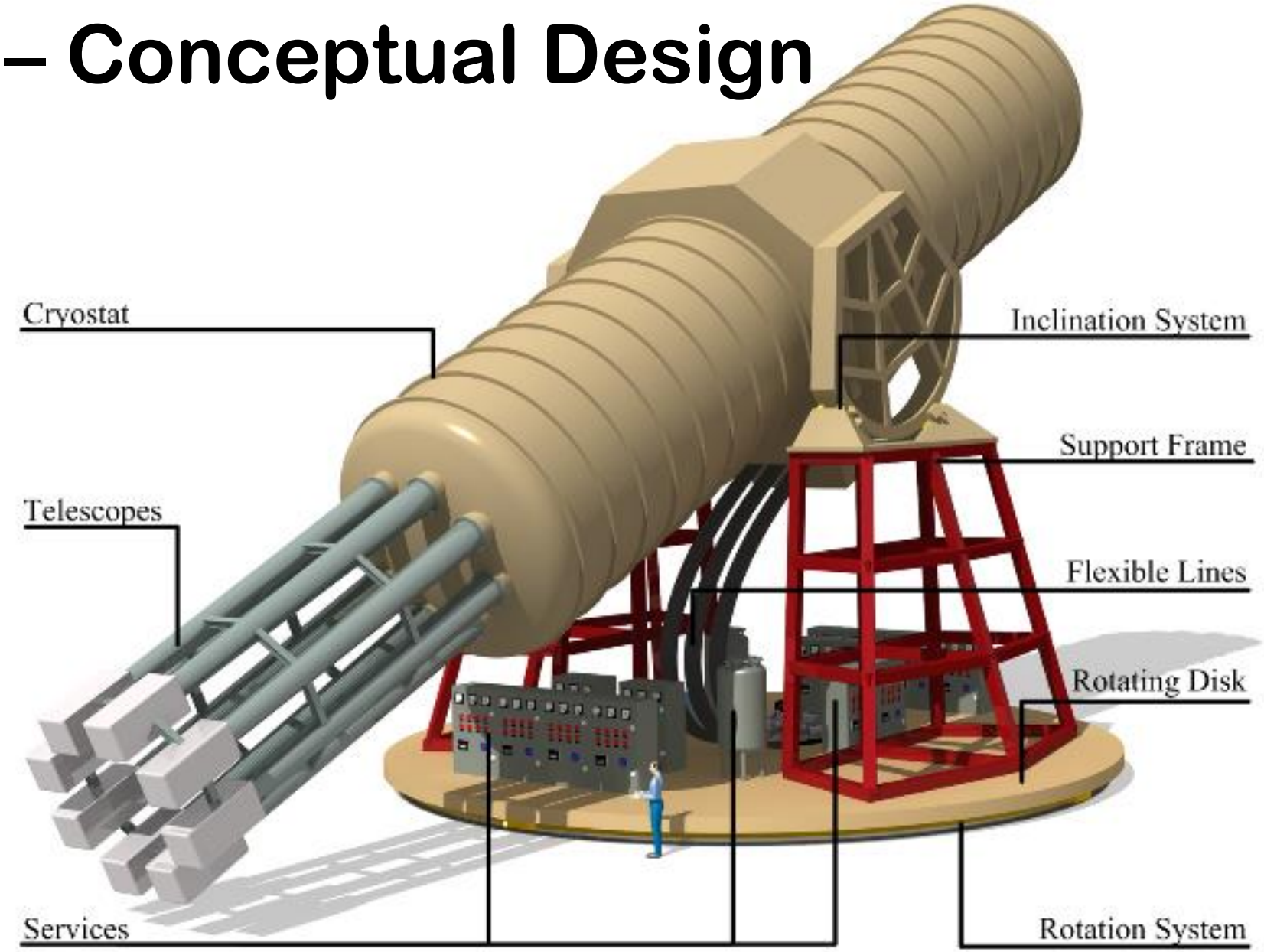
Enhanced axion helioscope:
JCAP 1106:013,2011

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

IAXO – Conceptual Design

- Large toroidal 8-coil magnet
  L =~20 m
- 8 bores: 600 mm diameter each
- 8 x-ray telescopes + 8 detection systems
- Rotating platform with services

IAXO CDR: JINST 9 (2014) T05002 (arXiv:1401.3233)



BabyIAXO timeline

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