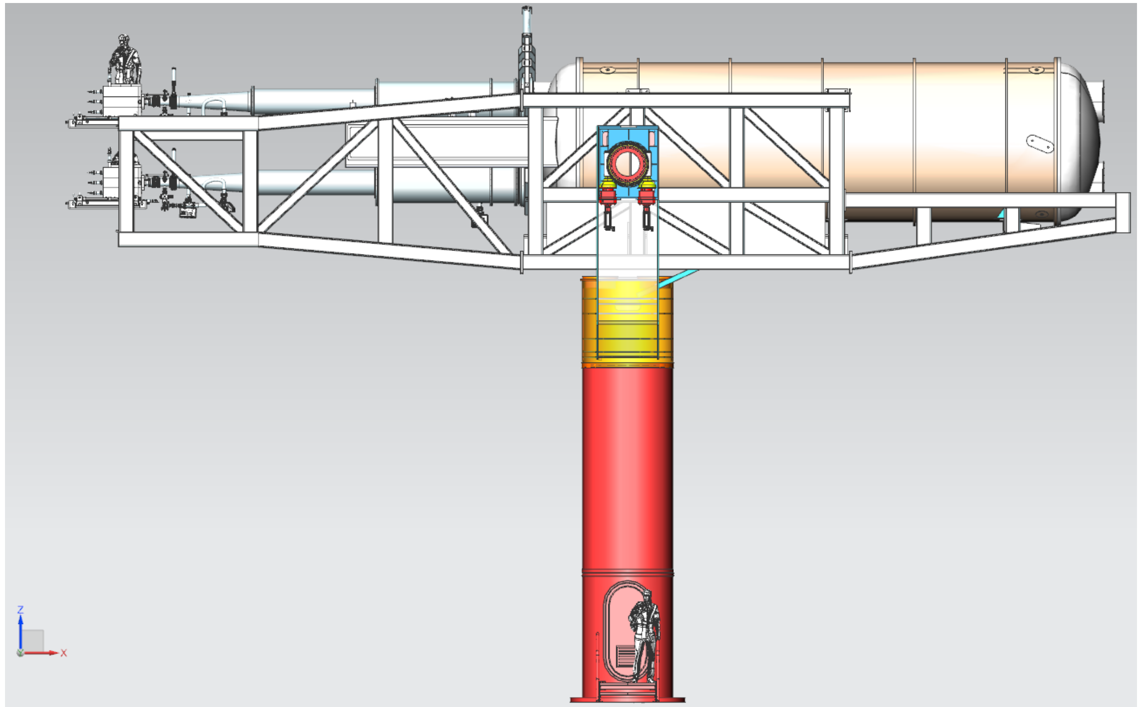
Status of BabyIAXO, the first stage towards the International AXion Observatory (IAXO)

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

10th Symposium on Large TPCs for low-energy Rare Event Detection, December 15th, 2021

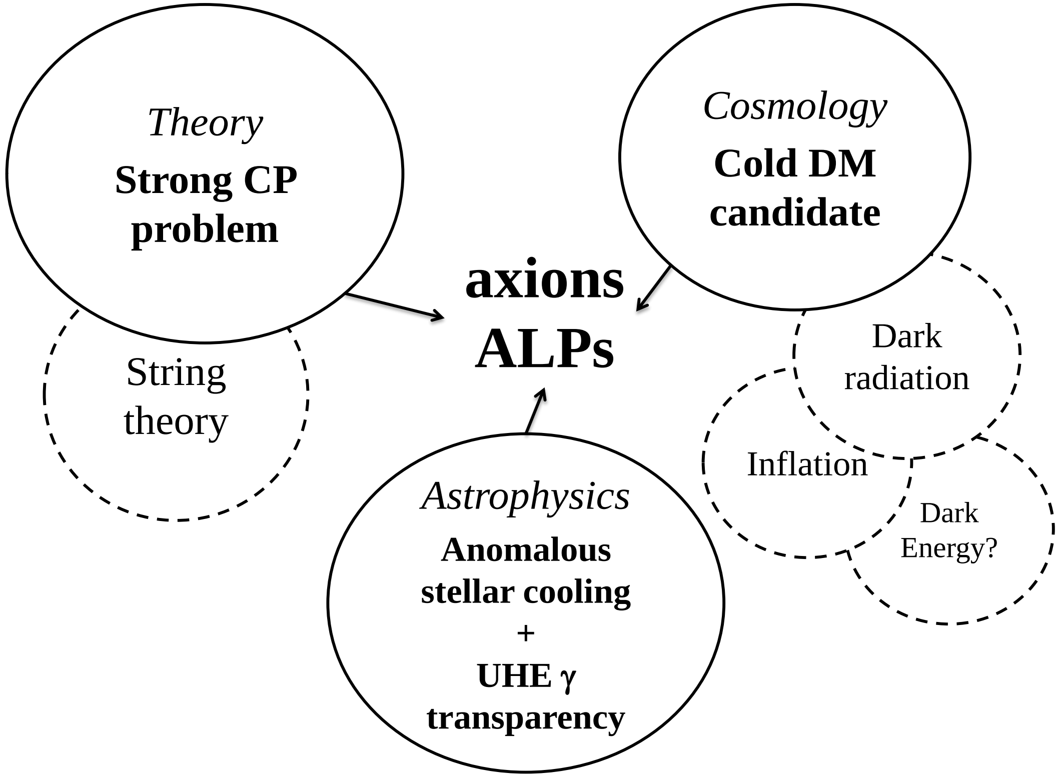


Axion motivation in a nutshell

- 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…)



Detection of axions

Large complementarity among categories

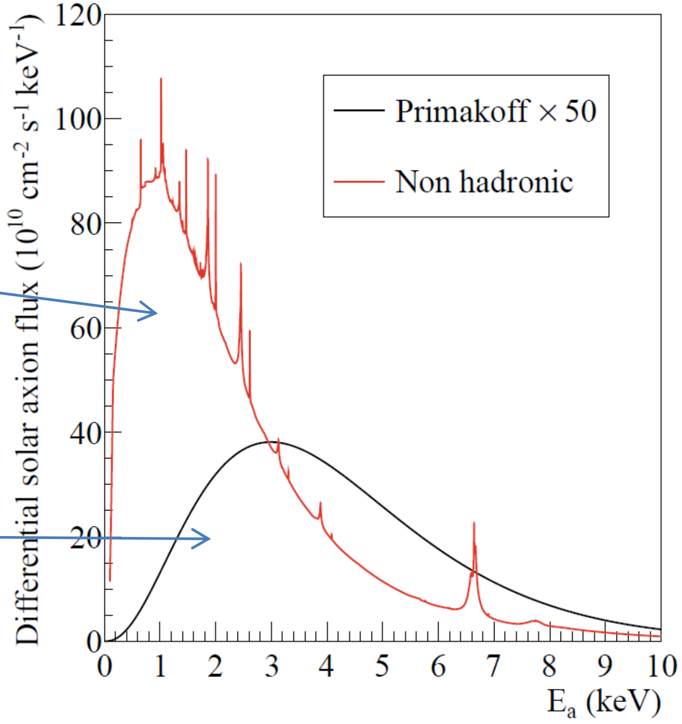
Source	Experiments	Model & Cosmology dependency	Technology
Relic axions 	ADMX, HAYSTAC, CASPEr, CULTASK, CAST-CAPP, MADMAX, ORGAN, RADES, QUAX, …	High	New ideas emerging, Active R&D going on,…
Lab axions 	ALPS, OSQAR, CROWS, ARIADNE,…	Very low	
Solar axions 	SUMICO, CAST, (Baby)IAXO	Low	Ready for large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

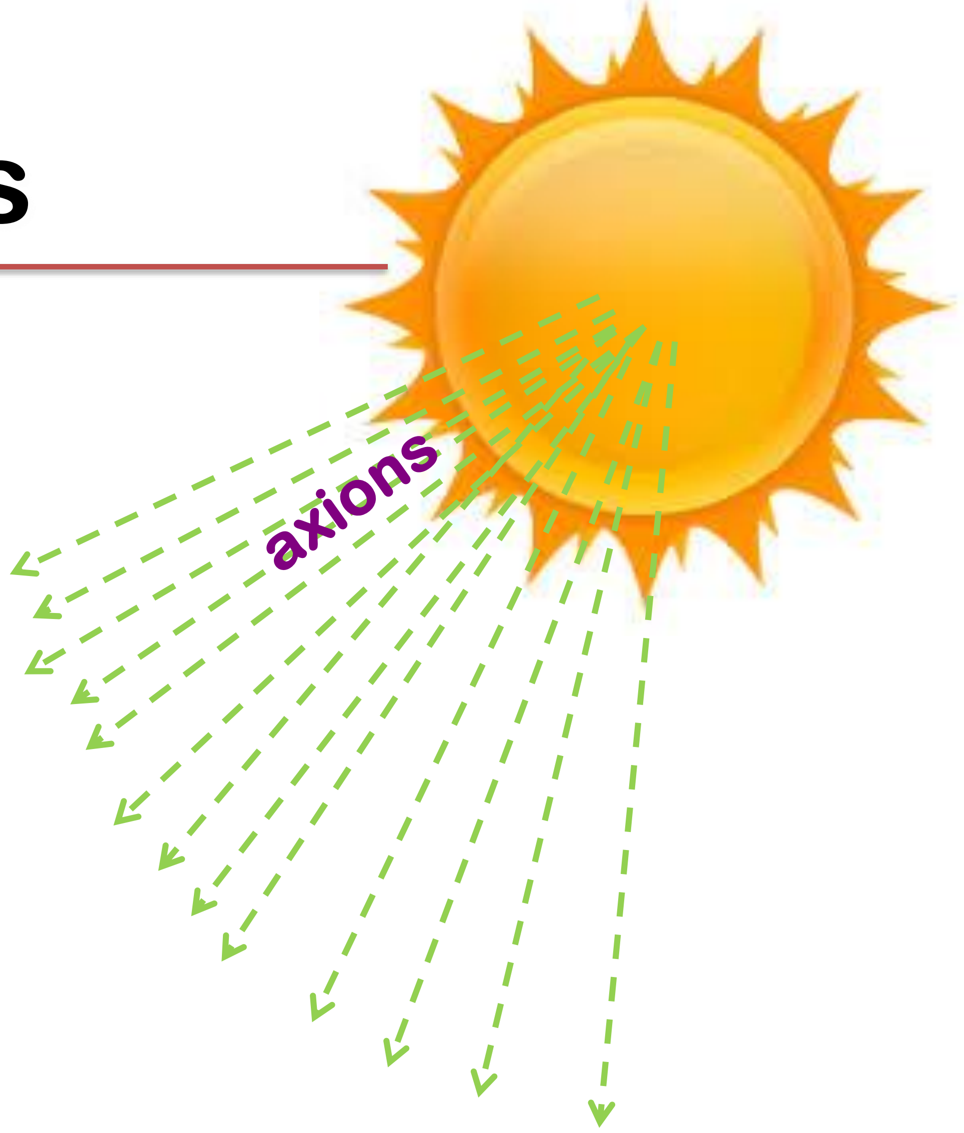
Solar Axions

- 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

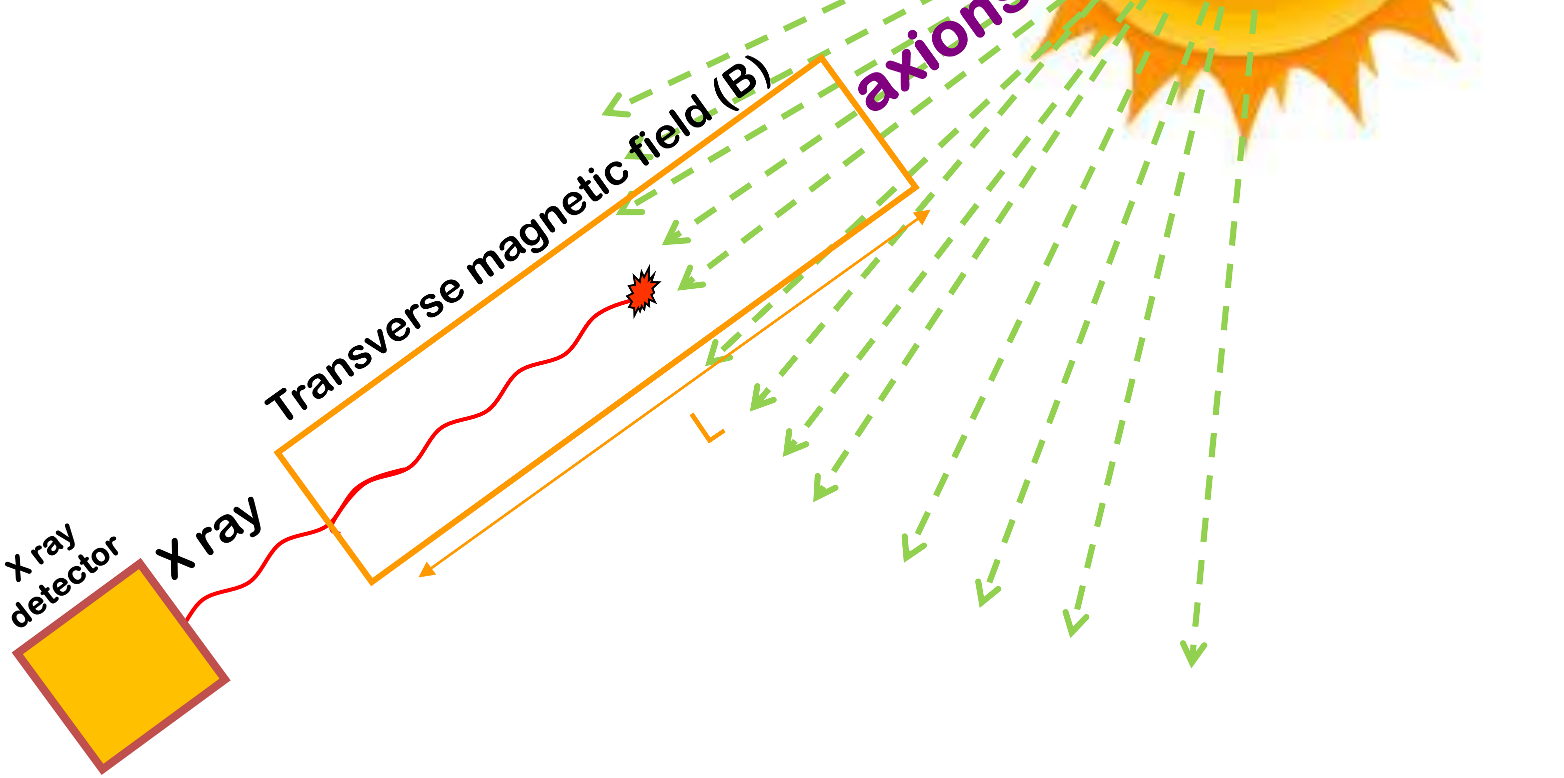




Axion helioscopes

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

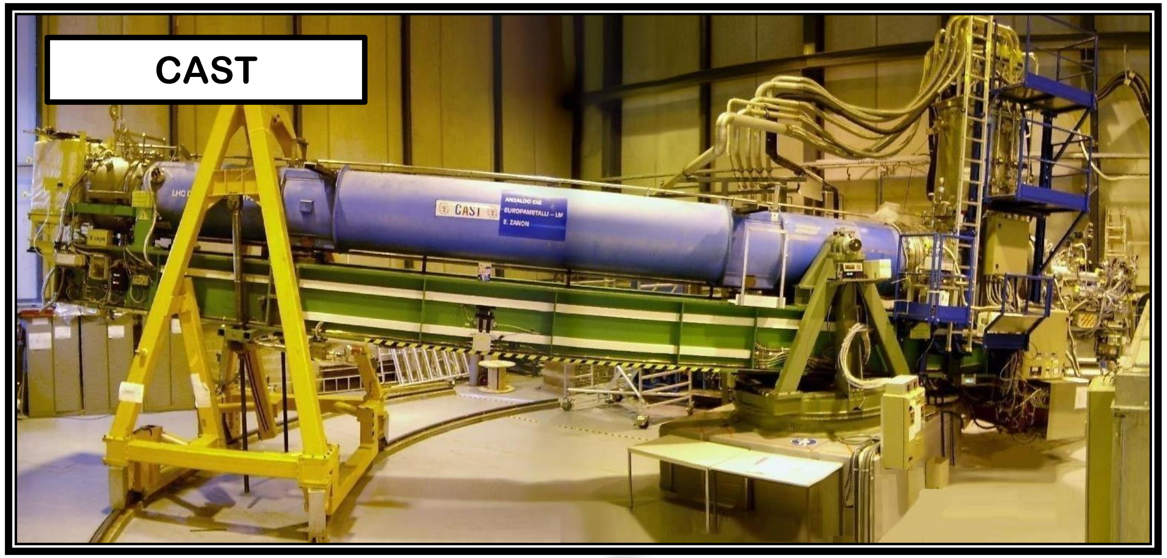
- **Previous helioscopes:**
  - First implementation at Brookhaven (just few hours of data) [Lazarus et at. PRL 69 (92)]
  - TOKYO Helioscope (SUMICO): 2.3 m long 4 T magnet

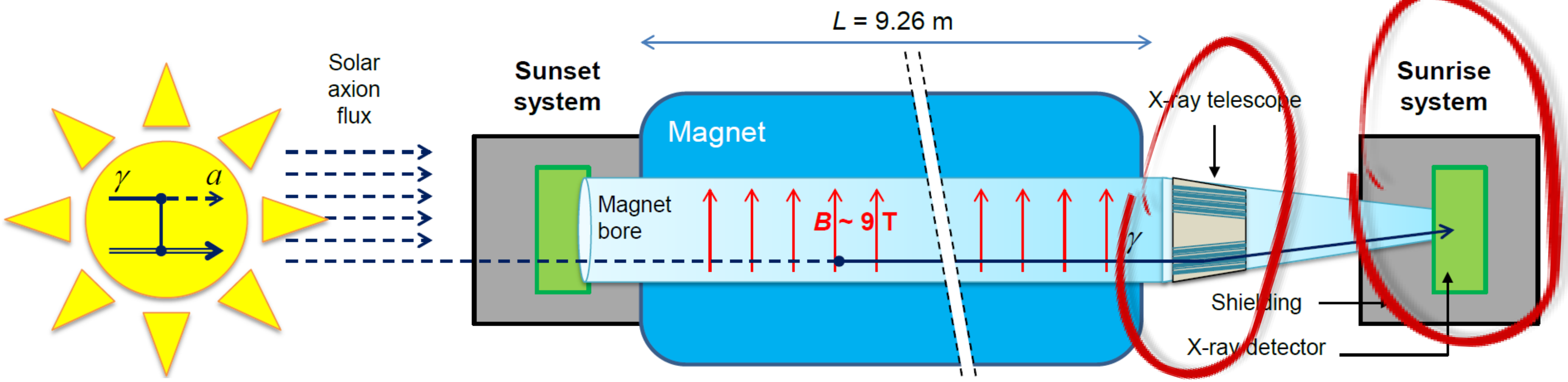


CAST: state-of-the-art

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

First helioscope using low background techniques & x-ray focusing

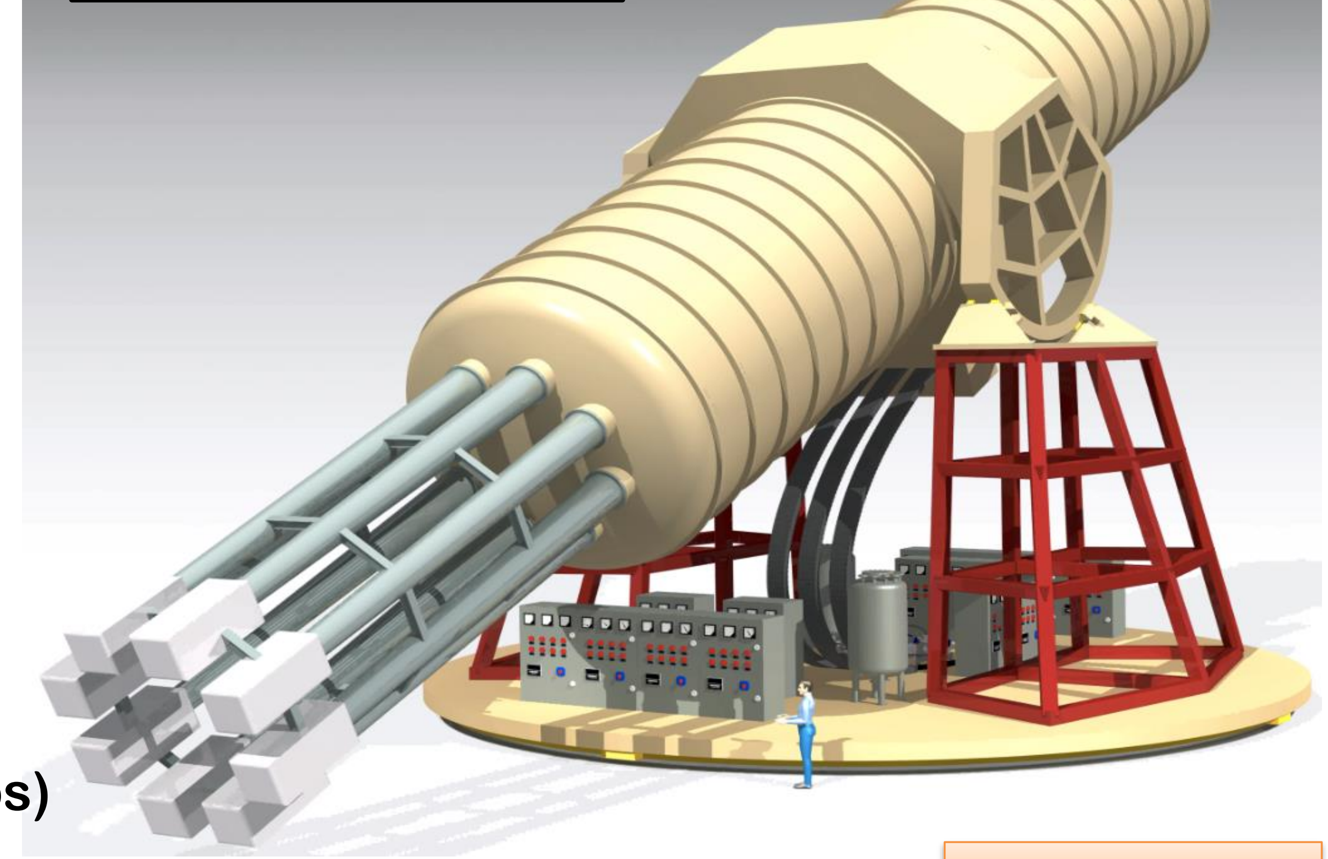




IAXO experiment summary

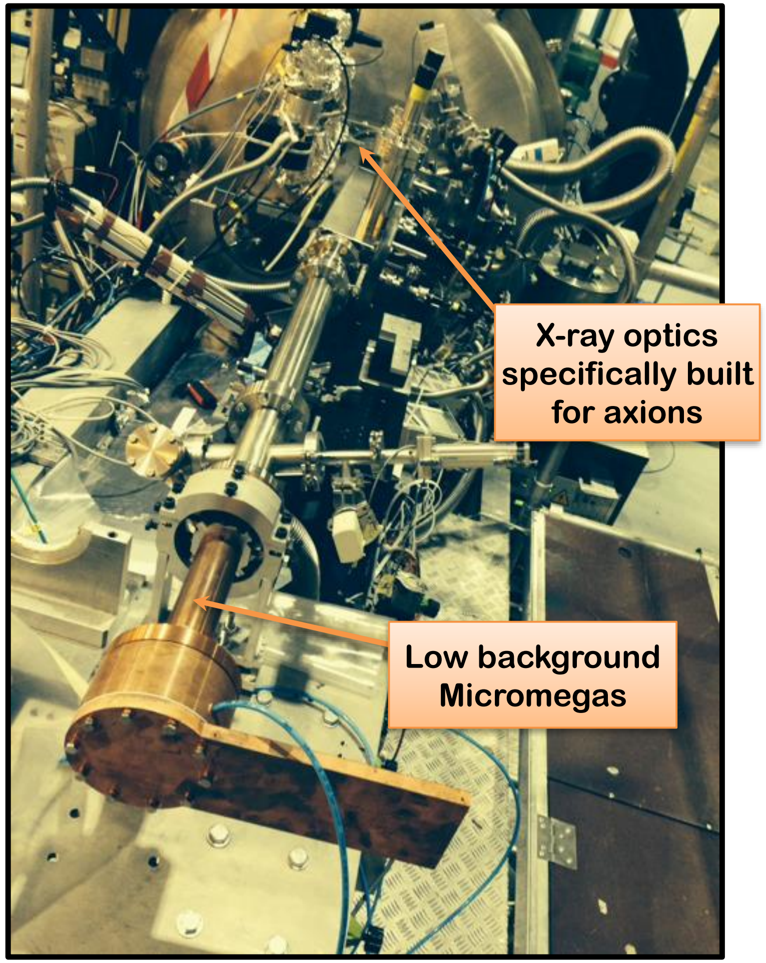
- Next generation "axion helioscope" after CAST
- Purpose-built large-scale magnet
  - >300 times larger B^2L^2A than CAST magnet
  - Toroid geometry
  - 8 conversion bores of 60 cm Ø, ~20 m long
- Detection systems (XRT+detectors)
  - Scaled-up versions based on experience in CAST
  - Low-background 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 conceptual design
JINST 9 (2014) T05002



~10^{4-5} x CAST SNR

IAXO pathfinder at CAST



nature physics

ARTICLES

PUBLISHED ONLINE: 1 MAY 2017 | DOI: 10.1038/NPHYS4109

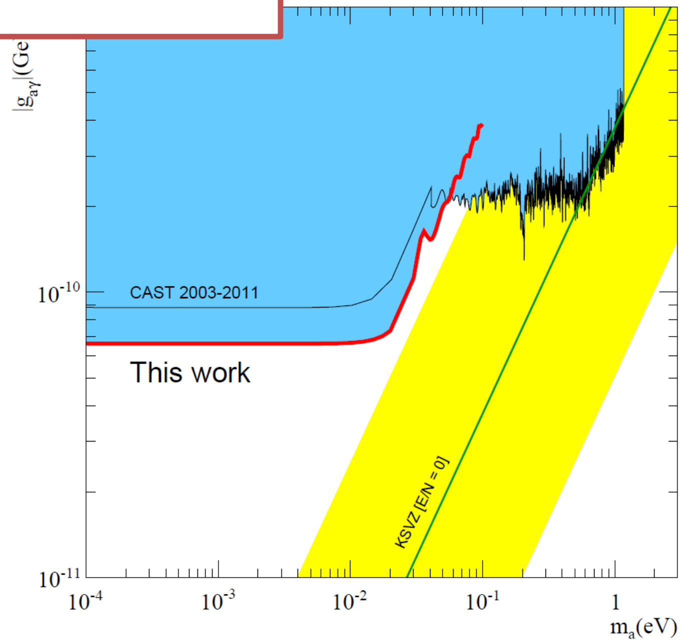
OPEN

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 ... directed towards the Sun. In the strong magnetic ... by X-ray detectors. In the 2013–2015 run, thanks

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



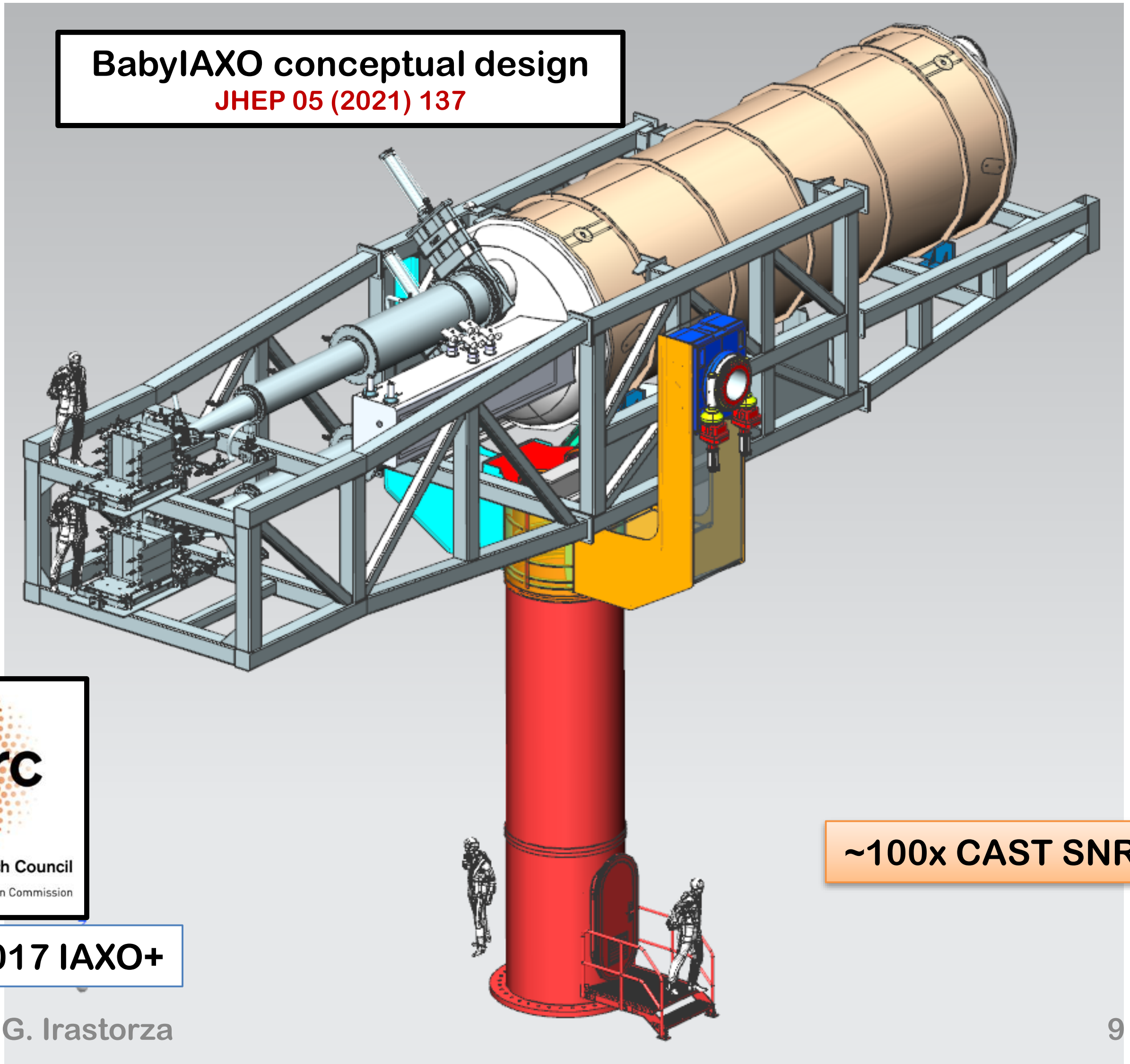
IAXO pathfinder system at CAST:
x-ray focusing + low background detector combined in same system
Small-scale version of IAXO baseline detection lines

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)

BabyIAXO conceptual design
JHEP 05 (2021) 137



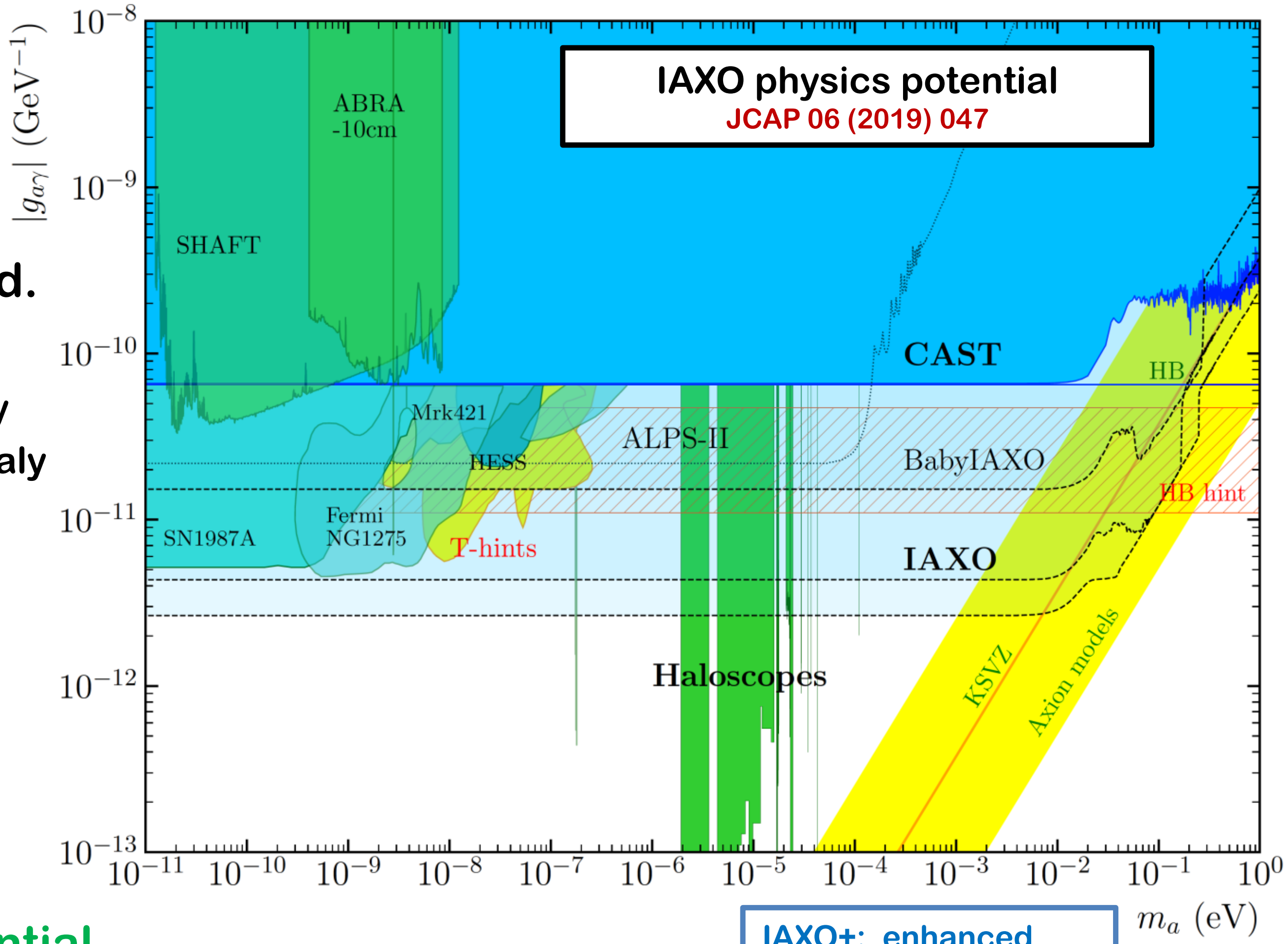
ERC-AvG 2017 IAXO+

~100x CAST SNR

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



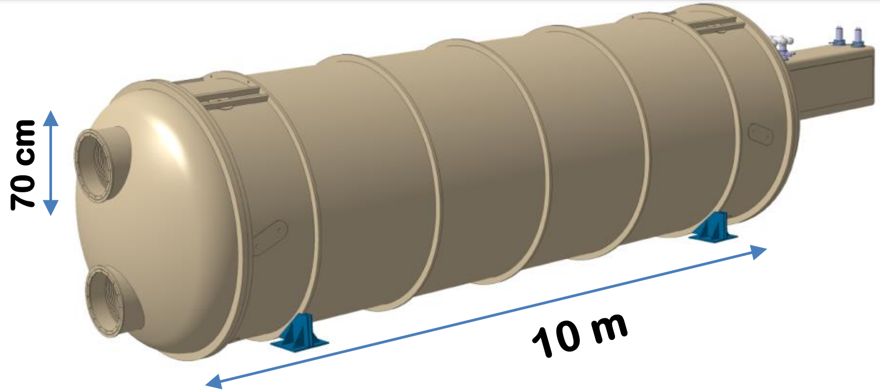
IAXO+: enhanced scenario with x10 (x4) higher FOM (MFOM) with respect LoI

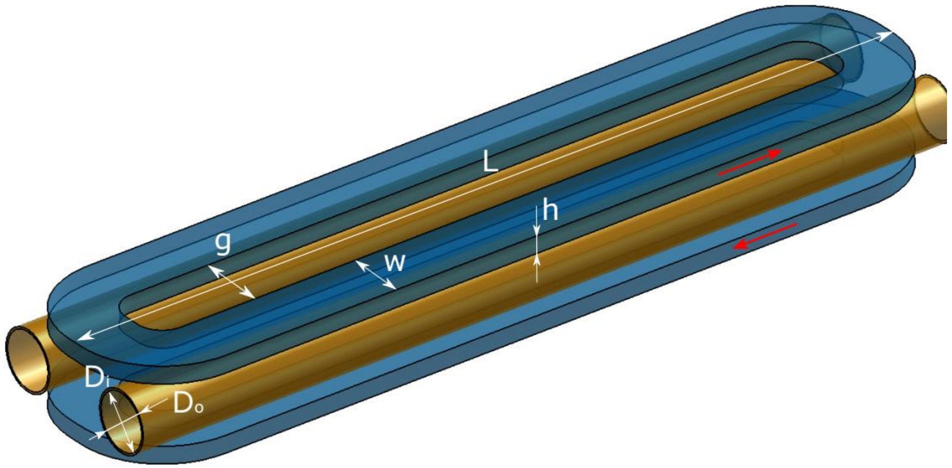
Important recent milestones

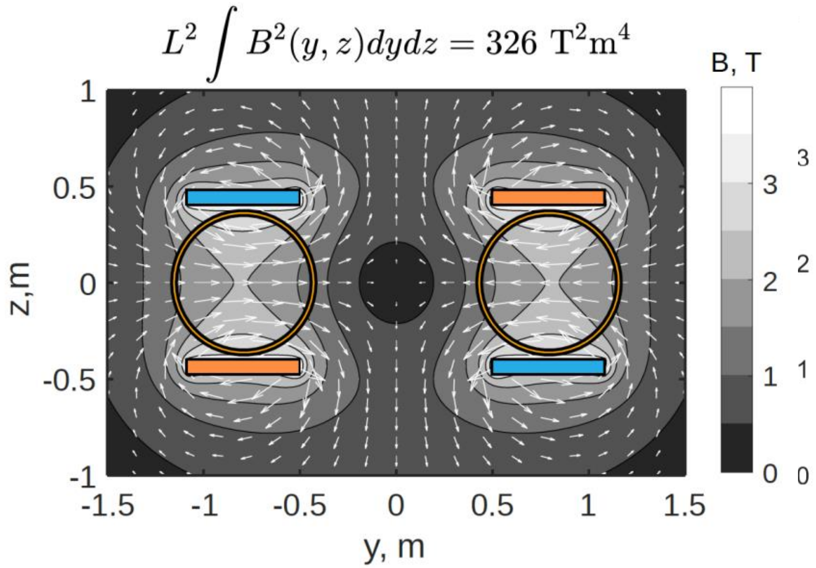
- Some history: first concept 2011, IAXO CDR (2014), BabyIAXO concept (2016), IAXO collaboration formally stablished in 2017.
- Project aproved by DESY after LoI (2018) and full proposal (2019). Project being monitored by DESY PRC since then.
- Funding almost secured: ERC-AdG @ UNIZAR (2018), DESY as 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 published (2021)
- Technical design very much advanced.
- First construction preparation steps being taken (first tenderings).

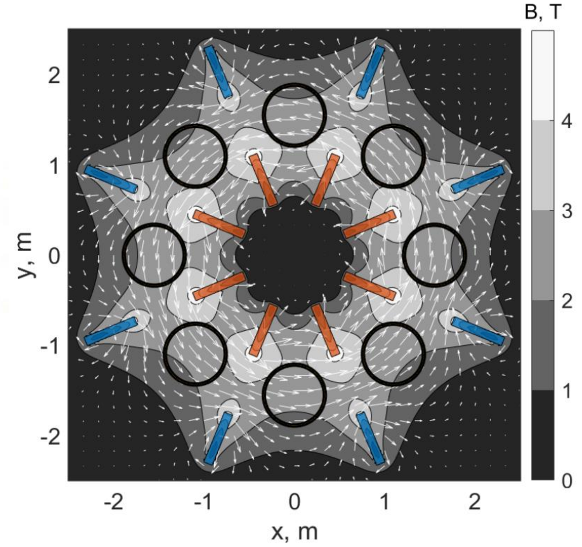
BabyIAXO magnet

- "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.



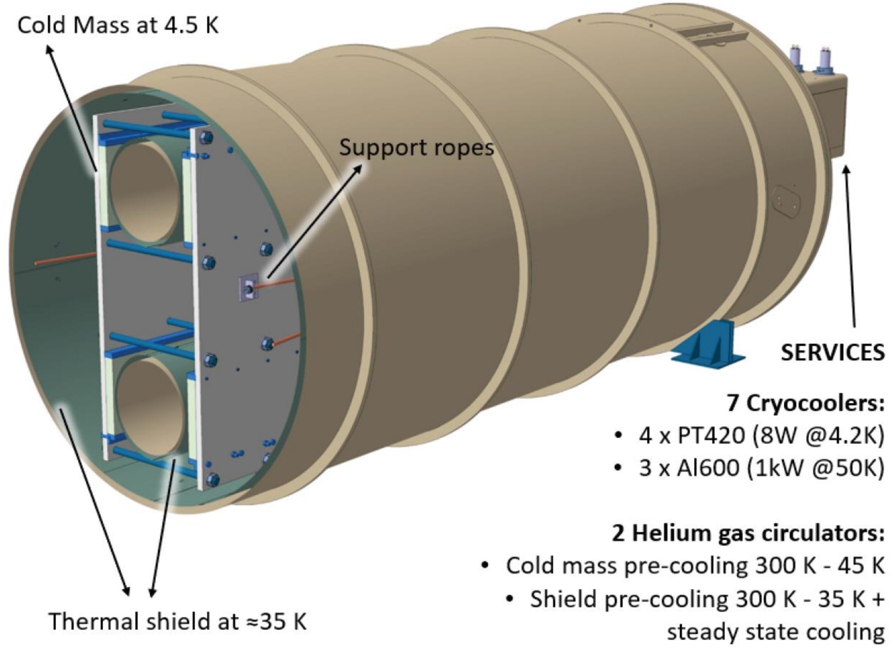


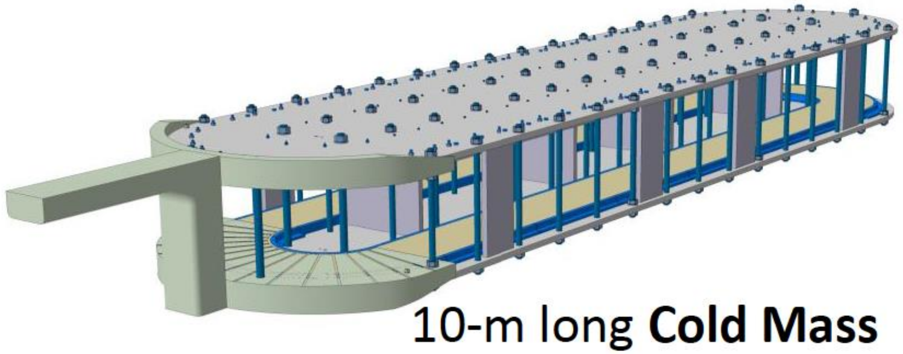




BabyIAXO magnet

- Technical in-depth review of magnet design (by DESY PRC) successfully passed last November.
- Now ongoing adaptations derived from difficulties to procure originally targeted SC cable.
- Request for quotations & tendering started for some subsystems.





BabyIAXO optics

2 detection lines in BabyIAXO:

Hybrid approach for custom BabyIAXO optic

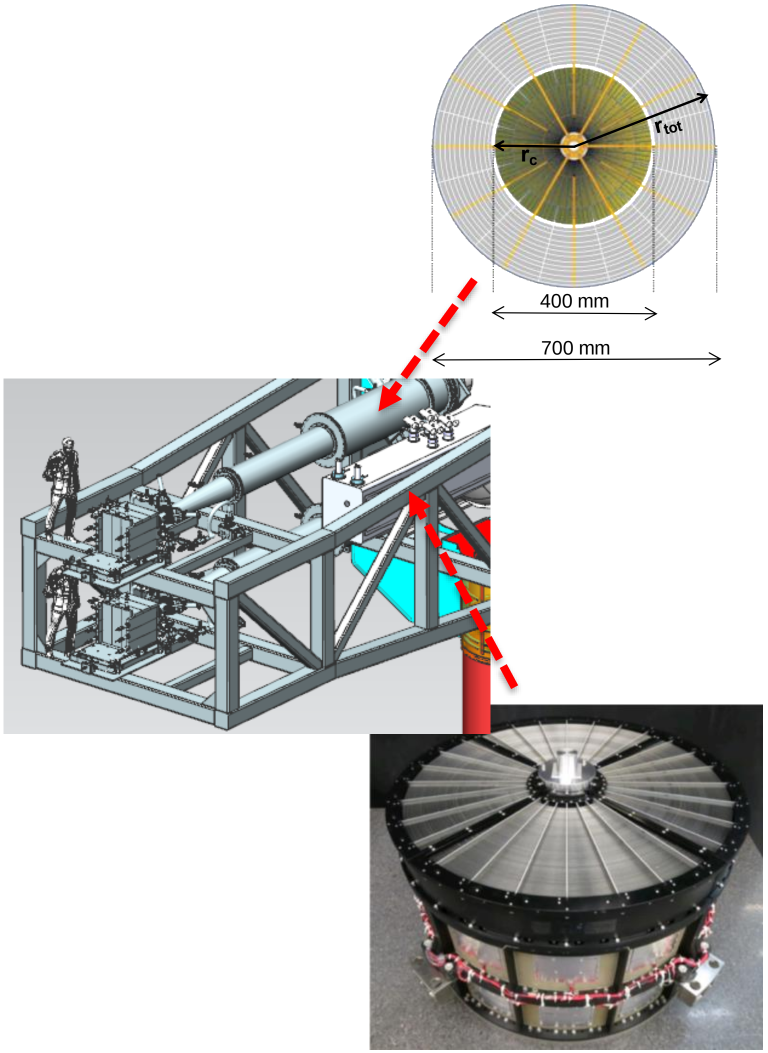
- Inner part Al-foil or segmented glass optic (NASA/LLNL/DTU/MIT/Columbia)
- Outer part cold-slumped Willow-glass technology (INAF/DTU)
- First multilayer deposition tests and characterization with NuSTAR flight glass and Willow glass completed → publication in preparation
- Design of support structure 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)

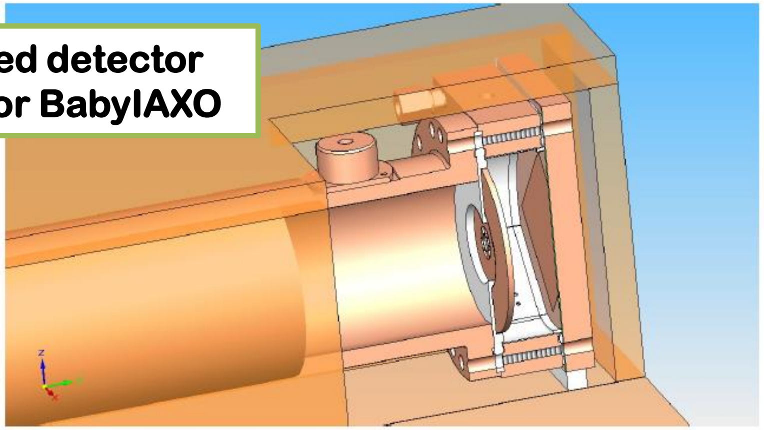
→ First collection of technical drawings at DESY, shipment is being arranged

- List for ESA operational requirements and loan agreement in preparation



BabyIAXO detectors

- Baseline detectors:
  - Low background Micromegas detectors of *microbulk* type
  - "Discovery detectors" (priority to low background).
  - Experience in CAST
  - Low background capability, radiopurity, shielding.
  - Goal is to reach 10^{-7} c/keV/cm^2/s



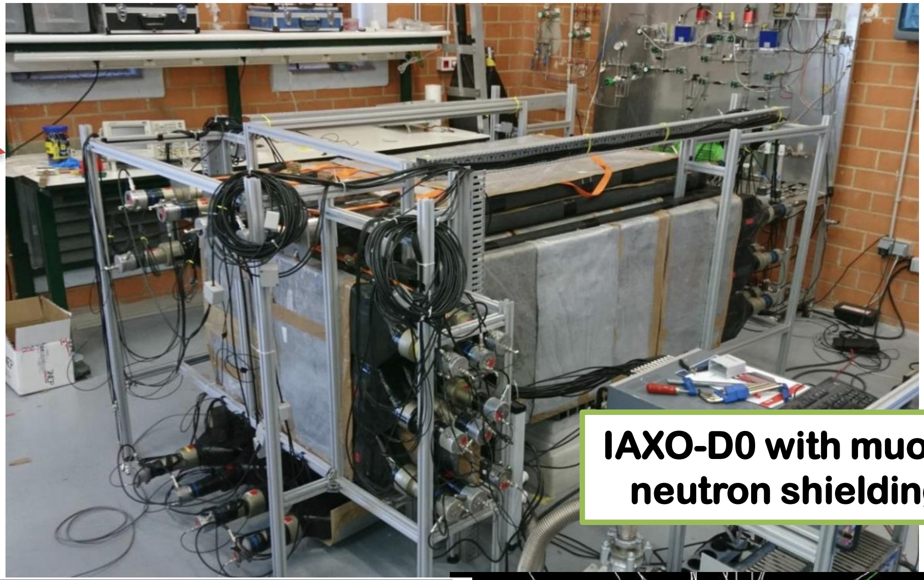
Improved detector design for BabyIAXO

IAXO-D0 prototype in its shielding

Baseline detectors

- **Tests at surface UNIZAR with IAXO-D0.**
  - Implementation of 4π muon veto + cosmic neutron tagger.
- **Tests at underground planned with a second prototype IAXO-D1 (being installed @ LSC)**
  - Determine part of intrinsic and cosmic induced events
- **Simulations**
  - Background might be limited by cosmic neutrons

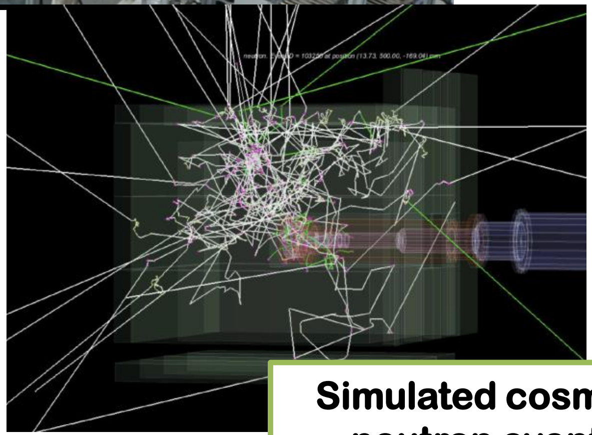
- Near term goal: confirm hypothesis cosmic neutrons main limitation to lower background



IAXO-D0 with muon+ neutron shielding

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



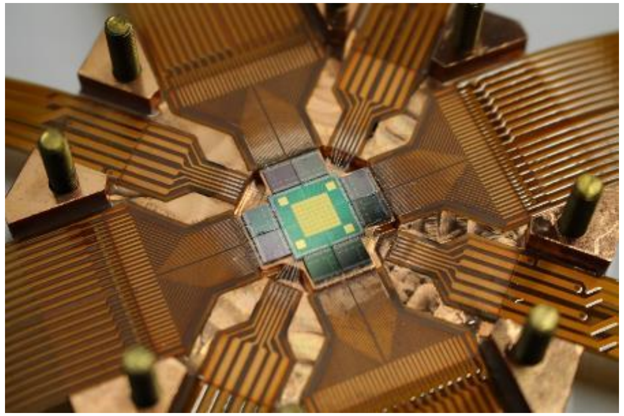
Simulated cosmic neutron event

Complementary technologies

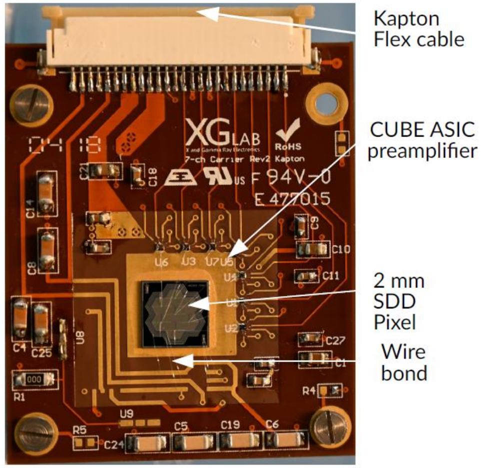
- Beyond baseline, “high precision” detectors
  - Better threshold & energy resolution
  - Design and material optimization ongoing in all fronts
  - Background studies with different shielding configurations
  - DALPS project (French ANR)

ERC-StG (2020)
M.Meyer/Hamburg
To understand bkg in TES

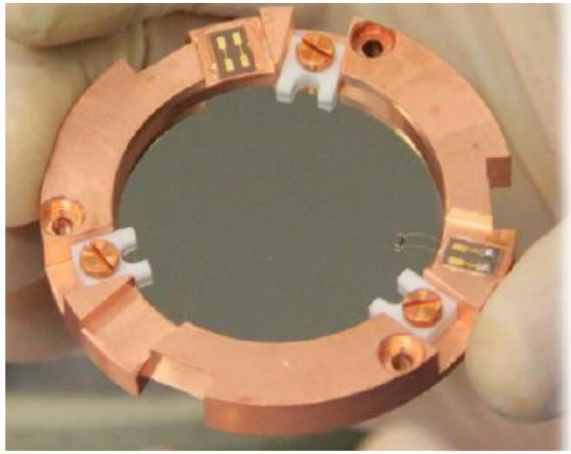
Gridpix



MMC: Metallic Magnetic calorimeters



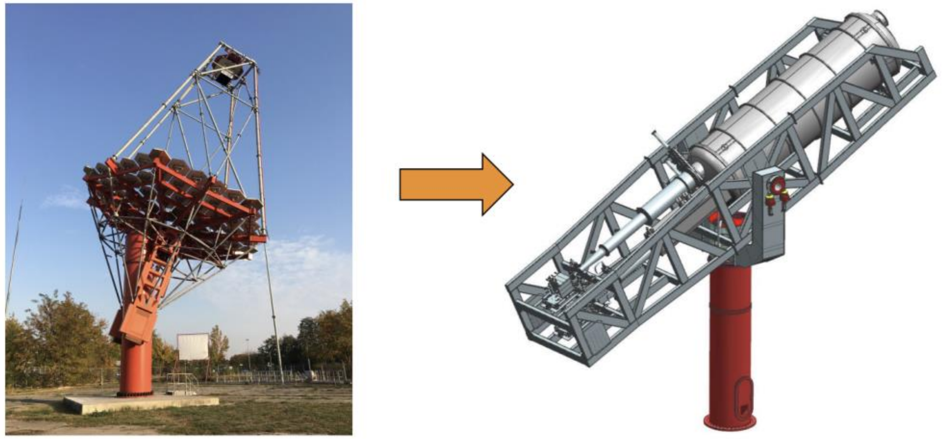
SDD: Silicon Drift Detectors

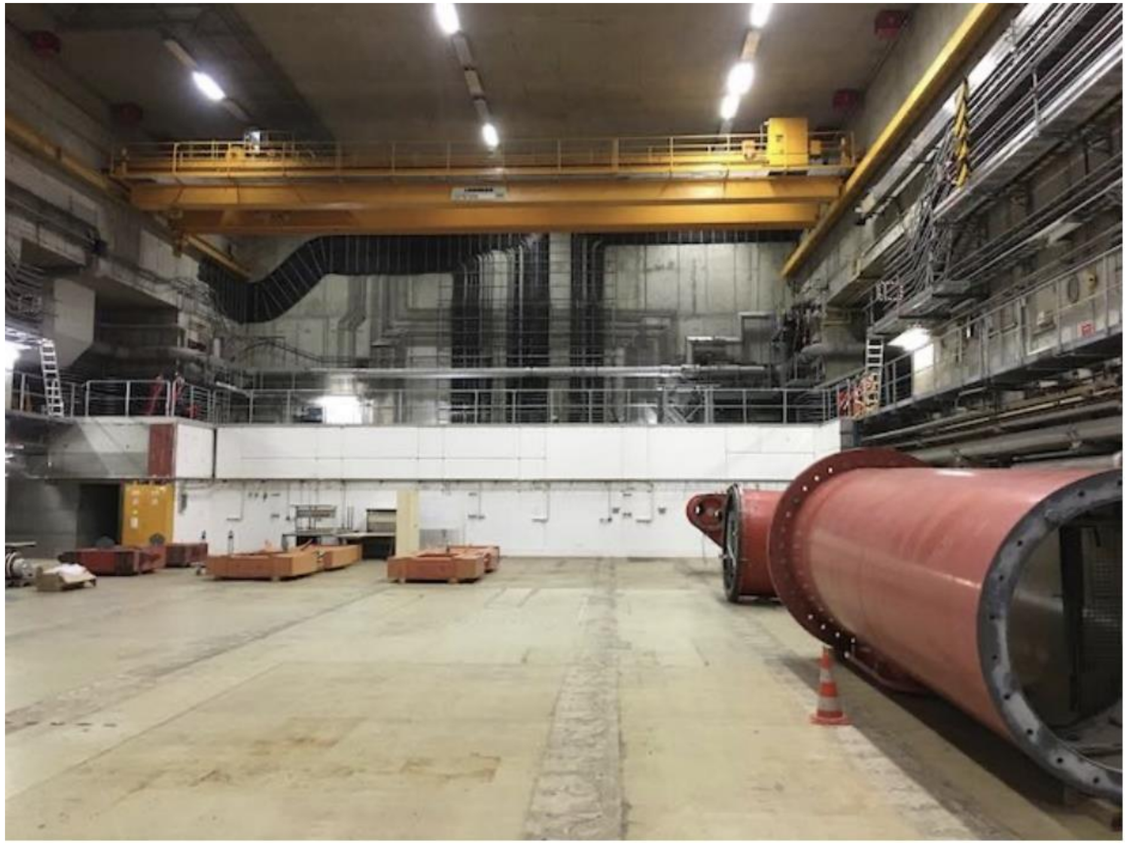


TES: Transition Edge senstors

Technical coordination at DESY

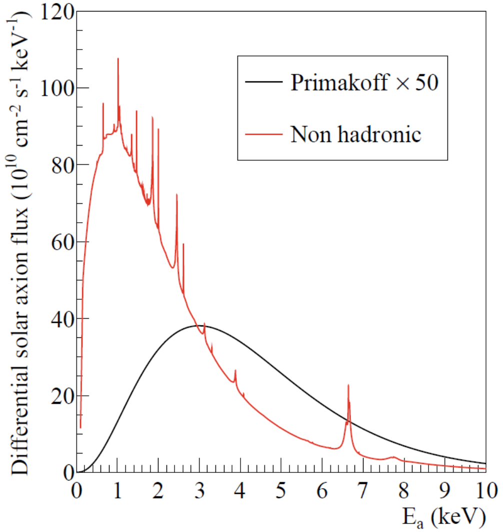
- **Site**: HERA South Hall, former ZEUS detector hall: 43 x 25m
- **Support and Drive System**: Reusing (parts of) CTA MST Prototype from Berlin.
- **Technical coordination and project office** very active, WBS, PBS, …

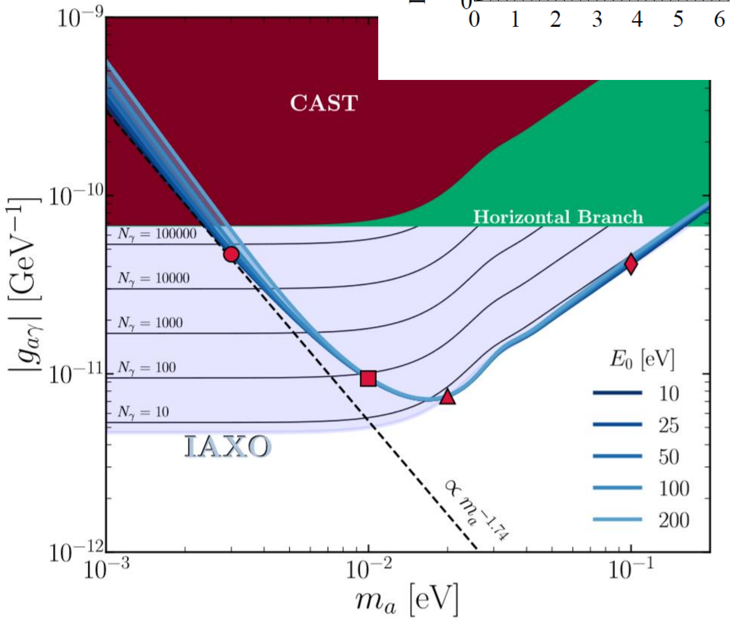




BabyIAXO: beyond baseline

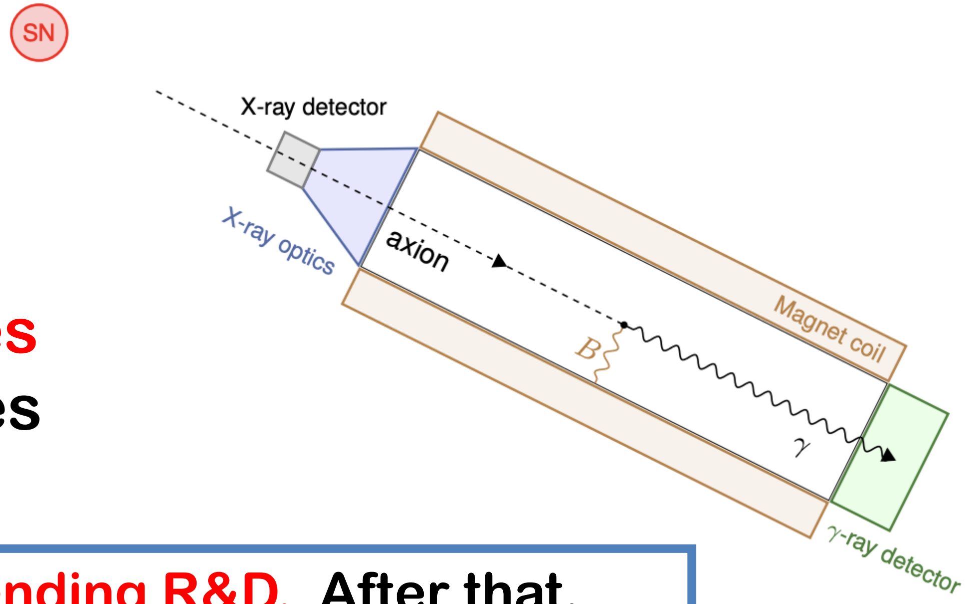
- Detection of both ABC and Primakoff axion spectrum would allow distinguishing axion models (g_{ae}, $g_{a\gamma}$) Jaeckel et al. arXiv:1811.09278
- Axion mass can be determined from the spectral shape. Dafni et al. arXiv:1811.09278
- Detection of 14 keV peak peak from 57Fe transitions add sensitivity to g_{an}. Di Luzio et al. 2111.06407
- Additional population of low energy axions, via plasmon-axion conversion in solar B-fields ($g_{a\gamma}$) e.g. Guarini et al. 2010.06601





BabyIAXO: beyond baseline

- **Axions from supernovae. Requires O(100MeV) γ-ray detector, and early warning for a galactic SN.** Ge et al. arXiv:2008.03924
- **Implementation of "haloscope" schemes inside the BabyIAXO magnet (RF cavities or other resonant structures)**

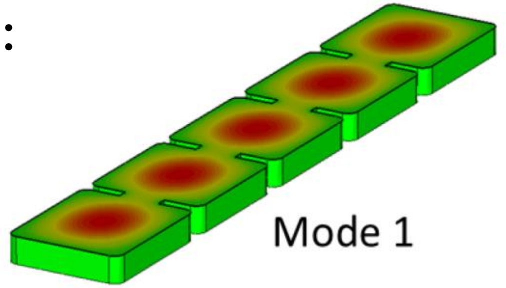


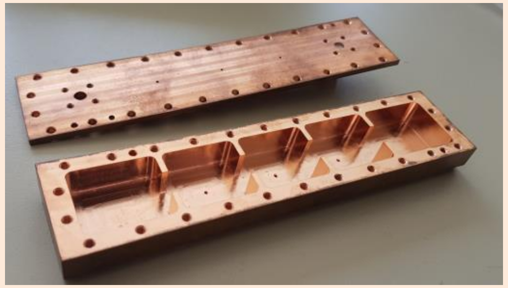
- **Baseline program is realistic and low-risk. No pending R&D. After that, the BabyIAXO infrastructure would be available for further activities "beyond-baseline", like new detectors with improved performance to: 1) extended physics runs or 2) preparatory tests for IAXO**
- **Definition of "beyond-baseline" 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?

RADES concept: array of small cavities interconnected with irises:

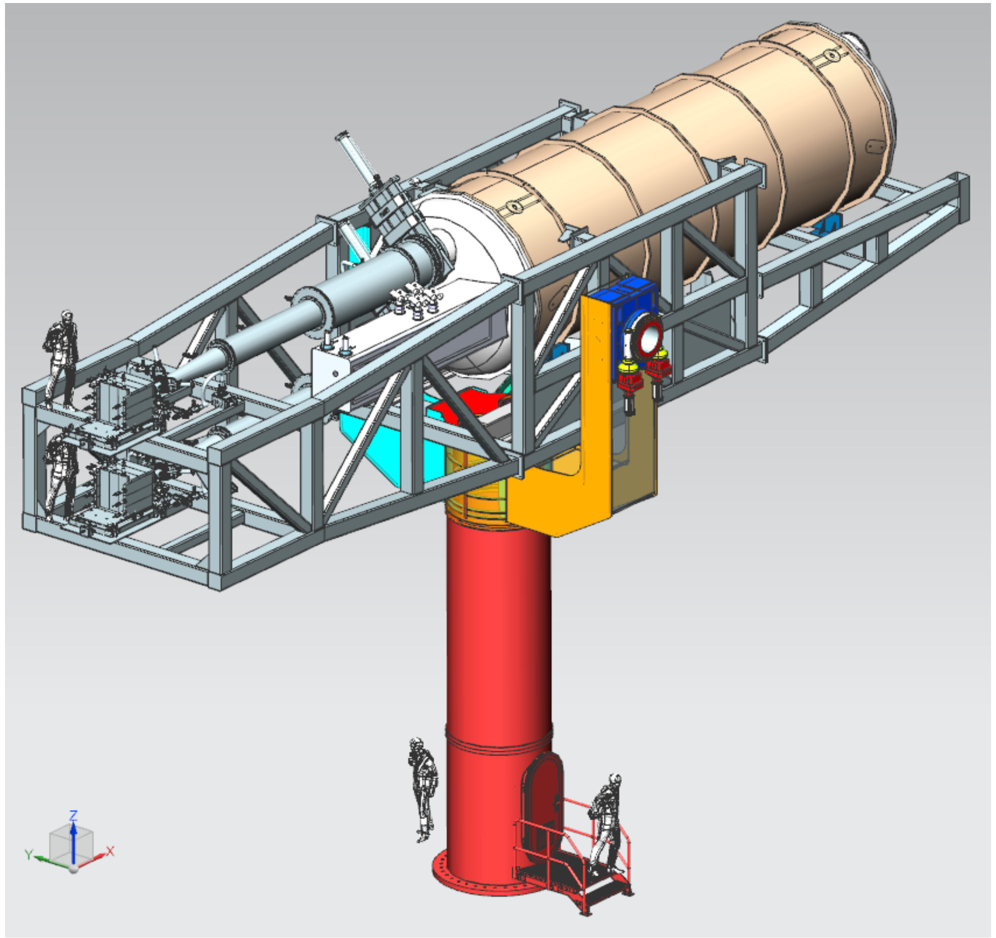




Part of ERC-StG (2018)
B. Döbrich/CERN

Conclusions

- CAST legacy: axion helioscopes can probe axion/ALP parameters beyond astro limits
- IAXO has a rich and unique potential to probe relevant region of axion models
- BabyIAXO on track for construction. Stay tuned for first “light” hopefully in (~)2024



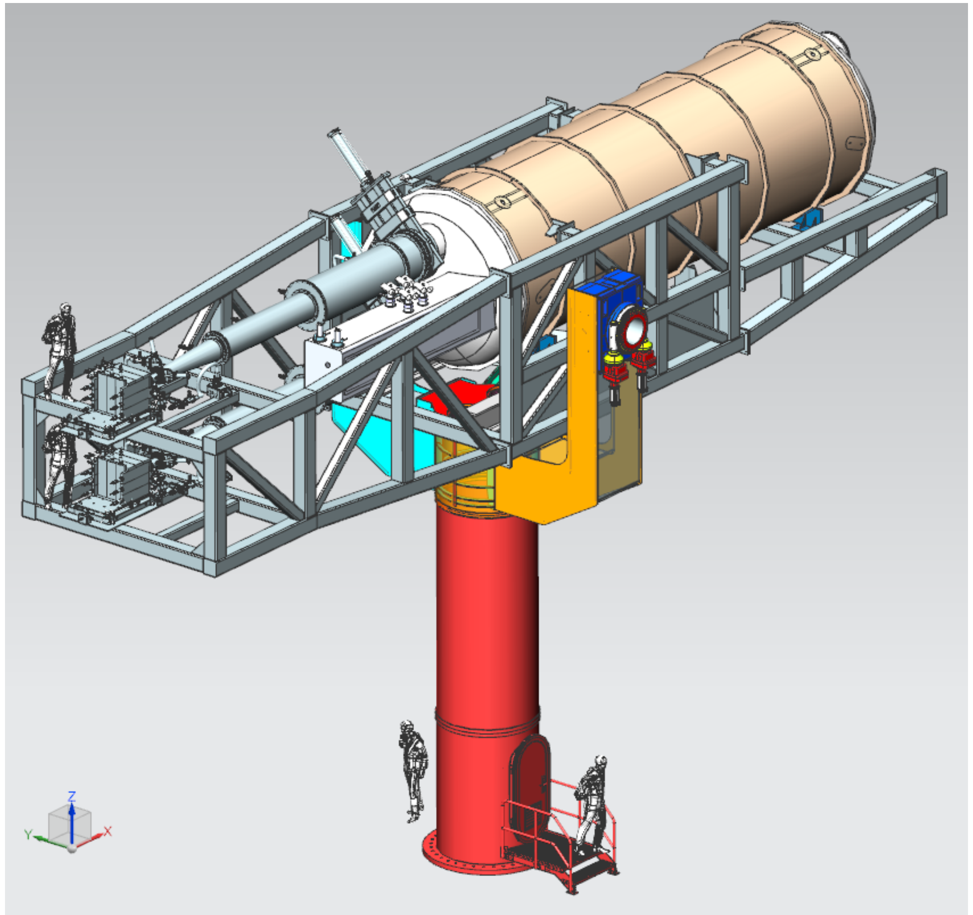
Thanks for your attention

IAXO collaboration: 125 scientists from 21 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) | 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) |

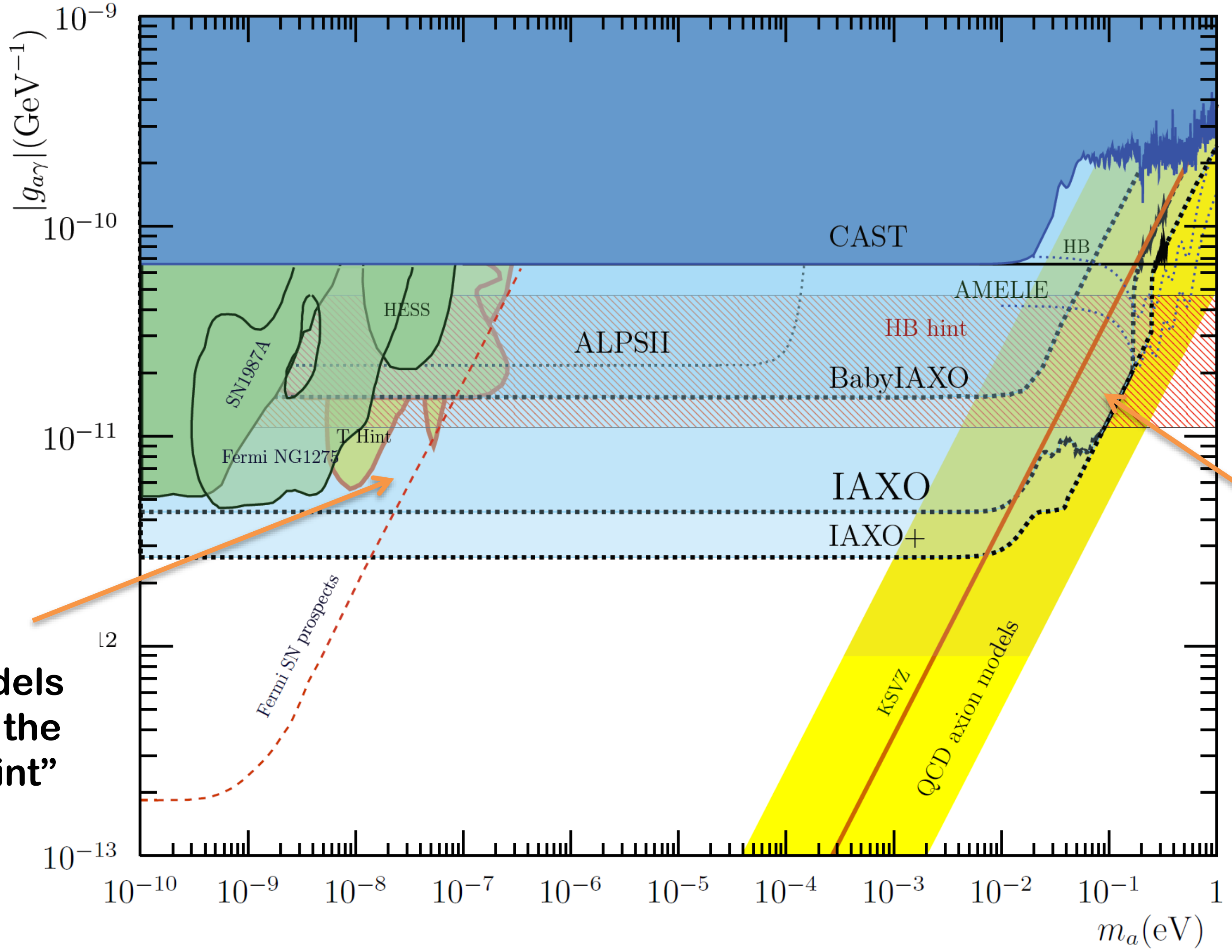
Associate members: DTU (Denmark) | U. Columbia (USA) | SOLEIL (France) | IJCLab (France) | LIST-CEA (France)

- **Backup slides**



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

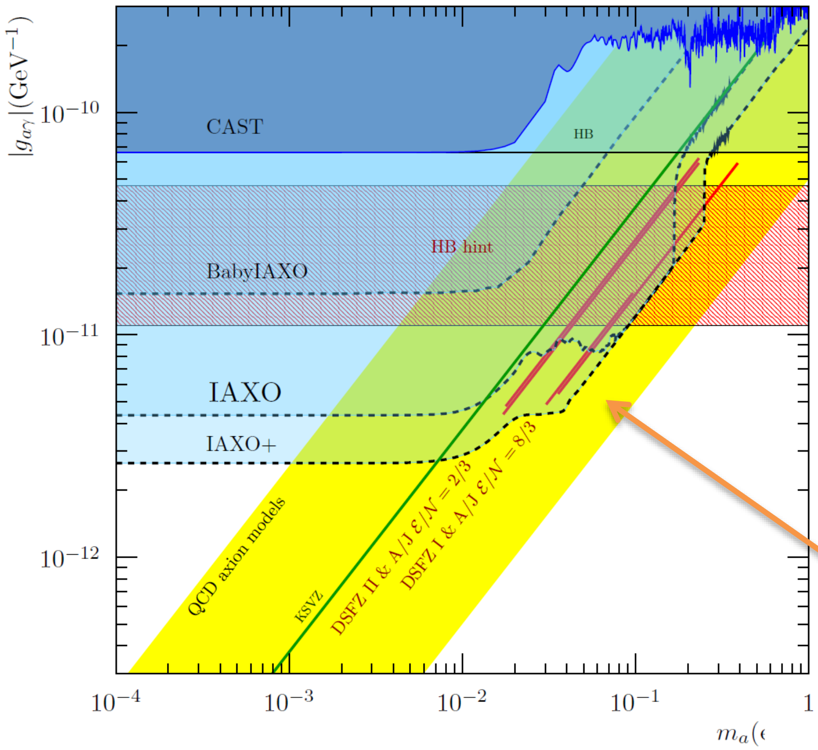
IAXO will fully explore ALP models invoked to solve the "transparency hint"

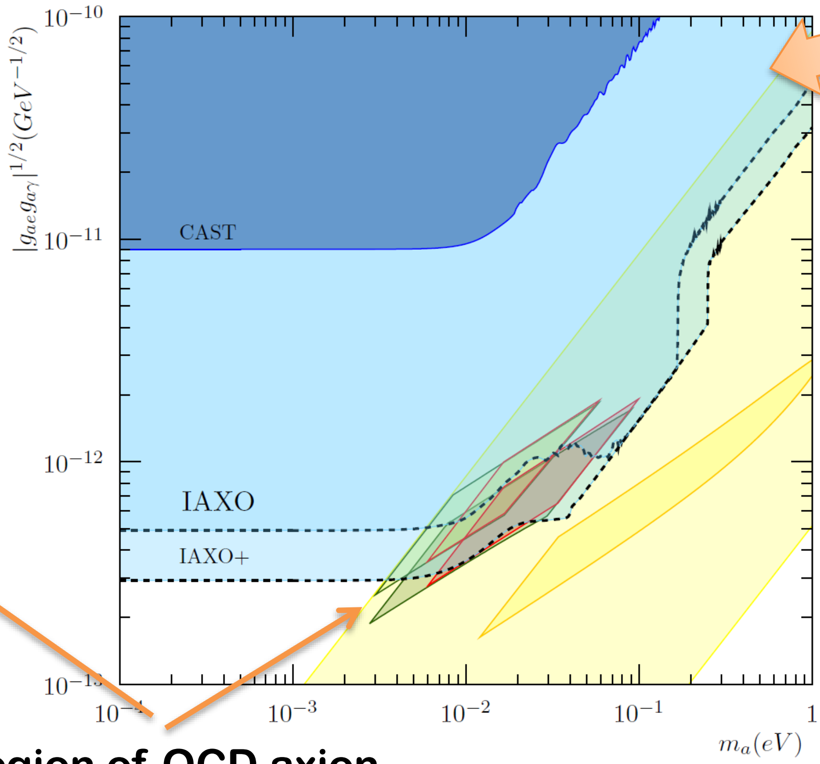
… as well as a large fraction of the axion & ALP models invoked in the "stellar cooling anomaly"
But for this the g_{ae} is particularly interesting

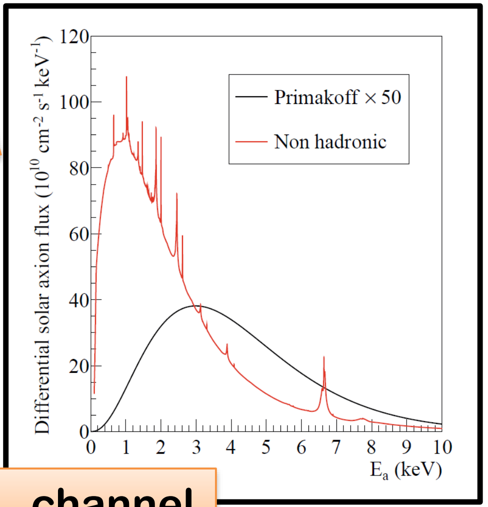
MFOM = Magnet FOM

IAXO & stellar cooling

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







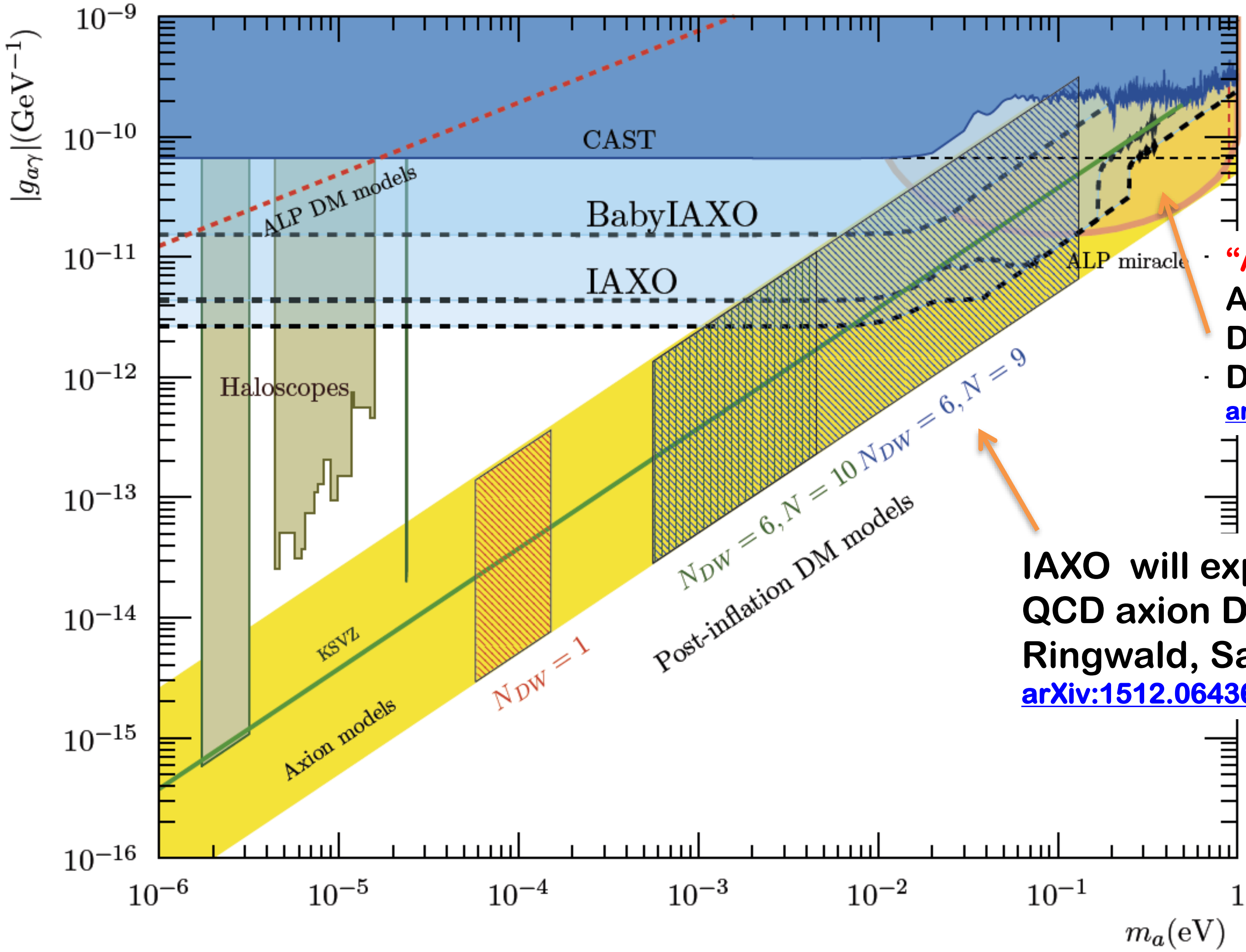
g_{ae} **channel**

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**

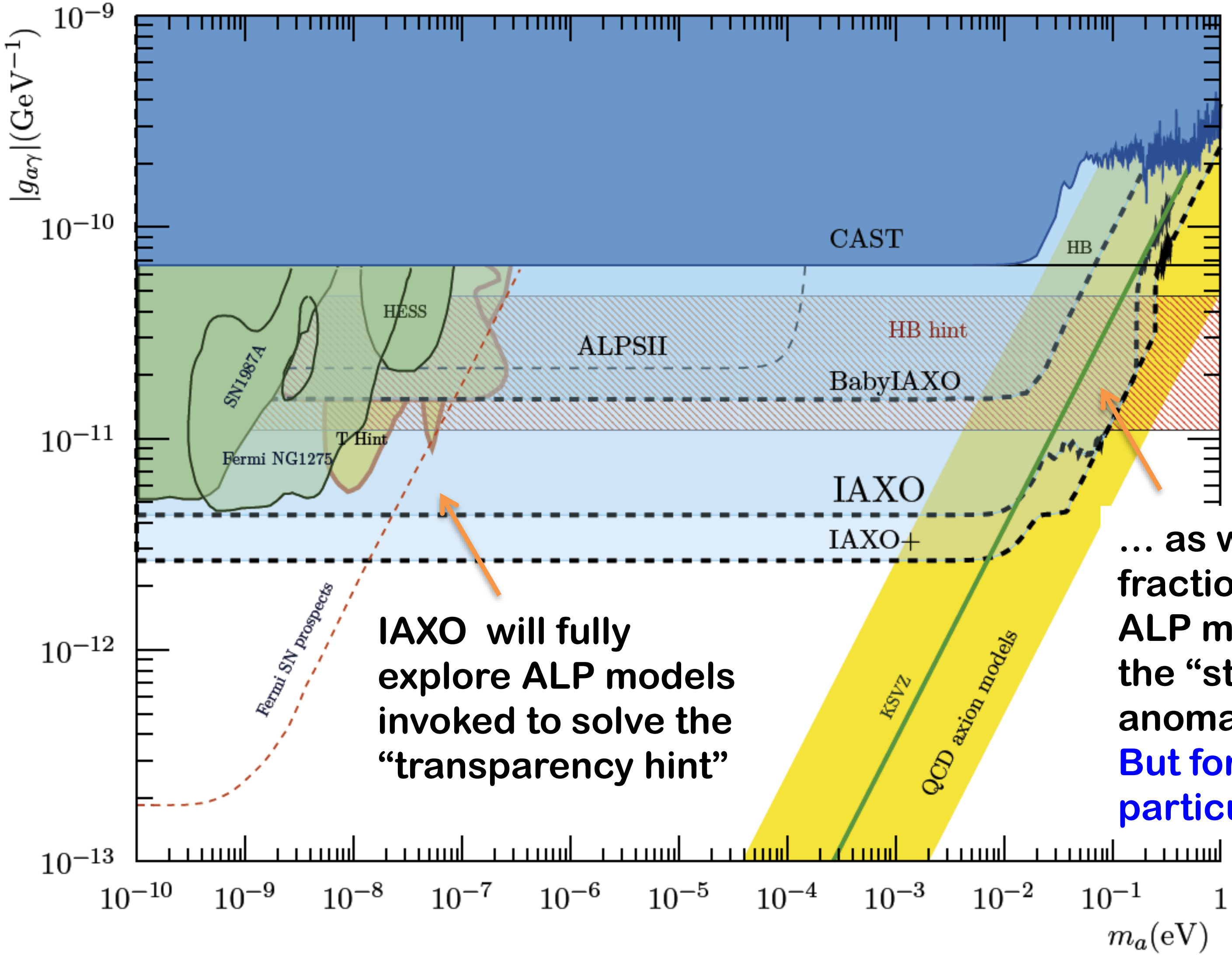
IAXO & meV axion cosmology



"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"

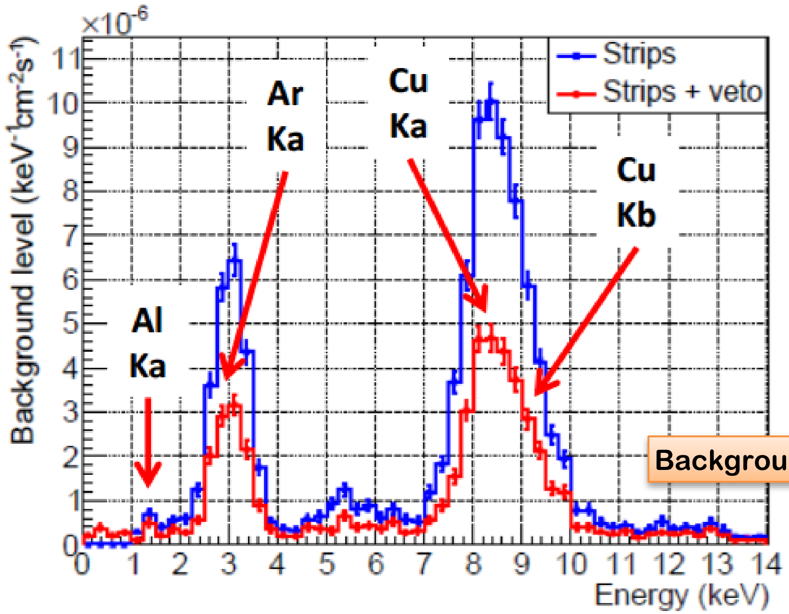
… as well as a large fraction of the axion & ALP models invoked in the "stellar cooling anomaly"

But for this the g_{ae} is particularly interesting

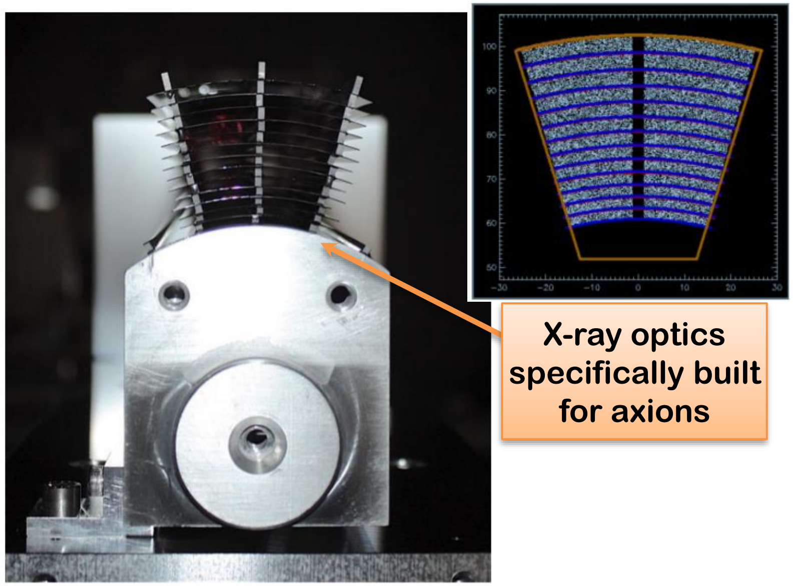
IAXO pathfinder system in CAST

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

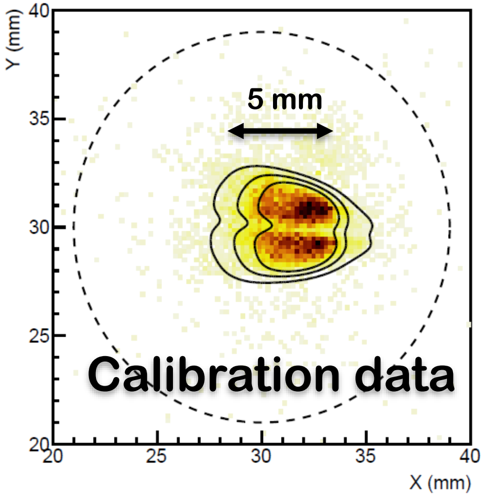
Detector: JCAP12 (2015)
Physics: Nature Phys. 13 (2017) 584-590

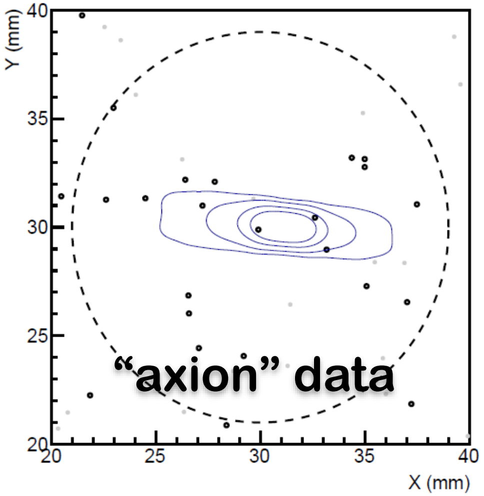


Background spectrum

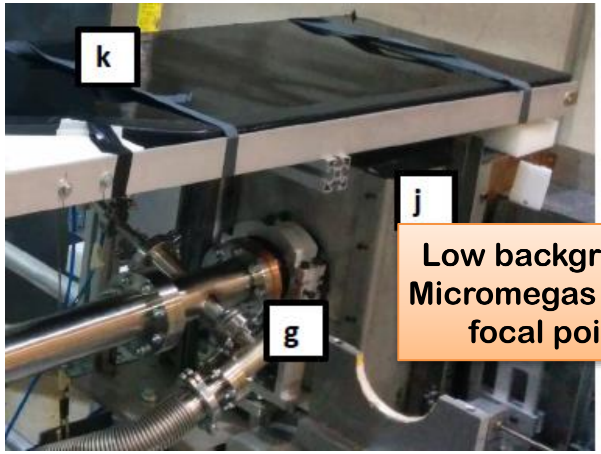


X-ray optics specifically built for axions



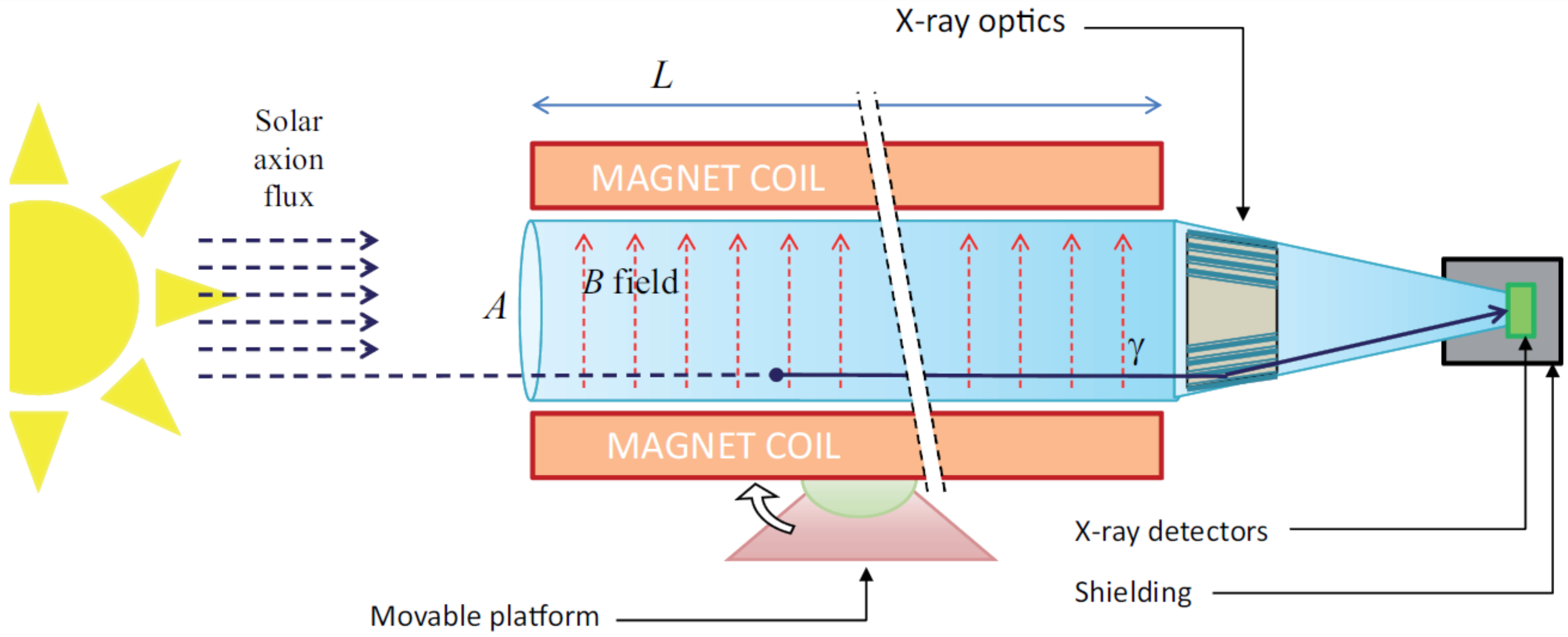


- Best SNR of any previous detector
- 290 tracking hour acquired (6.5 months operation)
- 3 counts observed in RoI (1 expected)



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

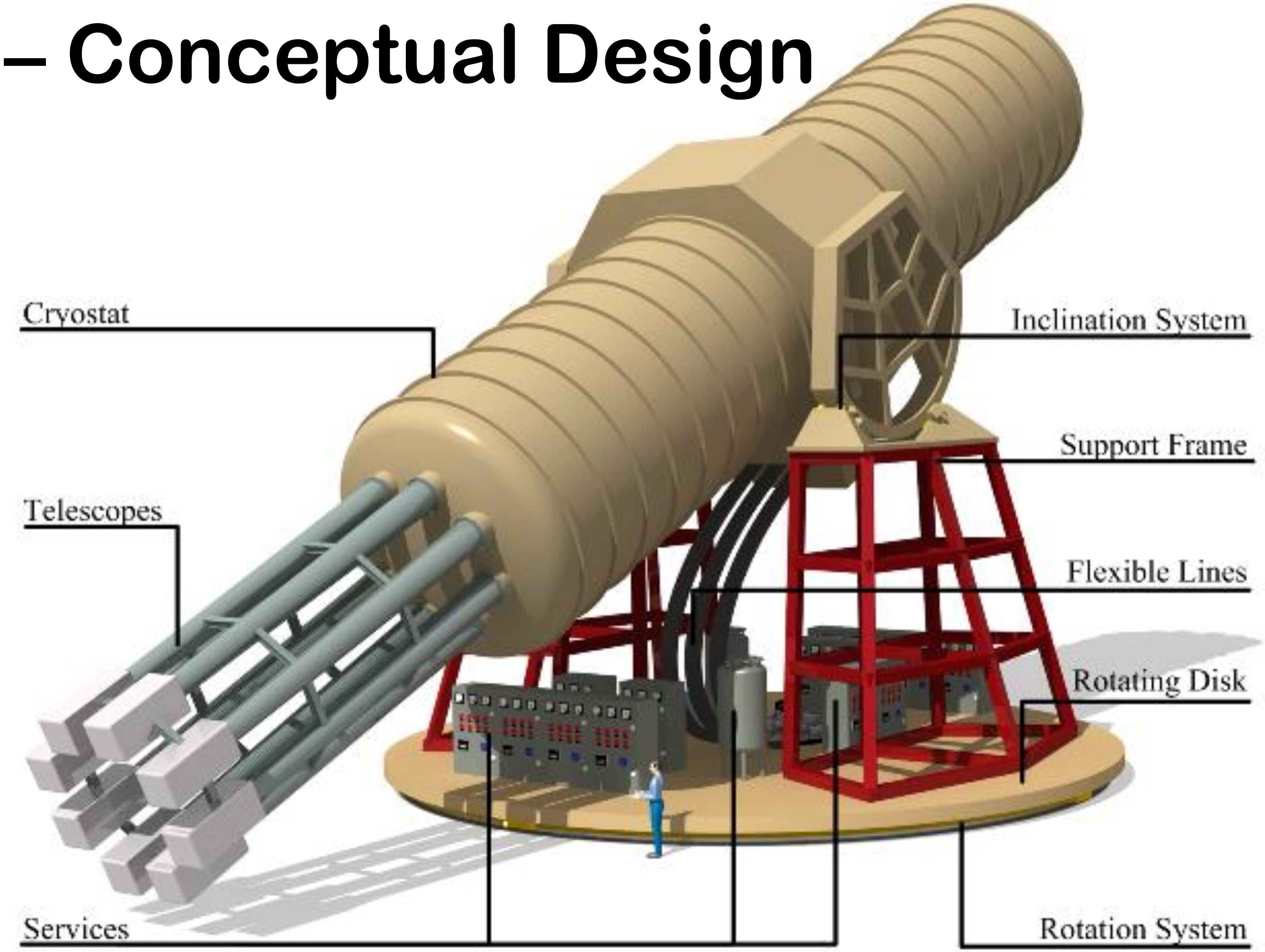
Enhanced axion helioscope:
JCAP 1106:013,2011

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

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

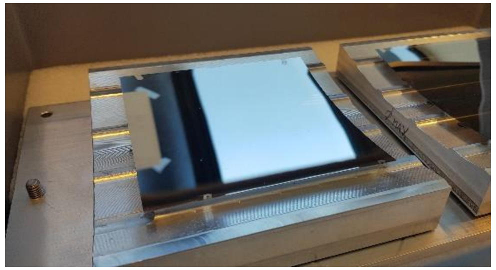
IAXO CDR: JINST 9 (2014) T05002 (arXiv:1401.3233)

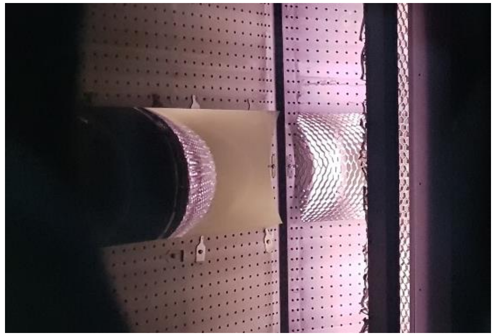


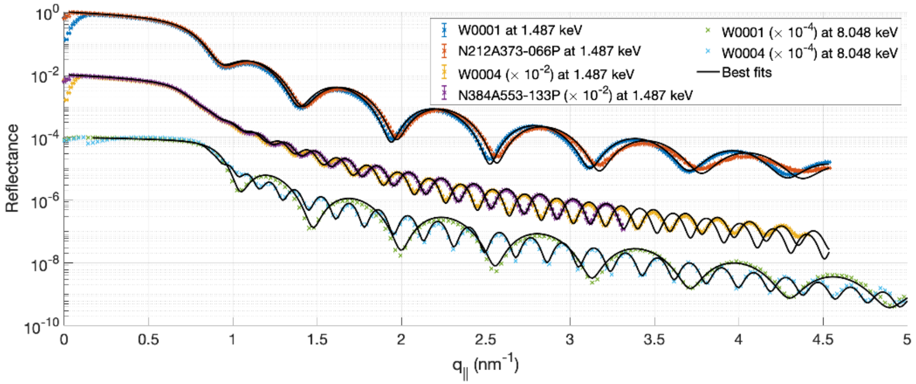
BabyIAXO optics: status

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 timeline