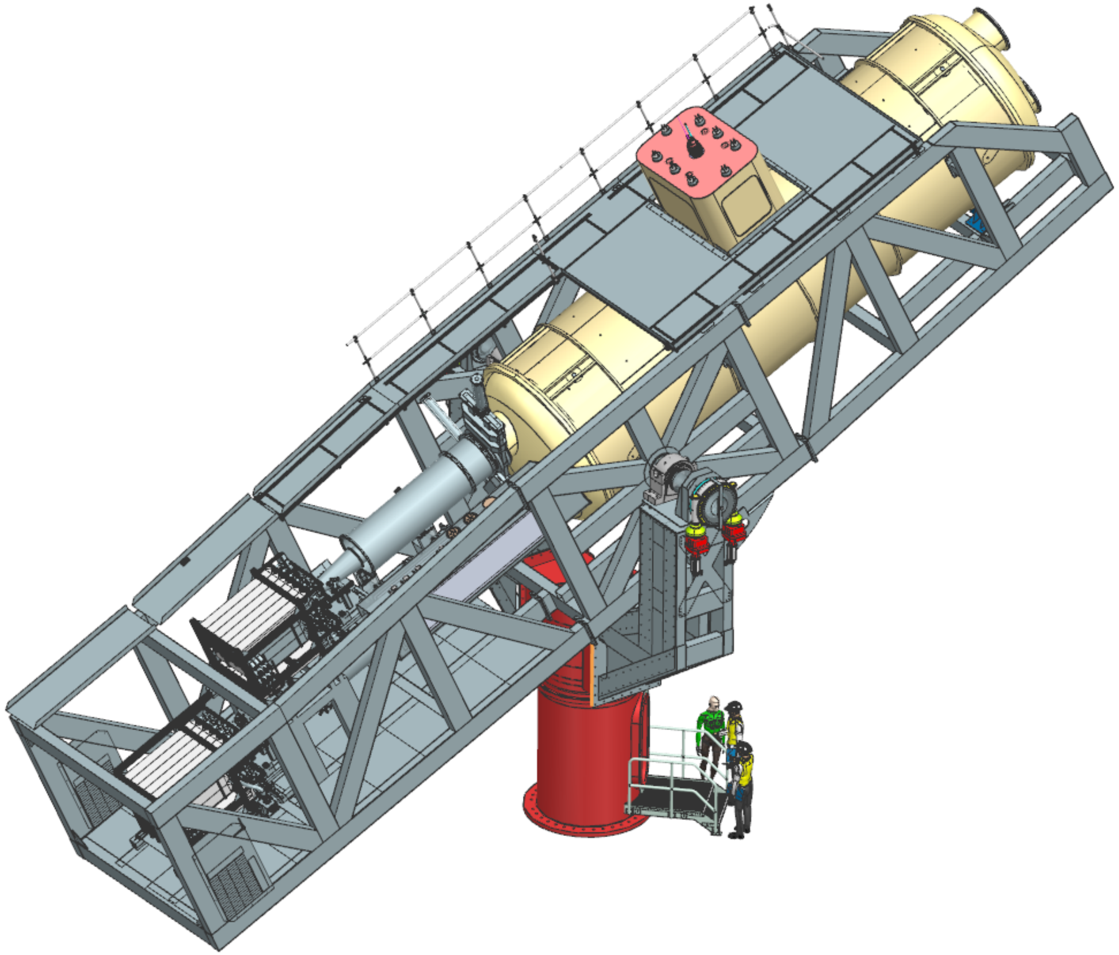
Searches for Axions/ALPS with (Baby)IAXO



Uwe Schneekloth, Univ. of Bonn
20th PATRAS Workshop
22.09.2025

On behalf of the IAXO Collaboration

UNIVERSITÄT BONN

Introduction

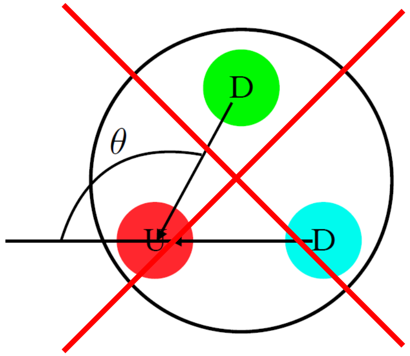
Axion Motivation

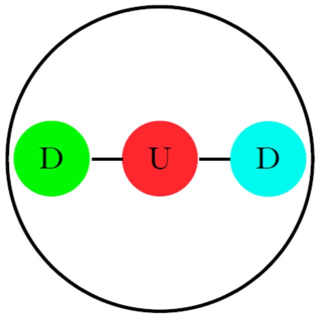
QCD CP violation

Axion originally proposed to solve Charge Parity violation problem in Quantum Chromo Dynamics (strong interaction)

- QCD CP violating term
- Expect electric dipole moment to the neutron, CP violation phase $\theta \neq 0$,
- Experiment $|d_n| < 1.8\ 10^{-13}$ e fm => $\theta < 10^{-10}$ *PDG*
- New symmetry: θ=0 (Peccei-Quinn 1977), axion (Wilczek)

Most compelling solution to strong CP problem





Dark matter

Standard Model only 15% of matter content in universe. Best motivated candidates those which occur in SM extensions solving also other problems

- Hierarchy problem: MSSM neutralino
- Strong CP problem: QCD axion

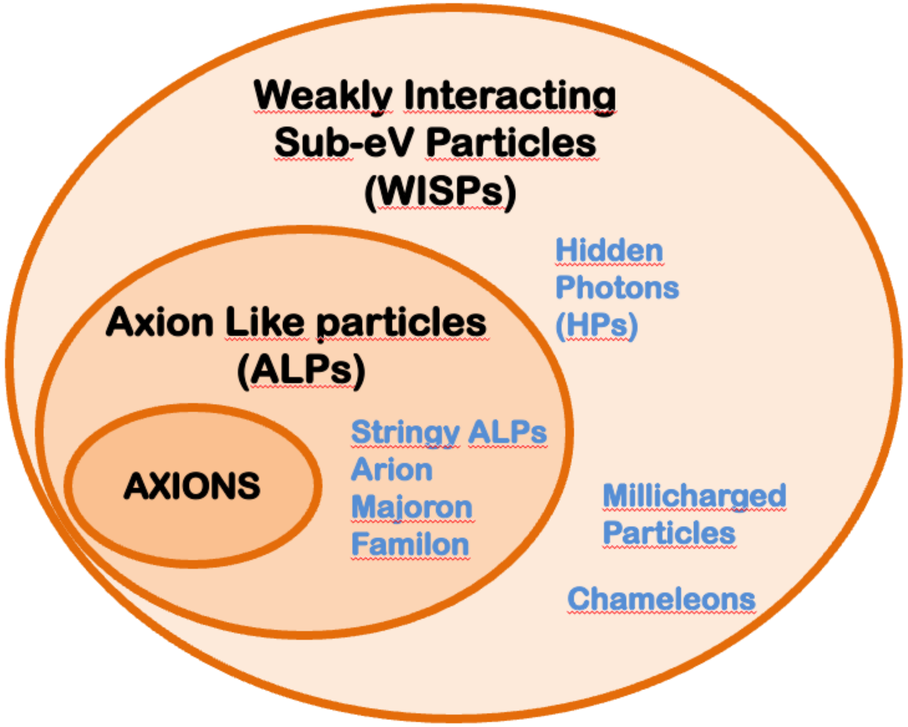
Apart from dark matter, other hints from astrophysics which might be explained by axions

- Excessive energy losses of stars in various stages of their evolution
- Excessive transparency of the universe for TeV gamma ray might be explained by photon - axion conversion

Beyond Axions

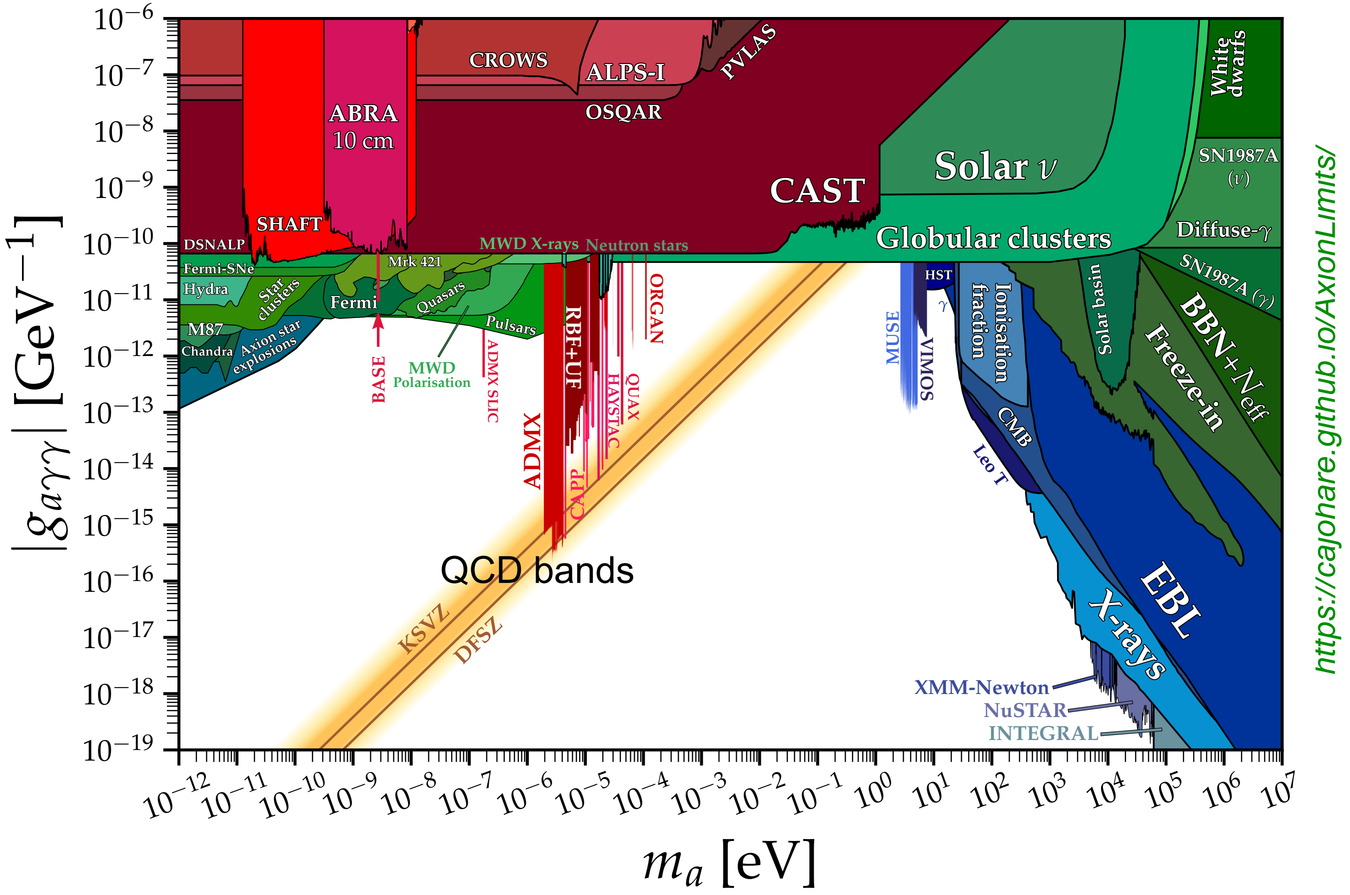
Standard Model Extensions

- Many extensions of SM predict axion-like particles
  - Higher scale symmetry breaking



Generic ALPs parameter space

Axion-photon coupling vs. axion mass

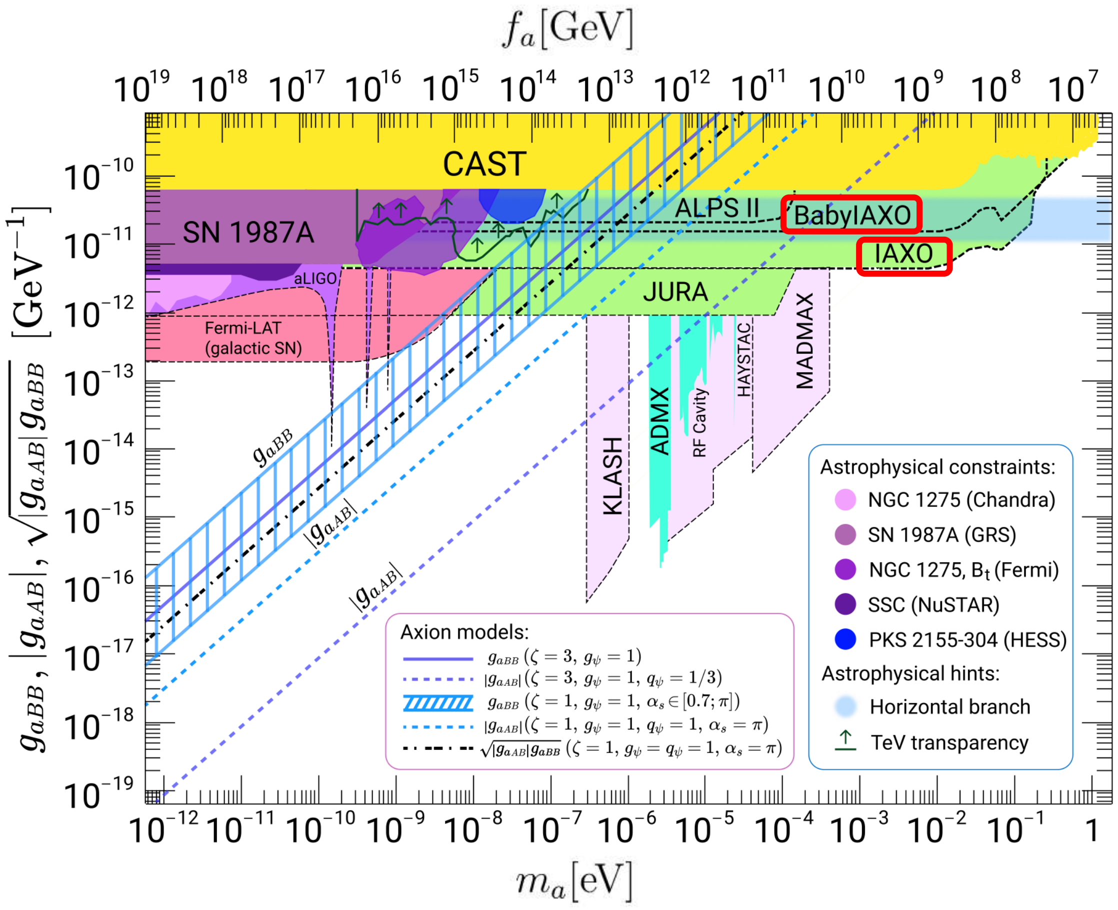


String theory predicts a plenitude of ALPs

Axions beyond the "Band"

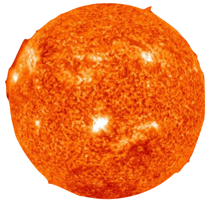
QCD Axions

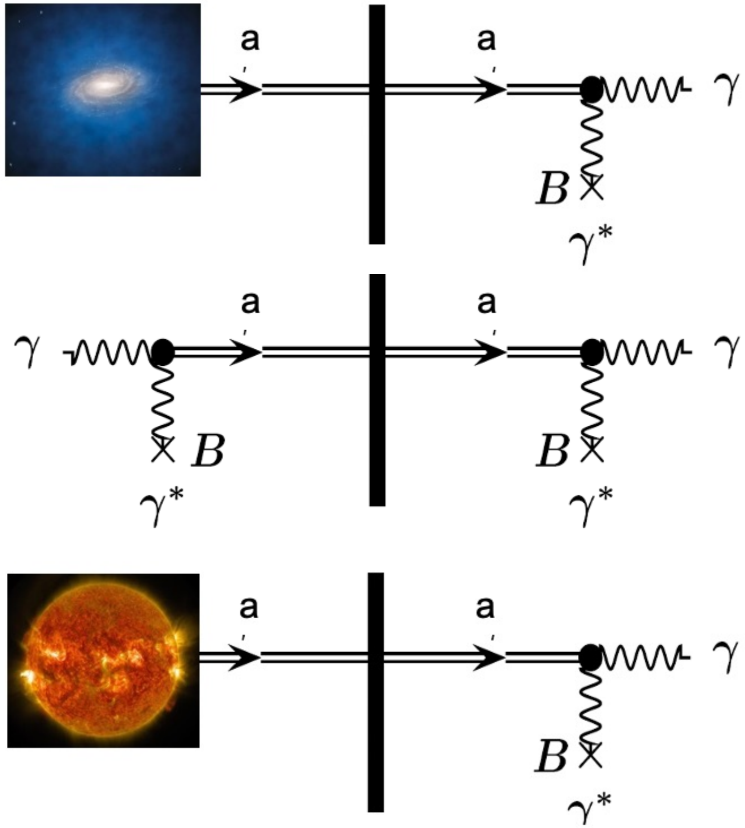
- Conventional QCD axion models lie on the "yellow band"
- Traditional benchmarks:
  - DFSZ (Dine, Fischler, Srednicki, Zhitniskii): axions couple to fermions.
  - KSVZ (Kim, Shifman, Vainshetein, Zakharov): axions couple to BSM quarks only.
- Outside the band typically ALPs
- BUT a lot of "model building" activity in recent years, leading to QCD axion models outside the conventional band…
  - Normally populating higher $g_{a\gamma}$.
  - Very interesting for experiments!
  - Example "Photophilic hadronic axion from heavy magnetic monopoles" *Sokolov-Ringwald arxiv 2205.02605*



Detection of Axions

Different Sources

Source	Experiments	Model & Cosmology dependency
Relic axions 	Haloscopes ADMX, HAYSTAC, CASPEr, CULTASK, CAST-CAPP, MADMAX, ORGAN, RADES, QUAX, …	High
Lab axions 	LSW ALPS II, OSQAR, CROWS, ARIADNE,…	Very low
Solar axions 	Helioscopes BNL, SUMICO, CAST, (Baby)IAXO	Low



ALPS II talk
D. Brotherton
on Tuesday,
…

Solar Axions

Different Sources

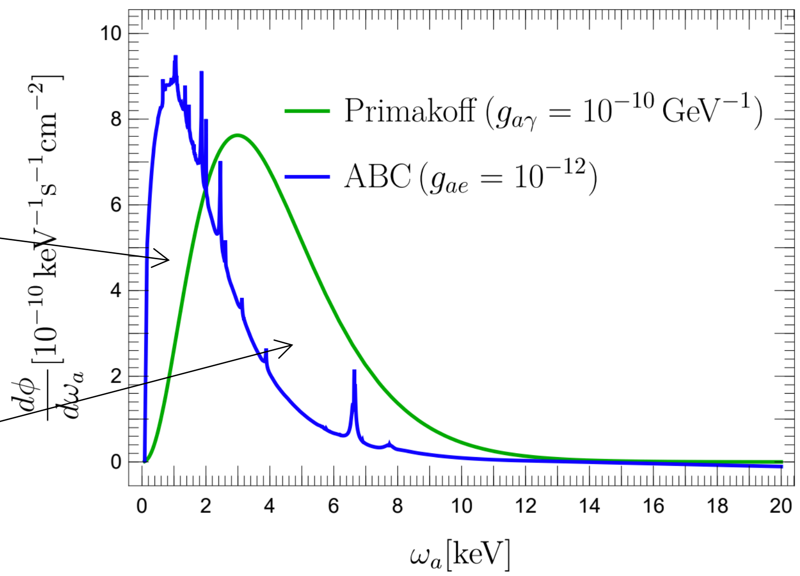
- Primakoff conversion of solar plasma photons
  → generic prediction of most axion models
- In addition, g_{ae}- and g_{aN} - mediated axions (model dependent)

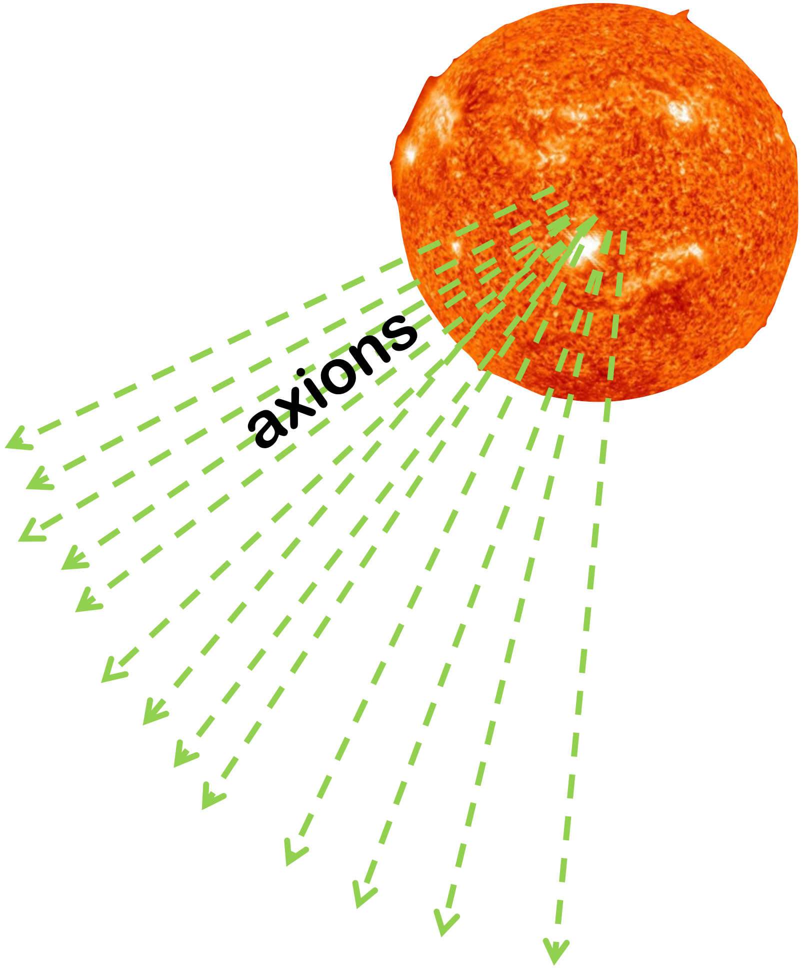
Non-hadronic "ABC" Solar axion flux at Earth (only if axion couples to electron)

Standard Primakoff spectrum

Thermal spectrum, corresponding to temperature of sun core

arXiv:2003.01100





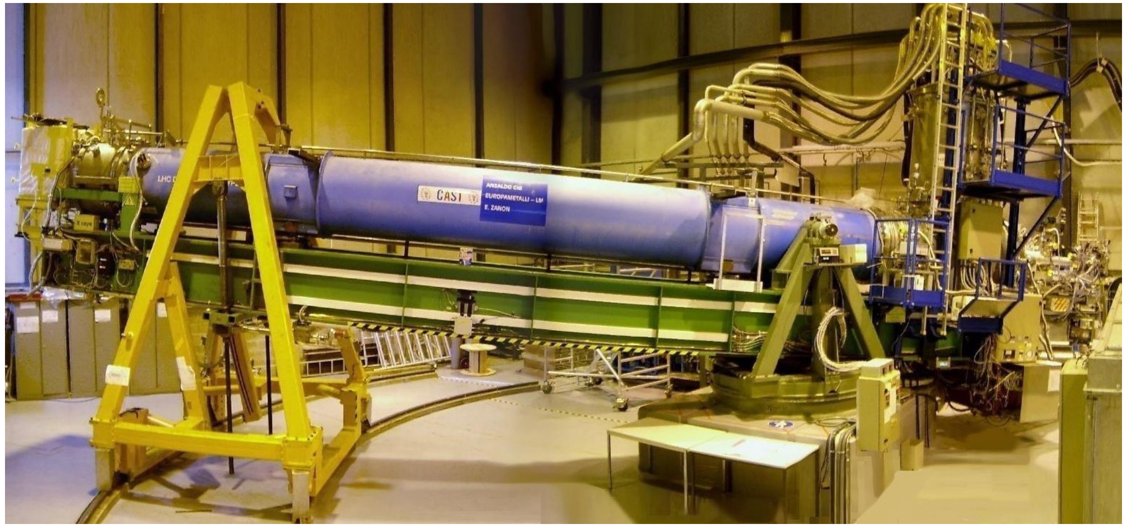
Helioscopes can distinguish between different couplings in contrast to haloscopes and LSW experiment

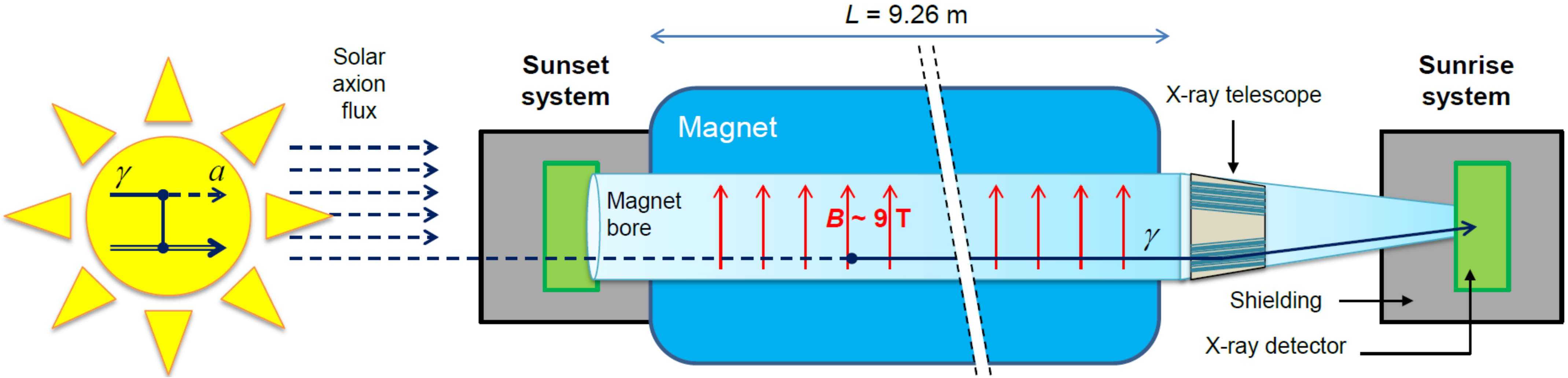
In addition, low-energy axions can be produced via plasmon-photon conversión and higher-E axions via nuclear transitions (axion nucleon coupling)

Searches for Solar Axions

CAST, CERN Axion Solar Telescope

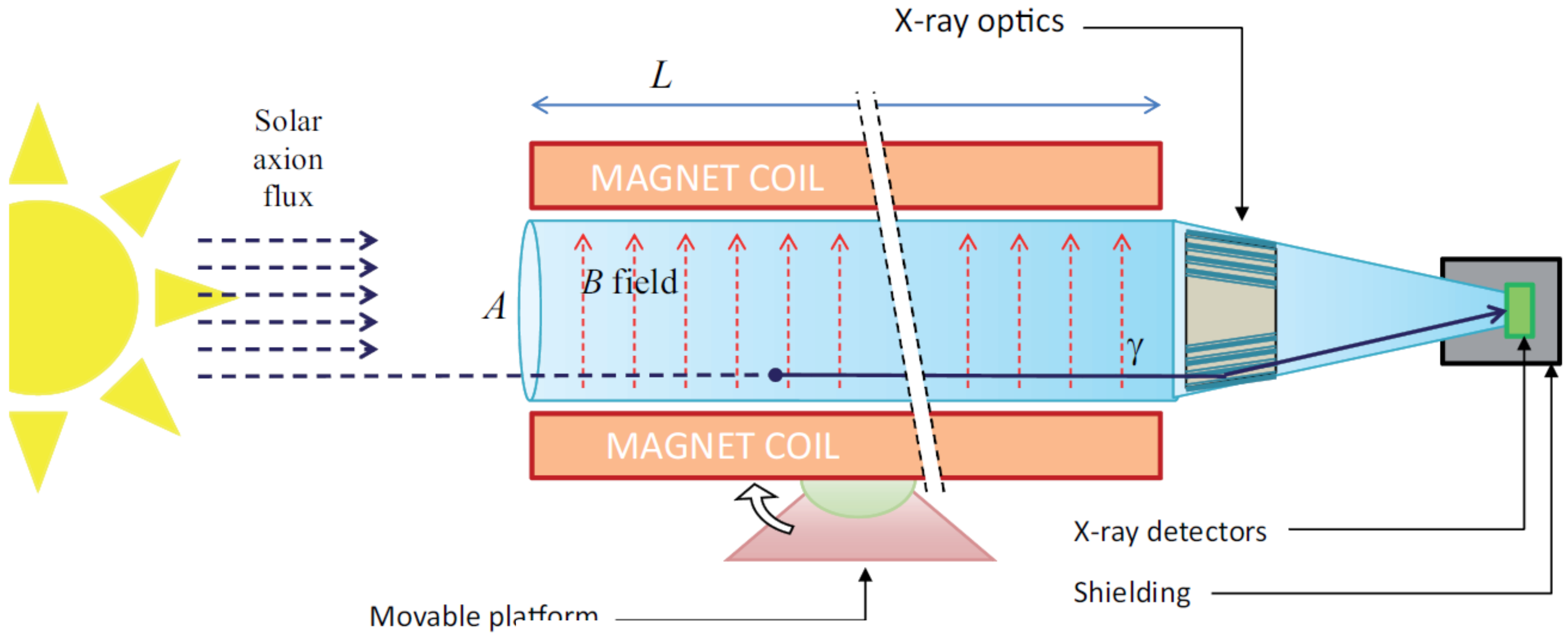
- First helioscope using low background techniques and x – ray focusing
  - Superconducting LHC dipole magnet
  - X-ray detectors
  - Use of buffer gas to extend sensitivity to higher masses (QCD axion band)
- Most sensitive measurements until now





Enhanced Axion Helioscope IAXO

International Axion Observatory



IAXO conceived as large-scale, realistic enhanced axion helioscope

>10^4 better SNR than CAST

Sensitive to g_{ag} ~ x 20 lower than CAST

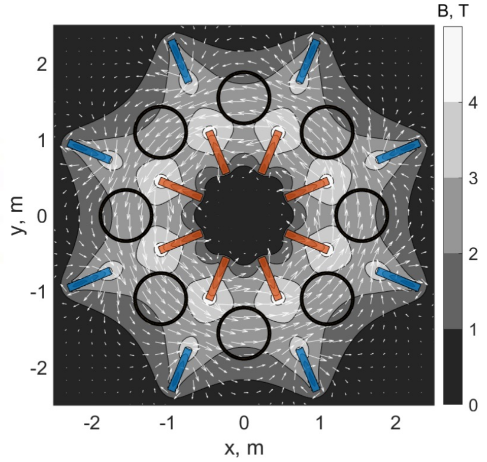
Sensitivity / figure of merit $$g^4_{a\gamma} \propto \underbrace{b^{1/2}\epsilon^{-1}}_{\text{detectors}} \times \underbrace{a^{1/2}\epsilon_o^{-1}}_{\text{optics}} \times \underbrace{(BL)^{-2}A^{-1}}_{\text{magnet}} \times \underbrace{t^{-1/2}}_{\text{exposure}}$$

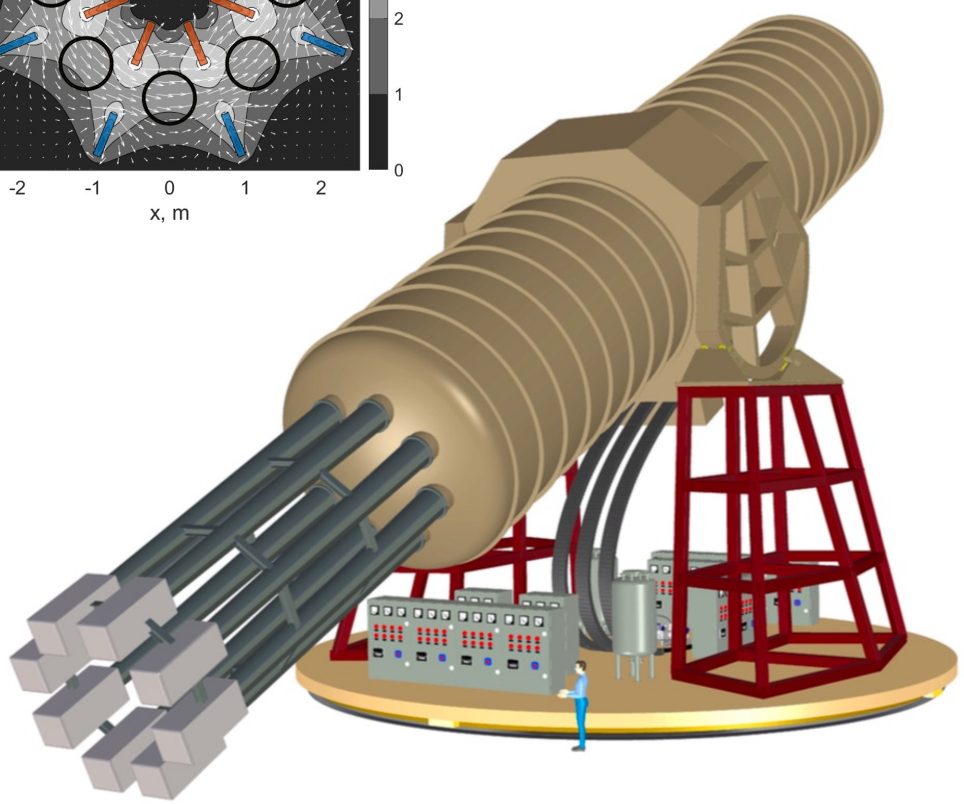
Enhanced axion helioscope:
Irastorza et al.,JCAP1106:013,2011

International Axion Observatory

IAXO Magnet

- Next generation “axion helioscope” after CAST
- Purpose-built large-scale magnet
  - >300 times larger B^2L^2A than CAST magnet
  - Toroidal geometry, very similar to ATLAS toroids
  - 8 conversion bores of 600mm Ø ~20 m long
- Detection systems (x-ray telescopes + detectors)
  - Scaled-up versions based on experience in CAST
  - Low-background techniques for detectors
  - Optics based on slumped-glass technique used in NuStar satellite
- ~50% Sun-tracking time / ~50% background data off sun
- Large magnetic volume available for additional “axion” physics (e.g. dark matter setups)
- Original plan: build one 10m long prototype coil





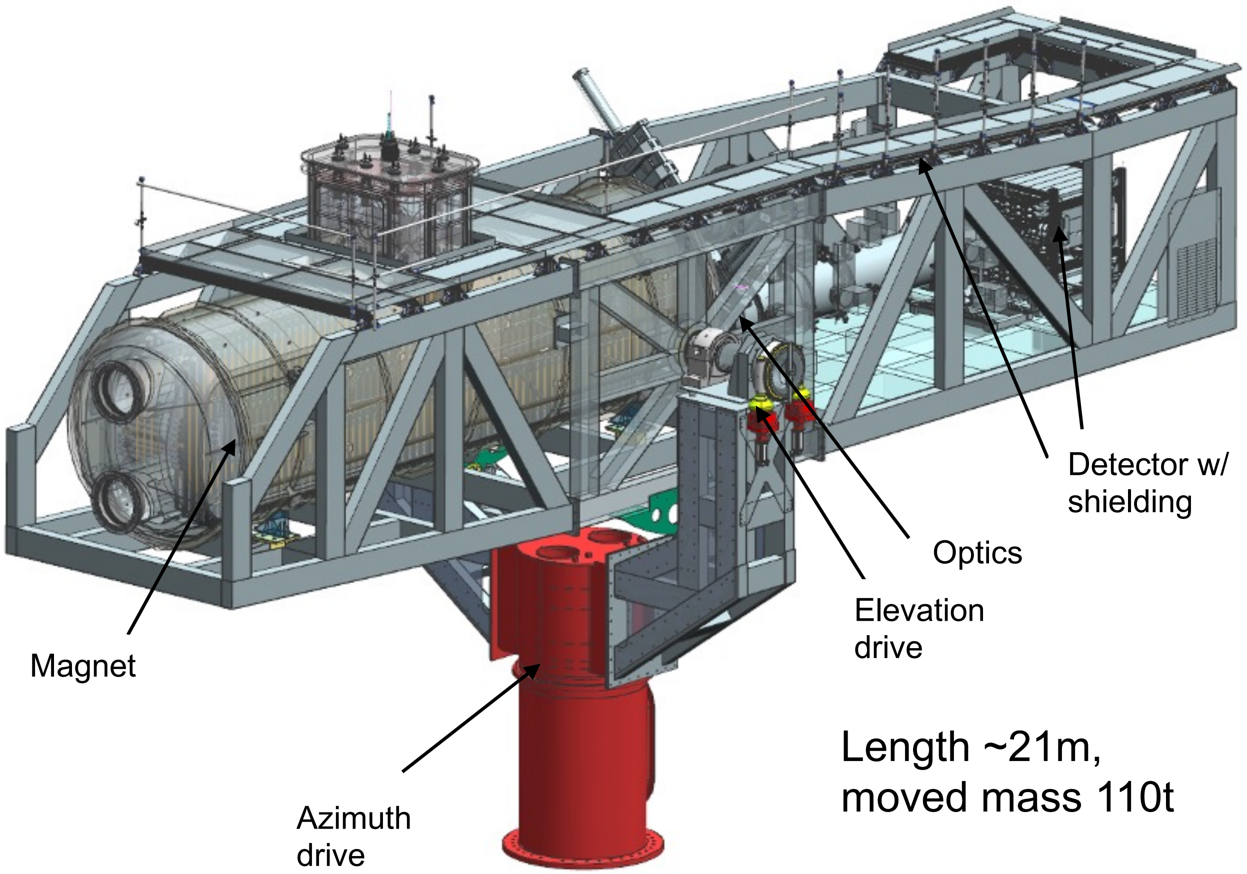
IAXO CDR: JINST 9 (2014) T05002 (arXiv:1401.3233)]

BabyIAXO Overview

IAXO Prototype

- Intermediate experimental stage before IAXO
  - Two bores of dimensions similar to final IAXO bores(700mm diameter)
    → 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
  - FOM (SNR) ~100 times larger than CAST

BabyIAXO conceptual design
JHEP 05 (2021) 137



Length ~21m, moved mass 110t

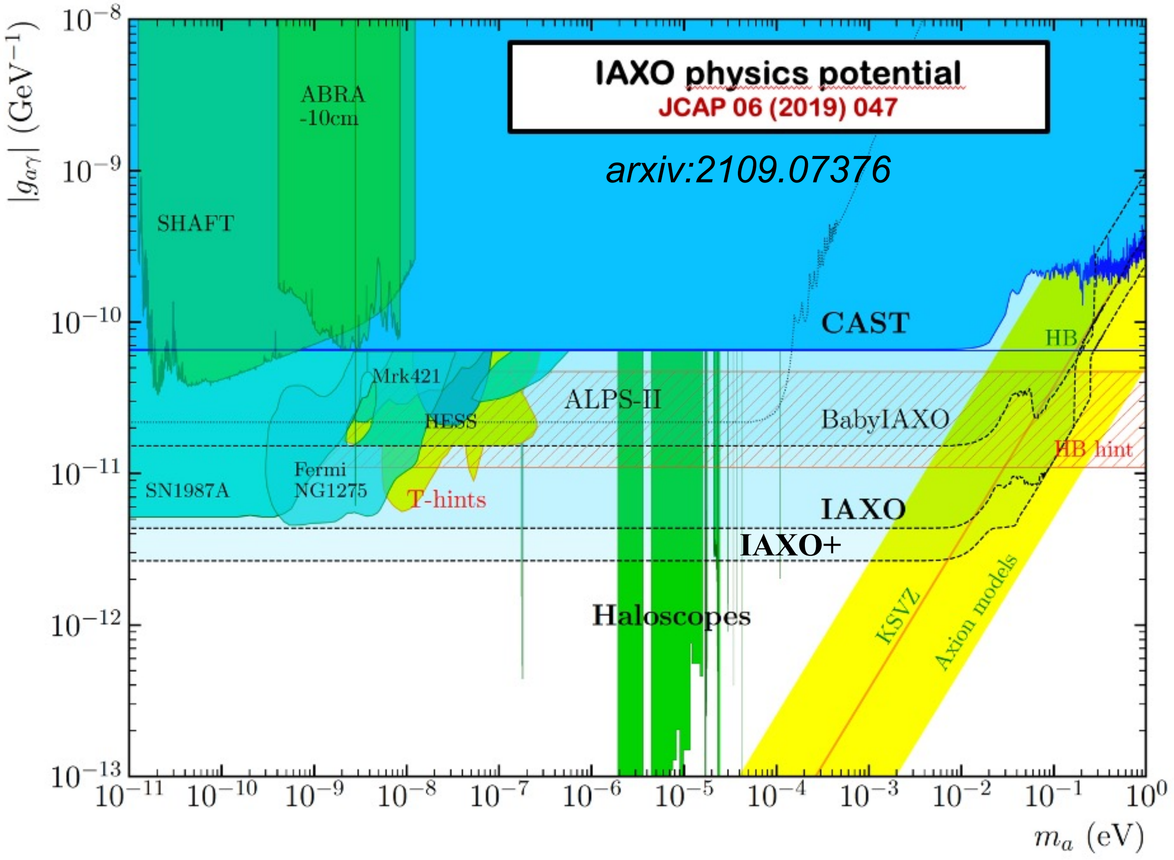
Pointed towards sun by azimuth and elevation drive systems, precision < 0.01°

European Research Council
Established by the European Commission

ERC-AvG 2017 IAXO+

(Baby)IAXO Physics Case

- Large generic unexplored ALP space
  - down to g_{ag} ~ 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 Dark Matter + inflation models
- All this, independent of the axion-as-DM hypothesis.
- BabyIAXO relevant intermediate physics potential



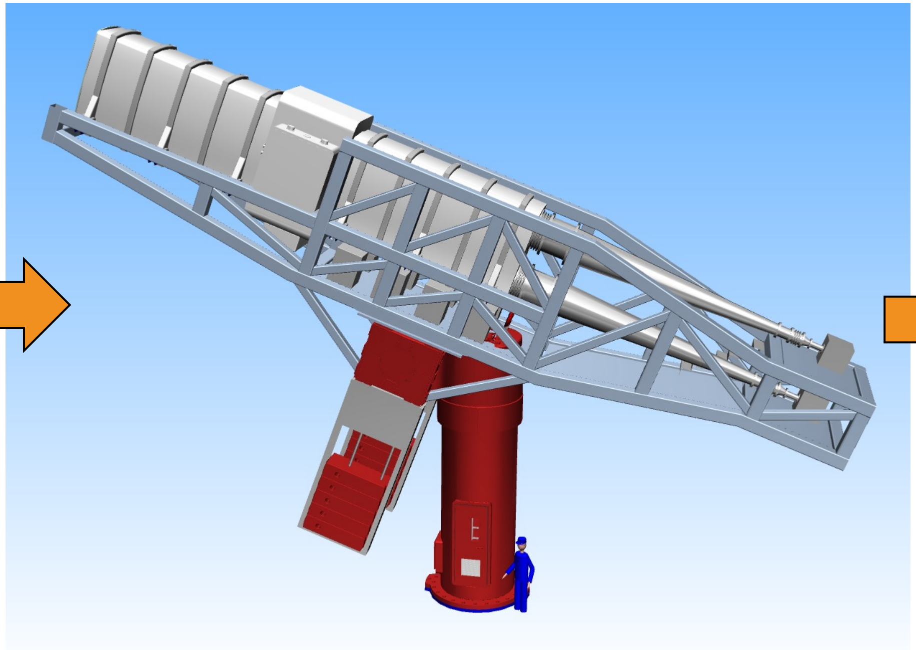
IAXO+: enhanced scenario with x10 (x4) higher FOM (MFOM) with respect LoI

BabyIAXO Status

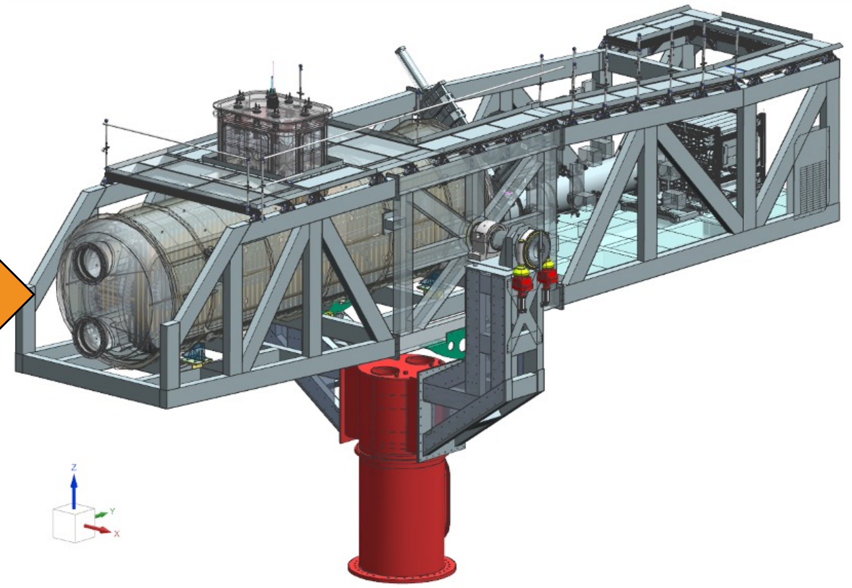
Structure and Drive System

- Reusing CTA MST prototype from Berlin (DESY Zeuthen). Dissembled, moved to HERA South Hall in May 2020
- Designed large support frame holding magnet, optics, vacuum system and detectors
- Redesigned elevation drive due do large torque. Finalizing tender documents, in contact with companies.

2019



Final design



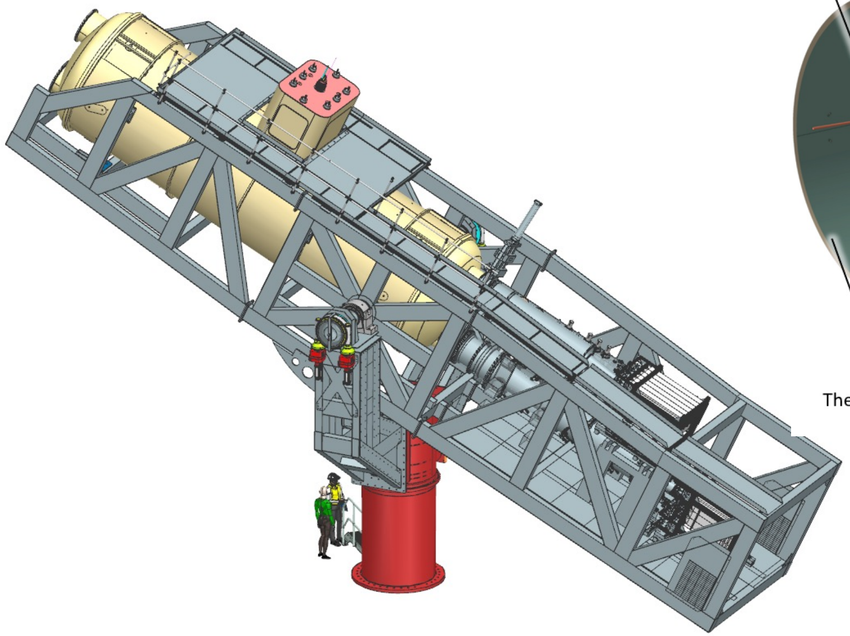
BabyIAXO Status

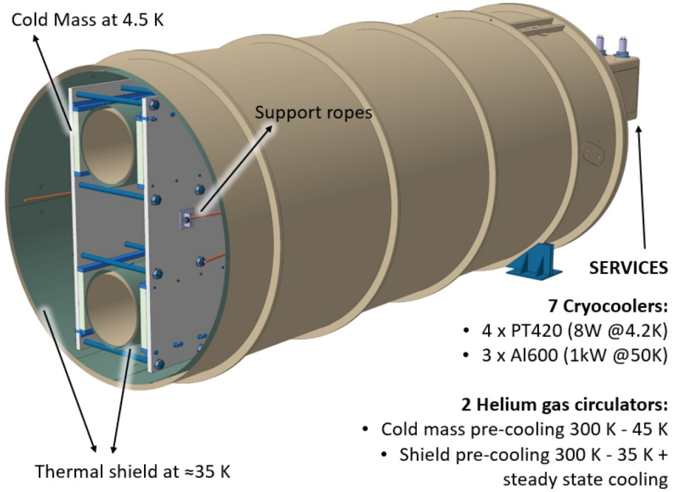
Magnet

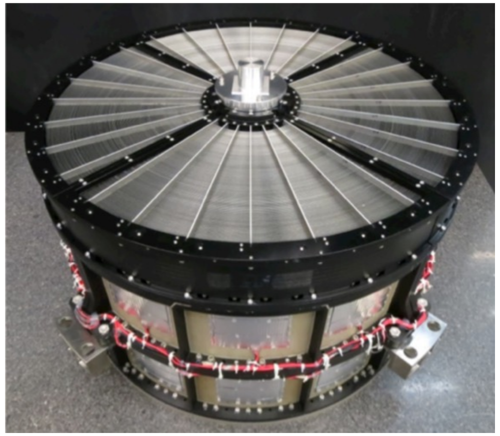
- Technical in-depth reviews of magnet design successfully passed at DESY PRC April 2024/25. Progress towards TDR and magnet construction.
- Magnet cable procurement: critical item, has caused delays. 1st km of Rutherford cable already produced. Good progress on aluminum co-extrusion.

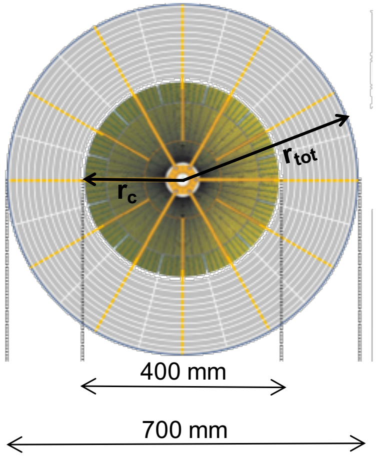
X-ray Optics

- Two detection lines in BabyIAXO with different solutions: existing XMM spare + custom-made slumped glass optics
- Collaboration effort: CAPA, Columbia, INAF, DTU, MPE-Panter
- First prototype sectors built and tested







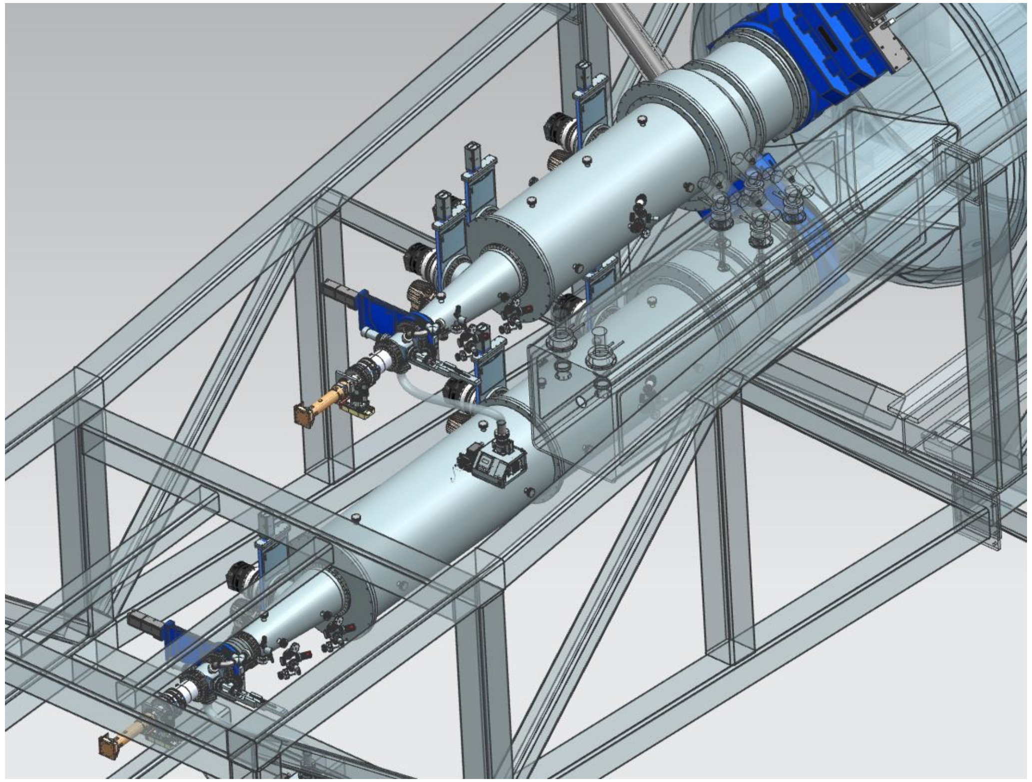


Magnet free bore volume about 8 m^3,
Combined free bore volume of 120 LHC dipoles.

BabyIAXO Status

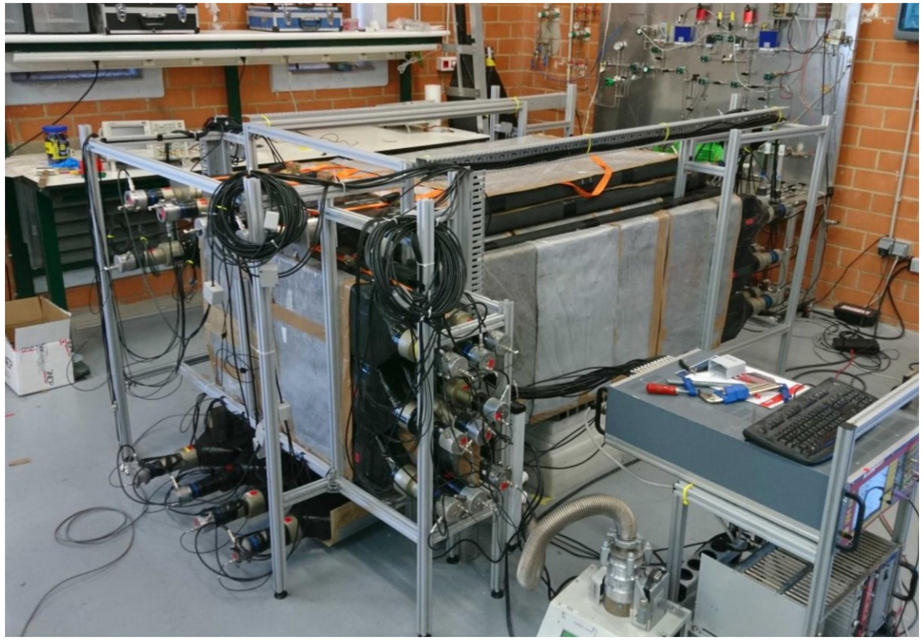
Beam line:

- Design finished
- Many parts ordered, some parts already delivered



Baseline detectors:

- Low background Micromegas detectors of *microbulk* type.
- Various alternative technologies being explored in the collaboration: TES, MMC, GridPix, SSDs,…
- Background goal is to reach 10^{-7} c/keV/cm^2/s



Various prototypes taking data at CAPA, LSC, Saclay and DESY

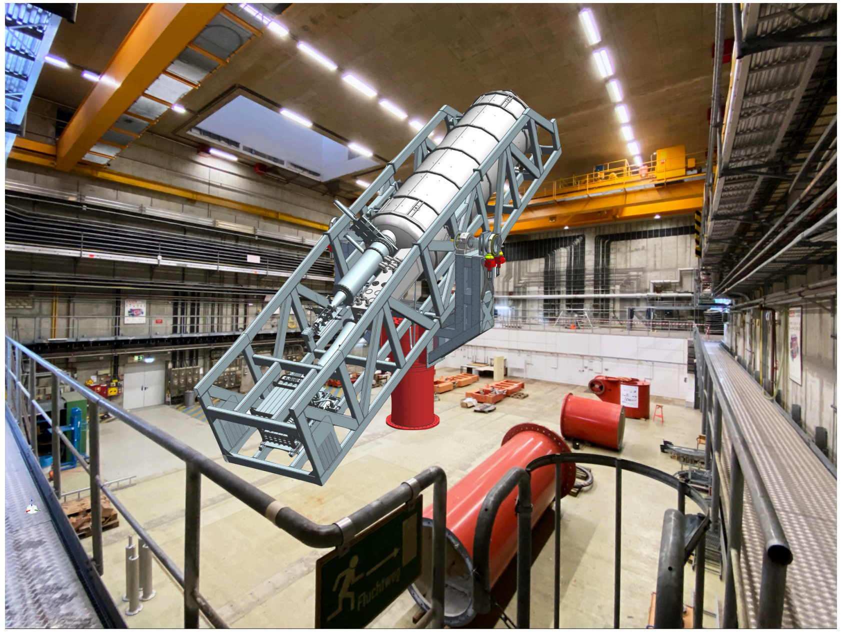
(Baby)IAXO Site

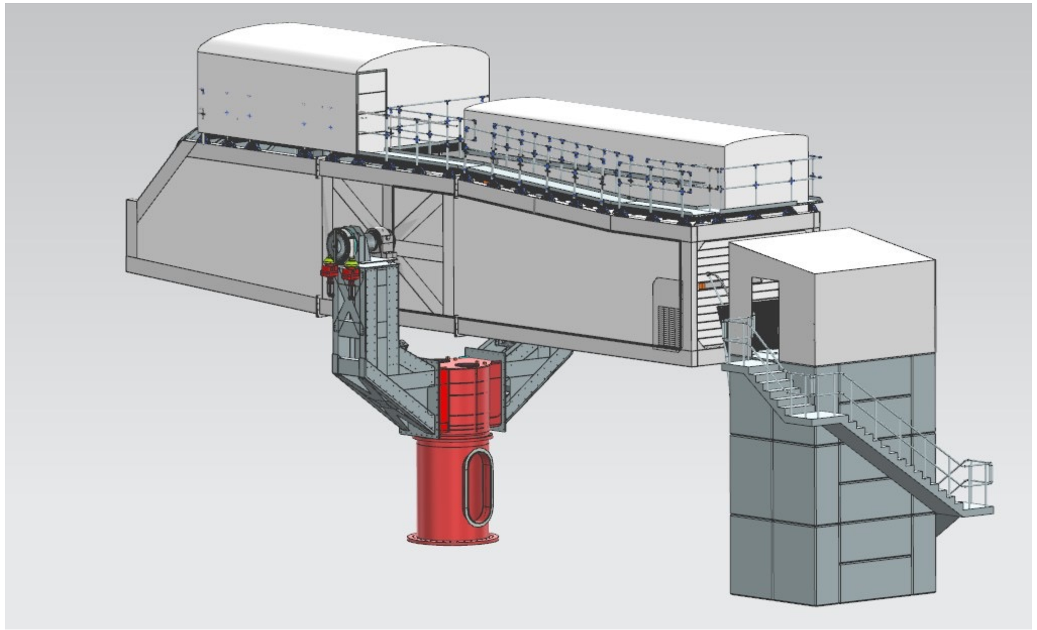
Originally planning to set up BabyIAXO in HERA South Hall

- Big underground hall (43m x 25m)
- Refurbishment issues due to insufficient resources (man power and funding)
- City of Hamburg interested in using hall

Now planning for outside/surface location

- Less expensive compared to HERA Hall
- Survey easier compared to underground hall
- Site/foundation should also be possible location for IAXO
- Local housing of support frame (magnet, optics, detectors,…)



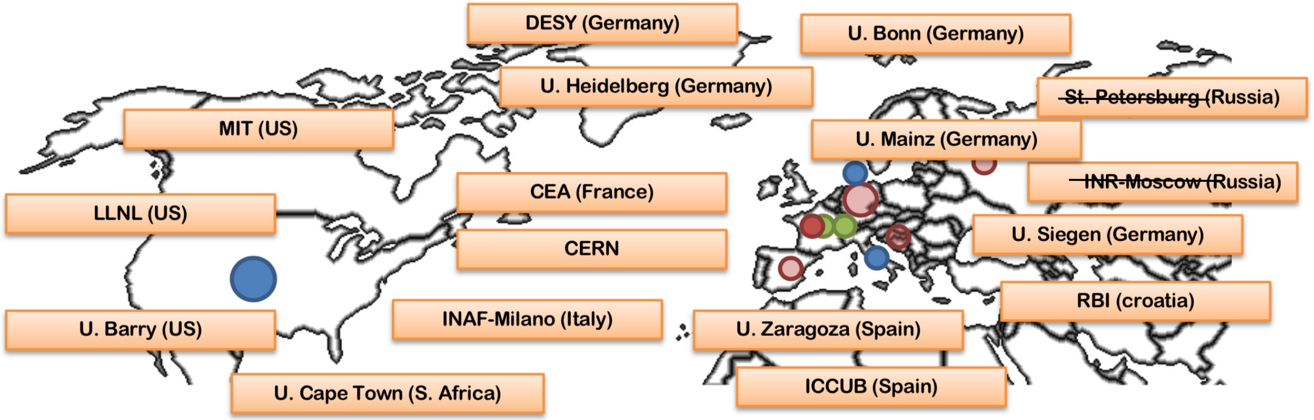


IAXO Collaboration and Achievements

Institutions

22 institutions from Germany, Spain, US, France, Italy, Croatia, S. Africa, CERN, (~~Russia~~)

Know-how portfolio nicely encompasses IAXO needs



Achievements

Component/Status	Technical	Funding
Structure & Drive System	(✓)	(✓)
Magnet	(✓)	*)
X – ray optics	✓	✓
Detectors	✓	✓

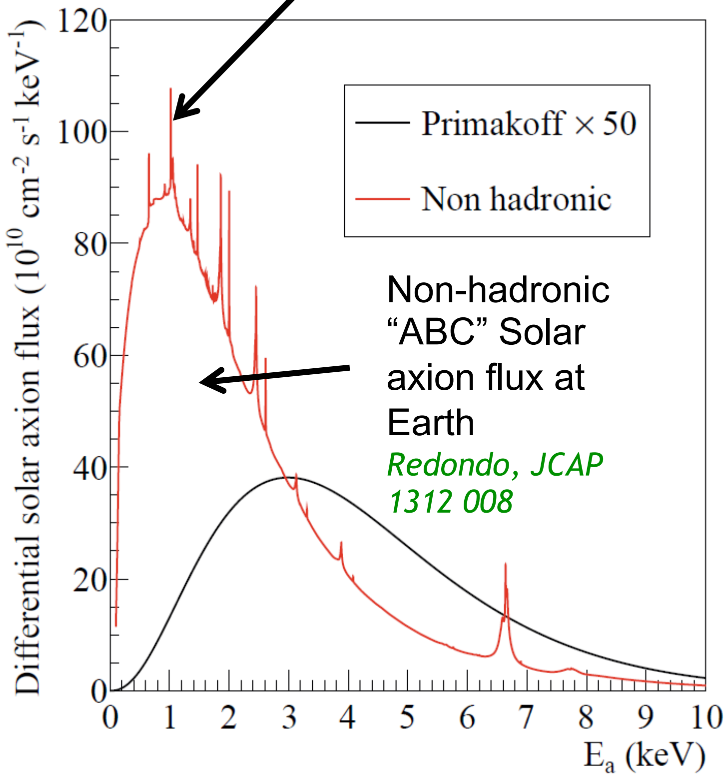
*) Have partial funding for magnet, going to submit proposal to DFG for remaining funds.

Other Solar Axion Sources / Post Discovery

“ABC Axions”

In addition to Primakoff, “ABC axions” may be x100 more intense… but model-dependent.

Atomic transitions

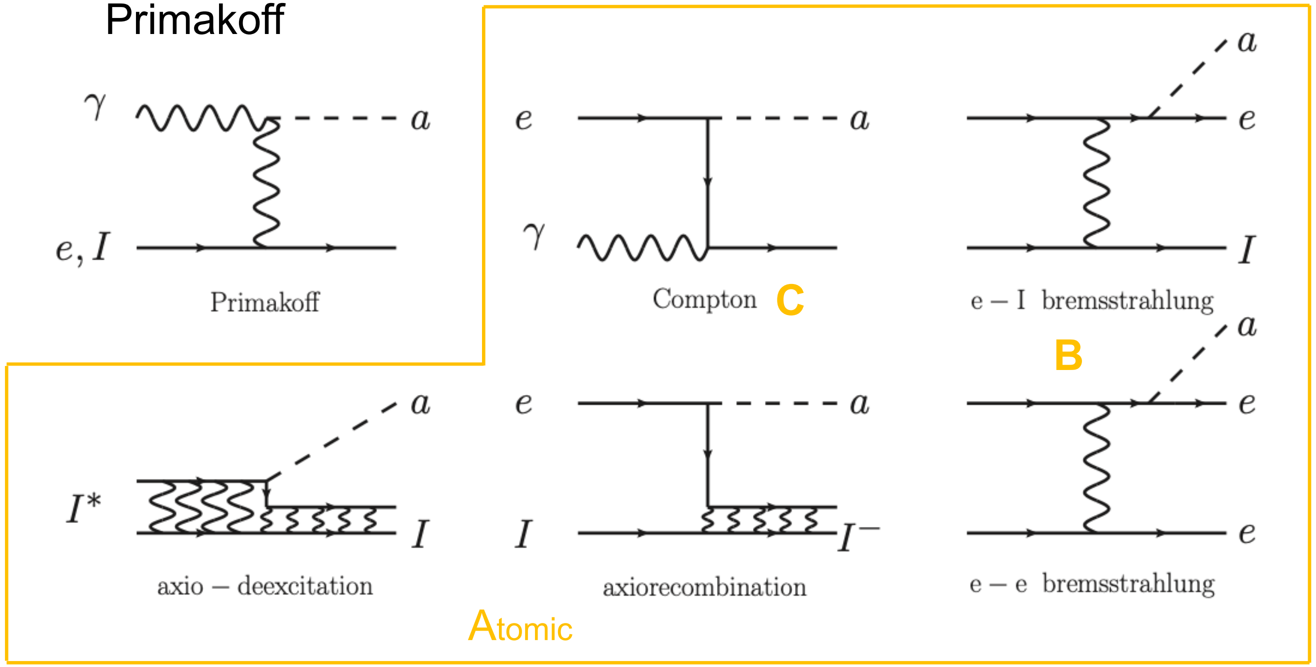


Non-hadronic “ABC” Solar axion flux at Earth

Redondo, JCAP 1312 008

“ABC solar axions” from axion-electron coupling

Primakoff

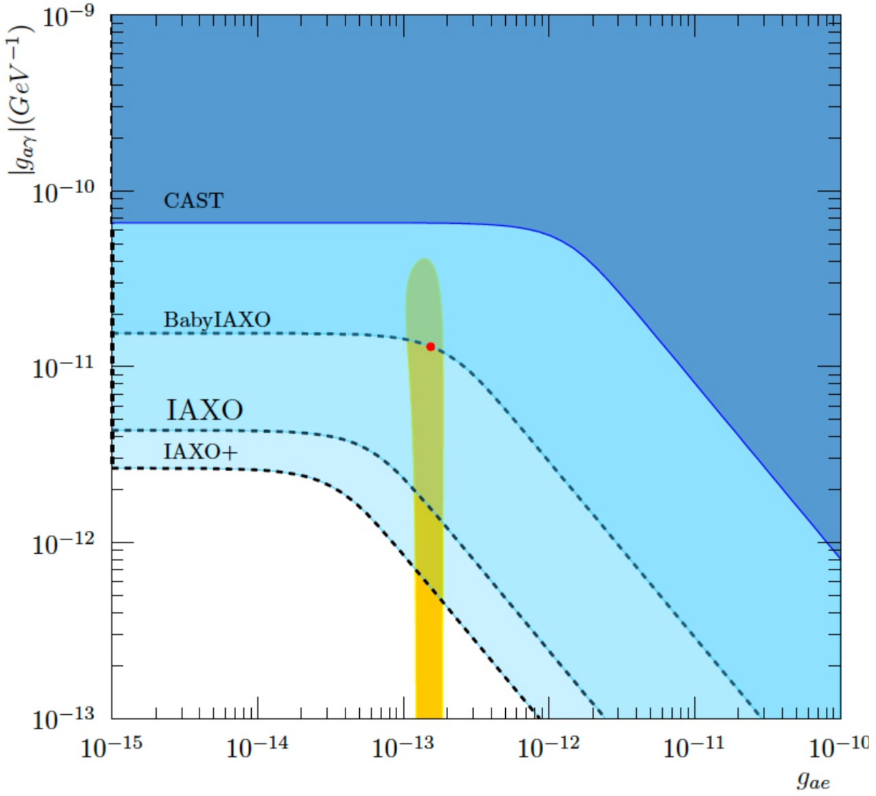


Other Solar Axion Sources / Post Discovery

Electron – Axion Coupling

g_{ae} vs. $g_{a\gamma}$ for $m_a \simeq$ 1meV

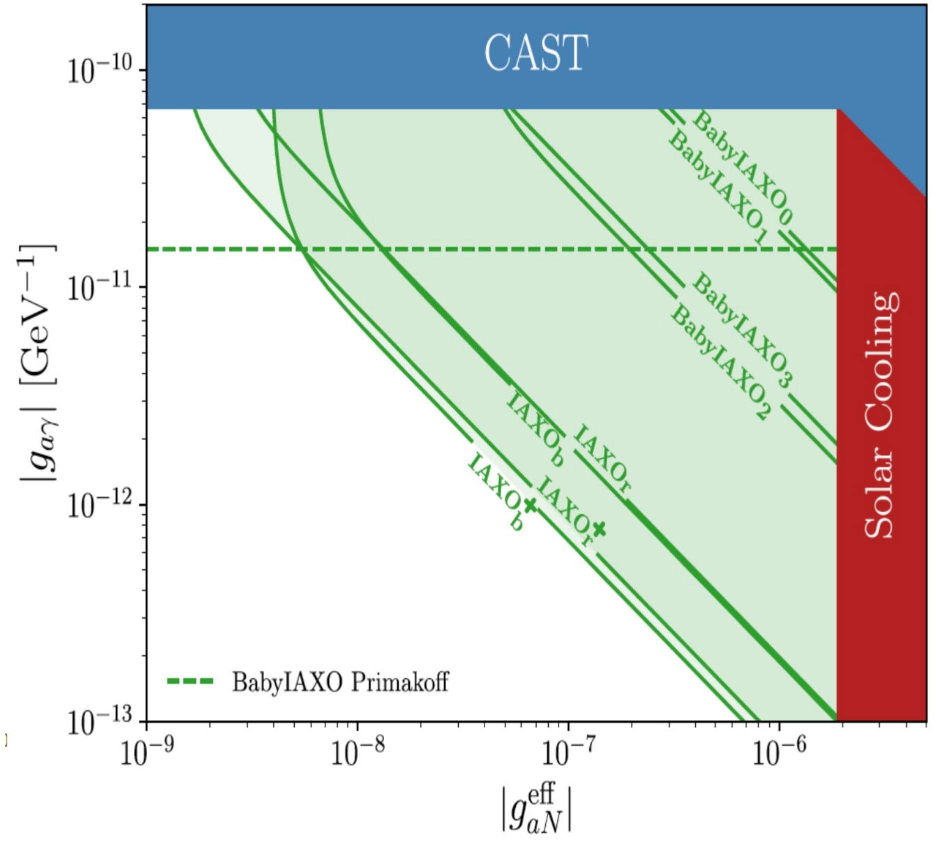
JCAP06(2019) 047



Nucleon – Axion Coupling

g_{ae} vs. g_{aN} for $m_a \simeq$ 20 meV

Eur. Phys.J. C 82, 120 (2022)



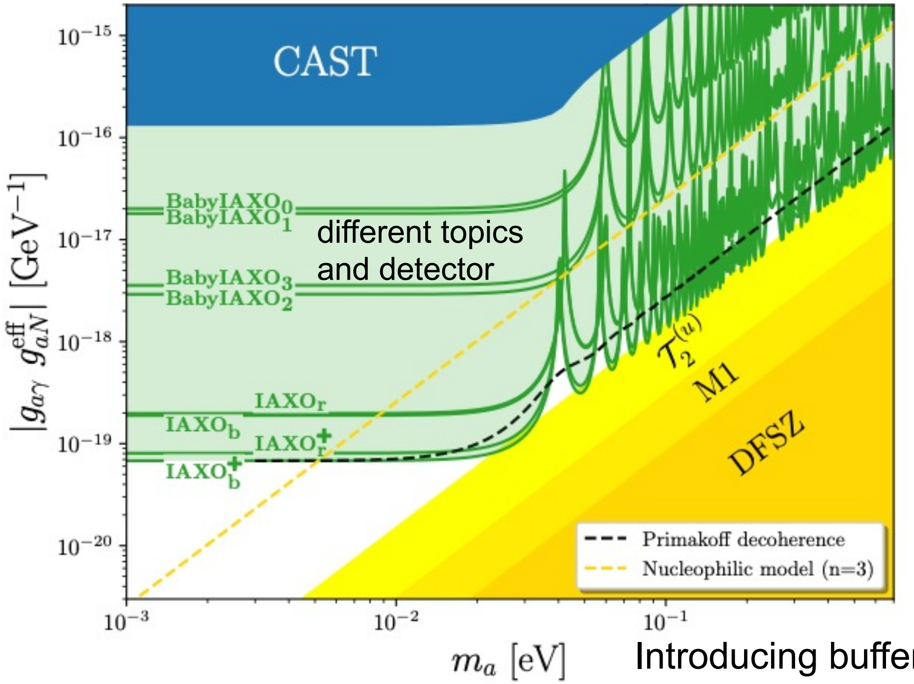
Not possible with light through wall experiments or haloscopes

Other Solar Axion Sources / Post Discovery

Axion Nucleon Coupling

Via axion-nucleon couplings: monochromatic lines from nuclear transitions:

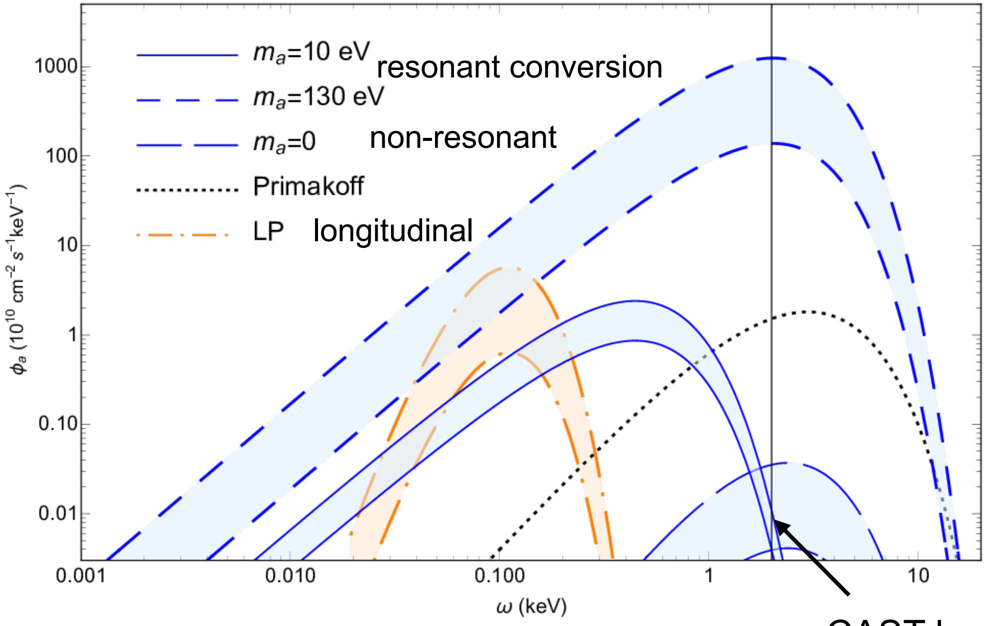
- E.g. 14.4 keV axions emitted in the M1 transition of Fe-57 nuclei, MeV axions from 7Li and D(p;g)^{3}He nuclear transitions or Tm-169. *Di Luzio et al. 2111.06407*



Introducing buffer gas would increase sensitivity

Large/scale Solar Fields

Large-scale solar magnetic fields produce additional ALPs via coherent conversion of thermal photon e.g. *Guarini et al. 2010.06601*



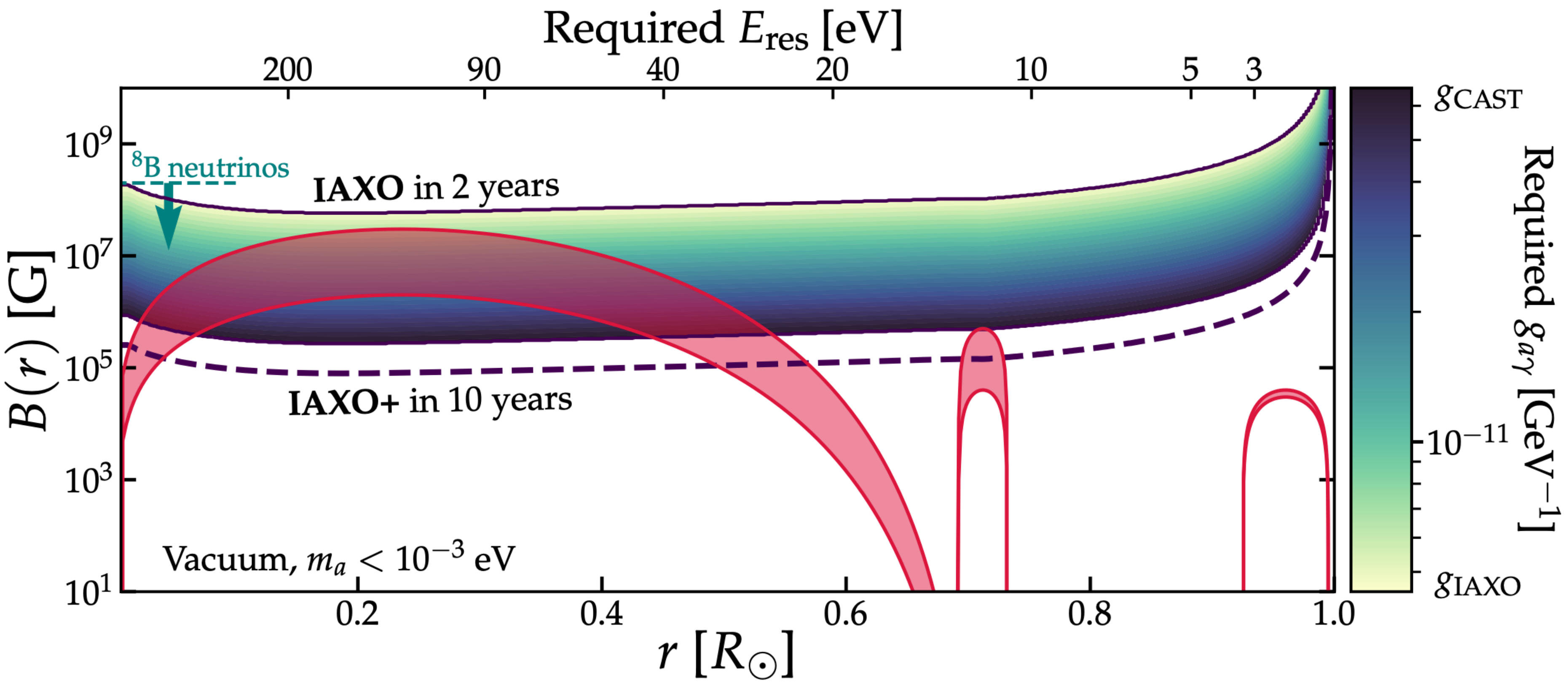
BabyIAXO sensitive to lower threshold

Post Discovery

Solar Magnetometers

Helioscopes as solar magnetometers using conversion of longitudinal plasmons

O'Hare et al. Arxiv:2006.10415

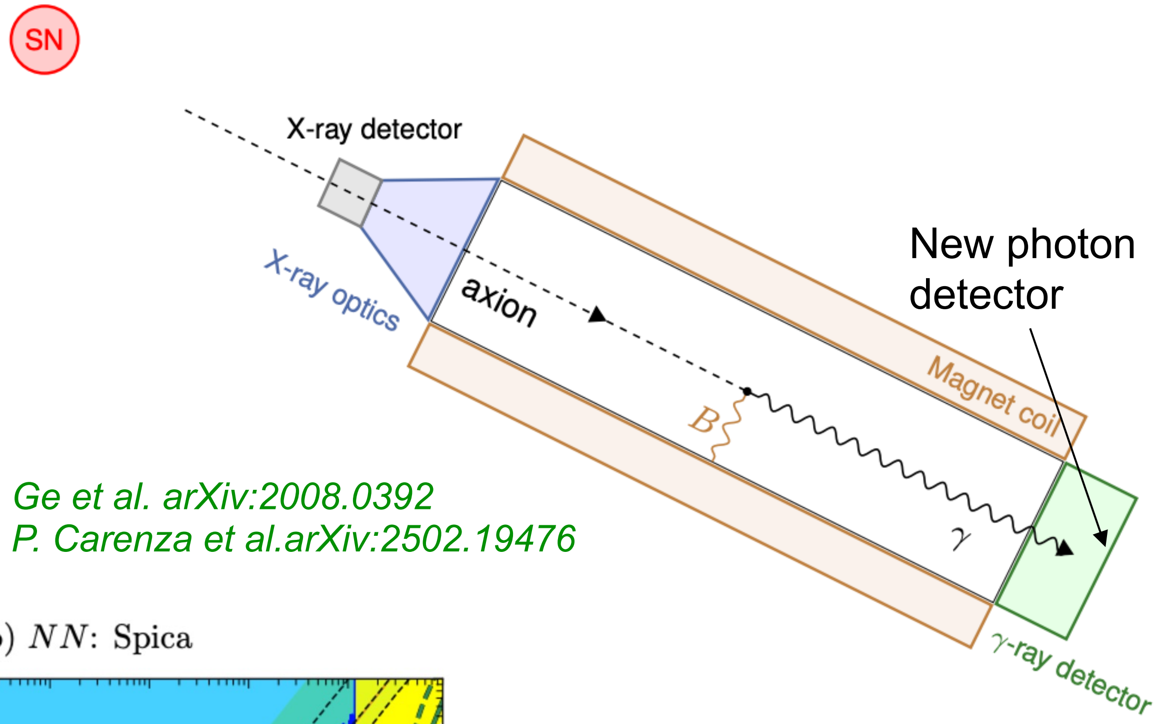


Saclay seismic model: radiative zone | tachocline | upper layers

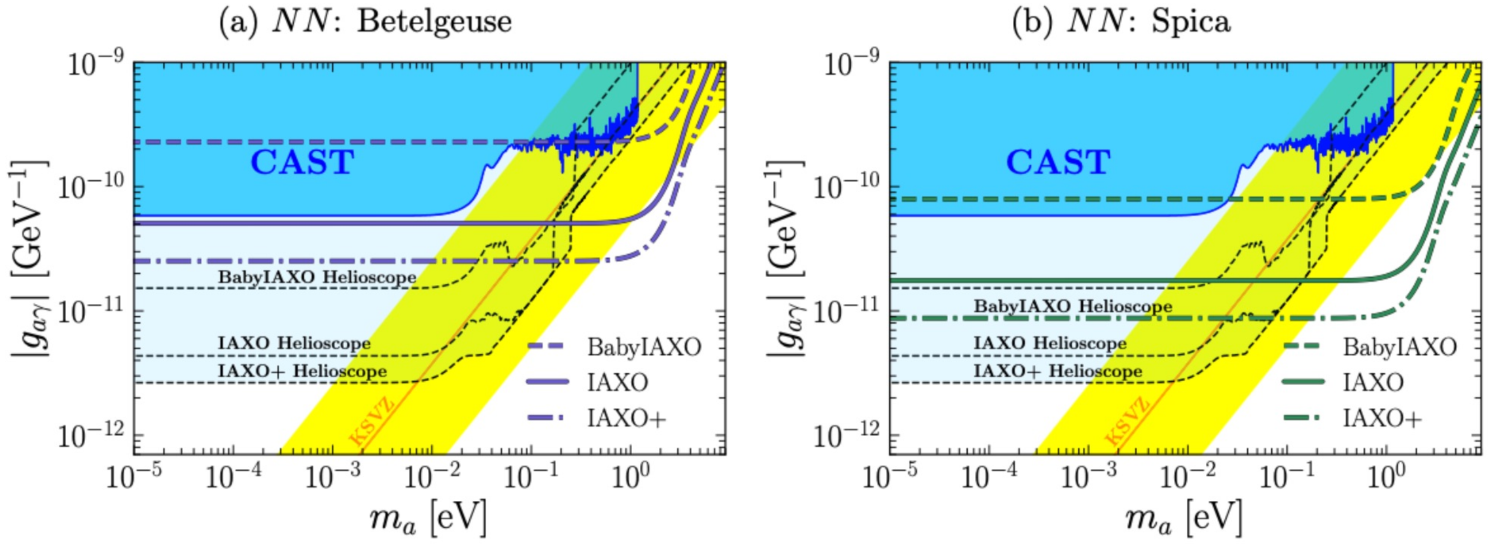
Post Discovery

Axions from a Galactic Super Nova

- If sufficiently close by galactic SN explodes, SN axions could be detectable at (Baby)IAXO.
- SN axions have O(100MeV) energies
- Requires IAXO to be equipped with large “high” energy photon detector, covering all magnet bore.
- Complementary implementation with baseline layout, using opposite side of magnet. Presently studying calorimeter options



Ge et al. arXiv:2008.0392
P. Carenza et al.arXiv:2502.19476



- Betelgeuse: 222 pc
- Spica: 77 pc
- $g_{aN} = 10^{-9}$
- no pion scattering

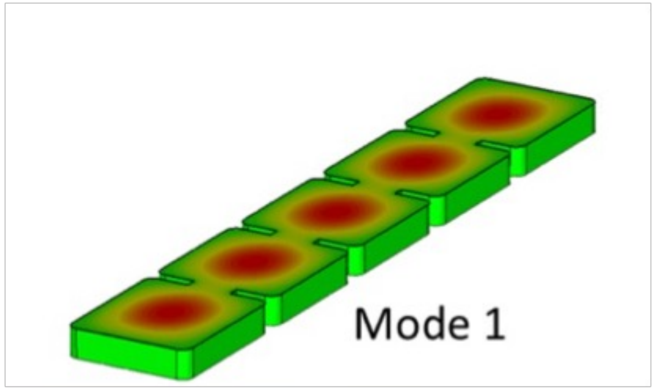
RADES

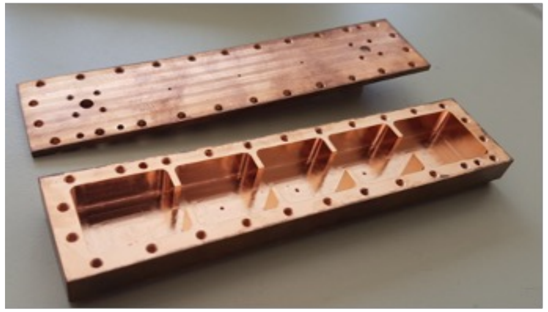
Helioscope as Haloscope Project

Use the magnetic volumes of helioscope for haloscope searches by integrating resonant cavity setups

- Small cavities for high frequencies/axion mass installed in CAST
- Planning to install large cavities (low frequencies/axion masses) in BabyIAXO magnet

- RADES talks:
  - David Diez Ibanez on Tuesday
  - Cristian Cogollos on Wednesday

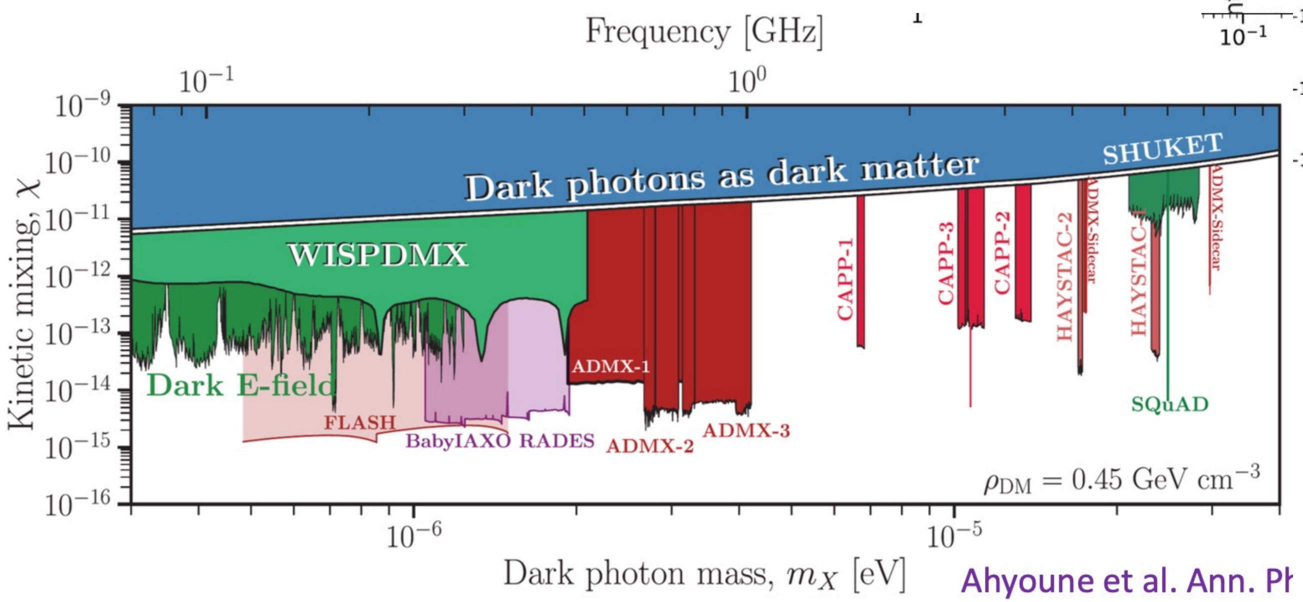




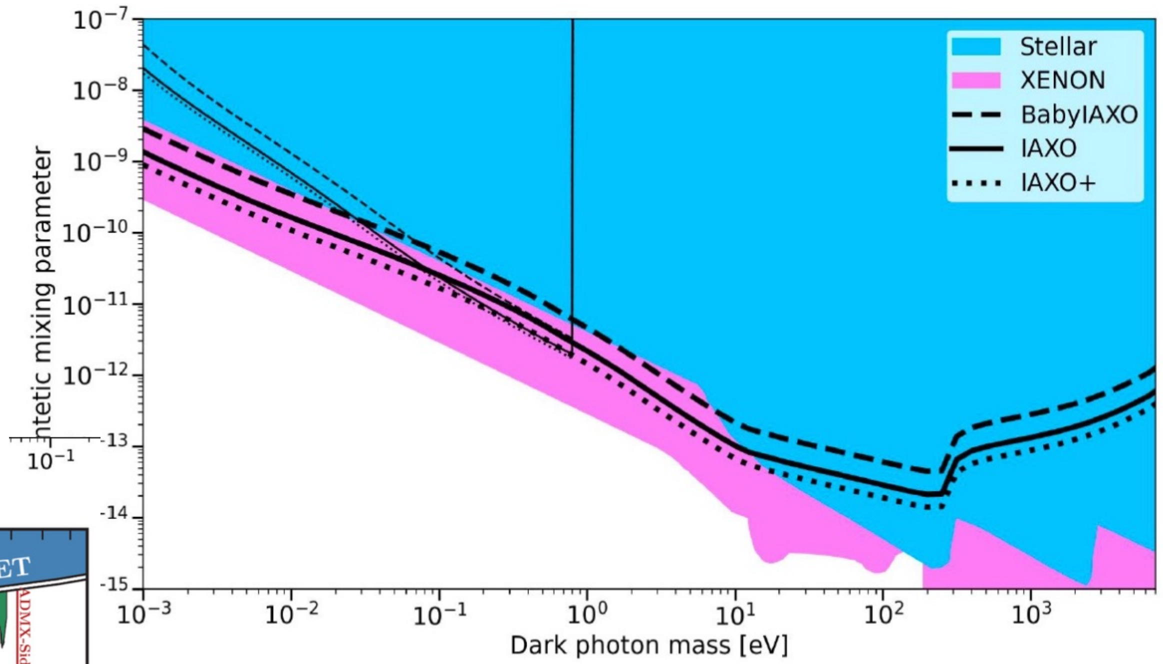
Part of ERC-StG
B. Döbrich, MPI

BabyIAXO – Hidden Photon Search

- Hidden photon search potentially possible
- Can use same setup for axion search but without B-field
  - Program in case setup is ready, but delays in magnet construction



Ahyoune et al. Ann. Ph



T. O'Shea et al.
JCAP06(2024)070

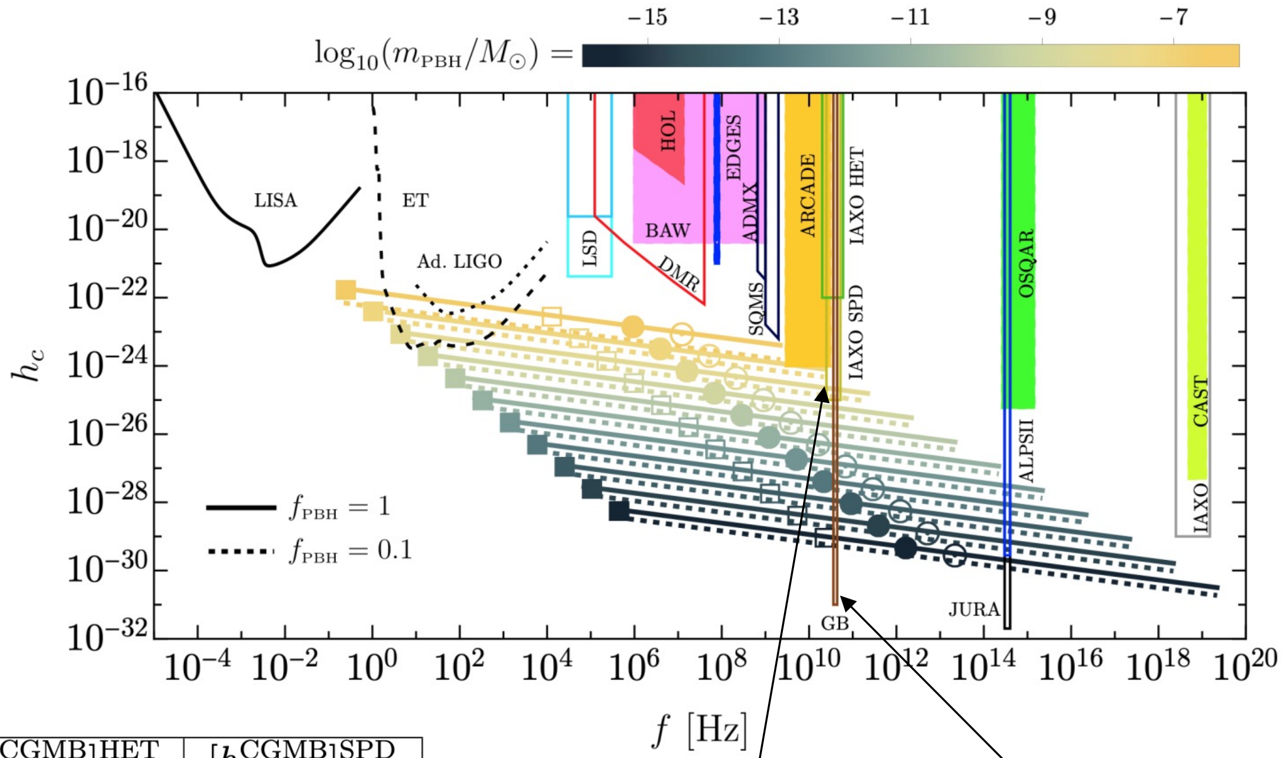
Potential improvement with lower energy thresholds for IAXO and/or BabyIAXO

Gravitational Waves

(Baby)IAXO

Franciolini et al. 2205.02153

Characteristic strain vs. frequency spiraling merger

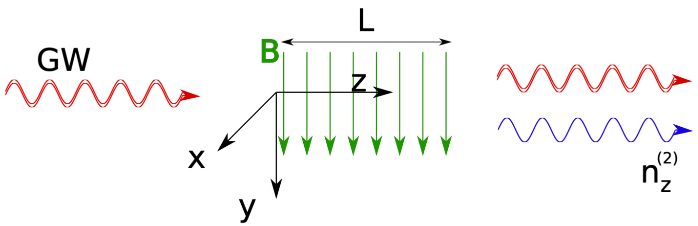


IAXO Single Photon Detector

IAXO Auxiliary oscillating EM fields

- High frequency GWs are expected in non-standard scenarios, e.g. primordial black holes.
- Emerging field of study, potential for synergy with axion experiments in the long term?

Inverse Gertsenshtein effect



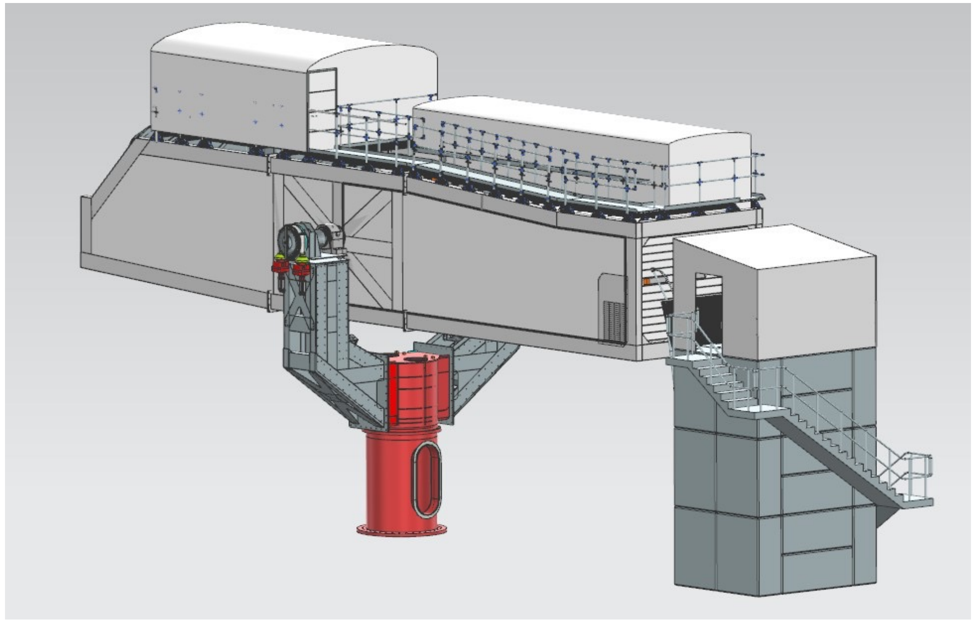
	B [T]	L [m]	d [m]	$n_{\rm tubes}$	$BLA^{1/2}$	f_c [Hz]	$[h_c^{\rm CGMB}]^{\rm HET}_{\rm sens}$	$[h_c^{\rm CGMB}]^{\rm SPD}_{\rm sens}$
ALPS IIc	5.3	211	0.05	1	49.6 Tm^2	4.6×10^{12}	–	–
BabyIAXO	2.5	10	0.7	2	21.9 Tm^2	1.1×10^{9}	4.41×10^{-22}	3.52×10^{-25}
MADMAX	4.83	6	1.25	1	32.1 Tm^2	1.9×10^{8}	3.01×10^{-22}	2.40×10^{-25}
IAXO	2.5	20	0.7	8	87.7 Tm^2	2.2×10^{9}	1.10×10^{-22}	8.79×10^{-26}

Ringwald et al. 2011.04731v2

Conclusions

- (Baby)IAXO helioscope can probe axion/ALP parameters beyond astrophysical limits
  - CAST legacy
  - Low background detectors + x-ray focusing
- IAXO has a rich and unique potential to probe relevant regions and to distinguish between axion models.
- In addition, a facility for more generic axion-related searches.
  - Dark Matter axions, hidden photons, gravitational waves, other astrophysical sources, etc…
- Recently, significant progress on magnet design with successful reviews and good progress on funding
  - ERC Starting and Synergy (Dark Quantum) grants, Bonn/Dortmund/Siegen and Hamburg University Clusters of Excellence, DFG proposal

BabyIAXO outside setup



Thanks to my IAXO colleagues