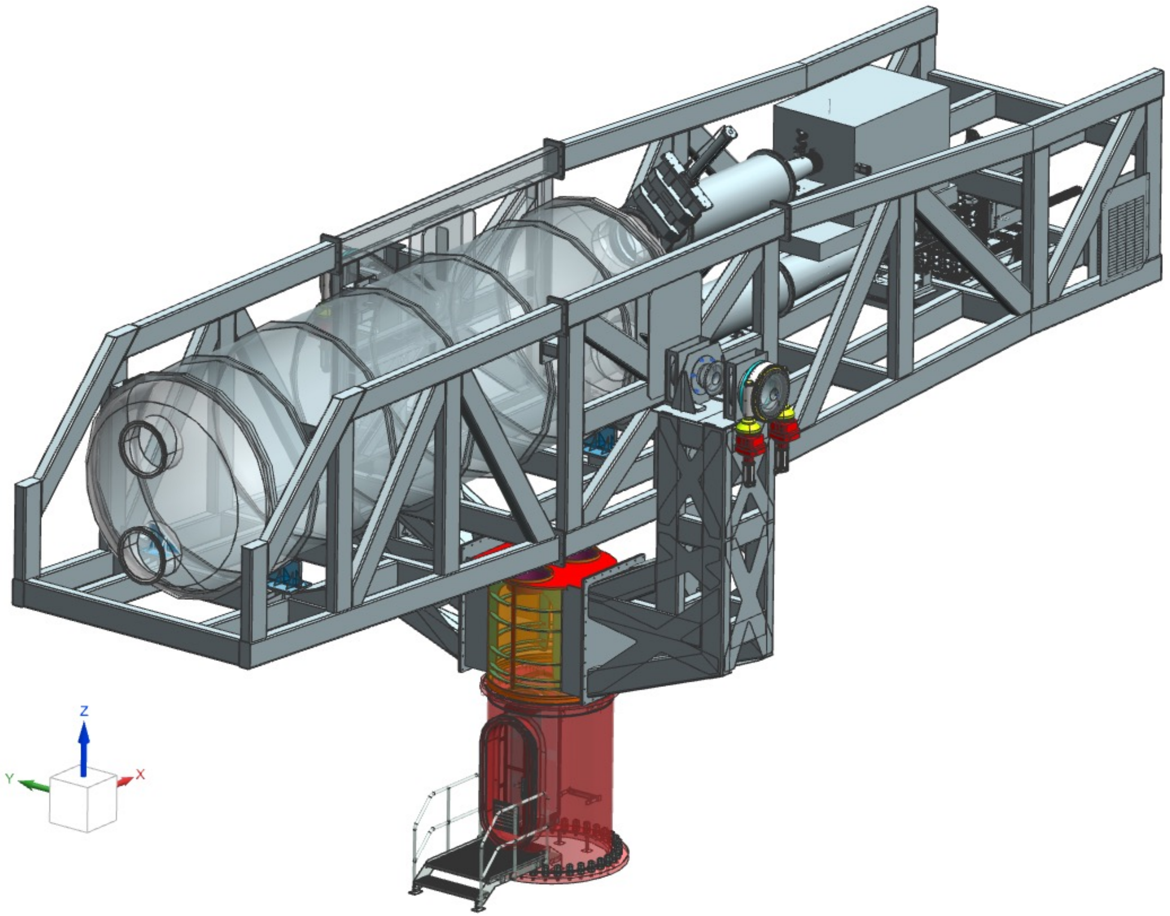
Searches for Axions/ALPS with (Baby)IAXO



Uwe Schneekloth, DESY
18th PATRAS Workshop

On behalf of the IAXO Collaboration

Introduction

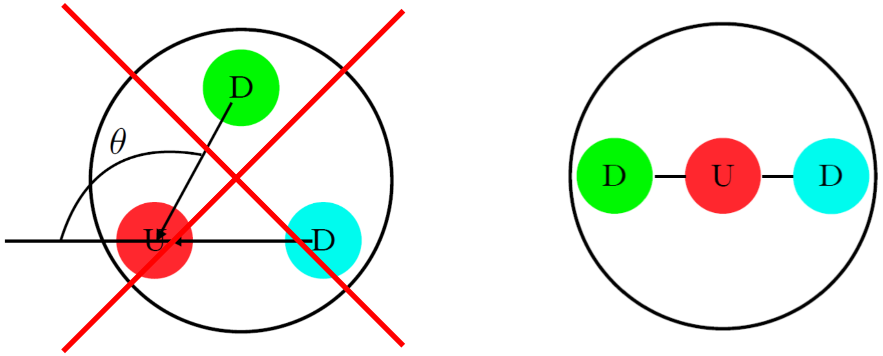
Axion Motivation

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

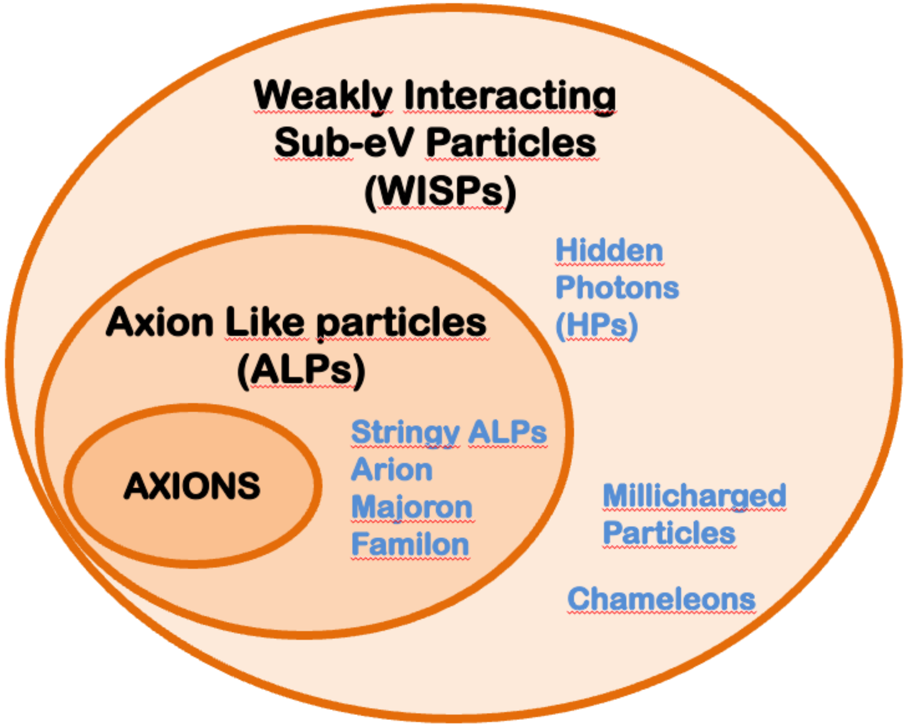
Apart from dark matter, other hints from astrophysics which might be explained by axions

- 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

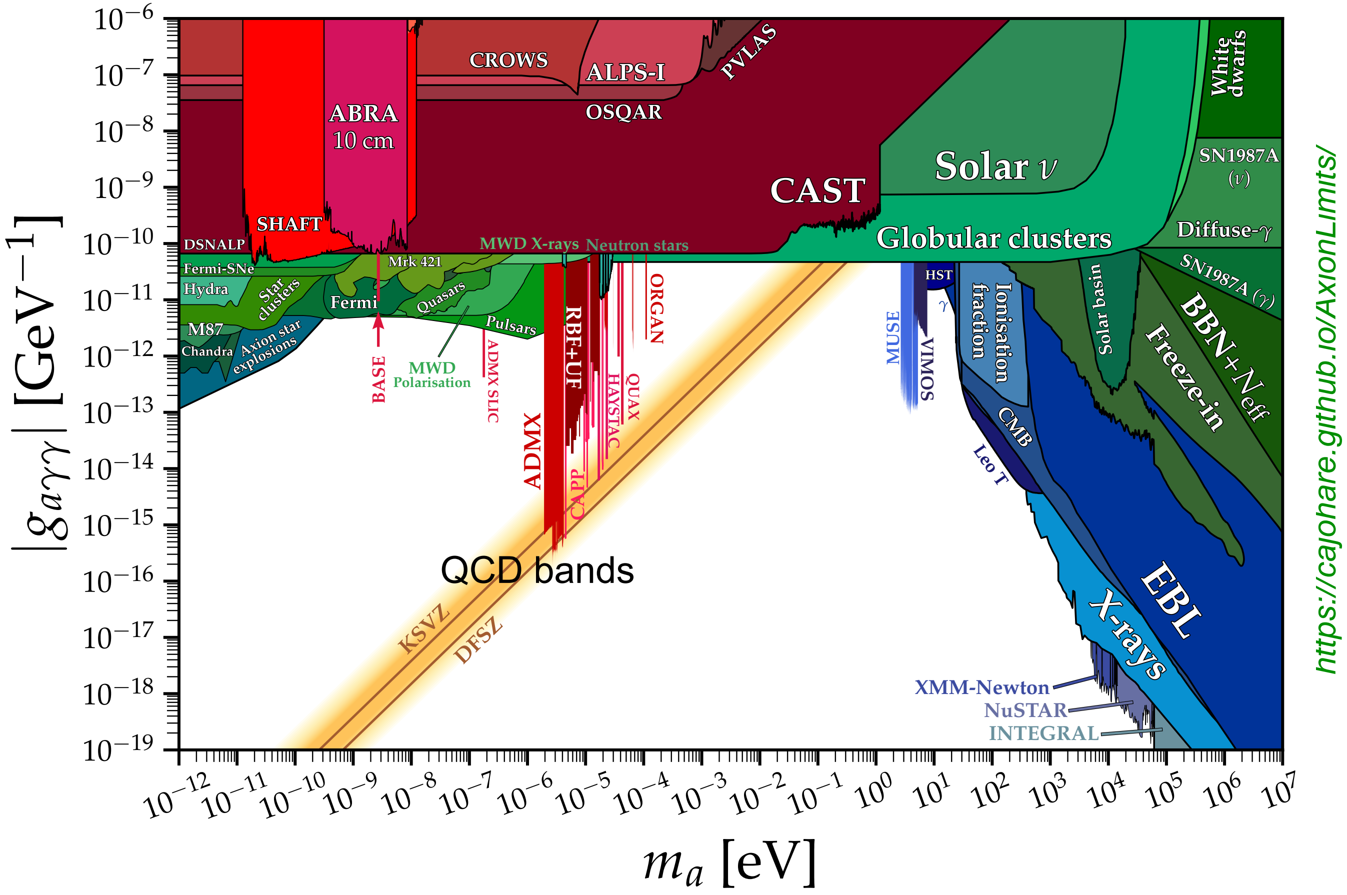
Standard Model Extensions

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



Generic ALPs parameter space

Axion-photon coupling vs. axion mass

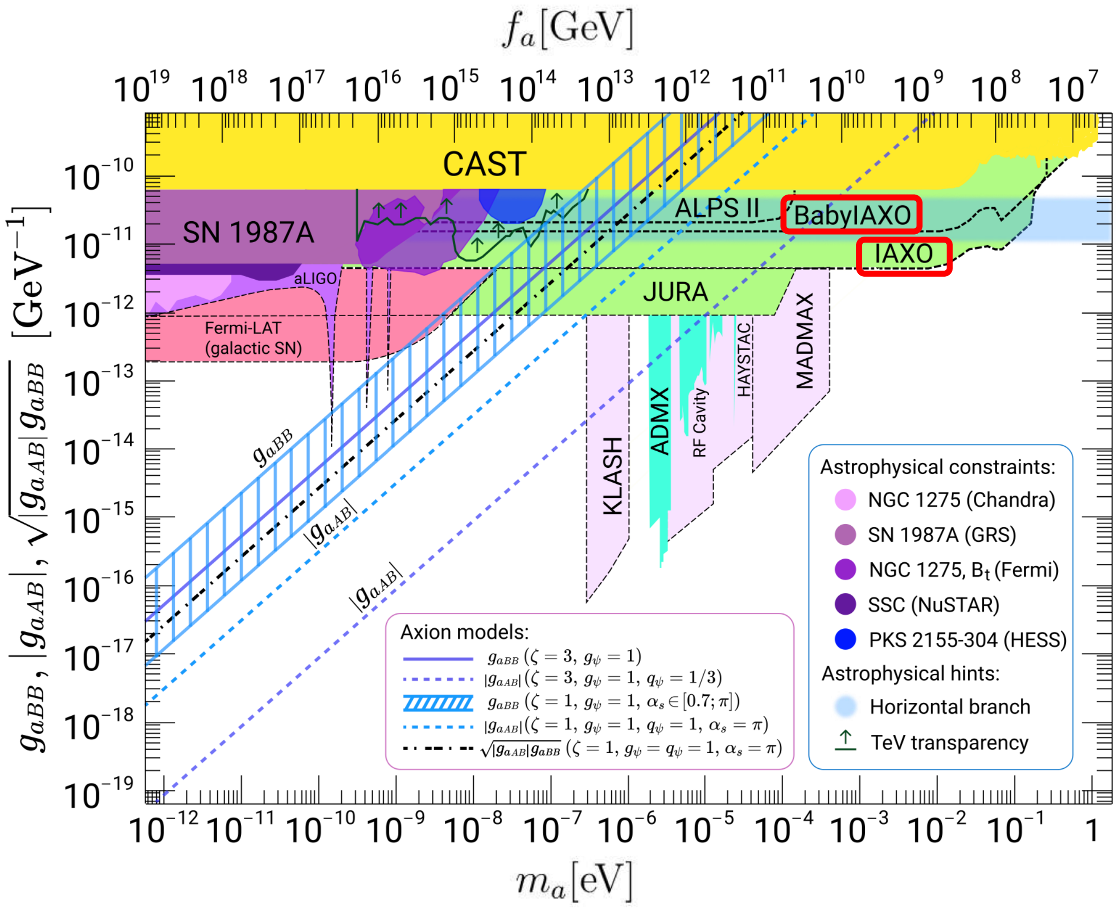


String theory predicts a plenitude of ALPs

Axions beyond the "Band"

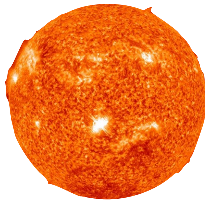
QCD Axions

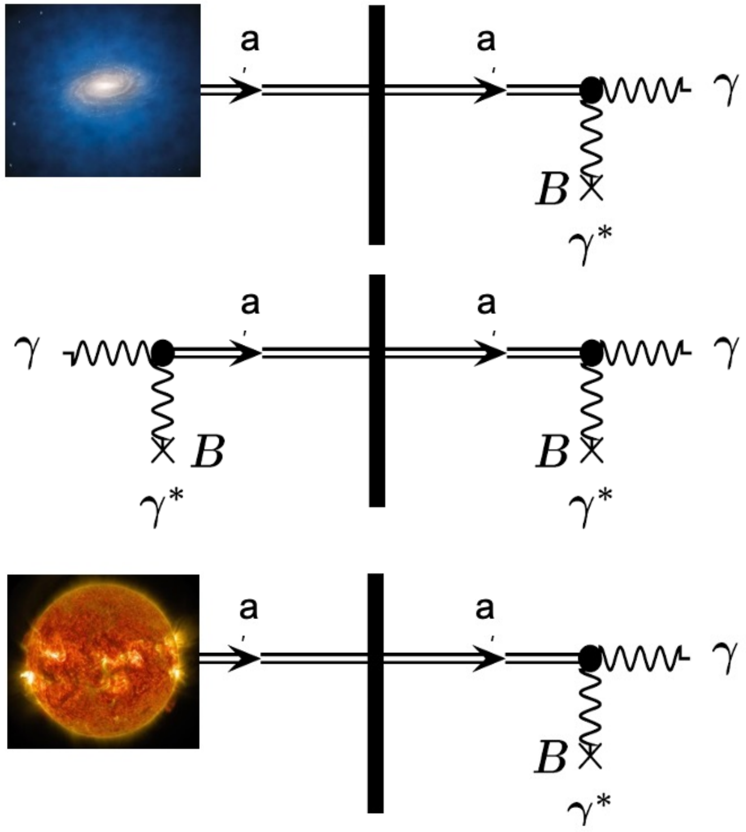
- Conventional QCD axion models lie on the "yellow band"
- Traditional benchmarks:
  - DFSZ (Dine, Fischler, Srednicki, Zhitniskii): axions couple to fermions.
  - KSVZ (Kim, Shifman, Vainshetein, Zakharov): axions couple to BSM quarks only.
- Outside the band typically ALPs
- BUT a lot of "model building" 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 SUMICO, CAST, (Baby)IAXO	Low



ALPS talk
A. Spector
on Thursday

Solar Axions

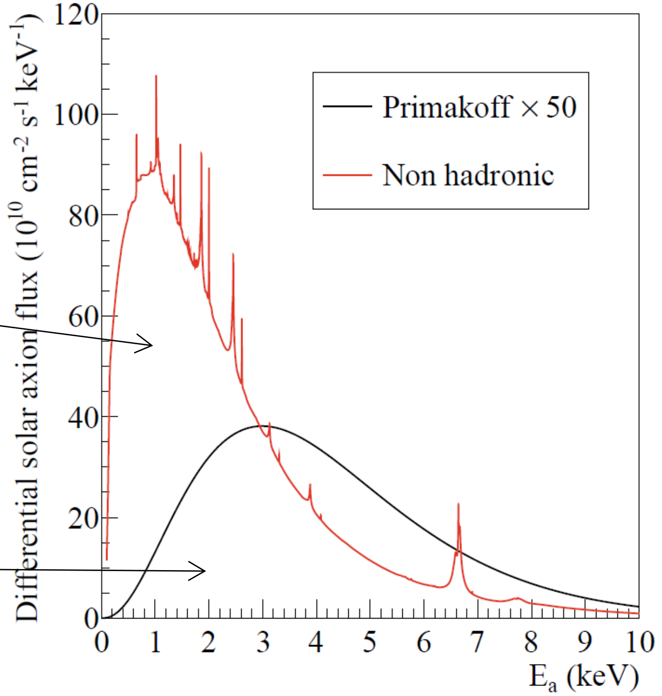
Different Sources

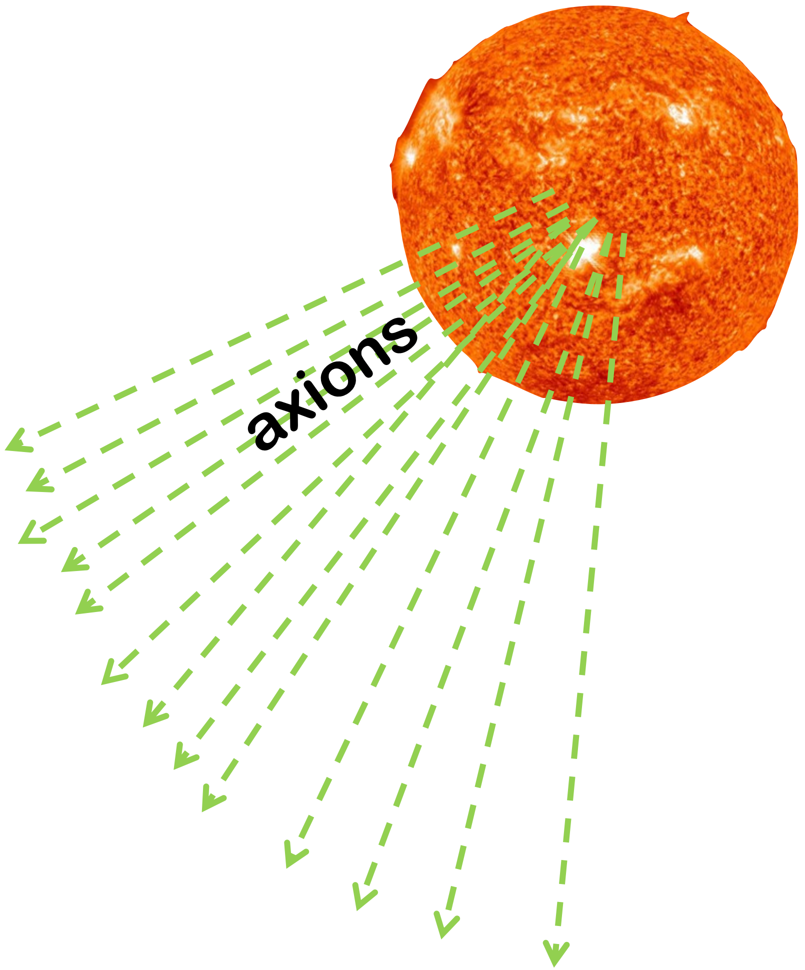
- Primakoff conversion of solar plasma photons
  → generic prediction of most axion models
- In addition, g_{ae}- and g_{aN} - mediated axions (model dependent)

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

Standard Primakoff spectrum

Thermal spectrum, corresponding to temperature of sun core





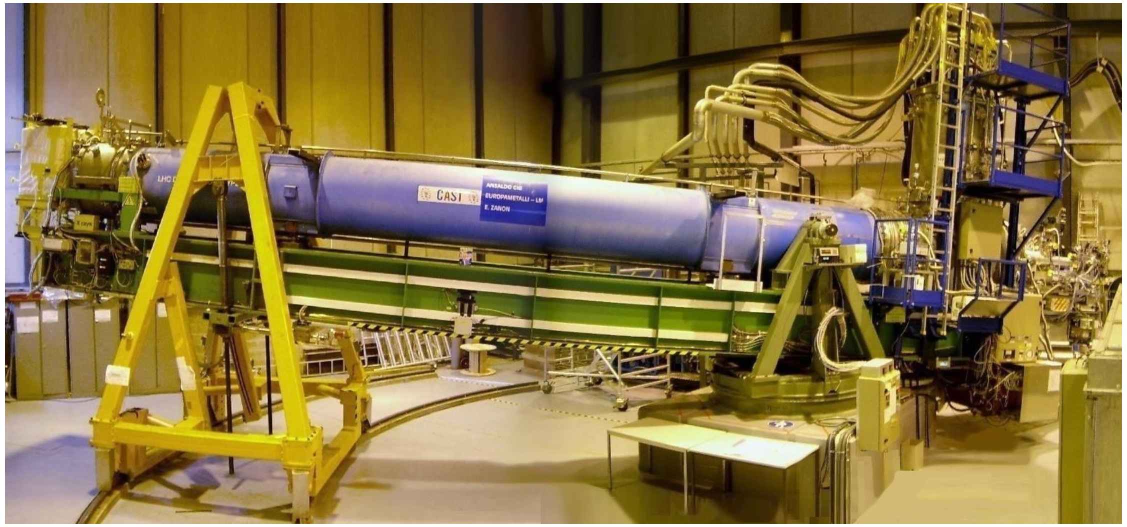
Helioscopes can distinguish between different couplings in contrast to haloscopes and LSW exp.

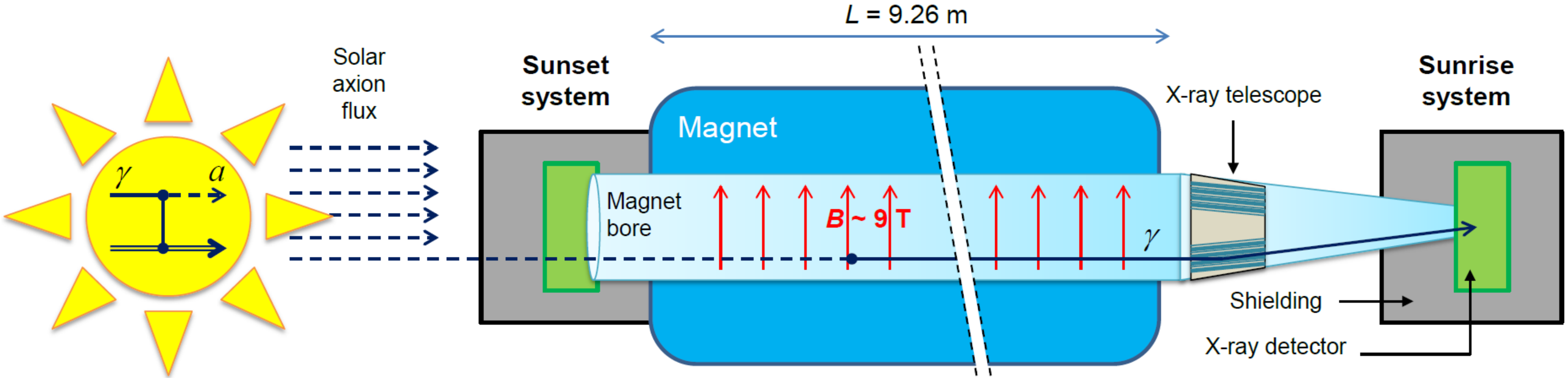
In addition, low-energy axions can be produced via plasmon-photon conversión and higher-E axions via nuclear transitions (axion nucleon coupling)

Searches for Solar Axions

CAST, CERN Axion Solar Telescope

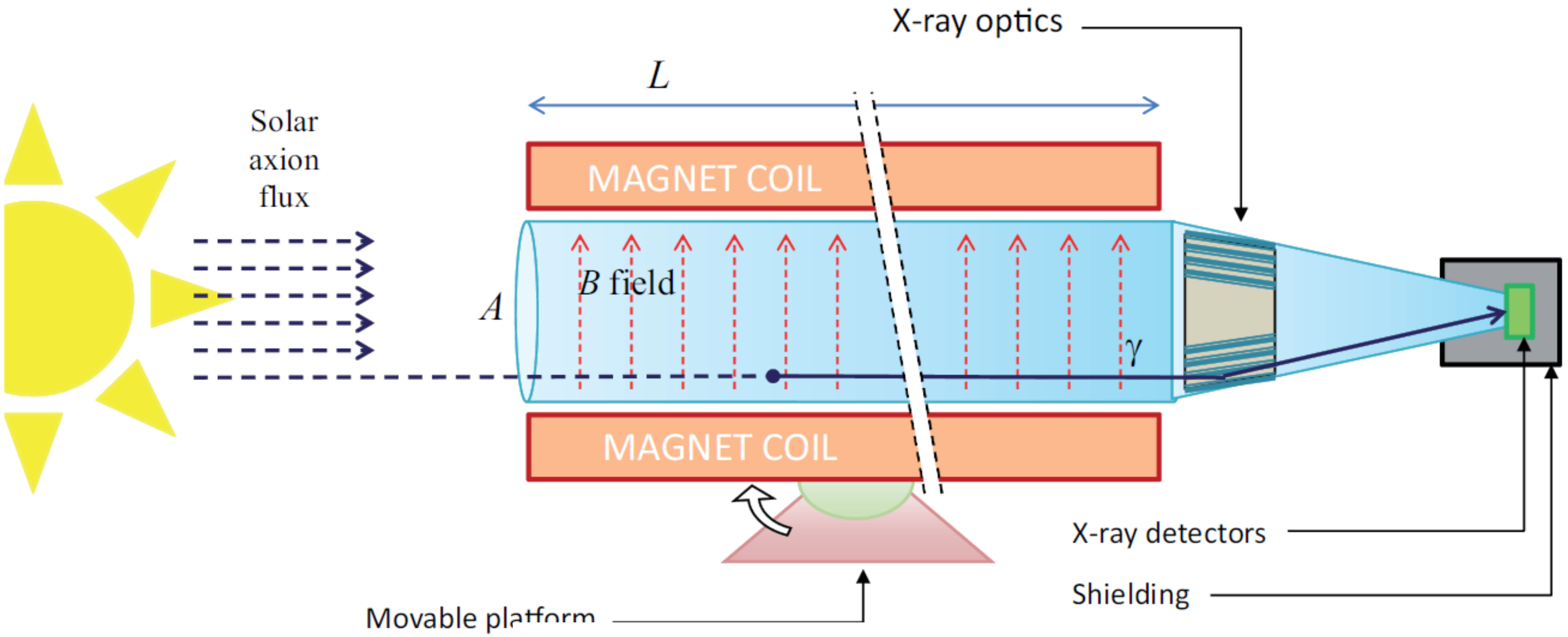
- First helioscope using low background techniques and x – ray focusing
  - Superconducting LHC dipole magnet
  - X-ray detectors
  - Use of buffer gas to extend sensitivity to higher masses (QCD axion band)
- Most sensitive measurements until now





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

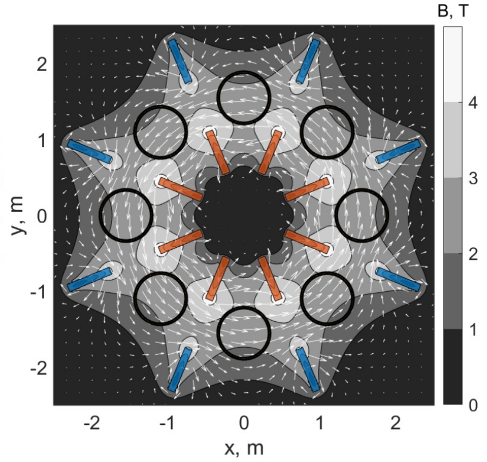
$$g_{a\gamma}^4 \propto \underbrace{b^{1/2}\epsilon^{-1}}_{\text{detectors}} \times \underbrace{a^{1/2}\epsilon_o^{-1}}_{\text{optics}} \times \underbrace{(BL)^{-2}A^{-1}}_{\text{magnet}} \times \underbrace{t^{-1/2}}_{\text{exposure}}$$

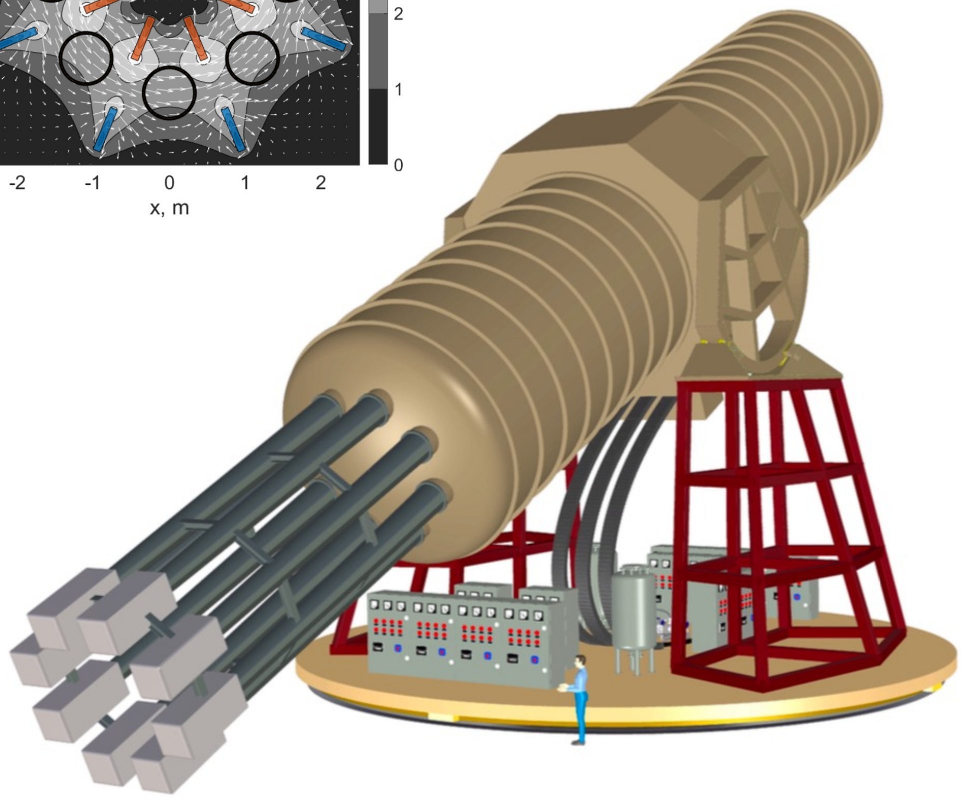
Enhanced axion helioscope:
Irastorza et al.,JCAP1106:013,2011

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
  - Toroid geometry, very similar to ATLAS μ toroid
  - 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)





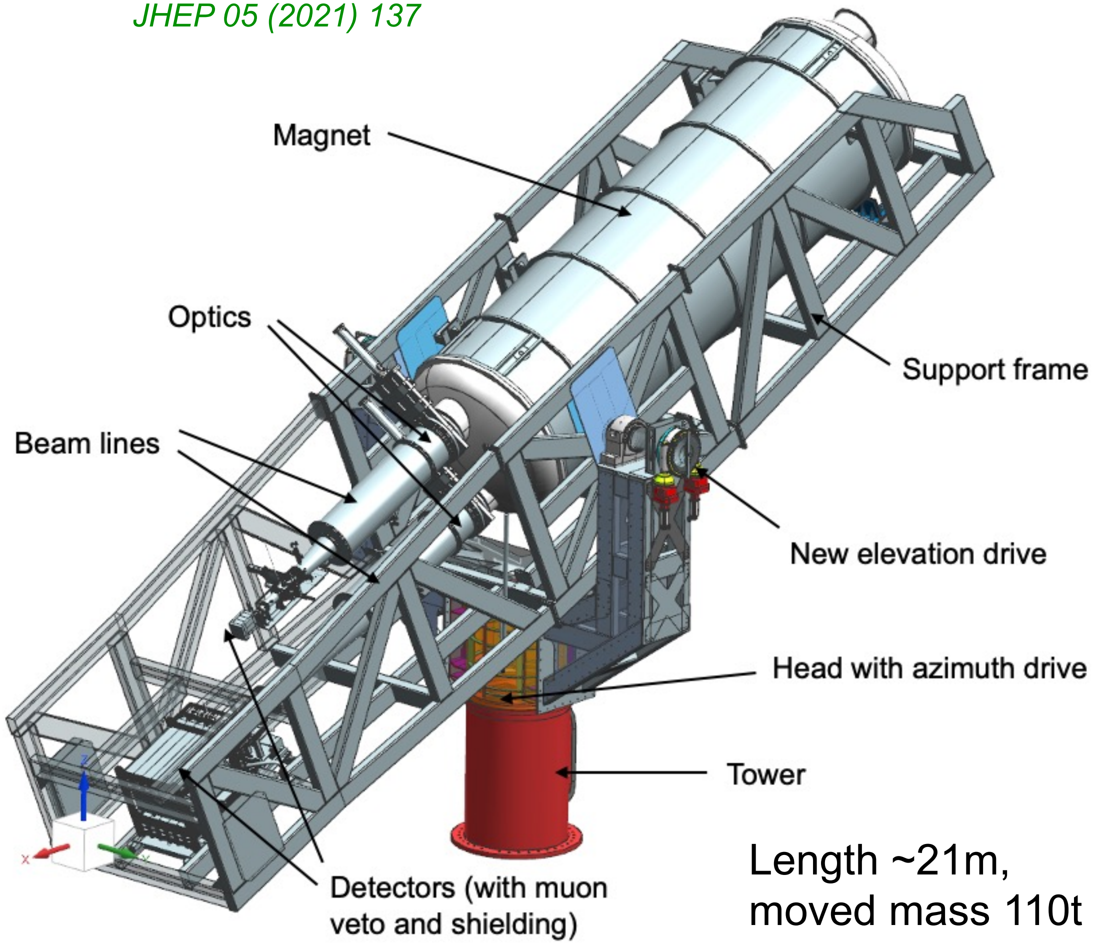
IAXO CDR: JINST 9 (2014) T05002 (arXiv:1401.3233)]

BabyIAXO Overview

IAXO Prototype

- Intermediate experimental stage before IAXO
  - Two bores of dimensions similar to final IAXO bores → 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

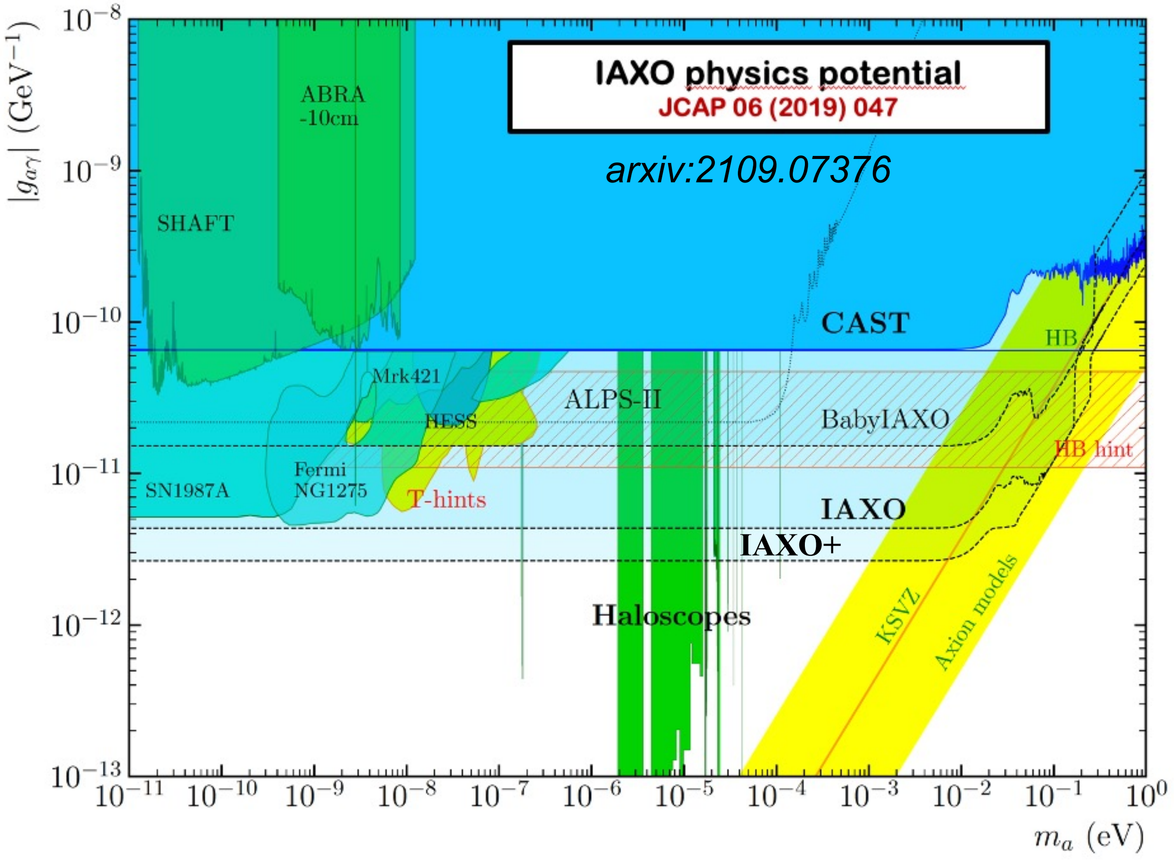
Pointed towards sun by azimuth and elevation drive systems, precision < 0.01°

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

Important recent Milestones

Some History

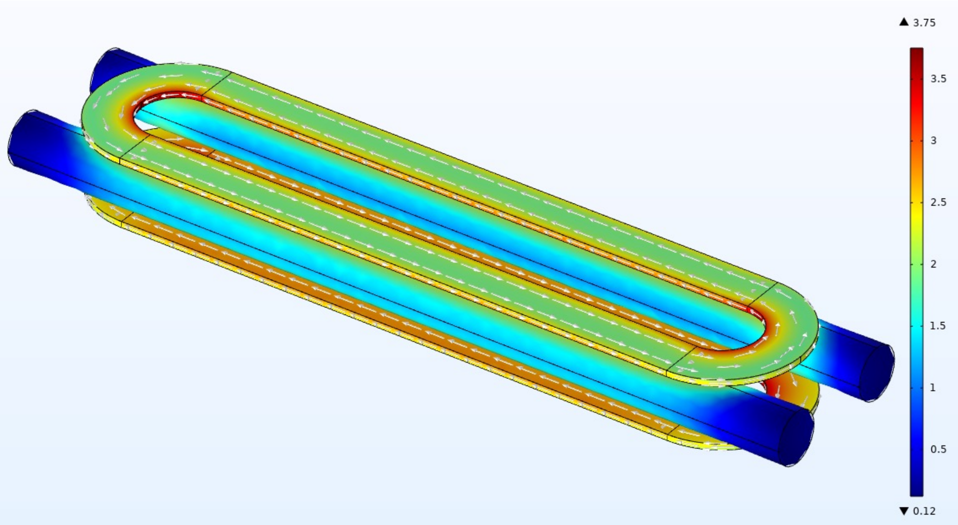
- First concept 2011, IAXO CDR (2014), BabyIAXO concept (2016), IAXO collaboration formally stablished in 2017.
- BabyIAXO conditionally approved by DESY after LoI (2018) and full proposal (2019). Project being monitored by DESY PRC since then. 1st PRC magnet review in 2020.
- Good part of funding secured: ERC-AdG @ UNIZAR (2018), DESY as host + many other institutions.
- CERN crucial participation in magnet expertise: DESY-CERN MoU on magnet signed in 2020.
- Two other ERC-StG attracted for related technologies…
- BabyIAXO conceptual design published (2021), technical design very much advanced. Management in place.
- First construction preparation steps being taken (first tenderings).
- Some magnet issues: Aluminum-stabilized super conducting cable not available due to the Russian invasion, presently optimizing cryogenics design, magnet integration at CERN not realistic anymore due to lacking technicians and engineers. (All DESY co-operations with Russian institutes suspended.)

BabyIAXO

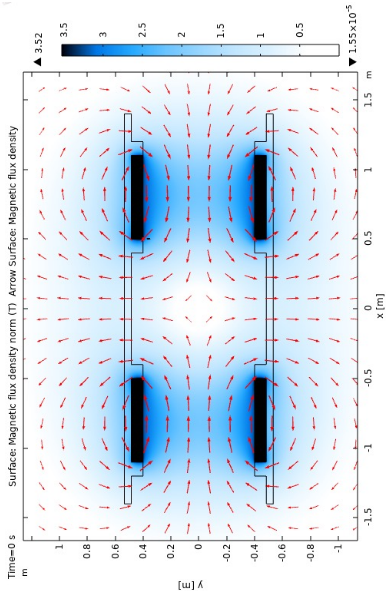
Magnet Design

"Common coil" configuration

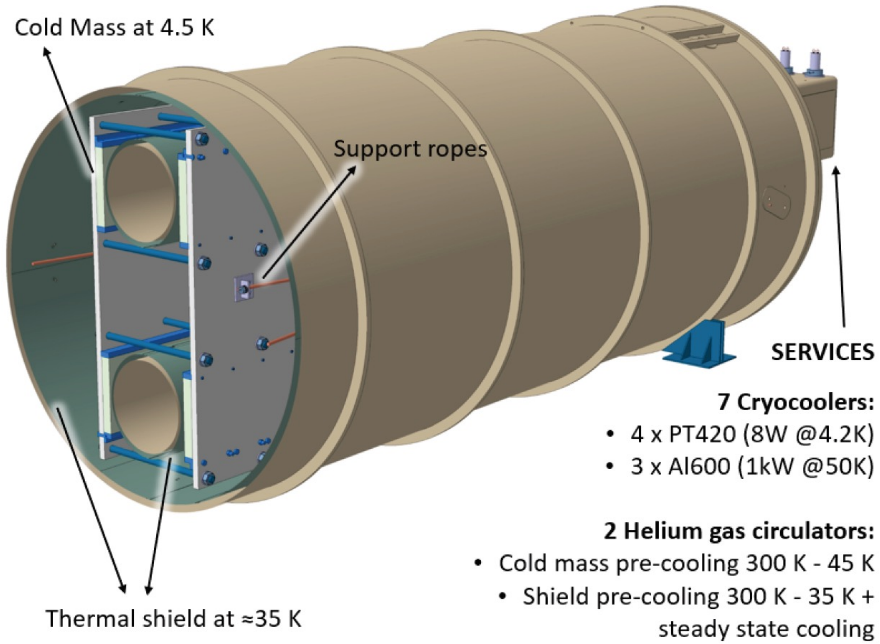
- Minimal risk: conservative design choices
- Cost-effective: Best use of existing infrastructure and experience at CERN
- Prototyping character: winding layout very close to that of IAXO toroidal design.



10m long coils, 700mm bores



Cryostat



7 Cryocoolers:

- 4 x PT420 (8W @4.2K)
- 3 x Al600 (1kW @50K)

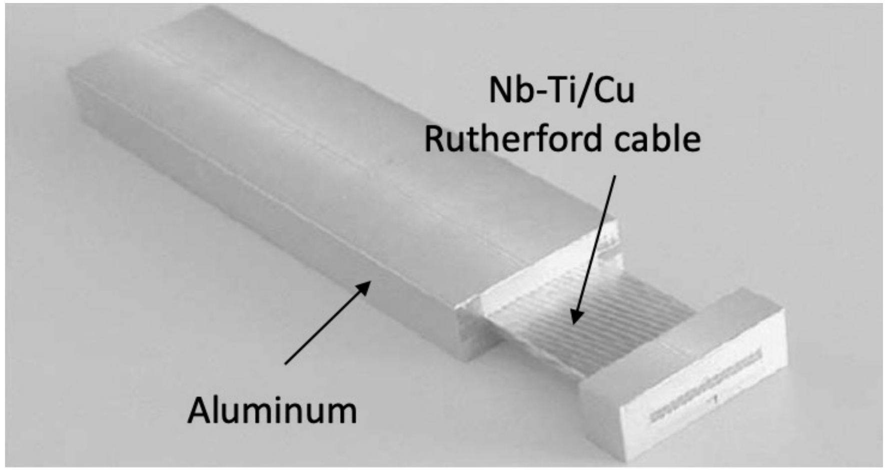
2 Helium gas circulators:

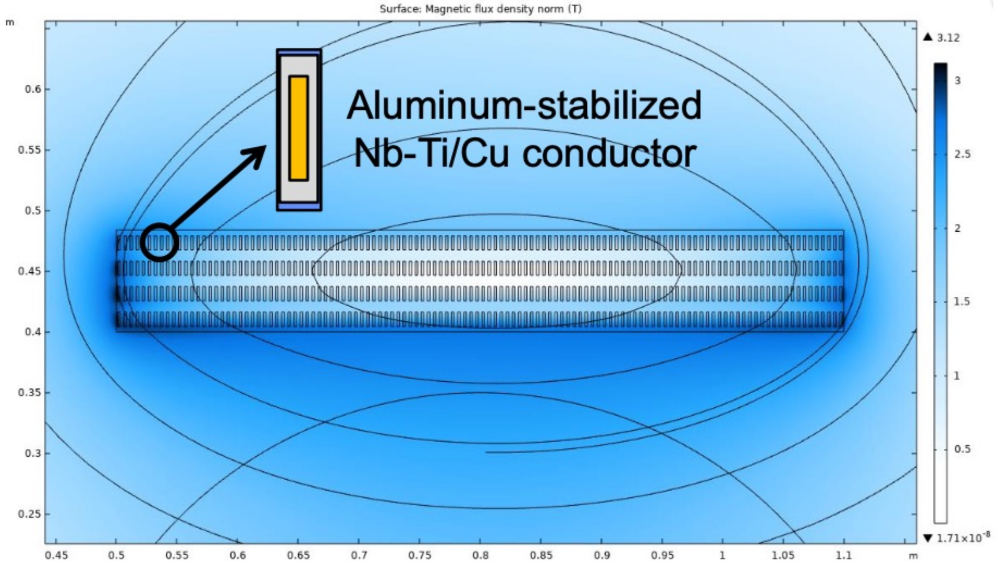
- Cold mass pre-cooling 300 K - 45 K
- Shield pre-cooling 300 K - 35 K + steady state cooling

BabyIAXO Magnet Design

Main challenges

- Availability of aluminum-stabilized conductor
  - Originally foreseen cable, developed in Russia for PANDA and IAXO, not available anymore
  - Currently, not commercially available
  - Workshop at CERN was organized to discuss with world-wide colleagues from institutes and industry in Sept 2022
  - Planning to set up co-extrusion facility at CERN (~3 years)
  - Going to order first half of Rutherford cables
- Complex cryogenics featuring cryo-coolers
  - Novel cryogenic design, using of cryo-coolers is a first for a magnet of this size
  - Presently, optimizing cryogenic design
- Unfortunately, causing delays and cost increase

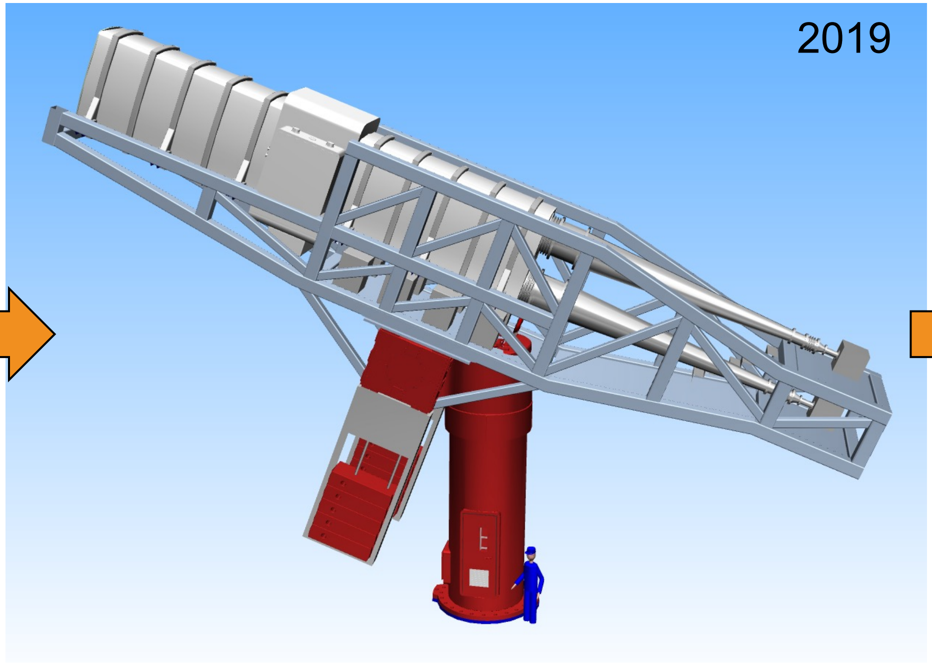


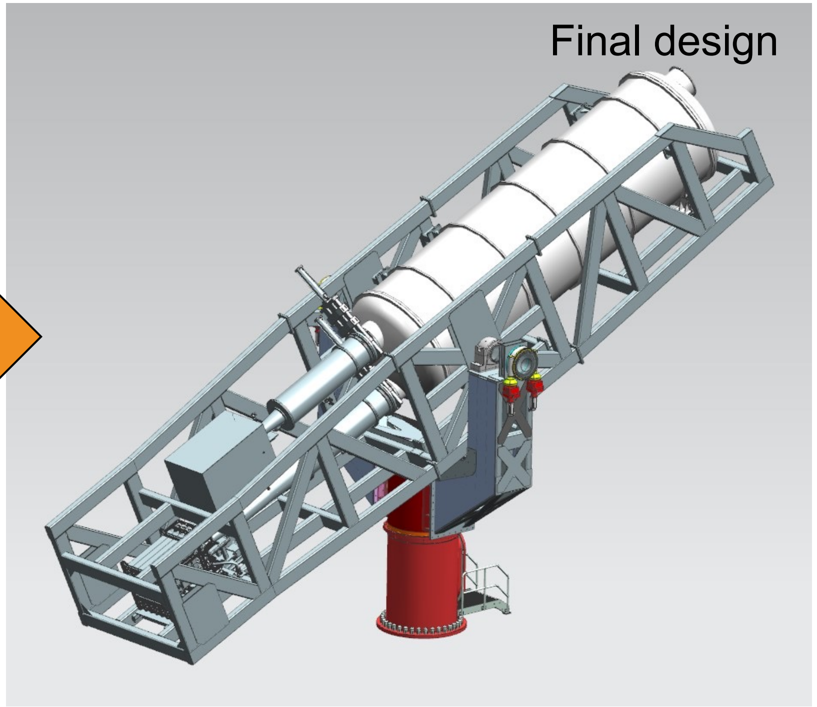


Structure and Drive System

Based on CTA MST Prototype

- 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.





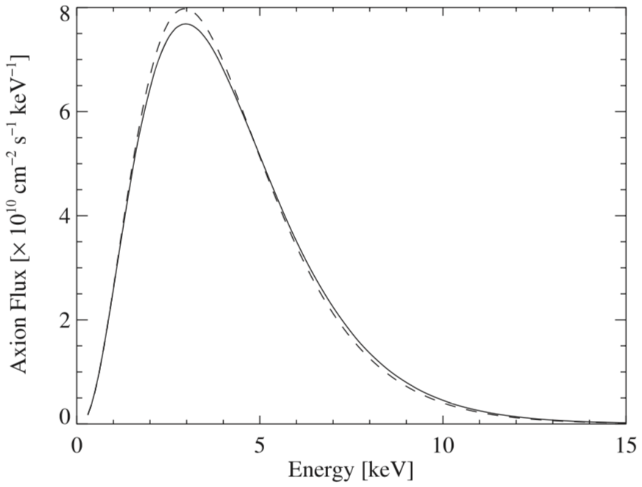
BabyIAXO Optics

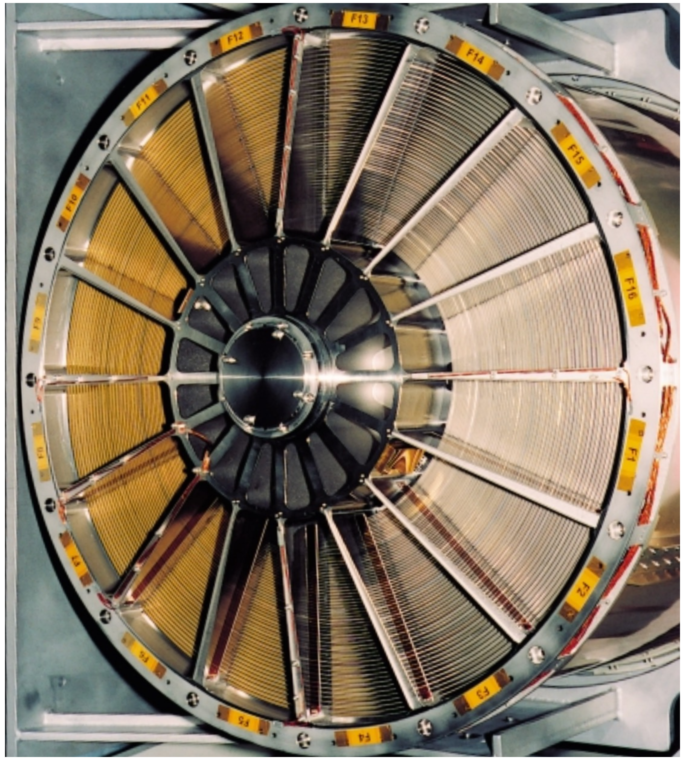
Two detection lines

ESA XMM Newton Flight Spare XRT

- Will get flight spare module from ESA
- Will be recalibrated at PANTER (Munich)
- Engineering model at DESY

x-ray spectrum





BabyIAXO Optics

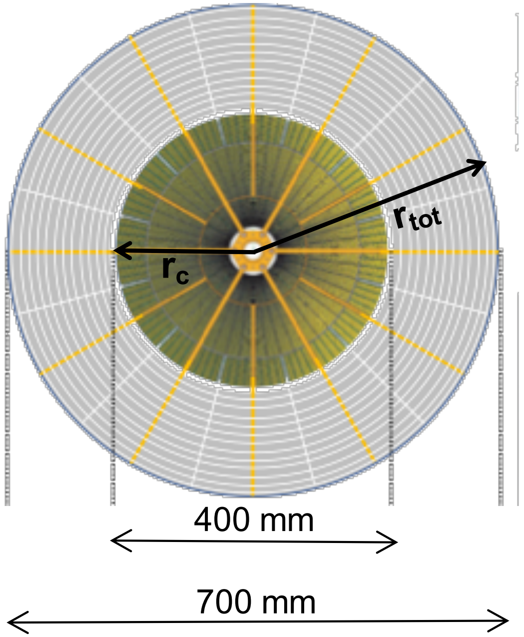
Two detection lines

Hybrid approach for custom BabyIAXO optics

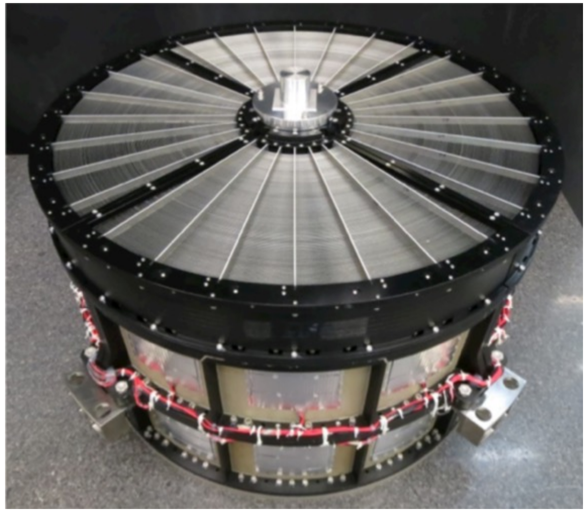
- Inner part Al-foil or segmented glass optics (NASA/LLNL/DTU/MIT/Columbia)
- Outer part cold-slumped Willow-glass technology (INAF/DTU)
- Multilayer deposition tests and characterization with NuSTAR flight glass and Willow glass completed
- First outer part prototype tested at PANTER (Munich)
- Preparing facility for assembly of optics

Design of support structure, vacuum vessel and alignment system in progress

Sketch of hybrid optics



ASTRO-H optics (Al shells)

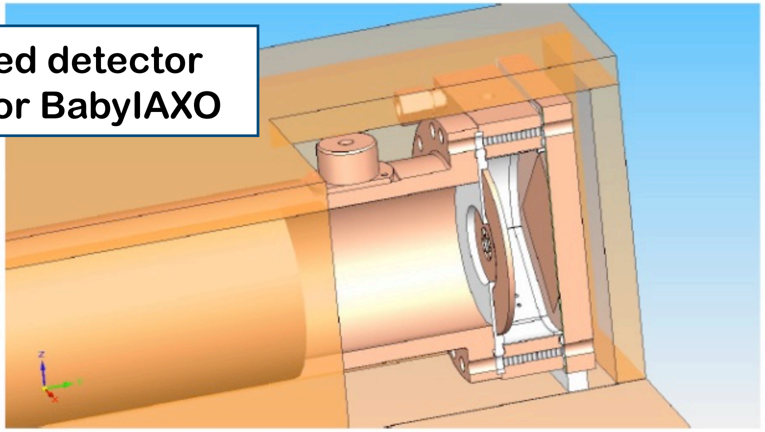


BabyIAXO Detectors

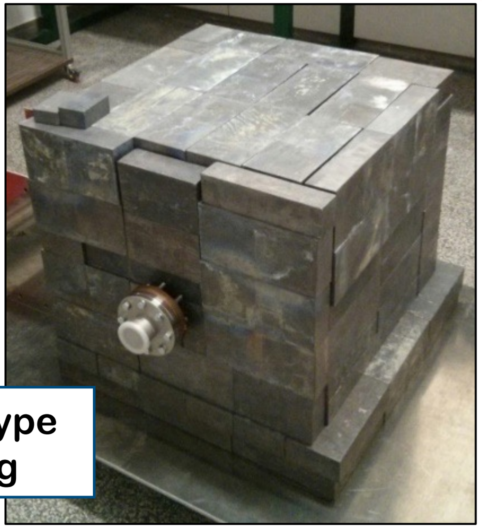
Low background Micromegas detectors

- “Discovery detectors” (priority to low background)
- Experience in CAST
- Low background capability, radiopurity, shielding.

- Tests at surface UNIZAR with IAXO-D0.
  - Implementation of 4 pi muon veto.
  - Enough to obtain 10^{-7} cts/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 cosmogenic neutrons



Improved detector design for BabyIAXO



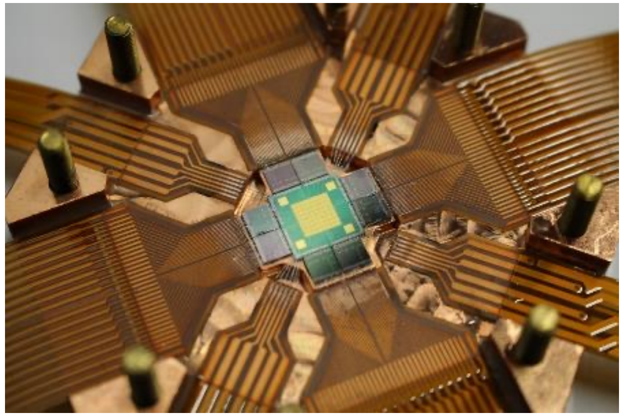
IAXO-D0 prototype in its shielding

BabyIAXO Detectors

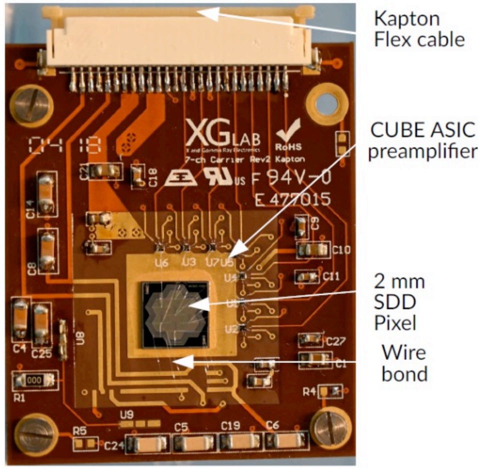
“High precision” detectors (post-discovery?)

- Lower threshold & better energy resolution
- Design and material optimization ongoing in all fronts
- Background studies with different shielding configurations
- DALPS project (French ANR)

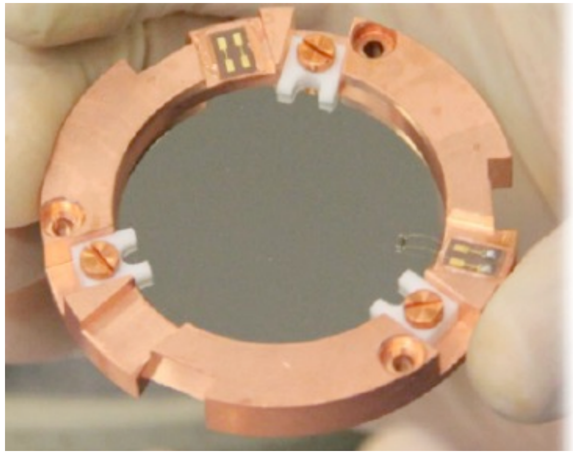
ERC-StG (2020)
M.Meyer/Hamburg



MMC: Metallic Magnetic Calorimeters



SDD: Silicon Drift Detectors



TES: Transition Edge Senstors

Gridpix

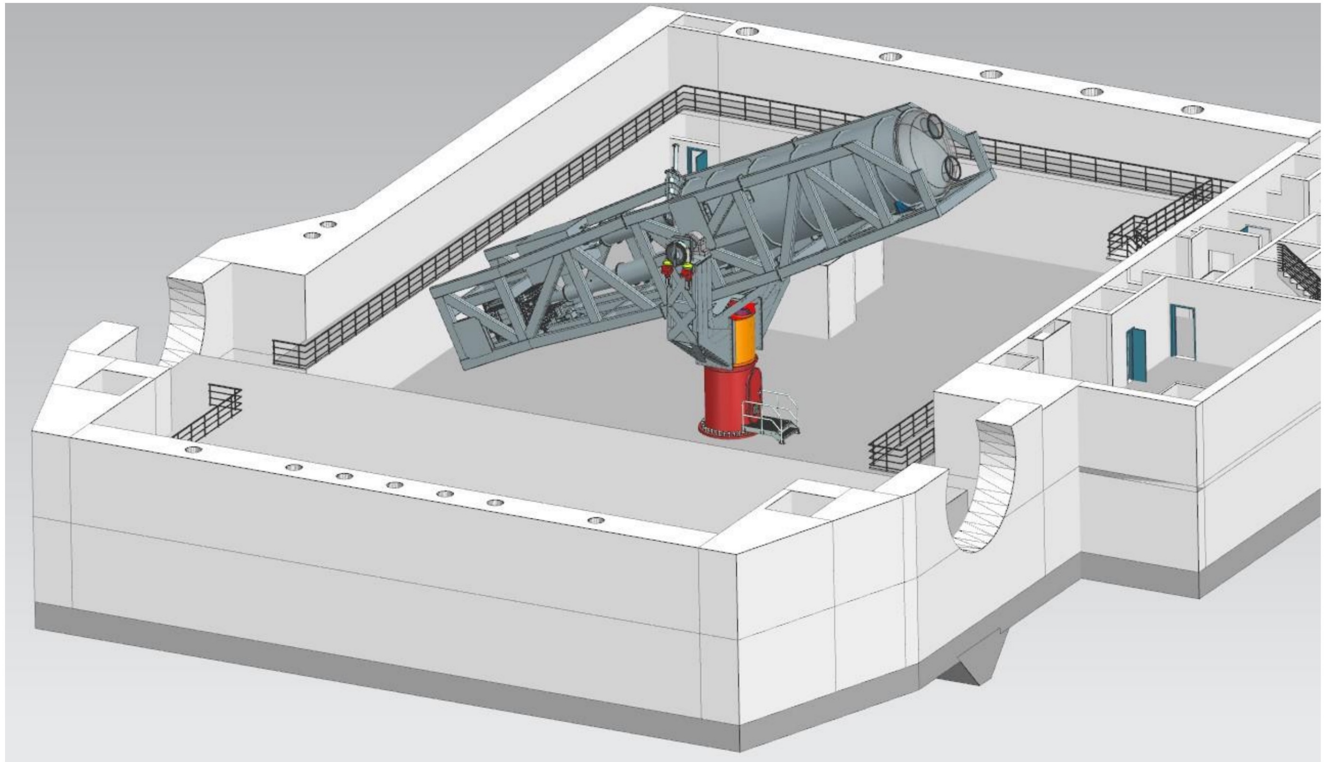
Technical Coordination (at DESY)

Main Activities

Coordinating, jointly with Project Office,

- Component/work package design, integration and preparation of assembly
- Design, fabrication, assembly and commissioning of structure and drive system
- Survey/alignment
- Site and infrastructure

- Planning “magnet-less” assembly and commissioning with all components before magnet is ready and do a “dry run”

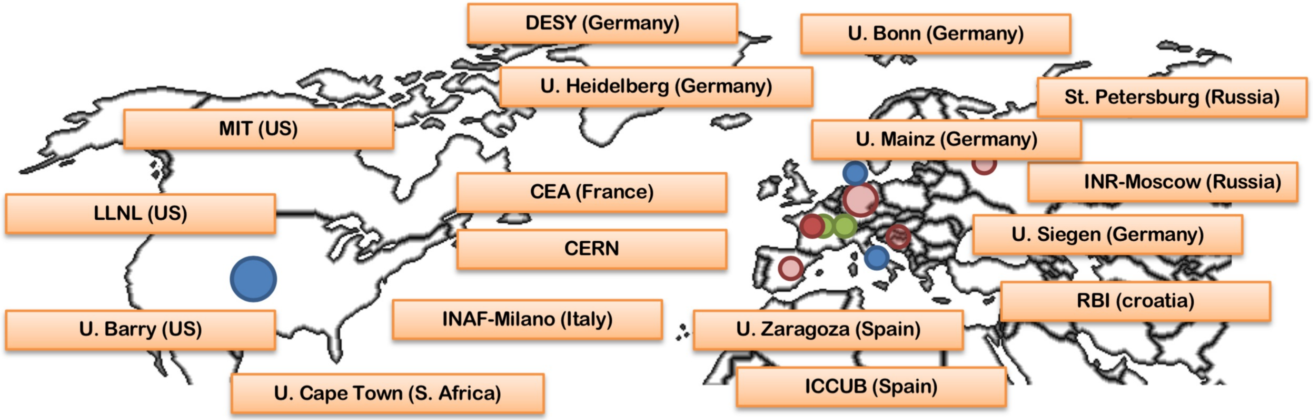


IAXO Collaboration

Institutions

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

Know-how portfolio nicely encompasses IAXO needs



Institution	short name	(*)	Superconducting magnets	X-ray optics	Detector & electronics	Axion phenomenology	Low background techniques	General infrastructures & engineering
Barry U. (USA)	BARRY	10				x		
Irfu/CEA-Saclay (France)	IRFU	1	x		x	x	x	x
U. Cape Town (S. Africa)	UCT	16				x		
ICCUB Barcelona (Spain)	ICCUB	5			x			
LLNL (USA)	LLNL	7		x		x		
St. Petersburg NPI (Russia)	PNPI	6				x		
Heidelberg U. (Germany)	UHEI	9			x		x	
U. of Zaragoza (Spain)	UNIZAR	4			x	x	x	
MIT (USA)	MIT	14		x				
INR Moscow (Russia)	INR	11	x			x		
RBI Zagreb (Croatia)	RBI	12				x		
U. Bonn (Germany)	UBONN	8			x			
U. Siegen (Germany)	USIEGEN	17			x			
JGU Mainz (Germany)	JGUM	15			x			
INAF - Brera (Italy)	INAF	2		x				
DESY (Germany)	DESY	13				x	x	x
CERN (Switzerland)	CERN	3	x					x
(**) CEFCA (Spain)	CEFCA							x
(**) CNM-IMB Barcelona (Spain)	CNM				x			
(**) DTU (Denmark)	DTU			x				
(**) U. Columbia (US)	UC			x				
(**) MPI-Munich (Germany)	MPI				x			
(**) CSNSM-Orsay (France)	CSNSM				x			

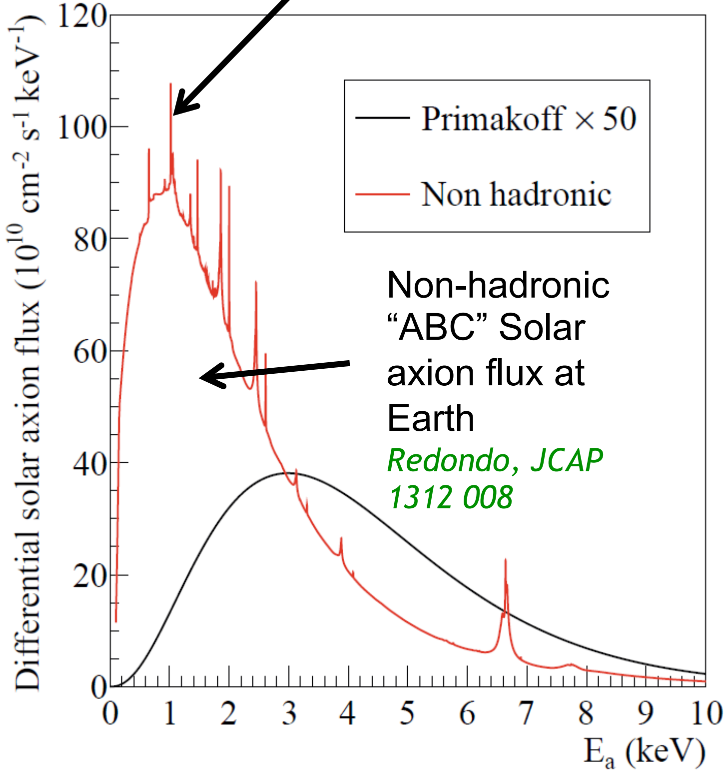
+ TUM Munich, MPE Munich, (MITP Moscow)

Other Solar Axion Sources / Post Discovery

“ABC Axions”

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

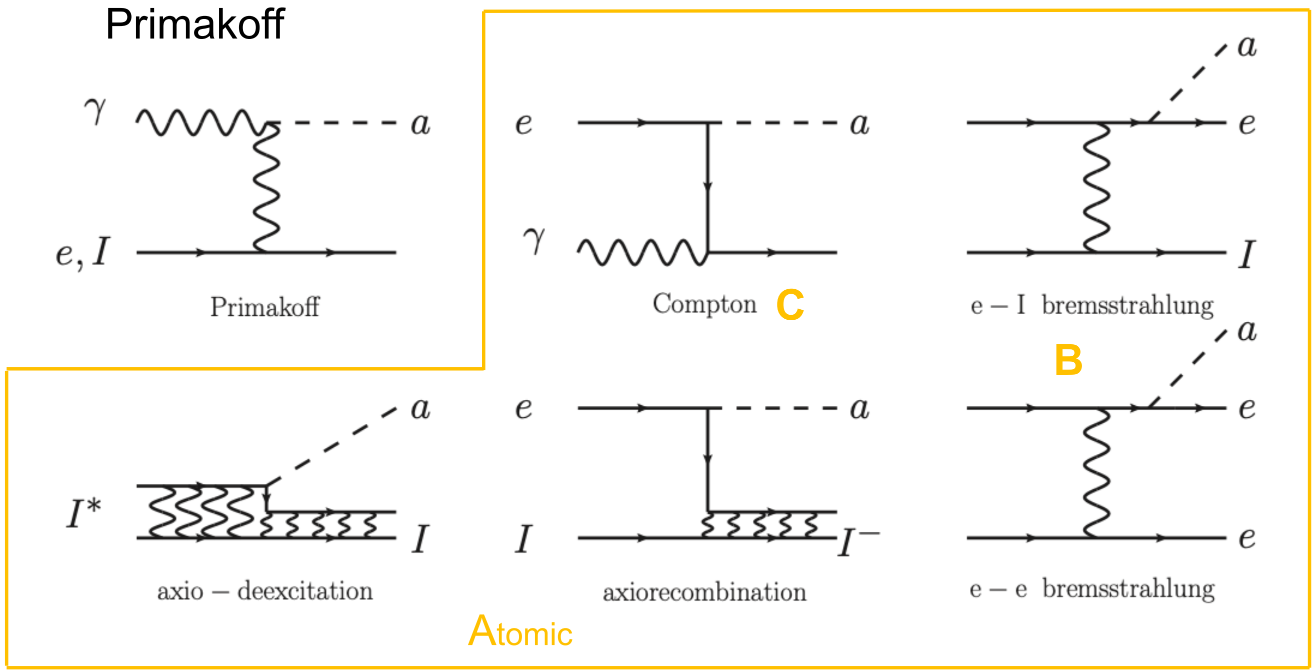
Atomic transitions



Non-hadronic “ABC” Solar axion flux at Earth

Redondo, JCAP 1312 008

“ABC solar axions” from axion-electron coupling



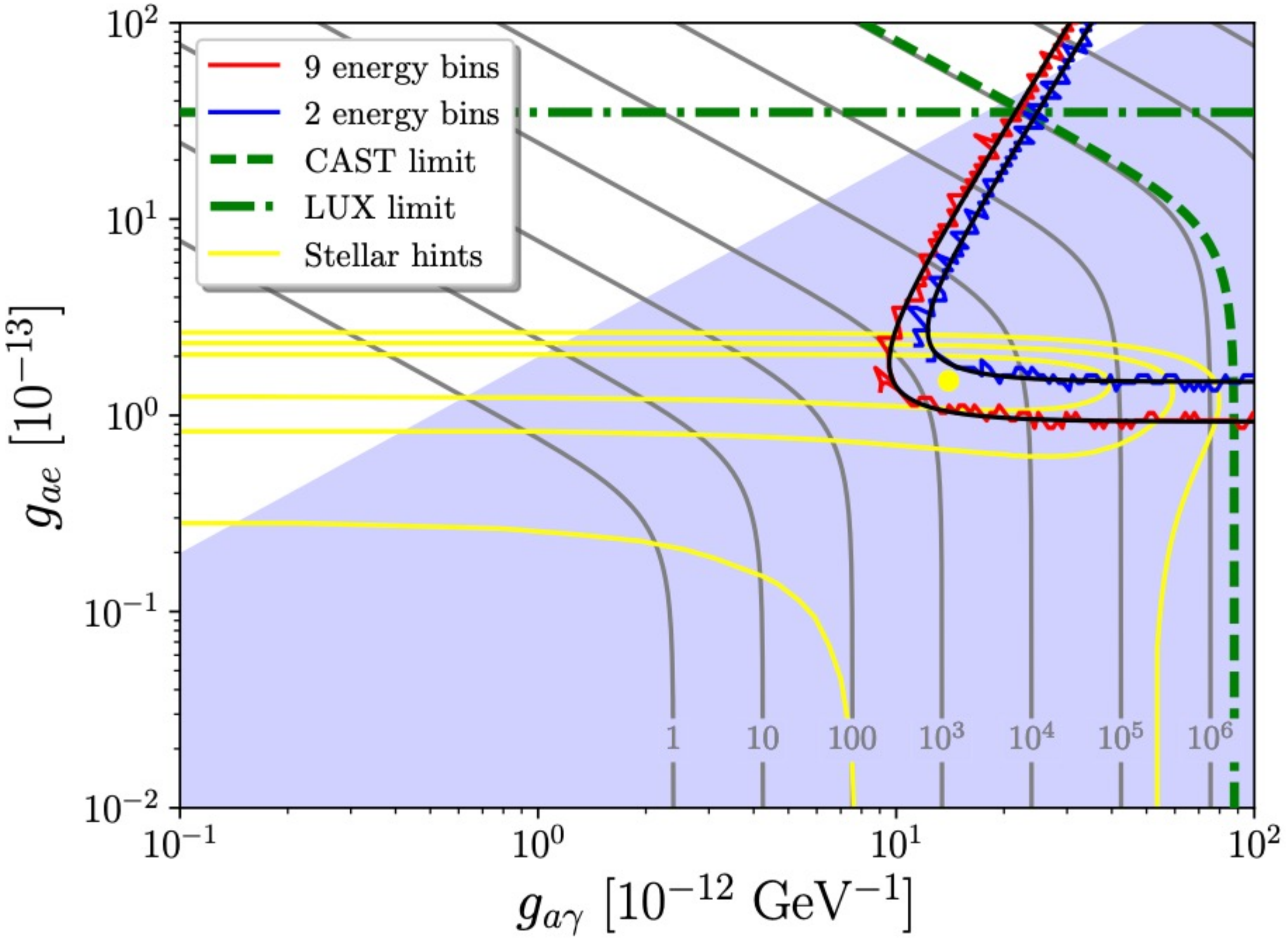
Other Solar Axion Sources / Post Discovery

"ABC Axions"

Detection of both ABC and Primakoff axion spectrum would allow distinguishing axion models (g_{ae}, $g_{a\gamma}$)

Jaeckel et al. arXiv:1811.09278

g_{ae} vs. $g_{a\gamma}$

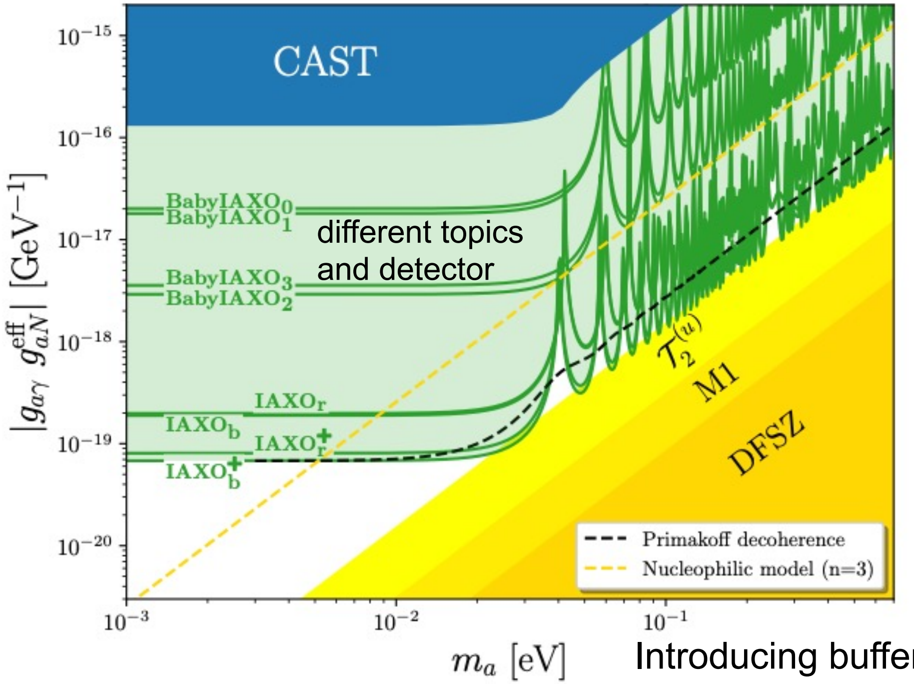


Other Solar Axion Sources / Post Discovery

Axion Nucleon Coupling

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

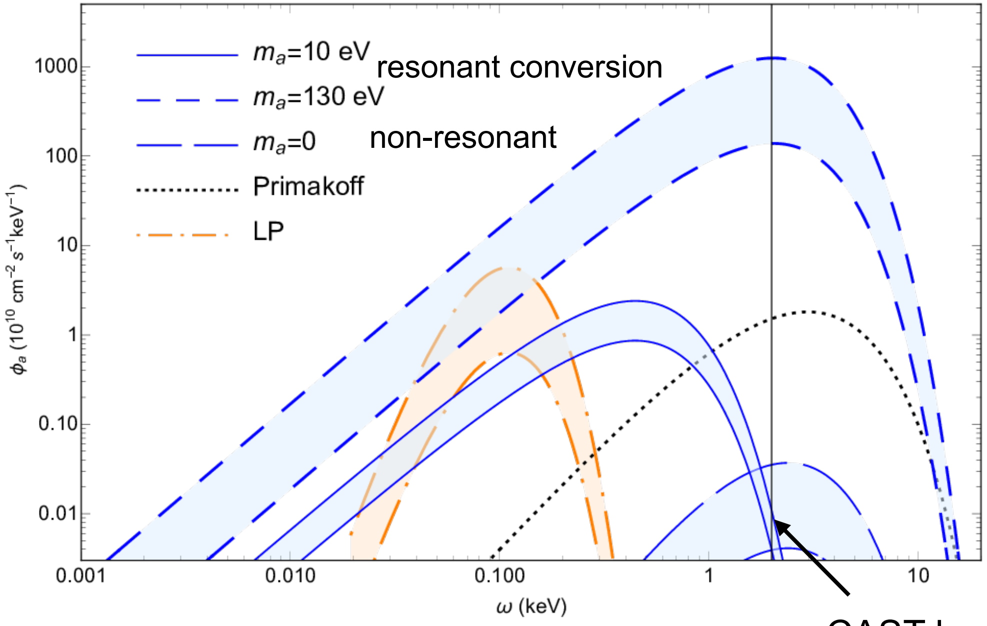
- E.g. 14.4 keV axions emitted in the M1 transition of Fe-57 nuclei, MeV axions from 7Li and D(p;g)^{3}He nuclear transitions or Tm-169. *Di Luzio et al. 2111.06407*



different topics and detector

Introducing buffer gas would increase sensitivity

More recently proposed: photons interacting with macroscopic solar B-fields. e.g. *Guarini et al. 2010.06601*



CAST bound

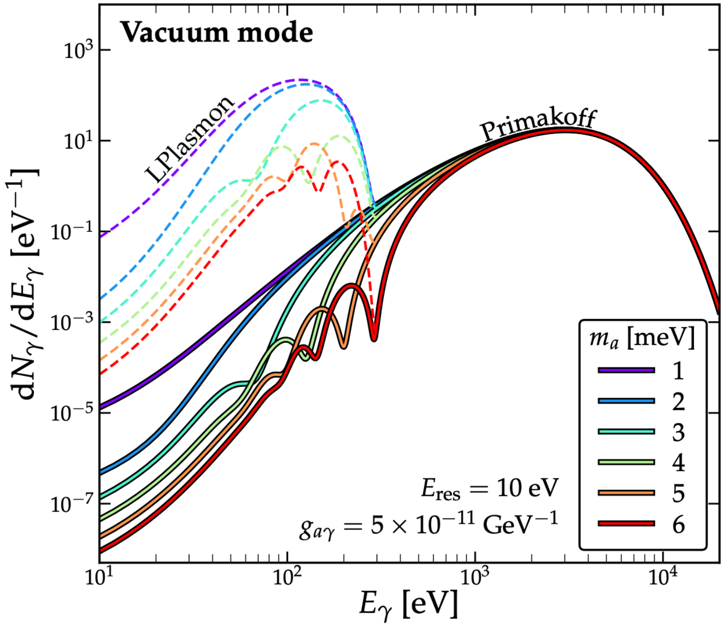
BabyIAXO sensitive to lower threshold

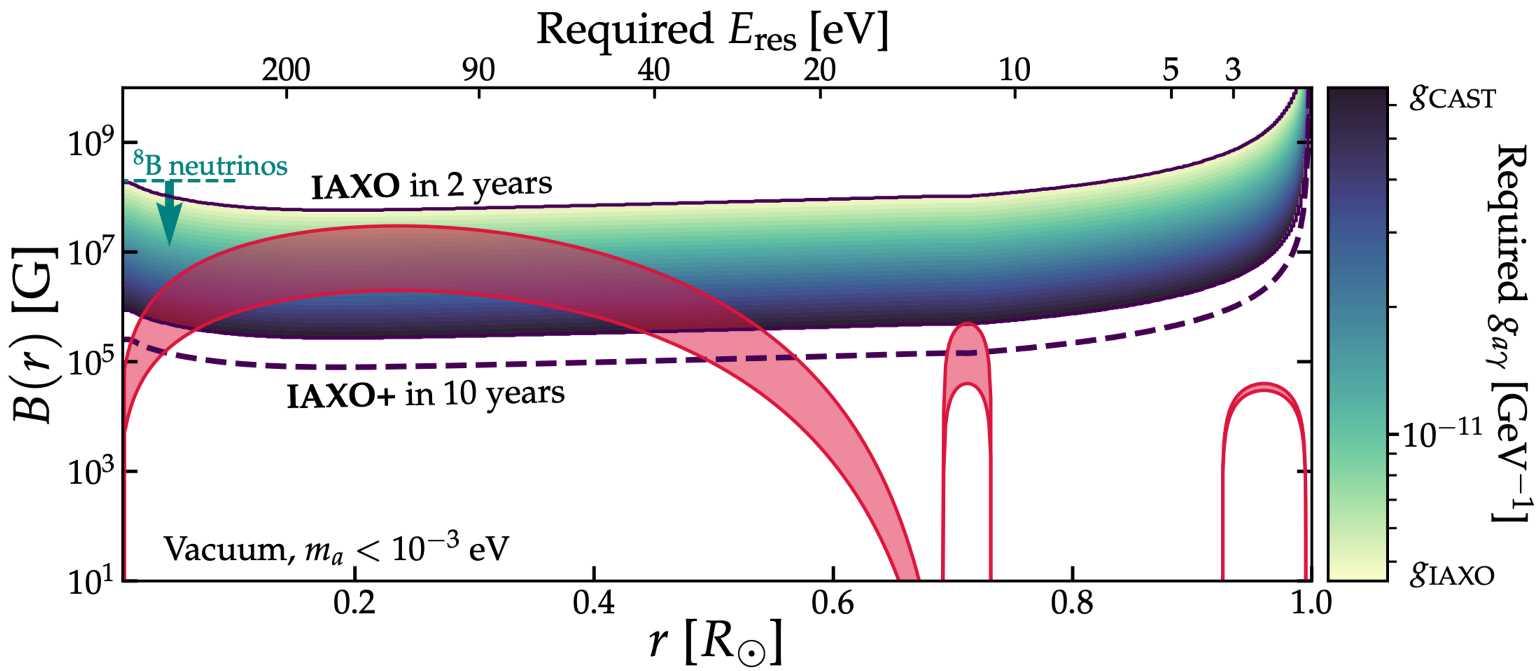
Post Discovery

Solar Magnetometers

Helioscopes as solar magnetometers using conversion of longitudinal plasmons

O'Hare et al. Arxiv:2006.10415





In addition, as solar thermometer *S.Hoof Poster Session*

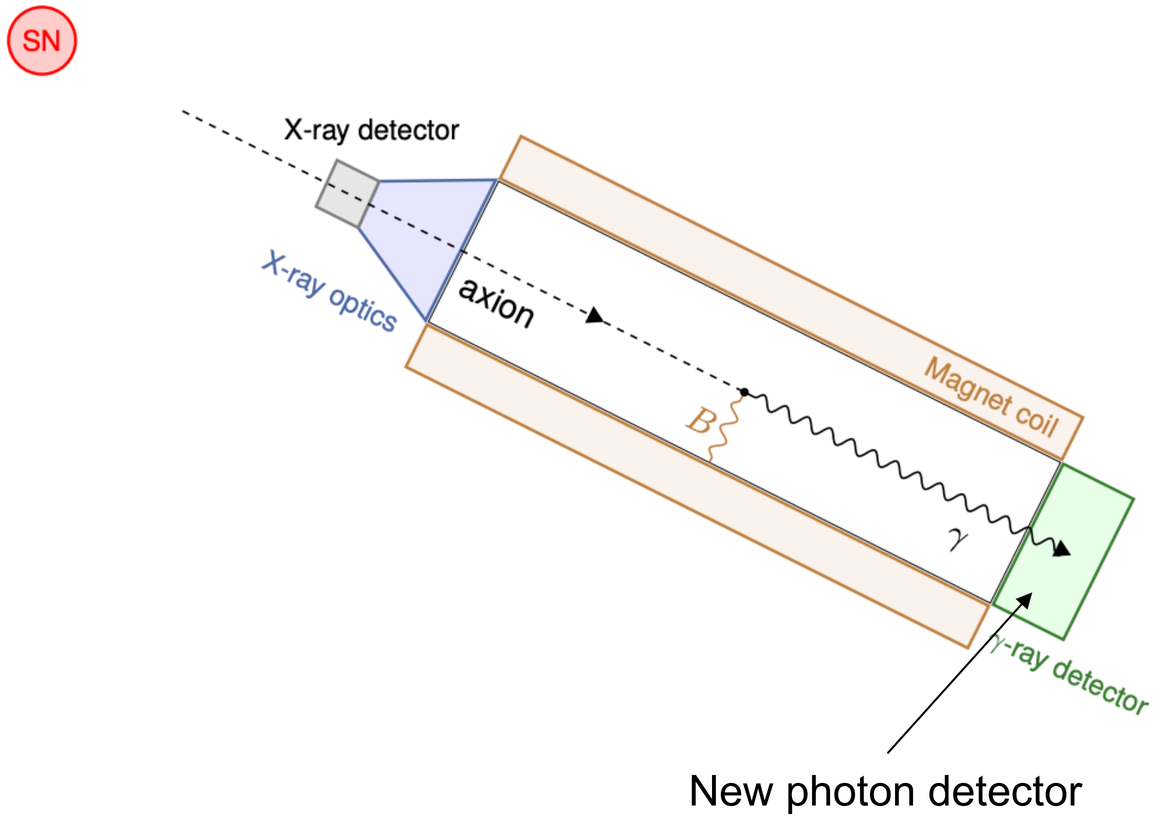
Post Discovery

Axions from a Galactic Super Nova

- If a sufficiently closeby galactic SN explodes, SN axions could be detectable at (Baby)IAXO.

  Ge et al. arXiv:2008.0392

- 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.

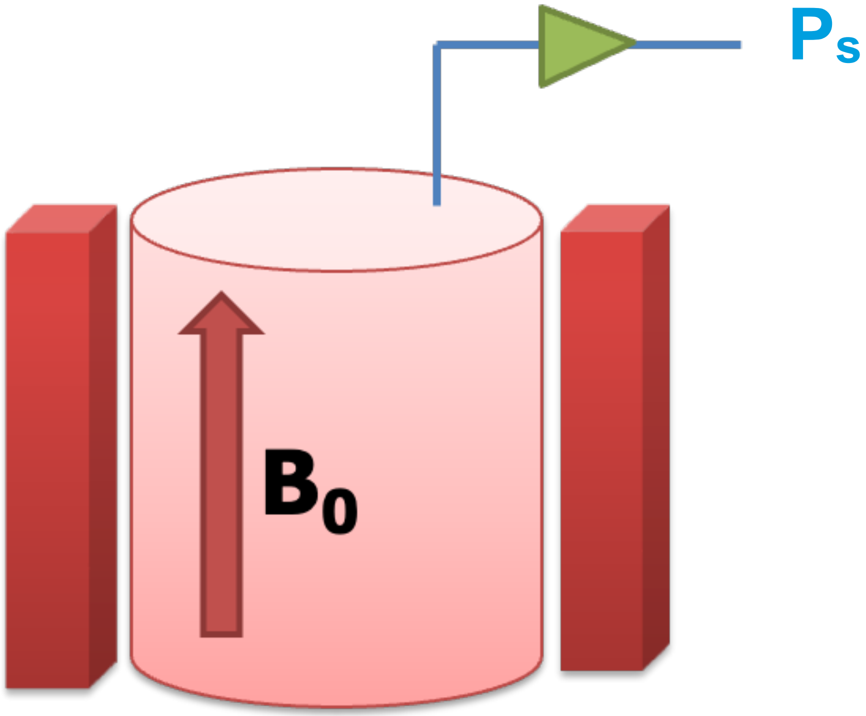


DESY. (Baby)IAXO | Uwe Schneekloth | PATRAS 2023

Haloscopes

Detecting Dark Matter Axions

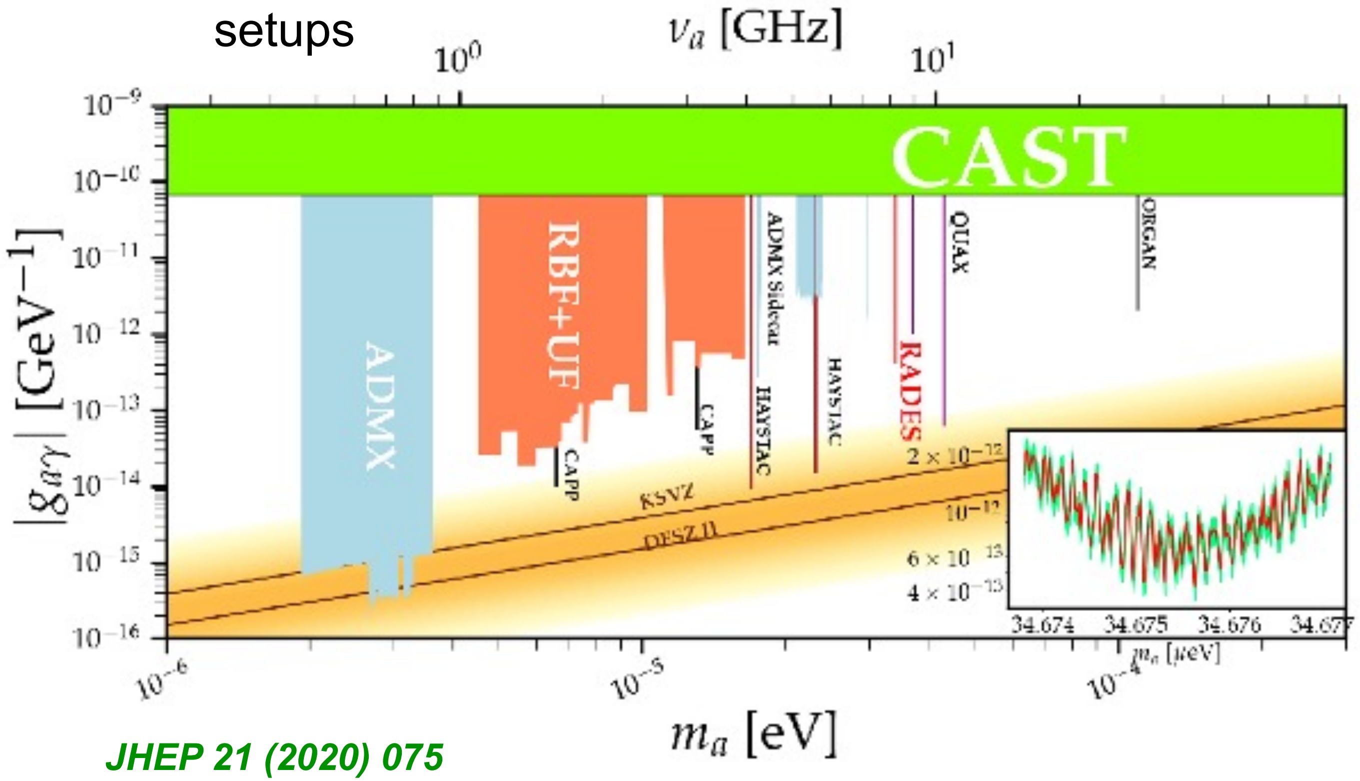
- Assumption for haloscope: DM halo is mostly made of axions
  - Axions non-relativistic: $m_a \rightarrow f_{a,\gamma}$
- Resonant “Sikivie” cavities
  - Axion-photon conversion in tunable resonant cavity
  - Typically in frequency ranges of microwaves
- If cavity is tuned to axion frequency: Boost of conversion by resonant factor
  - Excess in measured output power P_s



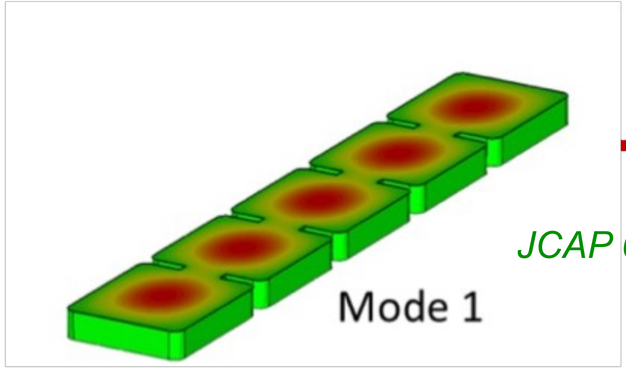
RADES

Helioscope as Haloscope Project

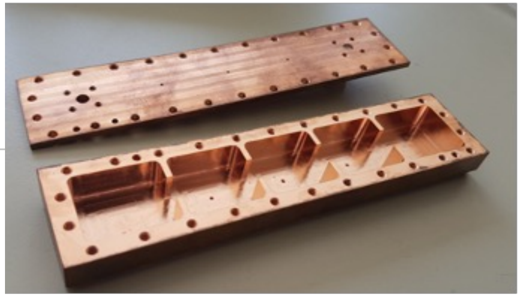
- During late years in the CAST experiment the RADES project emerged
  - Reuse the magnetic volumes of helioscope for haloscope searches by integrating resonant cavity setups



JHEP 21 (2020) 075



JCAP 05 (2018) 040



- Single frequency point measurement at 37 μeV in the CAST experiment

- Developments continued after CAST times
  - Optimizing geometries of cavities
  - Improving coating for improving boost factor, etc.

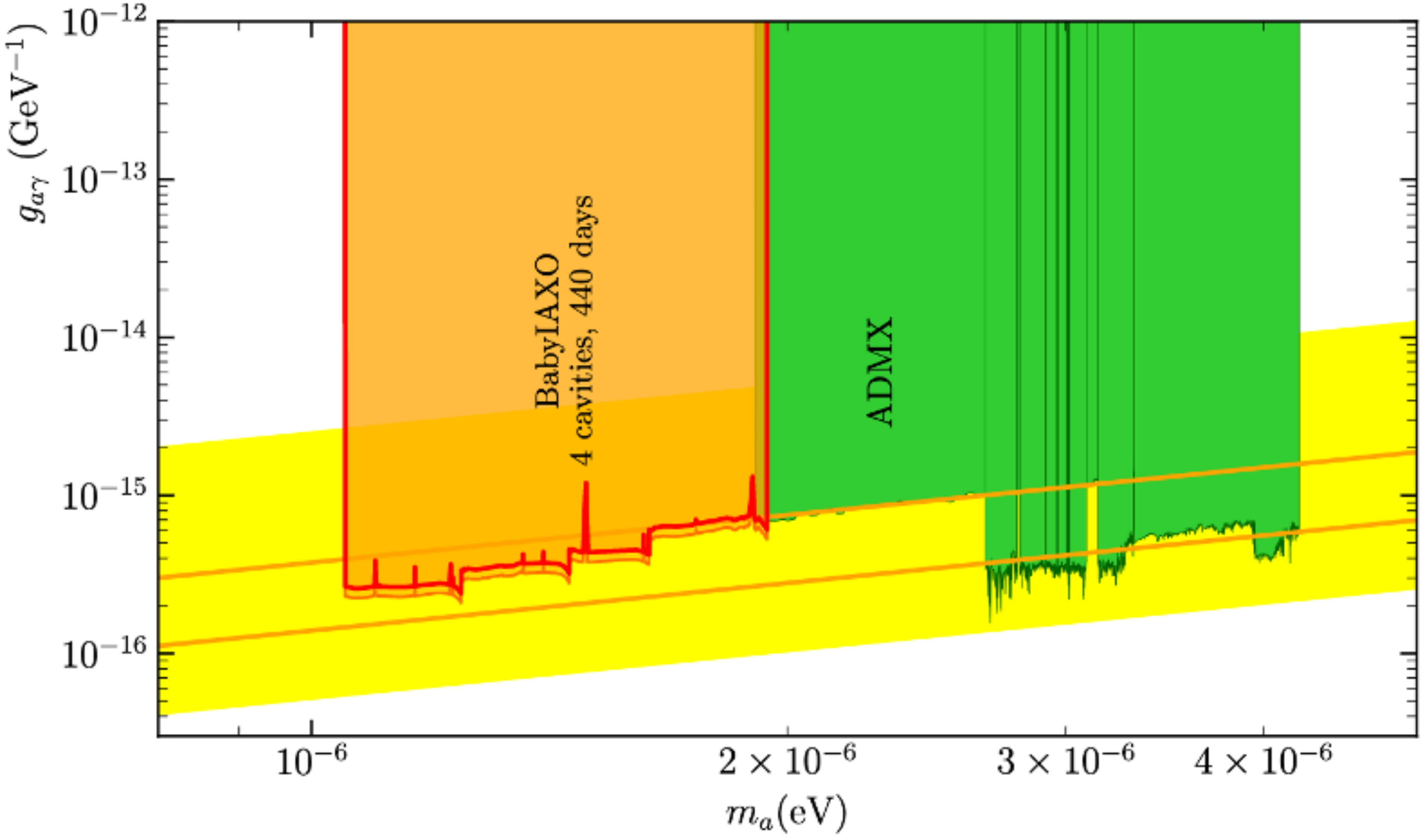
Part of ERC-StG
B. Döbrich, CERN/MPI

BabyIAXO - Preliminary Projected Sensitivities

Haloscope Mode

- Use 4 x 5m long cavities in the BabyIAXO magnetic bores
    - May enable sensitivity to 1-2 µeV DM axions close to ADMX limits
    - Within 2 years of data taking reaching the KSVZ band
- Further implementations actively being discussed by collaboration

RADES collaboration *arxiv:2306.17243*



*Haloscope bounds shown assume axion to be 100% of DM. In general, scale as $\sqrt{\rho_{DM}/\rho_a}$

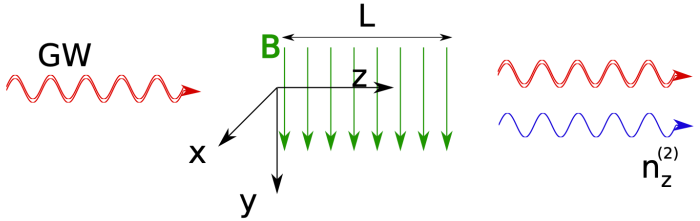
assume
general,

Gravitational Waves

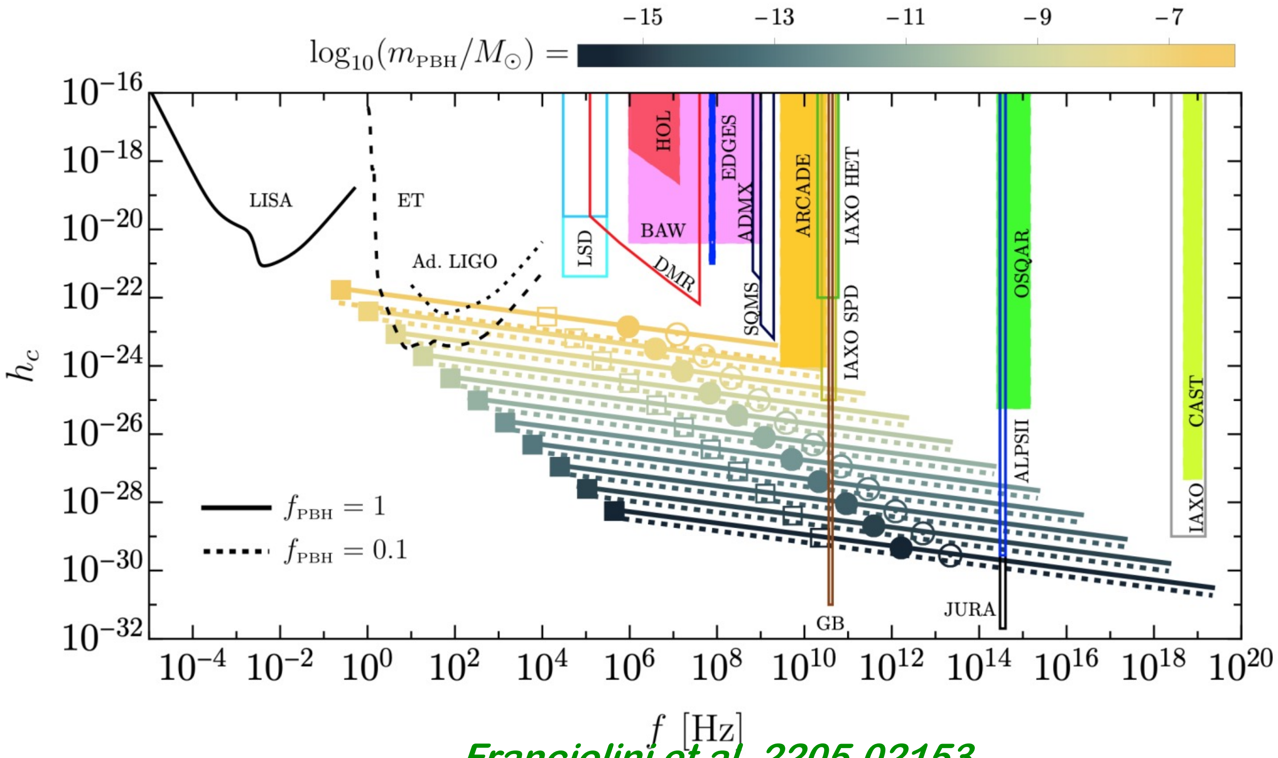
(Baby)IAXO

- 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



Characteristic strain vs. frequency spiraling merger



Franciolini et al. 2205.02153

	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 para-meters 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, GWs, other astrophysical sources, etc…
- Only remaining technical challenges in magnet construction.

Thanks to my IAXO colleagues