Recherche d'axions :
haloscopes et helioscopes

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21st March 2024

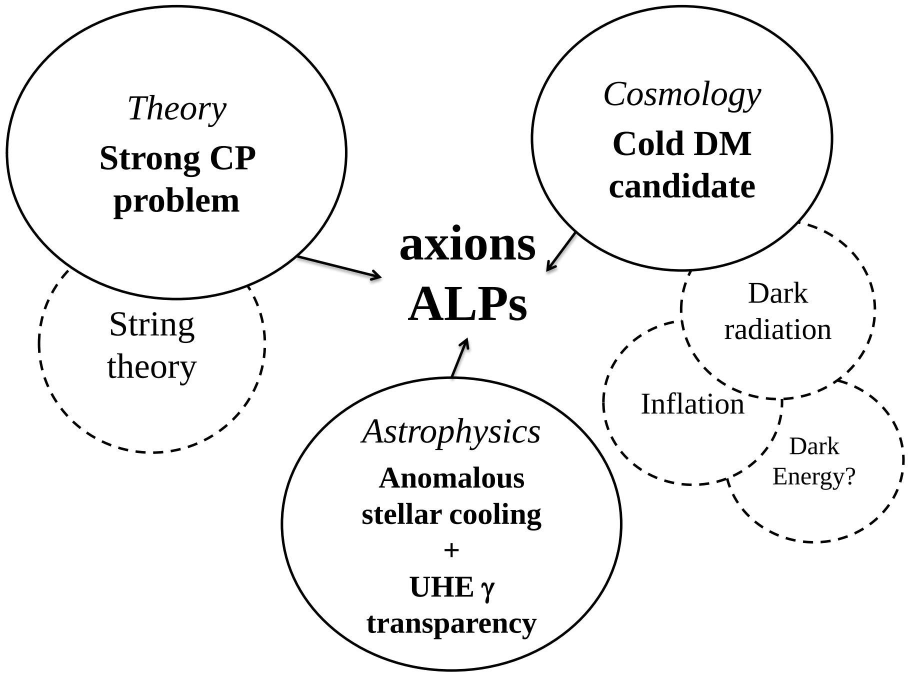
Journée thématique SFP : Lumière sur la matière noire

Axions in a nut shell

- 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 → $g_{ag} \sim$ few 10^{-11} GeV^{-1} / m_a ~few meV ?

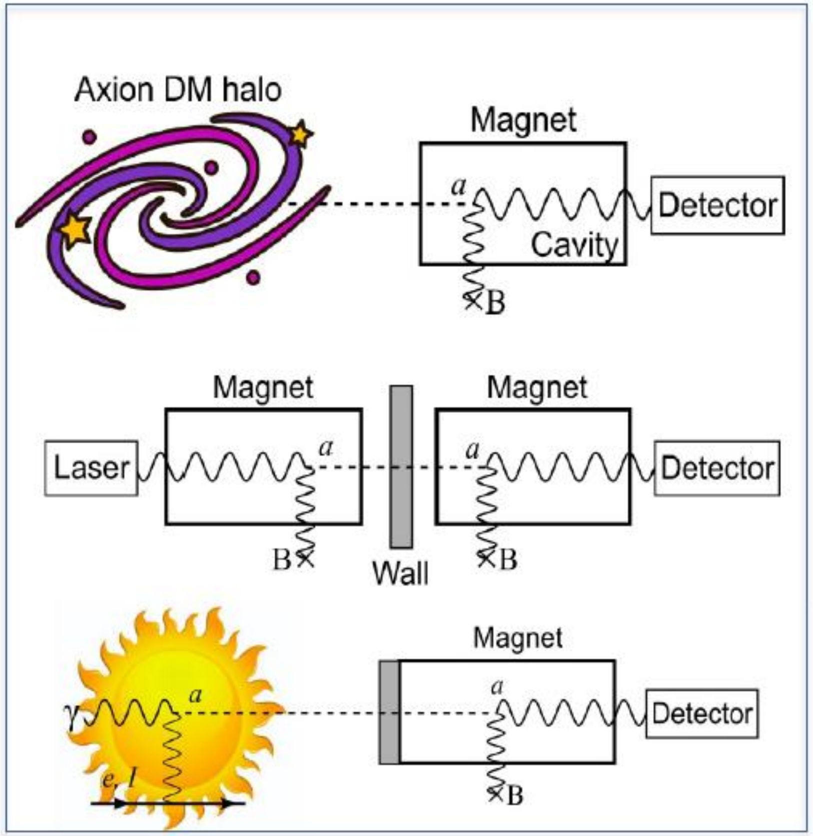
- Relevant axion/ALP parameter space at **reach of current and near-future experiments**
- Experimental efforts growing fast but still small



See talk Jérémie Quevillon

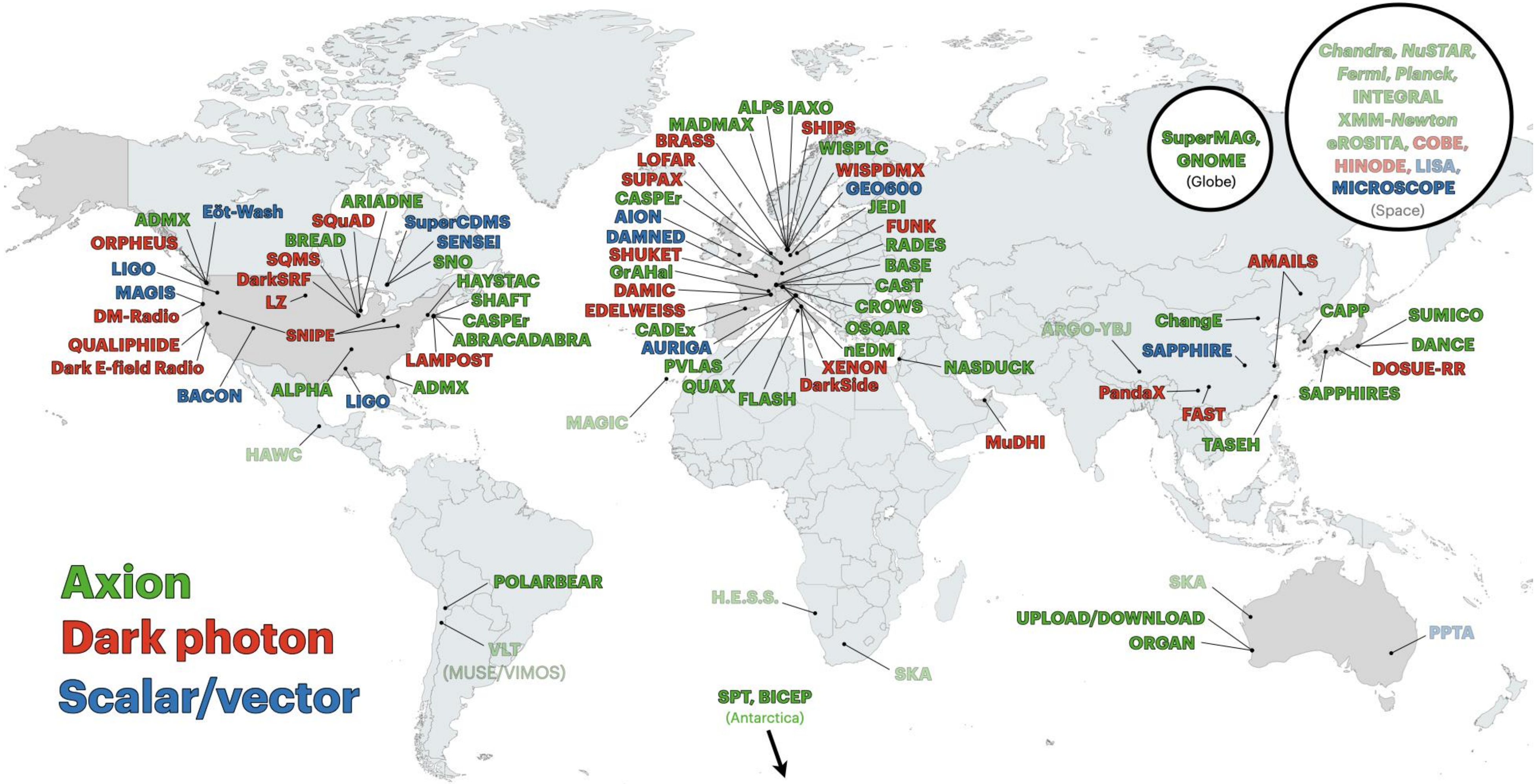
Detection of axions

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



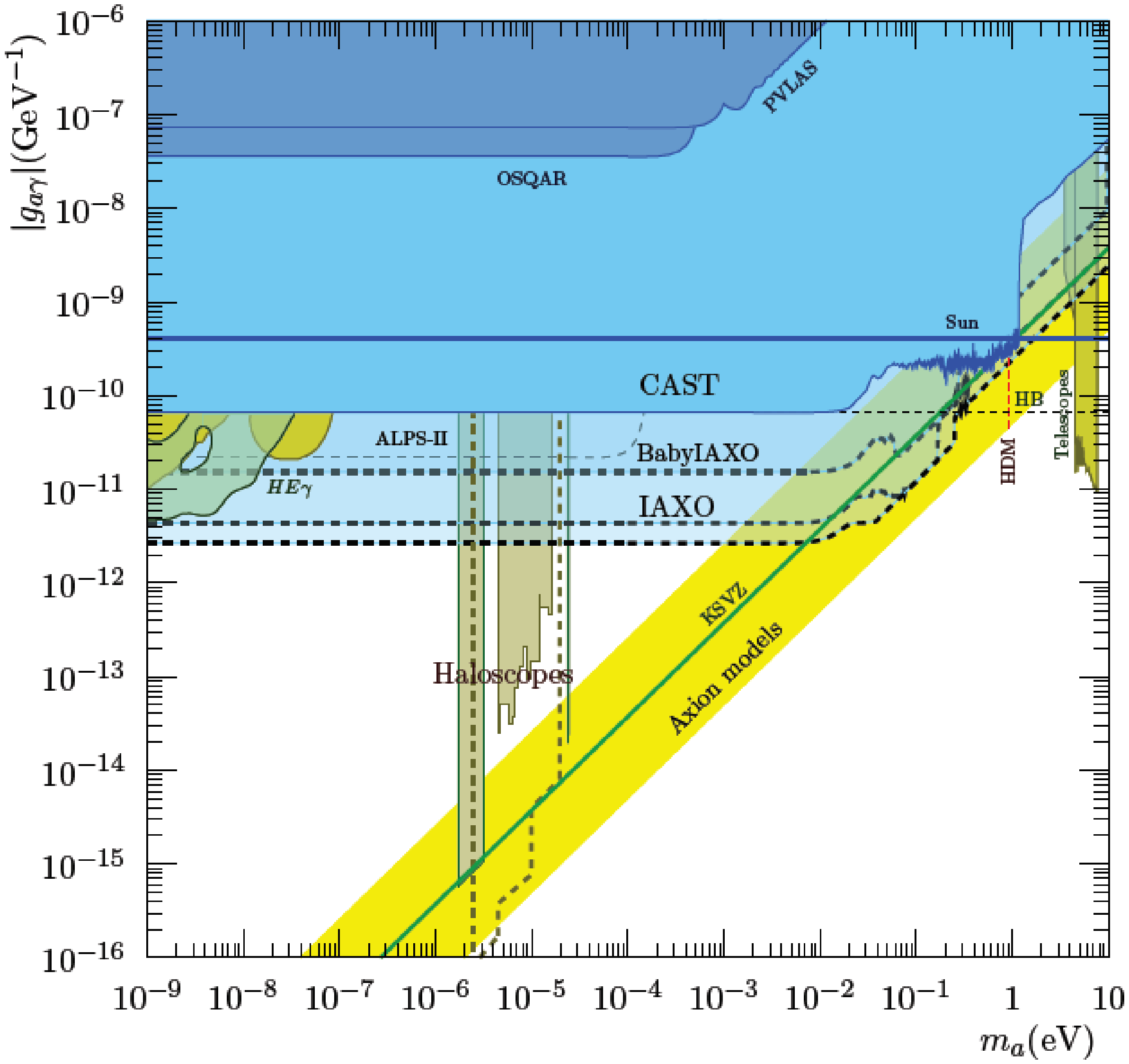
Large complementary between the different approaches

Lots of experiments



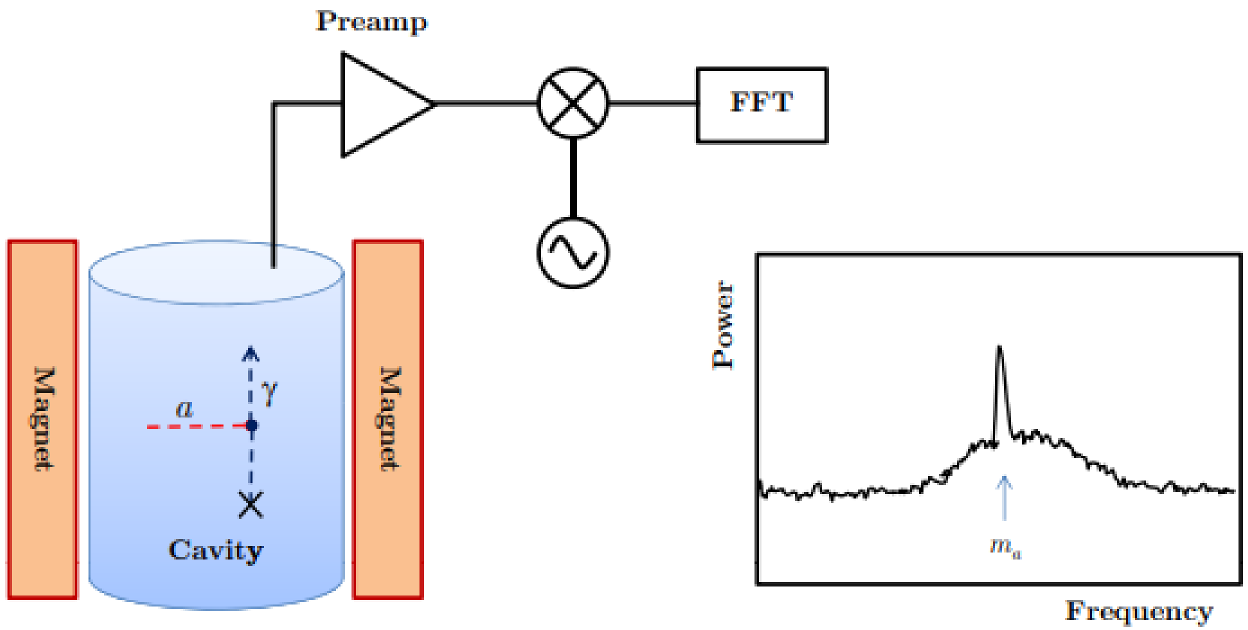
[https://github.com/cajohare/AxionLimits]

Parameter space



Armengaud et al. JCAP (2019) 06 047

Haloscopes : microwave cavities



Axion can convert into a photon in a miacrowave cavity places in a magnetic field

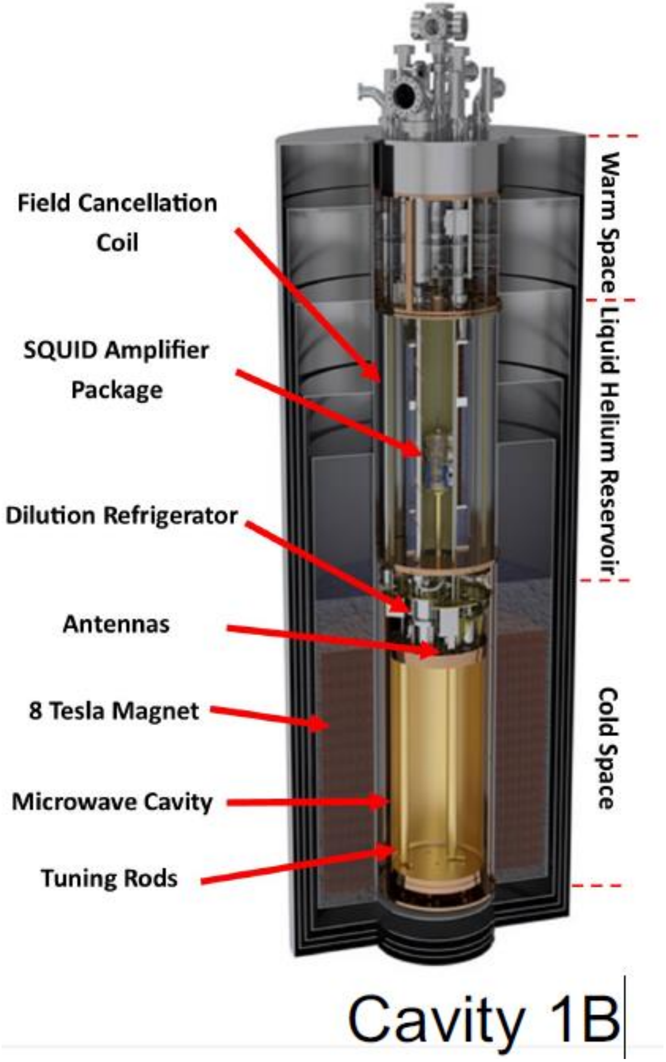
If the axion mass matches the resonance frequency of the cavity, axion will show as peak in the power spectrum

$$P_{sig} \sim (B^2 V\, Q_{cav} C_{010})\, (g_{a\gamma}^2\, m_a\, \rho_a) \sim 10^{-24}\ \mathrm{W}$$

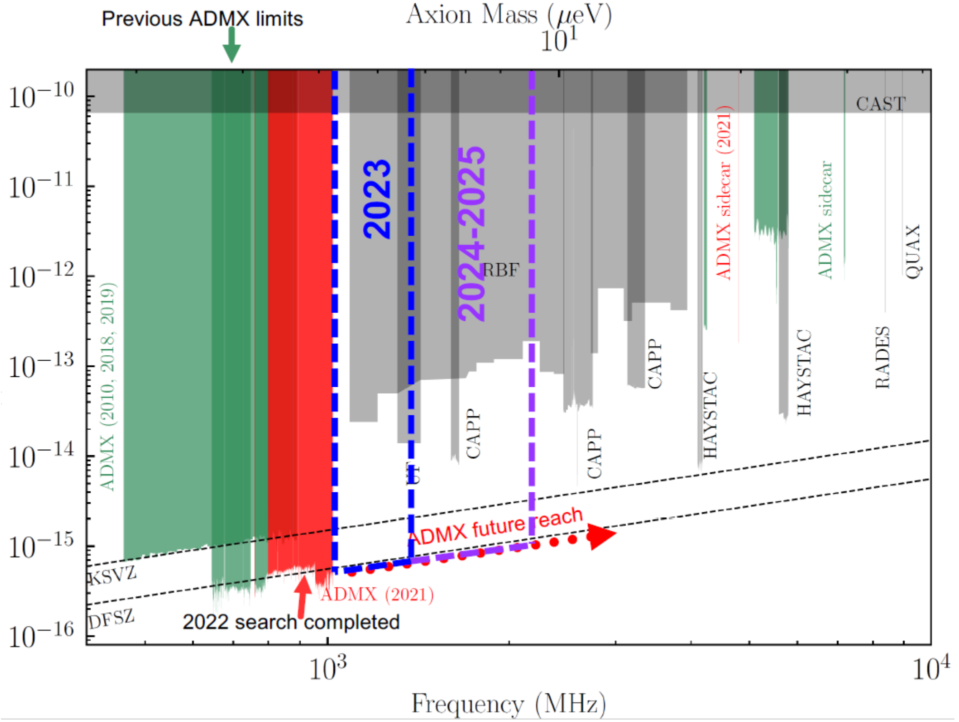
Irastorza, e-Print: 2109.07376 [hep-ph]

ADMX: Axion Dark Matter eXperiment

Since 1995



8 T Large magnet
Tunable Microwave cavity
Ultra-sensitive low-noise quantum electronics (SQUID)

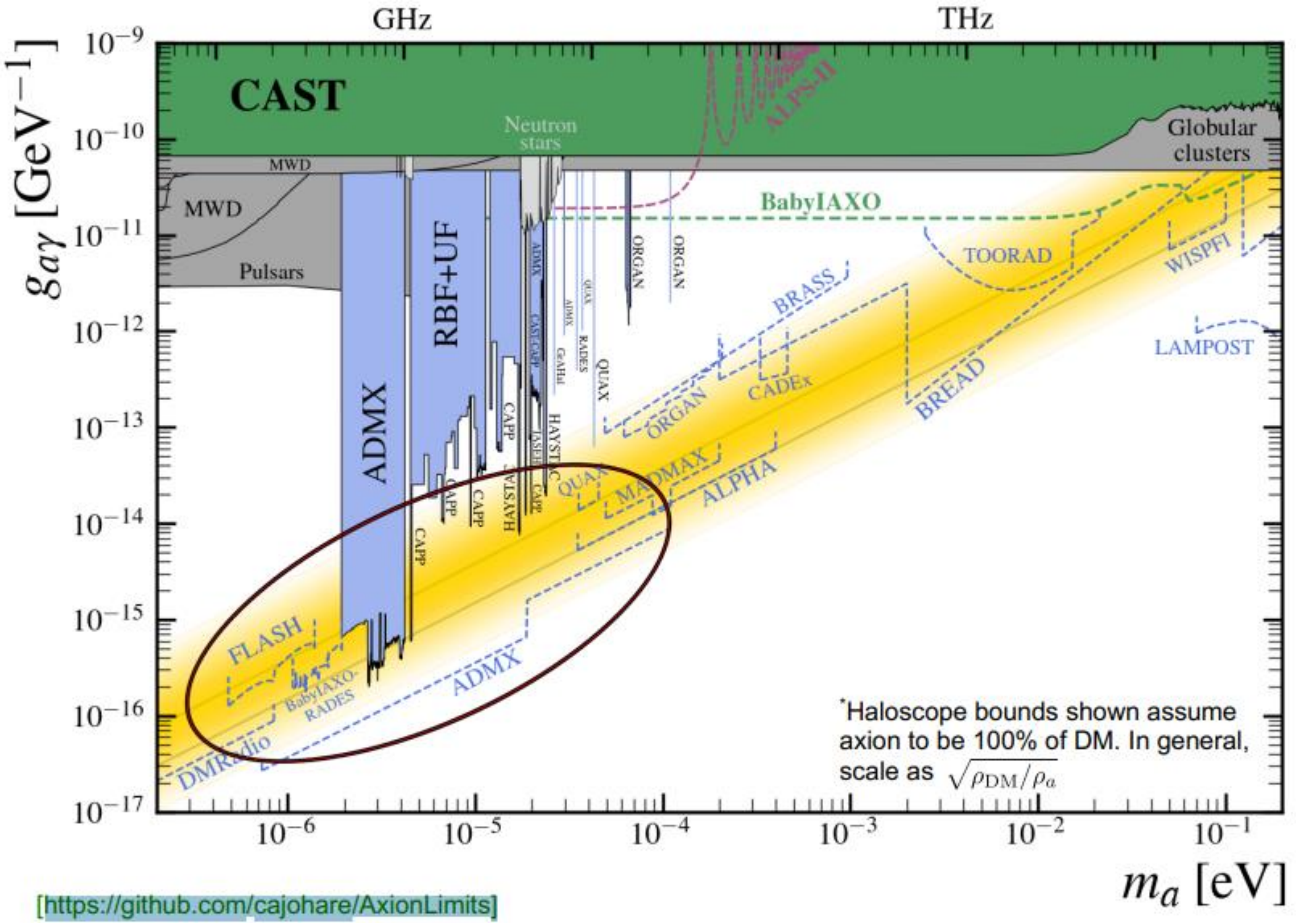


Phys. Rev. Lett. 127, 261803

Microwave cavities haloscopes

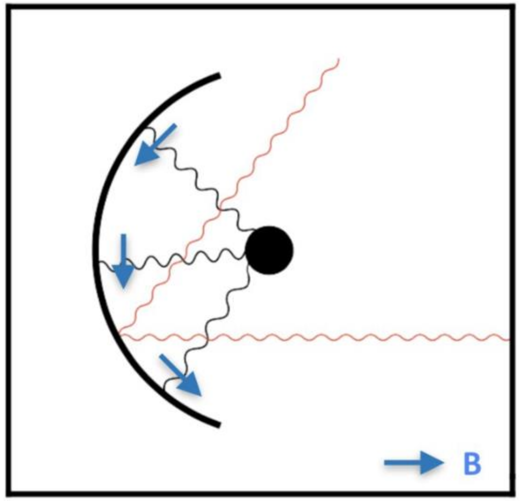
Currently running

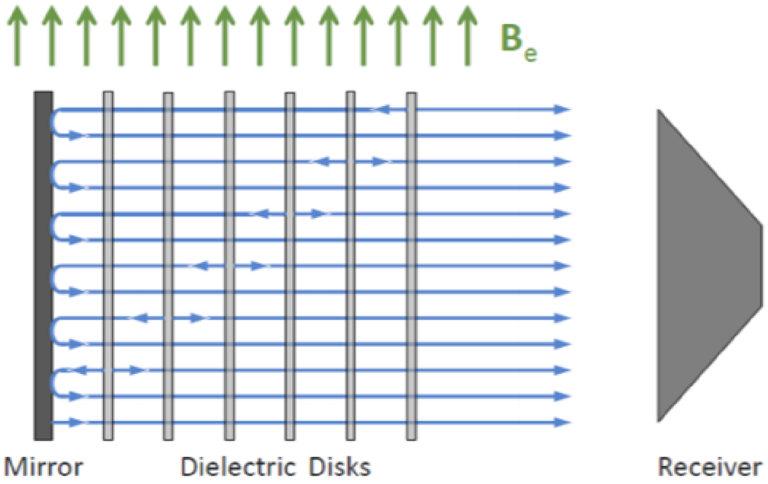
ADMX
CAPP
CAST-CAPP
GrAHal See talk Jérémie Quevillon
ORGAN
QUAX
RADES
TASEH



[https://github.com/cajohare/AxionLimits]

Haloscopes: dish antenna / dielectric





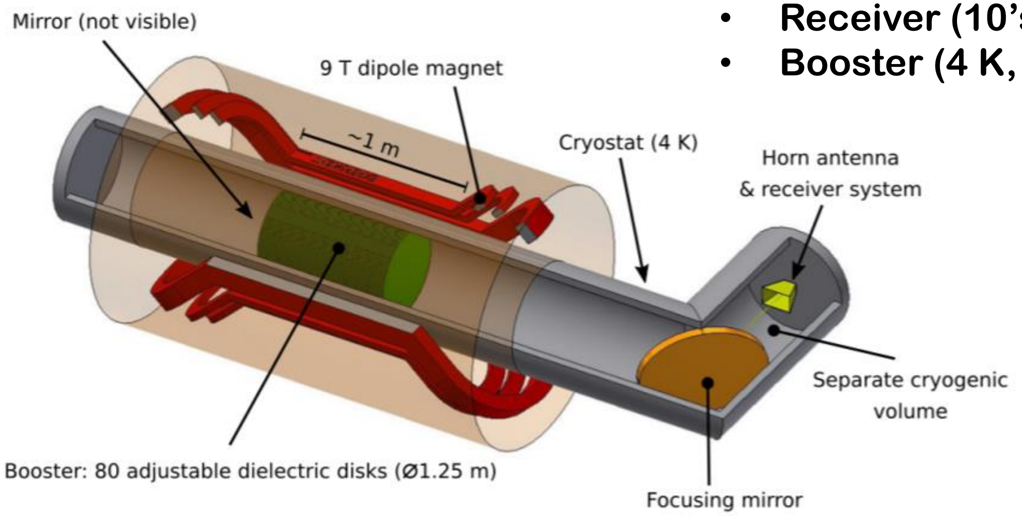
Axions in the presence of dielectric interface (mirror/dielectric slab) in a magnetic field parallel to the surface can emit EM radiation perpendicular to its surface.
Very small signal but with large surface and concentrated in a small point

Evolution➔Dielectric haloscopes ➔ increasing the number of emitting surfaces and constructive interference➔ amplifies the signal

Dielectric Haloscope: MADMAX

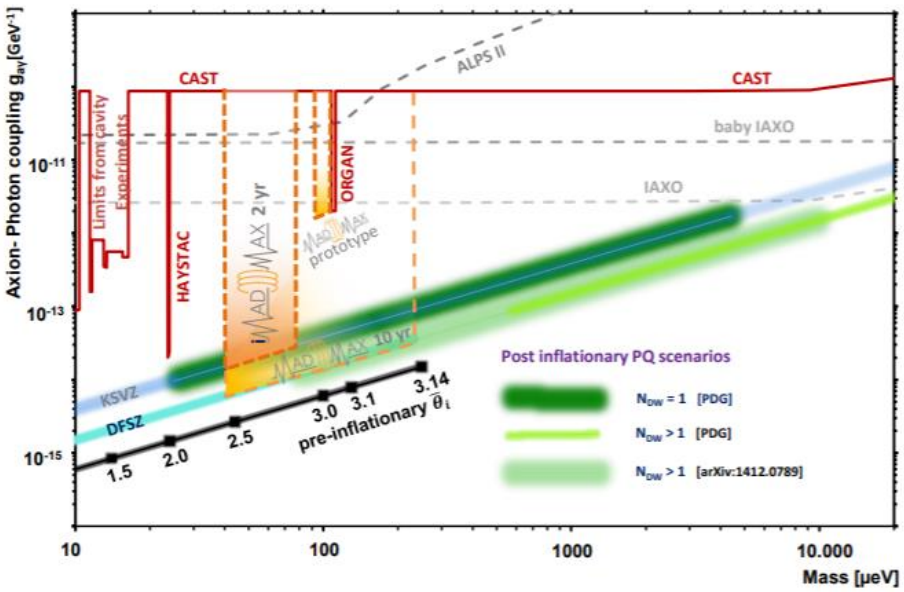
Dielectric dark matter haloscope:

- **Probe uncharted phase space around 100 μeV, favored by post-inflationary scenario**
- **Axion conversion into photons in a strong magnetic field at the interface between media of different dielectric constants.**
- **Power produced by axion-photon conversion is enhanced by constructive interferences from photon-emission from multiple dielectric disks**
- **Changing the position of the disks will allow to scan different frequency range (axion mass)**



3 main challenges :

- High field dipole magnet
- Receiver (10's GHz, 4 K)
- Booster (4 K, B field)



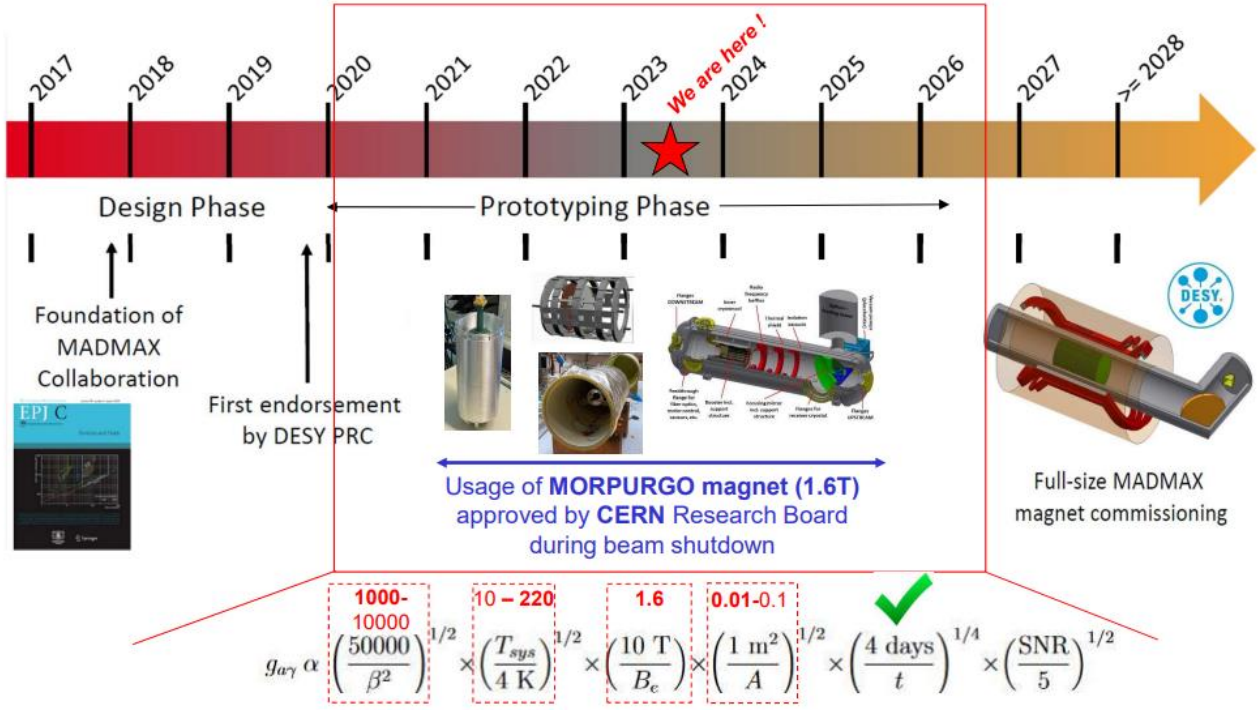
MADMAX

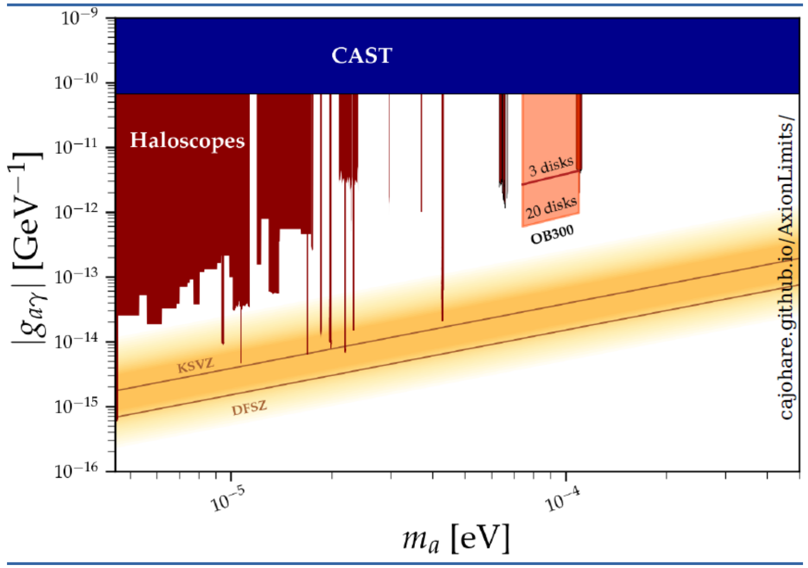
Prototype phase to validate the new dielectric haloscope concept
Morpurgo magnet @ CERN (1.6 T)

CPPM, Institut Néel, IJCLAB, IRFU/CEA

CNRS HELMHOLTZ DARK MATTER LAB

- **Precision mechanics**
- **Tests coordination @ CERN**
- **Analysis and simulation**

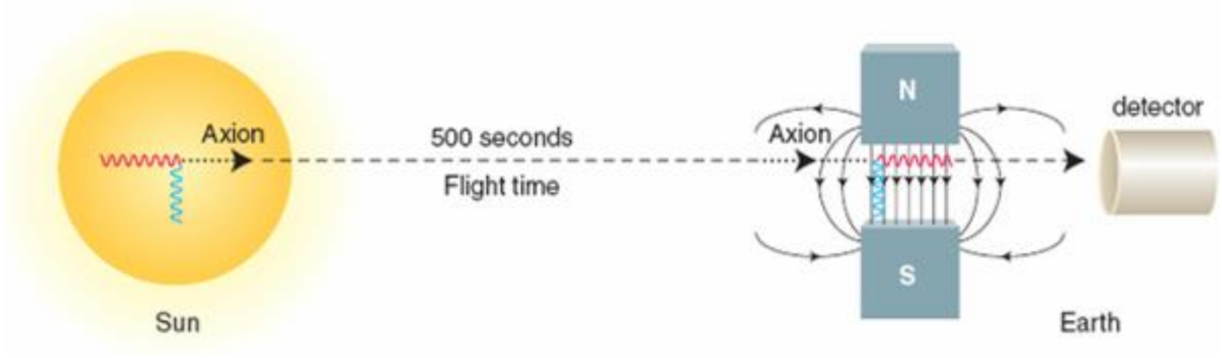


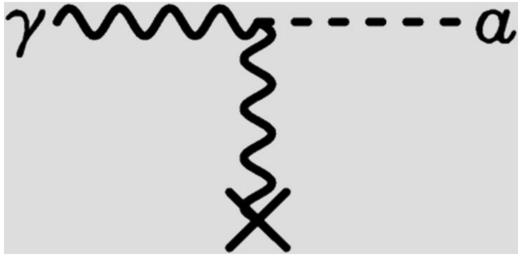


From presentations of P. Pralavorio @ Axions ++ 2023 (Annecy) and J. Egge @ Axions Fest (Hamburg)

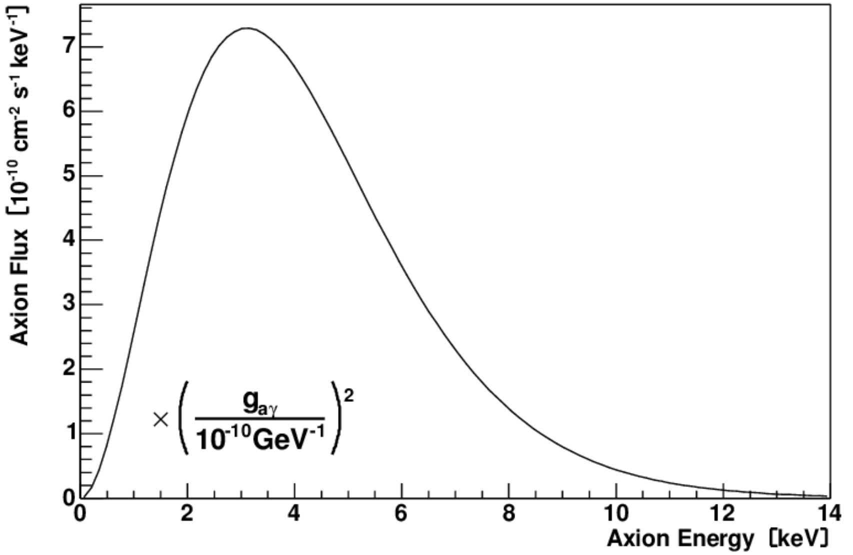
SOLAR AXIONS

Photons (keV) in solar core can be converted into axions in the presence of a strong electromagnetic field via the **Primakoff Effect**





$$\frac{d\Phi_a}{dE} = 6.02\times10^{10}\left(\frac{g_{a\gamma}}{10^{-10}\mathrm{GeV}^{-1}}\right)^2 E^{2.481} e^{-E/1.205}\,\frac{1}{\mathrm{cm}^2\ \mathrm{s\ keV}}$$



Van Bibber et al. Phys. Rev D39:2089 (1989)
CAST JCAO 04 (2007)010

SOLAR HELIOSCOPES

1st generation: Brookhaven (a few hours of data):
1.8 m, 2.2 T

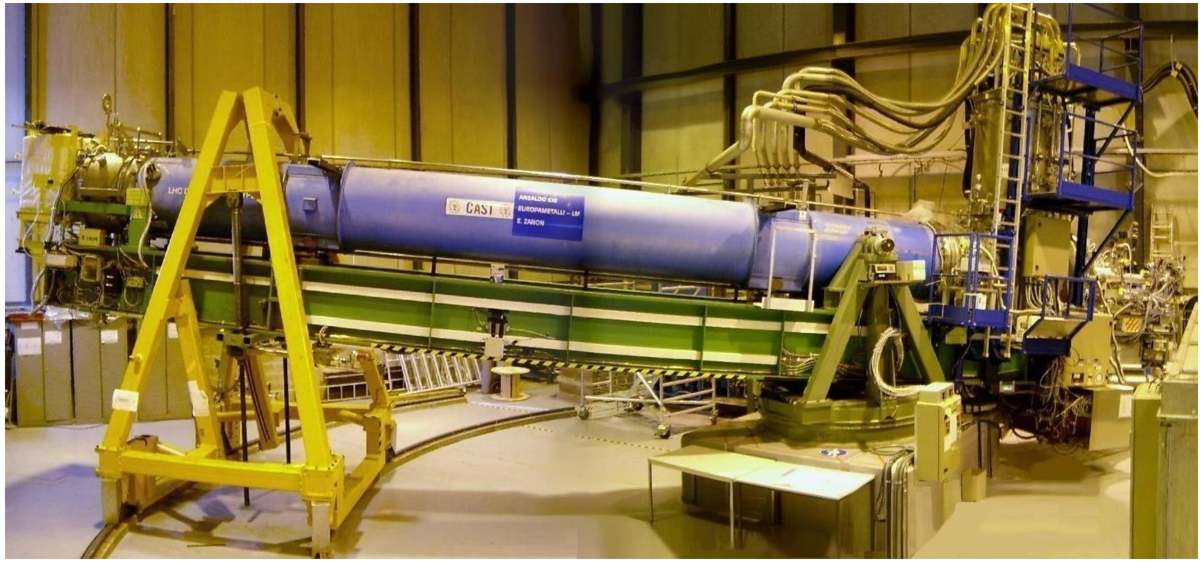
Lazarus et al. PRL 69 (92)

2nd Generation: Tokyo Helioscope (SUMICO):
2.3 m long 4 T

Inoue et al. Phys.Lett.B668:93-97,2008.

3rd Generation: CAST (CERN Axion Solar Telescope):
10 m long, 9 T 2002-2022

Nature Phys. 13 (2017) 584-590
JHEP 2021 75, (2021)
Nature Commun. 13 (2022) 1, 6180



CAST

Decommissioned LHC dipole magent (L= 10 m, 9 T)

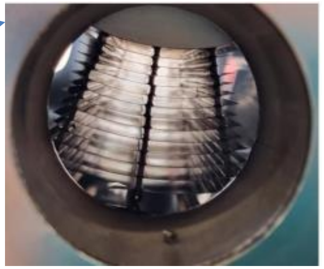
X-ray focussing and using low background techniques for detection: active and passive shieldings, low background materials, discrimination techniques

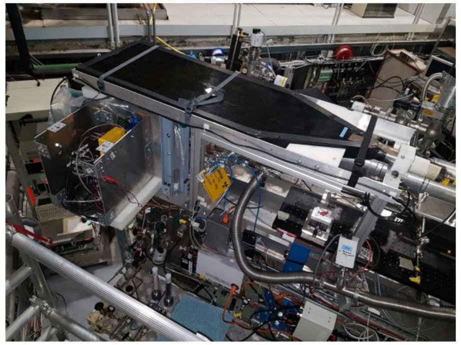
Solar tracking possible suring sunrise and sunset (2x 1.5 h per day)

Phases
- Phase I, vacuum: 2003-2004
- Phase II, buffer gas: 2006-12
- Improved vacuum run I: 2013-15
- Improved vacuum run II: 2019-21 (with improved detectors performances, Neon)

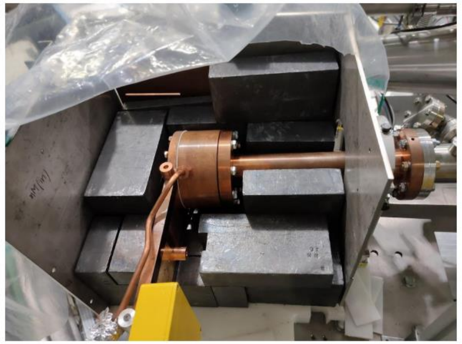
Cavities RADES + CAPP

X-rays optics



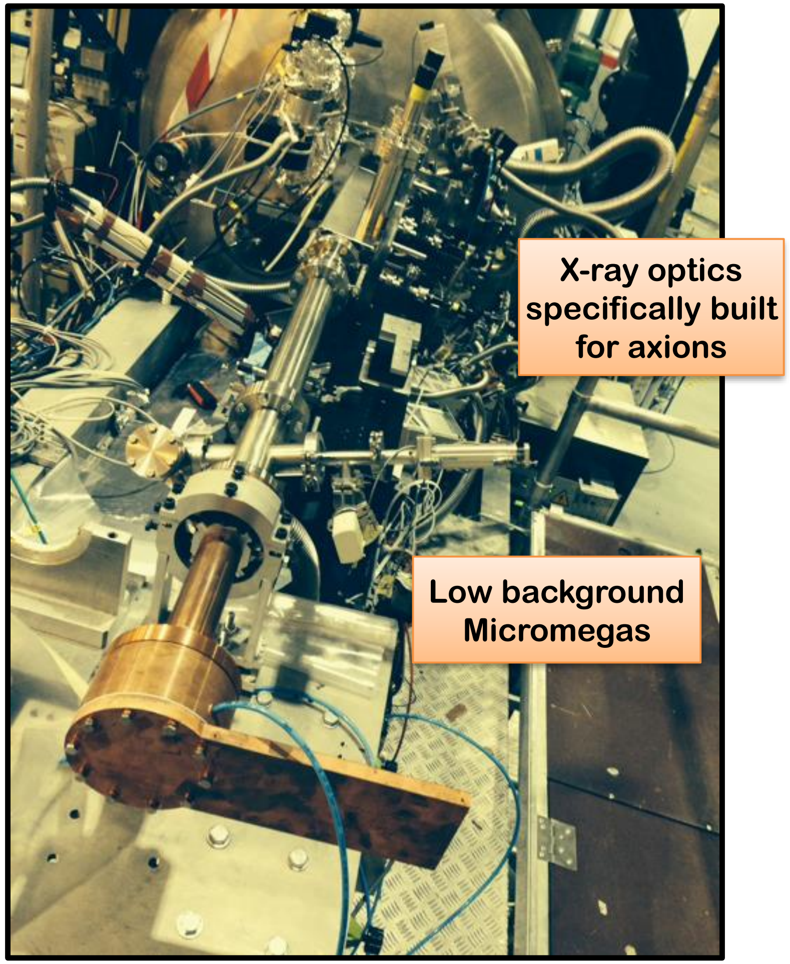


Muon veto



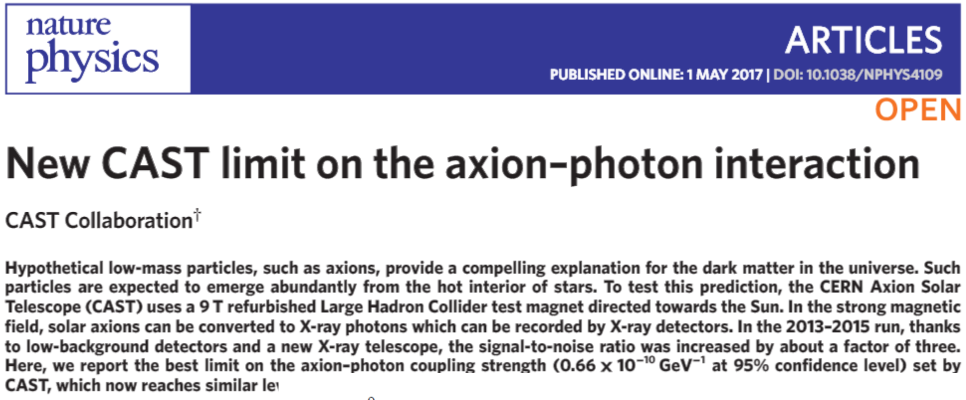
Passive shielding

CAST



Data taking 2013-2015 at CAST:

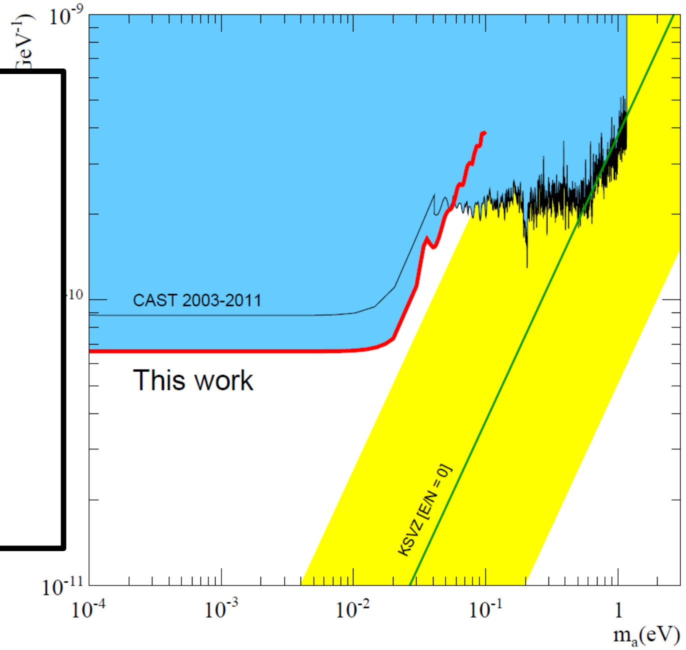
x-ray focusing + low background Micromegas detector
Small-scale version of IAXO baseline detection lines


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

New CAST limit on the axion-photon interaction

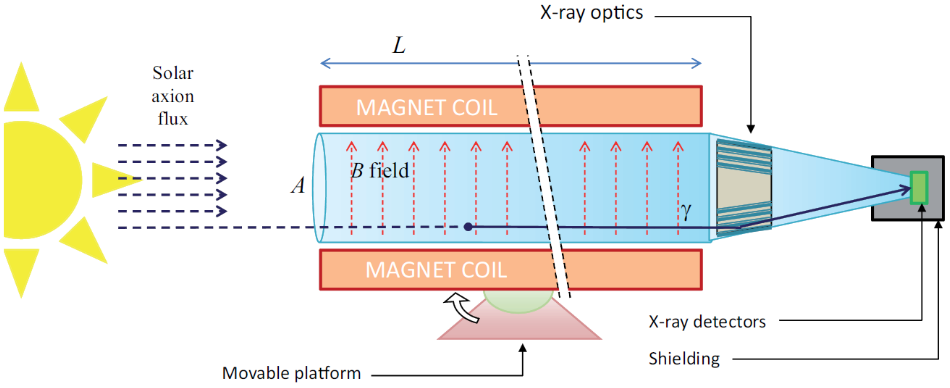
CAST Collaboration†

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 Telescope (CAST) uses a 9 T refurbished Large Hadron Collider test magnet directed towards the Sun. In the strong magnetic field, solar axions can be converted to X-ray photons which can be recorded by X-ray detectors. In the 2013–2015 run, thanks to low-background detectors and a new X-ray telescope, the signal-to-noise ratio was increased by about a factor of three. Here, we report the best limit on the axion-photon coupling strength (0.66 x 10^{-10} GeV^{-1} at 95% confidence level) set by CAST, which now reaches similar le



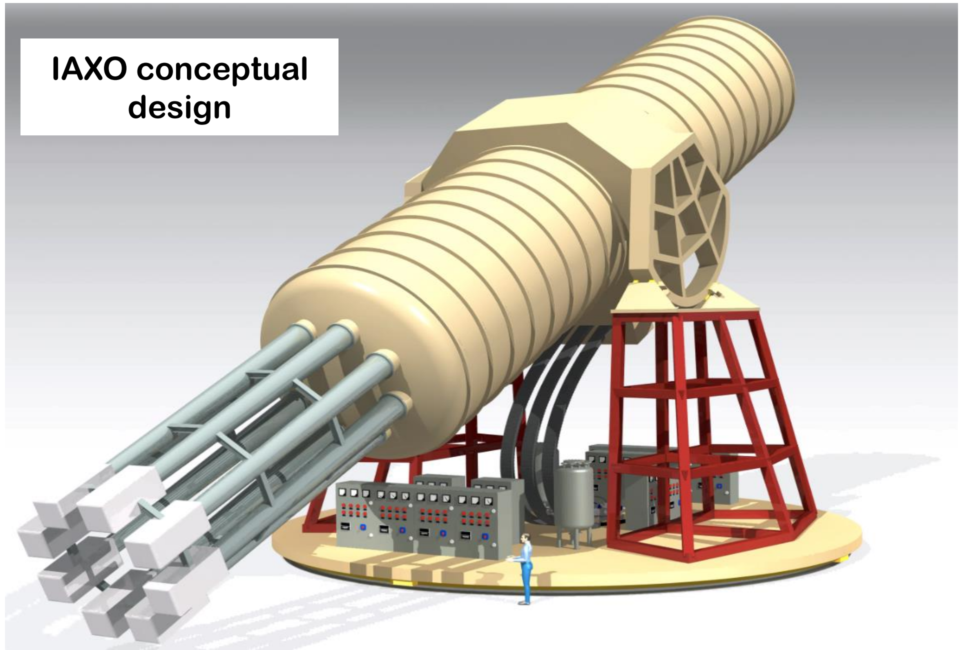
$$g_{a\gamma} < 0.66 \times 10^{-10}\, \mathrm{GeV}^{-1} \text{at 95\% CL}$$

International Axion Observatory



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

- **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**



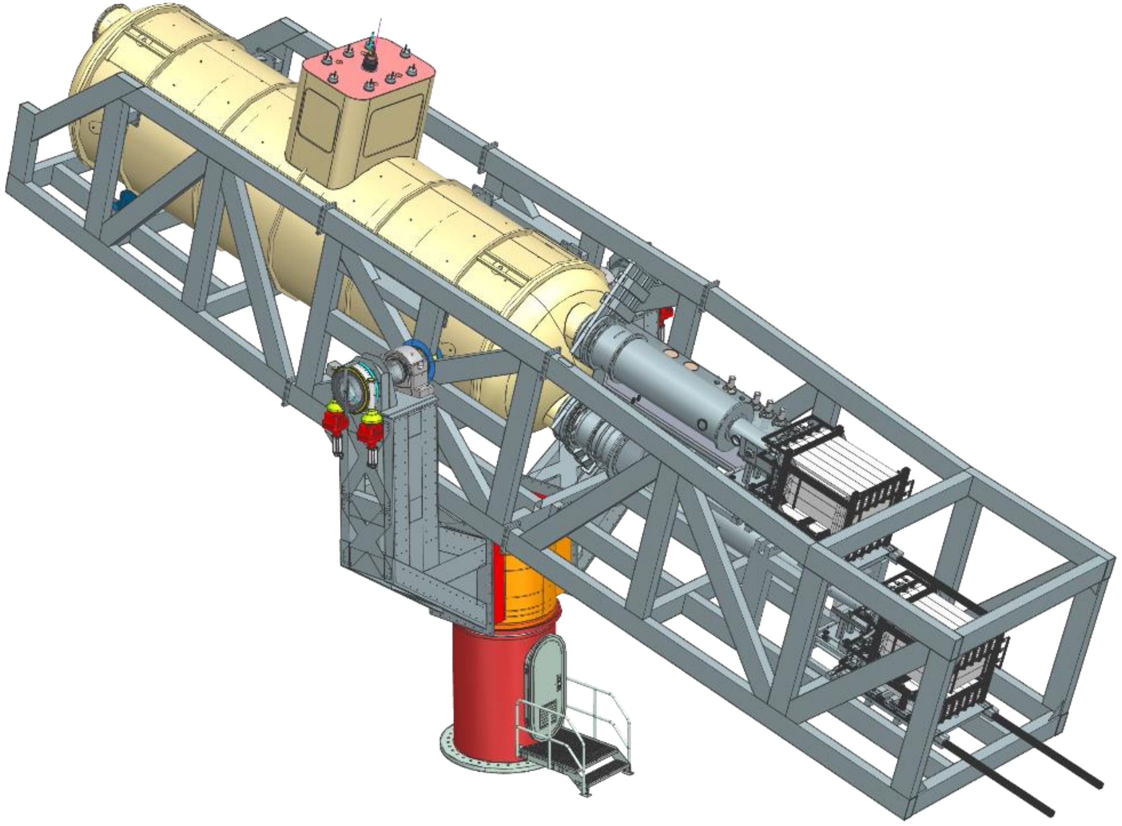
$>10^4$ better SNR than CAST

Sensitive to g_{ag} ~ x20 lower than CAST

Armengaud et al, 2014 JINST 9 T05002

BabyIAXO

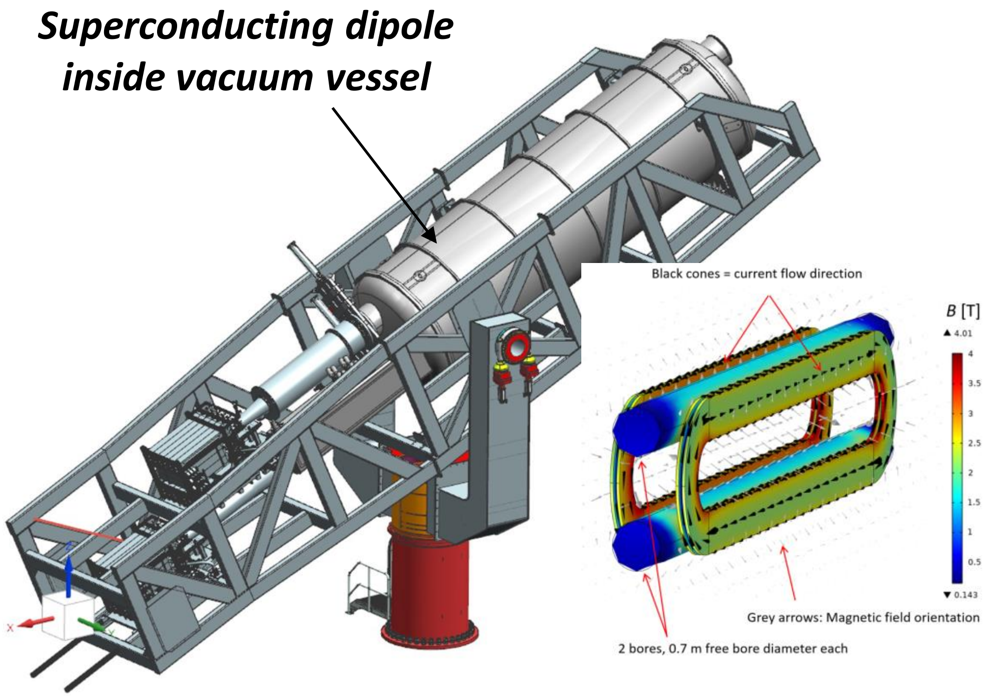
- **Prototype:** Intermediate experimental stage before IAXO
  - Two bores of dimensions similar to final IAXO bores → detection lines representative of final ones.
  - Magnet will test design options of final IAXO magnet
  - Test & improve all systems. Risk mitigation for full IAXO
- **Physics:** will also produce relevant physics outcome
  (~100 times larger FOM than CAST)

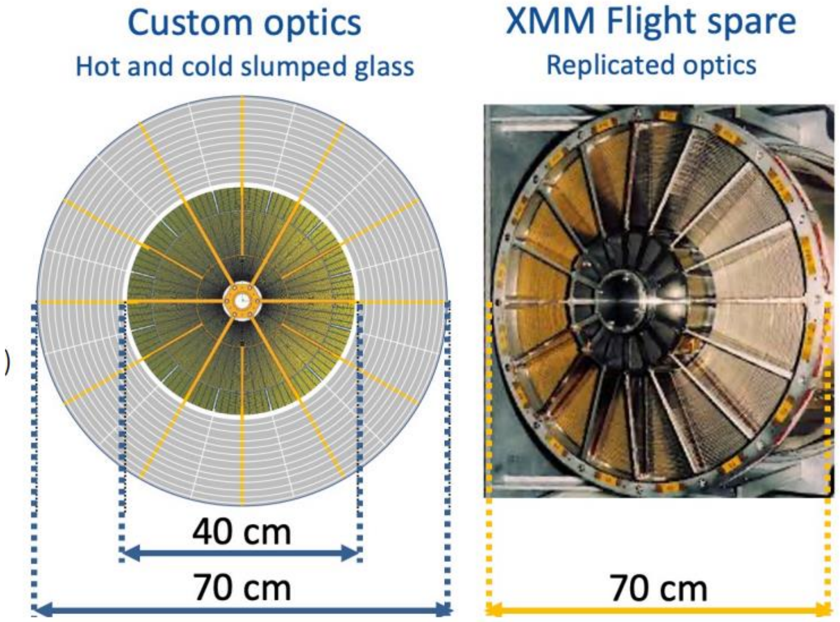


>100 x CAST SNR

Abeln et al. JEHP 05 (2021) 137

BabyIAXO magnet /optics

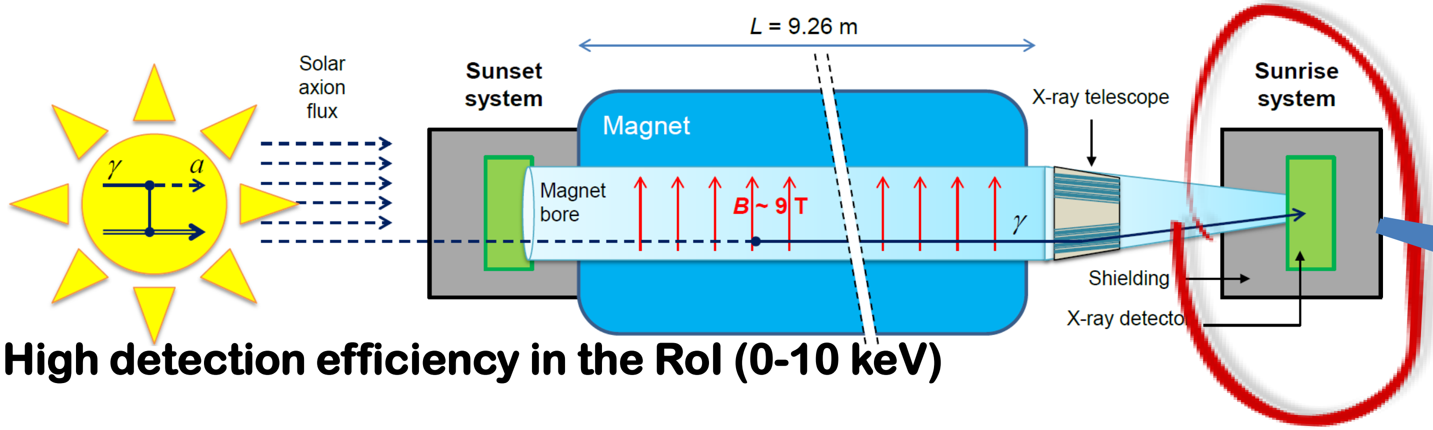


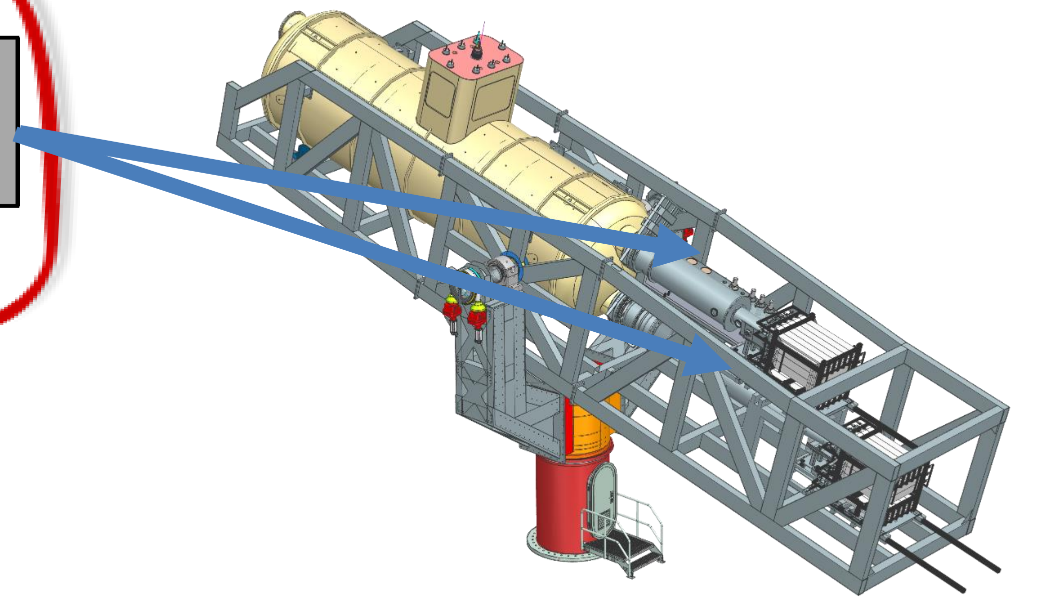


- ~2 T of transverse magnetic field over a free bore volume of about 8 m^3, i.e. the combined free bore volume of 120 LHC dipoles
- "Standard" Aluminum-stabilized Nb-Ti/Cu conductor: Nb-Ti/Cu Rutherford cable cladded with high-purity aluminum.
- Magnet CDR: 22nd and 23rd of April @ DESY

- Maximised throughput efficiency
- Minimised focal spot area (0.2 cm2/r<2.5 mm)
- Custom optics
  - Core: NUSTAR XRT for BIAXO (Columbia University/DTU/LLNL/Unizar
  - Corona: cold-slumped Willow-glass technology (INAF/DTU)
- XMM flight spare: loan from ESA, calibrated at PANTHER

BabyIAXO detectors





High detection efficiency in the RoI (0-10 keV)

Very low background < 10 keV: 10^{-7} c/keV/cm^2/s :
less than 1 event per 6 months of data taking!

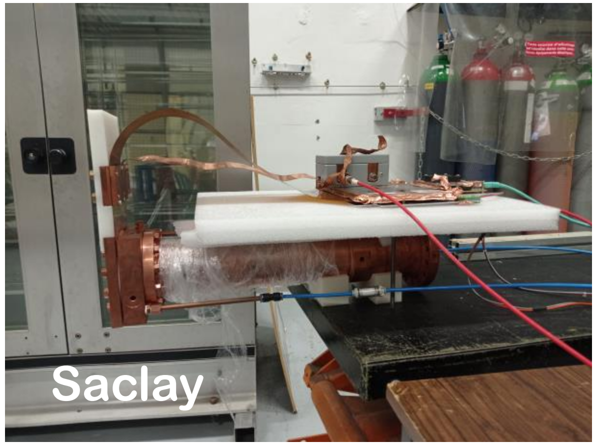
- ➔ use of shielding
- ➔ radiopurity
- ➔ advanced event discrimination strategies

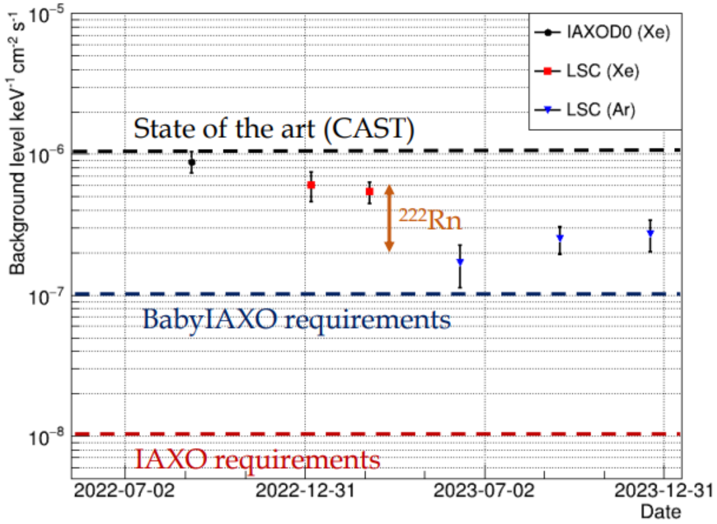
anr® ANR-19-CE31 0024

Baseline detector technology: Time Projection Chambers (TPC) based on the **Micromegas technology** after the experience of the CAST experiment.

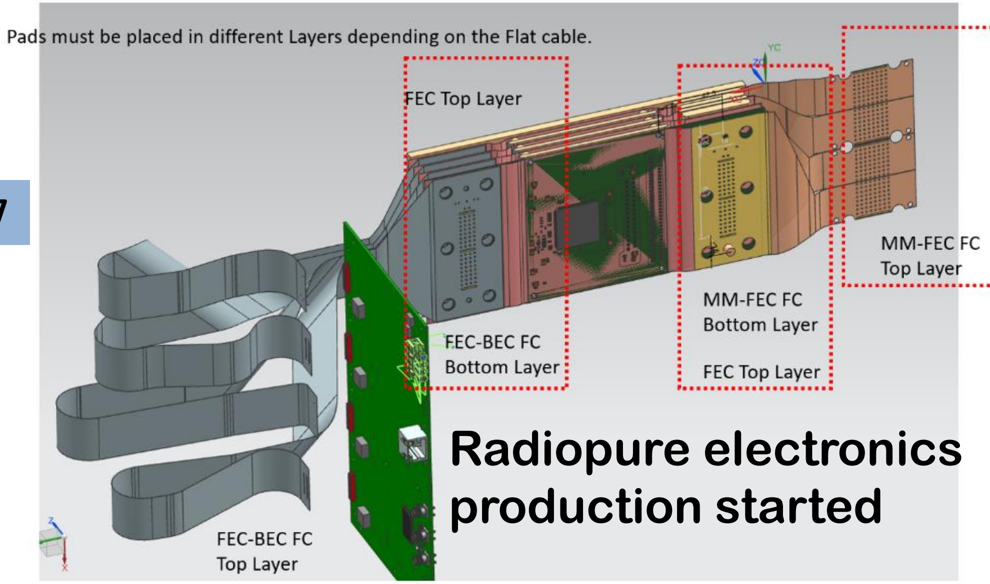
Alternative technologies under study: Gridpix, Metallic Magnetic Calorimeters (MMC), Transition Edge Sensors (TES) and Silicon Drift Detectors (SDD)

BabyIAXO Micromegas





K. Altenmüller et al. 2403.06316 [physics.ins-det]



Radiopure electronics production started

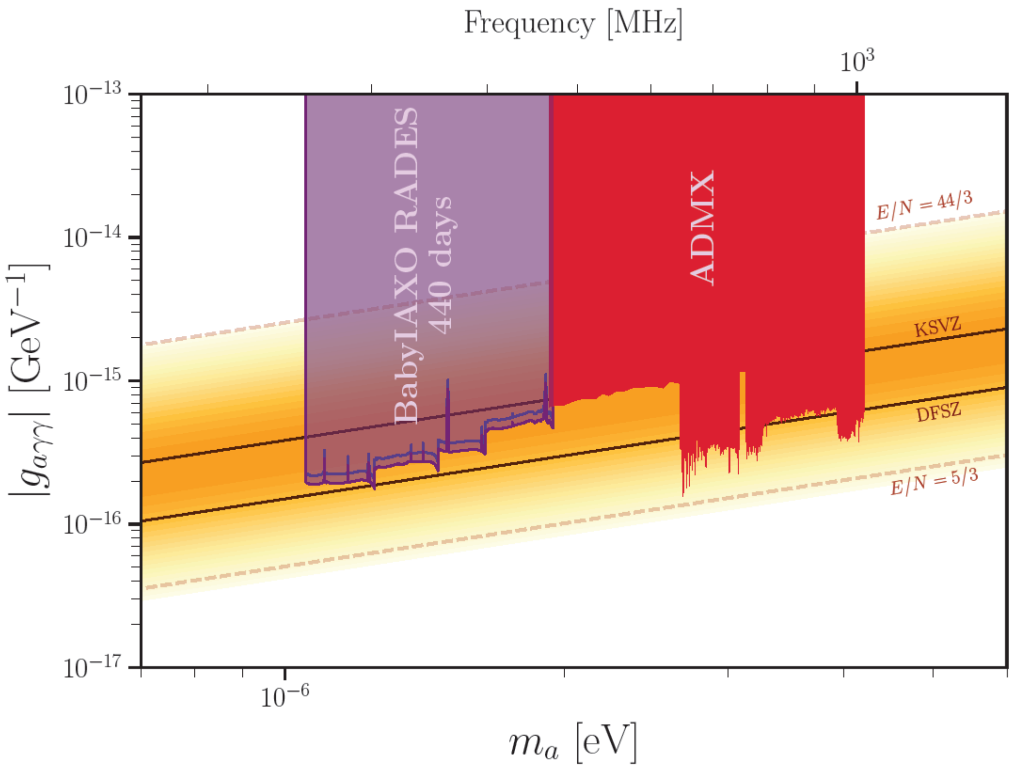
Best background levels from MM so far:

IAXO-D0 (Xe, surface, neutron shield): 9×10^{-7} c keV^{-1} cm^{-2} s^{-1}

IAXO-D1 (Ar, underground LSC): 1.7×10^{-7} c keV^{-1} cm^{-2} s^{-1}

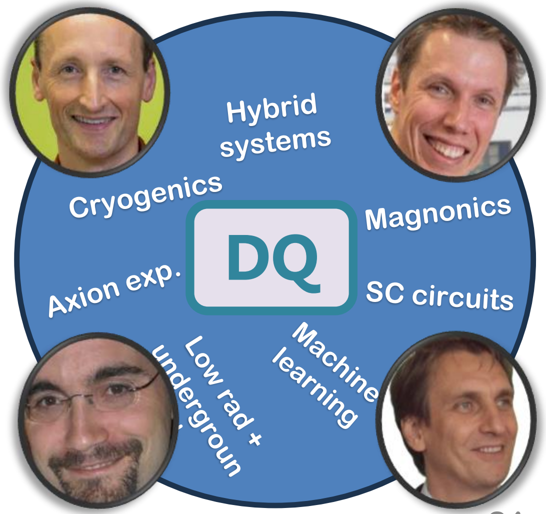
Cavities for BabyIAXO

R&D on cavities have started at CAST ➔ working for 5 m cavitiy for BabyIAXO



[ANNALEN DER PHYSIK 2023, 535, 2300326.]

I.G. Irastorza (Unizar) T. Kontos (ENS-Paris)
S. Paraoanu (Aalto U.) Wernsdorfer (KIT)



DarkQuantum: develop quantum technology for axion searches

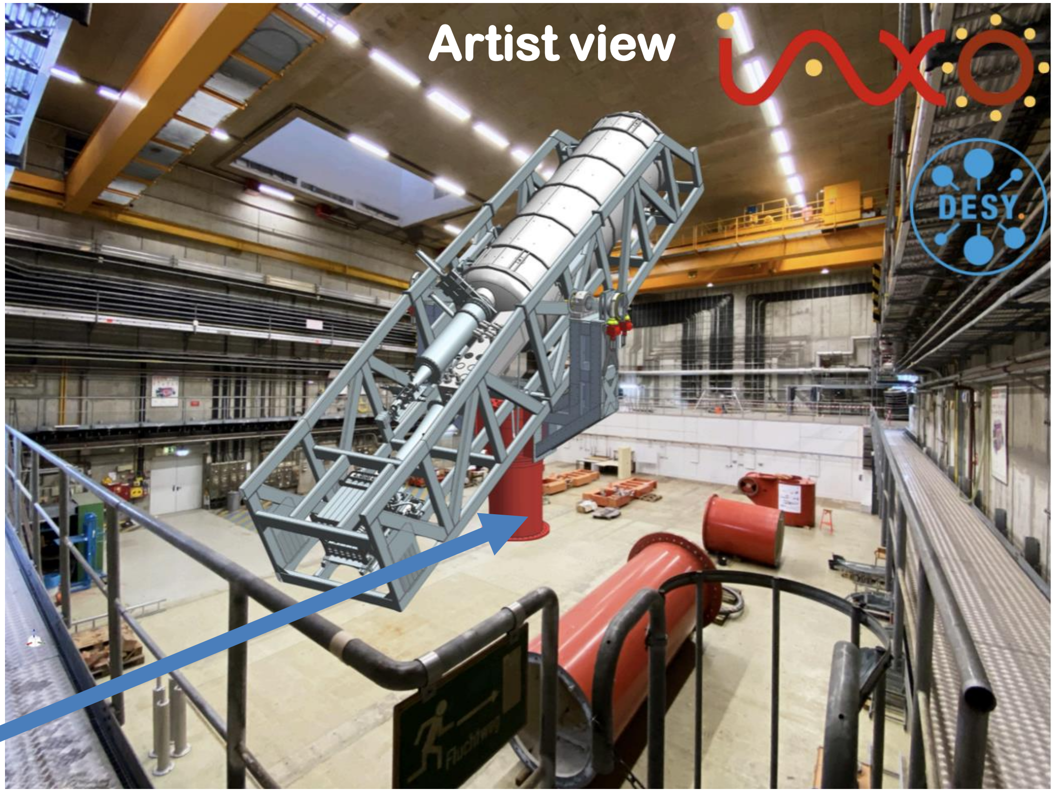
- Built on RADES plans for BabyIAXO
- Quantum-enhanced readout
- Ultra-cryogenics (few 10s mK)
- Connection with experts (cryo, quantum,…)

BabyIAXO @ DESY

DESY HERA South Hall

CTA Medium Sized Telescope (MST) suporty and drive system will be reused

Preparing background measurements with different detector prototypes before the end of the year



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CONCLUSIONS

- Large experimental efforts in a wide variety of experiments all over the world

- Very lively community
  - Axions ++ 2023 @ Annecy 25-28 September 2023
  - Axions fest @ DESY 29-31 January 2024

- In ten years, a large fraction of the unexplored parameter space will have been scanned, the axion might just be around the corner

BACK UP

BabyIAXO: beyond solar axions

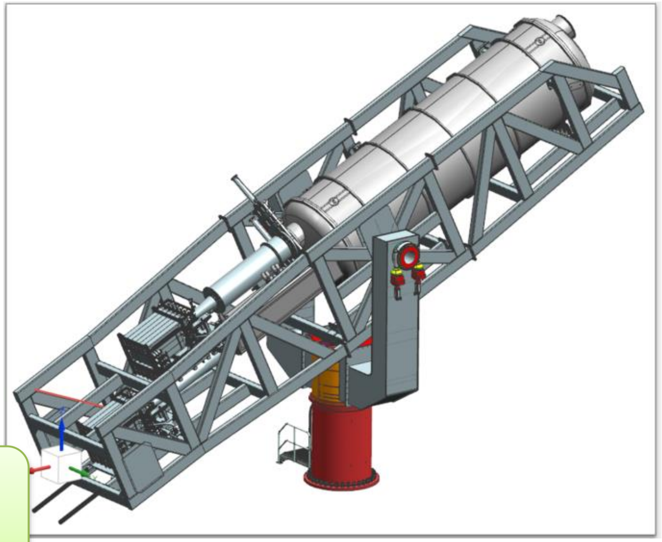
BabyIAXO as a generic axion(-like) facility

- BabyIAXO constitutes a great infrastructure that can be used to target other physics goals beyond Primakoff solar axions:

Other (non-Primakoff) solar axion production mechanisms

Axions from SN

post-Discovery "precision" physics

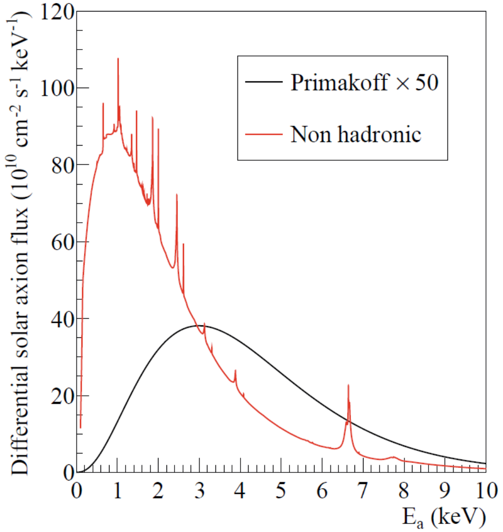


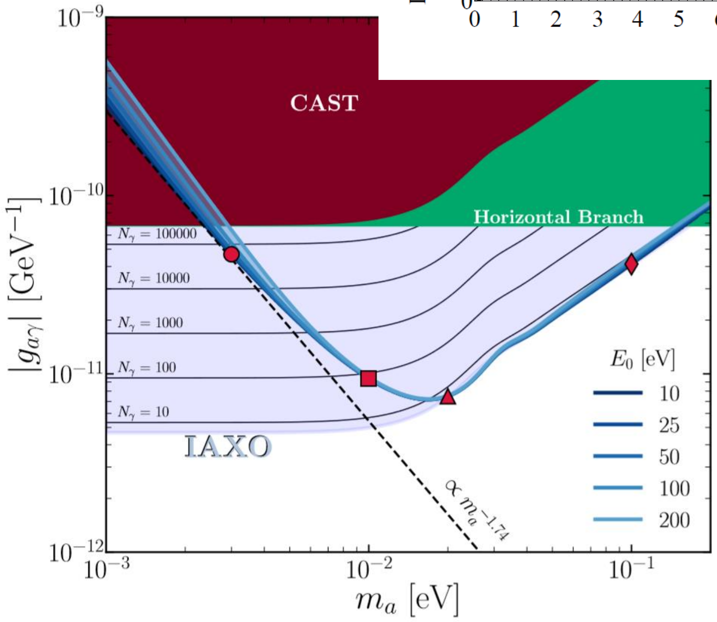
Dark Matter axions: haloscope setups inside the BabyIAXO bores

Other WISPs: hidden (dark) photons, chameleons, ...

BabyIAXO: beyond solar 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]
- 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





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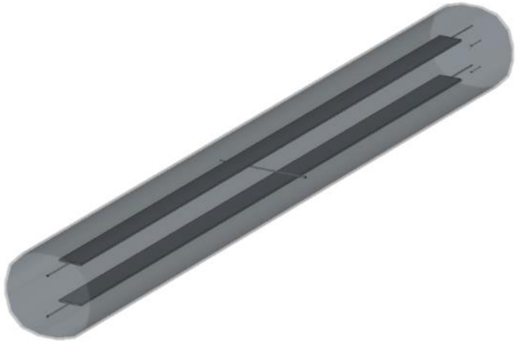
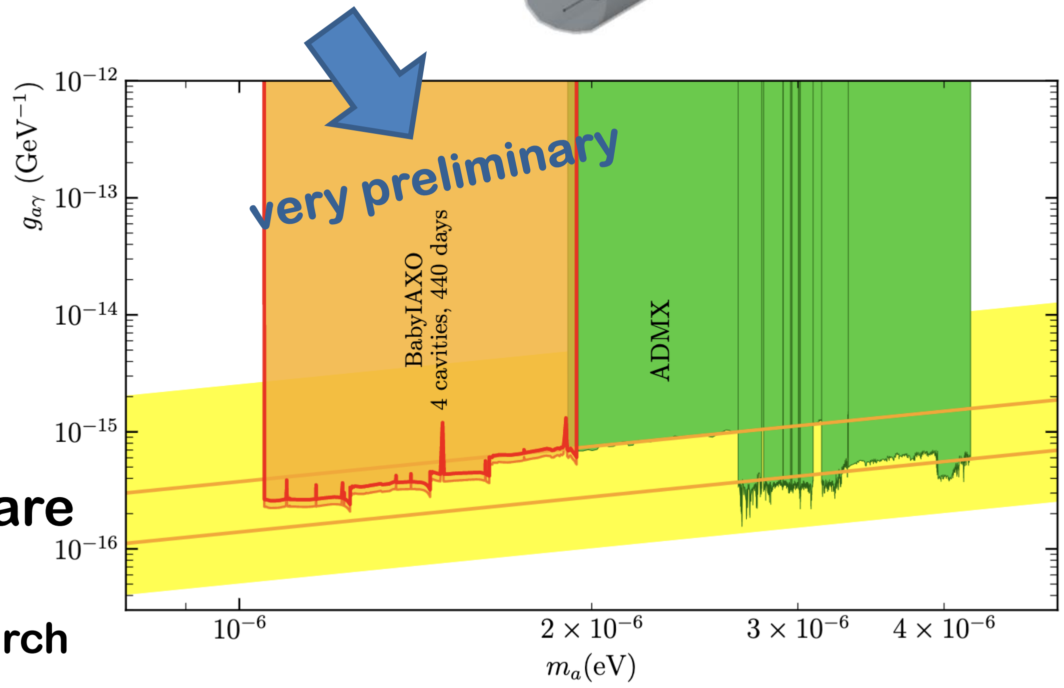
Haloscopes inside BabyIAXO:

- **Use of (Baby)IAXO large magnetic volume for axion DM setups.**
- **Very competitive prospects for 1-2 μeV axion searches.**
  - 4 x 5m long cavities with tuning slabs.
  - Low noise (standard) amplification + DAQ
  - Bores cooled down to 4-5 K
  - Sensitivity to KSVZ in < 2year data.



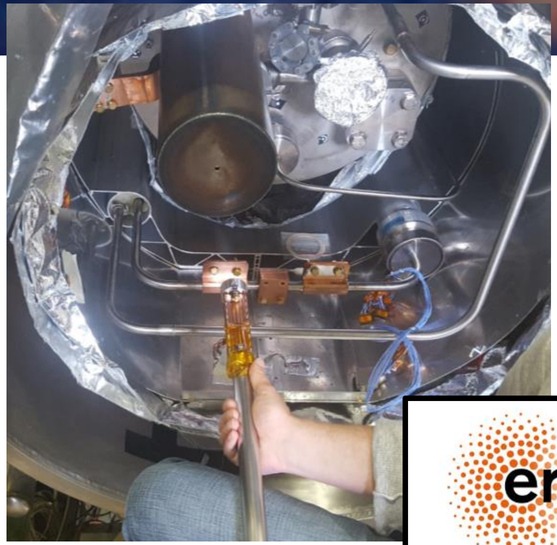


RADES coll. paper in preparation

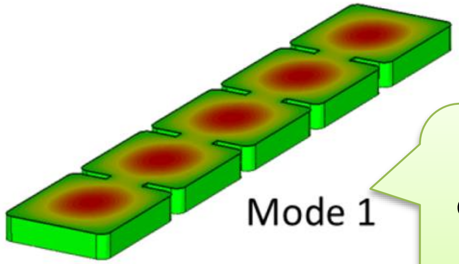
- **Other implementations (more speculative) are being discussed.**
  - E.g. extension to much low masses: BASE-like search inside BabyIAXO?

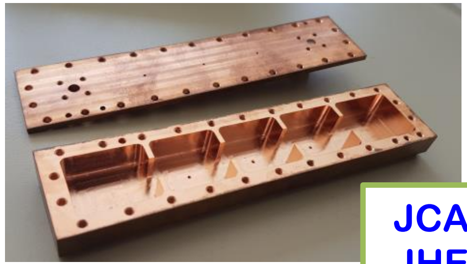
BabyIAXO: Helioscope/haloscope with RADES

- Exploratory project emerged at a later stage of CAST life: use of "helioscope" magnets for "haloscope" searches
- Creation of "axion haloscope" community in Europe (with basically no previous trajectory)
- Very interesting results so far:



ERC-StG 2018
B. Dobrich, CERN

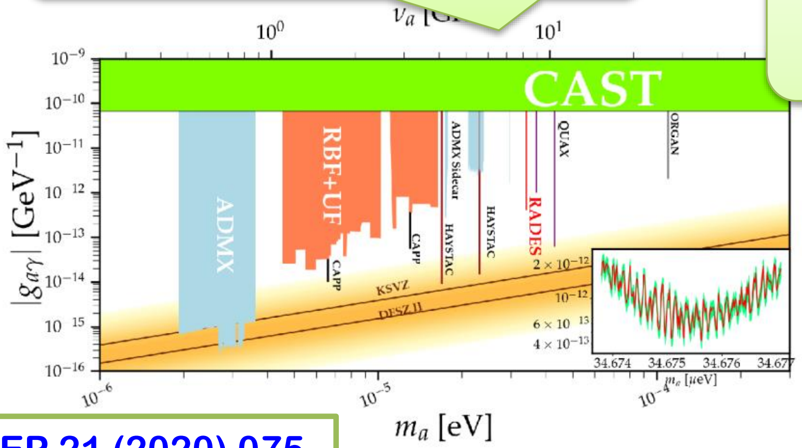




New geometry concepts to scale in V but keeping high resonant *f*

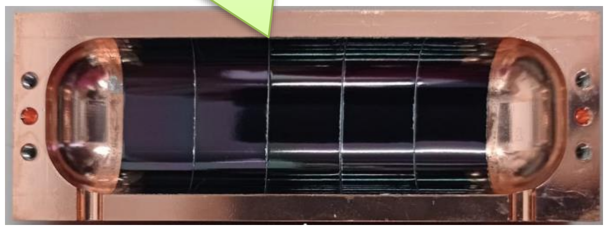
JCAP 05 (2018) 040
JHEP 07 (2020) 084

Physics result at single *f* point (37 μeV) in the CAST magnet



JHEP 21 (2020) 075

Inner HTS coatings to improve Q factor



IEEE Trans. Appl. Supercond. 32 (2022) 45

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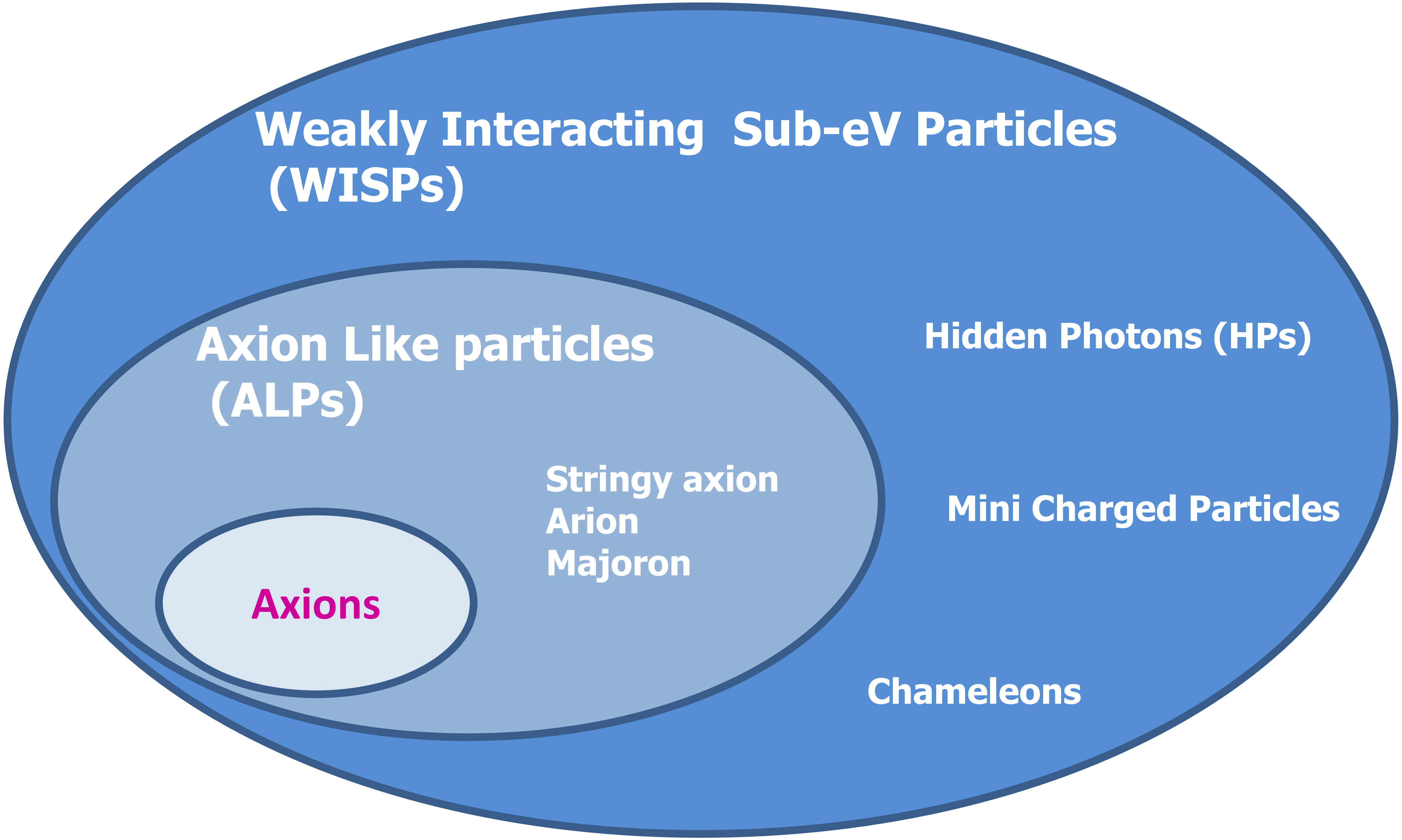
Weakly Interacting Sub-eV Particles
(WISPs)
Axion Like particles
(ALPs)
Stringy axion
Arion
Majoron
Axions
Hidden Photons (HPs)
Mini Charged Particles
Chameleons