Axion Searches

An experimentalist’s view

Friederike Januschek, DESY

Gravity, Strings and Supersymmetry Breaking

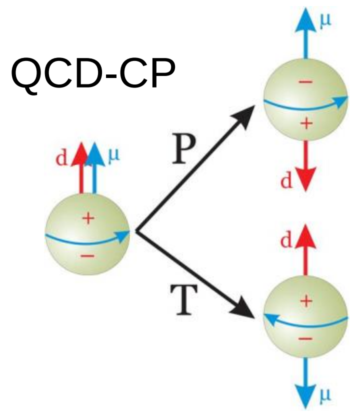
5 April 2025

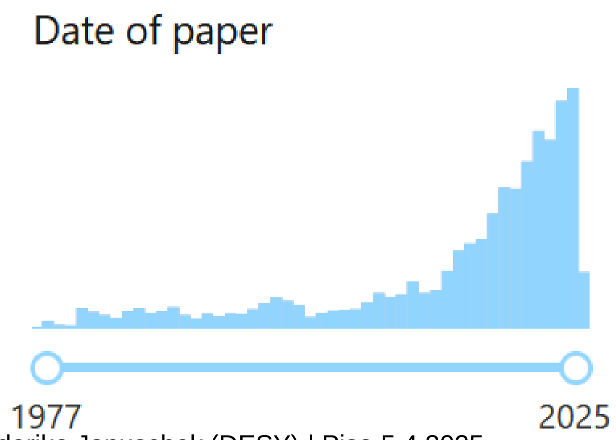
HELMHOLTZ RESEARCH FOR GRAND CHALLENGES

DESY.

Many of us agree that the axion is well-motivated!

- **1977** Peccei&Quinn: suggesting a new mechanism to solve **Strong CP problem** by promoting the $\overline{\theta}$-Term to a field, dynamically settling the $\overline{\theta}$-Term to 0.
- **1978** Weinberg& Wilczek: Showing that this gives rise to a Pseudo-Nambu-Goldstone boson which was called ***axion***
- **1983** Discovery that axion is also a promising **cold dark matter** candidate

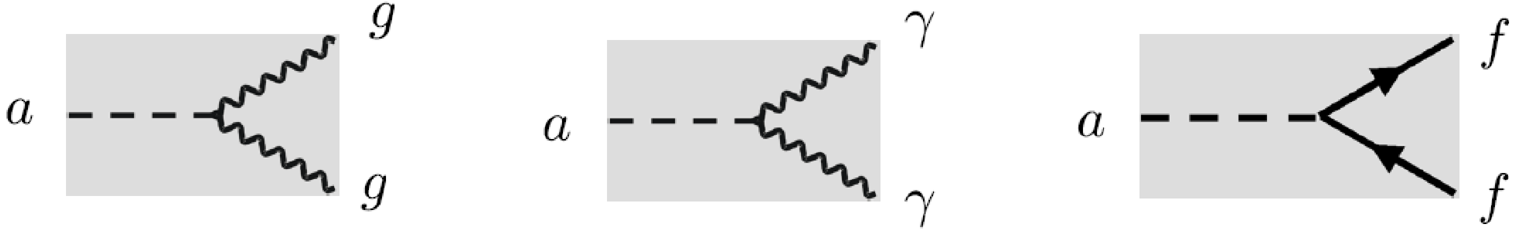




What do we “know“ about the axion?

Axion mass is related to coupling $m_a = 0.6\ \text{eV} \cdot (10^7 \text{GeV} / f_a)$
f_a: axion decay constant, couplings ~ $1/ f_a$ (hence ~ m_a) .

$$\mathcal{L} \supset -\frac{\alpha_s}{8\pi}\frac{C_{ag}}{f_a}\, a\, G^b_{\mu\nu}\tilde{G}^{b,\mu\nu} - \frac{\alpha}{8\pi}\frac{C_{a\gamma}}{f_a}\, a\, F_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{1}{2}\frac{C_{af}}{f_a}\partial_\mu a\, \overline{\psi}_f\gamma^\mu\gamma_5\psi_f$$



Courtesy A. Ringwald

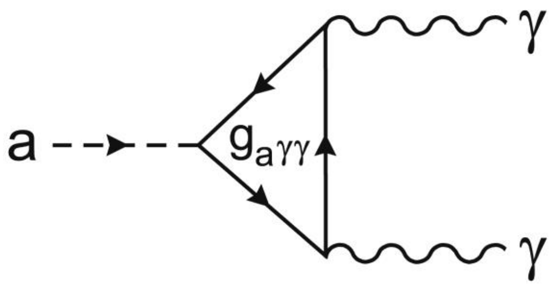
The factors *C* depend on the axion model. Benchmark models are the KSVZ and DFSZ model.

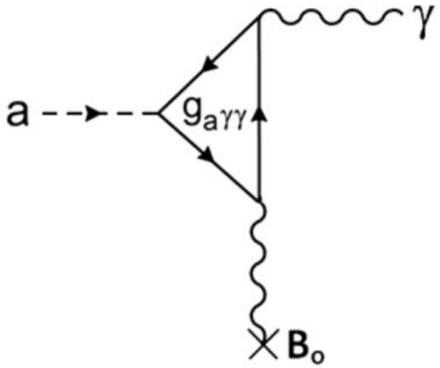
Other light bosons arising from spontaneously broken symmetries at high energy scales have similar phenomenology➔ new class of possible BSM particles: Axion-like particles (ALPs).

The axion–photon coupling is the key to most experiments

Exploited by most experiments for lightweight ALPs / axions

- Low-mass axions have extremely weak couplings
  ➔ the “invisible” axion
- **Sikivie**: decay of dark matter axions is accelerated within a magnetic field through the inverse Primakoff effect (Sikivie effect).
- The axion can – through its coupling with photons- become visible in magnetic fields.





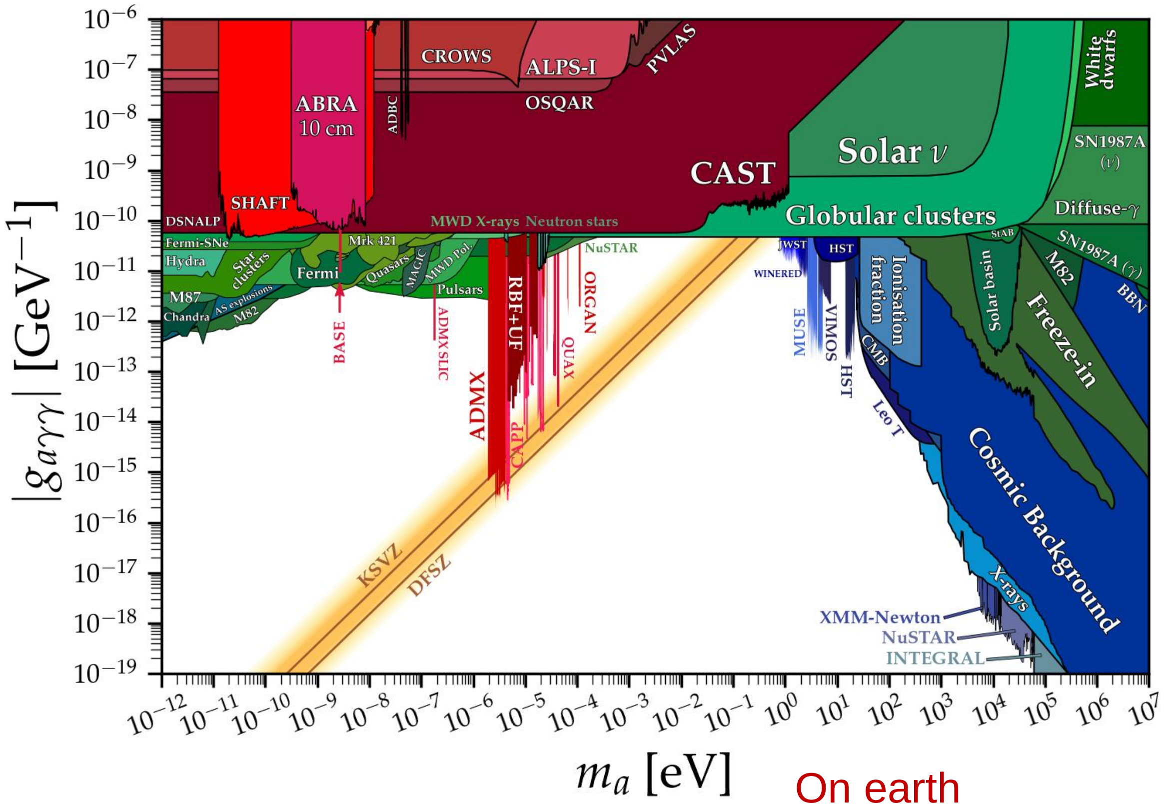
Experimentalist‘s note

Strong and Large Magnet

Very Sensitive Detector

There is a lot of „space“ to find the axion

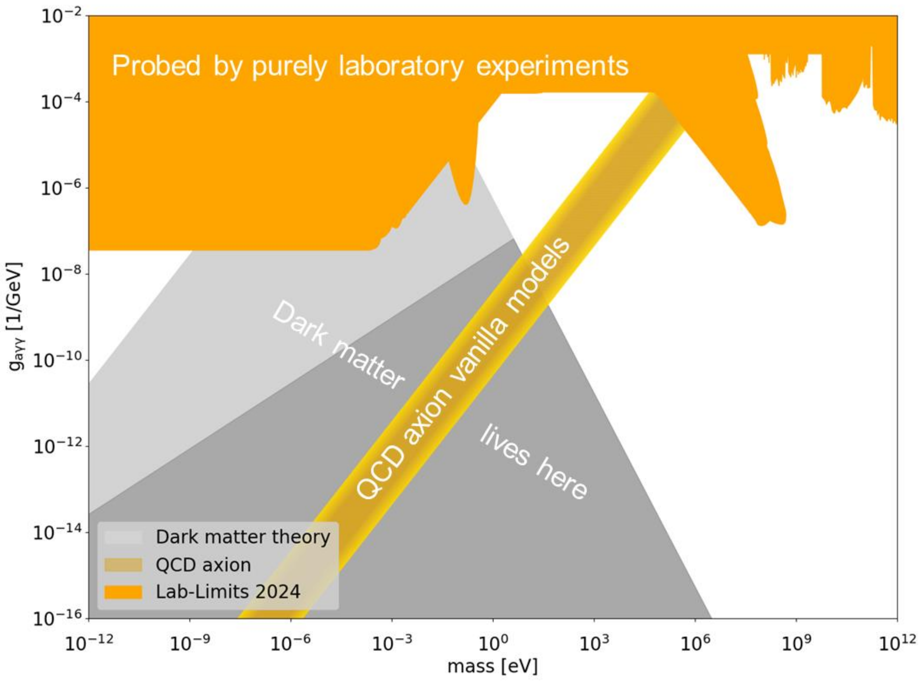
Possibility and Challenge



On earth
Astrophysics
Cosmology

<u>Ciaran O'Hare</u>:
https://github.com/cajohare/AxionLimits

- Many orders of magnitude in mass and coupling
- Very many activities/experiments and constraints
- Depending also on the assumptions (e.g. axions as dark matter)
- Plot for laboratory limits e.g. looks more like this



Courtesy A. Lindner

No way to cover all of this…

Ciaran O'Hare:
https://github.com/cajohare/AxionLimits

No way to cover all of this…

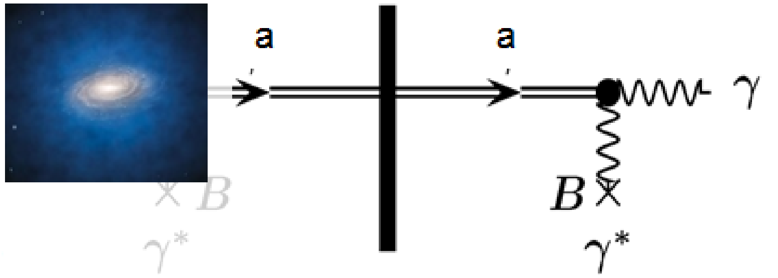
I will concentrate on a (biased) selection of mostly axion-photon coupling experiments

Ciaran O'Hare: https://github.com/cajohare/AxionLimits

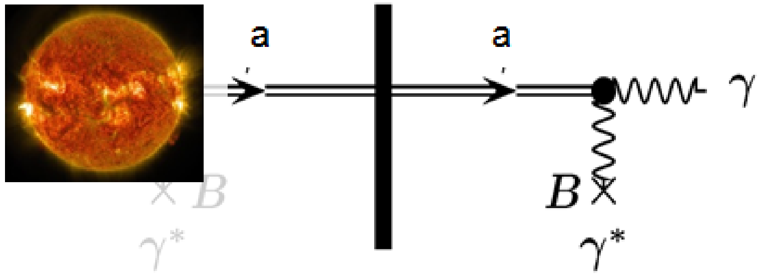
Three ways to exploit the axion-photon coupling

Different axion production sites open up different possibilities

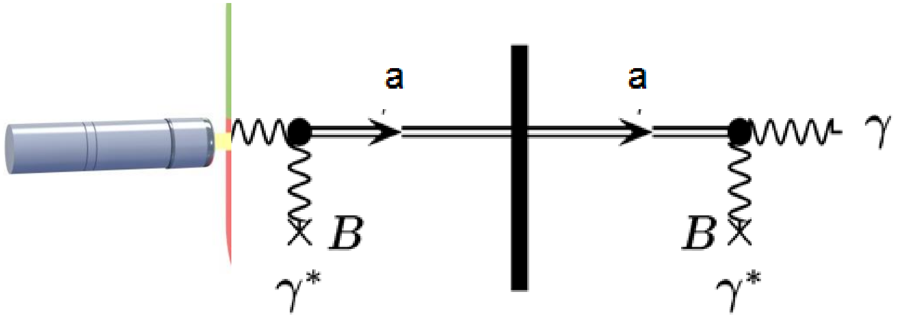
- Haloscopes
  looking for dark matter constituents, microwaves



- Helioscopes
  Axions/ALPs emitted by the sun, X-rays



- Purely laboratory experiments
  "light-shining-through-walls", optical/infrared photons



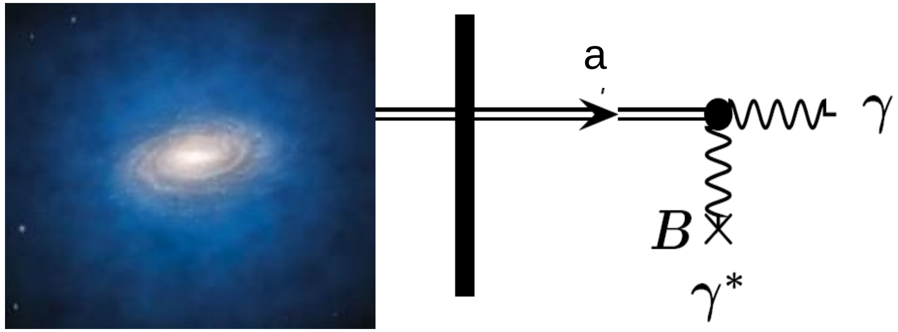
Looking for dark matter axions

Haloscopes

- Assuming a local dark matter density of $0.4\,\frac{GeV}{cm^3}$ and most of dark matter being axions, the axion density would be around

$$n_a \sim 4 \cdot 10^{13} (\frac{10\mu eV}{m_a}) \frac{1}{cm^3}$$

- Velocity of the axions would be spread around about 230 km/s
- Dark matter axions are non-relativistic particles: photon energy from axion conversion given by m_a.
- Power from axion-photon conversion is too low to measure, need to boost it somehow
- *Advantages*: high axion numbers „for free“, possibility to reach QCD axion band of key theories with advanced concepts
- *Disadvantages*: mostly narrowband, dependent on assumption that dark matter is (mostly) axions



The classical haloscope approach

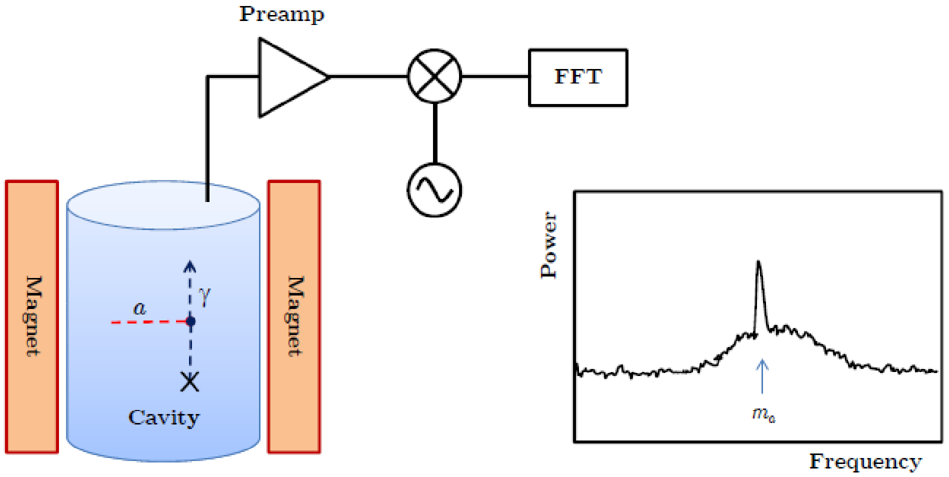
Looking at the universe with microwave cavities

- Original concept of the classical haloscope by Sikivie (1983): Microwave cavity in a magnetic field➔ convert dark matter axions into photons.
  - Amplification with the cavity‘s quality factor and volume when the axion‘s mass aligns with the cavity‘s resonance frequency

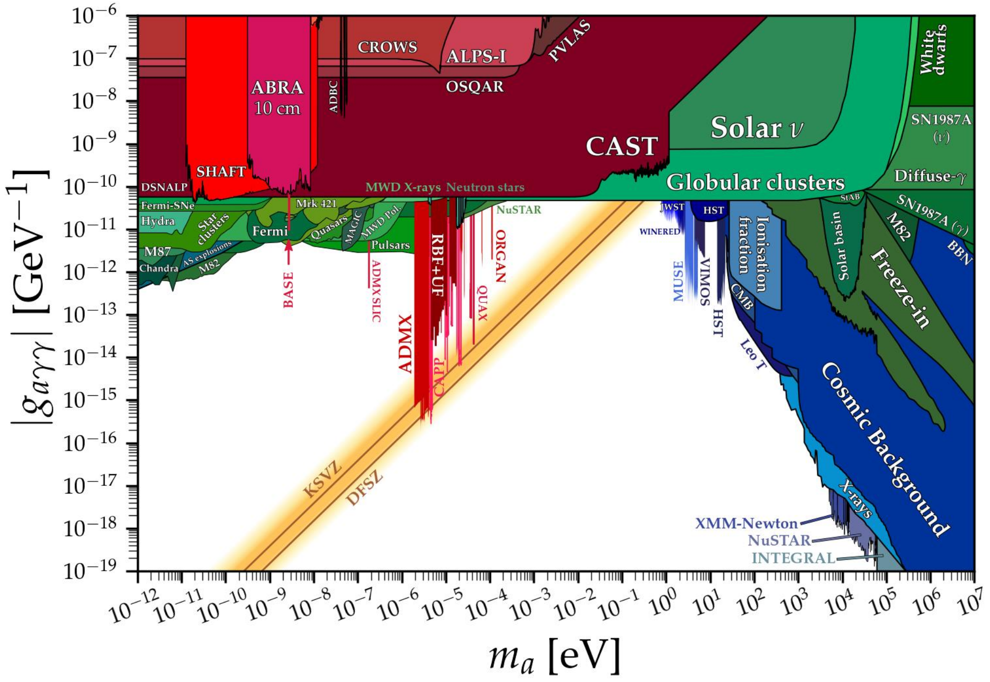
$$P_{out} \sim g_{a\gamma}^2 \rho_a B_0^2 Q V$$

  - Need to scan through frequencies

- The ADMX and CAPP experiments have probed DFSZ sensitivity within certain mass ranges.



Igor Irastorza, arXiv:2109.07376



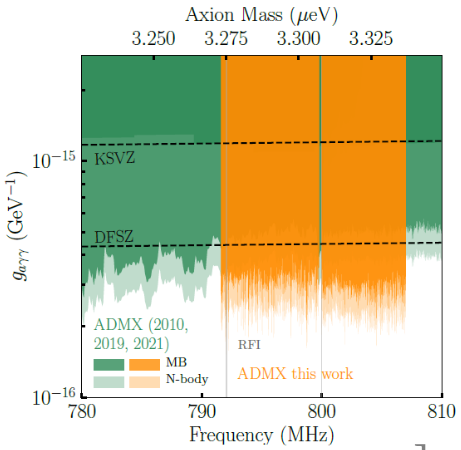
Microwave cavity experiments reach QCD axion band (DFSZ)

- ADMX in the USA is the pioneer haloscope.
- Main ADMX setup: 60 cm diameter, 1m long cavity inside a solenoidal 8 T magnet.
- The cavity can be tuned in frequency by rod movement.
- Sensitivity to axion models in the μeV range.

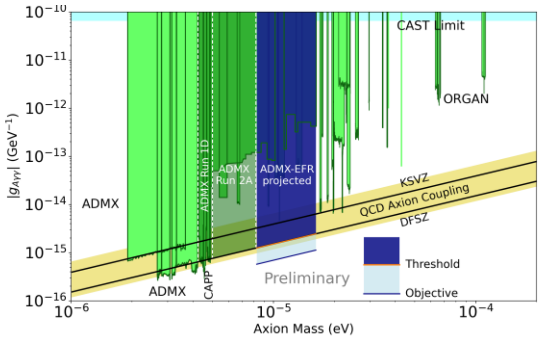
ADMX: Rakshya Khatiwada UW

CAPP: Yannis Semertzides

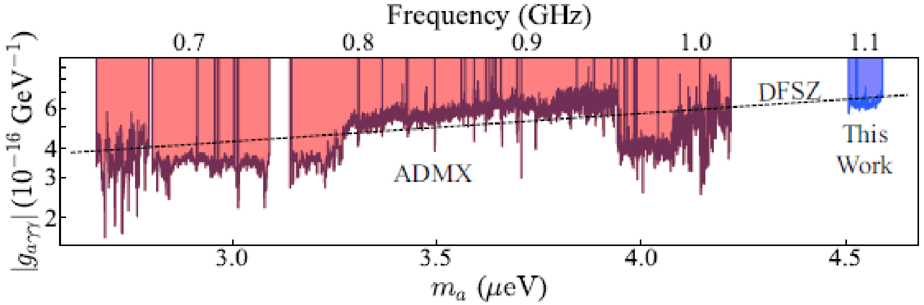
- CAPP in South Korea has also reached DFSZ sensitivity for slightly higher masses with a similar approach.
- Magnetic field: 10 T, bore: 32 cm.



arXiv:2408.15227v2 [hep-ex]



Stefan Knirck, PATRAS 2024



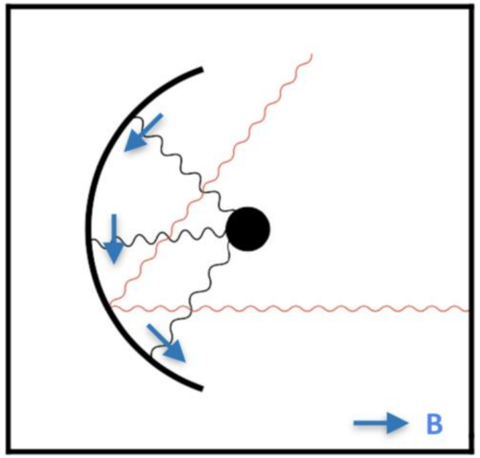
arXiv:2210.10961 [hep-ex]

DISH Antenna BRASS & BREAD

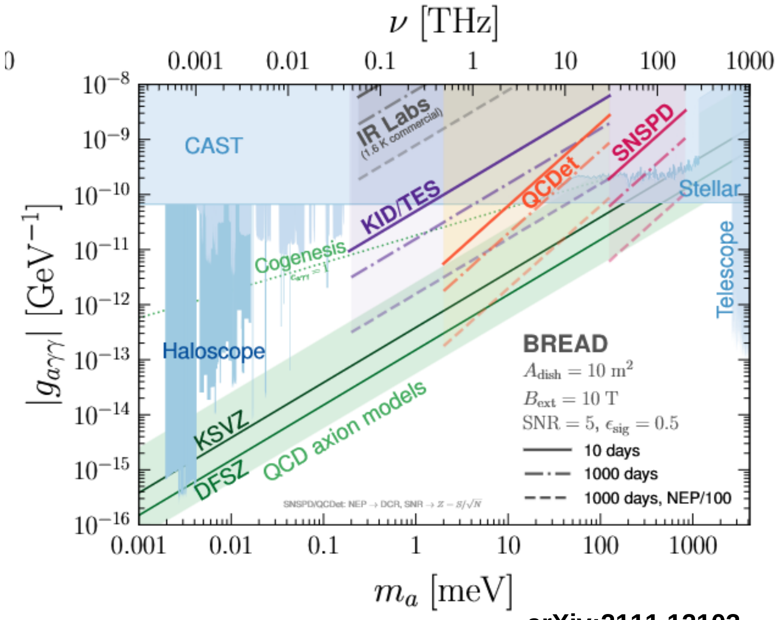
- Different concepts are needed for reaching to higher masses:
- **Idea**: using the electromagnetic radiation emitted by conducting surfaces when excited by axions
- **BRASS** (University of Hamburg) is presently establishing a pilot dish antenna sensitive to axion masses of about 50µeV≤m_a≤meV.

arXiv:2306.05934

- **BREAD** (Fermilab) is setting up a similar experiment with the potential of a larger magnet sensitive to axion masses of about 20 meV≤m_a≤0.1eV or similar, depending on sensor technology.



arXiv:1212.2970



arXiv:2111.12103

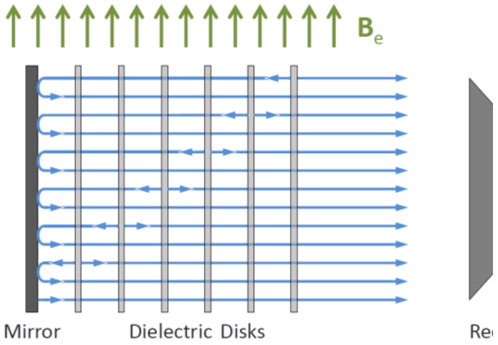
BREAD Projection for axions

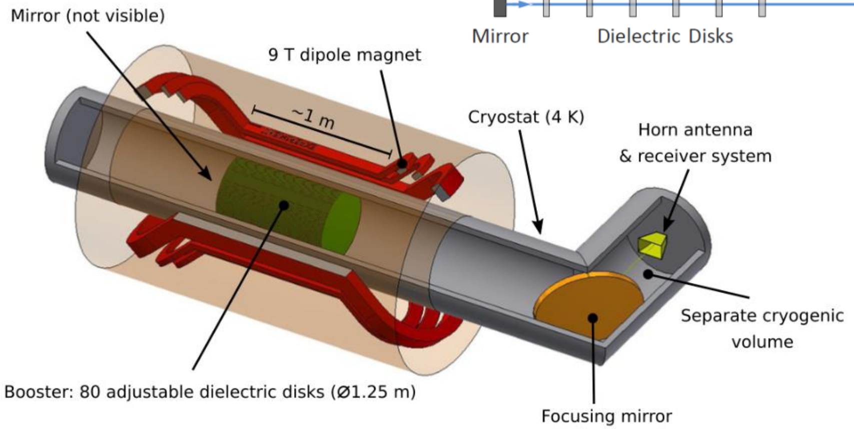
MADMAX: boosting with dielectric disks

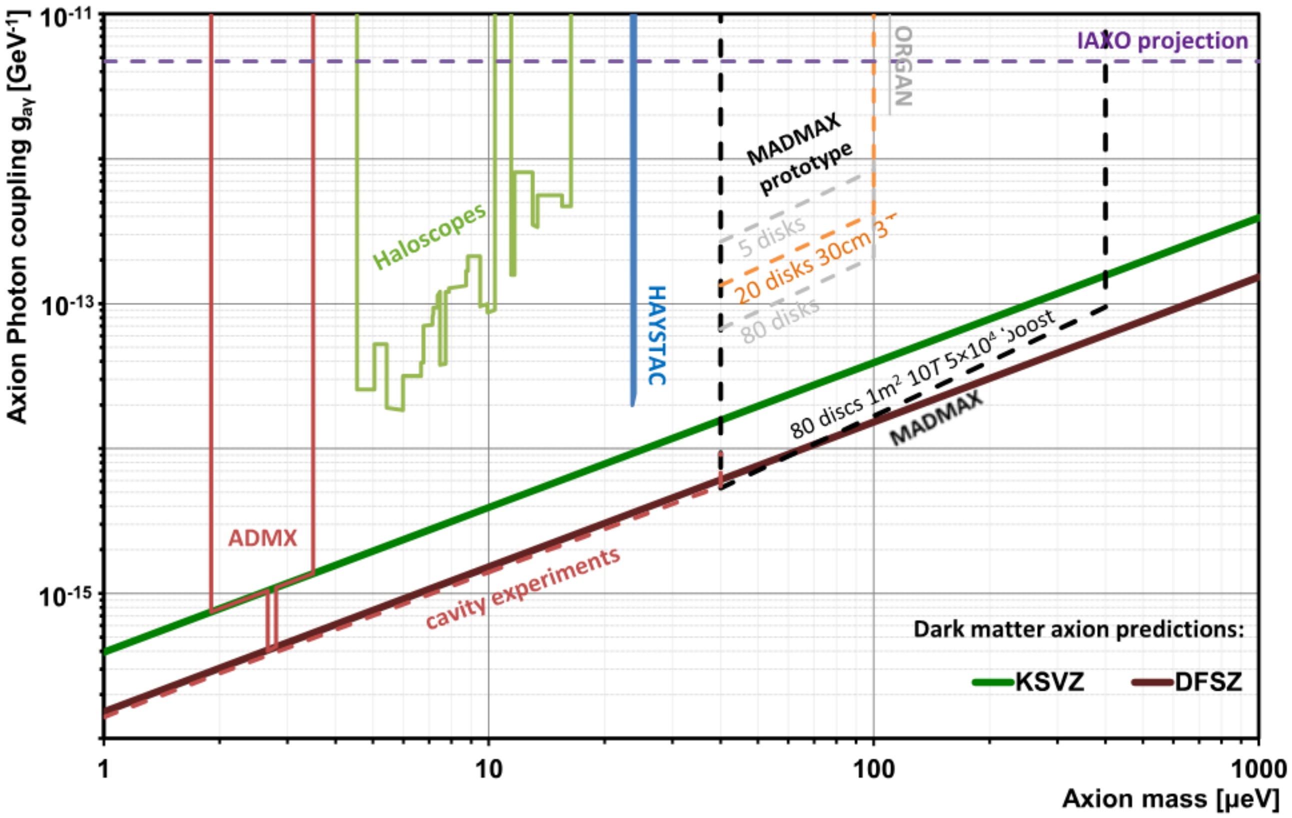
- **MADMAX** is a dielectric haloscope planned at Hamburg: boosting the emitted power from dielectric surfaces by coherent emission from multiple interfaces and constructive interference effects

arXiv:1611.05865

- Effective area of approximately A ~ 1m^2 within a dipole magnet of around ~ 9T







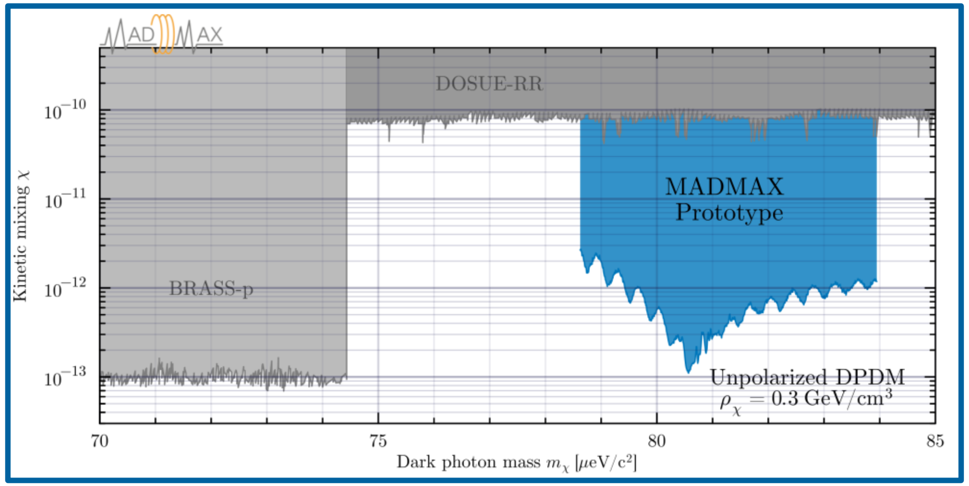
Eur. Phys. J. C 79 (2019) 186, [arXiv:1901.07401]

First searches with MADMAX prototypes

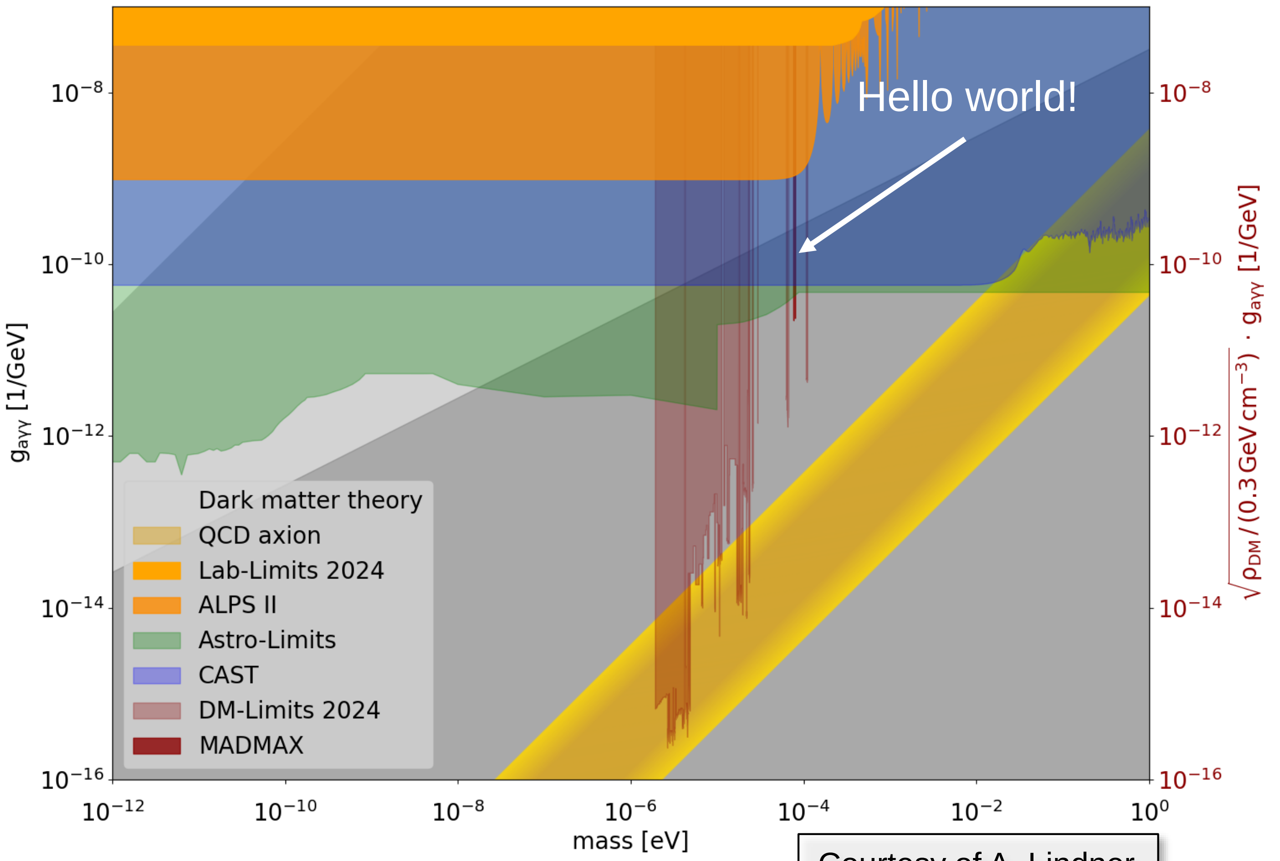
Search for dark photons and axions

Recently:

- First successful science run (dark photon) with a prototype 2408.02368



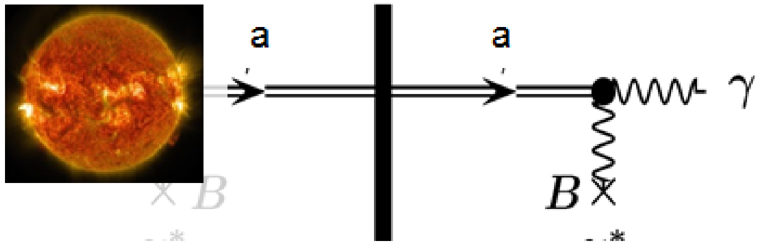
- First axion search with a prototype (at CERN)
- Successful "Hello World" limit setting 2409.11777
- First tests of cryogenic operation



Courtesy of A. Lindner

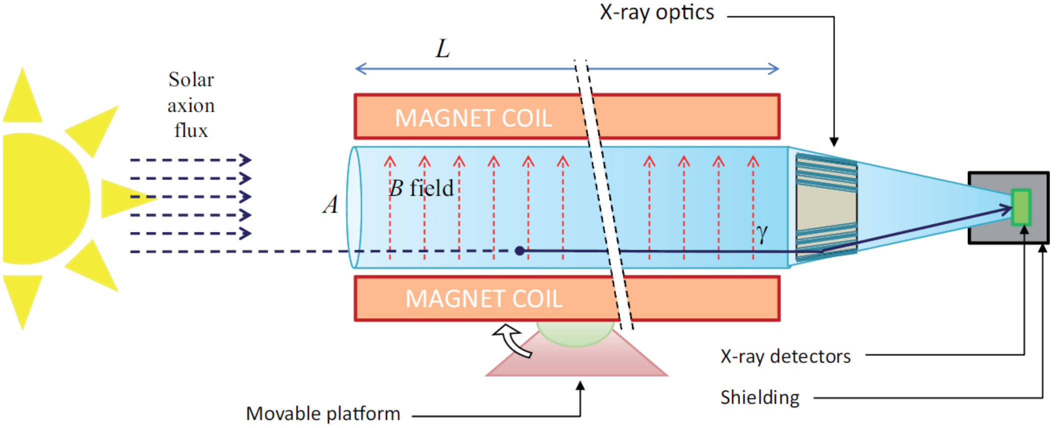
Using the sun as a source

Helioscopes



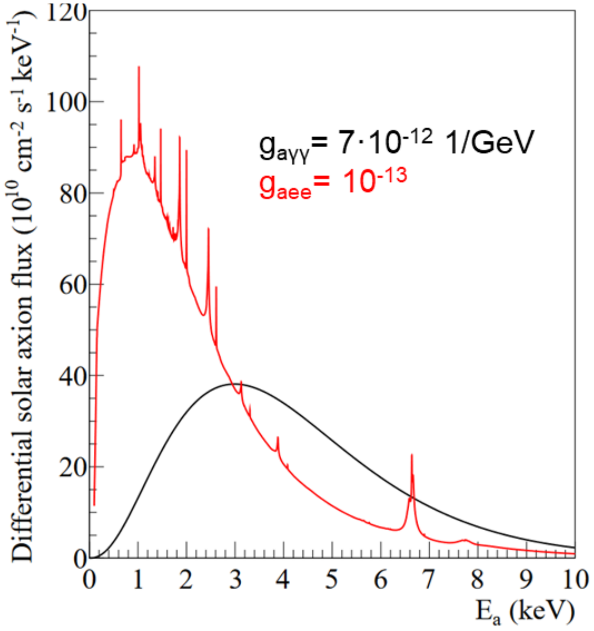
- The sun should be a source of axions at X-ray energies (few keV) via the interactions of photons with the Coulomb field of the nuclei in the solar plasma.
- **Concept**: Point a telescope with a dipole magnet at the sun and look for appearing X-rays from axion-photon conversion

Figure of merit $\sim B^2 L^2 A$



doi:10.1088/1475-7516/2011/06/013

- *Advantages*: Strong source, on/off possibility by (not) pointing at the sun, higher energies make detection much easier, broadband, sensitivity also to g_{ae}, g_{an}
- *Disadvantages*: dependence on assumptions (e.g. solar model), difficult to reach QCD axion band in benchmark models



Solar axions generated via couplings to photons, electrons.

JCAP01(2016)034

There is a Helioscope benchmark

CERN Axion Solar Telescope CAST

- The CAST Helioscope was active for more than 15 years at CERN and has been the leading helioscope
- LHC test magnet that provides a length of 10 m and 9 T with two bores
- First helioscope with X-ray optics
- Detector: small gaseous time projection chambers with micromegas readout
- Limit on the axion-photon coupling of

$g_{\alpha\gamma} < 0.66 \times 10^{-10} GeV^{-1}$ (95%CL)

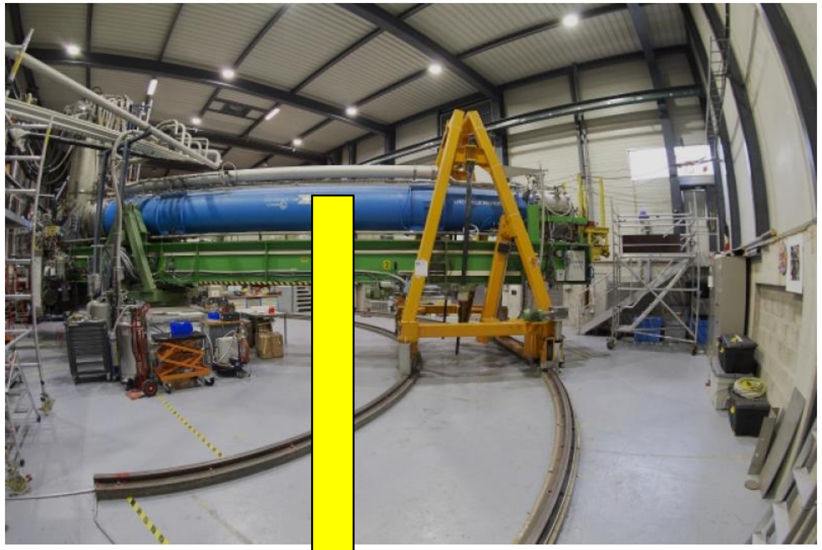
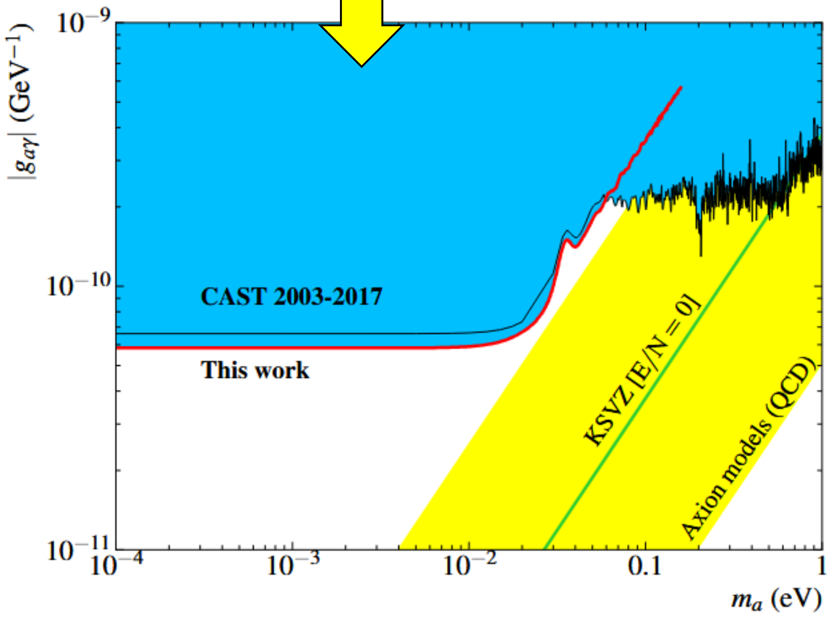


Image: Max Brice, CERN



Phys. Rev. Lett. 133, 221005, 2024

Ciaran O'Hare:https://github.com/cajohare/AxionLimits

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  $g_{\alpha\gamma} < 0.66 \times 10^{-10} GeV^{-1}$ (95%CL)
- CAST setup now being used for other experiments

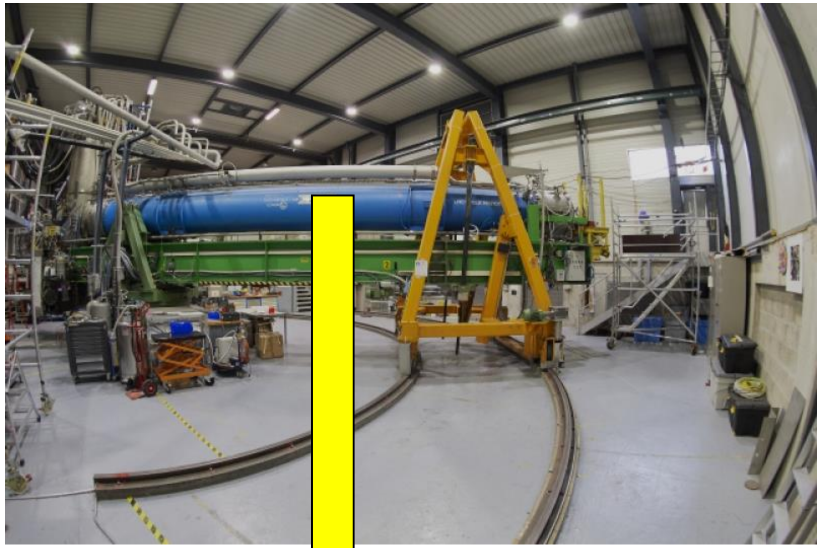
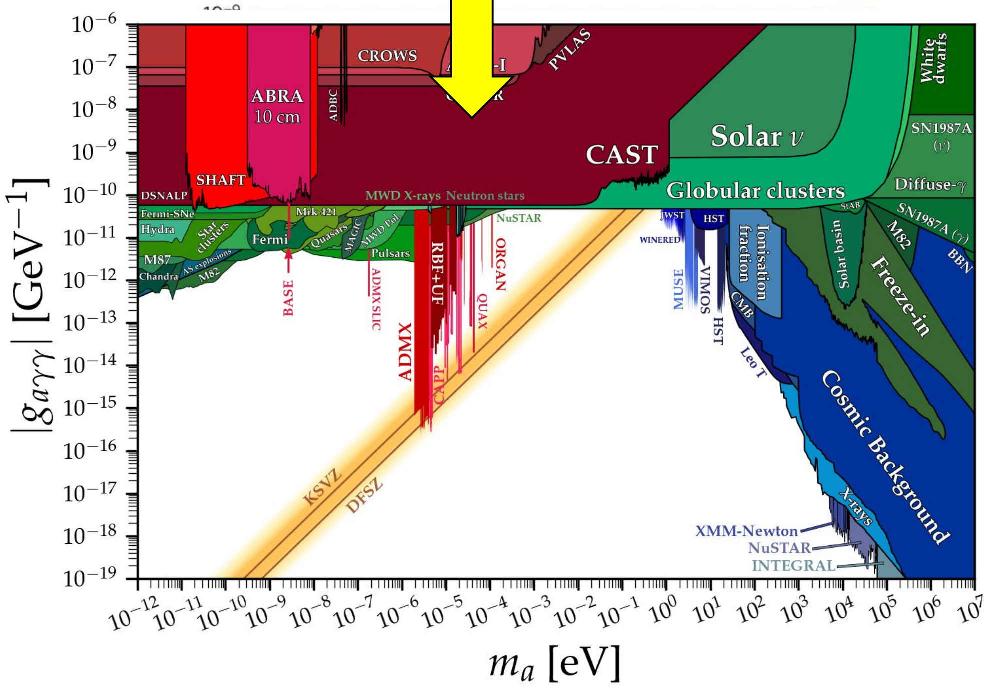


Image: Max Brice, CERN



Nature Physics **volume 13**, pages 584–590 (2017)

Ciaran O'Hare:https://github.com/cajohare/AxionLimits

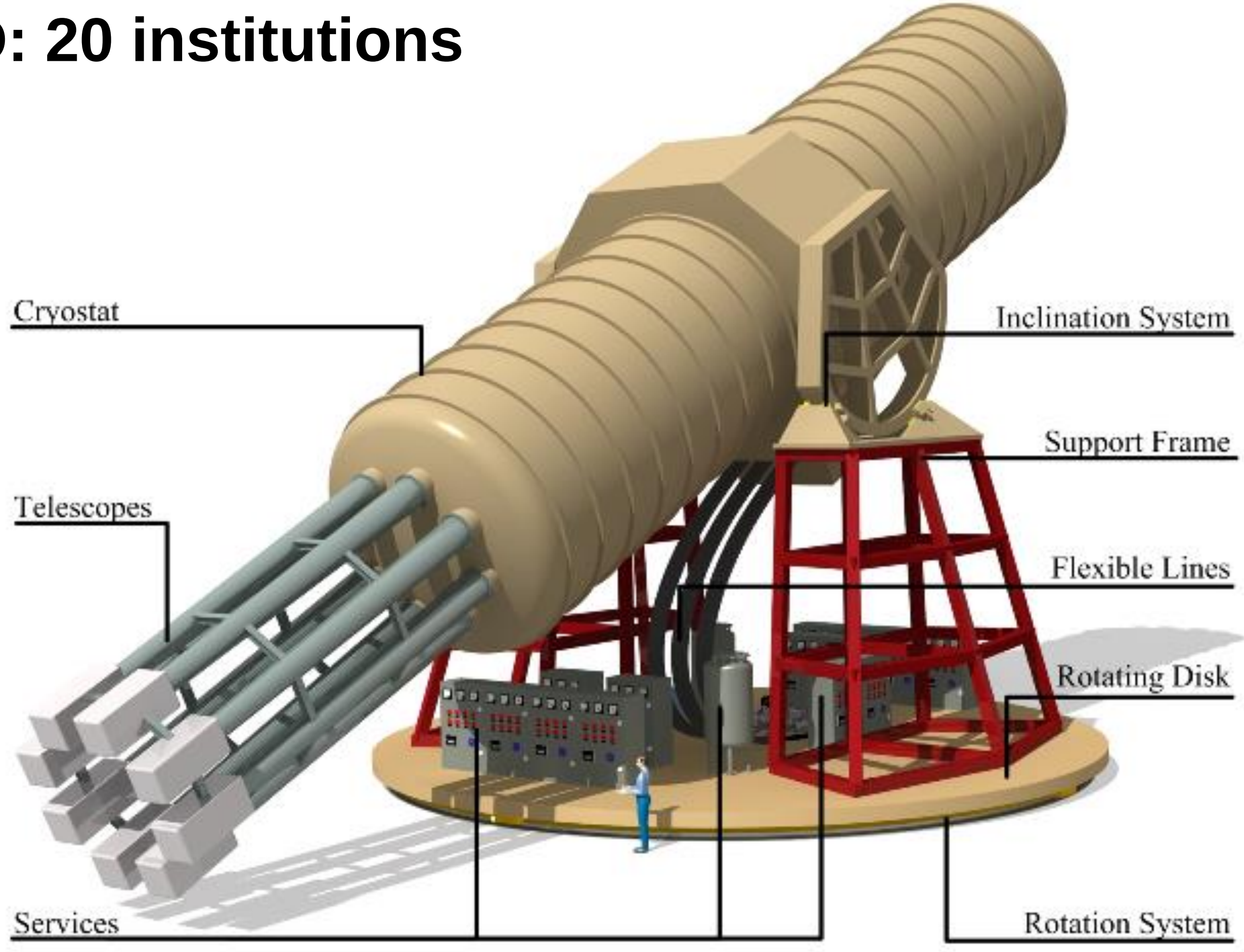
IAXO:

International Axion Observatory IAXO

Full members: Kirchhoff Institute for Physics, Heidelberg U. (Germany) | Siegen University (Germany) | University of Bonn (Germany) | DESY (Germany) | University of Mainz (Germany) | Technical University Munich (TUM) (Germany) | University of Hamburg (Germany) | MPE/PANTER (Germany) | MPP Munich (Germany) | IRFU-CEA (France) | CAPA-UNIZAR (Spain) | INAF-Brera (Italy) | CERN (Switzerland) | ICCUB-Barcelona (Spain) | Barry University (USA) | MIT (USA) | LLNL (USA) | University of Cape Town (S. Africa) | CEFCA-Teruel (Spain) | U. Polytechnical of Cartagena (Spain)
Associate members: DTU (Denmark) | U. Columbia (USA) | SOLEIL (France) | IJCLab (France) | LIST-CEA (France)

- Largest current axion collaboration
- Aiming at an improvement in the S/N of 10^4 , reaching a sensitivity to $g_{a\gamma}$ of a few $10^{-12} GeV^{-1}$
- This will be only possible with a dedicated large and strong magnet (20 m magnet, 2-3 T) as well as improved optics and detectors
- 8 bores (d = 60 cm each)
- Technology will profit from LHC experience (magnet) and satellite missions (Xray optics)

IAXO: 20 institutions



Not only a prototype…

BabyIAXO

Basically ready for construction

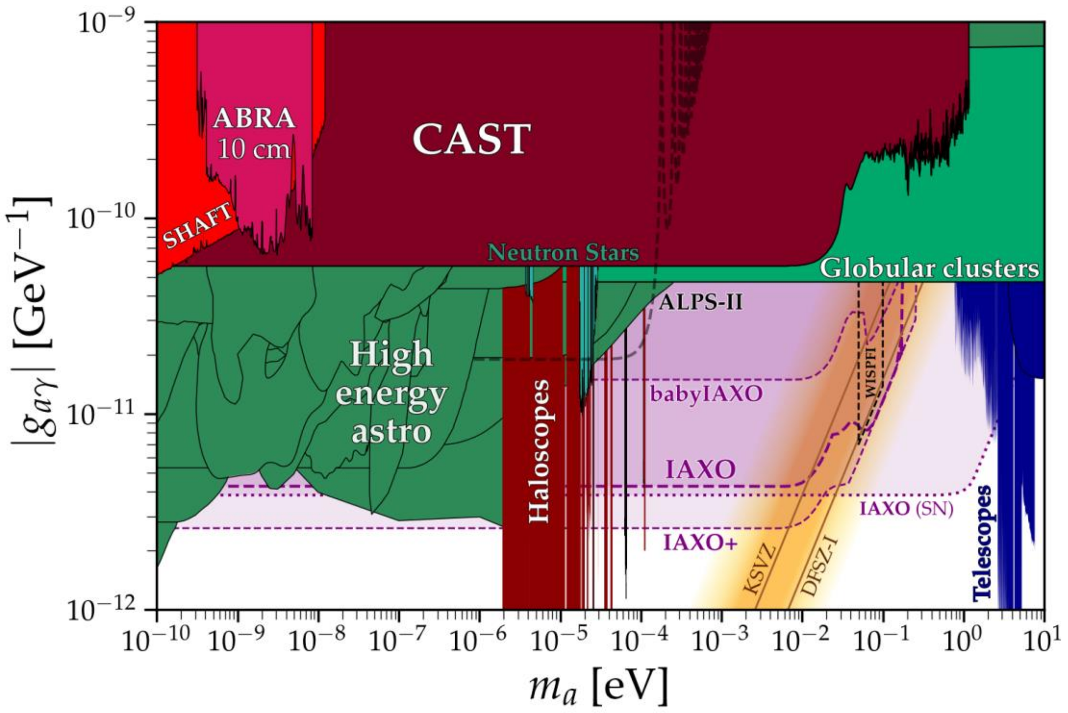
- Prototype for all IAXO sub-systems with comparable specs, but smaller:
  - Aim: test and improve all systems
  - 10 m magnet, 2-3 T, 2 bores (d = 70 cm each)

Parameter [units]	BabyIAXO	IAXO
B [T]	~2	~2.5
L [m]	10	22
A [m^2]	0.77	2.3
f_M [T^2m^4]	~230	~6000

- But: BabyIAXO will already have significant physics output and a much better reach than the CAST helioscope before (Sensitivity FOM: **~100x CAST)**

➔**Fully-fledged helioscope that will study uncharted parameter space = potential for discovery**

- Sites:
  - BabyIAXO: DESY
  - IAXO: DESY?



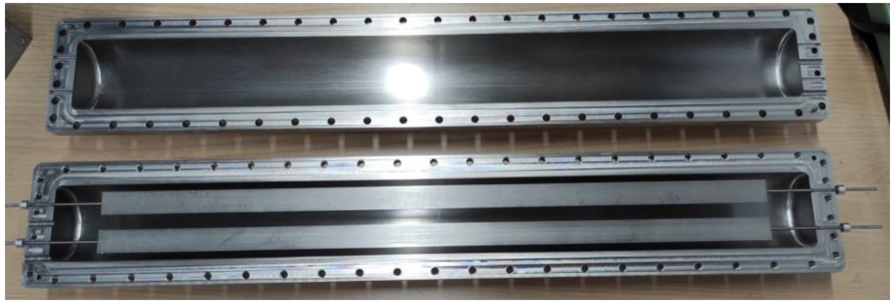
Ciaran O'Hare:https://github.com/cajohare/AxionLimits

Profiting twice: BabyIAXO for Haloscope Searches

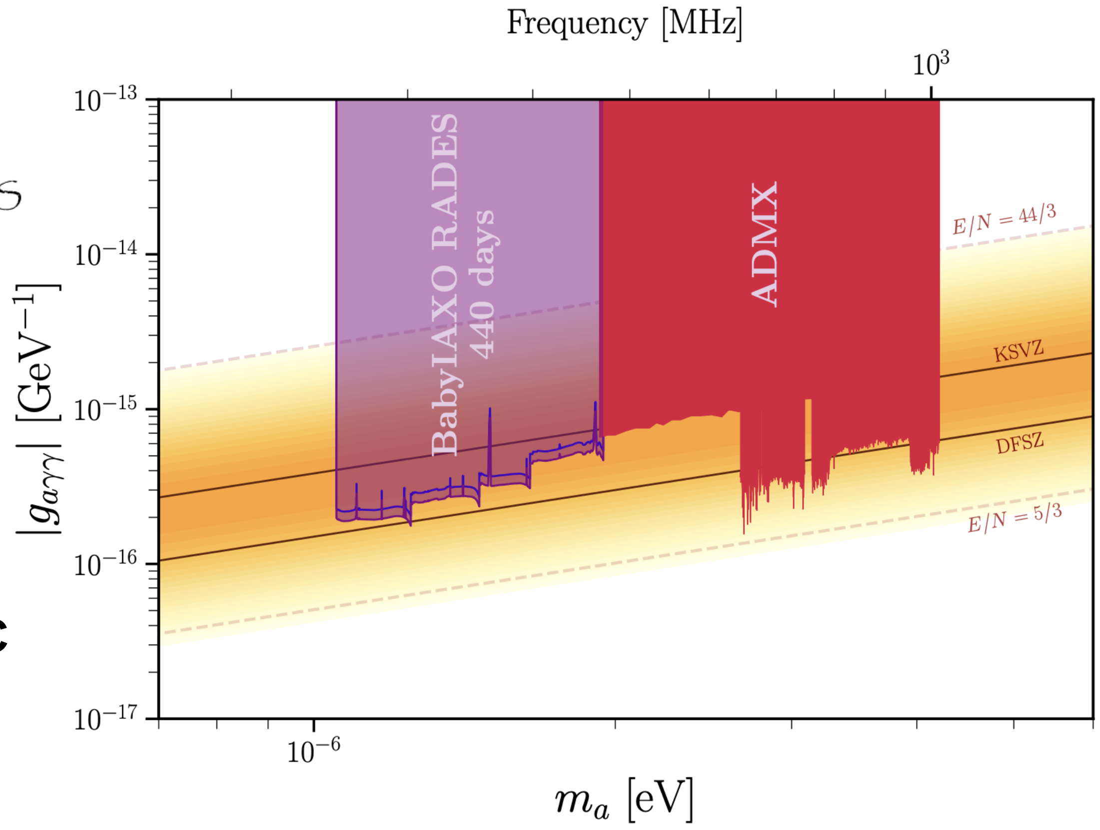
Searching for DM Axions

- Could also use BabyIAXO magnet for a haloscope searches
- Concrete project: RADES arXiv:2306.17243
- With BabyIAXO magnet bore: e.g. 4x 5m cavities to target 1-2 µeV range down to vanilla QCD axion band
- Multiple concepts under development and discussion

Recently attracted several grants for the prospect of quantum-limited detection, in particular ERC synergy grant *DarkQuantum* by I. Irastorza et al.



RADES-BabyIAXO Prototype



arXiv:2306.17243

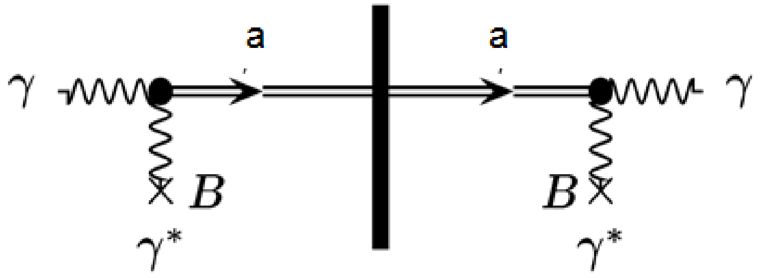
Being in control of our axions

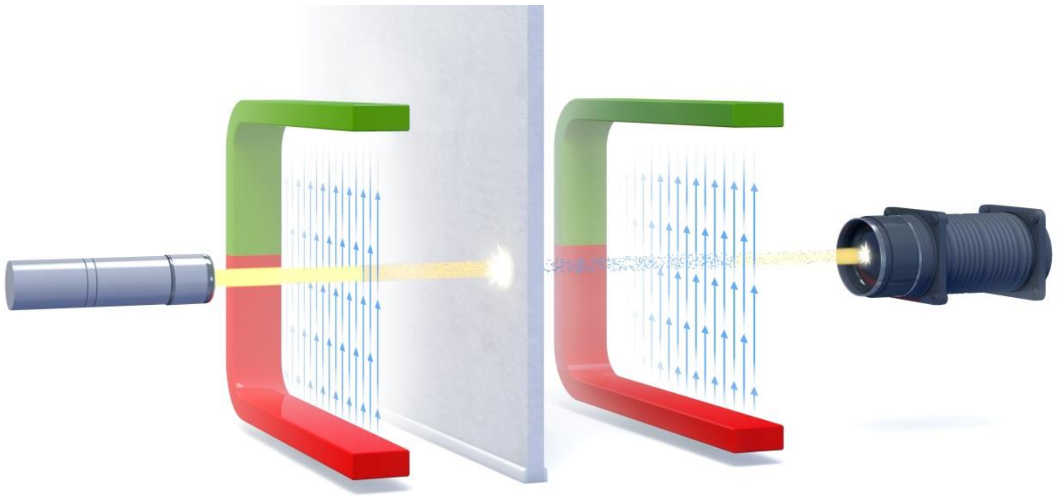
Making our own axions with the Light-Shining-Through-Walls approach

- **Idea**: producing axions and detecting them in the lab via using twice the (inverse) Primakoff effect
- Put a strong light source and a magnet in front of a light-tight wall and try to detect light on the other side (in a magnetic field) with a sensitive detector
- (Re)Conversion probability depends primarily on the length and field strength of the magnet

$$P_\gamma = \left(\frac{g_{a\gamma\gamma} B L}{2}\right)^4 \eta P_i$$

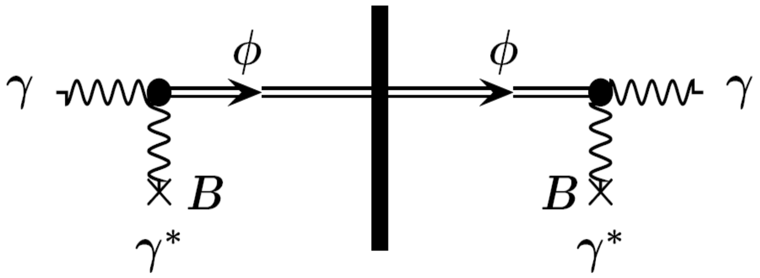
- *Advantages*: No dependence on additional assumptions, properties of the axions are well defined
- *Disadvantages*: probability very small, therefore limited reach

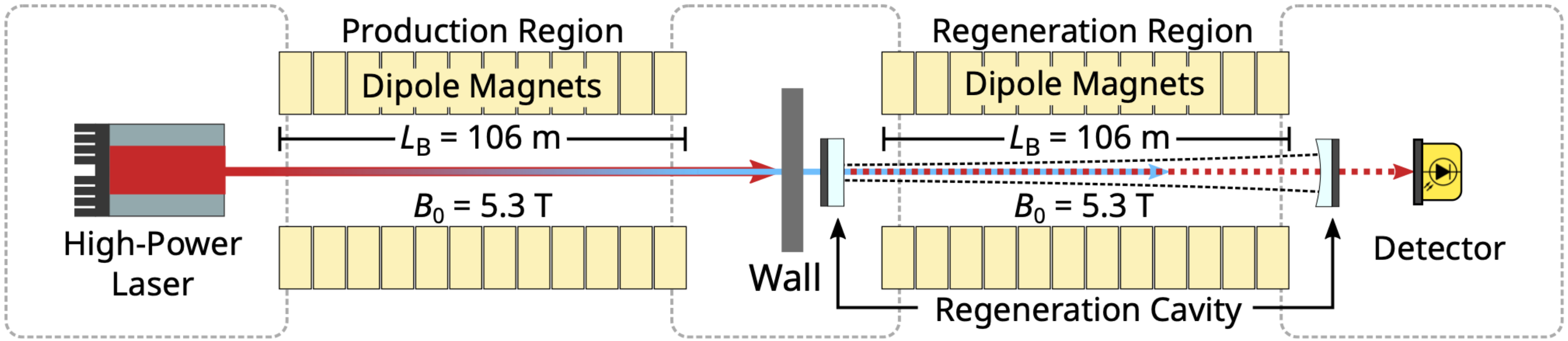


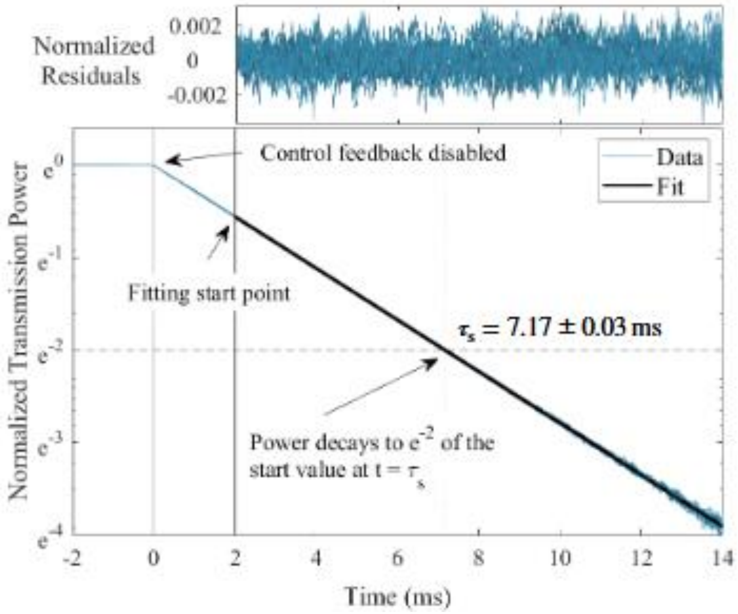


Boosting Probabilities

ALPS II: The most sensitive Light-Shining-Through-Wall Experiment





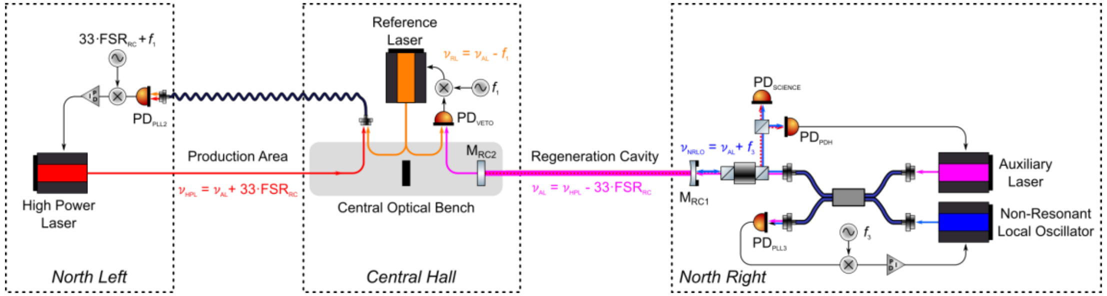


Storage time

arXiv:2408.13218

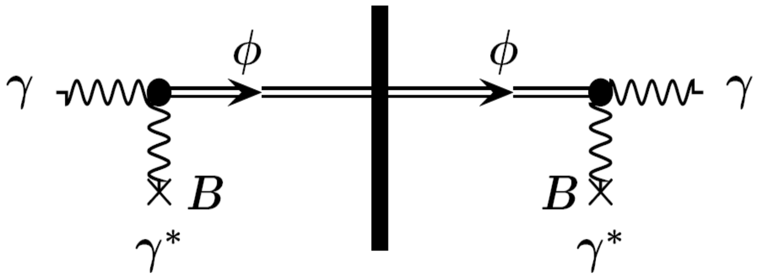
Idea at ALPS II:

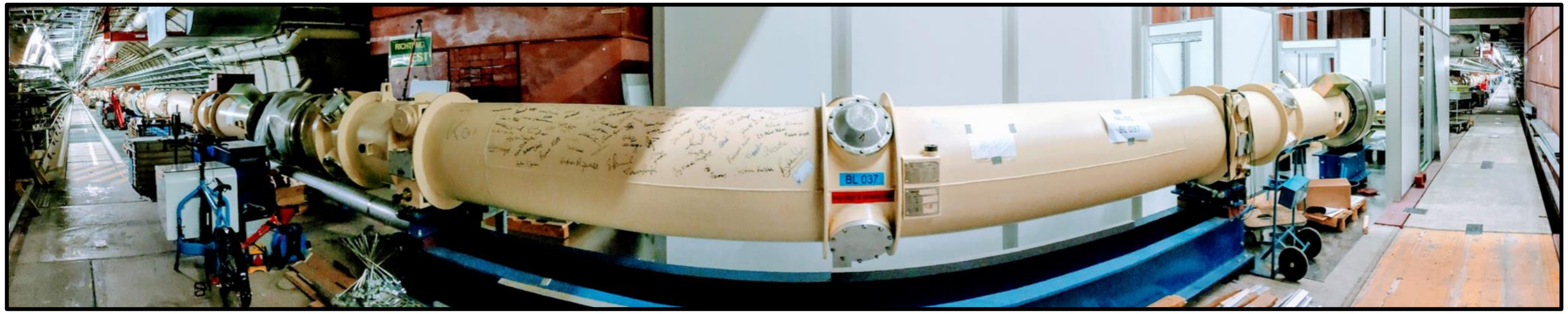
- Resonantly enhance axion-photon conversion with optical cavities ➔ sophisticated optics and control/synchronization scheme
- World-record long baseline interferometry (storage time)



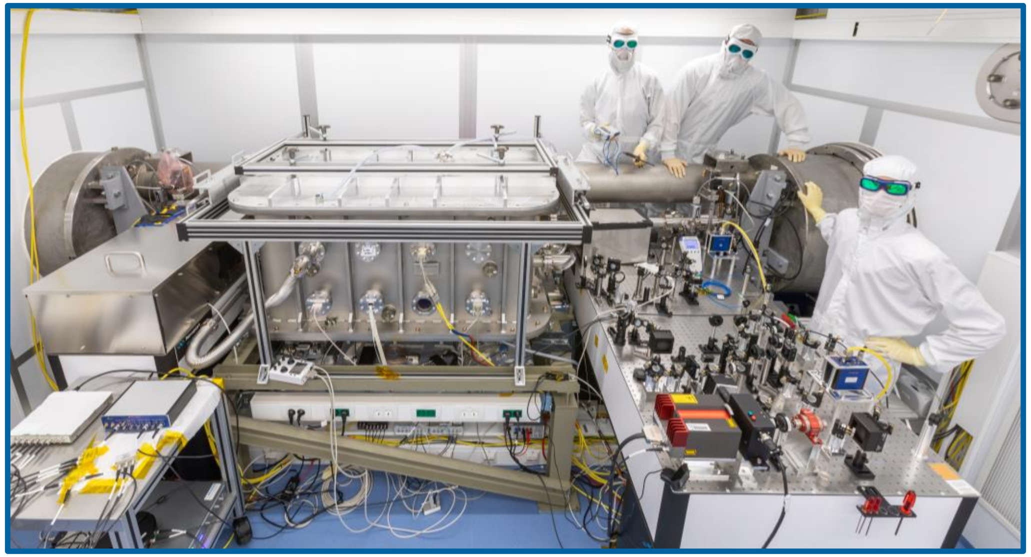
On the road to detectability

ALPS II: The most sensitive Light-Shining-Through-Wall Experiment





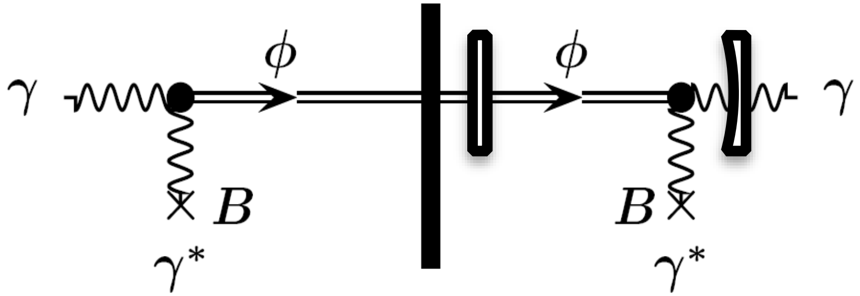
- Repurposed HERA dipole magnets with B=5.3 T
- Resonantly enhance axion-photon conversion with optical cavities
- Total length about 240 m (2 times 106 m cavities)
- High-power laser P_i=40W
- Sensitive heterodyne detection scheme (with cryogenic detectors as second option)



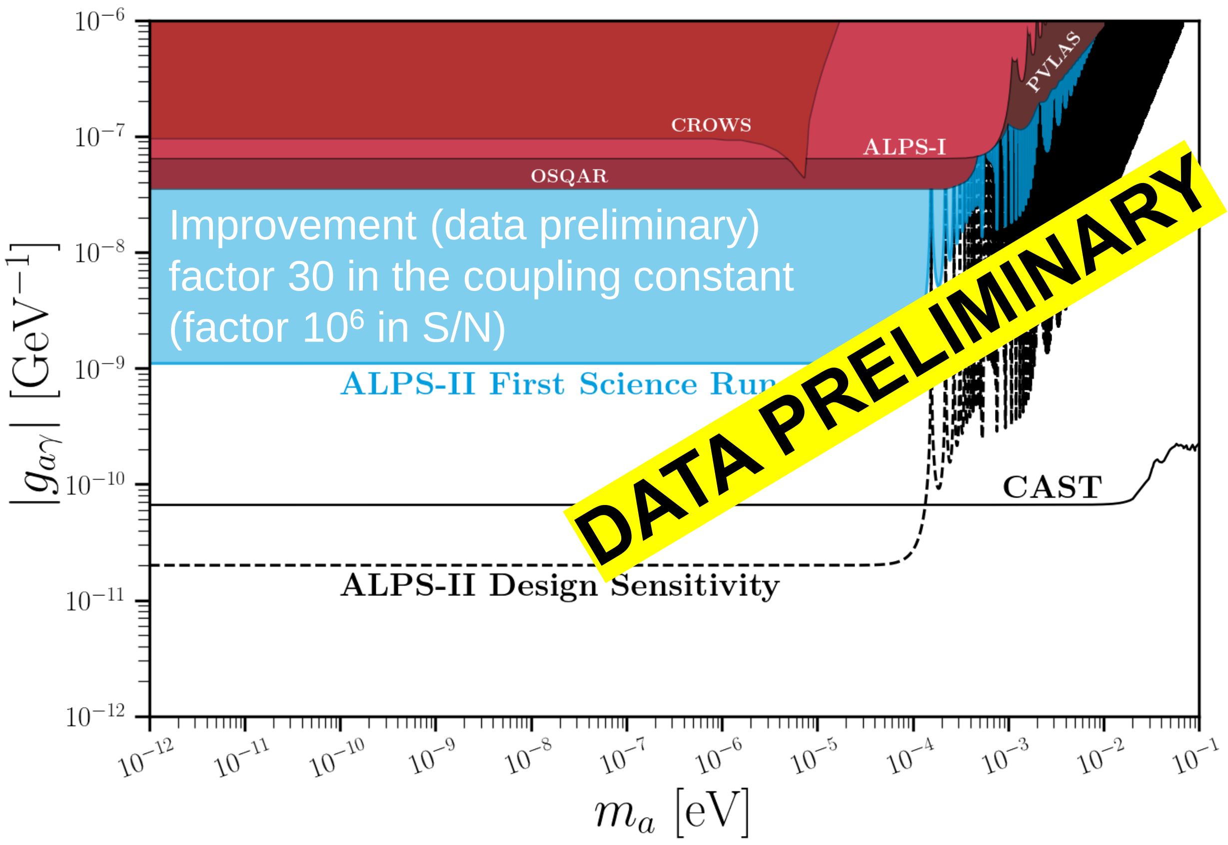
ALPS II: preview of first results

Best laboratory limits

- First science runs in 2024



- Search for axions (pseudo-scalar) and scalar BSM fields
- No signal discovered → Setting broadband limit
- Publication in preparation



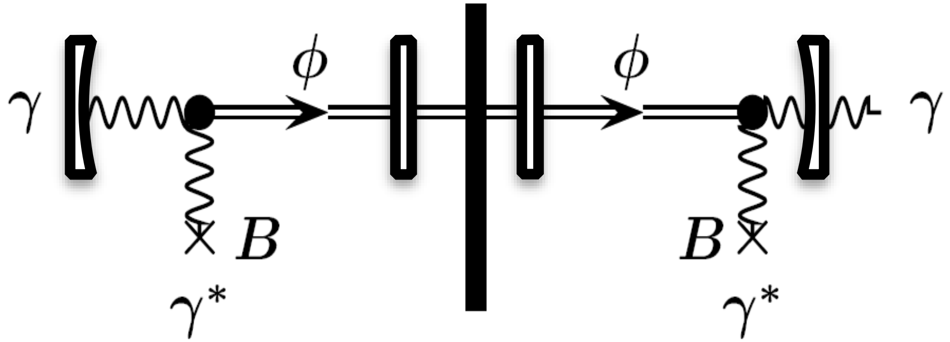
$$P_\gamma = \left(\frac{g_{a\gamma} B L}{2}\right)^4 \eta \beta_R P_i$$

ALPS II on the road to reach design sensitivity

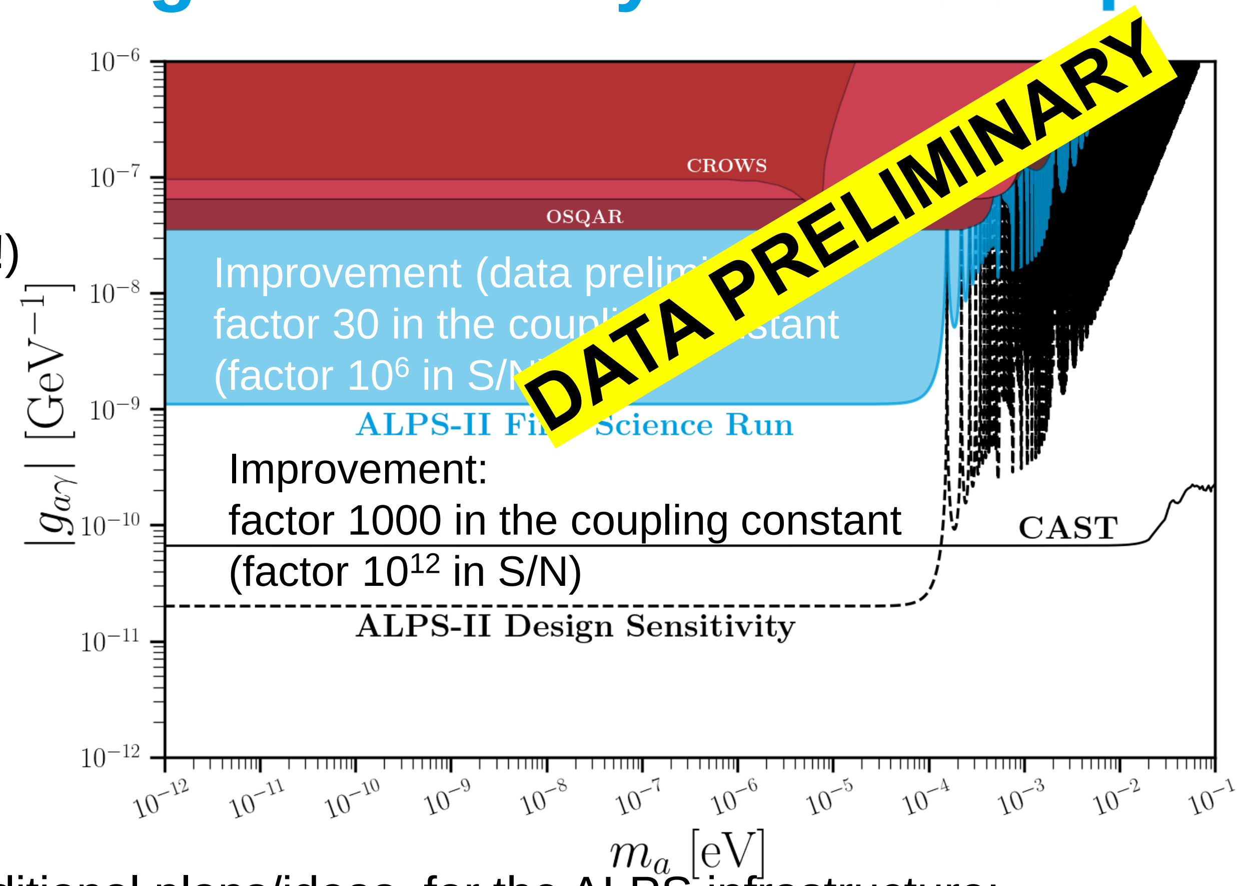
ALPS II plans

Next steps:

- Reduce remaining stray light (already at 10^{-22} W!)
- Install production cavity to boost photon-axion conversion
- Upgrade optics



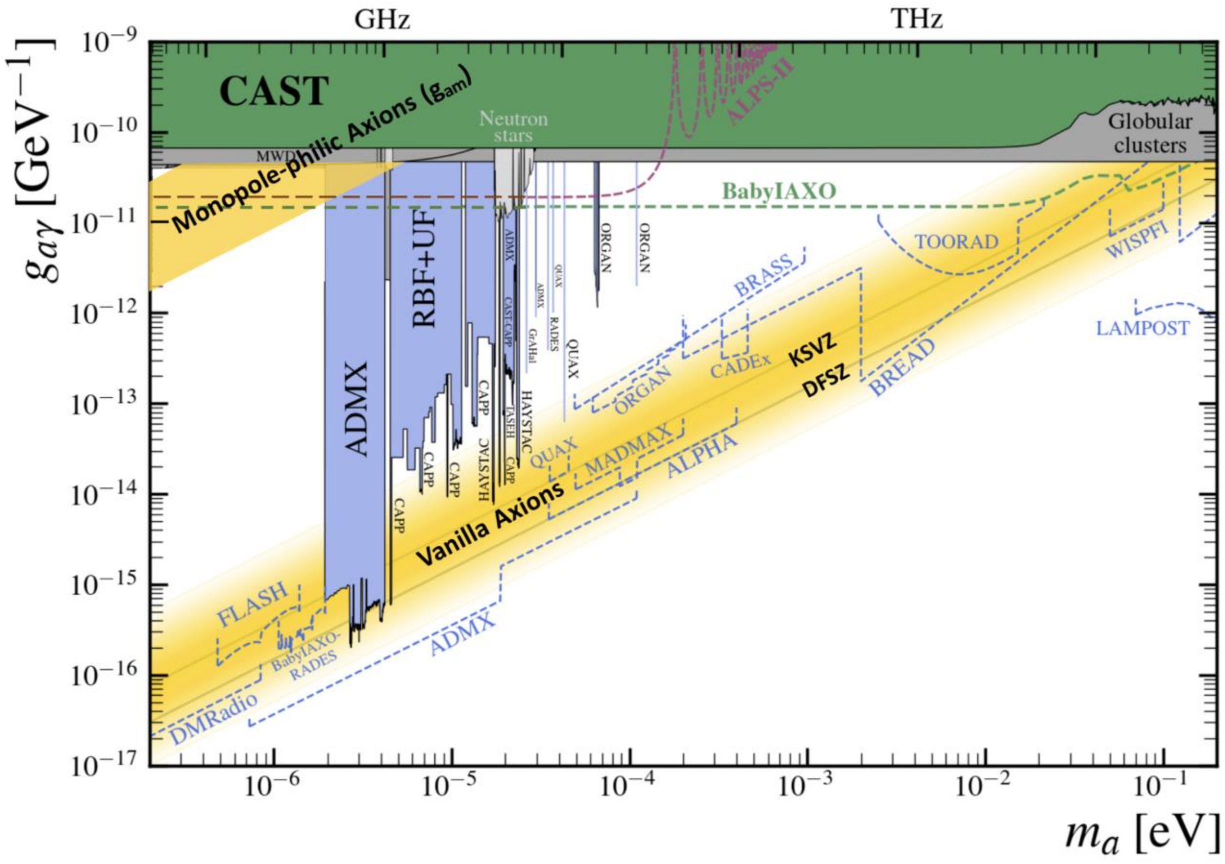
$$P_\gamma = \left(\frac{g_{a\gamma\gamma} BL}{2}\right)^4 \eta \beta_P \beta_R P_i$$



- Additional plans/ideas for the ALPS infrastructure:
  - High precision tests of QED (Vacuum magnetic birefringence)
  - Axion run with a cryogenic detector
  - Axion dark matter searches
  - High-frequency gravitational wave search

Summary & Outlook

- Axion searches are gaining more and more interest.
- Global effort is underway with a variety of experimental techniques focusing on the photon coupling.
- First haloscope searches reach the KSVZ and DFSZ axion band, but depend on the assumption of axions as dark matter.
- Field is dynamic and there is a large potential for new ideas and theory-experiment interactions!
- Technology development is key and new technologies might shed light on the “invisible” axion (quantum technologies!)
- Many new experiments are going to deliver results in the next years ➔ Stay tuned!



arXiv:2404.09036 [hep-ph]