Axion Searches

A *partial* overview of the experimental searches for axions and axion like particles

SOUP School ,16 October 2024

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Summary

- About Axion Physics
- Laboratory experiments
- Helioscopes
- Axion dark matter direct searches

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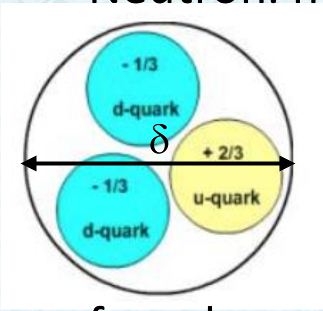
Some Open Questions …

- Despite remarkable success of:
  - Standard Model of particle physics (SM): discoveries of the weak gauge bosons, the top quark, tau neutrino, Higgs boson …
  - Standard cosmological model (ΛCDM): Consistent with all data from the Cosmic Microwave Background, large-scale structure, gravitational lensing, supernovae, clusters, light element abundances, …
- No doubt about need of new knowledge in physics:
  - CPT invariance of SM -> after Big Bang the Universe can't even exist!
    → **Matter-Antimatter asymmetry (violations of barion number, CP and equilibrium)**
  - QCD Lagrangian contains a CP violating term (strong CP problem)
    → EDM for hadrons ≠ 0
    → there should be CP violation in the strong sector
  - we don't understand the *physics* of dark matter, dark energy, or inflation.
    - What is the Dark Matter? No particle of SM can explain DM…
    - Who is the Inflaton?
    - What is the origin of Cosmic Acceleration?
    - Dark Energy or Modification of General Relativity?
      - Λ or dynamical component (e.g., an ultra-light scalar field)?
  - How DM, DE and inflaton fit into extensions of the Standard Model of Particle Physics?
- Beyond GR, ST, GUT, SuGra etc. towards Quantum Gravity?
  - Very hard to devise experiments to test theories

The strong CP problem in QCD

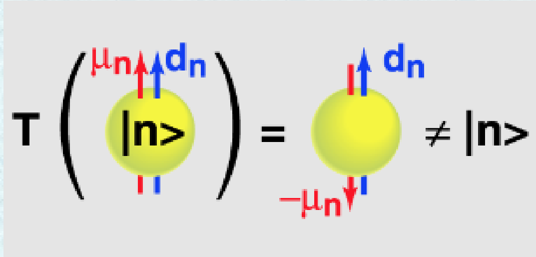
A (permanent) neutron EDM **d_n** that violates CP is expected from simple arguments:

- Neutron: neutral particle but consists of charged quarks



If δ H 0.1 $r_n \rightarrow d_n$ H 4 10^{-14} e cm

experiment says d_n δ 3 10^{-26} e cm

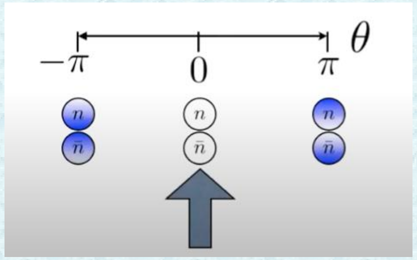


- from low energy effective lagrangian of QCD in standard model

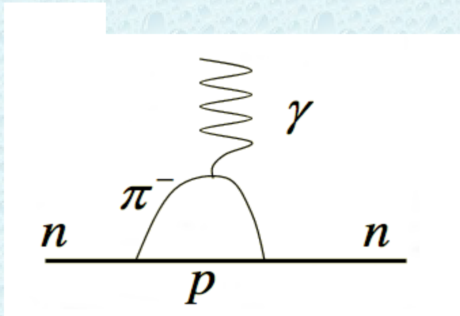
$$\mathcal{L}_{\theta\mathrm{QCD}} = \frac{\theta_{\mathrm{QCD}}}{32\pi^2} \mathrm{Tr}\, G_{\mu\nu}\tilde{G}^{\mu\nu}$$

a term that violates CP (non trivial θ-vacua)

- QCD calculations (perturbative and lattice) lead to a nEDM



$$d_n \approx 3.6 \times 10^{-16} \theta_{\mathrm{QCD}}\, e\ \mathrm{cm},$$



- If besides QCD one includes the weak interactions,
  the quark mass matrix (CKM matrix) is non-diagonal and complex

$$\mathcal{L}_M = \overline{\psi_{iR}}\, M_{ij}\, \psi_{jL} + \text{h.c.}$$

CP is conserved if $M_{CKM} = (M_{CKM})^*$

To diagonalize M one must perform a chiral transformation by an angle of Arg det M which changes θ into

$$\theta_{total} = \theta_{QCD} + \text{Arg det M}$$

Solutions to the Strong CP problem

R.D. Peccei Lect.Notes Phys. **741,** 3-17 (2008)

- The strong CP problem can be stated as follows:

why is the angle θ_{total}, coming from the strong and weak interactions, so small?

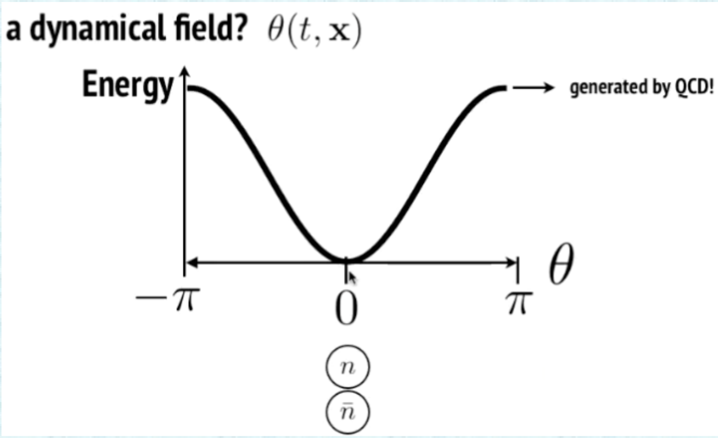
$$\boxed{\theta_{total} \approx 10^{-10}}$$

- There are only three known classes of solutions to the strong CP problem:

1) Anthropic principle: θ_{total} is small from initial conditions (fine tuning)

2) CP is broken spontaneously and the induced θ_{total} is small (the models which lead to $\theta_{total} \approx 10^{-10}$ are rather complex and often are at odds with cosmology)

3) A chiral global symmetry $U(1)_{PQ}$ drives $\theta_{total} \to 0$ i.e. to a CP conserving limit
(only this seems a viable solution, although it necessitates introducing new global, spontaneously broken, chiral symmetry)



QCD AXIONS

- Introducing a global $U(1)_{PQ}$ symmetry, which is necessarily spontaneously broken, replaces:

$$\psi \rightarrow e^{i\alpha\gamma_5}\psi$$

θ $\Rightarrow$ $a(t,x) / f_a$

Static CP Viol. Angle — Dynamical CP conserving Axion field

and, effectively, eliminates CP violation in the strong sector

$$L_\theta = \theta \frac{g^2}{32\pi^2} F_a^{\mu\nu} \tilde{F}_{a\mu\nu} \quad \Rightarrow \quad L_a = \frac{a}{f_a} \frac{g^2}{32\pi^2} F_a^{\mu\nu} \tilde{F}_{a\mu\nu}$$

f_a is the scale of the breaking of the $U(1)_{PQ}$ symmetry , while $a(x)$ is **the Nambu-Goldstone axion field** associated with the broken symmetry [Weinberg, Wilczek]

- Axion particles are excitations of a(t,x)

Almost model independent prediction: a | □^{0} and $m_\pi f_\square \cong m_a f_a$

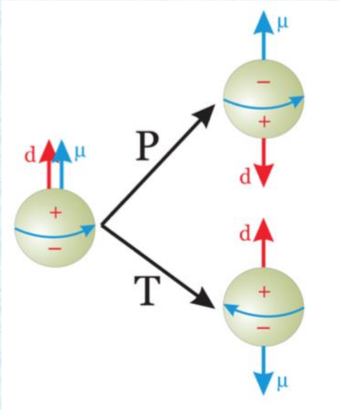
- QCD axion mass with per-mille accuracy!

M. Gorghetto, G.J. Villadoro.
High Energy Phys. **2019,** 33 (2019).

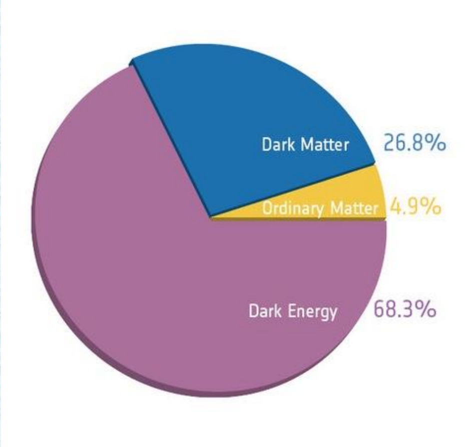
$$m_a = 5.691(51)\,\mu\text{eV}\,\frac{10^{12}\ \text{GeV}}{f_a}\,.$$

…Axion Tentative Solutions…

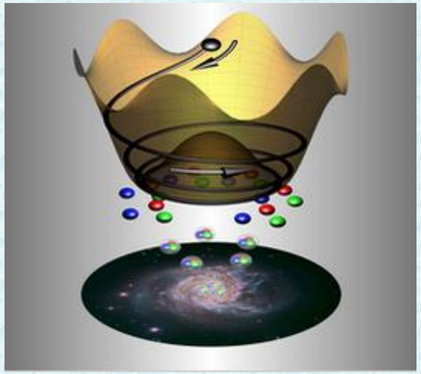
- Axions as solution of strong CP problem in QCD
  - neutron EDM ($d_n<10^{-26}$ e cm)
    - Why so small? (QCD prediction 10^{-16} e cm)
    - Solution as dynamical (CP conserving) axion field
    - Axion models DSKZ and SKVZ



- Axions as CDM in cosmology
  - Need for Dark Matter from precision cosmology
  - Axion can be efficiently produced in the Early universe
  - A **light axion** (m_a < eV) can solve DM mystery
    - Axion & Cosmology, Axion & Astrophysics
    - DM Halo (different models)
    - Cosmic Axion Background (CaB)



- Axion as source of matter-antimatter asymmetry
  - Kinetic term θ from explicit breaking of the axion shift symmetry in the early Universe
  - Phys. Rev. Lett. 124, 251802 (2020); Phys. Rev Lett. 124, 111602 2020



- Axion field driving inflation

Axions?

PHYSICAL REVIEW D VOLUME 18, NUMBER 5 1 SEPTEMBER 1978

Do axions exist?

T. W. Donnelly, S. J. Freedman, R. S. Lytel, R. D. Peccei, and M. Schwartz
Institute of Theoretical Physics, Department of Physics, Stanford University, Stanford, California 94305
(Received 21 March 1978)

We critically examine various existing experiments which could provide evidence for the axion. Although our conclusions regarding the existence of this particle are somewhat pessimistic, we discuss other possible experiments which could throw additional light on this question.

- The Peccei Quinn Weinberg Wilczek (**PQWW**) axion model:

R. Peccei,H.R. Quinn, PRL38(1977)1440
R. Peccei,H.R. Quinn, PRD16(1977)1791
S. Weinberg, PRL40(1978)223
F. Wilczek, PRL40(1978)279

PQ simmetry breaking at the electroweak scale **f_a ~ 250 GeV -> m_a ~ 100 keV**

- Searched for and **ruled out in several beam dump experiments.**

Electron beam dump @ SLAC

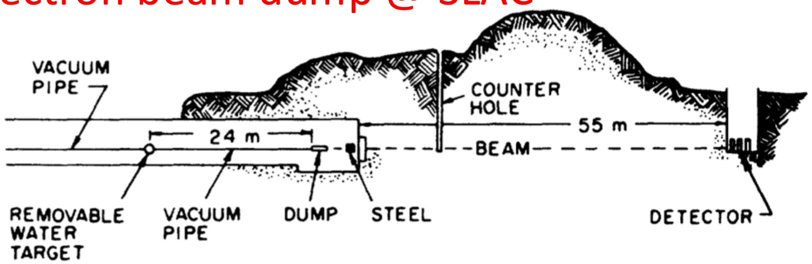
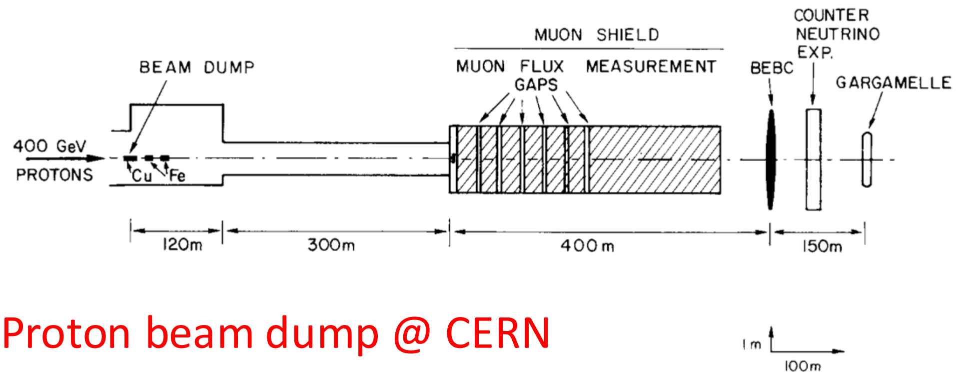


FIG. 2. Schematic of the SLAC beam-dump experiment showing the location of the detector and shielding in relation to the end station A beam dump.

PRD 18, 1607 (1978)



Proton beam dump @ CERN

Fig. 1. Layout of the CERN SPS proton beam dump experiments.

PLB 74, 143 (1978)

Other models for the axion

- However, other **axion models (QCD axion) have been devised**

Dine-Fischler-Srednicki-Zhitnitskii (DFSZ)

M.Dine,W.Fischler,M.Srednicki,Phys.Lett.104B(1981)199
A.R.Zhitnitsky,Sov.J.Nucl.Phys.31(1980)260

- 2 extra Higgs doublets
- New complex scalar

Kim-Shifman-Vainstein-Zakharov(KSVZ)

J.E.Kim,PRL43(1979)103
M.A.Shifman,A.I.Vainshtein,V.I.Zakharov,NPB166(1980)493

- New extra heavy quark
- New complex scalar

- solutions to the strong CP problem that conveniently avoid all constraints from laboratory searches and stellar evolution by making $\boldsymbol{f_a}$ **arbitrarily large**

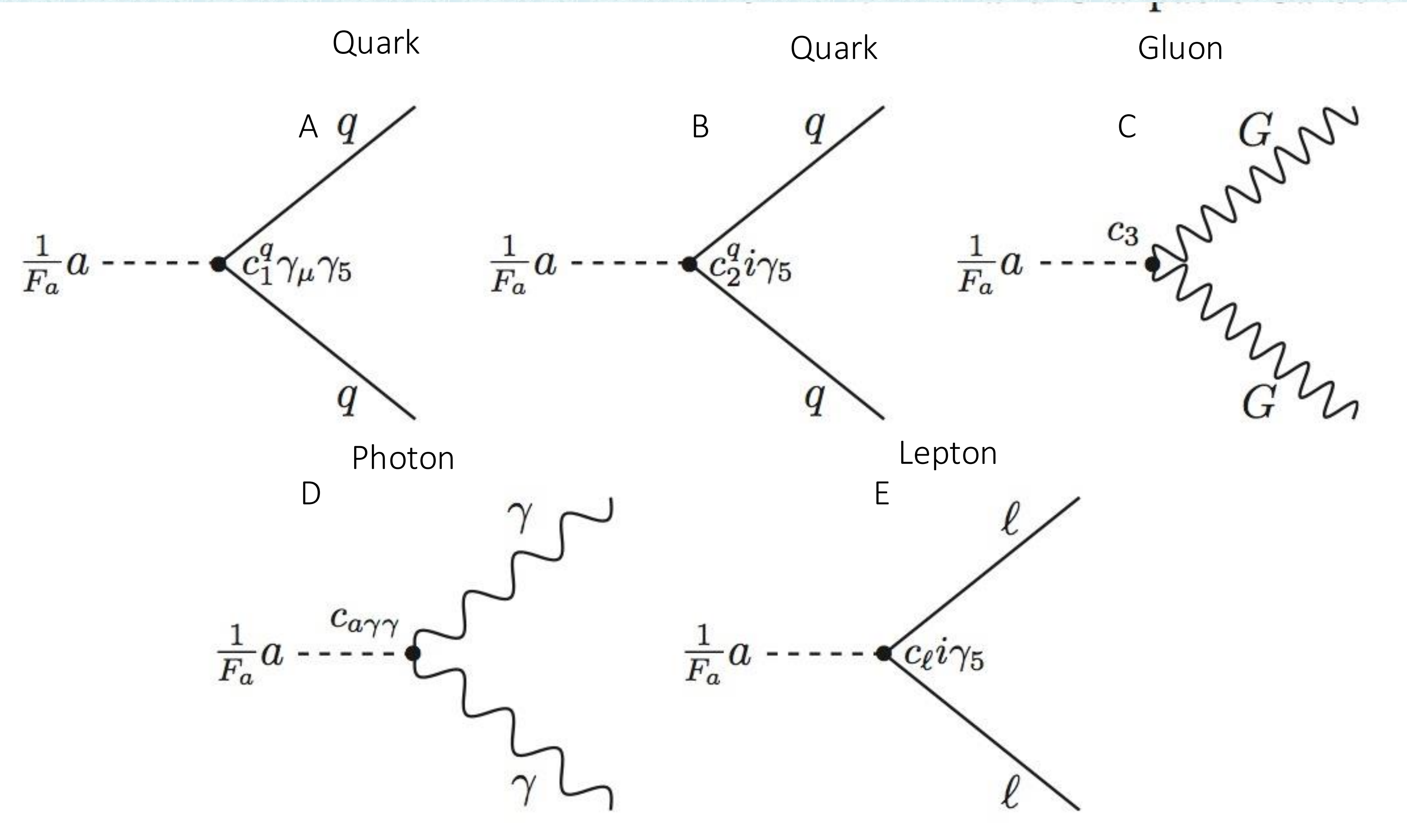
  - **low mass (*m_a* < eV)** and **very weak couplings** for $\boldsymbol{f_a} \gg v_{weak}$

- e.g. for PQ symmetry breaking at the grand unification scale 10^{15} GeV, all axion production and interaction rates suppressed by 25 orders of magnitude relative to those of the PQWW axion
- It was born the idea of the **"invisible axion",** that continues to **evade all current experimental searches**
- **Models list not exhaustive**, axions can be embedded in SUSY or GUT
- Fortunately, the **finite age of the Universe** implies a limit on how large $\boldsymbol{f_a}$, or equivalently **how small $\boldsymbol{m_a}$**, can be

The axion
- could affect **cosmology**
- could affect **stellar evolution**
- could mediate **new long range forces**
- could be **produced in terrestrial laboratory**
- could be a main component of **Dark Matter**

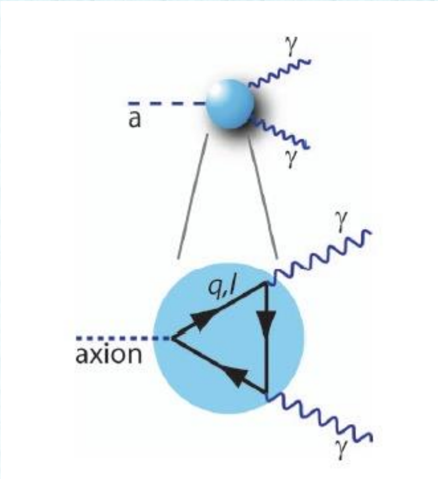
Axion interactions

- Several interactions are possible



Axion interactions 2

- Axion interactions are model dependent, normally small differences between models



Axion photon photon

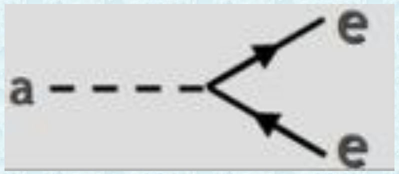
$$\mathcal{L}_{a\gamma\gamma} = -\left(\frac{\alpha}{\pi}\frac{g_\gamma}{f_a}\right) a\vec{E}\cdot\vec{B} = -g_{a\gamma\gamma}\, a\vec{E}\cdot\vec{B}$$

g_γ = 0.36 (DFSZ)

g_γ = - 0.97 (KSVZ)

$$g_{a\gamma\gamma} = g_\gamma \frac{\alpha}{\pi}\frac{m_a}{m_\pi f_\pi}$$

Axion electron electron



$$L_{aee} = -\, g_e \bar{e} i \gamma_5 e a$$

$$g_e \approx \frac{m_a m_e}{m_\pi f_\pi} = 4.07 \times 10^{-11} m_a$$

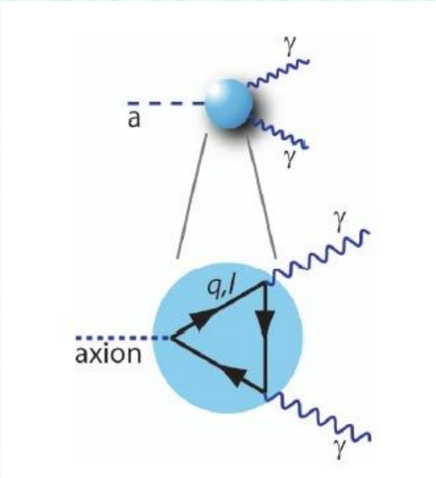
(DFSZ)

g_e ~ 0 (Strongly suppressed) (KSVZ)

All couplings are extremely weak!

Axion interactions 3

- Axion interactions are now model dependent



Axion photon photon

$$\mathcal{L}_{a\gamma\gamma} = -\left(\frac{\alpha}{\pi}\frac{g_\gamma}{f_a}\right) a\vec{E}\cdot\vec{B} = -g_{a\gamma\gamma} a\vec{E}\cdot\vec{B}$$

g_γ = 0.36 (DFSZ)

g_γ = - 0.97 (KSVZ)

- If the axion mass is lighter than 2 m_e, we can calculate its lifetime

$$\tau(a\to 2\gamma) = \frac{2^8\pi^3}{g_\gamma^2\alpha^2}\frac{f_a^2}{m_a^3} \approx \frac{3.65\times 10^{24}}{g_\gamma^2}\left(\frac{\mathrm{eV}}{m_a}\right)^5 \mathrm{s}$$

$$\approx \frac{0.8\times 10^{7}\, t_U}{g_\gamma^2}\left(\frac{\mathrm{eV}}{m_a}\right)^5$$

Where $t_U \approx 4\ 10^{17}$ s is the age of the Universe

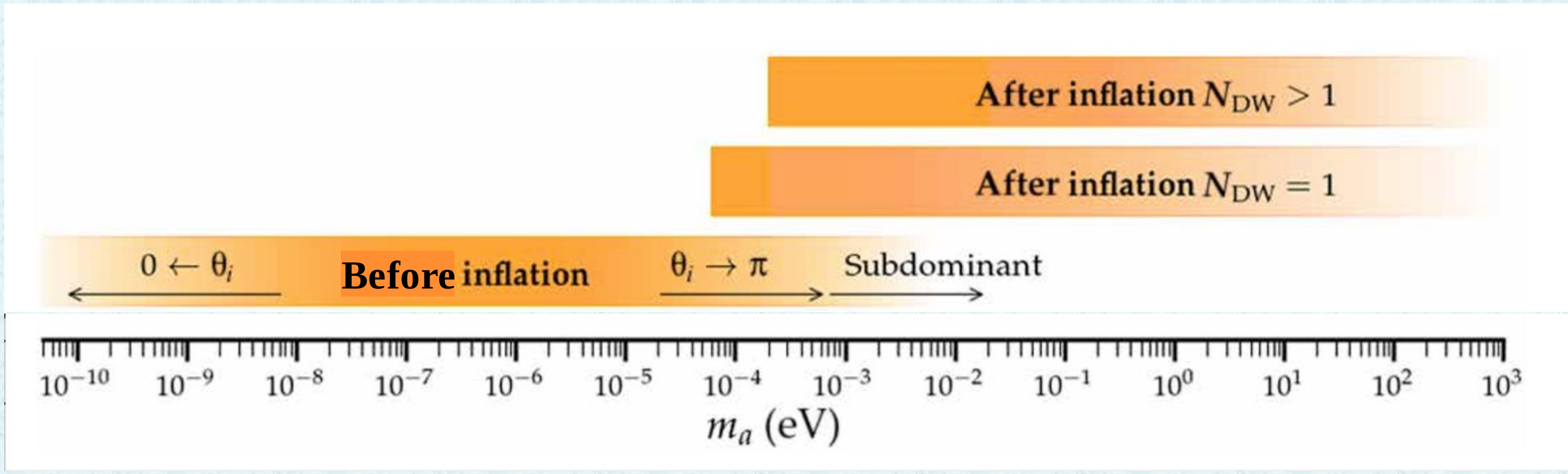
For $g_\gamma \approx 1$ an axion of mass 24 eV has the lifetime corresponding to t_U.

Cosmological axion origin

- In the early universe axions are produced by processes involving quarks and gluons -> **Hot dark matter (BAD)**
- Other mechanisms in the early Universe are non-thermal: the *vacuum realignment mechanism* and the *decay of topological defects* (axion strings and domain walls) → **Cold dark matter (GOOD)**
- *Vacuum realignment mechanism*: relaxation of the axion field after breakdown of the PQ symmetry → The expected cosmic mass density of axions depends on whether inflation happens after or before PQ breakdown

Allowed regions of mass (decay constant)

- These regions obtained by **assuming axion saturate DM density**. Lower values of m_a would overproduce DM while higher masses would lead to subdominant amount of axion DM
- If axions exist at least a fraction of DM are axions



The pre- and post- inflationary scenarios

- Difference between the pre- and post- inflationary scenarios is **predictability**:

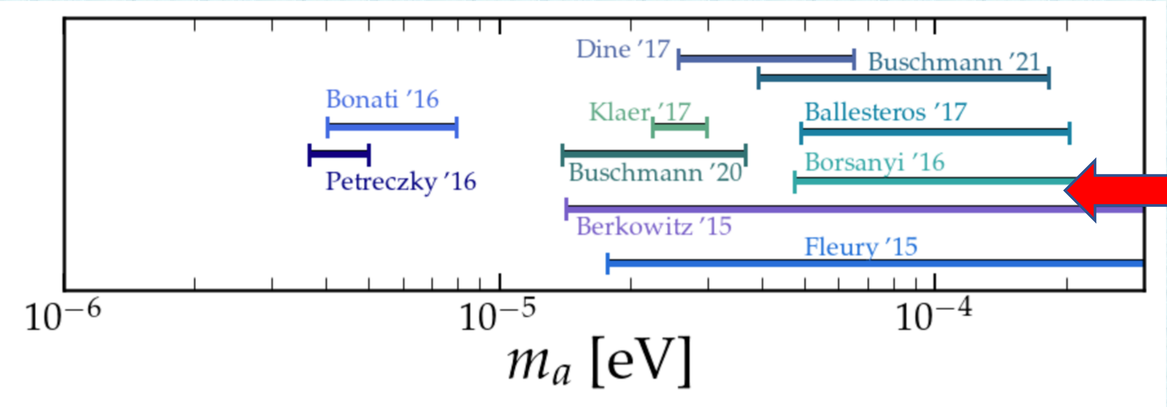
  - In **pre-inflationary** there are **two continuous free parameters**, an angle θ and the mass m_a, to obtain the observed dark matter density

  - In **post-inflationary** there is one continuous parameter, m_a, and a discrete one N.
    - ➢ **In principle the observed DM density predicts the value of m_a**
    - ➢ Due to nonlinearities, computing this mass accurately is a real challenge
    - ➢ Recent works make use of large static lattice simulations

SciPost Select — SciPost Phys. 10, 050 (2021)

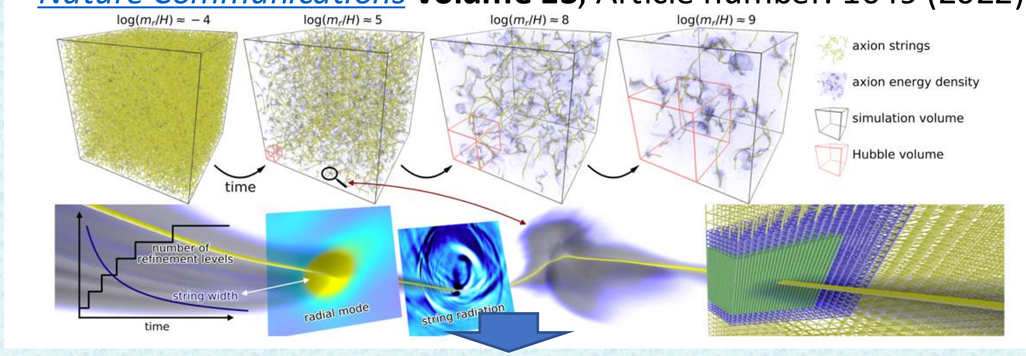
More axions from strings

Marco Gorghetto[1], Edward Hardy[2] and Giovanni Villadoro[3]



Post-inflationary scenario

Nature Communications **volume 13**, Article number: 1049 (2022)



ARTICLE — Check for updates

https://doi.org/10.1038/s41467-022-28669-y OPEN

Dark matter from axion strings with adaptive mesh refinement

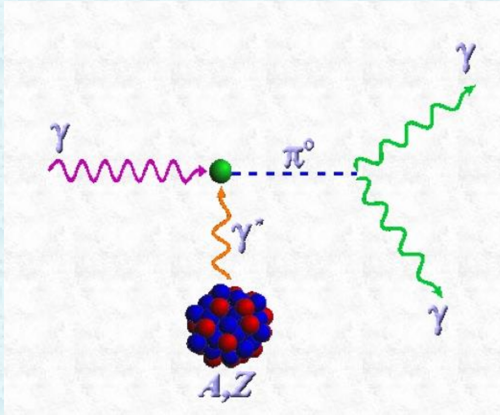
Malte Buschmann[1✉], Joshua W. Foster[2,3,4✉], Anson Hook[5], Adam Peterson[6], Don E. Willcox[6], Weiqun Zhang[6] & Benjamin R. Safdi[3,4✉]

$m_a \in (40, 180)$ **microeV**

Can we detect axions?

- Searching for axion extremely challenging
- Exploit coherence effect over macroscopic distance/long times
- Most promising approach: use axion-photon-photon vertex

Primakoff effect:
scattering from an electromagnetic field (virtual photon)

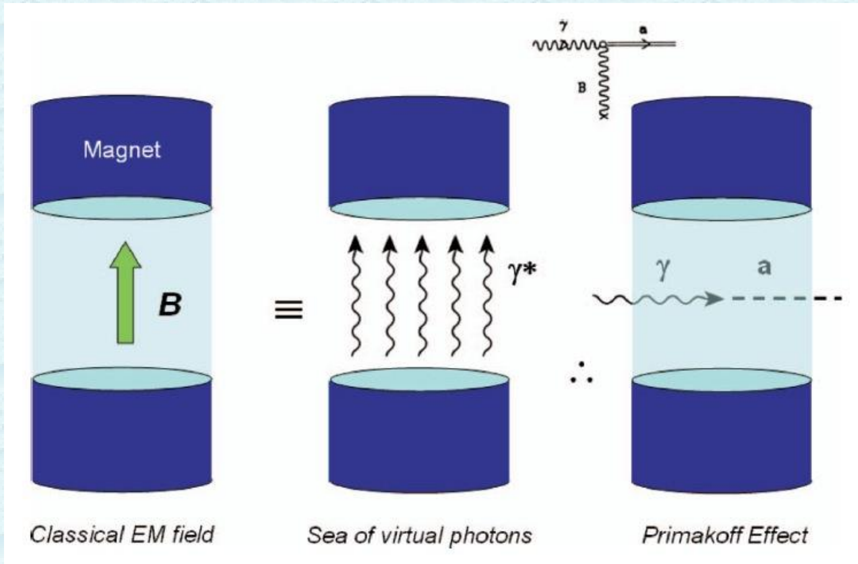


In the presence of an **external field** (magnetic or electric) the **axion and the photon mix** and give rise to **oscillation/conversion**

$$-g_{a\gamma\gamma} a \vec{E}\cdot\vec{B}$$

- **Higher magnetic field are easily obtainable than electric fields.**
- **Strong magnetic fields are key ingredient of all axion searches**

$$g_{a\gamma\gamma} = g_\gamma \frac{\alpha}{\pi}\frac{m_a}{m_\pi f_\pi}$$



G. Carosi et al, Contemp. Phys. 49, 281 (2008)

Axion Like Particles (ALPs)

- An ALP is a particle having **interactions similar to the axion**, whose origin is expected to be similar, but with **different relation**, respect to the axion, between coupling constants and mass → **in general UNRELATED**
- For example, string theory predicts a large spectrum of ALPs, pseudo Nambu Goldstone boson of a symmetry spontaneously broken at very high energy
- For example, in the case of the photon coupling

$$\boxed{L_{ALP} = \frac{1}{2}\partial^{\mu} a\, \partial_{\mu} a - \frac{1}{2} m^2_{ALP} a^2 - g_{a\gamma\gamma} \vec{E}\cdot\vec{B}\, a}$$

With $g_{a\gamma\gamma}$ a free parameter to be determined experimentally

- **Experimental searches are mainly directed to ALPs**, in order to relax the coupling parameter. Experiments looking for the ALPs are, in principle, sensitive also to the axions.
- We will often be using the word axion in a generic way including ALPs, explicitly saying **QCD axion for that ALP that solves the strong CP problem**

WISPs

- **W**eakly **I**nteracting **S**lim **P**articles include a much wider lists:
  - Axion and Axion Like Particles
  - Hidden Photons
  - Milli Charged Particles
  - Chameleons, massive gravity scalars
- Many of them share properties of the axion, and in principle could be searched for by the experiments that will be showed
- It will be difficult to attribute a possible **discovery signal** to exactly the QCD axion → as **many different signals as possible needed in order to discriminate between QCD axion and ALPs**

Main detection strategies

A global list – not necessarily complete

A. Pure laboratory experiments:
   1. Polarization experiments
   2. Light shining through walls (LSW)
   3. Fifth force measurements

B. Solar helioscopes

C. Dark matter haloscopes and other DM receivers

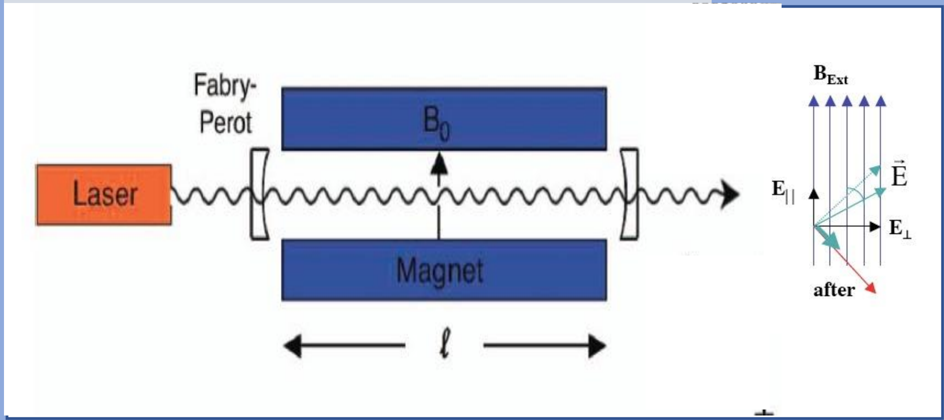
D. Astrophysics, cosmology: stellar evolution/dynamics, γ ray transparency

Detection schemes

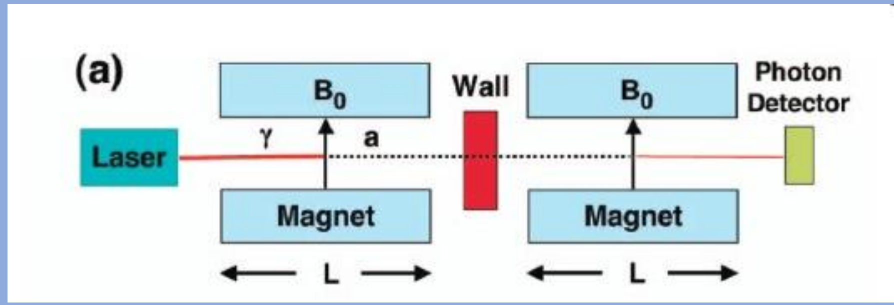
- Most of the searches based on the **axion-photon coupling**

A **Production and detection of axions in a terrestrial laboratory**

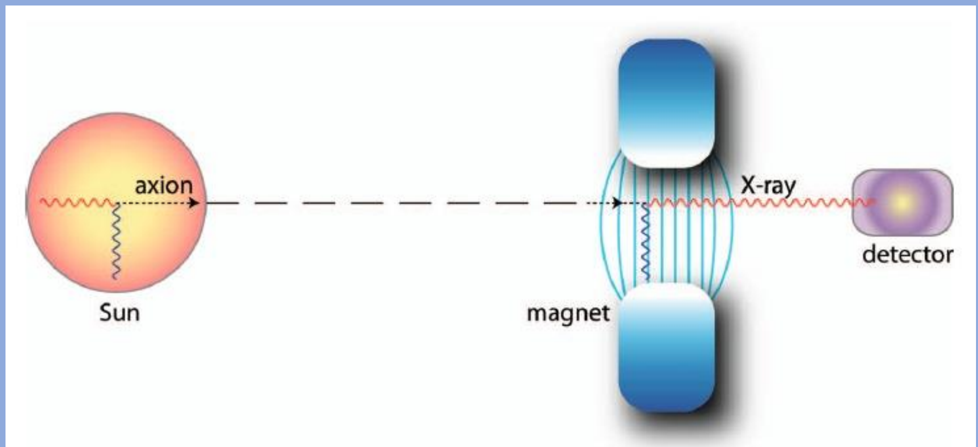
Polarization experiments



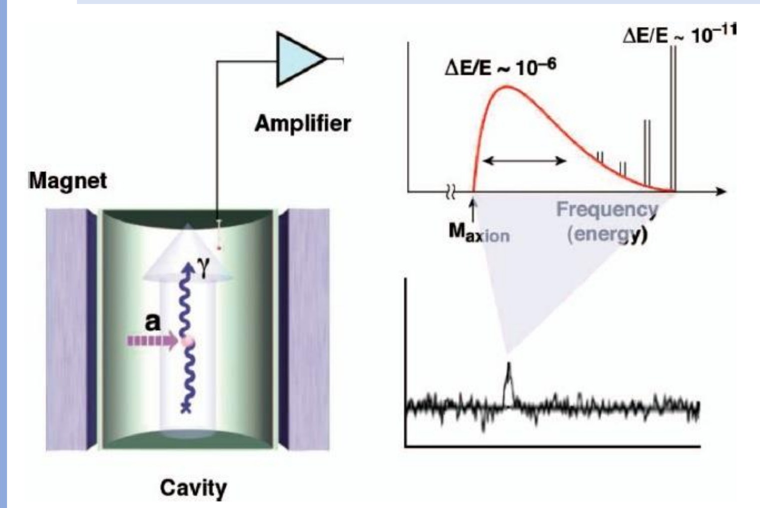
Light shining through walls



B **Detection of axions coming from external sources (Sun)- Helioscopes**

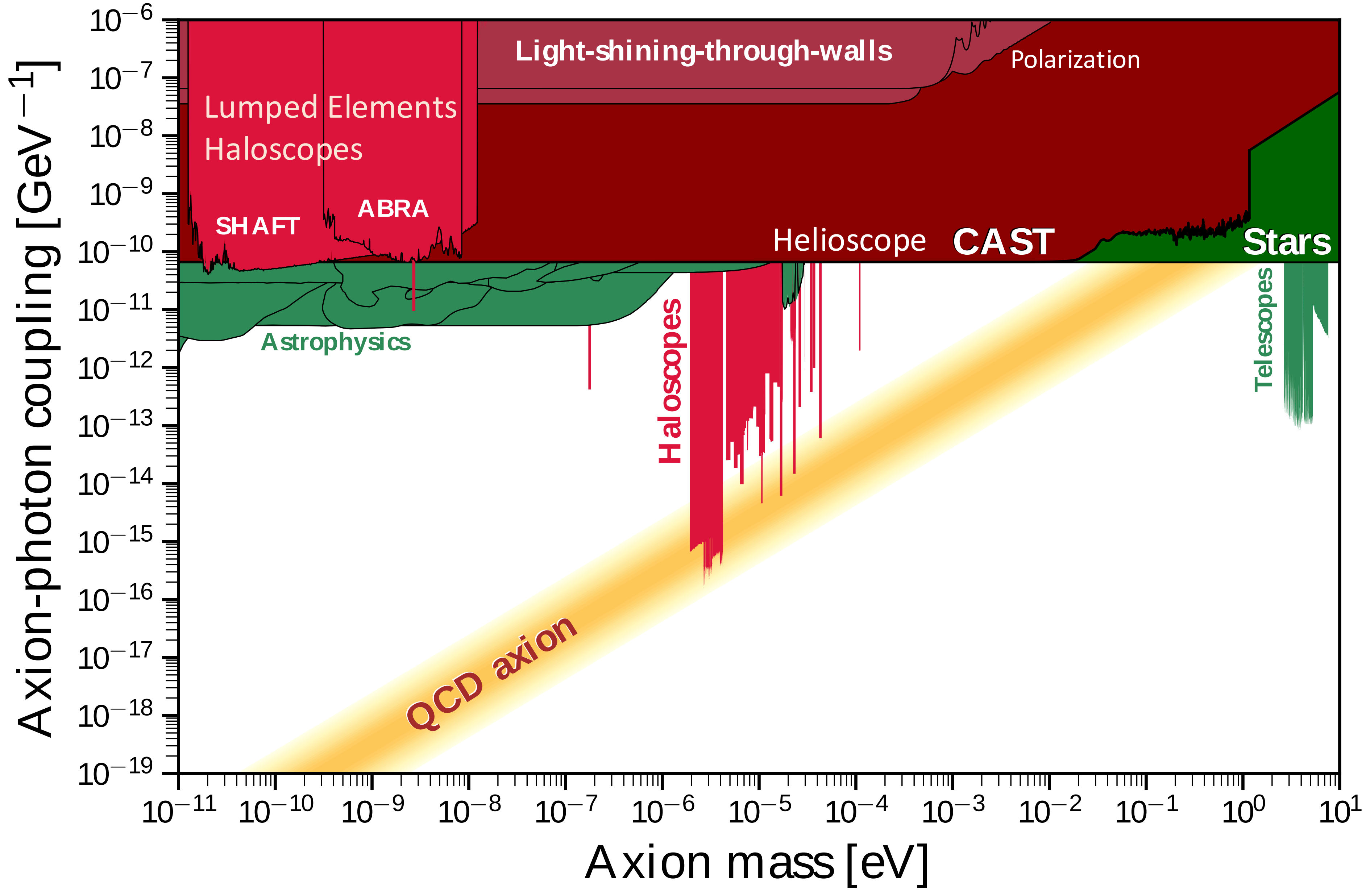


C **Detection of axions present into the Galactic Halo -Haloscopes**



All pictures from: G. Carosi et al, Contemp. Phys. 49, 281 (2008)

Current constraint – Axion Photon Coupling

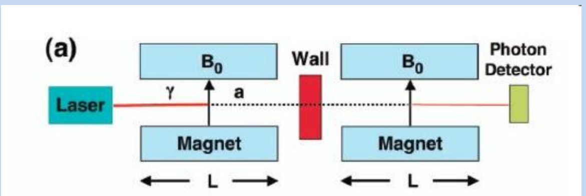


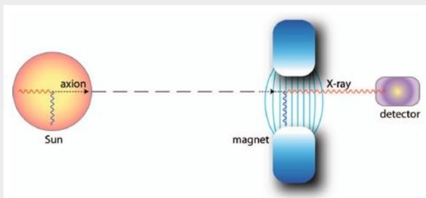
https://cajohare.github.io/AxionLimits/docs/ap.html

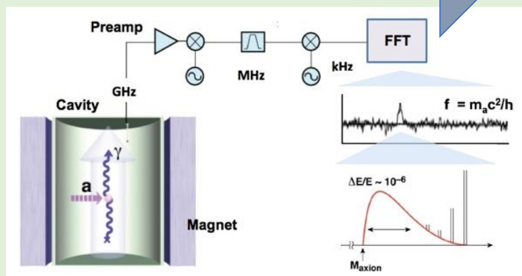
$$\nu_a = 0.24\left(\frac{10^{-6}\ eV}{m_a}\right)\ \text{GHz}$$

Comparison

Lab Experiments	Helioscopes	Haloscopes
Axion Like Particle	ALPS & QCD Axion	ALPS & **QCD Axion**
Wide band experiment	Wide band experiment	Resonance experiment
Optical photons	X rays photons	Microwave photons
Model independent	Model dependent	Strong model dependency
Low axion flux	Medium axion flux	High axion flux
Low sensitivity to alps coupling	Good sensitivity to alps coupling; high mass axion	Reaches axion models

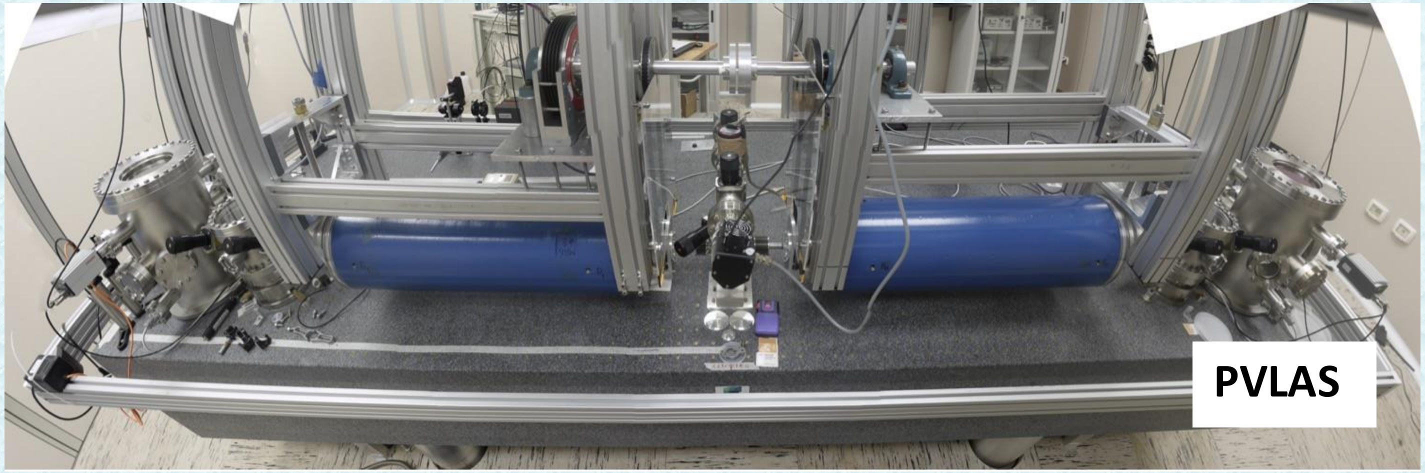




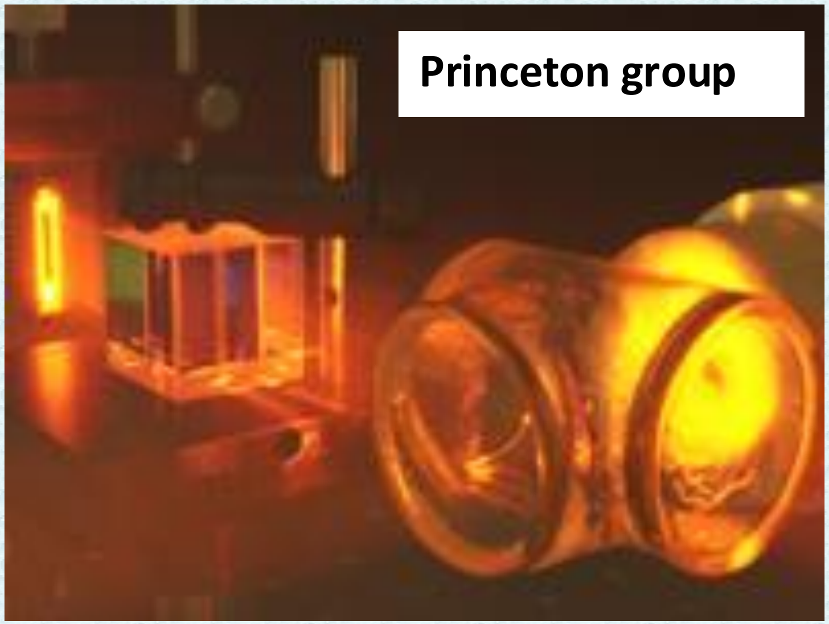


[A] Pure laboratory experiments

Polarization experiments



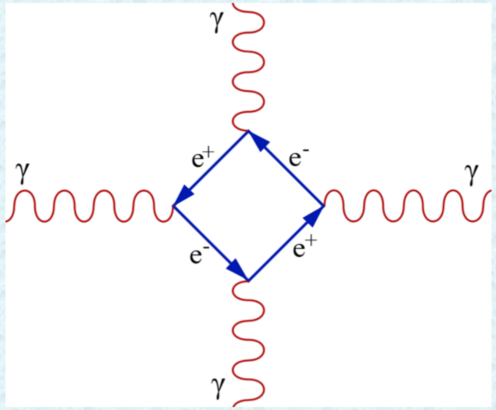
Fifth force measurements



Light shining through walls

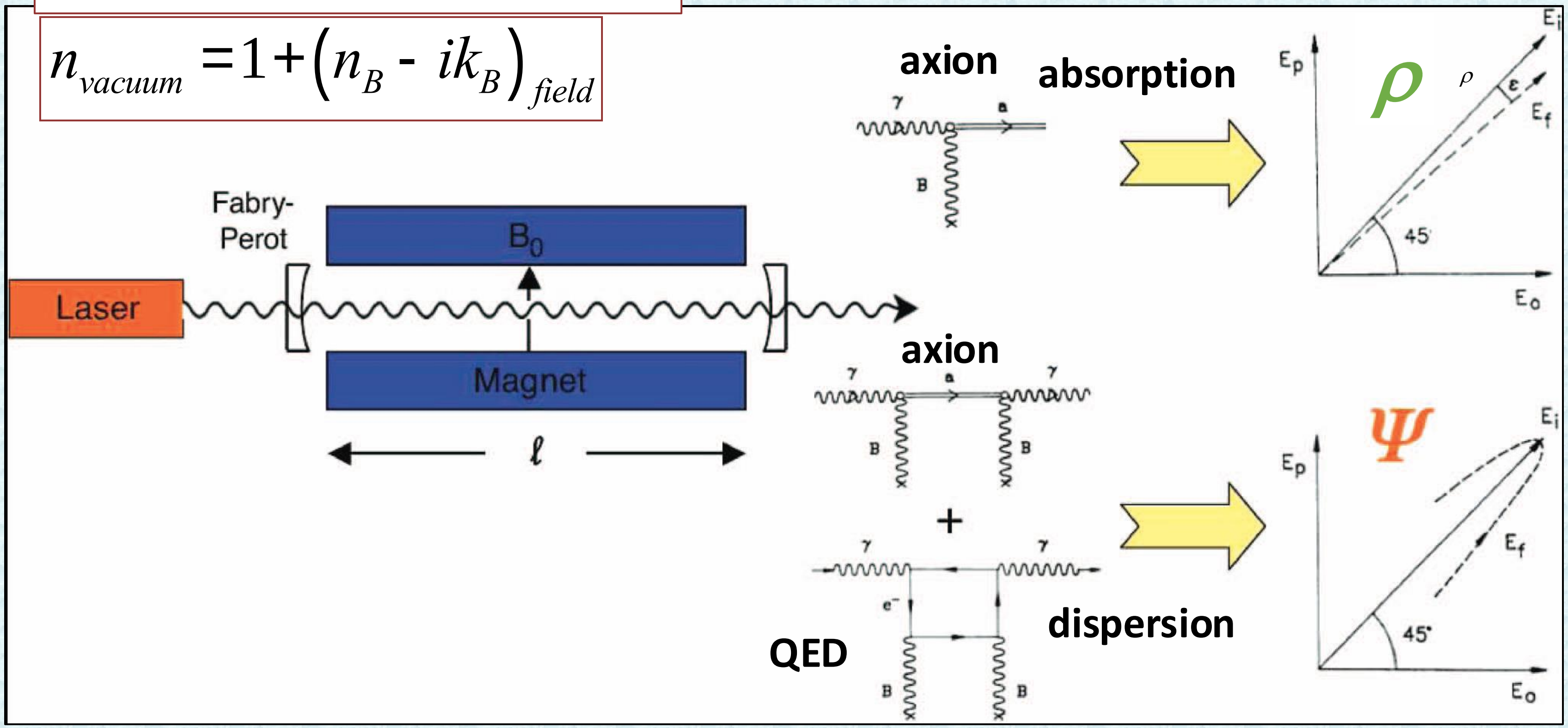
[A.1] Pure lab: Polarization experiments

- Seminal paper by Maiani, Petronzio and Zavattini (1986)
- Experiments aiming at measuring the **magnetic birefringence of vacuum (QED)**
- A **linearly polarised optical** beam traverses a static dipolar magnetic field region: an **ellipticity ψ** and a **dichroism ρ** indicate **virtual and real production of axions**



Index of refraction of vacuum

$$n_{vacuum} = 1 + \left(n_B - ik_B\right)_{field}$$



Two independent measurements: rotation ρ and ellipticity ψ

[A.1] Pure lab: Polarization experiments II

- A **linearly polarised optical** beam (frequency ω) traverses a static dipolar magnetic field region: an **ellipticity** ψ and a **dichroism** ρ indicate **virtual and real production of axions**

Index of refraction of vacuum

$$n_{vacuum} = 1 + \left(n_B - ik_B\right)_{field}$$

$$\Delta n = n_{\parallel} - n_{\perp} \neq 0$$
$$\Delta k = k_{\parallel} - k_{\perp} \neq 0$$

$$\Delta n^{(QED)} = 4 \times 10^{-24}\ \mathrm{T}^{-2}$$

Measured effects | **Relation with axion parameters**

$$\rho = \frac{2\pi LN}{\lambda} \Delta k \sin 2\vartheta \qquad |\Delta k| = 2\left(\frac{g_{a\gamma\gamma} B_0 L}{4}\right)^2 \left(\frac{\sin x}{x}\right)^2$$

$$x = \frac{m_a^2 L}{4\omega}$$

$$\psi = \frac{\pi LN}{\lambda} \Delta n \sin 2\vartheta \qquad |\Delta n| = \frac{g_{a\gamma\gamma}^2 B_0^2}{2m_a}\left(1 - \frac{\sin 2x}{2x}\right)$$

Natural Heaviside – Lorentz units

N – number of passes, L – length of magnetic field region
ϑ – angle between light polarization and magnetic field B_0

From two independent measurement we get coupling constant $g_{a\gamma\gamma}$ and mass m_a

[A.1] Pure lab: Polarization experiments III

- A **linearly polarised optical** beam (frequency ω) traverses a static dipolar magnetic field region: an **ellipticity** ψ and a **dichroism** ρ indicate **virtual and real production of axions**

High magnetic dipolar field B

$$\psi, \rho \propto B^2$$

Optical cavity to **amplify** signal:
Fabry Perot resonator with **finesse F**

$$N = \frac{2F}{\pi}$$

Ultra high sensitivity polarimetry: modulation of the effect for heterodyne/homodyne detection scheme

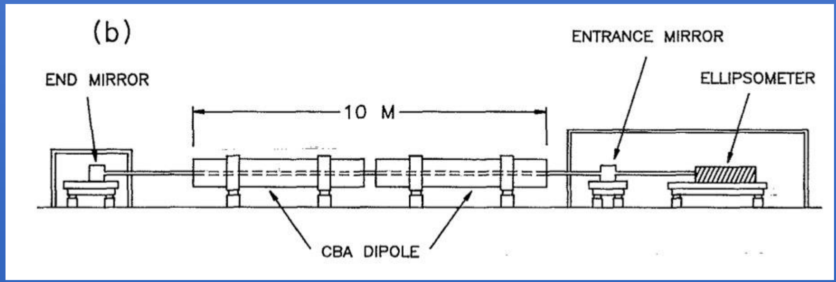
Peak sensitivity depends on magnet length *L*

$$m_a \leq \sqrt{\frac{2\pi\omega}{L}} \approx 1\,\mathrm{meV}$$

Polarization experiments apparatuses

BFRT (Brookhaven-Fermilab-Rochester-Trieste)
1988 - 1992

Multipass cavity
N ~ 500



PVLAS @ Legnaro (1992 – 2008)

Fabry-Perot
N ~ 50 000

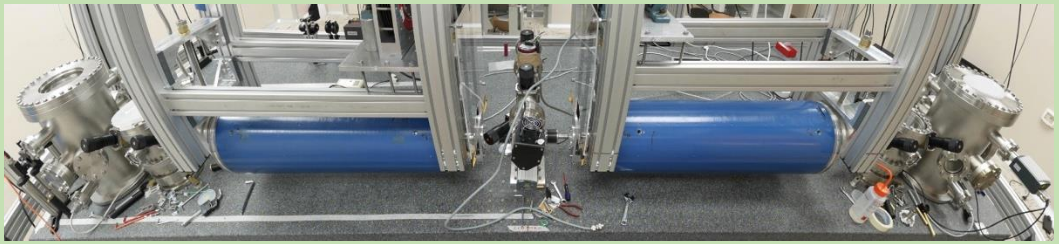
5 T
Rotating Super-conducting Magnet

BMV @ Toulouse (going on)

Fabry Perot
N ~ 300k

Pulsed Magnets

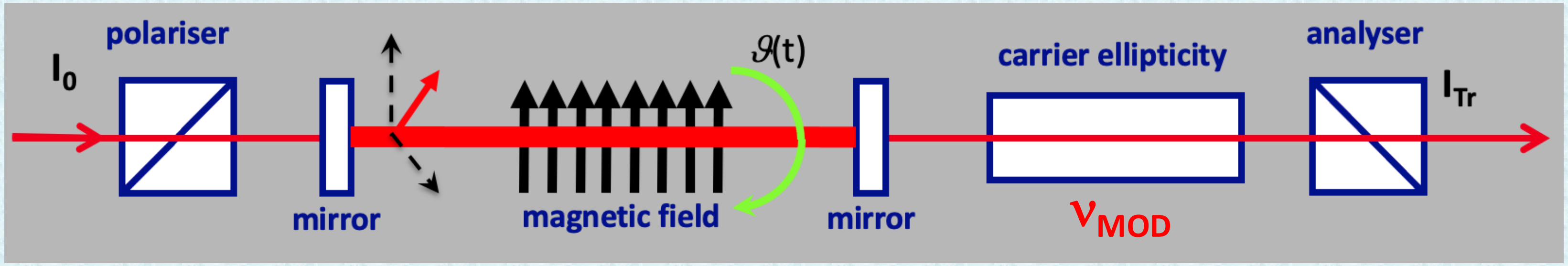
PVLAS @ Ferrara (2009-2019)
Rotating permanent magnets
Fabry Perot N ~ 500k



Other apparatuses: **Q&A (Taiwan), OSQAR (CERN)**

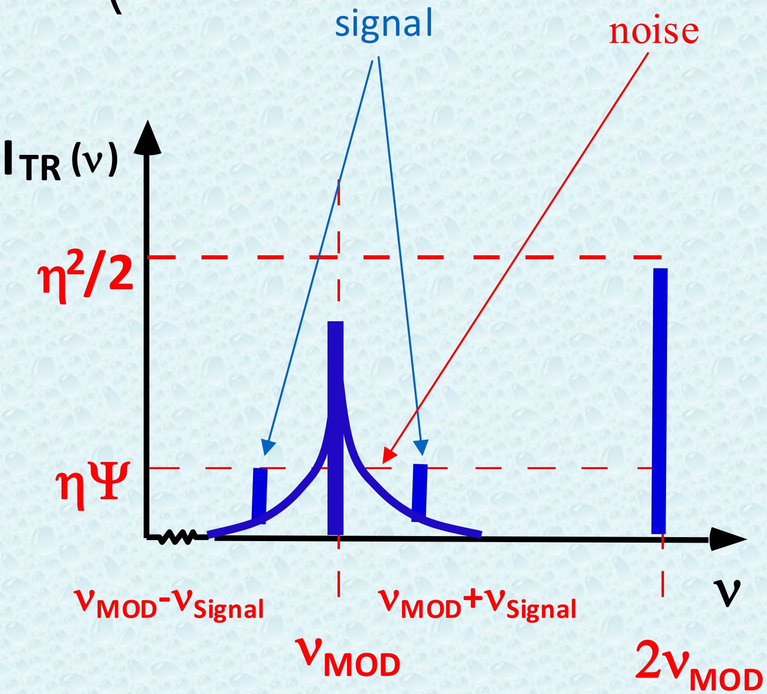
Experimental scheme – Heterodyne (PVLAS)

Modulation of the effect allows to increase sensitivity



$$I_{Tr} = I_0\left[\sigma^2 + \left(\psi(t) + \eta(t) + \alpha_s(t)\right)^2\right]$$

$$= I_0\left[\sigma^2 + \left(\eta(t)^2 + 2\psi(t)\eta(t) + 2\alpha_s(t)\eta(t) + \ldots\right)\right]$$



$$\psi(t) \propto \frac{\pi L N}{\lambda} B^2 \sin 2\theta(t)$$

Modulations:

- Field direction
- Field amplitude
- Polarization direction

Integration with time allows to look for weak signal since noise scales as 1/√t

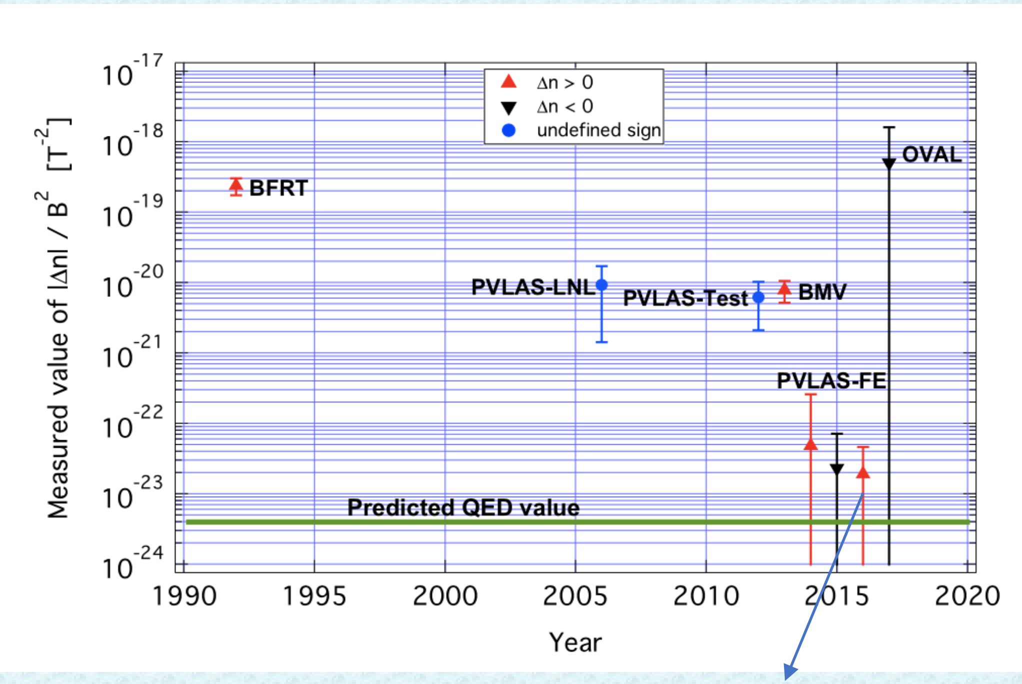
PVLAS @ Ferrara

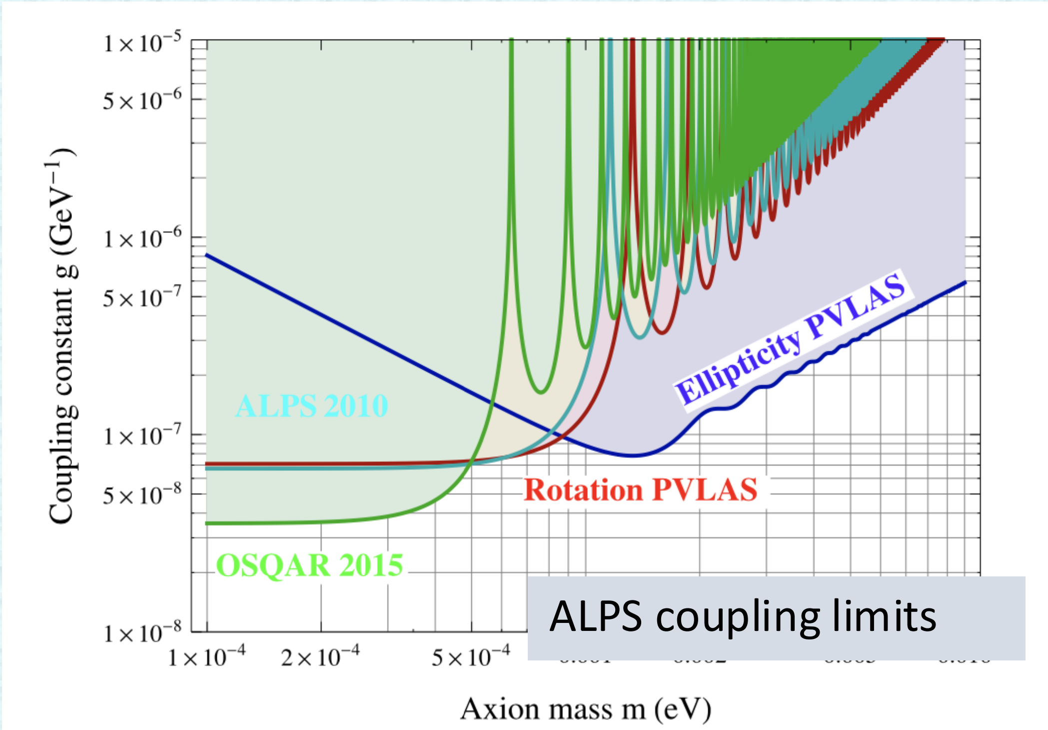
- A **new redesigned apparatus** with respect to Legnaro
- Based on **two permanent magnet 1-m long, 2.5 T** rotating up to **10 Hz** (reduced 1/f noise)
- **Ultra high finesse optical cavity: L = 3.3 m ; F = 770 000 ; amplification factor N = 450 000**
- Optics suspended on a **single granite optical table 4.8 m long**

Final results

$$\Delta n^{(\mathrm{PVLAS-FE})} = (12 \pm 17) \times 10^{-23} \qquad @\, B = 2.5\ \mathrm{T}$$
$$|\Delta\kappa|^{(\mathrm{PVLAS-FE})} = (10 \pm 28) \times 10^{-23} \qquad @\, B = 2.5\ \mathrm{T}.$$

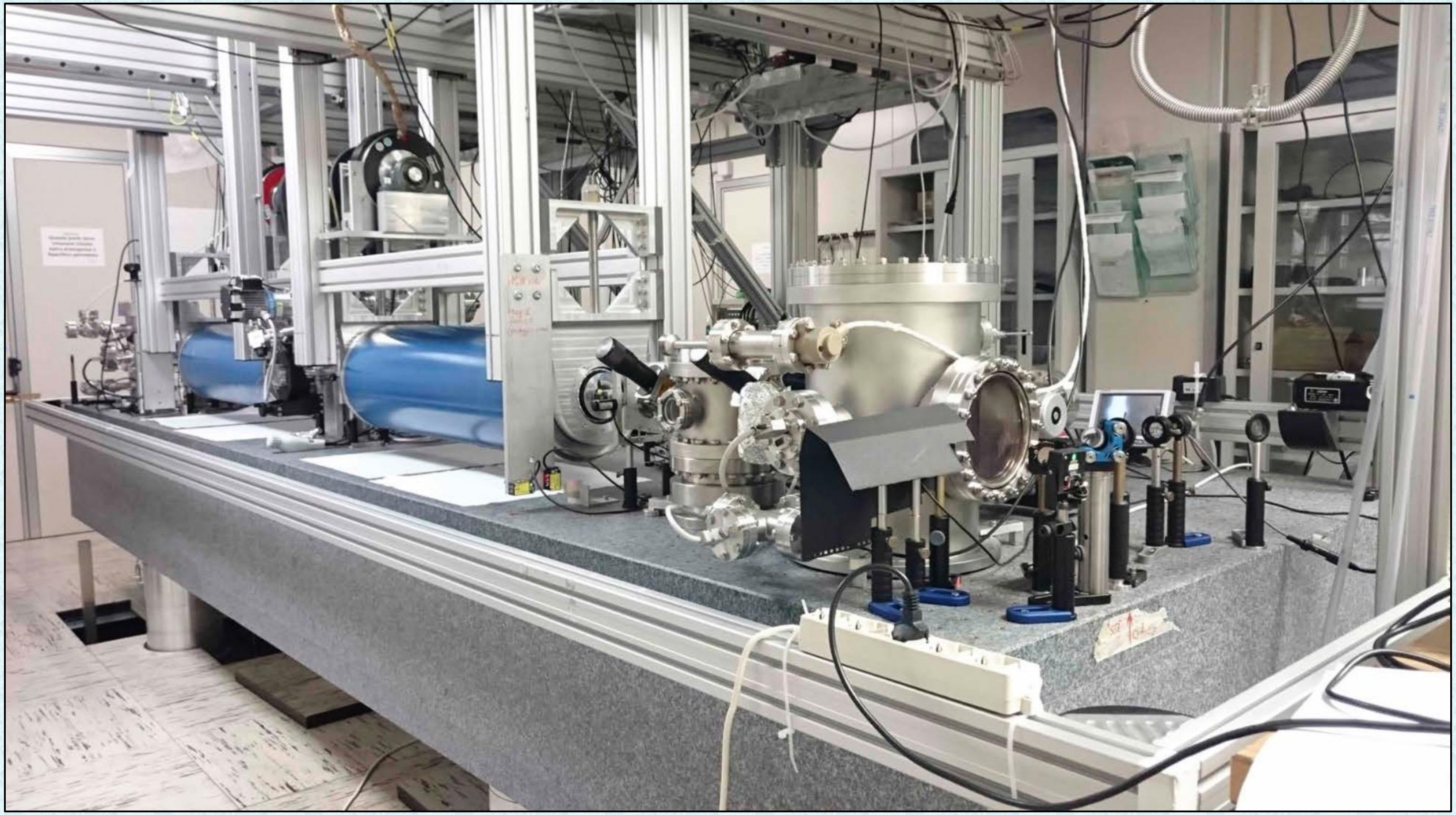
Physics Report 871, 1 (2020)



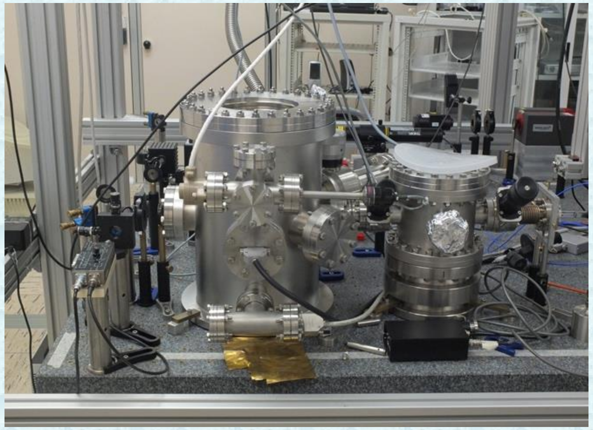


PVLAS total integration time 5 10^6 s

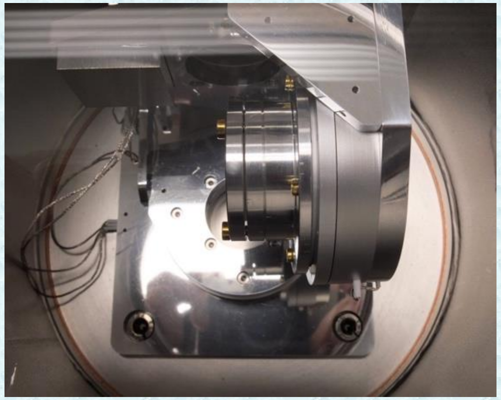
PVLAS @ Ferrara



Complete apparatus



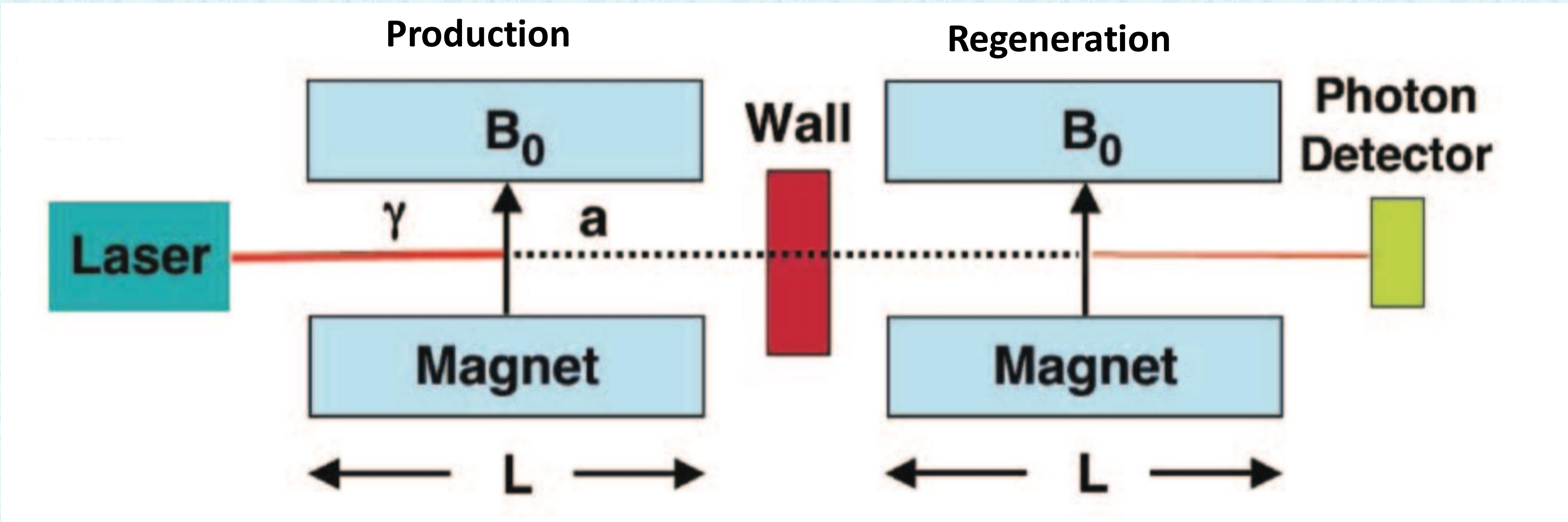
Vacuum chambers



Movable mirror holder

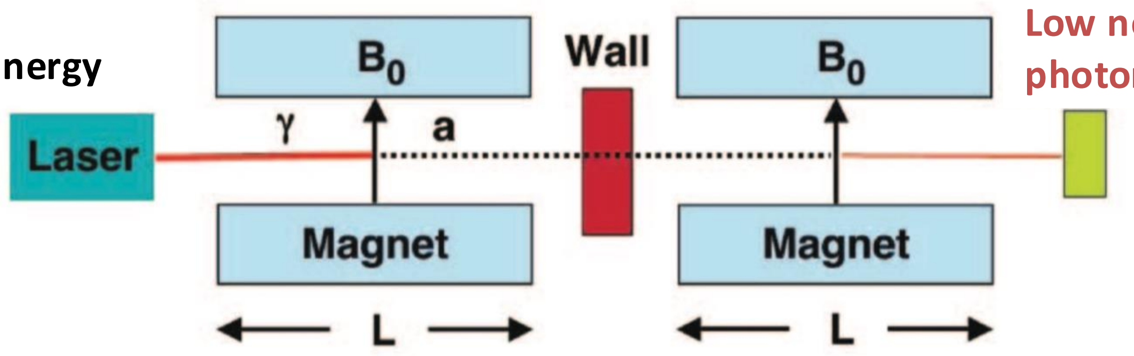
[A.2] Pure lab: light shining through walls (LSW)

- **Production-detection type**: seminal ideas in Okun (1982), Sikivie (1983), Ansel'm (1985), Van Bibber et al. (1987)
- Due to their **very weak interaction** axion may **traverse any wall** opaque to most standard model constituent
  - Axion can transfer information through a shield
  - Axion can convert back – **regenerate** – photons behind a shield



Pure laboratory: LSW

ω – photon energy



Low noise
photon detector

Conversion probability in a magnet

$$\mathrm{P} = \frac{1}{4}\left(g_{agg}B_0L\right)^2\left|\frac{\sin x}{x}\right|^2 \text{»} \frac{1}{4}\left(g_{agg}B_0L\right)^2$$

Total probability

$$P(g \rightarrow a \rightarrow y) = \mathrm{P}^2 \propto g_{agg}^4$$

Coherent process

$$x = \frac{m^2 L_a}{4w} << 1$$

Phase difference between axion and photon fields

Coherence can be tuned using a buffer gas in the second magnet

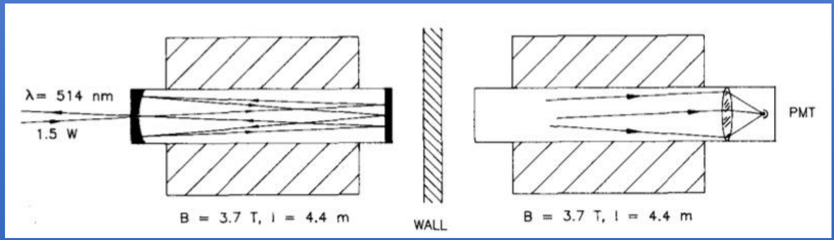
Figure of merit

$$\mathrm{sens}(g_{a\gamma\gamma}) \propto \frac{1}{BL}\frac{\omega}{P^{1/4}}\frac{N^{1/8}}{t^{1/8}}$$

- **High magnetic field *B***
- **Long magnets *L***
- **High laser power *P***
- **Ultra low noise *N* receiver**

(Some) LSW apparatuses

BFRT (Brookhaven-Fermilab-Rochester-Trieste) 1991 -1992



Multipass cavity **Two 3.7 T Magnets**

OSQAR @ CERN

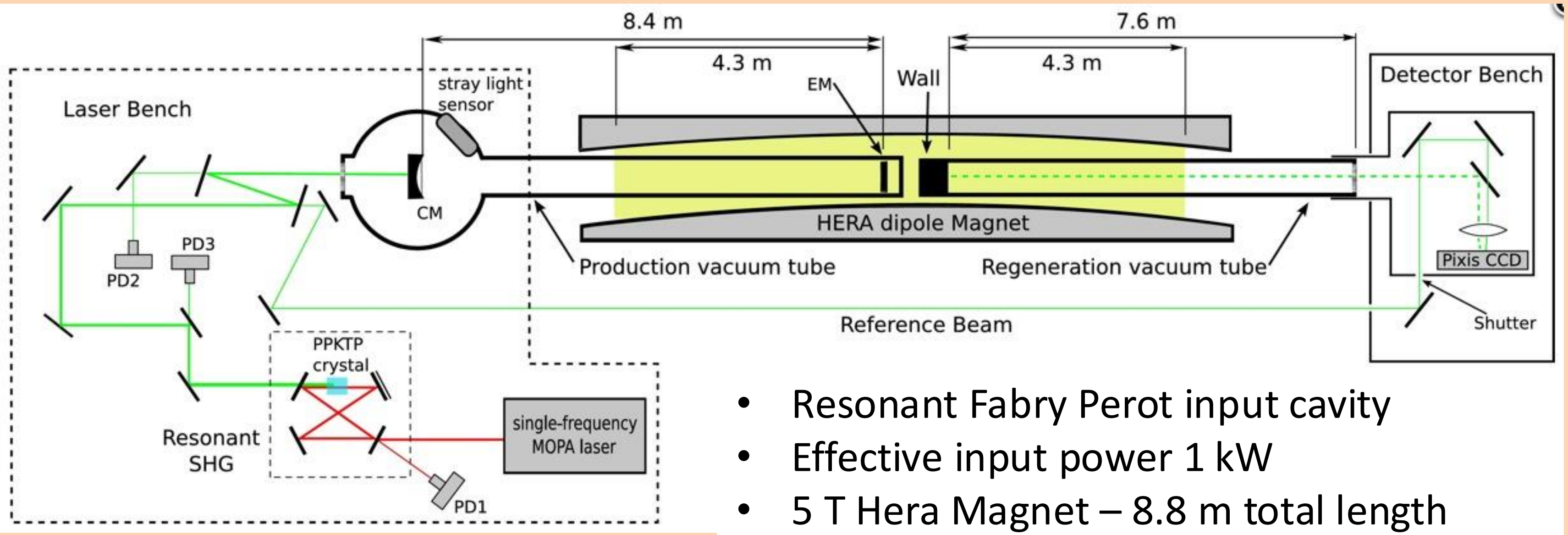
Spare LHC Dipoles

9 T over 14.3 m

20 W cw Laser

State of the art CCD detector

ALPS I experiment @ DESY



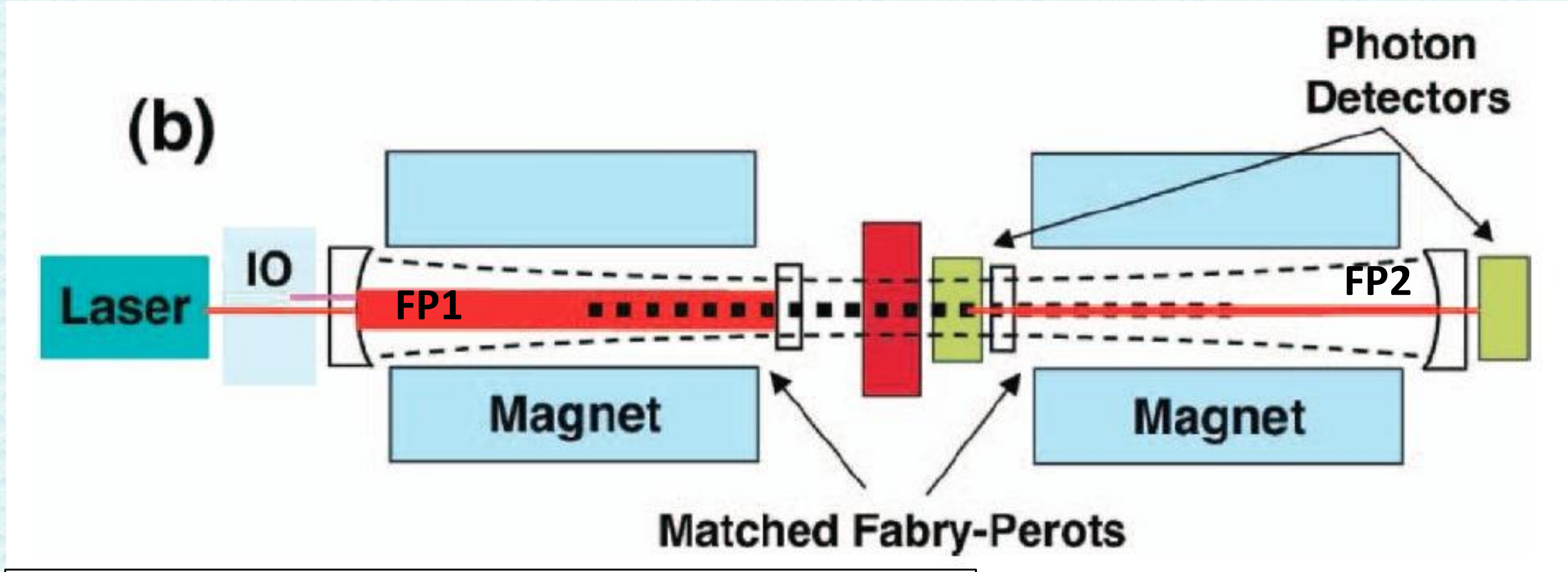
- Resonant Fabry Perot input cavity
- Effective input power 1 kW
- 5 T Hera Magnet – 8.8 m total length
- CCD detector

Others exps

- **BMV @ LULI**
- **GammeV @ Fermilab**
- **CROWS @CERN (Microwave photons)**

Resonant LSW: ALPS II @ DESY

- Resonantly enhance production and regeneration process by using **matched Fabry Perot (FP) cavities within both magnets**



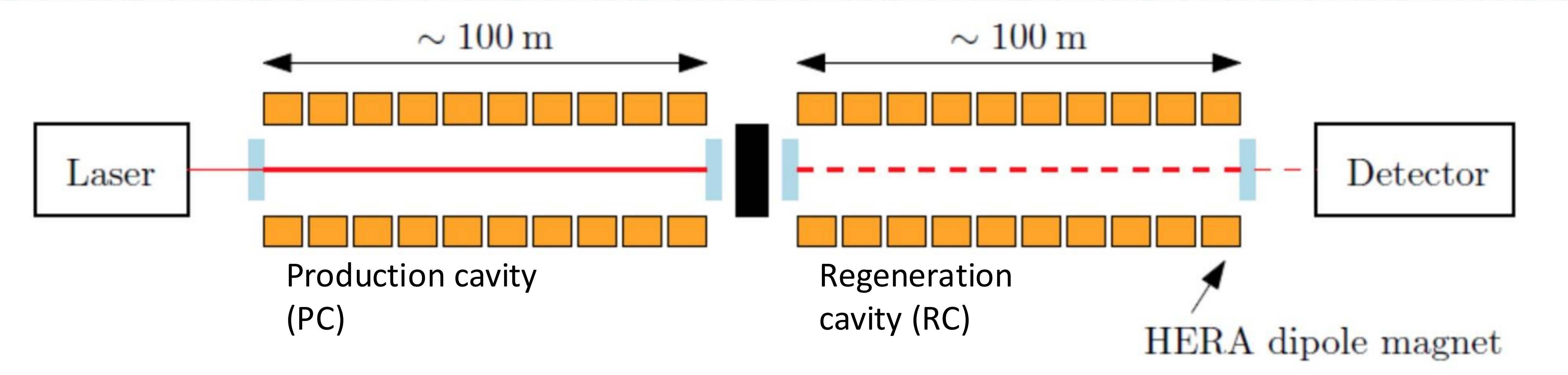
$$\mathrm{sens}(g_{a\gamma\gamma}) \propto \frac{1}{BL}\frac{\omega}{P^{1/4}(F_1F_2)^{1/4}}\frac{N^{1/8}}{t^{1/8}}$$

- Extra gain with the two matched FPs
- Finesses F_1, F_2 larger than 10^4

This is the task of the ALPS II project in DESY – Hamburg

- **120 + 120 m resonant Fabry Perot cavities**
- **12 + 12 High magnetic field HERA magnets**
- **Transition Edge low noise sensor (or optical heterodyning)**

Resonant LSW: ALPS II @ DESY



Improvement with respect to previous generation experiment

Parameter	Scaling	ALPS-I	ALPS-IIc	Sens. gain
Effective laser power P_{laser}	$g_{a\gamma} \propto P_{\text{laser}}^{-1/4}$	1 kW	150 kW	3.5
Rel. photon number flux n_γ	$g_{a\gamma} \propto n_\gamma^{-1/4}$	1 (532 nm)	2 (1064 nm)	1.2
Power built up in RC P_{RC}	$g_{a\gamma} \propto P_{reg}^{-1/4}$	1	40,000	14
BL (before& after the wall)	$g_{a\gamma} \propto (BL)^{-1}$	22 Tm	468 Tm	21
Detector efficiency QE	$g_{a\gamma} \propto QE^{-1/4}$	0.9	0.75	0.96
Detector noise DC	$g_{a\gamma} \propto DC^{1/8}$	$0.0018\,\text{s}^{-1}$	$0.000001\,\text{s}^{-1}$	2.6
Combined improvements				3082

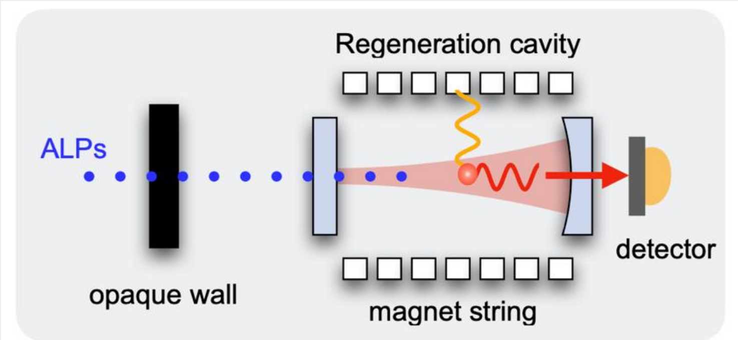
Among the challenges to be addressed:

- Frequency matching of two high finesse FP cavity (mode matching by design)
- Single photon detection with ultra low noise
- Adaptation of HERA magnets (curved) to linear cavity

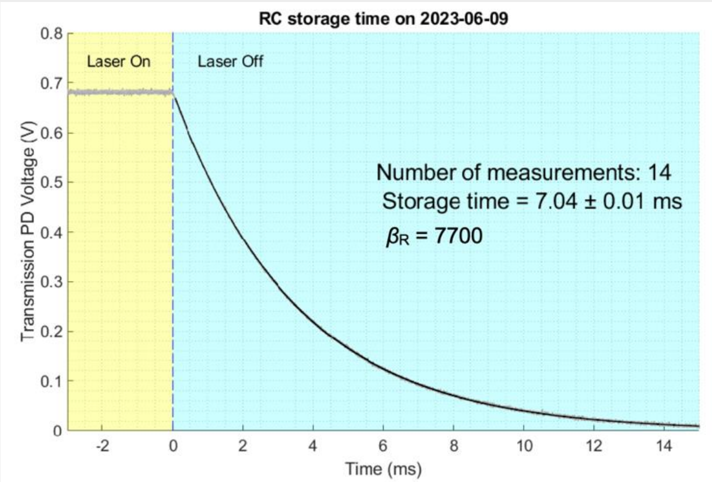
ALPS II: status / progress

Longest storage time Fabry Perot cavity ever!

Length: 124.6m, FSR: 1.22 MHz
Storage time: 7.04 ms



Graphic from Katharina-Sophie Isleif

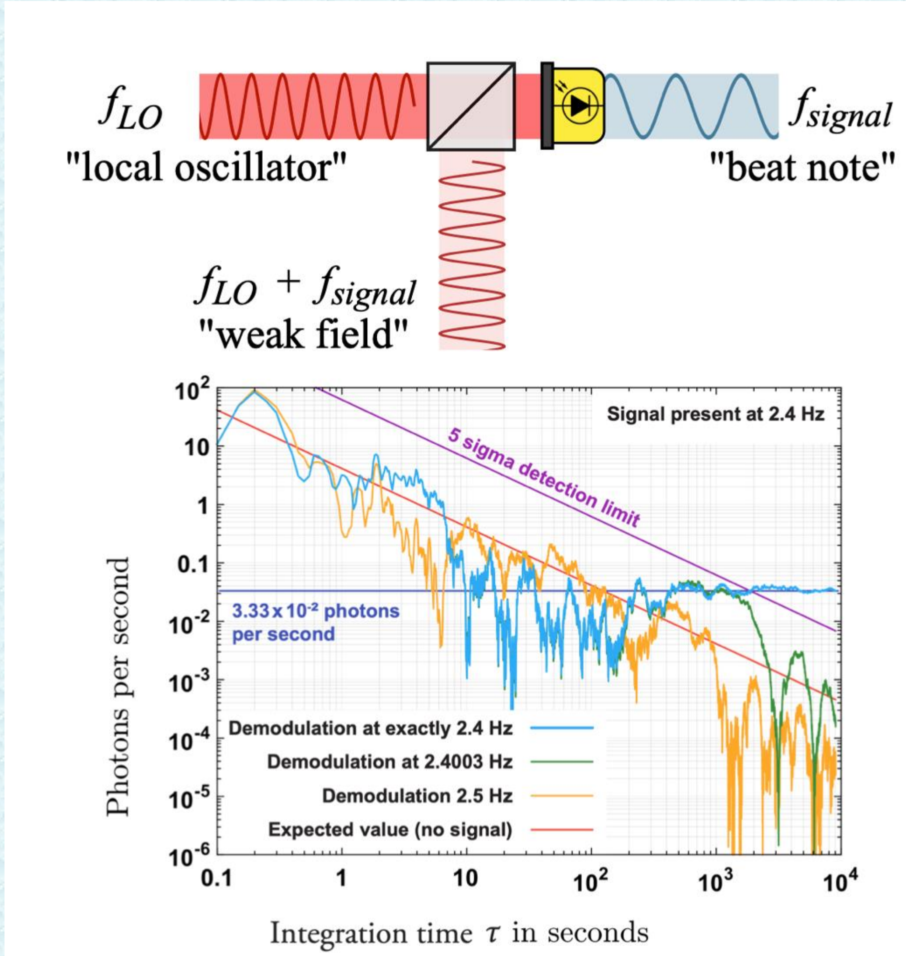


β – resonant enhacement vs single pass

The ALPS II First Science Run | Aaron Spector | Patras 18 | Rijeka, Croatia | July 6, 2023

Heterodyne sensing

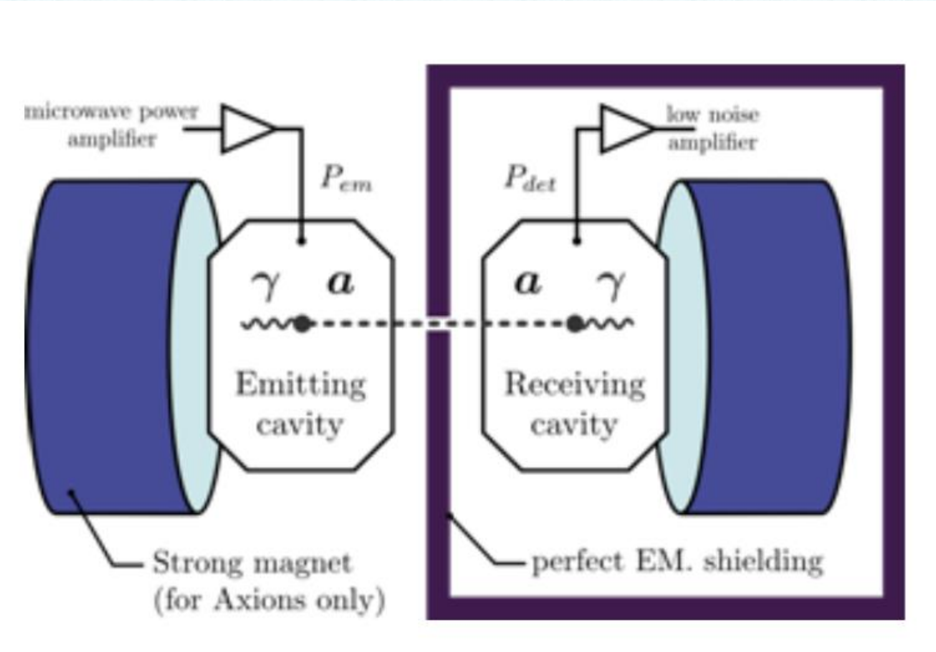
- Mix weak signal with a frequency f shifted local oscillator ➔ beat note signal
- Detection of a photon flux corresponding to $5 \cdot 10^{-21}$ W demonstrated.
- Sensitivity of 10^{-24} W demonstrated.

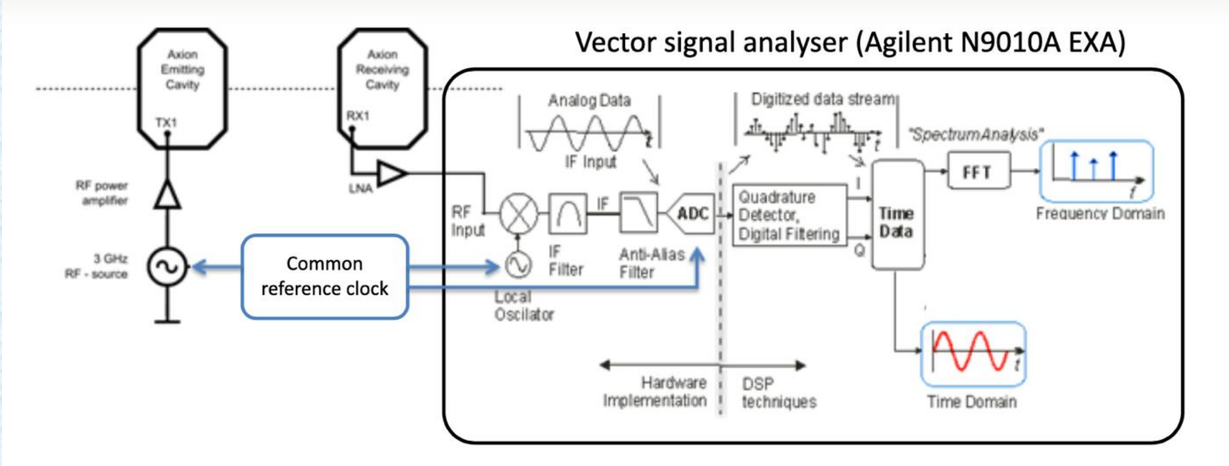


Z. Bush et al., Phys. Rev. D 99, 022001 (2019)

Microwave LSW

CROWS @ CERN





EMI Shielding challenge - Homodyne detection

Resolution bandwidth in the 10 μHz range

FFT on a 24 h time trace - Frequency drift under control

Large 3 T MRI magnet – 20 h of data taking

Room temperature set-up

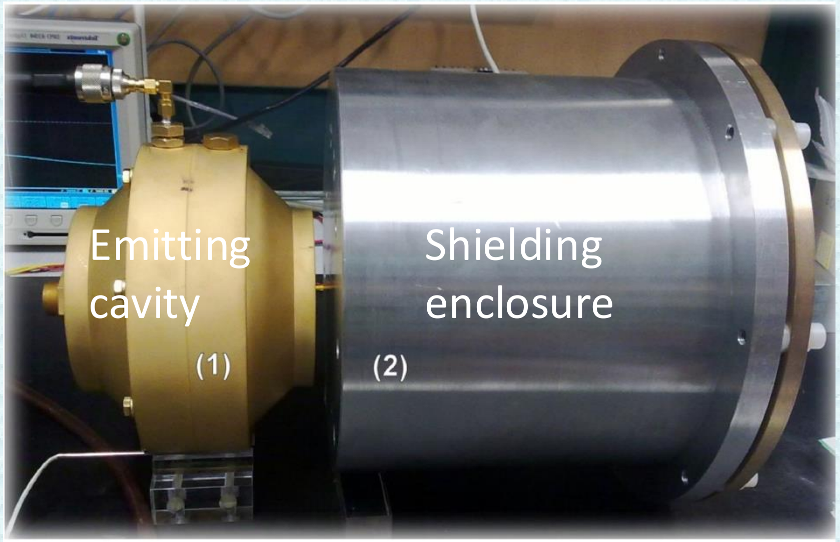


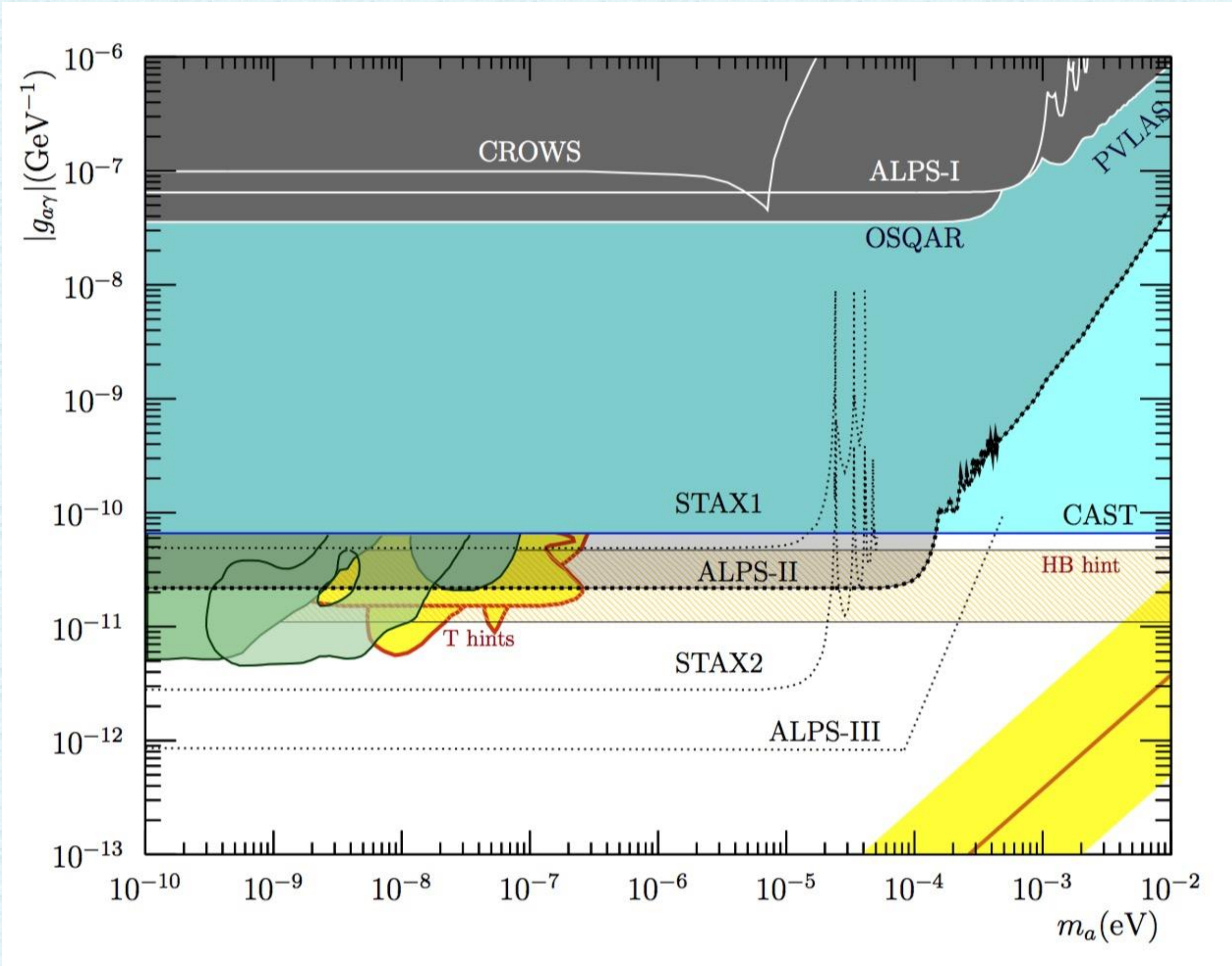
TABLE IV: Parameters of the ALP run in June 2013

$f_{\rm sys} = 1.739990$ GHz	$Q = 11392, 12151$	B $= 2.88$ T
$P_{\rm sig} = 9.8 \cdot 10^{-25}$ W	$P_{\rm em} = 47.9$ W	$\lvert G\rvert_{\rm max} = 0.94$

PRD 88, 075014 (2013)

Pure Lab: results and perspectives

Excluded regions in the axion-photon coupling $g_{a\gamma\gamma}$ vs mass



- None of these experiments capable of exploring the QCD axion model
- They set exclusion regions for Axion Like Particles coupling in a truly independent manner
- ALPS II will increase physics reach by several orders of magnitude, exploring regions where hints are present
- STAX Italian LSW effort using high power microwave sources

[A.3] Pure lab: fifth force experiments

Very light particles with weak couplings to ordinary matter, such as axions or axionlike particles, can mediate long-range forces between polarized and unpolarized fermions.
Different type of interactions: **mass-mass, spin-mass, spin-spin**

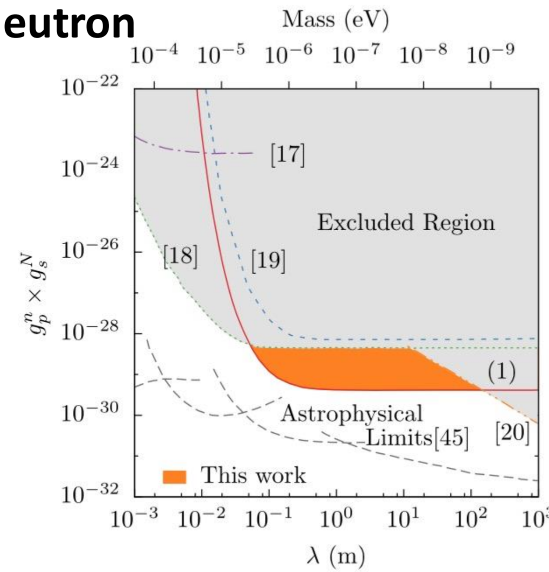
PHYSICAL REVIEW LETTERS **120**, 161801 (2018)

Improved Limits on Spin-Mass Interactions

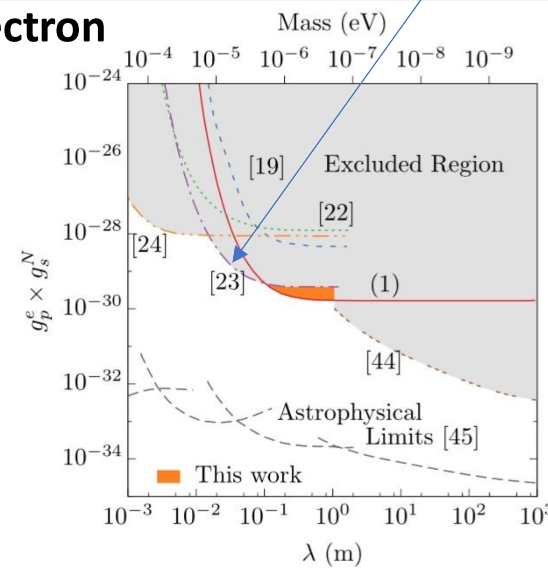
Junyi Lee,* Attaallah Almasi, and Michael Romalis
Department of Physics, Princeton University, Princeton, New Jersey 08544, USA

K-3He comagnetometer and a movable unpolarized source mass

neutron



electron



Ref [23] is the experiment **QUAX gpgs**

Physics Letters B 773 (2017) 677–680
Contents lists available at ScienceDirect
Physics Letters B
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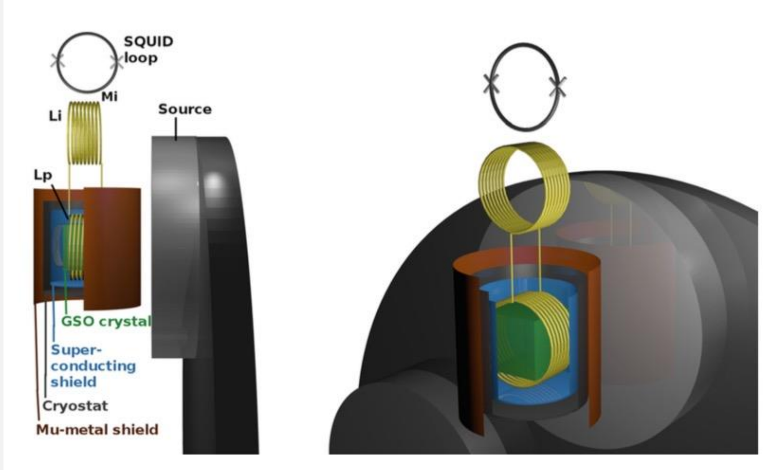
www.elsevier.com/locate/physletb

Improved constraints on monopole–dipole interaction mediated by pseudo-scalar bosons

N. Crescini [a,b,*], C. Braggio [c], G. Carugno [c], P. Falferi [d], A. Ortolan [b], G. Ruoso [b]

ALP-induced magnetization on GSO crystal



ARIADNE
US based collaboration developing a new experimental apparatus for spin – spin interaction with expected improvement in sensitivity by two orders of magnitude

The axion as a mediator of fifth forces?

Moody and Wilczek suggests that the axion mediates spin-dependent forces.

PHYSICAL REVIEW D VOLUME 30, NUMBER 1 1 JULY 1984

New macroscopic forces?

J. E. Moody* and Frank Wilczek
Institute for Theoretical Physics, University of California, Santa Barbara, California 93106
(Received 17 January 1984)

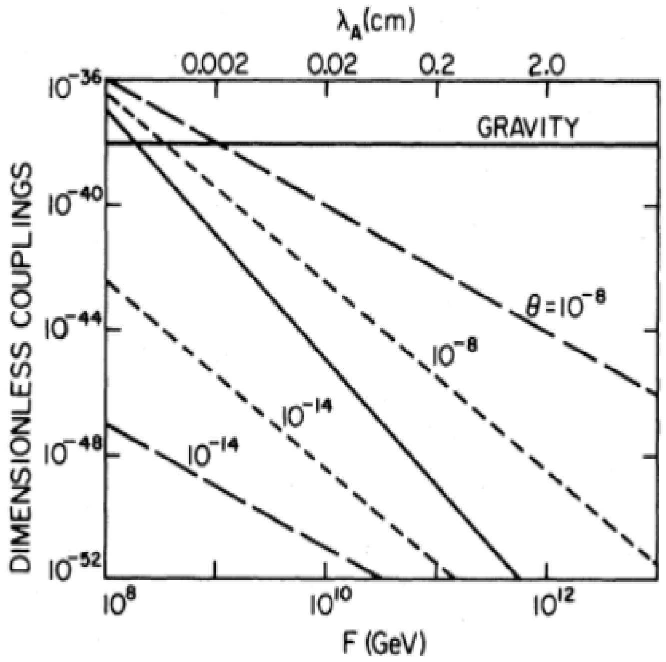


FIG. 2. Dimensionless axion couplings (at scale λ_A) as functions of F and θ. Long dashed lines are $G_{NN}/4\pi$ for $\theta=10^{-8}$ and $\theta=10^{-14}$. Short-dashed lines are $G_{Ne}/4\pi$ for $\theta=10^{-8}$ and $\theta=10^{-14}$. Solid diagonal line is $G_{ee}/4\pi$. Gravitational coupling between two nucleons $(M_N/M_{Pl})^2$ shown for comparison.

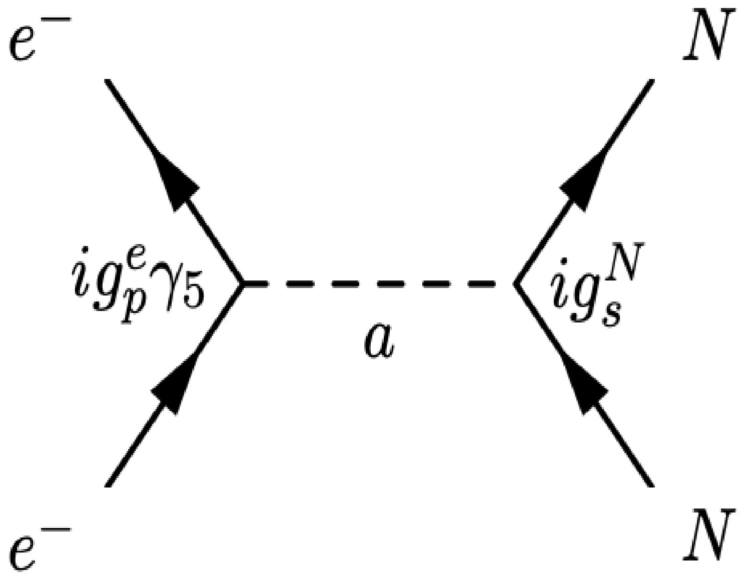
This idea opens the way to different approaches.

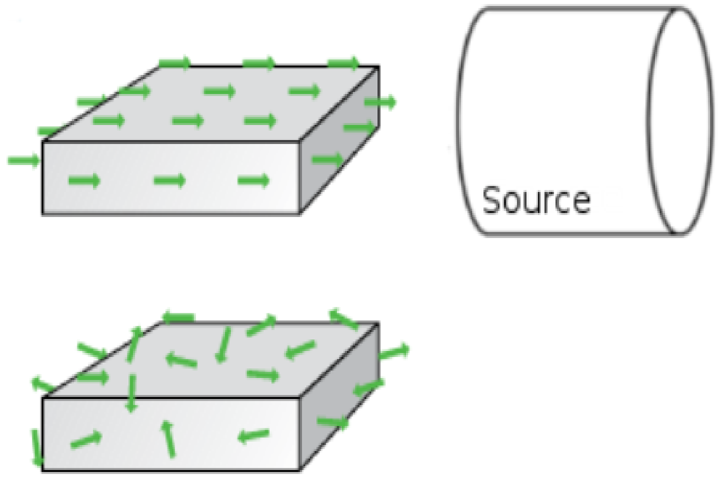
New table-top experiments can be performed:

- High precision measurements
- Broadband axion detection
- Sensitive to any pseudo-scalar boson

Experimental Approach

The axion mediates an interaction between mass and spin : the $g_p g_s$ coupling (scalar-pseudoscalar or monopolo-dipole).

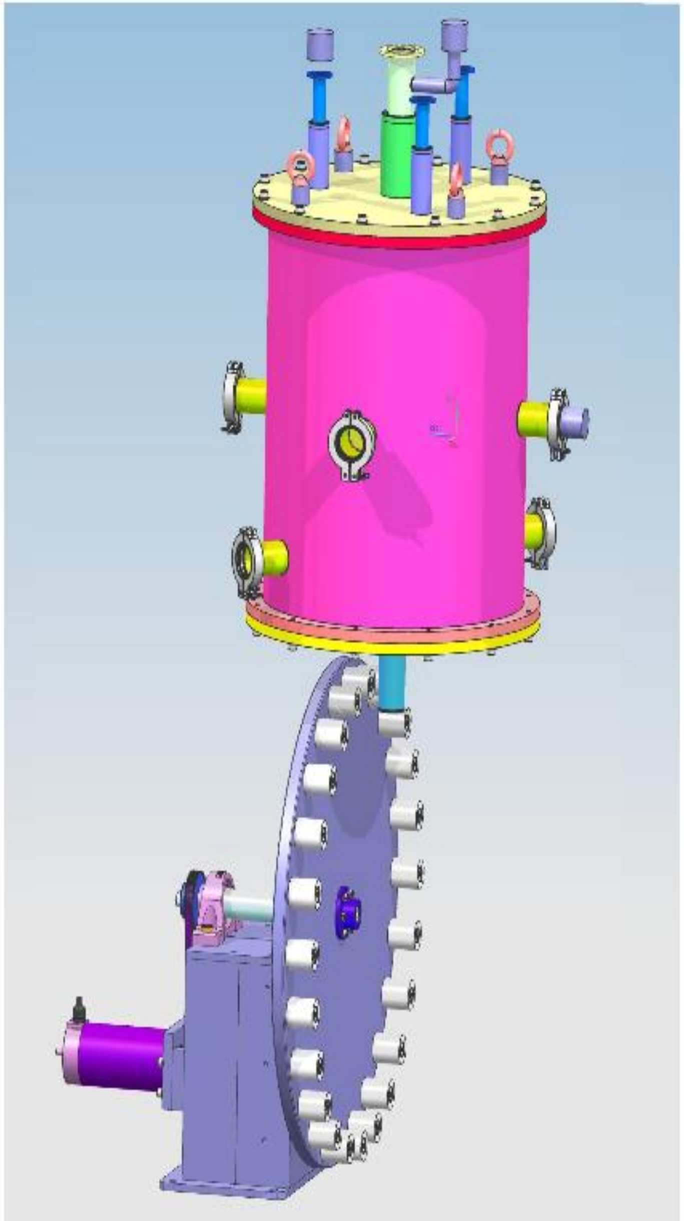




$$V_{md}(\boldsymbol{r}) = \frac{\hbar g_p^e g_s^N}{8\pi m_e c}\left[(\hat{\boldsymbol{\sigma}}\cdot\hat{\boldsymbol{r}})\left(\frac{1}{r\lambda_a}+\frac{1}{r^2}\right)\right]e^{-\frac{r}{\lambda_a}}, \quad \boxed{U = \mu_e\hat{\boldsymbol{\sigma}}\cdot\boldsymbol{B}}$$

Effective field: $$\boldsymbol{B}_{\text{eff},md}(\boldsymbol{r}) = -\frac{g_p^e g_s^N}{4\pi e c}\hat{\boldsymbol{r}}\left(\frac{1}{r\lambda_a}+\frac{1}{r^2}\right)e^{-\frac{r}{\lambda_a}}$$

Detector and Source

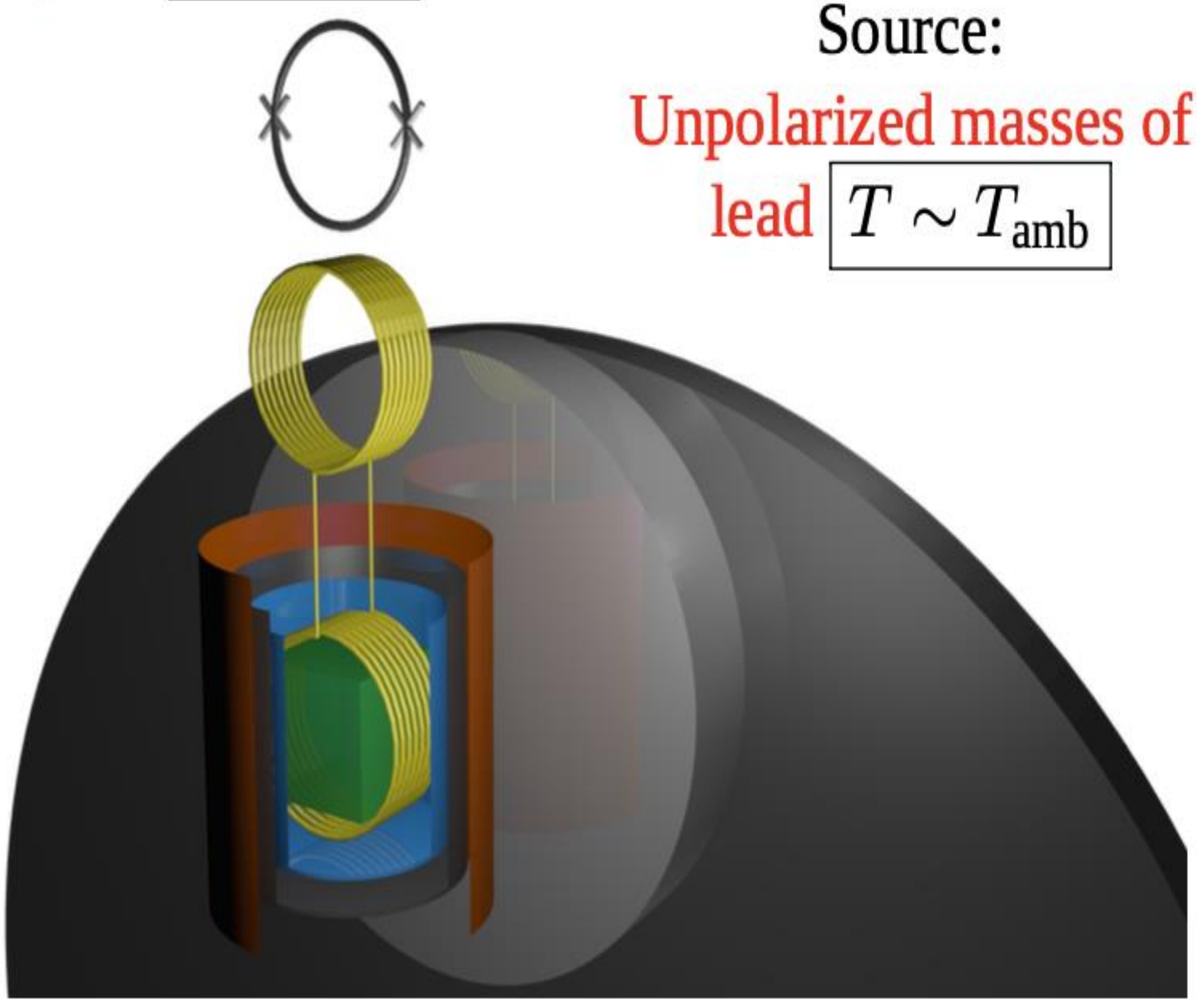


Detector:

Paramagnetic GSO crystal $\boxed{T \sim 4\,\mathrm{K}}$

Source:

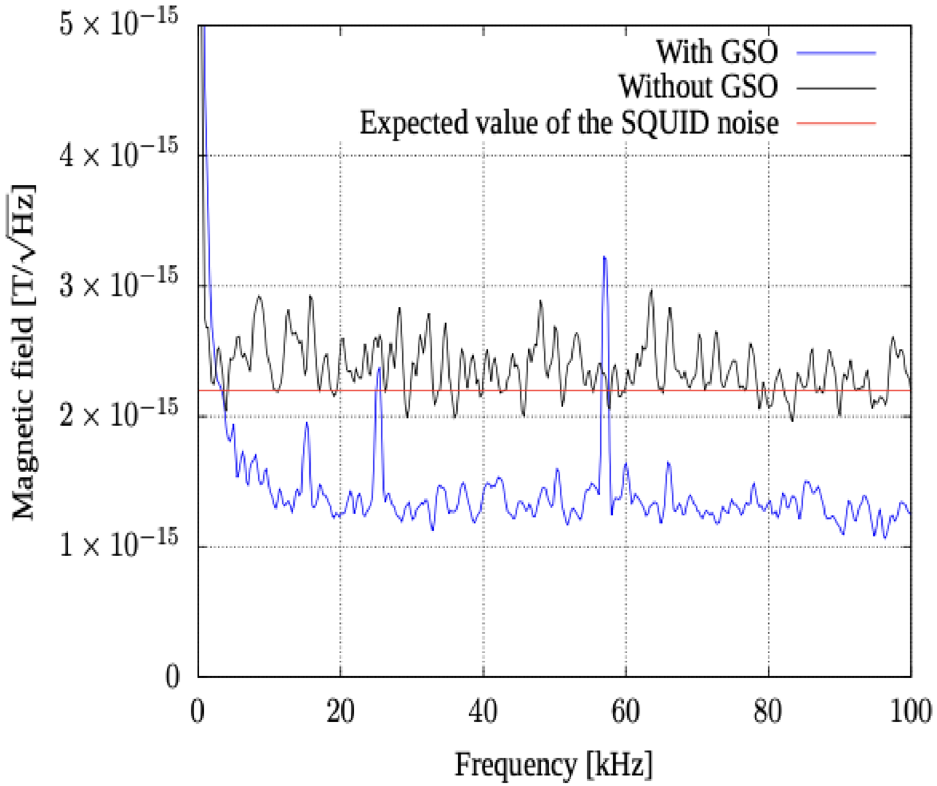
Unpolarized masses of lead $\boxed{T \sim T_{\mathrm{amb}}}$



Noise and sensitivity

The main sources of noise are the crystal and the SQUID

- $S_B^{(\mathrm{GSO})}(\omega) = \frac{4\mu_0 k_B T \chi \tau_M}{V} \to B \simeq 1.2 \times 10^{-16}\,\mathrm{T}/\sqrt{\mathrm{Hz}}$
- $S_B^{(\mathrm{SQ})}(\omega) = \frac{1}{(n\pi r^2)^2} \frac{(L_i + L_p)^2}{M_i^2} S_\phi(\omega) \to B \simeq 7.3 \times 10^{-16}\,\mathrm{T}/\sqrt{\mathrm{Hz}}$



Measures are compatible with the SQUID noise estimation:

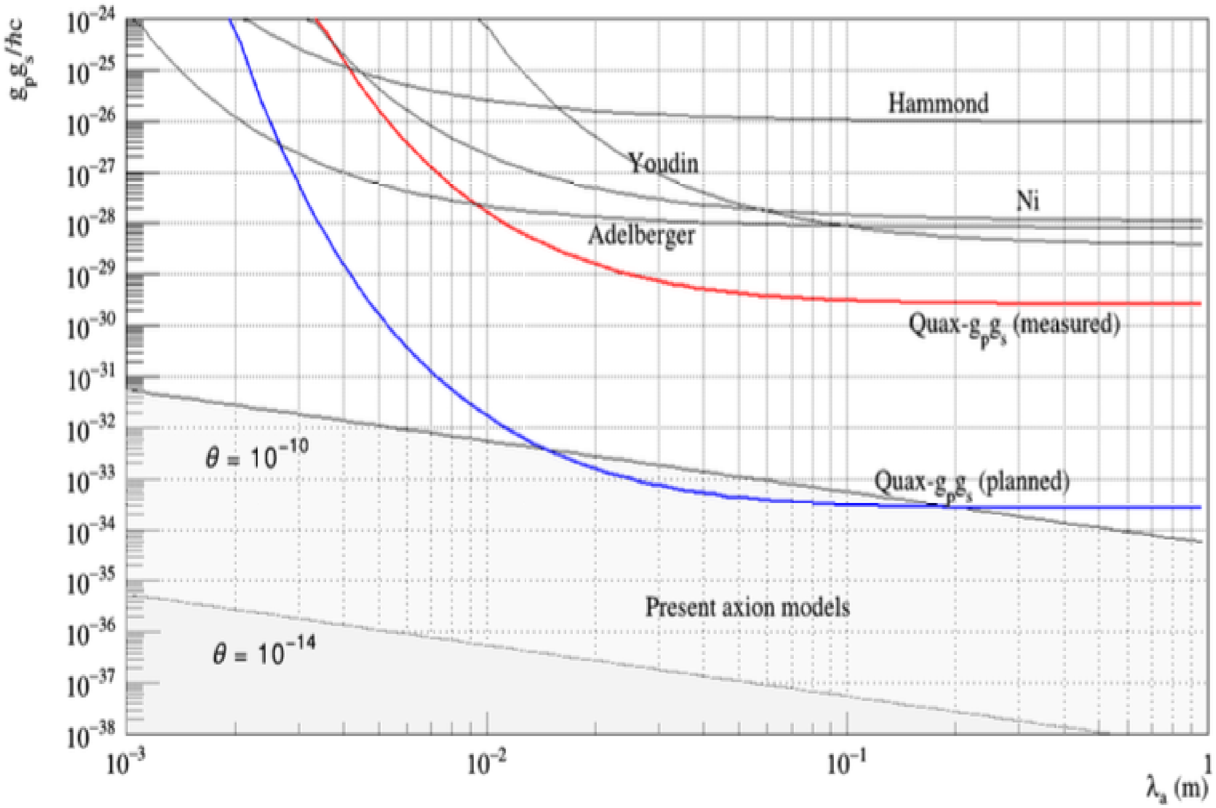
Main noise = SQUID noise.

$\Downarrow$

$$\chi S_B^{1/2} = \int_V \rho_N \boldsymbol{B}_{\mathrm{eff}}(\boldsymbol{r})\,dV$$

The upper limits on the couplings with a 95% CL are:

$$\boxed{g_p^e g_s^N/\hbar c \le 4.3 \times 10^{-30}} \xrightarrow{\text{to } \theta=10^{-10}} g_p^e g_s^N/\hbar c \lesssim 10^{-34}$$



How is it possible to reach the $\boxed{\theta = 10^{-10}}$ limit?

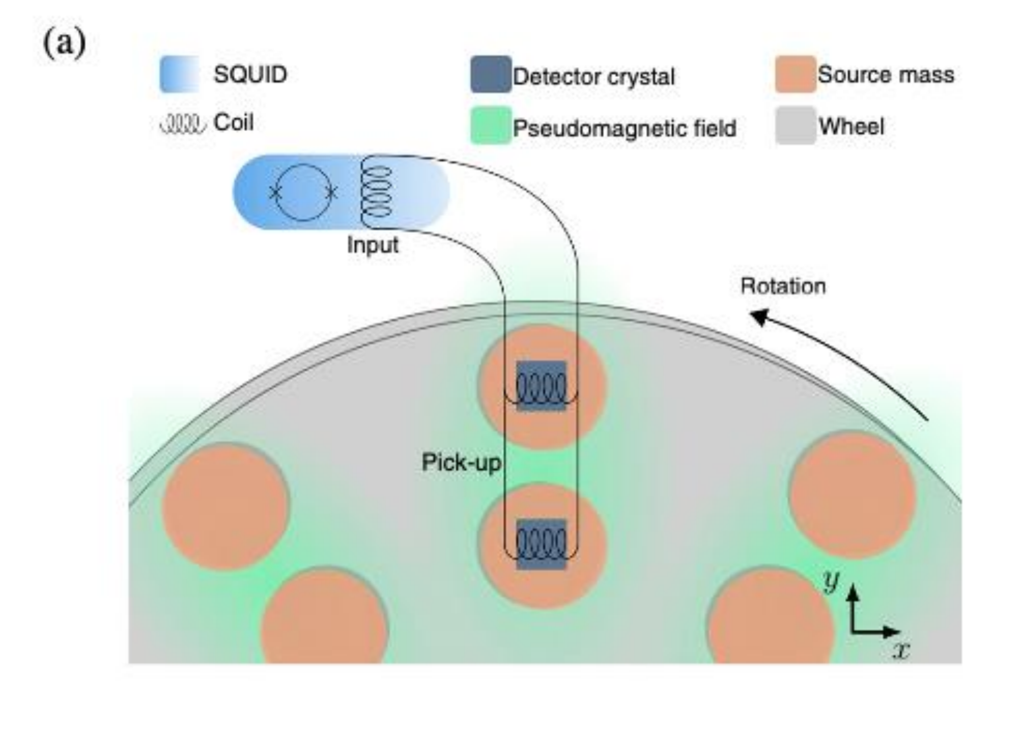
$\Downarrow$

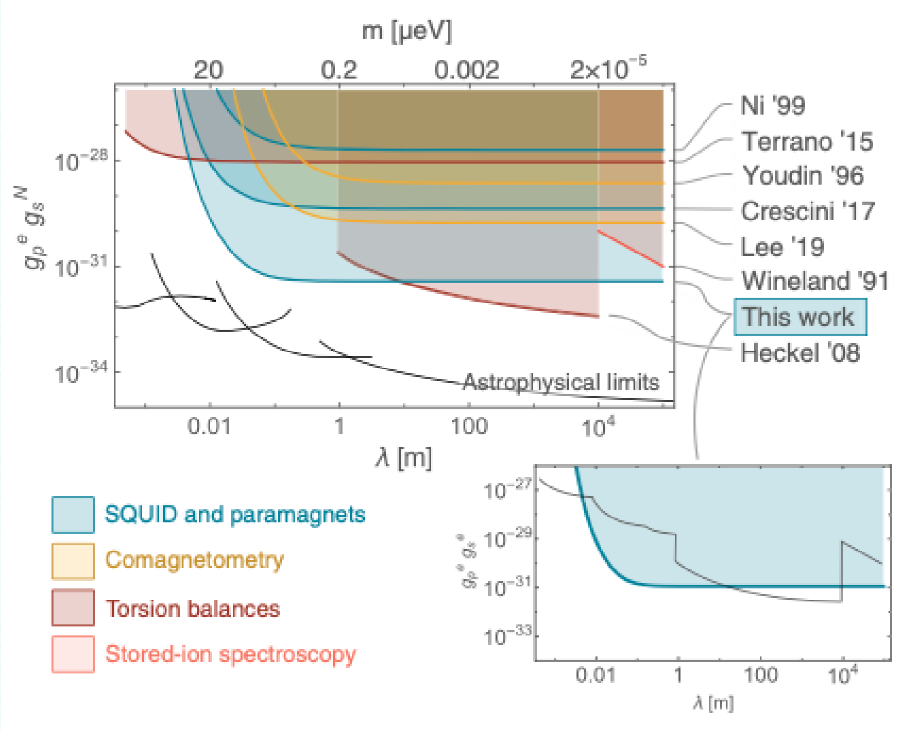
4 orders of magnitude improvement in respect of this measurement. ~ 8 to reach the predicted $\boxed{\theta \sim 10^{-14}}$ level.

Lab Experiments – Fifth Force

Axion-like particles can mediate forces between baryons that compete with gravity at distances $1/m_a$ and have been constrained by precision measurements of Newton's law and searches of violations of equivalence principle

The **QUAX collaboration** has recently used a novel scheme to search for the **monopole–dipole** (mass – spin) force coupled to *electron*-spins





- A variable macroscopic ALP field generated by **moving lead masses** resembles a magnetic dipole interaction with **electrons in a paramagnetic salt** , thus acting as an **"equivalent" magnetic field**
- A SQUID is used to detect the magnetization change

QUAX gp-gs
N. CRESCINI et al.
PHYS. REV. D 105, 022007 (2022)

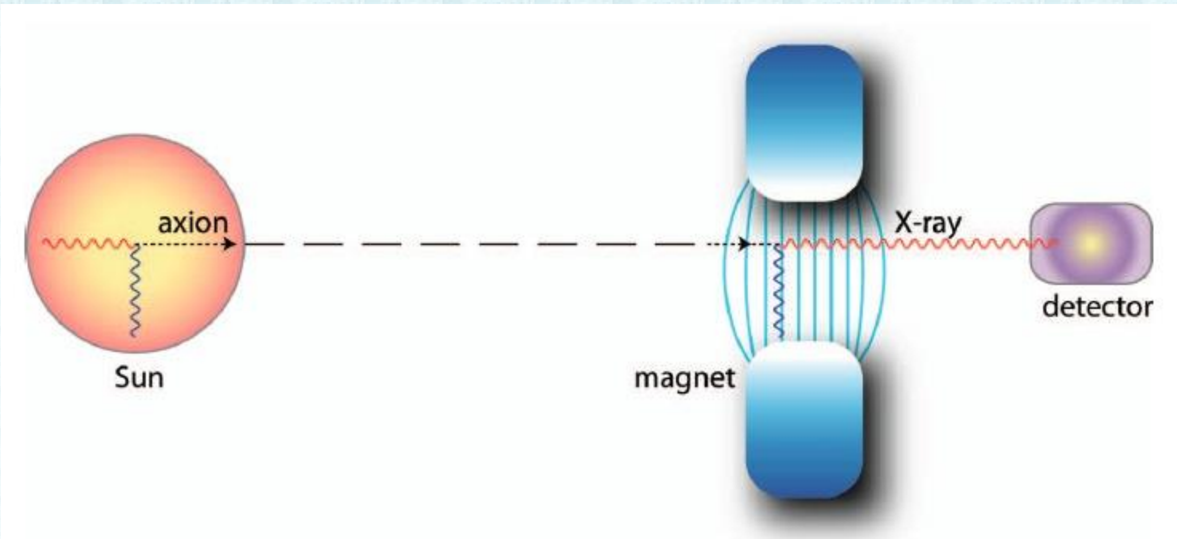
[B] Detection of axion from the Sun

Helioscopes

[B] Detection of axion from the Sun

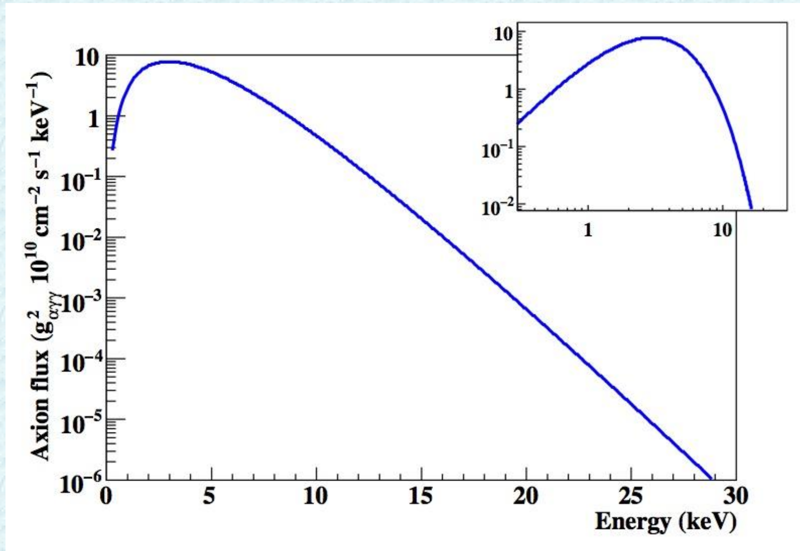
- **Helioscope**: originally proposed by P. Sikivie (1983)
- Axion produced in the Sun by the **Primakoff process**: **blackbody photons** in the EM fields associated with stellar plasma (also other mechanisms through electron coupling)
- **Thermal axion spectrum** with **mean energy 4.2 keV (X rays)**
- **Axion production rate depends on Solar model and production model**
- **Axion converted to X rays in terrestrial detectors**

G. Carosi et al, Contemp. Phys. 49, 281 (2008)



Axion flux on Earth

$$\Phi_a = 4 \times 10^{11} \frac{g_{a\gamma\gamma}^2}{10^{-10}\,\mathrm{GeV}^{-1}}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$$



[B] Detection of axion from the Sun

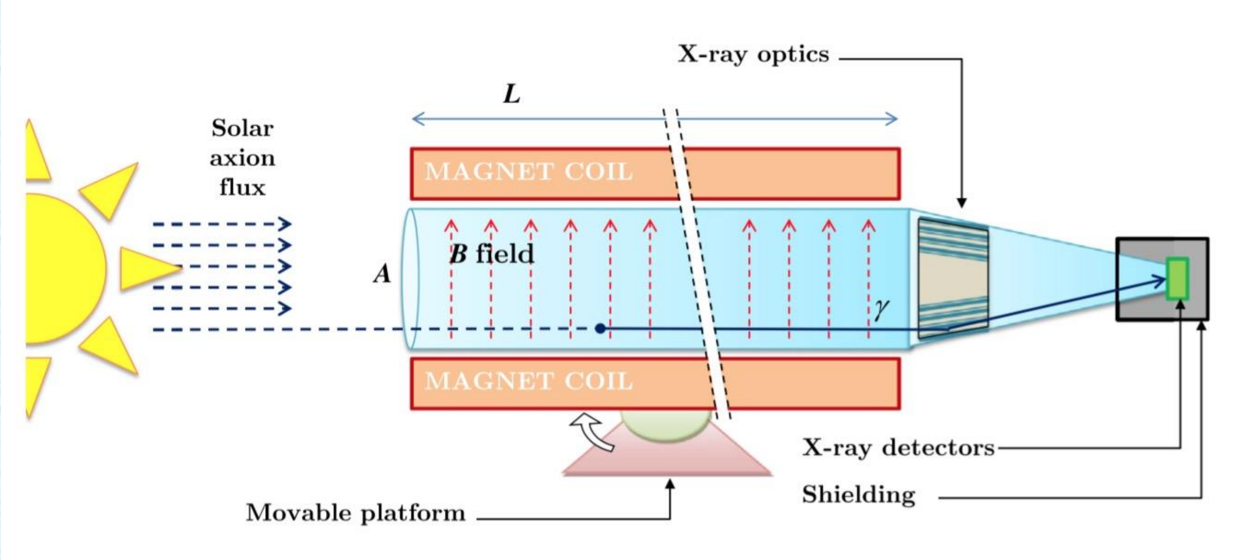
Conversion probability in the detecting magnetic field

$$P = \frac{1}{4}\left(g_{a\gamma\gamma} B L\right)^2 |F(q)|^2$$

$$F(q) = \left(\frac{2}{qL}\right)^2 \sin^2\left(\frac{qL}{2}\right)$$

$$q = k_\gamma - k_a \approx \frac{m_a^2}{2\omega}$$

The factor ***F*****(q) ~ 1 reflects the coherence** between axion and produced x rays. Can be changed with **buffer gas**.



from I.G. Irastorza and J. Redondo, *Prog. Part. Nucl. Phys.* 102 (2018), pp. 89–159

- F(q) ~ 1 for masses < 10 meV
- With buffer gas good up to 1 eV
- Scheme to determine m_a

Figure of merit

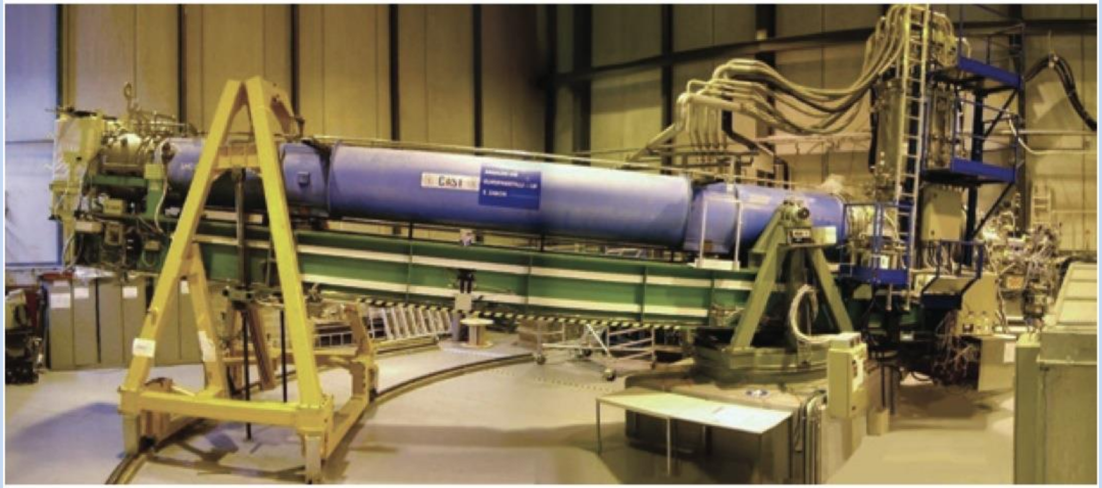
$$\mathrm{sens}(g_{a\gamma\gamma}) \propto \frac{b^{1/8}}{B^{1/2} L^{1/2} A^{1/4} t^{1/8}}$$

- **High magnetic field *B***
- **Long magnets *L***
- **Large bore A**
- **Ultra low background *b* X-ray receiver**
- **Sun tracking**

Detection of axion from the Sun - apparatuses

- First experiment performed in **Brookhaven in 1992** by the BFR collaboration
  - **2.2 T fixed magnet** Proportional Chamber as detector
- Second generation experiment in Tokyo - **SUNICO**
  - **4 T magnet on a rotating platform**

The CAST experiment (CERN Axion Solar Telescope)



- **10 m - 9 T - LHC prototype magnet pointing to the sun with some tracking capability**

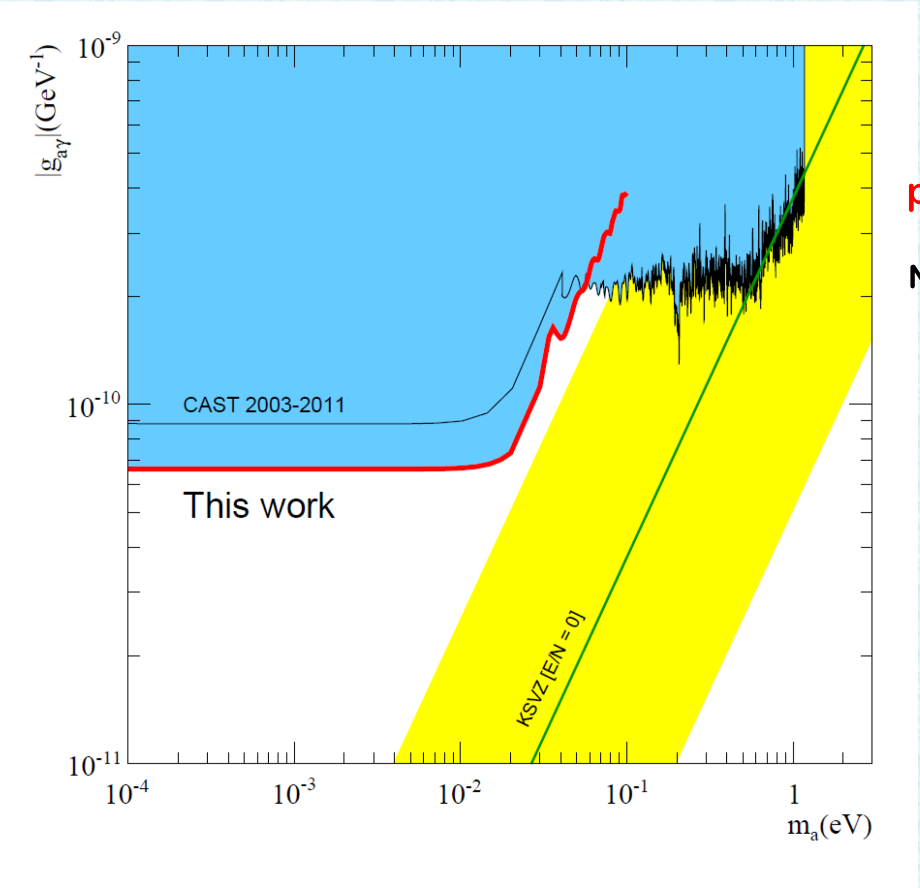
- **So far most sensitive experiment** looking for axion-like particles

Solar axions can be detected also by **other techniques**

- Primakoff-Bragg conversion in crystalline detectors
- Ionisation detectors via axioelectric effect (different axion coupling)
- In general competitive only for axion electron coupling studies

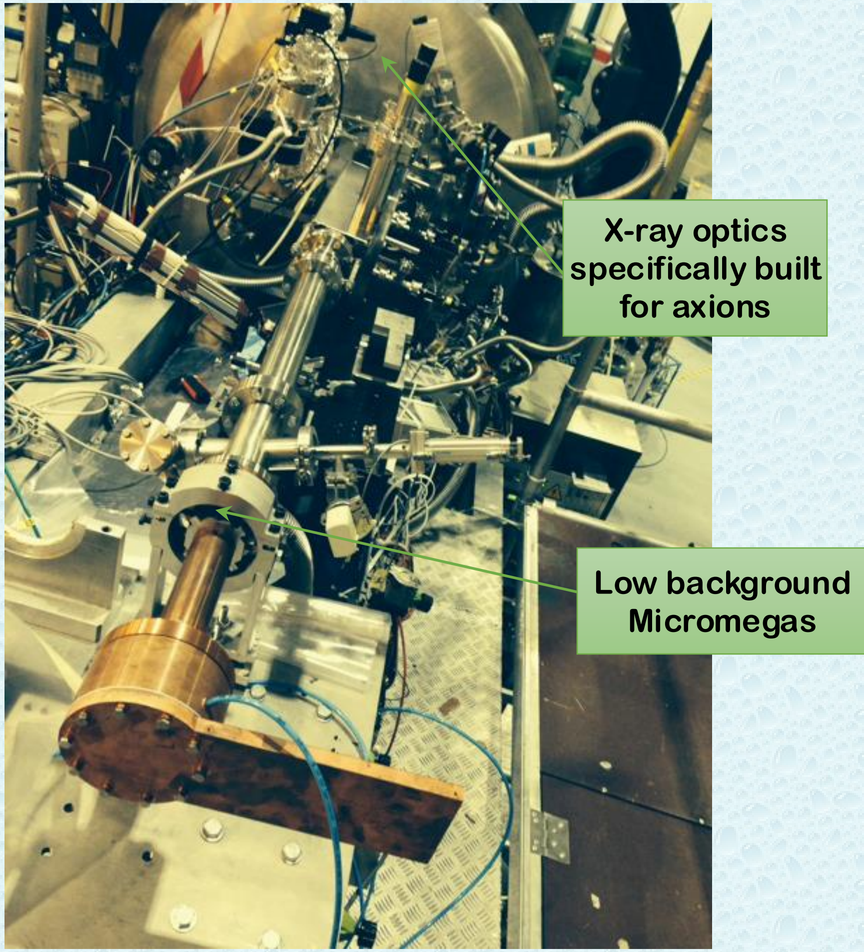
CAST results

- 9 T LHC magnet 9.3 m long
- **Tracking** of the Sun for several hours per day
- X ray **focusing optics** to increase SNR
- Low background techniques employed
- First Observational program 2003 – 2011 (vacuum + gas)
- New vacuum run 2013 – 2015 with **improved optics and detector**
- Total tracking exposure 1133 hours



Last CAST results published in Nature Physics May-2017

Nature Phys. 13 (2017) 584-590



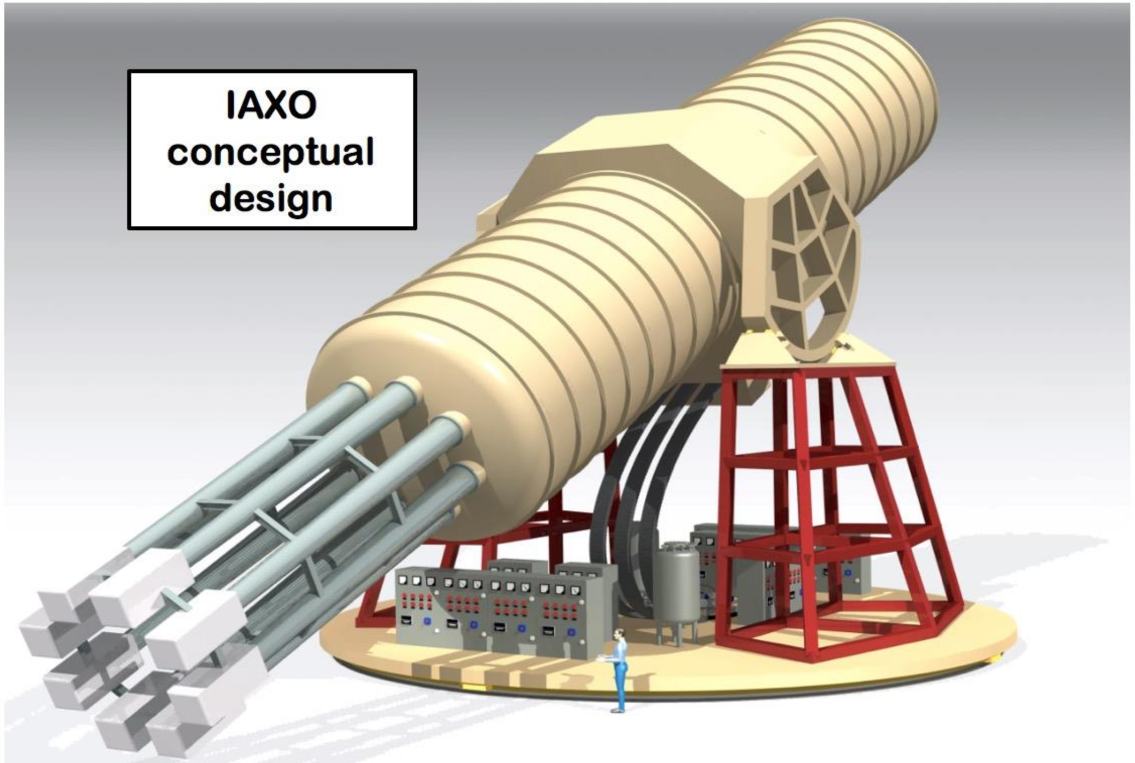
Enabled by the IAXO pathfinder system

Record background rate < 0.003 counts per hour in the signal region

Prospects: the IAXO experiment

- The **I**nternational **AX**ion **O**bservatory proposal is a dramatic push up of CAST performances:

- **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)**



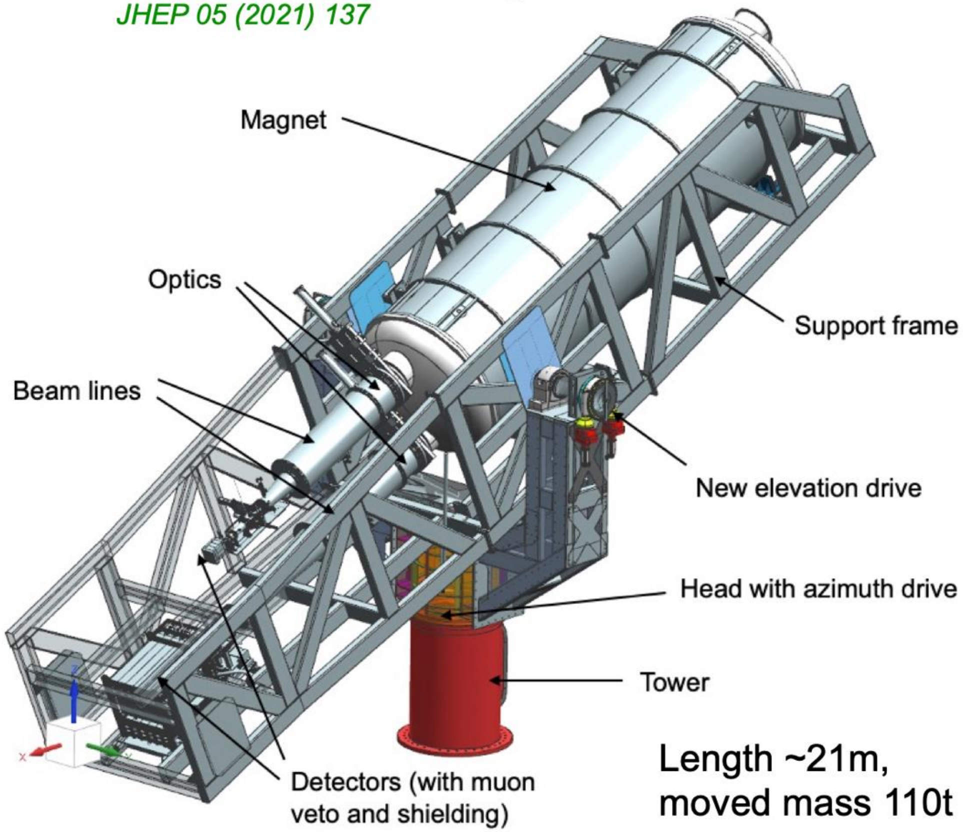
IAXO intermediate step

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



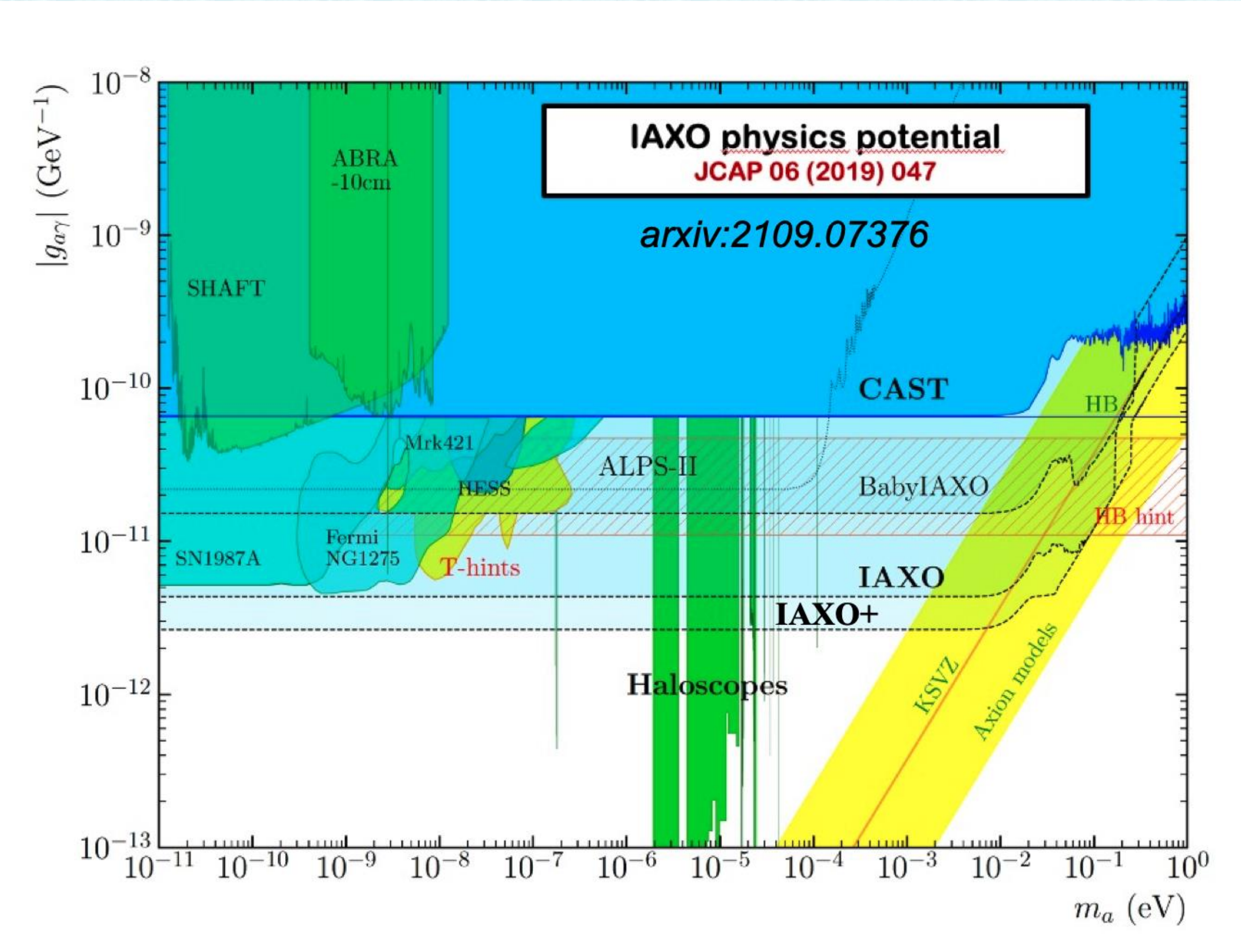
Length ~21m, moved mass 110t

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

European Research Council
Established by the European Commission

ERC-AvG 2017 IAXO+

Helioscopes: results and perspectives

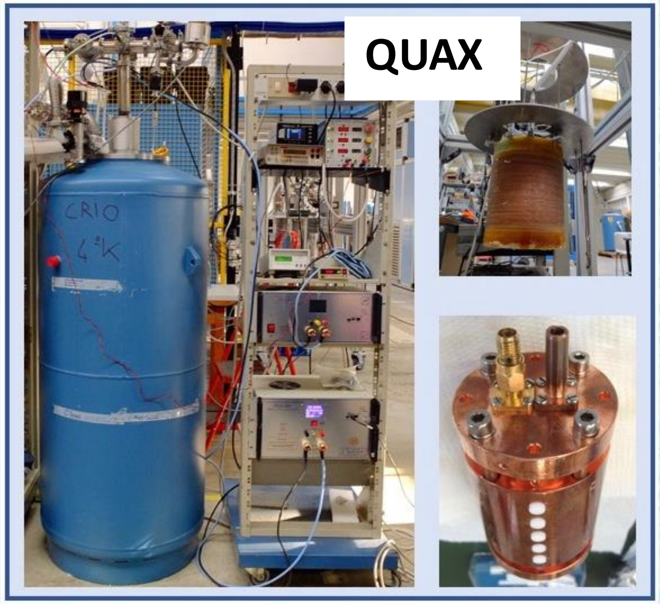


- Helioscopes results competitive with Astrophysics limits but much less model dependent
- Limits on other couplings have been obtained too (not presented here)
- IAXO and BabyIAXO will be exploring important regions where hint of astrophysics origin are present

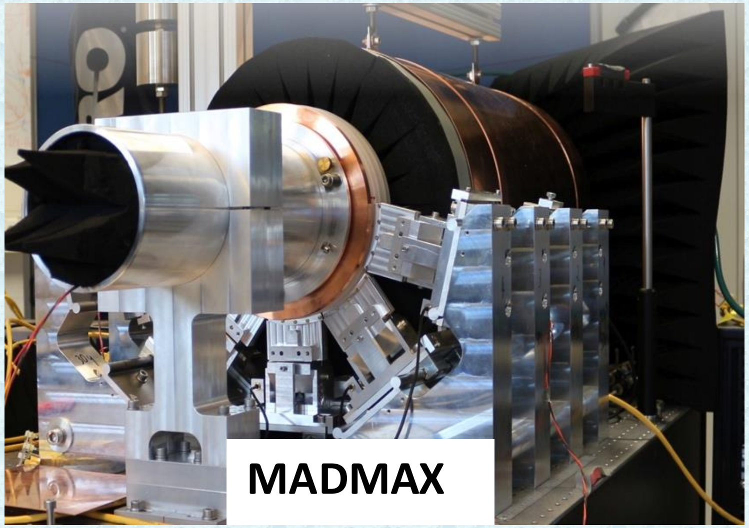
- The physics reach of IAXO will be covering a large and significant range of the **QCD axion** mass span

[C] Haloscopes – Galactic axions

Magnetic haloscopes



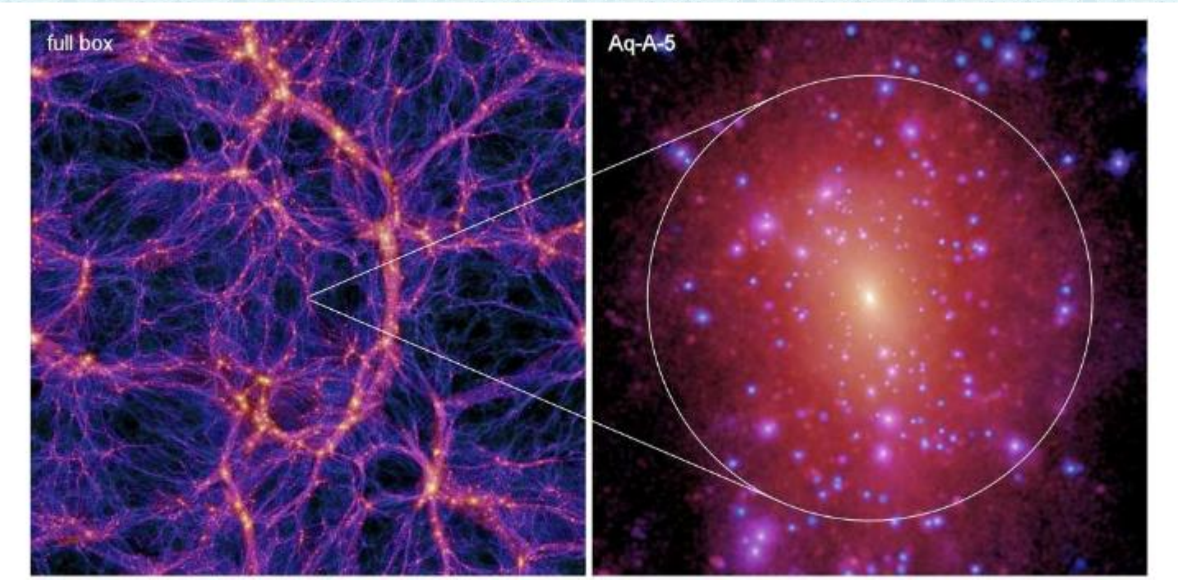
Dielectric haloscopes

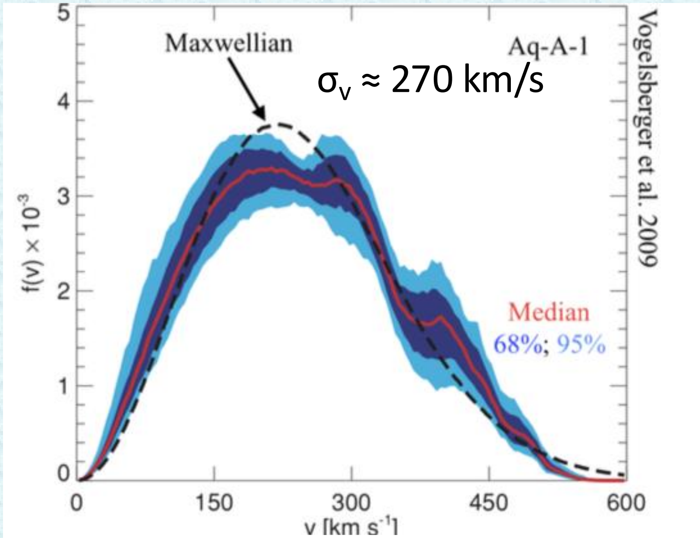


CDM local distribution

1) Coarse grained DM velocity distribution for an Equivalent MW

- Aquarius simulation http://wwwmpa.mpa-garching.mpg.de/aquarius/

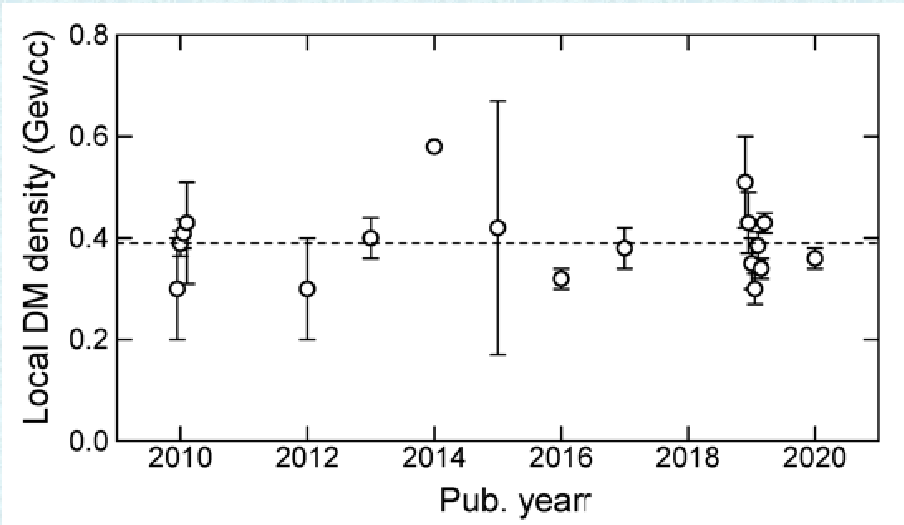




Velocity distributions in a 2 kpc box at the Solar Circle (8 kpc)

2) Fine grained DM velocity distribution :

- [Y. Sofue, **Rotation curve od the Milky Way and dark matter density**, *Galaxies* **8**, 37(2020)]



- DM can have additional structures on small scales:
  - if axions continuously fall into galaxies they would form causitc rings [Sikivie 2011]
  - If axion DM density is dominated by few local streams, ts velocity distribution can be narrower by many orders of magnitude

Halo Dark Matter Axions

DM density $\rho = 0.4\ \mathrm{GeV/cm^3}$ → $n_a = 3\ 10^{11}$ axions/cm^3 → treat DM axions as a classical filed

$$a(t,\vec{x}) = \iiint d^3k\ e^{i[\omega(\vec{k})t+\vec{k}\cdot\vec{x}]} a(\vec{k})$$

$$\langle a(\vec{k}) \rangle = 0$$

$$\langle a(\vec{k}) a(\vec{k}')^* \rangle = f(|\vec{k}|)\,\delta^3(\vec{k}-\vec{k}')$$

Axion dispersion relations

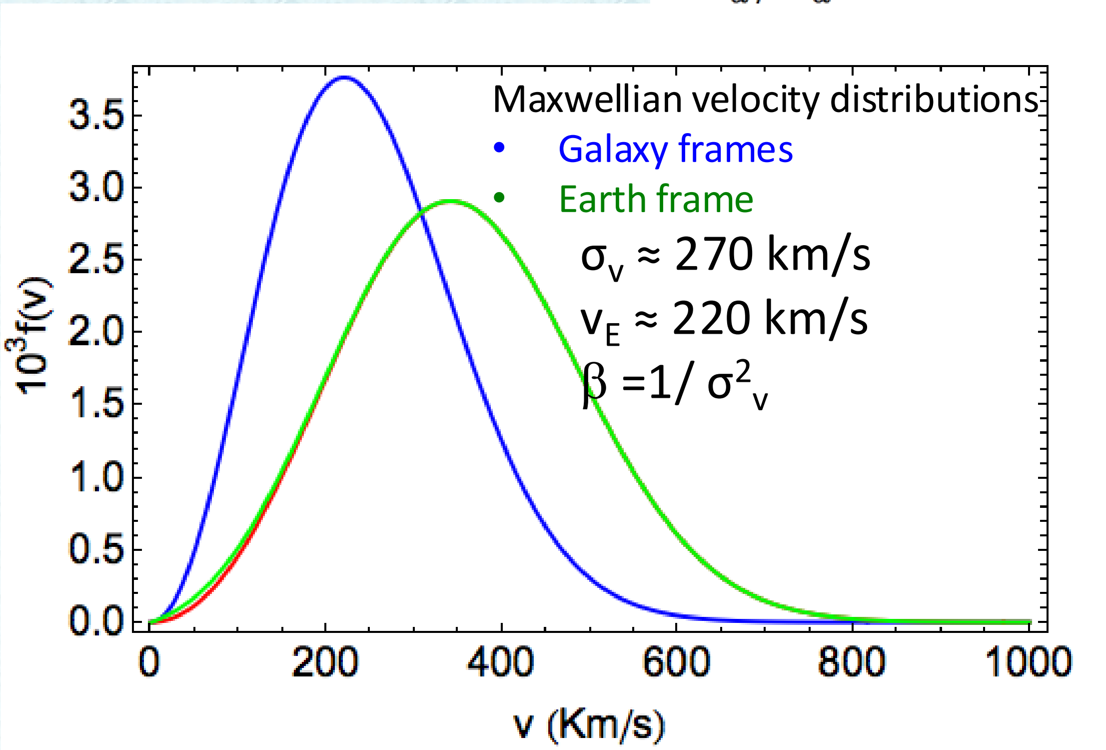
$$E = \hbar\omega = m_a c^2 + \frac{1}{2} m_a v_a^2$$

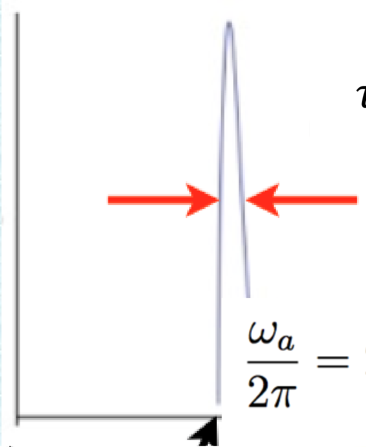
$$\vec{p} = \hbar\vec{k} = m_a \vec{v}_a$$

$$P_a(\omega) \propto \left(\frac{|\omega| - \omega_a}{\Delta\omega_a}\right)^{1/2} \exp\left(\frac{|\omega| - \omega_a}{\Delta\omega_a}\right) \theta\left(|\omega| - \omega_a\right)$$

$$\Delta\omega_a = \frac{\omega_a}{\beta c^2}$$

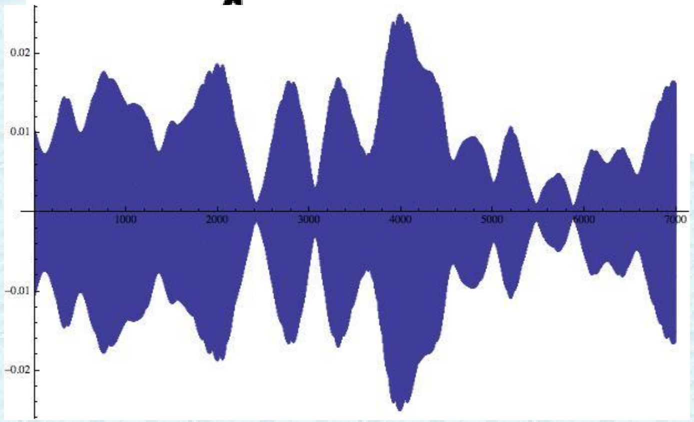
$$\Delta\omega_a/\omega_a \simeq 5 \times 10^{-7}$$





$$\tau_a = 5\left(\frac{10^{-6}\ eV}{m_a}\right)\ \mathrm{ms}$$

$$\frac{\omega_a}{2\pi} = 24\left(\frac{m_a}{10^{-4}\mathrm{eV}}\right)\ \mathrm{GHz}$$



Axions in the galactic halo

- In order to explain galaxy rotation curves, a **halo of dark matter** is hypothesized
- Accepted value for local dark matter **density**

$$\rho_{DM} \approx 0.3 \ - 0.45 \ \ \text{GeV/cm}^3$$

- Cold dark matter component is **thermalized** and has a Maxwellian velocity distribution, with a dispersion $\sigma_v \approx 270$ km/s
- There might be a non-thermalized component with sharper velocity distribution

- **Axion can be a dominant component of the galactic DM halo**
- Its **occupation number** is large

$$n_a \approx 3 \times 10^{14} \left(\frac{10^{-6}\ eV}{m_a}\right) \quad \text{axions/cm}^3$$

- It can be treated as a classical oscillating field with frequency given by the axion mass

$$\frac{\omega_a}{2\,\pi} = 2.4 \left(\frac{10^{-6}\ eV}{m_a}\right) \quad \text{GHz}$$

- It has **coherence length** and **time**

$$\lambda = 1400 \left(\frac{10^{-6}\ eV}{m_a}\right) \text{m}$$

$$t = 5 \left(\frac{10^{-6}\ eV}{m_a}\right) \text{ms}$$

[C] Haloscopes – Galactic axions – Sikivie Type

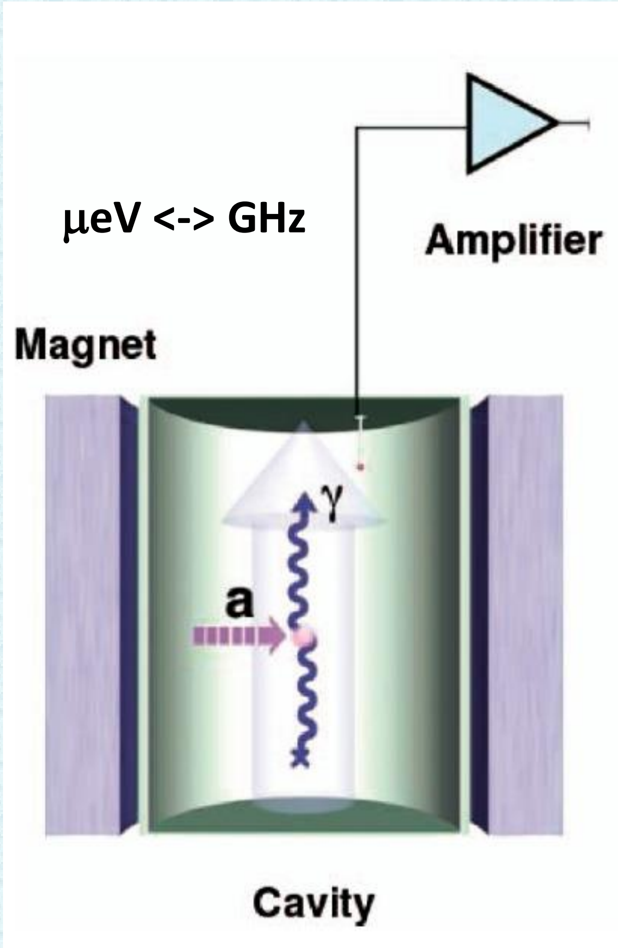
- Search for axions as cold dark matter constituent
- Original proposal by P. Sikivie (1983)
- **DM particles converted into photons inside a magnetic field (Primakoff effect), sensitivity to $g_{a\gamma\gamma}$**

  - **The mass** of the DM particle determines **the frequency of the photons** to be detected. For axions we are in the **microwave range**.

$$h\nu = E_{\mathrm{a}} = m_{\mathrm{a}}c^2\left(1 + \frac{1}{2}\beta_{\mathrm{a}}^2\right) = m_{\mathrm{a}}c^2(1 + O(10^{-6}))$$

$\beta_a \sim 10^{-3}$ axion velocity

  - **Use a microwave cavity** to enhance signal. Cavity must be tuned to axion mass. Being this unknown, **tuning is necessary**: very time consuming experiment!



Haloscopes – Galactic axions

- Search for axions as cold dark matter constituent
- Original proposal by P. Sikivie (1983)
- **DM particles converted into photons inside a magnetic field (Primakoff)**
  - Expected signal a **nearly monochromatic line**. Broadened by the **thermal distribution** of DM in the Milky Way

$$\frac{\Delta E}{E} \approx 10^{-6} = 1/Q_a$$

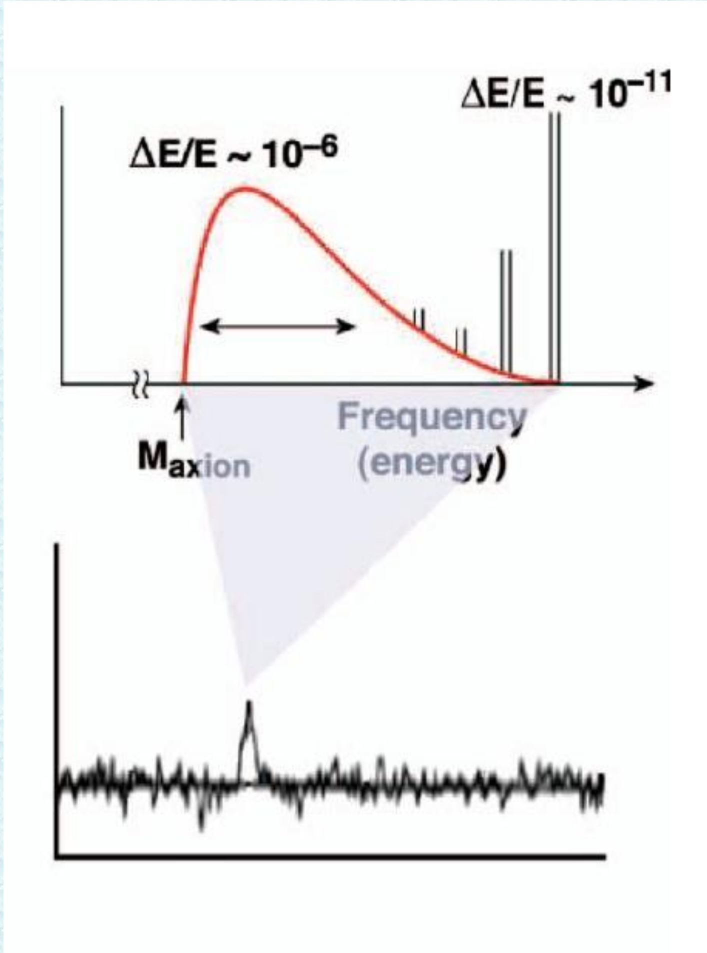
  - Possible **very sharp component due to non-thermalised** axion falling in and out of the Milky Way

$$\frac{\Delta E}{E} \approx 10^{-11}$$

  - **Power** proportional to the number density and the square of the axion-photon coupling

$$P_{a\to\gamma} \propto \left(B_0^2 V Q\right)\left(g_\gamma^2 \frac{\rho_a}{m_a}\right).$$

  - Typical powers to be measured below 10^{-23} W



Sensitivity

- When the frequency of the axion induced photon matches the frequency of the **cavity eigenmode**, the conversion power is **resonantly enhanced** via cavity Q_c ($Q_c \ll Q_a$) $Q_L = Q_c/(1+\beta)$

$$P_{\mathrm{axion}} = 1.1\times10^{-23}\,\mathrm{W}\left(\frac{g_\gamma}{1.92}\right)^2\left(\frac{\rho_a}{0.45\,\mathrm{GeV/cm^3}}\right)\left(\frac{\nu_a}{1\,\mathrm{GHz}}\right)\left(\frac{B_0}{10\,\mathrm{T}}\right)^2\left(\frac{V}{1\,\mathrm{liter}}\right)\left(\frac{C_{mnl}}{0.69}\right)\left(\frac{Q_L}{10^5}\right)\frac{\beta}{(1+\beta)}$$

- The **power is picked up by an antenna** with coupling β and read by an amplifier. Extremely low power levels are detected by sensitive amplifiers
- In the absence of a signal, the output of a receiver is noise measured on a **bandwidth B_a** corresponding to the axion linewidth

$$P_{\mathrm{noise}} = G k_B (T_{\mathrm{cav}} + T_{\mathrm{ampl}}) B_a = G k_B T_{\mathrm{sys}} B_a$$

Cavity noise + amplifier noise

T_{ampl} = amplifier noise temperature
G – gain ; k_B – Boltzmann constant
T_{sys} = total system noise temperature

- The **SNR** can be calculated with **Dicke's radiometer equation** for a **measurement time t_m**

$$\mathrm{SNR} = \frac{P_{\mathrm{axion}}}{k_B T_{\mathrm{sys}}}\sqrt{\frac{t_m}{B_a}}$$

- Since all the frequencies within a cavity bandwidth can be scanned simultaneously, we can calculate a **scanning rate** as

$$\frac{df}{dt} = \frac{1}{\mathrm{SNR}^2}\frac{P_{\mathrm{axion}}^2}{k_B^2 T_{\mathrm{sys}}^2}\frac{Q_a}{Q_L}$$

Major R&D efforts are made to **increase B_0^2 V C Q_c** and **minimizing T_{sys}**

Haloscopes – Galactic axions

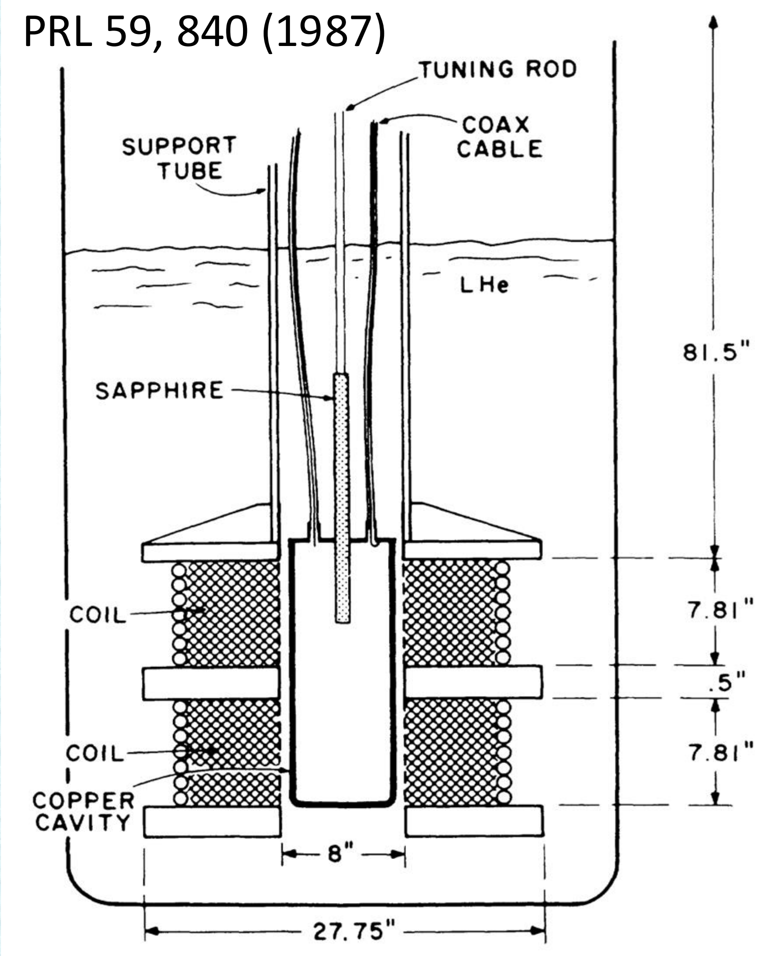
- Resonant detection of DM axions in a magnetic field. One measurement explores **only sharp cavity linewidth**.
  Scanning is necessary.

Figure of merit for scanning (mass or frequency)

$$\boxed{\frac{\Delta f}{\Delta t} \propto V^2 B^4 C^2 T_{sys}^{-2} \ Q}$$

- **High Q** microwave cavity operating inside a **strong magnetic field B**
- **Large volume *V*** cavity at **high rf frequency *f***
- **Low noise T_{sys}** radio frequency receiver
- Use cavity modes with **large form factor *C***

PRL 59, 840 (1987)



Schematic diagram of the RBF apparatus (1987)

- Scanning to high mass – high frequency very difficult due to reduced cavity volumes
- Scanning to low mass – low frequency implies large cavities and thus very big magnets

! All current limits assumes axion/ALPs saturate the local DM density

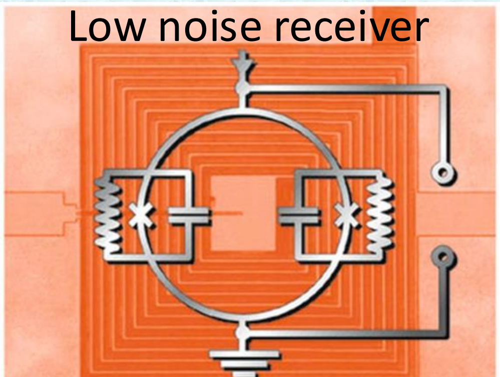
Main components of cavity haloscopes

Refrigeration system

Base temperature T

Microwave cavity

Quality Factor Qc
Form factor C_{mnl}
Volume V
Resonance frequency f
Tuning



Picture and scheme of a SQUID

Noise temperature T_n

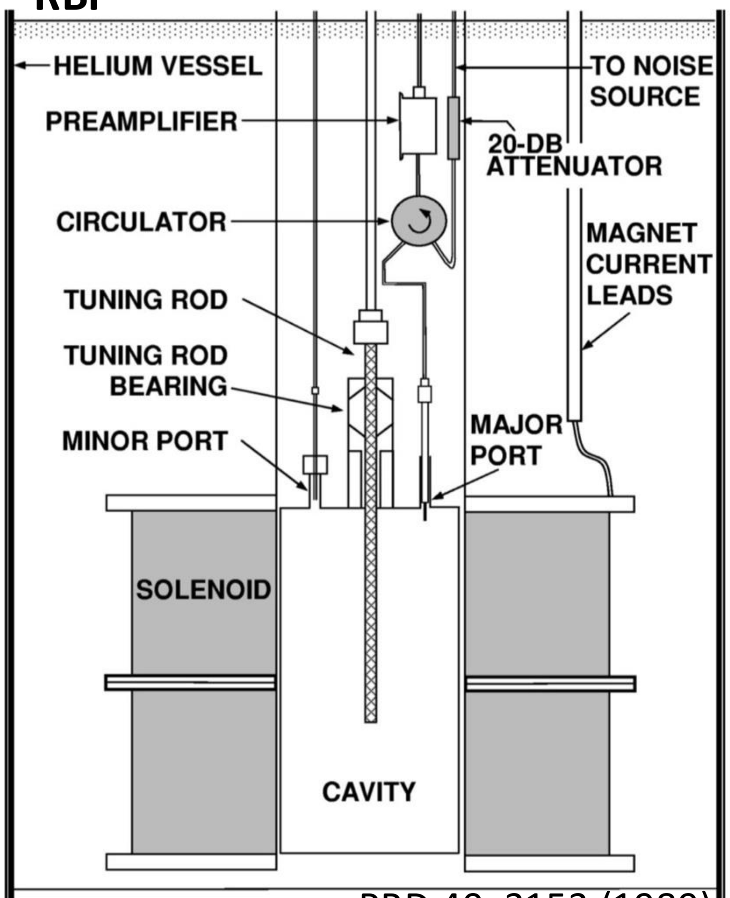
Magnetic source

Magnetic energy B^2 V

Haloscope detectors - precursors

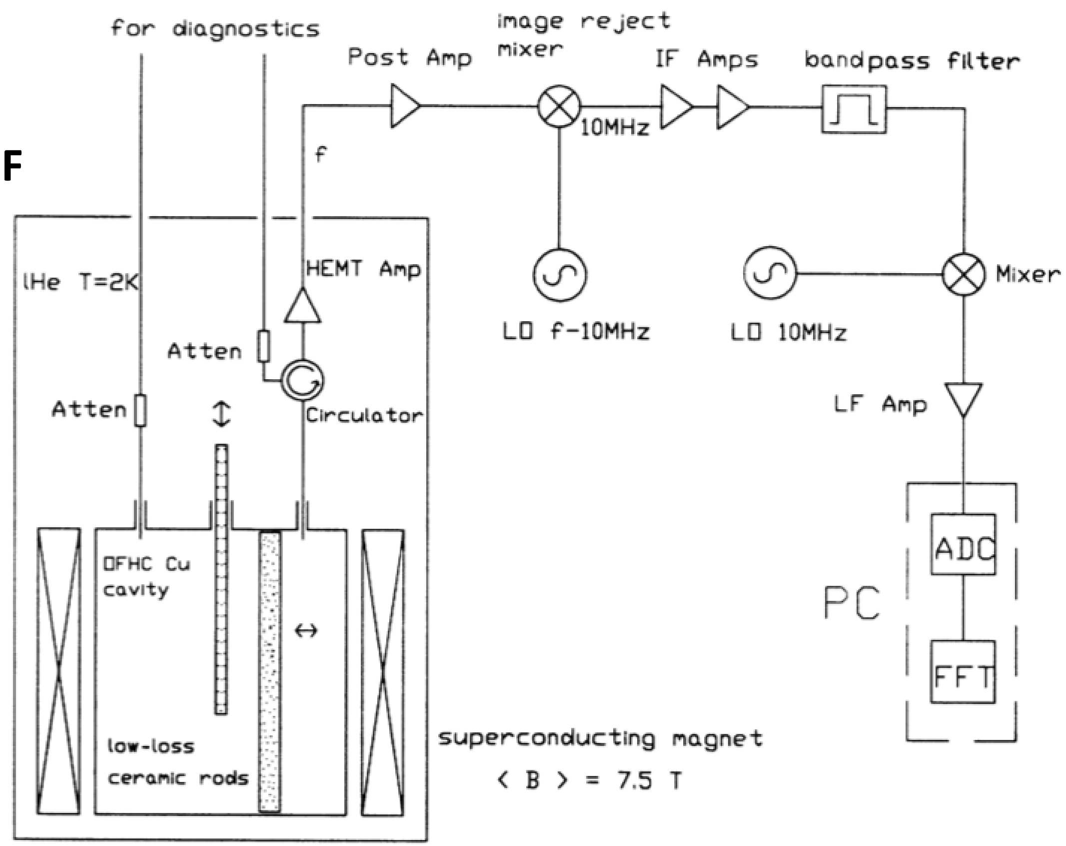
- **Pilot experiments in Brookhaven (RBF) (1988) and University of Florida (UF) (1990)**
- **Provided basic structure for even today's most sensitive experiments**

RBF



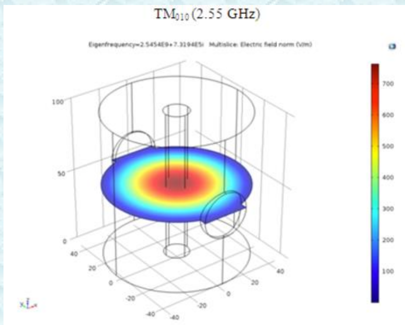
PRD 40, 3153 (1989)

UF



PRD 42, 1297 (1990)

7 cavities, Brms 7.5 T phi 20 cm, L 40 cm
Copper cavity TM010 with Q_L up to 70000
Cavity tuning with sapphire rods
7 GaAs FET amplifier, T_n 10-20 K



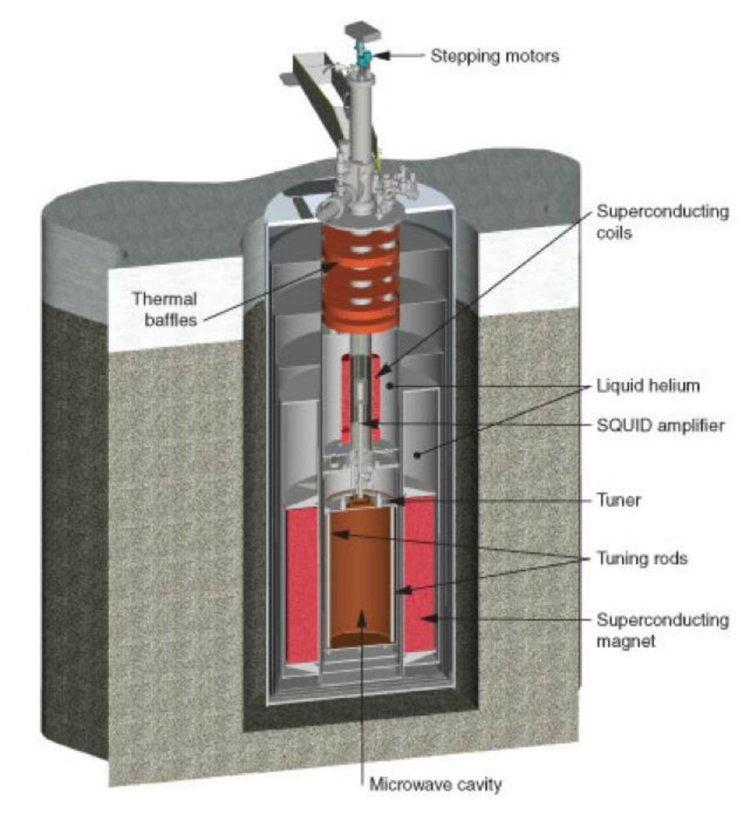
HEMT amplifier, T_n 3-6 K

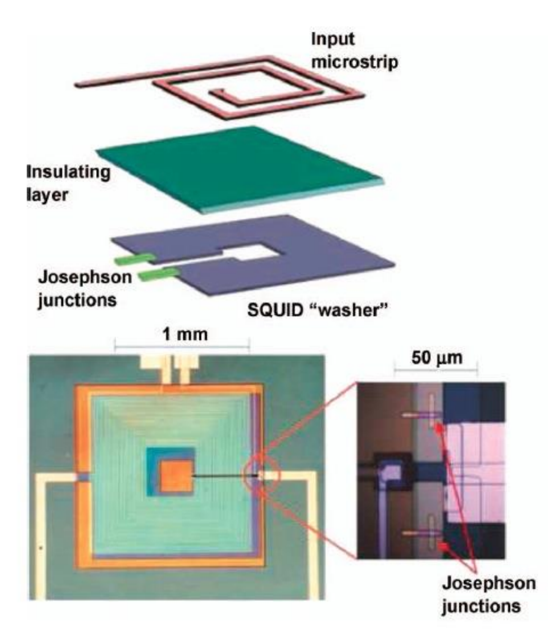
Haloscope detectors – 1^{st} gen - ADMX

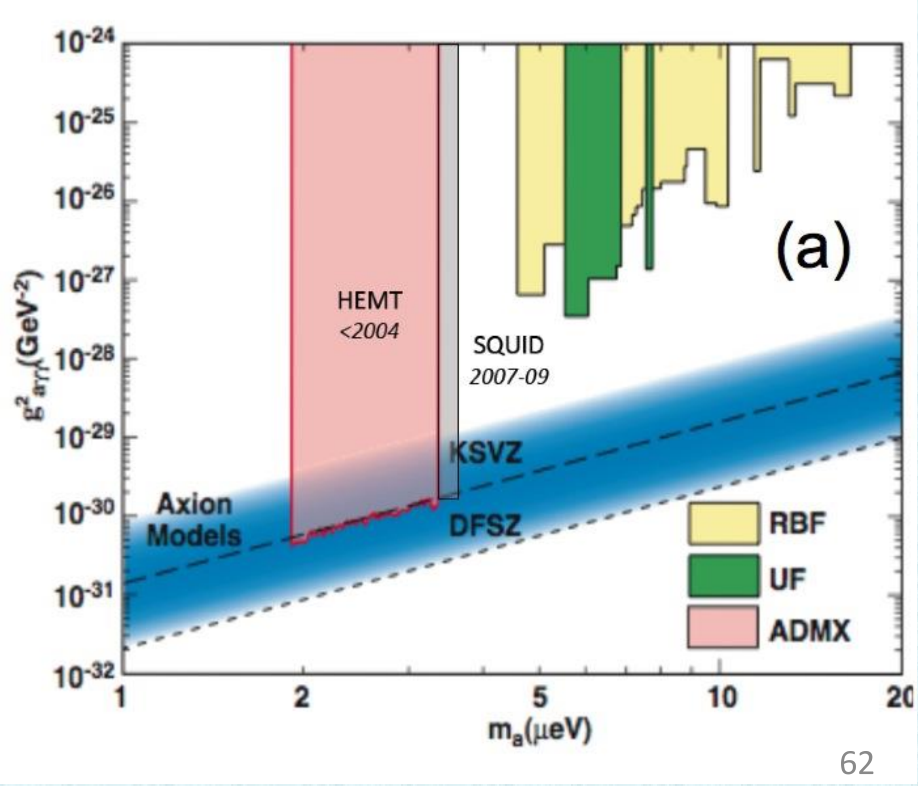
ADMX – Axion Dark Matter eXperiment – phase I

Collaboration started in 1990 to explore new ways forward:

- SC quantum interference device (SQUID) receiver
- Large size copper cavity inside 8.5 T magnet
- Running temperatures around 1.5 K
- System noise temperature at few K
- Cavity tuning with rods







- **Reached QCD axion model (KSVZ)**

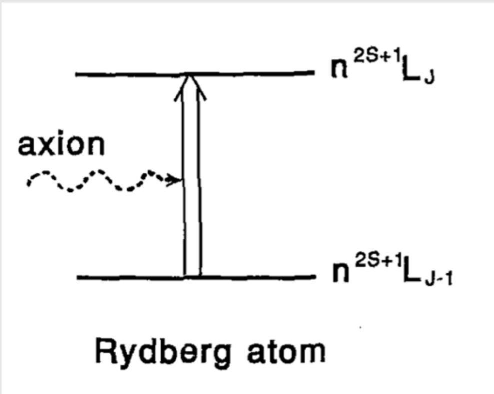
Haloscope detectors – precursors - CARRACK

Different ideas already from the beginning:
Rydberg atoms

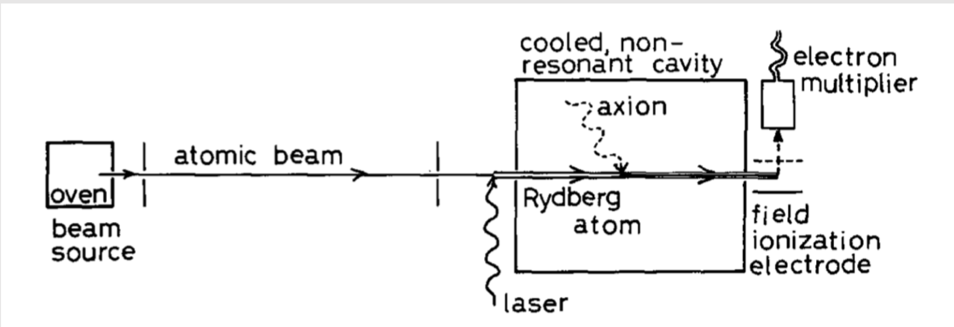
1. Rydberg atoms as direct axion DM detectors

Exploit the **axion-electron coupling** to excite Rydberg transitions

f ~ GHz Range

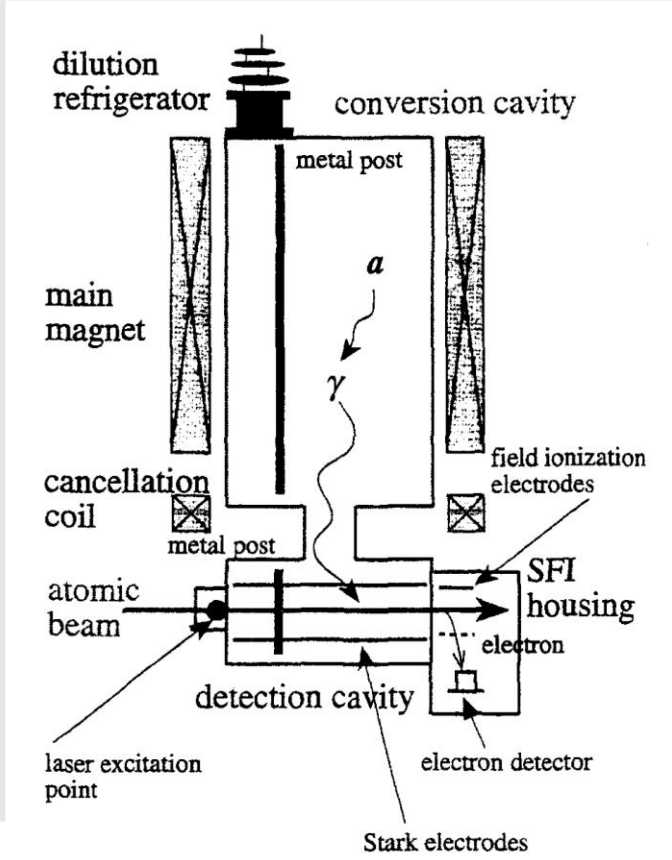


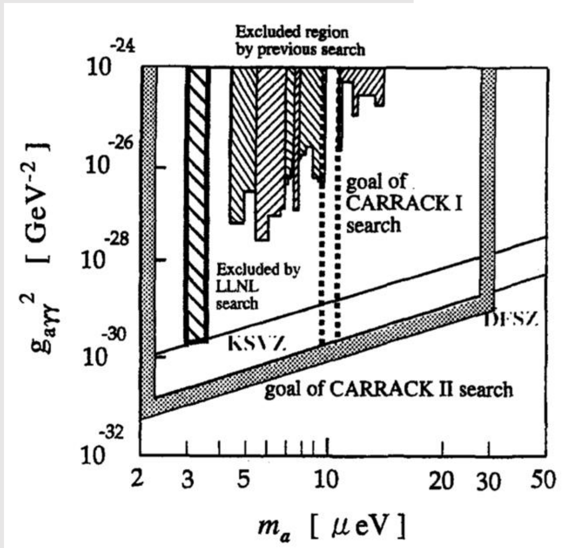
Use alkaline atomic beam in an inhibited cavity regime



PLB 263, 523 (1991)

2. Rydberg atoms as photon detectors in a Sikivie's type scheme

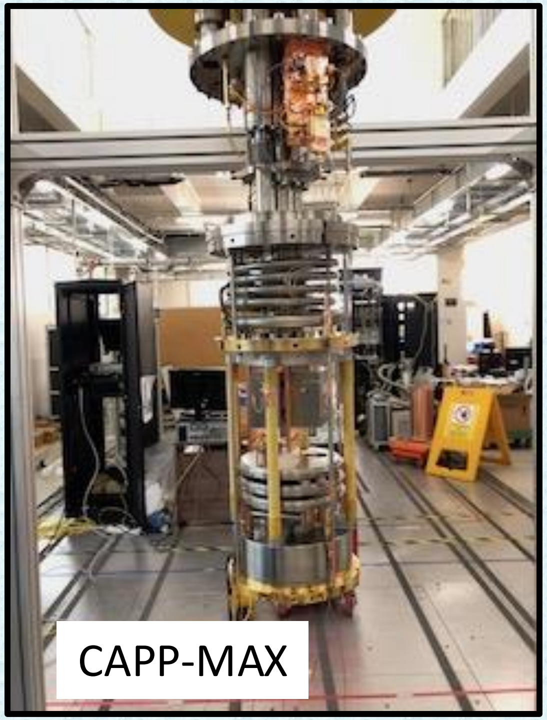


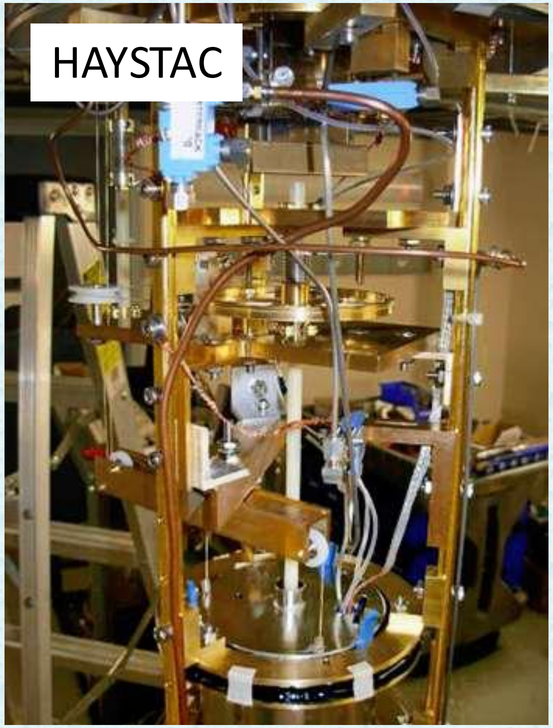


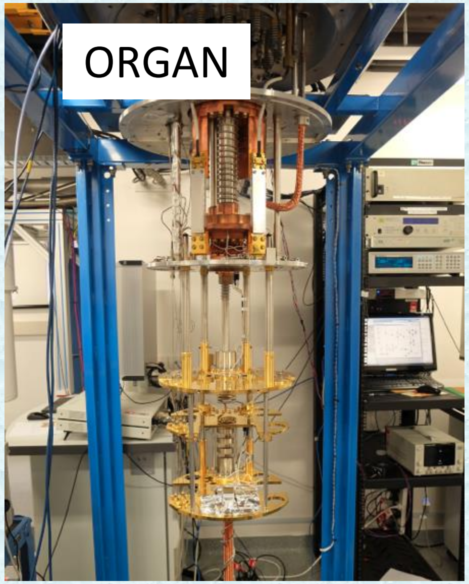
NPB (PS) 72, 164 (1999)

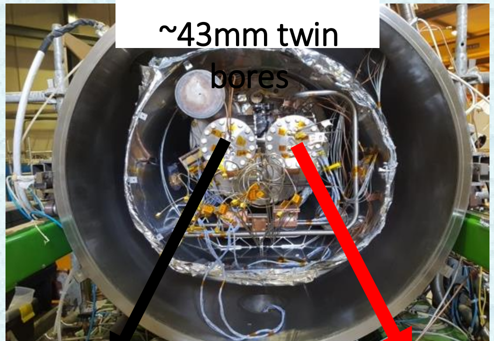
Haloscope detectors – current situation

- Within the last 10 years ADMX has evolved and a large number of new apparata based on Sikivie's scheme came into play





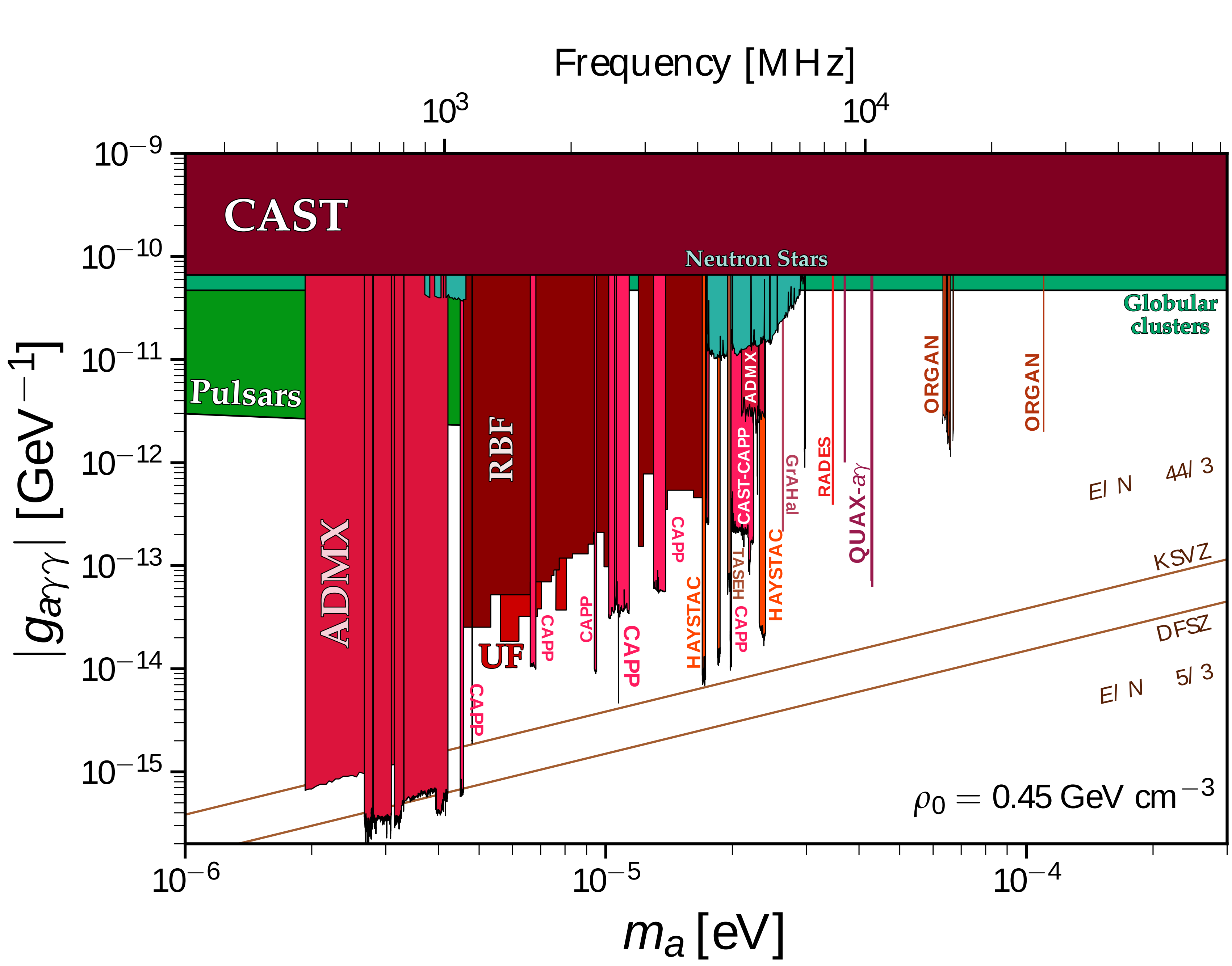




CAST-RADES

CAST-CAPP

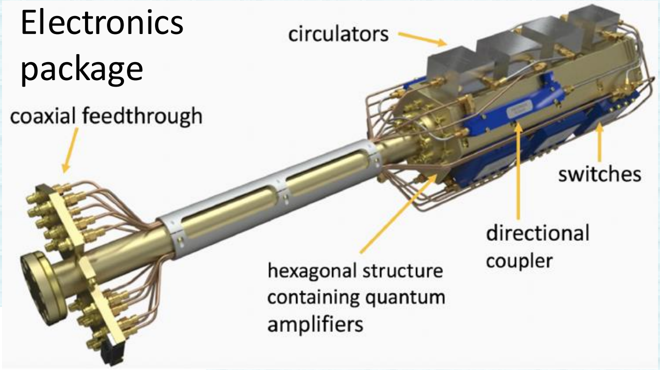
Current limits – Sikivie's haloscopes

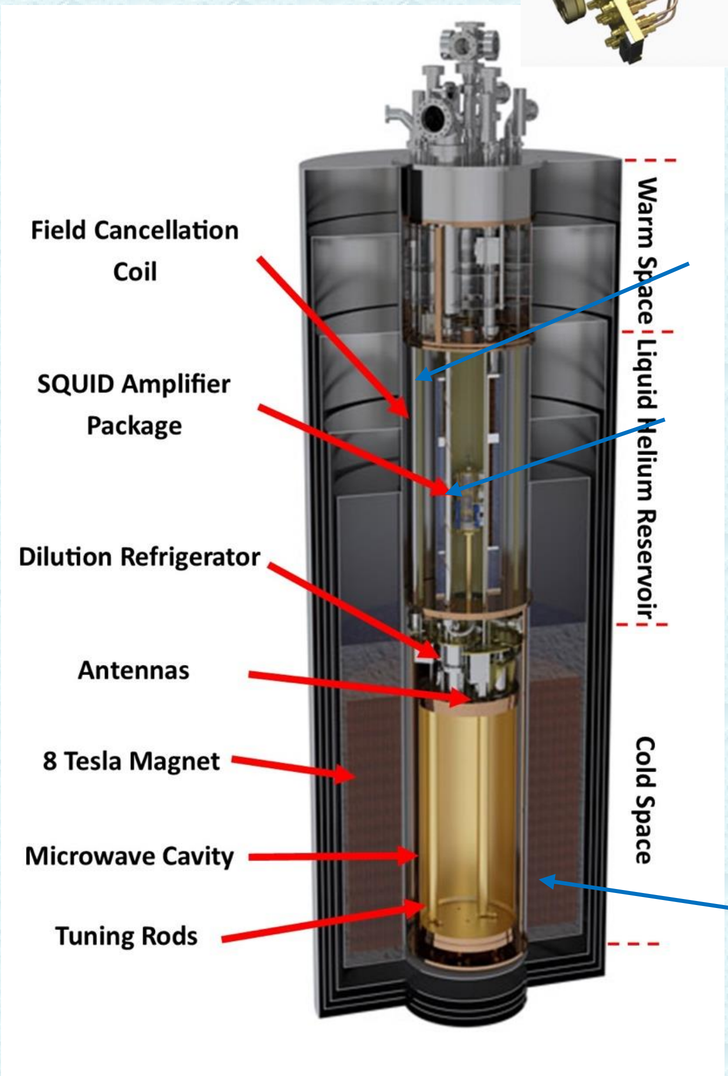


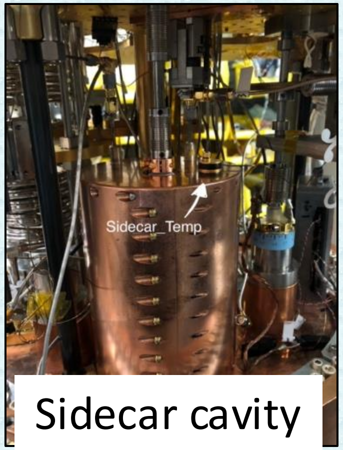
AxionLimits by cajohare.

ADMX – Axion Dark Matter EXperiment

University of Washington





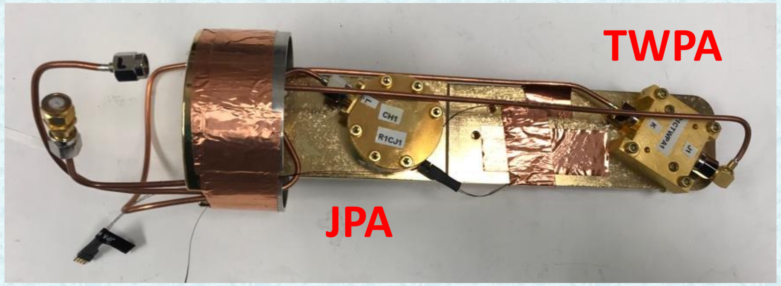


Sidecar cavity

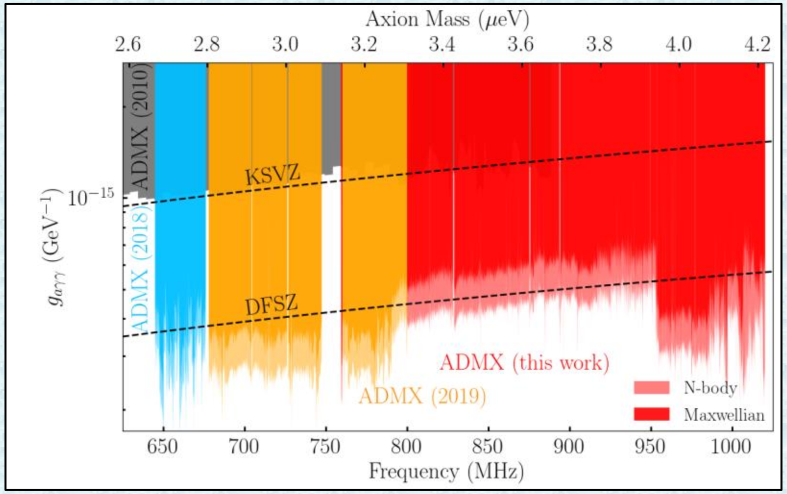
Main cavity

ADMX has evolved in time with the implementation of several improvements:

- Dilution refrigerator with lower base temperature : cavity @ 150 mK
- SQUID, JPA and TWPA amplifiers
- Multimode searches

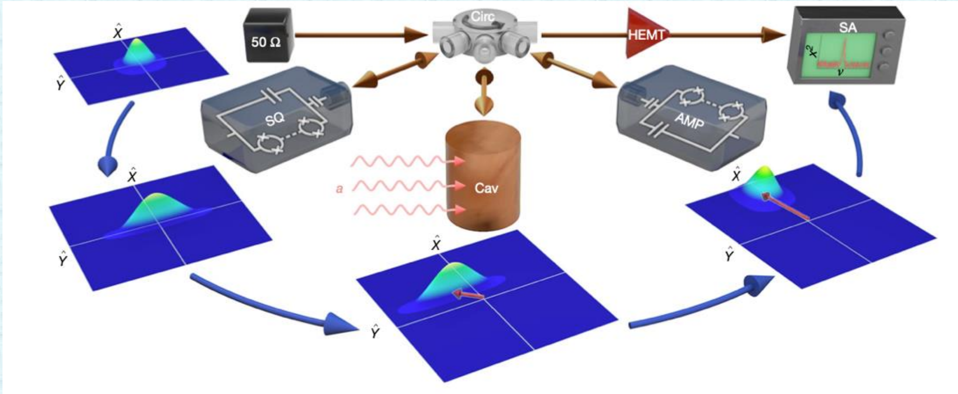


First haloscope to reach DFSZ axion model sensitivity

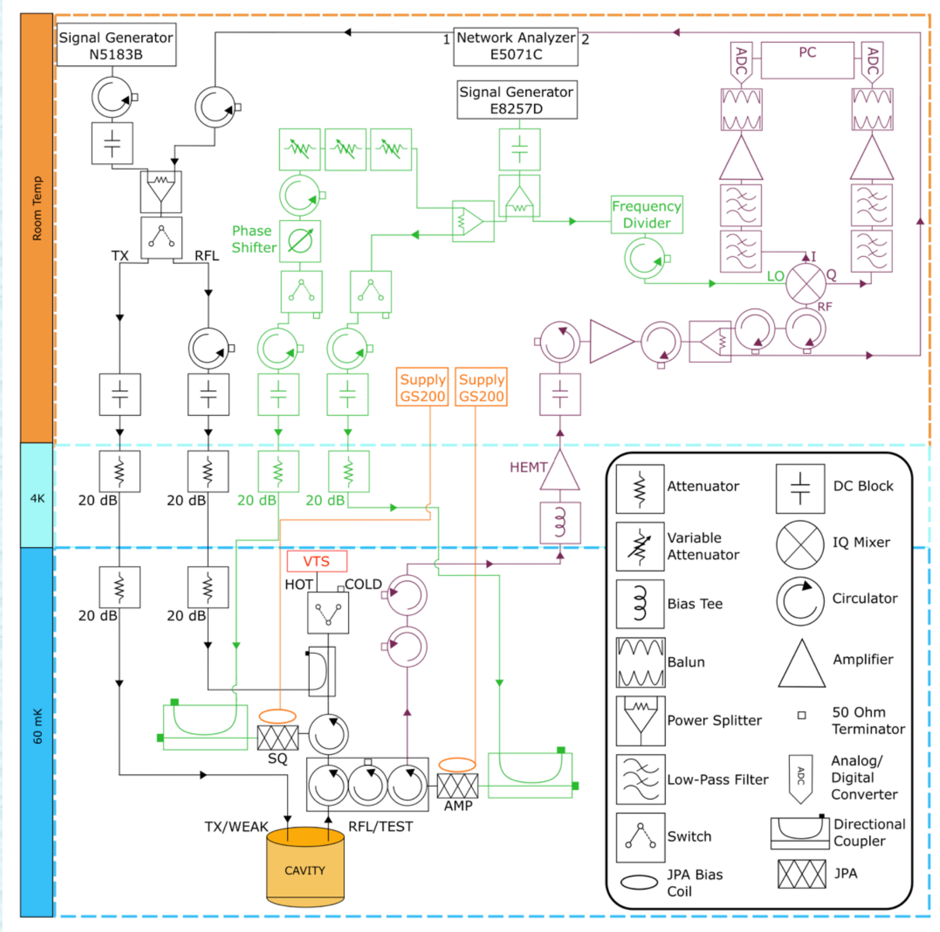


Phys. Rev. Lett. **127**, 261803 (2021)

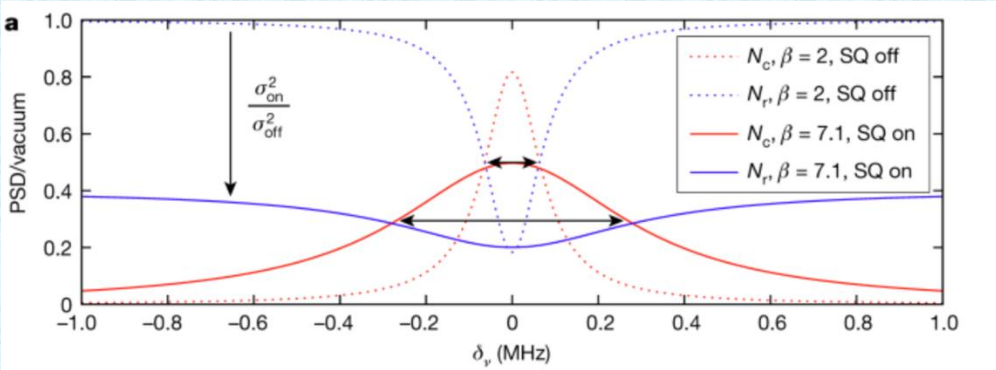
HAYSTAC – Haloscope at Yale Sensitive To Axion CDM

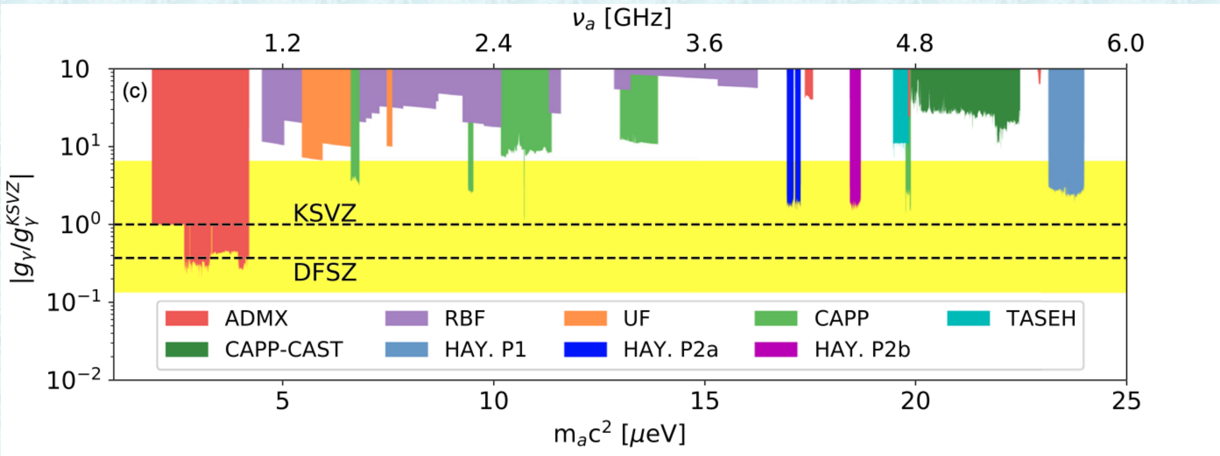


- Designed to search for dark matter axions with masses above 10 μeV
- First haloscope to use a Josephson Parametric Amplifier
- First haloscope to employ a Squeezed-state receiver (SSR)



Scan rate enhancement 1.9 over quantum limit





Jewell et al. PRD 107, 072007 (2023)

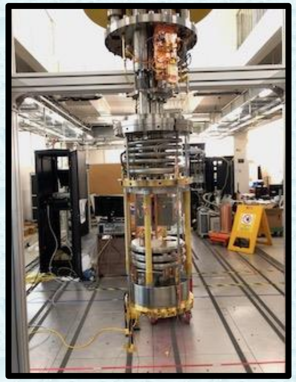
IBS-CAPP Institute of Basic Science

- IBS – CAPP was established in Korea with the aim of building a laboratory equipped with top infrastructure for cavity haloscope searches with enhanced sensitivities over a broader range in the microwave region.

CAPP
Center for Axion and Precision Physics Research

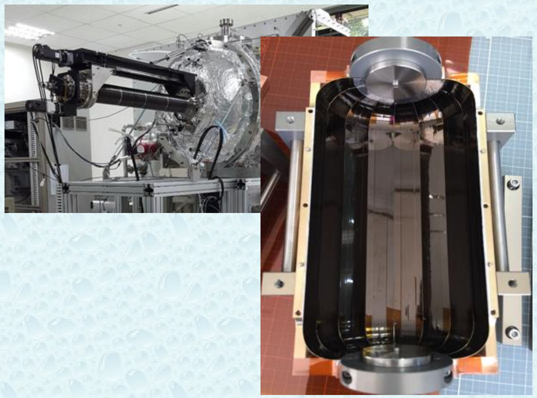
Cryogenics (<40mK)
Dilution Refrigerators

High Field & Big bore Magnet
12T LTS Big Bore SC Magnet

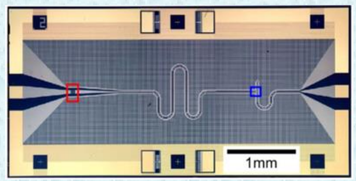


- **High Temperature Magnets** based on ReBCo tape
- **High field and large volume** Low Temperature magnet
- Powerful **dilution refrigerators** to achieve ultralow temperature
- Design and construction of **large-effective-volume high-frequency high-Q** microwave resonator
- Use of very low noise Josephson Parametric Amplifiers working at different frequencies

High Q Tunable Cavity
Superconducting tapes



Quantum Amplifier
SQUID and/or JPA (T_N ~ SQL)



Several running experiments

Axion experiments at CAPP

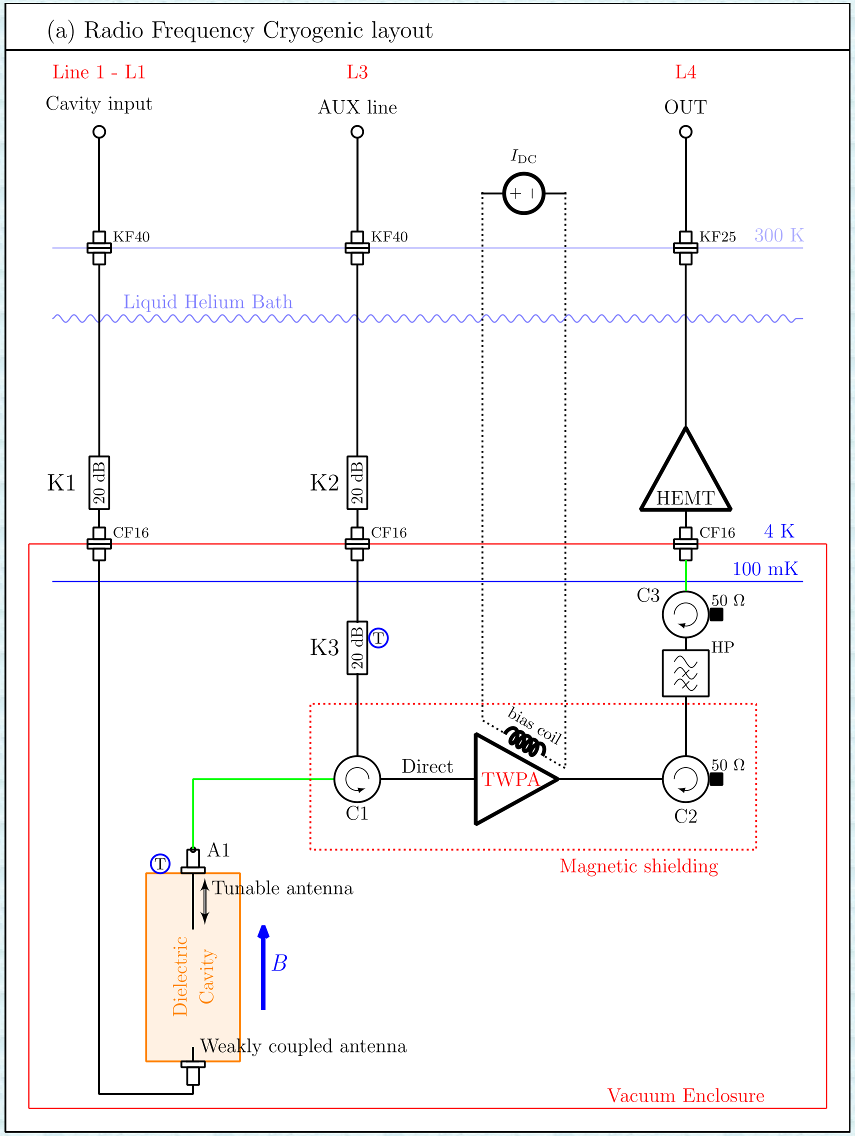
	CAPP-PACE	CAPP-8TB	CAPP-HF	CAPP-PACE -JPA	CAPP-PACE -JPA-6cell	CAPP-8TB -JPA-8cell	CAPP-PACE -JPA-SC	CAPP-MAX	CAPP-AQN-SC	CAPP-HeT-SC	CAPP-12T-HF-3cell
Year	2018	2019	2019	2020	2021	2021	2021	2021	2023	2023	2023
Magnet [T]	8	8	9	8	8	8	8	12	8	8	12
m_a [GHz]	~2.5	~1.6	~4.0	~2.3	~5.6	~5.8	~2.3	1.0 ~ 2.0	~2.3	~5.4	~5.3
Δm_a [MHz]	250	200	250	30	80	>100	30	20 ~ 300	-	> 50	~30
Sensitivity	10*KSVZ +KSVZ	4*KSVZ	10*KSVZ	2*KSVZ	3*KSVZ	KSVZ	KSVZ	DFSZ	DFSZ	KSVZ	KSVZ
T_{phy} [K]	< 0.05	< 0.05	~2	~0.05	~0.05	~0.03	~0.04	~30 mK	60 mK	30 mK	30 mK
T_{sys} [K, mK]	~1 K (HEMT)	~1 K (HEMT)	~2 K (HEMT)	~200 mK	<300 mK	<300 mK	<200 mK	<300 mK	~200 mK	~400 mK	~400 mK
Comments	R&D machine: First physics run (coldest axion data)	First result published by CAPP	First multi-cell cavity result	First run with JPA	First run with JPA+6-cell	First run with JPA+8-cell	First run with JPA+SC	CAPP's main axion detector with JPA	Axion Quark Nugget + SC cavity (Q~1.6M)	First run with He tuning + SC cavity (Q~10M)	3-cell with 12T mag + JPA SC cavity (future)
Publication	Published in PRL	Published in PRL	Published in PRL	Published in PRL	--	Will publish	Will publish	Published in PRL			

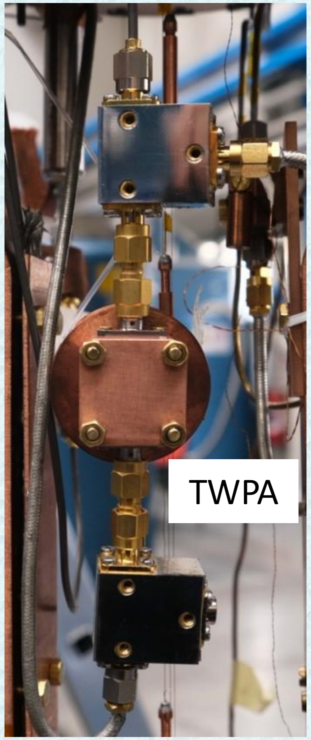
QUAX – QUaerere AXion – QUest for AXion

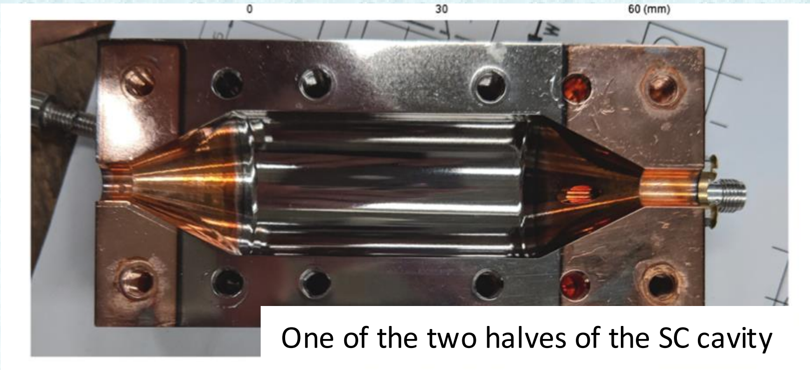
Experiment designed to look for dark matter axion in the 10 GHz region

- First apparatus to use a superconducting cavity in a strong magnetic field $Q0 = 4.5\ 10^5$ @ 2 T
- Operation of a quantum limited JPA at high frequency
- Operation of a near quantum limited TWPA at high frequency
- Use of hybrid cavity design (copper-sapphire) to get high Q and large volume
- First haloscope employing a cavity with Qc > Qa

Layout with novel calibration scheme







One of the two halves of the SC cavity

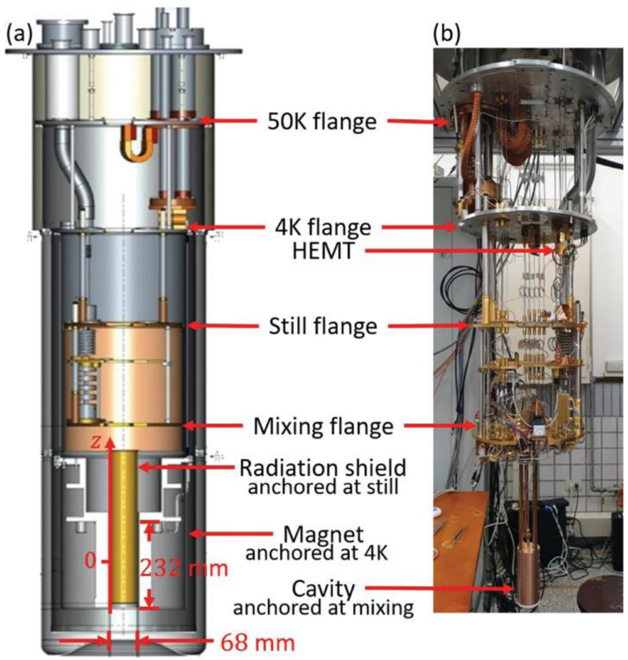
Achieved Tsys = 2.1 K @ 10.5 GHz
Reached QCD axion models sensitivity

Others running

TASEH

PRD 106, 052002 (2022)
PRL 129, 111802 (2022)

Range (4.70750 – 4.79815) GHz



- OFHC copper, split cavity
- Volume V: ~ 0.234 L
- $Q0$: ~ 62000
- C010 ~ 0.62

- B = 8 T
- Tsys 2.1 – 2.4 K

- Reach ~ 10 times KSVZ sensitivity over a 100 MHz window

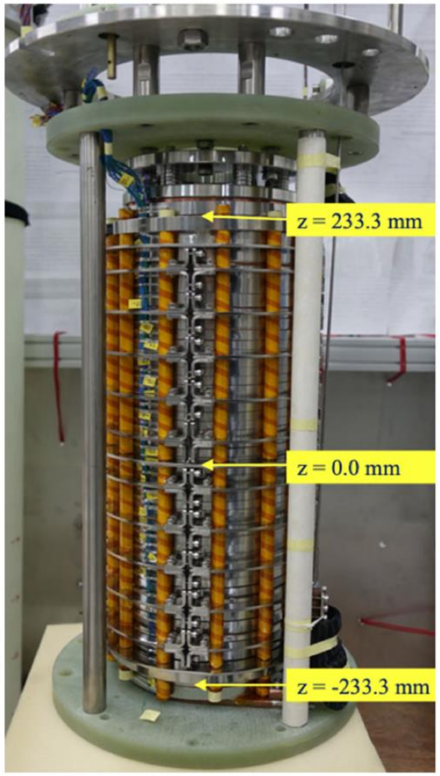
Next steps:
- New dilution unit for lower temperature
- Magnet upgrade 9 T and larger volume
- Use of a JPA
- New conical tunable cavity (see next)

CAPP18T

PRL 128, 241805 (2022)
PRD 106, 092007 (2022)
PRL 131, 081801 (2023)

Range (4.7789 – 4.8094) GHz

- **Strongest magnet for haloscope 18 T**
- JPC amplifier
- Tsys 0.62 K
- Reach KSVZ sensitivity over a 40 MHz window



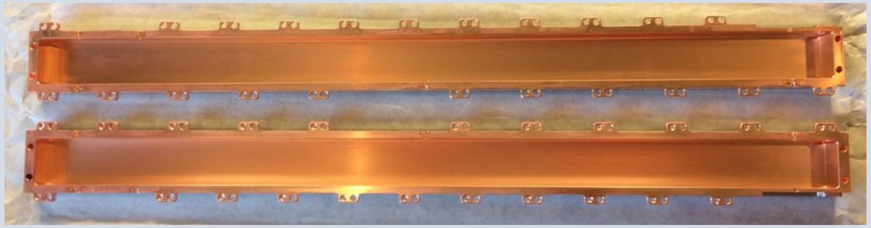
Others running II

CAST – CAPP

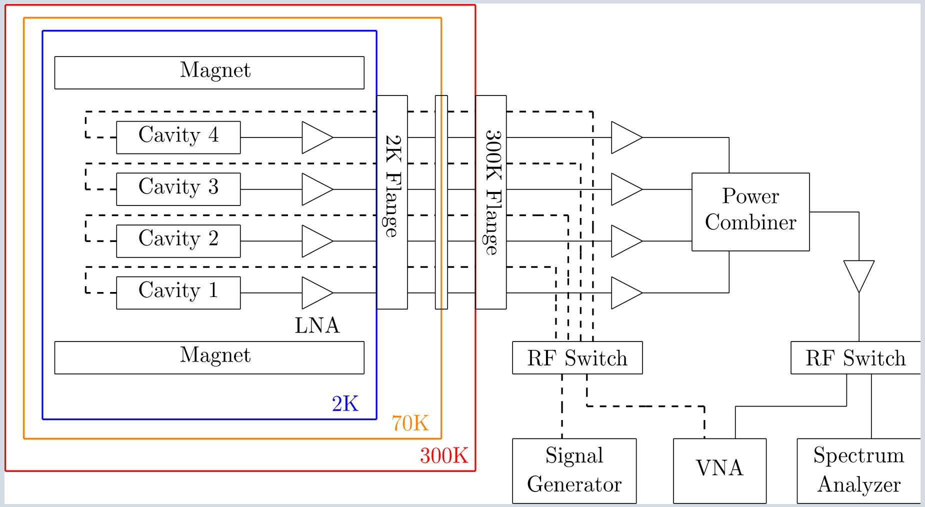
NatComm 13, 6180(2022)

Use of the LHC – CAST magnet as an haloscope

4 identical stainless steel tunable cavities



Increase the sensitivity via ***coherent* combination** of the power outputs of 4 frequency-matched cavities *after* individual signal amplification.



- No phase-matching: $SNR_N = \sqrt{N} \cdot SNR_{single}$
- With phase-matching: $SNR_N = N \cdot SNR_{single}$

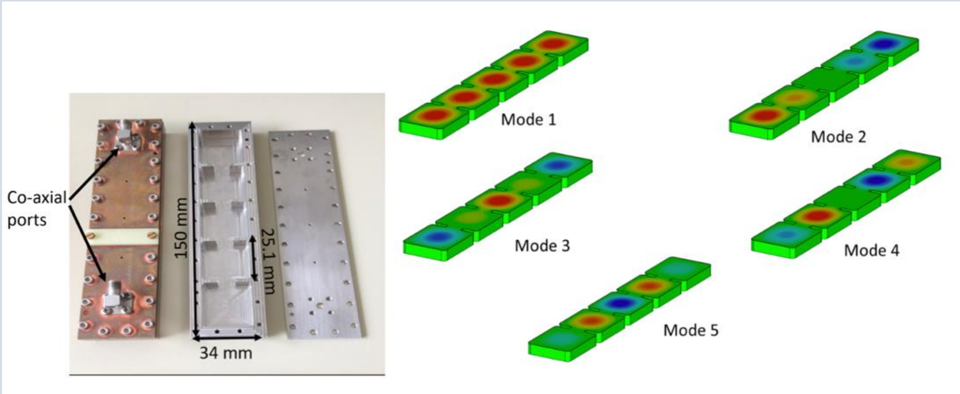
- Frequency range: ~4.8 – 5.4 GHz (660 MHz)
- Axion mass range: ~19.7 – 22.4 μeV

CAST – RADES

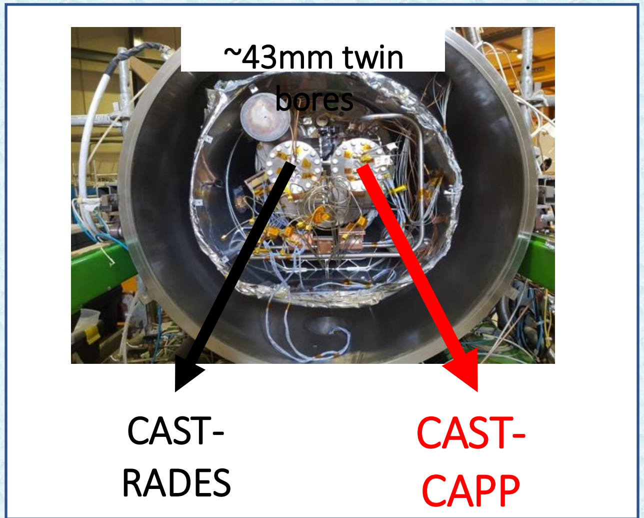
JHEP10(2021)075

Use of the LHC – CAST magnet as an haloscope

A radio frequency cavity consisting of 5 sub-cavities coupled by inductive irises took physics data inside the CAST dipole magnet for the first time using this filter-like haloscope geometry.



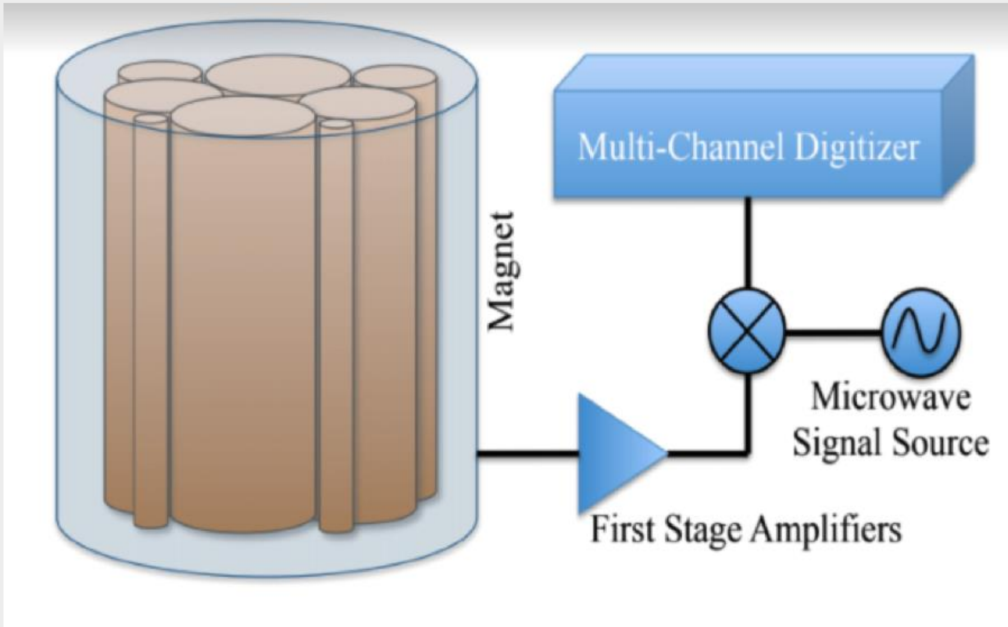
Q_L ~ 11000 @ Frequency 8.384 GHz (34.67 eV)



Others running III

The Grenoble Axion Haloscope project (**GrAHal**) aims at developing a haloscope platform in Grenoble (France), able to run detectors of different sizes and designs for the search of galactic axions and ALPs at the best sensitivity in the 0.3 − 30 GHz frequency range

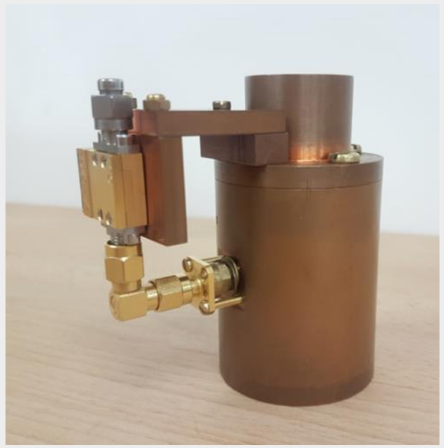
Pilot experiment with a 14 T magnet
And 6.4 GHz cavity



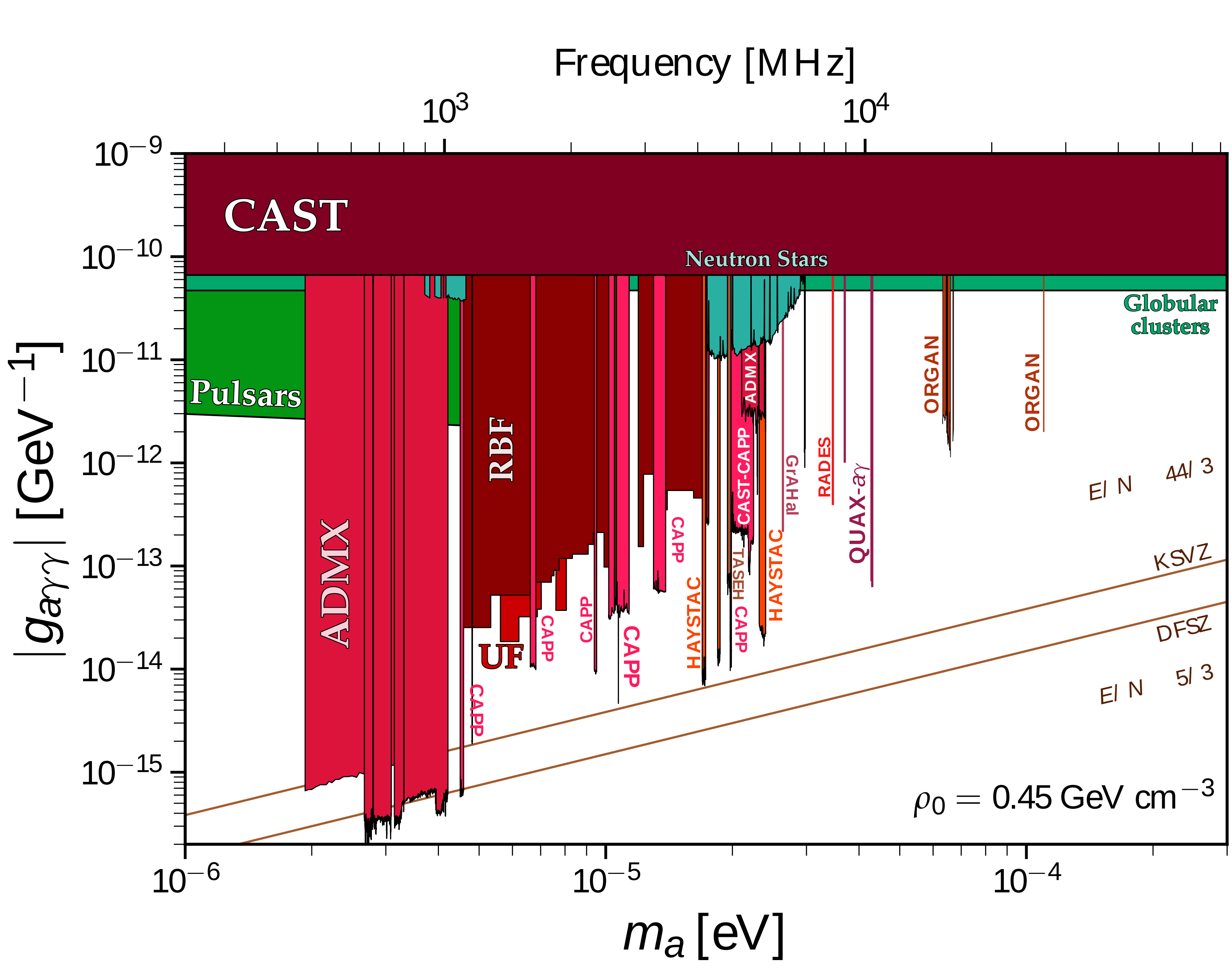
The **ORGAN** experiment (situated in Perth, Australia) is a microwave cavity axion haloscope that aims to search the mass range of ▯▯–▯▯▯▯▯**eV using a multi-cavity design**.

Pathfinder meas
@ 26.5 GHz

@ 15.3 – 16.2 GHz



Current limits – Sikivie's haloscopes



AxionLimits by cajohare.

Cavity Haloscopes: what next?

- **Haloscopes** seems to be CURRENTLY the most promising detectors to search for QCD axion dark matter – bandwidth limited – scanning required
- BEWARE: limits always assume axion as the dominant (100%) DM component

- **How fast can we scan** with a resonant detector?

$$\frac{df}{dt} = \frac{1}{SNR^2} \frac{g_{a\gamma\gamma}^4 \rho_a^2}{m_a^2} \frac{B_0^4}{k_B^2 T_{sys}^2} \frac{\beta^2 C_{mnl}^2 V^2}{(1+\beta)^2} \frac{Q_c Q_a^2}{(Q_c + Q_a)}$$

SNR - target signal to noise ratio

Dark matter axion parameters – independent of detector

Magnetic field B_0 and system noise temperature T_{sys} (related to apparatus environment)

Resonant cavity volume V, mode form factor C_{mnl}, coupling β and Q factor

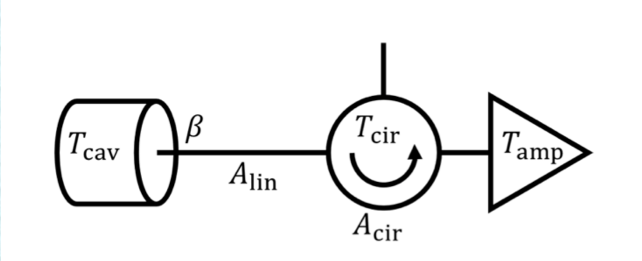
Optimization of values of technical parameters will be strongly dependent on the frequency range where the detector is operated

The road to the future: detectors

- **Frequency scan** inversely proportional to square of detection noise level
- Linear amplifiers limited to the Standard Quantum Limit (SQL)

$$k_B T_N = h\nu\left(\frac{1}{e^{h\nu/k_B T}-1}+\frac{1}{2}\right)+k_B T_A.$$

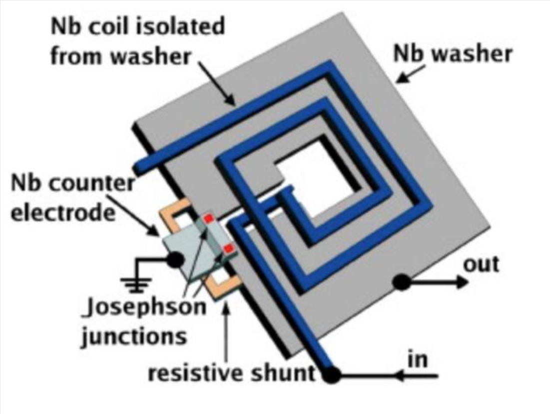
Total System Noise Level = cavity temperature + detector noise temperature



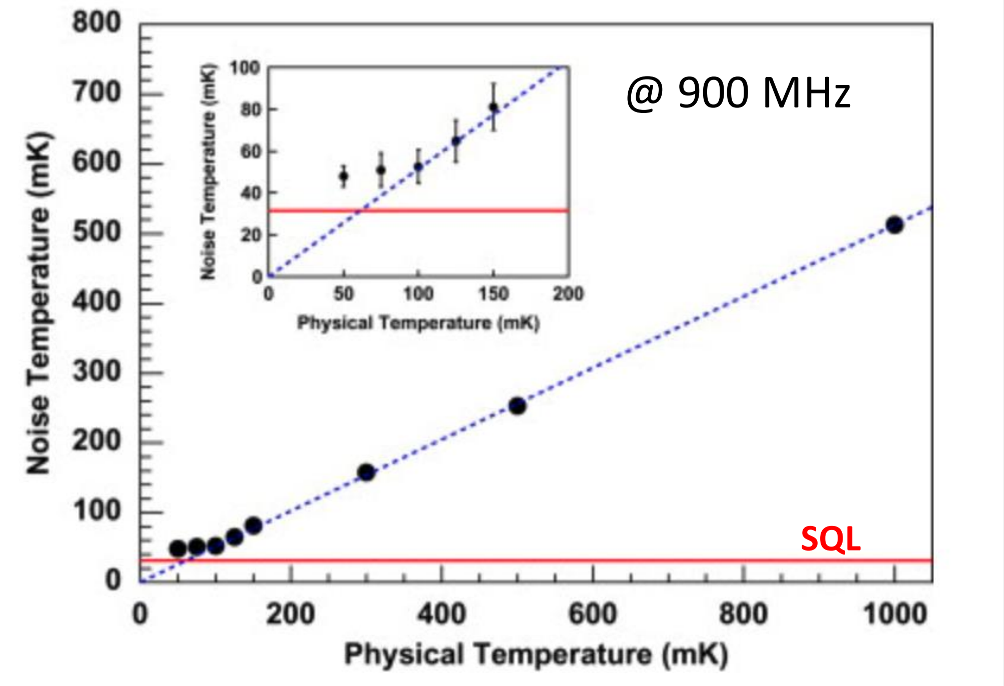
- **Irreducible noise** $k_B T_{SQL} = h\nu$, dominant noise above 2 GHz @ 100 mK

Low frequency

Microstrip SQUID amplifier (ADMX) almost reached SQL



Nucl. Instrum. Methods Phys. Res. A 656, 39 (2011).



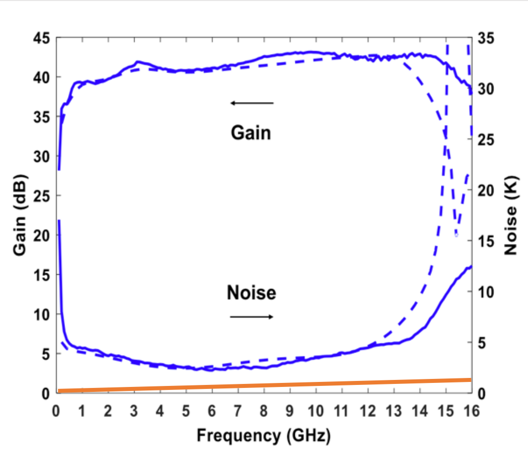
Performances drops for frequencies above a few GHz

https://doi.org/10.1016/j.nima.2011.07.019

The road to the future: detectors (high frequency)

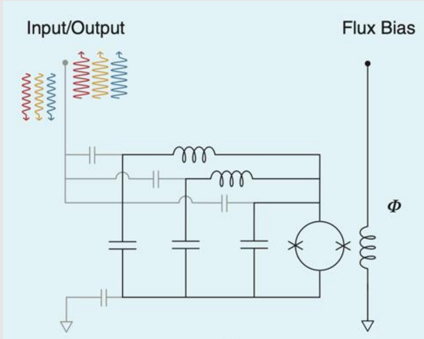
- For **frequencies above a few GHz**, it is much difficult to reach the limit of a linear amplifier

HEMT - high electron mobility transistor

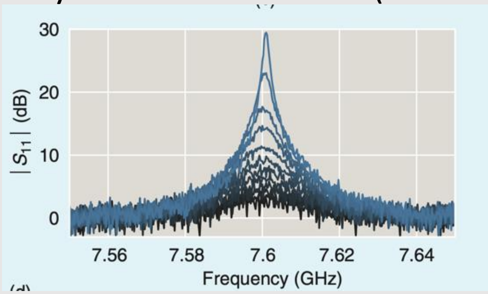


Cannot be used in ultra cryogenic environment due to power dissipation

JPA – Josephson Parametric Amplifier

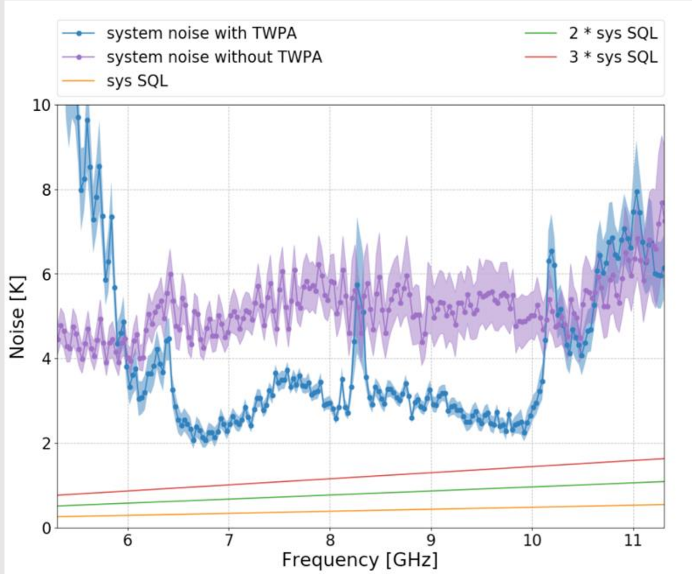


- Non linear drive of combination of Josephson Junctions
- Nominally **noiseless** parametric amplifiers → @ 1-2 SQL
- Very Limited bandwidth (10 MHz)



JTWPA – Josephson Travelling Wave Parametric Amplifier

- Transmission lines comprised of series connected junctions
- Can operate over a wide bandwidth (GHz)
- Still @ a development level



Other options :

Squeezing → Increase the measurement bandwidth

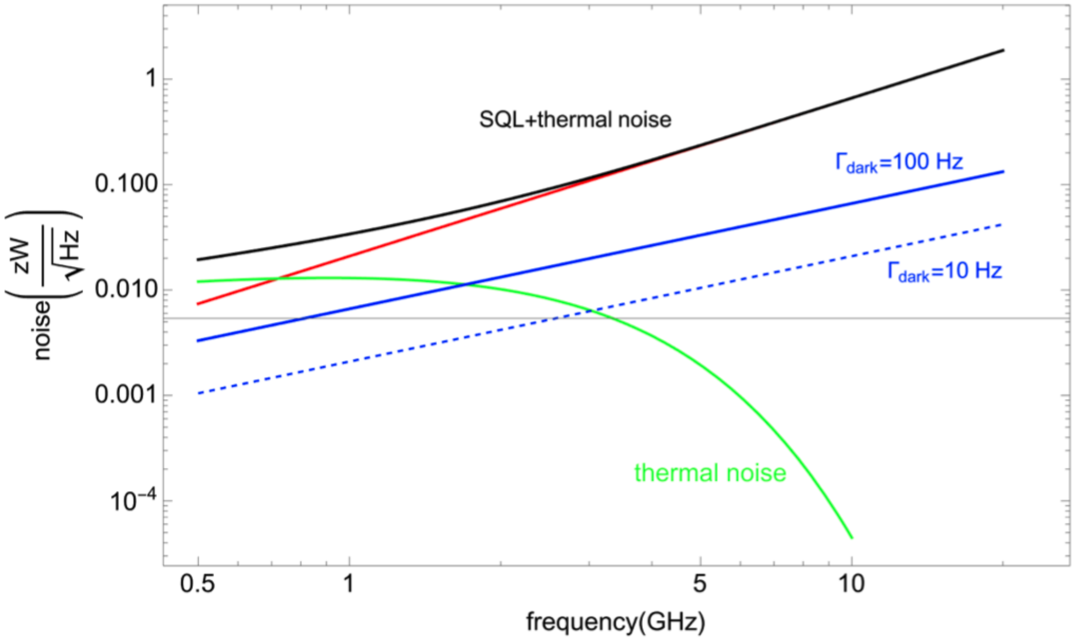
Single photon counter → Lots of R&D on the way

Single photon counting

Why do we need Single Microwave Photon Detectors (SMPD) in haloscope search?

Using quantum-limited **linear amplifiers** (Josephson parametric amplifiers) the **noise set by quantum mechanics** exceeds the **signal** in the high frequency range, whereas **photon counting** has no intrinsic limitations

	ν_c [GHz]	Q_0	B T	V [liter]	$P_{a\gamma\gamma}$ [10^{-24} W]	Γ_{sig} [Hz]
QUAX$_{a\gamma}$	10.48	1×10^6	14 T	1.15	439 (KSWZ) 60 (DFSZ)	63 8.7
Pilot exp.	7.3	1×10^6	2 T	0.11	0.8 (KSWZ) 0.11 (DFSZ)	0.16 0.02



axion linewidth $= \Delta\nu_a$

$$P_n^{\mathrm{SQL}} = h\nu_a\sqrt{\Delta\nu_a}$$

$$P_n^{\mathrm{th}} = h\nu_a\bar{n}\sqrt{\Delta\nu_a},\ \text{with}\ \bar{n} = \frac{1}{e^{h\nu/kT}-1},\ \text{T=50 mK}$$

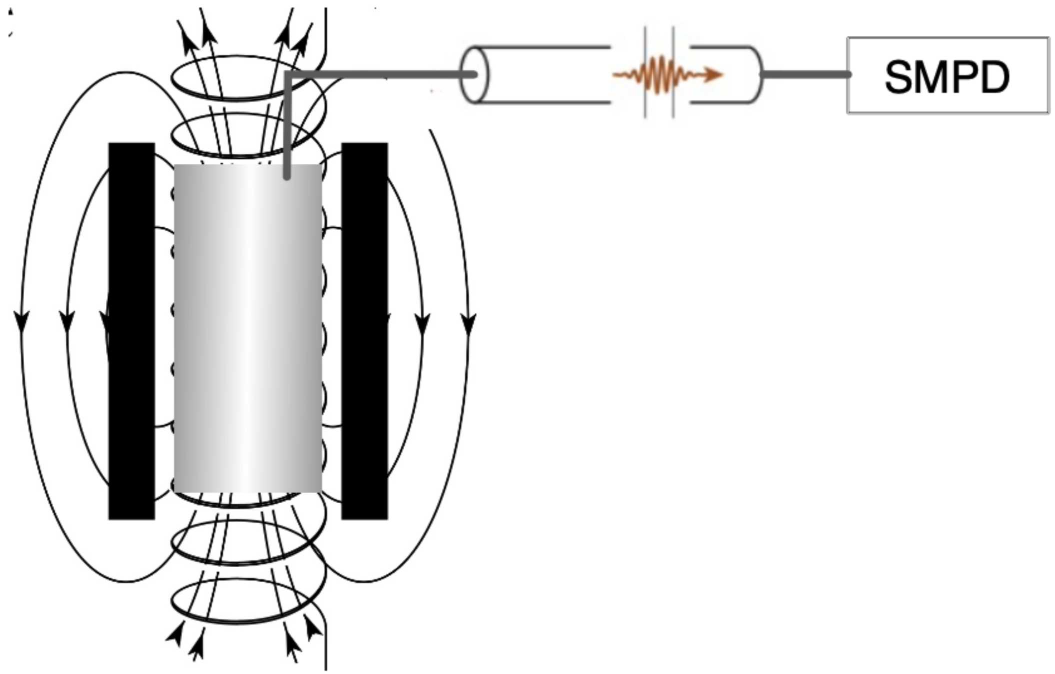
$$P_n^{\mathrm{SMPD}} = h\nu_a\sqrt{\Gamma_{\mathrm{dark}}}$$

- Detection of individual microwave photons is a challenging task because of their **low energy** e.g. $h\nu = 2.1 \times 10^{-5}$ eV for ν = 5 GHz

Single photon counting

Requirements for axion dark matter search:

- detection of *itinerant photons* due to involved intense **B** fields
- lowest dark count rate Γ < 100 Hz
- ≳ 40−50% efficiency
- large “dynamic” bandwidth ∼ cavity tunability

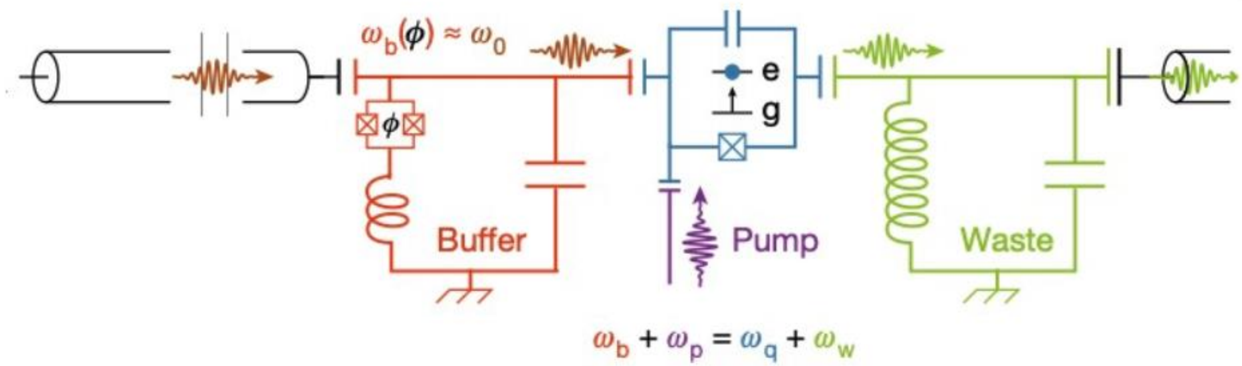


detection of *itinerant photons*
applicable to axion searches (multi-Tesla fields)

Single microwave photon counter (SMPD)

Most advanced schemes for the detection of **itinerant photons**

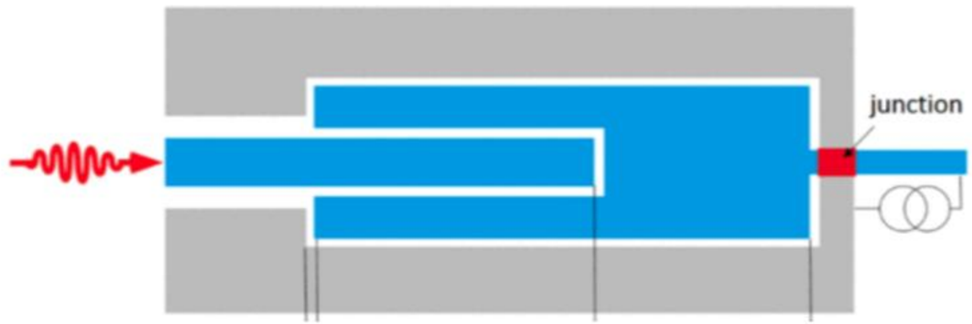
- "**artificial atoms**" introduced in circuit QED, their transition frequencies lie in the ∼GHz range



E. Albertinale *et al*, Nature **600**, 434–438 (2021)

R. Lescanne *et al*, Phys. Rev. X 10, 021038 (2020)

- single **current-biased Josephson junction (JJ)**



npj Quantum Information **8**, 61 (2022)

IEEE Tras. Appl. Supercond. **33**, 1-9 (2023)

Details in the tutorial this afternoon

SMPD Haloscopes

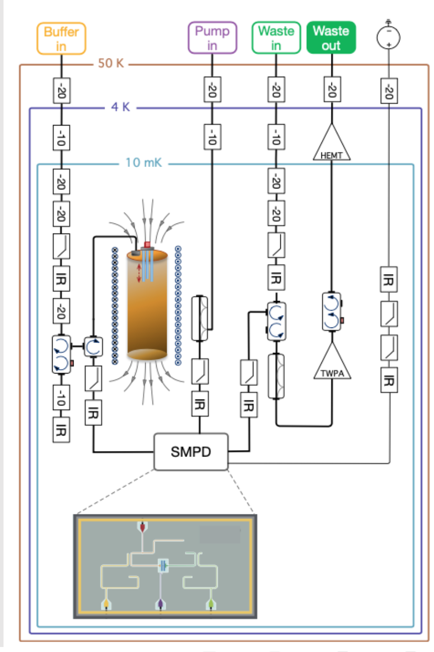
Pilot experiment conducted @ Quantronics lab in Saclay (Paris)
SMPD @ 7 GHz, 2 T Magnetic field
Hybrid cavity with small tuning
Manuscript in preparation

SMPD (top) and cavity

SC magnet

A copy of the Saclay device will be installed in Padova for an haloscope with:

- Larger tuning (200 MHz)
- Higher Magnetic field (9 T)



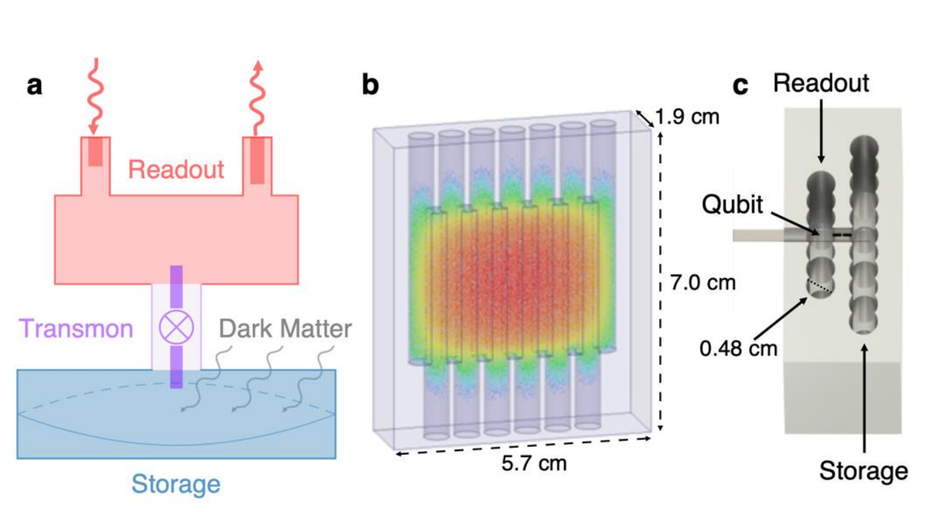
building a SMPD-HALOSCOPE IN PADOVA

INFN
Istituto Nazionale di Fisica Nucleare

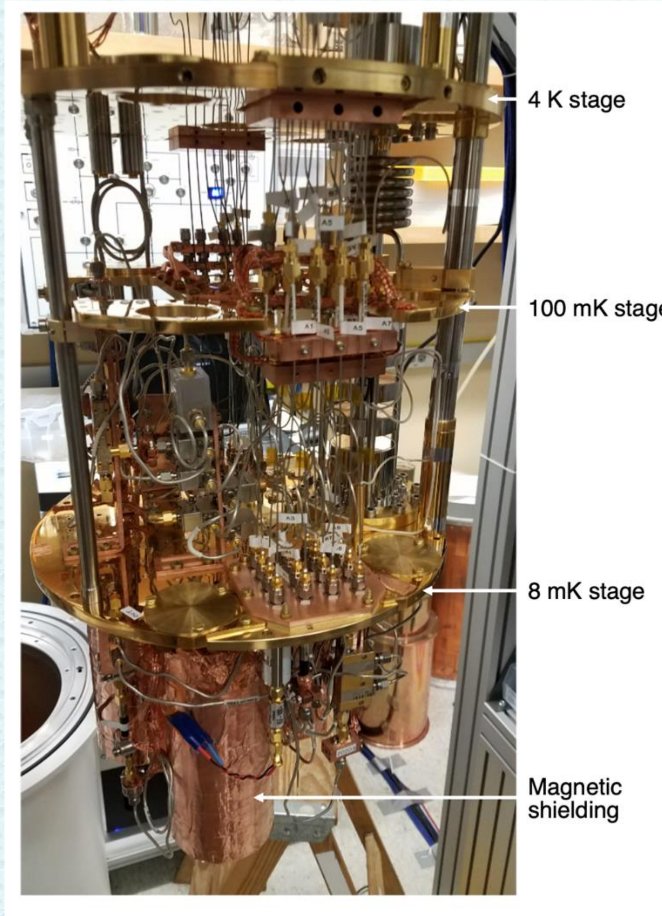
SQMS
SUPERCONDUCTING QUANTUM MATERIALS & SYSTEMS CENTER

Dark photon haloscopes – quantum sensing

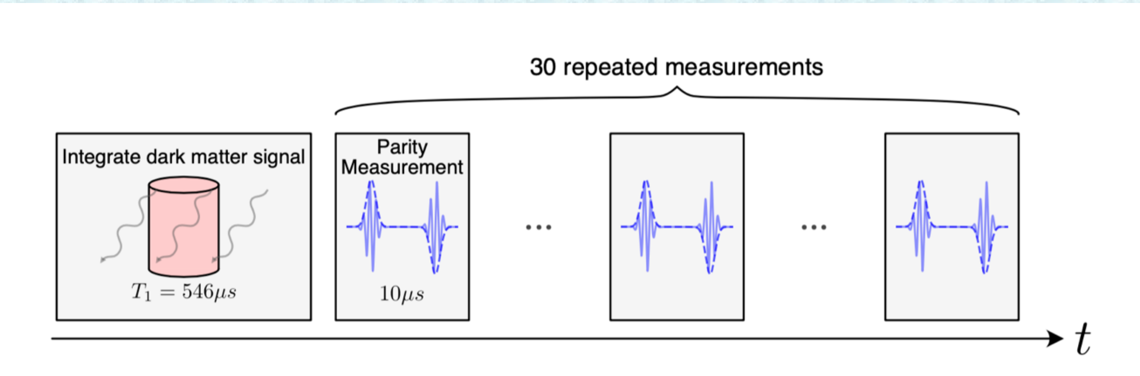
A transmon qubit coupled to a microwave cavity has been used to search for dark photons - A. Dixit et al. Phys. Rev. Lett. **126**, 141302 (2021)



Storage Cavity 6.011 GHz
Readout Cavity 8.052 GHz
Qubit 4.749 GHz



- A superconducting qubit bridges the storage and readout cavities.
- The storage is used to hold the dark matter generated photon
- The readout is used to measure the state of the qubit.
- Dedicated **dark matter search protocol** to look for qubit state changes induced by the presence of a photon in the cavity



Sensitivity improved by factor 37 over SQL
1300 x faster scanning rate

No tuning
No magnetic field
Axion searches needs more development

The road to the future: microwave cavities

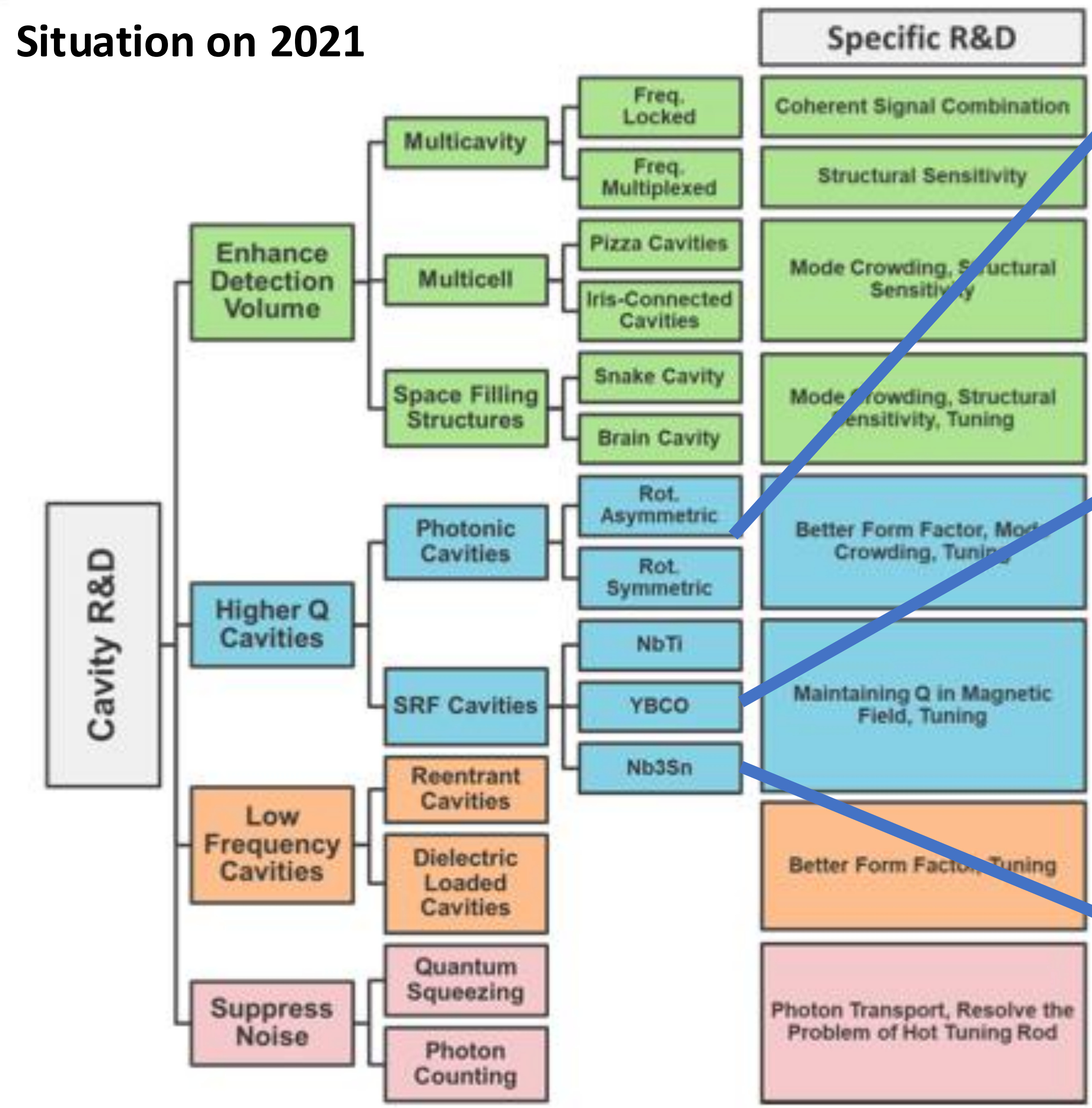
Figure of merit
F = C²_mnl V² Q₀

+ Tuning

$$C_{mnl} = \frac{\left|\int_V \mathbf{E}_{\mathbf{mnl}} \cdot \mathbf{B}\, d^3x\right|^2}{\int_V |\mathbf{B}|^2 d^3x \int_V \varepsilon |\mathbf{E}_{\mathbf{mnl}}|^2 d^3x},$$

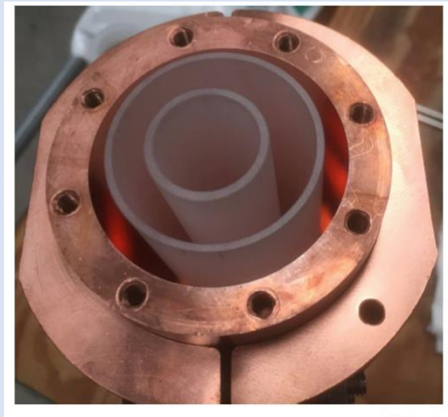
Snowmass 2021 White Paper Axion Dark Matter

Situation on 2021



QUAX dielectric cavity

- Two nested sapphire cylinders configuration
- Q > 9x10^6 in a 8T field @ 10.4 GHz

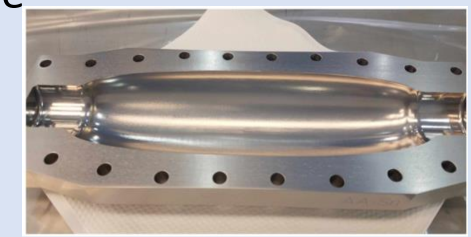


- **CAPP** biaxially textured YBa2Cu3O7−x cavity
- Q ~ 500 000 @ 8T field @ 2.3 GHz

(Patras workshop 2021)

Fermilab (SQMS) - QUAX arXiv 2201.10733

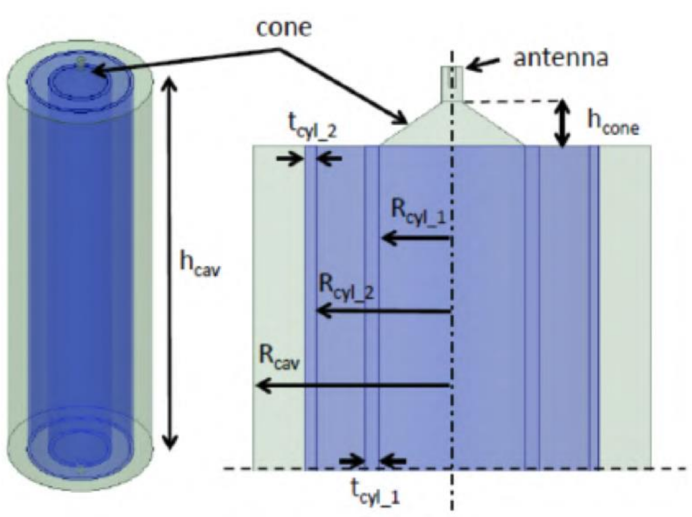
- SC cavity with optimized geometry and choice of fabrication technique
- Q ~ 500 000 @ 6T field @ 3.9 GHz



Cavities developments – larger Q

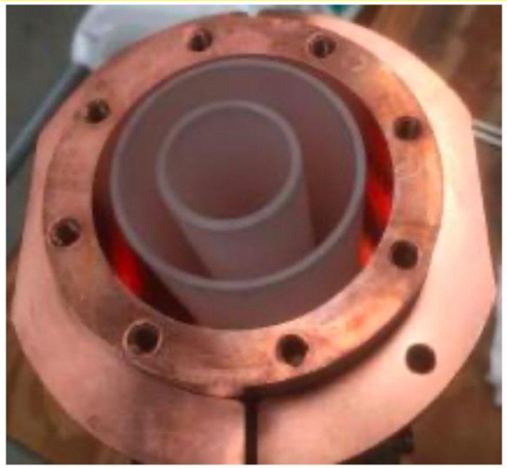
QUAX double shell dielectric cavity

R_{cav}	28.55
R_{cyl_1}	10.88
R_{cyl_2}	20.90
t_{cyl_1}	2.35
t_{cyl_2}	1.94
h_{cone}	6.00
h_{cav}	420



- **dielectric materials** properly placed inside traditional cylindrical resonant cavities, operated in TM modes of higher order

PHYS. REV. APPLIED **17,** 054013 (2022)



- Exploit TM030 mode
- High Q-factor due to field confinement by dielectric shells
- Q0 = 9.3 million in a 8 T magnetic field
- Small cavity tuning (few MHz) with sapphire rods

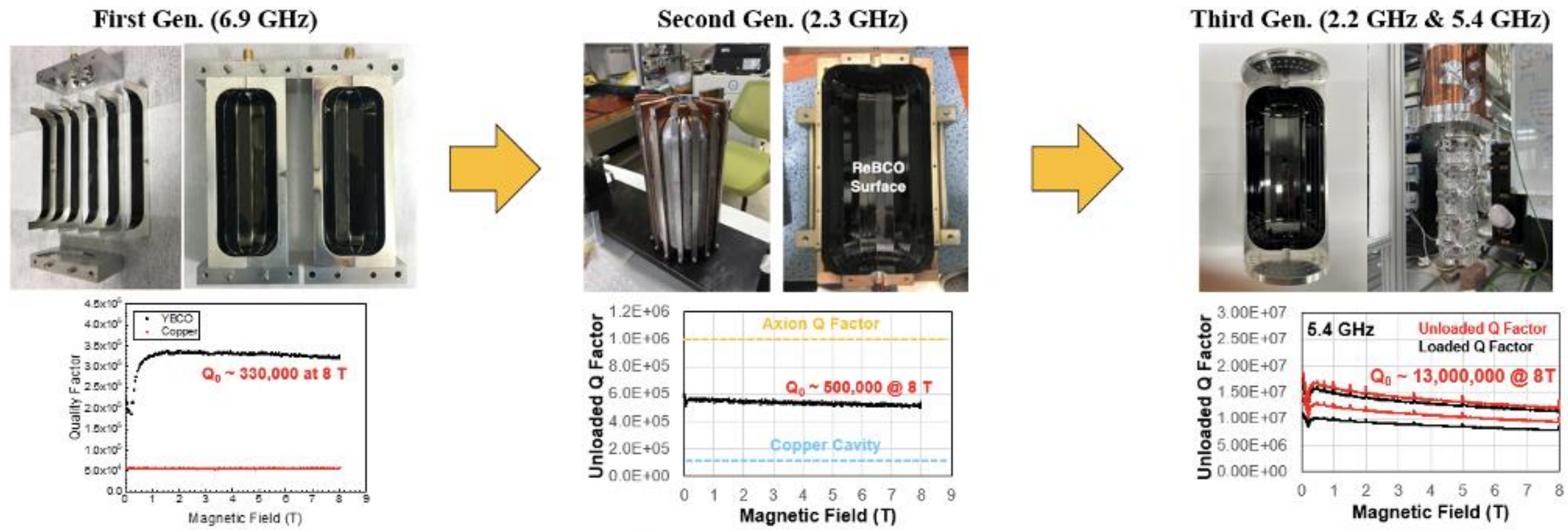
Q value @ 4 K

Cavity	ν_{cav}	V	C_{nml}	$V_{eff}=C \cdot V$	Q_0
QUAX 2020	10.4 GHz	80 cm^3	0.69	55.6 cm^3	76000
QUAX 2022	10.35 GHz	1056 cm^3	0.033	34.7 cm^3	$9.1 \cdot 10^6$

Cavities developments – larger Q

CAPP High Temperature Superconductor cavities

- A polygon-shaped cavity design with biaxially textured ReBCO superconducting tapes covering the entire inner wall.
- Using a 12-sided polygon cavity, substantially improved *Q* factors
- No considerable degradation in the presence of magnetic fields up to 8 T



Generation	Material	Substrate	Volume [liters]	Frequency [GHz]	Q-factor
1st Gen	YBCO	NiW	0.3	6.9	150,000 @ 8 T
					330,000 @ 8 T
2nd Gen	GdBCO	Hastelloy	1.5	2.3	500,000 @ 8 T
3rd Gen	EuBCO + APC	Hastelloy	0.2	5.4	13,000,000 @ 8 T
	EuBCO + APC	Hastelloy	1.5	2.3	4,500,000 @ 7 T
	EuBCO + APC	Hastelloy	36	~ 1	?

From Woohyun Chung talk @ Patras 2023

HTS cavity can reach 10 times larger than axion quality factor (~ 10^6)

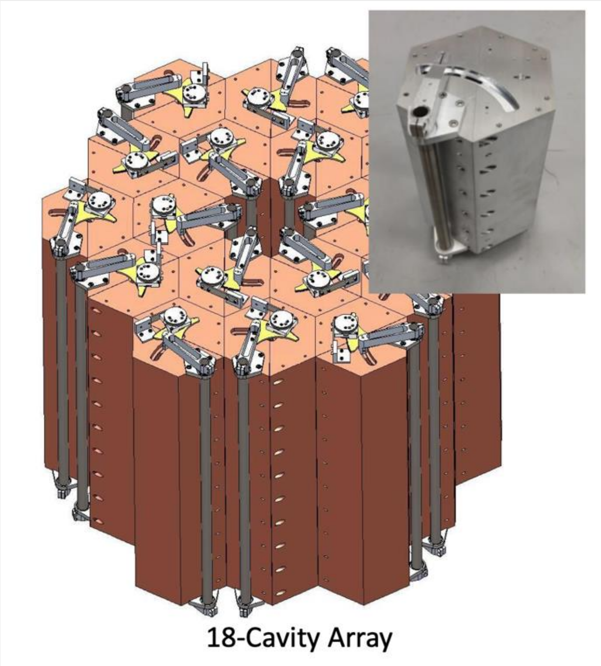
Cavities developments - new geometries

Find ways to increase volume at high frequency while keeping tuning

For right cylindrical cavity, main mode volume

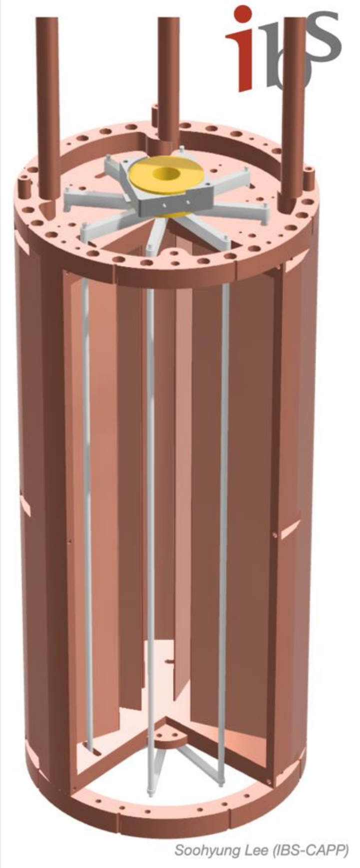
$V \sim 1/d^2 \sim 1/f^2$

ADMX Extended frequency range (2-4GHz): cavity array

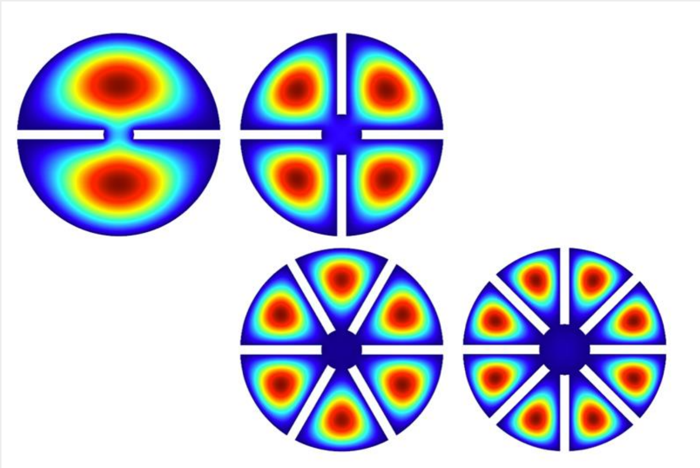


80 liters
Avg C ~ 0.4
Q ~ 90 000

Multiple cell cavity at CAPP

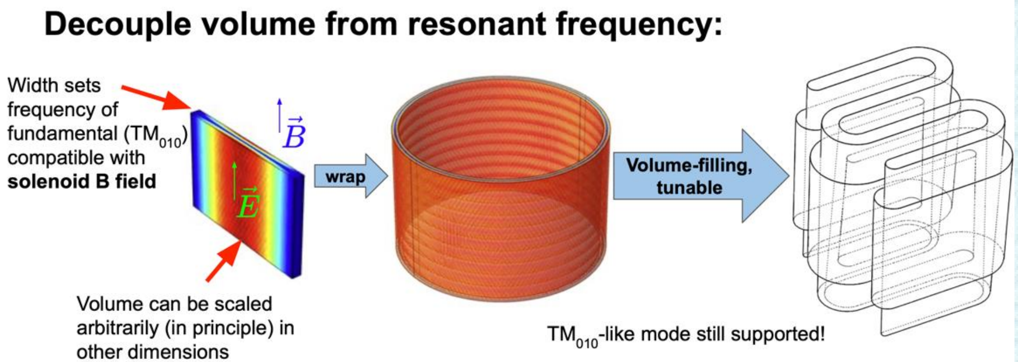


- Resonant frequency increases with the cell multiplicity.
- Same frequency tuning mechanism as multiple cavity system can be employed.
- A single RF antenna extracts the signal out of the cavity.



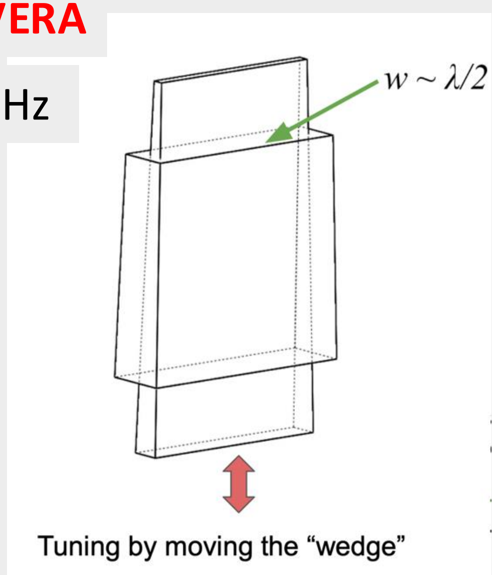
Frequency up to 8 GHz

Cavities developments – new geometries

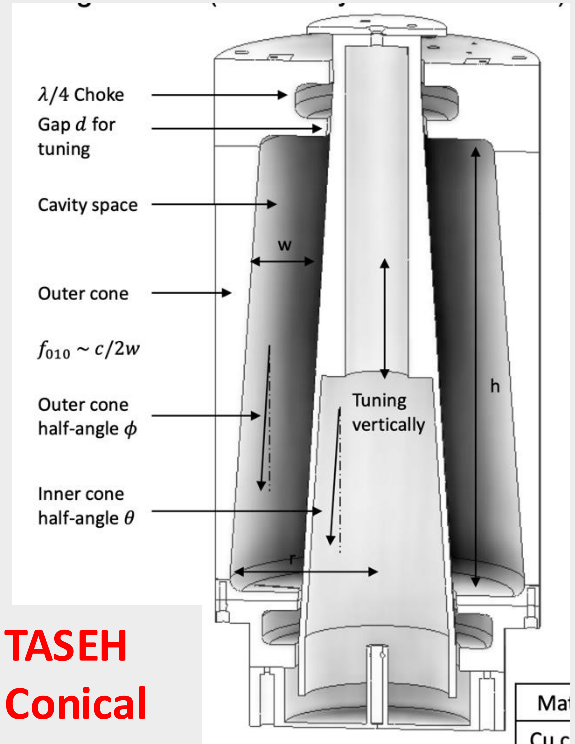


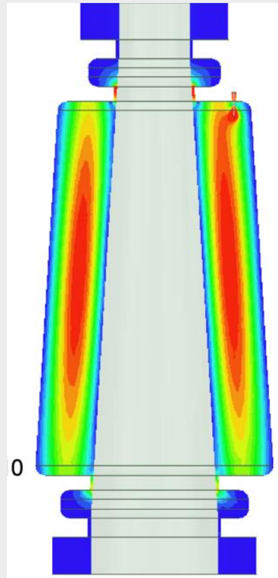
ADMX VERA

f > 4 GHz



E field pattern



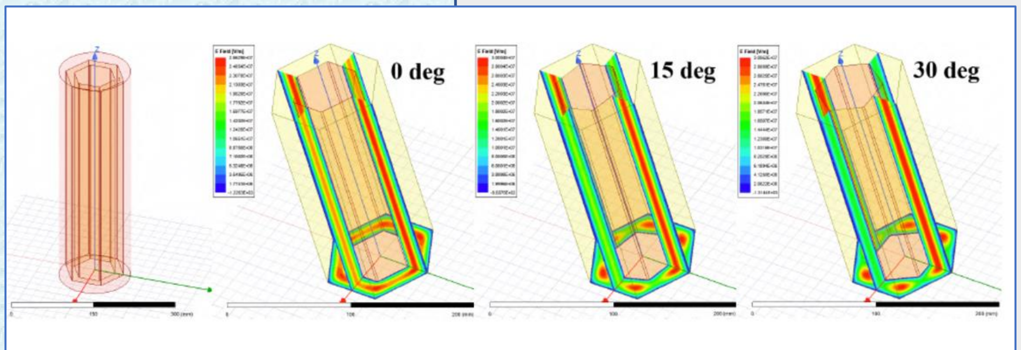


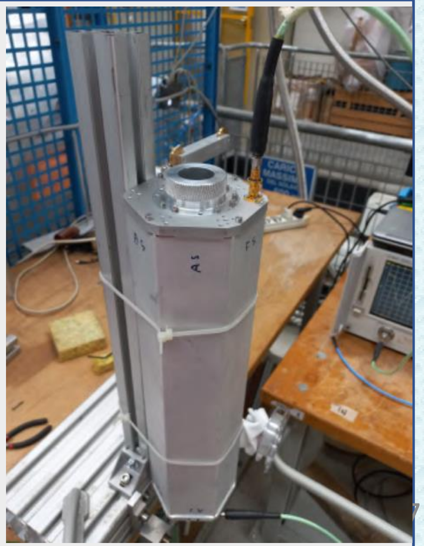
TASEH Conical cavity

f ~ 5 GHz

QUAX Polygonal cavity

f ~ 10 GHz





Major issues for all:
- Surface quality
- Alignment
- Spurious modes
- All degrade Cmnl
- Q factor?

Cavities developments – tuning

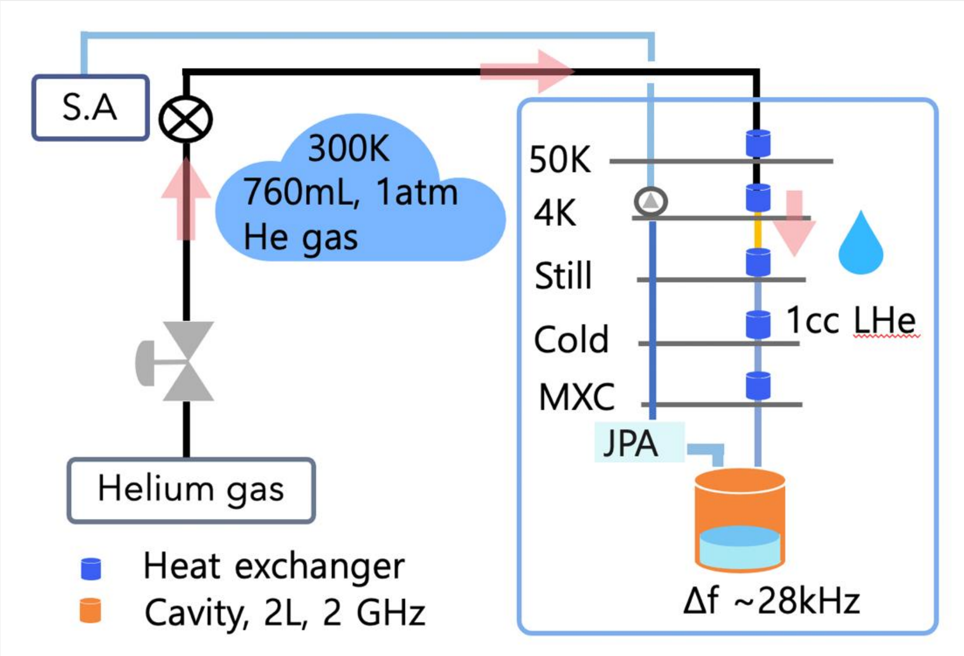
CAPP Superfluid Helium Tuning

- Fill SC cavities with He
- He Level set the frequency change

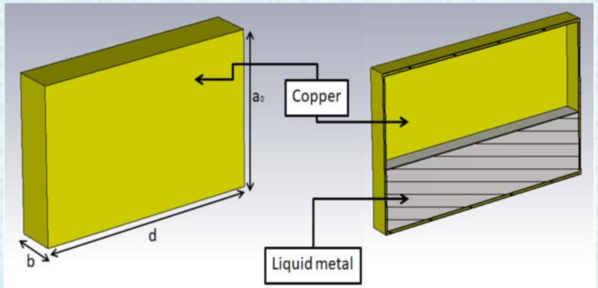
Superfluid Helium ($\epsilon_r \approx 1.057$) tuning

- $f_{TM010} = \frac{1}{2\pi\sqrt{\mu\epsilon}} \frac{2.405}{R}$
- $\frac{f_{empty} - f_{LHe}}{f_{LHe}} = \sqrt{\epsilon_{LHe}} - 1 \approx 0.028$,

~3 % frequency shift

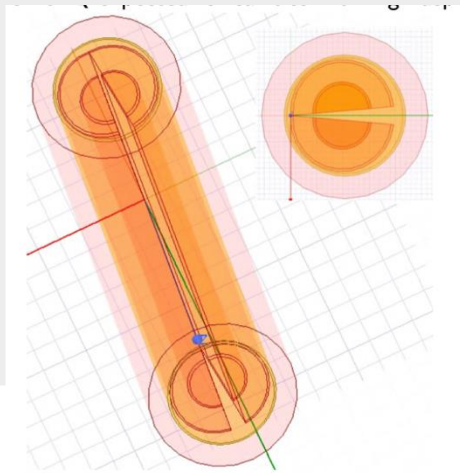


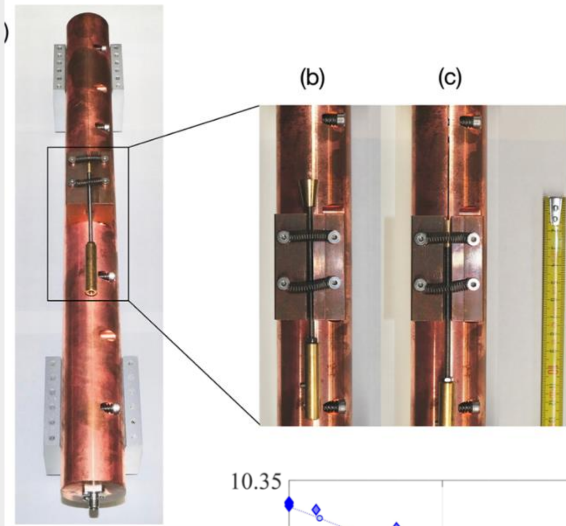
arXiv:1804.03443v1
QUAX
Liquid Metal Tuning of a resonator



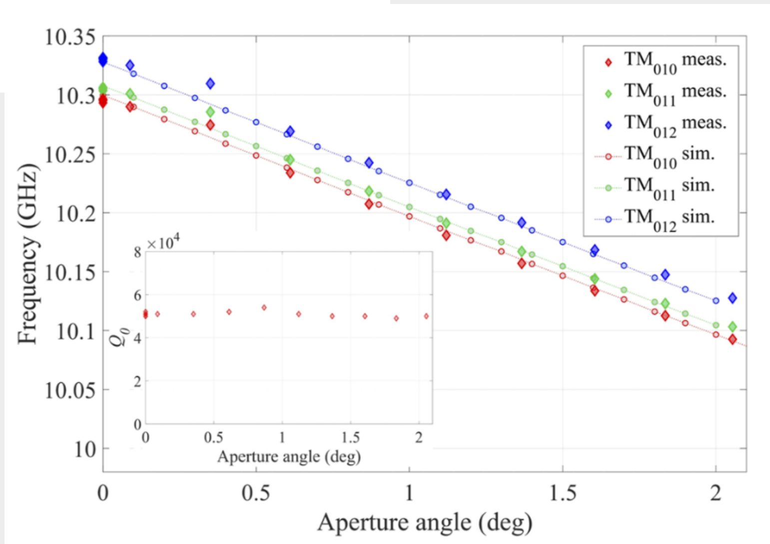
QUAX Clamshell cavity

- Simple way to tune right circular cavities
- Effective radius can be modified by separating the two halves of a clamshell





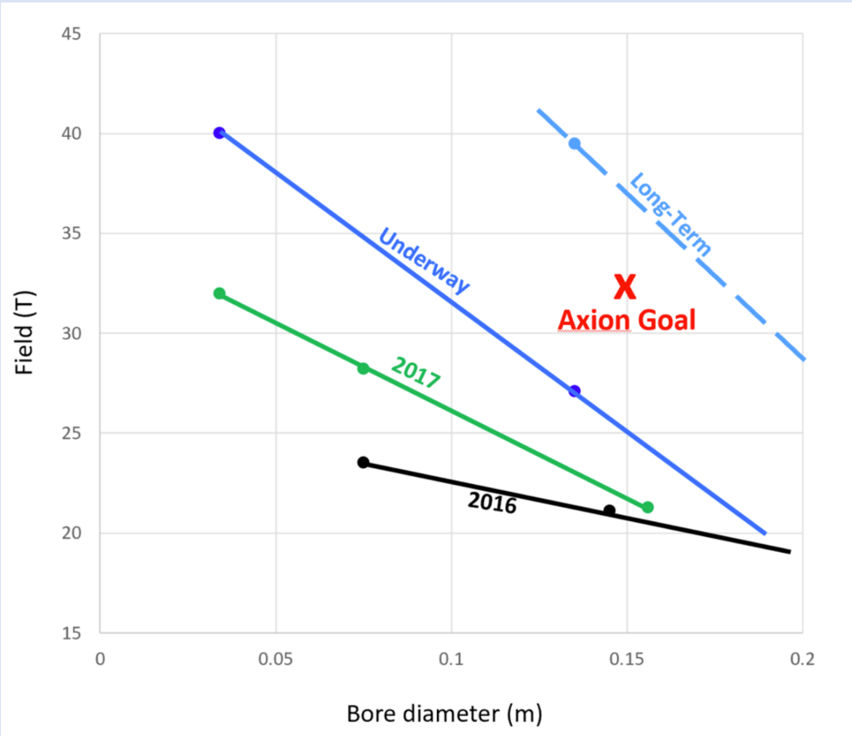
- Lack of mode crossings
- Tuning linear with aperture



The road to the future: magnets

- For haloscope a dedicated **magnet R&D program** for higher strength (up to 45+ Tesla) and optimized magnet designs is needed to maximize B^2 V
- Up to now standard superconducting magnets provided field up to about 12-14 T
- Hybrid magnets are foreseen to be used in next generation haloscopes

In the **US the National High Magnetic Field Laboratory (MagLab)** has been developing higher field REBCO (Rare Earth barium copper oxide) inserts with current designs reaching a maximum field of 45 T



From Snowmass 2021 Axion Dark Matter White Paper

In **Grenoble** a combination of resistive polyhelix and Bitter coils inserted within a large bore superconducting one, a maximum field of at least **43 T** will be produced in a 34 mm diameter aperture with 24 MW of electrical power

Several lower field option will also be available

GraHal Project

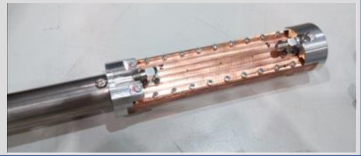
arXiv:2110.14406

Dark matter haloscopes – what's going on

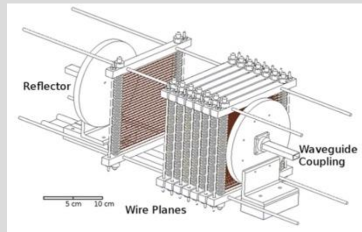
- Several other activities are starting or being proposed in the very recent time
- It is a field which is expanding very rapidly

CULTASK
CAPP

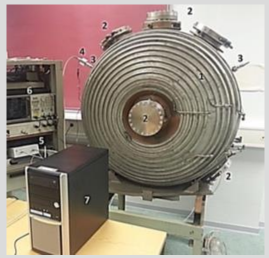
RADES / CAPP – cavities inside CAST



ORPHEUS

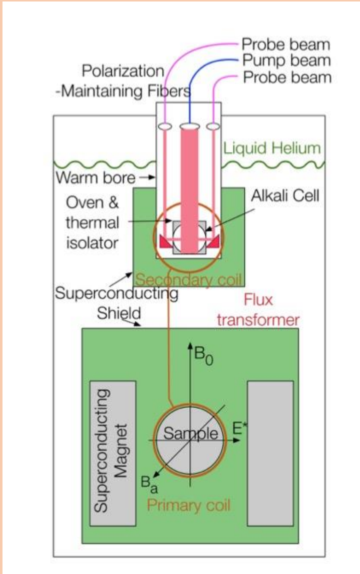


WISPDMX @DESY

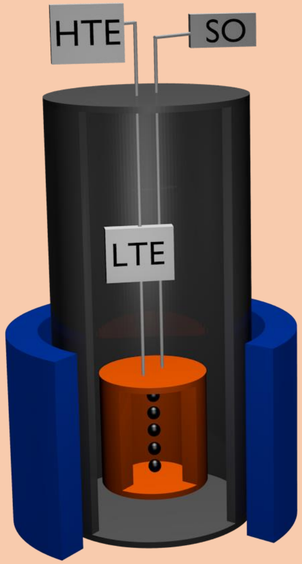


Standard Sikivie's detectors

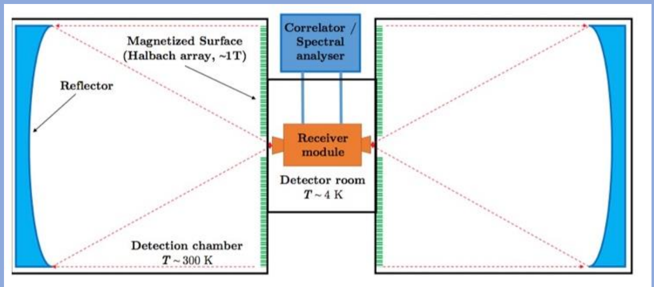
CASPER wind – NMR
Axion - nucleon



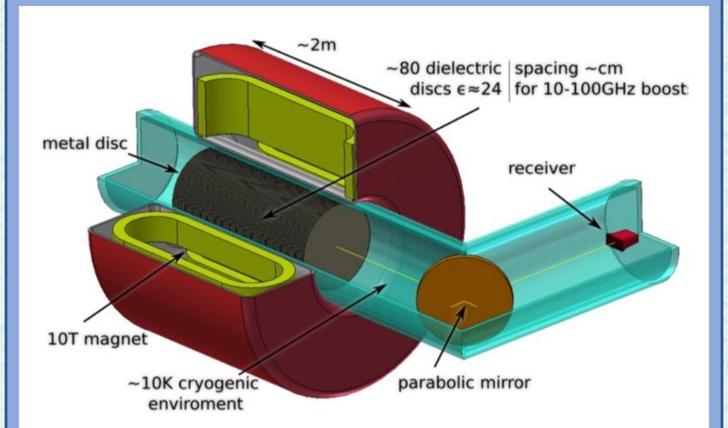
QUAX – EPR
Axion - electron



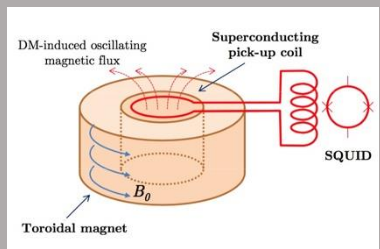
BRASS – dish antenna



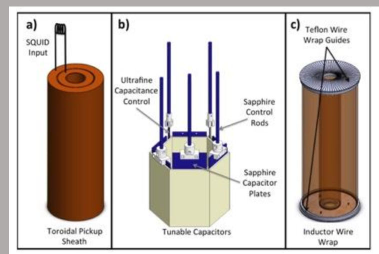
MADMAX - Dielectric haloscope



ABRACADABRA



DM Radio



LC circuit

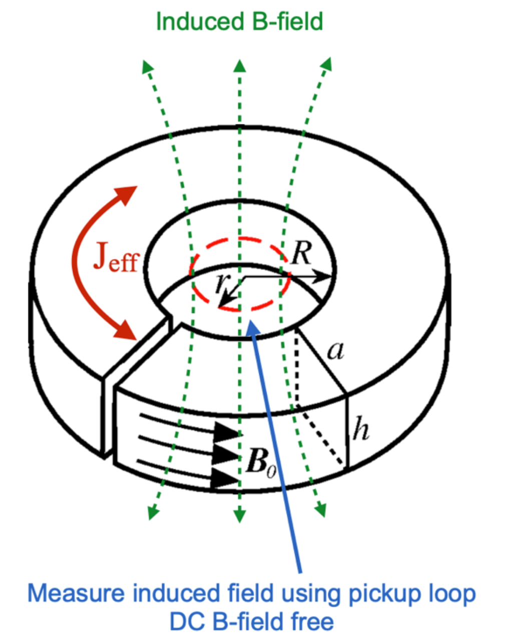
ONLY A SELECTION!!!!!

Update: Dark Matter Haloscopes – Lumped elements

- A new way to look for dark matter axion of **very low mass : m_a << 1 μeV**
- Measure axion induced electric current in a strong magnetic field

$$\mathbf{J}_{\rm eff} = g_{a\gamma\gamma}\sqrt{2\rho_{\rm DM}}\cos(m_a t)\mathbf{B_0}$$

- **Toroidal** magnet configuration
- **Broadband** and resonant detection of induced ac magnetic field

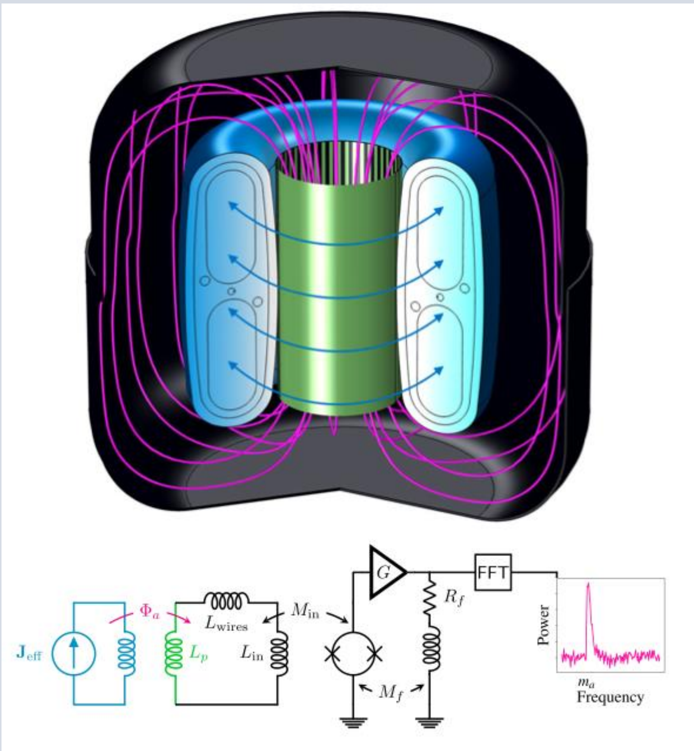


ABRACADABRA (PRL 127, 081801 (2021))

12 cm x 12 cm 1 T toroid

SQUID detection

m_a range 0.41–8.27 neV (50 kHz – 2 MHz)



See also **DM-RADIO**

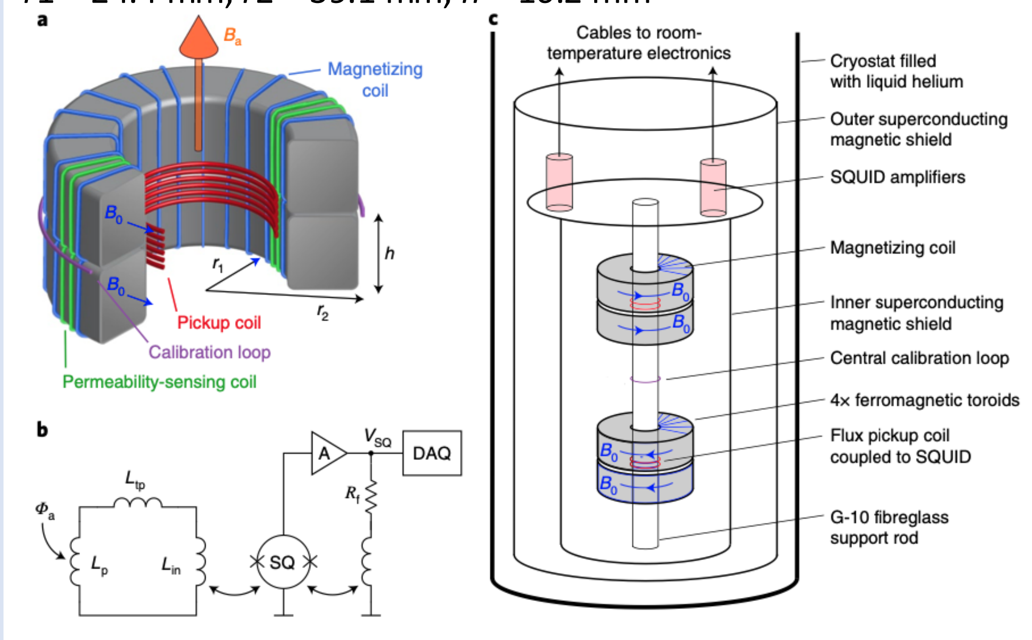
SHAFT *Nature Physics 17 (2021) 79*

1.5 T toroid with FeNi alloy core

SQUID detection @ s = 150 aT/√Hz

m_a range 0.012 –12 neV (3 kHz – 2.9 MHz)

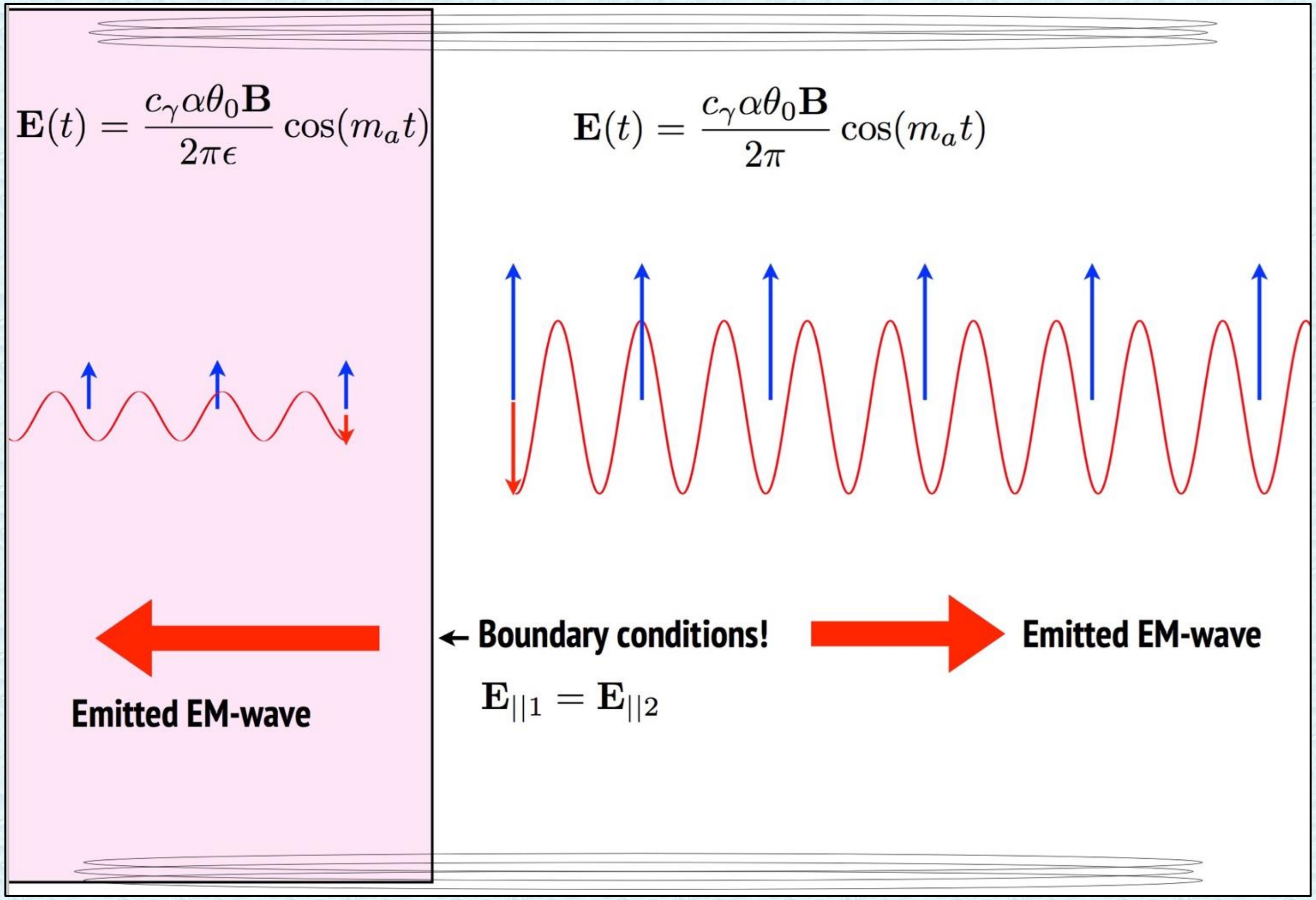
*r*1 = 24.4 mm, *r*2 = 39.1 mm, *h* = 16.2 mm



Other techniques for DM detection: dish antenna

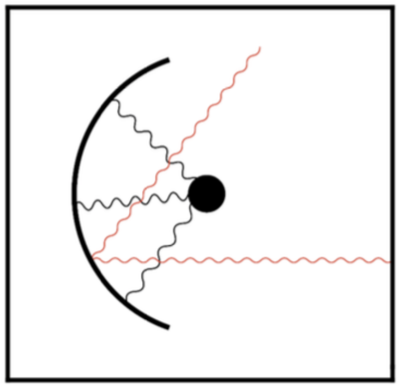
Axion-Induced Electromagnetic Radiation from Reflecting/Refractive Surface in Magnetic Field

- Very hard to reach high masses (tens of μeV) with resonant cavities
- New techniques exploits alps induced effects in a magnetized boundary



- A dielectric/conductive interface **immersed in** a static homogeneous **magnetic field** will **radiate EM-wave** at the frequency corresponding to the mass of the ALP dark matter surrounding it

- Wide band system



"Dish Antenna" Horns, Jaeckel, Lindner, Lobanov, Redondo & Ringwald, 2012

Emtted power $\boxed{P \propto AB^2 f^{-2}}$

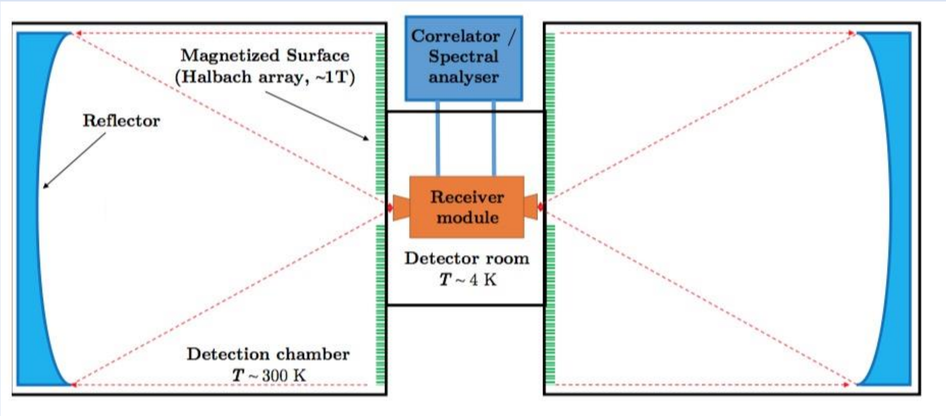
Large area A, Strong Fields B

Other techniques: proposals

Conductive mirror

BRASS experiment (Hamburg)

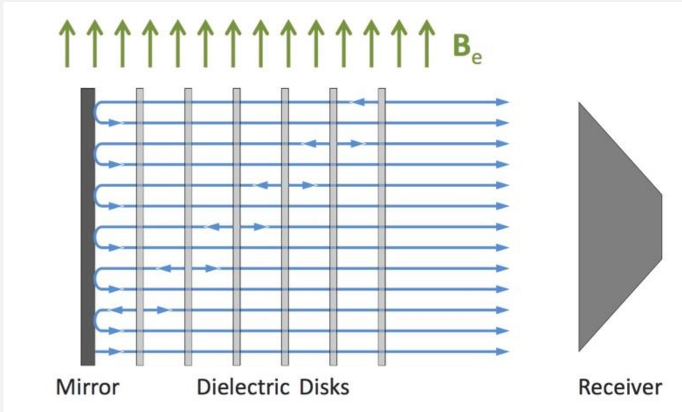
- Large surface mirror; 8 m radius
- Halbach array of permanent magnets
- Rejection of background thanks to spherical shape

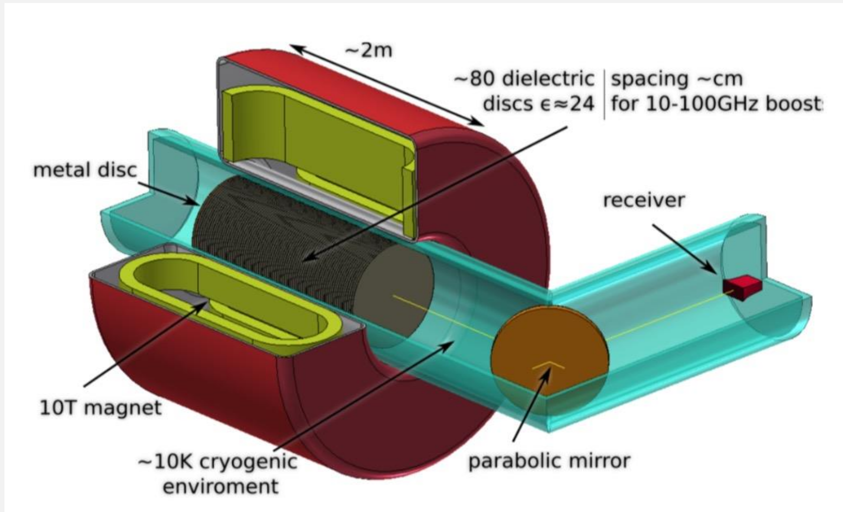


Stacked dielectric mirrors

MADMAX experiment (Germany)

- Stacked structure of dielectric plates
- Interference between each emission boost sensitivity





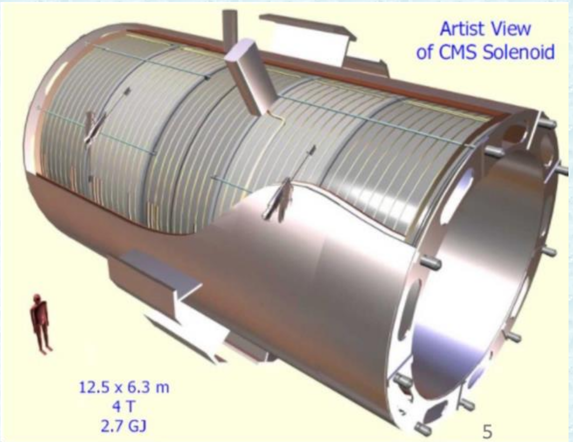
- 80 dielectric discs with 60 cm diameter (1 m^2) each
- 10 T magnetic field
- Large epsilon material to increase boost factor
- Tuning mechanism (interference is not broadband)

More details in the tutorial this afternoon

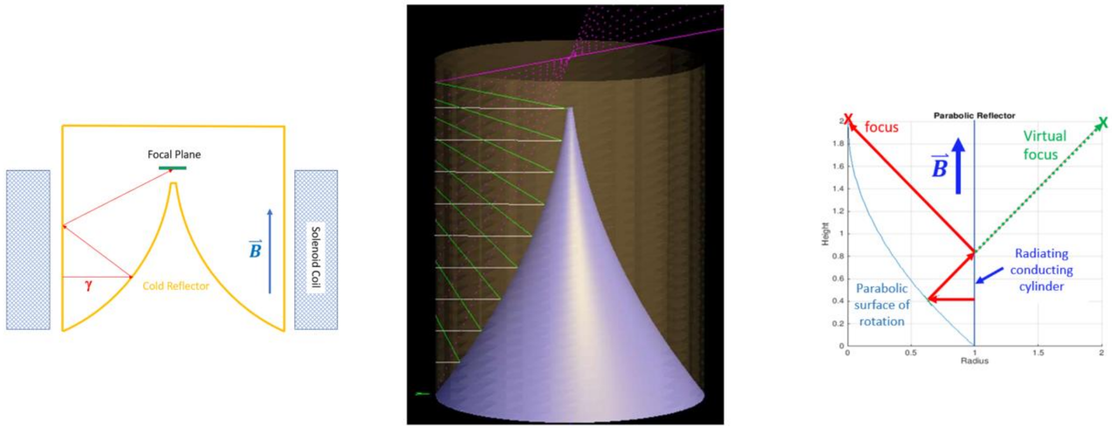
Large volume dish antenna

Broadband Reflector Experiment for Axion Detection (BREAD) - PRL **128**, 131801 (2022)

Find solution for large solenoids

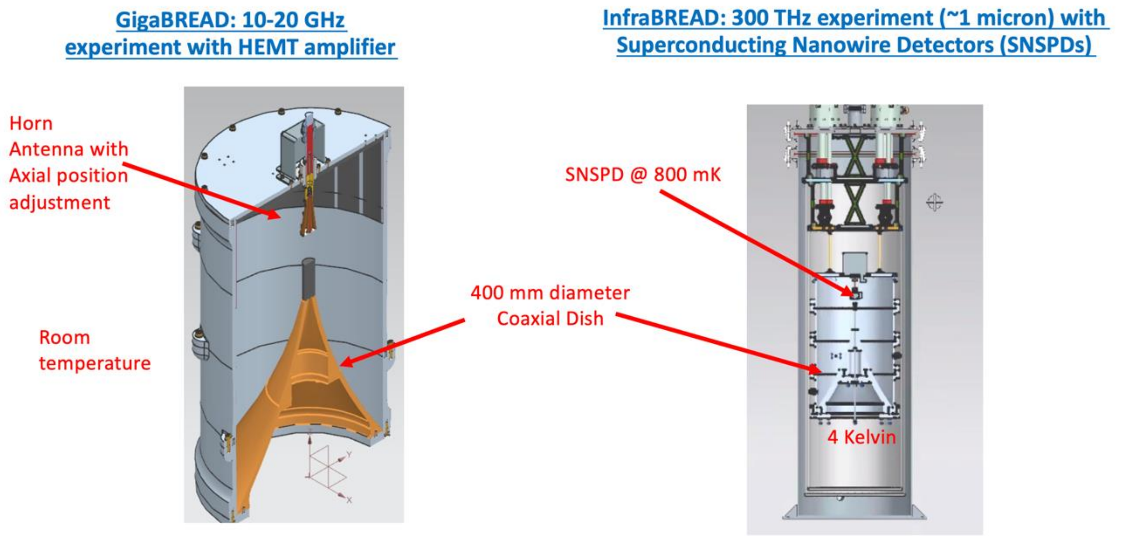


"Coaxial Dish": Optical Concentrator for Solenoid Magnets

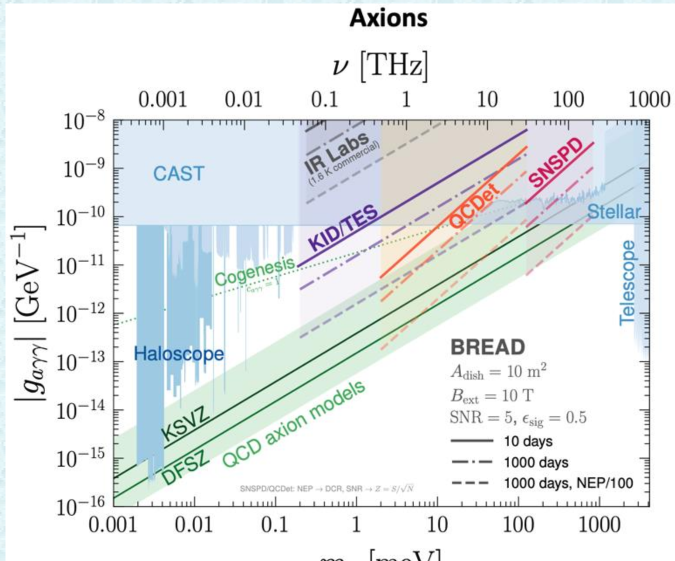


- Rays emitted from cylindrical inner surface of solenoid are focused to a point after two reflections.

Proof of Concept Experiments: GigaBREAD and InfraBREAD



With state of the art sensors QCD axion sensitivity



[Liu *et al*, BREAD collab., PRL 128 (2022) 131801]

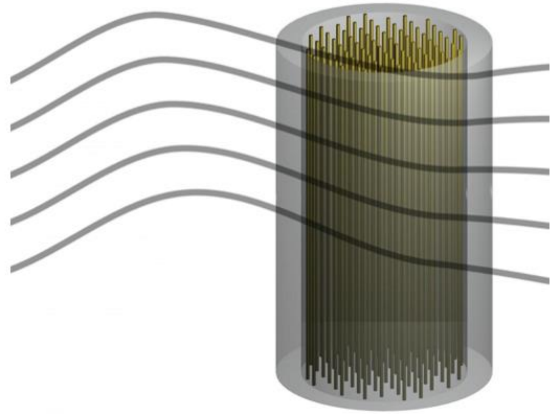
The road to the future: high frequency (>20 GHz)

Plasma haloscopes use a wire metamaterial to create a tuneable artificial plasma frequency, decoupling the wavelength of light from the Compton wavelength and allowing for much stronger signals.

Plasma haloscope: project ALPHA

- **Meta material composed by a dense array of parallel wires** electrically connected to top and bottom walls.
- **Large conversion volume** in a magnetic field even for high frequency
- Recent experimental work on seems to confirm feasibility

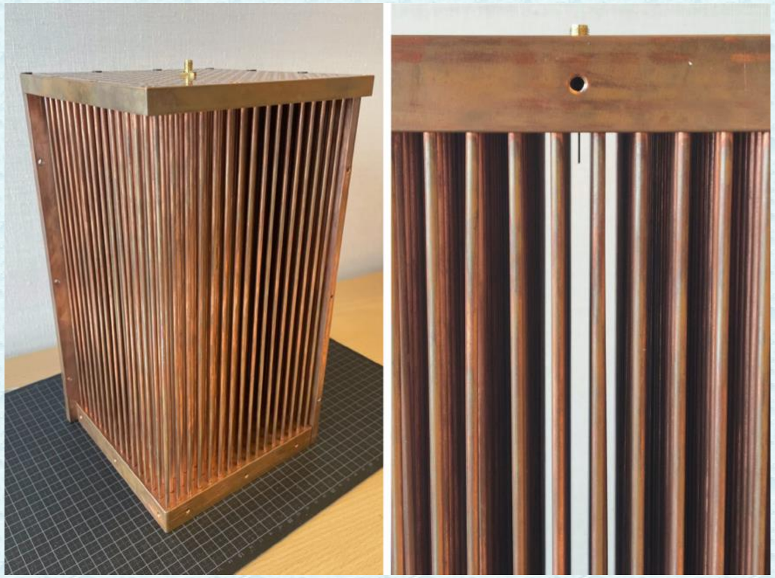
- *Resonance w/ plasma frequency*

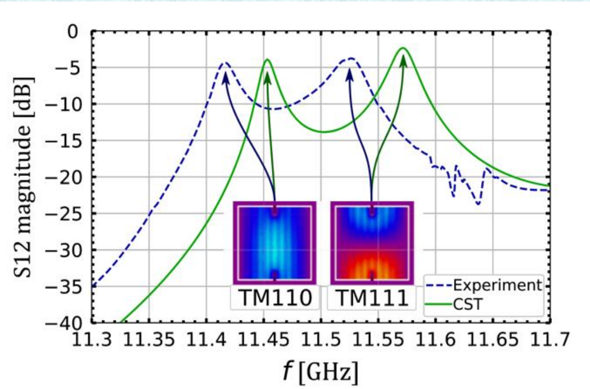


$$\omega_p^2 = \frac{n_e e^2}{m_{eff}} = \frac{2\pi}{s^2 \log(s/d)}$$

ω_p depends on s & d

- *s: inter space*
- *d: wire radius*





Phys. Rev. D **107**, 055013 (2023)

ALPHA PHASE I

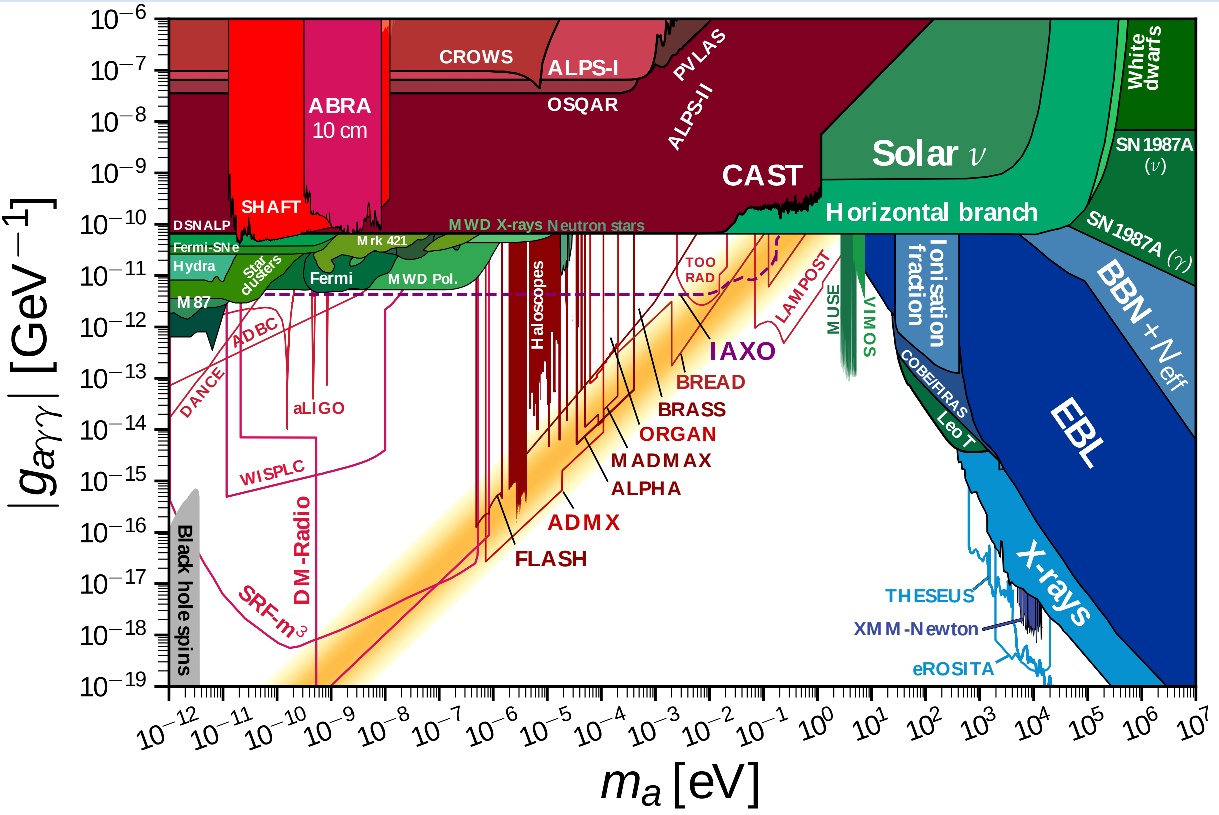
- 2 years run
- $(5 \div 40)$ GHz
- HEMT amplifiers
- Single scan (see [8])

ALPHA PHASE II

- 2 years run
- $(5 \div 45)$ GHz
- Quantum limited
- Single scan (see [8])

$(Q \sim 10^4,\ B \sim 10\,\mathrm{T},\ V \approx 0.3\,\mathrm{m}^3)$

Photon coupling – what next

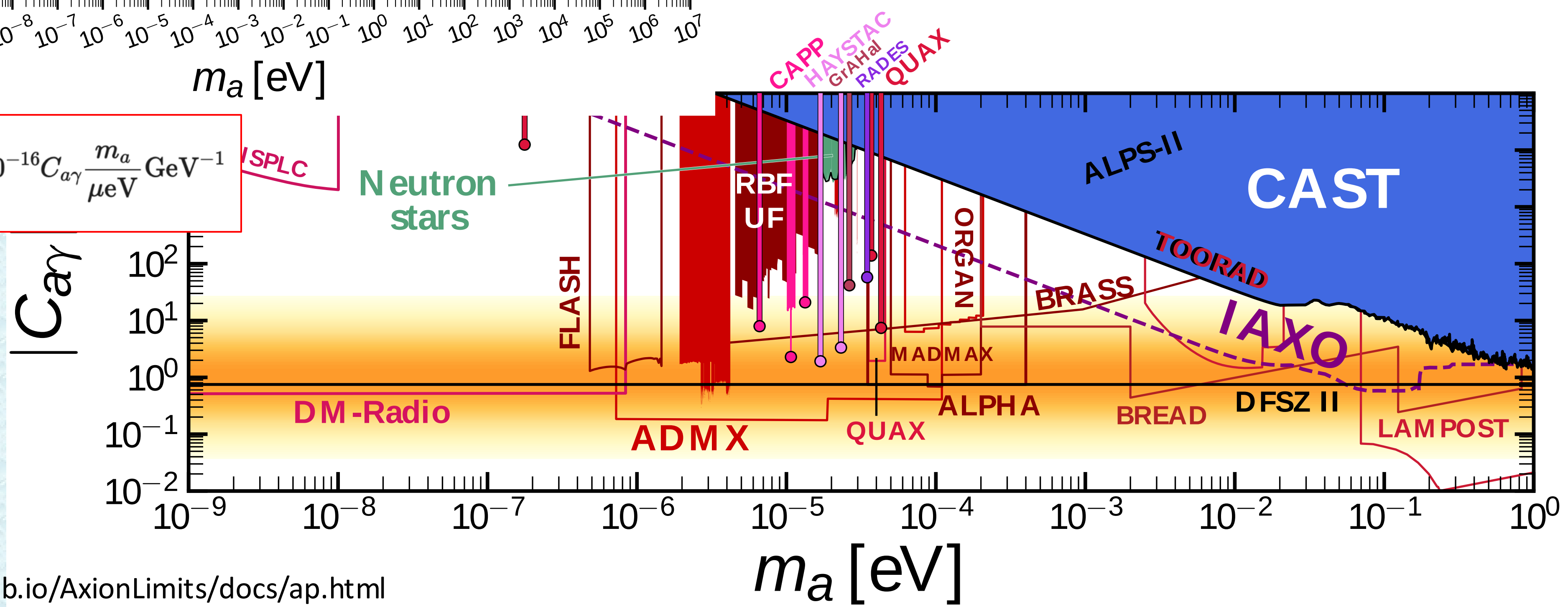


FLASH – Italian based proposal to use FINUDA 1.1 T magnet

TOORAD – International collaboration planning to use metamaterials - topological insulators allowing axion quasiparticles @ THz

- Preliminary material study in CSN5 – project TERAPOL

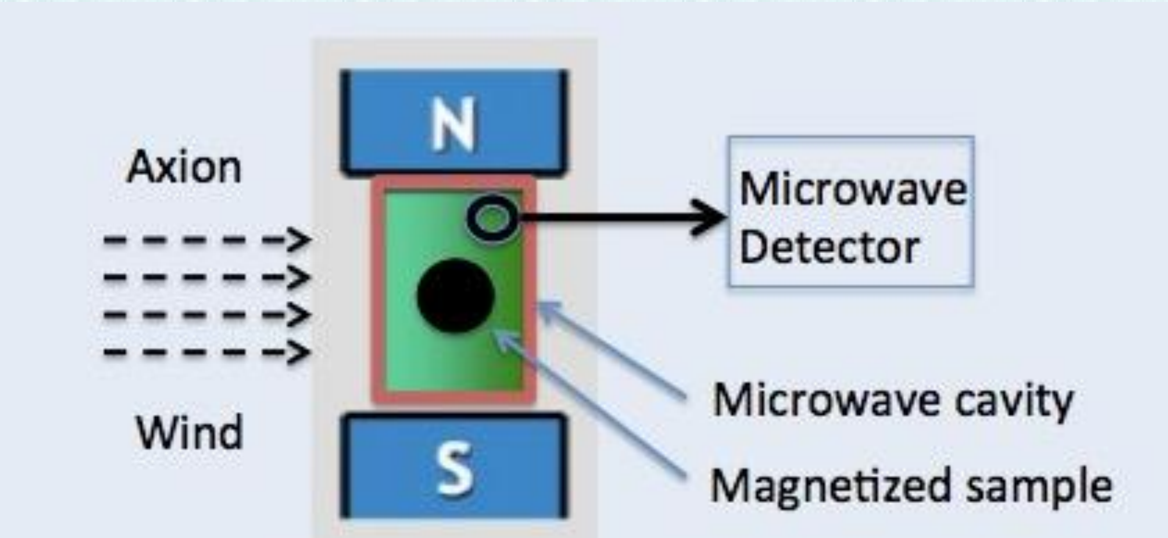
$$g_{a\gamma} \equiv \frac{\alpha}{2\pi}\frac{C_{a\gamma}}{f_a} = 2.0 \times 10^{-16} C_{a\gamma} \frac{m_a}{\mu\text{eV}}\,\text{GeV}^{-1}$$



https://cajohare.github.io/AxionLimits/docs/ap.html

Electron Paramagnetic Resonance: the QUAX proposal

- A new proposal tries to exploit the axion electron coupling $\boldsymbol{g_{aee}}$
- Due to the motion of the solar system in the galaxy, the axion DM cloud acts as an **effective magnetic field on electron spin** $\boldsymbol{g_{aee}}$
- The **ferromagnetic transition in a magnetized sample** can be excited and thus **emits microwave photons**



Effective magnetic field

$$B_a = 2.0 \cdot 10^{-22} \left(\frac{m_a}{200\,\mu\text{eV}} \right) \text{ T},$$

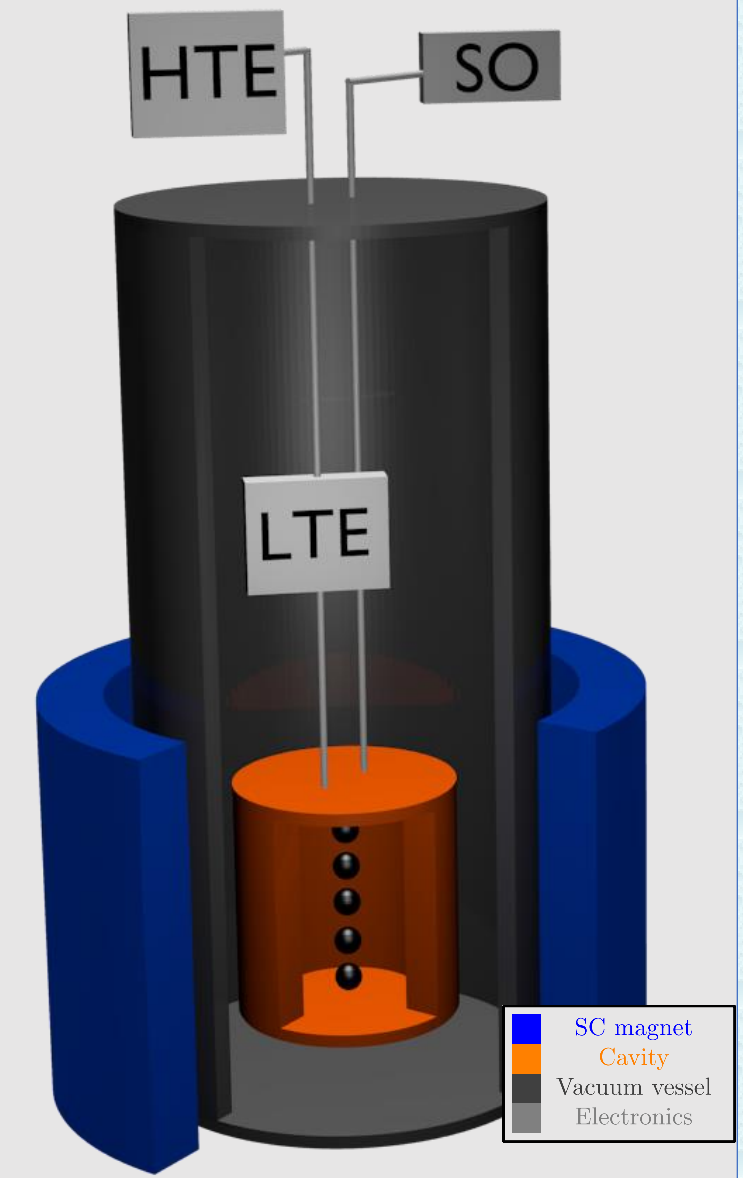
$$B_a \equiv \frac{g_p}{2e} \nabla a$$ directionality

Expected RF power

$$P_{\text{out}} = \frac{P_{\text{in}}}{2} = \mathbf{3.8 \times 10^{-26}} \left(\frac{m_a}{200\,\mu\text{eV}} \right)^3 \left(\frac{V_s}{100\text{ cm}^3} \right) \left(\frac{n_S}{2 \cdot 10^{28}/\text{m}^3} \right) \left(\frac{\tau_{\text{min}}}{2\,\mu\text{s}} \right) \text{W}$$

Large **volume *V*** material; high **spin density** $\boldsymbol{n_s}$; long **coherence time** $\boldsymbol{t_{min}}$

First prototype of QUAX - 2018



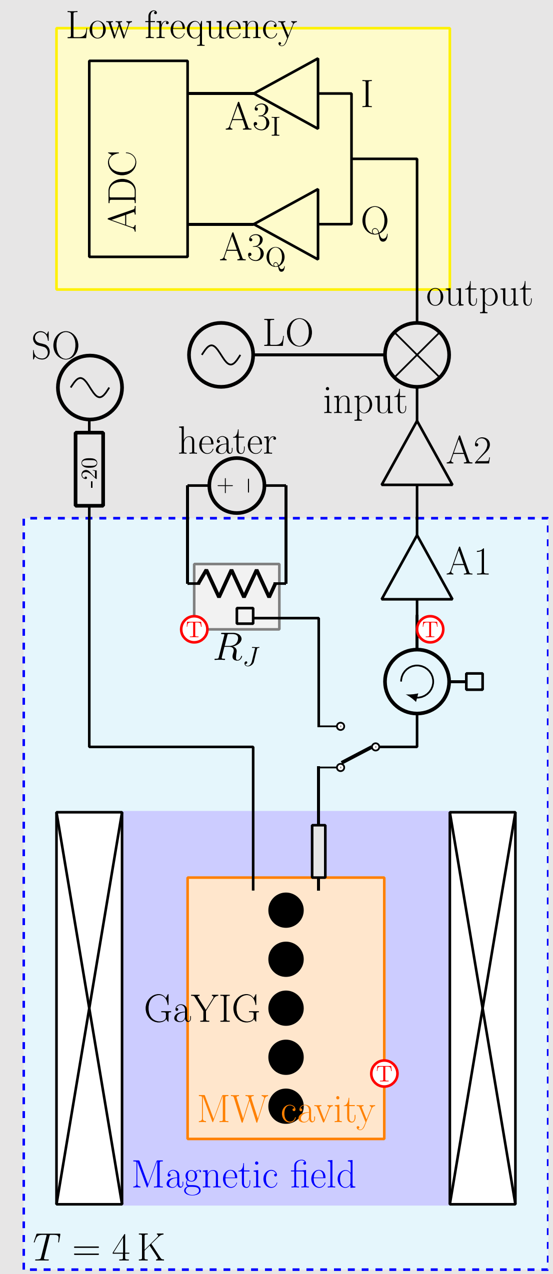
HTE – high temp electronics
LTE – low temp electronics
SO – source generator

Resonant cavity with 5 GaYIG spheres inside

GaYIG holders

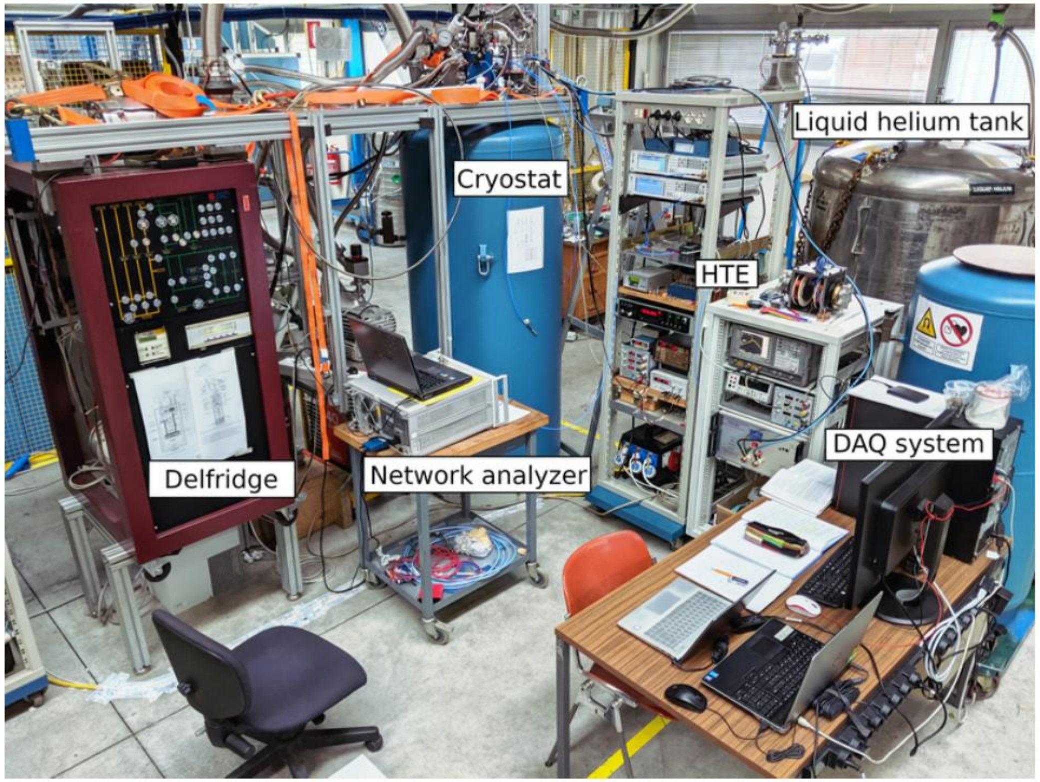
Spheres are free to rotate for correct alignment (easy axis || B)

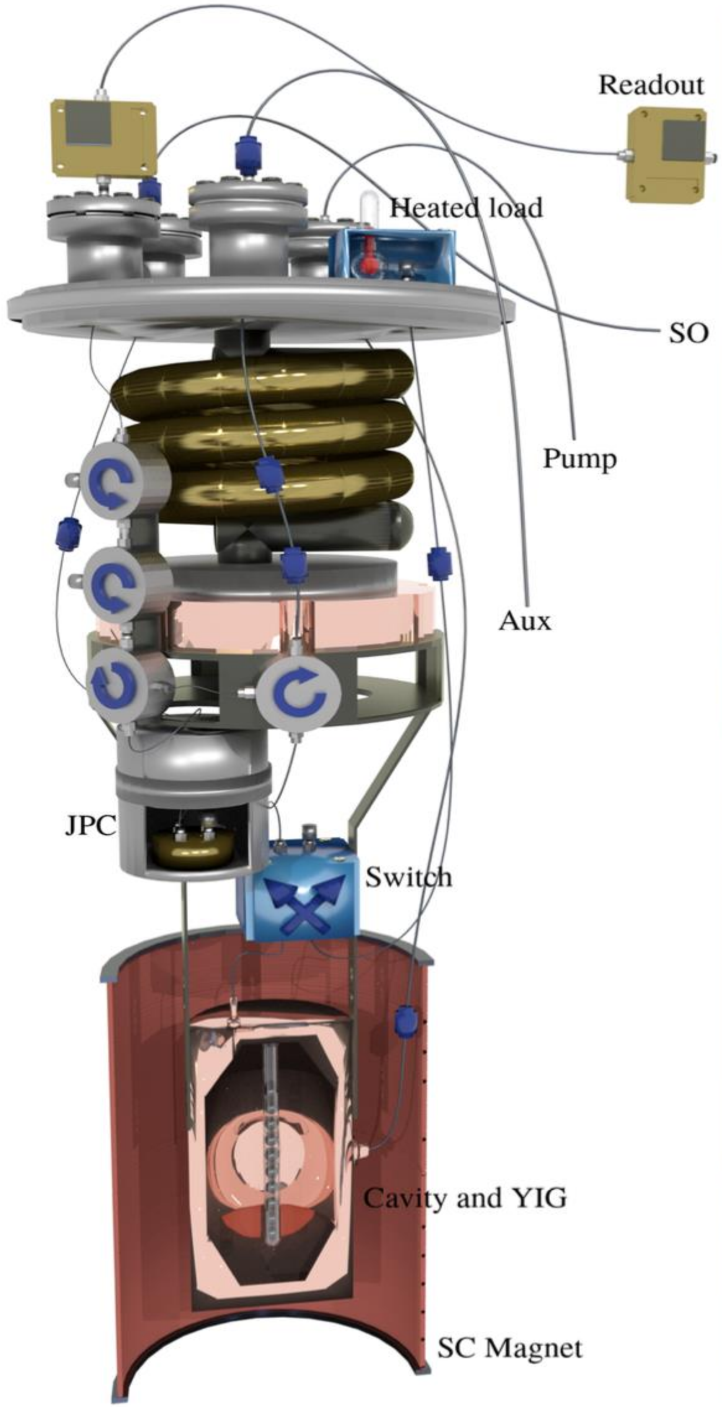
Detection chain



2nd prototype of QUAX

- **Increase signal**
  10 YIG sphere 2.1 mm diameter
- **Reduce noise**
  Quantum limited amplifier (JPC)
  Dilution refrigerator (100 mK)
- **Scan axion mass range**
  Magnetic field tuning





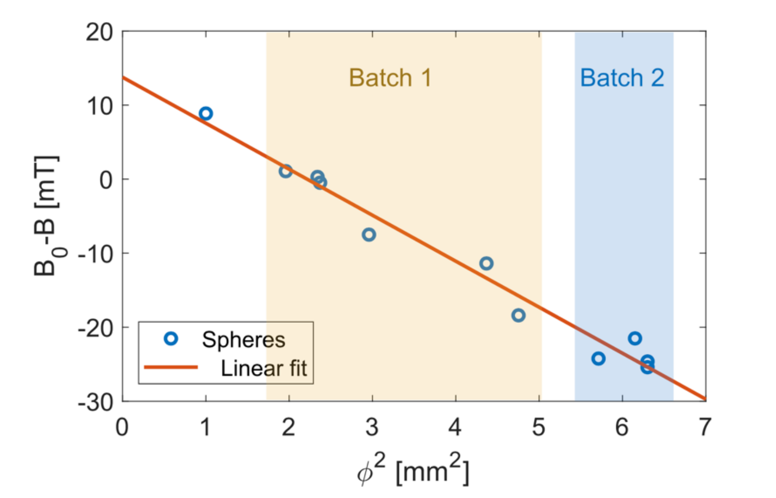
QUAX - Multi sphere system

A new cavity with resonance frequency of 10.7 GHz was realize to match the JPC amplifier working frequency

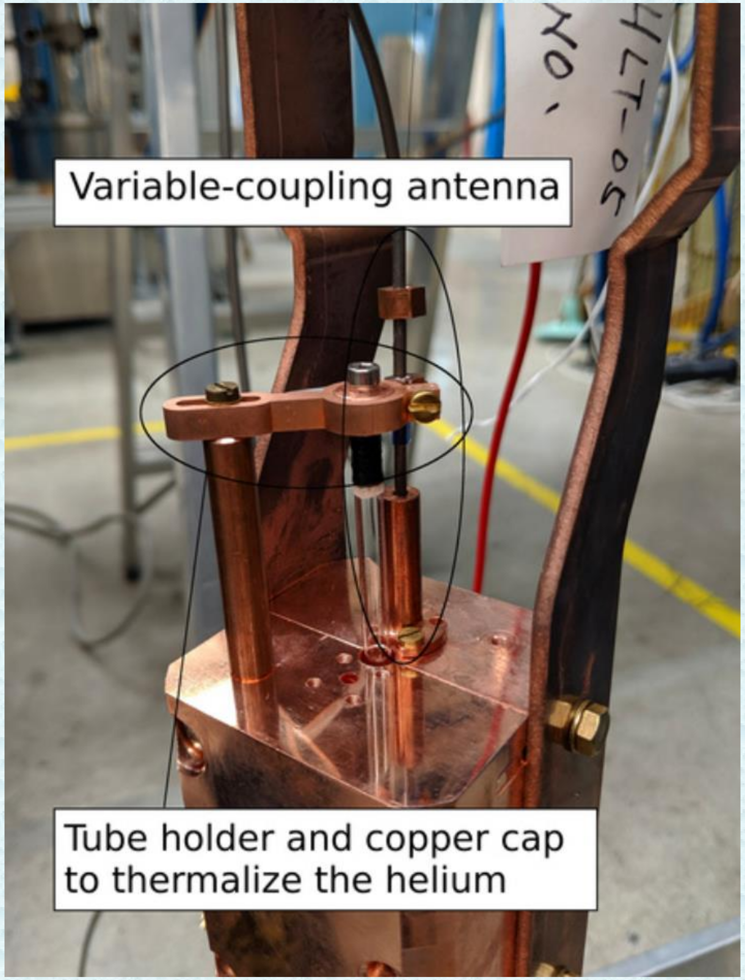
YIG spheres were produced with diameter ~ 2.1 mm, maximum value to avoid non linear effects with rf coupling

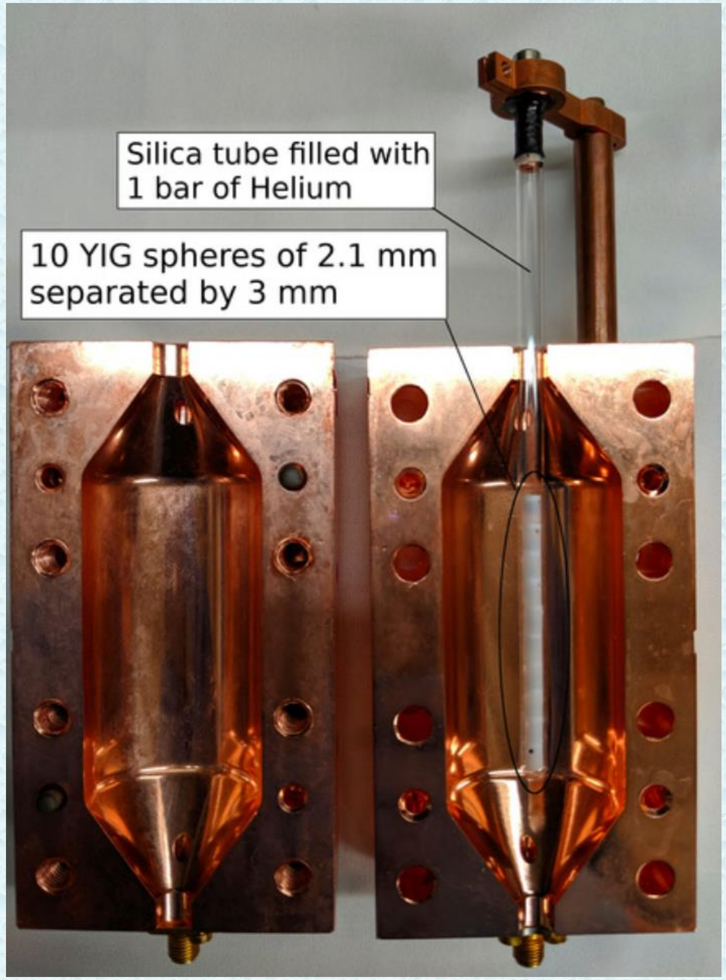
Ten good spheres were selected out of about 20

- Best linewidth
- Same Larmor frequency for a given external static field



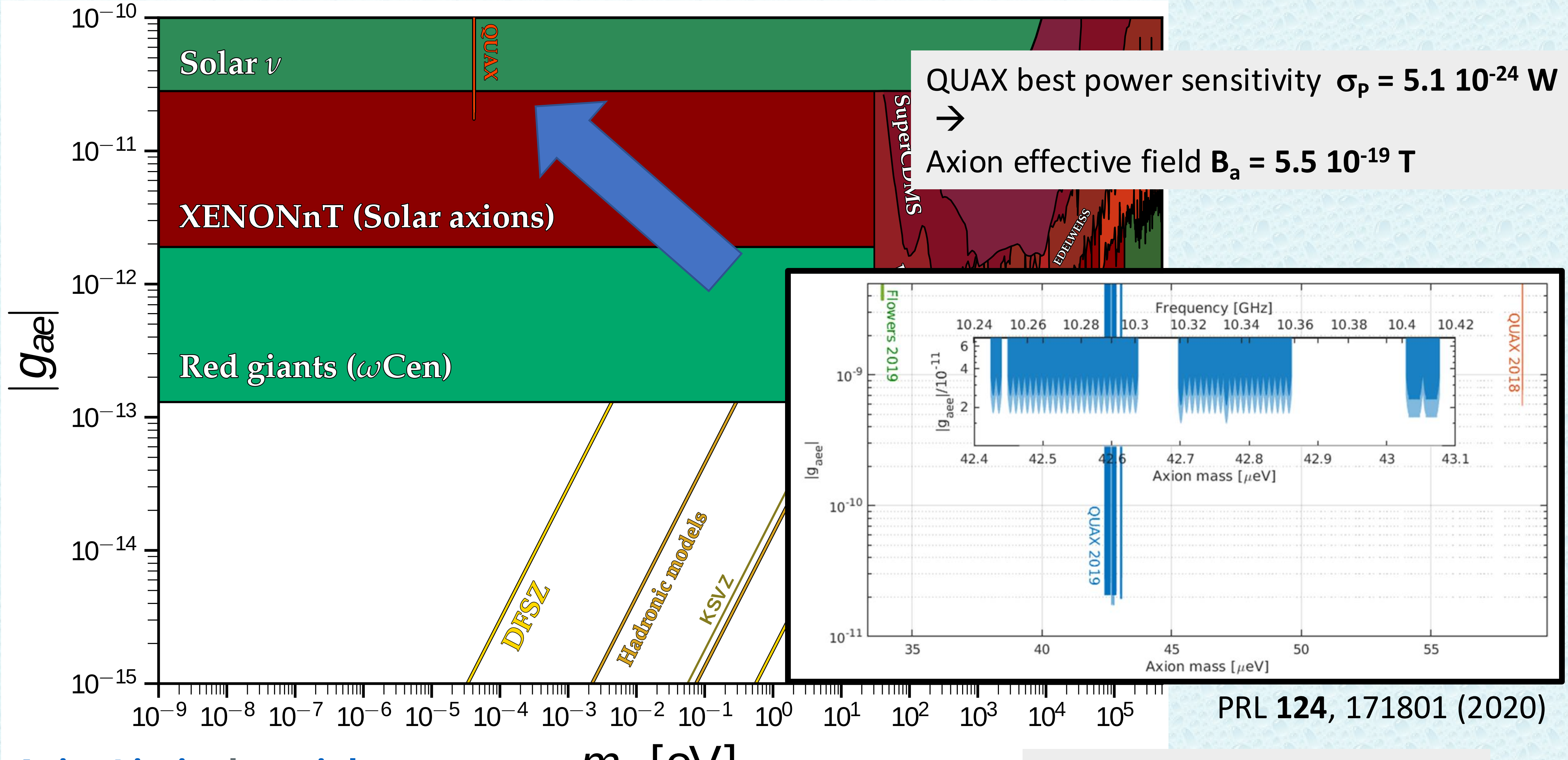
Magnetizing field for a given frequency vs sphere diameter





All the sphere must couple coherently to the cavity resonance

Axion electron coupling



AxionLimits by cajohare.

QUAX best power sensitivity **σ_P = 5.1 10^{-24} W**
→
Axion effective field **B_a = 5.5 10^{-19} T**

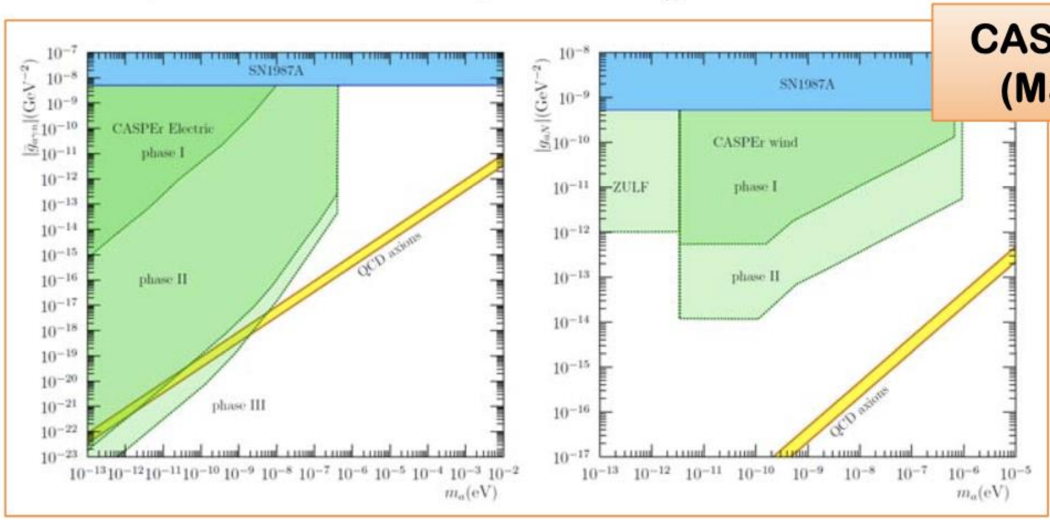
PRL **124**, 171801 (2020)

New prospects:
Increase number of spheres
Single photon counter detector

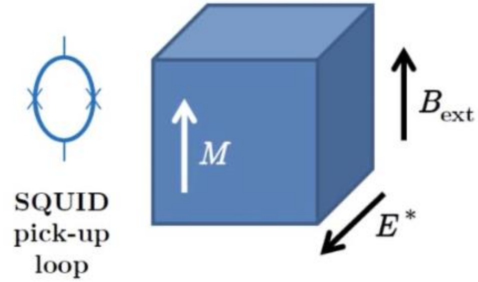
Probing a different coupling gives prospects for model discrimination in the event of discovery

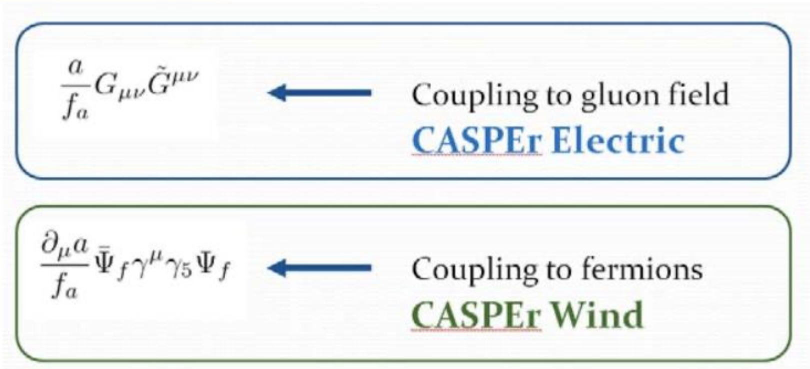
NMR Casper

- **DM-induced spin precession → it can be detected with very sensitive NMR techniques**
- **Directly sensitive to the gluon term (also to fermionic couplings)**
- **Maybe important at very low m_a**



CASPEr experiment (Mainz-Berkeley)

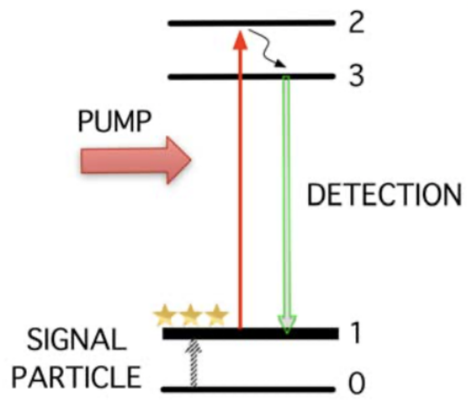




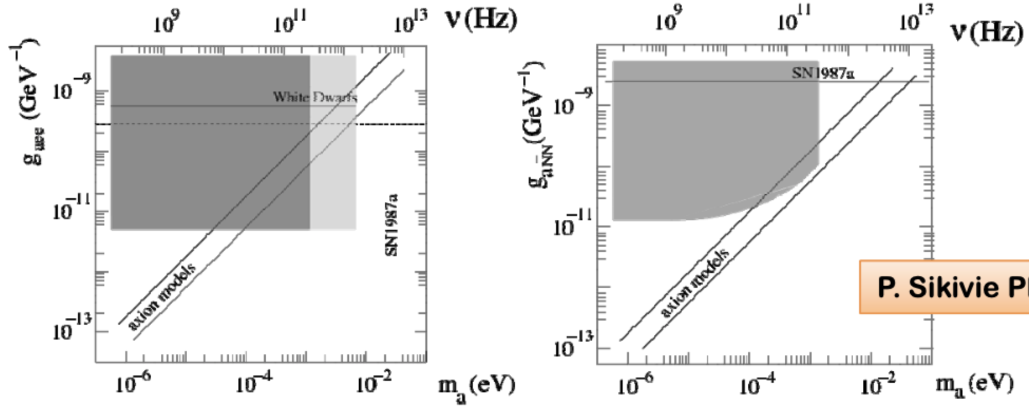
Phys. Rev. X 4, 021030 (2014)

Dark matter induced atomic transitions

- **DM can induce atomic excitations equal to m_a.**
- **Sensitive to axion-electron and axion-nucleon coupling**
- **Zeeman effect → create atomic transitions tunable to m_a**
- **Detection of excitation via pump laser**
- **AXIOMA → recent project aiming at an implementaiton**



Relevant sensitivity for $m_a \sim 10^{-4}$ eV seems possible for kg-sized samples



P. Sikivie PRL 113(14)

SCIENTIFIC REPORTS

OPEN

Axion dark matter detection by laser induced fluorescence in rare-earth doped materials

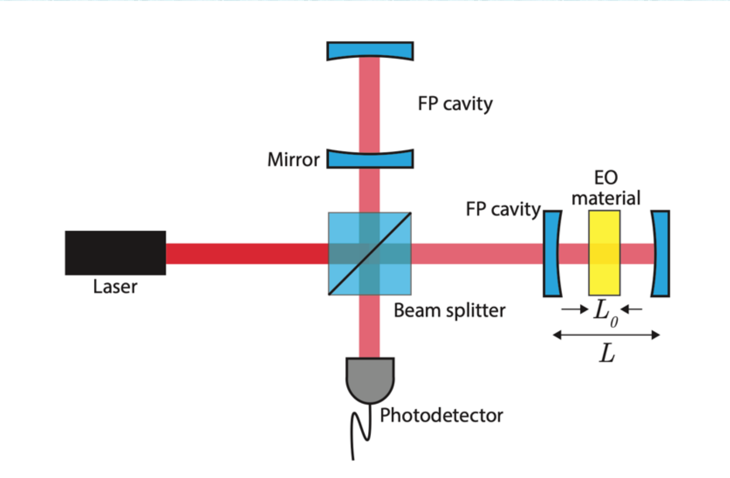
Received: 1 September 2017
Accepted: 25 October 2017
Published online: 09 November 2017

Caterina Braggio[1], Giovanni Carugno[1], Federico Chiossi[1], Alberto Di Lieto[2], Marco Guarise[1], Pasquale Maddaloni[3,4], Antonello Ortolan[5], Giuseppe Ruoso[5], Luigi Santamaria[6], Jordanka Tasseva[4] & Mauro Tonelli[2]

Other ideas – Optical devices

arXiv:2306.02168
Galactic Axion Laser Interferometer Leveraging Electro-Optics: GALILEO

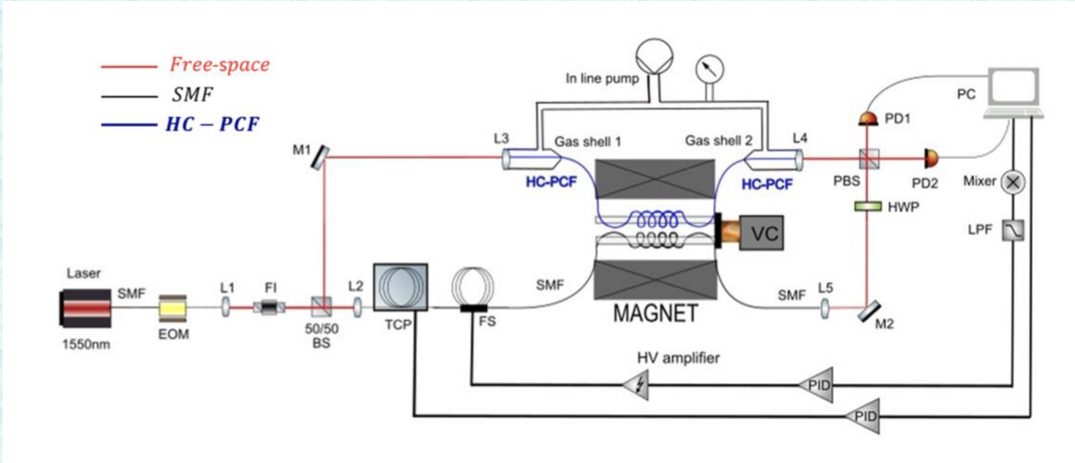
electro-optical material's refractive index modified by the presence of a coherently oscillating dark matter background

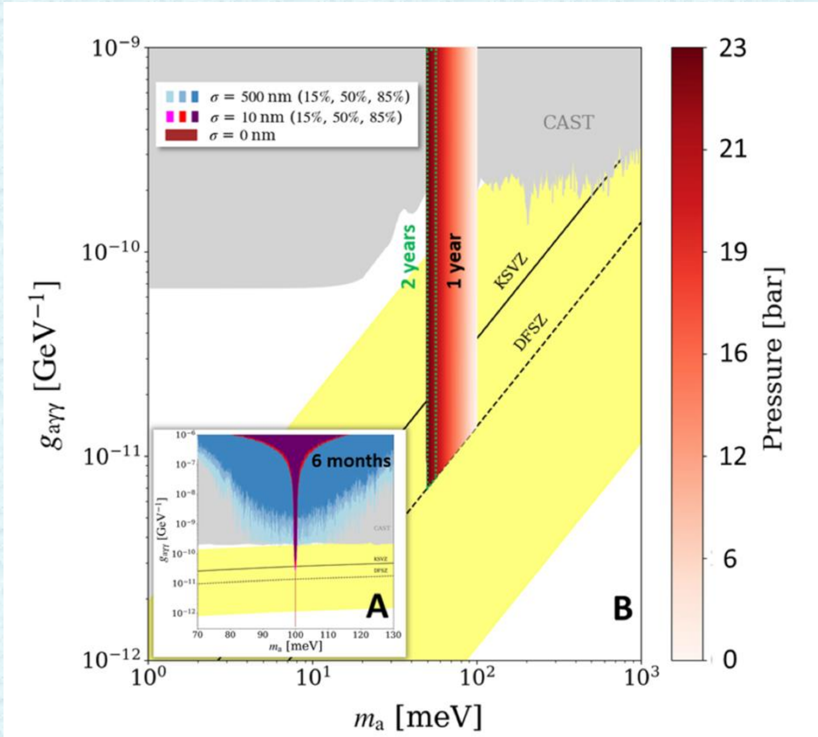


$$\mathrm{SNR} \simeq \left(\frac{L_0 N \mathcal{F}}{6.7\,\mathrm{mm} \times 1.5 \times 10^5}\right)\left(\frac{\lambda}{1064\,\mathrm{nm}}\right)^{-1/2}\left(\frac{P_{\mathrm{in}}}{5\,\mathrm{W}}\right)^{1/2}\left(\frac{T}{\mathrm{s}}\right)^{1/4} \times \begin{cases} 20\left(\frac{g_{a\gamma\gamma}}{10^{-10}\,\mathrm{GeV}^{-1}}\right)\left(\frac{B}{10\,\mathrm{T}}\right)\left(\frac{m_{\mathrm{DM}}}{100\,\mu\mathrm{eV}}\right)^{-5/4} \\ 120\left(\frac{\kappa}{10^{-11}}\right)\left(\frac{m_{\mathrm{DM}}}{100\,\mu\mathrm{eV}}\right)^{-1/4} \end{cases}$$

WISP Searches on a Fiber Interferometer under a Strong Magnetic Field: WISPFI

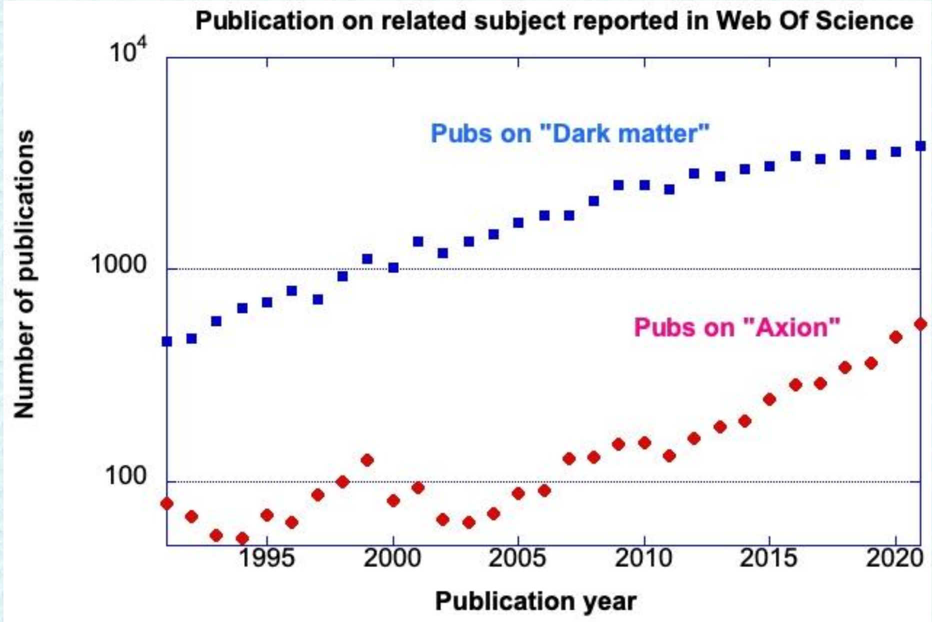
arXiv:2305.12969

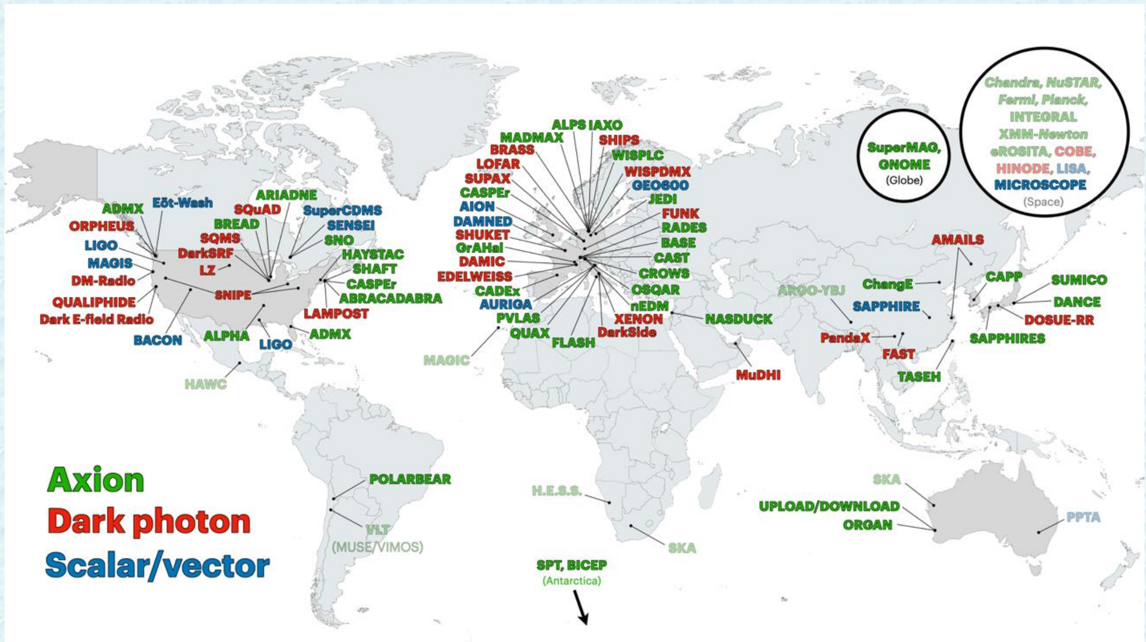




Summarizing the axion

- The research on axion is showing an **increasing interest in the physics community**
- **Different detection schemes** have been developed to probe **different mass ranges – different couplings (useful to obtain axion DM fractional density)**
- The **haloscope experiments have entered a very exciting phase**, reaching the theoretically interesting territory to test the **favoured axion models** (QCD axion)
- We are still in a pioneering era with **several small scale experiments** running and being proposed





Thanks to my everyday Collaborators

G.Ruoso
C.Braggio
A.Ortolan
R.Di Vora

https://cajohare.github.io/AxionLimits/

Thank you

Axions for amateurs

David J. E. Marsh[a]

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ARTICLE HISTORY
Compiled October 30, 2023

ABSTRACT
Axions are an increasingly popular topic in theoretical physics, and are sparking a global experimental effort. In the following I review the motivations for the existence of axions, the theories underlying them, and the methods to search for them. The target audience is an interested amateur, physics undergraduate, or scientist in another field, and so I use no complicated mathematics or advanced theoretical topics, and instead use lots of analogies.

KEYWORDS
axions, dark matter, haloscope, superradiance, axion electrodynamics, strong cp problem

1. Invitation: a century of progress and problems

We live at an extraordinary time in scientific history: never before have we known so much about the Universe, yet been so certain about our ignorance of it.

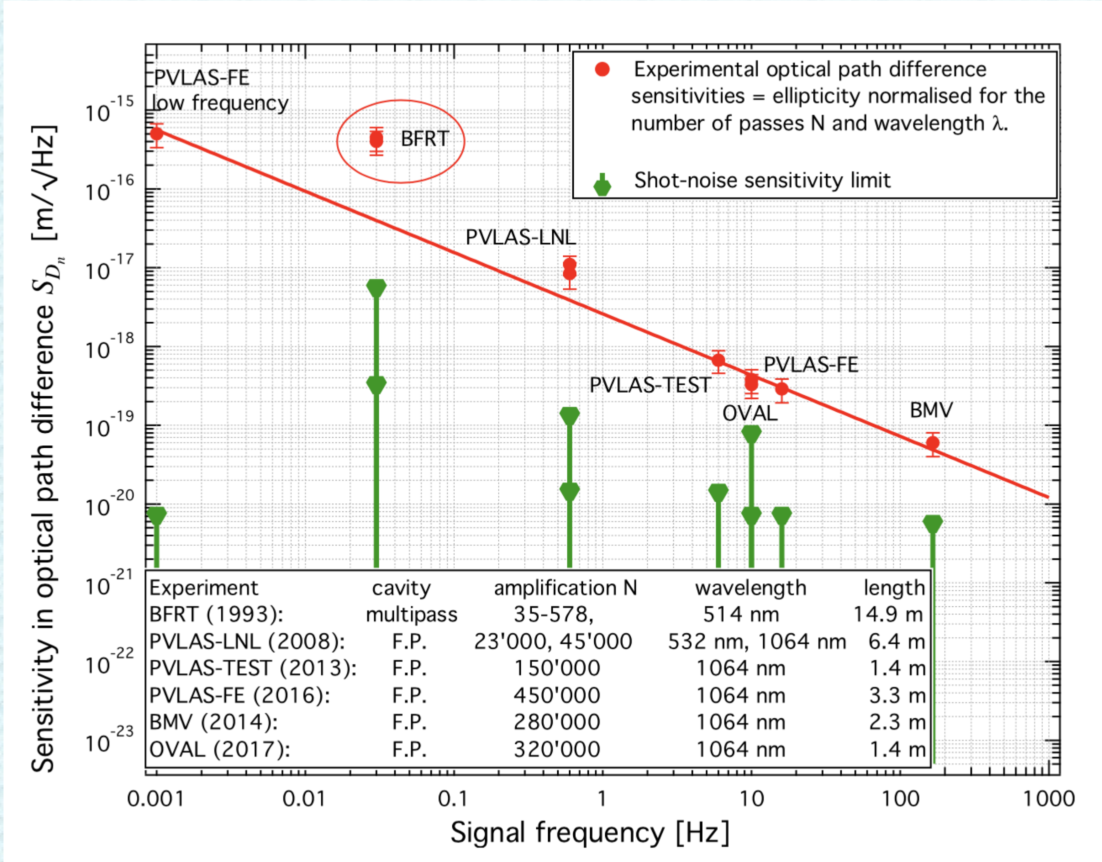
PVLAS extension: VMB@CERN

- Sensitivity is limited by extra noise originating in the optical elements (well above shot noise)

- Cavity amplification not effective for F > 10 000 , SNR does not improve

We must increase the signal strength

VMBCERN tries to overcome the limit of PVLAS by employing higher field magnets, namely a prototype **LHC magnet**, and a **new detection scheme**



Competing experiments:

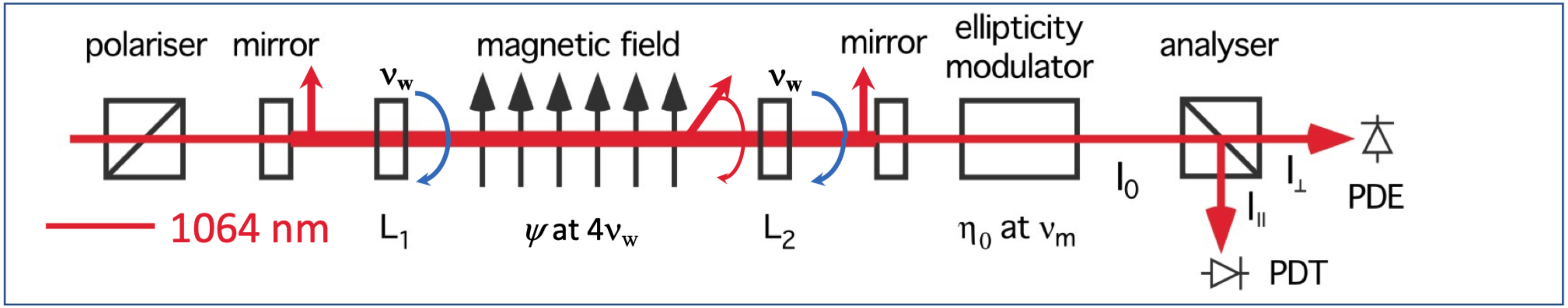
- **BMV** – a french project based on pulsed magnets. New type of magnet without cooling (10 T, 0.8 m). arXiv:2110.03398

- **OVAL** – a japanese effort as well on pulsed magnet. See S. Kamioka PhD thesis @ https://tabletop.icepp.s.u-tokyo.ac.jp/wp-content/uploads/2021/02/Dron-kamioka.pdf

VMBC@CERN detection scheme

Two co-rotating half wave plates inside a Fabry-Perot

- Polarization rotation inside the magnetic field but fixed on mirrors to avoid mirror birefringence signal
- Maximum finesse ≈ 1000 - 5000 (depending on the losses of the wave-plates)
- A detailed study of systematics performed: identified a serious one due to mechanical defects → solution: **slightly modulate also the magnetic field**



$$\Psi(t) = \Psi_0 \sin 4\phi(t) + N\frac{\alpha_1(t)}{2}\sin 2\phi(t) + N\frac{\alpha_2(t)}{2}\sin[2\phi(t) + 2\Delta\phi(t)]$$

Signal @ $4\nu_w$

Spurious signals
Contain harmonics of ν_w

Relative rotation phase error
Degrades extinction

$\alpha_{1,2}$ are the phase errors from π of the two HWPs and $\phi(t)$ is their rotation angle

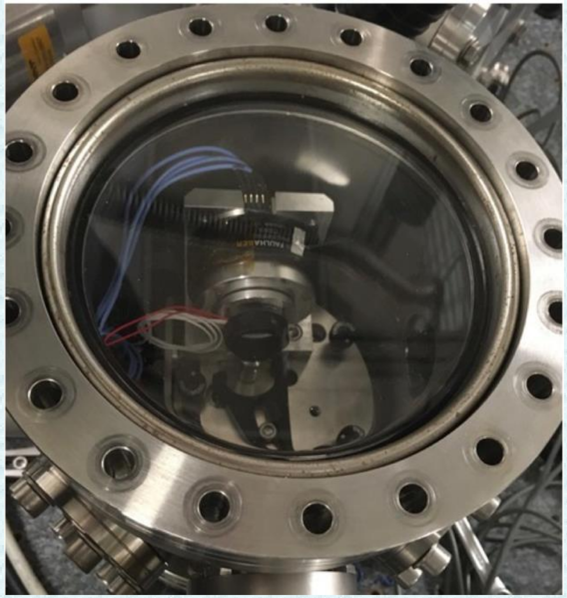
Allows the use of (quasi) static superconducting fields with $B_{ext}^2L \approx 1000\ T^2m$ (LHC dipole)

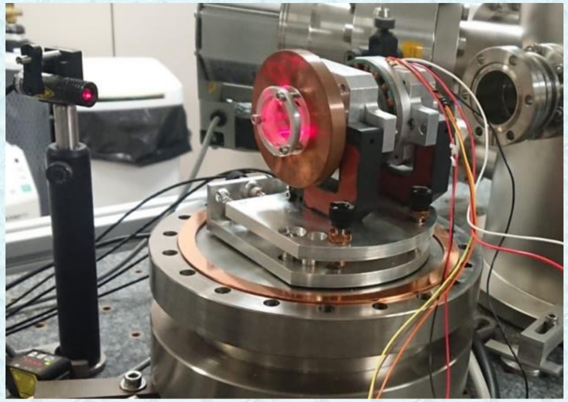
Eur. Phys. J. C (2016) 76:294

VMB@CERN : project postponed

- Careful experimental studies of several critical points

Rotating waveplate with temperature stabilization system





- **Method issues**
  - ✓ Synchronous rotation of the wave-plates for good extinction ratio
  - ✓ Understand and workaround the systematic effects at $4\nu_w$ and mitigate all other harmonics
  - ✓ Total wave-plate ellipticity $\alpha_{1,2} \ll 1/N$ for correct functioning of the F.P.
  - ✓ Lock the laser to the F.P. with the rotating HWPs inside

- **Noise issues without F.P.**
  - ✓ Shot-noise without the HWPs (beam pointing stabilization)
  - ✓ Shot-noise with the HWPs but non-rotating (beam pointing stabilization)
  - ✗ Shot-noise with the rotating HWPs (not even with beam pointing stabilization)
  - ➢ Feedback implementation to maintain systematic harmonics at the noise level

- **Cavity issues**
  - ✓ Cavity locking with non-rotating HWPs and noise determination
  - ✓ Cavity locking with rotating HWPs: (dust issues, intensity noise, extinction)
  - ➢ Noise determination with the F.P. and rotating HWPs
  - ➢ Required optical path difference noise $S_{OPD} \approx 10^{-18}$ m/√Hz @ $4\nu_w$ with the F.P.

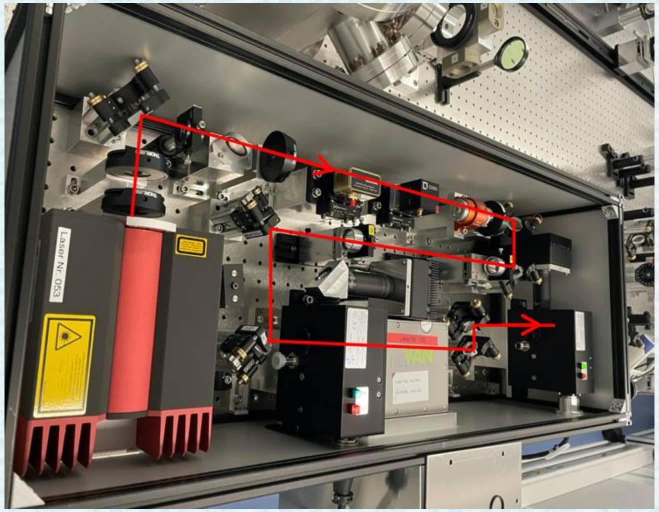
- **The presence of a wide band noise with the rotating waveplates has not been understood and it is at present a showstopper**
- R&D activities will continue at low pace on the properties of mirror coating
- Side results interesting also for gravitational wave interferometers

ALPS II @ DESY

HIGH POWER LASER SOURCE

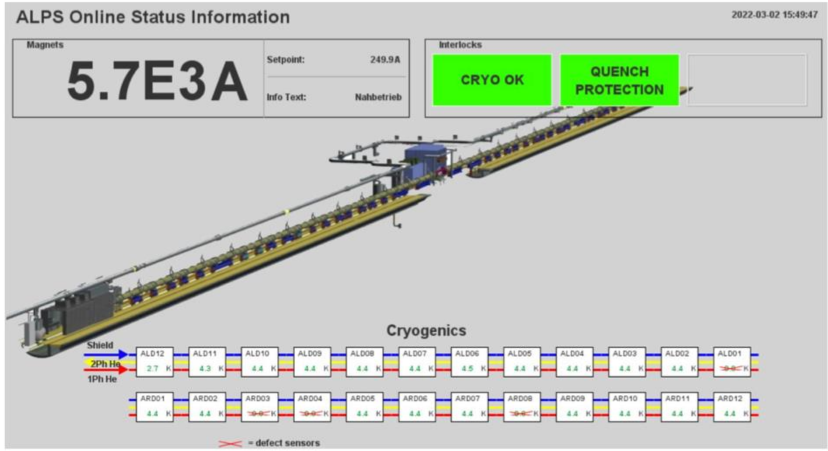
Amplified Non Planar Ring Oscillator (NPRO)

- Demonstrated over 60 W of power at 1064 nm
- > 90% of power in fundamental mode



MAGNET STRINGS

- 24 HERA dipole magnets
- October 2020: Magnets installed and aligned
- March 2022: Magnet strings run successfully at full curren
  - 5.7 kA, 5.3 T



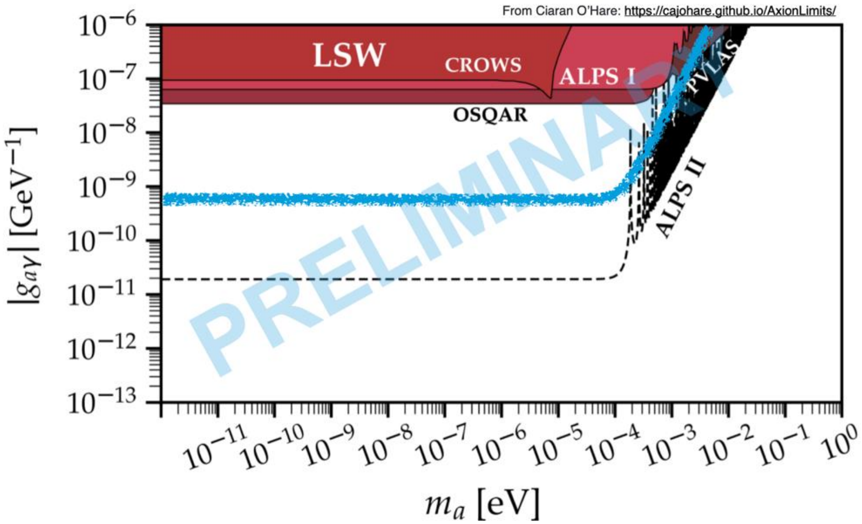
Status of the ALPS II Experiment | PATRAS 2022 | 09 August, 2022

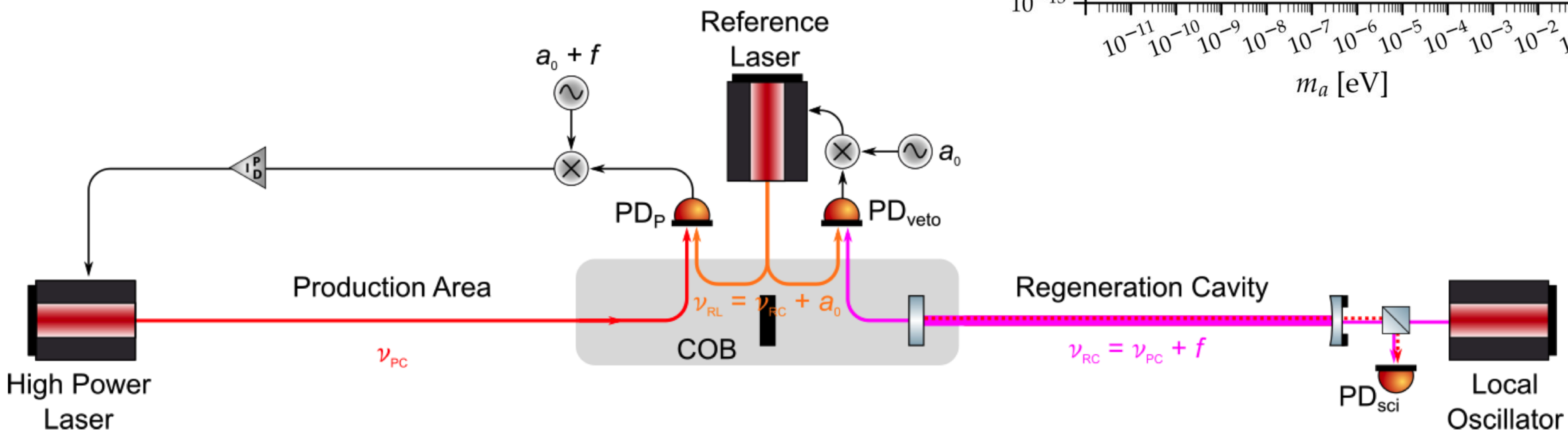
ALPS II first science run

Simplifying the optical system

Operate without production cavity

- Simplifies control system
  - Feedback directly to laser frequency rather than PC length
- Light injected to COB increased by a factor of 40x
  - Faster identification of 'light leaks'

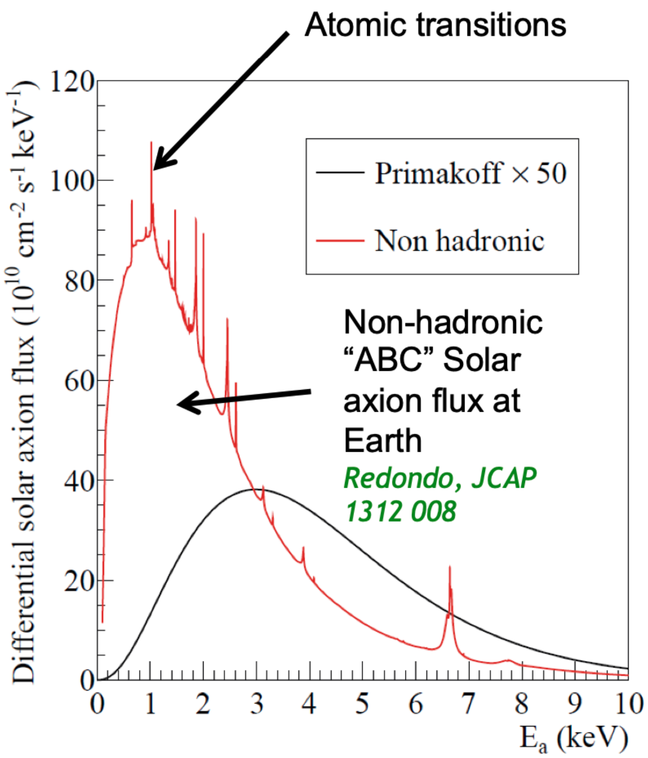




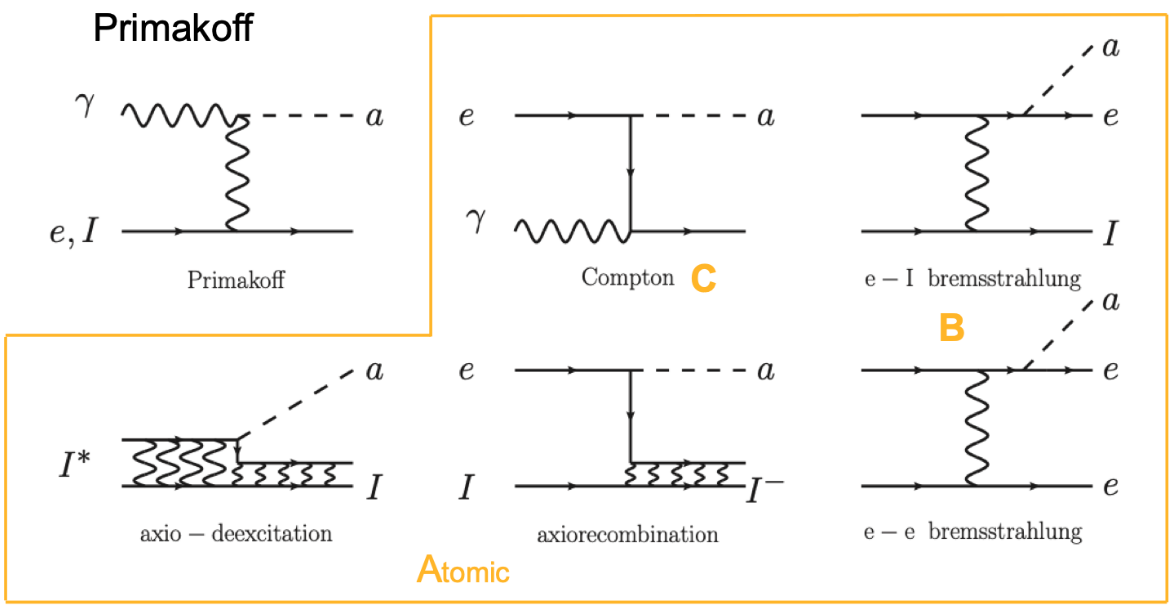
Other Solar Axion Sources / Post Discovery

"ABC Axions"

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



"ABC solar axions" from axion-electron coupling

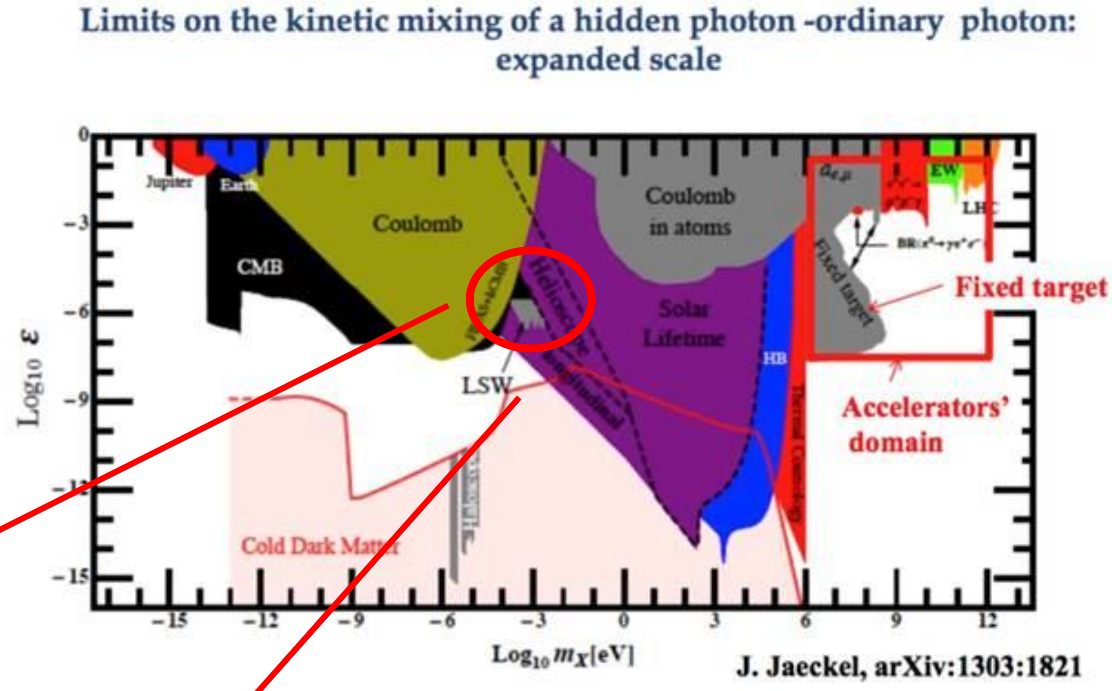


Detection of both ABC and Primakoff axion spectrum would allow distinguishing axion models (g_{ae}, $g_{a\gamma}$)
Jaeckel et al. arXiv:1811.09278

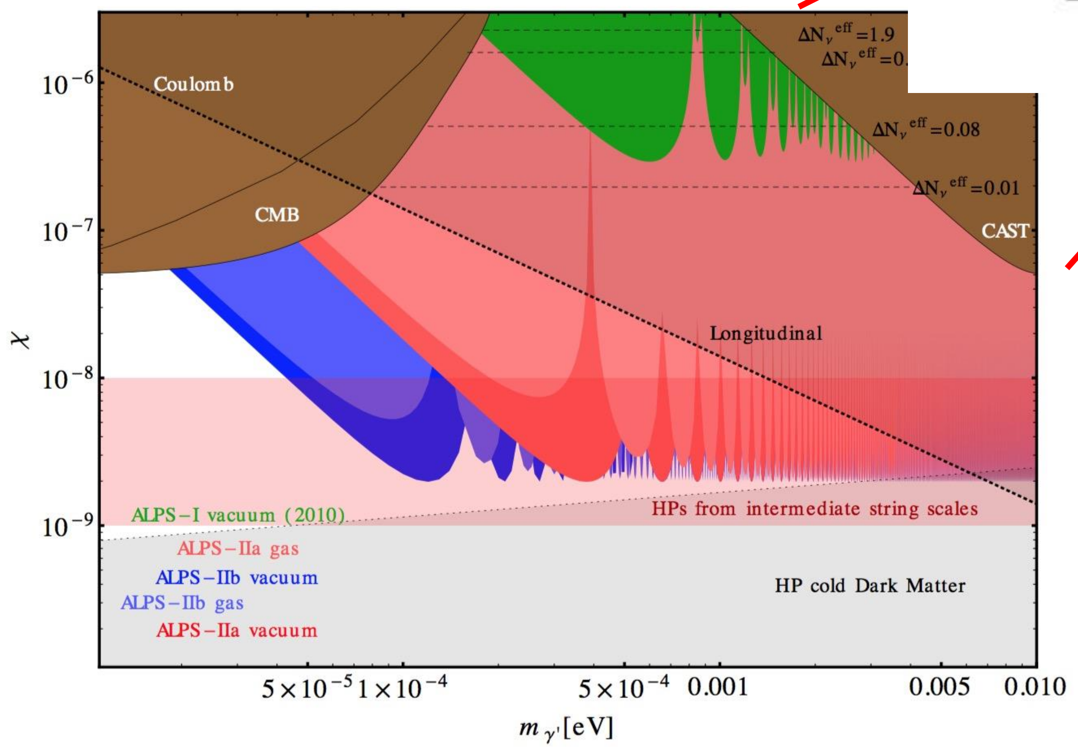
Hidden/dark photons

- Regeneration experiments can probe the existence of **hidden photons** coupled to the **classical photons** (actually also helioscopes and haloscopes)

- Sensitivity in the low mass region due to coherence: $m_{\gamma'} \approx 1$ meV



From ALPS-II TDR



- Hidden photon measurements does not need magnetic field

- Little improvements expected after ALPS-II

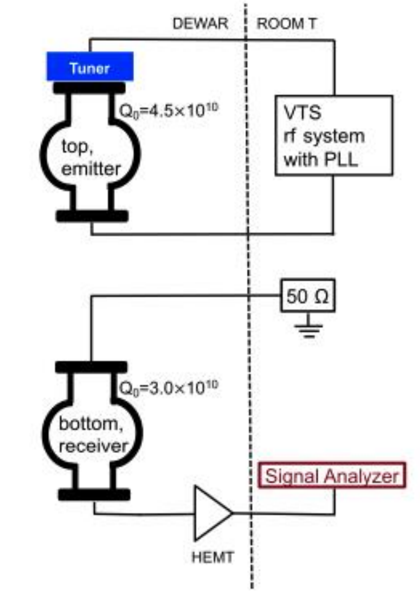
SRF Cavities

LSW search for **dark photons** using two state-of-the- art high-quality-factor superconducting radio frequency (SRF) cavities

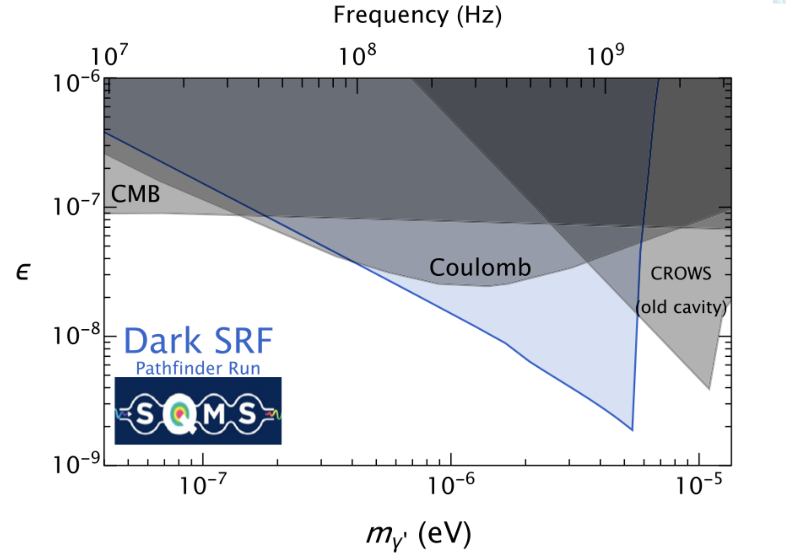
A. Romanenko et al PRL 130, 261801 (2023)

- Operation in a 1.5 K environment
- HEMT readout (T_n ~ 4 K @ 1.3 GHz)
- Very good long term stability of cavities

Parameter	Emitter	Receiver
Q_0	4.5×10^{10}	3.0×10^{10}
Q_{in}	1.8×10^{9}	4.5×10^{11}
Q_t	2.9×10^{11}	1.3×10^{10}
Frequency drift	5.7 Hz	3.0 Hz



Final measurement compatible with thermal noise with P = -152 dBm with input power 30 dBm



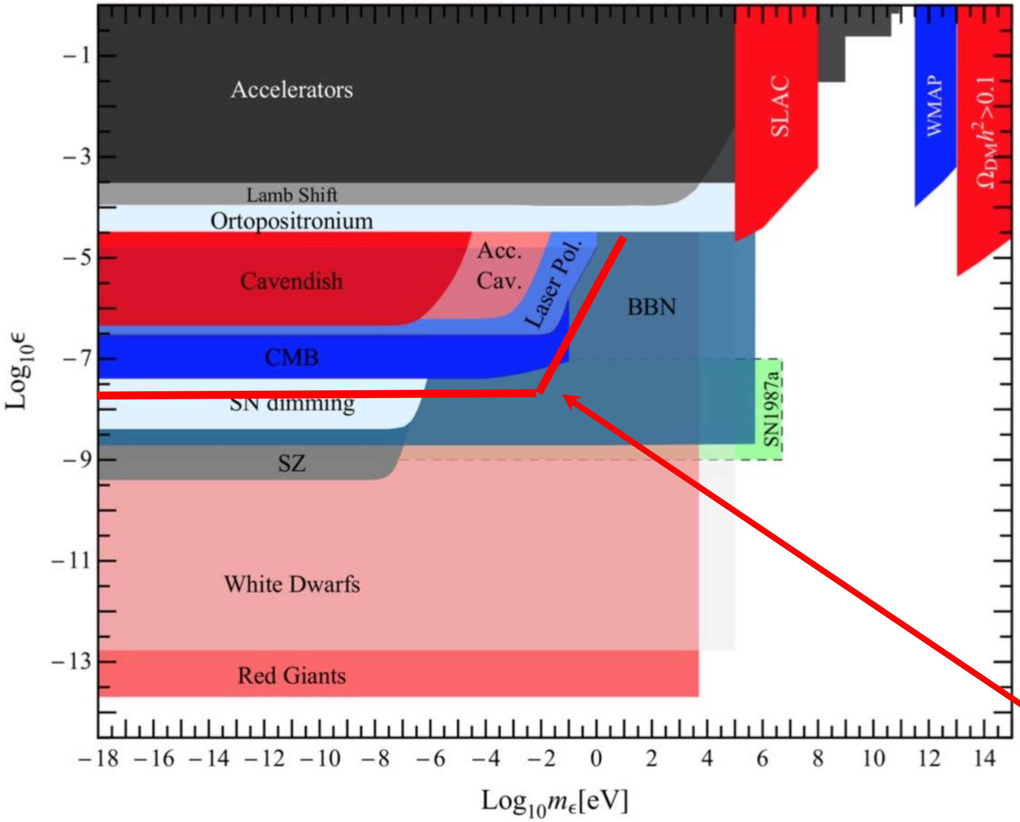
Future improvements:
- Use of a dilution refrigerator – improve temperature stability
- Quantum limited detector
- Magnetic field for **axion search (?)**

Milli-charged particles – sub eV range

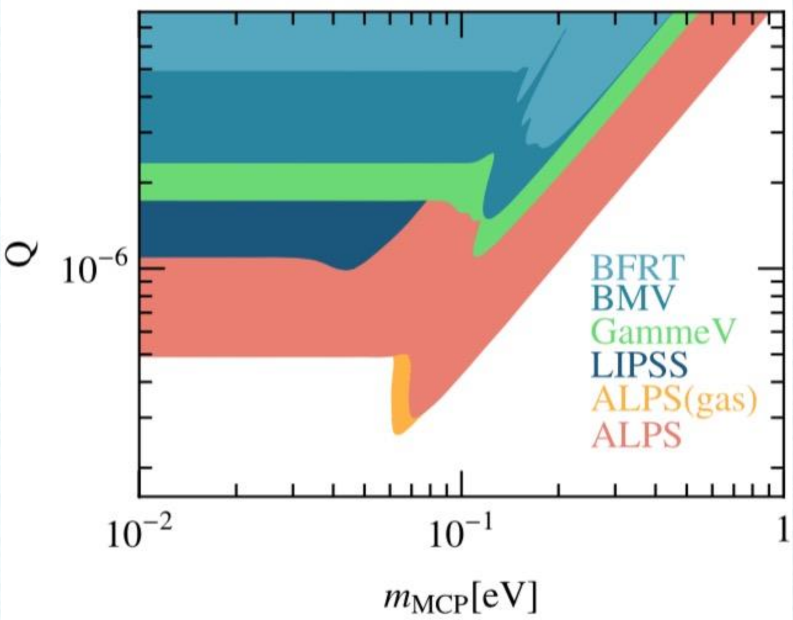
Particles with **{mass, electric charge}** = $\{m_\chi, \varepsilon e\}$

$\varepsilon = Q_\chi / e$

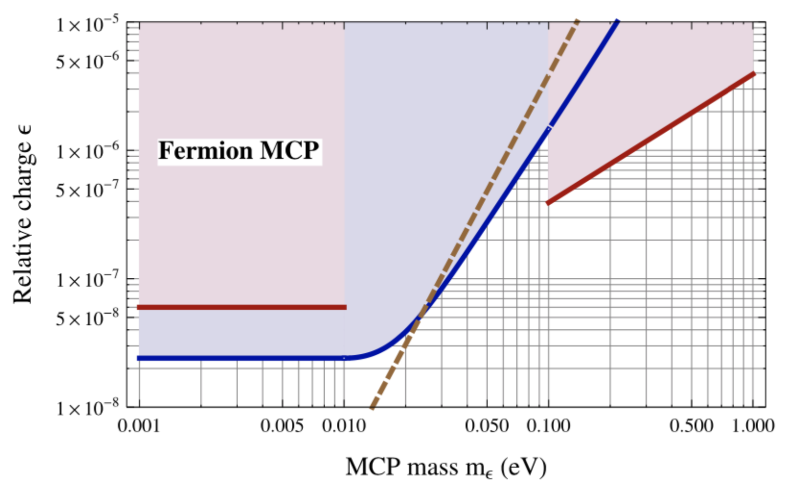
Mark Goodsell[a,c], Joerg Jaeckel[b], Javier Redondo[c,d] and Andreas Ringwald[c]
Published 6 November 2009 • Journal of High Energy Physics, Volume 2009, JHEP11(2009)



From LSW experiments (ALPSI)
Physics Letters B 689 (2010) 149–155



From polarization experiments (PVLAS)
Eur. Phys. J. C (2016) 76:24



Laboratory experiments can put model independent limits also in the sub eV region

Thank you

The axion

- The axion is a **light pseudoscalar boson**, its properties can be derived using current algebra techniques
- The axion is the light cousin of the π^0 :

$m_a f_a$ » $m_p f_p$

***m_p* = 135 MeV – pion mass**
***f_p* = 93 MeV – pion decay constant**

- The most recent calculation using lattice QCD

$$\boxed{m_a = 5.70(6)(4)\,\mu\text{eV}\,\left(\frac{10^{12}\text{GeV}}{f_a}\right)}$$

G.Grilli di Cortona et al J. High Energy Phys. 01 (2016) 034

- f_a is the axion decay constant, related to the scale of spontaneous breaking of the PQ simmetry
- the strong CP problem is solved regardless of the value of f_a
- f_a is the quantity that determines all the low energy phenomena of the axion

- **Axion couplings** with ordinary matter depends on the model implementing the PQ simmetry

- Extensions of the standard model including the PQ symmetry need **extra degrees of freedom:**
  1. new scalars or fermions
  2. new quarks

Axion Model Benchmarks

PQWW (Peccei, Quinn, Weinberg, Wilczeck)

R.Peccei,H.R.Quinn, PRL38(1977)1440
R.Peccei,H.R.Quinn, PRD16(1977)1791
S.Weinberg, PRL40(1978)223
F.Wilczek, PRL40(1978)279

- Introduces in the SM 2 extra Higgs doublets
- f_a is at the electroweak scale (250 GeV)

$m_a \approx 100$ keV → **RULED OUT BY ACCELERATOR EXPERIMENTS (axion coupling too large)**

"Invisible" axion models

Dine-Fischler-Srednicki-Zhitnitskii (DFSZ)

M.Dine,W.Fischler,M.Srednicki,Phys.Lett.104B(1981)199
A.R.Zhitnitsky,Sov.J.Nucl.Phys.31(1980)260

- 2 extra Higgs doublets
- New complex PQ scalar
- Tree level coupling with leptons of SM

Kim-Shifman-Vainstein-Zakharov(KSVZ)

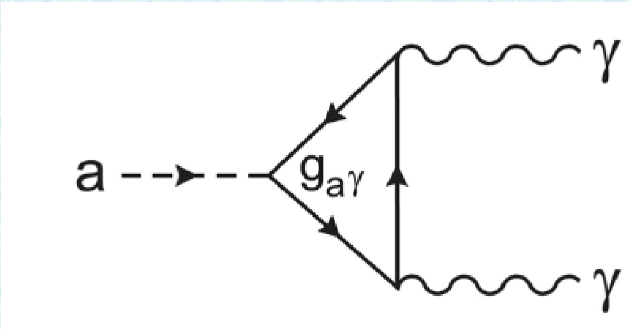
J.E.Kim,PRL43(1979)103
M.A.Shifman,A.I.Vainshtein,V.I.Zakharov,NPB166(1980)493

- New extra heavy quark with mass $m_Q=f_a$
- New complex PQ scalar
- No direct coupling (at tree level) to lepton of SM.

- **Very light (m_a < eV)** and **very weak couplings** for **f_a >>** electroweak scale
- The strength of the axion interaction depends on the assignment of the $U_{PQ}(1)$ charge to quarks and leptons (model class dependent)
- **Models list not exhaustive**, axions in String theory, SUperGRAvity, SUSY or GUT

Axion interactions

All couplings are extremely weak (**Invisible Axion models**)!



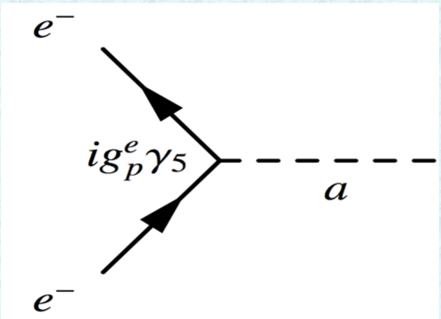
Axion photon photon (Inverse Primakoff effect)

$$\mathcal{L}_{a\gamma\gamma} = -\left(\frac{\alpha}{\pi}\frac{g_\gamma}{f_a}\right) a\vec{E}\cdot\vec{B} = -g_{a\gamma\gamma} a\vec{E}\cdot\vec{B}$$

$$g_{agg} = g_g \frac{a}{p}\frac{m_a}{m_p f_p}$$

g_γ = 0.36 (DFSZ)

g_γ = - 0.97 (KSVZ)



Axion electron electron

$$L_{aee} = - g_e \bar{e} i g_5 e a$$

$$\boxed{\frac{g_p\hbar}{2m}\boldsymbol{\sigma}\cdot\nabla a}$$

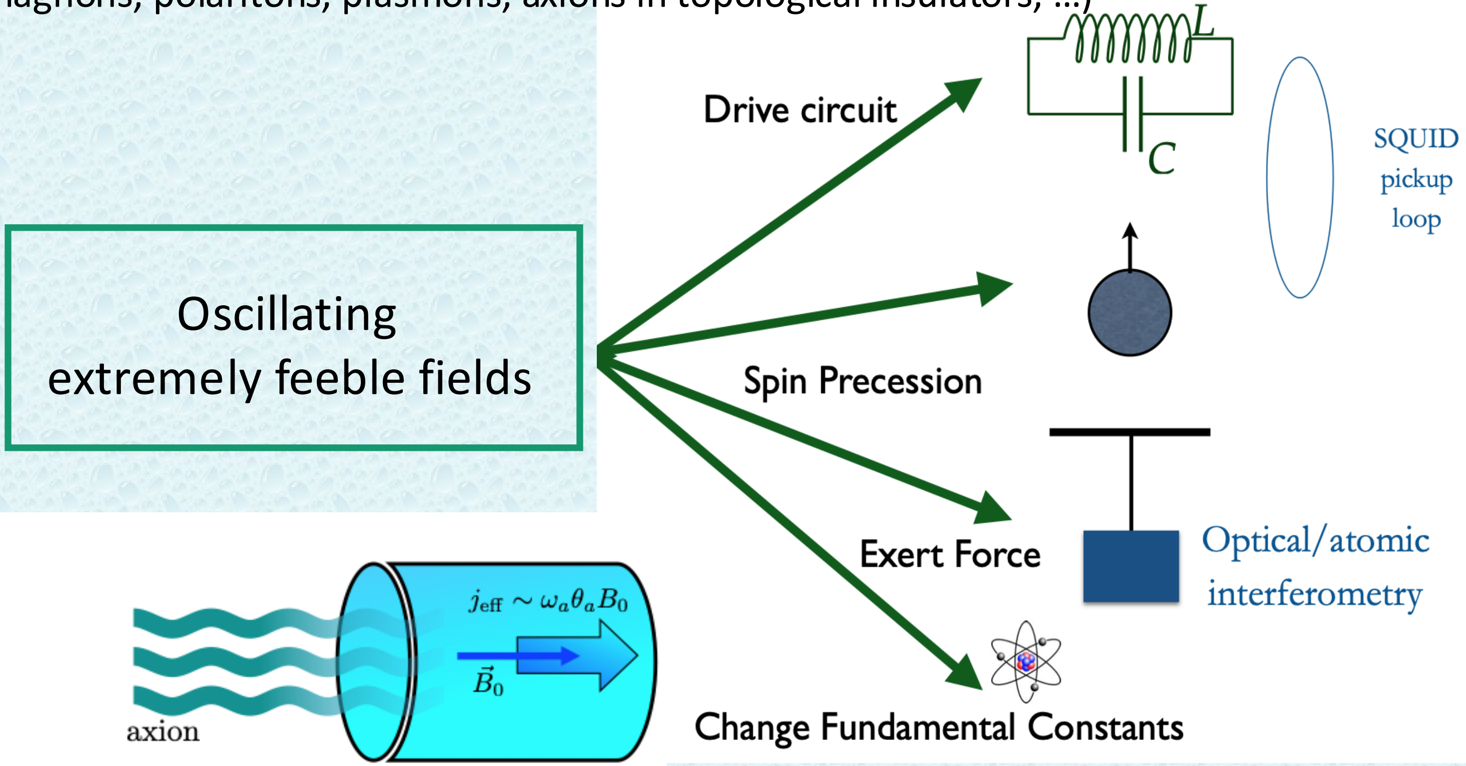
Non relativistic electron

$$g_e \text{ » } \frac{m_a m_e}{m_p f_p} = 4.07\text{´ } 10^{-11} m_a$$ **(DFSZ)**

g_e ~ 0 (Strongly suppressed) (KSVZ)

Axion probes (observable effects)

- The “invisible” axion models DFSZ and KSVZ are in good shape but axions are still evading current experimental searches in many areas
    - Cosmology: axion as DM candidate
    - Astrophysics: axions as additional energy dissipation channels
    - Sun production
- Osservable effects in laboratory experiments
    - Axion production /detection
    - “Axion mediated” fifth force (Monopole-dipole, dipole-dipole)
    - Change of fundamental constants (Axion Moduli)
    - Quasi-particles (magnons, polaritons, plasmons, axions in topological insulators, …)



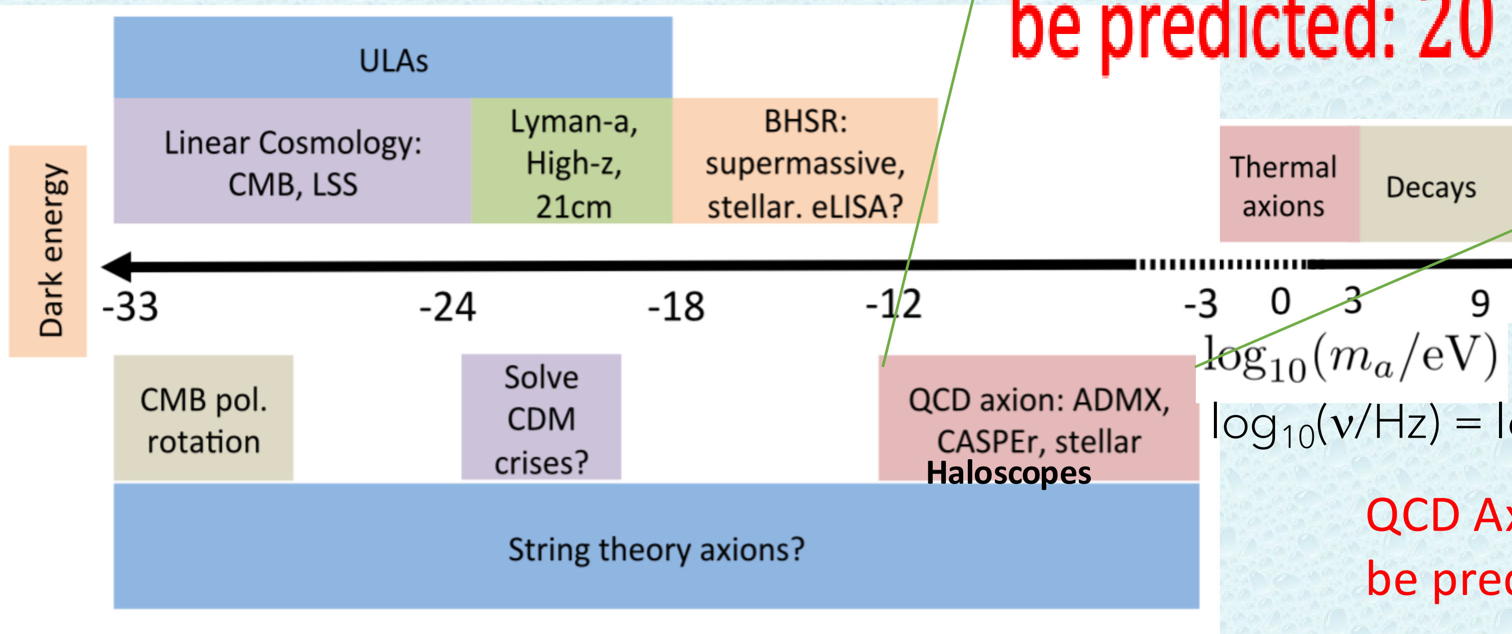
Axion & Cosmology

D.J.E. Marsh / Physics Reports 643 (2016) 1–79

"Axion" in cosmology can take on a variety of meanings:

- QCD axion: the Peccei–Quinn solution to the strong-CP problem $m_a \alpha\ 1/f_a$.
- ALP: any pseudoscalar Goldstone bosons with a two parameter model (m_a, f_a)
- ST&SUGRA: either matter fields or pseudoscalar fields associated to the geometry of compact spatial dimensions
- 50 order of magnitude uncertainty!
- **QCD axions can be the DM constituent with mass range predicted by high temperature lattice QCD**

QCD Axion DM mass range can be predicted: 20 ÷ 200 μeV



$\log_{10}(\nu/\mathrm{Hz}) = \log_{10}(m_a/\mathrm{eV}) + 14.4$

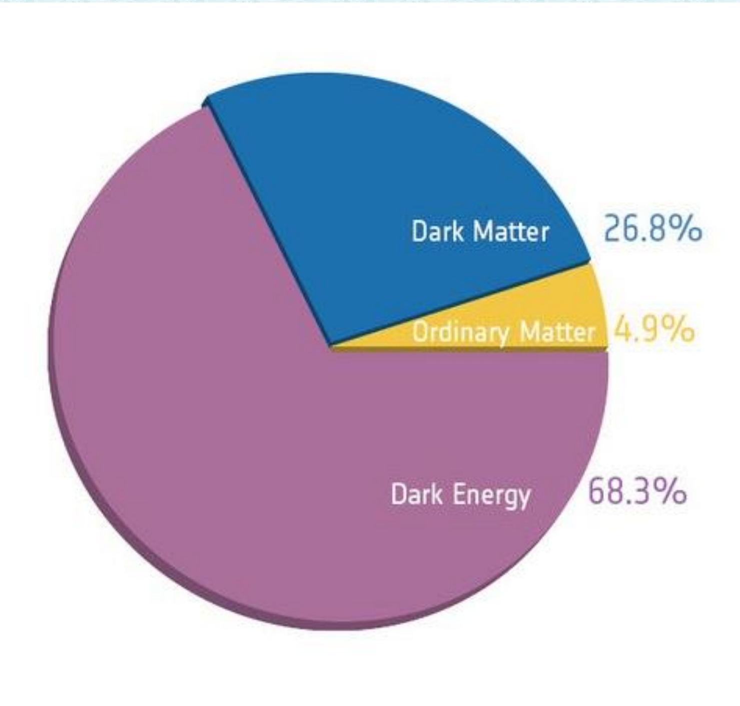
QCD Axion DM mass range can be predicted: 20 ÷ 200 μeV

Axions in the outer space

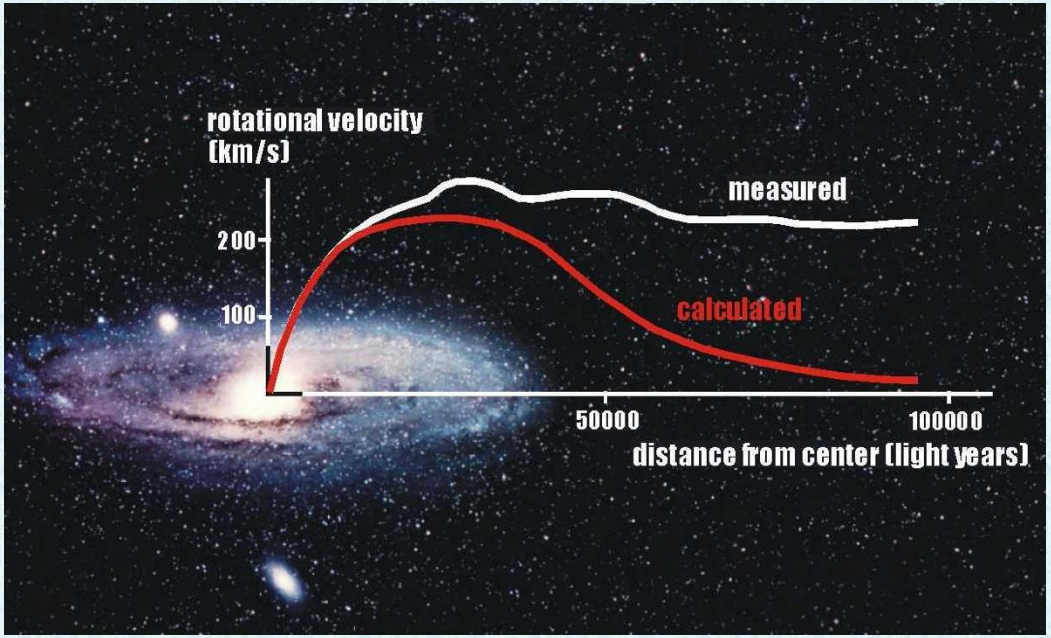
- A **light axion** (m_a < eV) has lifetime that can be longer than the age of the Universe. This kind of axion is indeed important for cosmology.
- **Is it a main component of Dark Matter?**

http://www.esa.int/For_Media/Photos/Highlights/Planck

Composition of the Universe after Planck precise measurement of CMB



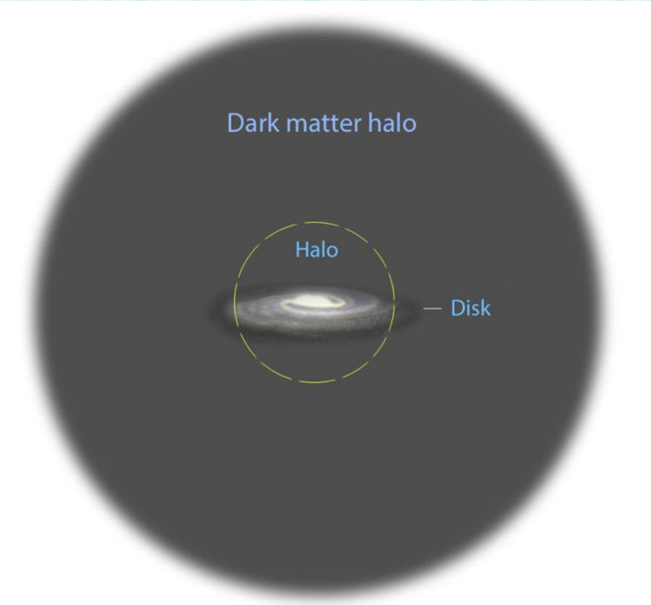
Typical rotational curve of galaxys



Axions are weakly interacting, stable on cosmological times, non relativistic

Standard Halo Model for ρ_{DM} and $f(v_a)$

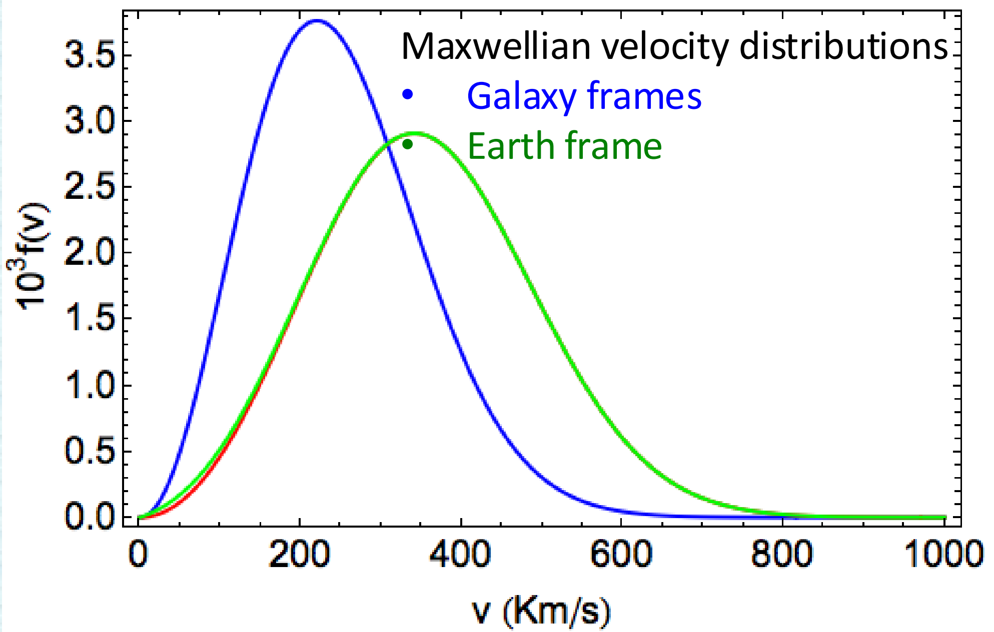
Standard Halo Model: Isothermal, isotropic Maxwell-Boltzmann Distribution of DM assuming ρ_{DM}=0.3 – 0.45 Gev/cm^3



Milky Way model

$$f(v) = 4\pi\left(\frac{\beta}{\pi}\right)^{3/2} v^2 \exp(-\beta v^2)$$

M. S. Turner, Periodic signatures for the detection of cosmic axions, Phys. Rev. D 42, 3572 (1990).



Observed axion velocity $\mathbf{v}_a = \mathbf{v} - \mathbf{v}_E$, where the Earth velocity $\mathbf{v}_E = \mathbf{v}_{sun} + \mathbf{v}_{orb}$

$$f(v_a) = 2\left(\frac{\beta}{\pi}\right)^{1/2} \frac{v_a}{v_E} \exp(-\beta v_a^2 - \beta v_E^2)\sinh(2\beta v_E v_a)$$
$$\simeq 2\left(\frac{\beta}{\pi}\right)^{1/2} \frac{v_a}{v_E} \exp(-\beta(v_a - v_E)^2)$$

Axions in the galactic halo

- In order to explain galaxy rotation curves, an **halo of dark matter** is hypothesized

- Accepted value for local dark matter **density**

$$\rho_{DM} \approx 0.3 \; - 0.45 \;\; \mathrm{GeV/cm^3}$$

- Cold dark matter component is **thermalized** and has a Maxwellian velocity distribution, with a dispersion $\sigma_v \approx 270$ km/s

- There might be a non-thermalized component with sharper velocity distribution

- **Axion can be a dominant component of the galactic DM halo**

- Its **occupation number** is large

$$n_a \approx 3 \times 10^{14} \left(\frac{10^{-6}\, eV}{m_a}\right) \quad \text{axions/cm}^3$$

- It can be treated as a classical oscillating field with frequency given by the axion mass

$$\frac{\omega_a}{2\,\pi} = 2.4 \left(\frac{10^{-6}\, eV}{m_a}\right) \quad \text{GHz}$$

- It has **coherence length** and **time**

$$\lambda = 1400 \left(\frac{10^{-6}\, eV}{m_a}\right) \text{ m}$$

$$t = 5 \left(\frac{10^{-6}\, eV}{m_a}\right) \text{ ms}$$