Overview of axion physics

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Outline

- Short theoretical introduction
- Current situation
- Experimental searches for the axion
- Perspectives

Some open problems in particle physics

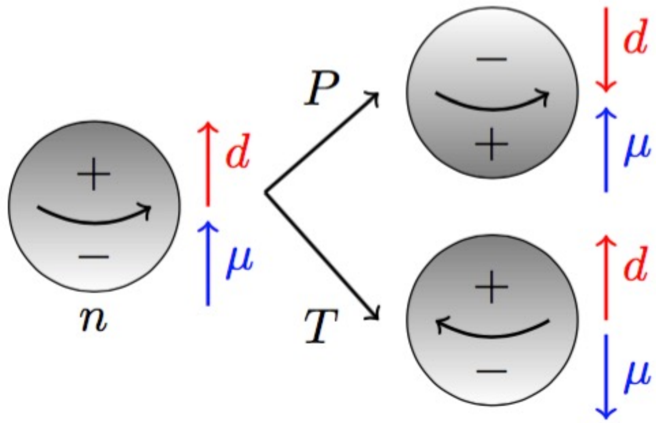
- The Standard Model (SM) of elementary particles provides an accurate description of the phenomena occurring in the particle physics sector

- It is not the ultimate theory → Many problems are still open

➢ SM does not include gravity

➢ Matter – antimatter asymmetry in the Universe

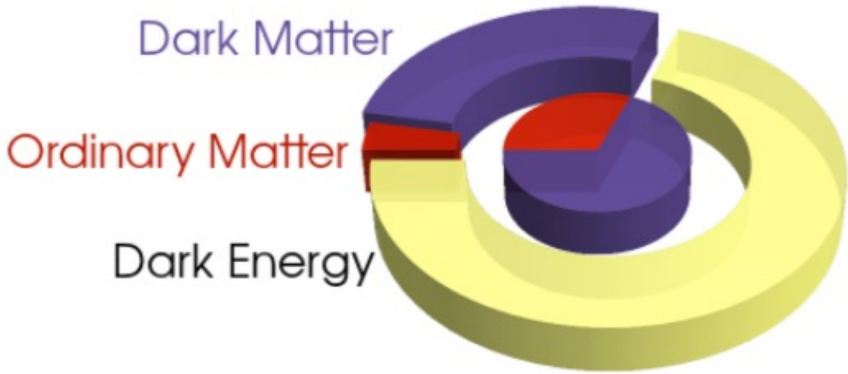
➢ **Strong CP problem** ←→ **neutron EDM**



➢ Neutrino mass

➢ Muon g-2

➢ **Dark matter** and dark energy



➢ ...and many more

Today we will try to understand how we could solve **two of them**....

The strong CP problem

- The QCD lagrangian contains a term that foresees CP violation (CPV)

$$\mathcal{L}_{CPV} = -\frac{\alpha_S}{8\pi} G^a_{\mu\nu} \tilde{G}^{\mu\nu}_a \theta$$

$G^a_{\mu\nu}$ – gluon field strength tensor
α_S - QCD equiv. of fine-structure constant
θ - angle determining the QCD vacuum

The parameter θ is unprescribed by the theory, it is expected to be $\theta \sim 1$. QCD interaction actually depends on θ through its difference with the **phase of the quark mass matrix** M_q:

$$\bar{\theta} = \theta - \arg\det M_q$$

PREDICTION:

-> electric dipole moment for hadrons $d_n \neq 0$
-> there should be CP violation in the strong sector

In particular for the **neutron**, by using QCD sum rules, one obtaines

$$d_n = (2.4 \pm 1.0)\bar{\theta}\times 10^{-16} \text{ e cm}$$

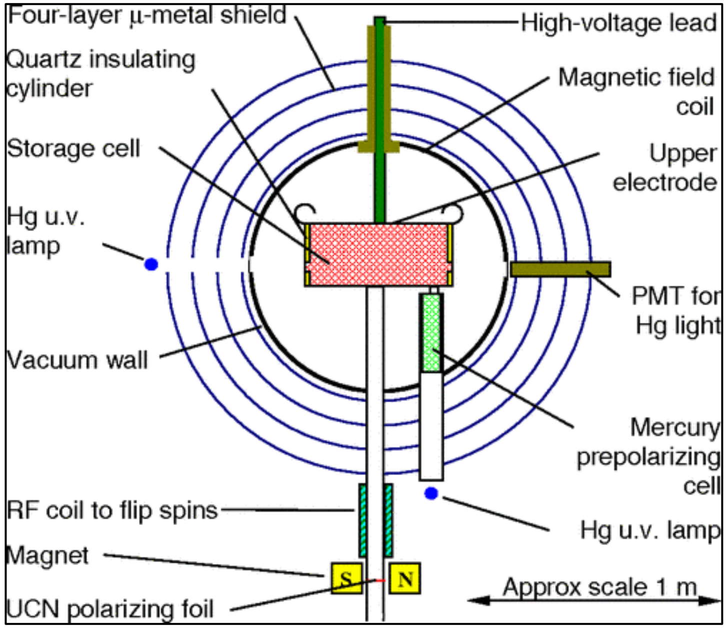
M.Pospelov,A.Ritz,NuclearPhys.B573(2000)177–200

The strong CP problem: neutron EDM

The most recent measurement of the **neutron EDM**, performed with Ultra Cold Neutrons

$$d_n^{\exp} < 3.0\times10^{-26}\ \mathrm{e\ cm}\ (90\%\ \mathrm{C.L.})$$

C.Baker, et al.,Phys.Rev.Lett.97(2006)131801
J.M.Pendlebury, et al., Phys.Rev. D92 (2015) 092003



$$\bar{\theta} < 1.3\times10^{-10}$$

Why so small?
This angle is the sum of two a priori arbitrary phases of unrelated origin.

THIS VERY FINE TUNING! → STRONG CP PROBLEM

- Different solutions proposed
- Among them for example one with one quark having zero mass
- Of course, it might be possible that, as a result of some anthropic reasons $\bar{\theta}$ just turns out to be of $O(10^{-10})$, but researcher doubt this…

Peccei Quinn solution

- Peccei and Quinn (1977) proposed to solve the strong CP problem by postulating the existence of a global $U_{PQ}(1)$ *quasi*-simmetry (it is spontaneously broken).
- The **axion *a*** (Weinberg 1978, Wilczeck 1978) is the **pseudo Goldstone boson** associated with the spontaneous breakdown of the PQ simmetry.
- With the PQ quasi-simmetry the fine tuning problem can be solved. In fact, the low energy effective theory of the axion has a term:

$$\mathcal{L}_a \supset -\frac{\alpha_S}{8\pi} G^a_{\mu\nu} \tilde{G}^{\mu\nu}_a \frac{a(x)}{f_a}$$

***a*(x) – axion field**
f_a – axion decay constant

$$\bar{\theta} = \theta - \arg\det M_q - \frac{a(x)}{f_a}$$

- 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

The “standard” 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 :

$$m_a f_a \approx m_\pi f_\pi$$

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

- The most recent calculation using lattice QCD

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

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

- **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 Models

1. 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 v_{weak}(250 GeV)

$m_a \approx 100$ keV → **RULED OUT BY ACCELERATOR EXPERIMENTS**

"Invisible" axion models (classes)

Dine-Fischler-Srednicki-Zhitnitskii (DFSZ)	**Kim-Shifman-Vainstein-Zakharov(KSVZ)**
M.Dine,W.Fischler,M.Srednicki,Phys.Lett.104B(1981)199 A.R.Zhitnitsky,Sov.J.Nucl.Phys.31(1980)260	J.E.Kim,PRL43(1979)103 M.A.Shifman,A.I.Vainshtein,V.I.Zakharov,NPB166(1980)493
• 2 extra Higgs doublets • New complex scalar	• New extra heavy quark • New complex scalar

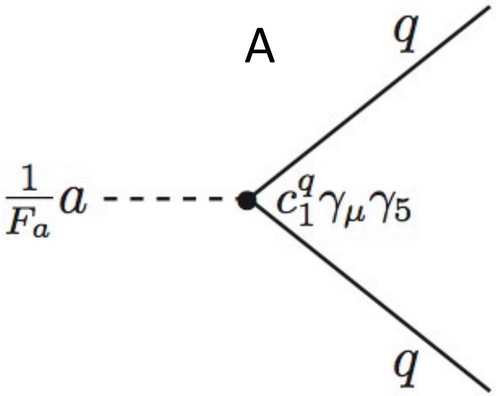
- For this models no prescription for f_a, hence
  - **low mass (m_a < eV)** and **very weak couplings** for $f_a \gg v_{weak}$
- The strength of the axion interaction depends on the assignment of the $U_{PQ}(1)$ charge to quarks and leptons (model dependent)
- **Models list not exhaustive**, axions can be embedded in SUSY or GUT

Axion interactions

- Several interactions are possible

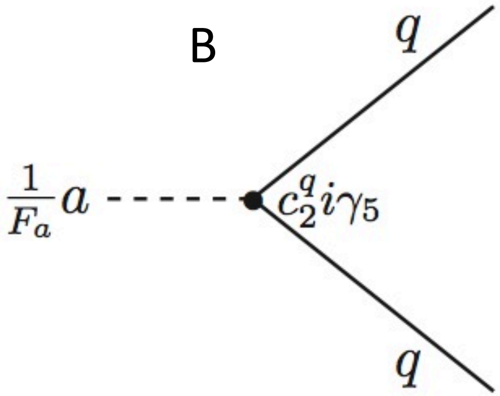
Quark

A



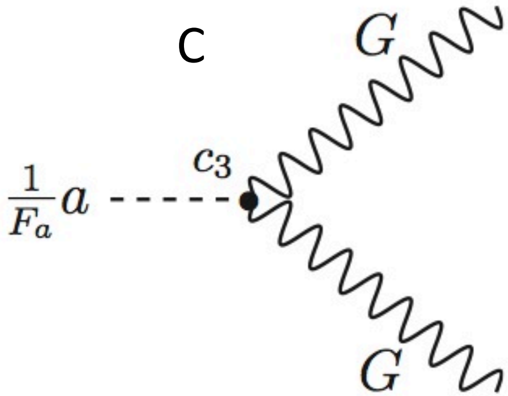
Quark

B



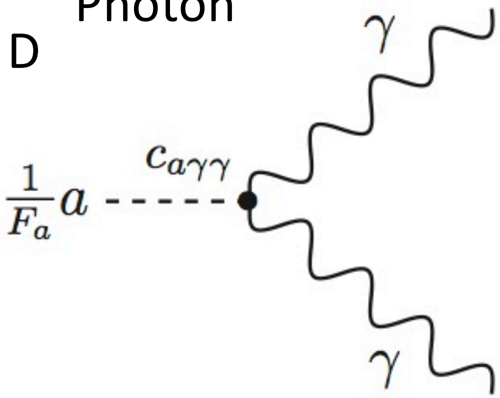
Gluon

C



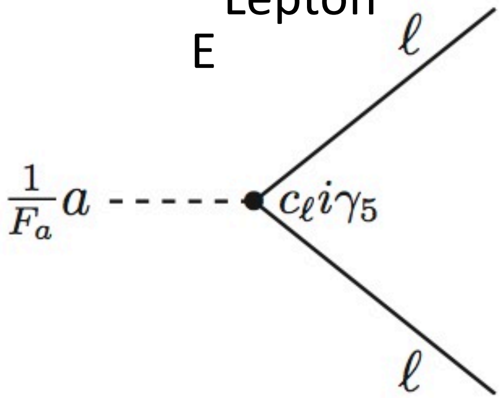
Photon

D



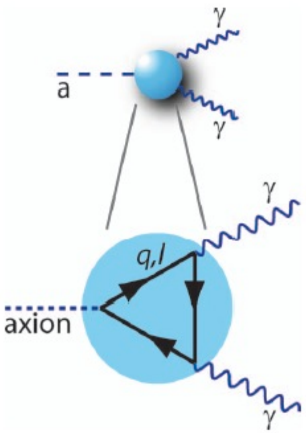
Lepton

E



Axion interactions 2

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



Axion photon photon

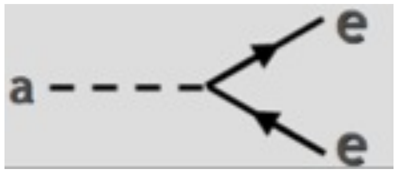
$$\mathcal{L}_{a\gamma\gamma} = -\left(\frac{\alpha}{\pi}\frac{g_\gamma}{f_a}\right) a\vec{E}\cdot\vec{B} = -g_{a\gamma\gamma} a\vec{E}\cdot\vec{B}$$

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

g_γ = 0.36 (DFSZ)

g_γ = - 0.97 (KSVZ)

Axion electron electron



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

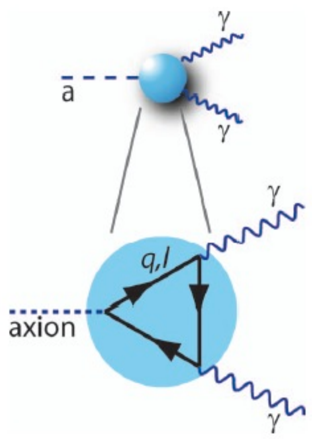
$$g_e \approx \frac{m_a m_e}{m_\pi f_\pi} = 4.07\times 10^{-11} m_a$$ **(DFSZ)**

g_e ~ 0 (Strongly suppressed) (KSVZ)

All couplings are extremely weak!

Axion interactions 3

- Axion interactions are 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

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

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

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.

Does the axion exist?

- The standard Peccei Quinn Weinberg Wilczeck (PQWW) axion was soon ruled out in beam dump experiments

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.

- However, the other “invisible” **axion (DFSZ, KSVZ) continues to evade all current experimental searches**

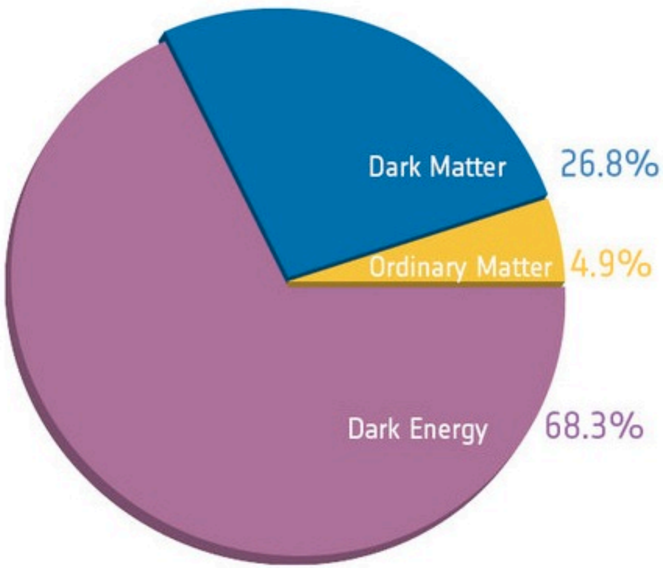
- Its phenomenology is determined by its **low mass** and **very weak interactions**
  - could affect **cosmology**
  - could affect **stellar evolution**
  - could mediate **new long range forces**
  - could be **produced in terrestrial laboratory**
  - could be a main component of **Dark Matter**

Axions in the outer space

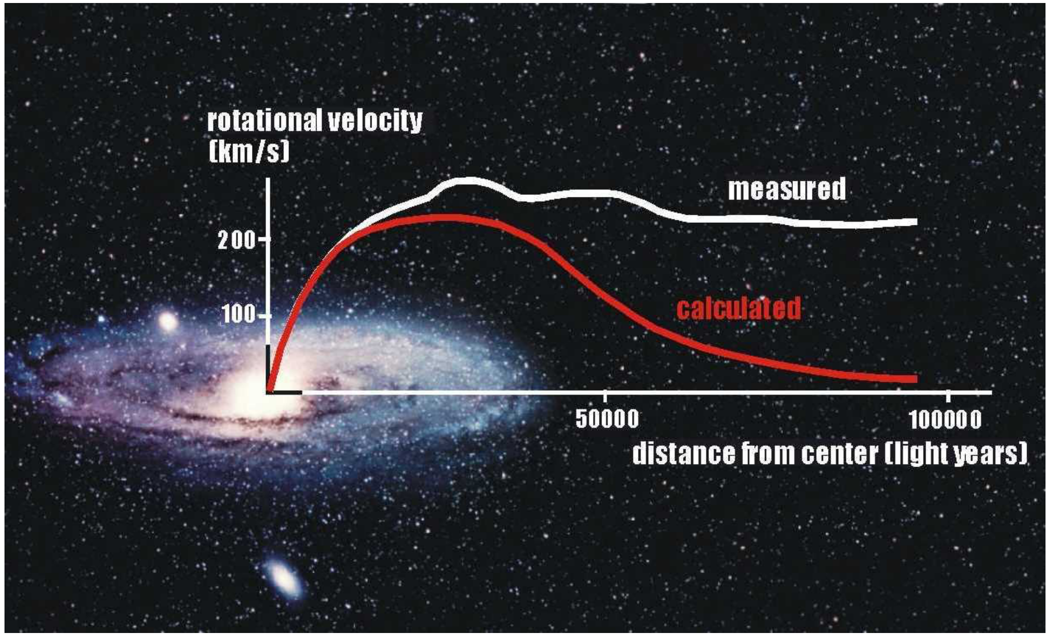
- As we have seen a **light axion** (m_a < eV) has lifetime that can be longer than the age of the Universe. This kind of axion is indeed important for cosmology.
- **Is it a main component of Dark Matter?**

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

Composition of the Universe after Planck precise measurement of CMB



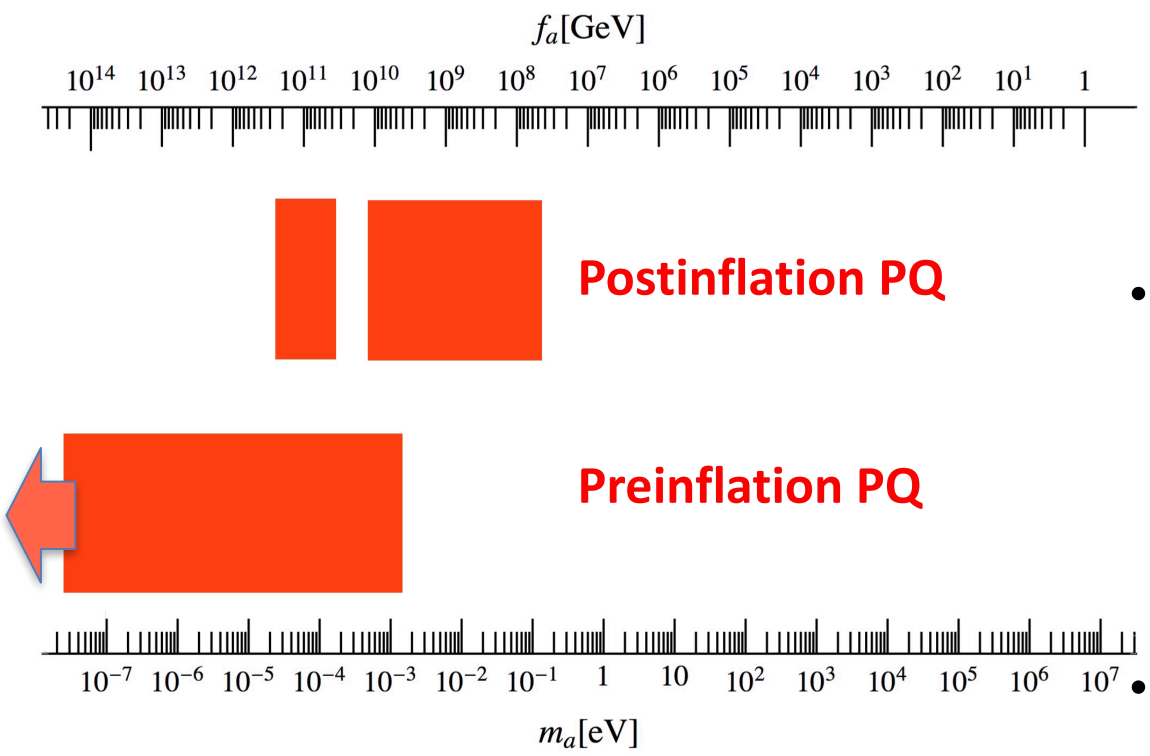
Typical rotational curve of galaxys



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

Cosmological axion

- In the early universe axions are produced by processes involving quarks and gluons -> **hot dark matter (BAD)**
- More, axions produced by the *vacuum realignment mechanism*: relaxation of the axion field after breakdown of the PQ simmetry → **Cold dark matter (GOOD)**
- The expected cosmic mass density of axions depends on whether inflation happens after or before PQ breakdown



Allowed regions of mass/decay constant

- This 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

Axions in the galactic halo

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

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

- 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

$$n_a \approx 3\times10^{14}\left(\frac{10^{-6}\ eV}{m_a}\right) \quad \text{axions/cm}^3$$

- 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**

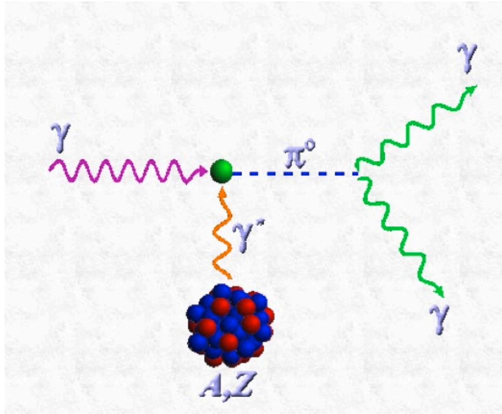
$$\lambda = 1400\left(\frac{10^{-6}\ eV}{m_a}\right)\ \text{m}$$

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

Can we detect axions?

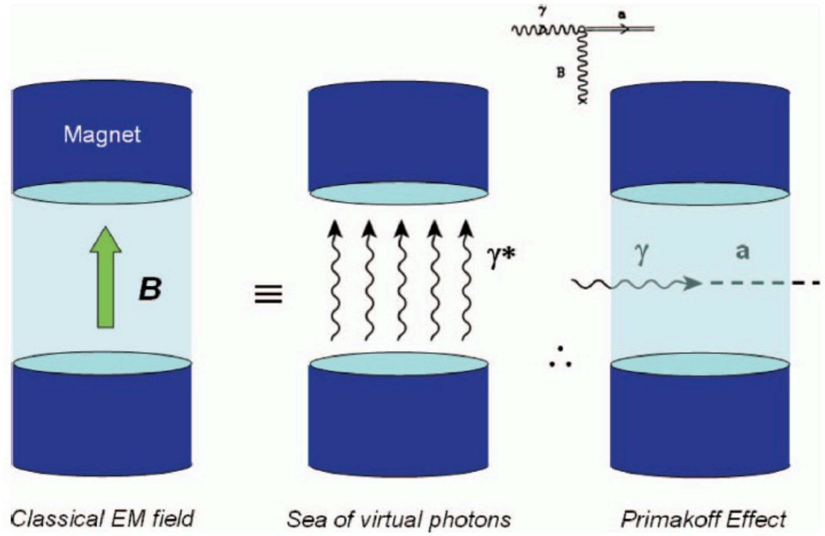
- Searching for axion extremely challenging
- Exploit coherence effect over macroscopic distance/long times
- Most promising approach: use axion-photon-photon vertex

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**

Higher magnetic field are easily obtainable than electric fields



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

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

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

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

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 ALPs that solves the strong CP problem**

WISPs

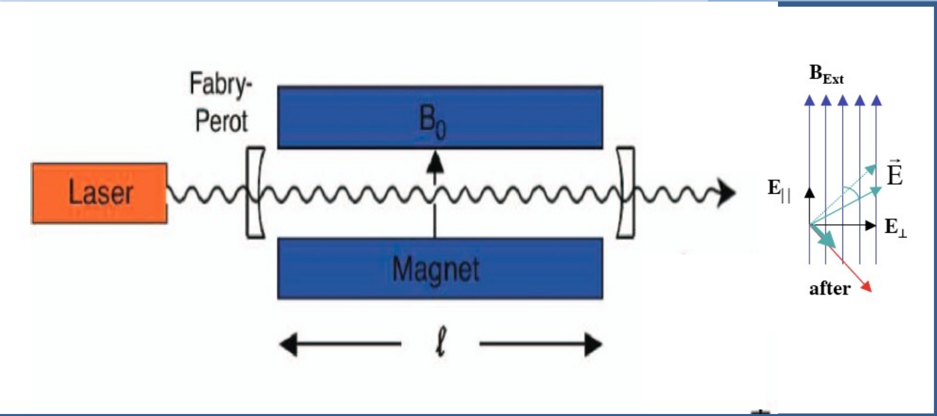
- **W**eakly **I**nteracting **S**lim **P**articles include a much wider lists:
  - Axion and Axion Like Particles
  - Hidden Photons
  - Milli Charged Particles
  - Chameleons, massive gravity scalars
- Many of the share properties of the axion, and in principle could be searched for by the experiments 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**

Detection schemes

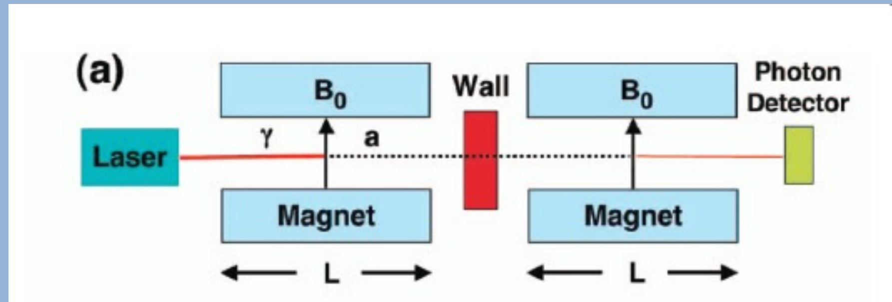
- Most of the searches based on the **axion-photon coupling**

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

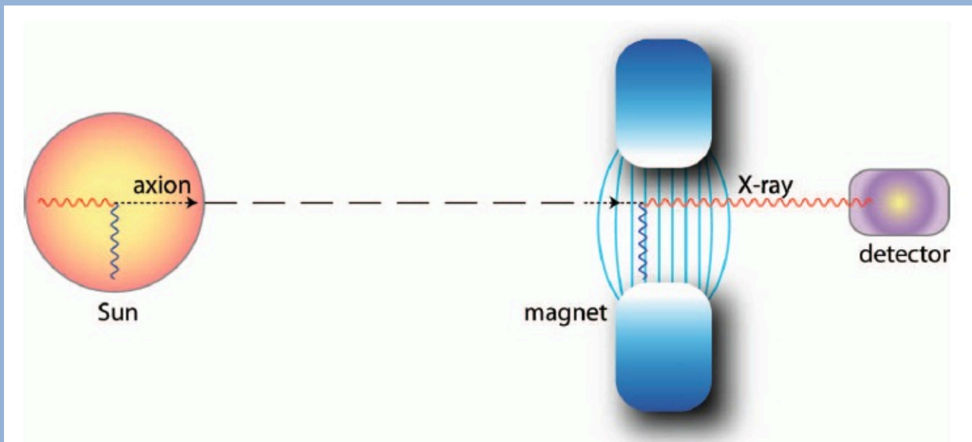
Polarization experiments



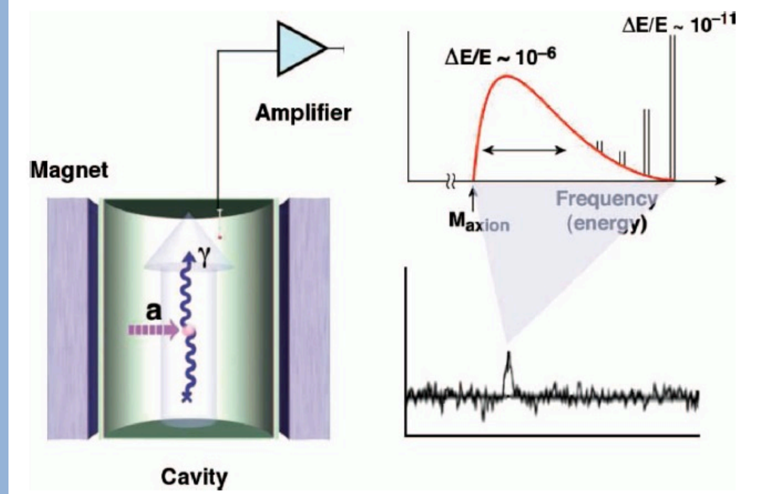
Light shining through walls



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



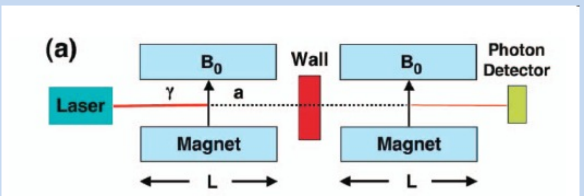
C **Detection of axions present into the Galactic Halo -**

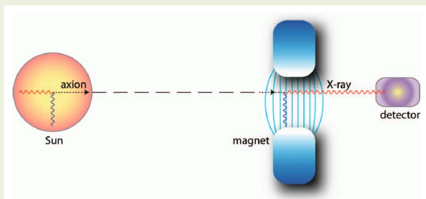


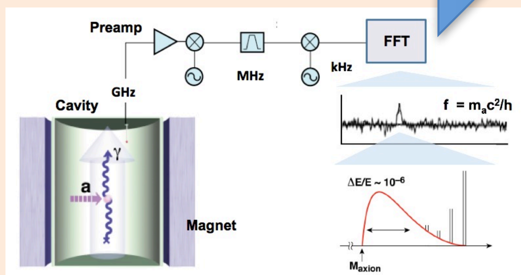
All pictures from: G. Carosi et al, Contemp. Phys. 49, 281 (2008)

Comparison

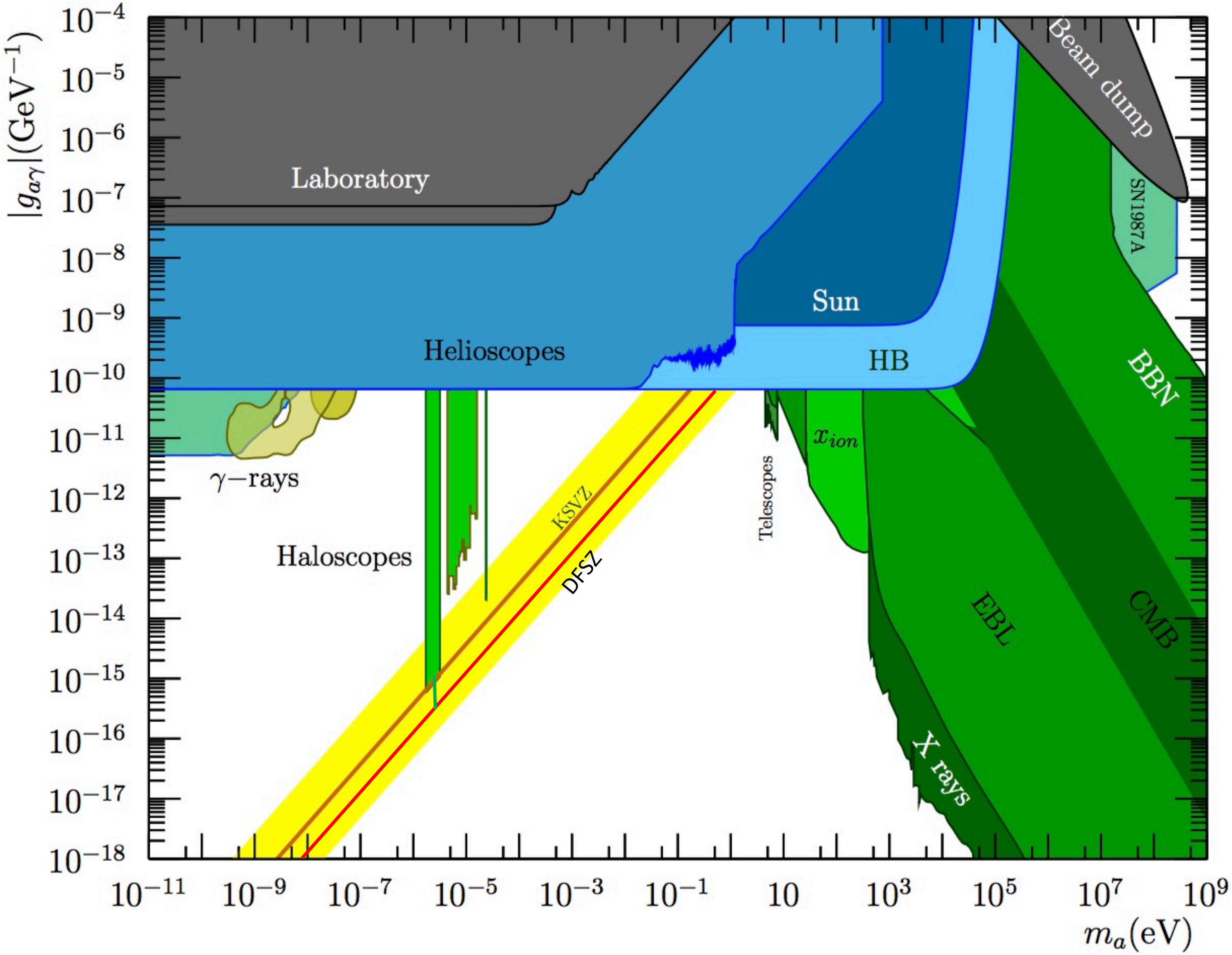
Lab Experiments	Helioscopes	Haloscopes
Axion Like Particle	ALPS & QCD Axion	ALPS & **QCD Axion**
Wide band experiment	Wide band experiment	Resonance experiment
Optical photons	X rays photons	Microwave photons
Model independent	Model dependent	Strong model dependency
Low axion flux	Medium axion flux	High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







Current constraints for ALPs: photon coupling



A. LABORATORY RESULTS

B. HELIOSCOPES / STELLAR PHSYICS

C. HALOSCOPES / COSMOLOGY

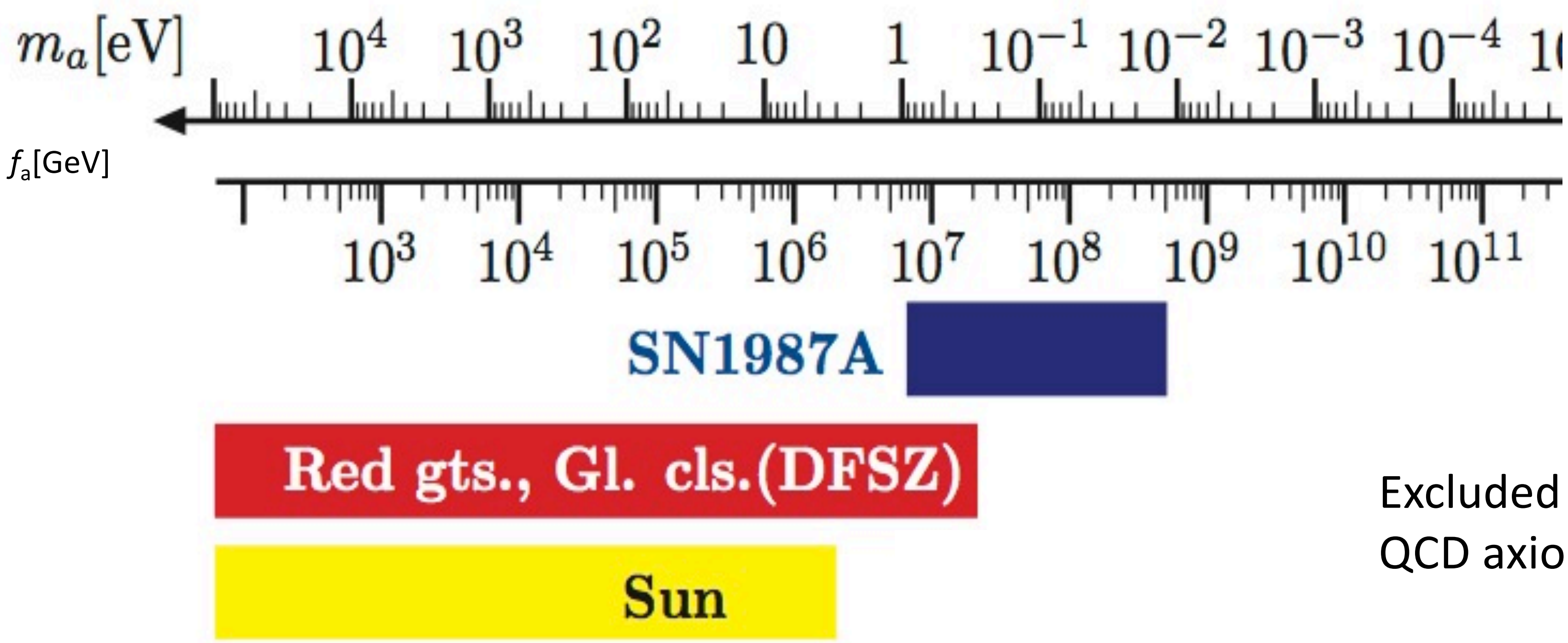
D. HINTED REGIONS

E. QCD AXION BAND

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

Axion and stars

- Axions have very small masses and therefore **can be emitted without important threshold effects from stars**, in analogy to neutrinos
- The method to constrain axion models is basically the overall **energy loss rate**
- We may use the **axion couplings to γ, p, n, and e to study the core evolution of a star**. Simple bounds, for example, are obtained by comparing the energy loss rates by axion and by neutrino emission



Excluded region of QCD axion mass

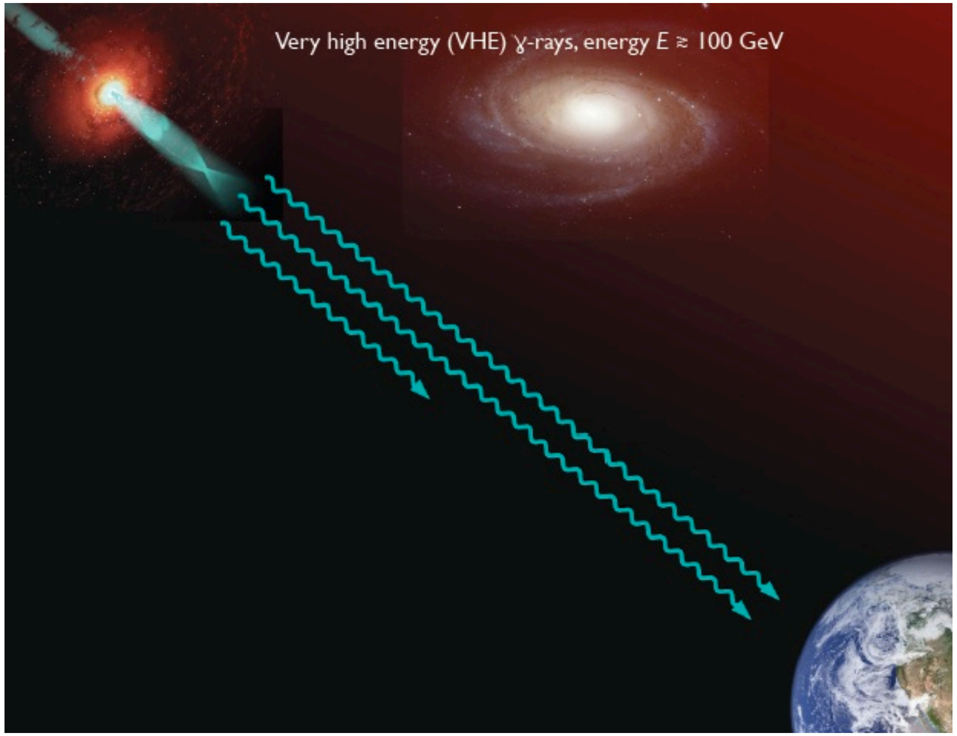
- In some cases the fit of stellar data improves with some axion cooling → these are considered **hints of the axion existence**

Propagation of the photon in the cosmo

- Magnetically induced oscillations between photons and Axion-like particles can **modify the photon flux from distant sources**, featuring:
  - Frequency dependent dimming
  - Modified polarization
  - **Avoiding absorption by propagation in the form of axion**

This modification can be crucial in the behavior of Very High Energy (VHE, energy > 100 GeV) γ **rays from extragalactic sources**

Typical sources: Active Galactic Nuclei (**AGN**) measured with Imaging Air Cherenkov Detector (**IACT**)



Astrophysical bounds and hints – recent updates

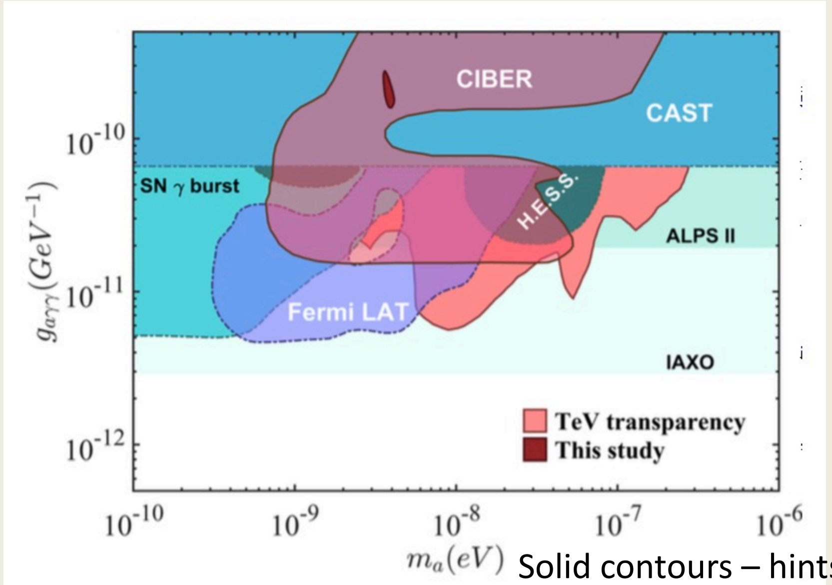
Journal of Cosmology and Astroparticle Physics
An IOP and SISSA journal

Search for gamma-ray spectral modulations in Galactic pulsars

Jhilik Majumdar,[a] Francesca Calore[b] and Dieter Horns[a]

 https://doi.org/10.1088/1475-7516/2018/04/048

significance of 4.6 σ. We determine the most-likely values for mass m_a and coupling $g_{a\gamma\gamma}$ to be $m_a = (3.6^{+0.5}_{-0.2}{}_{\text{stat.}} \pm 0.2_{\text{syst.}})$ neV and $g_{a\gamma\gamma} = (2.3^{+0.3}_{-0.4}{}_{\text{stat.}} \pm 0.4_{\text{syst.}}) \times 10^{-10}$ GeV^{-1}. In the error



Solid contours – hints
Dotted contours - limits

PHYSICAL REVIEW D 97, 063003 (2018)

Searching for spectral oscillations due to photon-axionlike particle conversion using the Fermi-LAT observations of bright supernova remnants

Zi-Qing Xia,[1,2] Cun Zhang,[1,3] Yun-Feng Liang,[1,*] Lei Feng,[1,†] Qiang Yuan,[1,2,‡] Yi-Zhong Fan,[1,2,§] and Jian Wu[1,2]

However, the best-fit parameters of ALPs ($m_a = 6.6$ neV, $g_{a\gamma} = 13.4 \times 10^{-11}$ GeV^{-1}) are in tension with the upper bound ($g_{a\gamma} < 6.6 \times 10^{-11}$ GeV^{-1}) set by the CAST experiment. It is difficult to explain the

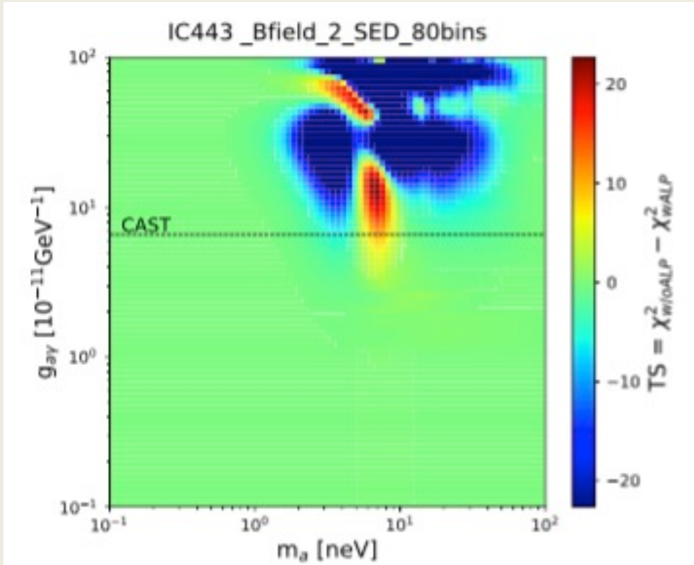
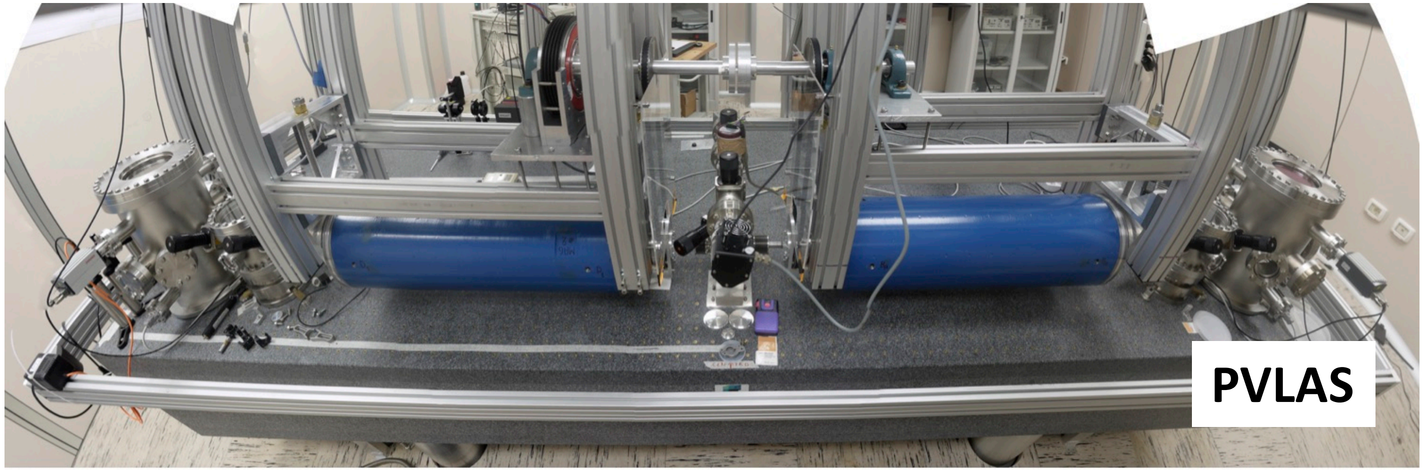


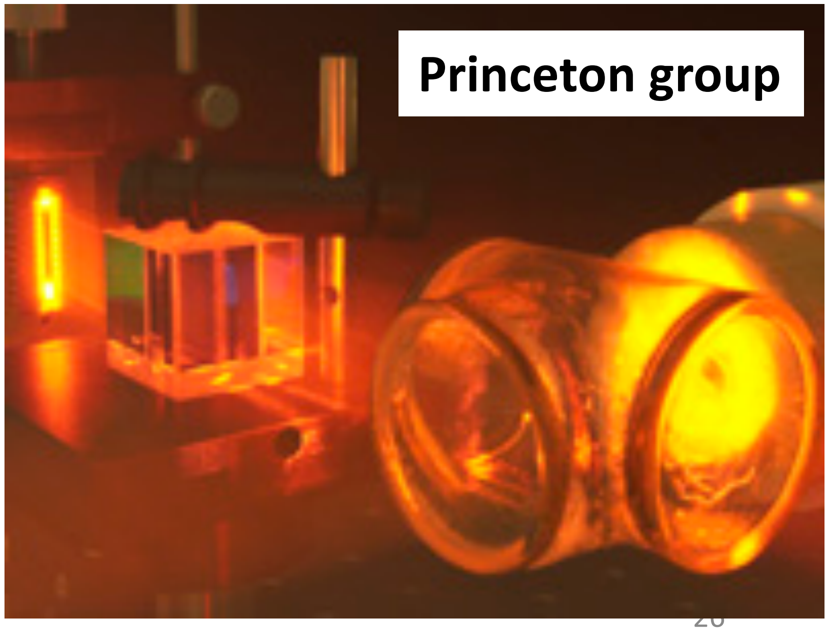
FIG. 4. The TS value as a function of ALP mass m_a photon-ALP coupling constant $g_{a\gamma}$ for IC443 with 80 energy bins, for the case of Bfield2.

[A] Pure laboratory experiments

Polarization experiments



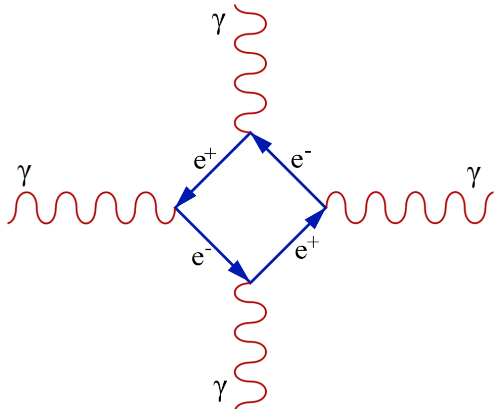
Fifth force measurements



Light shining through walls

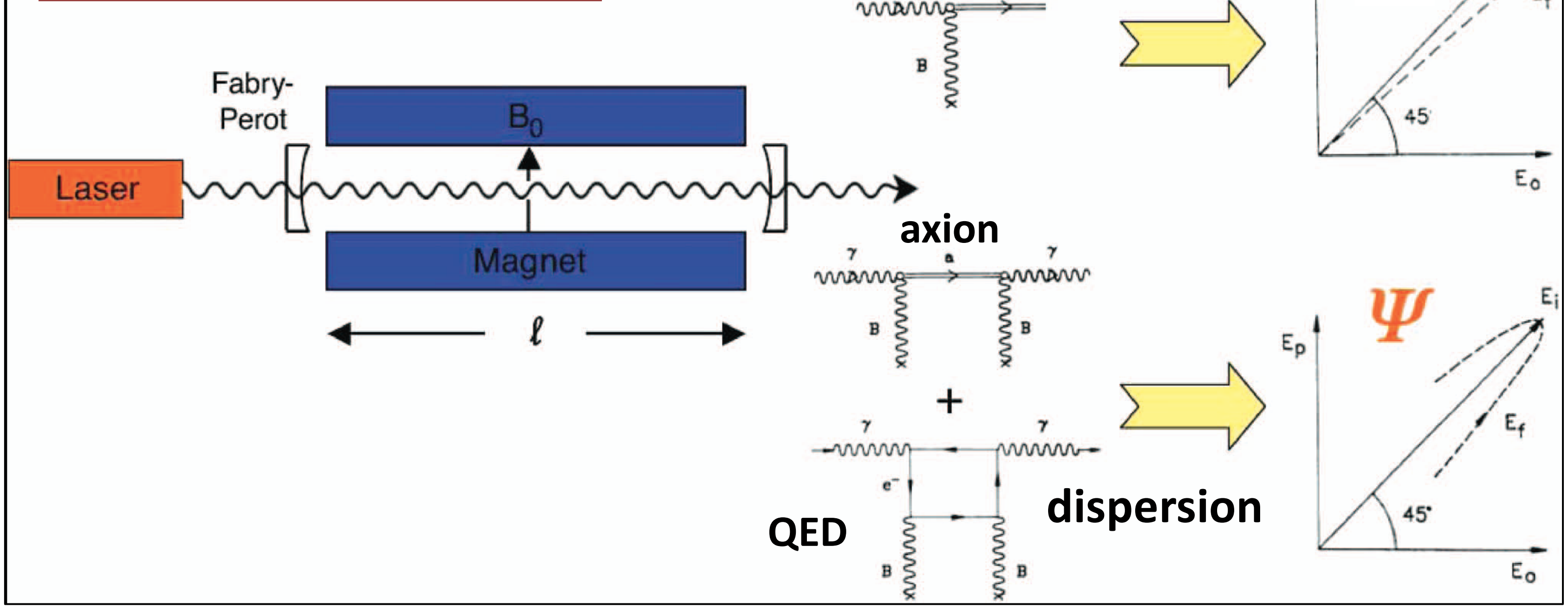
[A.1] Pure lab: Polarization experiments

- 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

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

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

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

Measured effects | **Relation with axion parameters**

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

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

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

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 measurements 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

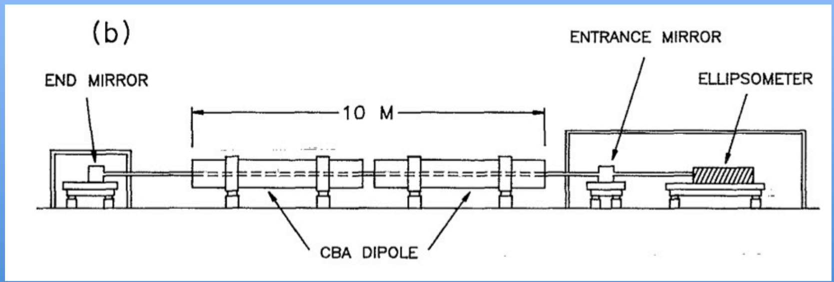
Peak sensitivity depends on magnet length *L*

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

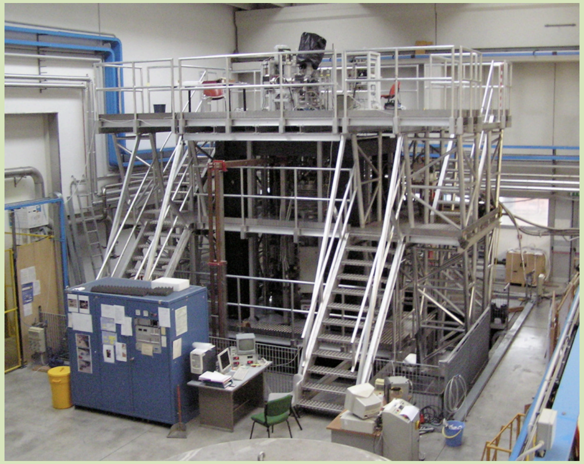
Polarization experiments apparatuses

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

Multipass cavity
N ~ 500



PVLAS @ Legnaro (1992 – 2008)



Fabry-Perot
N ~ 50 000

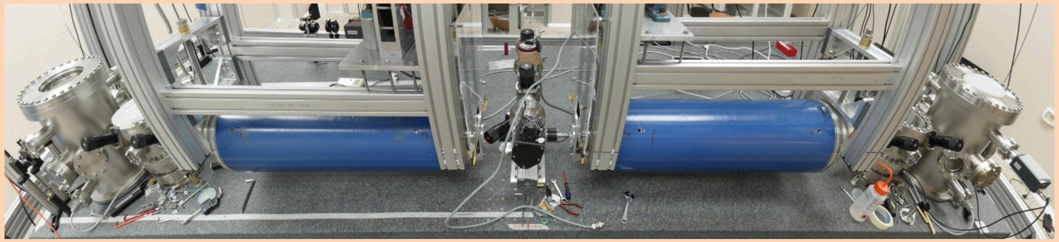
5 T
Rotating Super-conducting Magnet

BMV @ Toulouse (going on)

Fabry Perot
N ~ 300k

Pulsed Magnets

PVLAS @ Ferrara (going on)
Rotating permanent magnets
Fabry Perot N ~ 500k

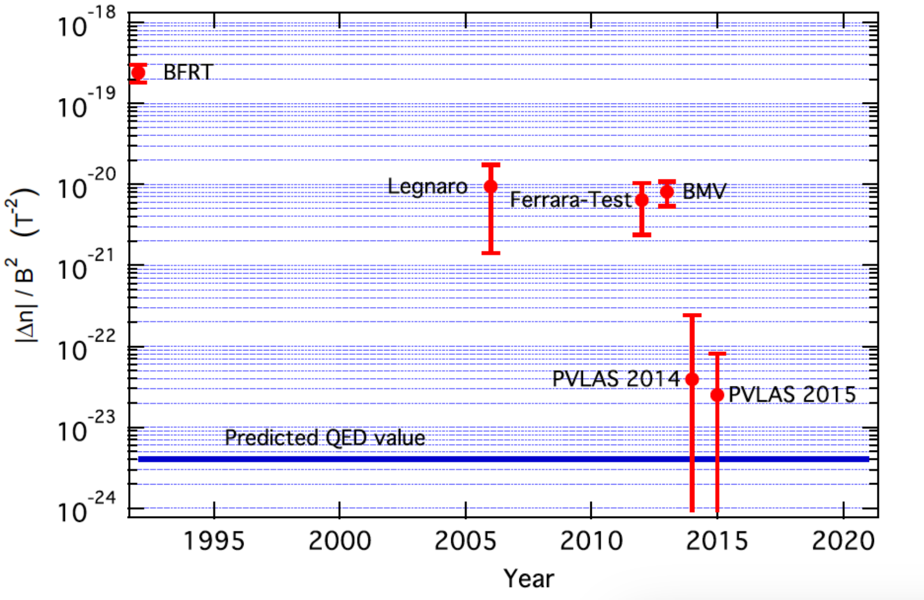


Other apparatuses: **Q&A (Taiwan), OSQAR (CERN)**

PVLAS @ Ferrara

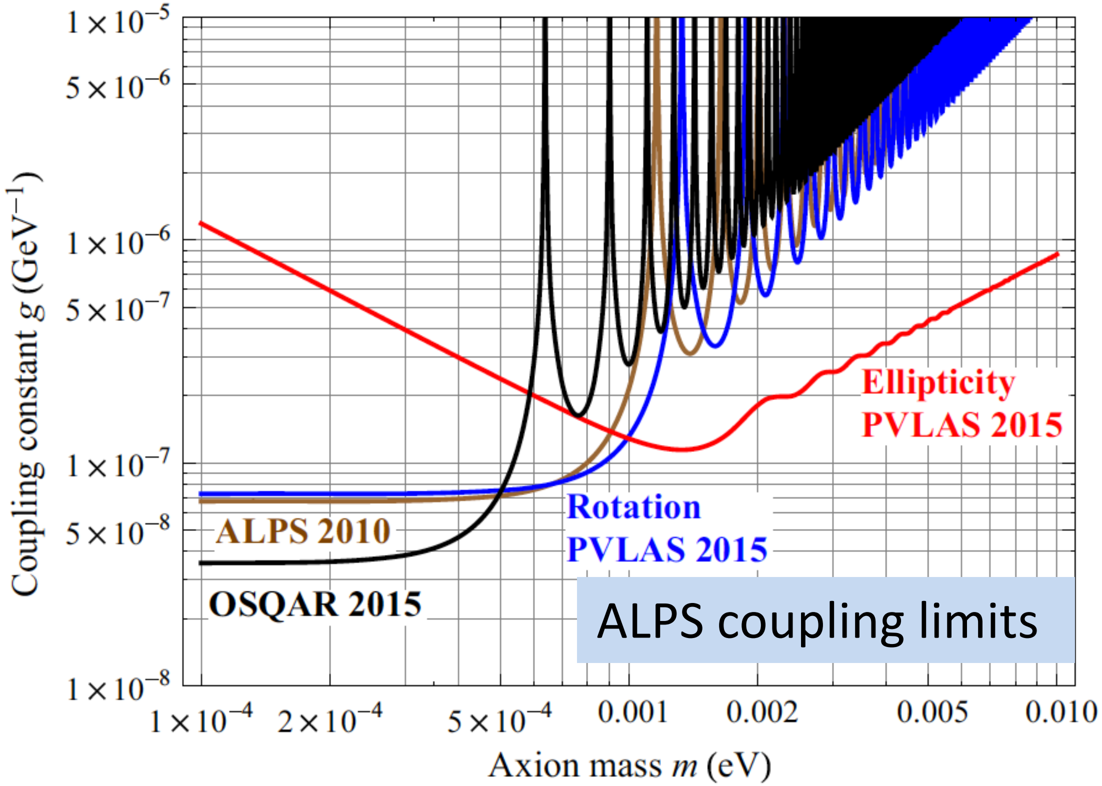
- A **new redesigned apparatus** with respect to Legnaro
- Based on **two permanent magnet 1-m long, 2.5 T** rotating up to **10 Hz** (reduced 1/f noise)
- **Ultra high finesse optical cavity: L = 3.3 m ; F = 770 000**
- Optics suspended on a **single granite optical table 4.8 m long**

Final results



$$\Delta n^{(\mathrm{PVLAS})} = (-1.5 \pm 3.0) \times 10^{-22} \quad @\ B = 2.5\ \mathrm{T}$$

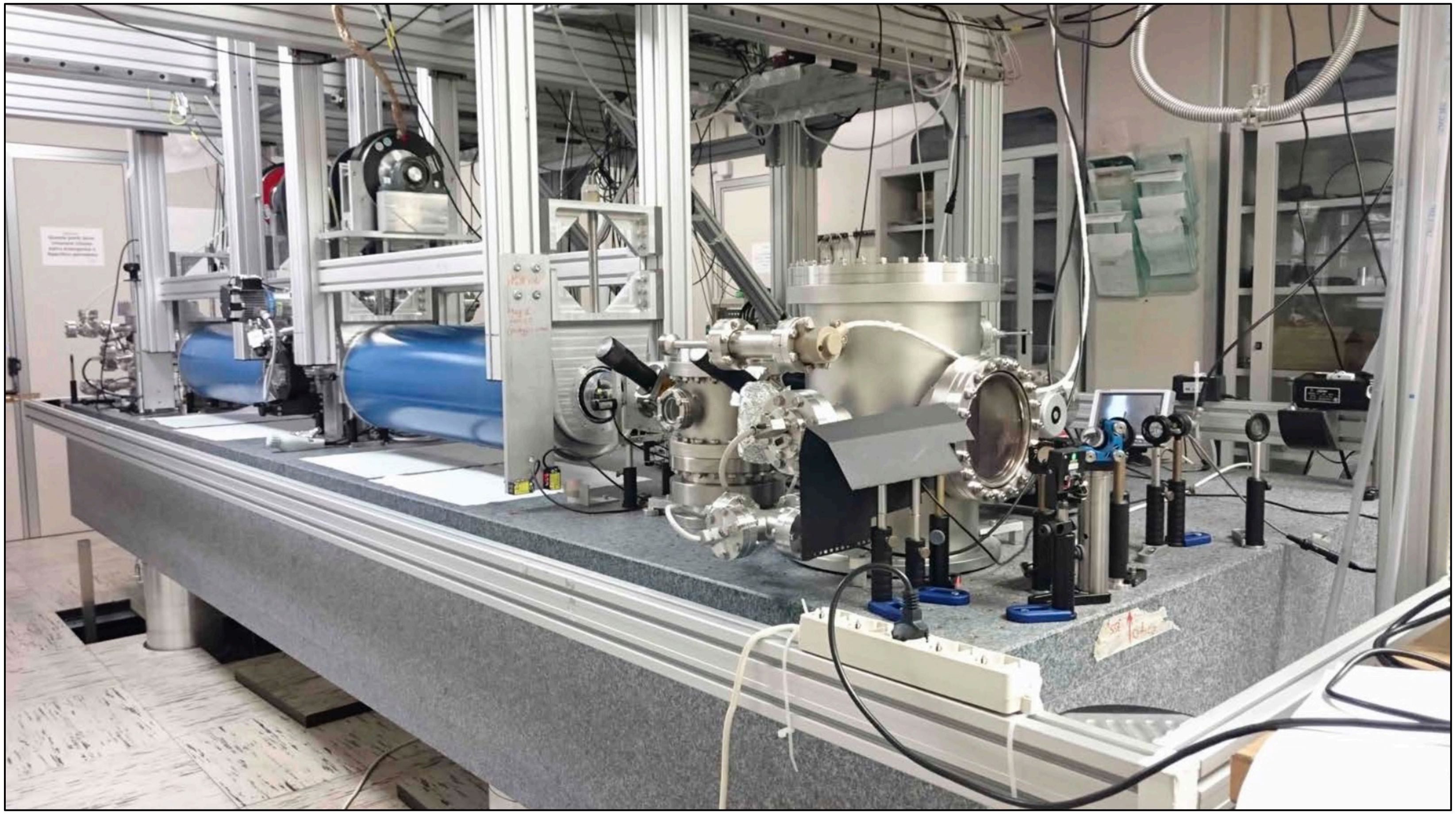
$$\Delta \kappa^{(\mathrm{PVLAS})} = (-1.6 \pm 3.5) \times 10^{-22} \quad @\ B = 2.5\ \mathrm{T}$$



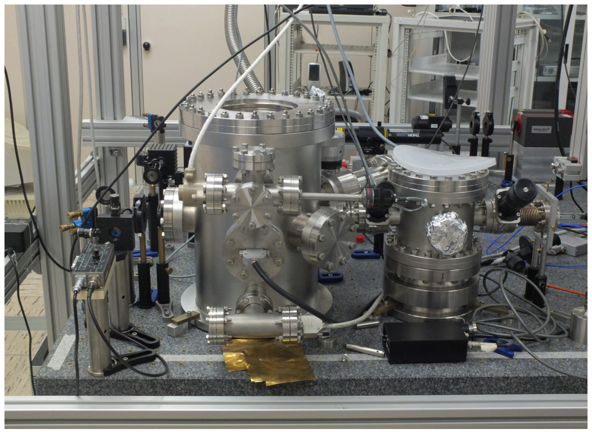
ALPS coupling limits

Next steps:
- R&D to increase sensitivity
- New apparatus @ CERN

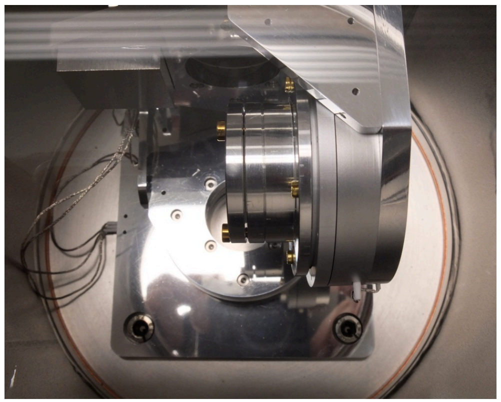
PVLAS @ Ferrara



Complete apparatus



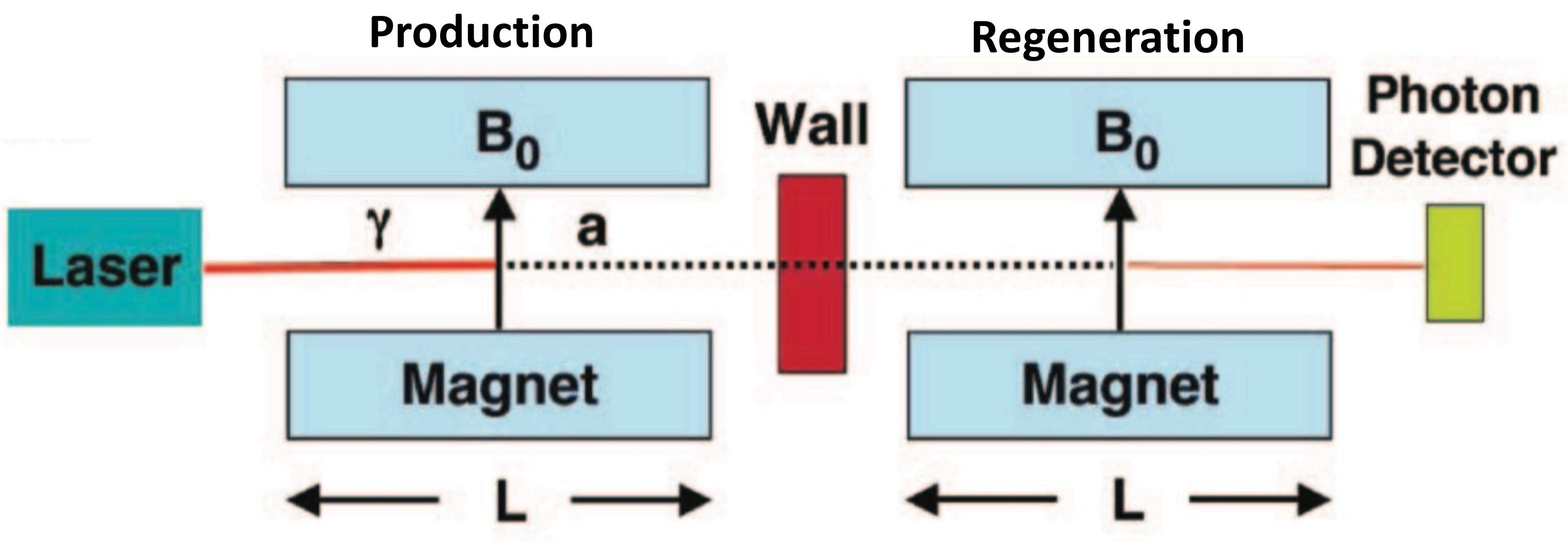
Vacuum chambers



Movable mirror holder

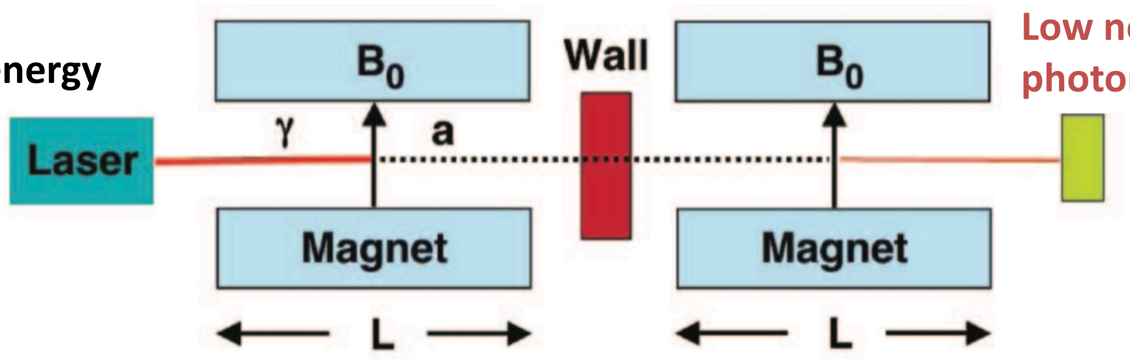
[A.2] Pure lab: light shining through walls (LSW)

- **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



Conversion probability in a magnet

$$\Pi = \frac{1}{4}\left(g_{a\gamma\gamma}B_0L\right)^2\left|\frac{\sin x}{x}\right|^2 \approx \frac{1}{4}\left(g_{a\gamma\gamma}B_0L\right)^2$$

Coherent process

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

Phase difference between axion and photon fields

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

Total probability

$$P(\gamma \rightarrow a \rightarrow y) = \Pi^2 \propto g_{a\gamma\gamma}^4$$

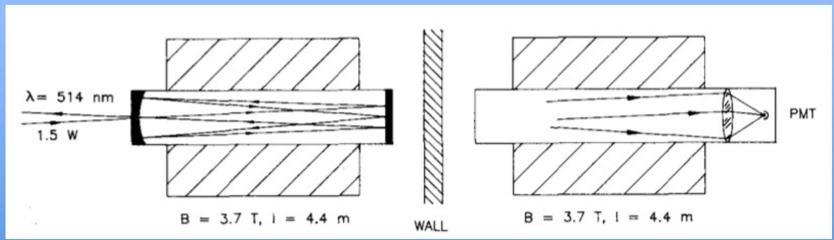
Figure of merit

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

- **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

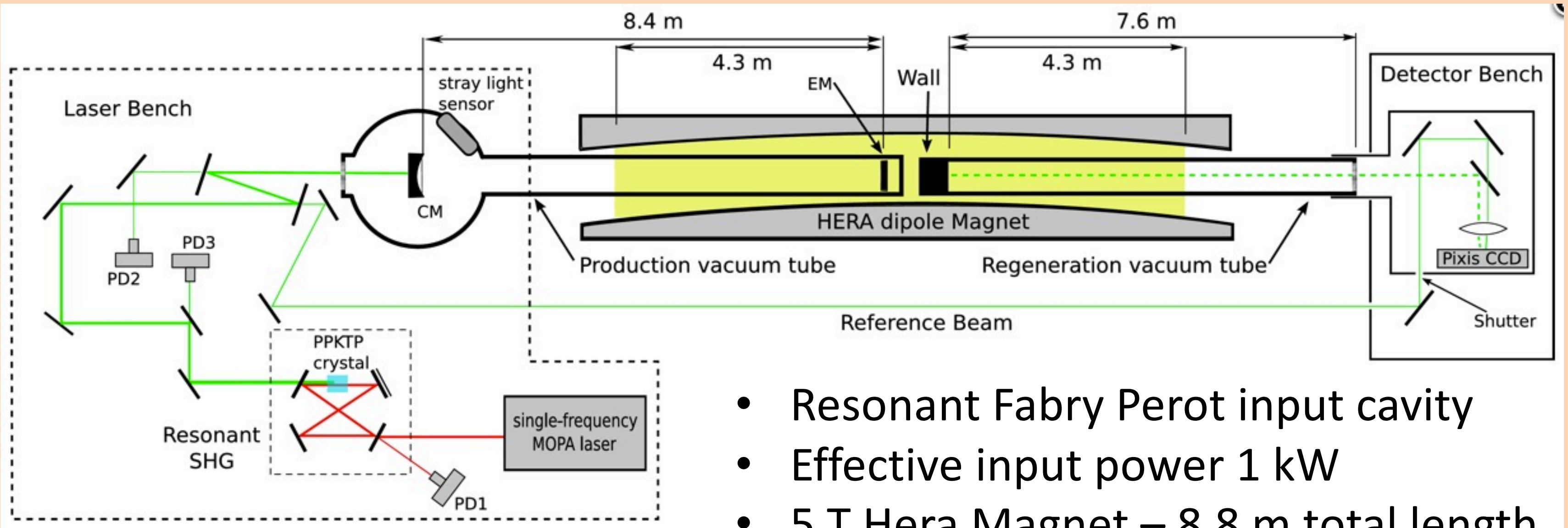
Spare LHC Dipoles

9 T over 14.3 m

20 W cw Laser

State of the art CCD detector

ALPS I experiment @ DESY



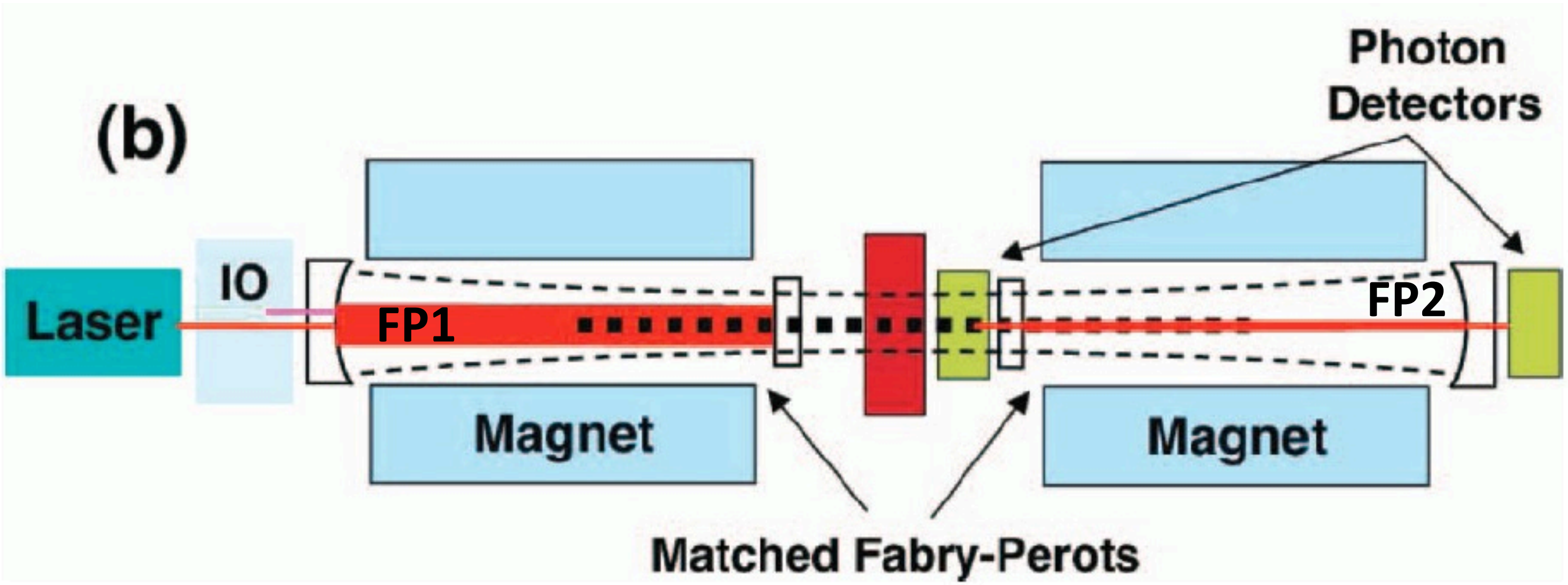
- Resonant Fabry Perot input cavity
- Effective input power 1 kW
- 5 T Hera Magnet – 8.8 m total length
- CCD detector

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**



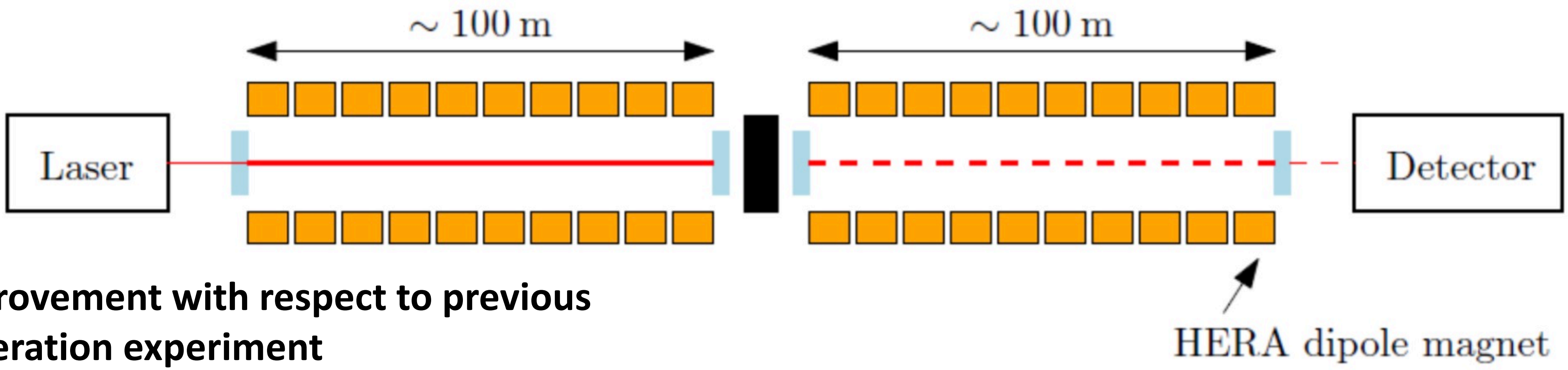
$$\mathrm{sens}(g_{a\gamma\gamma}) \propto \frac{1}{BL} \frac{\omega}{P^{1/4}(F_1 F_2)^{1/4}} \frac{N^{1/8}}{t^{1/8}}$$

- 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

- **100 + 100 m resonant Fabry Perot cavities**
- **10 + 10 High magnetic field HERA magnets**
- **Transition Edge low noise sensor (or optical heterodyning)**

Resonant LSW: ALPS II @ DESY

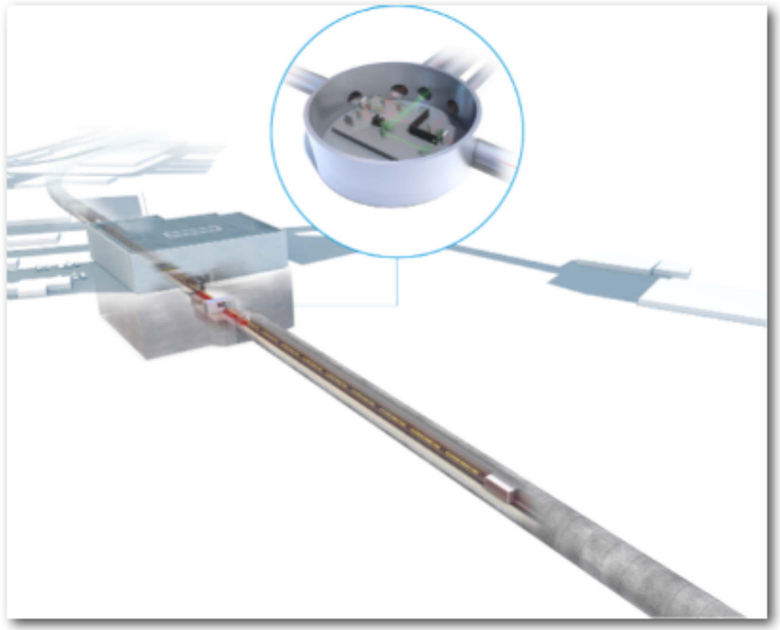


Improvement with respect to previous generation experiment

Parameter	Scaling	ALPS-I	ALPS-IIc	Sens. gain
Effective laser power P_{laser}	$g_{a\gamma} \propto P_{\mathrm{laser}}^{-1/4}$	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	$g_{a\gamma} \propto DC^{1/8}$	$0.0018\,\mathrm{s}^{-1}$	$0.000001\,\mathrm{s}^{-1}$	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



How ALPS II will stay in the Hera Tunnel

ALPS II: status / progress

Many progresses going on:
- **Magnets straightening**
- **Optics – cavities locking, effective point of reflection**
- **Detectors**

Optical set-up: 10 m long cavities

	Requirement	Status
PC circulating power	150 kW	50 kW
RC power buildup factor	40,000	23,000
CBB mirror alignment	< 5 µrad	< 1 µrad
Spatial overlap	> 95%	work ongoing
RC length stabilization	< 0.5 pm	< 0.3 pm

Likely related to mirror properties.
New mirrors are ordered.

University of Florida:

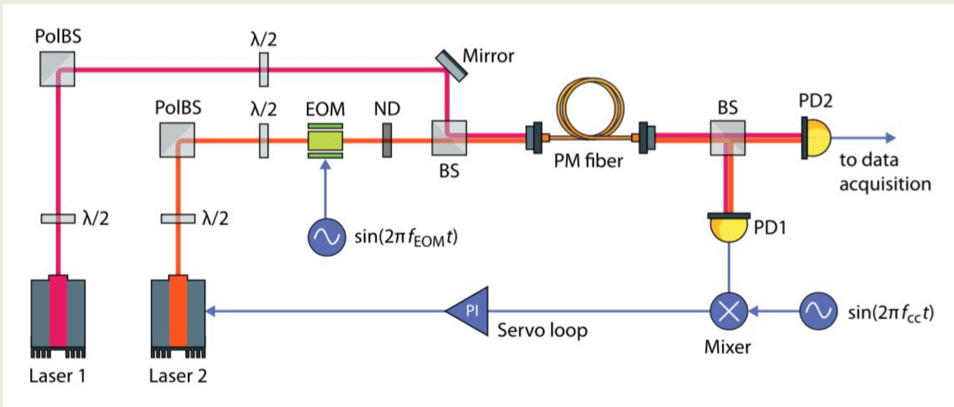
> Heterodyne detection scheme.

> **About mHz photon rate detected.**

PHYSICAL REVIEW D **99,** 022001 (2019)

Coherent detection of ultraweak electromagnetic fields

Zachary R. Bush,[1] Simon Barke,[1] Harold Hollis,[1] Aaron D. Spector,[2] Ayman Hallal,[1] Giuseppe Messineo,[1] D. B. Tanner,[1] and Guido Mueller[1]
[1]*Department of Physics, University of Florida, P.O. Box 118440, Gainesville, Florida 32611, USA*
[2]*Deutsches Elektronen-Synchrotron (DESY), Notkestrae 85, D-22607 Hamburg, Germany*



ALPS II @ DESY

ALPS II main components: magnets from HERA

- 10+10 dipoles from HERA, each 5.3 T on 8.8 m.
- To be straightened to achieve ≈ 50 mm aperture.
- **All magnets straightened successfully**

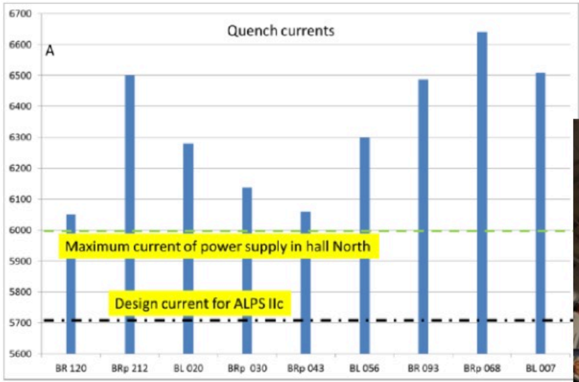


Figure 6.1: Obtained quench currents of straightened HERA dipoles

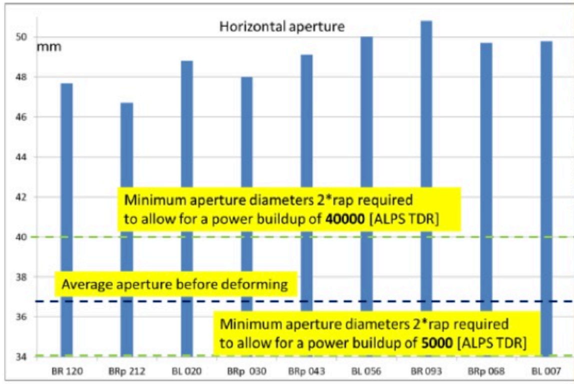
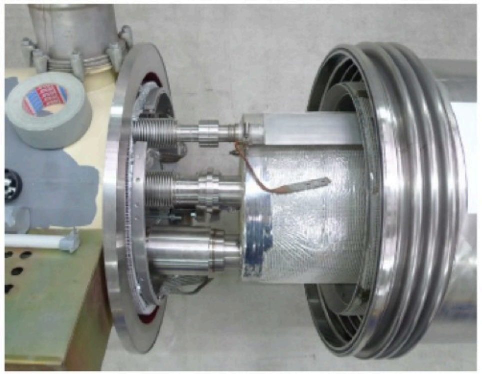


Figure 6.2: Horizontal aperture of HERA dipoles after straightening



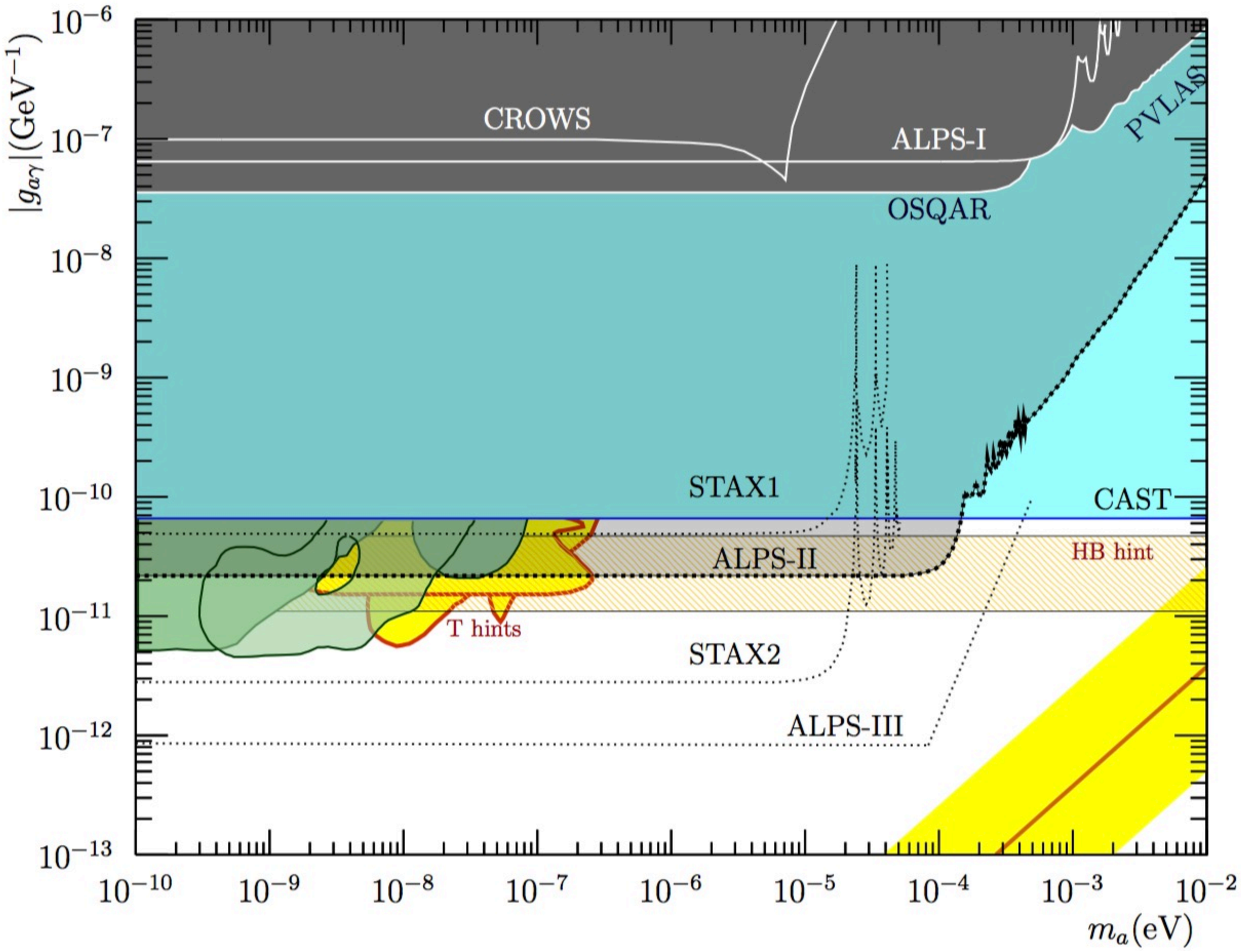
HELMHOLTZ SPITZENFORSCHUNG FÜR GROSSE HERAUSFORDERUNGEN

Axel Lindner | Status of ALPS II | CERN PBC, June 2018 | Page 4

Aiming for data taking in 2020

Pure Lab: results and perspectives

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



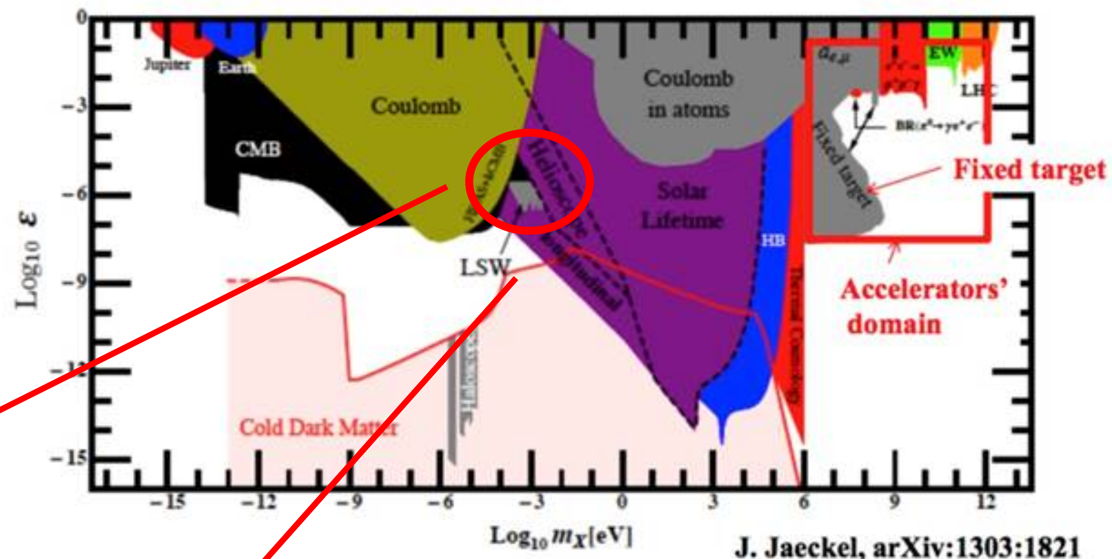
- None of these experiments capable of exploring the QCD axion model
- They set exclusion regions for Axion Like Particles coupling in a truly independent manner
- ALPS II will increase physics reach by several orders of magnitude, exploring regions where hints are present

Hidden photons

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

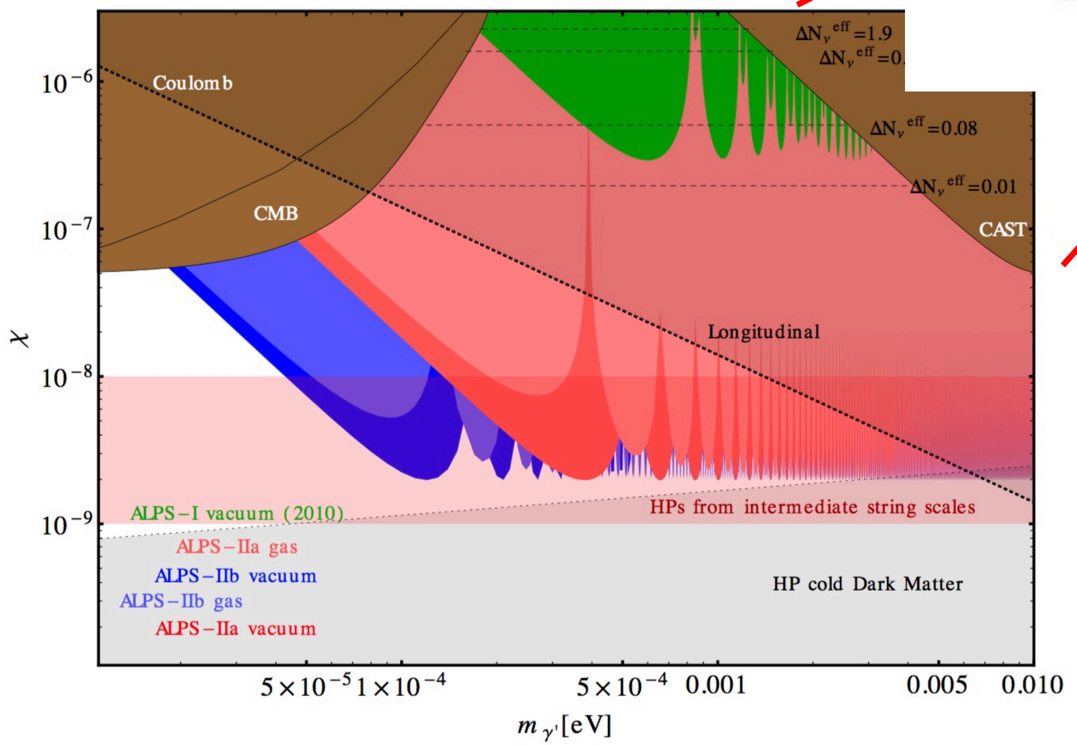
- Sensitivity in the low mass region due to coherence: $m_{\gamma'} \approx 1$ meV

Limits on the kinetic mixing of a hidden photon -ordinary photon: expanded scale



J. Jaeckel, arXiv:1303:1821

From ALPS-II TDR



- Hidden photon measurements does not need magnetic field

- Little improvements expected after ALPS-II

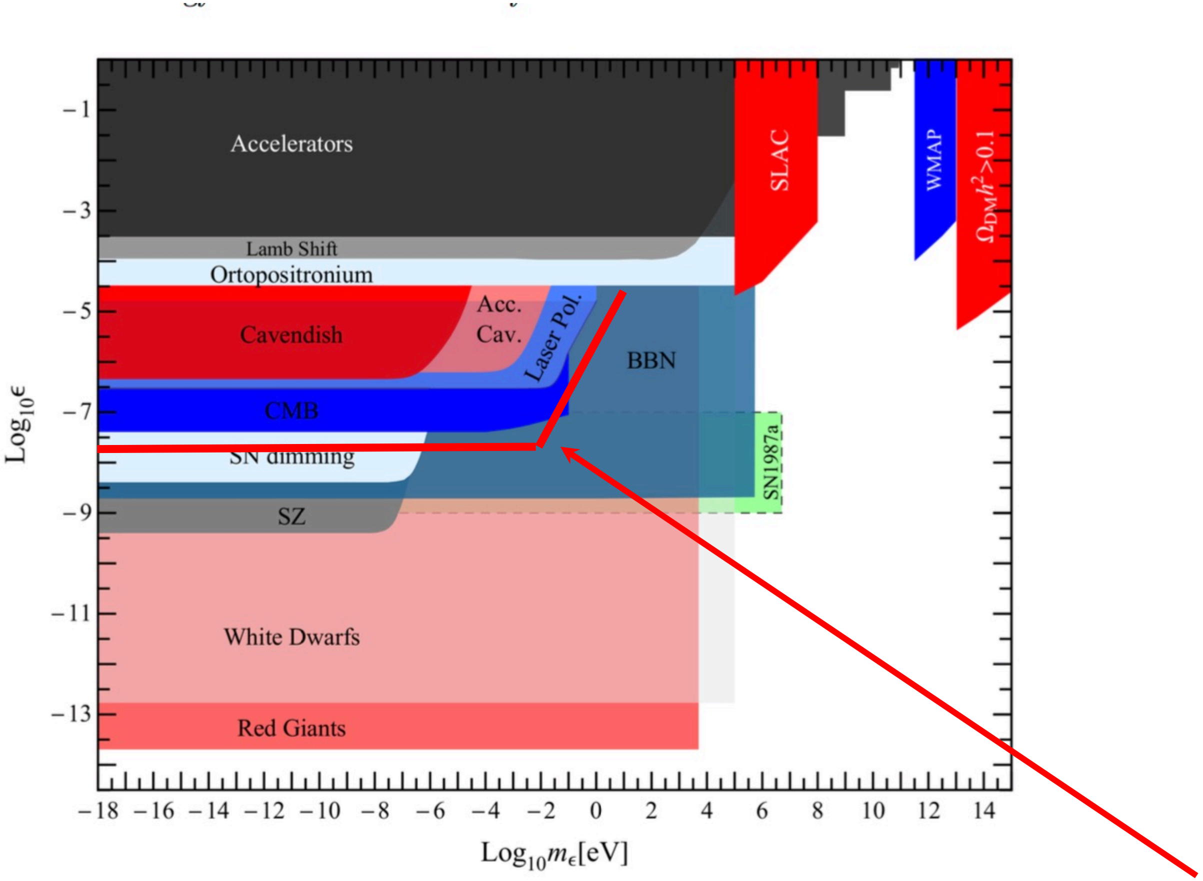
41

Milli-charged particles – sub eV range

Old summary from

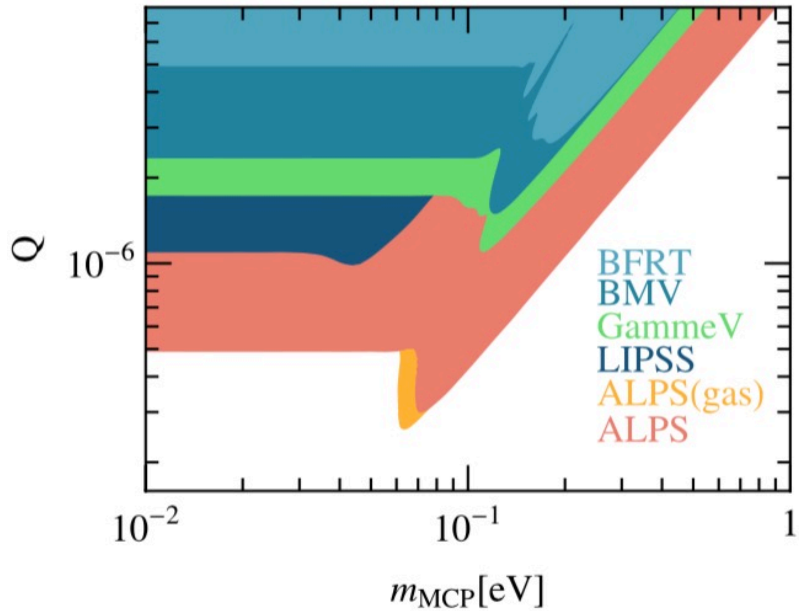
Mark Goodsell[a,c], Joerg Jaeckel[b], Javier Redondo[c,d] and Andreas Ringwald[c]

Published 6 November 2009 • Journal of High Energy Physics, Volume 2009, JHEP11(2009)



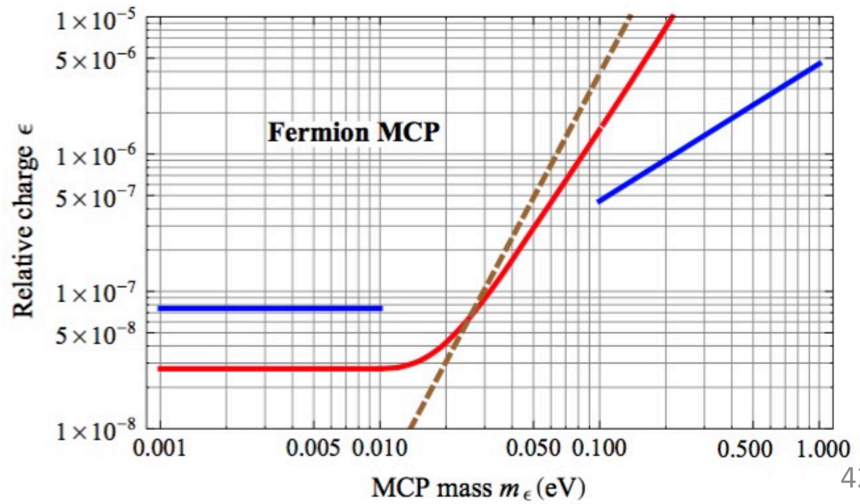
From LSW experiments (ALPSI)

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

[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**

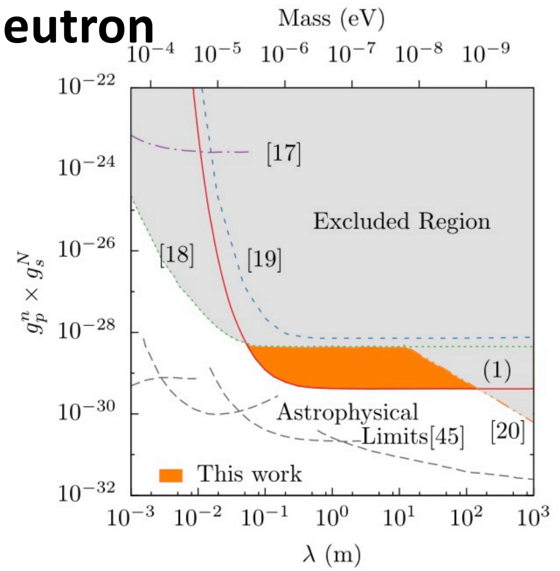
PHYSICAL REVIEW LETTERS **120**, 161801 (2018)

Improved Limits on Spin-Mass Interactions

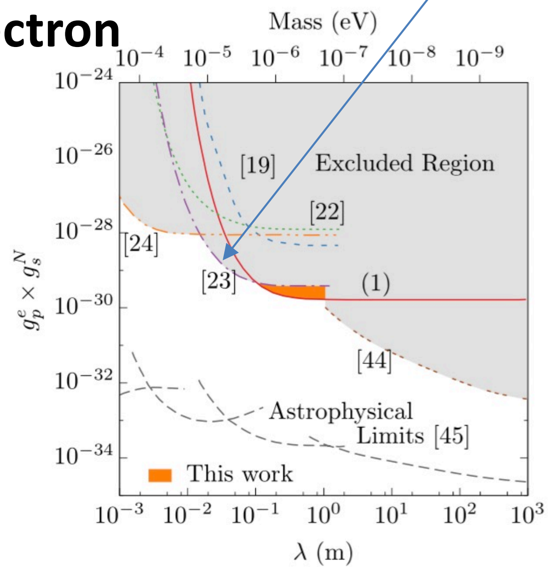
Junyi Lee,* Attaallah Almasi, and Michael Romalis
Department of Physics, Princeton University, Princeton, New Jersey 08544, USA

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
www.elsevier.com/locate/physletb
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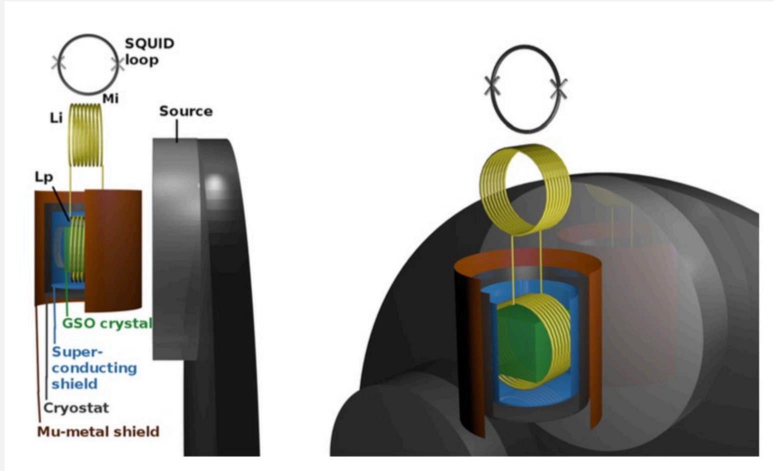
Improved constraints on monopole–dipole interaction mediated by pseudo-scalar bosons

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

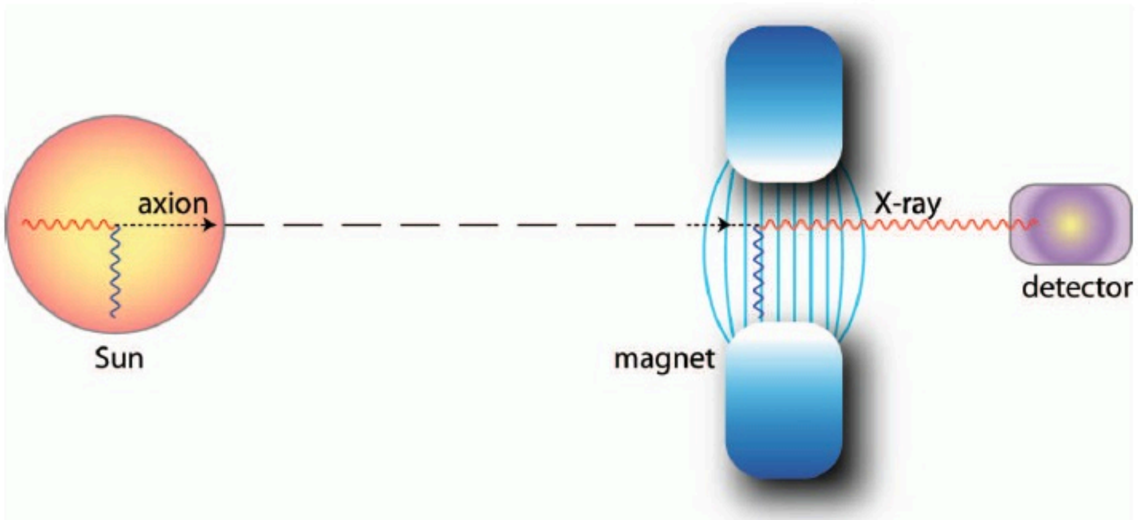
[B] Detection of axion from the Sun

Helioscopes

[B] Detection of axion from the Sun

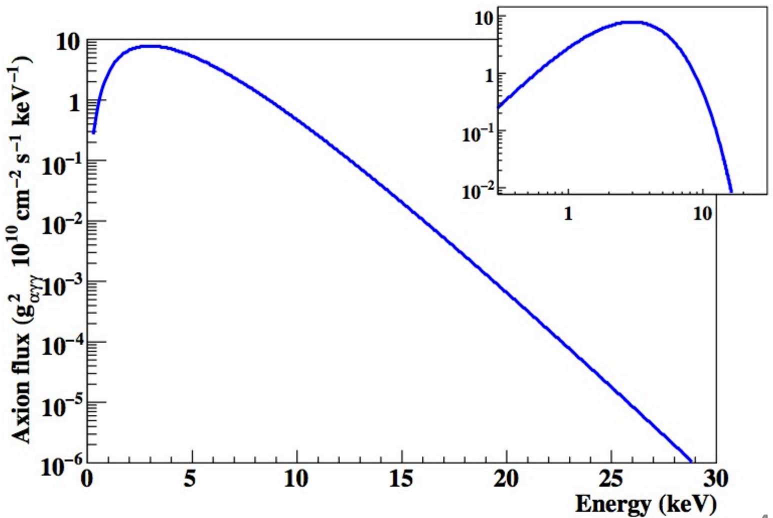
- **Helioscope**: originally proposed by P. Sikivie (1983)
- Axion produced in the Sun by the **Primakoff process**: **blackbody photons** in the EM fields associated with stellar plasma (also other mechanisms through electron coupling)
- **Thermal axion spectrum** with **mean energy 4.2 keV (X rays)**
- **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

$$\Phi_a = 4\times10^{11}\frac{g_{a\gamma\gamma}^2}{10^{-10}\,\mathrm{GeV}^{-1}}\,\mathrm{cm}^{-2}\mathrm{s}^{-1}$$



[B] Detection of axion from the Sun

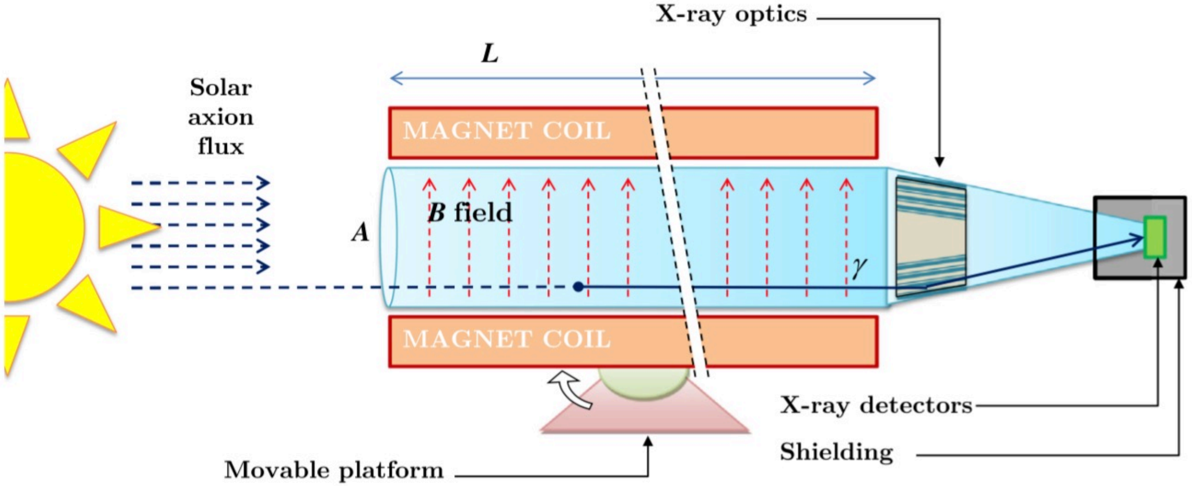
Conversion probability in the detecting magnetic field

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

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

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

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

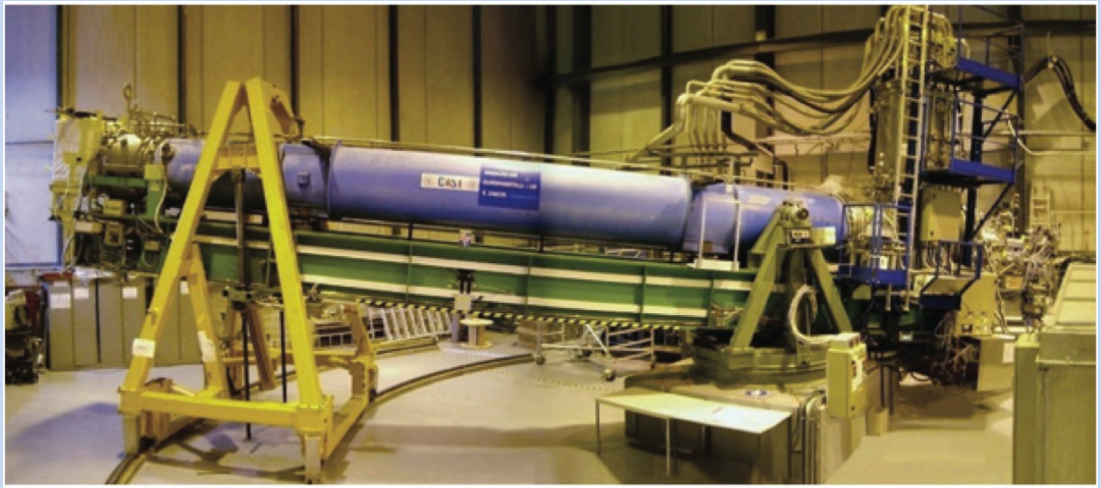
$$\text{sens}(g_{a\gamma\gamma}) \propto \frac{b^{1/8}}{B^{1/2} L^{1/2} A^{1/4} t^{1/8}}$$

- **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)



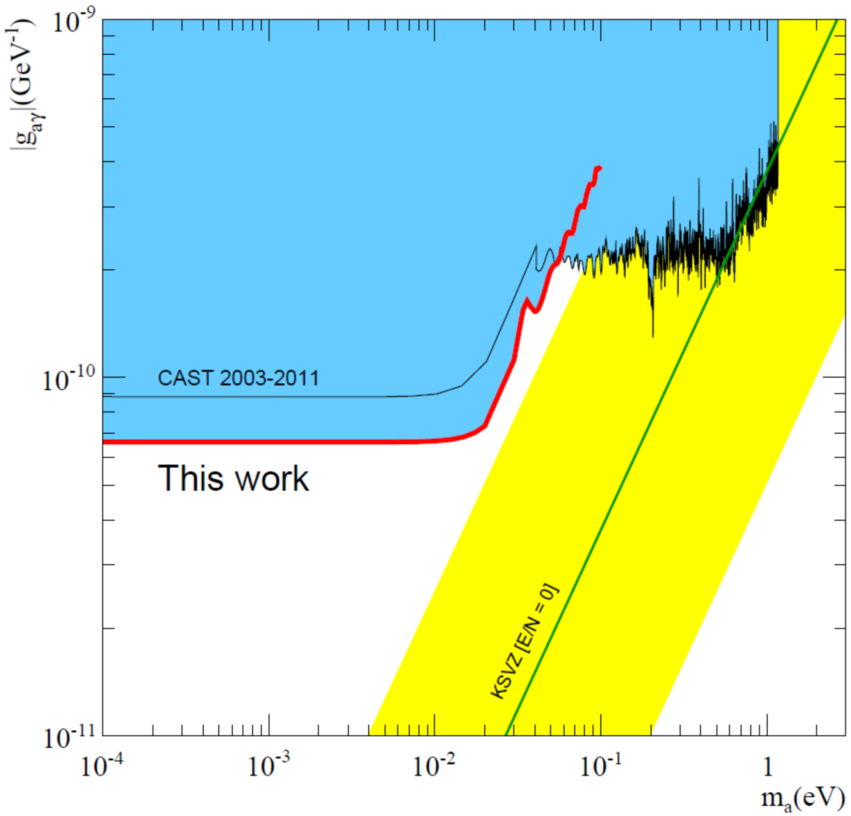
- **10 m - 9 T - LHC prototype magnet pointing to the sun with some tracking capability**
- **So far most sensitive experiment** looking for axion-like particles

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

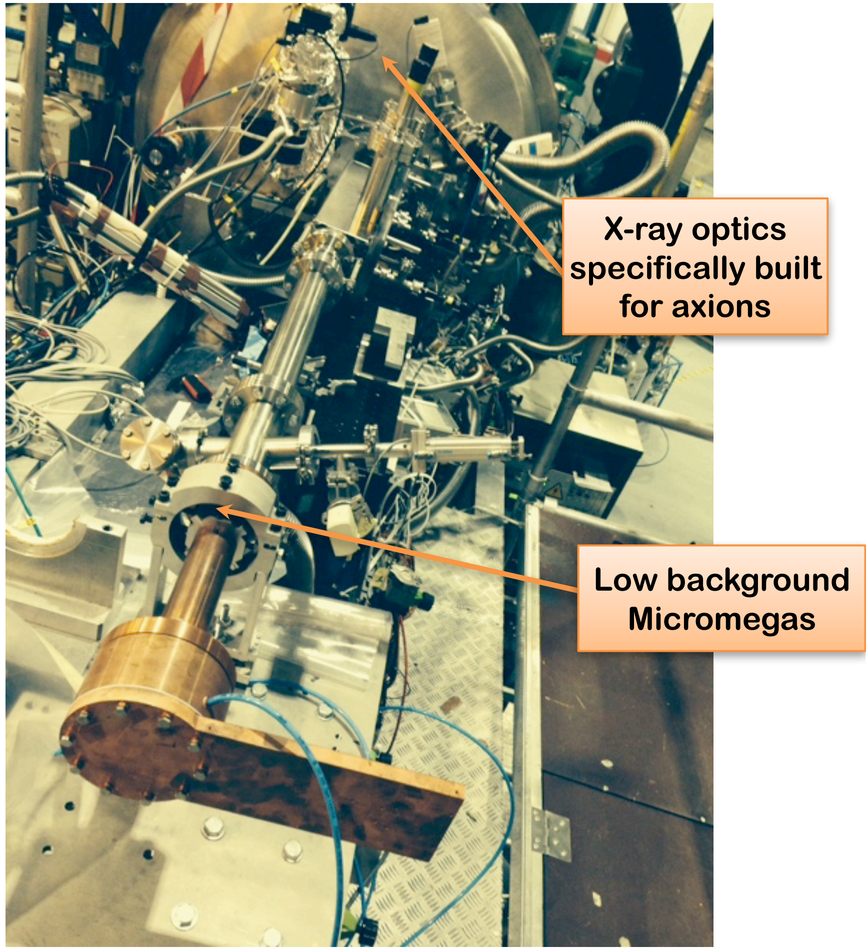
CAST results

- 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



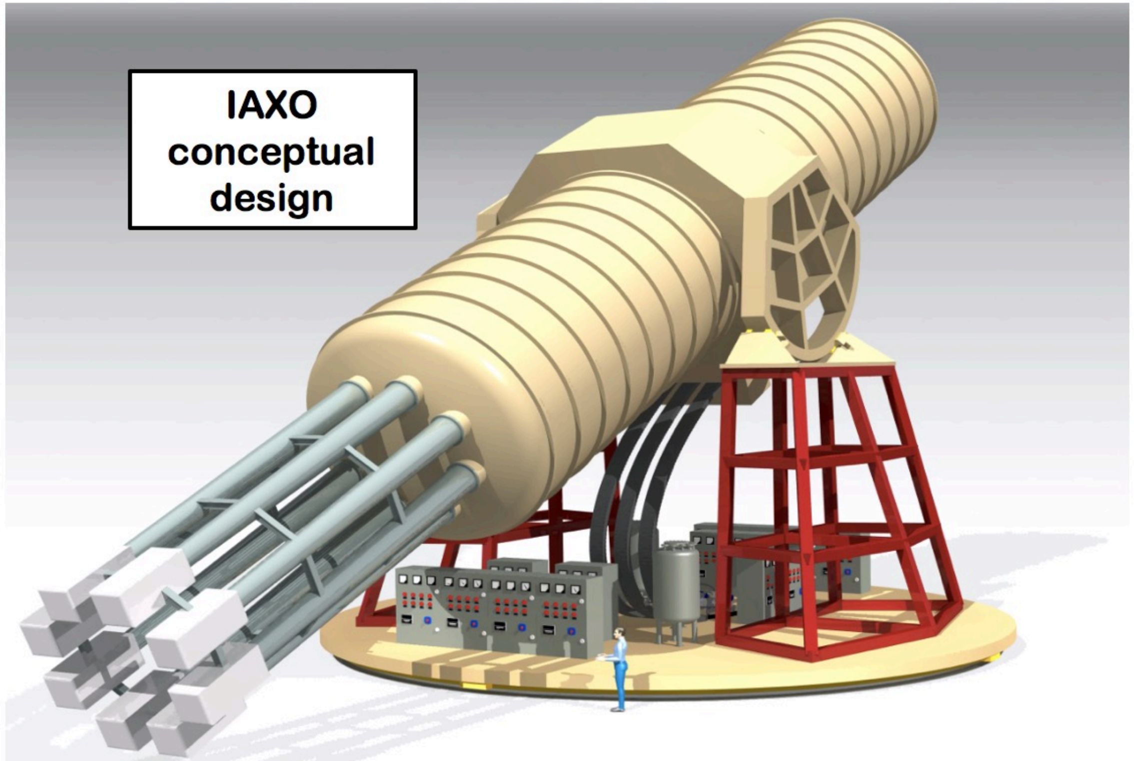
Enabled by the IAXO pathfinder system

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)**



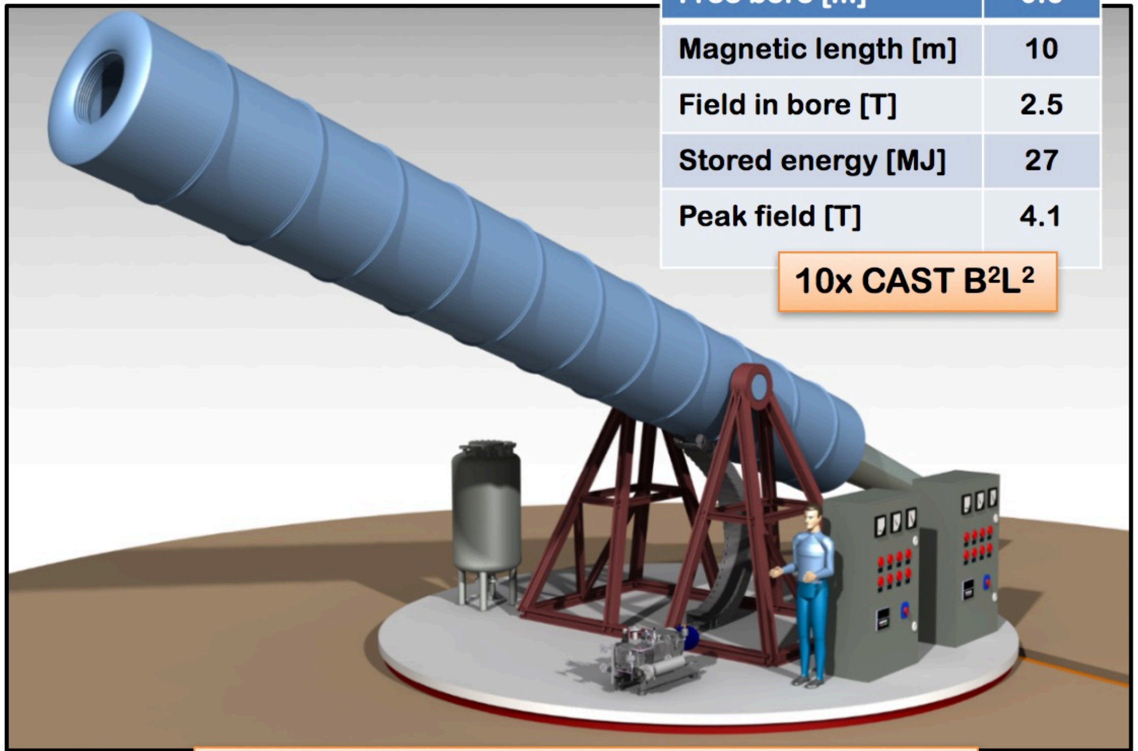
IAXO intermediate step

BabyIAXO

- Intermediate experimental stage before IAXO
- One single bore of similar dimensions of final IAXO bores → detection line representative of final ones.
- Test & improve all systems. Risk mitigation for full IAXO
- Will produce relevant physics
- Move earlier to "experiment mode"
- BabyIAXO Technical Design ongoing at CERN

Free bore [m]	0.6
Magnetic length [m]	10
Field in bore [T]	2.5
Stored energy [MJ]	27
Peak field [T]	4.1

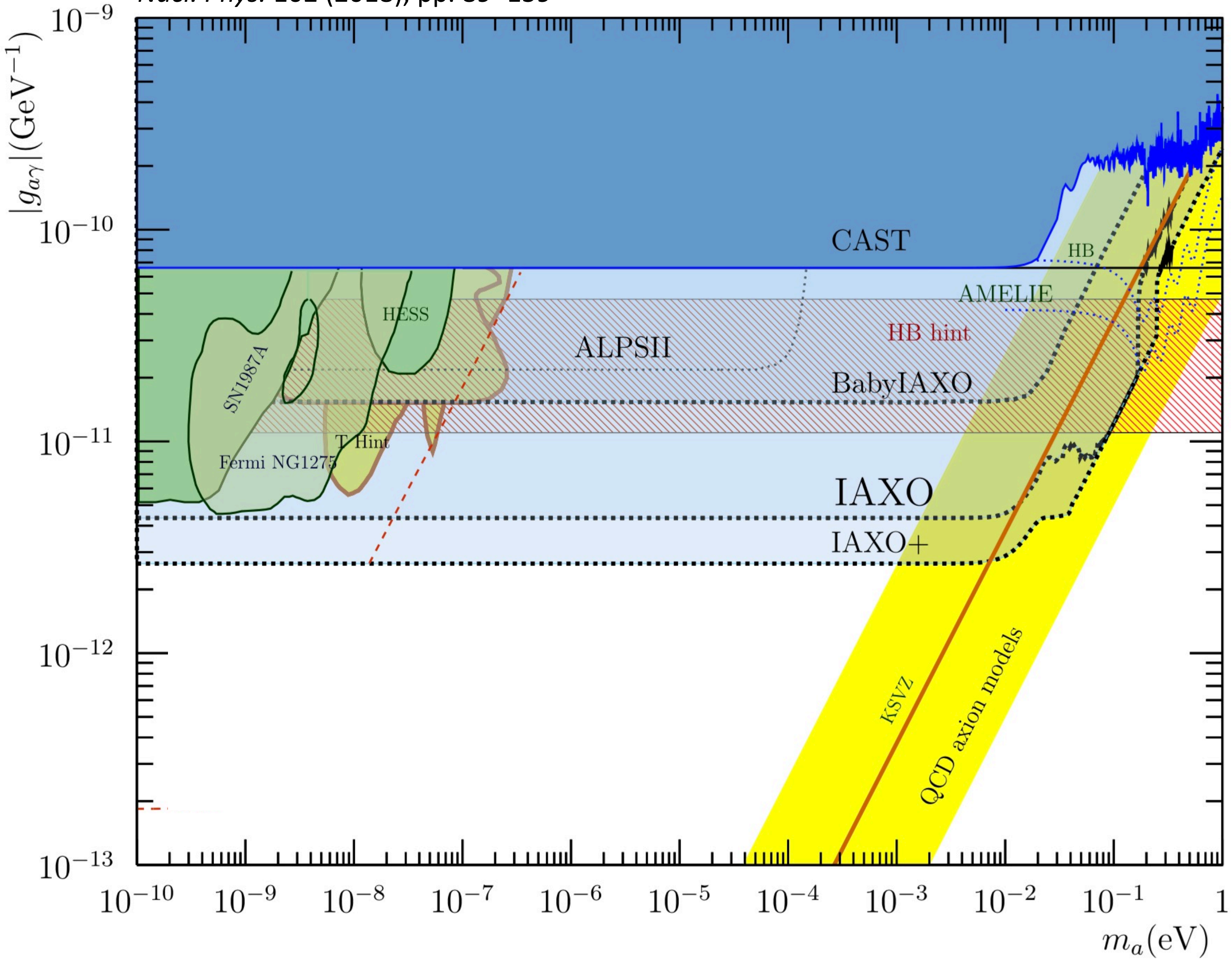
10x CAST B^2L^2



- Possible configuration of BabyIAXO. Representative FOM

Helioscopes: results and perspectives

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

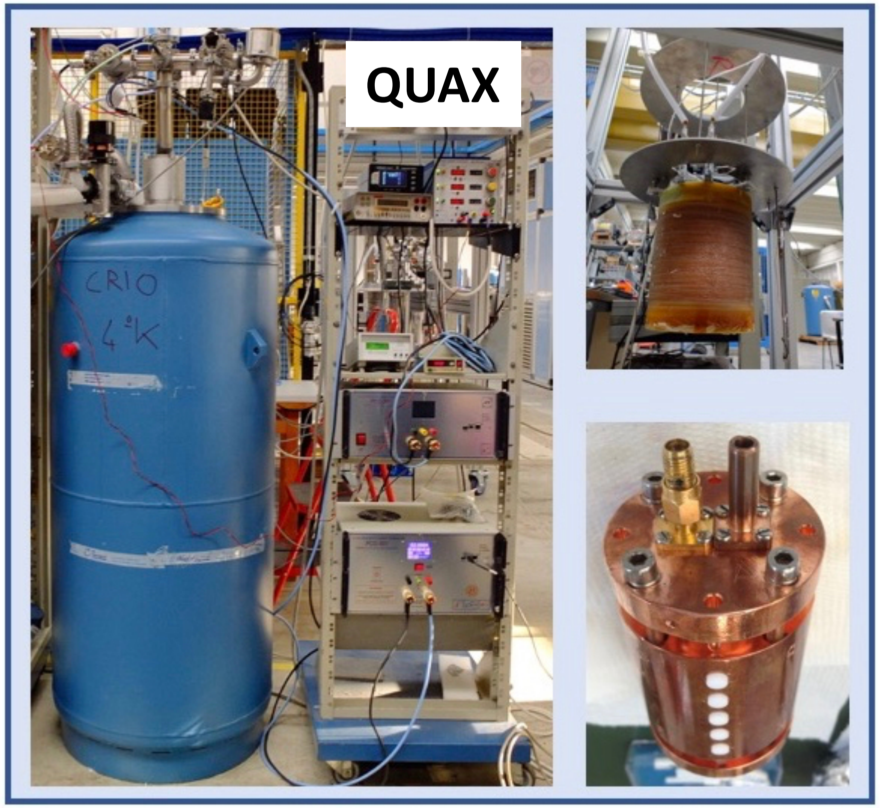


- Helioscopes results competitive with Astrophysics limits but much less model dependent
- Limits on other couplings have been obtained too (not presented here)
- IAXO and BabyIAXO will be exploring important regions where hint of astrophysics origin are present

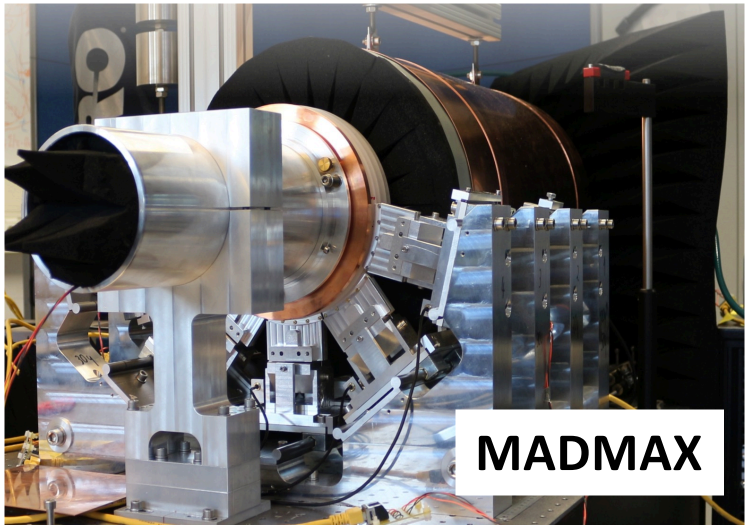
- The physics reach of IAXO will be covering a large and significant range of the **QCD axion** mass span

[C] Haloscopes – Galactic axions

Magnetic haloscopes



Dielectric haloscopes



[C] Haloscopes – Galactic axions

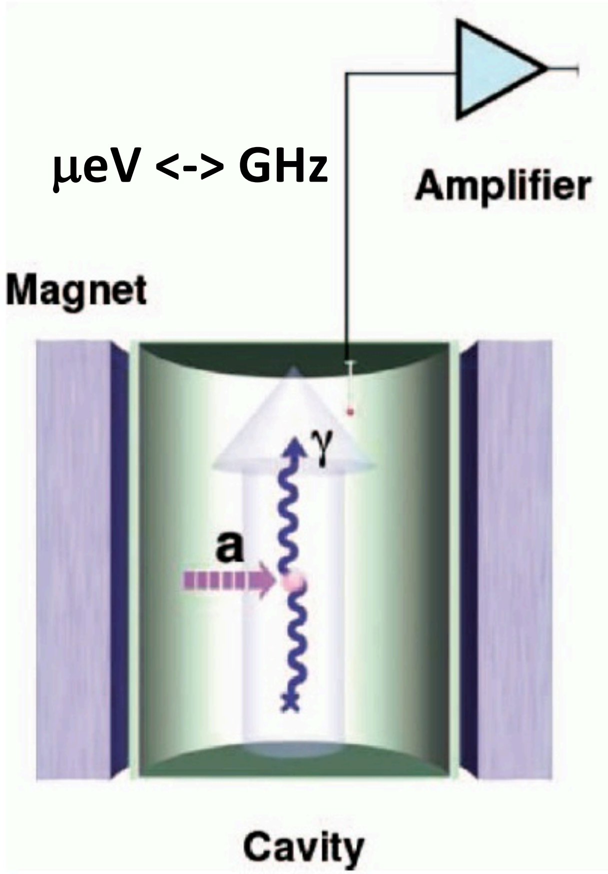
- Search for axions as cold dark matter constituent
- Original proposal by P. Sikivie (1983)
- **DM particles converted into photons inside a magnetic field (Primakoff effect), sensitivity to $g_{a\gamma\gamma}$**

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

    $$h\nu = E_a = m_a c^2 \left(1 + \frac{1}{2}\beta_a^2\right) = m_a c^2 (1 + O(10^{-6}))$$

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

$$\frac{\Delta E}{E} \approx 10^{-6}$$

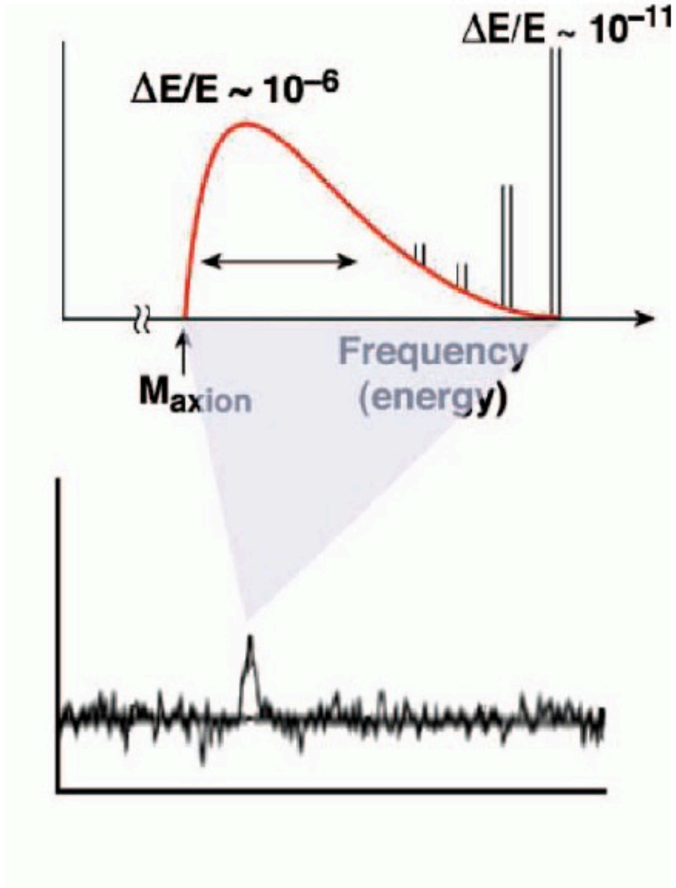
  - Possible **very sharp component due to non-thermalised** axion falling in and out of the Milky Way

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

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

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

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



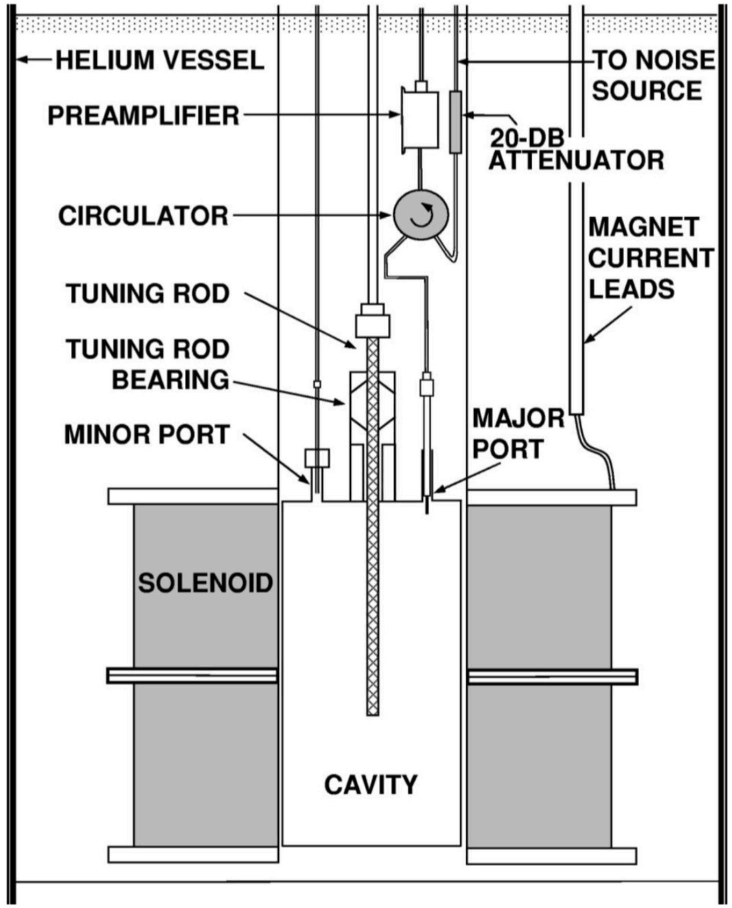
Haloscopes – Galactic axions

- 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)

$$\frac{\Delta f}{\Delta t} \propto V^2 B^4 C^2 T_{noise}^{-1} \; Q \; f$$

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



The RBF apparatus (1988)

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

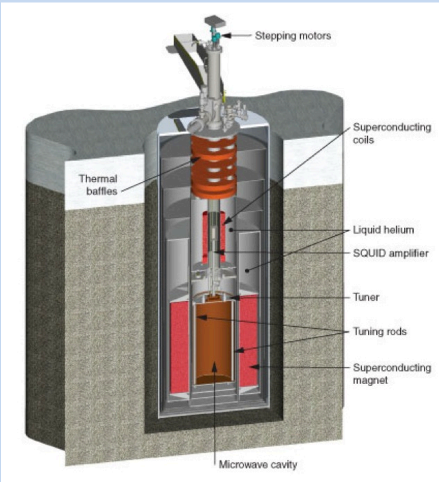
! All current limits assumes axion/ALPs saturate the local DM density

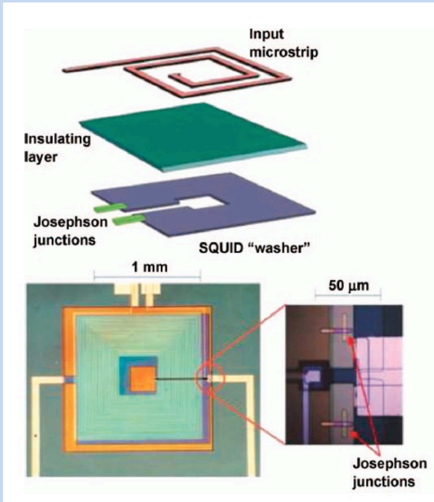
Haloscope detectors

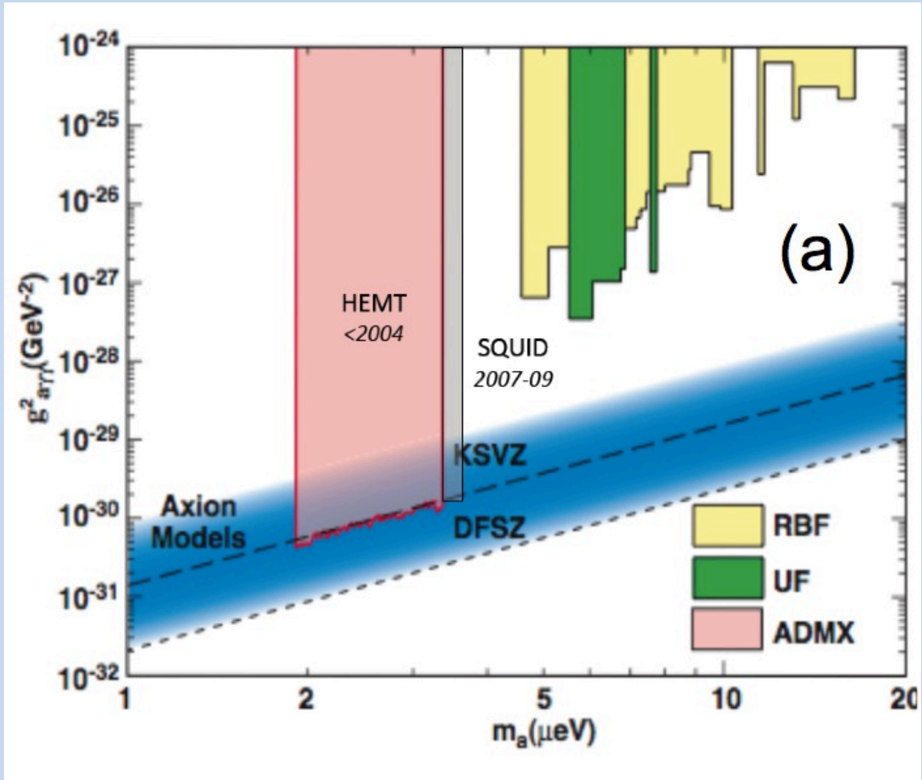
- Pilot experiments in Brookhaven (RBF) (1988) and University of Florida (UF) (1990)
- Second generation experiments:
  - ADMX @ Lawrence Livermore employing low noise amplifier detectors
  - CARRACK @ Kyoto employing Rydberg atom detectors

ADMX – Axion Dark Matter eXperiment – phase I

- High Q (>10^4) microwave **copper cavity** cavity inside an 8.5 T magnet
- Almost Quantum Limited SQUID detector







- Running temperature 1.5 K
- System noise temperature ~ K

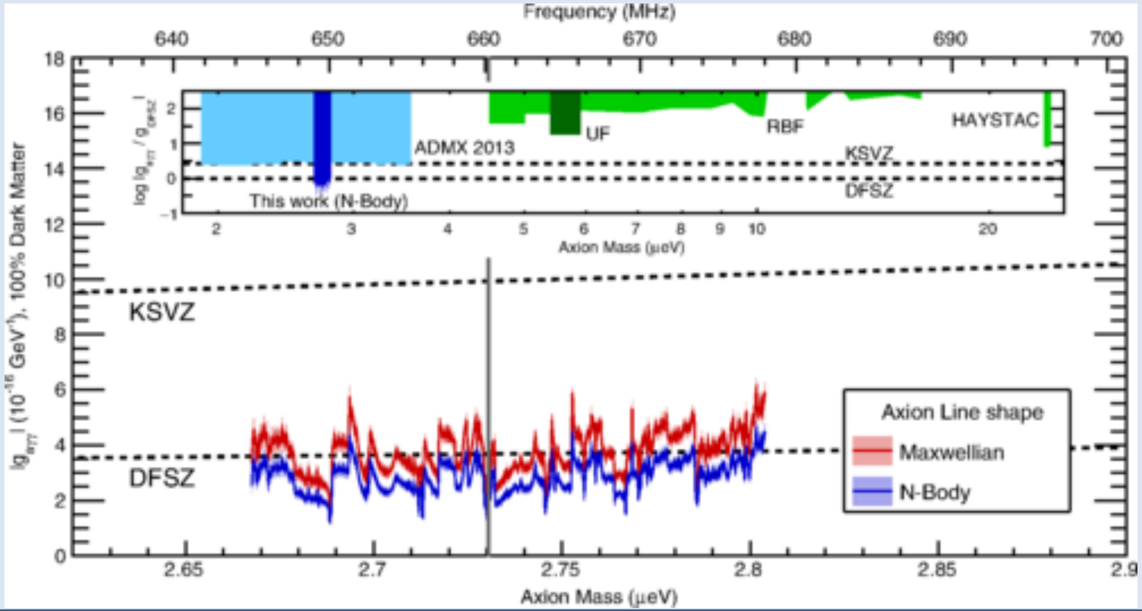
- **Reached QCD axion model (KSVZ)**

Dark matter haloscopes – recent results

- **Reached sensitivity to DFSZ axion models**
- Improvements mainly due to lower operational temperature (150 mK) of the cavity receiver
- Results only in a narrow mass range @ 2.75 μeV, measurements @ larger masses (10 μeV) foreseen

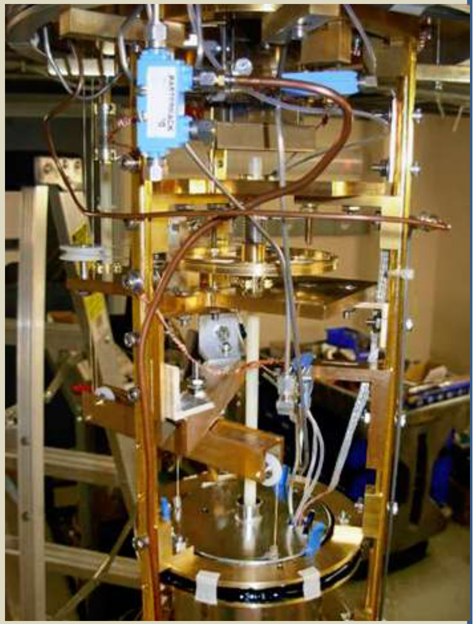
AXION DARK MATTER EXPERIMENT

PRL **120**, 151301 (2018)

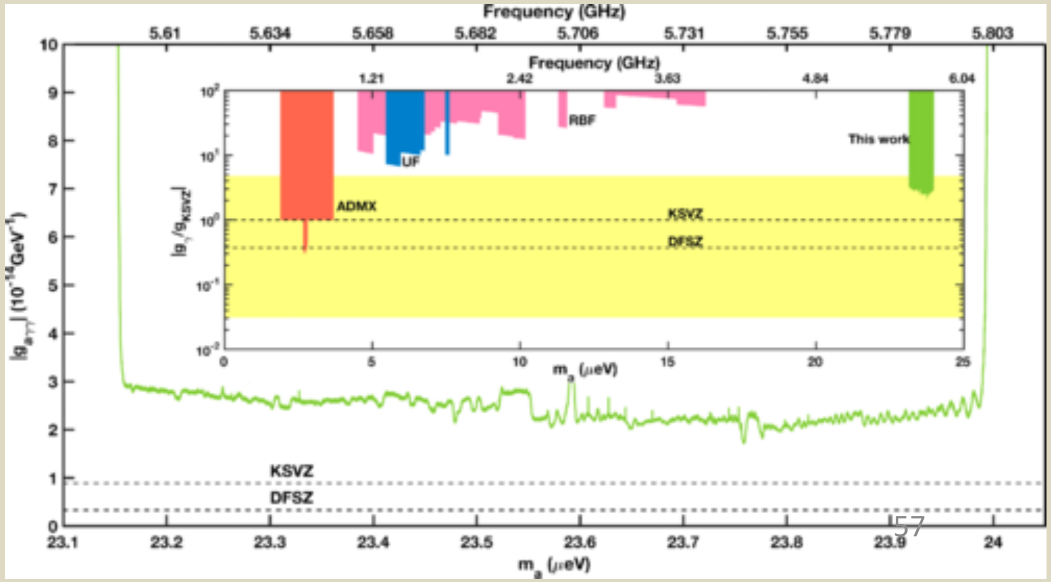


- HAYSTAC published results with cosmological sensitivity to axion like particles
- First results in a new mass range (24 μeV) pushing to **higher mass values**

HAYSTAC - Yale



PRD **97**, 092001 (2018)

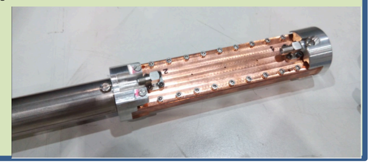


Dark matter haloscopes – what's going on

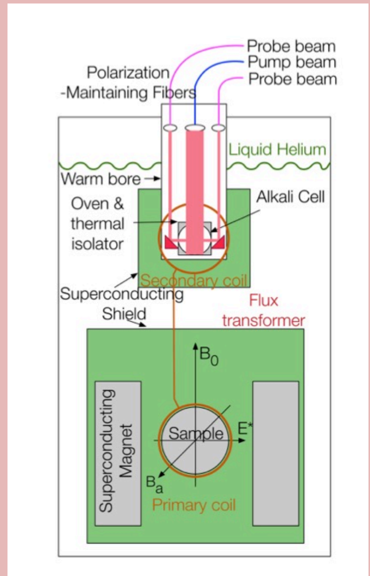
- Several other activities are starting or being proposed in the very recent time
- It is a field which is expanding very rapidly

CULTASK
CAPP

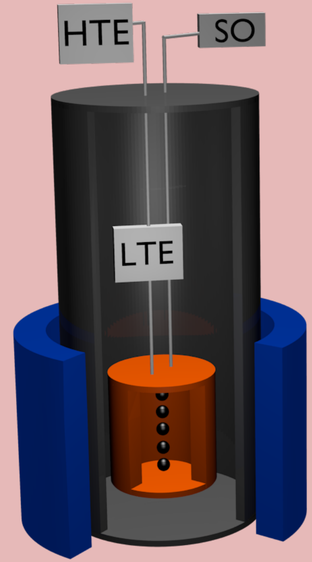
RADES / CAPP – cavities inside CAST



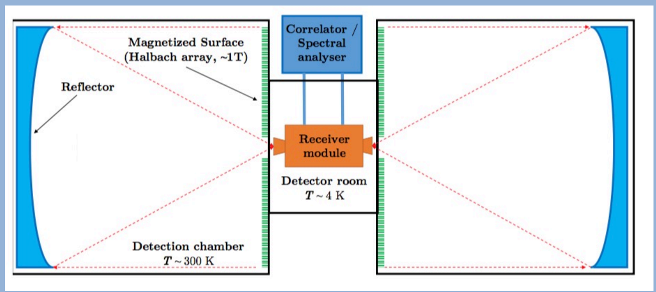
CASPER wind – NMR
Axion - nucleon



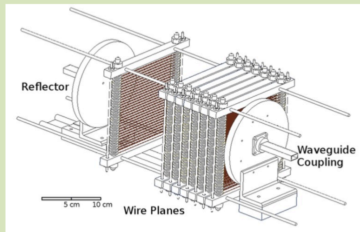
QUAX – EPR
Axion - electron



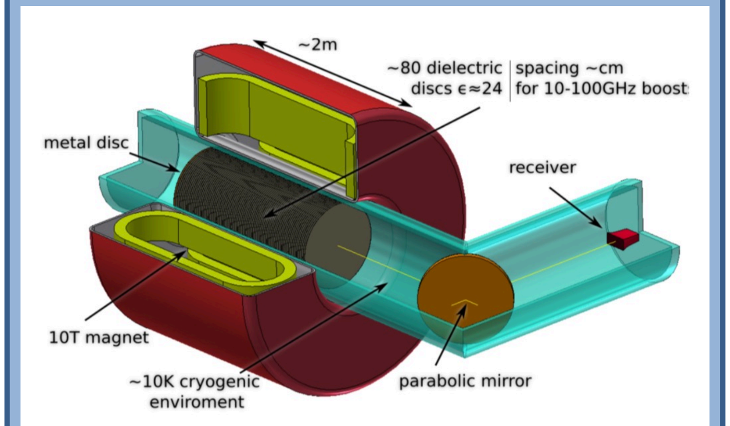
BRASS – dish antenna



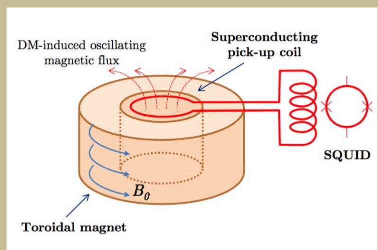
ORPHEUS



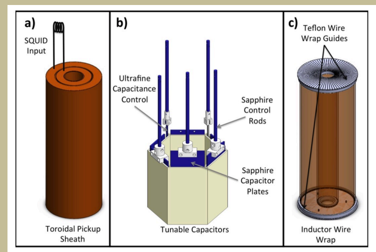
MADMAX - Dielectric haloscope



ABRACADABRA

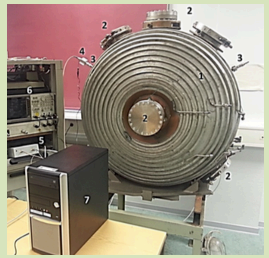


DM Radio



LC circuit

WISPDMX
@DESY

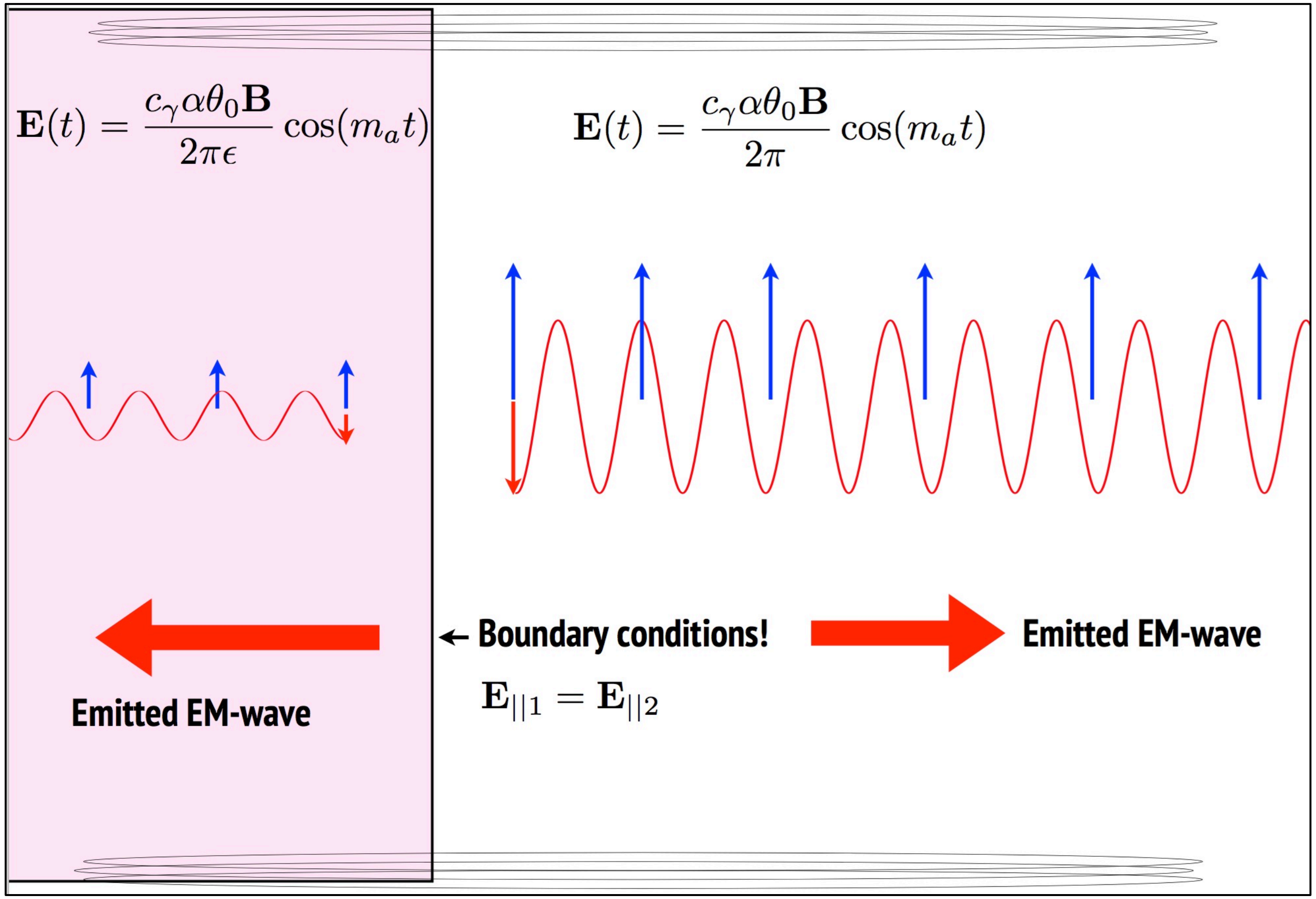


ONLY A SELECTION!!!!!!

Standard Sikivie's detectors

Other techniques for DM detection

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



- A dielectric 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
- Emitted power

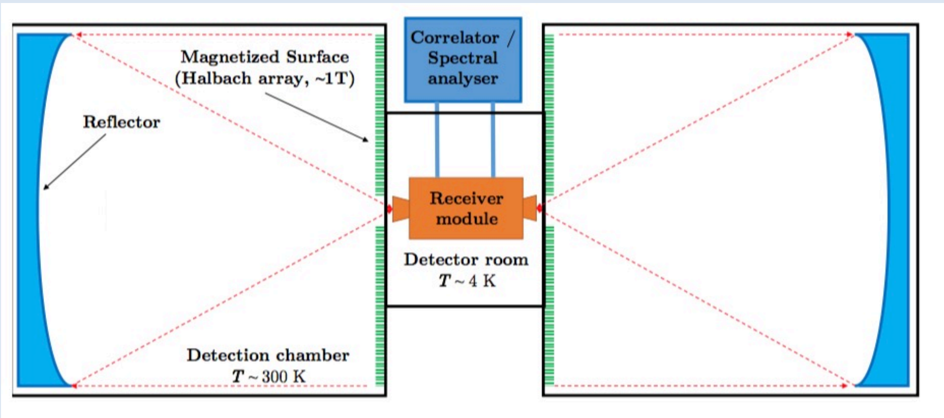
$$P \propto AB^2 f^{-2}$$

Large area A, Strong Fields B

Other techniques: proposals

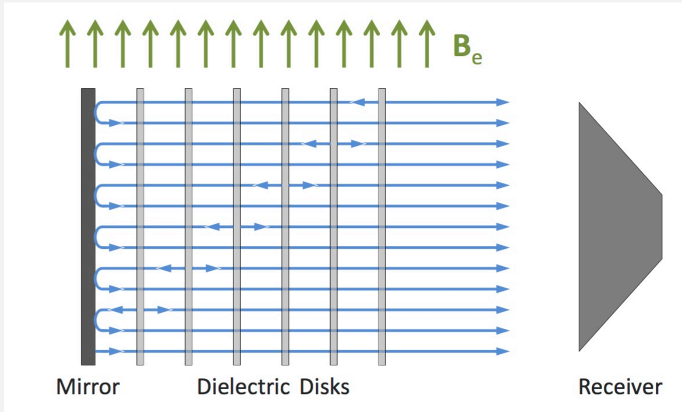
BRASS experiment (Hamburg)

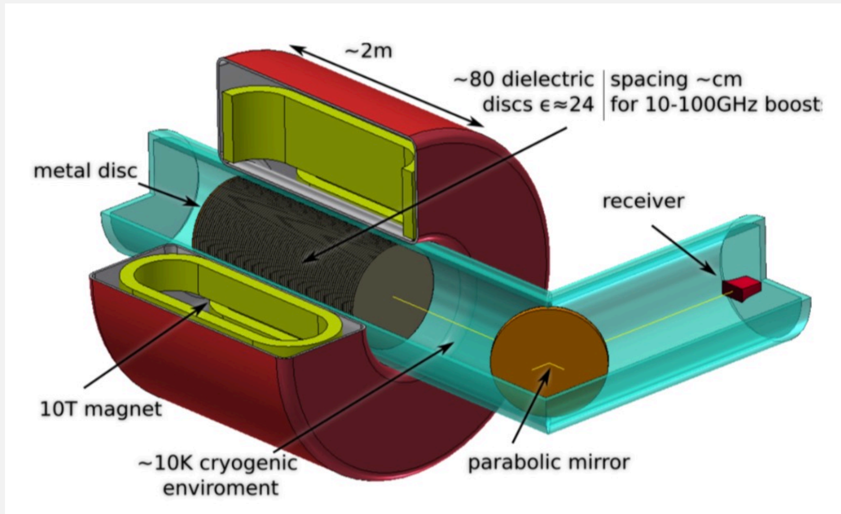
- Large surface mirror; 8 m radius
- Halbach array of permanent magnets
- Rejection of background thanks to spherical shape



MADMAX experiment (Germany)

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

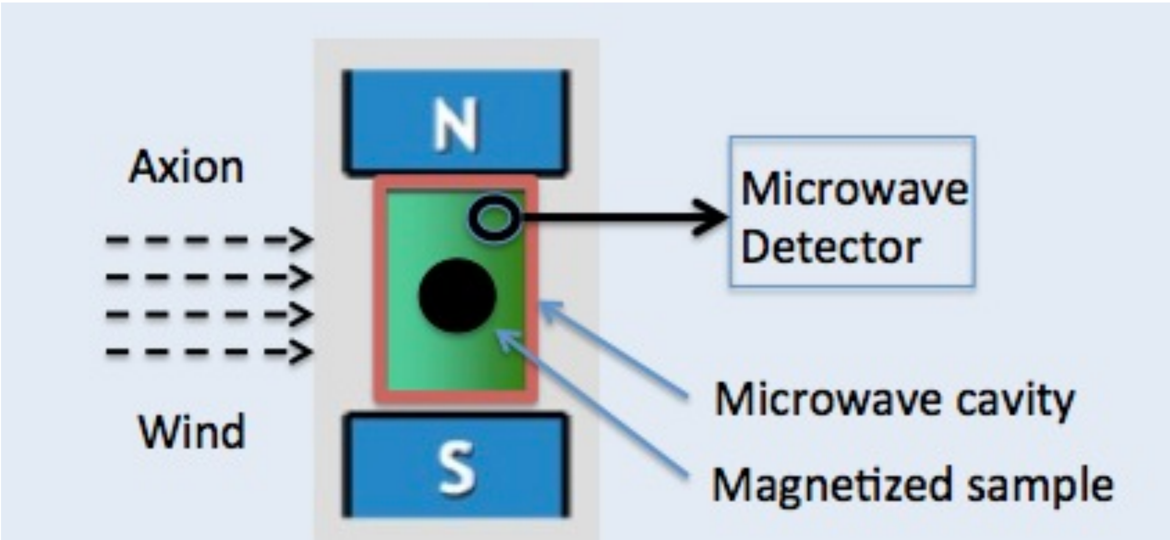




- 80 dielectric discs with 60 cm diameter (1 m^2) each
- 10 T magnetic field
- Large epsilon material to increase boost factor
- Tuning mechanism (interference is not broadband)

Electron Paramagnetic Resonance: the QUAX proposal

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



Effective magnetic field

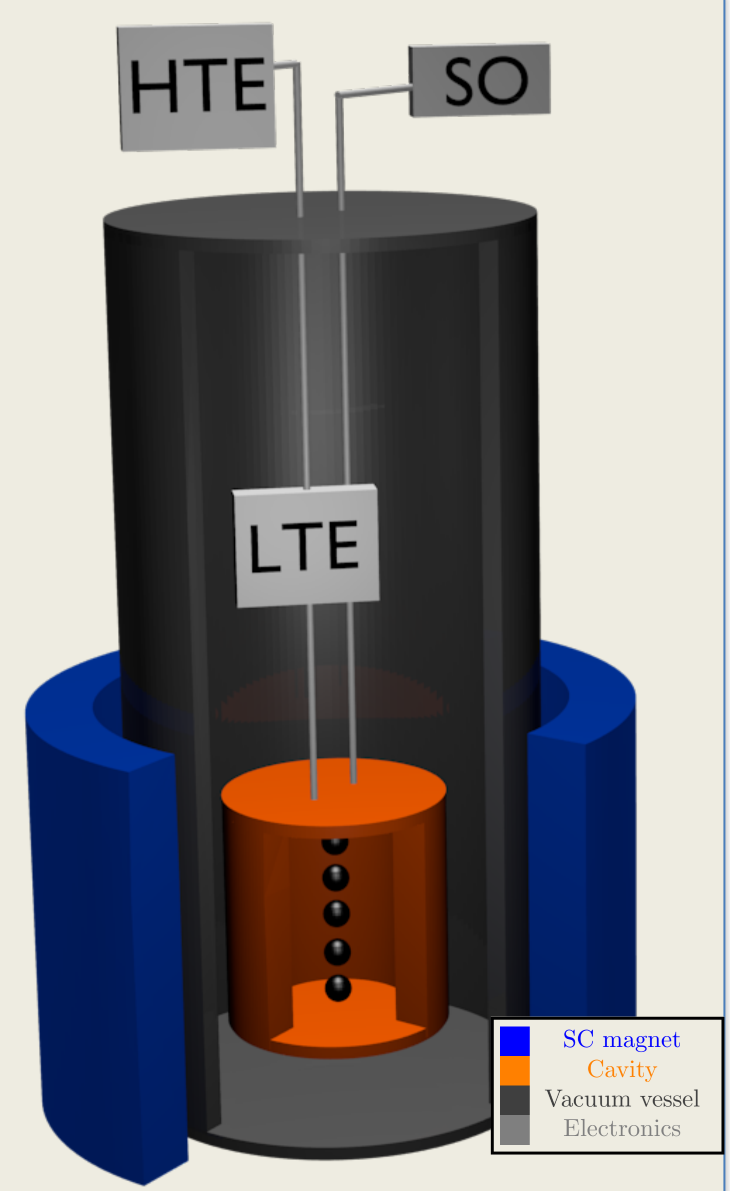
$$B_a = 2.0 \cdot 10^{-22} \left(\frac{m_a}{200\,\mu\text{eV}} \right) \text{ T},$$

Expected RF power

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

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

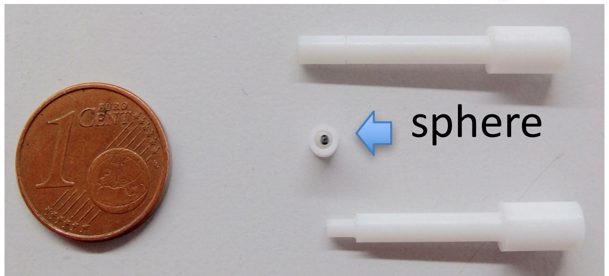
First small scale prototype of QUAX detector



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

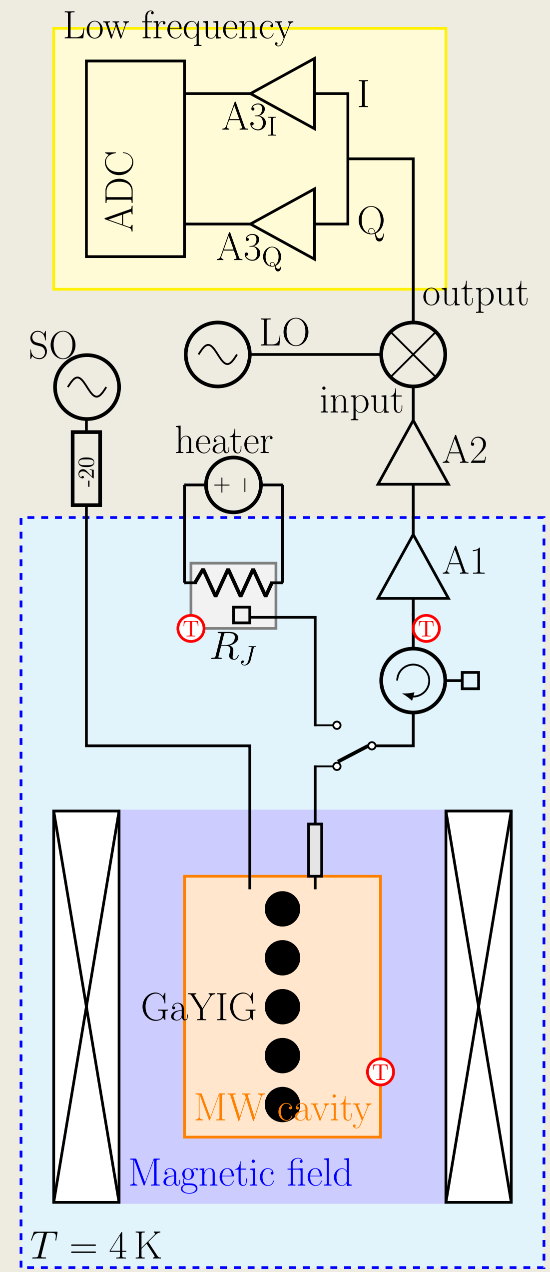
Resonant cavity (14 GHz) with 5 YIG spheres (ϕ = 1 mm) inside

YIG holders



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

Detection chain



QUAX limit on axion electron coupling

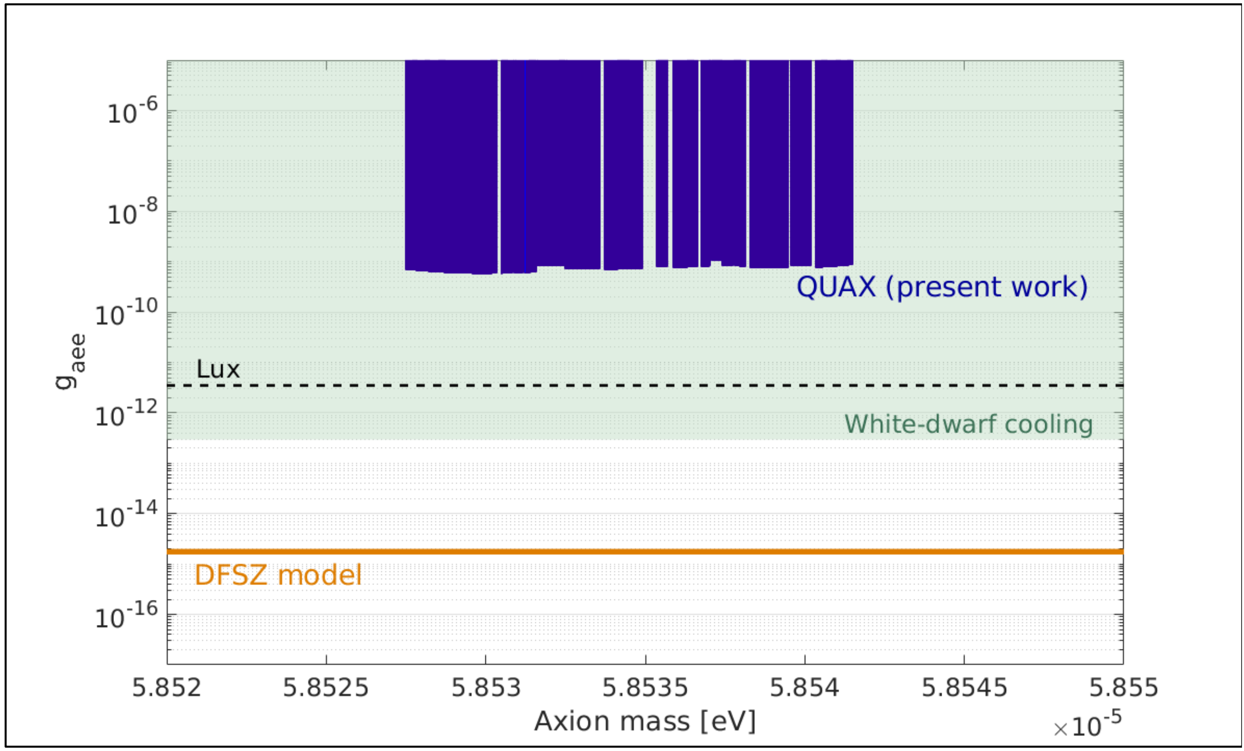
Eur. Phys. J. C (2018) 78:703
https://doi.org/10.1140/epjc/s10052-018-6163-8
THE EUROPEAN PHYSICAL JOURNAL C
CrossMark
Regular Article - Experimental Physics

Operation of a ferromagnetic axion haloscope at $m_a = 58\,\mu\text{eV}$

Residual power sensitivity can be recast directly into axion coupling, taking also into account the mode Lorentzian shape

$$g_{aee} > \frac{e}{\pi m_a v_a}\sqrt{\frac{2\sigma'_P}{\mu_B \gamma n_a n_s V_s \tau_+}},$$

The mass is fixed by the frequency



This is the first limit in the parameter space $\{m_a, g_{aee}\}$ obtained from an experiment searching for axions as the main Dark Matter component (Haloscope)

Limit is still poor but:	This results	QUAX R&D (2019)	QUAX (Expected)
• Material volume	2.6 mm^3	42 mm^3	10^5 mm^3
• System total noise temp.	15 K	0.5 K	counter (T_{eff} <1 mK)
• Relaxation time	0.1 ms	0.3 ms	2 ms

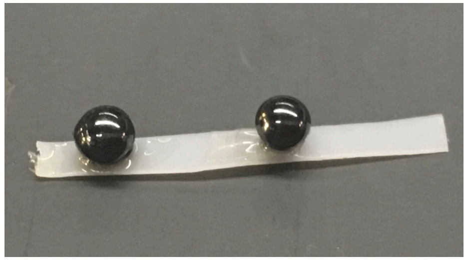
Current situation for QUAX

- Refurbishing of a **Low Power Dilution Refrigerator** completed
- First tests of a **Josephson Parametric amplifier (JPA)** @ 100 mK
  - Expected T_{noise} ~ 0.5 K
- New **in-house procedure for production of YIG spheres** up to 2.5 mm diameter
- Coupling of a **superconducting cavity loaded with YIG sphere** achieved
- New **photonic cavities** on the way
- A **concurrent experiment** started in Australia, copying our ideas, currently with **worse sensitivity**

Dilution system

Dilution insert with rf electronics and cavity

Home made YIG spheres (ϕ = 2 mm) glued on teflon support



Within 2019 new measurements are expected with increased volume and lower amplifier noise to improve previous limits by an order of magnitude

QUAX-aγ for the axion-photon coupling

QUAX shares with standard haloscopes (axion – photon coupling) the following points:

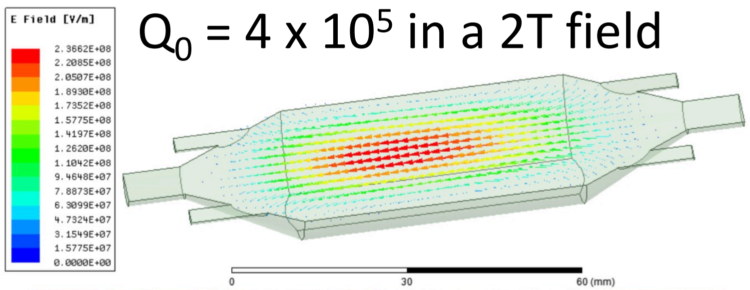
- Measurement of **excess power in a resonant cavity in the GHz range**
- Operation of a **high Q microwave cavity inside a magnetic field**
- Use of **low noise detection chain**
- **Cryogenic operation**

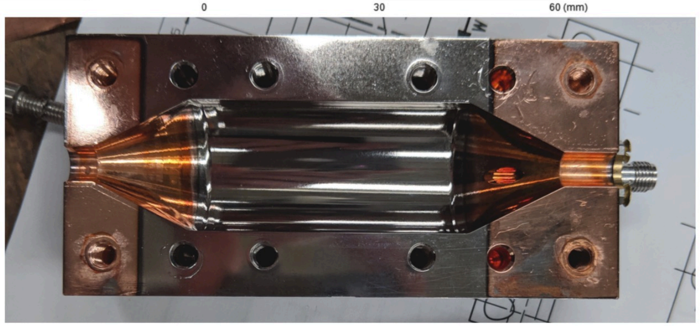
By operating the QUAX detector with an **empty cavity tuned to the TM010 mode** it is possible to search for axions by exploiting the the axion – photon vertex (Primakoff effect)

QUAX-aγ valuable points

(1) Hybrid cavity (NbTi sputtered Copper) for magnetic field operation

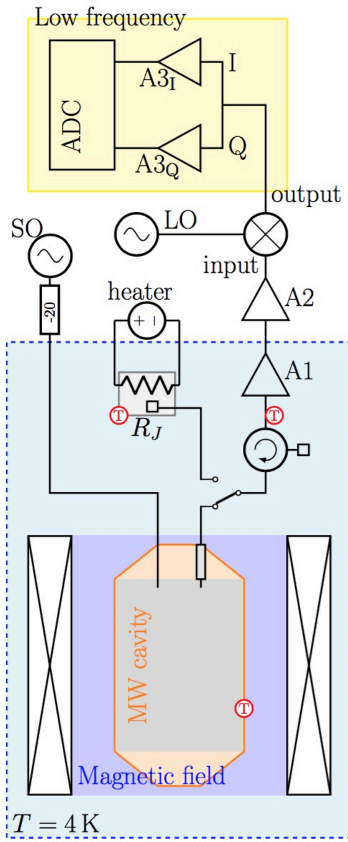
$Q_0 = 4 \times 10^5$ in a 2T field



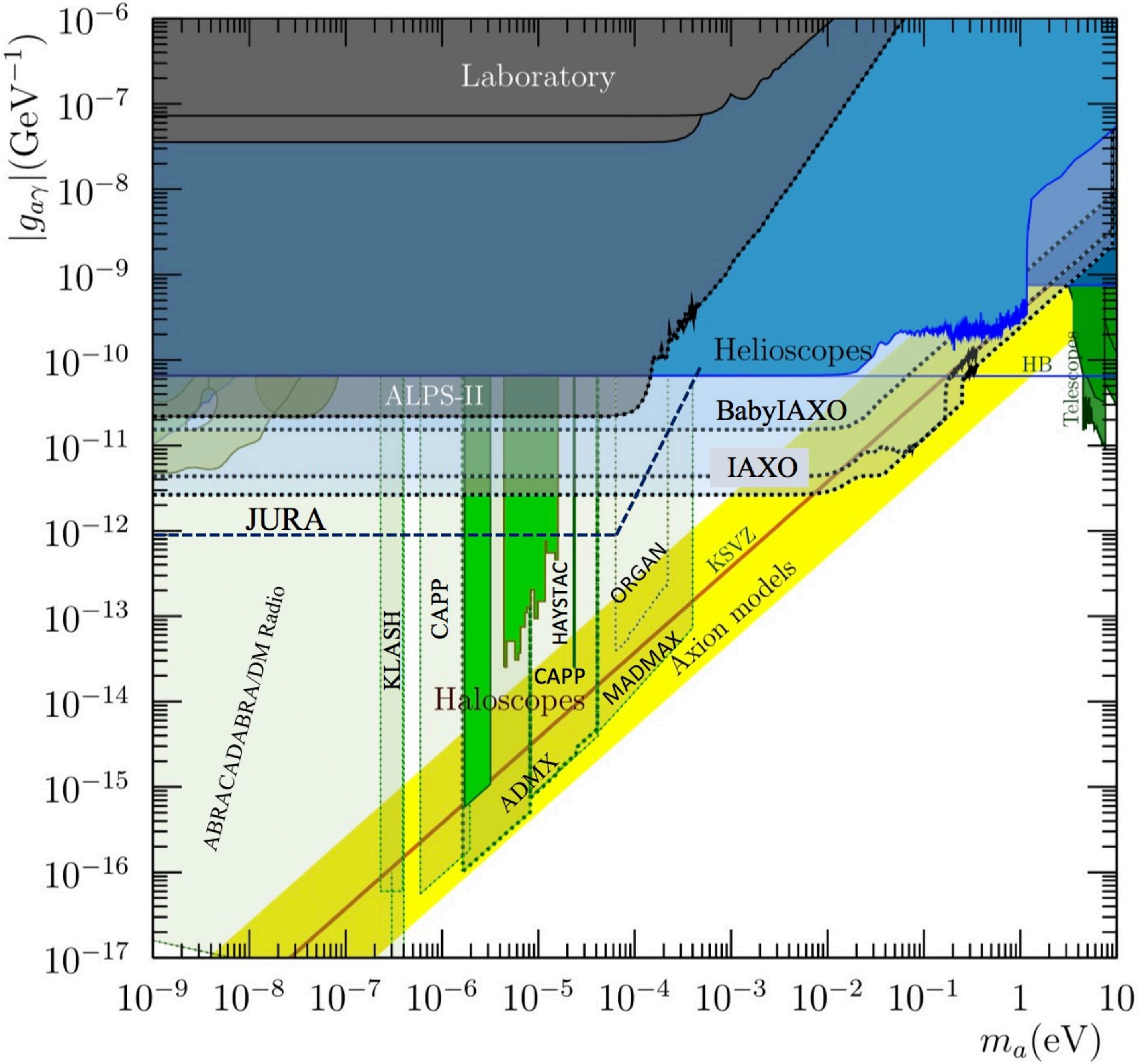


(2) Higher frequency (9 GHz) compared to other exps

$$P_a = 1.85 \times 10^{-25}\,\mathrm{W} \left(\frac{V}{0.0361}\right)\left(\frac{B}{2\,\mathrm{T}}\right)^2\left(\frac{g_\gamma}{-0.97}\right)^2 \left(\frac{C}{0.589}\right)\left(\frac{\rho_a}{0.45\,\mathrm{GeV cm^{-3}}}\right)\left(\frac{\nu_c}{9.067\,\mathrm{GHz}}\right)\left(\frac{Q_L}{201000}\right)$$



Summary plot for the axion-photon coupling



A. LABORATORY

B. HELIOSCOPES / STELLAR PHSYICS

C. HALOSCOPES / COSMOLOGY

D. HINTED REGIONS

E. QCD AXION BAND

- Physics reach of new experiment with dashed lines

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

Conclusions

- A partial review of experimental efforts in the search for Axion has been presented
- The Axion, invented to solve a specific problem of QCD, became a perfect Dark Matter candidate:
  - It can be searched for in dedicated experiments
  - Pure lab experiments don't seem to be able to reach the parameter space for a QCD axion DM candidate
- Axion like particles came also into the scene. They might be as well good DM candidates
- Several efforts with a large variety of techniques can help to find or rebut the existence of this exotic particle
- Suggested reading: I.G. Irastorza and J. Redondo, *Prog. Part. Nucl. Phys.* 102 (2018), pp. 89–159

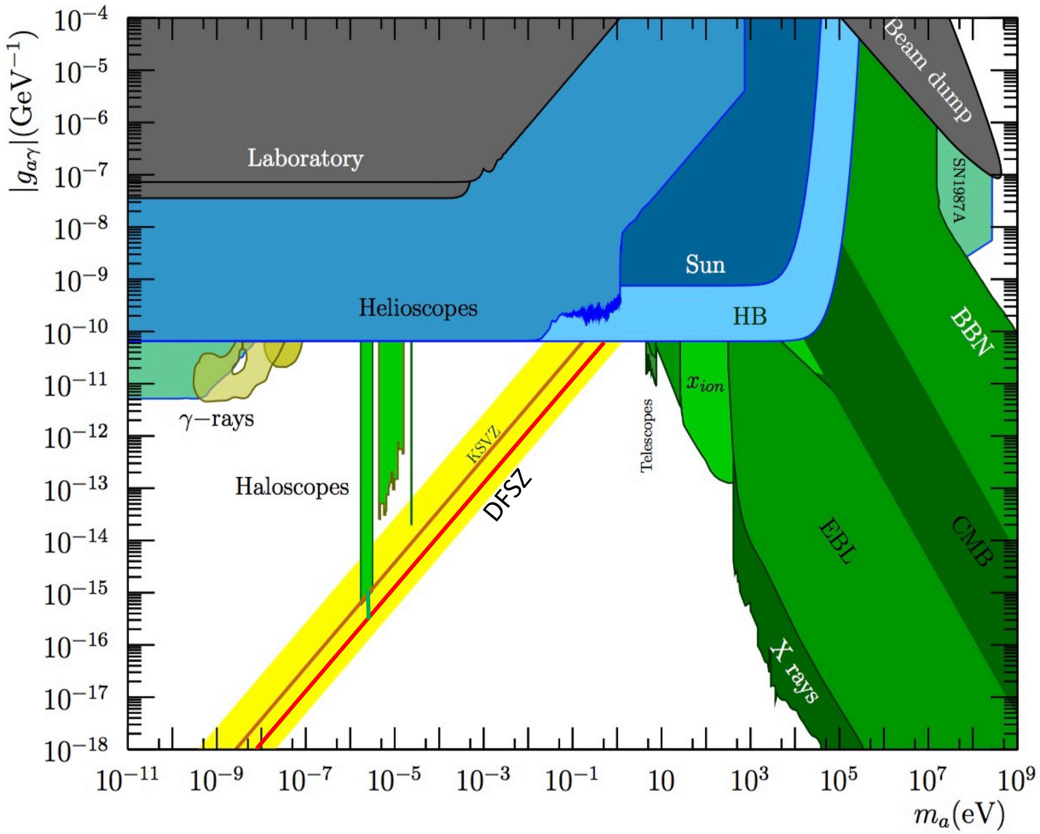
Thank you

After the end

Bck p

Current constraints for ALPs: photon coupling

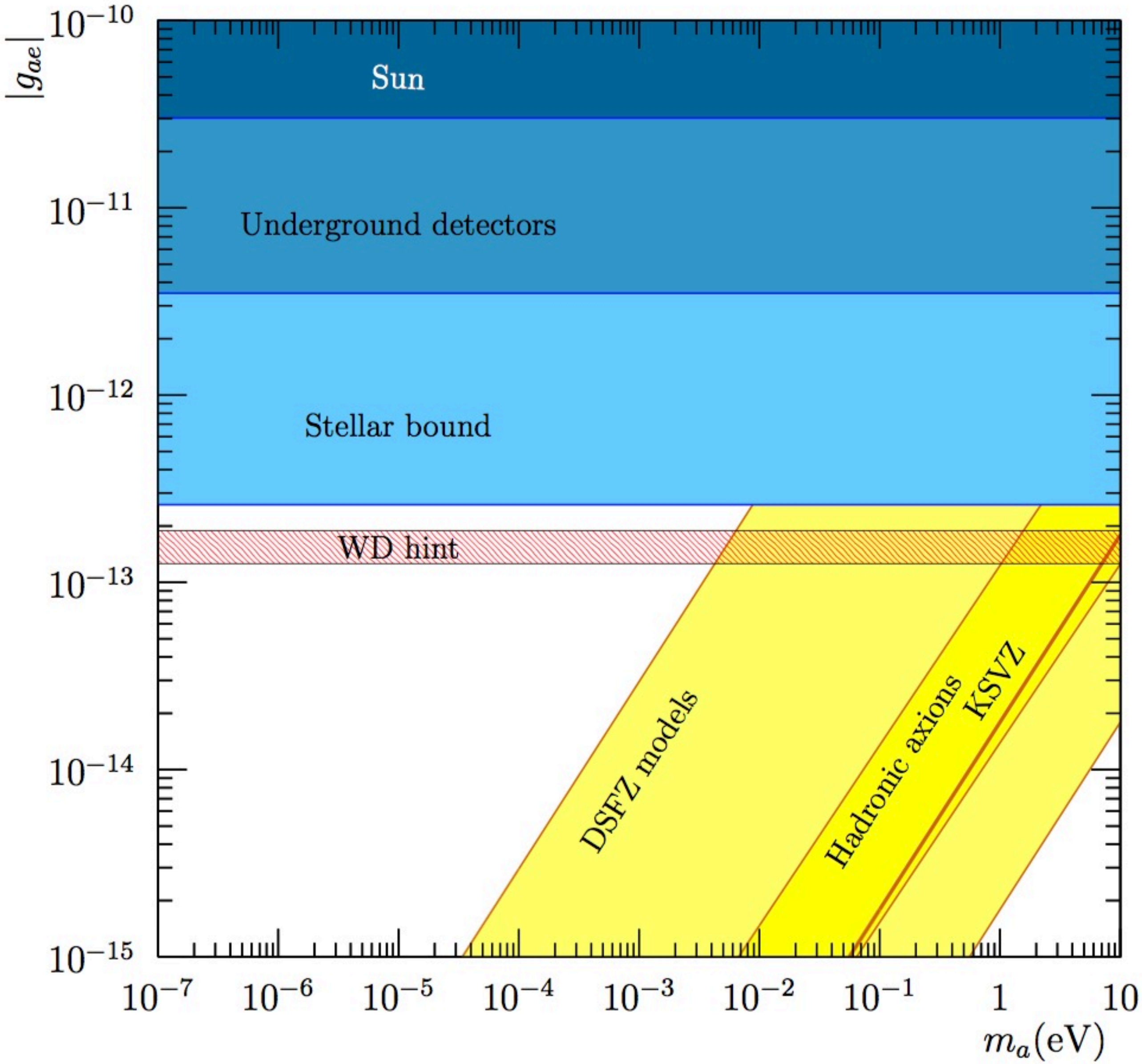
Cosmological and astrophysical bounds



D. Cadamuro et al., *J. of Cosm. and Astrop. Physics* 2011.02 (2011), p. 003
D. Cadamuro and J. Redondo, *J. of Cosm. and Astrop. Physics* 2012.02 (2012), p. 032

- **HB, Sun, SN1987a** - limits from **stellar evolution** obtained by studying the ratio of horizontal branch (HB) to red giants in globular clusters, by a combined fit of solar data (Sun), and by the study of the SN1987A neutrino pulse duration
- **Telescopes, X-rays, γ-rays** - photons produced in axions decays inside galaxies show up as a **peak in galactic spectra** that must not exceed the known background;
- **x_{ion}** - the ionization of primordial hydrogen caused by the decay photons of axions must not contribute significantly to the optical depth after recombination;
- **EBL** - photons produced in ALP decays when the universe is transparent must not exceed the extragalactic background light (EBL);
- **CMB** - axions decay photons must not cause spectral distortions in the CMB spectrum;
- **BBN** - the decay of high mass ALPs produces electromagnetic and hadronic showers that must not spoil the agreement of big bang nucleosynthesis with observations of primordial nuclei

Current constraints for ALPs: electron coupling

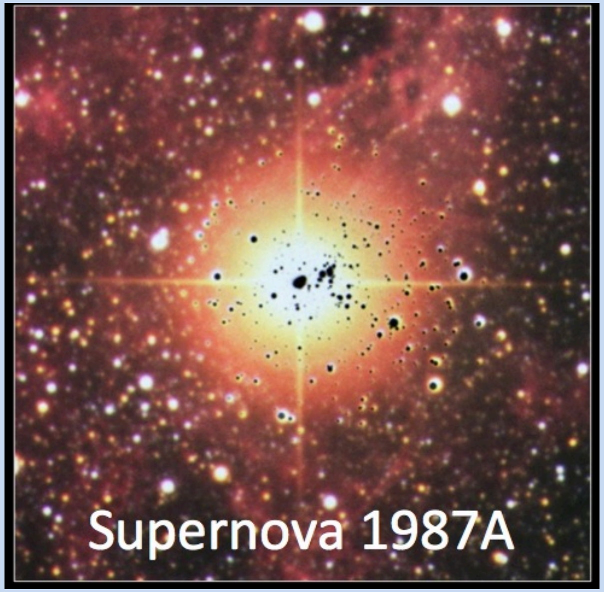


- **HELIOSCOPES / STELLAR PHYSICS**
- **HINTED REGIONS**
- **QCD AXION BAND**

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

Propagation of the photon in the cosmo

- Large scale magnetic B fields exist in astrophysics
- Even if fields are very low (μG, nG), they extend over a very large length L.
- The product BL can then be large: ALPs oscillation with the photon can then be studied



- **SN1987A: ALPs emission due to Primakoff production in core**
- **ALPs partially converted into γ rays in galactic magnetic field (GMF)**
- **No γ rays burst observed in coincidence with SN1987A neutrinos**

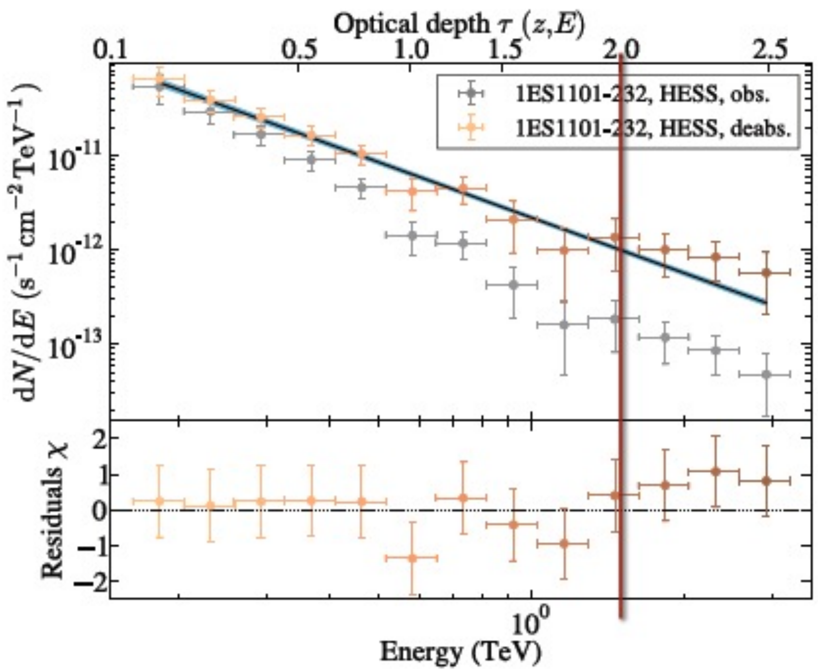
$$g_{a\gamma\gamma} \leq 1\times 10^{-11}\,\mathrm{GeV}^{-1} \text{ for } m_a \leq 10^{-9}\,\mathrm{eV}$$

VHE photons from distant sources

- Gamma rays can interact with **cosmic photon background** (EBL) and produce e-p pairs
- **Optical depth τ is not zero** and the flux follows an exponential law

$$\phi_{\rm obs}(E_\gamma) \;=\; \phi_{\rm s}(E_\gamma) \times \exp\left(-\tau(E_\gamma, z_{\rm s})\right)$$

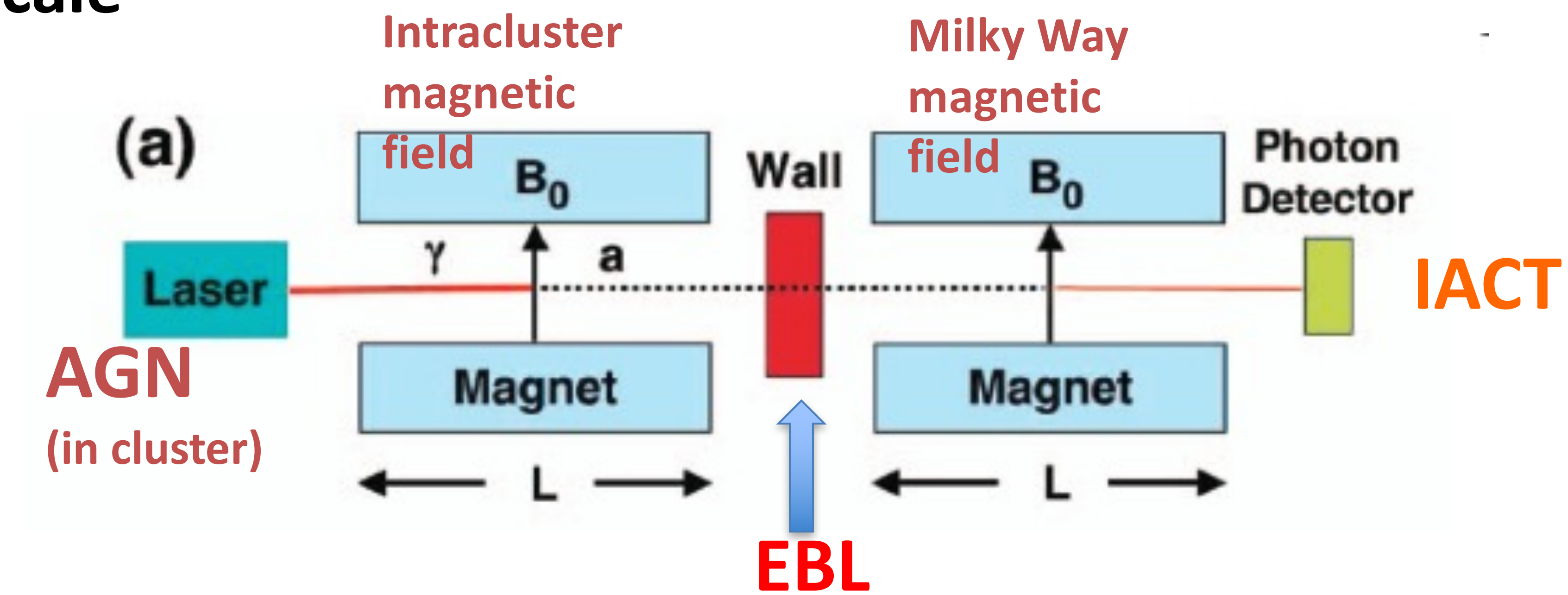
- At present there are **tension between models and data** for energies > 1 TeV



M. Meyer | EPS HEP Stockholm | July 18, 2013 |

ALPs reduced opacity

- An oscillation between VHE photon and ALPs could explain the reduced opacity
- It is like a **regeneration experiment on a cosmological scale**



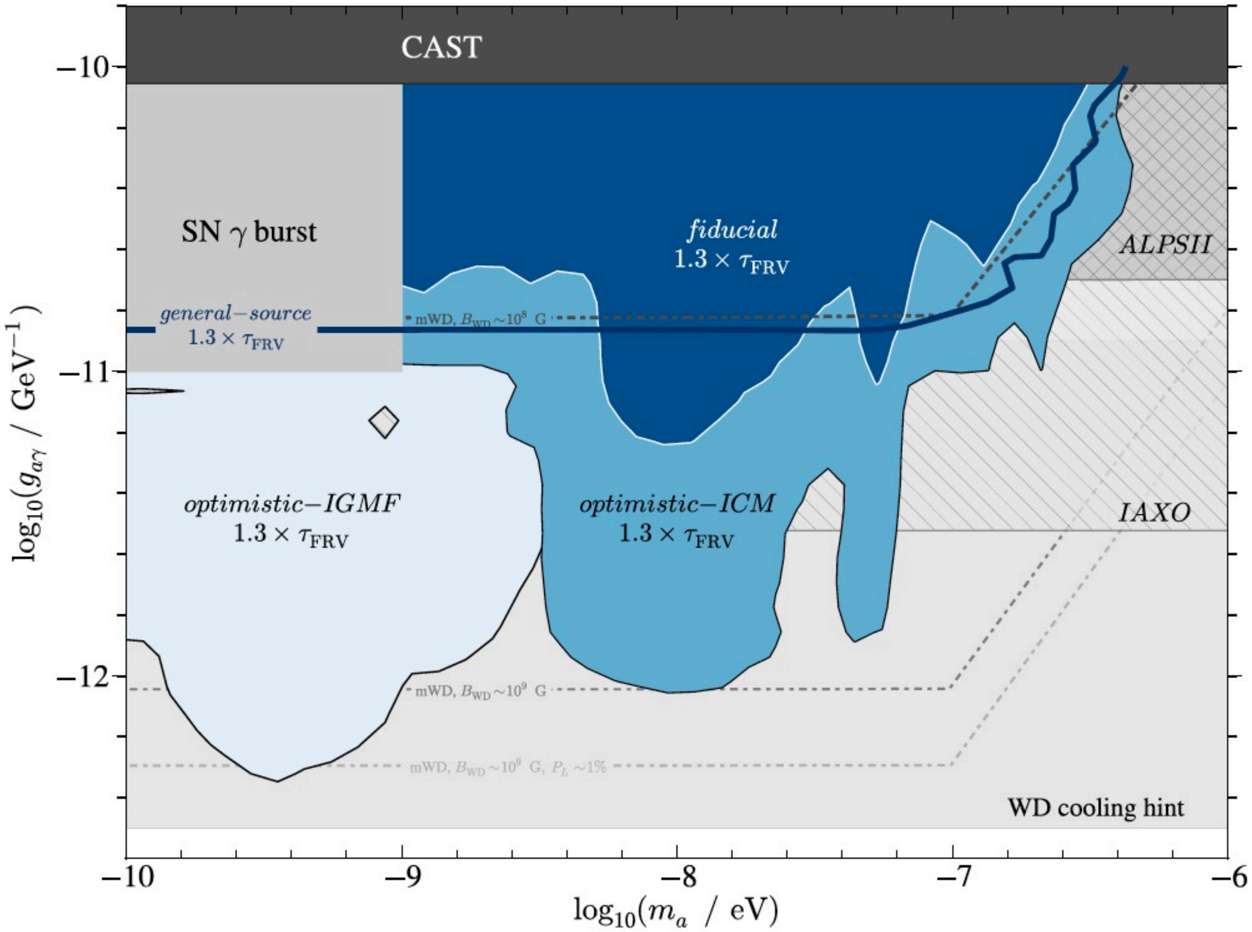
- **Magnetic field value and distribution not very well known (except Milky Way)**
- **Photon number density of EBL not very well known**
- **Not so many sources available**

Latest lower limits

- Meyer, Horns and Raue (2013) used a sample of AGN sources from several IACT to put **lower limits in the ALPs parameter space**

- Different models for magnetic fields

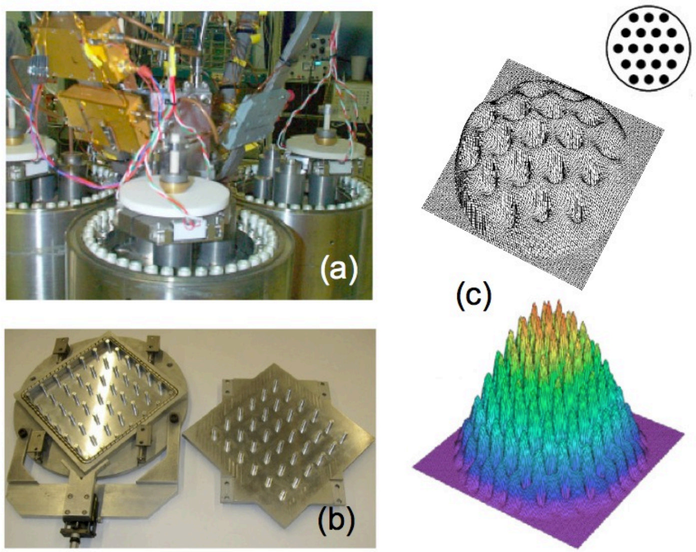
- Limits within the sensitivity estimates of future experiments like ALPS II



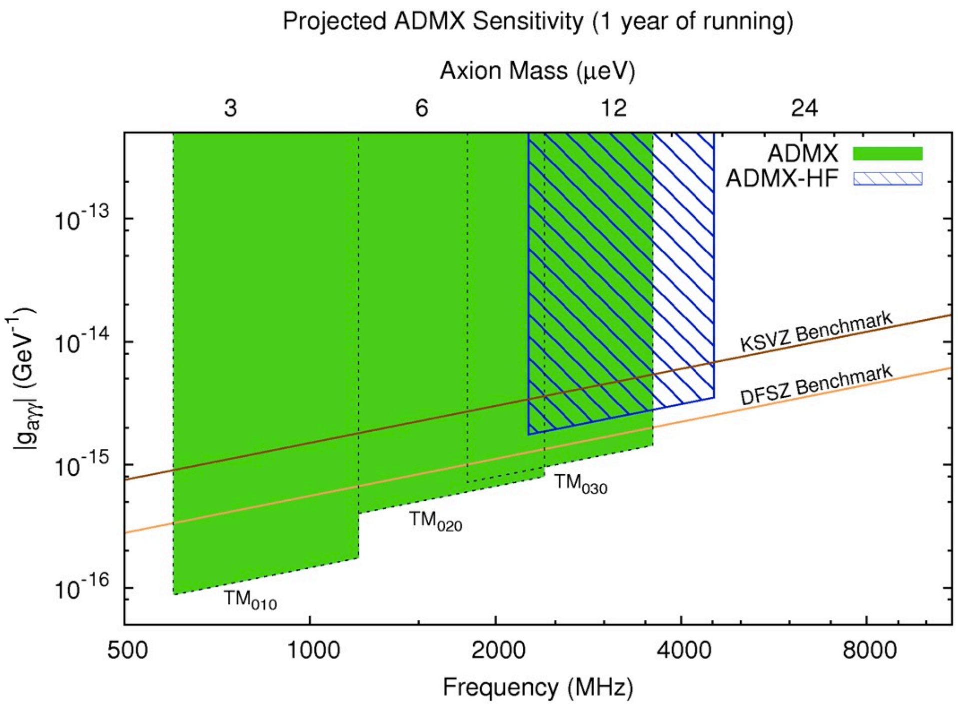
ADMX phase II

- The experiment goes to a second stage with a collaboration between University of Washington and Yale

- New scheme to employ SQUID at higher frequency
- New type of amplifier at frequencies above a few Ghz
- Use higher order modes in the resonant cavity
- Optimize cavity material to obtain higher Qs – hybrid superconducting cavities



Photonic band gap cavity in the multi-GHz range



http://www.phys.washington.edu/groups/admx/future.html