Axion experiments

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

Lecce, September 14th, 2023

COST «Cosmic Wispers» Training School

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Summary

- Axion phenomenology
- Laboratory experiments
- Helioscopes
- Axion dark matter direct searches

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 :

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

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

- The most recent calculation using lattice QCD

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

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

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

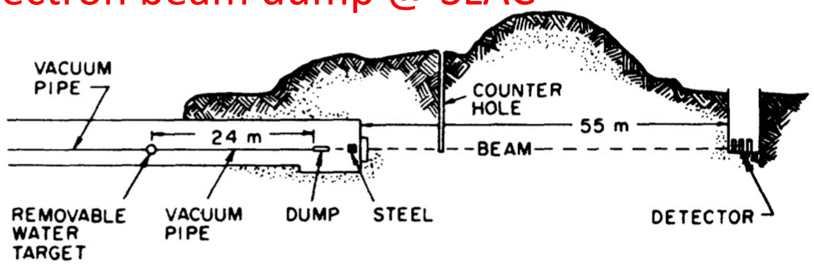
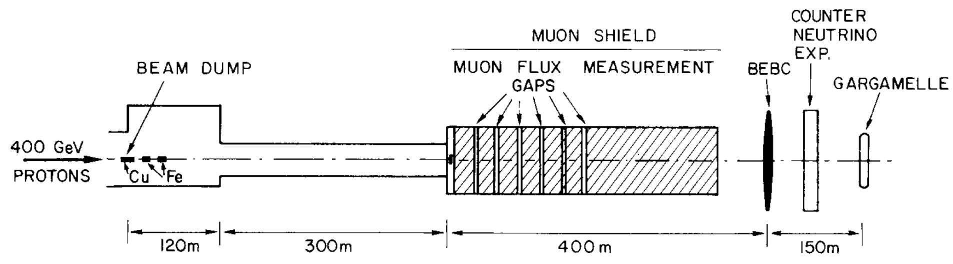


FIG. 2. Schematic of the SLAC beam-dump experiment showing the location of the detector and shielding in relation to the end station A beam dump.

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 f_a **arbitrarily large**

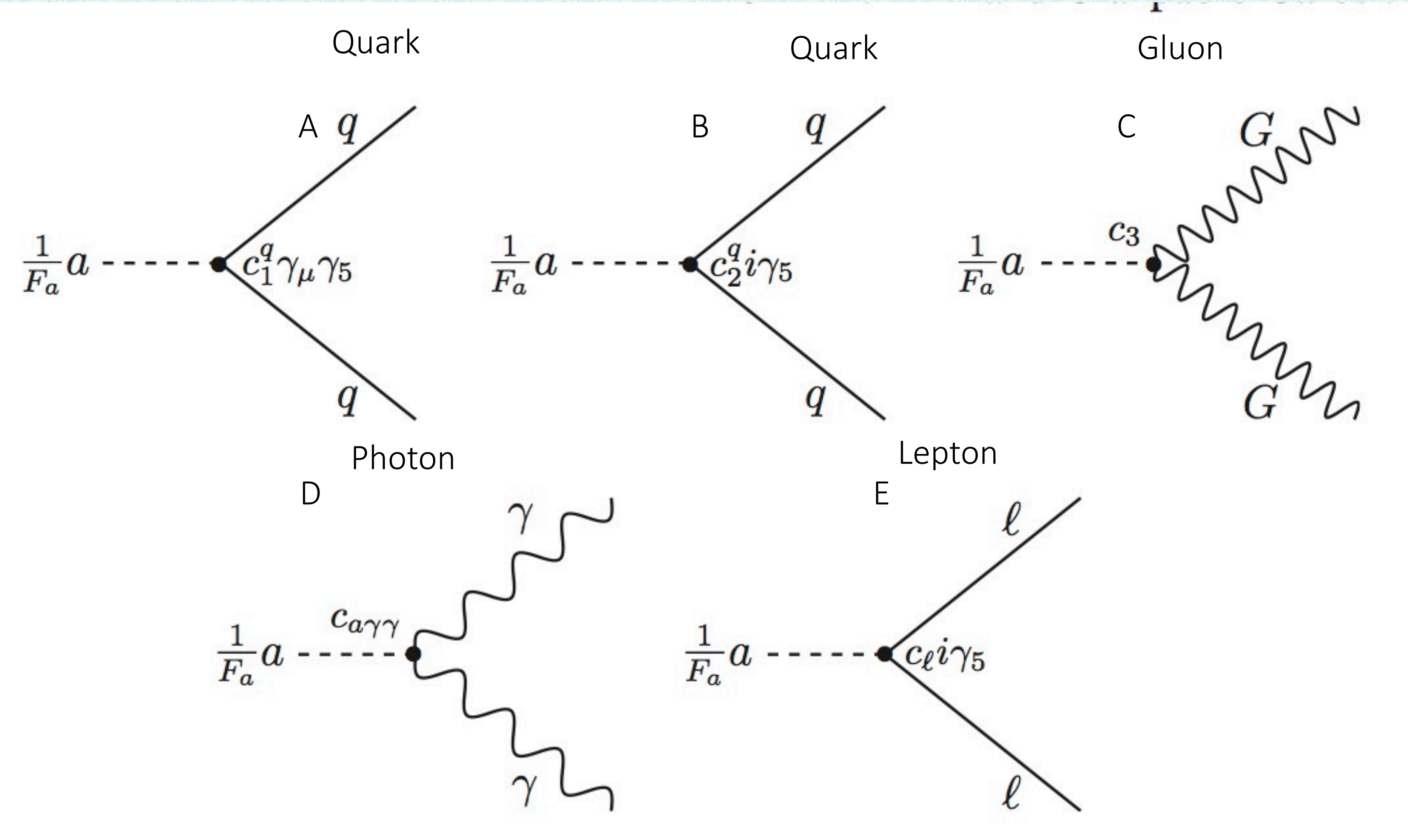
  - **low mass (m_a < eV)** and **very weak couplings** for $f_a \gg v_{weak}$

- 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 f_a, or equivalently **how small 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**

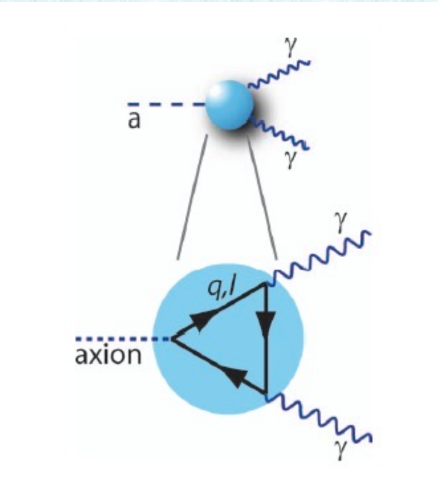
Axion interactions

- Several interactions are possible



Axion interactions 2

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



Axion photon photon

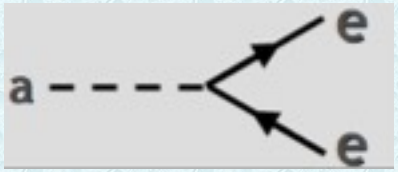
$$\mathcal{L}_{a\gamma\gamma} = -\left(\frac{\alpha}{\pi}\frac{g_\gamma}{f_a}\right) a\vec{E}\cdot\vec{B} = -g_{a\gamma\gamma} a\vec{E}\cdot\vec{B}$$

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

g_γ = 0.36 (DFSZ)

g_γ = - 0.97 (KSVZ)

Axion electron electron



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

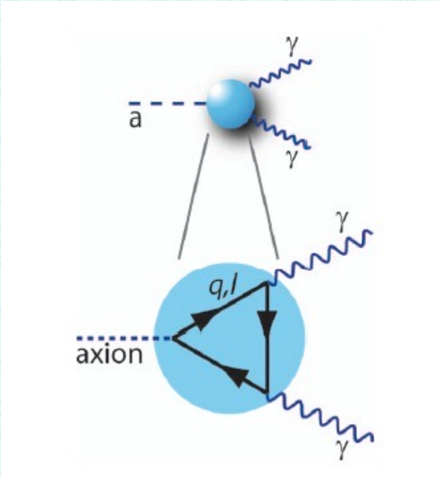
$$g_e \approx \frac{m_a m_e}{m_\pi f_\pi} = 4.07\times 10^{-11} m_a$$ **(DFSZ)**

g_e ~ 0 (Strongly suppressed) (KSVZ)

All couplings are extremely weak!

Axion interactions 3

- Axion interactions are 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

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

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

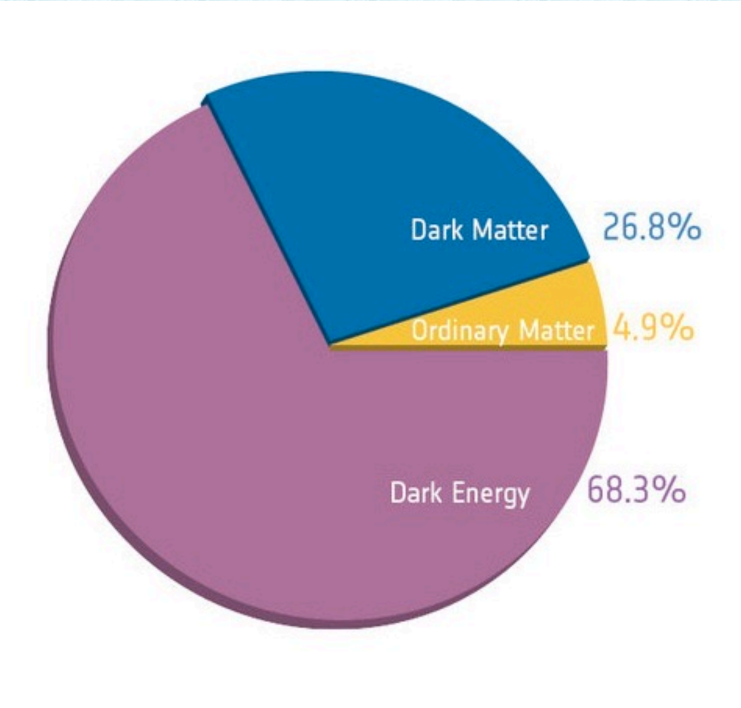
Where $t_U \approx 4\ 10^{17}$ s is the age of the Universe

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

Axions in the outer space

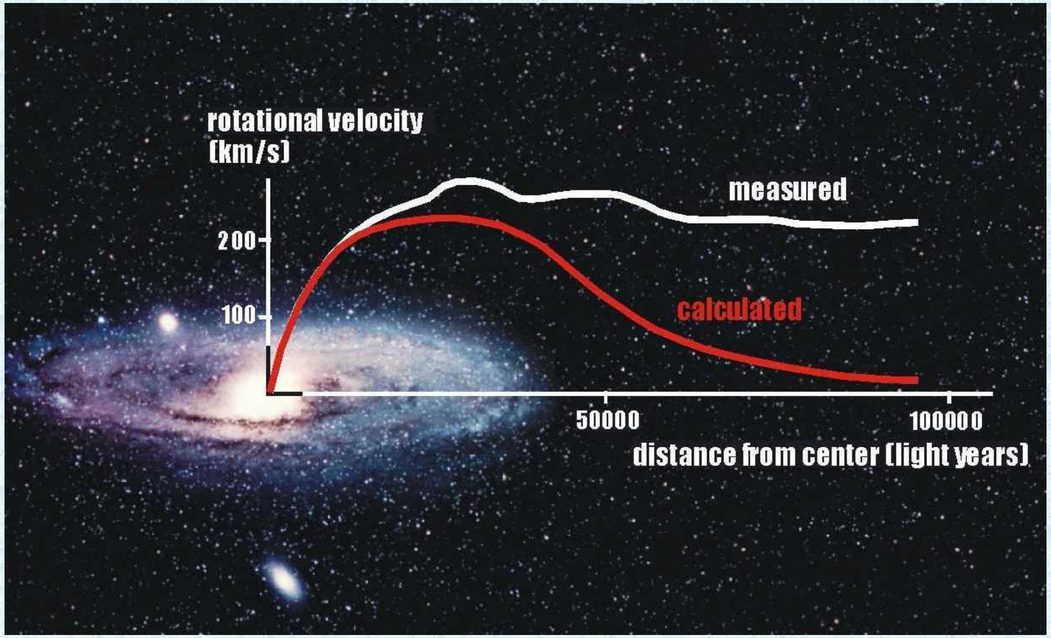
- A **light axion** (m_a < eV) has lifetime that can be longer than the age of the Universe. This kind of axion is indeed important for cosmology.
- **Is it a main component of Dark Matter?**

Composition of the Universe after Planck precise measurement of CMB



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

Typical rotational curve of galaxys



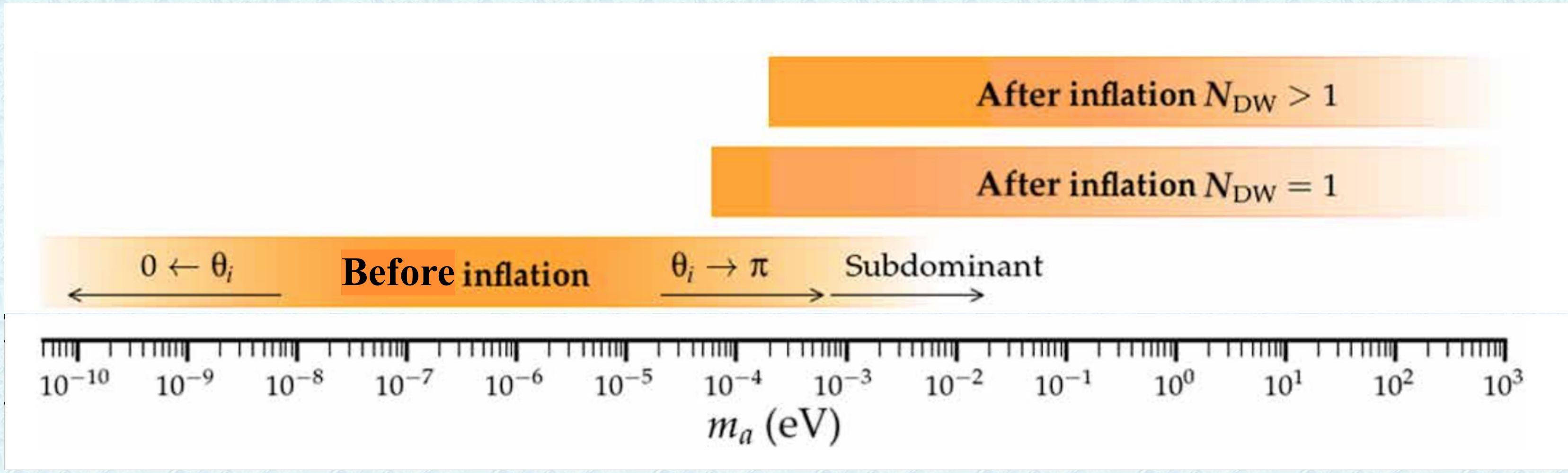
Axions are weakly interacting, stable on cosmological times, non relativistic

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

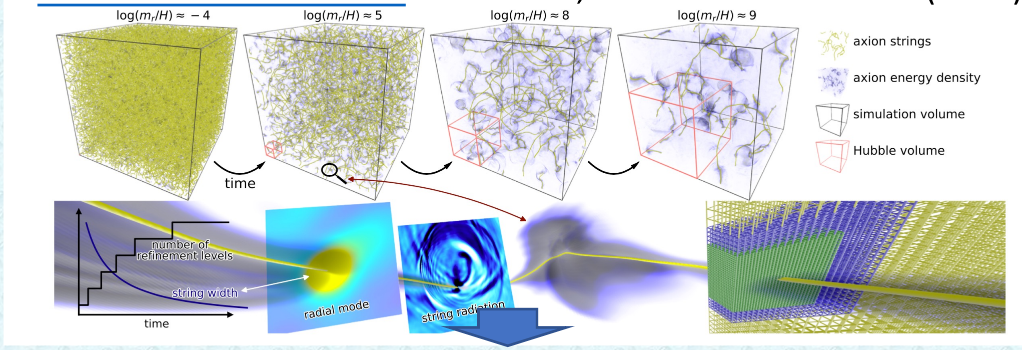
- Difference between the pre- and post- inflationary scenarios is **predictability**:
  - In **pre-inflationary** there are **two continuous free parameters**, an angle θ and the mass m_a, to obtain the observed dark matter density
  - In **post-inflationary** there is one continuous parameter, m_a, 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

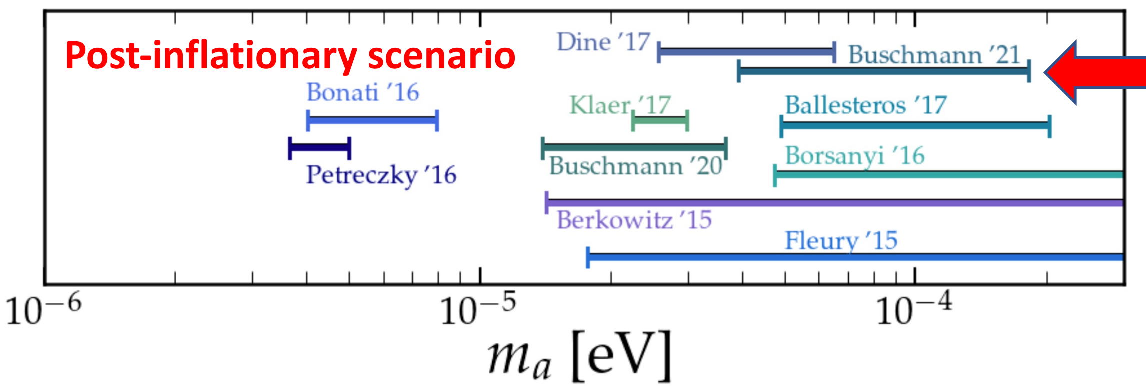
SciPost Select SciPost Phys. 10, 050 (2021)

More axions from strings

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

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**

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**

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

- 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**

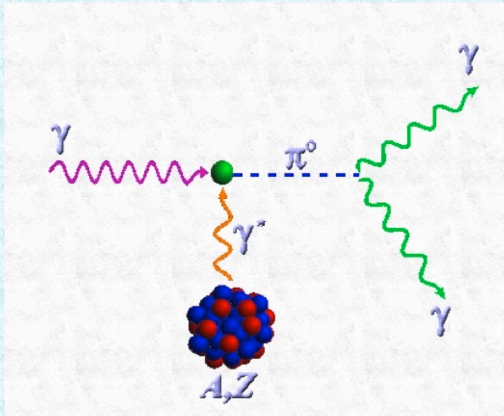
$$\lambda = 1400 \left(\frac{10^{-6}\, eV}{m_a}\right) \text{m}$$

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

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)

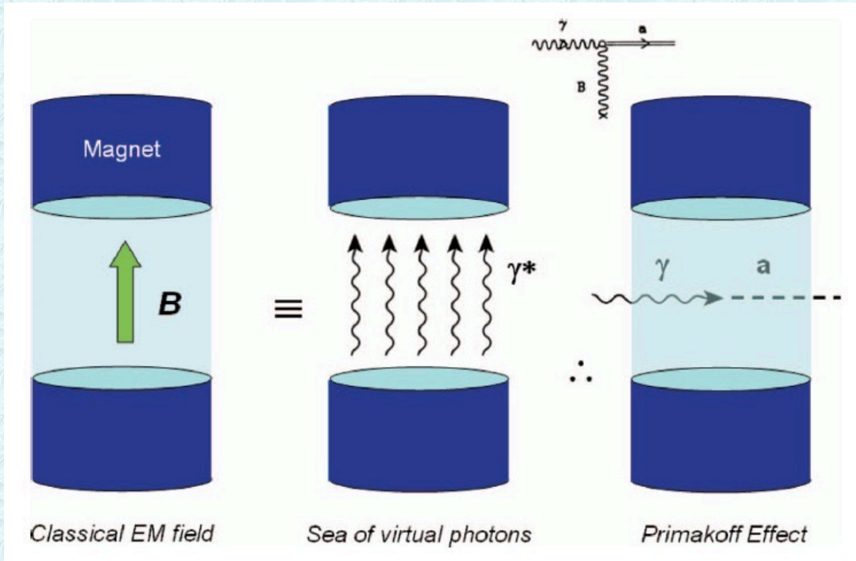


In the presence of an **external field** (magnetic or electric) the **axion and the photon mix** and give rise to **oscillation/conversion**

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

- **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

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

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

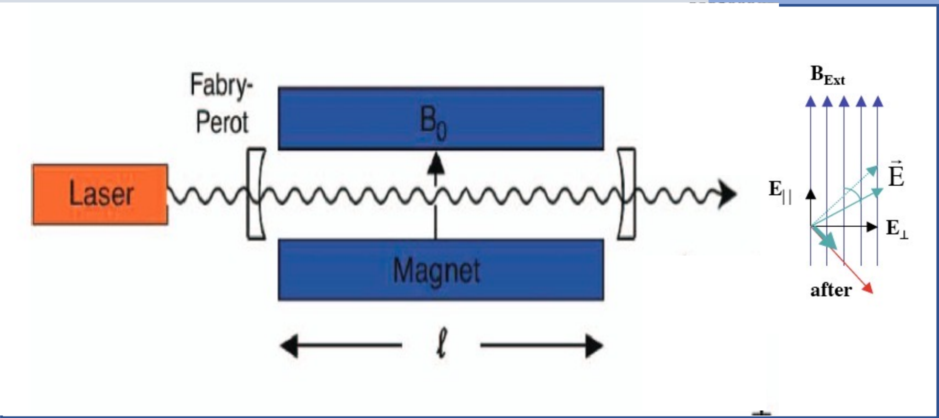
D. Astrophysics, cosmology: stellar evolution/dynamics, γ ray transparency

Detection schemes

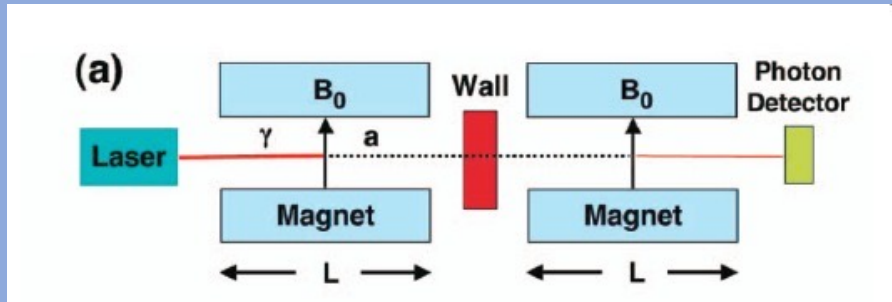
- Most of the searches based on the **axion-photon coupling**

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

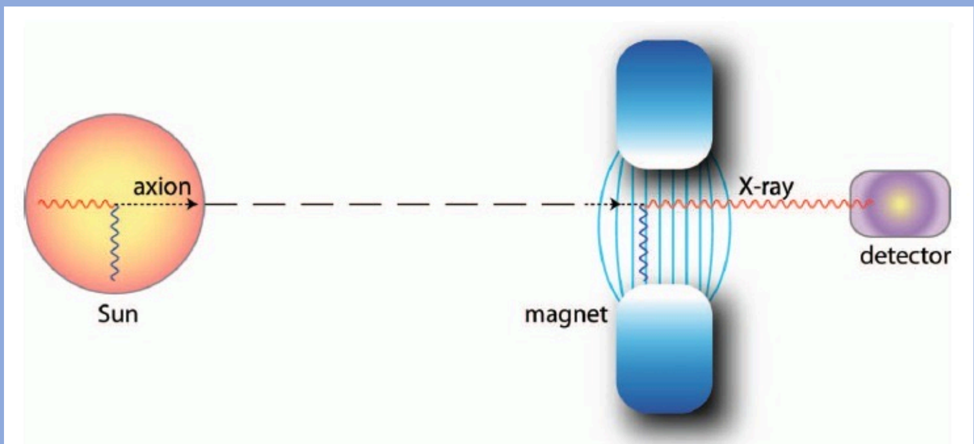
Polarization experiments



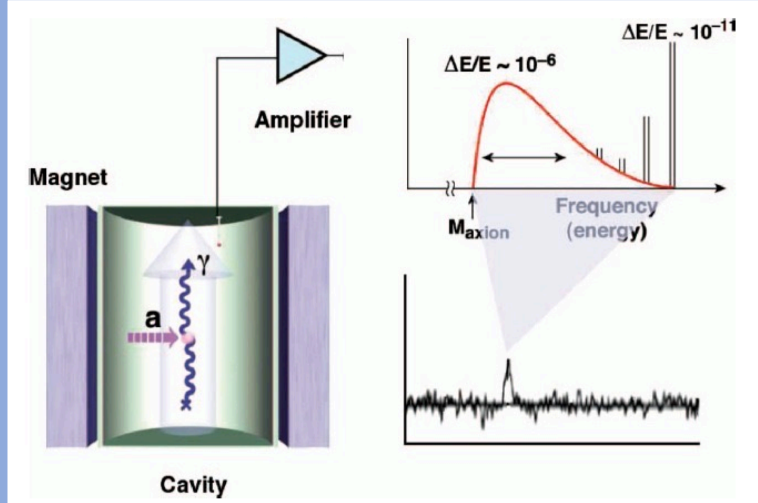
Light shining through walls



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

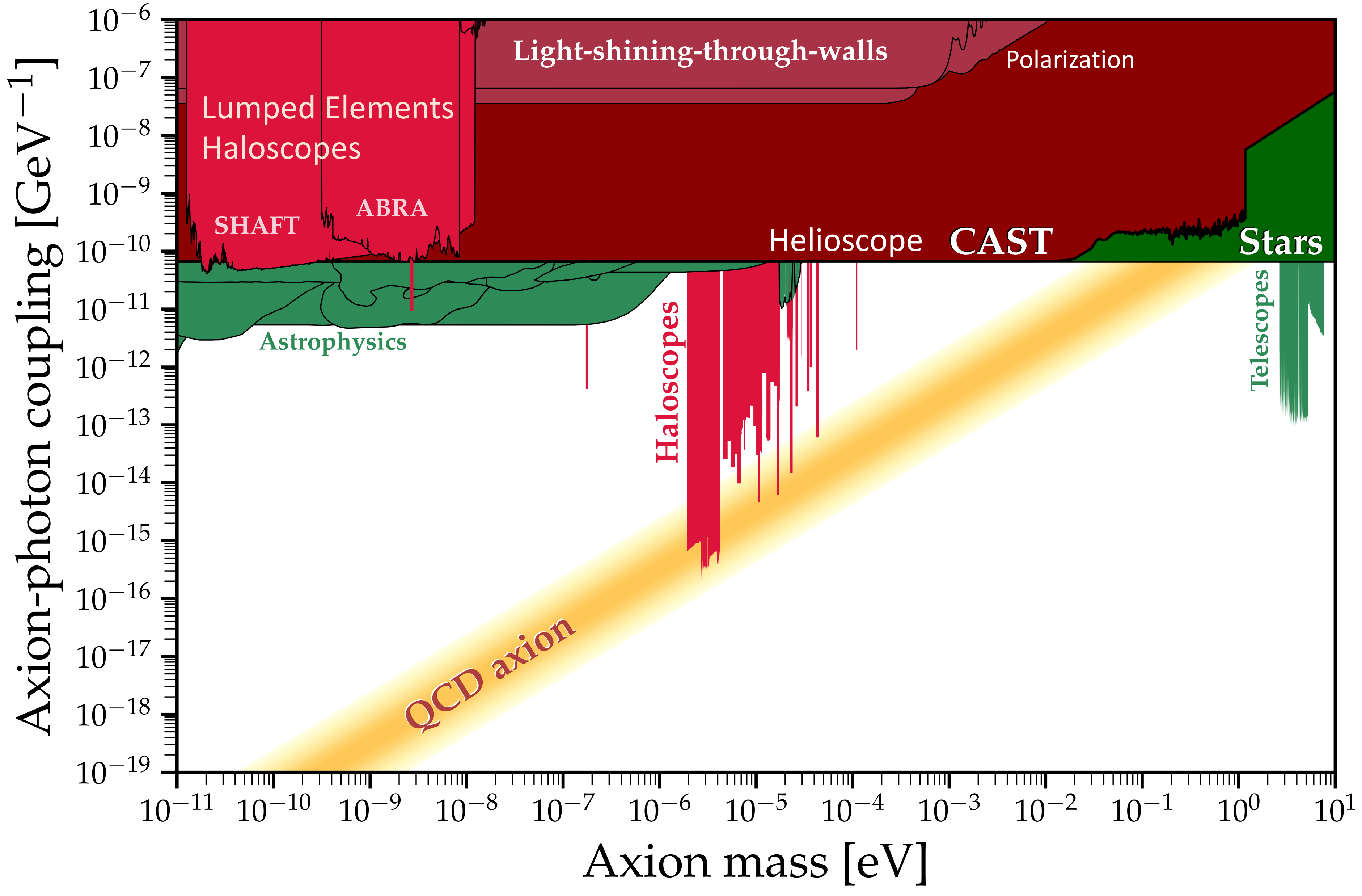


C **Detection of axions present into the Galactic Halo -Haloscopes**



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

Current constraint – Axion Photon Coupling

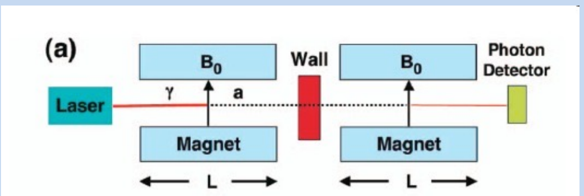


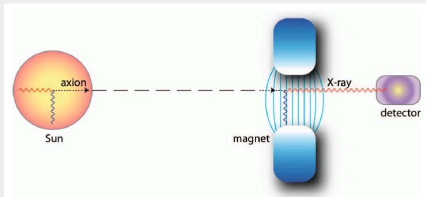
$$\nu_a = 0.24\left(\frac{10^{-6}\,eV}{m_a}\right)\ \text{GHz}$$

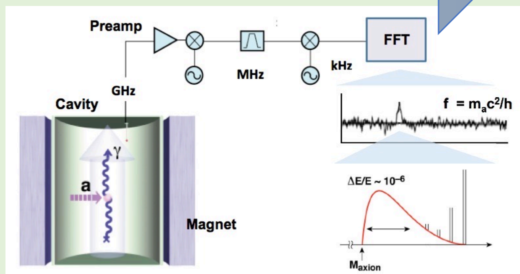
https://cajohare.github.io/AxionLimits/docs/ap.html

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

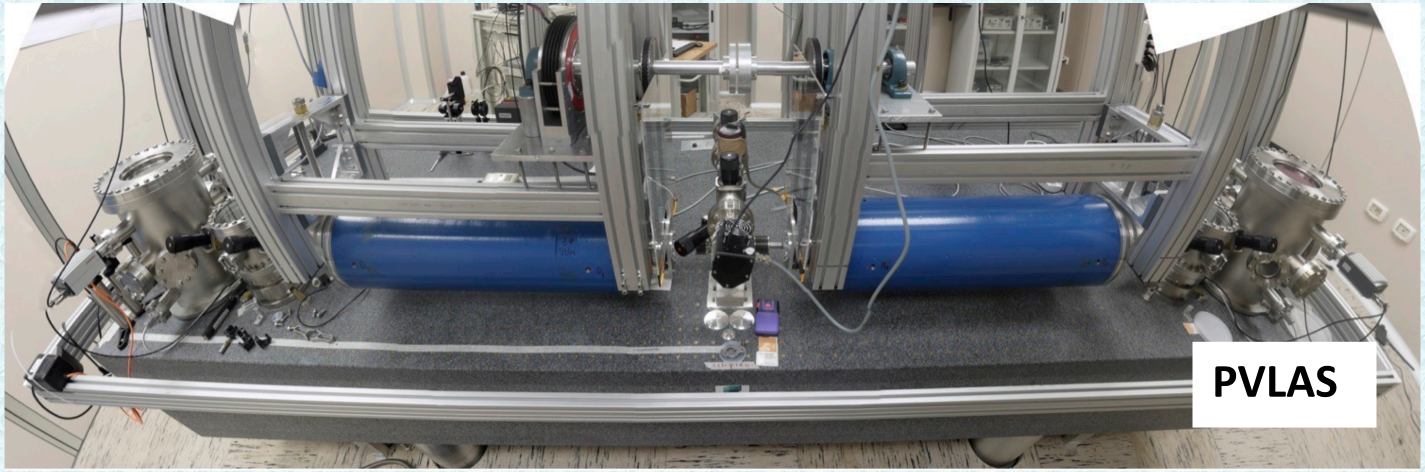




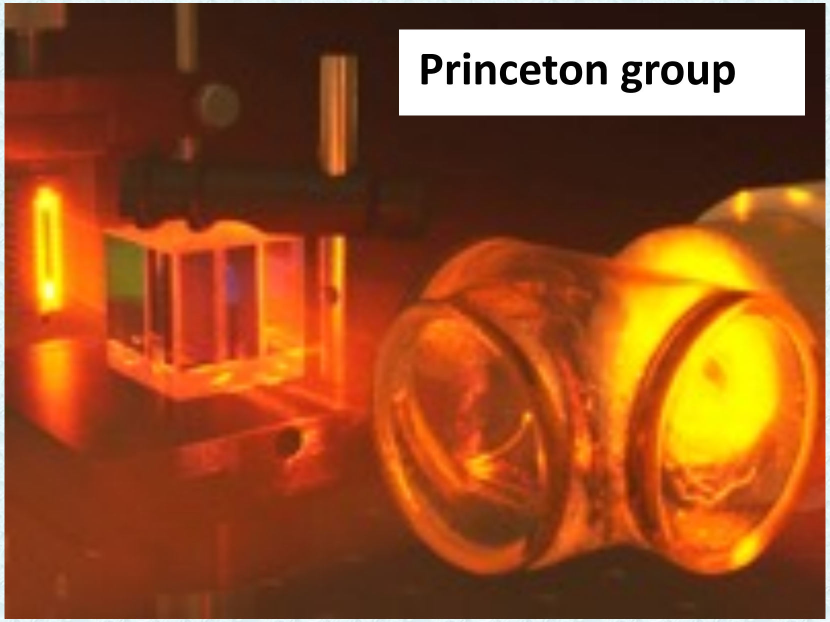


[A] Pure laboratory experiments

Polarization experiments



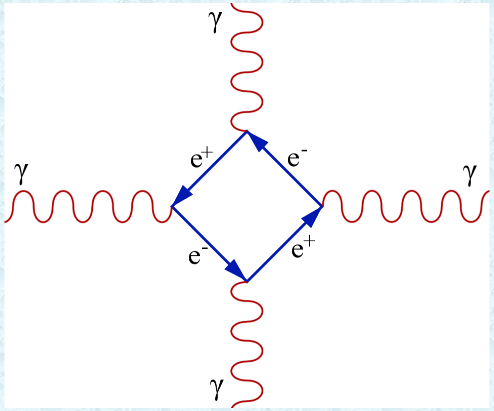
Fifth force measurements



Light shining through walls

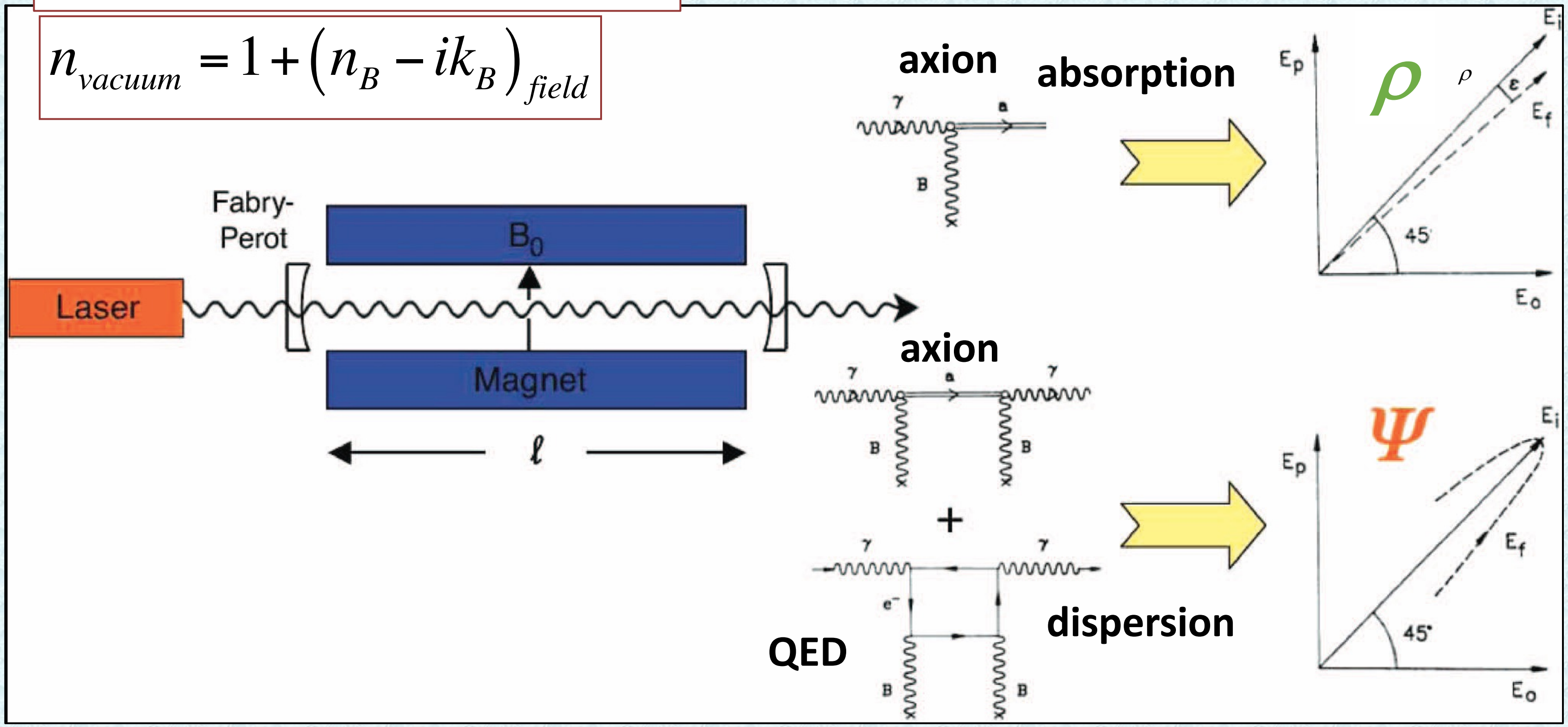
[A.1] Pure lab: Polarization experiments

- 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**

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

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

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

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 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

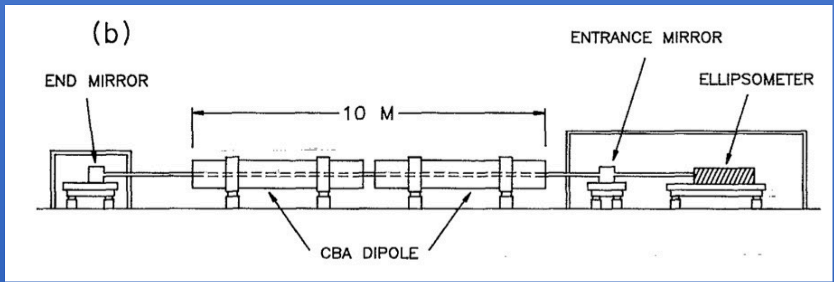
Peak sensitivity depends on magnet length *L*

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

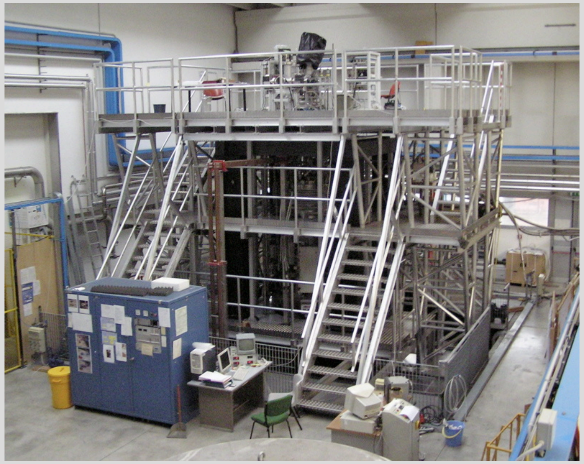
Polarization experiments apparatuses

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

Multipass cavity
N ~ 500



PVLAS @ Legnaro (1992 – 2008)



Fabry-Perot
N ~ 50 000

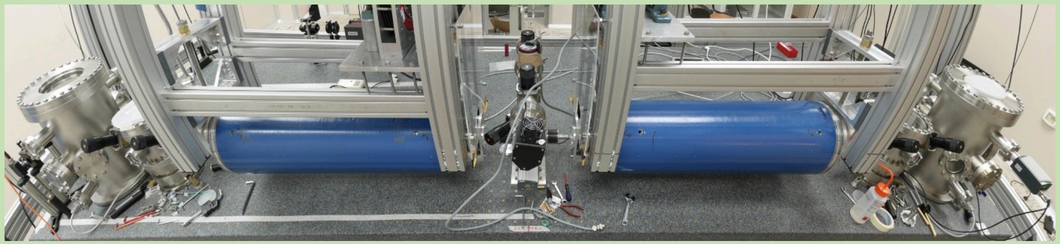
5 T
Rotating Super-conducting Magnet

BMV @ Toulouse (going on)

Fabry Perot
N ~ 300k

Pulsed Magnets

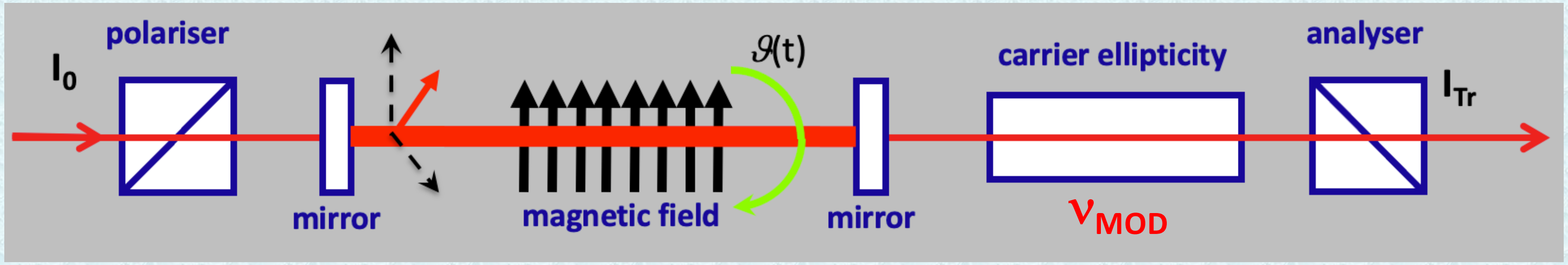
PVLAS @ Ferrara (2009-2019)
Rotating permanent magnets
Fabry Perot N ~ 500k



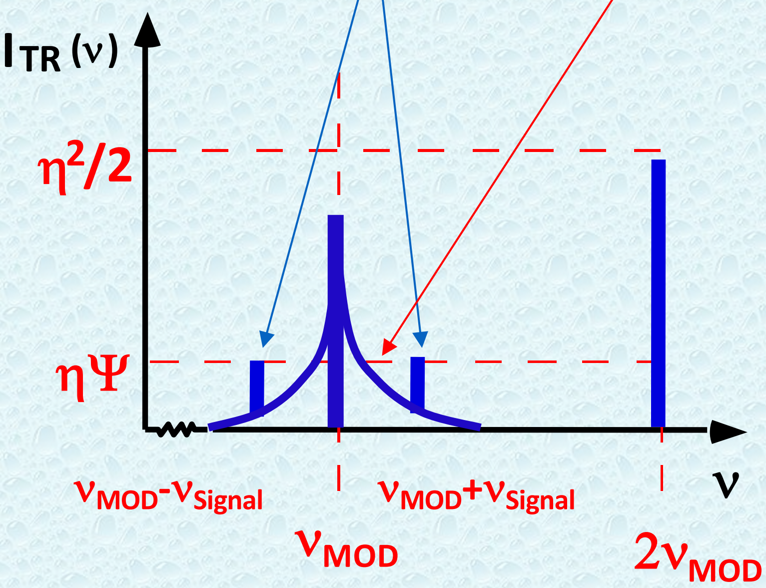
Other apparatuses: **Q&A (Taiwan), OSQAR (CERN)**

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

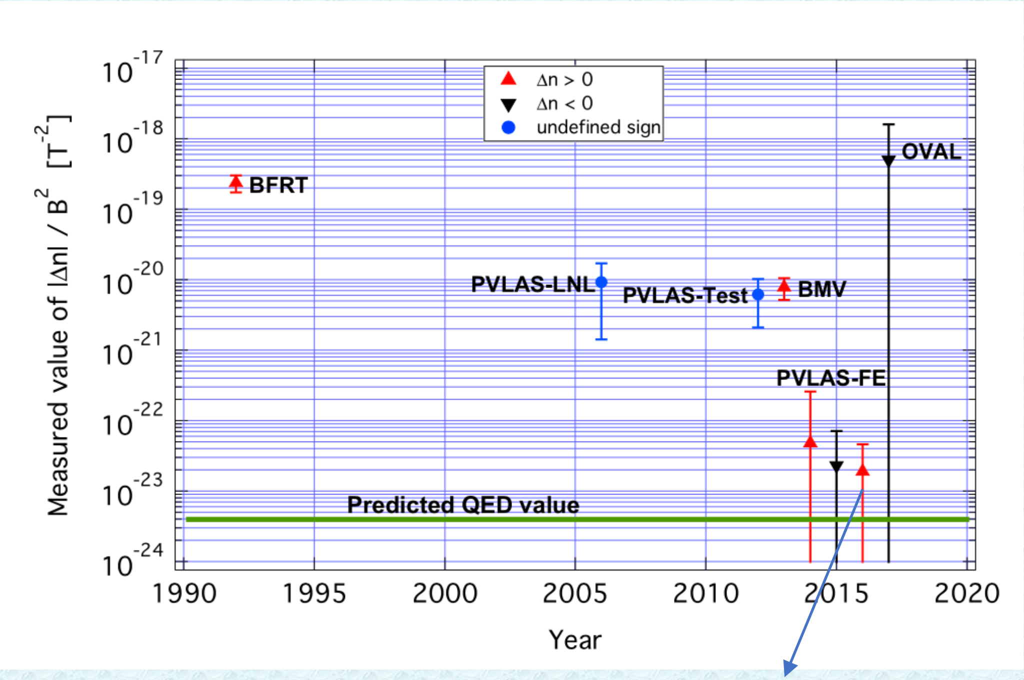
PVLAS @ Ferrara

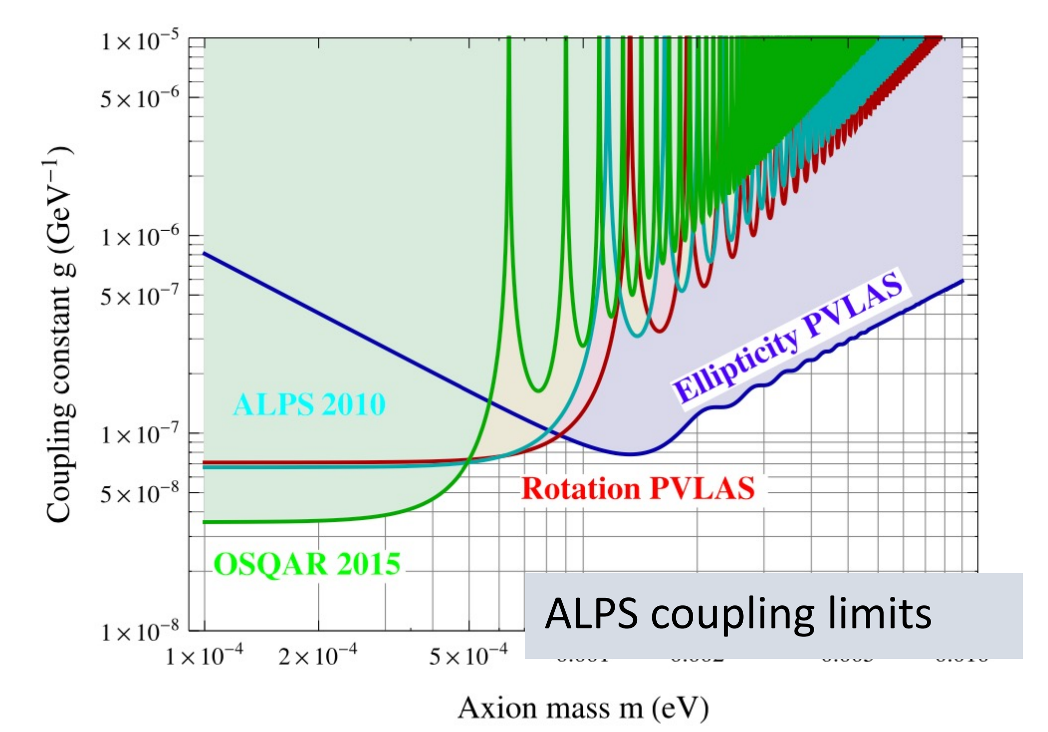
- A **new redesigned apparatus** with respect to Legnaro
- Based on **two permanent magnet 1-m long, 2.5 T** rotating up to **10 Hz** (reduced 1/f noise)
- **Ultra high finesse optical cavity: L = 3.3 m ; F = 770 000 ; amplification factor N = 450 000**
- Optics suspended on a **single granite optical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

Final results

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

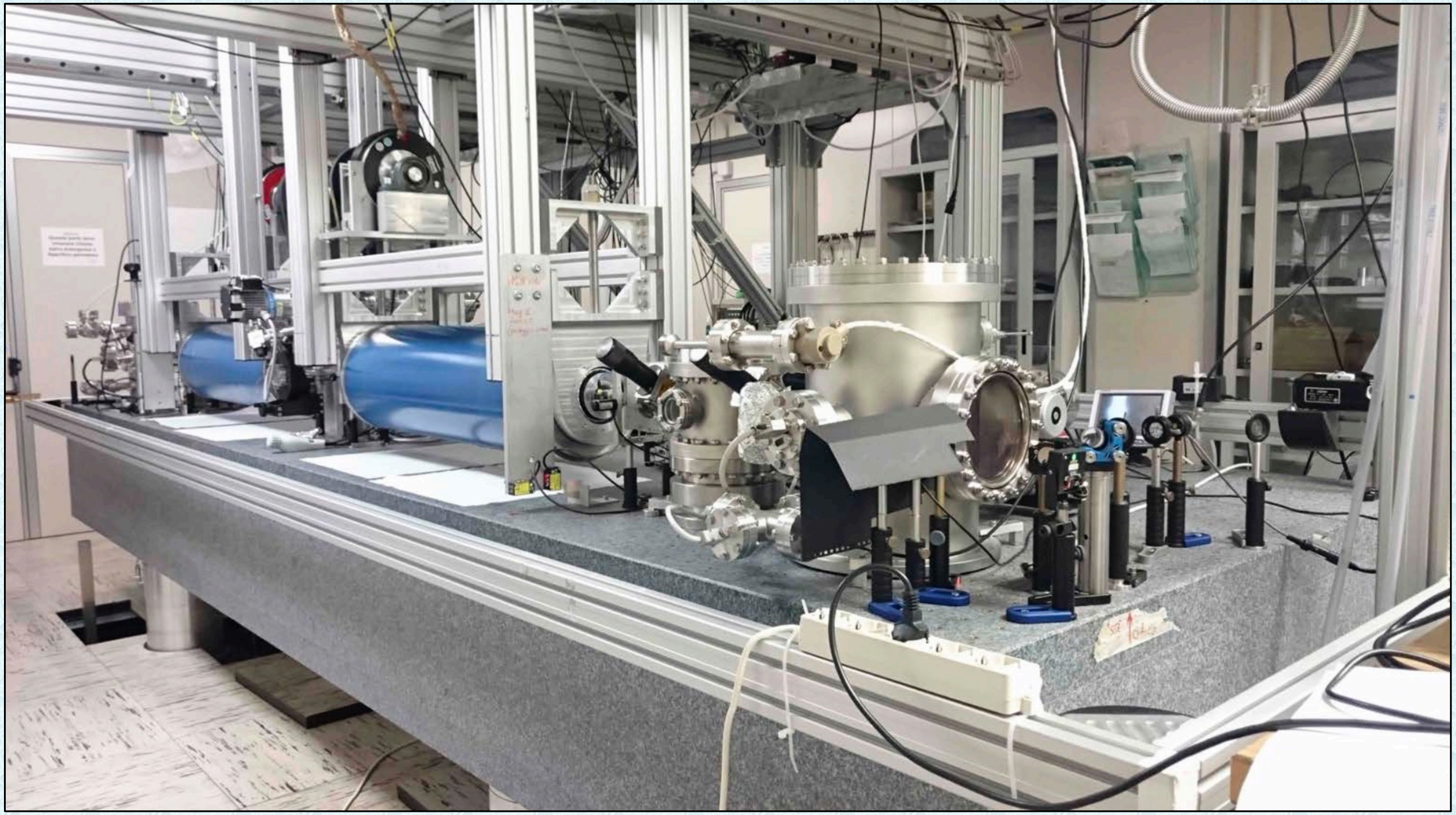
Physics Report 871, 1 (2020)



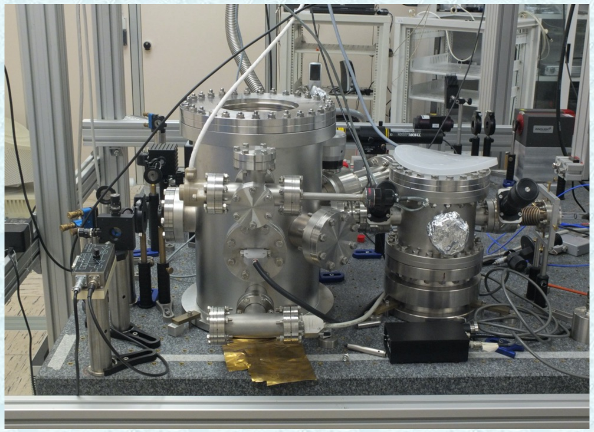


PVLAS total integration time 5 10^6 s

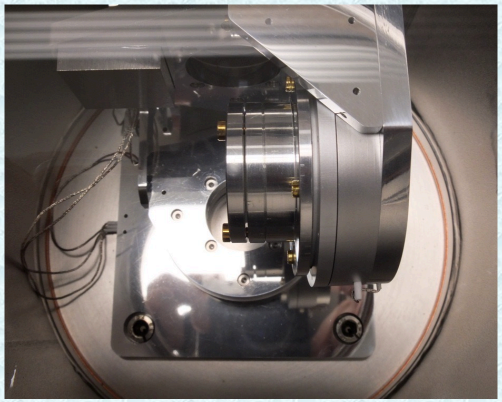
PVLAS @ Ferrara



Complete apparatus



Vacuum chambers



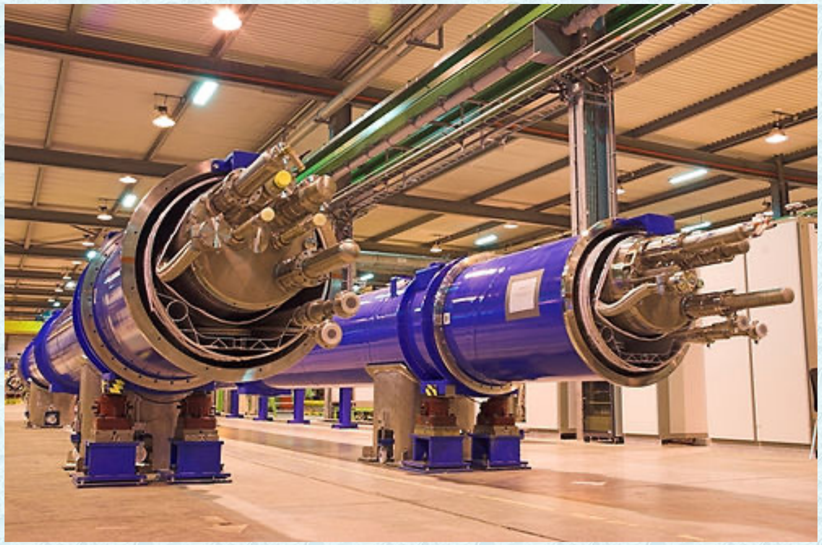
Movable mirror holder

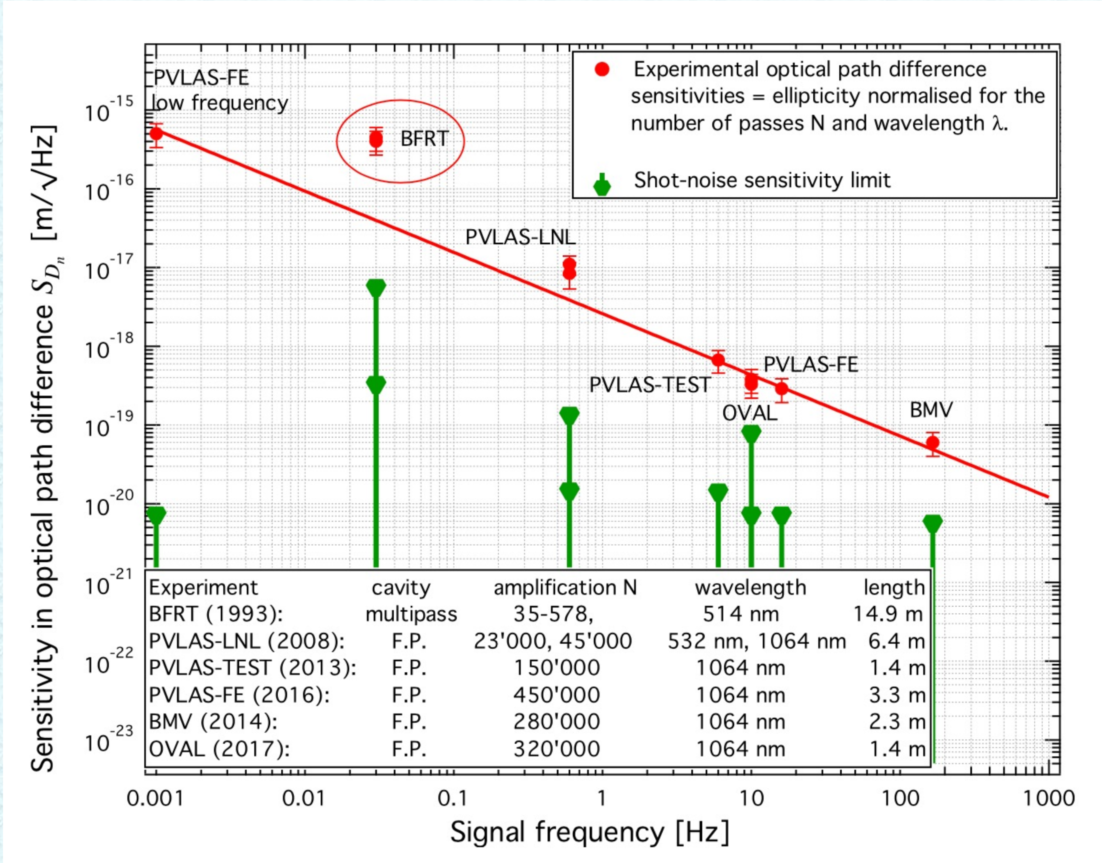
PVLAS extension: VMB@CERN

- 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**





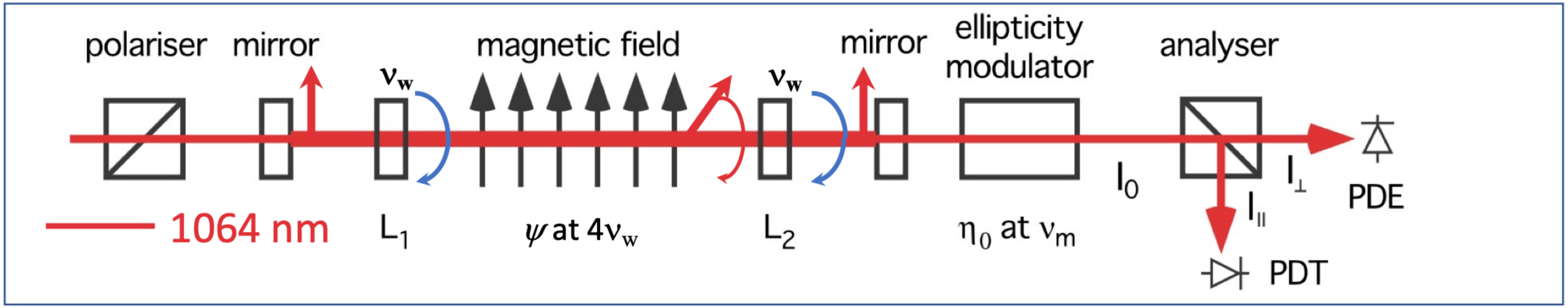
Competing experiments:

- **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

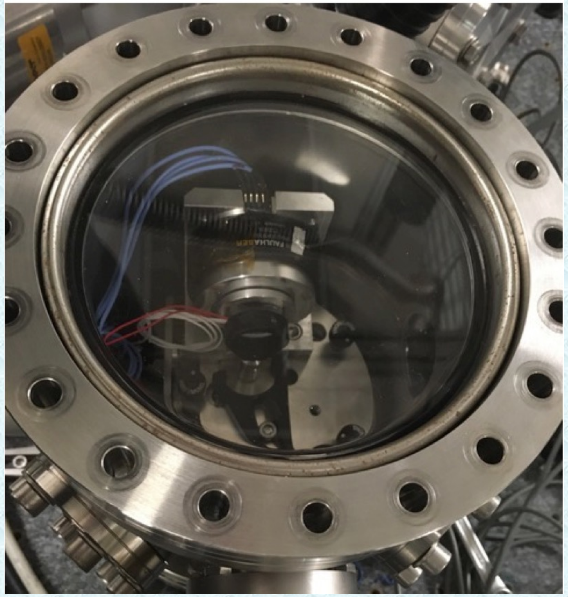
Allows the use of (quasi) static superconducting fields with $B_{ext}^2L \approx 1000\ T^2m$ (LHC dipole)

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

VMB@CERN : project postponed

- Careful experimental studies of several critical points

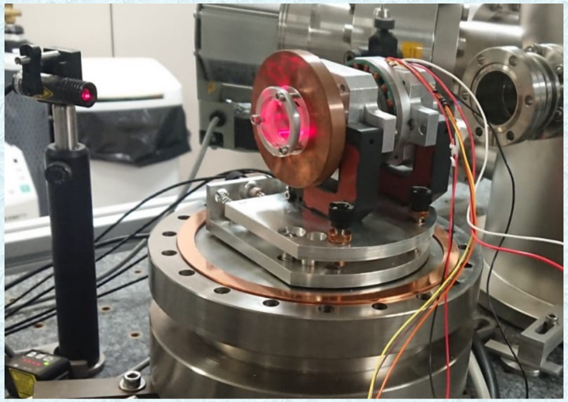
Rotating waveplate with temperature stabilization system



- <u>Method issues</u>
  - ✓ 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 $\alpha_{1,2} << 1/N$ for correct functioning of the F.P.
  - ✓ Lock the laser to the F.P. with the rotating HWPs inside

- <u>Noise issues without F.P.</u>
  - ✓ 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

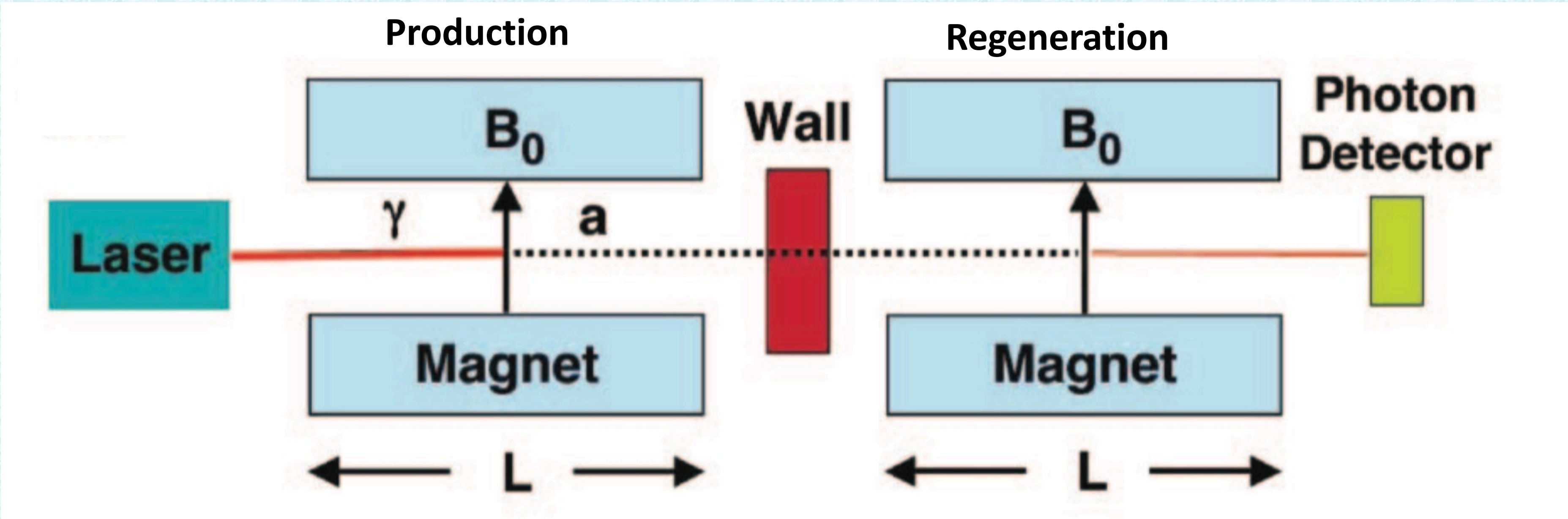
- <u>Cavity issues</u>
  - ✓ Cavity locking with non-rotating HWPs and noise determination
  - ✓ Cavity locking with rotating HWPs: (dust issues, intensity noise, extinction)
  - ➢ Noise determination with the F.P. and rotating HWPs
  - ➢ Required optical path difference noise $S_{\text{OPD}} \approx 10^{-18}$ 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

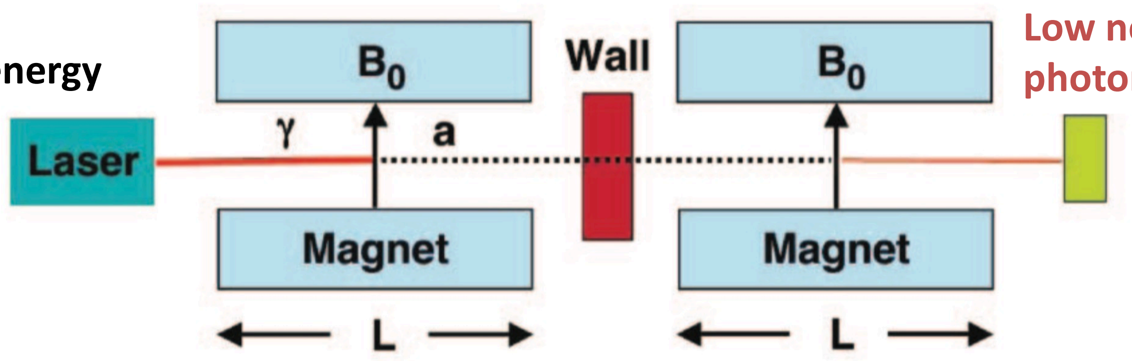
[A.2] Pure lab: light shining through walls (LSW)

- **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

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

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

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

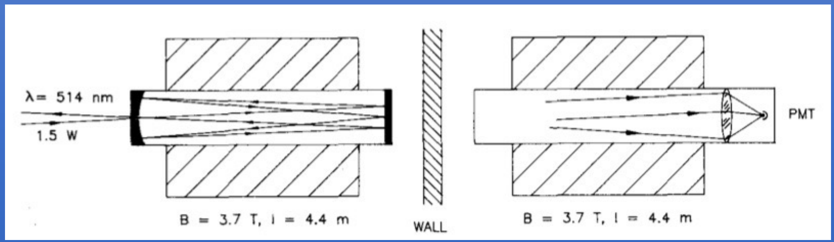
Figure of merit

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

- **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

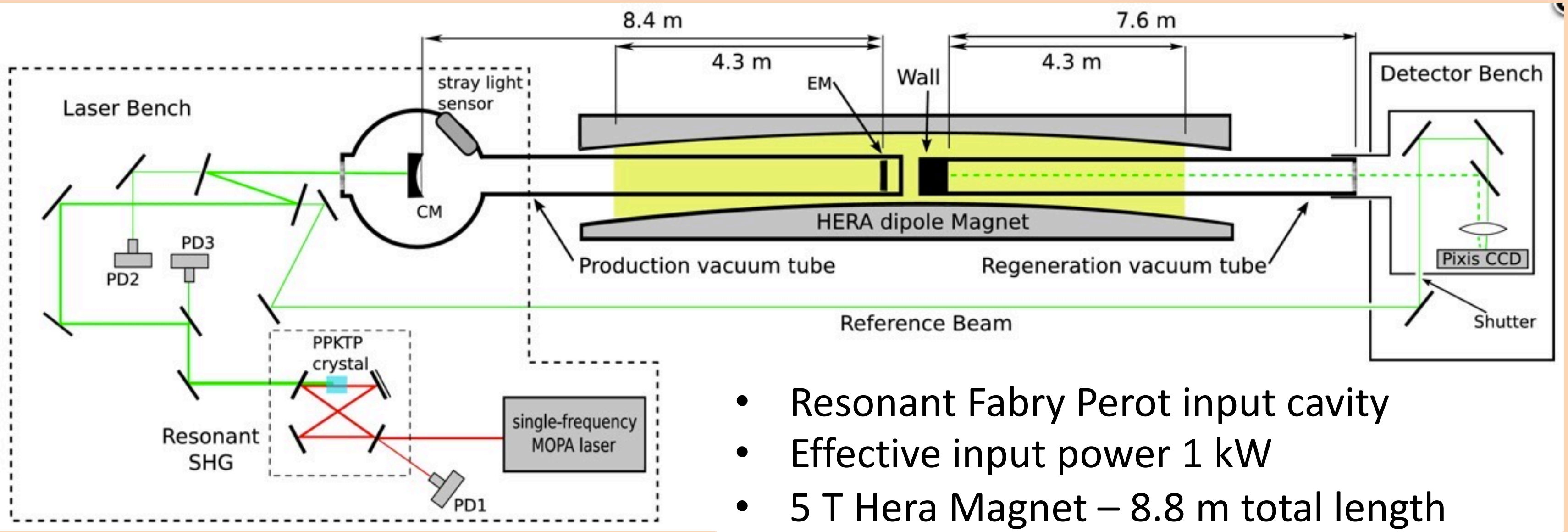
Spare LHC Dipoles

9 T over 14.3 m

20 W cw Laser

State of the art CCD detector

ALPS I experiment @ DESY



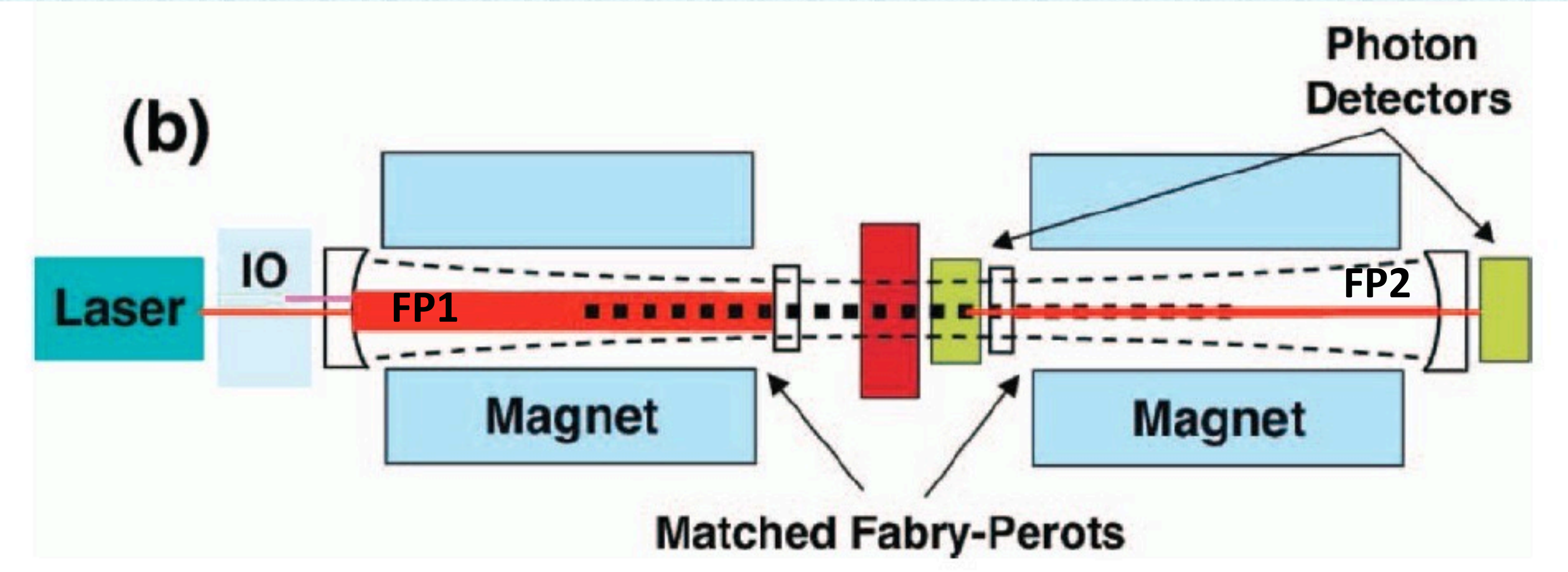
- Resonant Fabry Perot input cavity
- Effective input power 1 kW
- 5 T Hera Magnet – 8.8 m total length
- CCD detector

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**



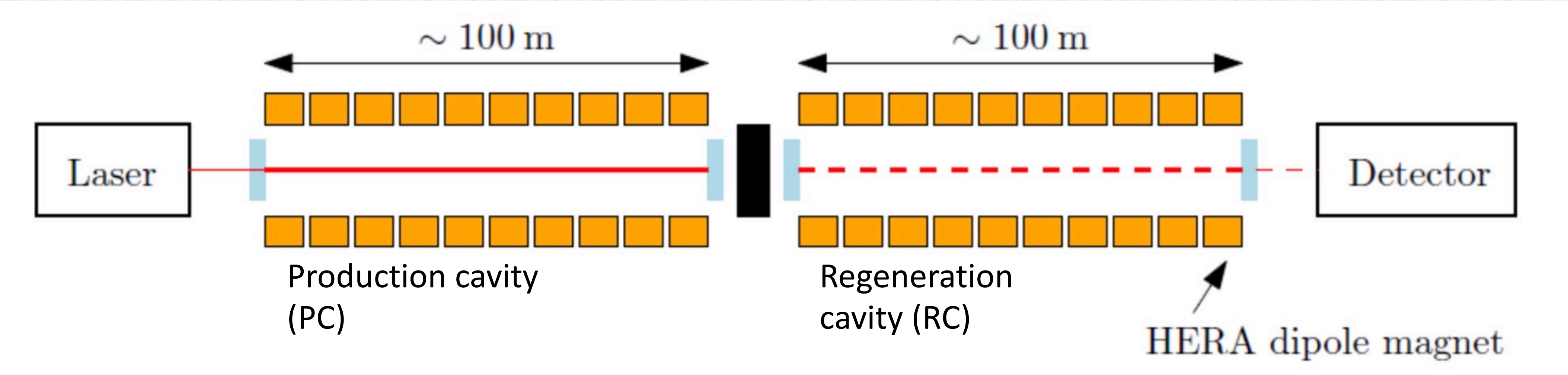
$$\mathrm{sens}(g_{a\gamma\gamma}) \propto \frac{1}{BL}\,\frac{\omega}{P^{1/4}(F_1F_2)^{1/4}}\,\frac{N^{1/8}}{t^{1/8}}$$

- 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				$\boxed{3082}$

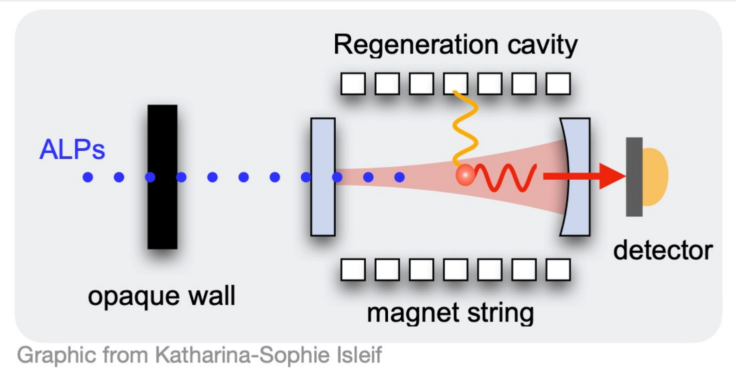
Among the challenges to be addressed:

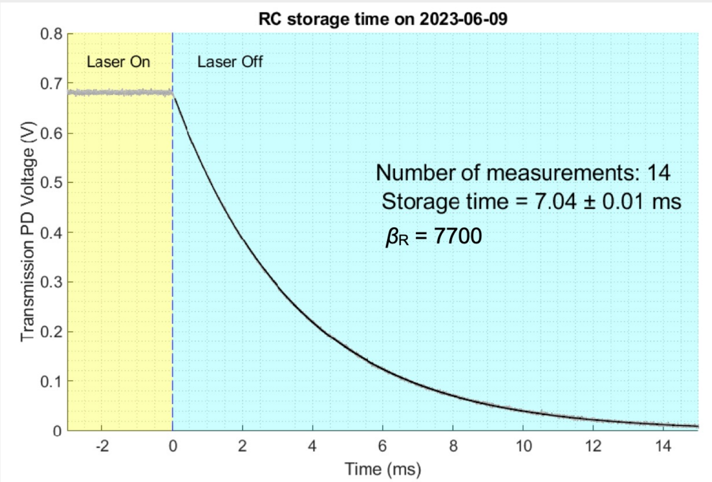
- Frequency matching of two high finesse FP cavity (mode matching by design)
- Single photon detection with ultra low noise
- Adaptation of HERA magnets (curved) to linear cavity

ALPS II: status / progress

Longest storage time Fabry Perot cavity ever!

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



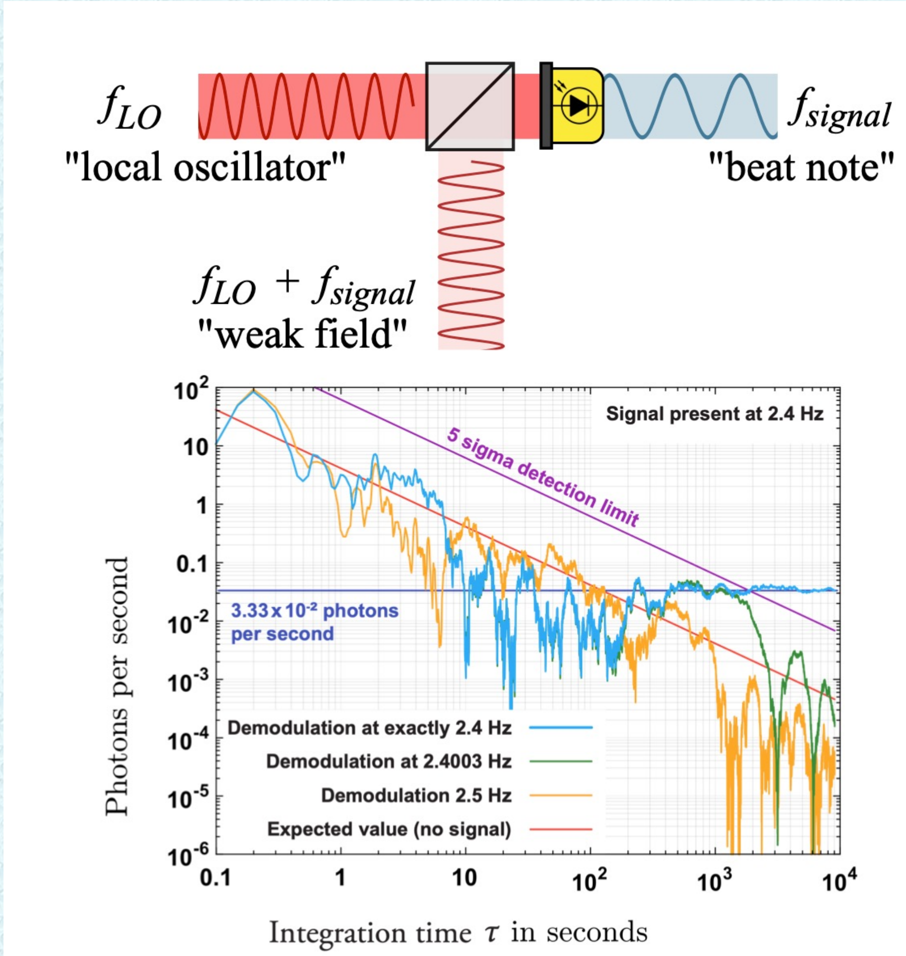


β – resonant enhacement vs single pass

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 $5\cdot10^{-21}$ W demonstrated.
- Sensitivity of 10^{-24} W demonstrated.



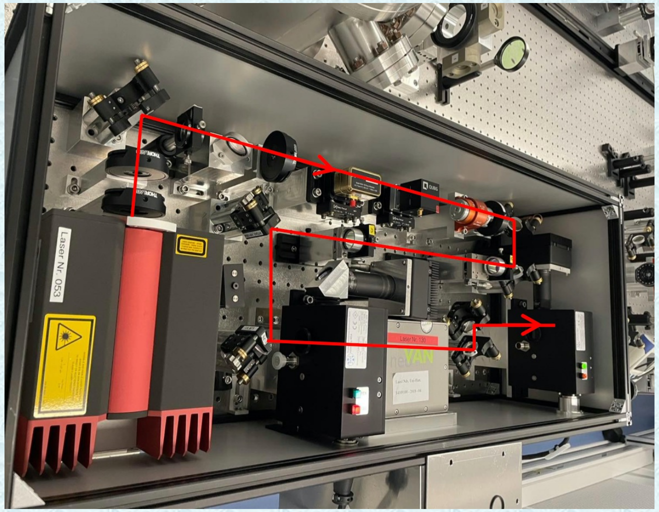
Z. Bush et al., Phys. Rev. D 99, 022001 (2019)

ALPS II @ DESY

HIGH POWER LASER SOURCE

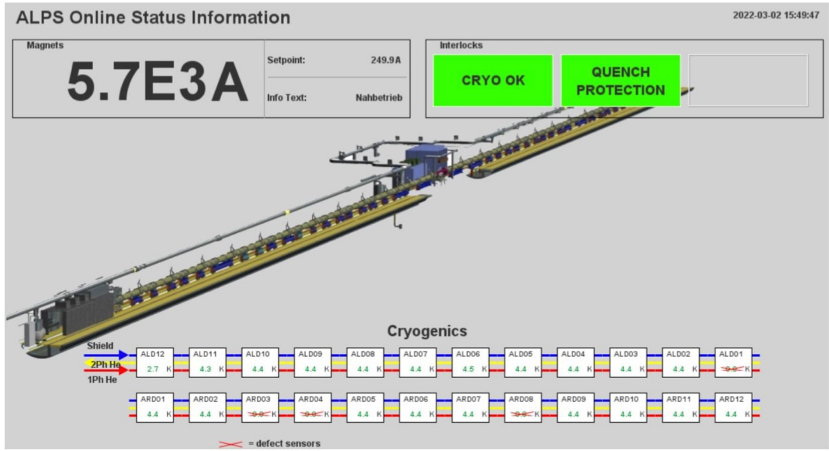
Amplified Non Planar Ring Oscillator (NPRO)

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

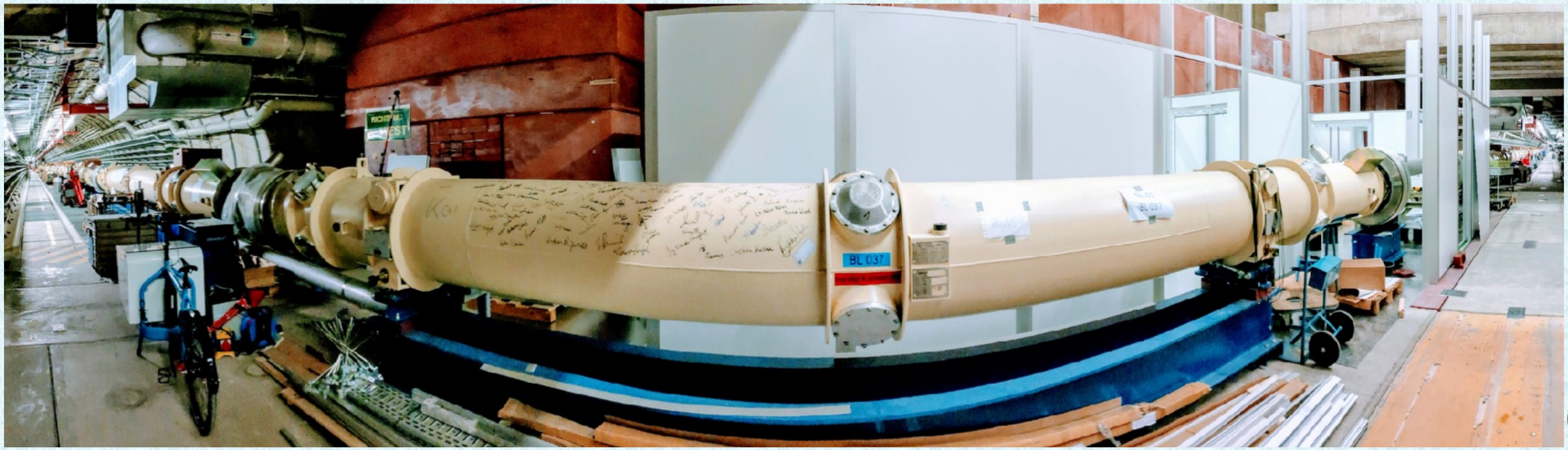


MAGNET STRINGS

- 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

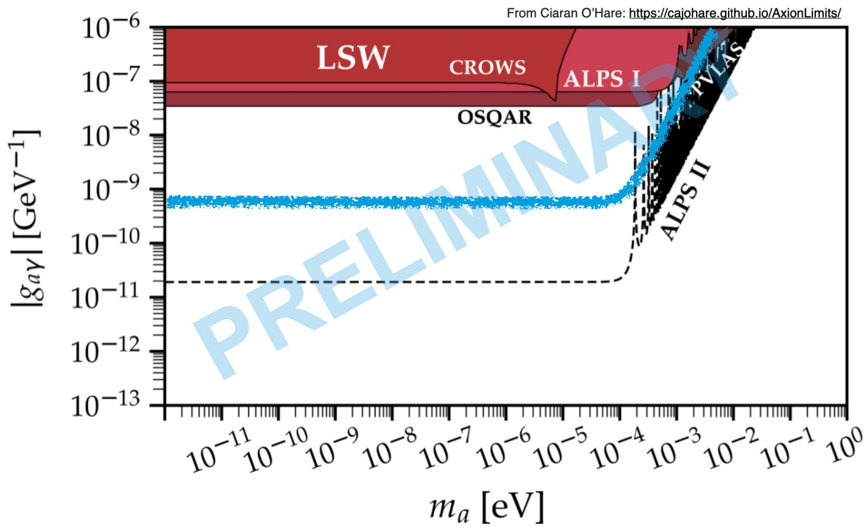


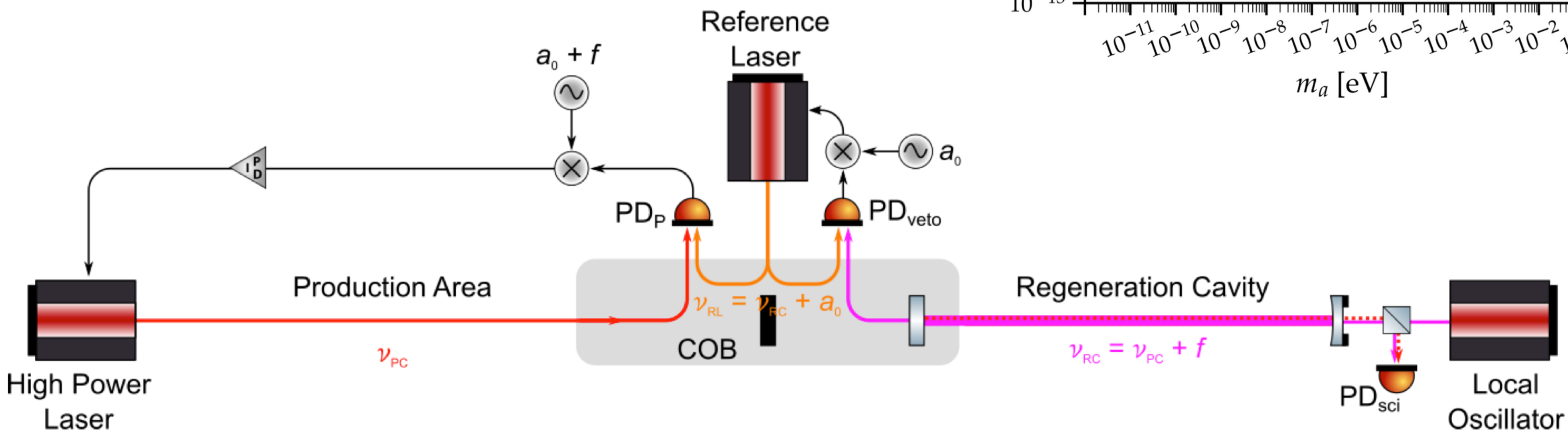
ALPS II first science run

Simplifying the optical system

Operate without production cavity

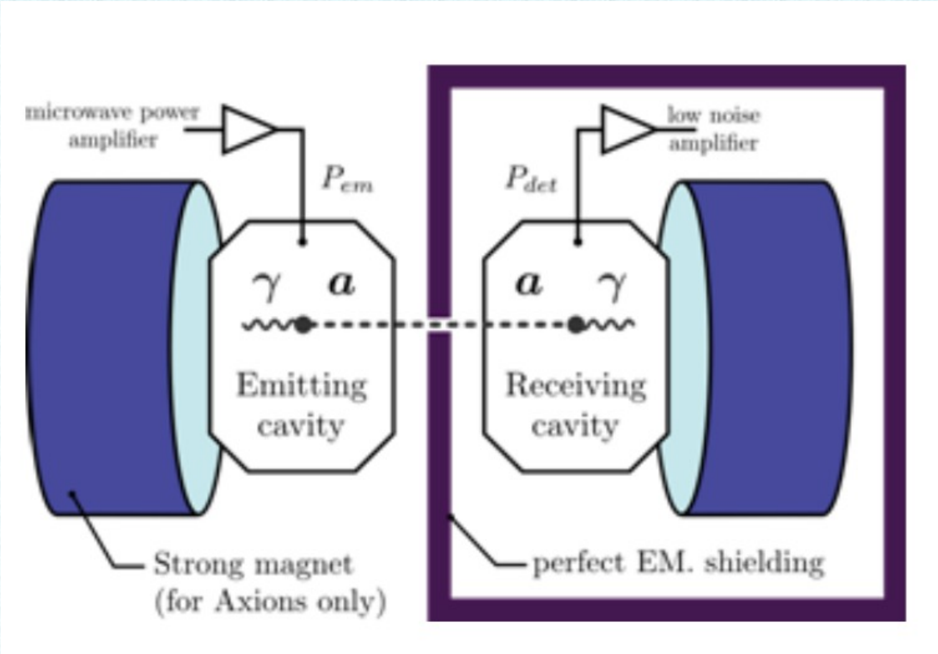
- Simplifies control system
  - Feedback directly to laser frequency rather than PC length
- Light injected to COB increased by a factor of 40x
  - Faster identification of ‘light leaks’

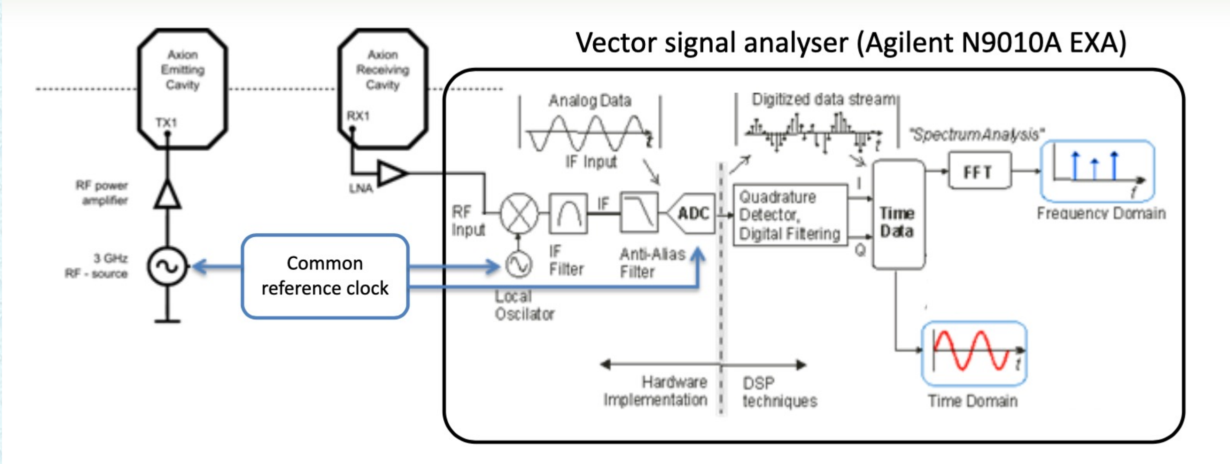




Microwave LSW

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

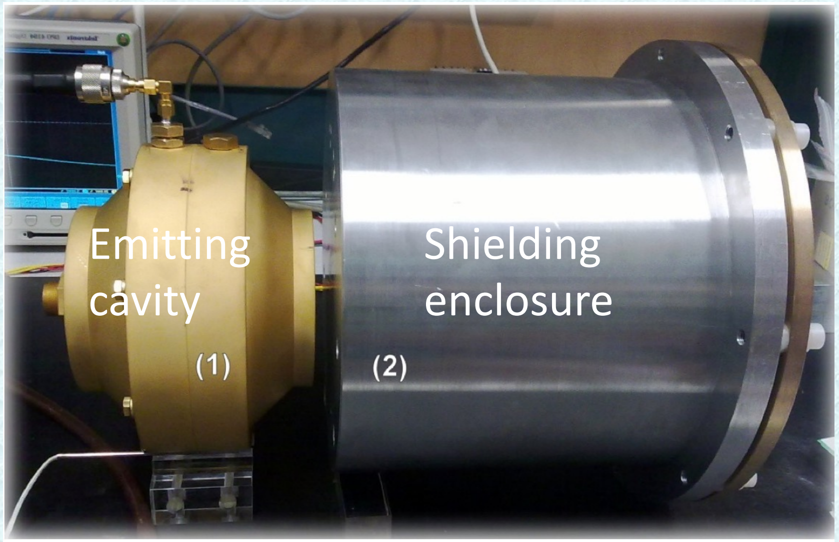


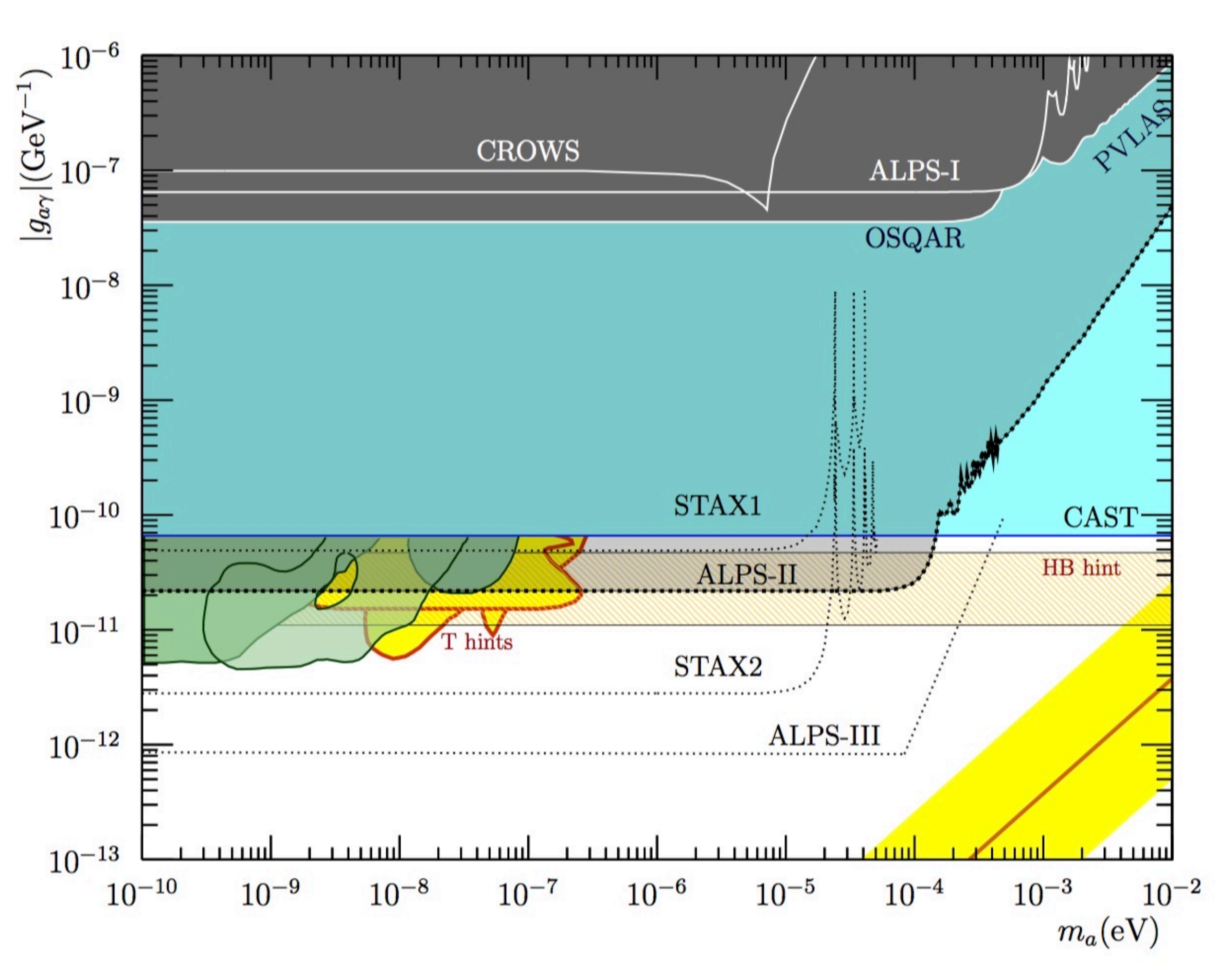
TABLE IV: Parameters of the ALP run in June 2013

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

PRD 88, 075014 (2013)

Pure Lab: results and perspectives

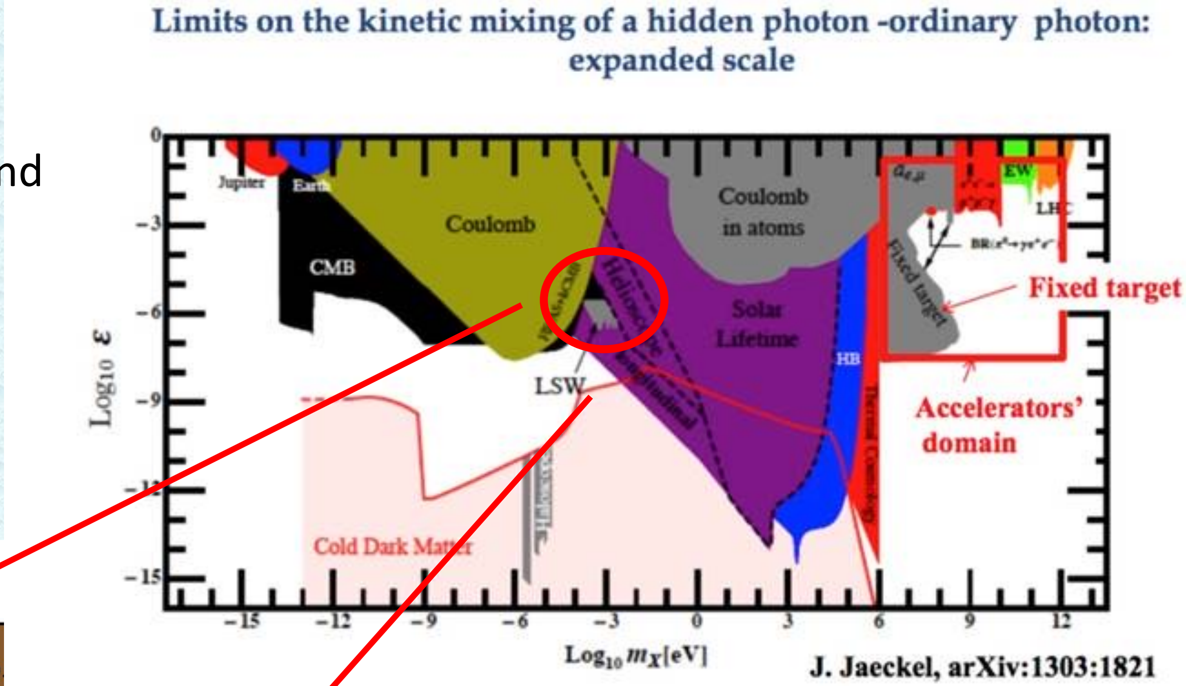
Excluded regions in the axion-photon coupling $g_{a\gamma\gamma}$ vs mass



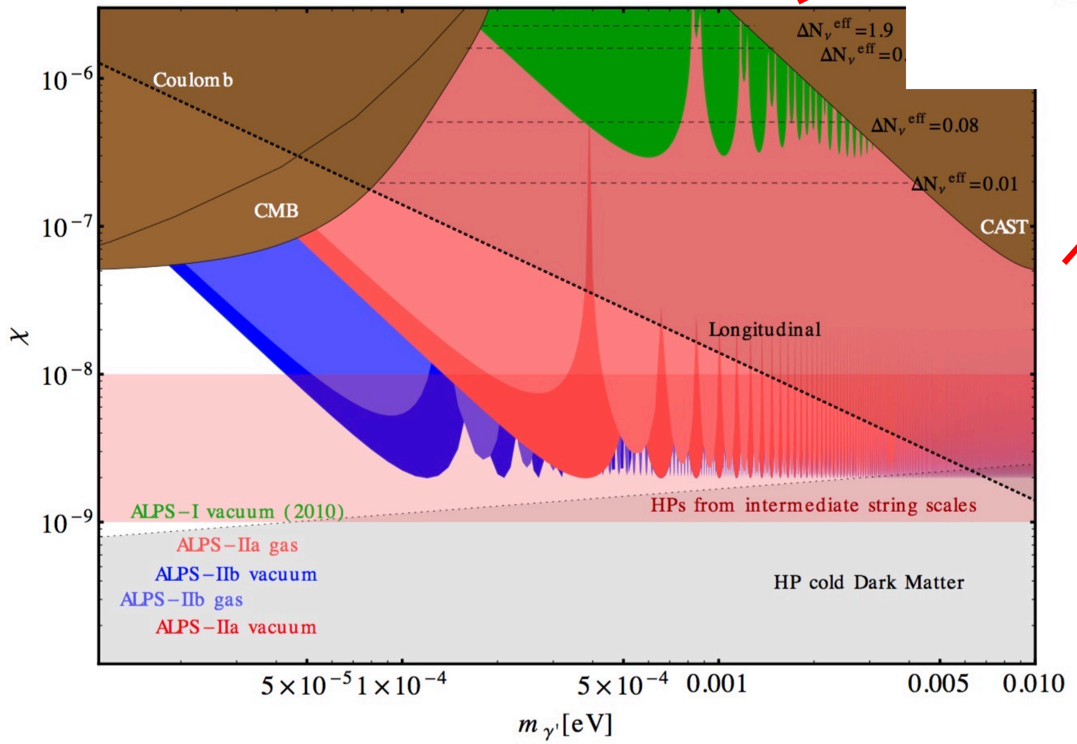
- None of these experiments capable of exploring the QCD axion model
- They set exclusion regions for Axion Like Particles coupling in a truly independent manner
- ALPS II will increase physics reach by several orders of magnitude, exploring regions where hints are present
- STAX Italian LSW effort using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

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

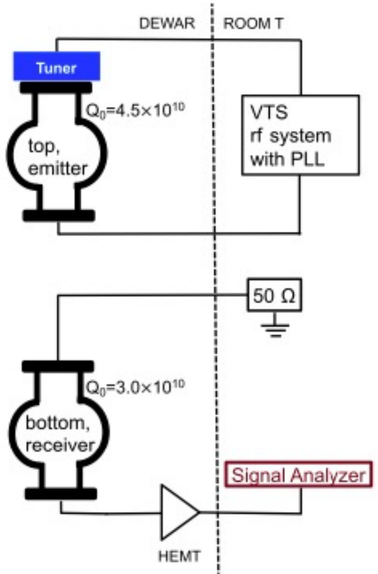
A. Romanenko et al PRL 130, 261801 (2023)

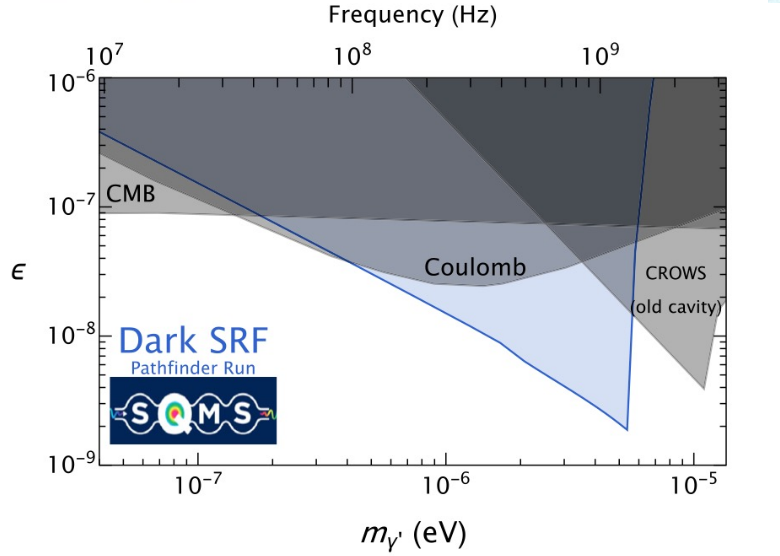
- Operation in a 1.5 K environment
- HEMT readout (T_n ~ 4 K @ 1.3 GHz)
- Very good long term stability of cavities

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 (?)**



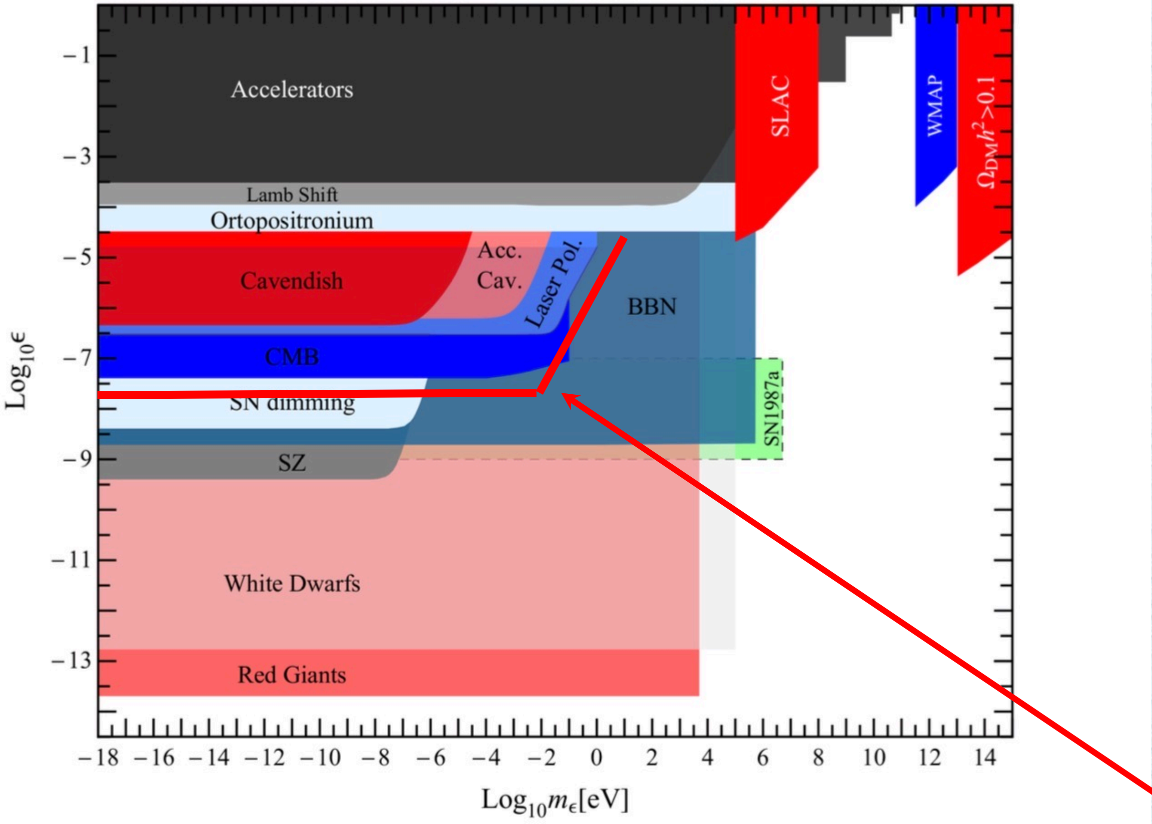


Milli-charged particles – sub eV range

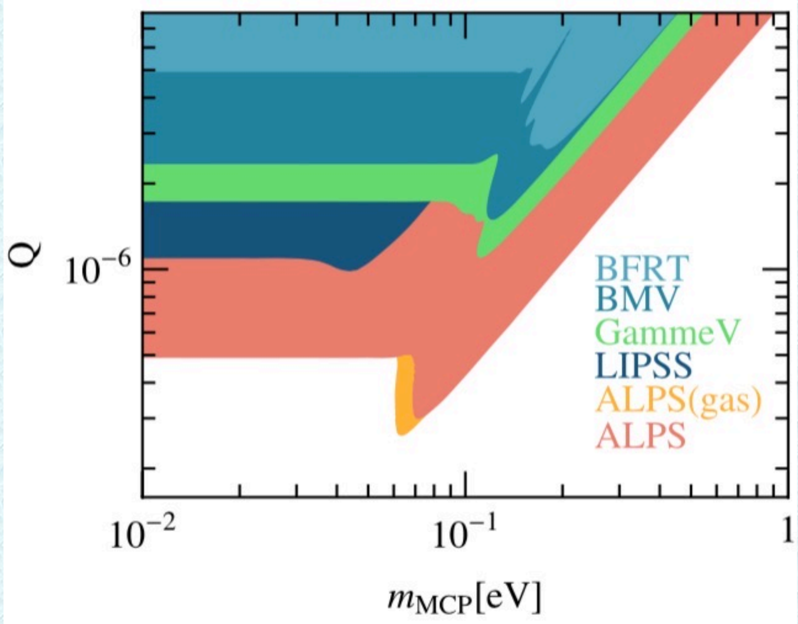
Particles with **{mass, electric charge}** = $\{m_\chi, \varepsilon e\}$

$$\varepsilon = Q_\chi / e$$

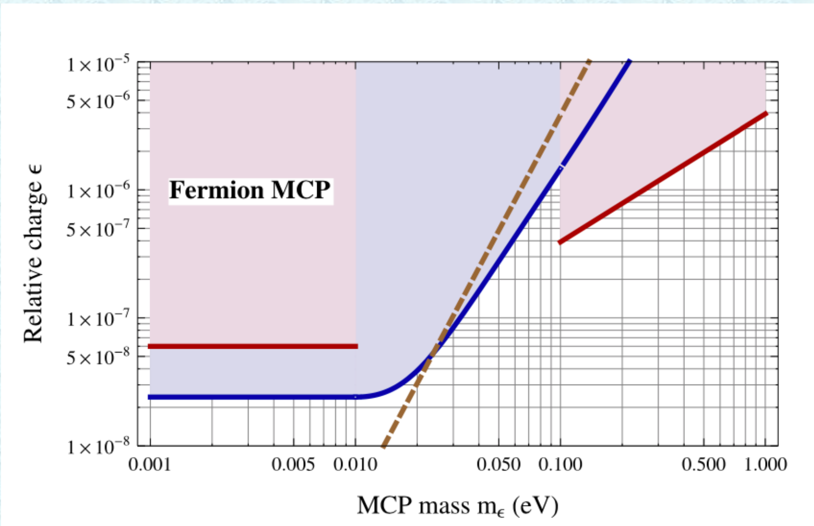
Mark Goodsell[a,c], Joerg Jaeckel[b], Javier Redondo[c,d] and Andreas Ringwald[c]
Published 6 November 2009 • Journal of High Energy Physics, Volume 2009, JHEP11(2009)



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

[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**

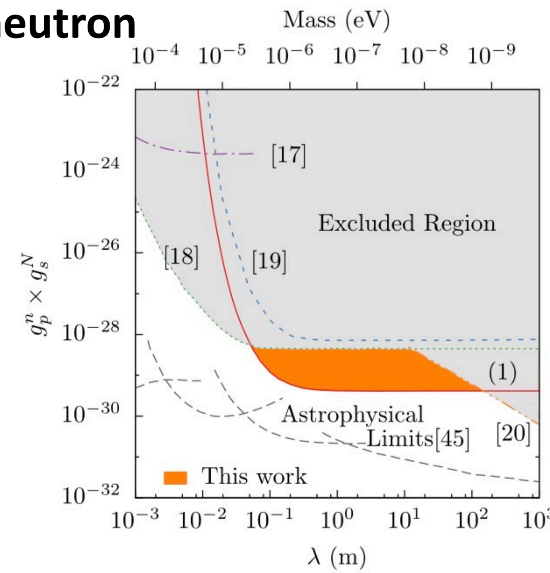
PHYSICAL REVIEW LETTERS **120**, 161801 (2018)

Improved Limits on Spin-Mass Interactions

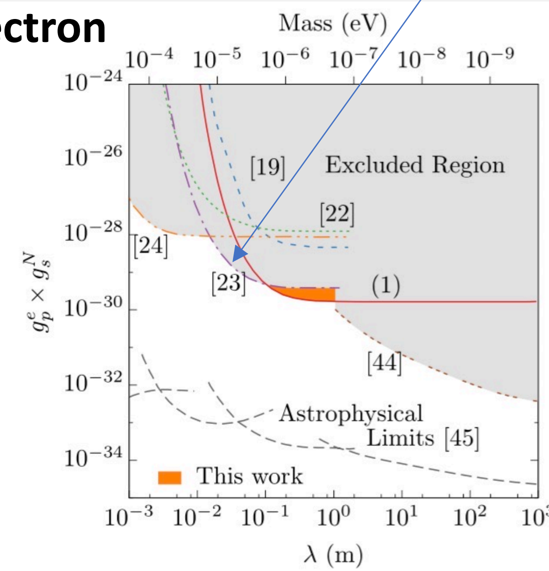
Junyi Lee,* Attaallah Almasi, and Michael Romalis
Department of Physics, Princeton University, Princeton, New Jersey 08544, USA

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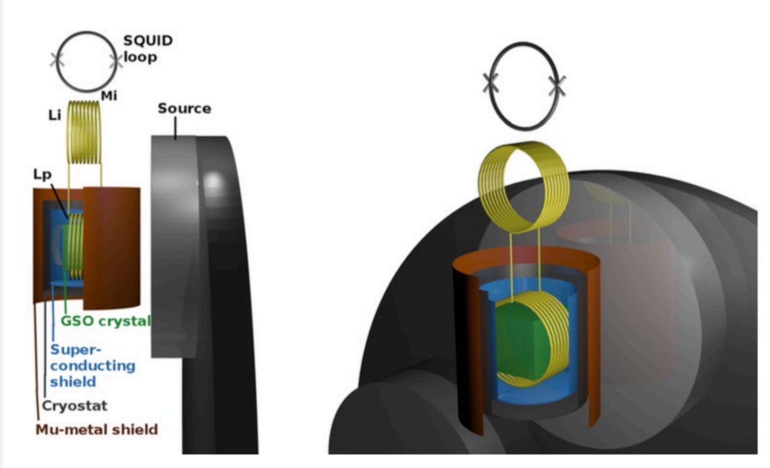
Improved constraints on monopole–dipole interaction mediated by pseudo-scalar bosons

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

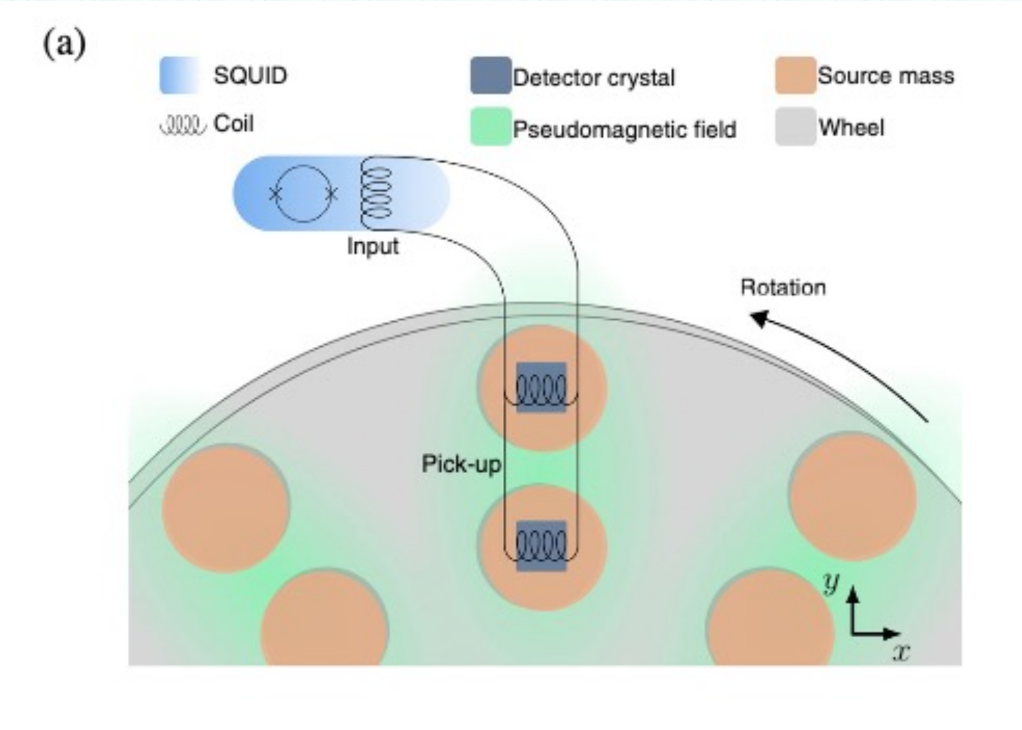


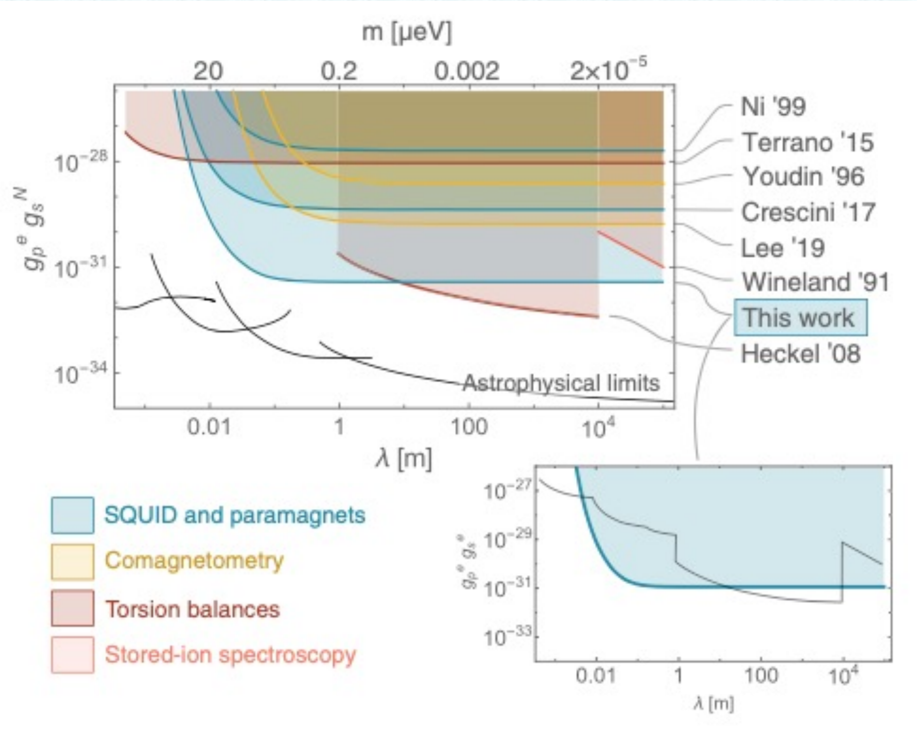
ARIADNE
US based collaboration developing a new experimental apparatus for spin – spin interaction with expected improvement in sensitivity by two orders of magnitude

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

N. CRESCINI et al.
PHYS. REV. D 105, 022007 (2022)

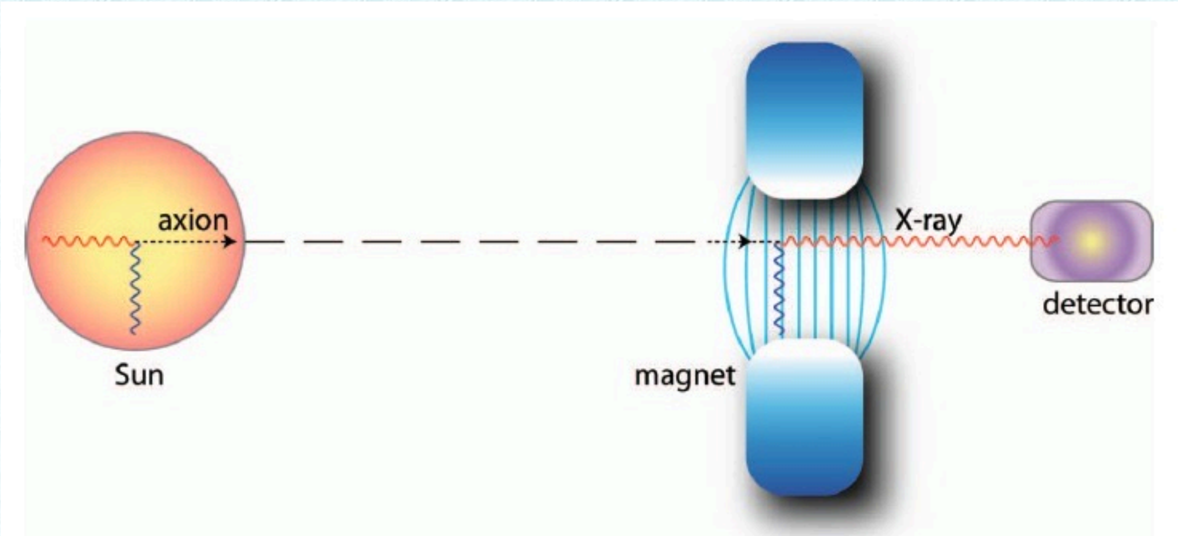
[B] Detection of axion from the Sun

Helioscopes

[B] Detection of axion from the Sun

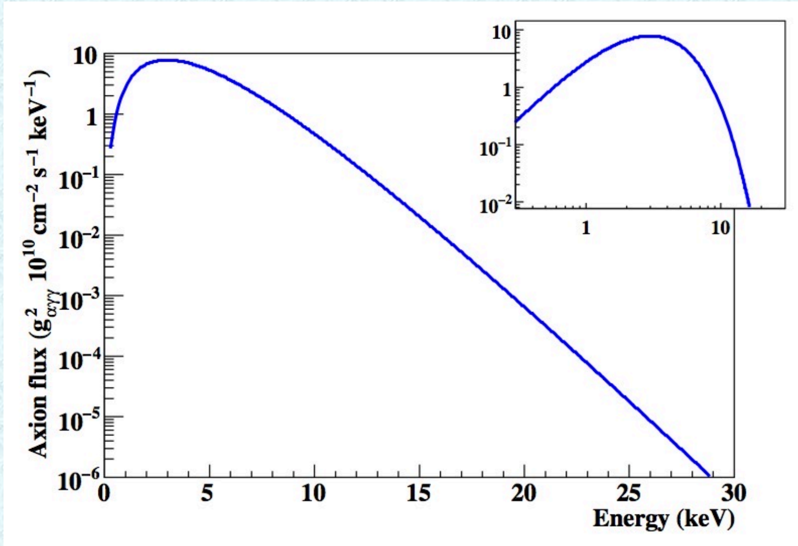
- **Helioscope**: originally proposed by P. Sikivie (1983)
- Axion produced in the Sun by the **Primakoff process**: **blackbody photons** in the EM fields associated with stellar plasma (also other mechanisms through electron coupling)
- **Thermal axion spectrum** with **mean energy 4.2 keV (X rays)**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

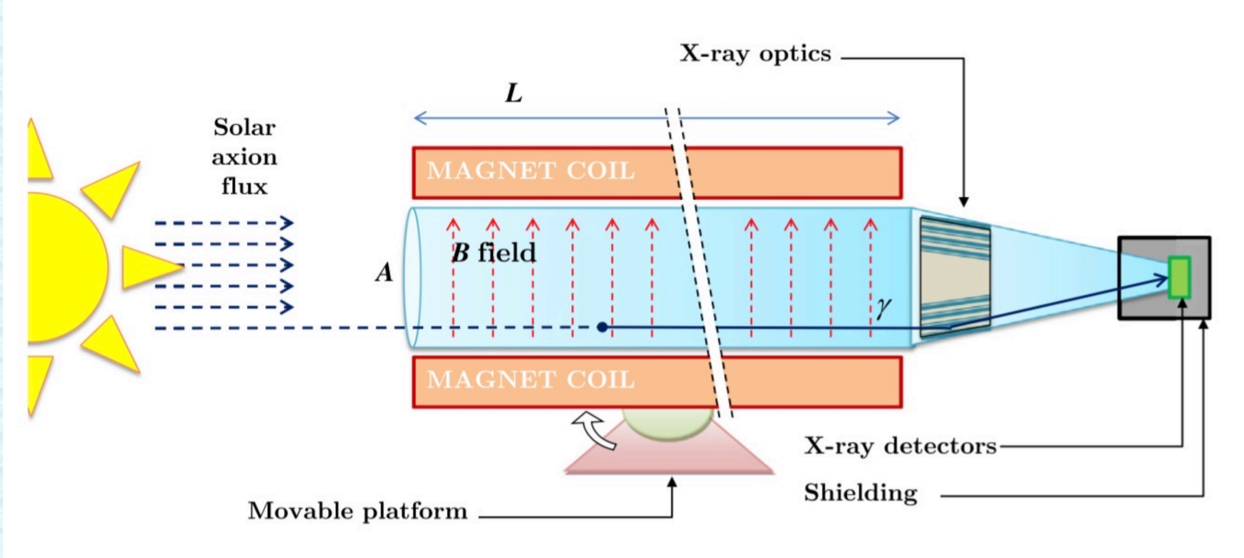
Conversion probability in the detecting magnetic field

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

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

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

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

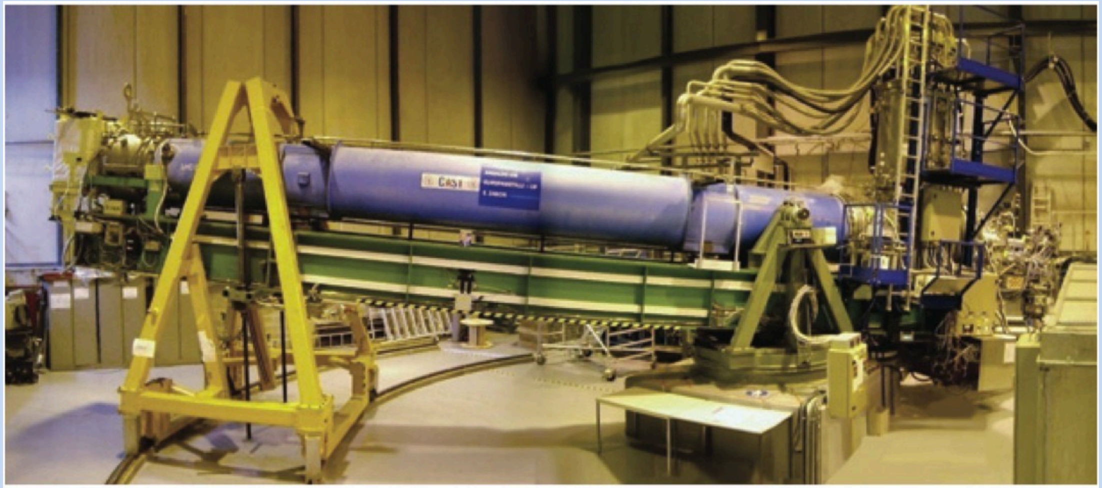
$$\mathrm{sens}(g_{a\gamma\gamma}) \propto \frac{b^{1/8}}{B^{1/2}L^{1/2}A^{1/4}t^{1/8}}$$

- **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)



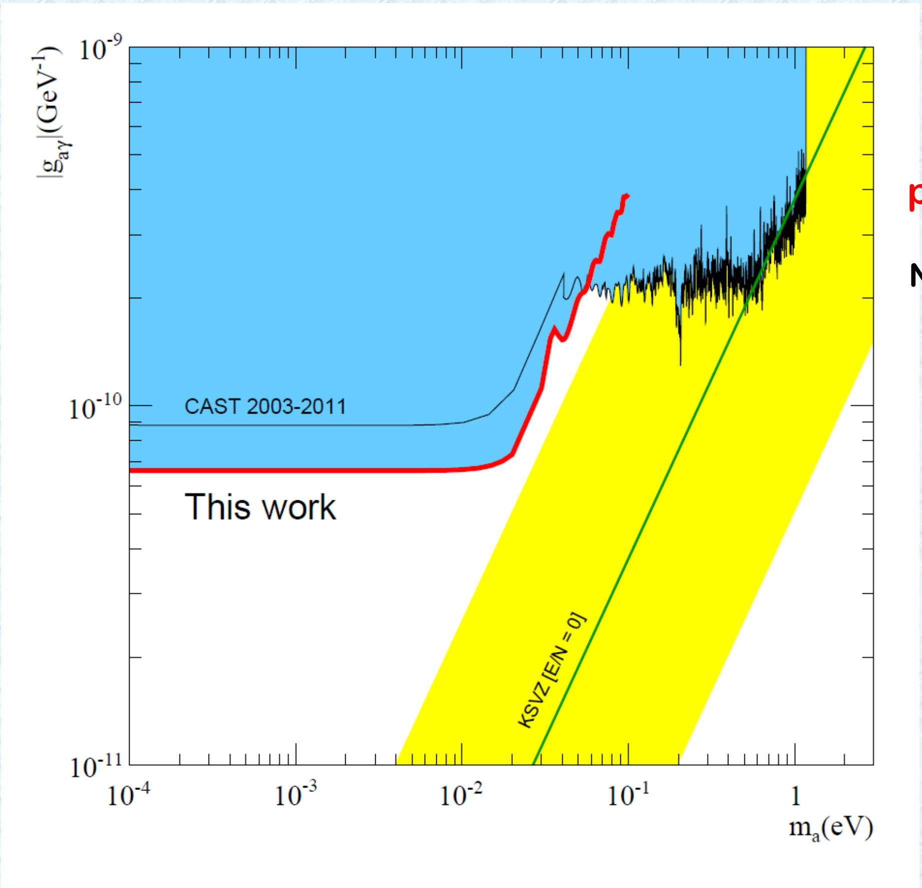
- **10 m - 9 T - LHC prototype magnet pointing to the sun with some tracking capability**
- **So far most sensitive experiment** looking for axion-like particles

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

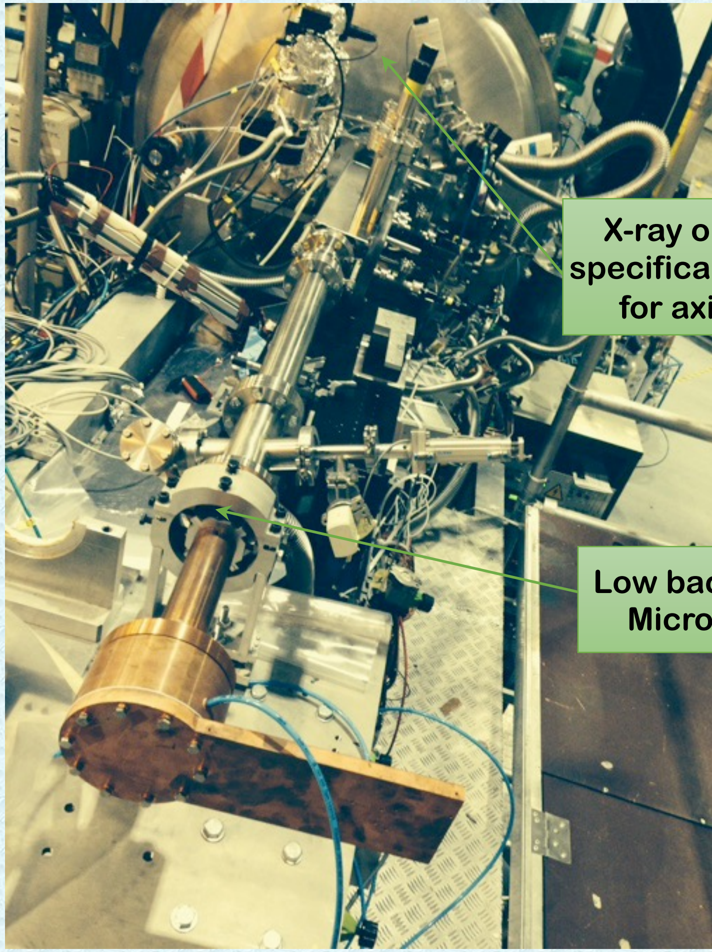
CAST results

- 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



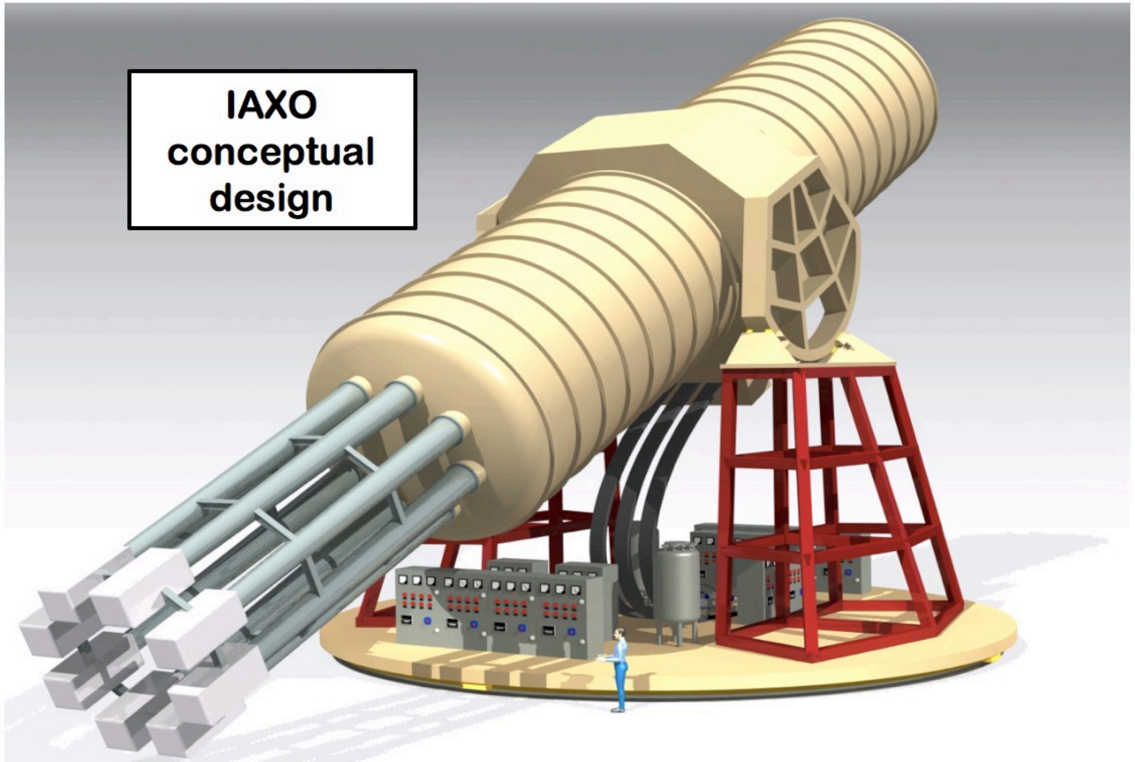
Enabled by the IAXO pathfinder system

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

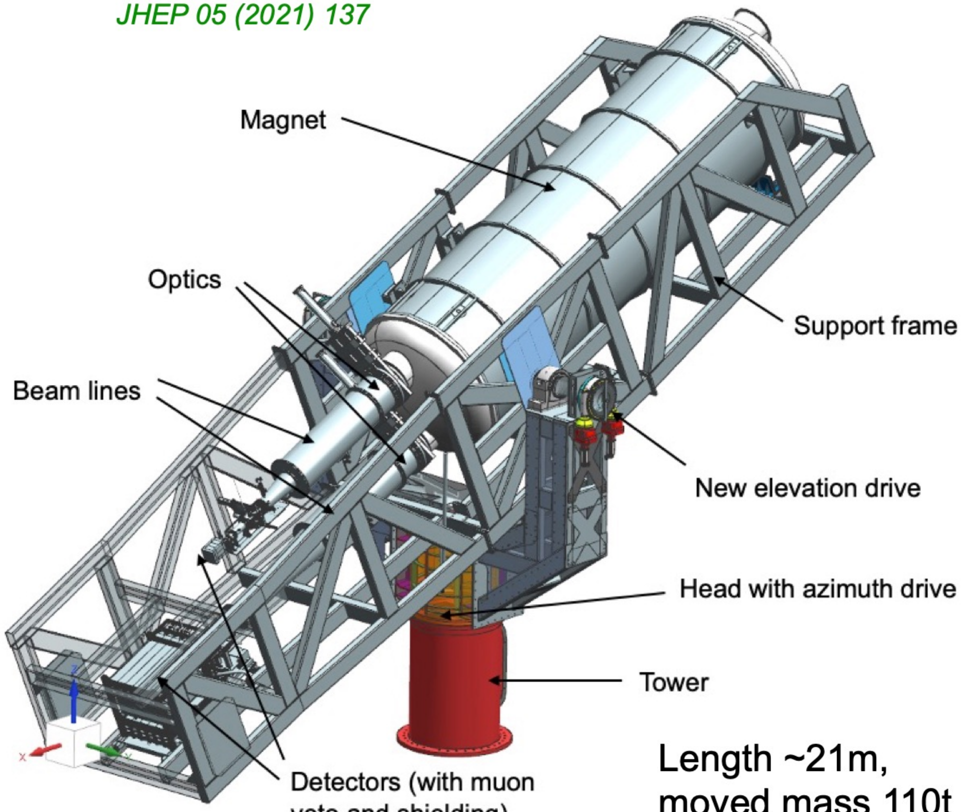
IAXO Prototype

- 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

European Research Council
Established by the European Commission

ERC-AvG 2017 IAXO+

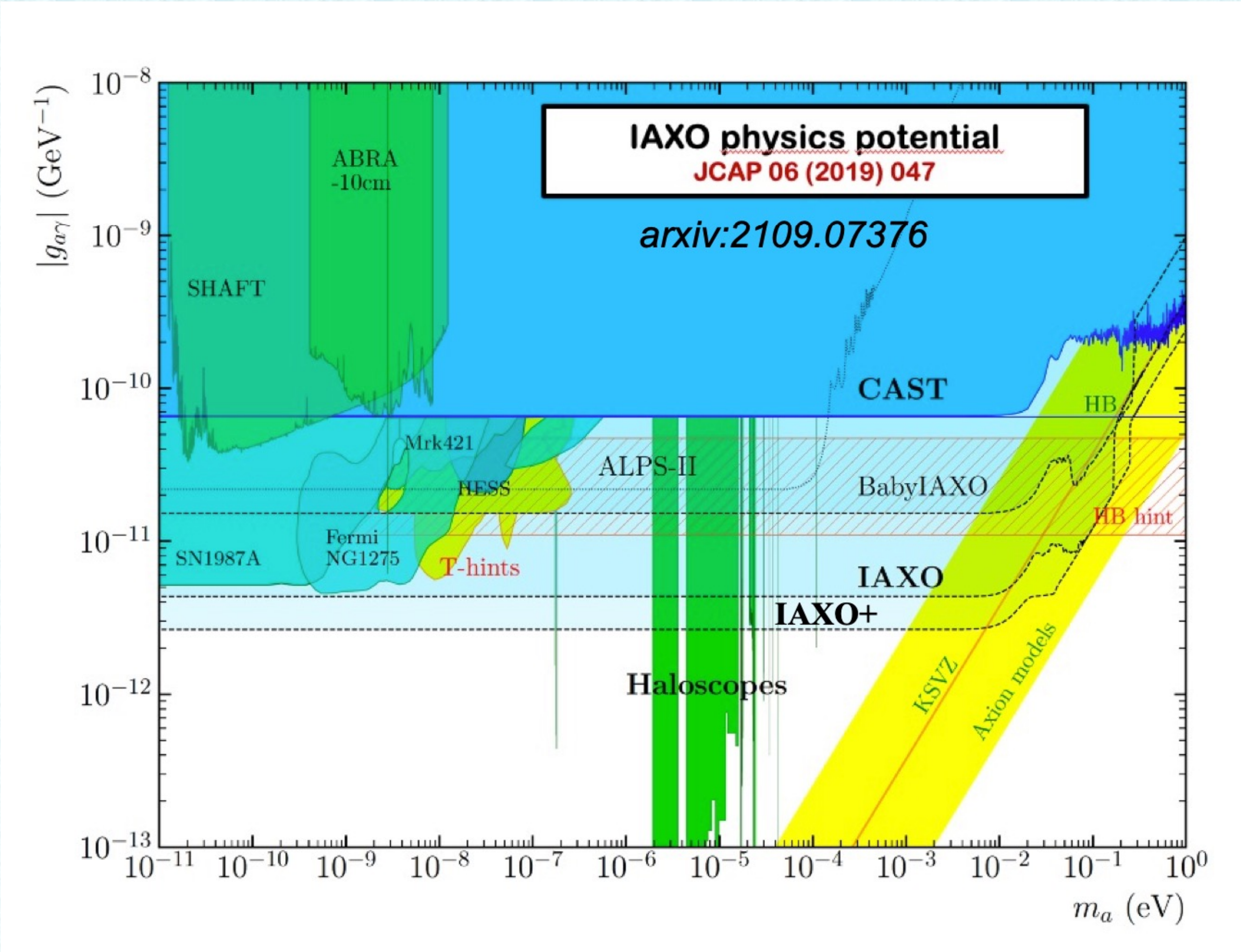
BabyIAXO conceptual design
JHEP 05 (2021) 137



Length ~21m, moved mass 110t

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

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

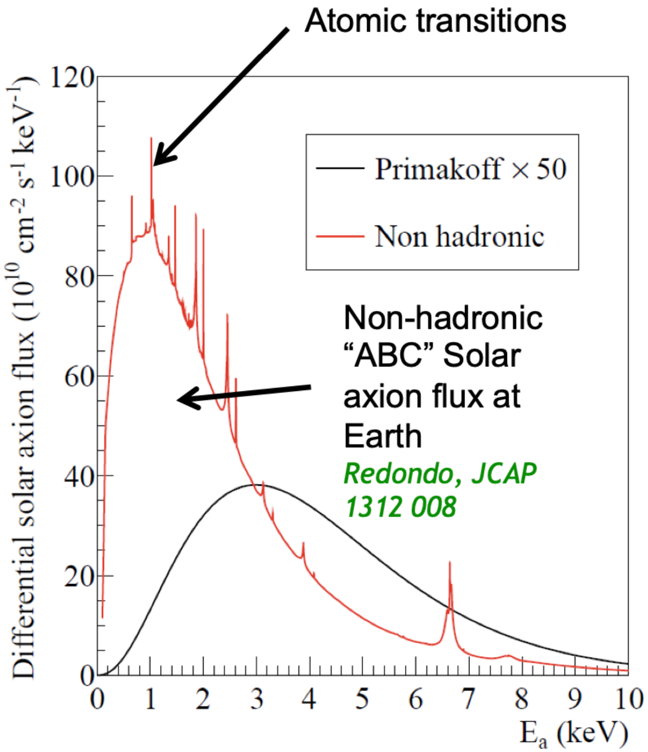
- The physics reach of IAXO will be covering a large and significant range of the **QCD axion** mass span

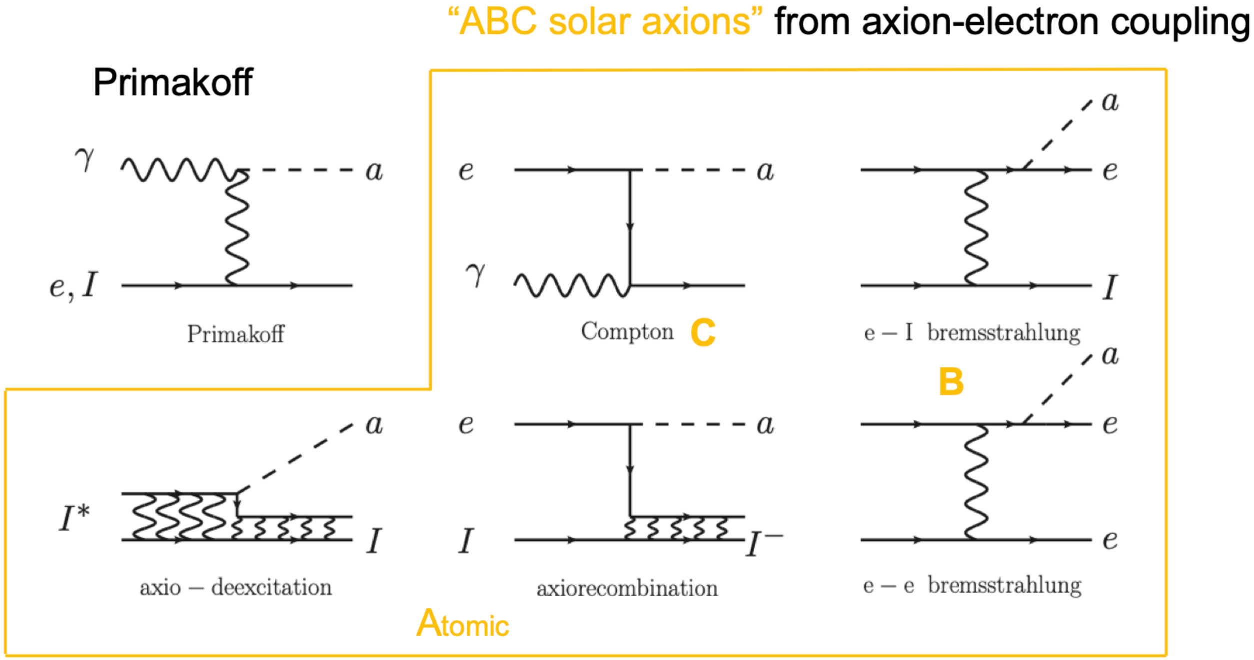
Helioscopes: models discrimination

Other Solar Axion Sources / Post Discovery

"ABC Axions"

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





Detection of both ABC and Primakoff axion spectrum would allow distinguishing axion models (gae, $ga\gamma$)
Jaeckel et al. arXiv:1811.09278

Part I over

- End of first part

Thank you