Study of the magneto-optical properties of quantum vacuum with high sensitivity polarimetry

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G.A. 754496

OUTLINE

- Classical and quantum vacuum
- Polarimetry
- Current landscape and future experiments for VMB detection
- Polarimetry for ALP detection

CLASSICAL VACUUM

The concept and existence of vacuum has been disputed for centuries

In ancient times

"Horror Vacui" : nature abhors vacuum

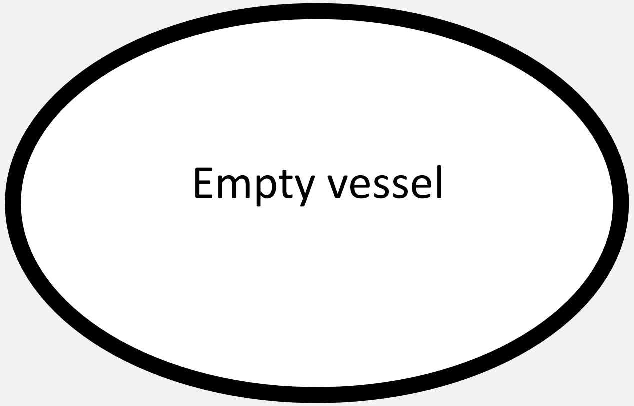
(Aristotle)

In classical physics

What is left when all that can be removed has been removed

(J.C. Maxwell)

COMMON UNDERSTANDING



Classical vacuum has no structure and electromagnetic fields are described by the classical Lagrangian density:

$$L_{em} = \frac{1}{2\mu_0}\left(\frac{E^2}{c^2} - B^2\right)$$

with speed of light

$$c = 299\,792\,458 \text{ m/s}$$

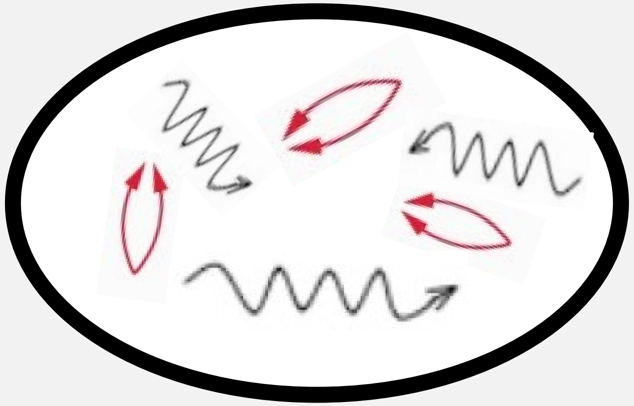
in vacuum

QUANTUM VACUUM

The Heisenberg uncertainty principle allows for field fluctuations

$$\Delta E \Delta t \approx \hbar$$

Vacuum fluctuations manifest themselves as virtual particles



Vessel filled with field fluctuations

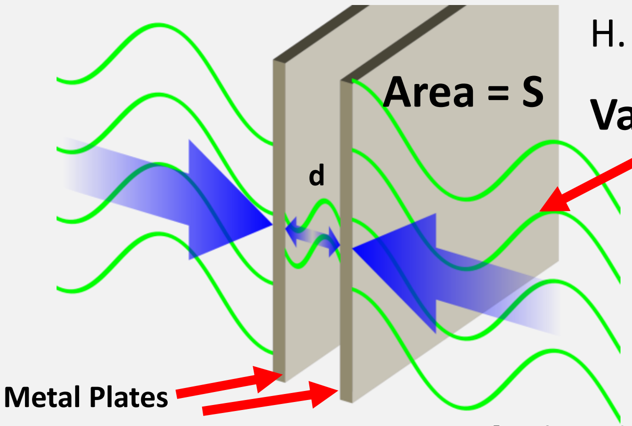
Evidence of microscopic structure of vacuum:

- Lamb Shift, ...

Manifestation at a macroscopic level:

- Casimir effect
- Velocity of light in an external field
- ....

H. Casimir (1948)



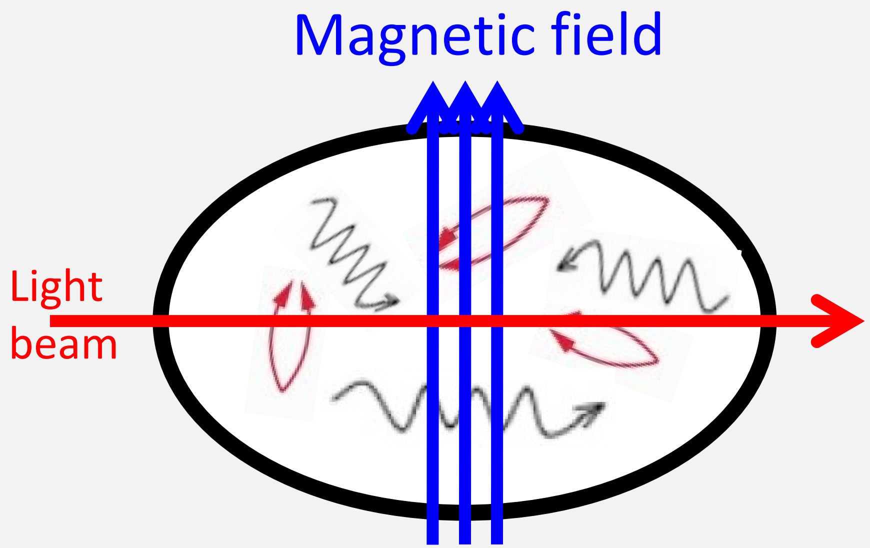
$$F_C = \frac{\pi^2 \hbar c}{240 d^4} S$$

[Wikipedia - Emok, CC BY-SA 3.0]

Vacuum has a structure and properties that can be studied.

EXPERIMENTAL STUDY OF THE QUANTUM VACUUM

Magneto-optical properties of vacuum



Light propagation in an external field

The complex index of refraction of vacuum is modified by an external magnetic field:

$$\tilde{n} = 1 + (n_B + i\,\kappa_B) \neq 1$$

The induced changes depend also on the direction of the applied field:

$$\Delta\tilde{n} = \Delta n_B + i\,\Delta\kappa_B$$

BIREFRINGENCE DICHROISM

VACUUM MAGNETIC BIREFRINGENCE

Lagrangian of the electromagnetic field by **Heisenberg, Euler and Weisskopf (1936)**
Maxwell's equations are still valid, but they are no longer linear.

At lowest order, for fields much smaller than the critical field (B ≪ $4.4 \cdot 10^9$ T; E ≪ $1.3 \cdot 10^{18}$ V/m):

$$L = L_{em} + L_{EH} = \frac{1}{2\mu_0}\left(\frac{E^2}{c^2} - B^2\right) + \frac{A_e}{\mu_0}\left[\left(\frac{E^2}{c^2} - B^2\right)^2 + 7\left(\frac{\vec{E}}{c} \cdot \vec{B}\right)^2\right]$$

$$A_e = \frac{2}{45\mu_0}\frac{\alpha^2\hbar^3}{m_e^4 c^5} = 1.32 \times 10^{-24}\ \mathrm{T}^{-2}$$

[W Heisenberg and H Euler, *Z. Phys.* **98**, 714 (1936)]
[H Euler, *Ann. Phys.* **26**, 398 (1936)]

This Lagrangian was later validated in **the framework of QED** [J. Schwinger, Phys. Rev., 82, 664 (1951)]

$$\Delta n_B = 3A_e B^2$$

VACUUM MAGNETIC BIREFRINGENCE

$$\left(n_{||} = 1 + 7A_e B_{\mathrm{ext}}^2 \quad n_{\perp} = 1 + 4A_e B_{\mathrm{ext}}^2 \right)$$

$$\Delta \kappa_B \simeq 0$$

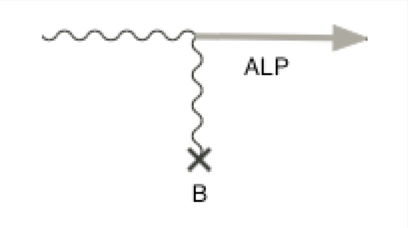
NO DICHROISM

AXION-LIKE PARTICLES (ALP)

Extra terms can be added to the EHW Lagrangian to include contributions from hypothetical neutral light particle, weakly interacting with two photons

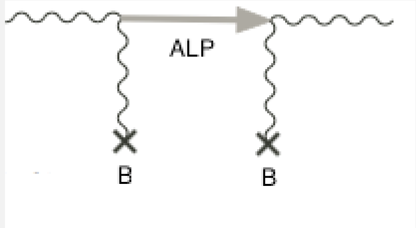
Effects on photon propagation

Absorption



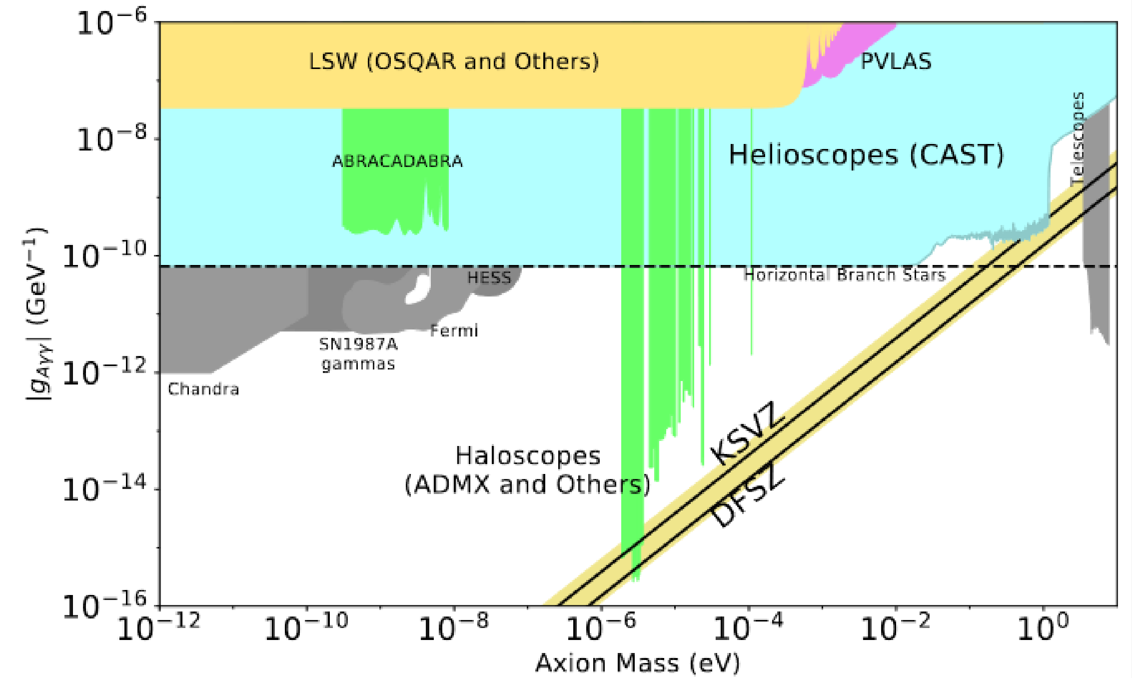
DICHROISM

Dispersion



BIREFRINGENCE

[L. Maiani, R. Petronzio, E. Zavattini Phys. Lett B 173, 359 (1986)]
[G. Raffelt, L. Stodolsky Phys. Rev. D 37, 1237 (1988)]



photon polarization <u>orthogonal</u> to B_{ext}:

$$L_{\sigma\gamma\gamma} = g_{s\gamma\gamma}\sigma\left(\vec{B}_\gamma \cdot \vec{B}_{\text{ext}}\right)$$

Scalar

photon polarization <u>parallel</u> to B_{ext}:

$$L_{\varphi\gamma\gamma} = g_{a\gamma\gamma}\varphi\left(\vec{E}_\gamma \cdot \vec{B}_{\text{ext}}\right)$$

Pseudoscalar

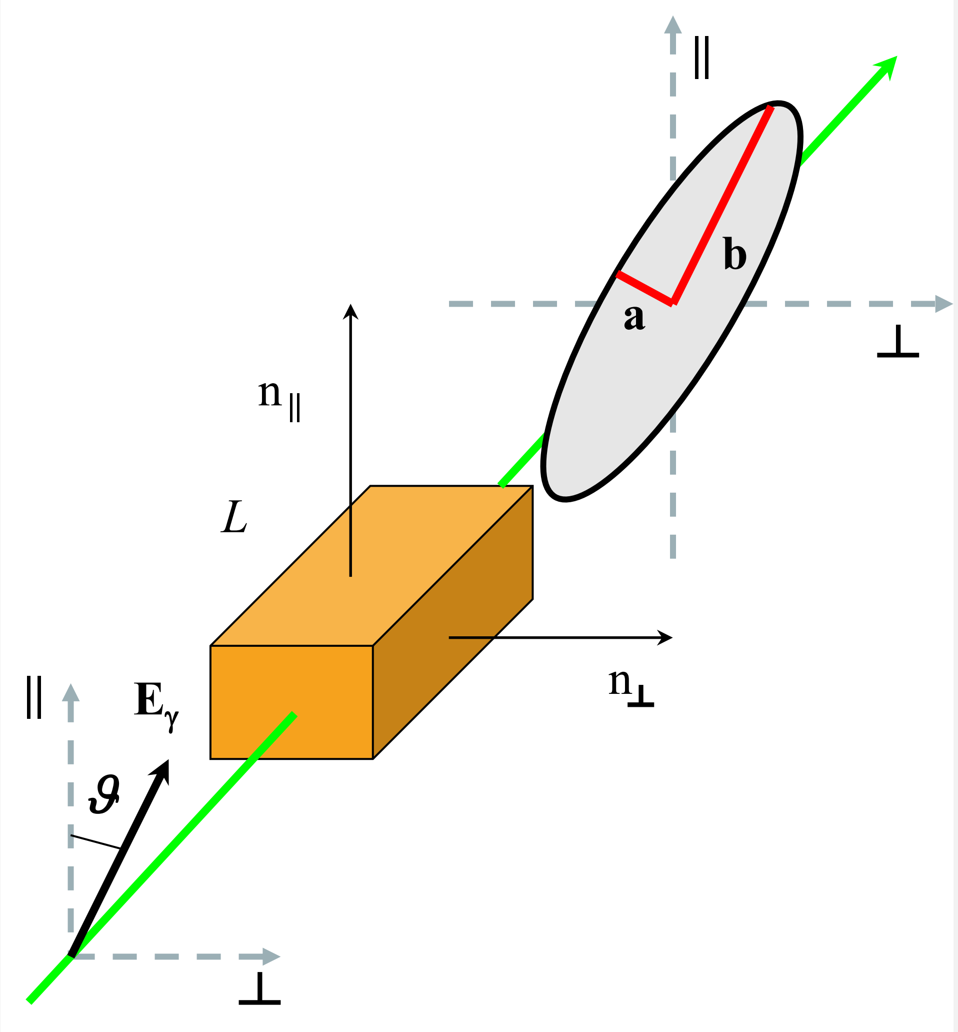
BIREFRINGENCE AND ELLIPTICITY

Index of refraction is different for the two orthogonal polarizations:

$$\Delta n = n_{||} - n_{\perp} \neq 0$$

A linearly polarized light beam propagating through a birefringent medium will acquire an **ellipticity** ψ:

$$\psi = \frac{a}{b} = \frac{\pi}{\lambda} \cdot \Delta n\, L \cdot sin(2\vartheta)$$

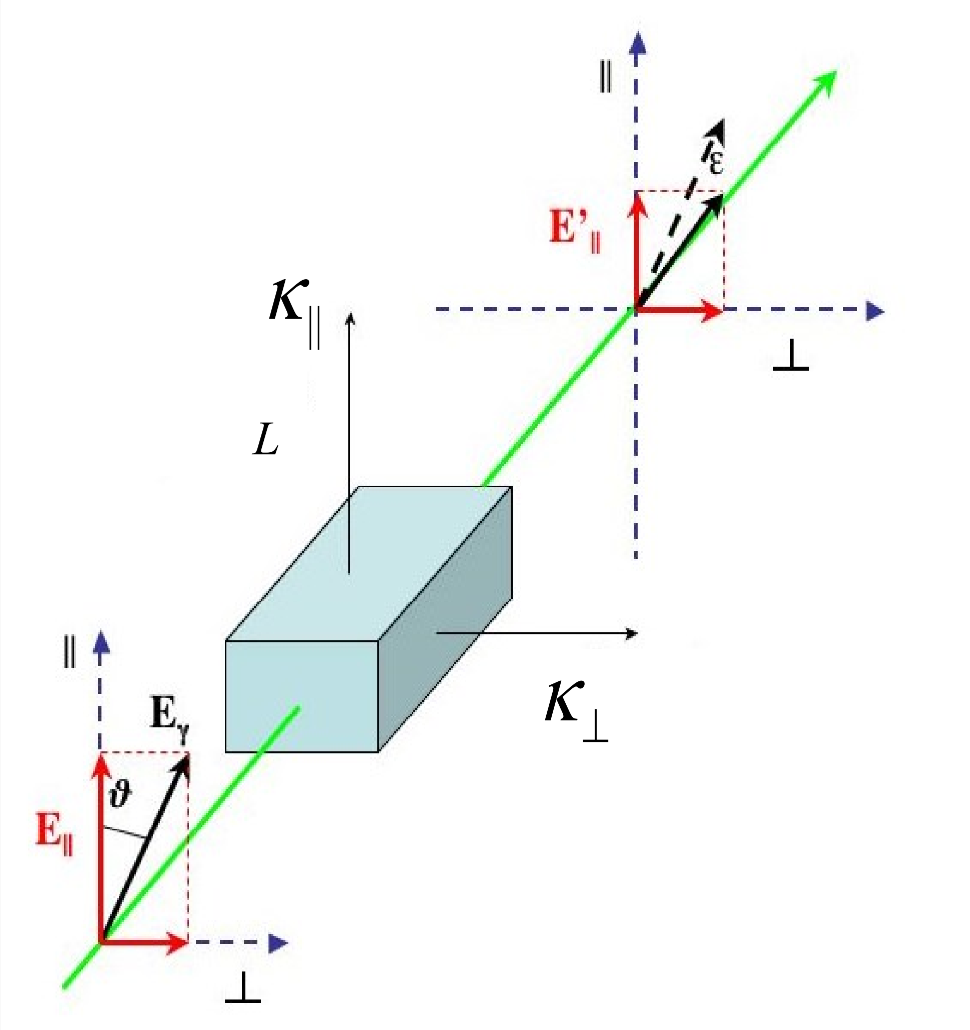


If the extinction coefficient is different for the two orthogonal directions:

$$\Delta \kappa = \kappa_{||} - \kappa_{\perp} \neq 0$$

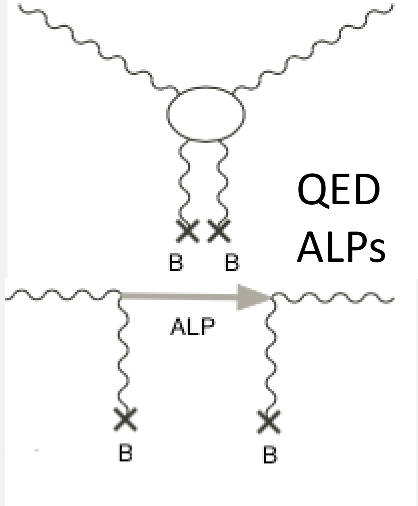
A linearly polarized light beam traversing a dichroic medium will be apparently rotated by an **angle ε :**

$$\varepsilon = \frac{\pi}{\lambda} \cdot \Delta\kappa\, L \cdot sin(2\,\vartheta)$$

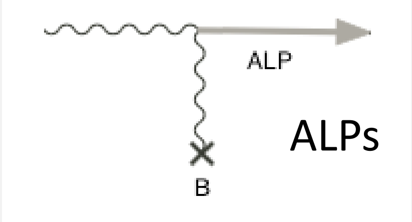


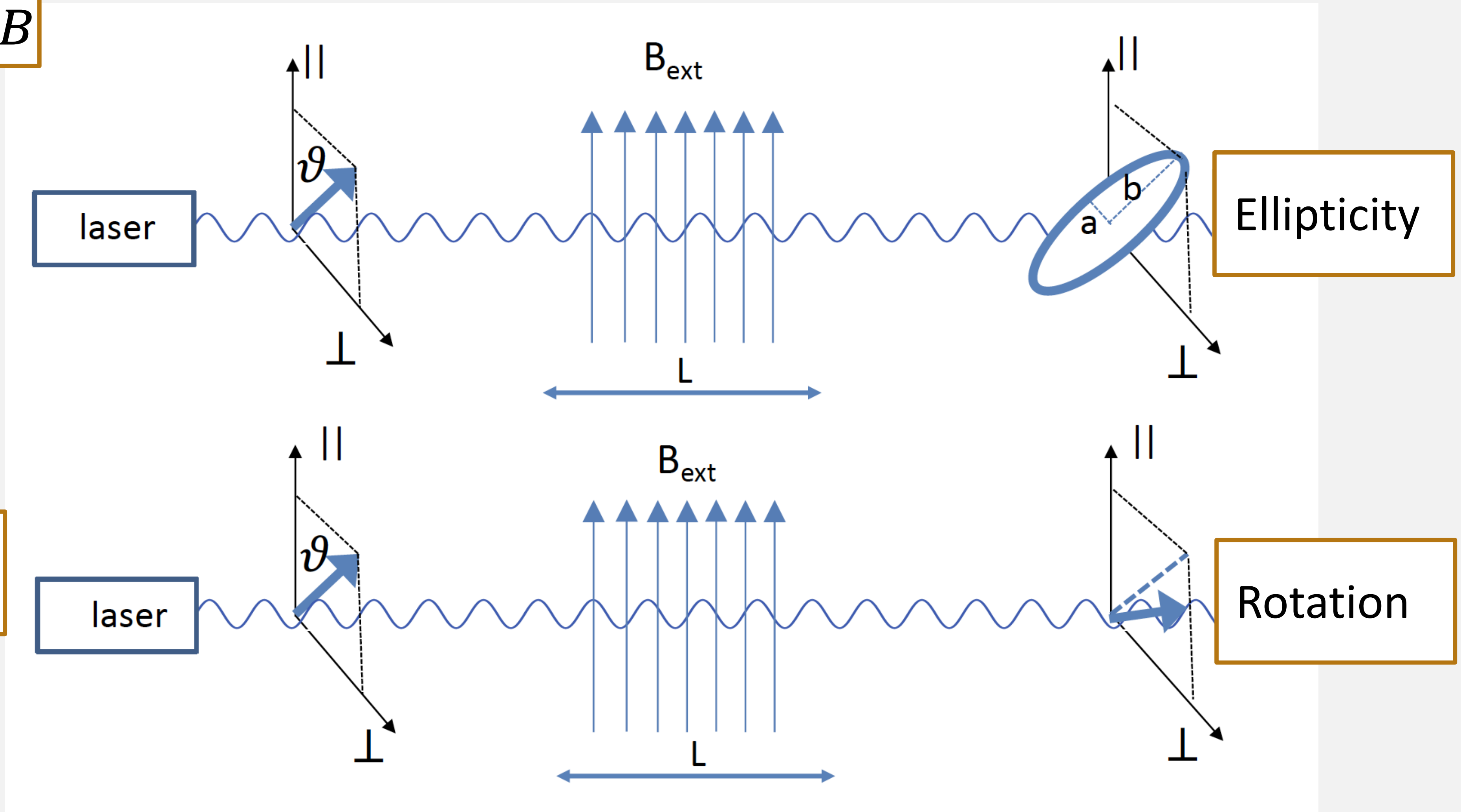
MEASURABLE QUANTITIES

Birefringence Δn_B

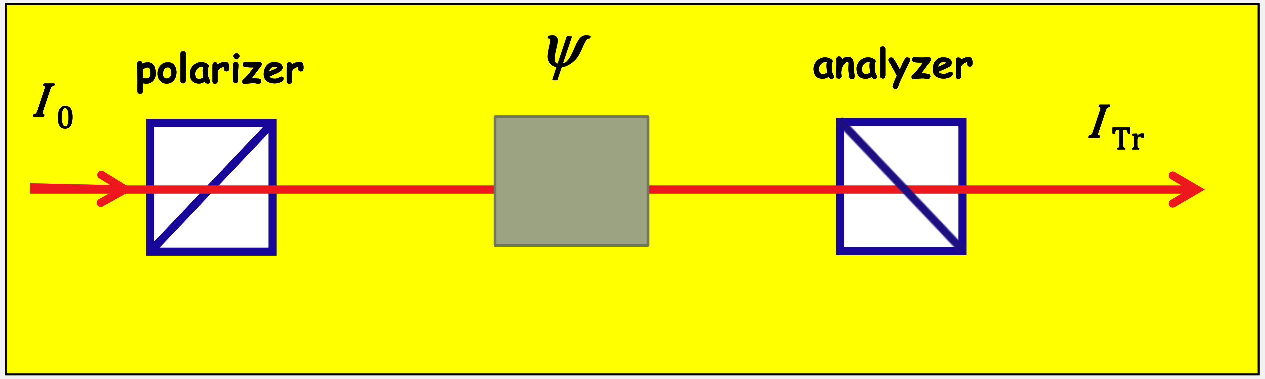


Dichroism $\Delta \kappa_B$





POLARIMETRY: BASIC PRINCIPLE



$$\psi = \frac{\pi}{\lambda} \cdot \Delta n \cdot L \cdot \sin(2\theta)$$

$$I_{Tr} = I_0\left[\sigma^2 + \psi^2\right]$$

extinction $\sigma^2 \sim 10^{-7}$–10^{-8}

Typical values:

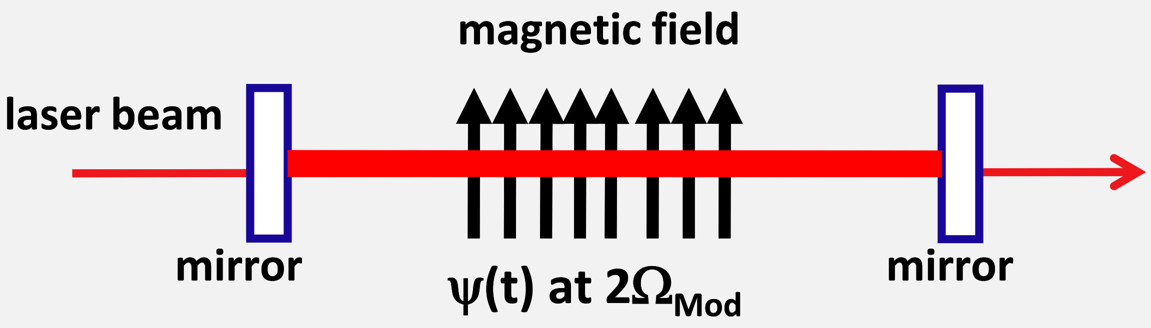
L = 1 m, λ = 1064 nm, B = 5 T

$\Delta n_{QED} = 10^{-22}$

$\psi_{QED} \approx 3 \times 10^{-16}$

Static detection not possible

POLARIMETRY: KEY INGREDIENTS



IDEA

Volume 85B, number 1 PHYSICS LETTERS 30 July 1979

EXPERIMENTAL METHOD TO DETECT THE VACUUM BIREFRINGENCE INDUCED BY A MAGNETIC FIELD

E. IACOPINI and E. ZAVATTINI
CERN, Geneva, Switzerland

Received 28 May 1979

In this letter a method of measuring the birefringence induced in vacuum by a magnetic field is described: this effect is evaluated using the non-linear Euler–Heisenberg–Weisskopf lagrangian. The optical apparatus discussed here may detect an induced ellipticity on a laser beam down to 10^{-11}.

Experimental method:

- Perturb with an external B field
- Probe with a linearly polarized light beam
- Detect changes in the polarization state

High magnetic field

Long optical path

High sensitivity polarimeter

Signal α B^2

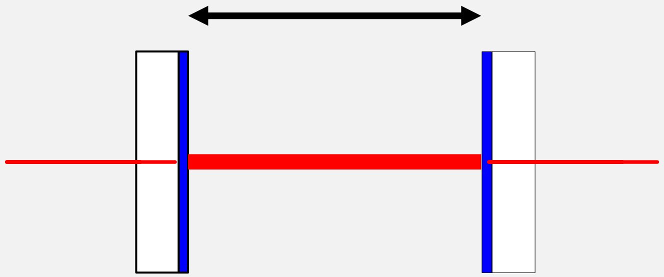
Optical cavity

Signal Modulation (decoupling from static effects)

POLARIMETRY: OPTICAL CAVITY

A Fabry-Perot cavity increases the effective optical path inside the magnetic field region.

$$d = n\frac{\lambda}{2}$$



Amplification of optical path

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

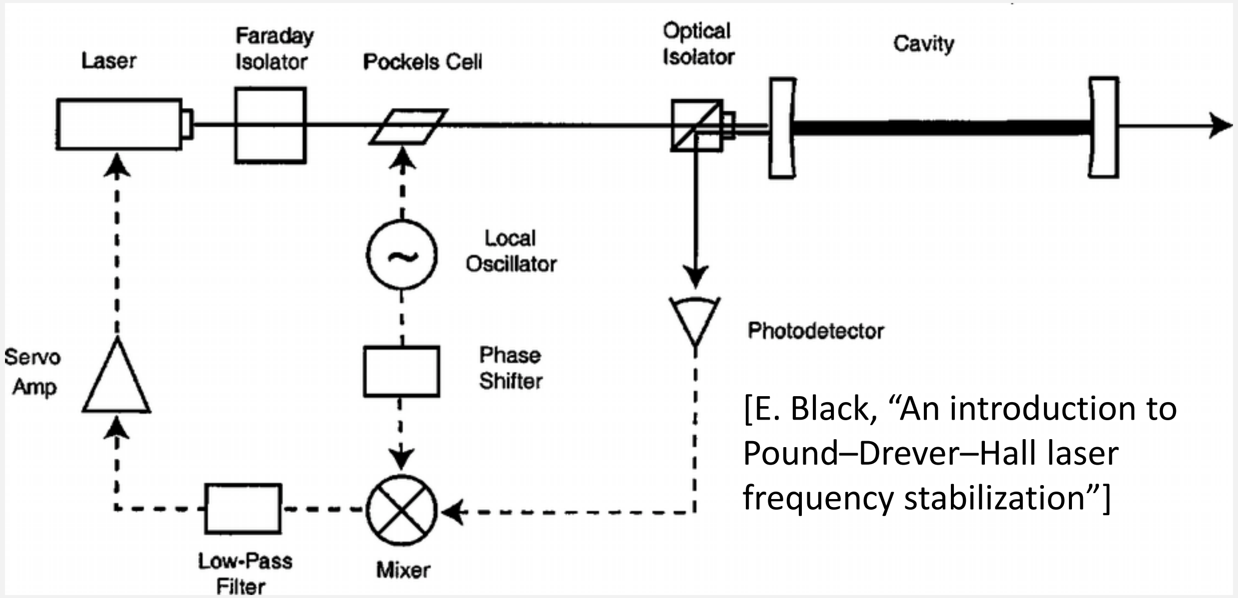
Finesse

$$F = \frac{\pi c \tau}{d}$$

Mirrors:
High reflectivity
Low losses

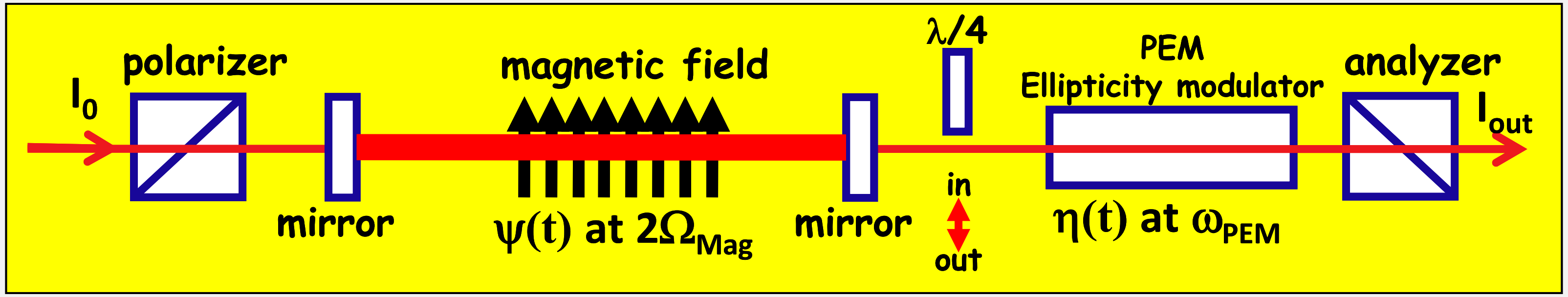
- Constructive interference
- Build-up of a resonant field inside the cavity

Laser light is frequency locked to the cavity length using a feedback circuit (Pound-Drever-Hall technique)



[E. Black, "An introduction to Pound–Drever–Hall laser frequency stabilization"]

POLARIMETRY: HETERODYNE DETECTION



Signal is modulated in time and beats with a calibrated effect:

- Magnetic field is rotated at Ω_{Mag} → ellipticity at $2\Omega_{Mag}$
- A (known) carrier $\eta(t)$ at ω_{PEM} is added to the signal

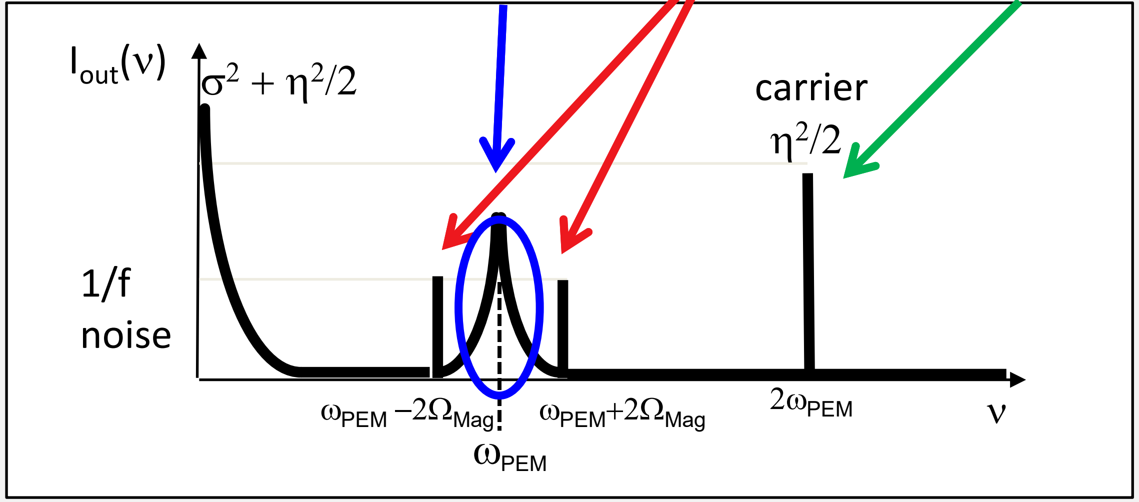
$$I_{\rm out}(t) \simeq I_0 \left[\sigma^2 + \underbrace{2\eta(t)\alpha(t)}_{\text{noise}} + \underbrace{2\eta(t)\psi \sin 2\vartheta(t)}_{\text{signal}} + \underbrace{\eta(t)^2}_{\text{normalization}}\right]$$

$$\eta(t) = \eta_0 \cos(\omega_{PEM} t + \phi)$$

$$\psi(t) = \psi_0 \sin(2\Omega_{Mag} t + \Phi)$$

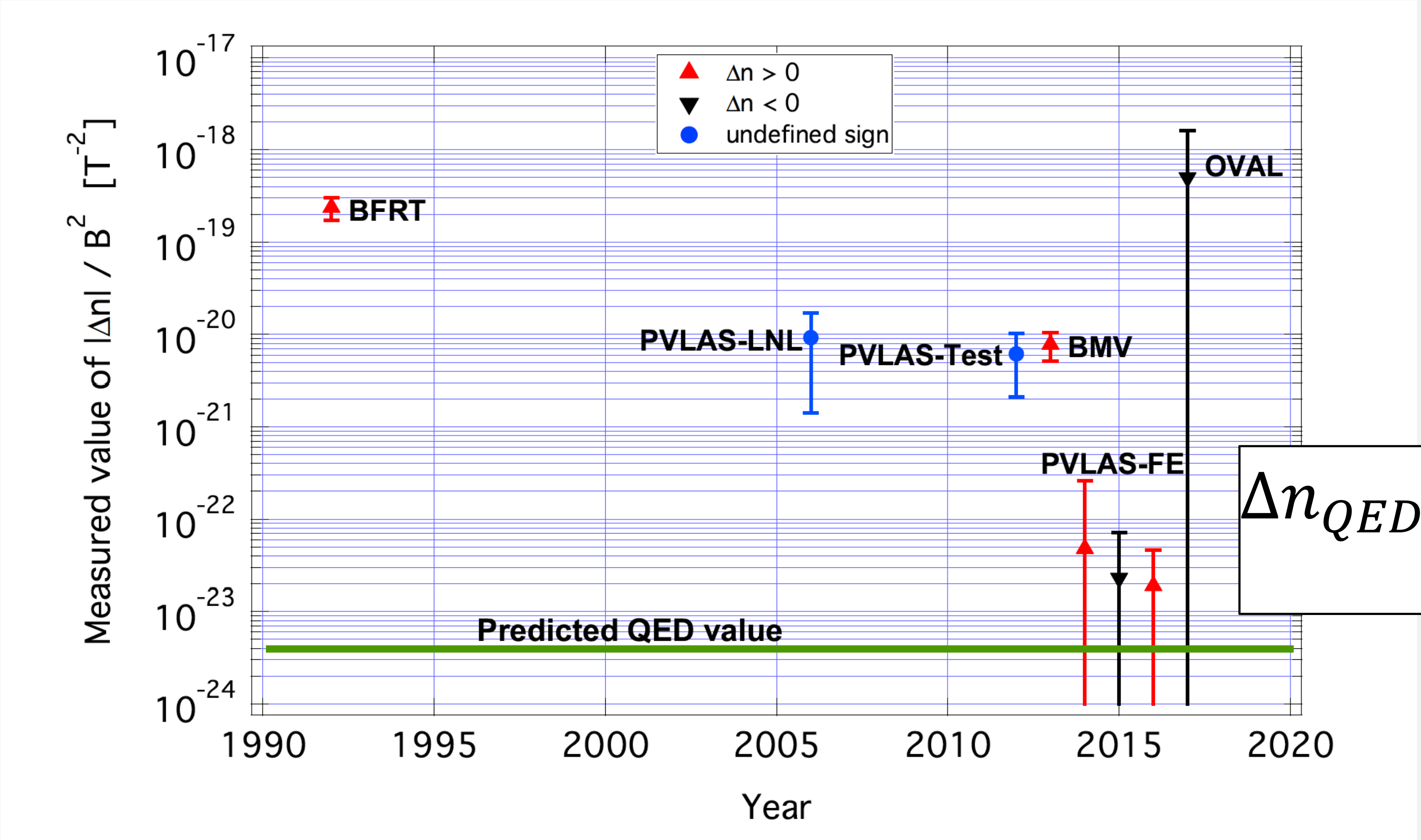
$$\alpha(t) = \text{ellipticity noise}$$

$$\sigma^2 = \text{extinction}$$



- Signal linear in the birefringence
- Smaller 1/f noise
- Phase relationship between signal and field modulation

CURRENT STATUS



$$\Delta n_{QED} = 3A_e B^2 = 4\times10^{-24}$$

(for a 1 T magnetic field)

[A. Ejlli et al. Phys. Reports, 871 1-74 (2020)]

COMPARISON WITH GW SEARCHES

VMB searches are sensitive to optical path length differences between two perpendicular polarizations.

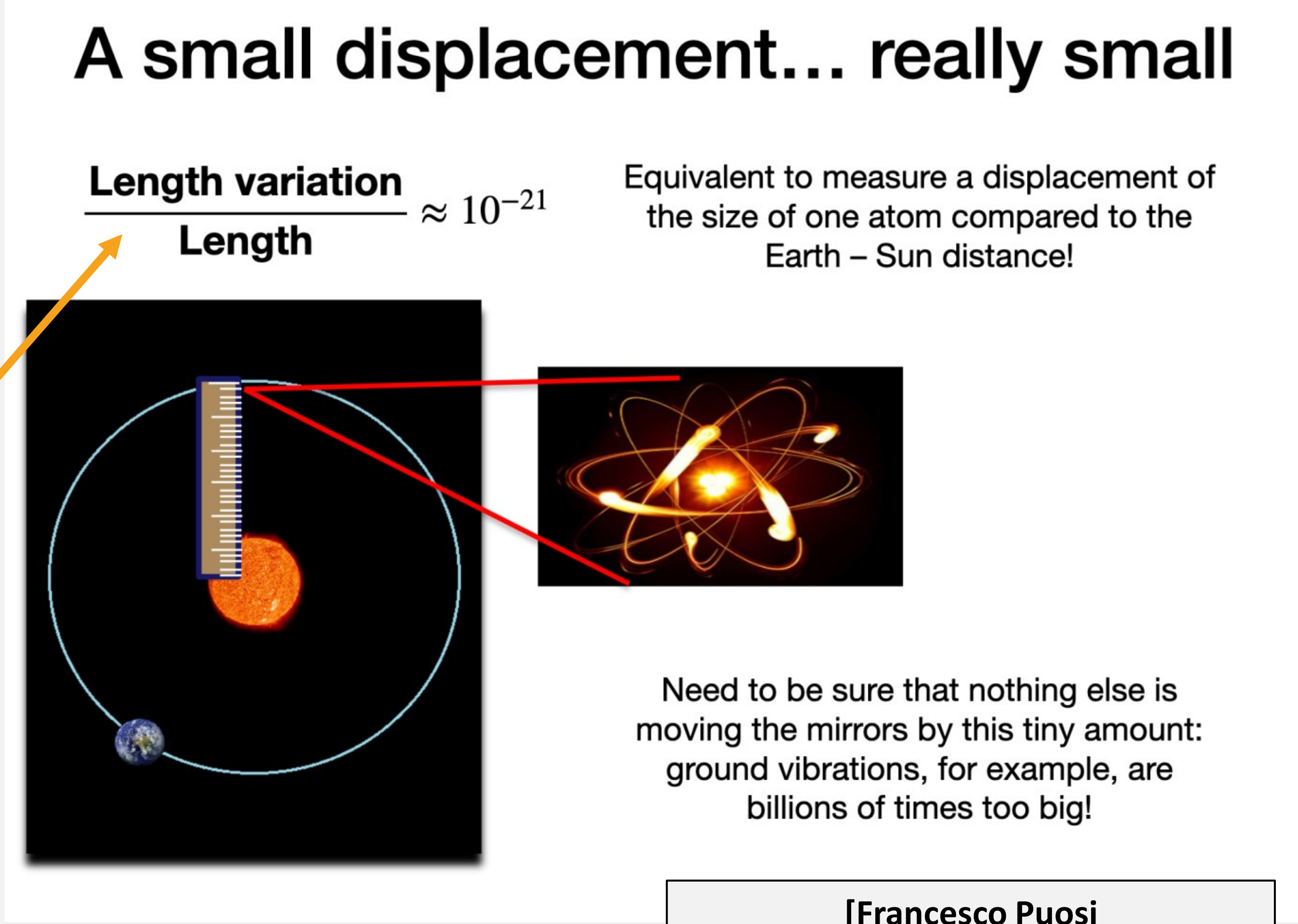
GW interferometers look at a differential change along two separate optical paths.

$$\Delta n_{QED} = 3A_e B^2 = 4\times10^{-24}\ T^{-2}$$

B = 5 T

$$\frac{\Delta OPL_{QED}}{L} = \Delta n_{QED} \approx 10^{-22}$$

(between orth. polarizations in the same optical path!)



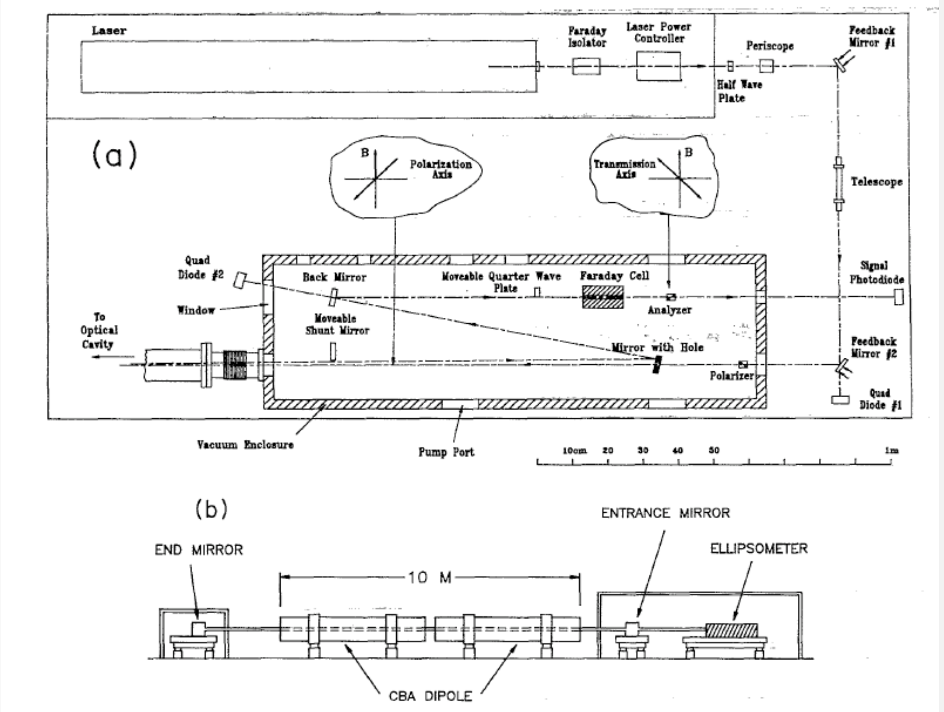
[Francesco Puosi
Fellini General Meeting March 2021]

BRFT

(**B**rookhaven **R**ochester **F**ermilab **T**rieste)

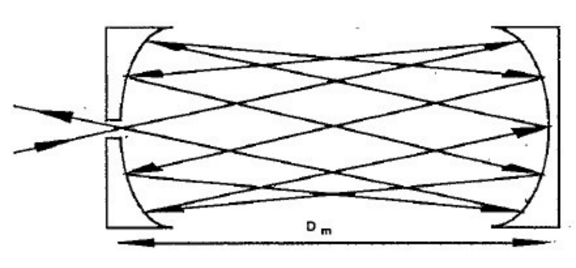
Mainly dedicated to the axion search

1988-1992



Main characteristics:

- Two 4.4 m long magnets, B_0 = 3.25 T
- Field modulation ΔB = 0.62 T @ 30 mHz
- Delay line optical cavity $\sim$500 passes



PHYSICAL REVIEW D VOLUME 47, NUMBER 9 1 MAY 1993

ARTICLES

Search for nearly massless, weakly coupled particles by optical techniques

R. Cameron,* G. Cantatore,† A. C. Melissinos, G. Ruoso,‡ and Y. Semertzidis§
Department of Physics and Astronomy, University of Rochester, Rochester, New York 14627

H. J. Halama, D. M. Lazarus, and A. G. Prodell
Brookhaven National Laboratory, Upton, New York, 11973

F. Nezrick
Fermi National Accelerator Laboratory, Batavia, Illinois 60510

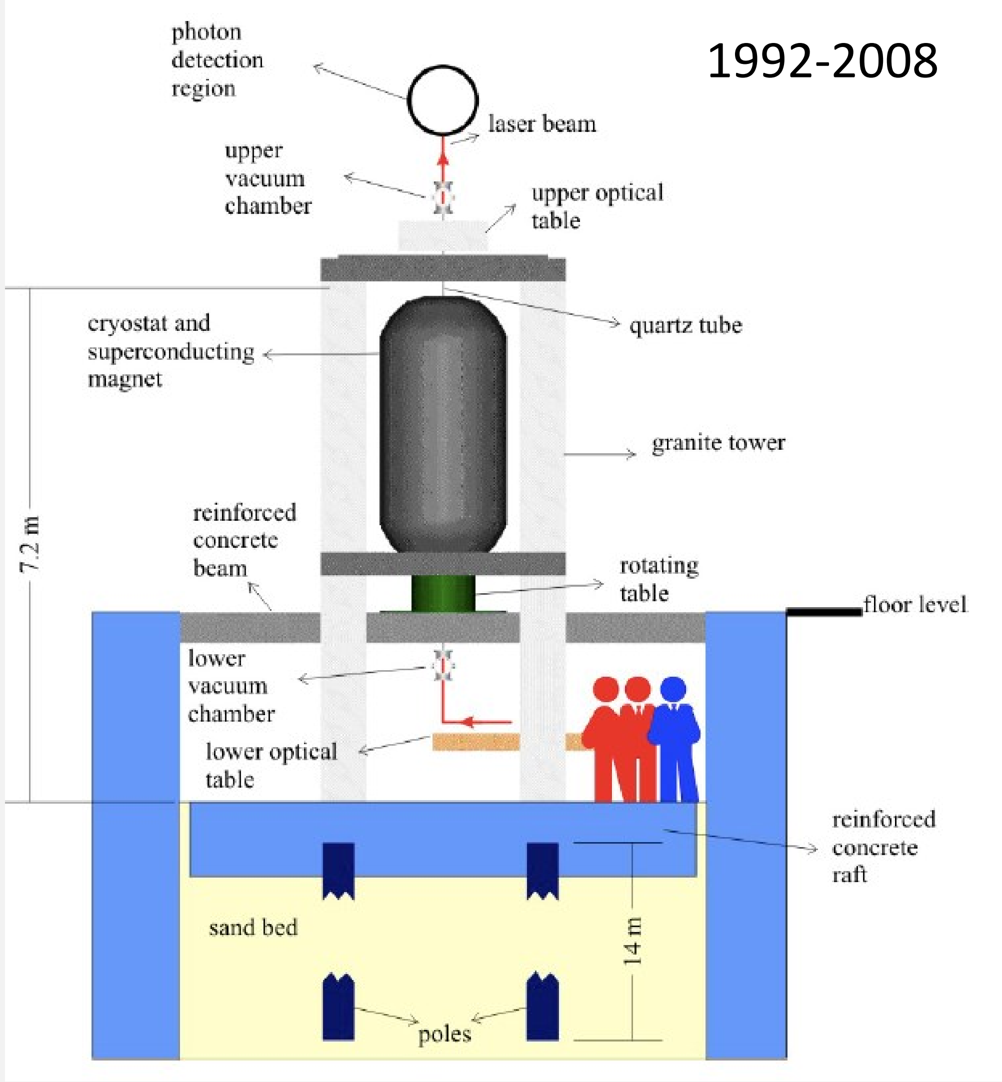
C. Rizzo and E. Zavattini
Dipartimento di Fisica, University of Trieste and Istituto Nazionale di Fisica Nucleare Sezione di Trieste, 34127 Trieste, Italy

(Received 5 October 1992)

Results:

- No VMB signal detected
- Limits on the coupling constant of light scalar/pseudoscalar particles to two photons

PVLAS – LEGNARO (LNL)



Main characteristics:

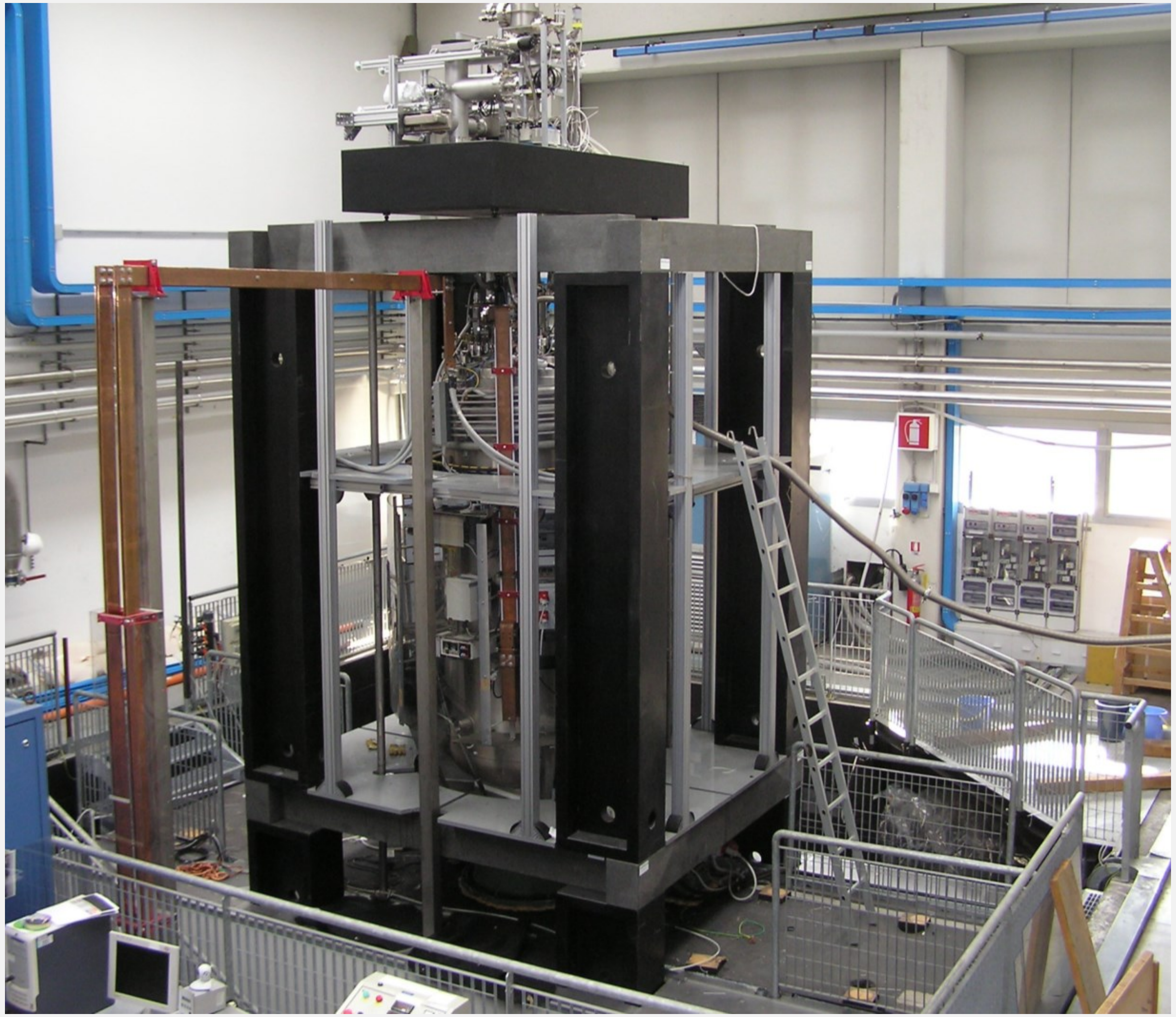
- Fabry-Perot cavity (6.4 m), amplification factor N > $5\text{x}10^4$
- Rotating cryostat (up to 0.4 Hz)
- Superconducting magnet (up to 5.5 T), used 2.3 T
- Optical system mechanically decoupled from magnetic system
- Laser: green (532 nm) or infrared (1064 nm)

Results:

$$\Delta n_{1064} / B^2 = 2 \times 10^{-20}\, T^{-2}$$
$$\Delta n_{532} / B^2 = 1.9 \times 10^{-20}\, T^{-2}$$

[Bregant *et al*, PRD 78, 032006 (2008)]

LIMITATIONS OF THE LNL APPARATUS



Superconducting magnet:

- stray field when operated at high field
- running time limited due to liquid helium consumption
- no zero measurement with field turned ON

Correlation between seismic and ellipticity noise:

- difficult to isolate seismically a large apparatus

Sensitivity:	
short term	3×10^{-7} 1/√Hz
long term	10^{-6} 1/√Hz
Shot-noise limit	3.5×10^{-9} 1/√Hz

DEVELOPMENT STRATEGY

Reverse the logic of designing the apparatus:

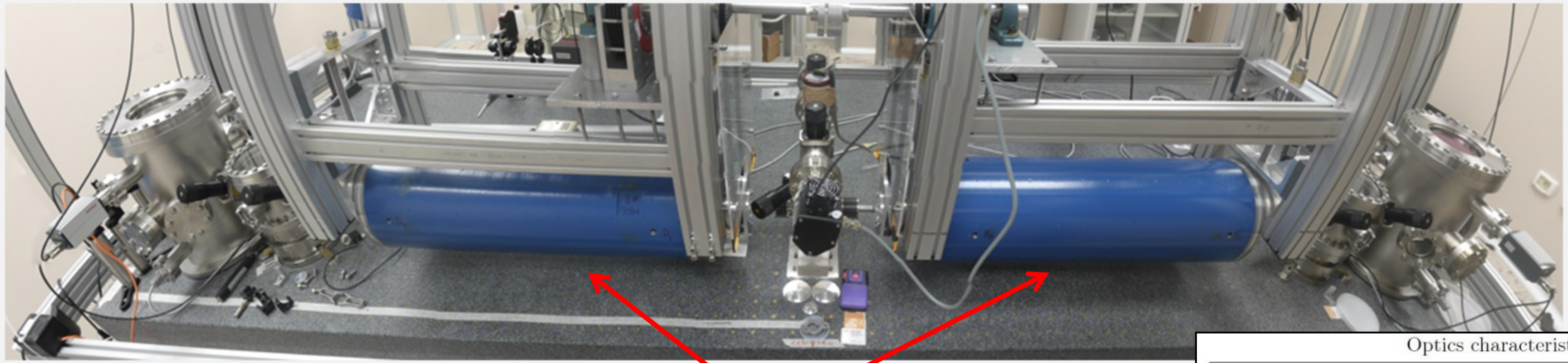
Old - highest magnetic field available and build the optical system around it

New - build up an polarimeter with best sensitivity and find a suitable magnetic source

Elements:

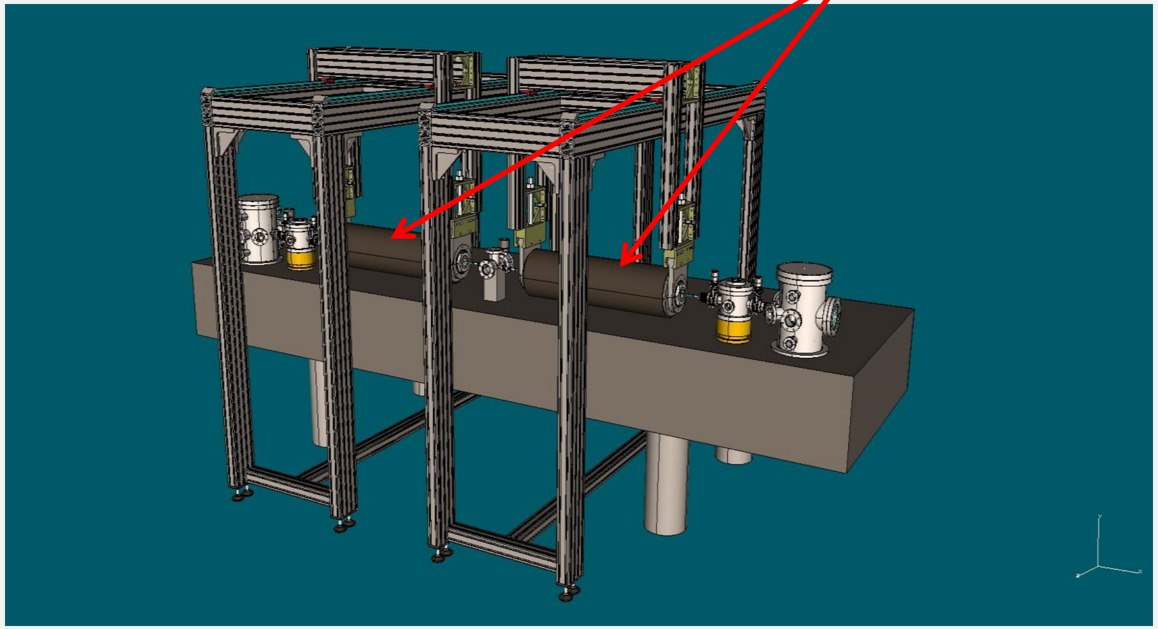
- Polarimeter coupled to a very high finesse Fabry-Perot cavity
- Permanent dipole magnets up to 2.5 T (Halbach configuration)
- System with built-in capability of “bad” signal rejection (two magnet system)

THE PVLAS EXPERIMENT IN FERRARA



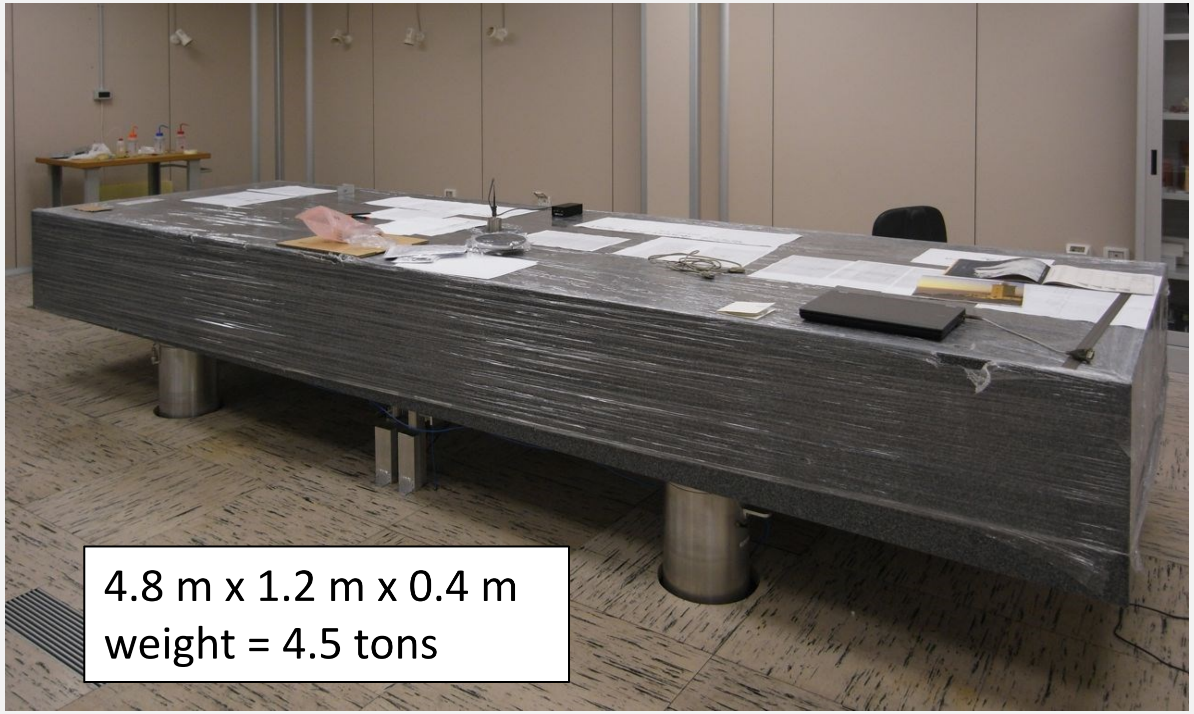
2010-2016

permanent magnets 2.5 T, L= 0.9 m each

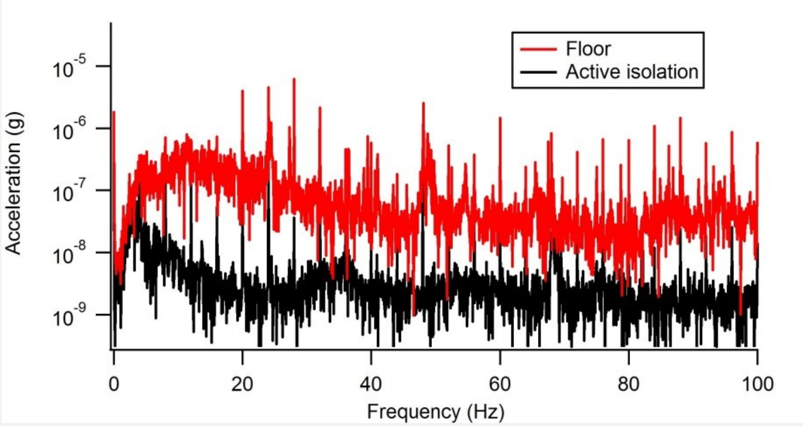


Optics characteristics	
Optical bench	Material: granite, dimensions: $4.8 \times 1.5 \times 0.5$ m^3
Laser	Nd:YAG NPRO, $\lambda = 1064$ nm, maximum power: 2 W
Fabry-Perot	Length: 3.303 m Finesse: 670000
Fabry-Perot mirrors	Radius of curvature: 2 m Reflectivity: $R > 0.999996$, Transmission: $T \approx 2 \times 10^{-6}$
Photo Elastic Modulator **PEM**	Fused silica bar coupled to a piezo transducer Resonance frequency: 50.047 kHz Typically induced ellipticity: $\approx 10^{-3}$
Polarisers	Nominal extinction ratio $\sigma^2 < 10^{-7}$
Magnet characteristics	
Components	2 permanent dipole magnets in Halbach configuration length 96 cm, magnetic field shielding.
Field strength	$B_{\rm max} = 2.6$ T, $\int B^2 dl = 5.12$ T^{2}m each. Stray field < 1 gauss (along axis @ 20 cm).
Rotation frequency	Up to 10 Hz.
Vacuum system characteristics	
Components	Non magnetic materials Turbomolecular pumps Non-evaporable getter pumps
Total pressure	$\lesssim 10^{-7}$ mbar, mainly H_2O.

OPTICAL TABLE



4.8 m x 1.2 m x 0.4 m
weight = 4.5 tons

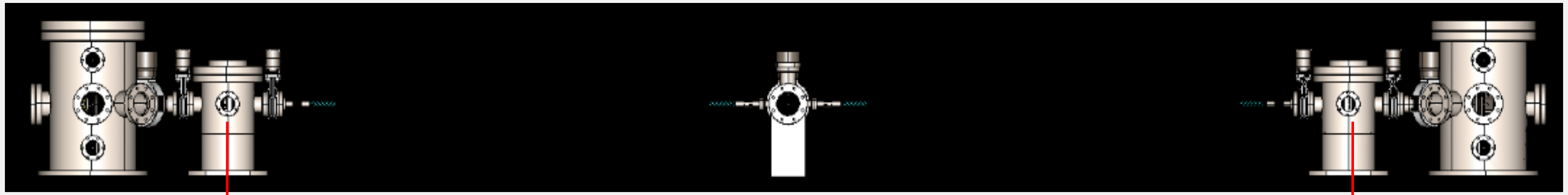


Actively isolated granite optical bench

Compressed air stabilization system with six degrees of freedom

Cut-off frequency ~ 3 Hz

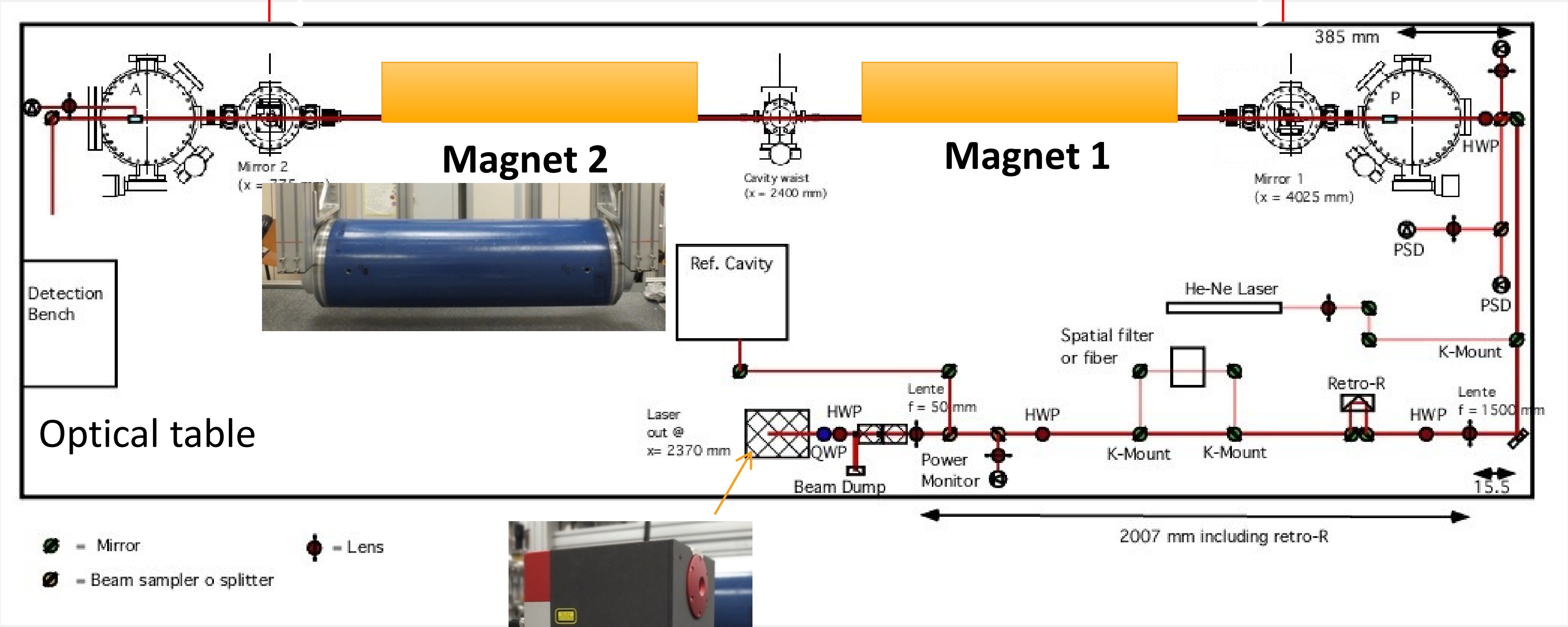
OPTICAL LAYOUT

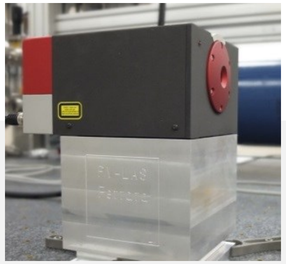


PEM
Analizer

3.3 m long Fabry Perot cavity

Polarizer





NPRO Nd:YAG Laser
2 Watt, λ = 1064 nm

FABRY PEROT CAVITY

Transmitted power up to 200 mW

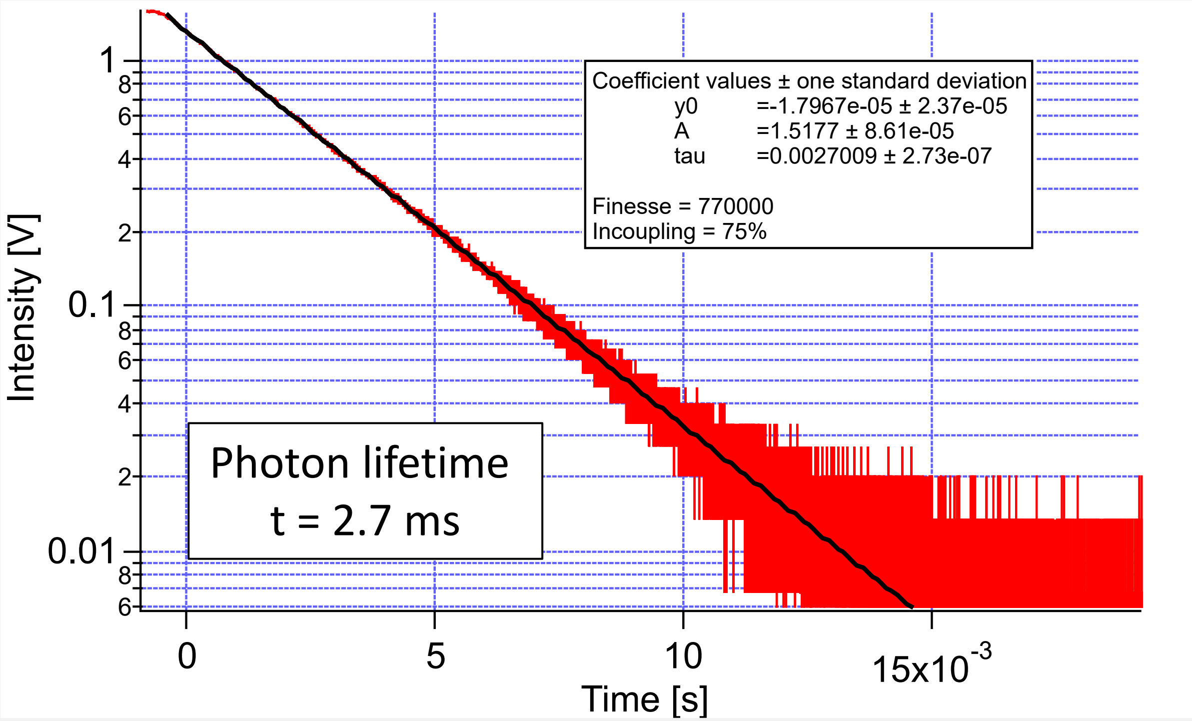
Finesse = 770 000   N = 480 000

Circulating power = 40 kW

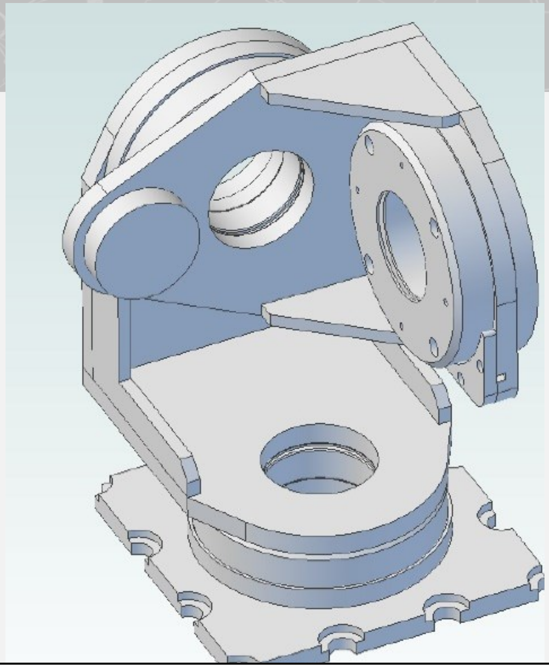
High reflectivity (R =0.999996)

Cavity length L = 3.3 m

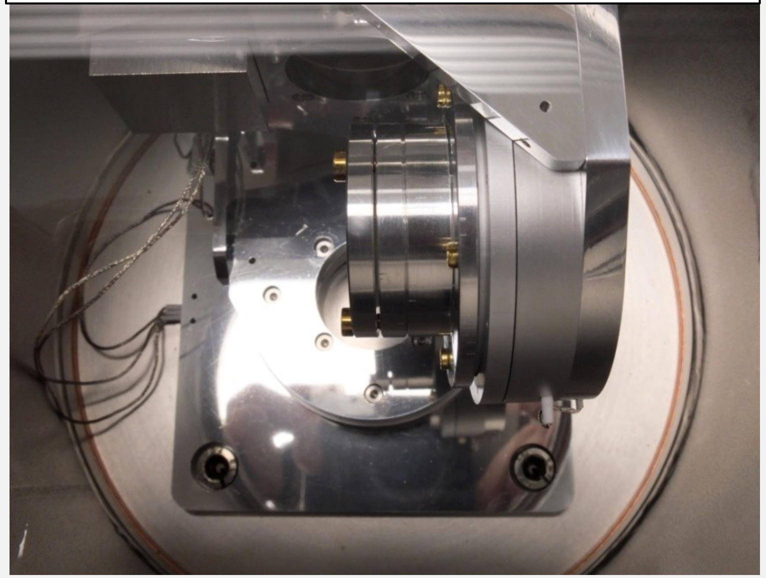
AT Films (Boulder, CO)



[Optics Express 22, (2014)]



3-axis mirror mount θ_x, θ_y, θ_z

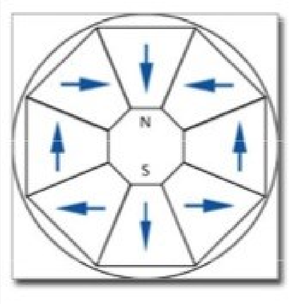


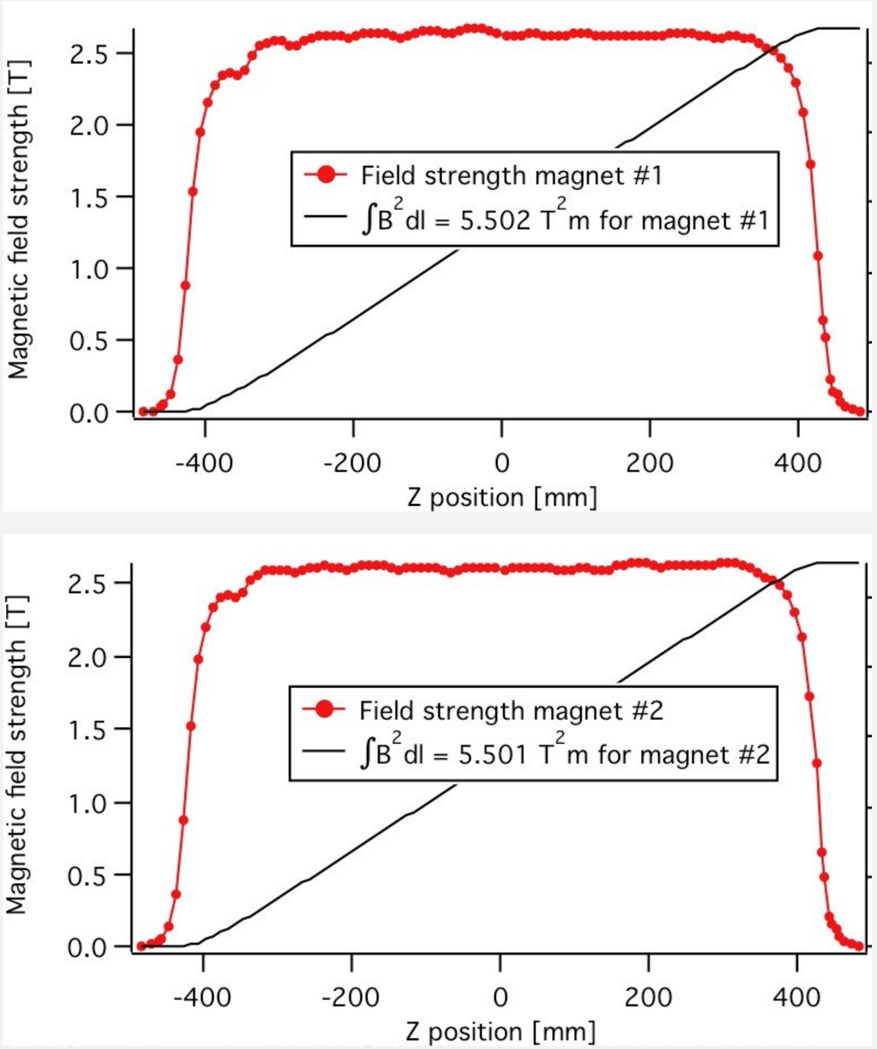
decay time a factor two larger than any previously reported optical resonator!

MAGNETS

Permanent dipole magnets

Halbach configuration





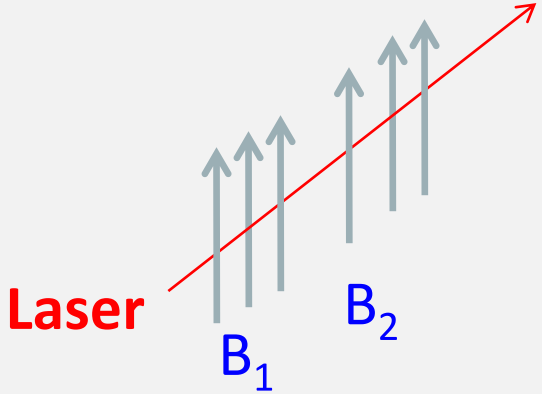
Magnets have a built-in **magnetic shielding**

Stray field < 1 G along the axis (@ 20 cm outside the magnets)

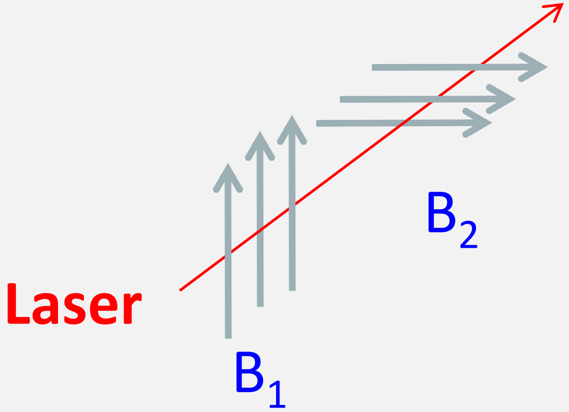
Total field integral = 10.25 T^2 m

TWO MAGNETS: "GOOD" SIGNAL TEST

Two magnets system to check that signal is due to magnetic birefringence



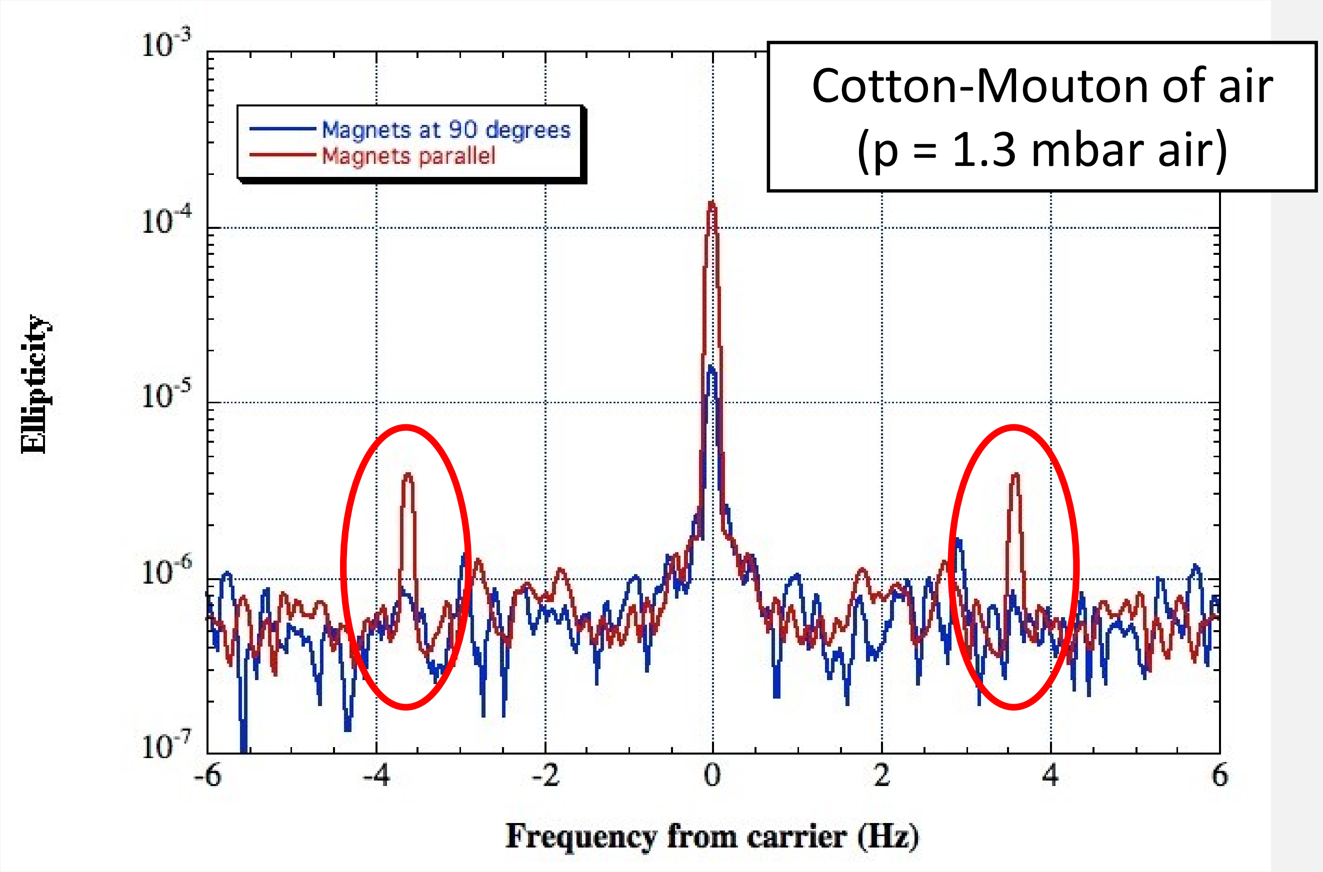
$$\Psi_{tot} = 2\Psi$$



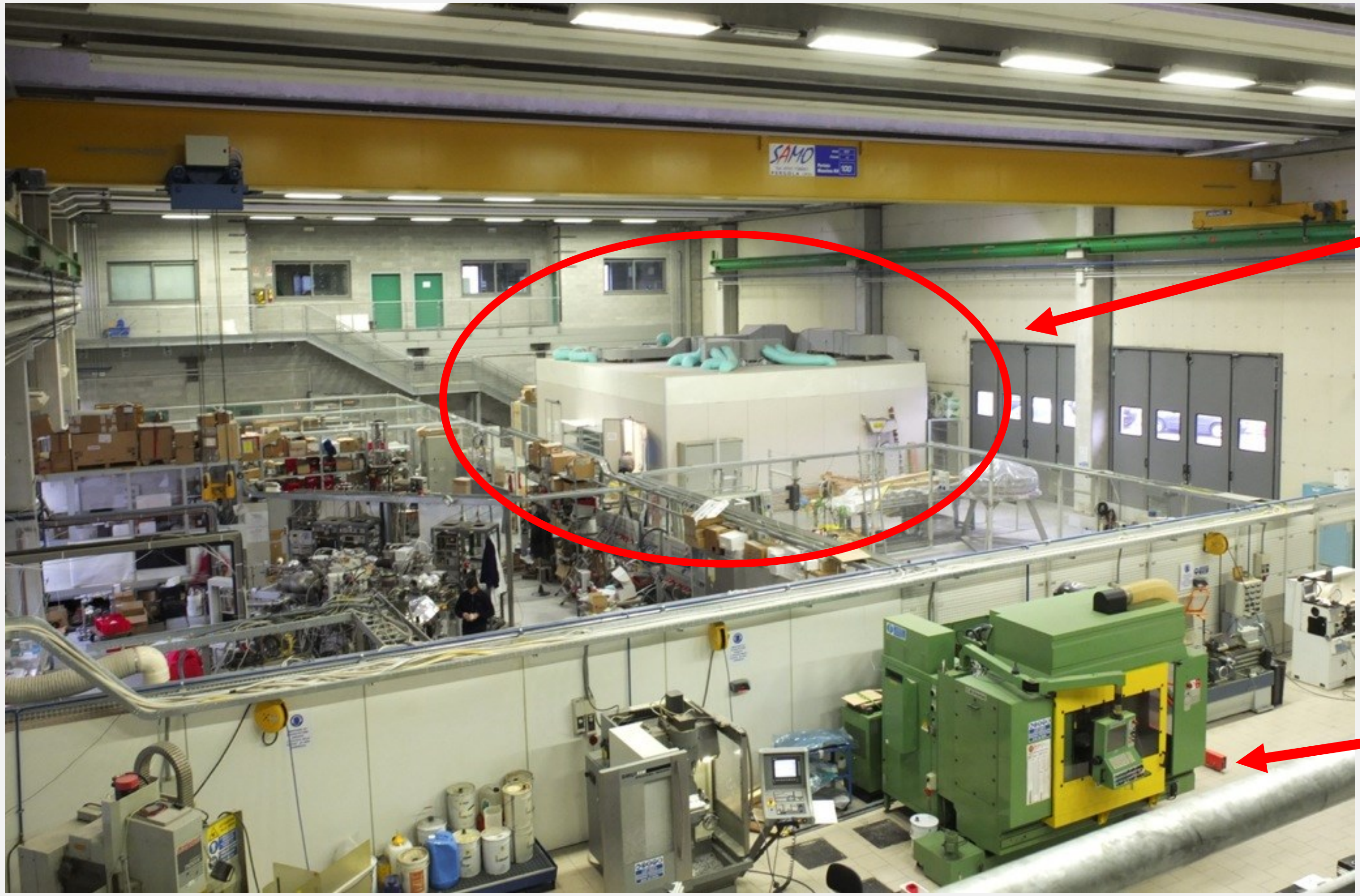
$$\Psi_{tot} = 0$$

Zero Measurement

(Cotton-Mouton effect = magnetic birefringence in gasses)



CLEAN ROOM FACILITY



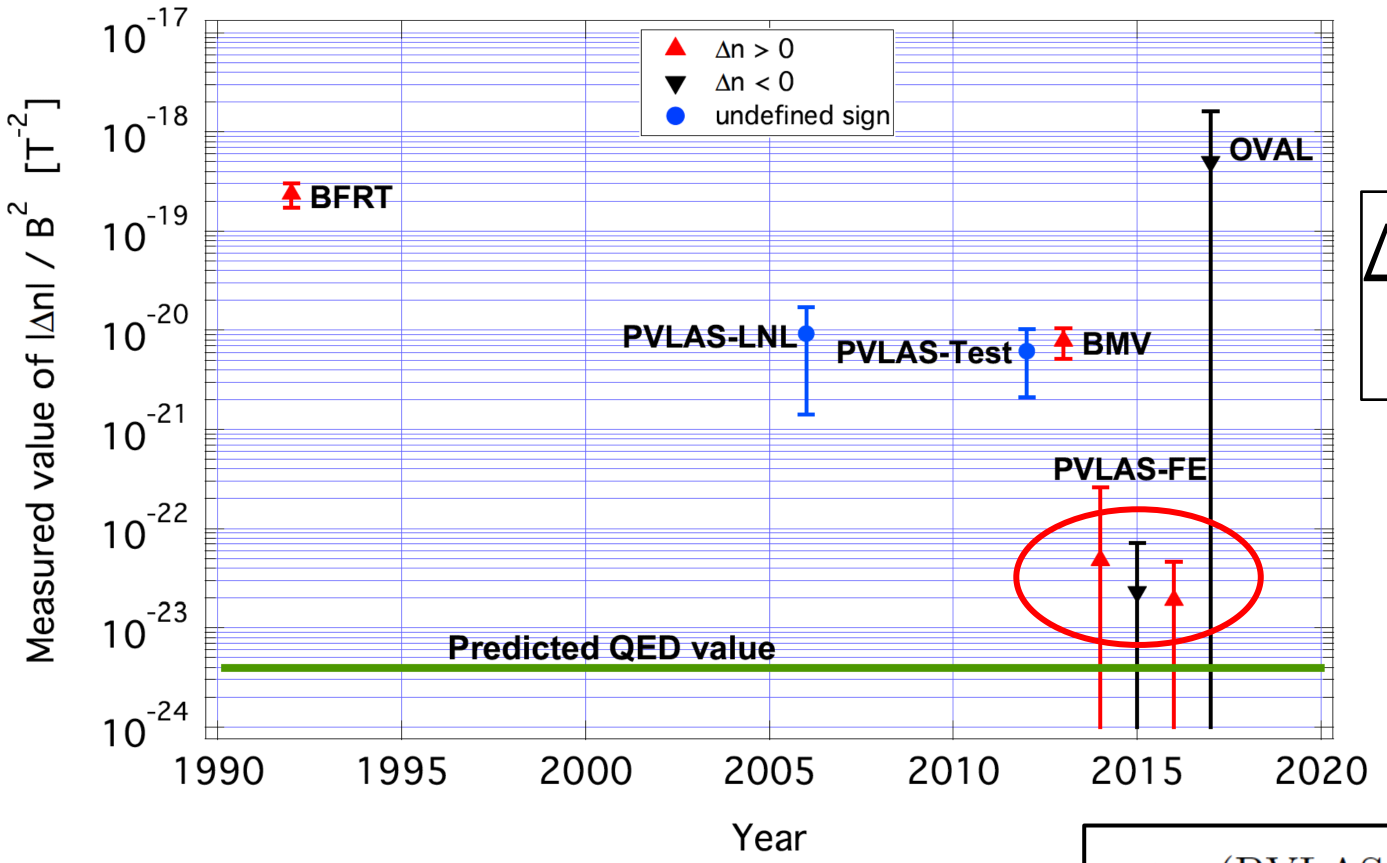
Clean room class 10000

Temperature stabilized

Mechanical Workshop

Environment with human activity during the day

PVLAS-FE RESULTS



[A. Ejlli et al. Phys. Reports, 871 1-74 (2020)]

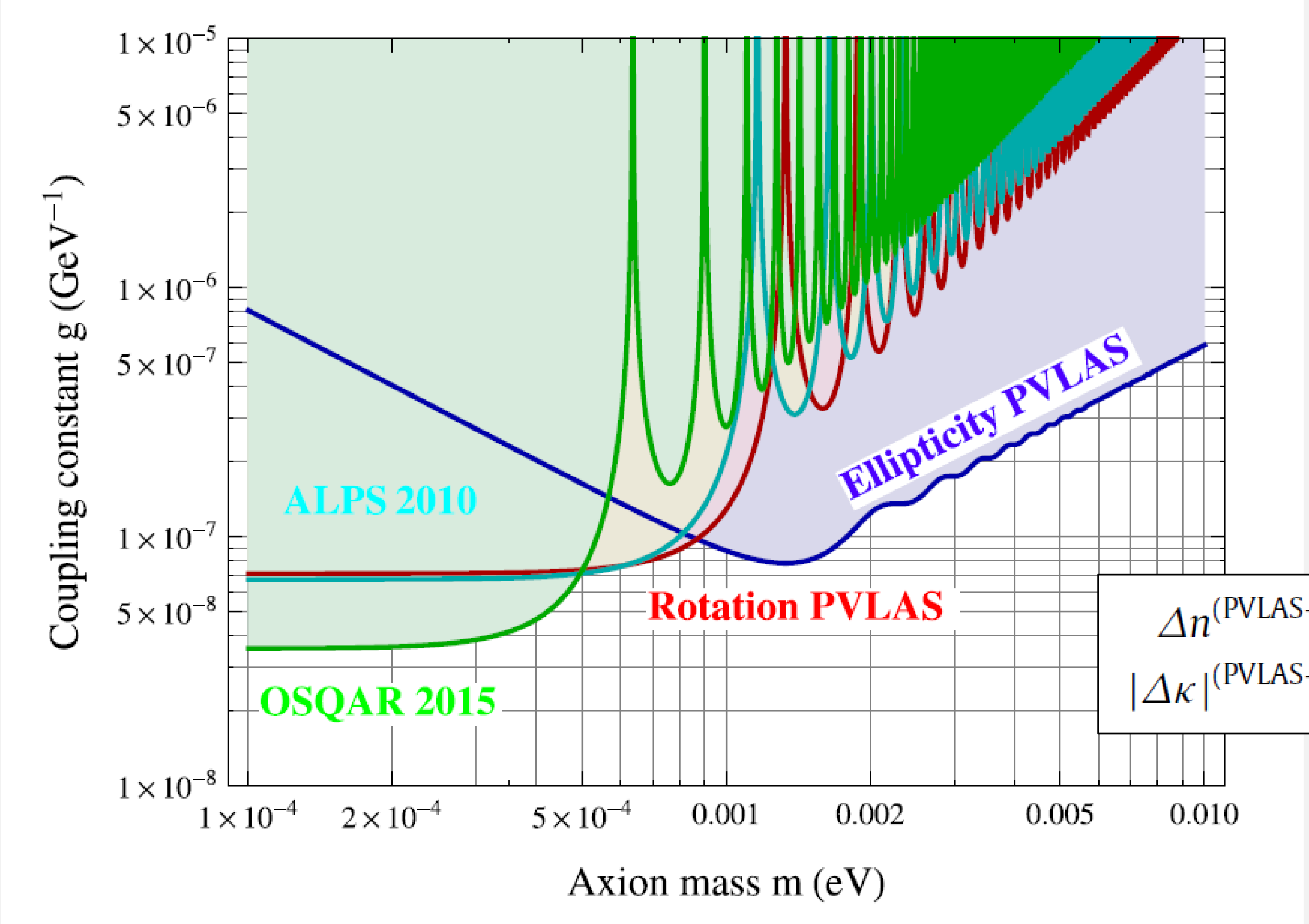
$\Delta n_{QED} = 3A_e B^2 = 4\times10^{-24}$

(for a 1 T magnetic field)

$$\frac{\Delta n^{(\mathrm{PVLAS-FE})}}{B^2_{\mathrm{ext}}} = (+19 \pm 27) \times 10^{-24}\ \mathrm{T}^{-2}$$

PVLAS-FE RESULTS II

Axion-like particles (ALPs) exclusion limits



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

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

[A. Ejlli et al. Phys. Reports, 871 1-74 (2020)]

QED ELLIPTICITY SIGNAL

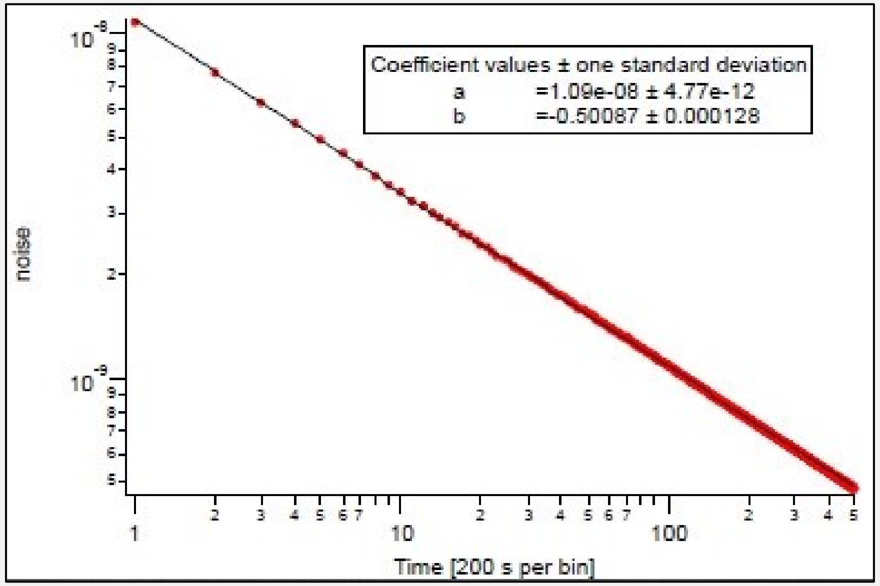
- B = 2.5 T, λ = 1064 nm, $F = 7\cdot10^5$ and L_{mag} = 1.64 m

$$\psi_{\mathrm{QED}} = 5.6\times10^{-11}$$

- Sensitivity required to reach SNR = 1 in T = 10^6 s:

$$s_{required} = \psi_{\mathrm{QED}}\cdot\sqrt{T} \approx 6\times10^{-8}\frac{1}{\sqrt{Hz}}$$

TARGET SENSITIVITY

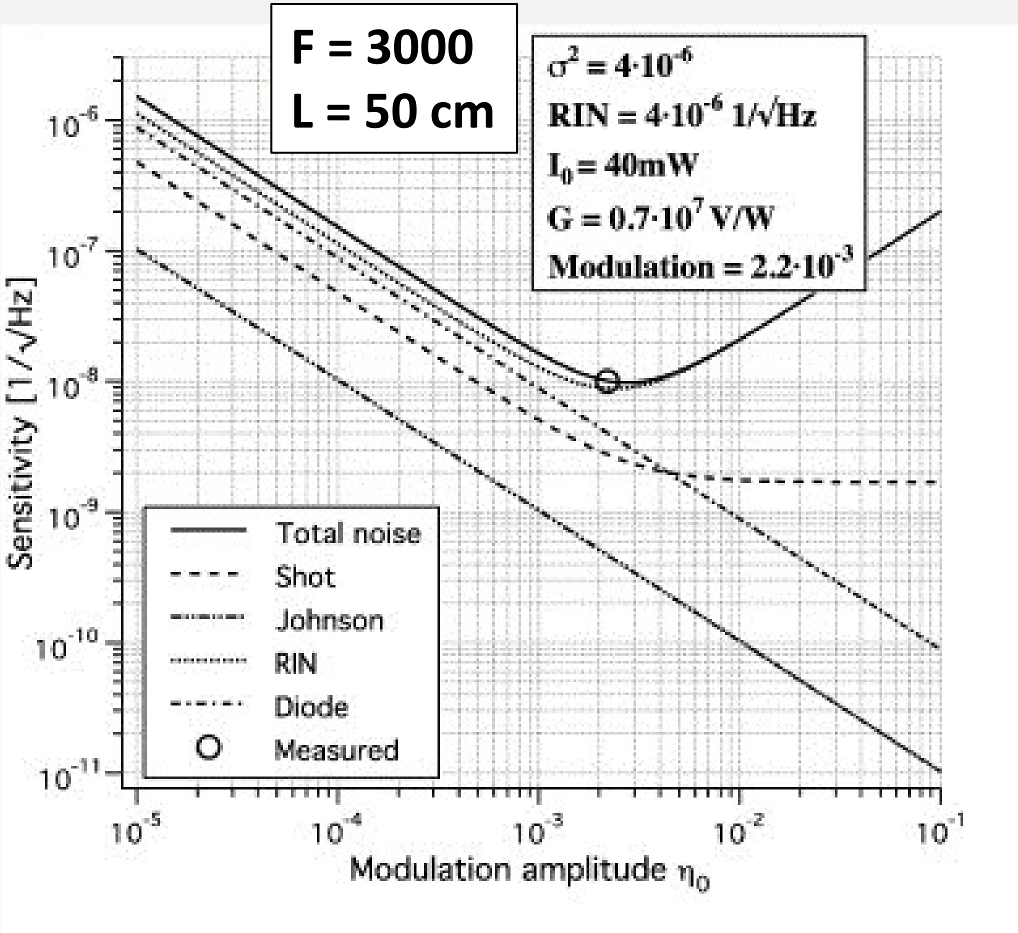


Integrated noise decreases as √T

$$\left(s_{shot} \approx 6\times10^{-9}\frac{1}{\sqrt{Hz}}\right)$$

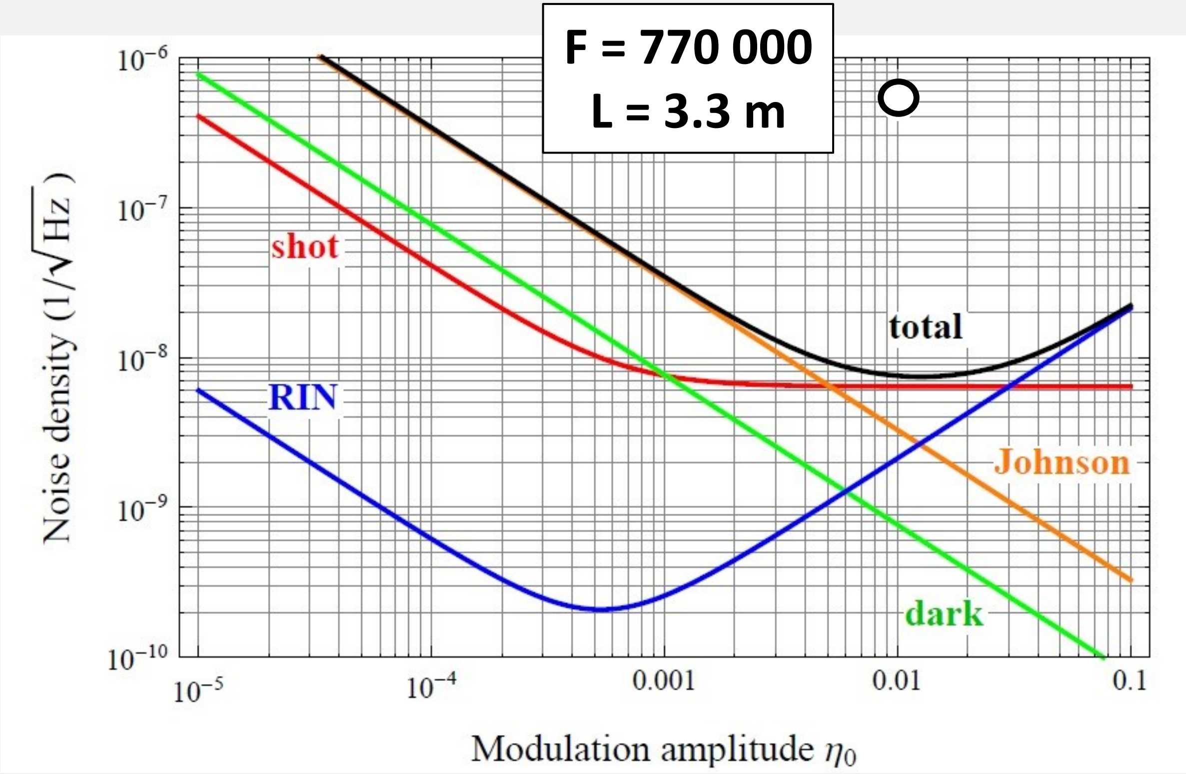
for $I_{output} \sim 8$ mW

ELLIPTICITY SENSITIVITY



Noise budget OK.

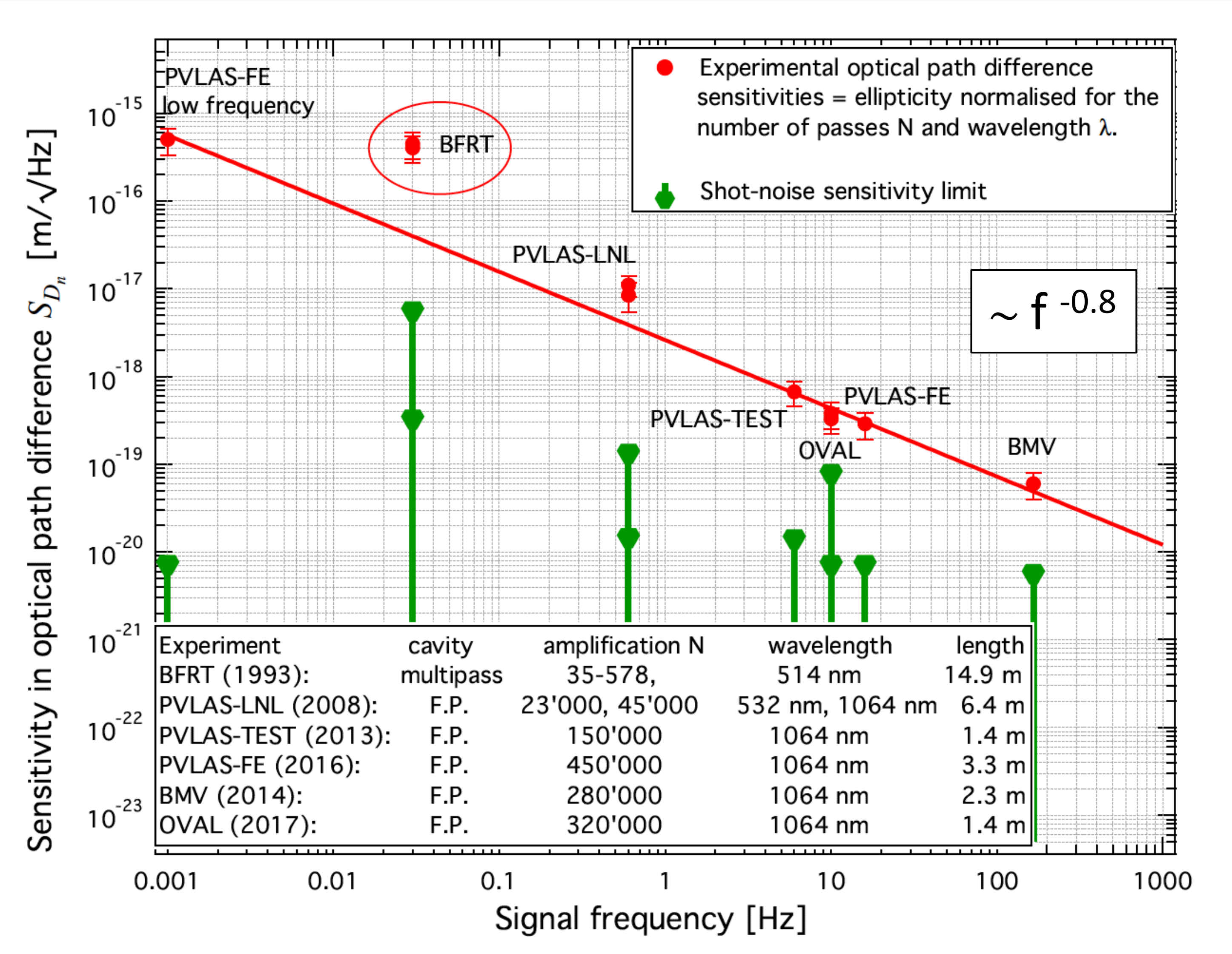
[F. Della Valle et al., Optics Communications **283**, 4194 (2010)]



With a high finesse cavity sensitivity gets worse!!

Measured sensitivity is more than one order of magnitude higher than expected!!

INTRINSIC NOISE



[A. Ejlli et al. Phys. Reports, 871 1-74 (2020)]

- None of the experiments reached shot-noise limited sensitivity
- Intrinsic noise coming from the cavity mirrors limits the sensitivity in optical path difference:

$$S_{\Delta\mathcal{D}} = \frac{\lambda}{N\pi} S_{\Psi}$$

(ΔD does not depend on finesse)

No need for high finesse, but rather increase the signal!

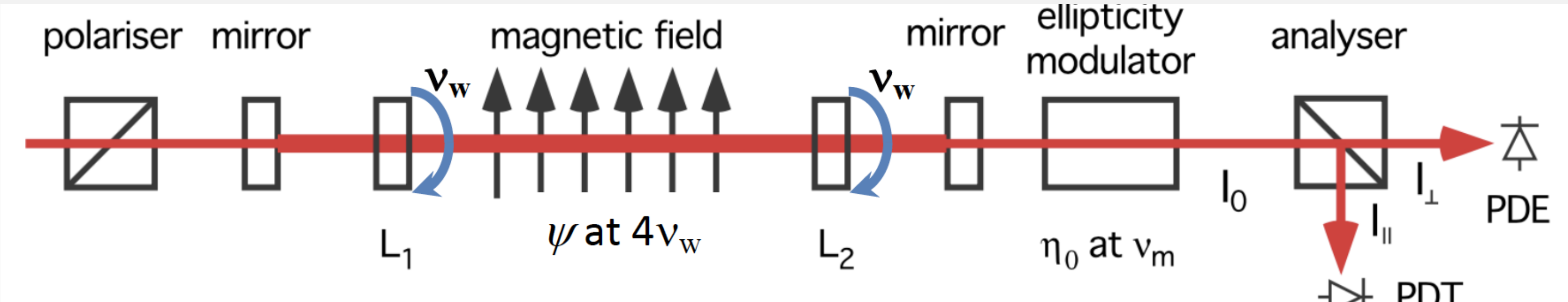
VMB@CERN INITIATIVE

Clear indication for future experimental efforts:

increase the signal with higher B^2 L → superconducting magnets

PVLAS permanent magnets B^2 L≈ 10 T^2 m → LHC dipole magnet B^2 L≈ 1200 T^2 m

CANNOT BE MODULATED FAST ENOUGH!!



G. Zavattini et al. Eur. Phys. J. C (2016) 76:294

Modulate the VMB signal using two co-rotating half waveplates inside the optical cavity:

- Polarization rotation inside the magnetic field but fixed on mirrors
- Maximum finesse ≈ 1000 - 5000 (depending on the losses of the waveplates)

ELLIPTICITY SPECTRUM

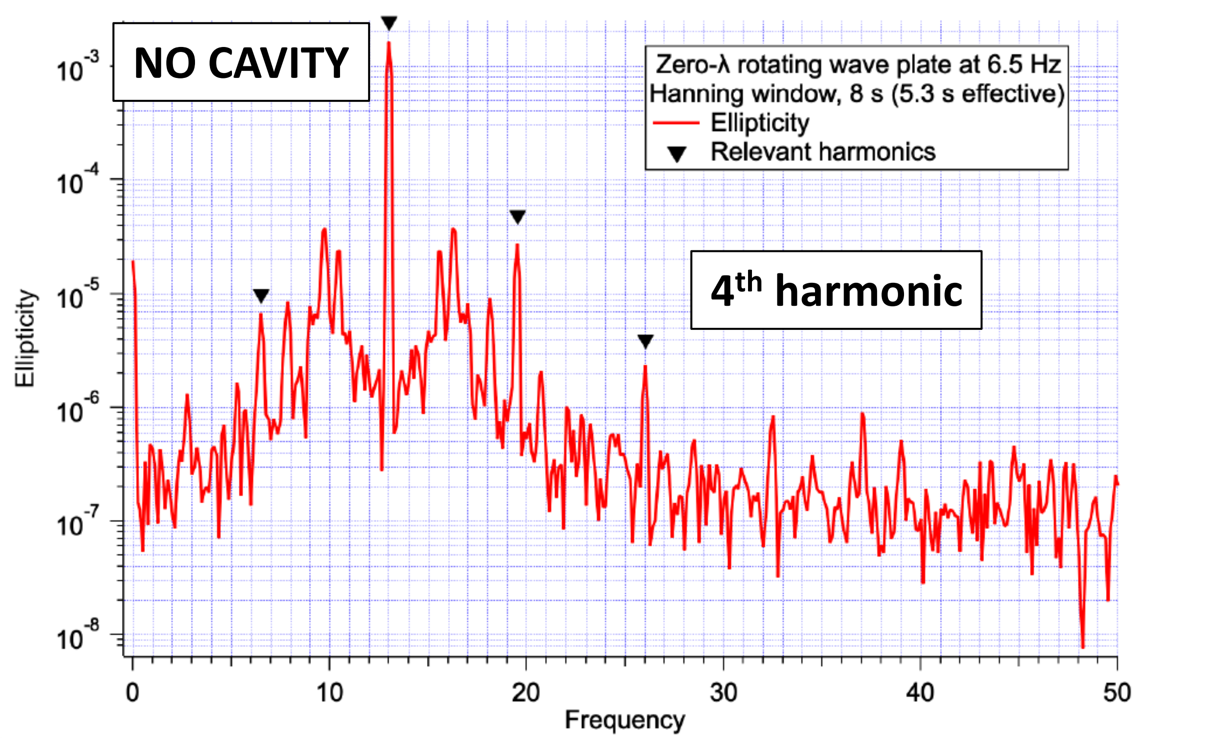
$\alpha_{1,2}$ are the phase errors from π of the two HWPs and $\phi(t)$ is their rotation angle

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

Signal is at 4th harmonic of the rotation frequency

Waveplate defects have different frequency components

$$\alpha = \alpha^{(0)} + \alpha^{(1)}\cos\phi + \alpha^{(2)}\cos 2\phi$$



FEATURES:

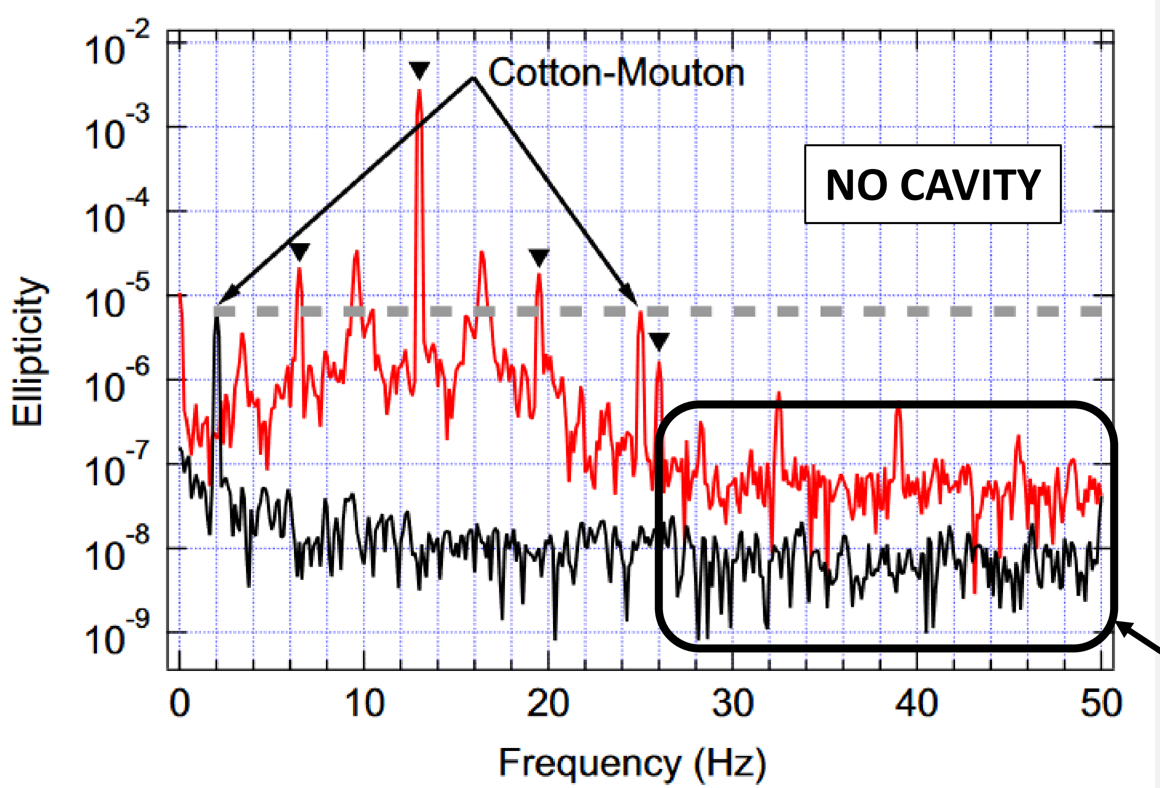
- ‘Large bump’ centered around 2^{nd} harmonic
- Broadband noise
- Peaks at various harmonics (triangles) are due to the rotating waveplate
- Presence of peak at 4^{th} harmonic

POSSIBLE SHOWSTOPPER!

WORKAROUND

Found a workaround: MODULATE THE MAGNETIC FIELD!

(Cotton-Mouton effect = magnetic birefringence in gasses)



10 vector averages: each 8 s with Hanning window

[G. Zavattini et al. Eur. Phys. J. C vol. 82: 159 (2022)]

- **Red** – magnet rotating at 0.5 Hz and HWPs at 6.5 Hz
- **Black** – magnet rotating at 1 Hz and non-rotating HWPs

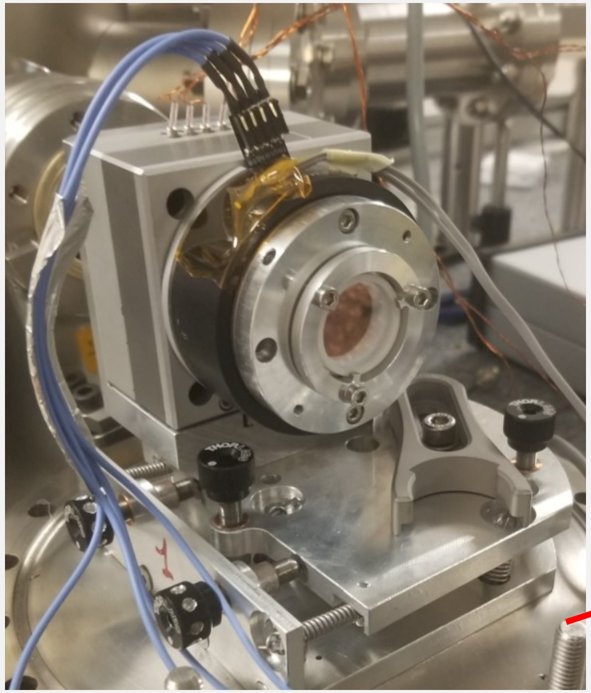
The peak in **red** at 25 Hz is due to the Cotton-Mouton of air and has the same amplitude as the signal in **black** at 2 Hz.
The 4th harmonic @ 26 Hz is very narrow (< 0.125 mHz with SNR ≈ 300).

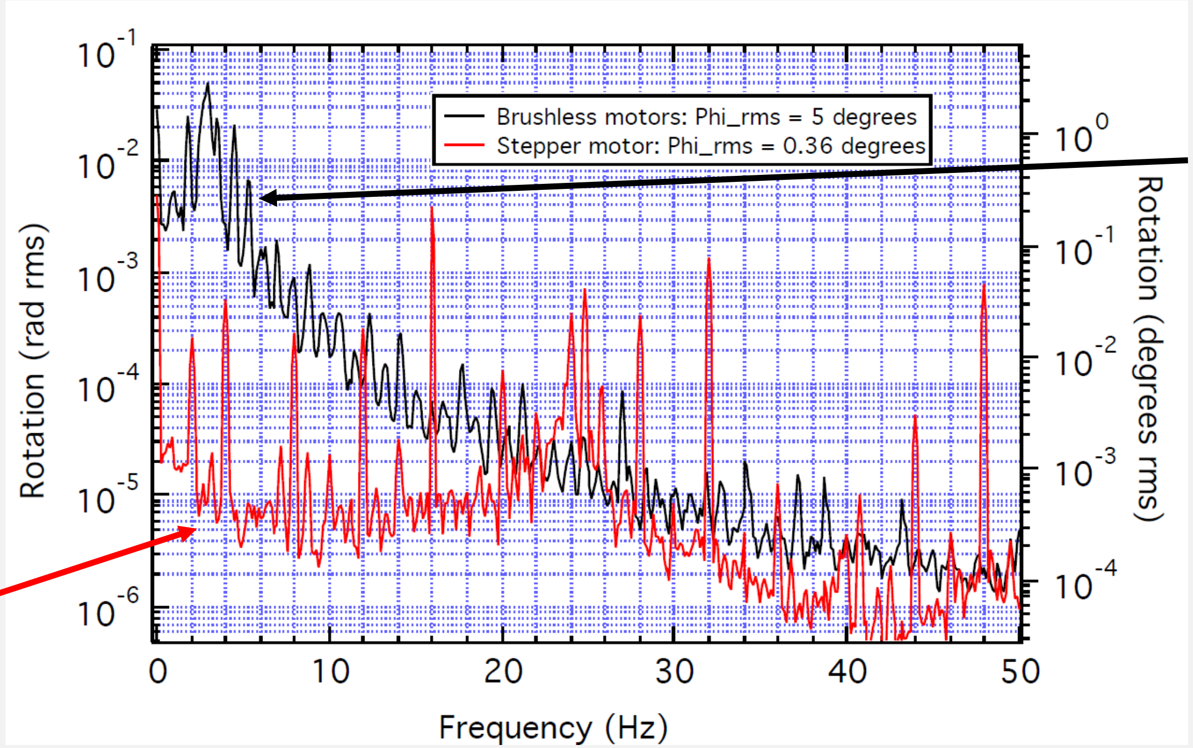
The difference in noise is due to the relative phase (rotation) noise of the HWPs motors.

WAVEPLATE MECHANICS

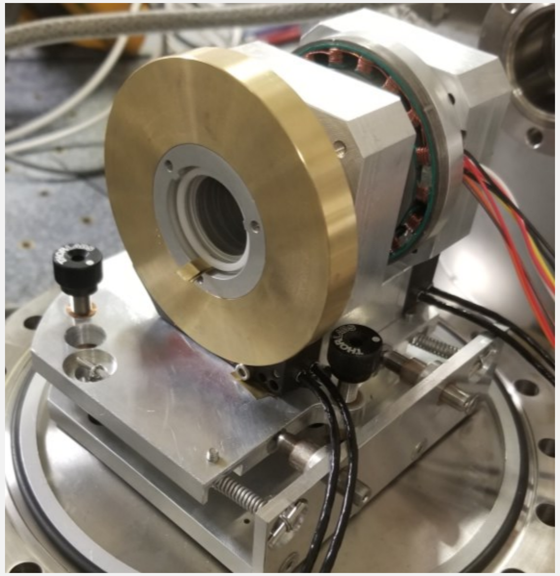
- Base plate alignment and centering of waveplates
- New stepper motors with a more accurate rotation (absolute phase) control: relative rotation rms noise between the two HWPs has improved by a factor ≥ 10 allowing an extinction ratio of $\sigma^2 = 5 \cdot 10^{-6}$

NEW

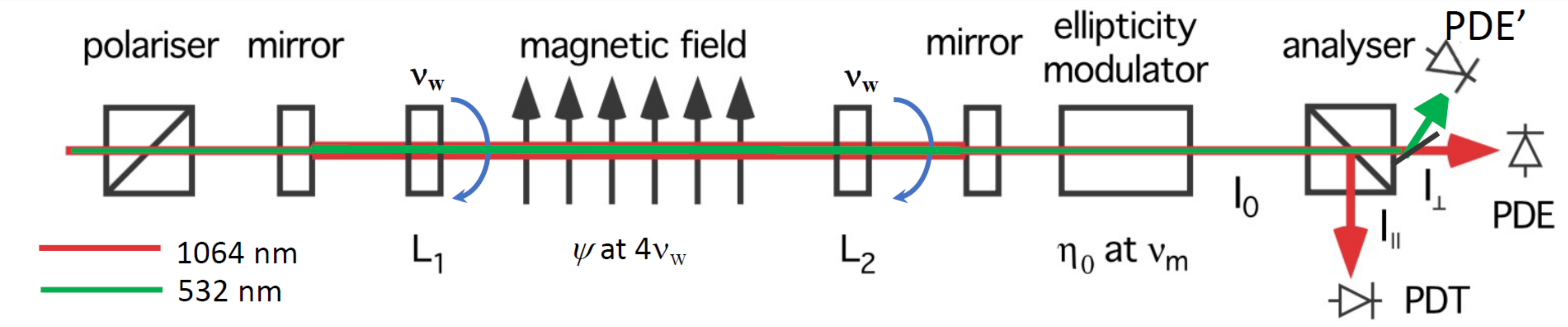




OLD



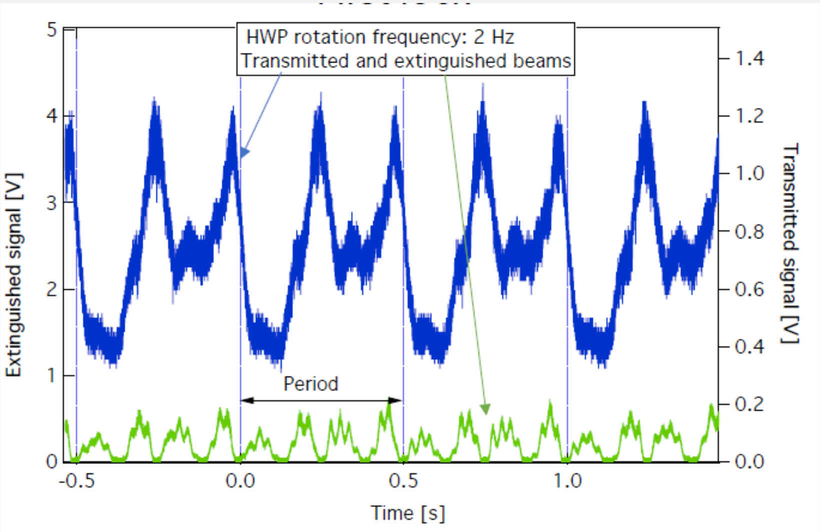
CONTROL OF SYSTEMATICS



Auxiliary laser beam @ 532 nm (HWP -> FWP) allows real-time control of the systematics due to the rotating HWPs

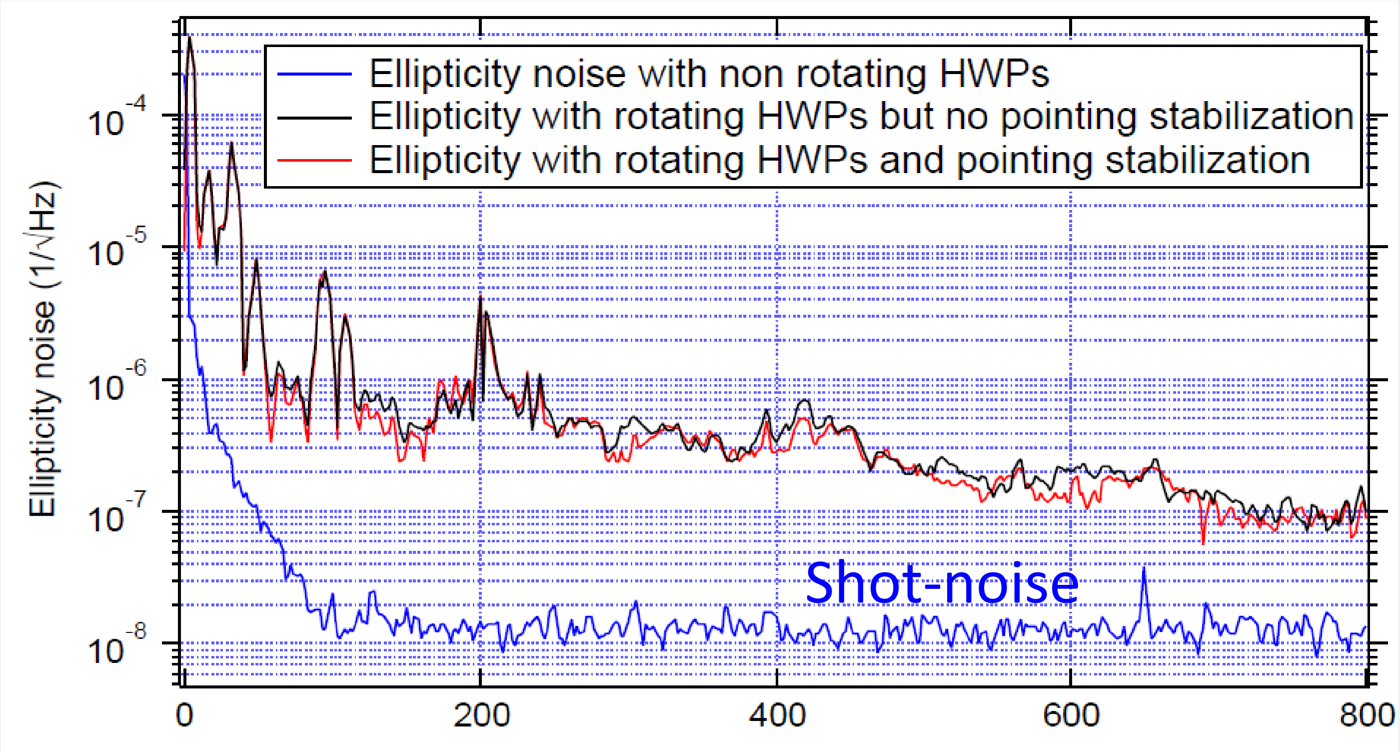
Reduction of peaks at harmonics

Demonstrated locking (noisy) of the cavity with the rotating HWPs



WIDEBAND ELLIPTICITY NOISE WITH ROTATING HWPS

Co-rotating HWPs at 2 Hz with stepper motors vs non-rotating HWPs



INTEGRATED ALIGNMENT STABILIZATION IN THE SYSTEM

Implemented a beam pointing stabilization system but…
there is a wideband ellipticity noise generated by the rotation of the HWPs that is not mitigated by beam pointing stabilization

ALTERNATIVES TO ROTATING HWPS

Currently the collaboration is evaluating possible alternatives

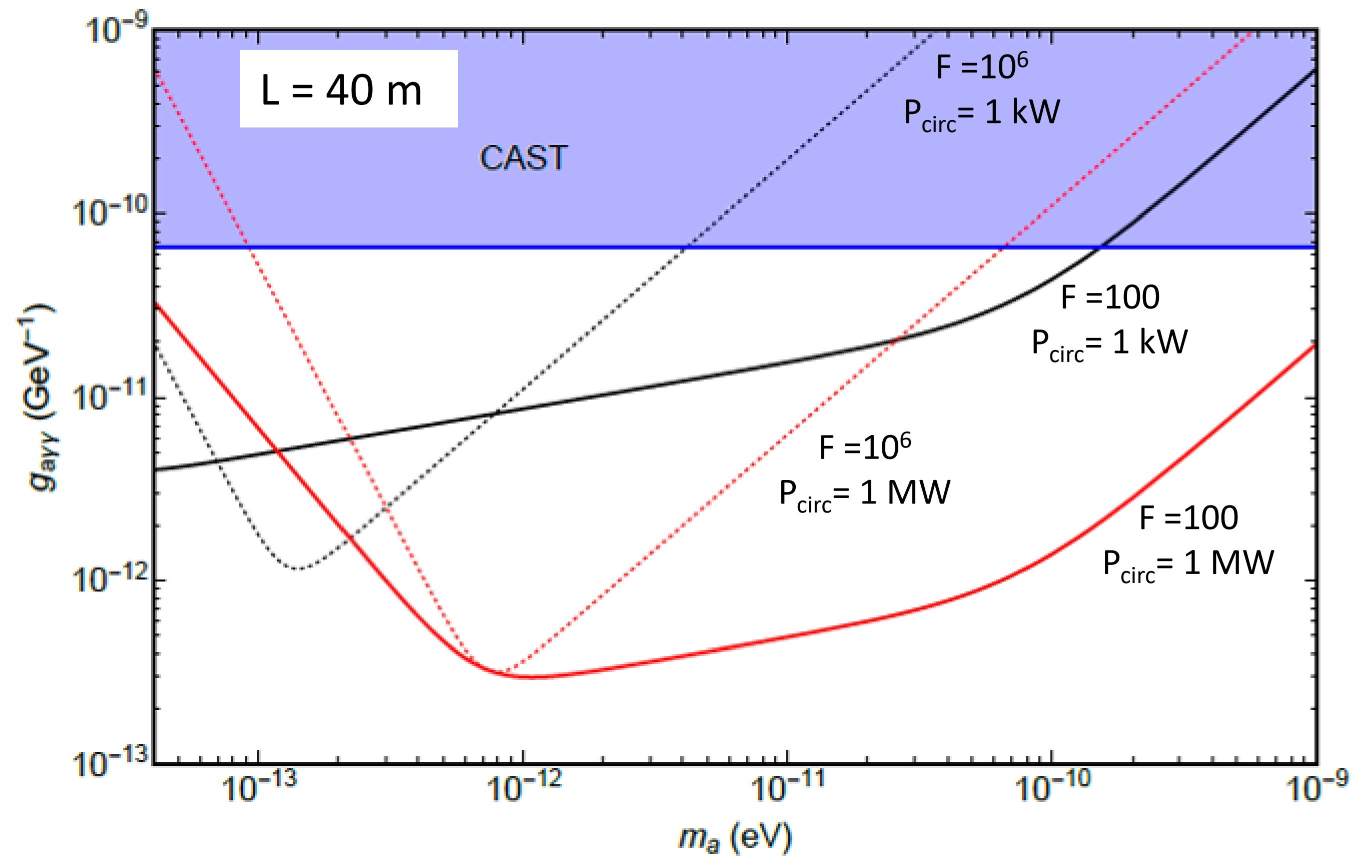
- Ways to rotate polarization without mechanical movement:
  - Faraday rotators
  - Electro-optic modulators
  - Nematic crystal modulators
  - Fixed quarter waveplates and orthogonal polarizations
  - ....
- Different cavity mirrors: crystalline coatings, low-loss amorphous silicon,..

Brainstorming is ongoing

POLARIMETRY FOR ALP DETECTION

$$a(t) = a_0 \cos(m_a t + k_a z)$$

ALP field behaves as a classical field



[W. DeRocco and A. Hook,Phys. Rev. D 98, 035021 (2018)]

In the presence of ALP dark matter there is a difference in phase velocity between right and left circularly polarized light.

$$v_{\circlearrowright,\circlearrowleft} \approx 1 \pm \frac{g_{a\gamma}\dot{a}}{k}$$

A background axion field causes linearly polarized light to slowly rotate!

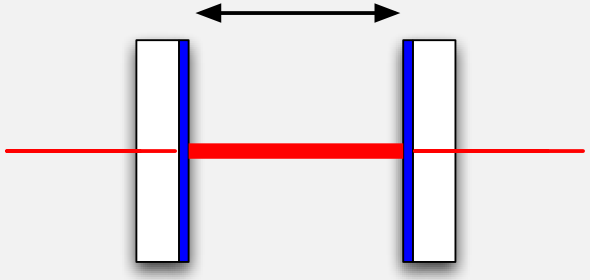
Alternative way to use polarimetry to detect ALPs!

EXTRA SLIDES

FABRY PEROT CAVITY

The Fabry-Perot cavity increases the effective optical path inside the magnetic field region.

$$d = n\frac{\lambda}{2}$$

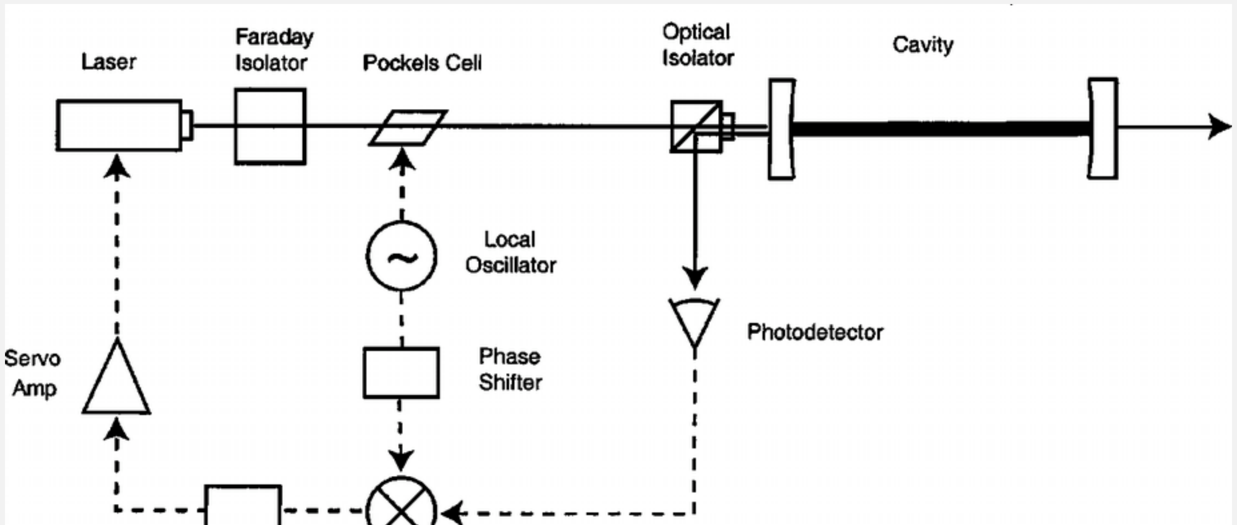


Amplification of optical path

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

Finesse

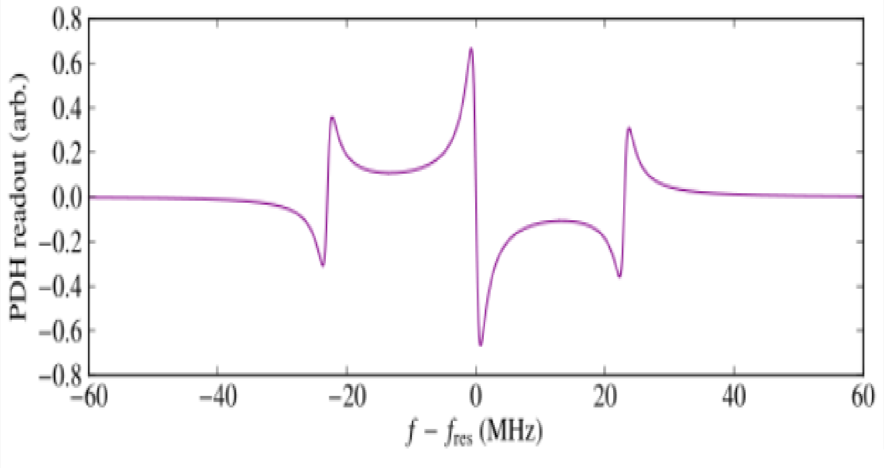
$$F = \frac{\pi c \tau}{d}$$



[E. Black, "An introduction to Pound–Drever–Hall laser frequency stabilization"]

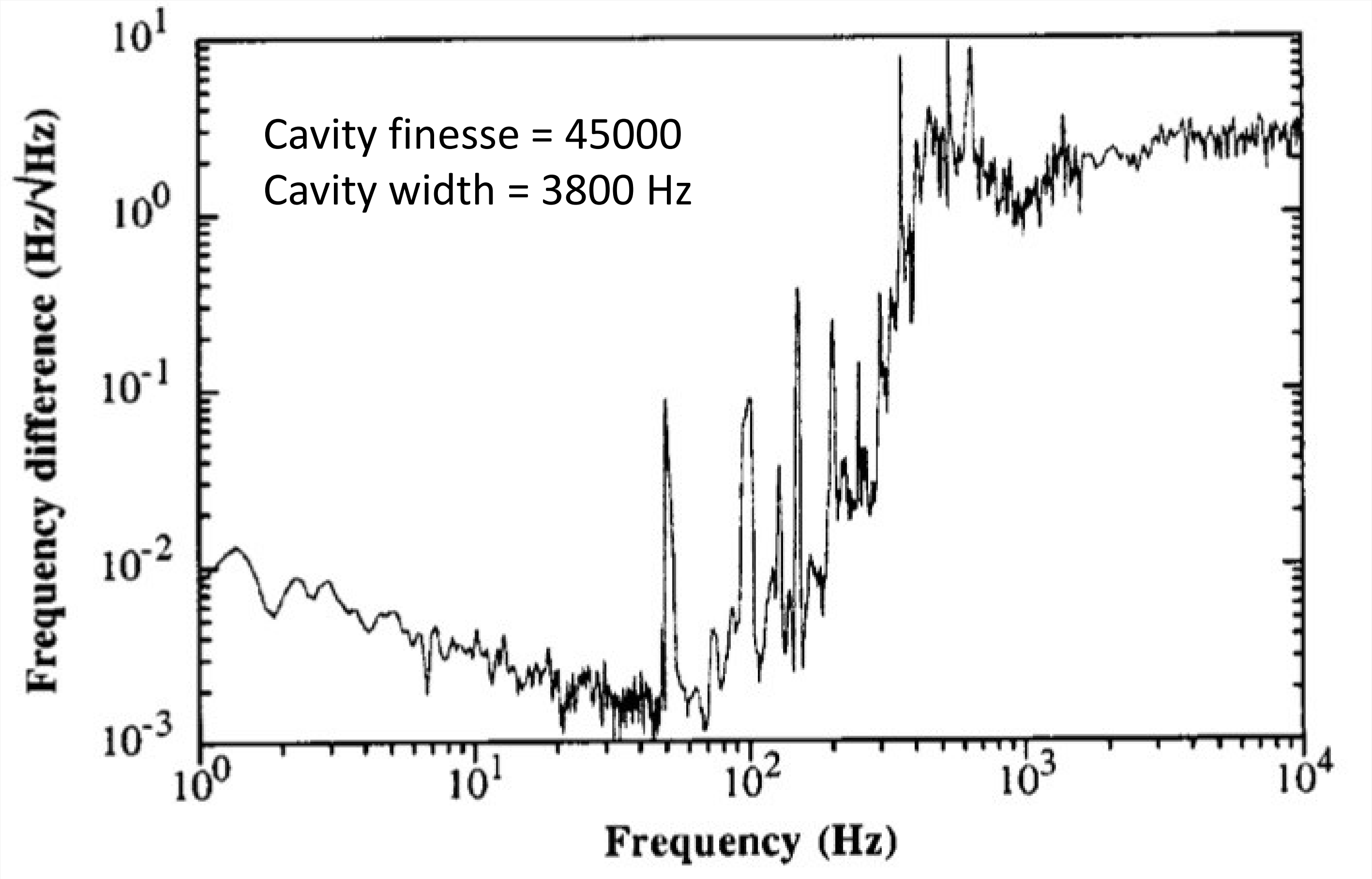
Injected laser light is frequency locked to the cavity length using a feedback circuit with the Pound-Drever-Hall technique:

- The laser is phase-modulated at a frequency greater than the feedback bandwidth -> PM sidebands
- The reflected light from the cavity beats with the PM sidebands and a locking error signal is generated.
- Light is detected in reflection with a photodiode and demodulated at the PM modulation frequency. The central part of the error signal is linear.

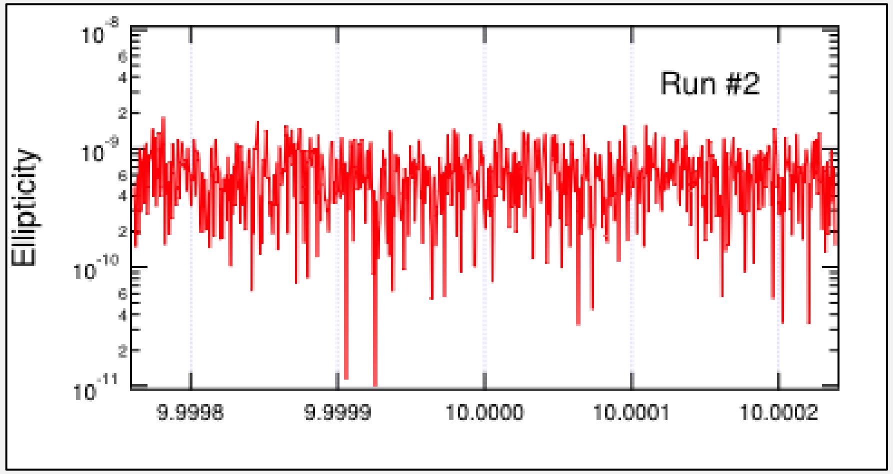


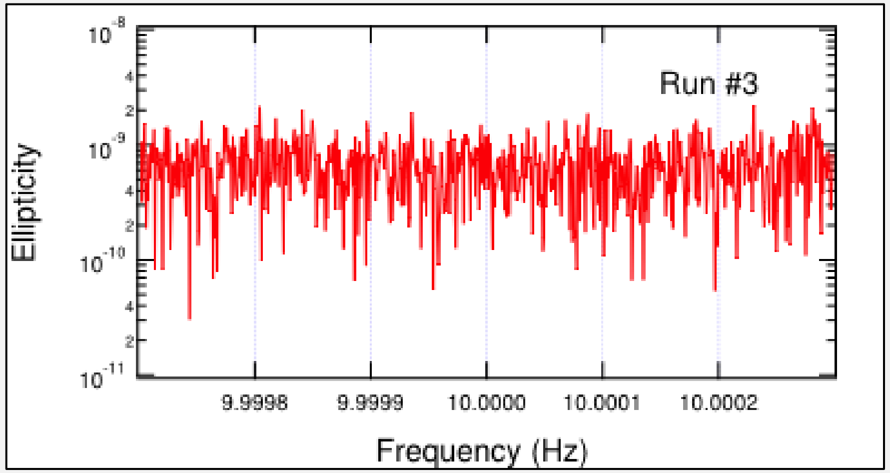
FABRY PEROT CAVITY: FREQUENCY LOCK

Noise spectral density of the error signal during lock.
This indicates the frequency **difference** between the cavity and the laser.



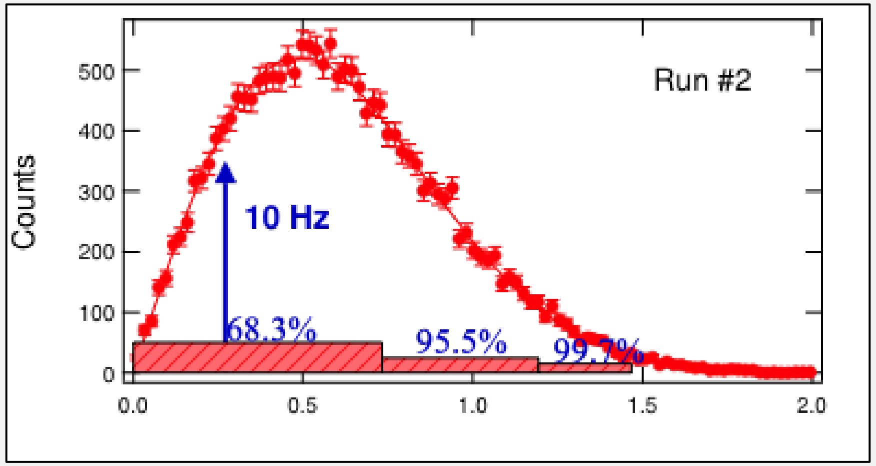
THE PVLAS EXPERIMENT IN FERRARA

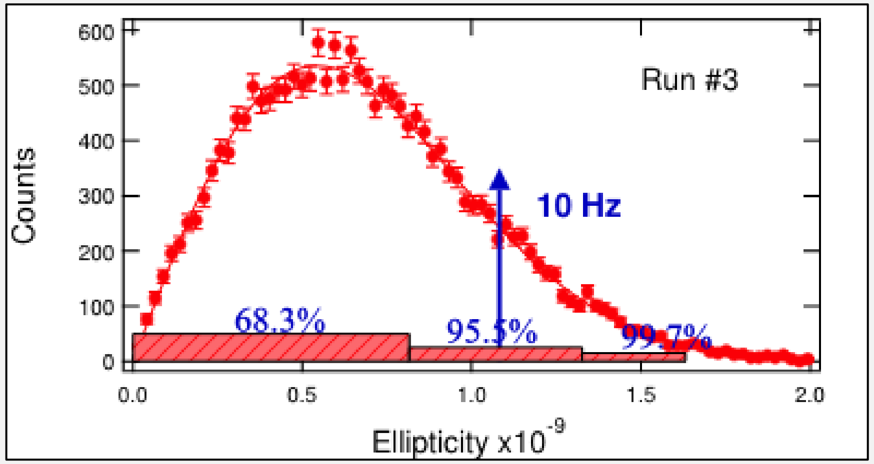




Noise follows Rayleigh distribution:

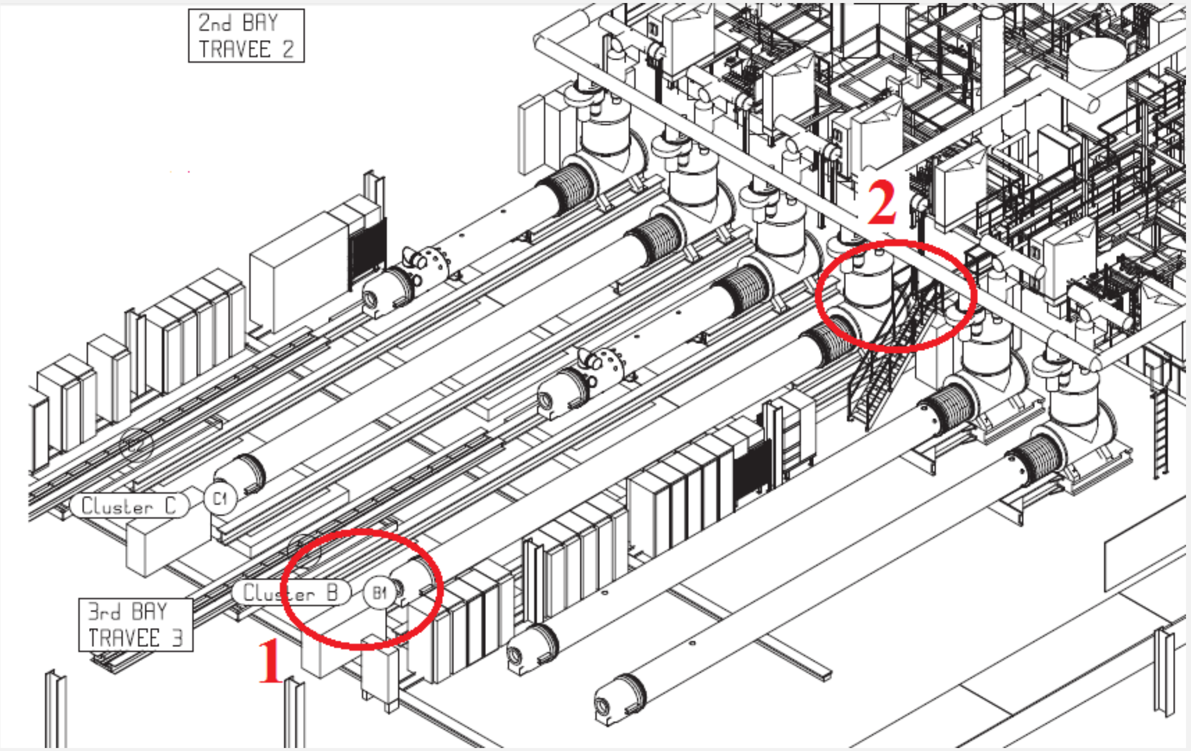
$$P_R = \frac{\rho}{\sigma^2} e^{-\frac{\rho^2}{2\sigma^2}} \quad \rho^2 = x^2 + y^2$$



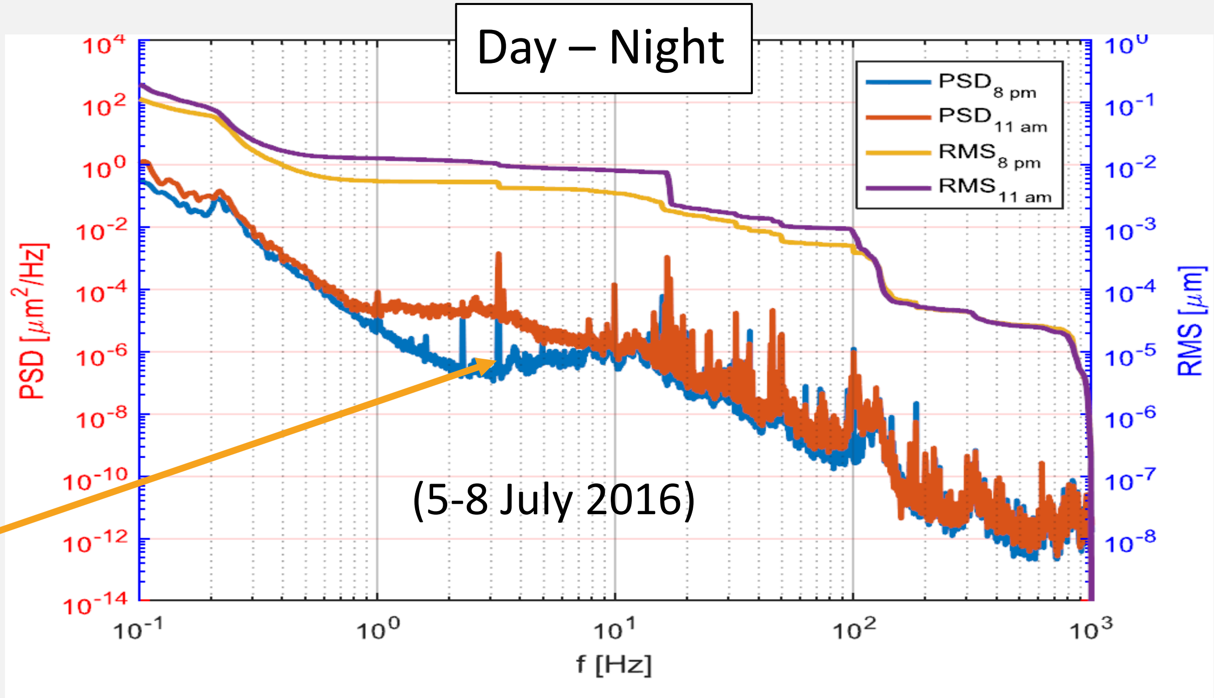


[F. Della Valle et al, Eur. Phys. J. C 76 (2016)]

SEISMIC NOISE MEASUREMENTS SM18



- 3-axis optical accelerometers
- 2 measurement points (sites)
- 65 hrs tot integration time



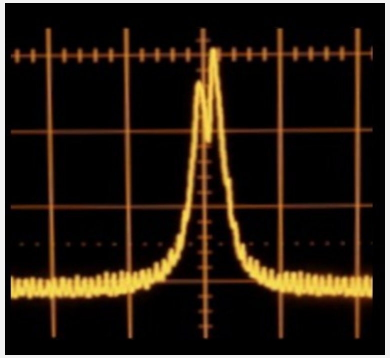
- Several peaks related to machinery and structural resonances
- Broadband noise (1-20 Hz) due to human activity in the hall.

OPTICAL CAVITY BIREFRINGENCE I

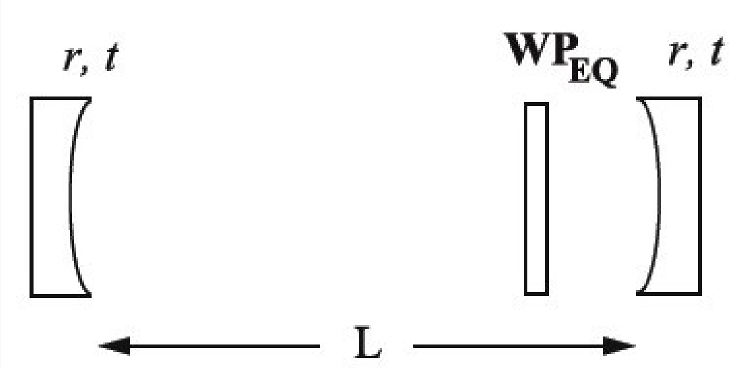
Fabry Perot cavity mirrors have **intrinsic static birefringence**

$$\mathbf{M}_{1,2} = \begin{pmatrix} e^{i\,\alpha_{1,2}/2} & 0 \\ 0 & e^{-i\,\alpha_{1,2}/2} \end{pmatrix}$$

Two polarization auto-states



$$\begin{pmatrix} \left[1 - R\,e^{i[\delta+(\alpha_1+\alpha_2)/2]}\right]^{-1} \\ 0 \end{pmatrix} \quad \begin{pmatrix} 0 \\ \left[1 - R\,e^{i[\delta-(\alpha_1+\alpha_2)/2]}\right]^{-1} \end{pmatrix}$$



The cavity behaves as a **wave-plate**:

- to make extinction: **align polarization to the equivalent wave-plate axis**

- to reduce total birefringence: **rotate cavity mirrors**

1) If one polarization is at maximum resonance, the other is filtered by the cavity

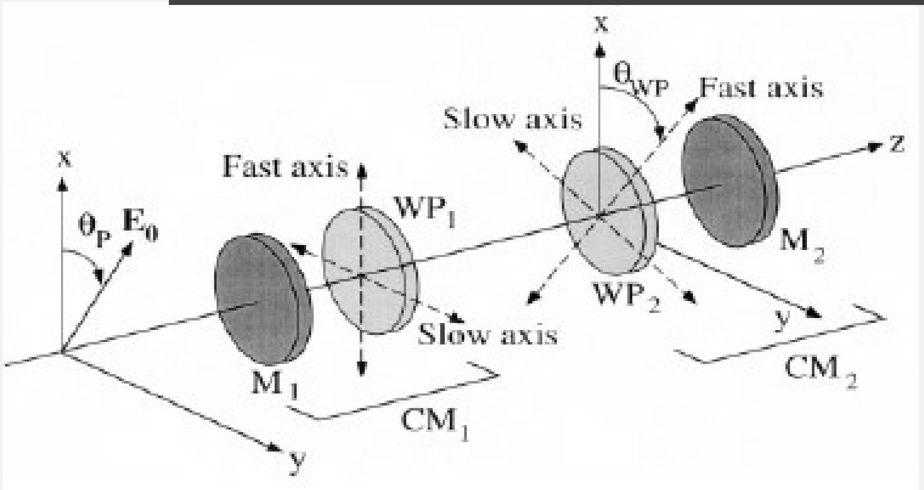
2) Mixing of ellipticity and rotation

$$k(\alpha) = \frac{1}{1 + N^2 \sin^2(\alpha/2)} \leq 1$$

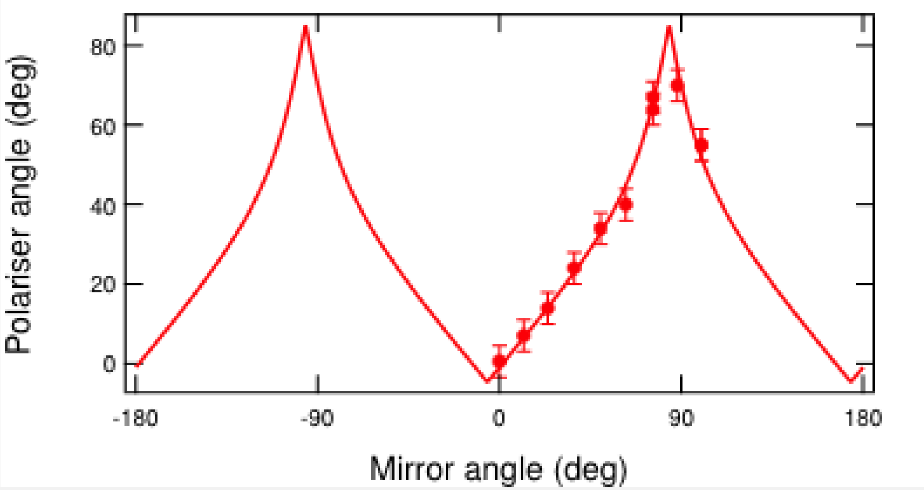
$$\alpha = \alpha_1 + \alpha_2$$

$$N = \frac{2}{1-R} \approx \frac{2\mathcal{F}}{\pi}$$

OPTICAL CAVITY BIREFRINGENCE I



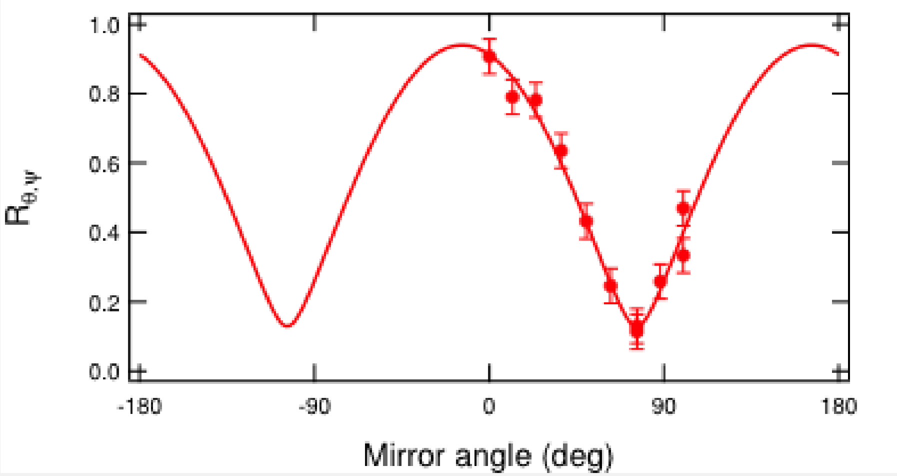
$$\cos 2\theta_{EQ} = \frac{\alpha_1/\alpha_2 + \cos 2\theta_{WP}}{\sqrt{(\alpha_1/\alpha_2 - 1)^2 + 4(\alpha_1/\alpha_2)\cos^2\theta_{WP}}}$$



[F. Della Valle et al, Eur. Phys. J. C 76 (2016)]

Rotate input mirrors
to reduce birefringence

$$\frac{N}{2}\alpha_{EQ} = \frac{N}{2}\sqrt{(\alpha_1 - \alpha_2) + 4\alpha_1\alpha_2\cos^2\theta_{WP}}$$

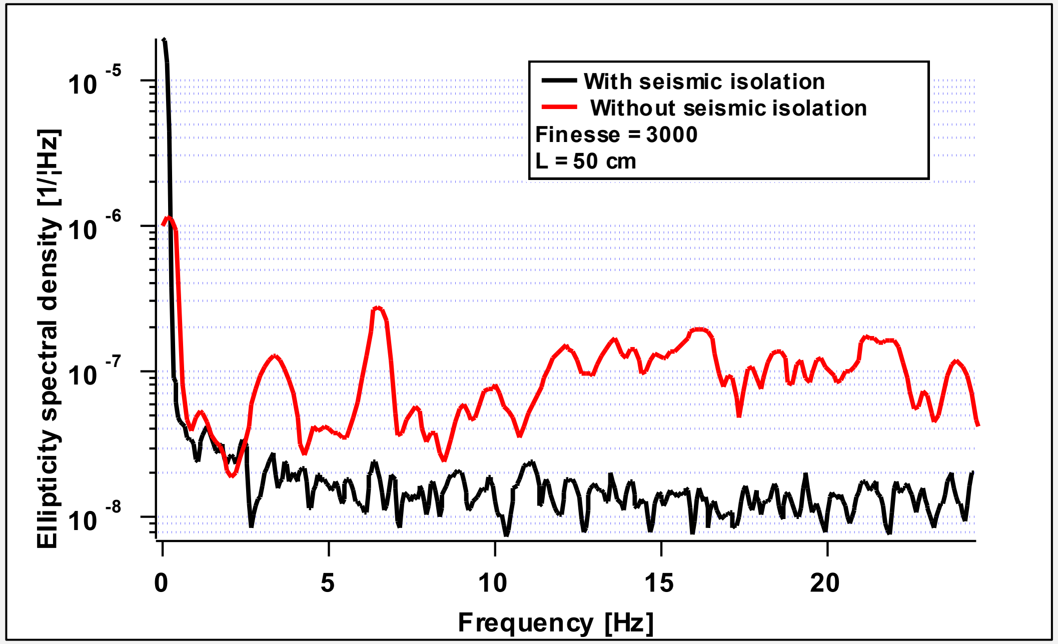


Polarizer angle follows the axes of the
equivalent wave-plate to preserve extinction

$\alpha_1 = 2.4$ μrad
$\alpha_2 = 1.8$ μrad

BIREFRINGENCE NOISE: EIGENMODE SPLITTING

Due to birefringence of the mirrors the resonance curves of the cavity are split and “perfect” common-mode rejection of length fluctuations is spoiled.



[F. Della Valle et al., Optics Communications **283**, 4194 (2010)]

Seismic noise has an impact on ellipticity sensitivity…

but “almost” common-mode rejection of length fluctuations <u>improves</u> with the fringe order number $2d/\lambda$.

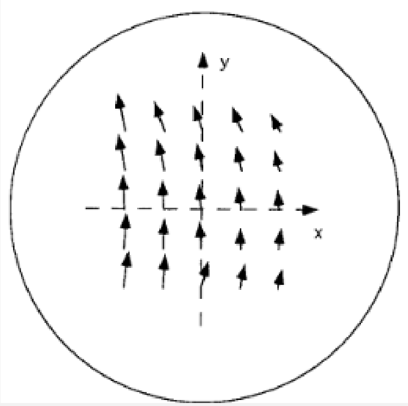
THIS DOES NOT REPRODUCE THE OBSERVED BEHAVIOUR!

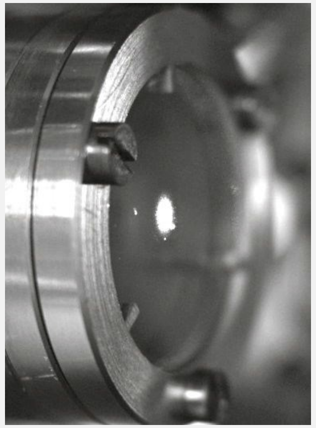
BIREFRINGENCE NOISE: CAVITY MIRRORS

TWO MECHANISMS UNDER CONSIDERATION:

1. Non-uniform birefringence on the surface of the mirror ("birefringence map")

2. Scattered light from point defects that is collinear with the cavity eigenmode





[P. Micossi et al., Appl. Phys. B **57**, 95 (1993)]

Bidirectional reflectance distribution function
BRDF (φ,θ)

$$P_{sl} \approx P_i\, BRDF_s(\theta_1)\left(\pi \frac{w_0^2}{L^2}\right)\left(\frac{w_0}{w}\right)^2 BRDF_m(\theta_0)\,\Delta\Omega$$

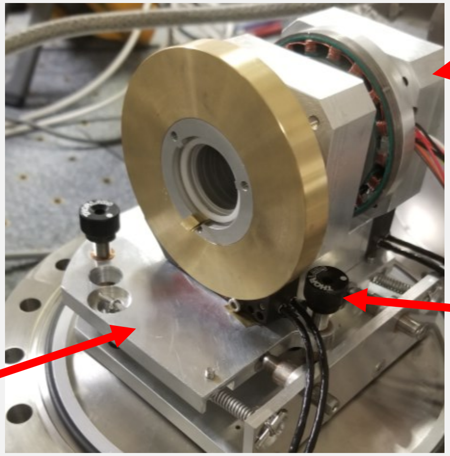
APNS PROJECT

("Alignment and Pointing Noise Suppression")

OBJECTIVES:

1. Control the alignment of the optics inside the cavity to reduce noise and systematics.

Waveplate alignment system



Motor

(Fine) Piezo actuator

(Coarse) alignment plate

2. Develop an automatic alignment system for a cavity built around a LHC magnet (SM18: noisy environment).

Differential wavefront sensing

(technique developed in GW interferometry)

Optical Simulations with:

Finesse 2

http://www.gwoptics.org/finesse/

APNS PROJECT

("Alignment and Pointing Noise Suppression")

Objective

Develop an automatic alignment system for the injection and cavity optics

- Use of techniques that have been developed and used with success in GW interferometers

- Modify them in order to satisfy the needs of VMB experiments:
  - Stabilizing the cavity axis is not sufficient but it is required, in addition, that the resonant beam in the cavity always hits the same spot of the mirrors.
  - Movements of the beam on optical components are responsible for ellipticity noise that, if generated inside the cavity, are amplified in the same way as the signal of interest.

- Activity is in synergy with the VMBCERN experiment where most of these technology developments could be implemented.

ALIGNMENT CONTROL

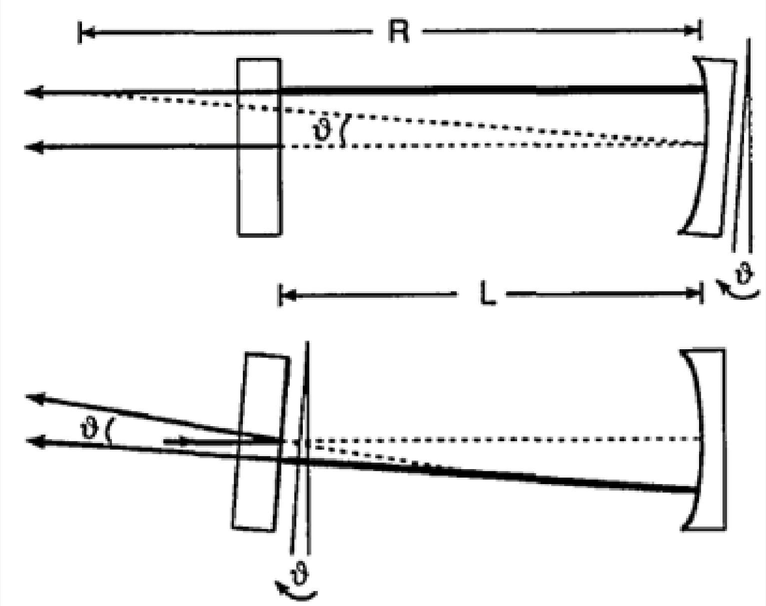
Center beam spot positions on mirrors — **Spot position sensing**

Superimpose cavity axis with incoming beam — **Differential wavefront sensing**

[www.first-sensor.com]

Consider a beam misaligned into an optical cavity:

- Describe the input beam in the cavity basis (HG: Hermite-Gauss)
- From the cavity's point of view, input beam has a high-order mode content



[D. Z. Anderson, Applied Optics, vol. 23, 17 (1984)]
[E. Morrison et al., Applied Optics (1994)]

Finesse 2

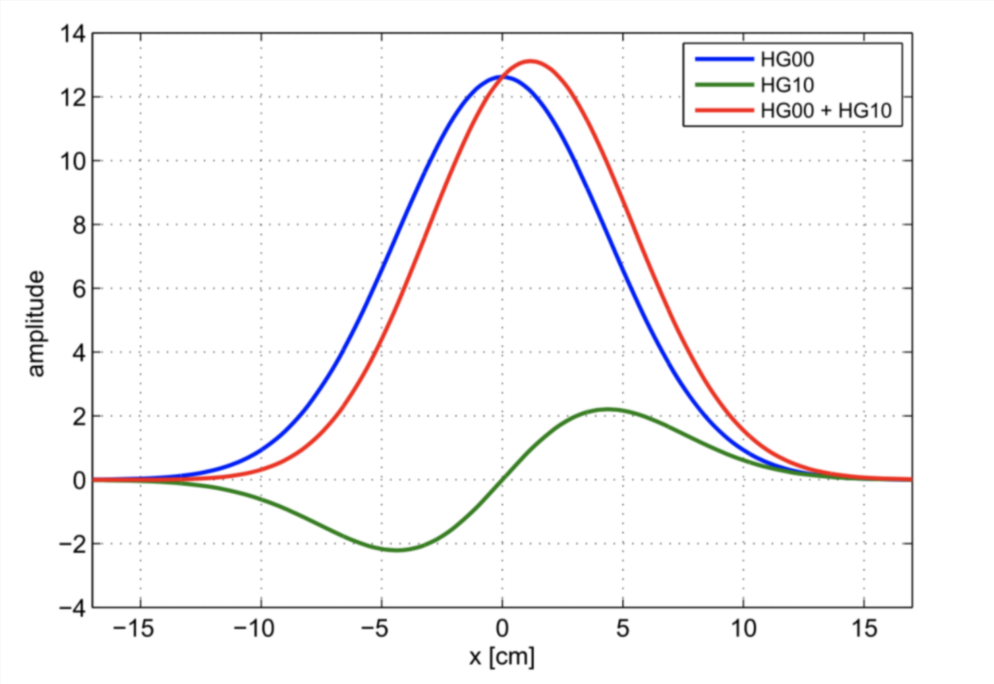
http://www.gwoptics.org/finesse/

DIFFERENTIAL WAVEFRONT SENSING

Displacing a HG_{00} beam by a, can be approximated by adding a HG_{10} mode in proportion a/ω_0:

$$u_{00}(x-a,y,z_0) \approx u_{00}(x,y,z_0) + \frac{a}{w_0} u_{10}(x,y,z_0)$$

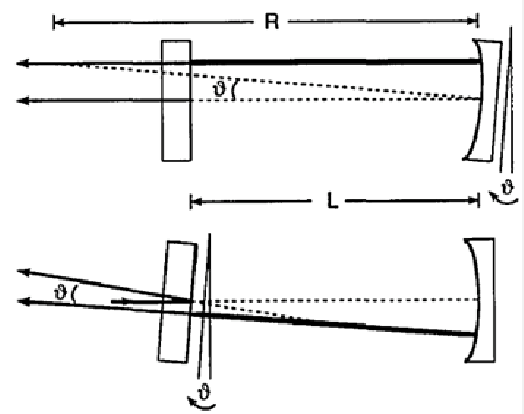
$$w(z) = w_0\sqrt{1+\left(\frac{z-z_0}{z_R}\right)^2}$$



In the same way an angular misalignment α is a HG_{10} mode added in proportion α/Θ, 90^o out of phase, with the HG_{00} mode:

$$u_{00}^{\alpha \mathrm{tilt}}(x,y,z_0) \approx u_{00}(x,y,z_0) + \mathrm{i}\frac{\alpha}{\Theta} u_{10}(x,y,z_0)$$

$$\Theta = \arctan\left(\frac{w_0}{z_R}\right) \approx \frac{w_0}{z_R} = \frac{\lambda}{\pi w_0}$$

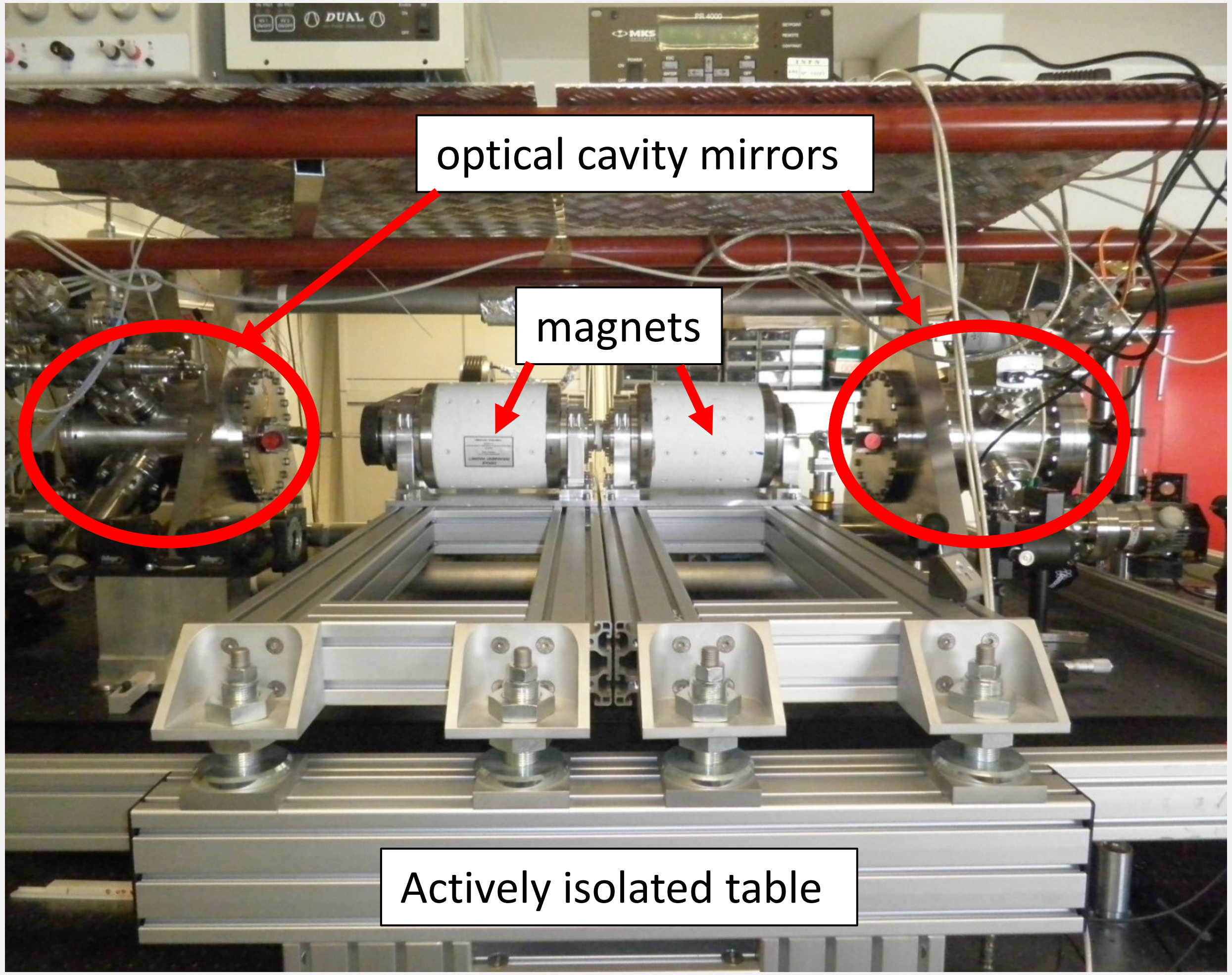


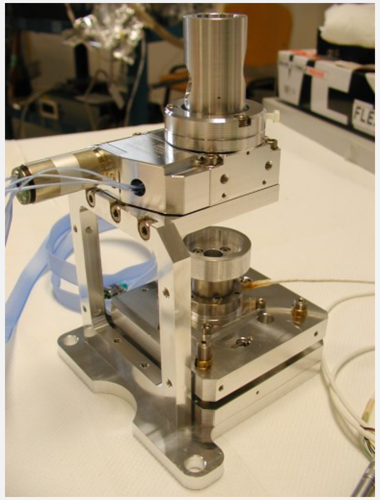
[www.first-sensor.com]

DWS TEST SETUP

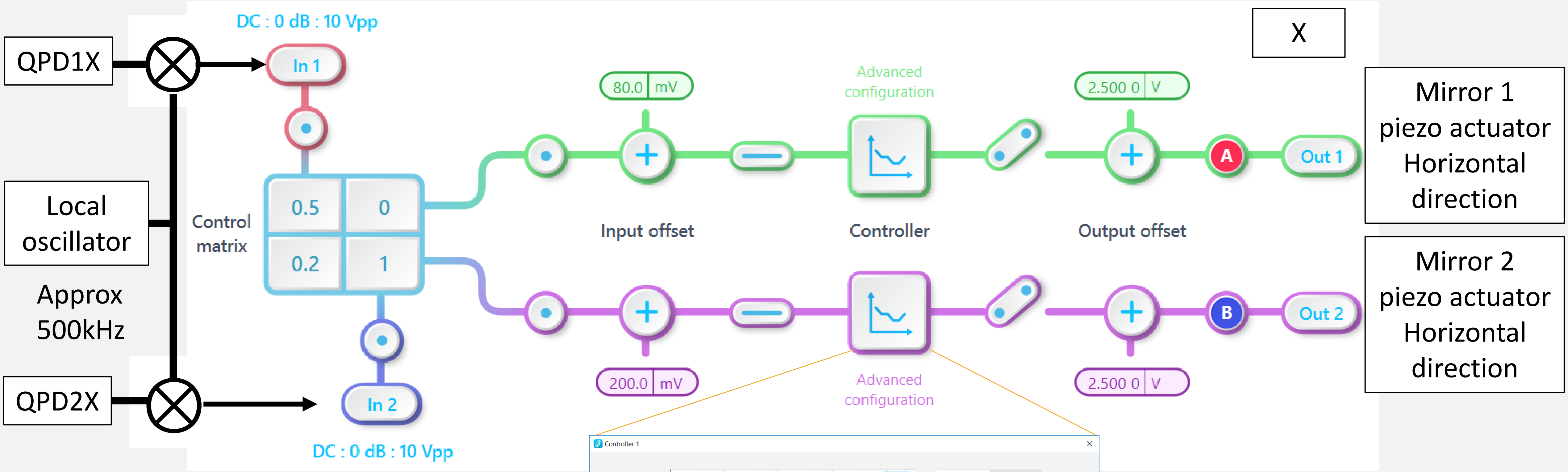
Polarimeter with Differential Wavefront Sensing

- 1.4 m Fabry-Perot optical cavity F = 3000
- Quadrant photodiodes to generate error signals for the alignment
- Vacuum-compatible actuators to move the cavity and beam injection optics





ALIGNMENT FEEDBACK



4 d.o.f. horizontal tilt and displacement
vertical tilt and displacement

2 separate feedback loops

FPGA-based system with GUI (no VHDL!!)