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The experiment PVLAS for the measurement of the magnetic birefringence of the vacuum

The PVLAS Collaboration:
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Edoardo Milotti

Hamburg – DESY – 02 November 2015

Summary

- Introduction
- The detection scheme
- The experiment in Legnaro
- The experiment in Ferrara
- Latest results

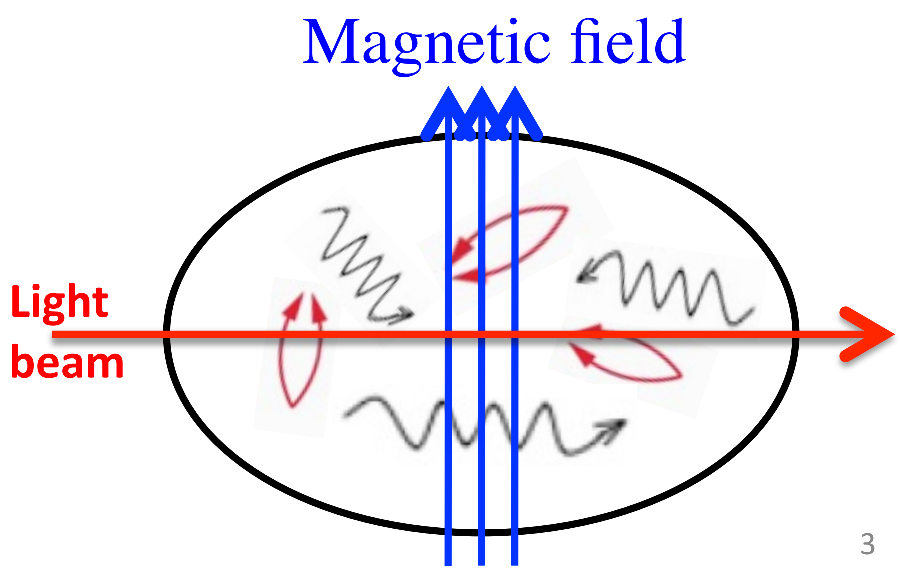
Light propagation in a magnetized vacuum

- Experimental study of the structure and nature of the quantum vacuum
- General plan:
  - **Perturb** the quantum vacuum with an **external field**
  - Use as a probe a **(polarized) light beam** to measure the effect of the external field on the structure of the electromagnetic vacuum
  - **Obtain from the effect information on the nature of the quantum vacuum**

We study **modifications of the index of refraction** on vacuum induced by an external magnetic field

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

$$n_{media} = \frac{c}{v_{light}}$$



QED vacuum birefringence

Lagrangian of the electromagnetic field by **Heisenberg, Euler, Kockel, and Weisskopf (1936)** considering the **virtual electron-positron** sea proposed by Dirac. Light propagation is still described by Maxwell's equations in media but they are no longer linear. At lowest order:

$$L = L_{em} + L_{EHW} = \frac{1}{2\mu_0}\left(\frac{E^2}{c^2} - B^2\right) + \frac{A_e}{\mu_0}\left[\left(\frac{E^2}{c^2} - B^2\right)^2 + 7\left(\frac{\vec{E}}{c}\cdot\vec{B}\right)^2\right] \qquad A_e = \frac{2}{45\mu_0}\left(\frac{\alpha^2 \lambda_e^3}{m_e c^2}\right) = 1.32\cdot 10^{-24}\ \mathrm{T}^{-2}$$

This Lagrangian was **validated in the framework of QED by Schwinger** (1951), and the processes can be represented using Feynman diagrams.

Linearly polarized light passing through a transverse external magnetic field perpendicular to *k*.

$$\begin{cases} \varepsilon_{\parallel} = 1 + 10A_e\mathbf{B}^2_{Ext} \\ \mu_{\parallel} = 1 + 4A_e\mathbf{B}^2_{Ext} \\ n_{\parallel} = 1 + 7A_e\mathbf{B}^2_{Ext} \end{cases} \qquad \begin{cases} \varepsilon_{\perp} = 1 - 4A_e\mathbf{B}^2_{Ext} \\ \mu_{\perp} = 1 + 12A_e\mathbf{B}^2_{Ext} \\ n_{\perp} = 1 + 4A_e\mathbf{B}^2_{Ext} \end{cases}$$

$$\Delta n = 3A_e B^2 = 4\times 10^{-24} B^2$$

Axion-Like Particles (ALPs)

Extra terms added to the EHW effective Lagrangian to include contributions from hypothetical **neutral light particles weakly interacting with two photons**

g_a, g_s coupling constants

pseudoscalar case

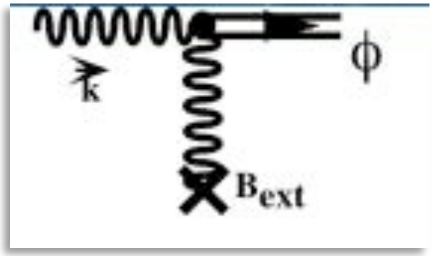
$$L_a = g_a \phi_a \left(\vec{E}_\gamma \cdot \vec{B}_{ext} \right)$$

scalar case

$$L_s = g_s \phi_s \left(\vec{B}_\gamma \cdot \vec{B}_{ext} \right)$$

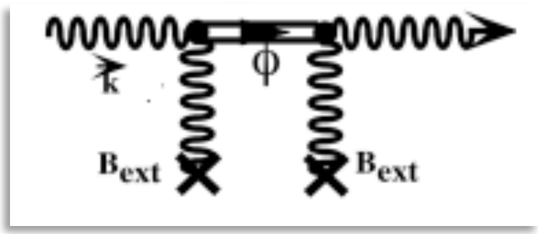
Polarisation dependent

Absorption



$$|\Delta\kappa^{(\mathrm{ALP})}| = \kappa_{\parallel}^{a} = \kappa_{\perp}^{s} = \frac{2}{\omega L}\left(\frac{g_{a,s} B_{\mathrm{ext}} L}{4}\right)^2 \left(\frac{\sin x}{x}\right)^2$$

Dispersion



$$|\Delta n^{(\mathrm{ALP})}| = n_{\parallel}^{a} - 1 = n_{\perp}^{s} - 1 = \frac{g_{a,s}^2 B_{\mathrm{ext}}^2}{2 m_{a,s}^2}\left(1 - \frac{\sin 2x}{2x}\right)$$

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

Milli-charged particles

$$m = m_\varepsilon$$

$$q = \varepsilon e$$

$$\chi \equiv \frac{3}{2}\frac{\hbar\omega}{m_\epsilon c^2}\frac{\epsilon e B_{\rm ext}\hbar}{m_\epsilon^2 c^2}$$

Gies H, Jaeckel J, and Ringwald A, PRL 97, 140402 (2006)
Ahlers M et al., PRD 75, 035011 (2007)

$$A_\epsilon = \frac{2}{45\mu_0}\frac{\epsilon^4\alpha^2\lambda_\epsilon^3}{m_\epsilon c^2}$$

Fermion

$$\Delta n^{(\rm Df)} = A_\epsilon B_{\rm ext}^2 \begin{cases} 3 & \text{for } \chi \ll 1 \\ -\frac{9}{7}\frac{45}{2}\frac{\pi^{1/2}2^{1/3}\left[\Gamma\left(\frac{2}{3}\right)\right]^2}{\Gamma\left(\frac{1}{6}\right)}\chi^{-4/3} & \text{for } \chi \gg 1 \end{cases}$$

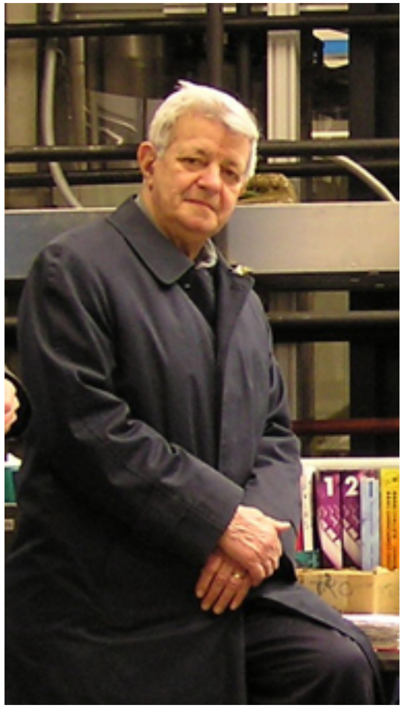
$$\Delta\kappa^{(\rm Df)} = \frac{1}{8\pi}\frac{\epsilon^3 e\alpha\lambda B_{\rm ext}}{m_\epsilon c}\begin{cases} \sqrt{\frac{3}{32}}\, e^{-4/\chi} & \text{for } \chi \ll 1 \\ \frac{2\pi}{3\,\Gamma(\frac{1}{6})\Gamma(\frac{13}{6})}\chi^{-1/3} & \text{for } \chi \gg 1 \end{cases}$$

Scalar

$$\Delta n^{(\rm sc)} = A_\epsilon B_{\rm ext}^2 \begin{cases} -\frac{6}{4} & \text{for } \chi \ll 1 \\ \frac{9}{14}\frac{45}{2}\frac{\pi^{1/2}2^{1/3}\left[\Gamma\left(\frac{2}{3}\right)\right]^2}{\Gamma\left(\frac{1}{6}\right)}\chi^{-4/3} & \text{for } \chi \gg 1 \end{cases}$$

$$\Delta\kappa^{(\rm sc)} = \frac{1}{8\pi}\frac{\epsilon^3 e\alpha\lambda B_{\rm ext}}{m_\epsilon c}\begin{cases} -\sqrt{\frac{3}{8}}\, e^{-4/\chi} & \text{for } \chi \ll 1 \\ -\frac{\pi}{3\,\Gamma(\frac{1}{6})\Gamma(\frac{13}{6})}\chi^{-1/3} & \text{for } \chi \gg 1 \end{cases}$$

Iacopini and Zavattini proposal (1979)



Emilio Zavattini
(1927 -2007)

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}.

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

Absolute changes in the index of refraction are difficult to measure, we study **anisotropic changes**

<u>Linear birefringence</u>

<u>Linear dichroism</u>

In the presence of an external transverse magnetic field

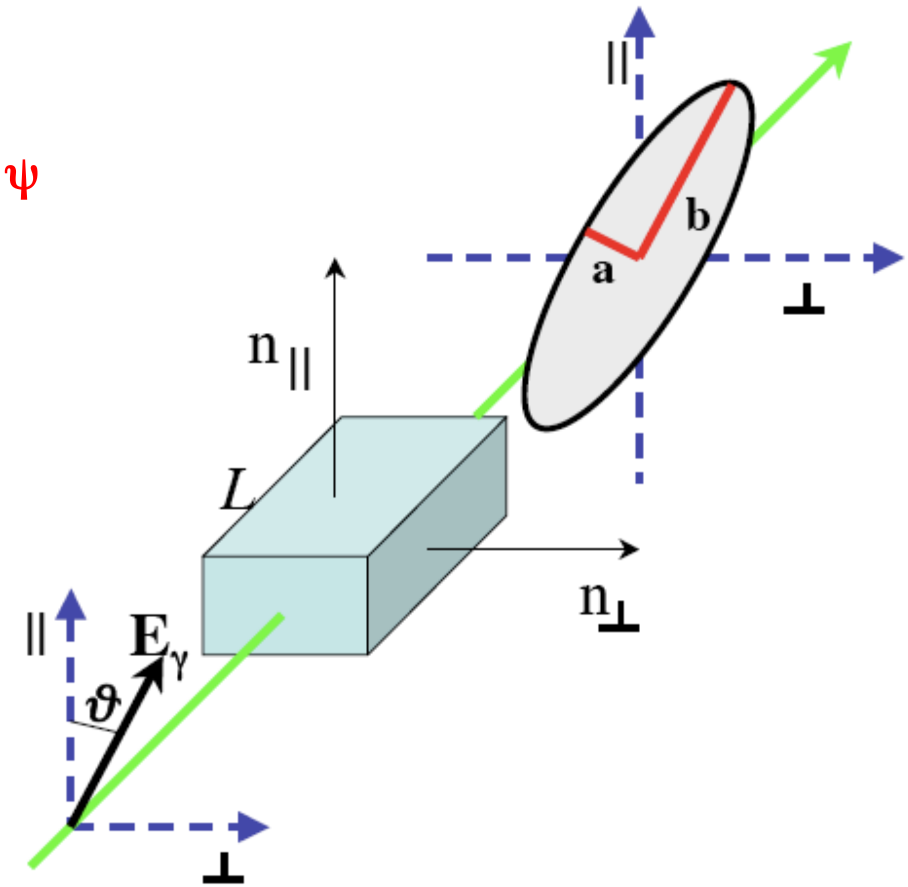
Linear birefringence

- Arises when the index of refraction (real part) is different on two orthogonal directions

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

- A linearly polarized light beam traversing a birefringent medium will acquire an **ellipticity ψ**

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



Vacuum magnetic birefringence:
L = 1.64 m, λ = 1064 nm, B = 2.5 T

$$\Delta n_{QED} = 2.5\times10^{-23}$$
$$\psi_{QED} = 1.2\times10^{-16}$$

Linear dichroism

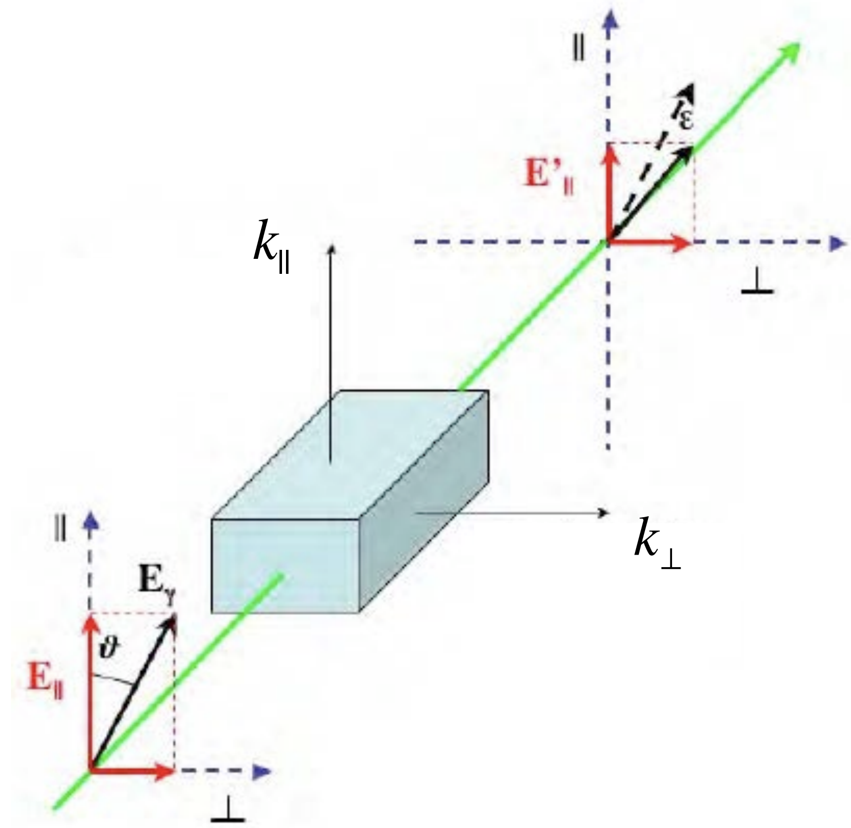
- Arises when the extinction coefficient is different on two orthogonal directions

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

$$n_{tot} = n + i\kappa$$

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

$$\varepsilon = \pi \frac{L}{\lambda} \Delta\kappa \sin 2\vartheta$$



Vacuum photon splitting (Adler 1971):
L = 1.64 m, λ = 1064 nm, B = 2.5 T

$$\Delta\kappa_{QED} = 4.0\times10^{-87}$$
$$\varepsilon_{QED} = 2.3\times10^{-80}$$

Larger effects are expected for ALPs

Measurement strategy

- **very sensitive ellipsometer**

  heterodyne detection: periodic change of the effect for signal modulation; beat with a known effect

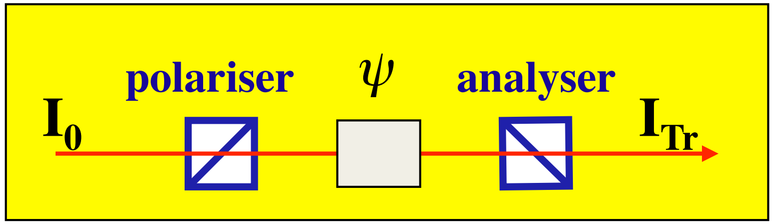
- **high magnetic field *B***

  high field dipole permanent magnets: long duty cycle; can be rotated at high frequency

- **largest possible optical path *L***

  very-high Q Fabry-Perot resonator to increase the effective length

Heterodyne detection - ellipticity



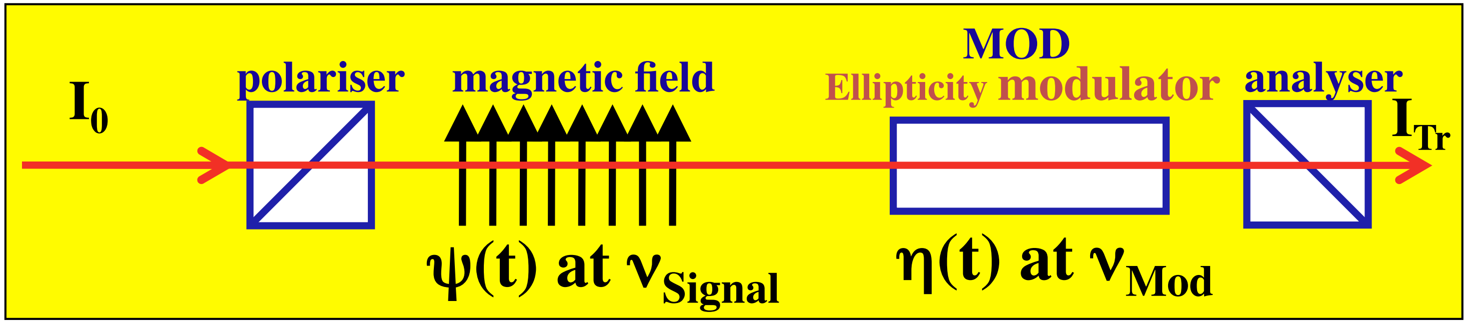
Static detection excluded

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

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

Signal is modulated in time and beats with a calibrated effect

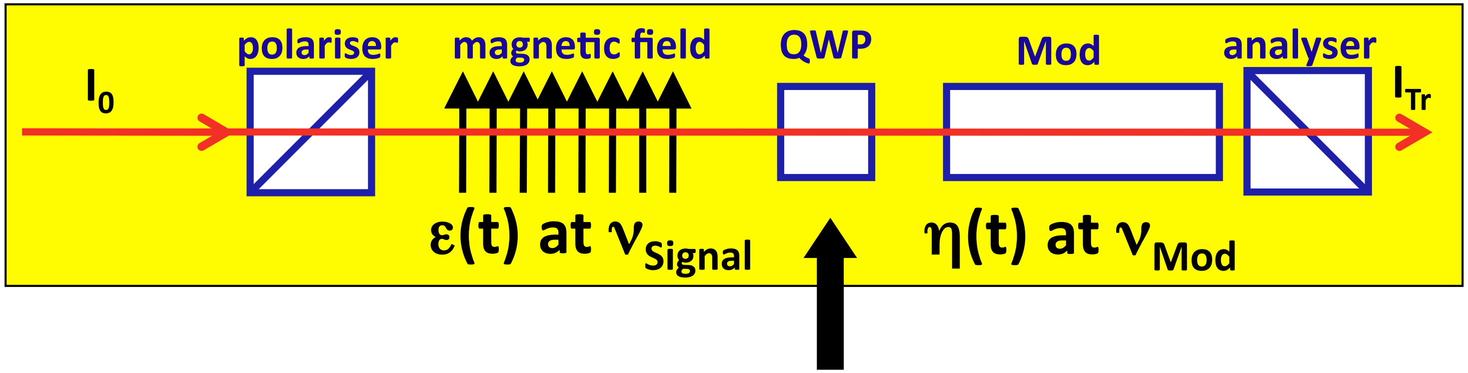
- **Signal linear in the birefringence**
- **Smaller 1/f noise**



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

Main frequency components at $\nu_{Mod} \pm \nu_{Signal}$ and $2\nu_{Mod}$

Heterodyne detection - rotation



QWP can be inserted to transform a rotation ε into an ellipticity ψ with the same amplitude. It can be oriented in two positions:

QWP slow axis along polarization
QWP slow axis normal to polarization

$$\varepsilon(t) \quad => \begin{cases} \psi(t) & \text{for QWP } \parallel \\ -\psi(t) & \text{for QWP } \perp \end{cases}$$

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

Main frequency components at $\nu_{Mod} \pm \nu_{Signal}$ and $2\nu_{Mod}$

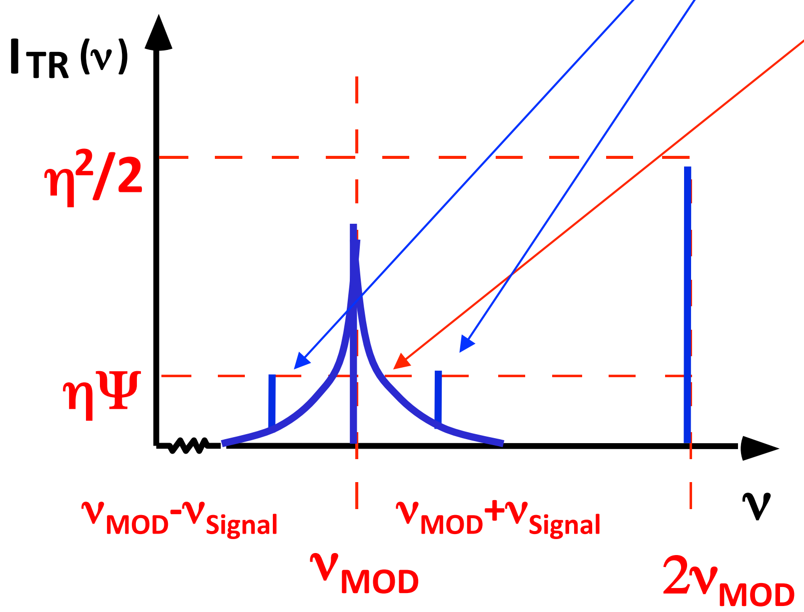
Signal layout

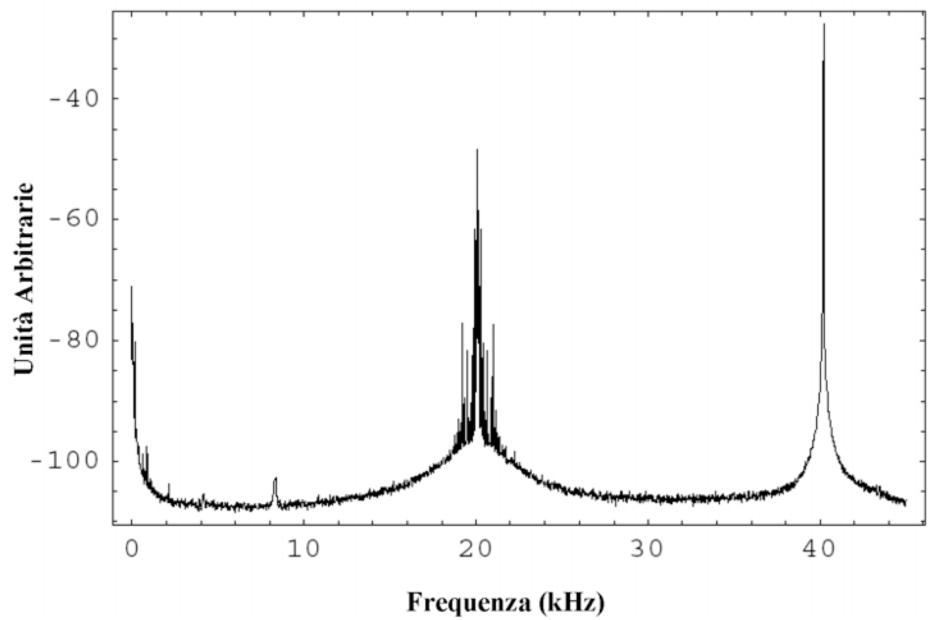
In practice, nearly static birefringences $\alpha_s(t)$ generate a 1/f noise centred at the carrier modulation frequency ν_{Mod}

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

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

signal noise





Frequency components / sensitivity

Frequency	Fourier component	Intensity/$I_{\rm out}$	Phase
dc	$I_{\rm dc}$	$\sigma^2 + \alpha_{\rm dc}^2 + \eta_0^2/2$	$-$
$\nu_{\rm Mod}$	$I_{\nu_{\rm Mod}}$	$2\alpha_{\rm dc}\eta_0$	$\theta_{\rm Mod}$
$\nu_{\rm Mod} \pm 2\nu_{\rm Mag}$	$I_{\nu_{\rm Mod}\pm 2\nu_{\rm Mag}}$	$\eta_0 \Psi$	$\theta_{\rm Mod} \pm 2\vartheta_{\rm Mag}$
$2\nu_{\rm Mod}$	$I_{2\nu_{\rm Mod}}$	$\eta_0^2/2$	$2\theta_{\rm Mod}$

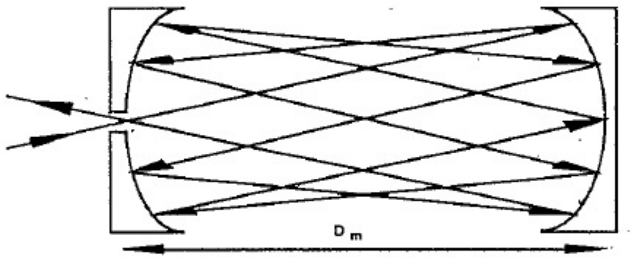
The signal amplitude can then be calculated from:

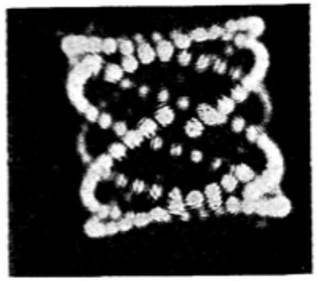
$$\Psi = \frac{1}{2}\left(\frac{I_{\nu_{\rm Mod}+2\nu_{\rm Mag}}}{\sqrt{2I_{\rm out}I_{2\nu_{\rm Mod}}}} + \frac{I_{\nu_{\rm Mod}-2\nu_{\rm Mag}}}{\sqrt{2I_{\rm out}I_{2\nu_{\rm Mod}}}}\right)$$

All sources of noises contributing at the spectral density of the photodiode signal at $\nu_{\rm Mod} \pm 2\nu_{\rm Mag}$ will limit the sensitivity

Signal amplification

Delay line optical cavity





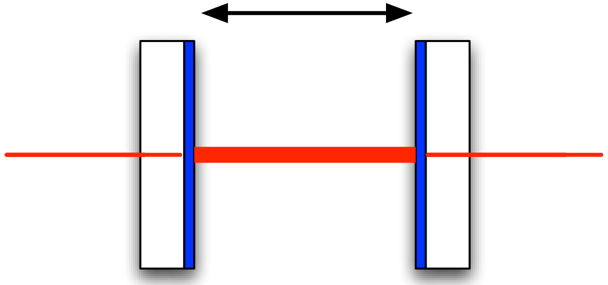
Amplification

N = number passes

$N_{max} \sim 1000$

Resonant Fabry Perot cavity

The **Fabry-Perot cavity** is a resonant optical cavity that **increases the effective optical path**. It is made by **two mirror placed at a separation d** which is an integer multiple of the light half wavelength. **To obtain this a laser is frequency locked to the cavity using a feedback circuit.**



τ - cavity decay time

Amplification

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

Finesse

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

$$N > 10^5$$

Vacuum magnetic birefringence:

L = 1,64 m, λ = 1064 nm, B = 2.5 T

N = 445000

$\Delta n_{QED} = 2.5\times10^{-23}$

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

Noise budget

$$s_{\rm shot} = \sqrt{\frac{2e}{I_{\rm out} q}\left(\frac{\sigma^2+\eta_0^2/2}{\eta_0^2}\right)}$$

Shot noise: increase power, reduce extinction σ^2

For 10 mW intensity **$s_{\rm shot}$ = 7×10^{-9} 1/√Hz**

$$s_{\rm dark} = \frac{V_{\rm dark}}{G}\frac{1}{I_{\rm out}\, q\, \eta_0}$$

Photodetector noise: increase power, better detector

$$s_{\rm J} = \sqrt{\frac{4k_BT}{G}\frac{1}{I_{\rm out}\, q\, \eta_0}}$$

Johnson noise: increase power

$$s_{\rm RIN} = {\rm RIN}(\nu_{\rm Mod})\,\frac{\sqrt{(\sigma^2+\eta_0^2/2)^2+(\eta_0^2/2)^2}}{\eta_0}.$$

Light amplitude noise: reduce extinction σ^2, stabilize power, increase $\nu_{\rm Mod}$

+ all other uncontrolled sources of **time variable birefringences α(t)**

1/f noise: increase $\nu_{\rm Mag}$

System test: Cotton-Mouton effect

A gas at a pressure *P* in the presence of a transverse magnetic field *B* becomes birefringent. Δn_u indicates the birefringence for unit field at atmospheric pressure

$$\Delta n = n_{\parallel} - n_{\perp} = \Delta n_u \left(\frac{B}{1\ \mathrm{T}}\right)^2 \left(\frac{P}{P_{\mathrm{atm}}}\right)$$

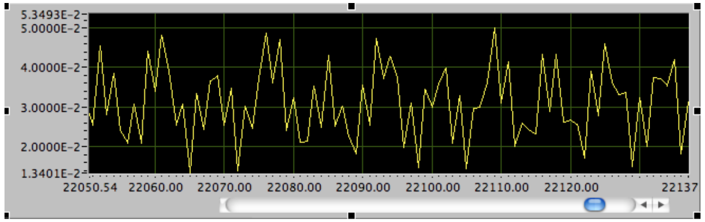
$$\psi_{gas} = N\pi \frac{L}{\lambda} \Delta n_u B^2 P \sin 2\vartheta$$

Gas	Δn_u (T ~ 293 K)
Nitrogen	$-(2.47 \pm 0.04) \times 10^{-13}$
Oxygen	$-(2.52 \pm 0.04) \times 10^{-12}$
Carbon Oxide	$-(1.83 \pm 0.05) \times 10^{-13}$

To avoid spurious effect the residual gas must be analysed:

e.g. $P(O_2) < 10^{-8}$ mbar

Data analysis



Diode signal

1) Photodiode signal is demodulated at ν_{Mod} using a lock-in amplifier

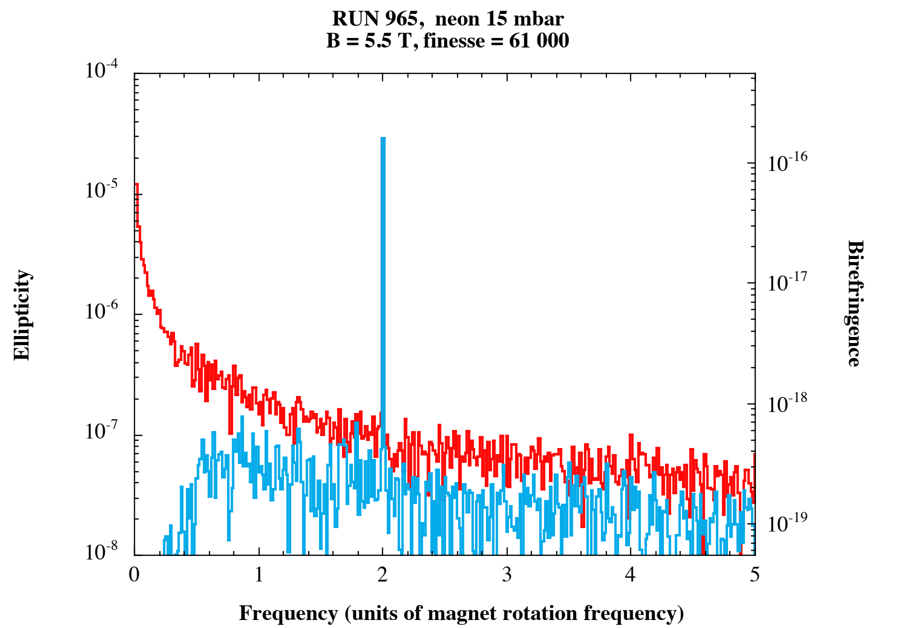
2) the demodulated signal is filtered to avoid aliasing

3) The filtered signal is sampled, the ellipticity/rotation signal is

$$\psi,\varepsilon = \frac{I_{2\nu_{Mag}}}{2\sqrt{2 I_{out} I_{2\nu_{Mod}}}}$$

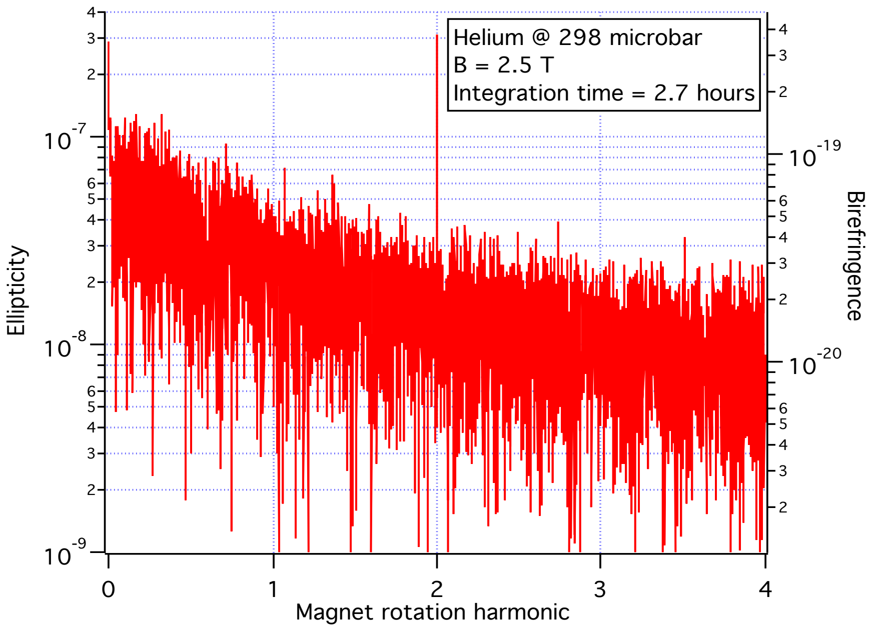
4) the data are divided into fixed length time records and then Fourier transformed

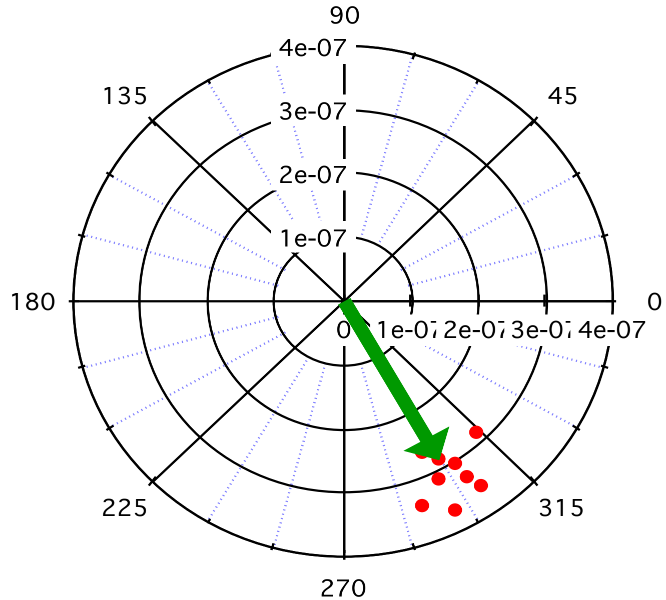
5) the partial results undergo a weighted vector average



ellipticity Fourier spectrum, DC and AC coupled

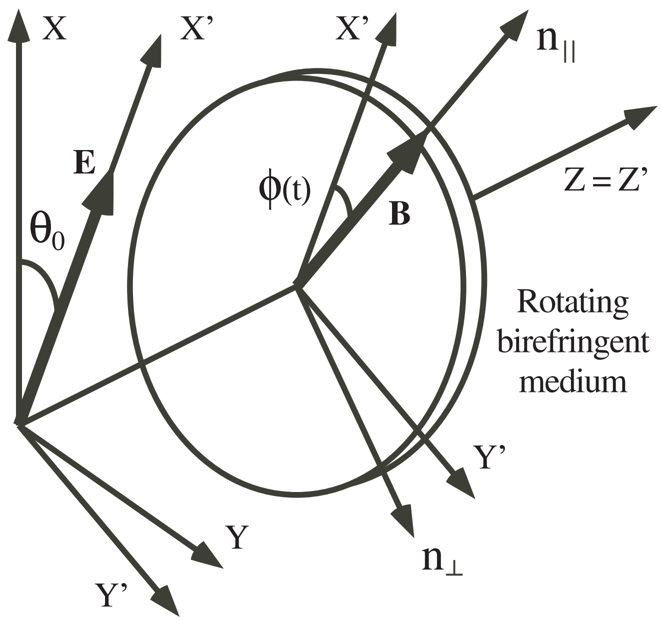
Measurement output





Measured effect given by Fourier amplitude and phase at signal frequency. **Vector in polar plane.** The **amplitude** measures the ellipticity/rotation. The **phase** is related to the triggers position and to the polarisation direction. **True physical signal must have a definite phase.**

$$\psi = \psi_0 \sin\left\{2\left[\phi_0 + \omega_{\mathrm{Mag}} t\right]\right\}$$



Zavattini 1st Try: CERN

First realization of a prototype apparatus

1979-1983

Delay line optical cavity ~100 passes
Rotating electromagnet B = 1 T

636 J. Opt. Soc. Am. B/Vol. 1, No. 4/August 1984 Carusotto *et al.*

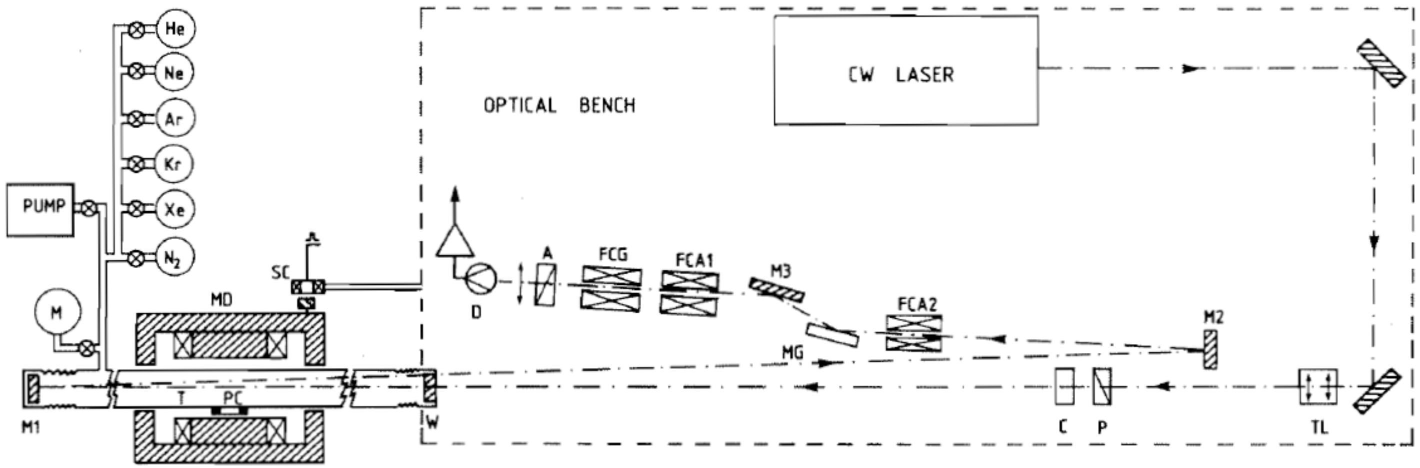


Fig. 1. Experimental apparatus: optical layout. A, analyzer prism; C, compensator; FCA1 and FCA2, air Faraday cells; FCG, glass Faraday modulator; MG, gold mirror; M3, aluminium mirror; P, polarizer prism; D, photodiode; SC, synchronizing coil; TL, telescope; W, window; M, manometer; MD, rotating dipole magnet; PC, pickup coil.

S Carusotto, E Iacopini, E Polacco, F Scuri, G Stefanini, and **E Zavattini**, JOSA B (1984)

Sensitivity not sufficient for vacuum measurement
Obtained result on magnetic polarizability of gases

The Brookhaven experiment (BFRT)

BNL - AGS E840 - LAS (Laboratory Axion Search)
Mainly dedicated to the axion search

1988-1992

PHYSICAL REVIEW D VOLUME 47, NUMBER 9 1 MAY 1993

ARTICLES

Search for nearly massless, weakly coupled particles by optical techniques

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(Received 5 October 1992)

We have searched for light scalar and/or pseudoscalar particles that couple to two photons by studying the propagation of a laser beam (λ=514 nm) through a transverse magnetic field. A limit of 3.5×10^{-10} rad was set on a possible optical rotation of the beam polarization for an effective path length of 2.2 km in a 3.25 T magnetic field. We find that the coupling $g_{a\gamma\gamma} < 3.6\times10^{-7}$ GeV^{-1} at the 95% confidence level, provided $m_a < 10^{-3}$ eV. Similar limits can be set from the absence of ellipticity in the transmitted beam. We also searched for photon regeneration in a magnetic field and found the limit $g_{a\gamma\gamma} < 6.7\times10^{-7}$ GeV^{-1} for the same range of particle mass.

PACS number(s): 14.80.Gt, 12.20.Fv, 14.80.Am

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

Results:

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

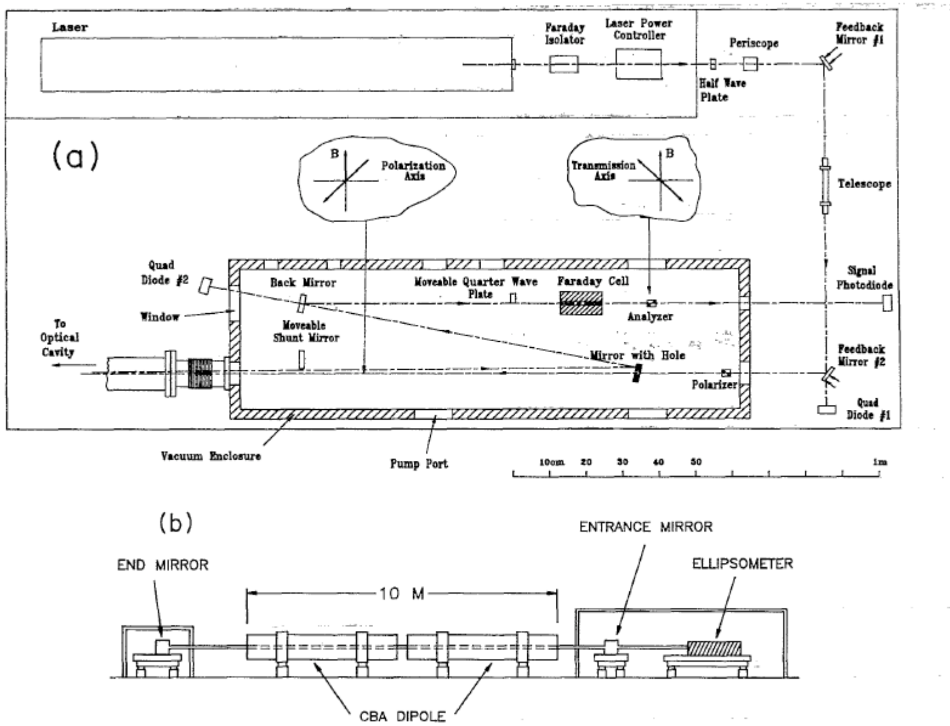


FIG. 4. (a) Schematic view of the ellipsometer; the volume inside the hatched area is evacuated. (b) Layout of the experiment and of the superconducting magnets.

PVLAS @ Legnaro (LNL)

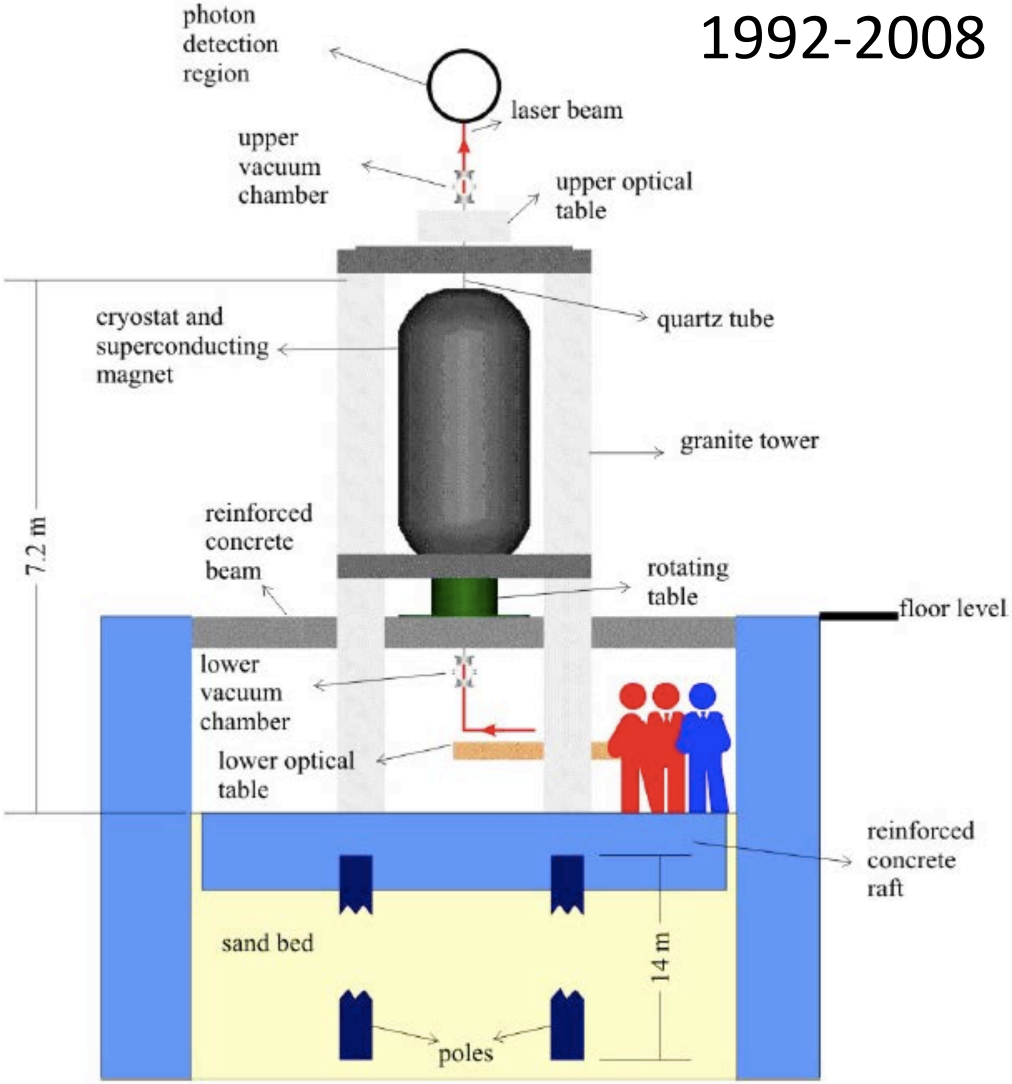
Focused on a general study of the vacuum in the presence of a magnetic field

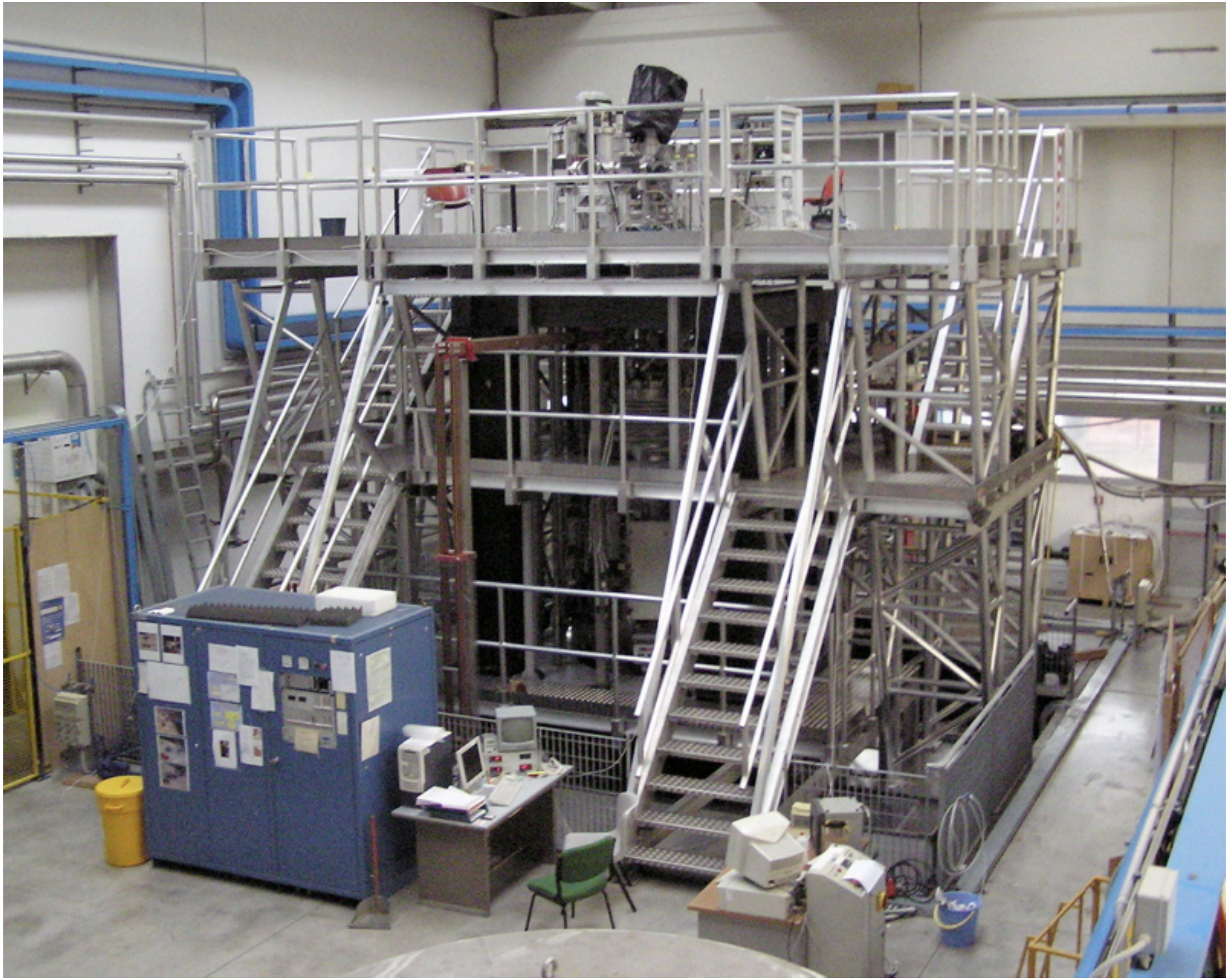
Polarizzazione del
Vuoto con **LAS**er

1992-2008

Major improvements:

- Resonant **FP cavity (6.4 m)** for large amplification factor (> 5×10^4)
- Rotating cryostat allows high modulation frequency (up to 0.4 Hz)
- Large magnetic field (up to 5.5 T)
- Optical system mechanically decoupled from magnetic system





PVLAS @ Legnaro - Results

Sensitivity for ellipticity and rotation ~ 10^{-6} 1/√Hz

Measured upper limits @ 95% c.l. @ B = 2.3 T

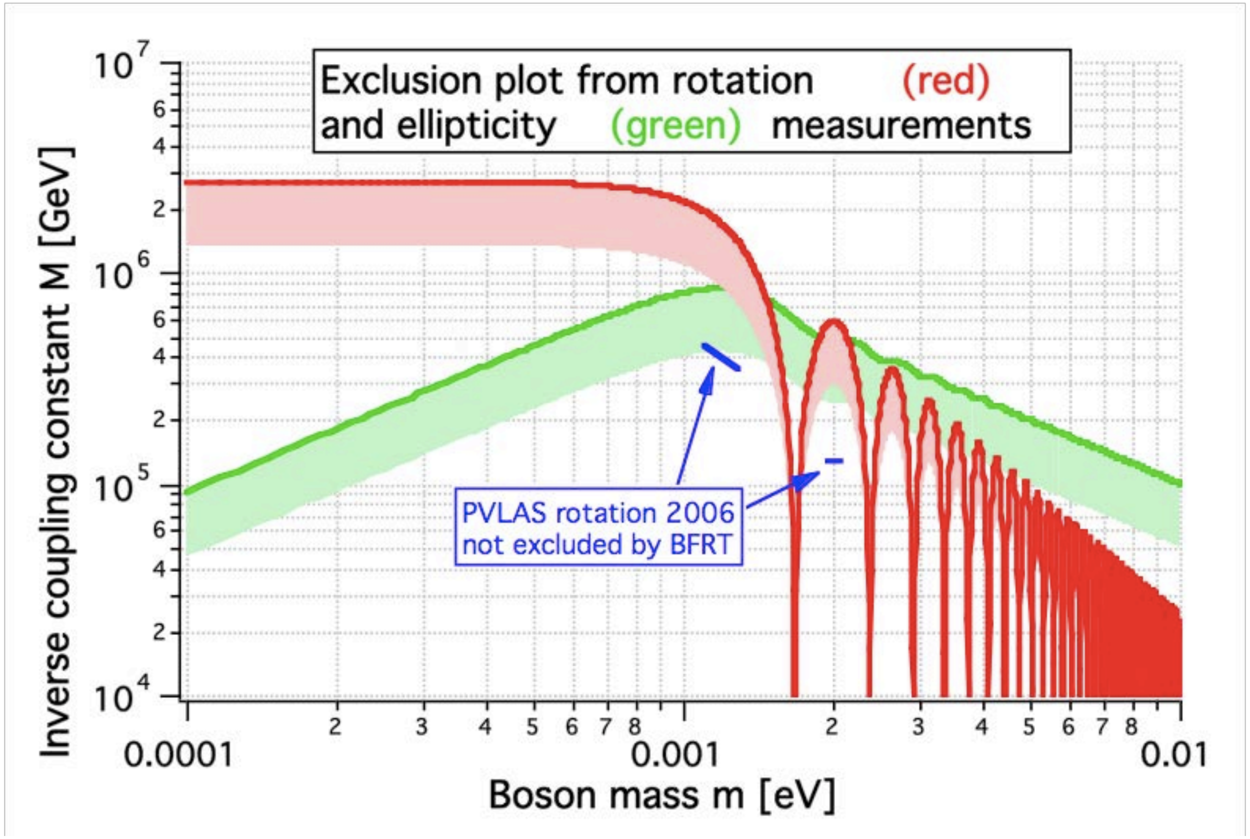
$\Delta n_{QED} = 3 A_e B_0^2$

$\Delta n < 6.6\times10^{-21}$ @ 1064 nm

$\Delta n < 6.3\times10^{-21}$ @ 532 nm

Bregant M et al., PRD 78, 032006 (2008)

Zavattini E et al, PRD 77, 032006 (2008)



Limitations of the LNL apparatus

- Superconducting magnets produce **stray field** when operated at high fields (saturated iron)

- **Running time limited** due to liquid helium consumption

- Short term sensitivity for ellipticity about **2–3×10^{-7} 1/√Hz**, but long term **1×10^{-6} 1/√Hz**

- Observed **correlation between seismic noise and ellipticity noise**. The Legnaro apparatus was large and therefore difficult to isolate seismically.

- **No zero measurement possible** with field turned ON.

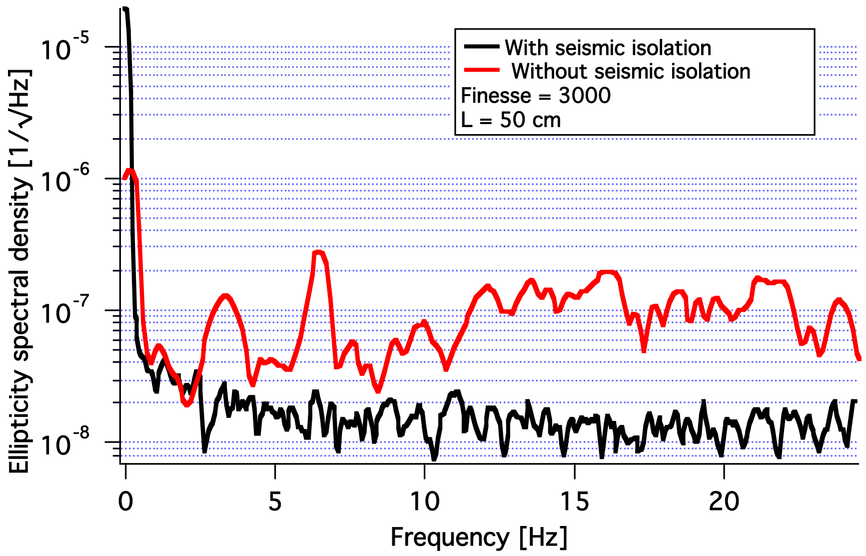
PVLAS development strategy

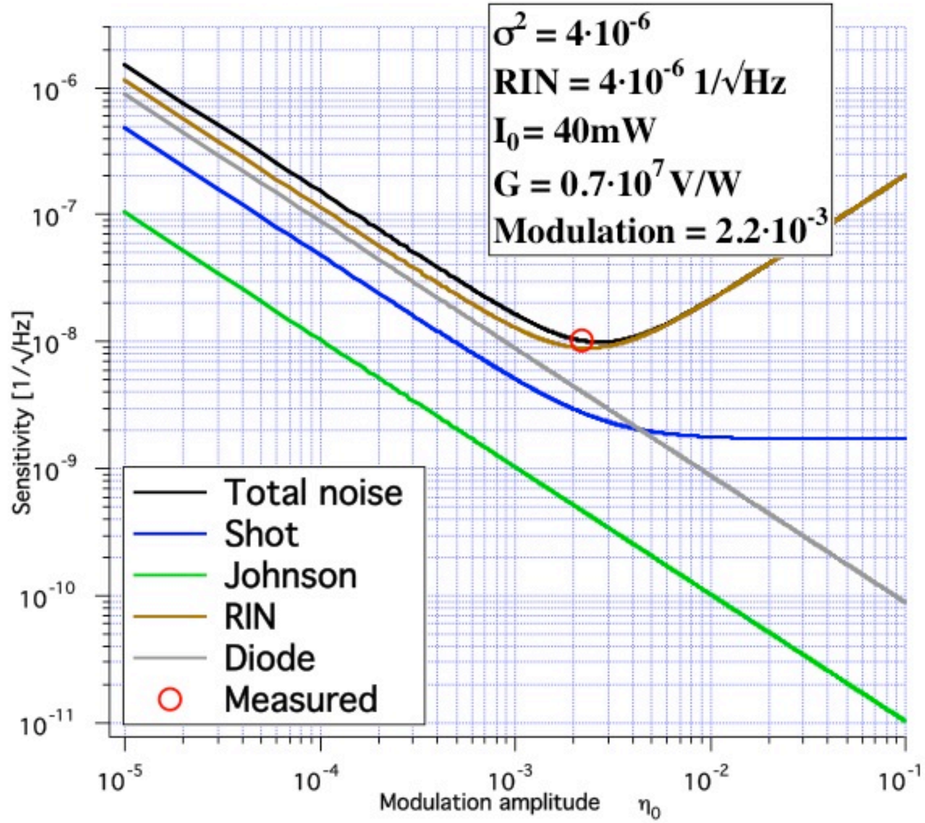
- Reverse the logic of designing the apparatus
  - Old - get the highest magnetic field and build the optical system around it
  - New - **build up an ellipsometer with best sensitivity and find a suitable magnetic source**
- New magnetic sources available: **permanent dipole magnets** with 2.5 T field almost on the shelf, up to 3 - 3.5 T for special orders
- Build up a test apparatus to **improve sensitivity** for an ellipsometer coupled to **very high finesse Fabry-Perot cavity**
- Design the system with built-in capability of **bad signal rejection** (two magnet system)

PVLAS @ Ferrara
Low finesse cavity

Compact system with **50 cm Fabry Perot cavity**
Cavity + ellipsometer inside a single vacuum pipe on top of a **seismically isolated optical table**

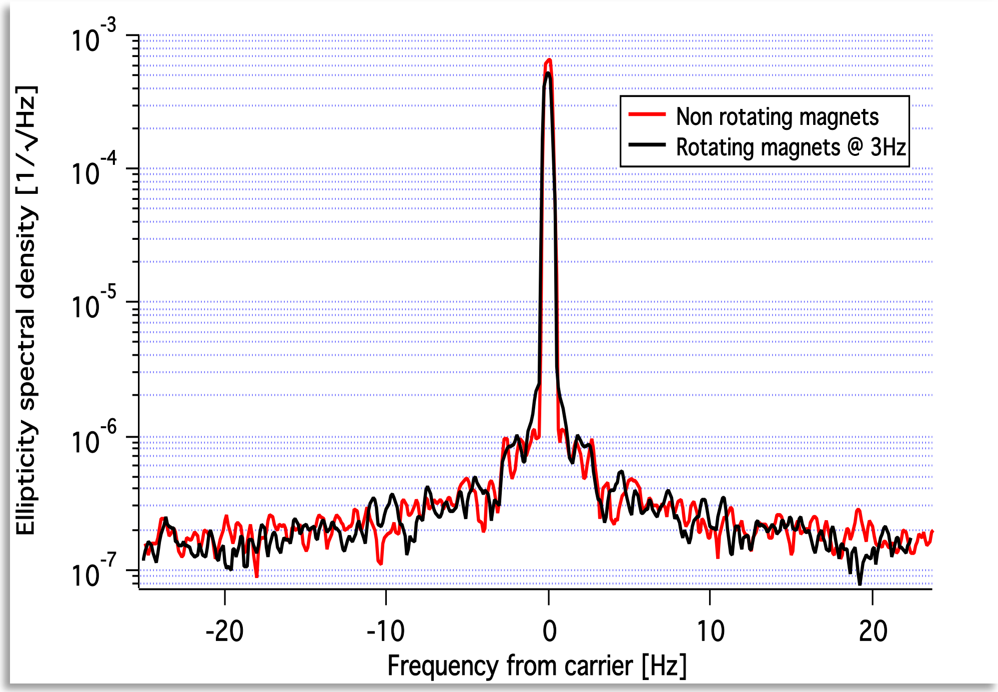
Finesse ~ 3000
Amplification ~ 2000

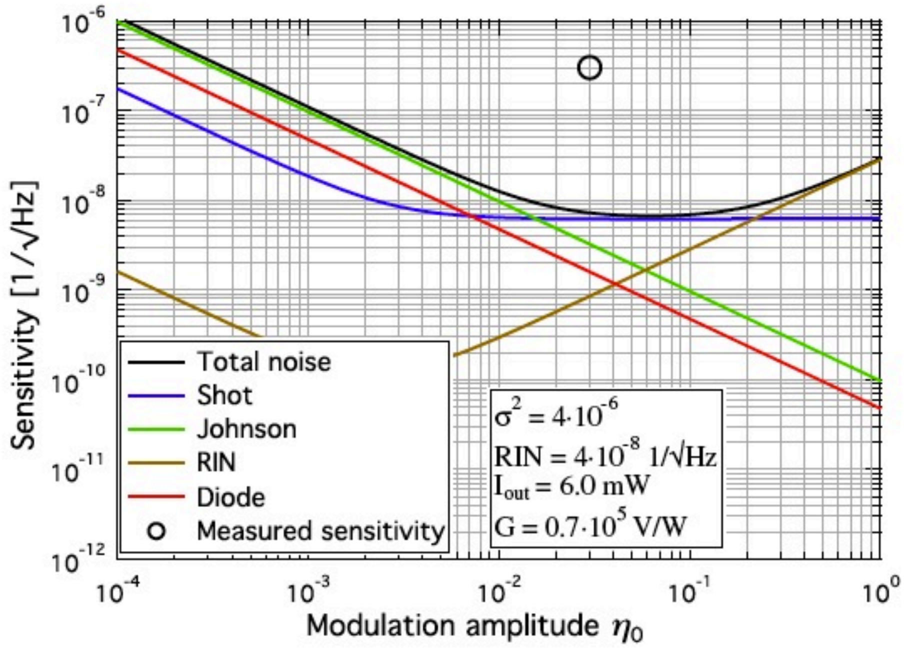




High finesse cavity

With high-finesse cavity: $F > 400\,000$
Sensitivity worsened





s_{total} (6 Hz) ~ 3×10^{-7} 1/√Hz
s_{total} (20 Hz) ~ 1.5×10^{-7} 1/√Hz

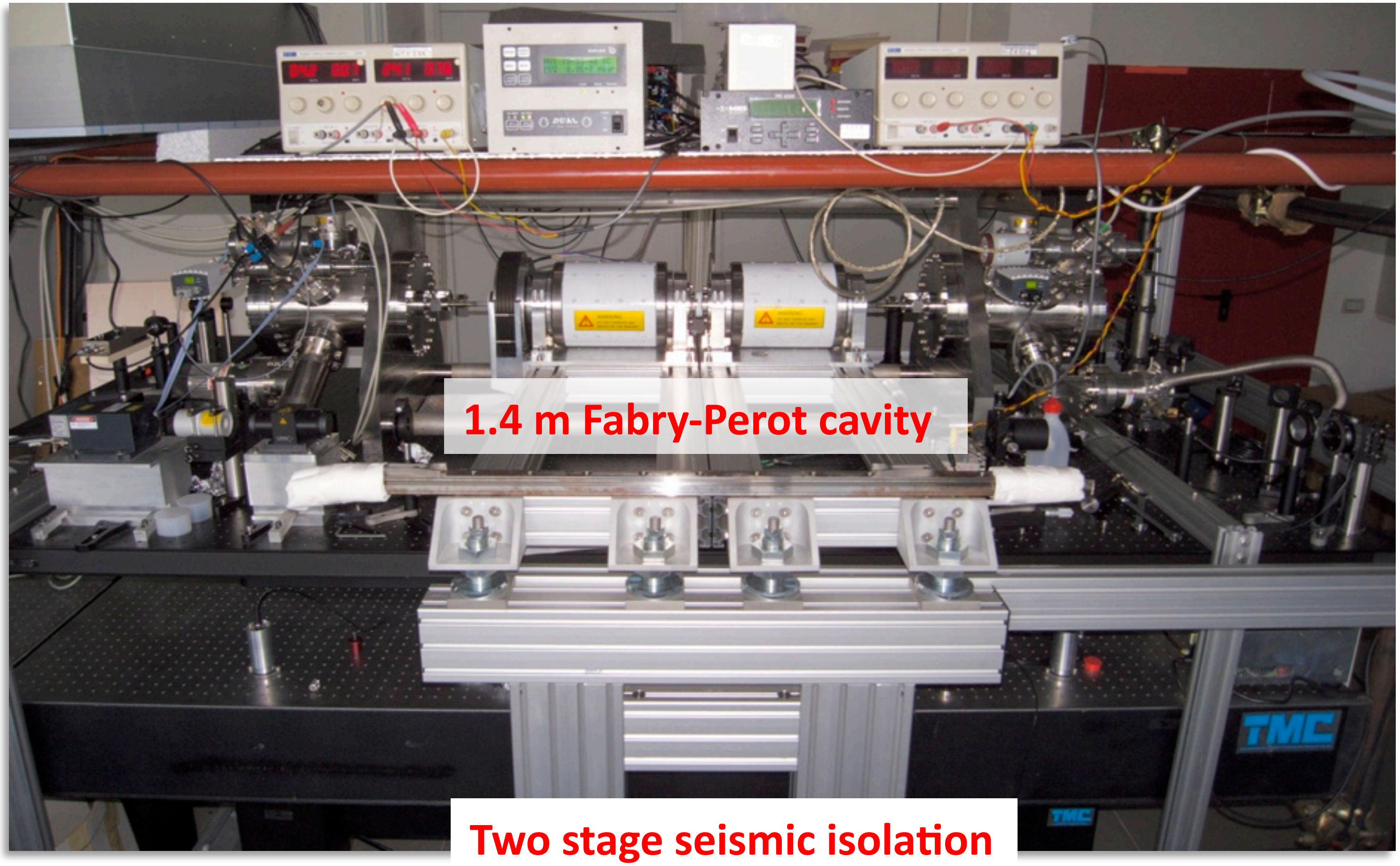
High finesse cavities are a strong source of 1/f birefringence noise

Ferrara test set-up

2.3 T, 20 cm long permanent magnets
rotation frequency ~ 3-4 Hz

2010-2013

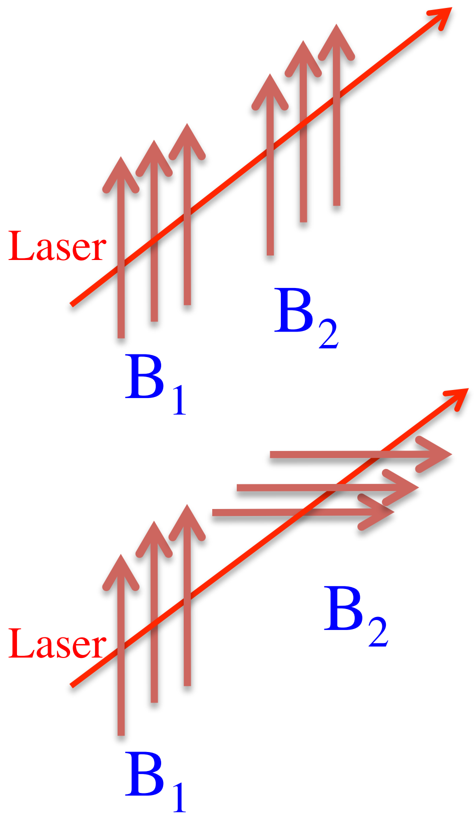
- Ellipsometer and optical cavity on **single optical table**
- Optical table with **active suspension system**
- **Two magnets**
- **High rotation frequency for the magnetic source**
- **High frequency polarization modulator**



Main limitations: - most of components **magnetic**
- optics support **not stable** enough
- unexplained **spurious peaks**

Two magnets: good signal test

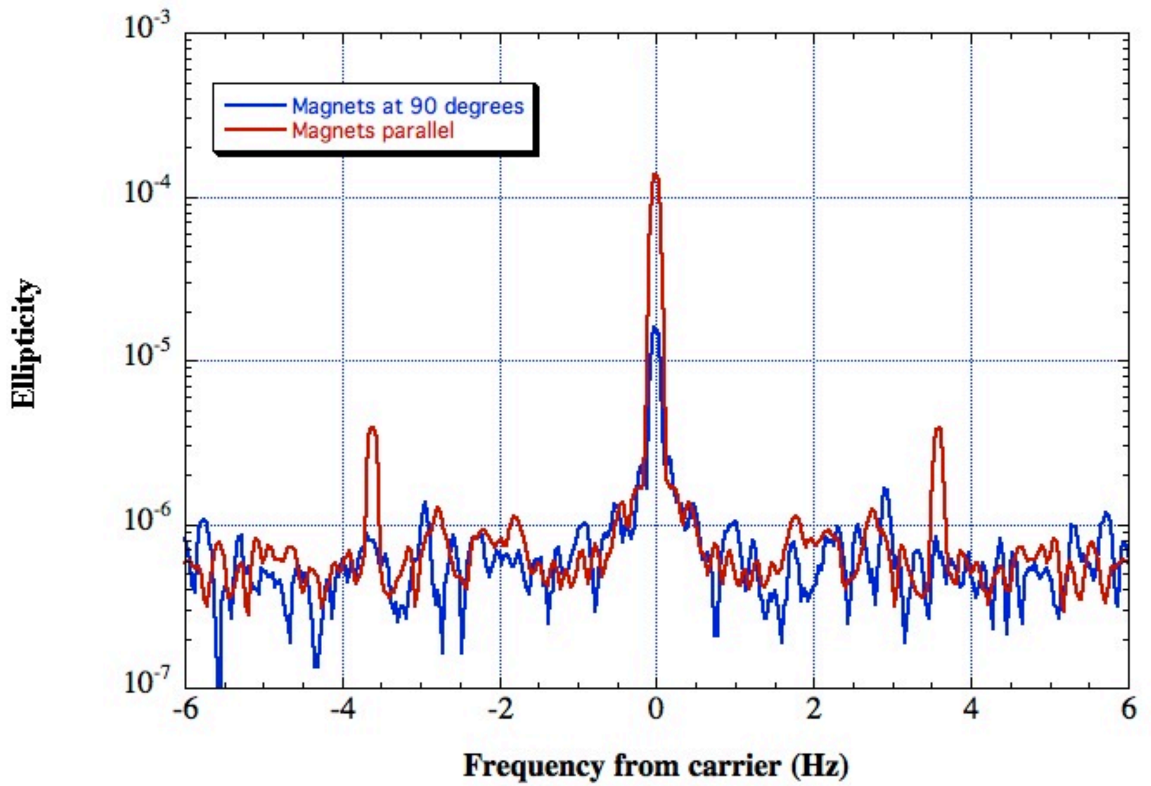
Two magnets system to check that signal is due to magnetic birefringence



$\Psi_{tot} = 2\Psi$

$\Psi_{tot} = 0$

Measurement with 1.3 mbar of air



The laboratory: clean room

Clean room class 10000

Air conditioned with fans

Environment with human noise sources during day

The optics support

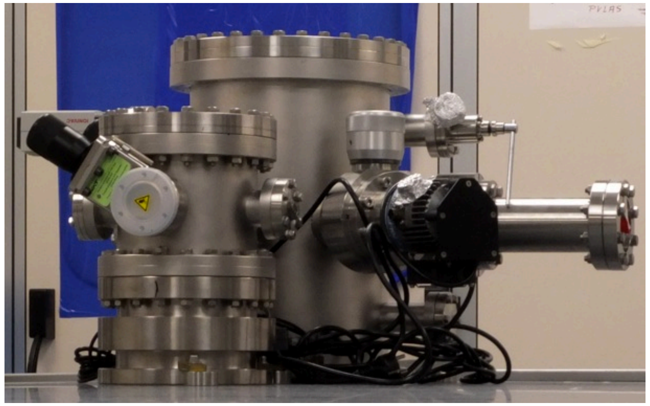
Actively isolated granite optical bench

Compressed air stabilization system for six degrees of freedom.
Resonance frequency down to 1 Hz

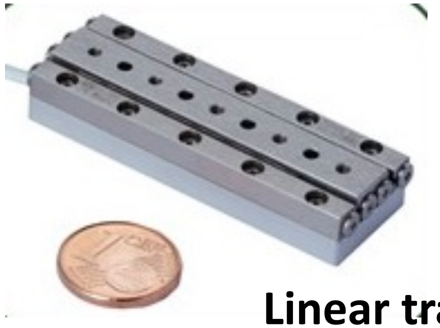
4.8 m length, 1.2 m wide, 0.4 m height, 4.5 tons

Vacuum system and pumping

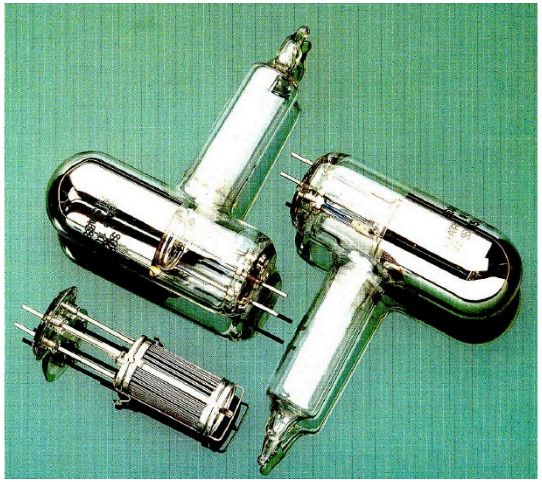
- All components of the vacuum system and optical mounts made with **non magnetic materials** (at best)
- Vacuum pipe through magnet made in **pyrex** to avoid eddy currents
- Motion of optical components inside vacuum chamber by means of **piezo-motor**
- Low pressure pumping (below 10^{-7} mbar) by using getter - NEG pumps – **noise free, magnetic field free**



Vacuum chambers

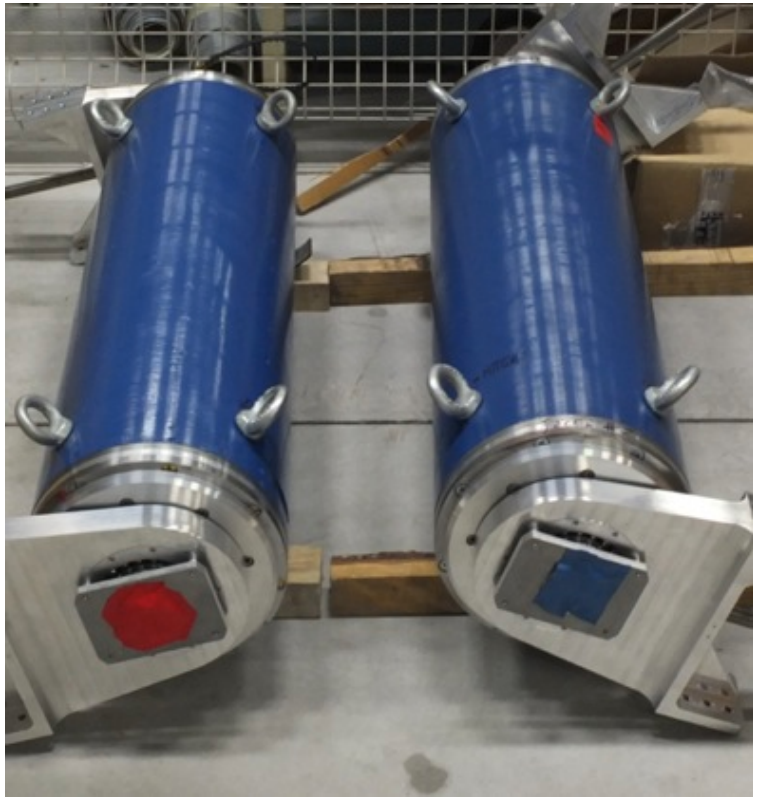


Linear translator

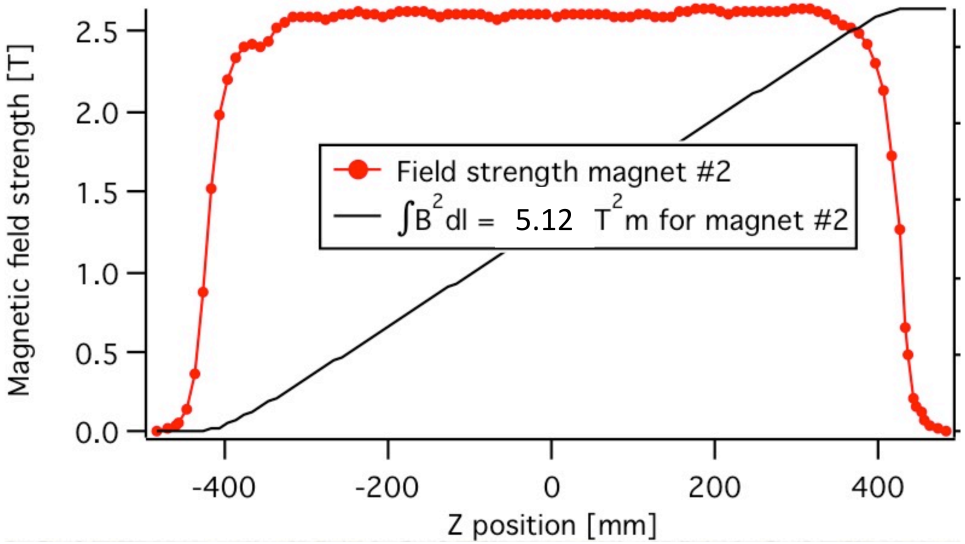


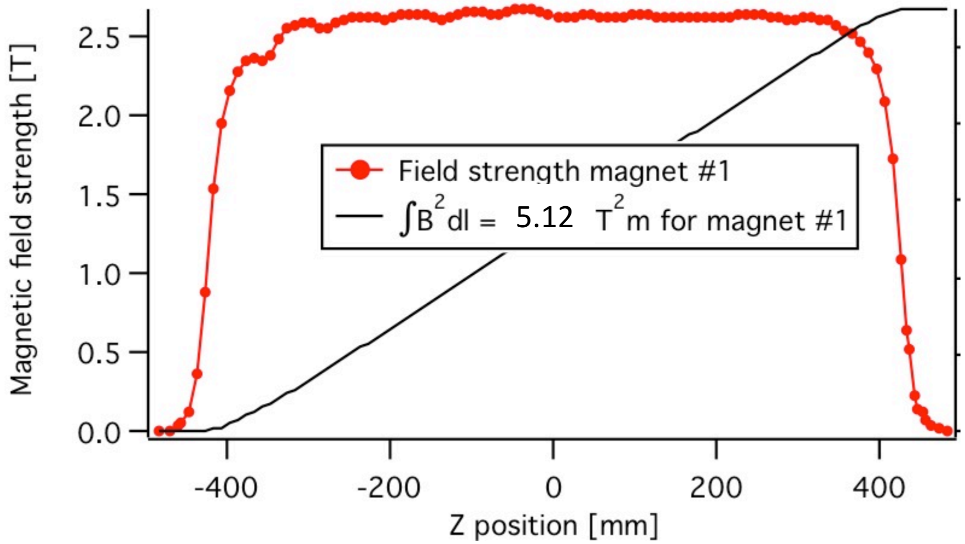
Getter pumps

The magnetic field sources

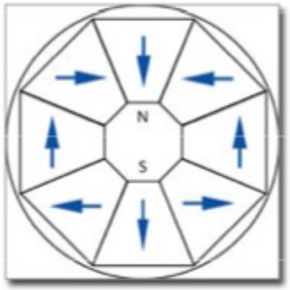


Total field integral = 10.25 T^2 m



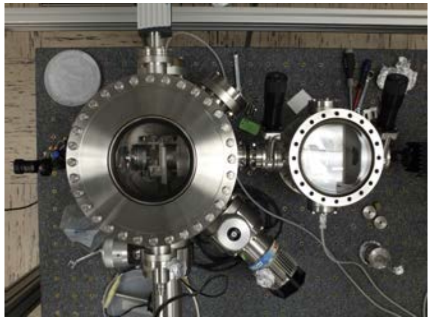


Permanent dipole magnets in Halbach configuration

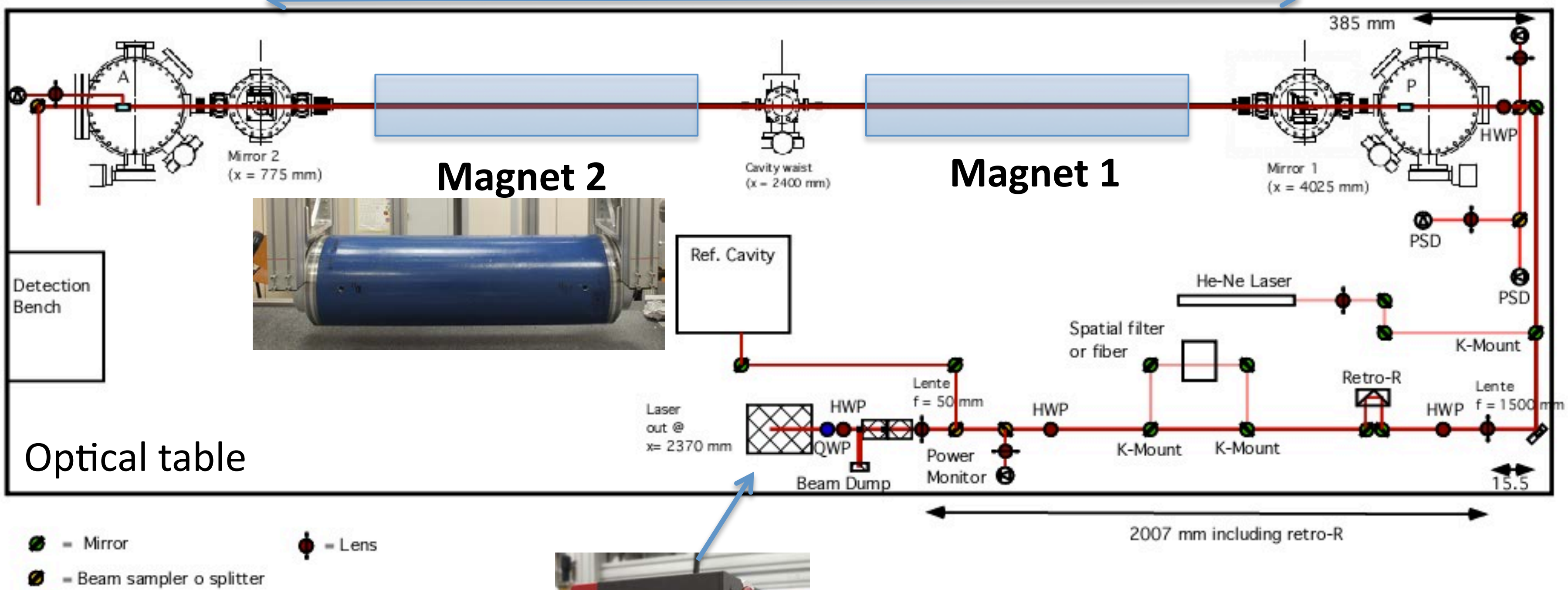


Magnets have built in **magnetic shielding**
Stray field below 1 G on side

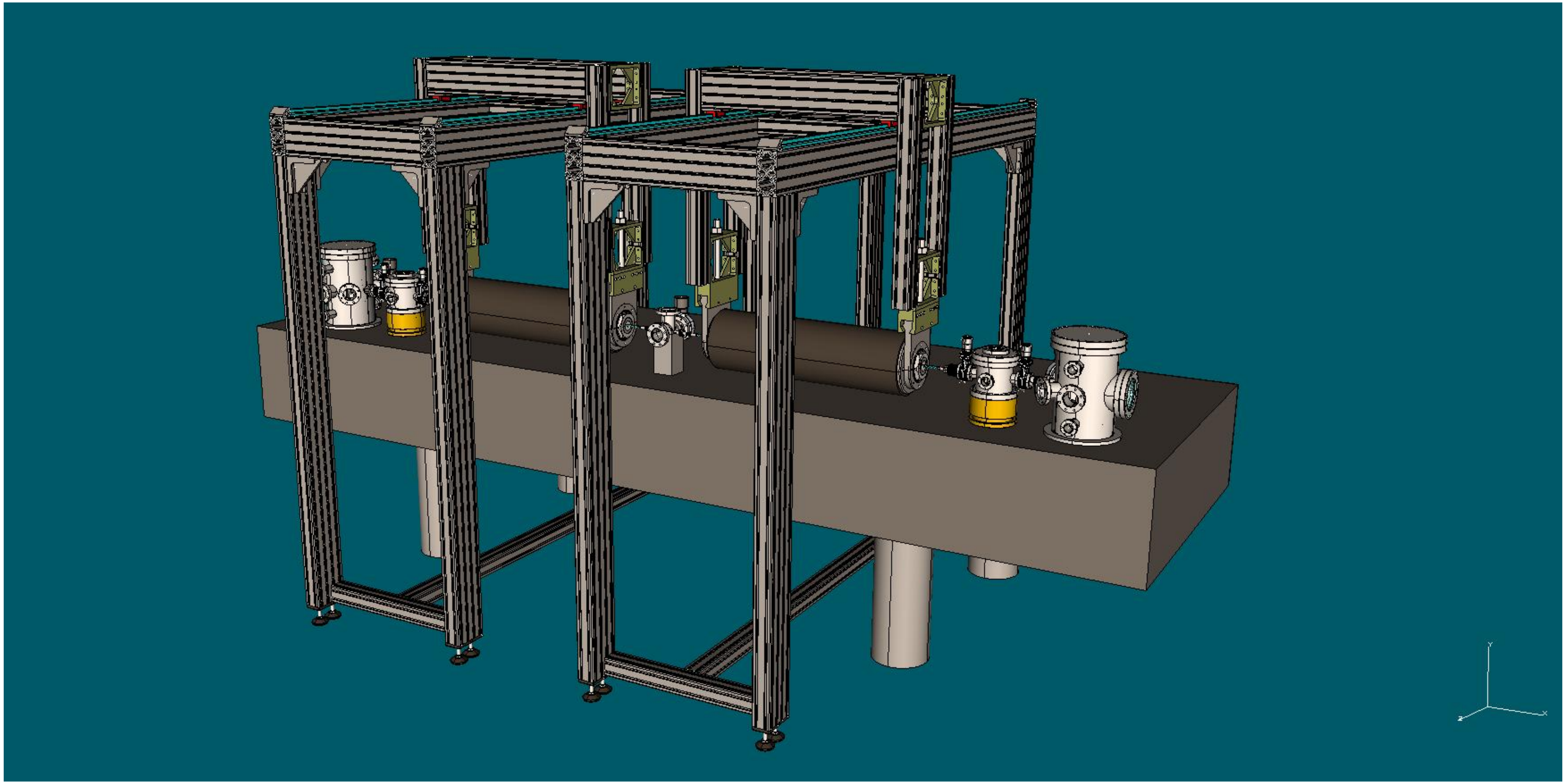
Optics layout



3.3 m long Fabry Perot cavity



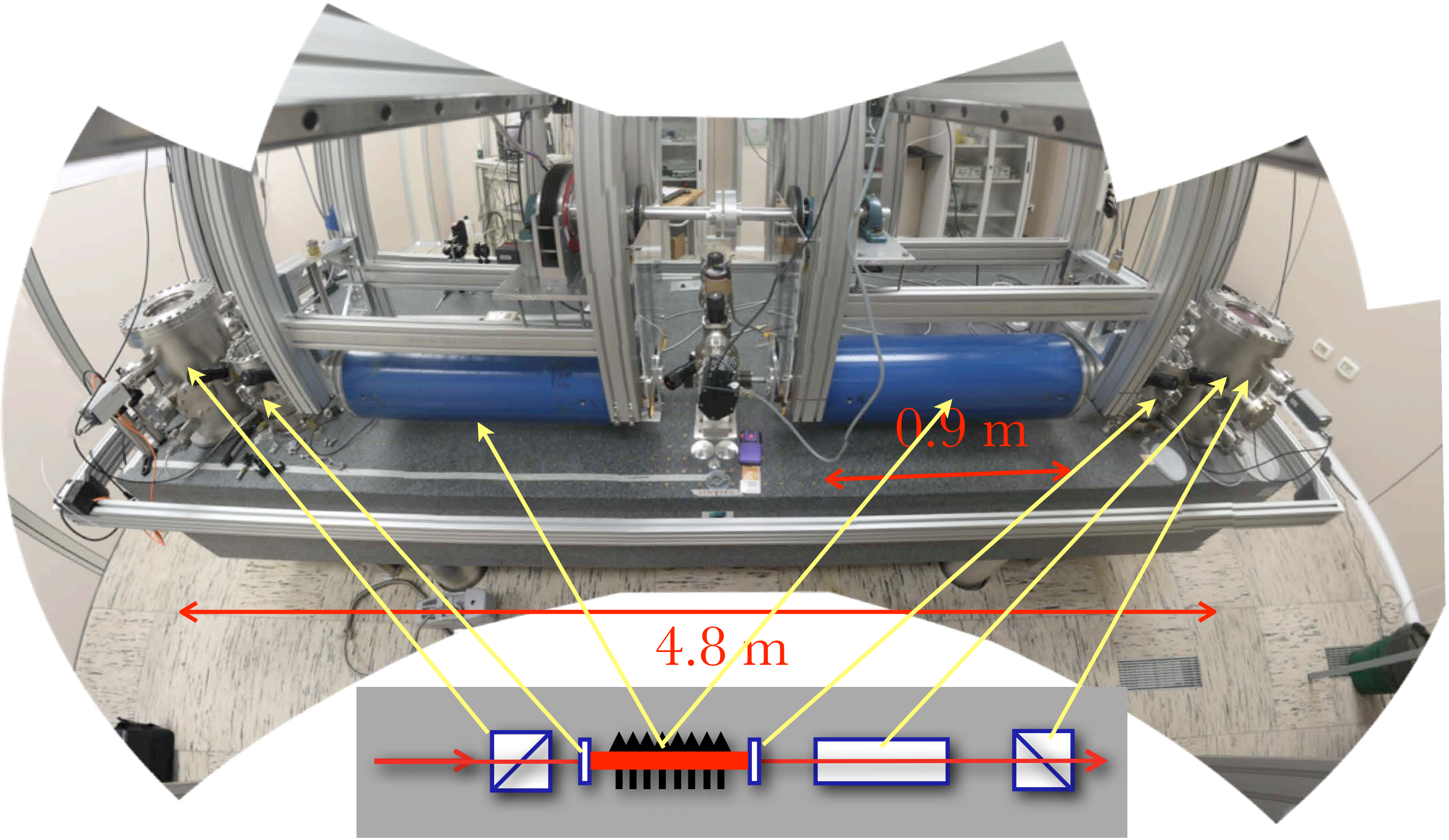
2 W NPRO Nd:Yag Laser
λ = 1064 nm



The apparatus

The apparatus

The apparatus

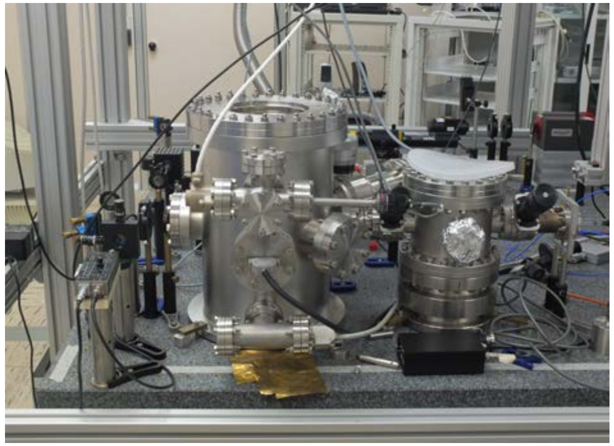


The rotating magnet

The compact structure of the permanent magnets allows for very high modulation frequency

Magnet rotating at 4 Hz – target: 20 Hz

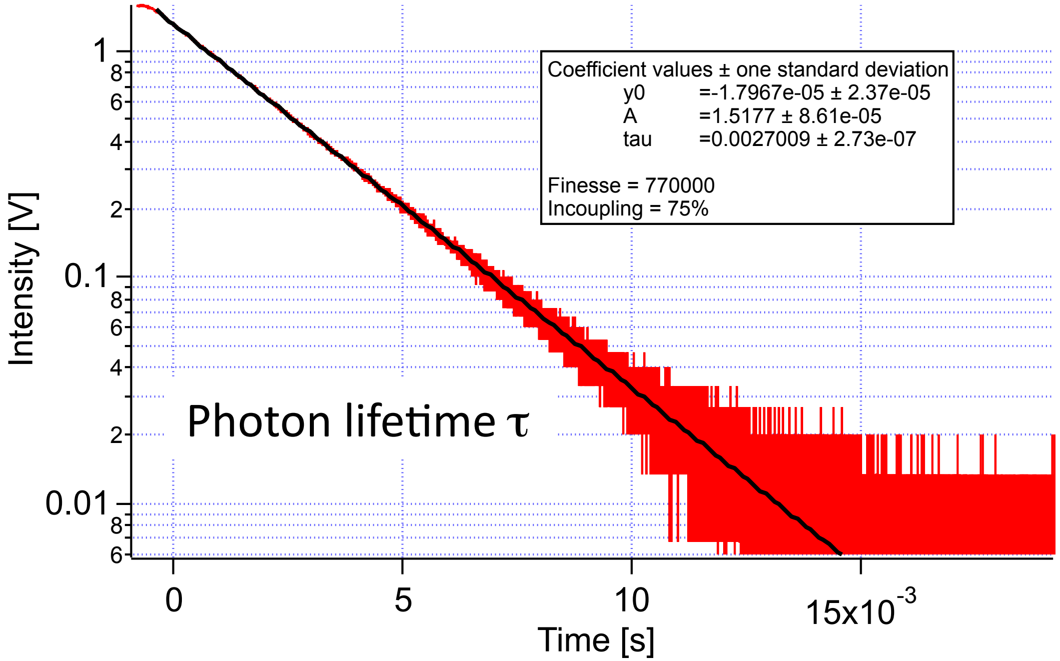
More pictures



The Fabry Perot cavity

High reflectivity (R = 0.999996)

spherical mirror with r = − 2 m



Transmitted power up to 200 mW

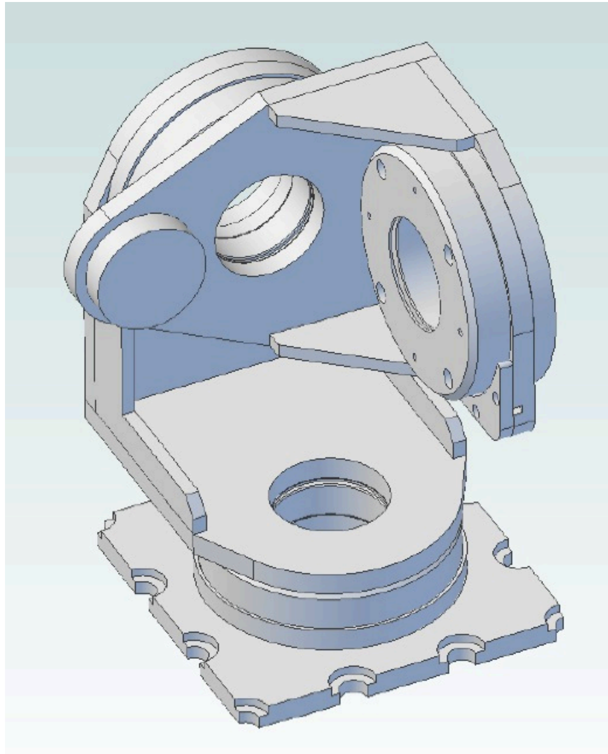
τ = 2.7 ms , d = 3.3 m

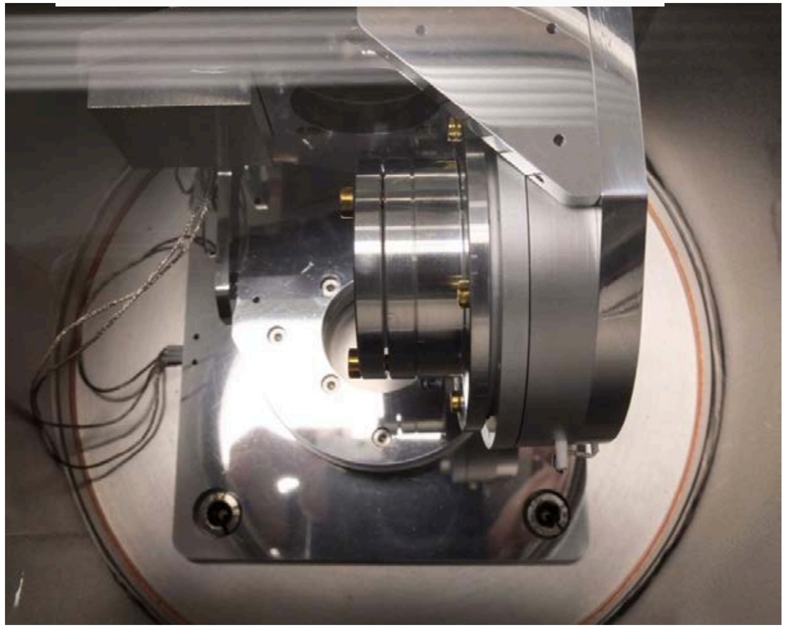
Finesse = 770 000   N = 480 000

Circulating power = 40 kW

Optics Express **22**, 11570 (2014)

ψ_{QED} = 5.6 10^{-11}

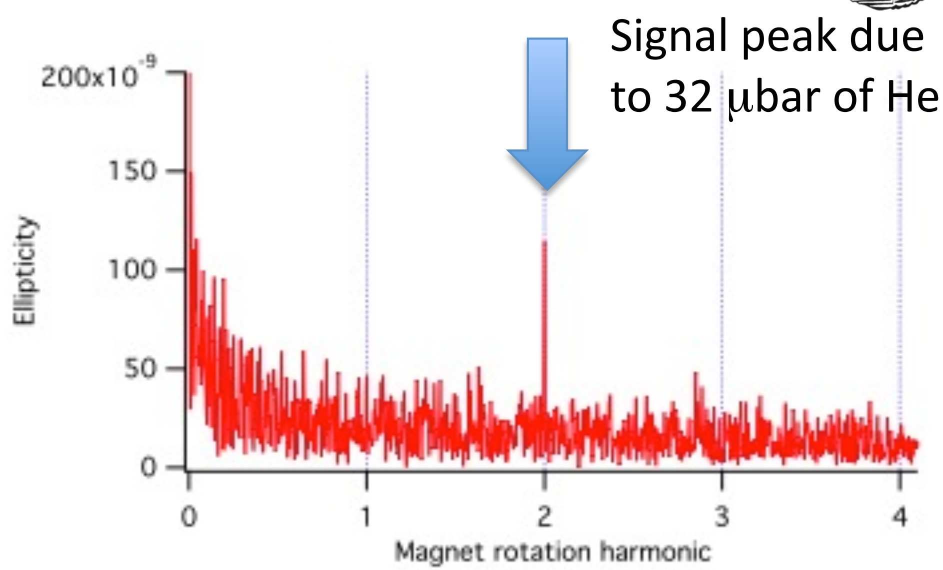


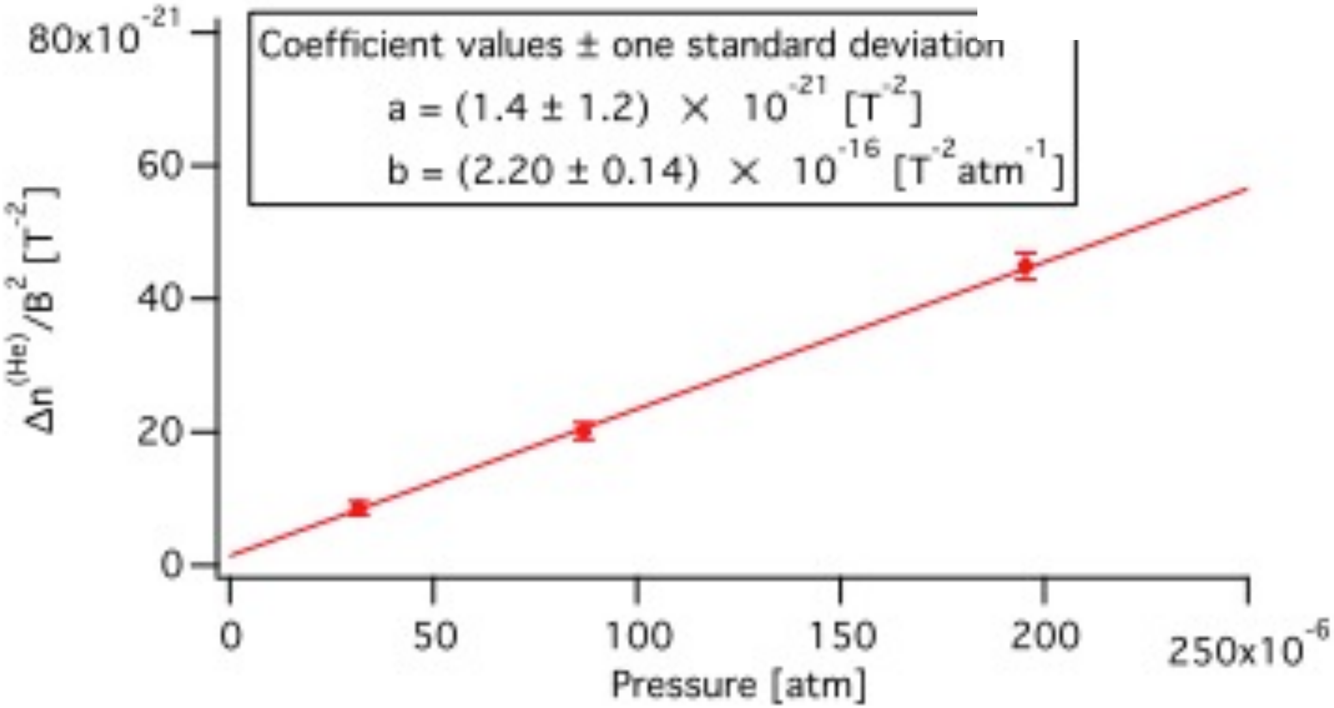


3-Motor Mirror tilter, θ_x, θ_y, θ_z

Calibration with He

We have calibrated the apparatus with a very low birefringence





Vacuum magnetic birefingence by QED is **equivalent to a He pressure** of about

20 nbar

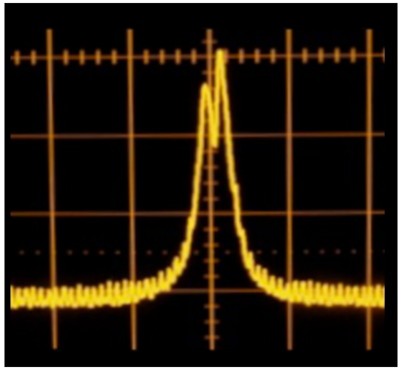
Systematics: cavity mirrors birefringence

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

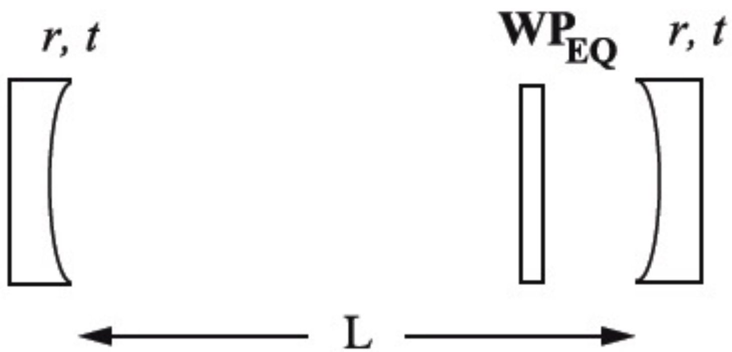
$$\mathbf{M}_{1,2} = \begin{pmatrix} e^{i\,\alpha_{1,2}/2} & 0 \\ 0 & e^{-i\,\alpha_{1,2}/2} \end{pmatrix}$$

Two polarisation auto-states

Contribution to noise?



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



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

- to make extinction: **align polarisation to the equivalent wave-plate axes**
- to reduce total birefringence: **rotate cavity mirrors**

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

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

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

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

2) Mixing of ellipticity and rotation

Mixing of ellipticity and rotation - I

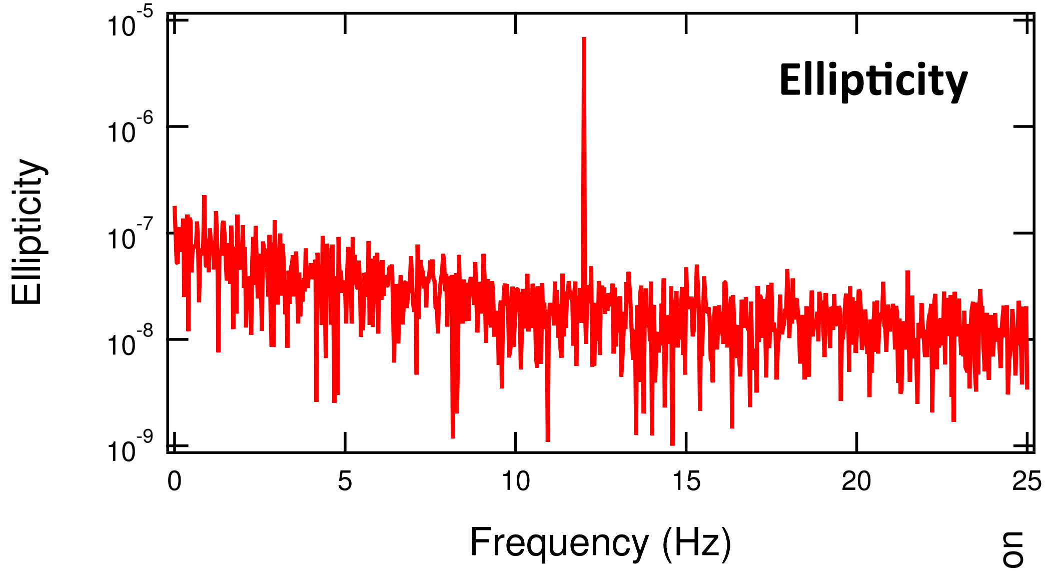
$$I_\perp^{\text{ell}}(\phi) = I_{||}\left[\eta^2 + \eta k(\alpha)(2N\psi + N^2\theta\alpha)\sin 2\phi\right]$$

$$I_\perp^{\text{rot}}(\phi) = I_{||}\left[\eta^2 + \eta k(\alpha)(2N\theta - N^2\psi\alpha)\sin 2\phi\right]$$

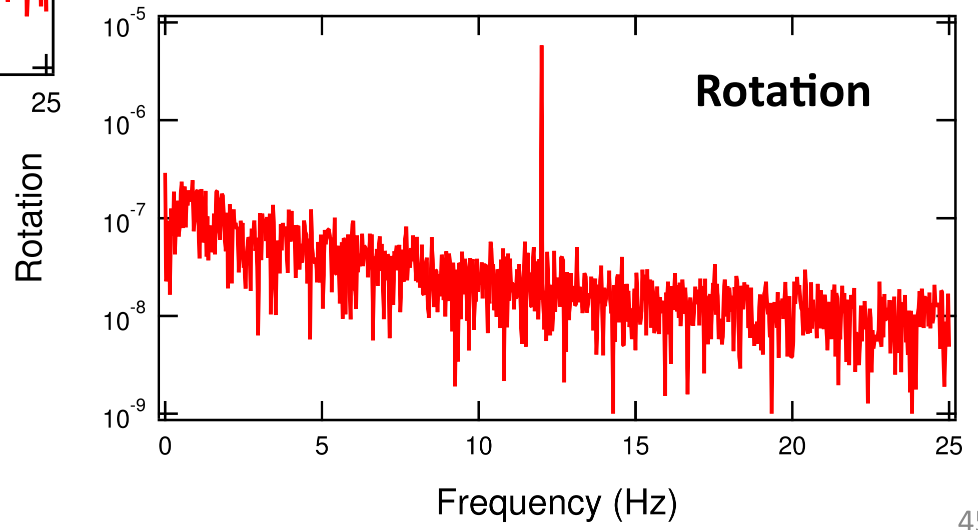
$$R_{\theta,\psi} = -\frac{N}{2}\alpha$$

“spurious” rotation divided by “true” ellipticity

α = 3.7 μrad
$k(\alpha)$ = 0.59



Cotton-Mouton 230 μbar Ar



Also true for noise: a noise level in one quantity translates in a noise level on the other

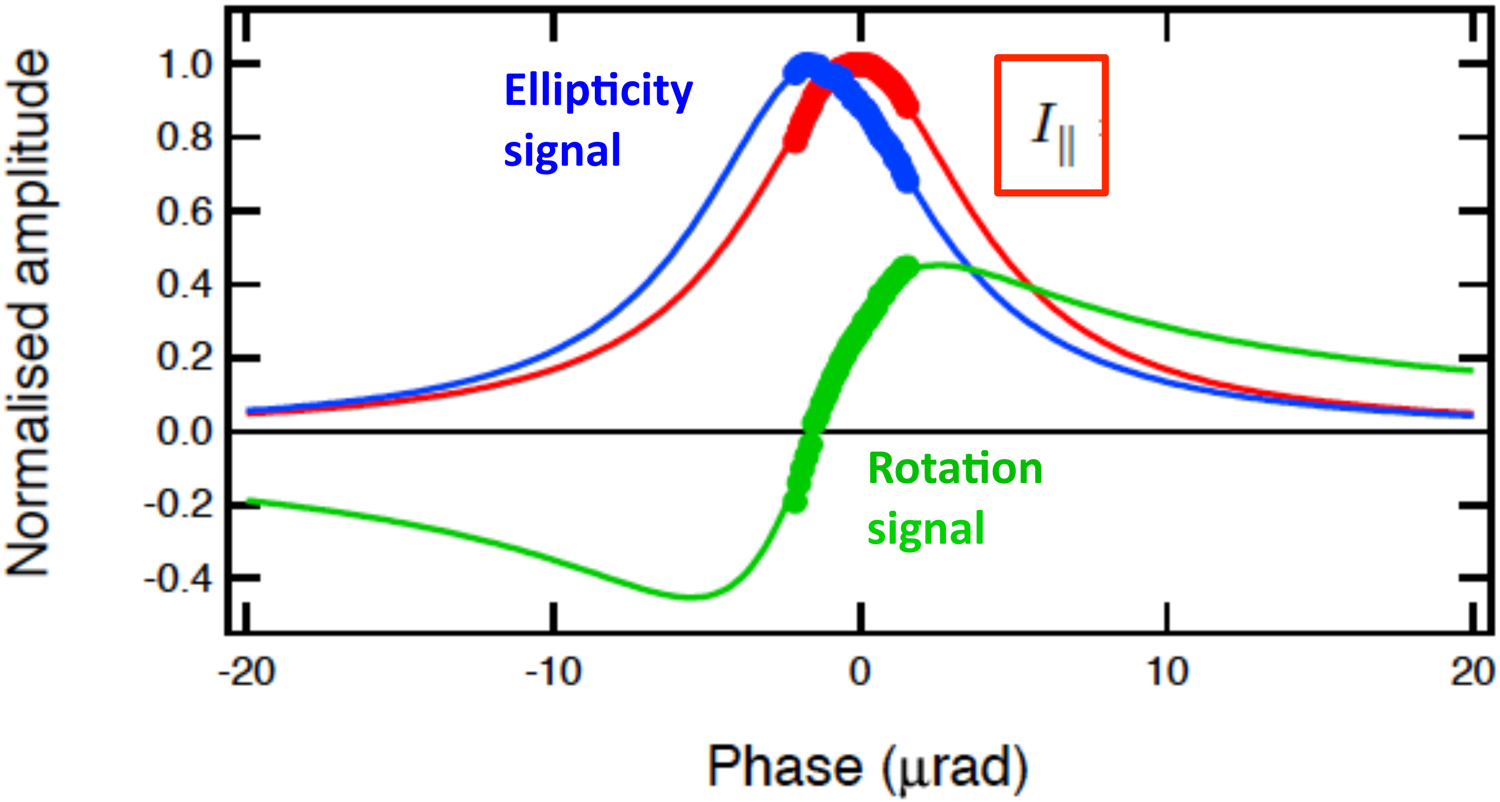
Mixing of ellipticity and rotation - II

$$I_\perp^{\rm ell}(\phi) = I_\parallel \left[\eta^2 + \eta \frac{2N\psi - N^2\theta\left(\delta - \frac{\alpha}{2}\right)}{1 + N^2\sin^2\left(\frac{\delta}{2} - \frac{\alpha}{4}\right)} \sin 2\phi\right]$$

$$I_\perp^{\rm rot}(\phi) = I_\parallel \left[\eta^2 + \eta \frac{2N\theta + N^2\psi\left(\delta - \frac{\alpha}{2}\right)}{1 + N^2\sin^2\left(\frac{\delta}{2} - \frac{\alpha}{4}\right)} \sin 2\phi\right]$$

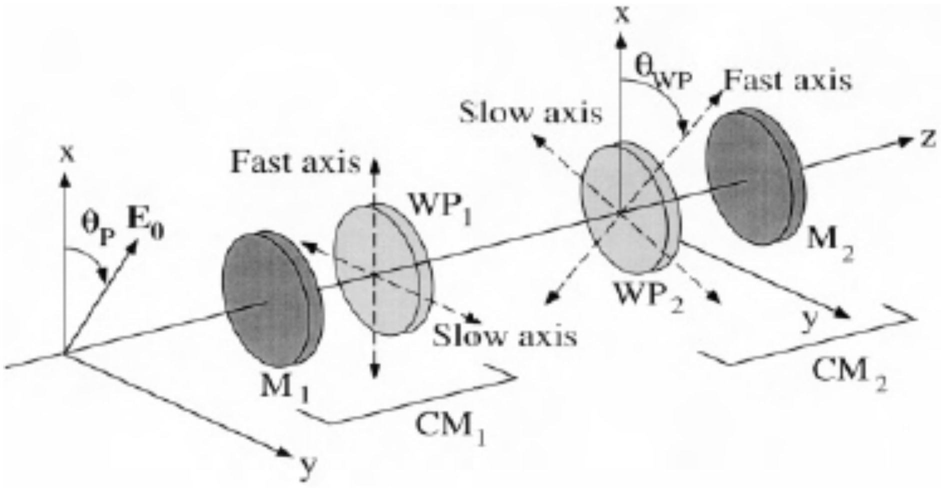
$$I_\parallel = \varepsilon_0 c \frac{E_0^2}{2} \frac{T^2N^2/4}{1 + N^2\sin^2\left(\frac{\delta}{2} + \frac{\alpha}{2}\right)}$$

Cotton-Mouton 230 μbar Ar

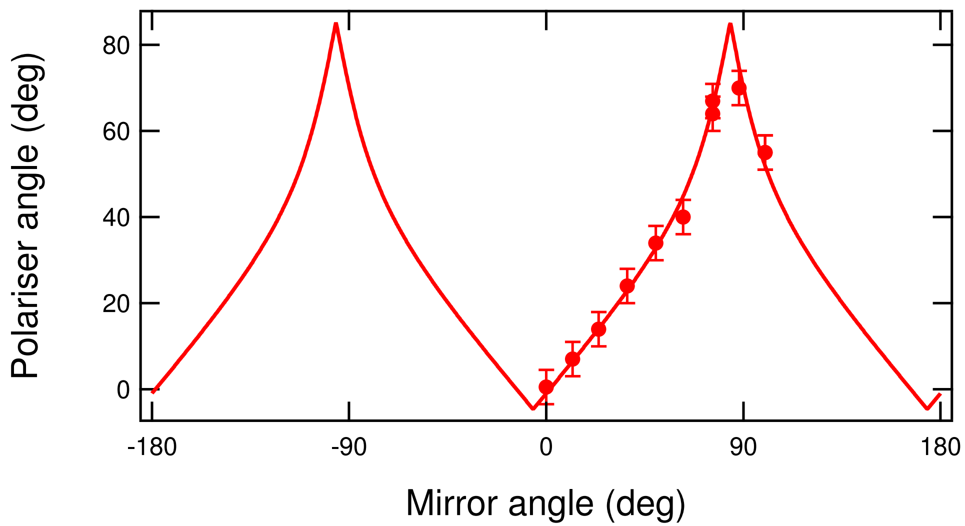


Della Valle F et al, arXiv:1510.08052v1

Optimising cavity mirrors

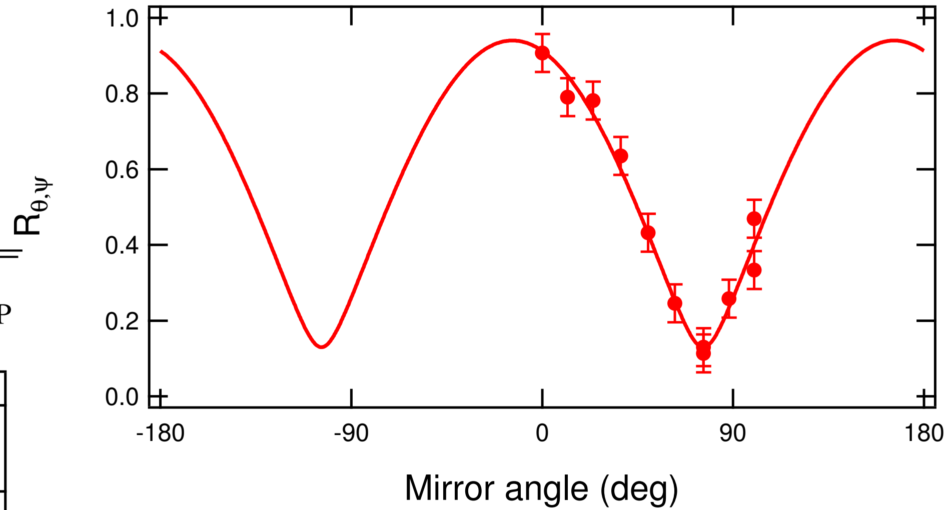


$$\cos 2\theta_{EQ} = \frac{\alpha_1/\alpha_2 + \cos 2\theta_{WP}}{\sqrt{(\alpha_1/\alpha_2 - 1)^2 + 4(\alpha_1/\alpha_2)\cos^2\theta_{WP}}}$$



Rotate input mirrors
to reduce birefringence

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



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

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

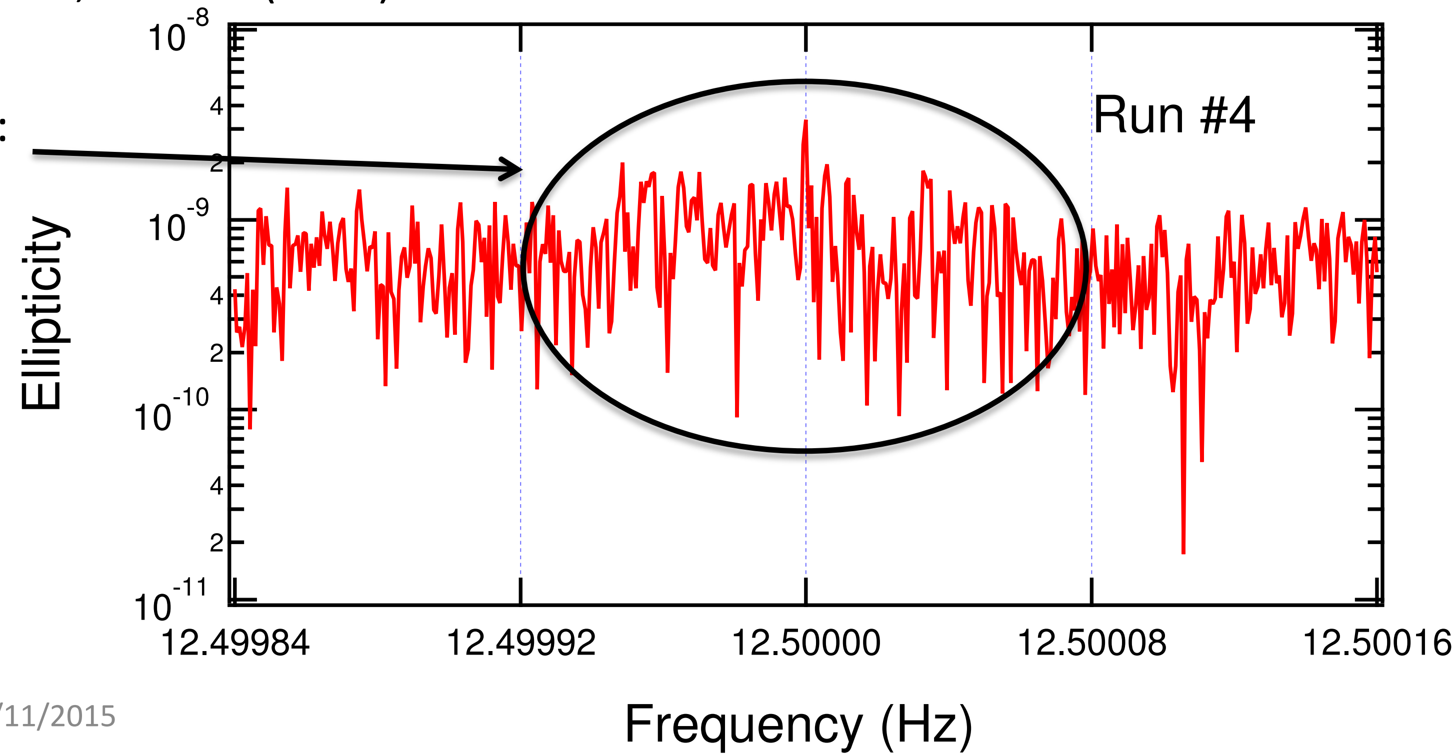
Della Valle F et al, arXiv:1510.08052v1

Vacuum magnetic birefringence results - I

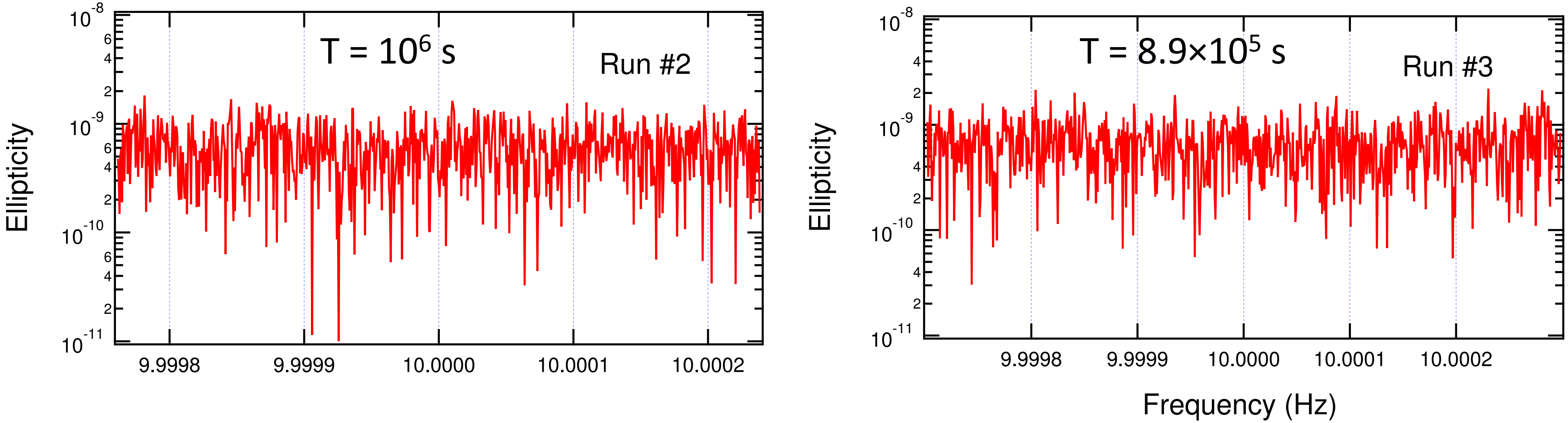
Run #	Quantity	Magnets	$2\nu_B$	T (s)	$\mathcal{F}$	$k(\alpha)$
0	ψ	MA+MB		6.7×10^5	6.7×10^5	0.50
~~1~~	~~ψ~~	~~MB~~	~~8 Hz~~	~~1.0×10^6~~	~~7.0×10^5~~	~~0.65~~
2	ψ	MA	10 Hz	1.0×10^6	7.0×10^5	0.65
3	ψ	MB	10 Hz	8.9×10^5	7.0×10^5	0.65
~~4~~	~~ψ~~	~~MA~~	~~12.5 Hz~~	~~8.9×10^5~~	~~7.0×10^5~~	~~0.65~~
5	θ	MA+MB	10 Hz	1.4×10^5	7.0×10^5	0.65

Run #0 from PRD 90, 092003 (2014)

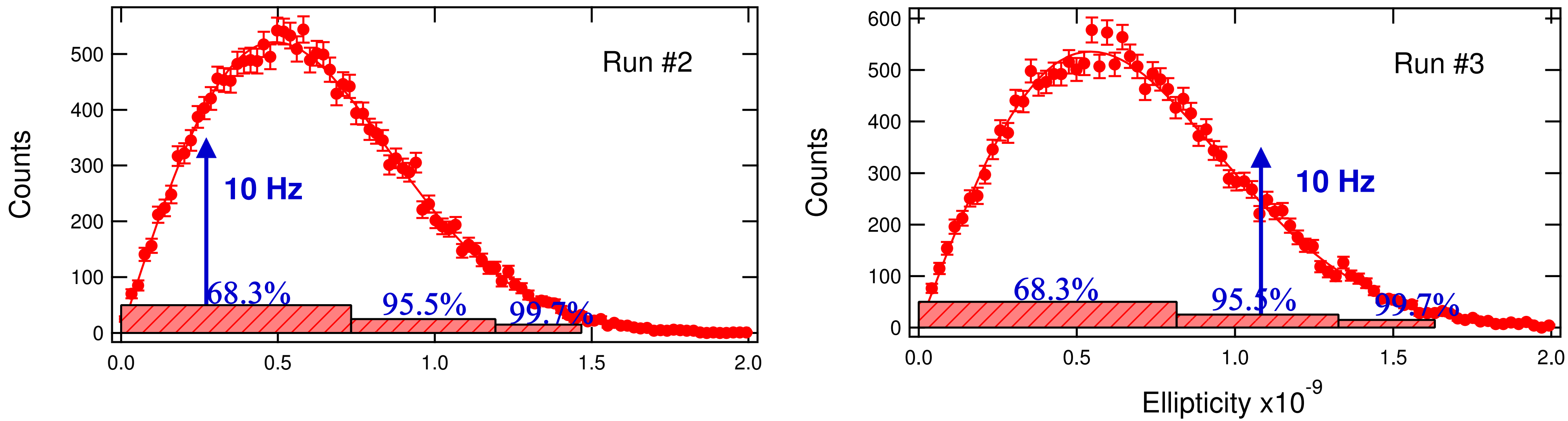
Structured noise: run rejected



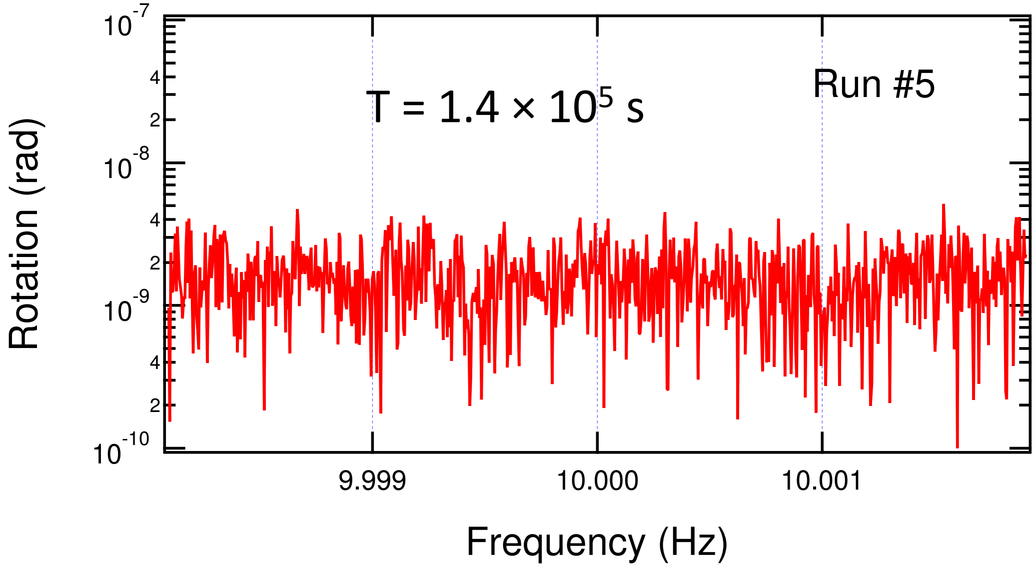
Vacuum magnetic birefringence results - II



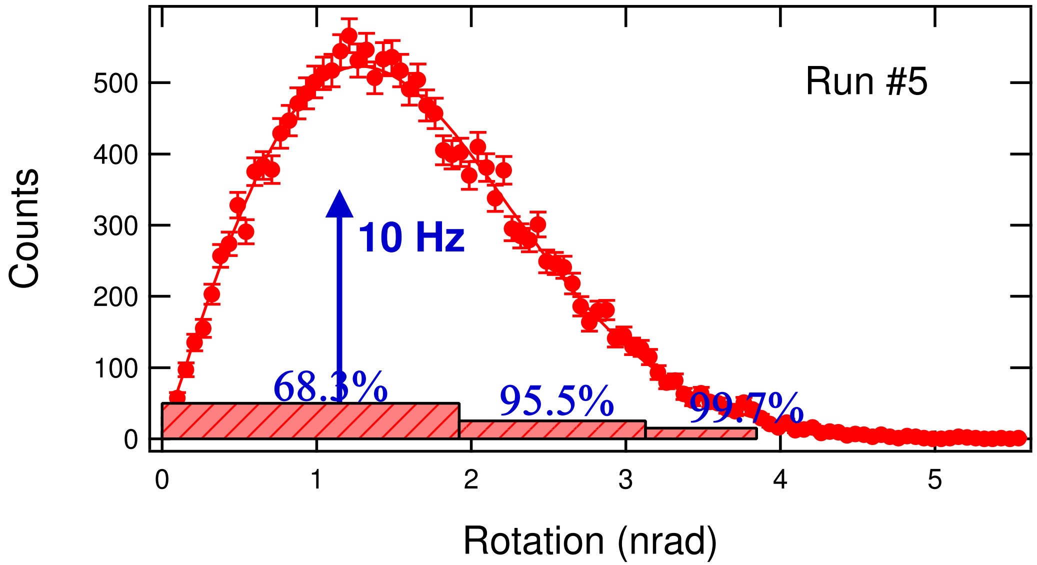
Noise follows Rayleigh distribution: $P_R = \frac{\rho}{\sigma^2} e^{-\frac{\rho^2}{2\sigma^2}}$ $\rho^2 = x^2 + y^2$



Vacuum magnetic dichroism results



QWP inserted



Vacuum measurements summary

Run #	Quantity	In-phase	Quadrature	σ	$S_{2\nu_B}^{\text{meas}}$ $(1/\sqrt{\text{Hz}})$
0	ψ	$+5.2\times10^{-10}$	$+6.5\times10^{-10}$	2.6×10^{-9}	2.1×10^{-6}
2	ψ	-6.9×10^{-11}	$+2.6\times10^{-10}$	4.9×10^{-10}	4.9×10^{-7}
3	ψ	-4.1×10^{-10}	$+1.0\times10^{-9}$	5.4×10^{-10}	5.1×10^{-7}
5	θ (rad)	-6.6×10^{-11}	-1.9×10^{-9}	1.3×10^{-9}	4.8×10^{-7}
0’	θ (rad)	$+5.2\times10^{-10}$		2.6×10^{-9}	2.1×10^{-6}
2’	θ (rad)	-9.4×10^{-11}		6.7×10^{-10}	6.7×10^{-7}
3’	θ (rad)	-5.6×10^{-10}		7.4×10^{-10}	6.9×10^{-7}
5’	ψ	$+9.0\times10^{-11}$		1.8×10^{-9}	6.5×10^{-7}

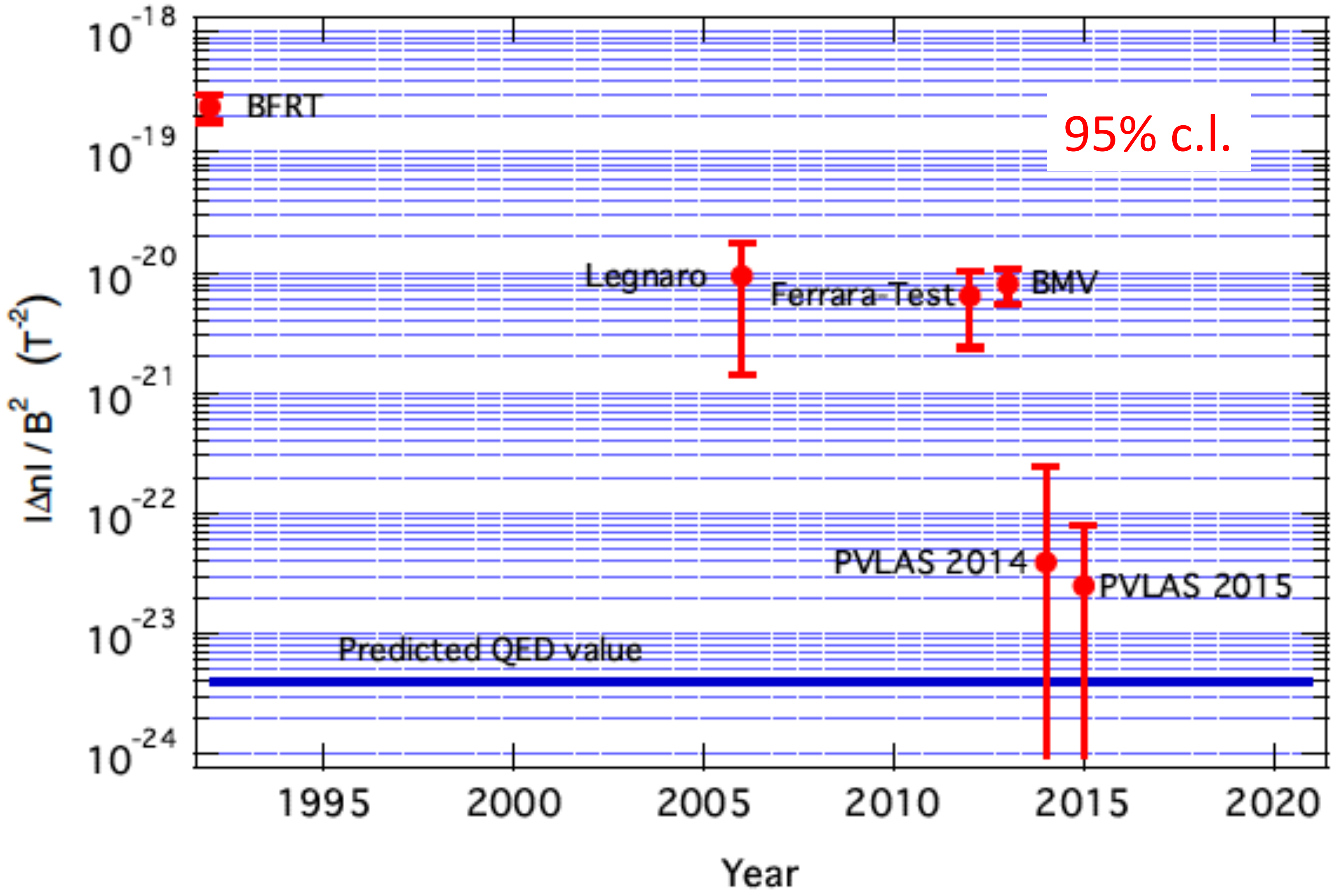
Run #	Quantity	In-phase	Quadrature	σ	$S_{2\nu_B}^{\text{meas}}$ $(1/\sqrt{\text{Hz}})$
0	Δn	$+2.5\times10^{-22}$	$+3.1\times10^{-22}$	1.3×10^{-21}	1.0×10^{-18}
2	Δn	-6.4×10^{-23}	$+2.4\times10^{-22}$	4.5×10^{-22}	4.5×10^{-19}
3	Δn	-3.8×10^{-22}	$+9.3\times10^{-22}$	5.0×10^{-22}	4.7×10^{-19}
5’	Δn	$+4.2\times10^{-23}$		8.2×10^{-22}	3.0×10^{-19}
0’	$\Delta\kappa$	$+2.5\times10^{-22}$		1.3×10^{-21}	1.0×10^{-18}
2’	$\Delta\kappa$	-8.7×10^{-23}		6.2×10^{-22}	6.2×10^{-19}
3’	$\Delta\kappa$	-5.2×10^{-22}		6.8×10^{-22}	6.4×10^{-19}
5	$\Delta\kappa$	-3.1×10^{-23}	-8.8×10^{-22}	6.0×10^{-22}	2.2×10^{-19}

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

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

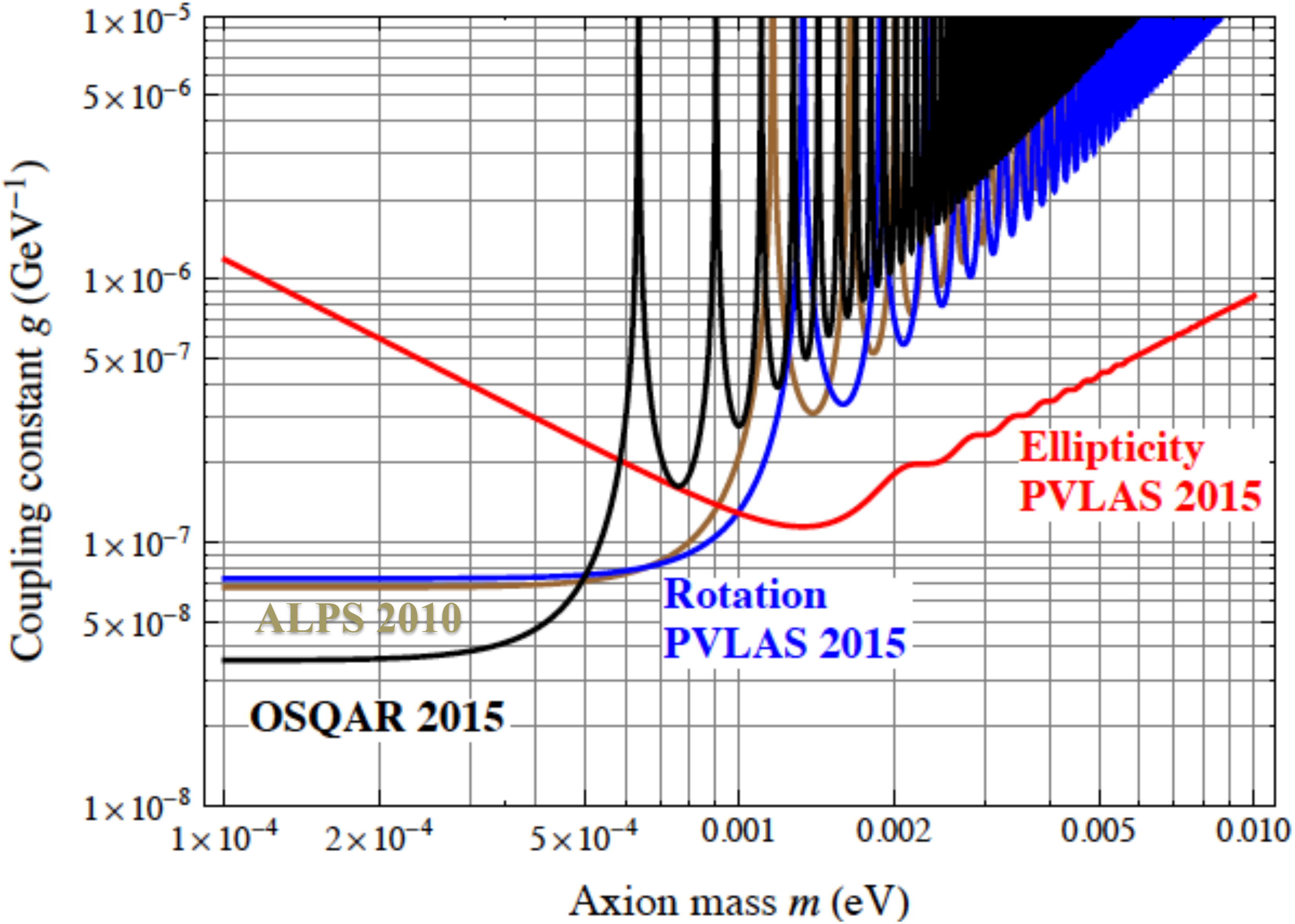
Della Valle F et al, arXiv:1510.08052v1

Timeline



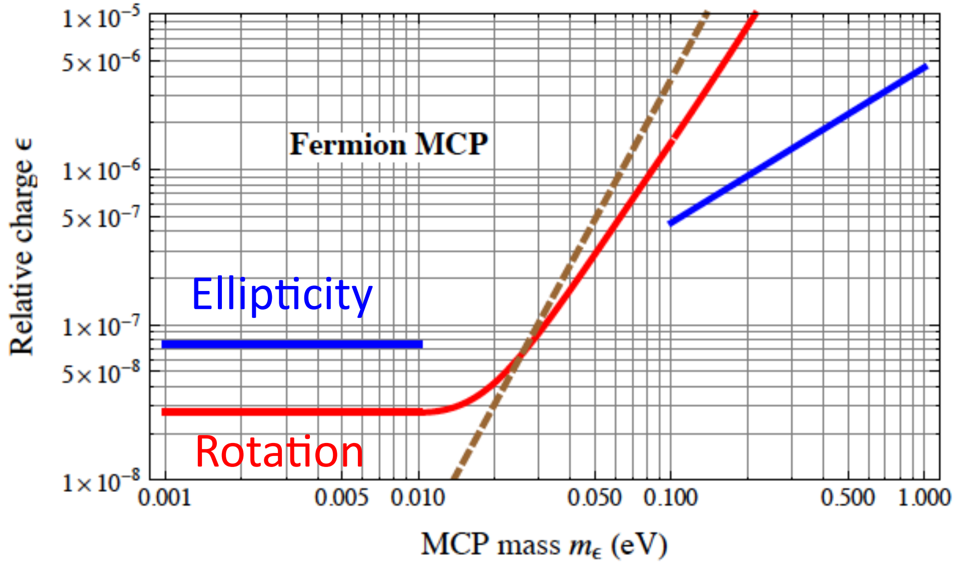
Will the trend continue?

Axion-like particles



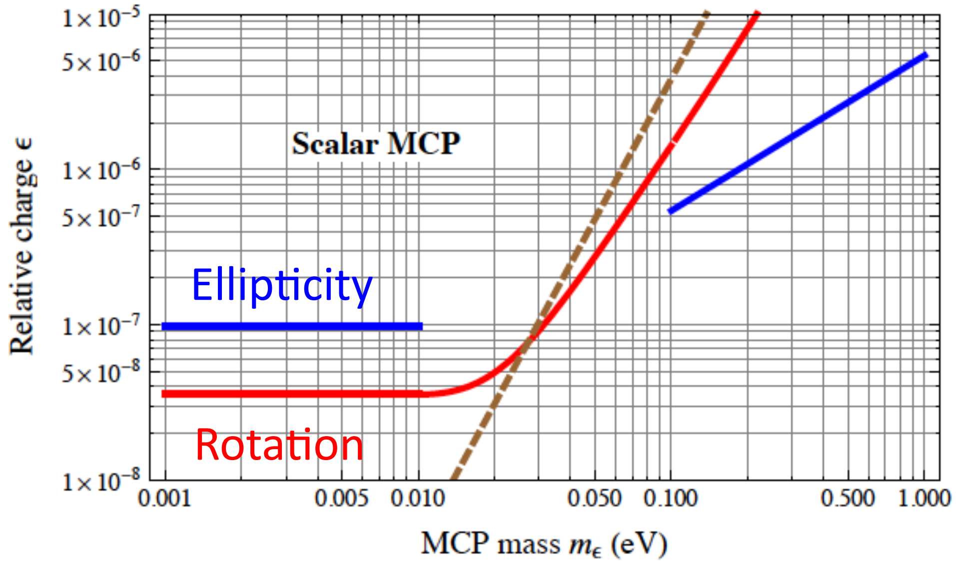
Della Valle F et al, arXiv:1510.08052v1

Milli-charged particles



Ellipticity

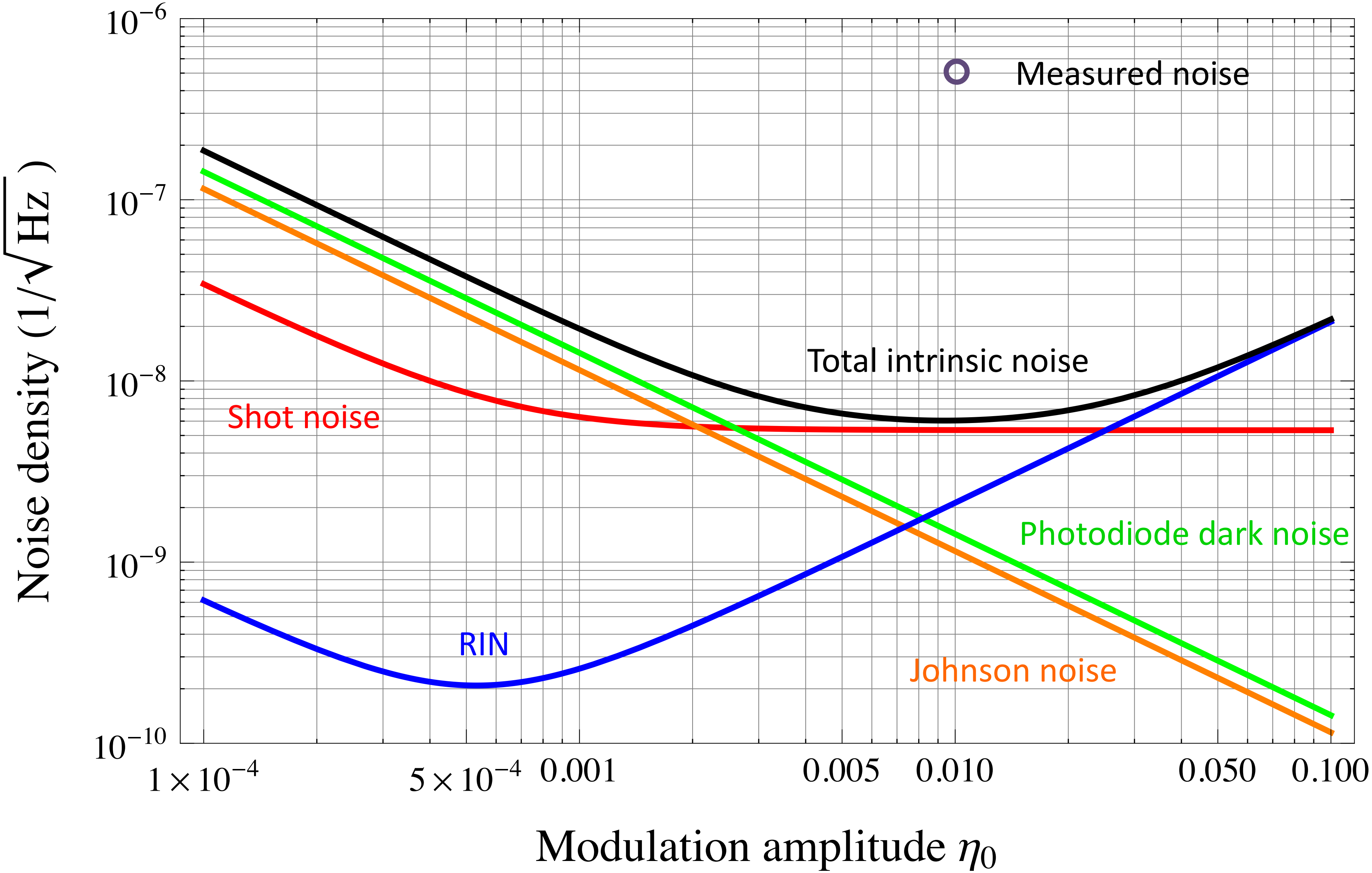
The two branches of the birefringence curve are not connected in the mass range around $\chi = 1$ (dashed line), where n changes sign



Ellipticity

Della Valle F et al, arXiv:1510.08052v1

Sensitivity



If we were limited by intrinsic noise …

- B = 2.5 T, $F = 7\cdot10^5$ and L = 1.64 m

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

- Integration time to reach a signal to noise ratio = 1

$$T = \left(\frac{s_{\rm shot}}{\psi_{\rm QED}}\right)^2 \approx 10^4\ \rm s$$

(Actual time ≈ 10^8 s ≈ 3 y)

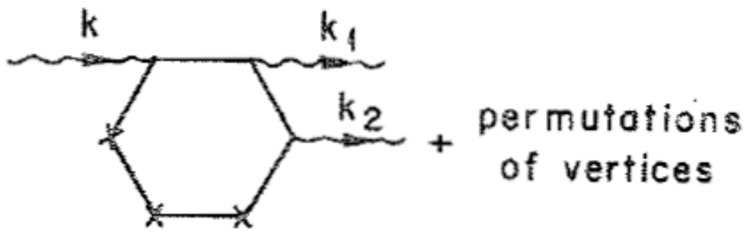
Conclusions

- PVLAS searches for the magnetic birefringence of vacuum as predicted by QED
- The actual noise limit is about one order of magnitude larger than the expected effect
- With current sensitivity too long integration time is needed
- We are completing the study of the noise sources
- Let's meet again in one year!!!

		L (m)	B (T)	LB^2	ψ_{1pass}	N	NLB^2	ψ_N	$\int dt$ (s)	S (Hz)$^{-\frac{1}{2}}$	ψ_n	$3\psi_n/\psi_N$
BNL Brookhaven	BFRT 1993 $\omega = 2.41$ eV	8.8	$B_0 = 3.25$ $\Delta B = 0.62$	39.6	$1.2\ 10^{-15}$	34 578	$1.3\ 10^3$ $2.3\ 10^4$	$4\ 10^{-14}$ $7\ 10^{-13}$			$> 10^{-9}$ $> 2\ 10^{-8}$	$7\ 10^4$
INFN Legnaro	PVLAS-LNL 2008 1064 nm	1	2.3	5.3	$6.7\ 10^{-17}$	$45\ 10^3$	$2.4\ 10^4$	$3\ 10^{-12}$	$2\ 10^4$	10^{-6}	$7\ 10^{-9}$	10^4
CERN Genève	OSQAR 2009	14.3	9	1158	$1.5\ 10^{-14}$							
Taiwan	Q&A 2010 (532) 1064 nm	0.6	2.3 (+1.8)	3.2	$4\ 10^{-17}$	$19\ 10^3$	$6\ 10^4$	$7.5\ 10^{-13}$	$7\ 10^4$	10^{-6}	$5\ 10^{-9}$	$2\ 10^4$
INFN Ferrara	PVLAS-Fe 2012 1064 nm	0.4	2.3	1.85	$2.3\ 10^{-17}$	$153\ 10^3$	$28\ 10^4$	$3.5\ 10^{-12}$	$8.2\ 10^3$	$3\ 10^{-7}$	$3.4\ 10^{-9}$	3000
LNGMI Toulouse	BMV 2014 1064 nm	0.14	6.5	6	$7.2\ 10^{-17}$	$283\ 10^3$	$1.7\ 10^6$	$2.1\ 10^{-11}$	2	$2\ 10^{-8}$	$1.4\ 10^{-8}$	2000
INFN Ferrara	PVLAS-Fe 2014 1064 nm	1.6	2.5	10.25	$12\ 10^{-17}$	$430\ 10^3$	$4.3\ 10^6$	$5\ 10^{-11}$	$6\ 10^5$	$2\ 10^{-6}$	$2.5\ 10^{-9}$	150
INFN Ferrara	PVLAS-Fe 2015 1064 nm	0.8	2.5	5	$6.3\ 10^{-17}$	$480\ 10^3$	$2.4\ 10^6$	$2.5\ 10^{-11}$	10^6	$5\ 10^{-7}$	$5\ 10^{-10}$	60

The index of refraction – absorption

Adler calculated the absorption due to QED which is of next order and connected to the phenomenon known as **photon splitting**



$$\alpha_{\left\{\substack{\perp\\ \parallel}\right\}} = \frac{2\pi}{\lambda} k_{\left\{\substack{\perp\\ \parallel}\right\}} = \left\{\begin{matrix} 0.51 \\ 0.24 \end{matrix}\right\} \left(\frac{\omega}{m_e}\right)^5 \left(\frac{B\sin\theta}{B_{cr}}\right)^6 \text{cm}^{-1}$$

Expected values

$$n_{\left\{\substack{\perp\\ \parallel}\right\}} = 1 + \left\{\begin{matrix} 4 \\ 7 \end{matrix}\right\} \times \underline{1.32\cdot 10^{-24}} \left(\frac{B}{1\ \text{T}}\right)^2 + i \left\{\begin{matrix} 0.24 \\ 0.51 \end{matrix}\right\} \times \underline{4.0\cdot 10^{-91}} \left(\frac{\lambda}{1\ \mu\text{m}}\right) \left(\frac{B}{1\ \text{T}}\right)^6 \left(\frac{\omega}{1\ \text{eV}}\right)^5$$

$$A_e = \frac{2}{45\mu_0} \left(\frac{\alpha^2 \lambda_e^3}{m_e c^2}\right)$$

Other proposals (Optical regime)

Using Gravitational Wave interferometers

PHYSICAL REVIEW D VOLUME 19, NUMBER 8 15 APRIL 1979

Testability of nonlinear electrodynamics

A. M. Grassi Strini, G. Strini, and G. Tagliaferri

Modern Physics Letters A, Vol. 6, No. 40 (1991) 3671–3678
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TEST OF QUANTUM ELECTRODYNAMICS USING ULTRA-HIGH SENSITIVE INTERFEROMETERS

WEI-TOU NI,* KIMIO TSUBONO,† NORIKATSU MIO,† KAZUMICHI NARIHARA,‡ SHEN-CHE CHEN,* SUN-KUN KING,* and SHEAU-SHI PAN*

Eur. Phys. J. C
DOI 10.1140/epjc/s10052-009-1079-y

THE EUROPEAN PHYSICAL JOURNAL C

Regular Article - Experimental Physics

Probing for new physics and detecting non-linear vacuum QED effects using gravitational wave interferometer antennas

Guido Zavattini[1,a], Encrico Calloni[2]

EPL, **87** (2009) 21002
doi: 10.1209/0295-5075/87/21002

Interferometry of light propagation in pulsed fields

B. Döbrich[(a)] and H. Gies

Using frequency measurements techniques instead of polarimetry

PHYSICAL REVIEW A, VOLUME 62, 013815

Measurement of mirror birefringence at the sub-ppm level: Proposed application to a test of QED

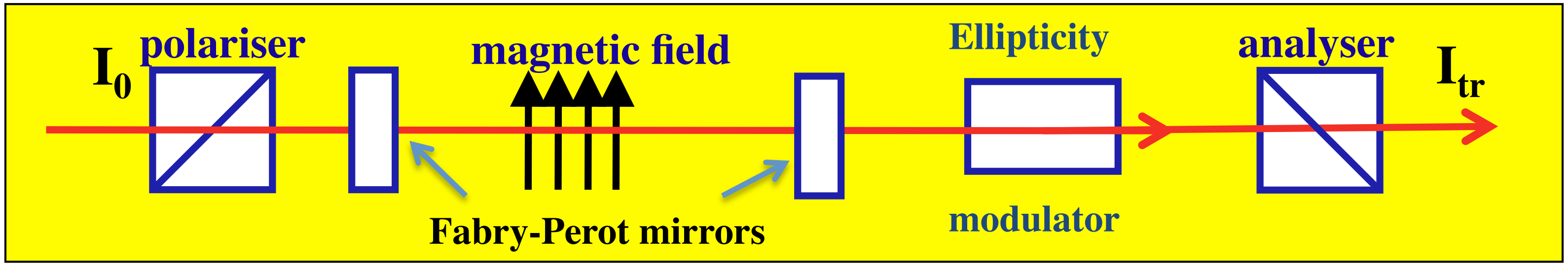
John L. Hall,* Jun Ye,* and Long-Sheng Ma†

REVIEW OF SCIENTIFIC INSTRUMENTS **81**, 033105 (2010)

Highly sensitive frequency metrology for optical anisotropy measurements

Gilles Bailly,[1,2] Raphaël Thon,[1,2] and Cécile Robilliard[1,2,a)]

Polarization noise in high finesse cavities



Conducted studies in order to identify 1/f birefringence noise in high finesse cavities

Mirrors birefringence axes aligned to light polarization

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

Studied noise sources

- Electronic noise in the cavity feedback
- Residual vibrations on cavity mirror
- Laser power instabilities
- Laser pointing instabilities
- Laser heating of cavity mirrors
- Modulator instabilities
- Compensated birefringences (partial)

The contributions of the studied sources are smaller than total measured noise

Next steps: Substrate material composition
Low stress mirror holders
Diffused light
Cooling of the mirrors?