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Model-independent search for axion-like particles in the PVLAS(*) experiment

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(*)PVLAS: Polarisation of Vacuum with LASer

LNF – 27 March 2017

Summary

- Introduction
- The detection scheme
- The experimental set-up
- Latest results
- Conclusions

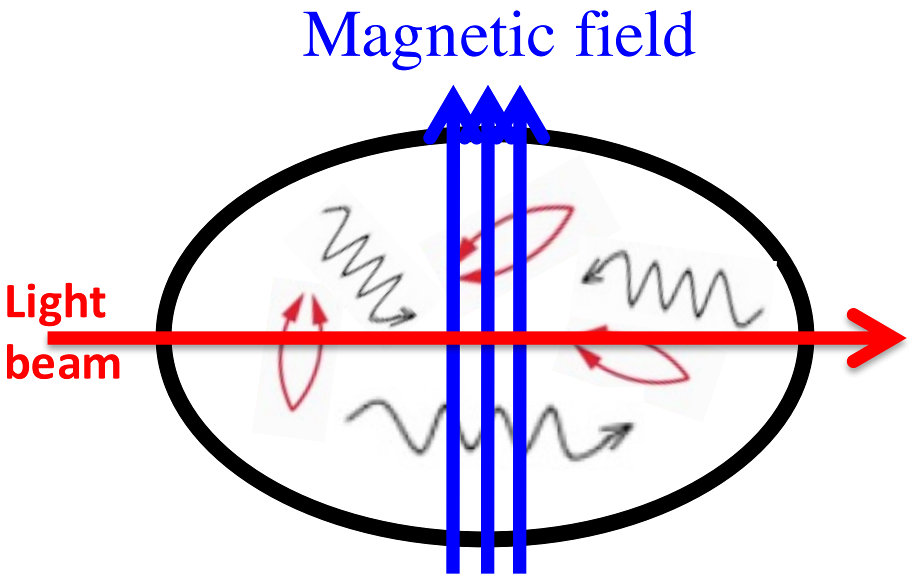
Light propagation in a magnetized vacuum

- Experimental study of the structure and nature of the quantum vacuum
- General plan:
  - **Perturb** the quantum vacuum with an **external field**
  - Use a **(polarised) light beam** as a probe 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** of vacuum induced by an external magnetic field

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

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



QED vacuum birefringence

Effective Lagrangian of the electromagnetic field by **Euler, Heisenberg and Weisskopf (1936)** considering the **virtual electron-positron** sea proposed by Dirac. 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.

Light propagation is still described by Maxwell's equations in media but they are no longer linear.

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

Linearly polarized light passing through a transverse external magnetic field (perpendicular to the wave-vector).

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

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

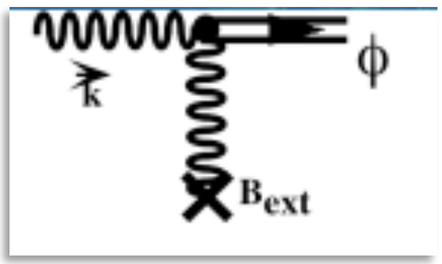
pseudoscalar case

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

scalar case

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

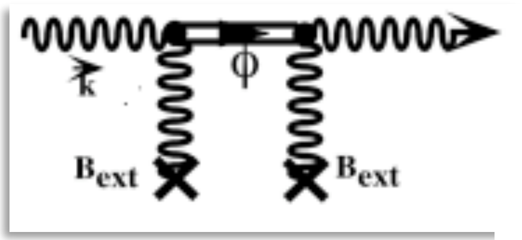
both interactions are polarisation dependent



Absorption

$$x = \frac{L m_{a,s}^2}{4\omega}$$

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



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)

Linear birefringence

- The **index of refraction** (real part) is different for two orthogonal directions

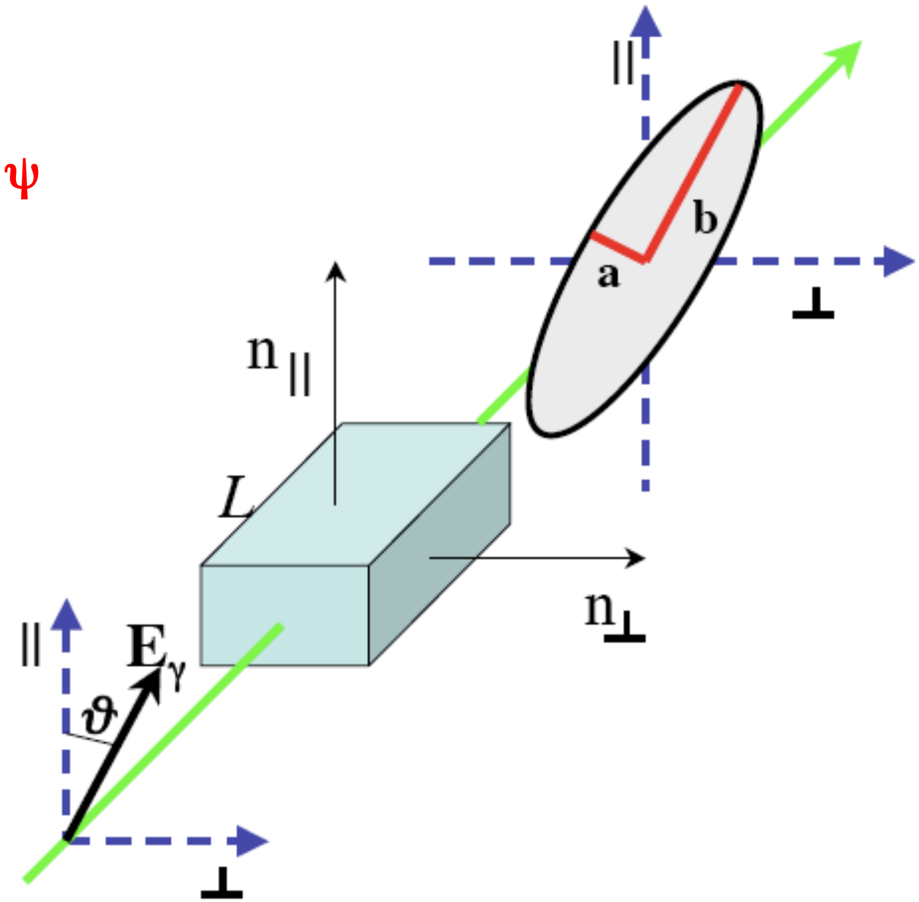
$$\Delta n = n_{\parallel} - n_{\perp} \neq 0$$

- 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

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



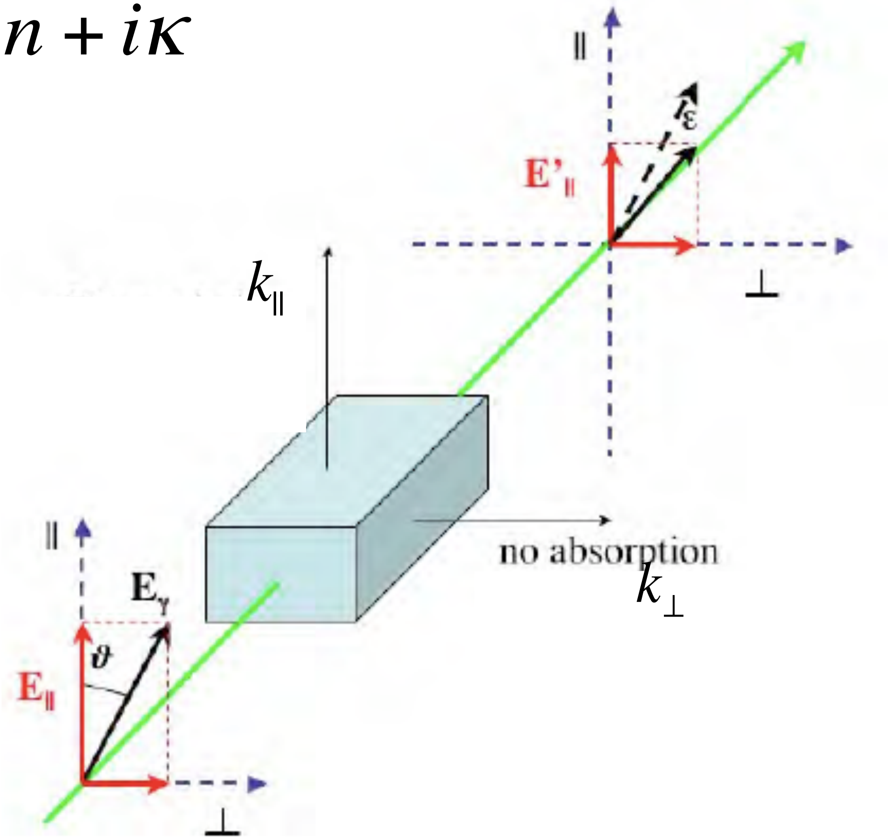
Linear dichroism

- The **extinction coefficient** is different for two orthogonal directions

$$\Delta\kappa = \kappa_{\parallel} - \kappa_{\perp} \neq 0 \qquad n_{tot} = n + i\kappa$$

- A linearly polarised 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

PVLAS strategy for magnetic polarimetry

Volume 85B, number 1 PHYSICS LETTERS 30 July 1979

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

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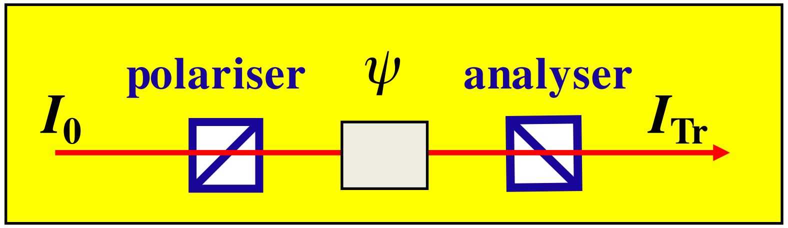
In this letter a method of measuring the birefringence induced in vacuum by a magnetic field is described: this effect is evaluated using the non-linear Euler–Heisenberg–Weisskopf lagrangian. The optical apparatus discussed here may detect an induced ellipticity on a laser beam down to 10^{-11}.

- **high sensitivity**
  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 (23 Hz, as of last week)
- **longest possible optical path *L***
  very-high Q Fabry-Perot resonator to increase the effective path length (a factor $\approx 4.5 \times 10^5$)

Heterodyne detection - ellipticity



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

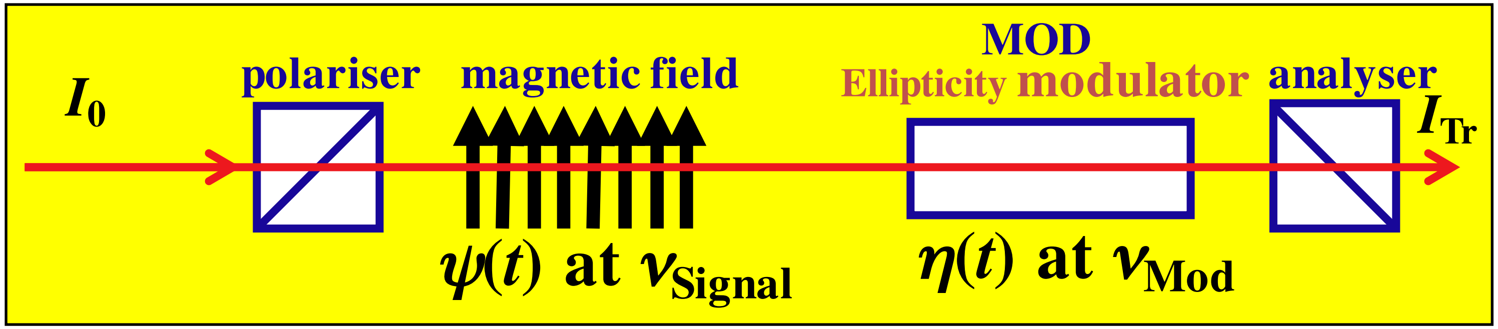
ψ_{QED} = 1.2 × 10^{-16}

extinction σ^2~10^{-7}÷10^{-8}

static detection excluded

Signal is modulated in time and beats with a calibrated effect

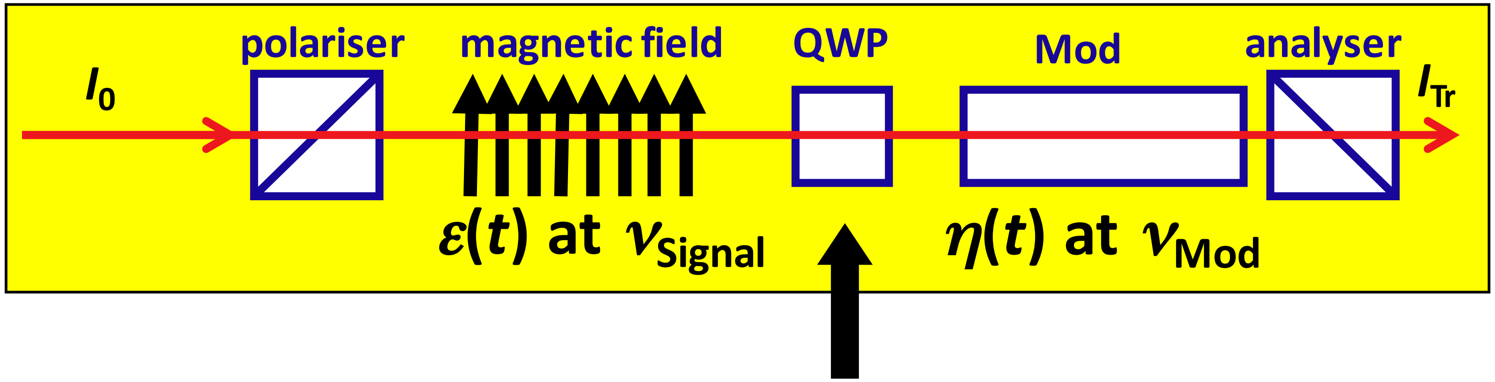
- **Signal linear in the birefringence**
- **Smaller 1/*f* noise**



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

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 polarisation
QWP slow axis normal to polarisation

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

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

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

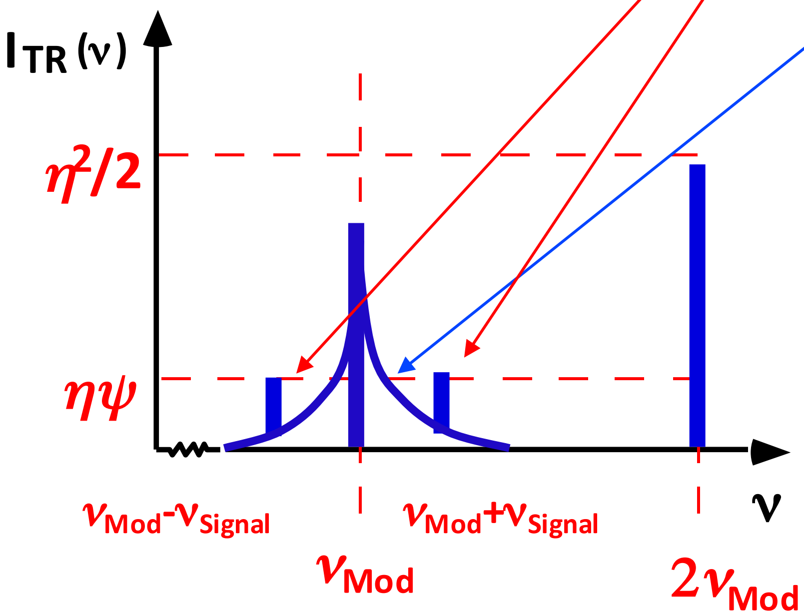
Signal frequency layout

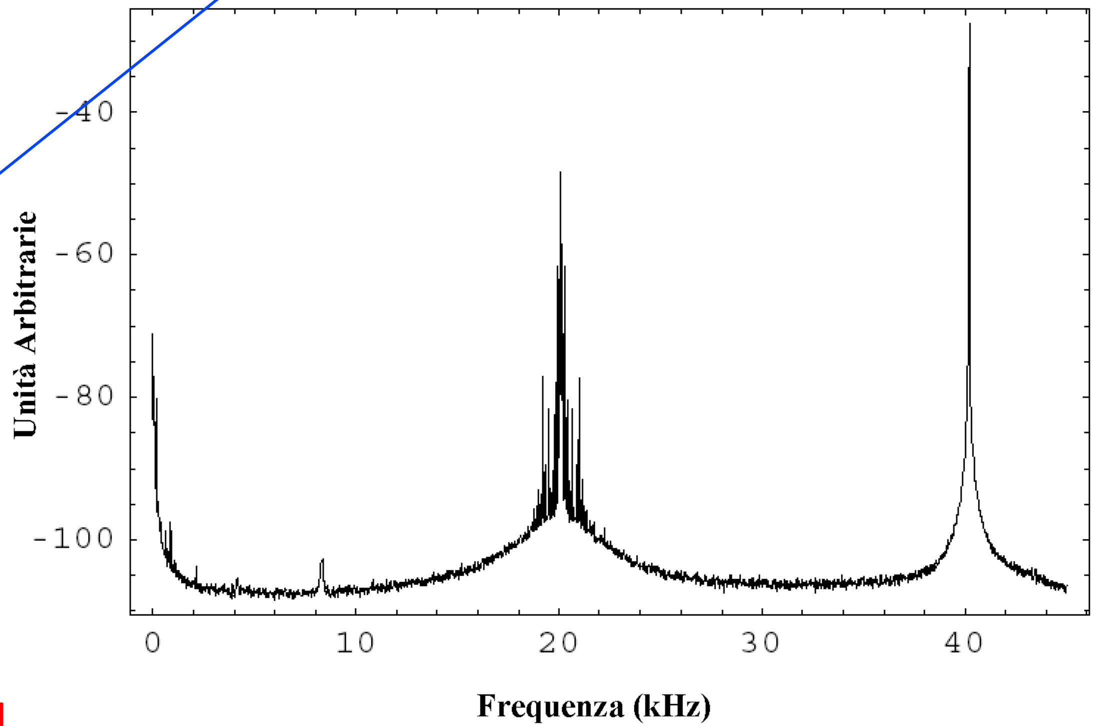
Nearly static birefringences $\alpha_s(t)$ generate a $1/f$ noise centred at the carrier modulation frequency ν_{Mod}

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

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

signal noise





Frequency components / sensitivity

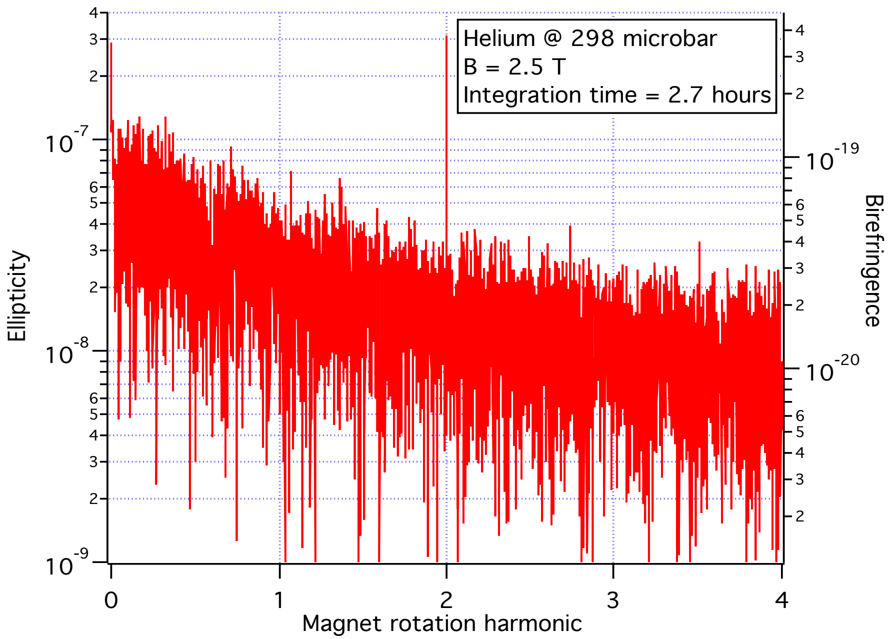
Frequency	Fourier component	Intensity/$I_{\rm out}$	Phase
dc	$I_{\rm dc}$	$\sigma^2 + \alpha_{\rm dc}^2 + \eta_0^2/2$	–
$\nu_{\rm Mod}$	$I_{\nu_{\rm Mod}}$	$2\alpha_{\rm dc}\eta_0$	$\theta_{\rm Mod}$
$\nu_{\rm Mod} \pm \nu_{\rm Signal}$	$I_{\nu_{\rm Mod}\pm\nu_{\rm Signal}}$	$\eta_0\psi$	$\theta_{\rm Mod} \pm \theta_{\rm Signal}$
$2\nu_{\rm Mod}$	$I_{2\nu_{\rm Mod}}$	$\eta_0^2/2$	$2\theta_{\rm Mod}$

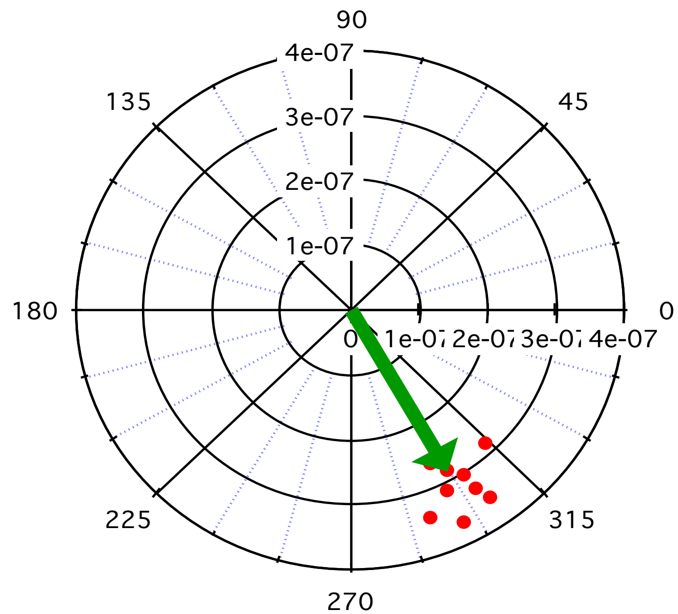
The signal amplitude (ellipticity or rotation) can be calculated as:

$$\psi, \epsilon = \frac{1}{2}\left(\frac{I_{\nu_{\rm Mod}+\nu_{\rm Signal}}}{\sqrt{2I_{\rm out}I_{\rm Signal}}} + \frac{I_{\nu_{\rm Mod}-\nu_{\rm Signal}}}{\sqrt{2I_{\rm out}I_{\rm Signal}}}\right)$$

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

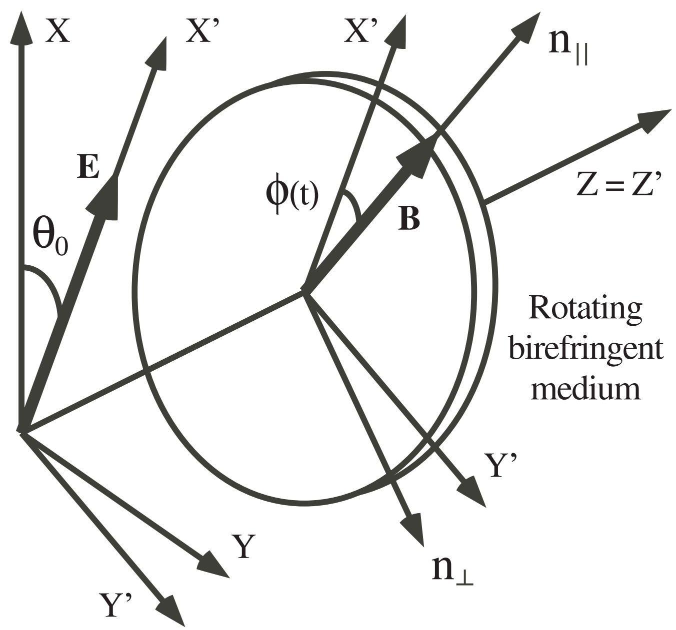
Measurement output



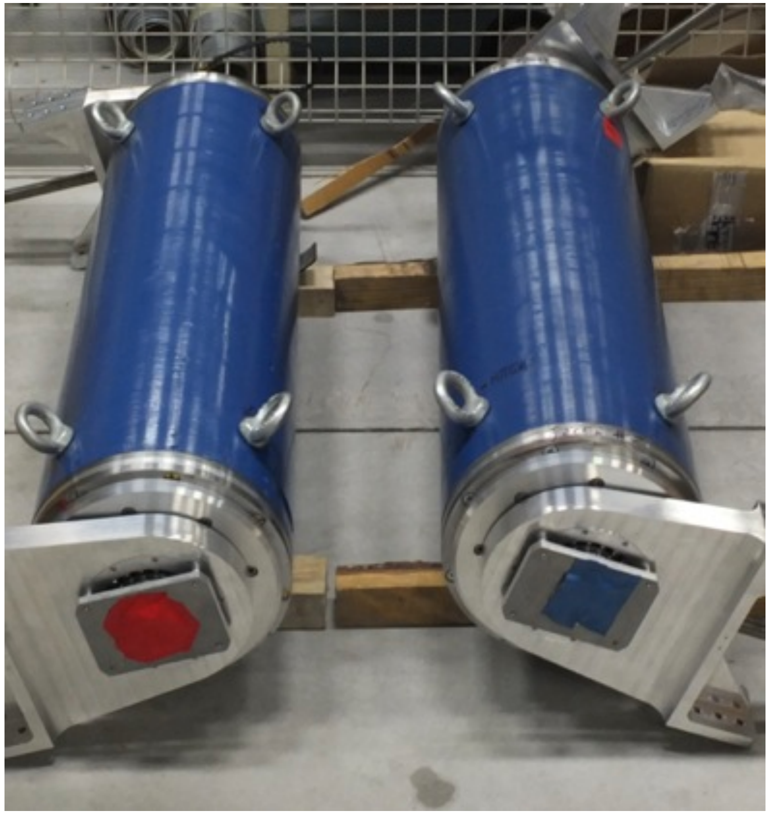


Measured effect is given by Fourier amplitude and phase at signal frequency. **Vector in polar plane.** The **amplitude** measures the ellipticity/rotation. The **phase** is related to the triggers position and to the polarisation direction. **True physical signals must have a definite phase.**

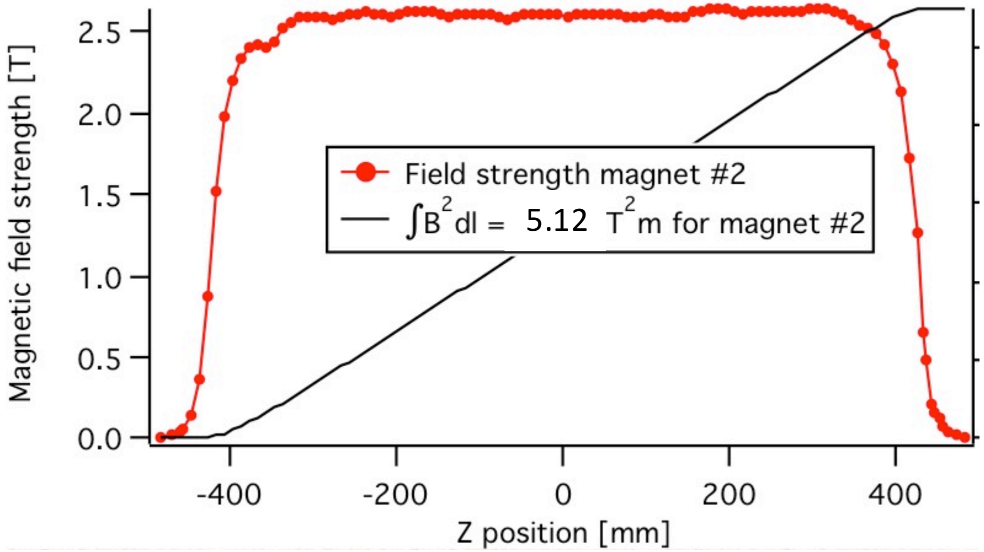
$$\psi = \psi_0 \sin\left\{2\left[\phi_0 + \omega_{\mathrm{Mag}} t\right]\right\}$$

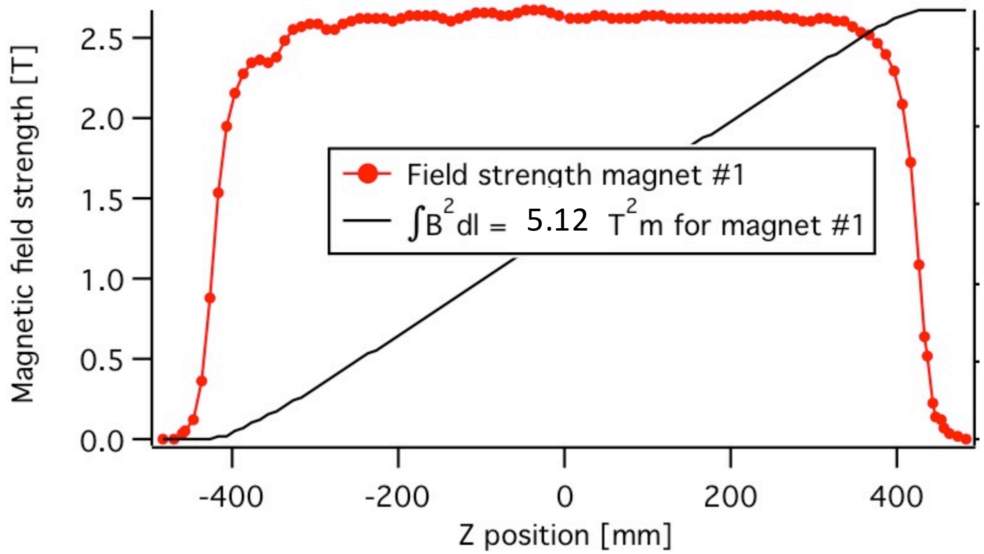


The magnetic field sources

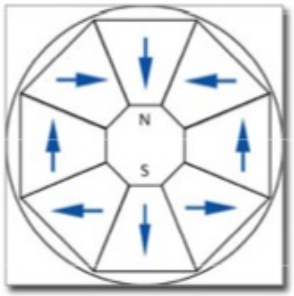


Total field integral = 10.25 T^2 m





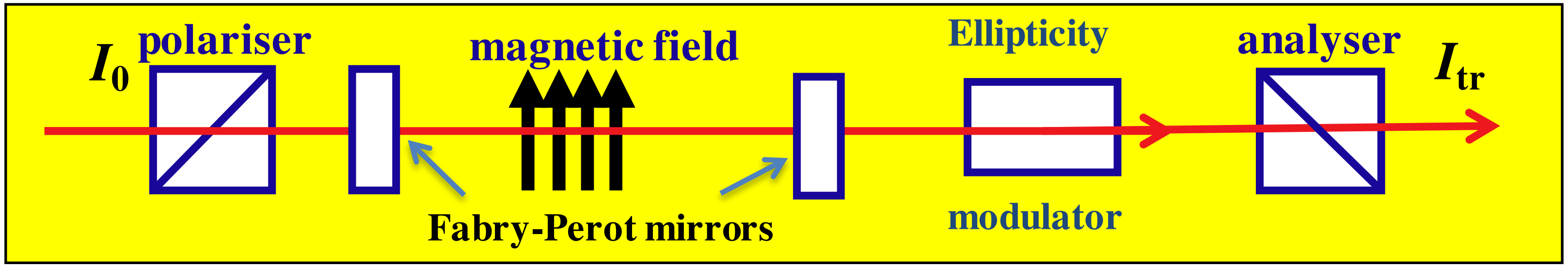
Permanent dipole magnets in Halbach configuration



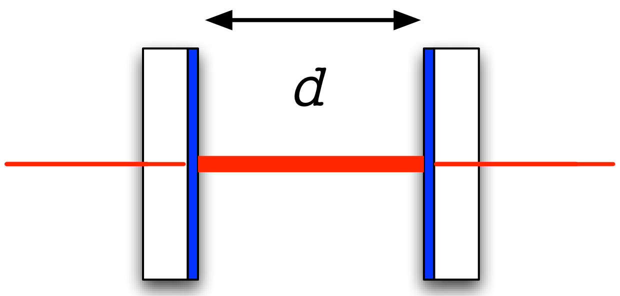
Magnets have a built-in **magnetic shielding**

Stray field is below 1 G on side

Signal amplification: 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 $\lambda/2$.
To obtain this, the laser is frequency-locked to the cavity using a feedback circuit.



τ - cavity decay time

Amplification

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

Finesse

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

$$N > 10^5$$

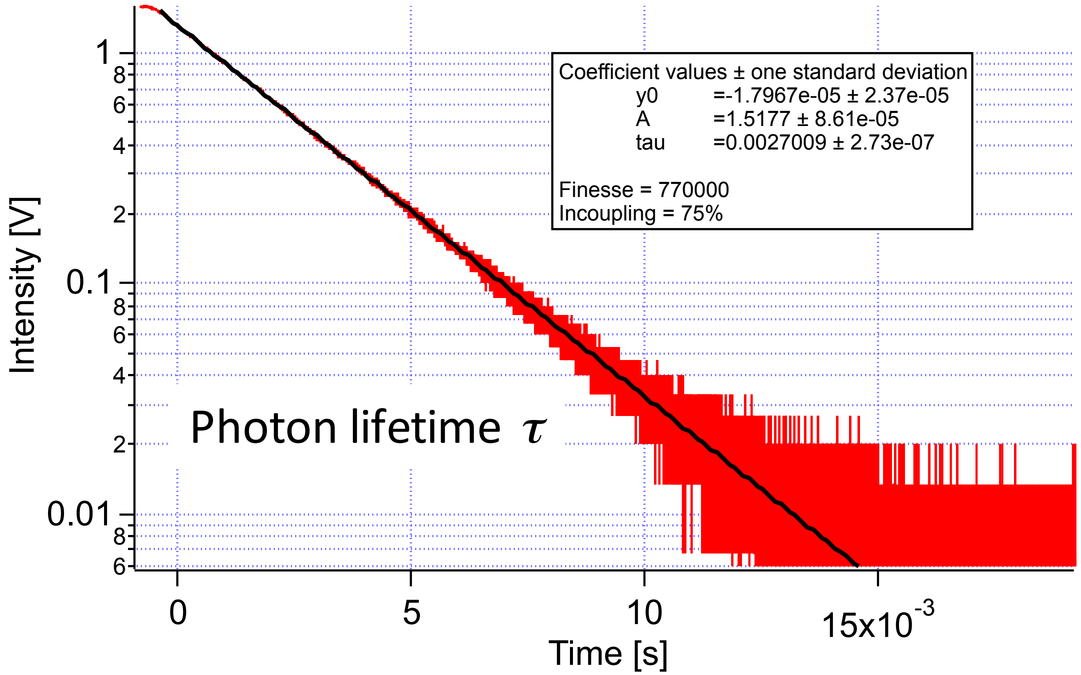
Vacuum magnetic birefringence:
L = 1.64 m, λ = 1064 nm, B = 2.5 T
N = 445000

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

$\boldsymbol{N\psi_{QED} = 5.4\times10^{-11}}$

The Fabry Perot cavity

High reflectivity (R = 0.999996)
spherical mirror with r = – 2 m



Transmitted power up to 200 mW

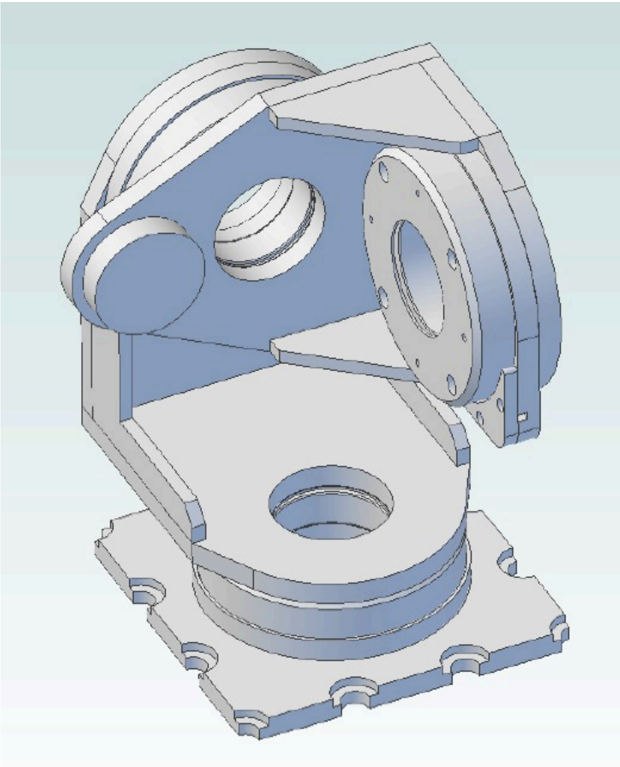
τ = 2.7 ms , d = 3.3 m

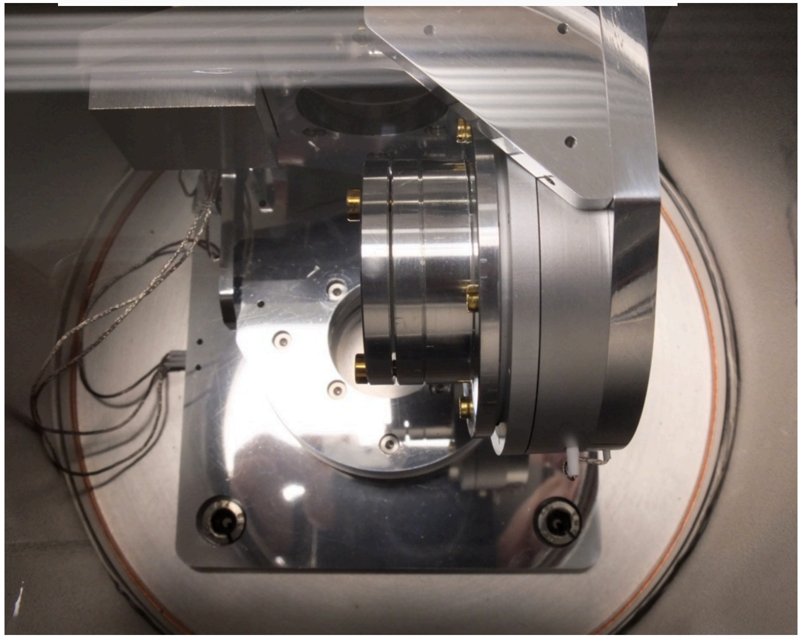
Finesse = 770 000 **N = 490 000**

Circulating power = 40 kW

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

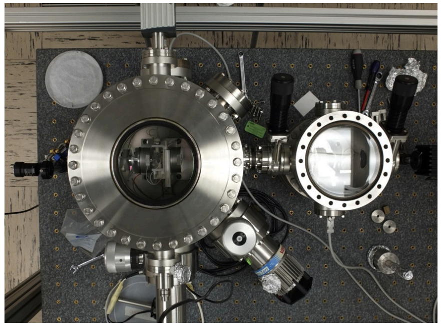
$\boldsymbol{\psi_{QED} = 5.9\ 10^{-11}}$

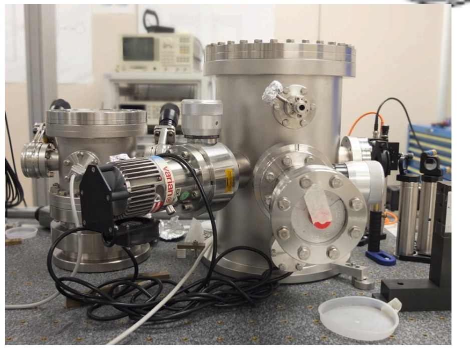




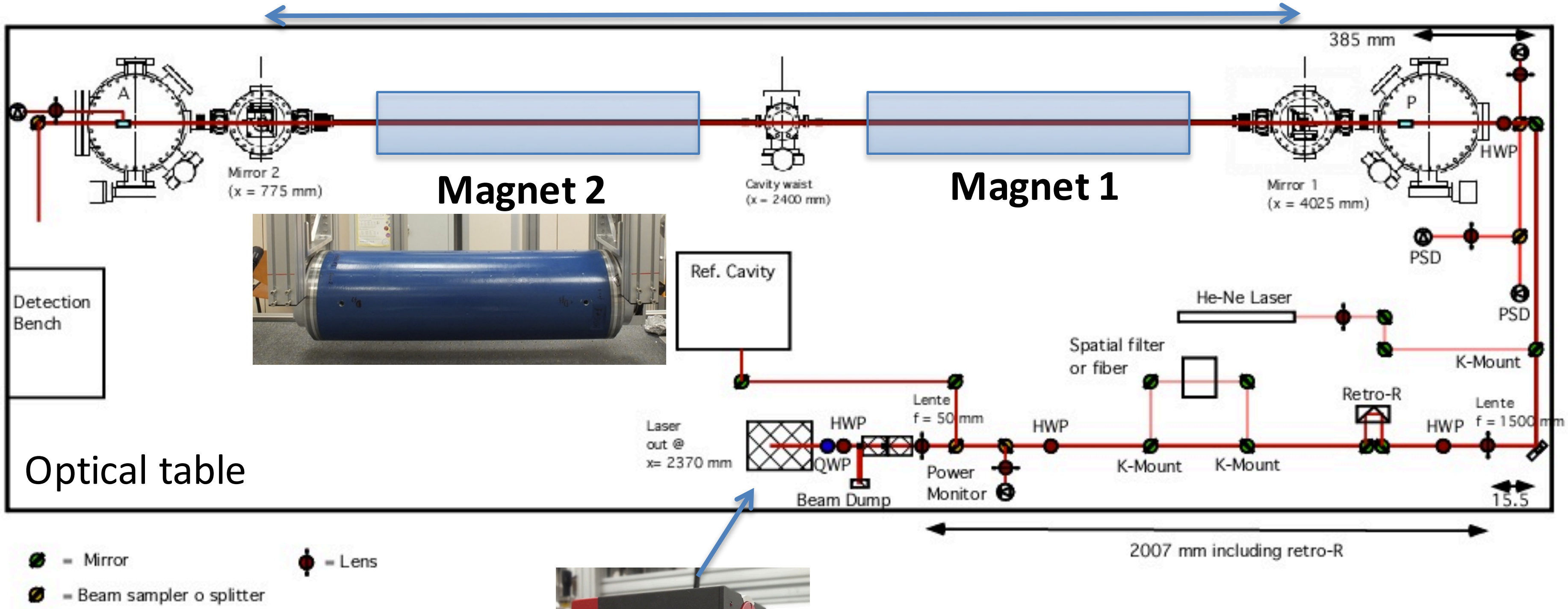
3-Motor mirror tilter, θ_x, θ_y, θ_z

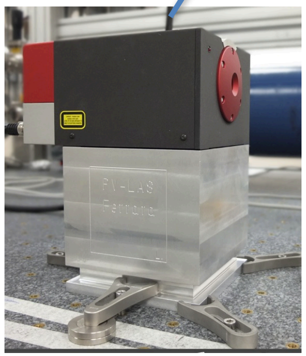
Optics layout



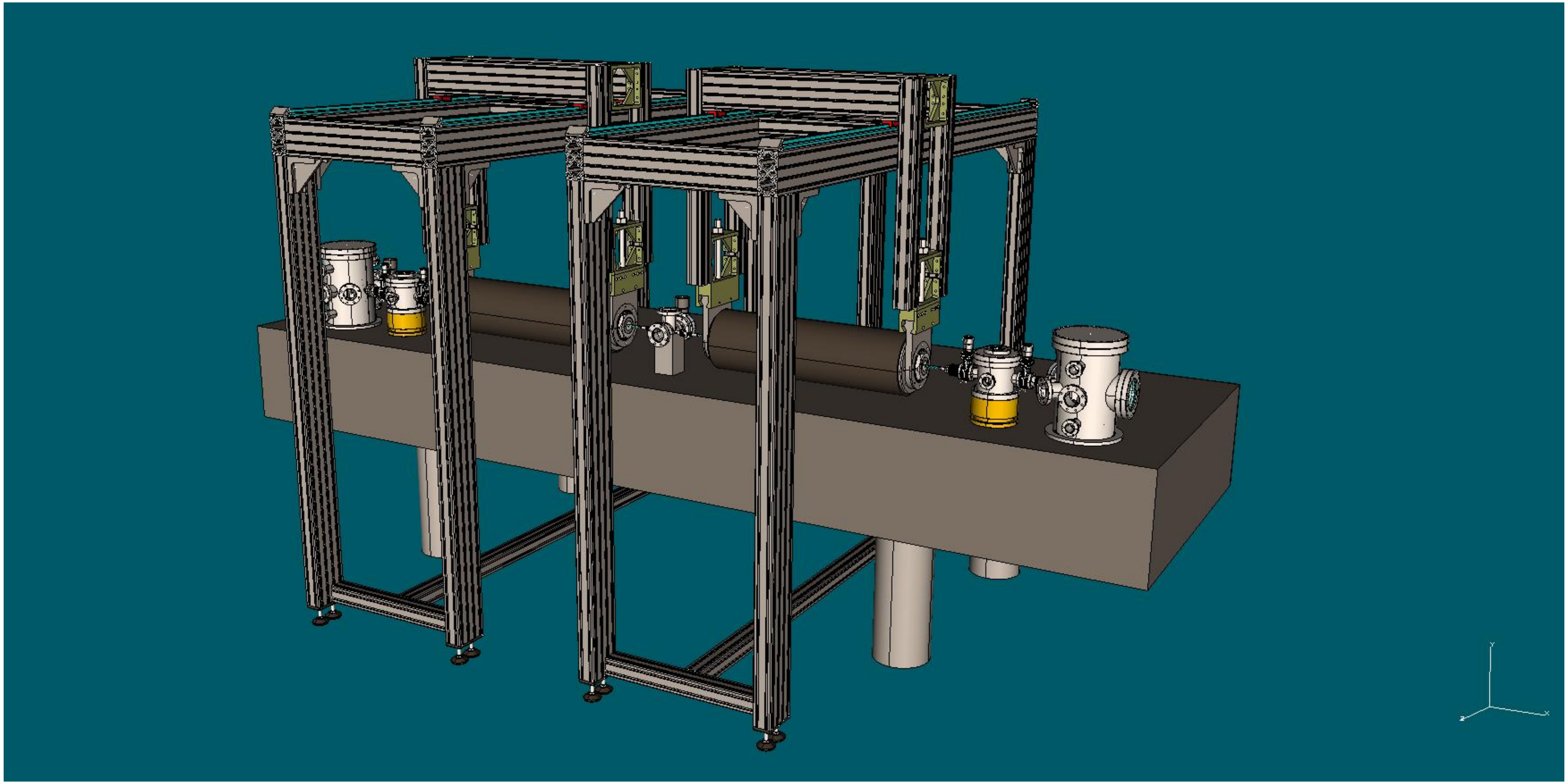


3.3 m long Fabry Perot cavity





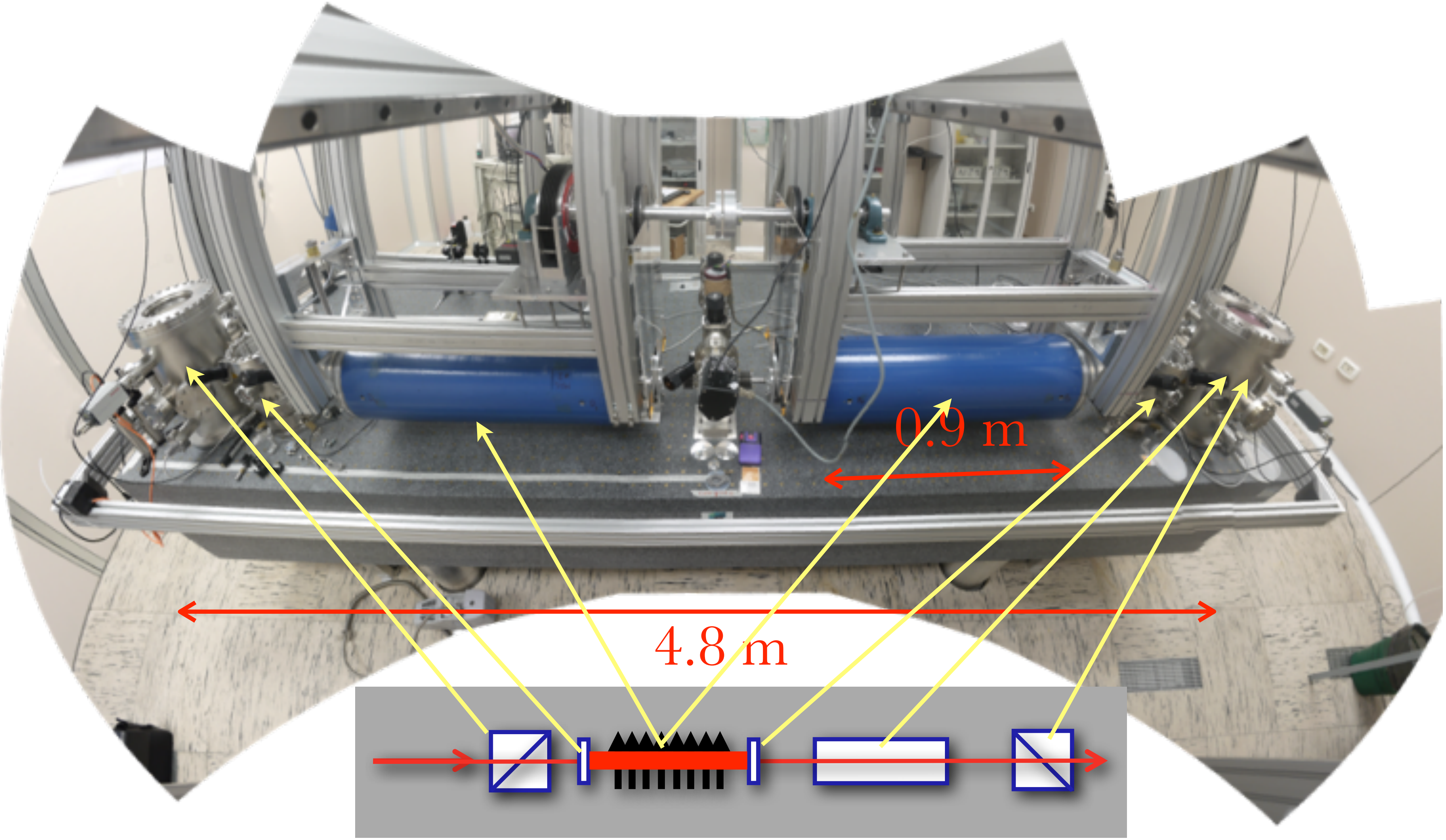
2 W NPRO Nd:Yag Laser
λ = 1064 nm



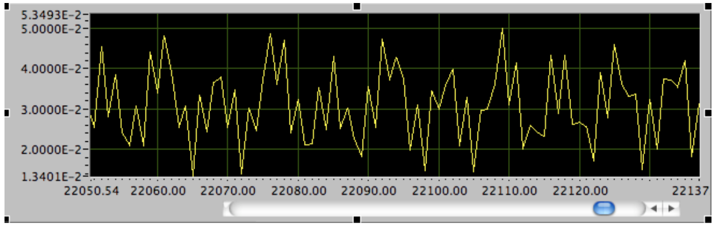
The apparatus

The apparatus

The apparatus



Data analysis



photodiode signal

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

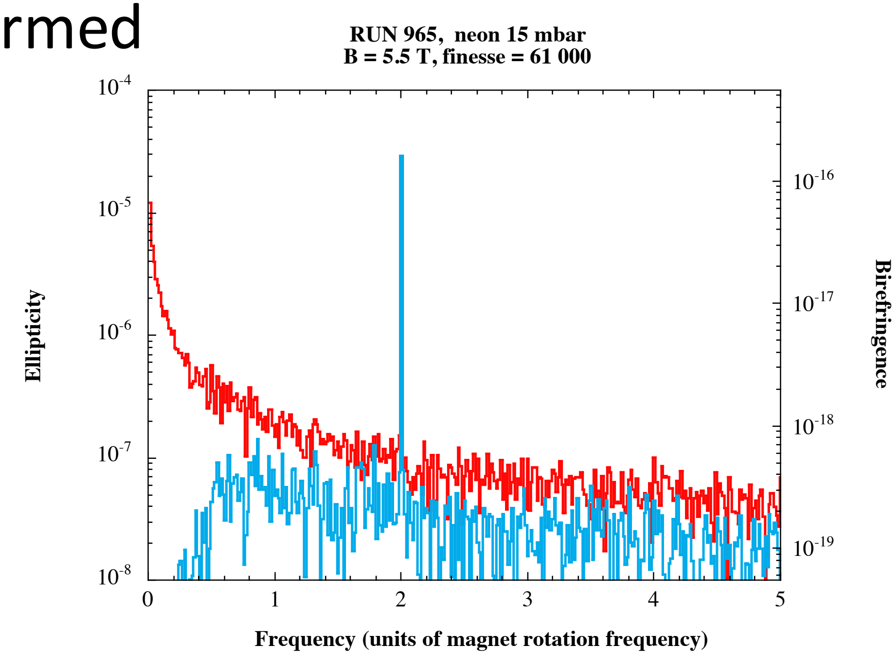
2) the demodulated signal is filtered to avoid aliasing

3) the filtered signal is sampled, the data are divided into fixed length time records and then Fourier transformed

4) the ellipticity/rotation signal is

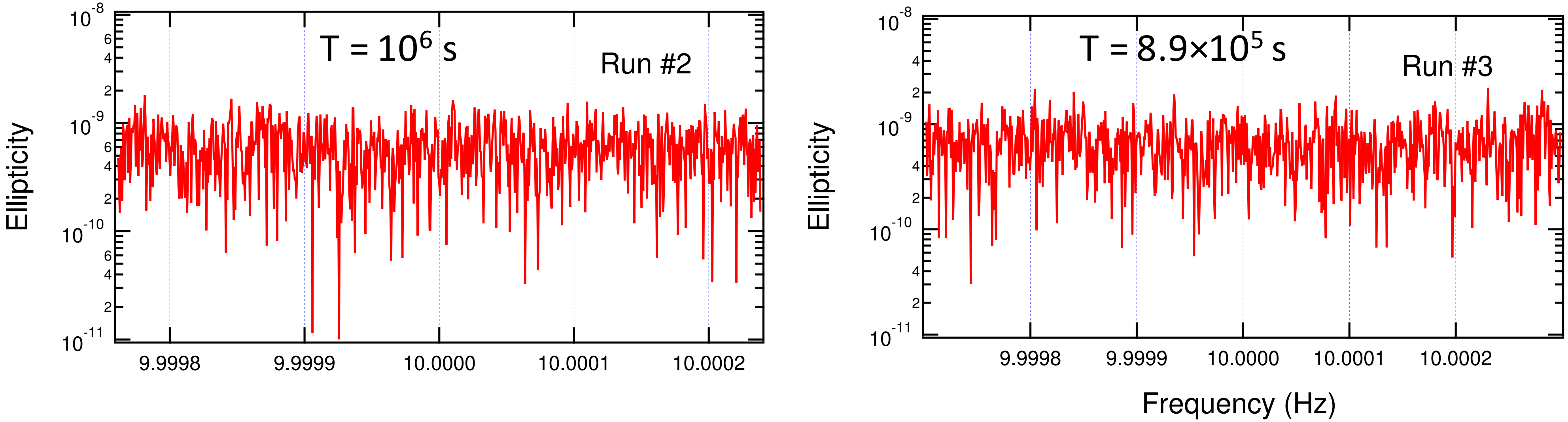
$$\psi,\varepsilon = \frac{I_{2\nu_{\mathrm{Mag}}}}{2\sqrt{2I_{\mathrm{out}}I_{2\nu_{\mathrm{Mod}}}}}$$

5) the partial results undergo a weighted vector average

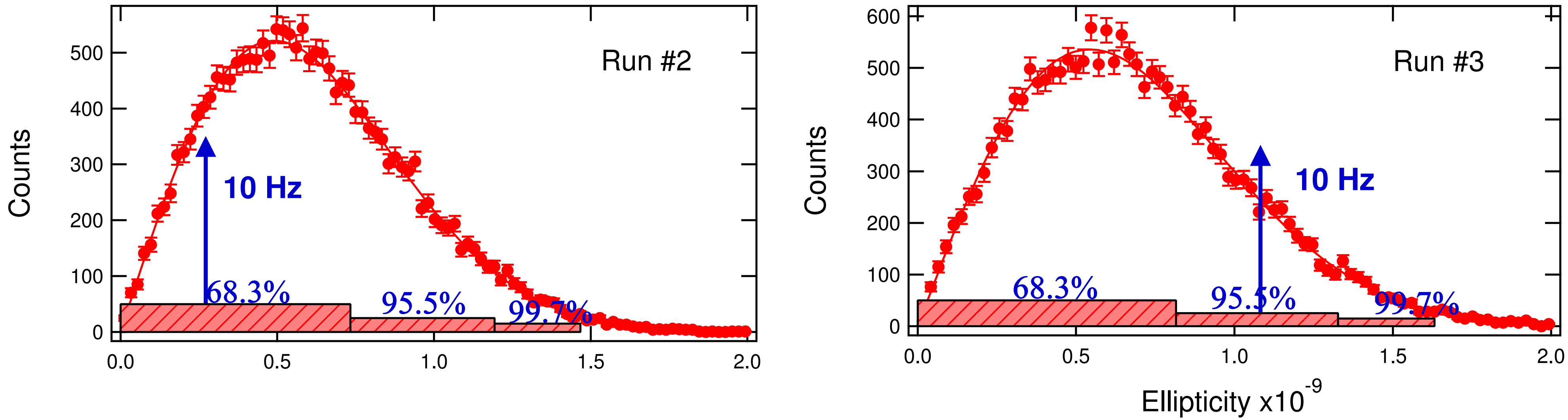


ellipticity Fourier spectrum, DC and AC coupled

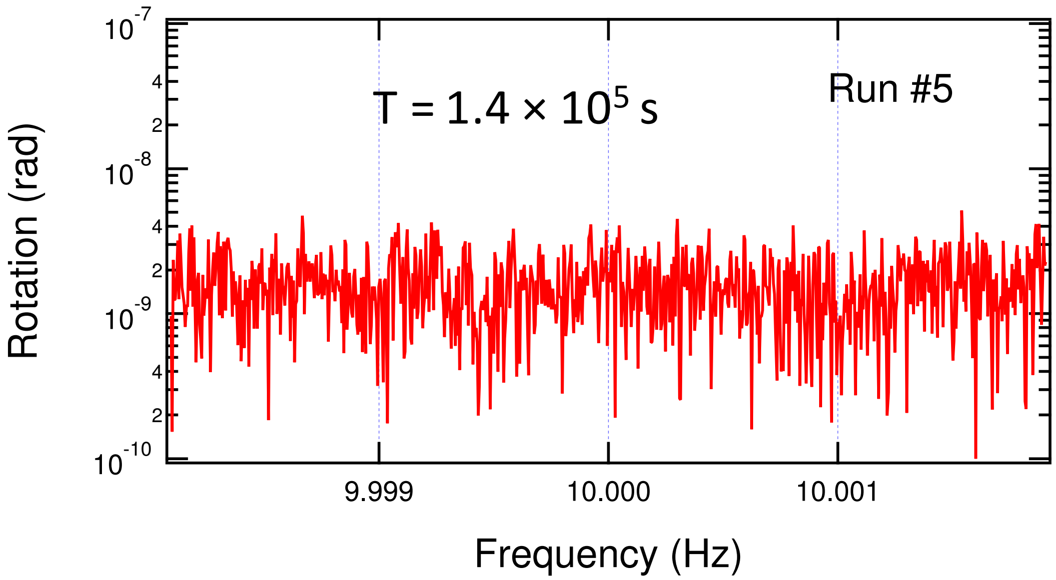
Vacuum magnetic birefringence results



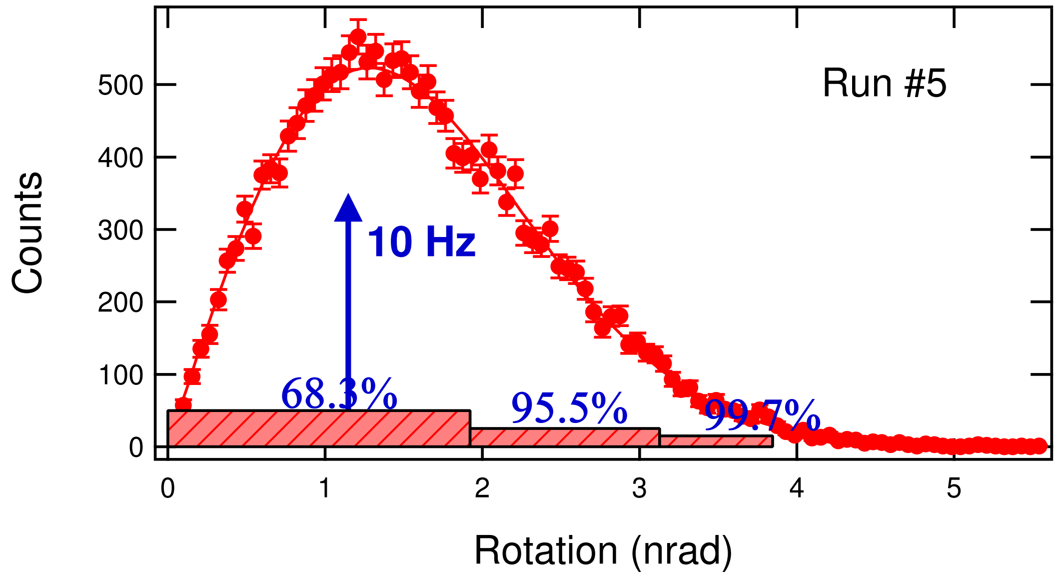
Noise follows Rayleigh distribution: $P_R = \dfrac{\rho}{\sigma^2} e^{-\frac{\rho^2}{2\sigma^2}}$ $\qquad \rho^2 = x^2 + y^2$



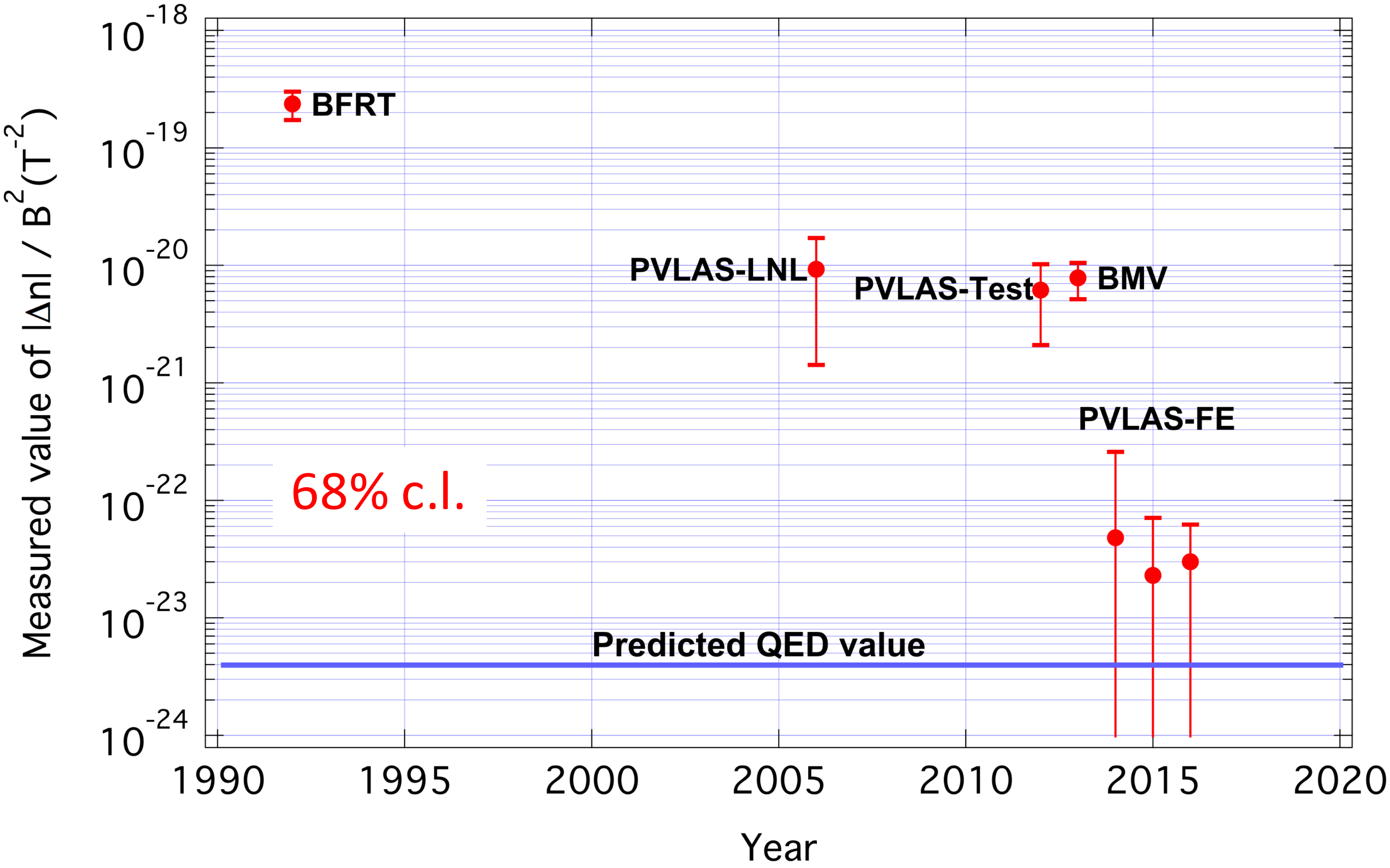
Vacuum magnetic dichroism results



QWP inserted



Timeline of vacuum birefringence

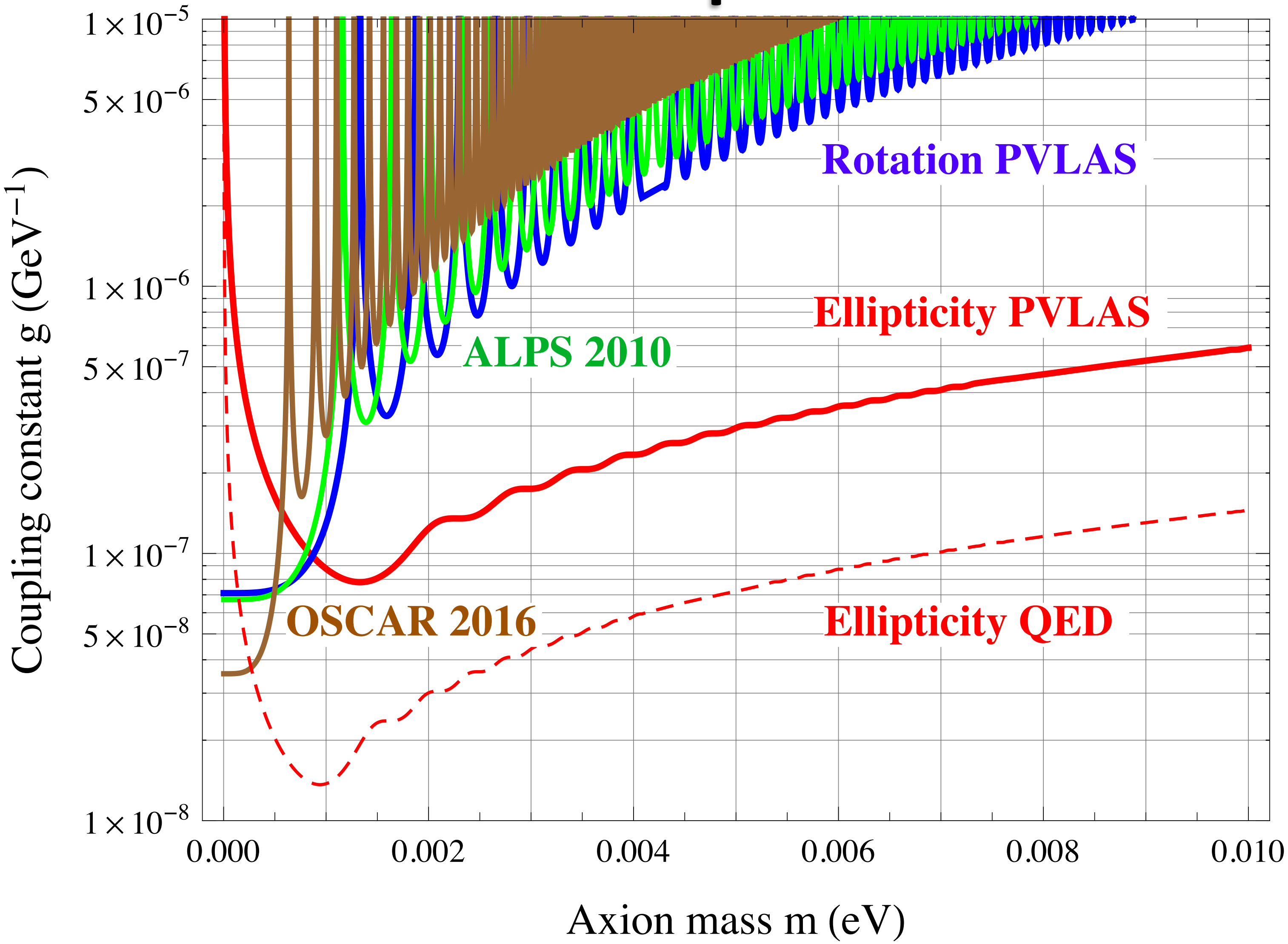


$\Delta n_{\text{PVLAS-2014}} = \ \ 4.0 \pm 20 \ \ \times 10^{-23}\ \text{T}^{-2}$ $\quad T_{2014} \approx 1 \times 10^6$ s $\quad$ PRD 90, 092003 (2014)

$\Delta n_{\text{PVLAS-2015}} = -2.4 \pm \ \ 4.8 \times 10^{-23}\ \text{T}^{-2}$ $\quad T_{2015} \approx 3 \times 10^6$ s $\quad$ EPJC 76, 24 (2016)

$\Delta n_{\text{PVLAS-2016}} = -3.0 \pm \ \ 3.2 \times 10^{-23}\ \text{T}^{-2}$ $\quad T_{2016} \approx 5 \times 10^6$ s

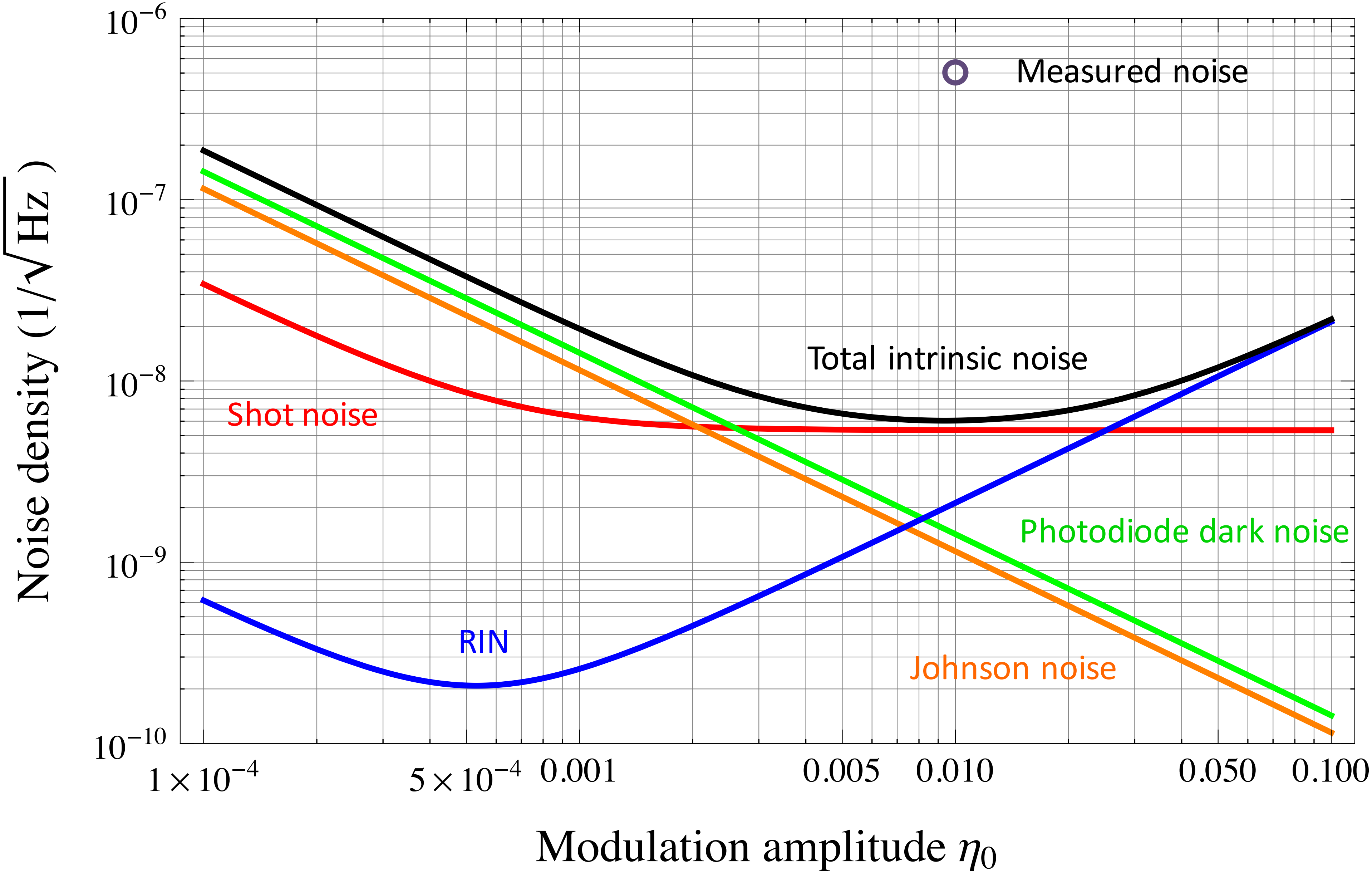
Axion-like particles



$$\Delta n^{\,(\mathrm{PVLAS})} = (-19 \pm 20) \times 10^{-23} \qquad @\; B = 2.5\ \mathrm{T}.$$

$$\Delta\kappa^{\,(\mathrm{PVLAS})} = (-24 \pm 30) \times 10^{-23} \qquad @\; B = 2.5\ \mathrm{T}$$

The sensitivity problem



PVLAS was designed with a factor 10 contingency, here we have 100... If we were limited by intrinsic noise:

- B = 2.5 T, *F* = 7·10^5 and L = 1.64 m

$$\psi_{\mathrm{QED}} = 5.6 \times 10^{-11}$$

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

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

(Actual time ≈ 10^8 s ≈ 3 y)

- Tentative solutions:

1. increase the rotation frequency of the magnets
2. lower the temperature of the mirrors

Conclusions

- PVLAS wants to measure for the first time the magnetic birefringence of vacuum as predicted by QED
- ALP's are a by-product but: model independent search
- actual integrated noise limit is about one order of magnitude larger than the expected effect
- with current sensitivity a too long integration time is needed