Model independent limits on Axion Like Particles from ellipticity measurements

Guido Zavattini

Università di Ferrara and INFN-Ferrara

On behalf of the PVLAS collaboration

People

Guido Zavattini

Edoardo Milotti

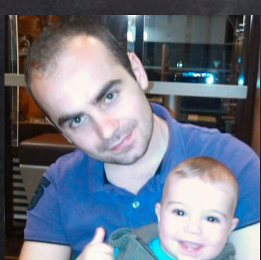
Ugo Gastaldi

Ruggero Pengo

Livio Piemontese

Federico Della Valle

Giuseppe Messineo



Aldo Ejlli

Pino Ruoso

Summary

- Introduction
  - Predicted non-linear QED effect
  - Axion search
- Experimental method
  - Heterodyne technique
  - Fabry-Perot interferometer
  - Noise considerations
- The PVLAS experiment in Ferrara
  - Calibration
  - Ellipticity and rotation results
  - Future

Predicted non-linear QED effect

Classical vacuum

The concept and/or existence of vacuum has been disputed for centuries

- One interesting definition by J.C. Maxwell is:

Vacuum is what is left when all that can be removed has been removed (J.C. Maxwell)

Classical vacuum (absence of charges and currents) has no structure and free electromagnetic fields are described by the classical Lagrangian density

With the speed of light

$$\mathcal{L}_{\mathrm{EM}} = \frac{1}{2\mu_0}\left(\frac{\vec{E}^2}{c^2} - \vec{B}^2\right) \qquad c = \frac{1}{\sqrt{\epsilon_0\mu_0}} = 2.9979 \cdot 10^8 \ \mathrm{m/s}$$

Classical vacuum

- The classical Lagrangian density leads to Maxwell's equations in vacuum

$$\vec{\nabla}\cdot\vec{D} = 0; \qquad \vec{\nabla}\cdot\vec{B} = 0$$

$$\vec{\nabla}\times\vec{E} = -\frac{\partial\vec{B}}{\partial t}; \qquad \vec{\nabla}\times\vec{H} = \frac{\partial\vec{D}}{\partial t}$$

with

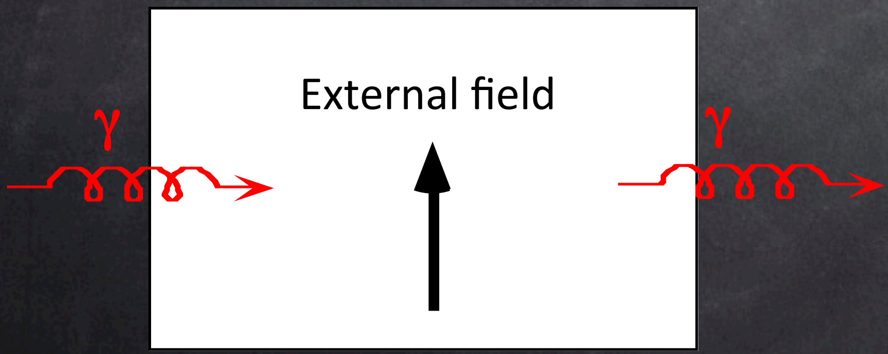
$$\vec{D} = \frac{\partial\mathcal{L}_{\mathrm{EM}}}{\partial\vec{E}}$$

$$\vec{H} = -\frac{\partial\mathcal{L}_{\mathrm{EM}}}{\partial\vec{B}}$$

<u>The superposition principle holds</u>

$$\vec{D} = \epsilon_0\vec{E}; \quad \vec{B} = \mu_0\vec{H}$$

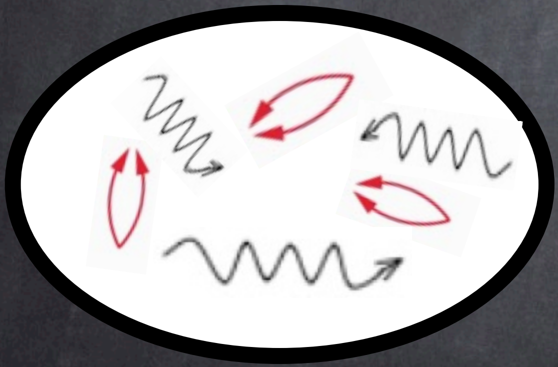
Index of refraction $n = 1$



Vacuum

What is left when all has been removed?

Vessel containing field fluctuations



The **Heisenberg uncertainty principle** allows for field fluctuations, thus the fundamental state of systems with finite and infinite degrees of freedom has non zero energy

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

These fluctuations manifest themselves as **virtual particles**

- Vacuum has a <u>structure</u> (microscopic and macroscopic) which can be perturbed and therefore studied

Vacuum

O. Halpern, Phys. Rev. 44, pp 885, (1934)

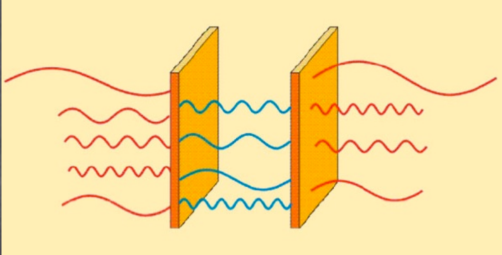
Scattering Processes Produced by Electrons in Negative Energy States

Recent calculations[1] of the changes in the absorption-coefficient of hard gamma-rays due to the formation of electron-positron pairs have lent strong support to Dirac's picture of holes of negative energy. Still, the almost insurmountable difficulties which the infinite charge-density without field offers to our physical understanding make it desirable to seek further tests of the theory. Here purely radiation phenomena are of particular interest inasmuch as they might serve in an attempt to formulate observed effects as consequences of hitherto unknown properties of corrected electromagnetic equations. We are seeking, then, scattering properties of the "vacuum."

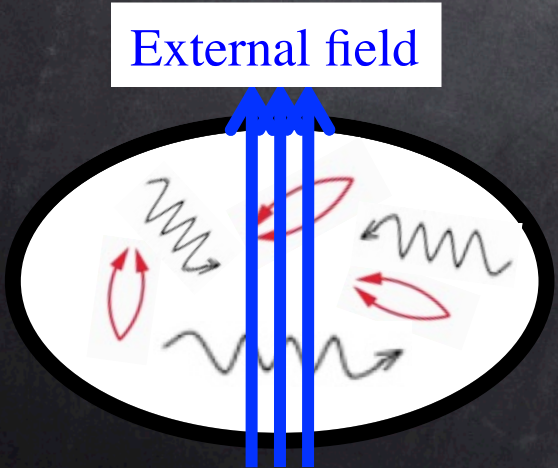
[1] J. R. Oppenheimer and M. S. Plesset, Phys. Rev. **44**, 53 (1933).

QED tests

- Microscopic tests
  - QED tests in bound systems – Lamb shift, Delbrück scattering
  - QED tests in charged particles – (g-2)
- Macroscipic tests
  - Casimir effect (photon zero point fluctations)



- QED tests with only photons is *still* missing



Macroscopically observable (small) non linear effects have been predicted since 1936 but have never been directly observed yet.

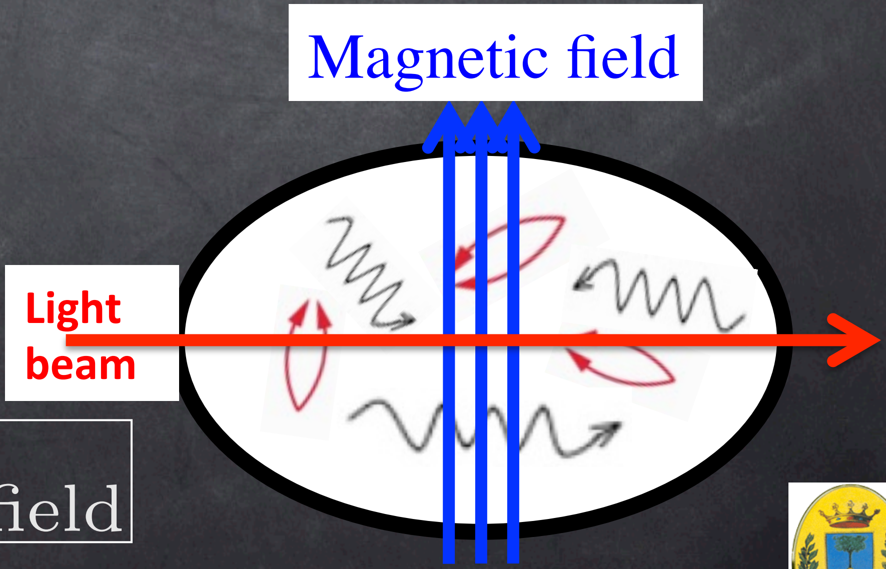
We will concentrate on the **electromagnetic vacuum**

Light propagation in an external field

- Experimental study of the propagation of light in an external field
- General method
  - **Perturb** the vacuum with an external field
  - **Probe** the perturbed vacuum with **polarized light**
  - Extract information on the electromagnetic structure of vacuum

We are aiming at measuring **variations of the index of refraction** in vacuum due to the external **magnetc** field

$$n_{\mathrm{vac}} = 1 + (n_{\mathrm{B}} - \imath\kappa_{\mathrm{B}})_{\mathrm{field}}$$



Heisenberg, Euler, Kochel and Weisskopf ('30)

They studied the electromagnetic field in the presence of the **virtual electron-positron** sea discussed a few years before by Dirac. The result of their work is an effective Lagrangian density describing the electromagnetic interactions. At lowest order (Euler – Kochel):

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

$$A_e = \frac{2}{45\mu_0}\frac{\alpha^2\bar{\lambda}_e^3}{m_e c^2} = 1.32\times10^{-24}\ \mathrm{T}^{-2}.$$

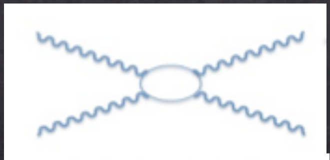
H Euler and B Kochel, *Naturwissenschaften* **23**, 246 (1935)
W Heisenberg and H Euler, *Z. Phys.* **98**, 714 (1936)
H Euler, *Ann. Phys.* **26**, 398 (1936)
V Weisskopf, *Mat.-Fis. Med. Dan. Vidensk. Selsk.* **14**. 6 (1936)

Which is valid for:

1) slowly varying fields
2) fields smaller than their critical value (B << $4.4\cdot10^{9}$ T; E << $1.3\cdot10^{18}$ V/m)

In **the presence of an external field vacuum is polarized**. It became evident that photon – photon interactions could occur in vacuum.

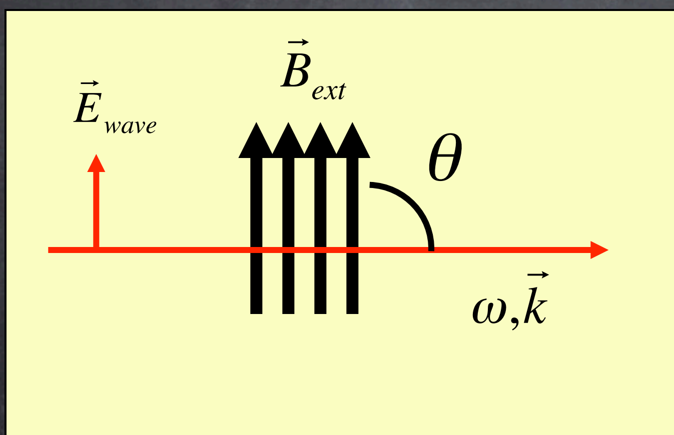
This lagrangian was **validated in the framework of QED by Schwinger** (1951), and the processes described by it can be represented using Feynman diagrams.



Index of refraction

Baier R and Breitenlohner P, *Acta Phys. Austriaca* **25**, 212 (1967); *Nuovo Cimento* 47, 117 (1967);
Bialynicka-Birula Z and Bialynicki-Birula I, *Phys. Rev. D* **2,** 2341 (1970);
Adler S L, *Ann. Phys.* **67**, 559 (1971);

Let us consider our experimental configuration:
linearly polarised light traversing an external transverse magnetic field



$$\hbar\omega << m_e c^2$$

$$B << B_{cr} = \frac{m_e^2 c^2}{\hbar e} = 4.41\times 10^9\,\mathrm{T}$$

$$\vec{\mathbf{E}} = \vec{\mathbf{E}}_{Wave} \quad ; \quad \vec{\mathbf{B}} = \vec{\mathbf{B}}_{Ext} + \vec{\mathbf{B}}_{Wave}$$

$$\left|\vec{\mathbf{B}}_{Ext}\right| >> \left|\vec{\mathbf{B}}_{Wave}\right|$$

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

Index of refraction - birefringence

- By applying the constitutive relations to L_{EH} one finds

$$\vec{\mathbf{D}} = \frac{\partial L_{EH}}{\partial \vec{\mathbf{E}}} \qquad \vec{\mathbf{H}} = -\frac{\partial L_{EH}}{\partial \vec{\mathbf{B}}}$$

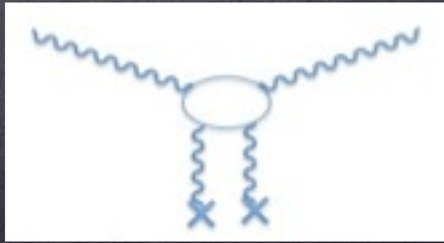
$$\vec{\mathbf{D}} = \varepsilon_0 \vec{\mathbf{E}} + \varepsilon_0 A_e \left[4\left(\frac{E^2}{c^2} - B^2 \right) \vec{\mathbf{E}} + 14 \left(\vec{\mathbf{E}} \cdot \vec{\mathbf{B}} \right) \vec{\mathbf{B}} \right]$$

$$\mu_0 \vec{\mathbf{H}} = \vec{\mathbf{B}} + A_e \left[4\left(\frac{E^2}{c^2} - B^2 \right) \vec{\mathbf{B}} - 14 \left(\frac{\vec{\mathbf{E}} \cdot \vec{\mathbf{B}}}{c^2} \right) \vec{\mathbf{E}} \right]$$

Light propagation is still described by Maxwell's equations in media but they <u>no longer are linear</u> due to E-H correction. **<u>The superposition principle no longer holds.</u>**

Index of refraction

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

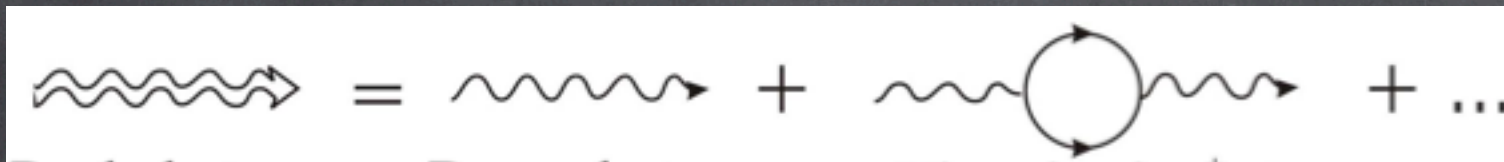


$$\Delta n = 3 A_e B^2$$

Propagation of light

Photon propagation in vacuum as depicted with Feynman diagrams

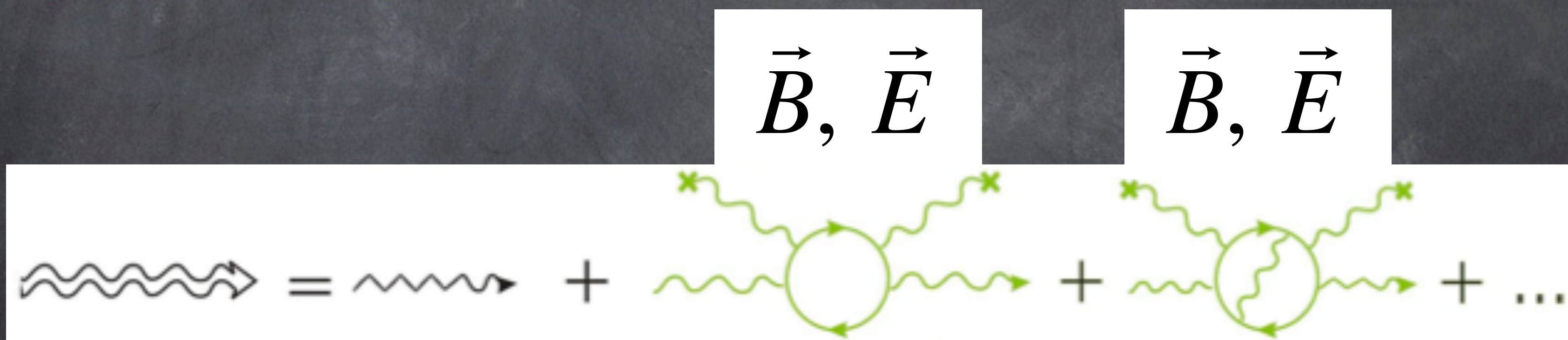
Without external field



= *c*

Real photon | Bare photon | Virtual pairs

With external field



Real photon | Bare photon | Virtual pairs | Radiative corrections

- *c* depends on the external field!
- *c* depends on light polarization!

Index of refraction - birefringence

$n_{\parallel,\perp} \neq 1$

$n_{\parallel} - n_{\perp} \neq 0$

- v ≠ c
- anisotropy

A_e can be determined by measuring the magnetic birefringence of vacuum.

$$\Delta n_{(\alpha^2)} = 3A_e B^2$$

$$\Delta n_{(\alpha^3)} = 3A_e B^2\left(1+\frac{25}{4\pi}\alpha\right) = \frac{2}{15}\frac{\alpha^2\hbar^3}{m_e^4 c^5}\left(1+\frac{25}{4\pi}\alpha\right)\frac{B^2}{\mu_0}$$

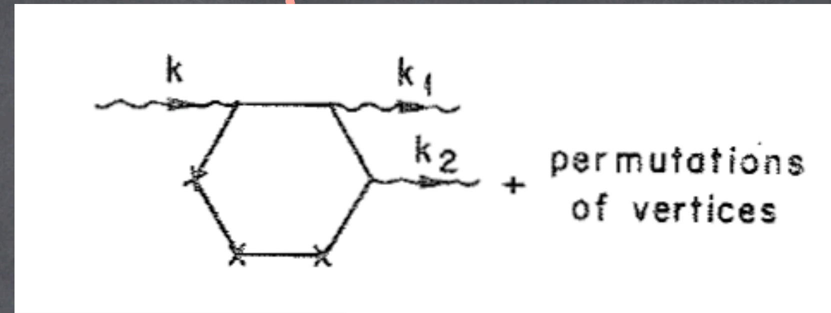
$$\Delta n = (4.031699 \pm 0.000002)\cdot 10^{-24}\left(\frac{B}{1T}\right)^2$$

$O(a^4)$, $O(a^5)$? Also a theoretical challenge

$$\Delta n^{(\mathrm{QED})} = 2.5 \times 10^{-23} \text{ @ } 2.5\ \mathrm{T}$$

Index of refraction - absorption

S. Adler (1971) calculated the absorption due to QED which is of next order and connected to the phenomenon known as **photon splitting**



$$\alpha_{\left\{\begin{smallmatrix}\perp\\ \parallel\end{smallmatrix}\right\}} = \frac{4\pi}{\lambda}\kappa_{\left\{\begin{smallmatrix}\perp\\ \parallel\end{smallmatrix}\right\}} = \left\{\begin{matrix}0.51\\ 0.24\end{matrix}\right\}\left(\frac{\hbar\omega}{m_e c^2}\right)^5\left(\frac{B\sin\theta}{B_{cr}}\right)^6 \text{ cm}^{-1}$$

Expected values

$$n_{\mathrm{vac}} = 1 + (n_{\mathrm{B}} - \imath\kappa_{\mathrm{B}})_{\mathrm{field}}$$

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

$$A_e = \frac{2}{45\mu_0}\frac{\alpha^2 \lambda\!\!\!^{-}{}_e^3}{m_e c^2}$$

Unmeasureably small

Axion like particles

Axion-like particles

One can add extra terms [*] to the E-H effective lagrangian to include contributions from hypothetical **neutral light particles interacting weakly with two photons** (Heaviside – Lorentz units)

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

pseudoscalar case: Interaction if polarization is perpendicular to B_{ext}

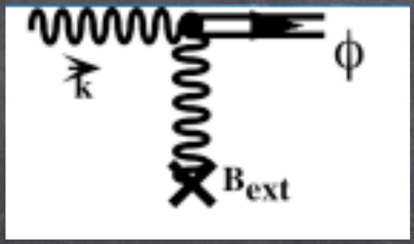
$$L_\sigma = g_\mathrm{s}\sigma\left(\vec{B}_\gamma \cdot \vec{B}_\mathrm{ext}\right)$$

scalar case: Interaction if polarization is perpendicular to B_{ext}

Effects on photon propagation

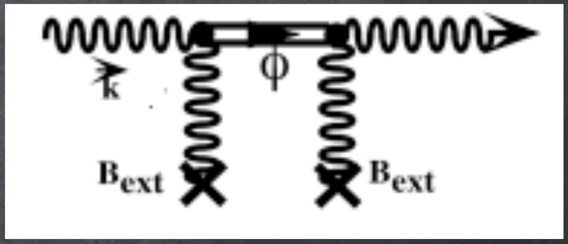
The photon will oscillate with the axion

Absorption



DICHROISM

Dispersion



BIREFRINGENCE

g_a, g_s are the coupling constants

[L.Maiani, R. Petronzio, E. Zavattini, Phys. Lett B, Vol. 173, no.3 1986]
[E. Massò and R. Toldrà, Phys. Rev. D, Vol. 52, no. 4, 1995]

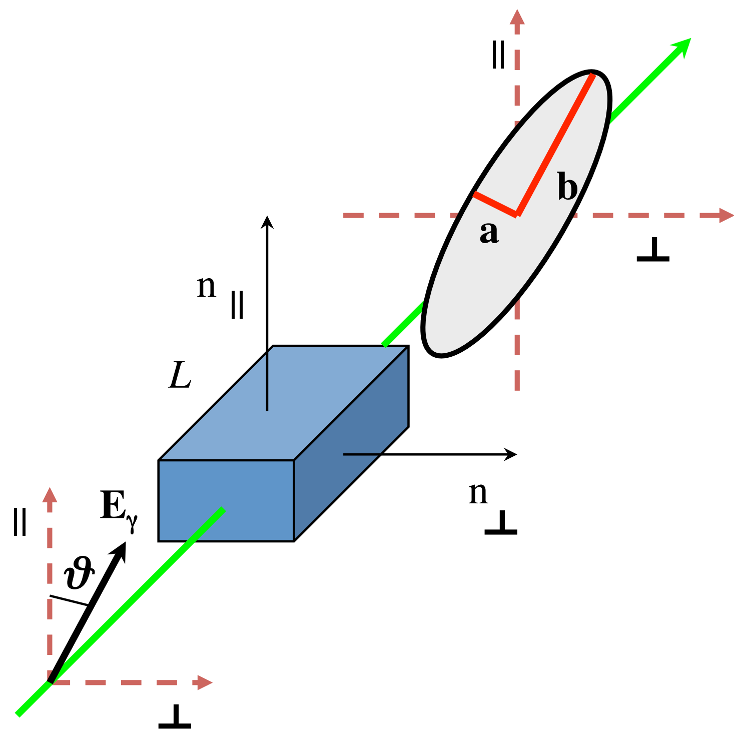
Linear birefringence

- A birefringent medium has $n_{||} \neq n_{\perp}$
- A linearly polarized light beam propagating through a birefringent medium will acquire an **ellipticity** ψ

A linearly polarized light beam can be written as $\vec{E}_\gamma = E_\gamma e^{\imath\xi}\begin{pmatrix}1\\0\end{pmatrix}$

If the light polarization forms an angle ϑ with respect to the magnetic field **B** then after a relative phase delay $\phi = \frac{2\pi}{\lambda}(n_\parallel - n_\perp)L$

$$\vec{E}_\gamma = E_\gamma e^{\imath\xi}\begin{pmatrix}1+\imath\left(\frac{\phi}{2}\right)\cos 2\vartheta\\ \imath\left(\frac{\phi}{2}\right)\sin 2\vartheta\end{pmatrix}$$



Ellipticity

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

Linear dichroism

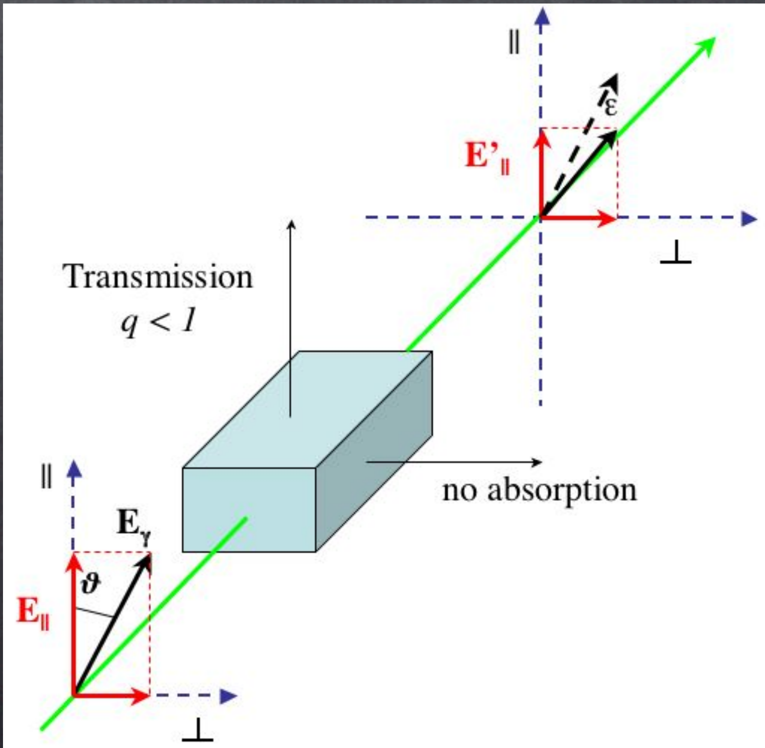
- A dichroic medium has different extinction coefficients: $\kappa_{||} \neq \kappa_{\perp}$
- A linearly polarized light beam propagating through a dichroic medium will acquire an apparent **rotation** ε

After a reduction of the field component parallel to **B** with respect to the component perpendicular to **B** by $q-1 = \frac{2\pi}{\lambda}(\kappa_{\|} - \kappa_{\perp})L$

$$\vec{E}_\gamma \approx E_\gamma e^{\imath\xi} \begin{pmatrix} 1 + \left(\frac{q-1}{2}\right)\cos 2\vartheta \\ \left(\frac{q-1}{2}\right)\sin 2\vartheta \end{pmatrix}$$

Apparent rotation

$$\epsilon \approx \left(\frac{q-1}{2}\right)\sin 2\vartheta = \frac{\pi \Delta\kappa L}{\lambda}\sin 2\vartheta$$



Axion-like particles

- Dichroism induces an apparent rotation ε

$$\epsilon = -\sin 2\vartheta \left(\frac{g_{\mathrm{a,s}} B_{\mathrm{ext}} L}{4}\right)^2 N \left(\frac{\sin x}{x}\right)^2$$

N = number of passes through the magnetic field

- Birefringence induces an ellipticity ψ

$$\psi = \sin 2\vartheta \frac{g_{\mathrm{a,s}}^2 B_{\mathrm{ext}}^2 k L}{4 m_{\mathrm{a,s}}^2} N \left(1 - \frac{\sin 2x}{2x}\right)$$

Units

$$1\ \mathrm{T} = \sqrt{\frac{\hbar^3 c^3}{e^4 \mu_0}} = 195\ \mathrm{eV}^2$$

$$1\ \mathrm{m} = \frac{e}{\hbar c} = 5.06 \cdot 10^6\ \mathrm{eV}^{-1}$$

Where $x = \frac{L}{2}\left[\frac{m_{\mathrm{a,s}}^2}{2k}\right]$ and *k* is the wave number

- Both ε and ψ are proportional to N
- Both ε and ψ are proportional to B^2
- ε depends only on $g_{a,s}$ for small x
- **the ratio ψ / ε depends only on $m^2_{a,s}$**

Both $g_{a,s}$ and $m_{a,s}$ can be disentangled

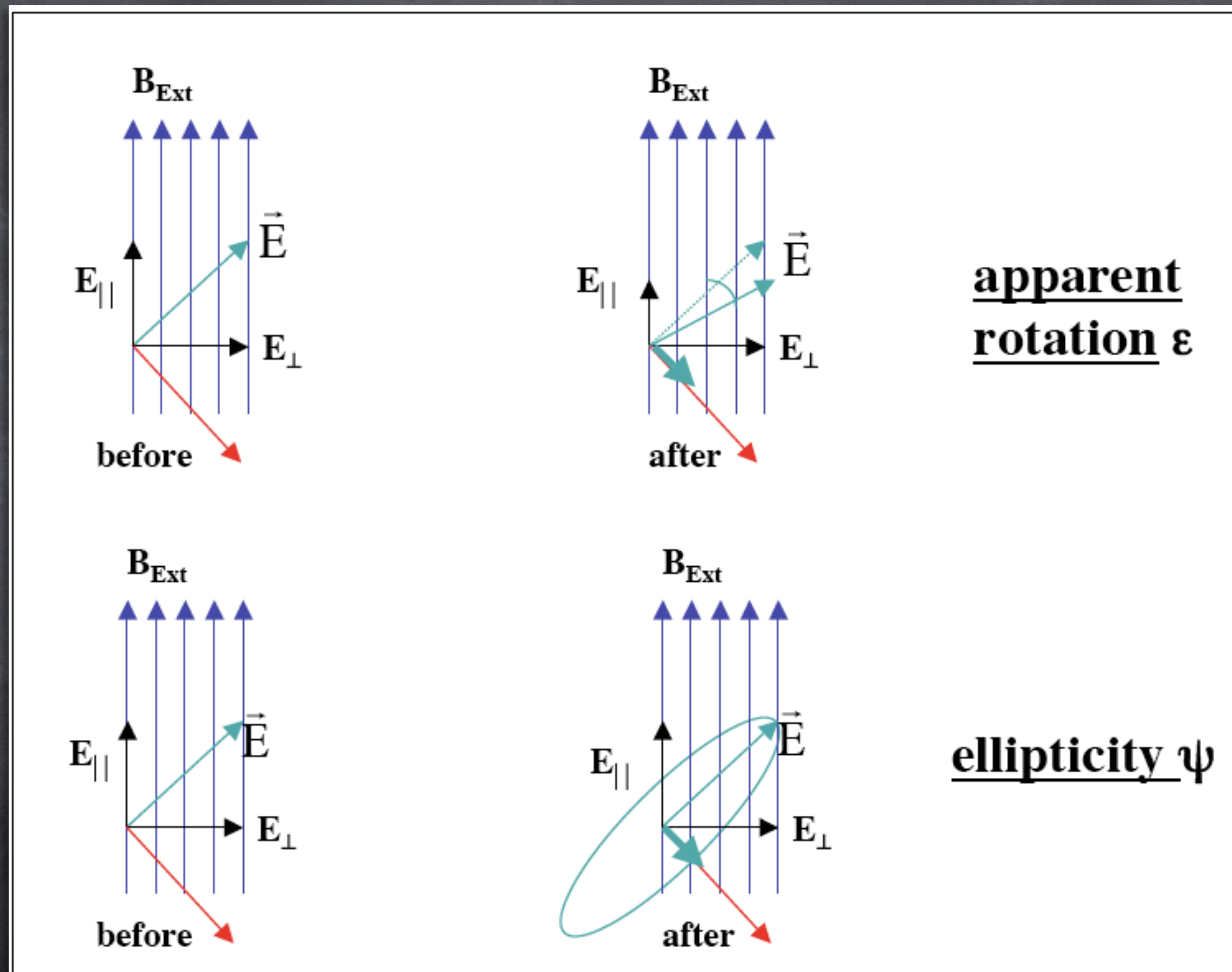
Summing up …

Dichroism ΔK

- (Photon splitting)
- Real particle production

Birefringence Δn

- QED
- Virtual particle production



Both Δn and Δκ are defined with sign

Aim of PVLAS

The PVLAS experiment was designed to obtain experimental information on vacuum using optical techniques.

The full experimental program is to detect and measure

- **LINEAR BIREFRINGENCE**
- **LINEAR DICHROISM**

acquired by vacuum induced by an external magnetic field **B**

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

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

Gas	Δn_u (T ~ 293 K)
Nitrogen	- (2.47± 0.04) x 10^{-13}
Oxygen	- (2.52± 0.04) x 10^{-12}
Carbon Oxide	- (1.83± 0.05) x 10^{-13}
Helium	(2.2±0.1) x 10^{-16}

Total ellipticity

$$\psi_{\mathrm{gas}} = \frac{\pi L_{\mathrm{eff}}}{\lambda} \Delta n_u B^2 p \sin 2\vartheta$$

To avoid spurious effects the residual gas must be analysed:

Ex. $p(O_2) < 10^{-8}$ mbar

Experimental method

Key ingredients

Experimental study of the quantum vacuum with:

- magnetic field perturbation
- linearly polarised light beam as a probe
- changes in the polarisation state are the expected signals

$$\psi = \frac{\pi L_{\rm eff}}{\lambda}\Delta n(B^2)\sin 2\vartheta(t)$$

- high magnetic field
  rotating high field permanent magnet
- long optical path
  very-high finesse Fabry-Perot resonator: $N = 2\mathcal{F}/\pi$
- ellipsometer with heterodyne detection for best sensitivity
  periodic change of field amplitude/direction for signal modulation

Numerical values

Main interest of PVLAS is the Euler-Heisenberg birefringence

- $B = 2.5$ T
- $F = 7 \cdot 10^5$
- $L = 1.6$ m

$\Delta n = 2.5 \cdot 10^{-23}$ ⇒ $\psi = 5 \cdot 10^{-11}$

If we assume a maximum integration time of 10^6 s (= 12 days)

The necessary ellipticity sensitivity is < $5 \cdot 10^{-8}$ 1/√Hz
Birefringence sensitivity < $2.5 \cdot 10^{-20}$ 1/√Hz

Shot noise limit = $\sqrt{\frac{e}{I_0 q}} = 3.8 \cdot 10^{-9} \frac{1}{\sqrt{\text{Hz}}}$ for I_0 = 16 mW

(I_0 = output intensity reaching the analyzer, q = 0.7 A/W)

Numerical values

Main interest of PVLAS is the Euler-Heisenberg birefringence

- $B = 2.5$ T
- $F = 7 \cdot 10^5$
- $L = 1.6$ m

$$\Delta n = 2.5 \cdot 10^{-23} \rightarrow \psi = 5 \cdot 10^{-11}$$

If we assume a maximum integration time of 10^6 s (= 12 days)

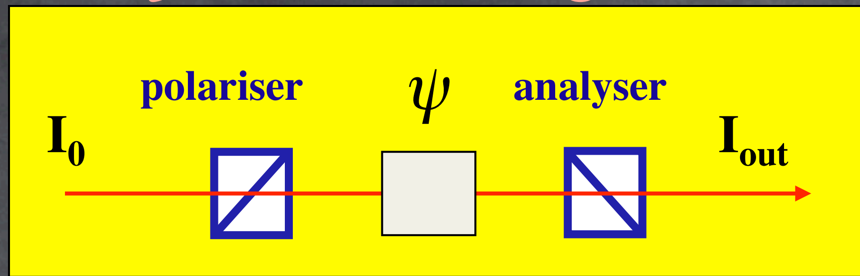
Ellipticity sensitivity of < $5 \cdot 10^{-8}$ $1/\sqrt{\text{Hz}}$
Birefringence sensitivity < $2.5 \cdot 10^{-20}$ $1/\sqrt{\text{Hz}}$

Present sensitivity in $\Delta n = 5 \cdot 10^{-19}$ $1/\sqrt{\text{Hz}}$

Shot noise limit = $\sqrt{\frac{e}{I_0 q}} = 3.8 \cdot 10^{-9} \frac{1}{\sqrt{\text{Hz}}}$ for I_0 = 16 mW

(I_0 = output intensity reaching the analyzer, q = 0.7 A/W)

Crossed polarizers



Two crossed polarizers with birefringent medium:

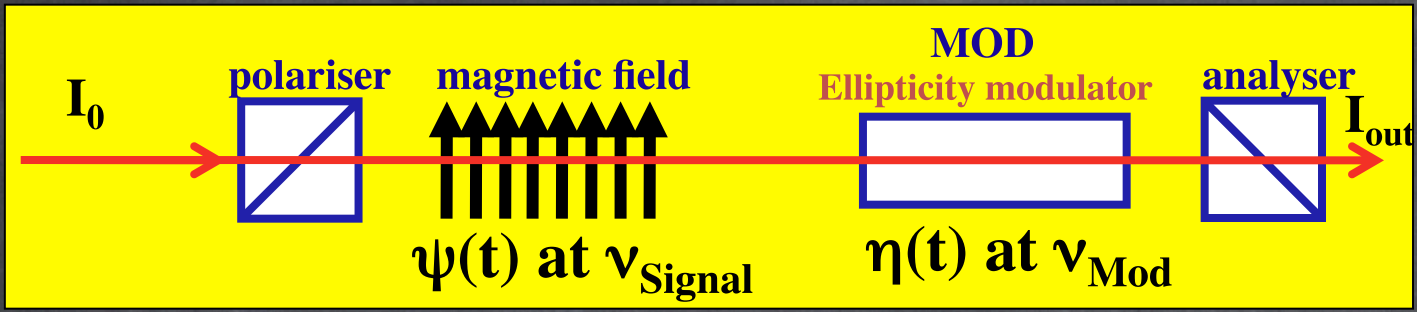
$$\vec{E}_{\mathrm{BRF}} = E_0 \begin{pmatrix} 1 + \imath\psi \cos 2\vartheta \\ \imath\psi \sin 2\vartheta \end{pmatrix}$$

and after the analyzer the intensity will be

$$I_{\mathrm{out}} = I_0 |\imath\psi \sin 2\vartheta| = I_0 \psi^2 \sin^2 2\vartheta$$

The output intensity is proportional to ψ^2: very small!

Heterodyne detection



- By adding a known ellipticity with a time dependent modulator placed with $\vartheta = 45^o$ and keeping only first order terms

$$\vec{E}_{\rm out} = E_0 \cdot [A] \cdot [MOD] \cdot [BRF] \cdot \begin{pmatrix} 1 \\ 0 \end{pmatrix} = E_0 \begin{pmatrix} 0 \\ \imath\psi \sin 2\vartheta + \imath\eta(t) \end{pmatrix}$$

Ellipticities add up algebraically. The intensity is now linear in ψ

$$I_{\rm out} \simeq I_0 \left[\eta(t)^2 + 2\eta(t)\psi \sin 2\vartheta + \ldots \right]$$

Heterodyne detection

- In practice slowly varying spurious ellipticities α(t) are also present and the crossed polarizer-analyzer pair transmit a fraction σ^2 of I_0 (at best $\sigma^2 \approx 5\cdot10^{-8}$).
- $\psi \sin 2\vartheta$ can also be modulated by either rotating the magnetic field or by ramping it. In PVLAS we have permanent magnets and therefore rotate the magnetic field.
- By modulating both η and ϑ the double product leads to frequency sidebands around the $\eta(t)$ carrier frequency.
- The $\eta^2(t)$ term results at twice the carrier frequency and is used to measure η directly.
- The expression PVLAS is based on is

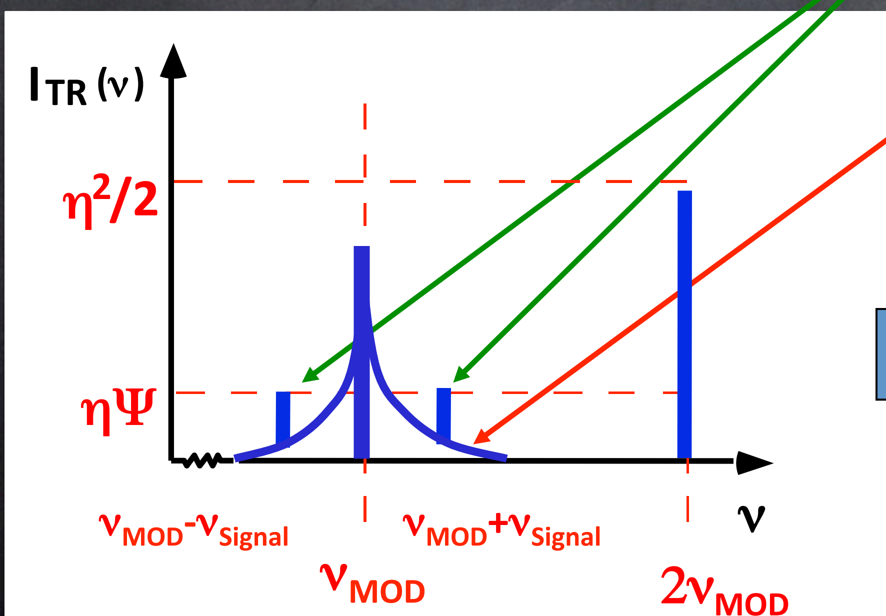
$$I_{\rm out} = I_0 \left[\sigma^2 + \eta(t)^2 + \alpha(t)^2 + 2\eta(t)\psi \sin 2\vartheta(t) + 2\eta(t)\alpha(t)\right]$$

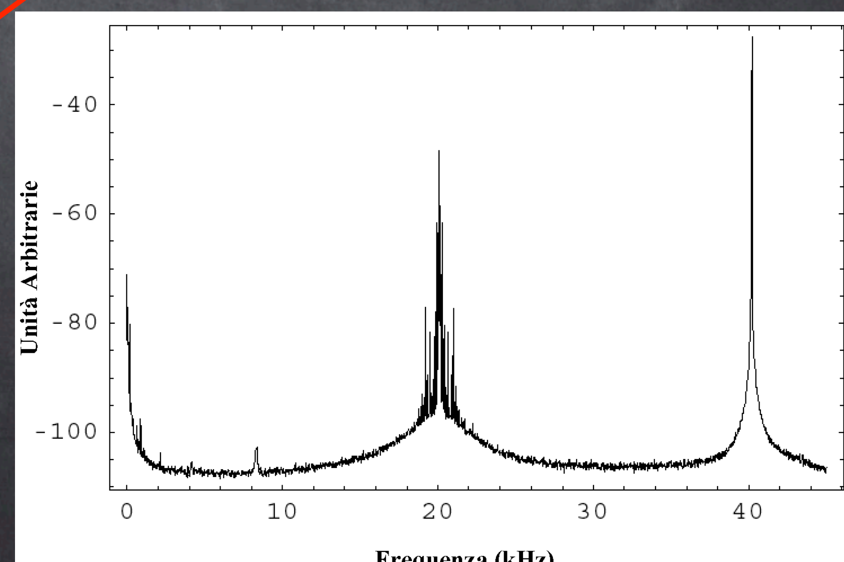
Fourier spectrum

With η(t) and ψ(t) sinosoidal functions

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

$$= I_0\left[\sigma^2 + \left(\eta(t)^2 + \underbrace{2\psi(t)\eta(t)}_{\text{signal}} + \underbrace{2\alpha(t)\eta(t)}_{\text{noise}} + \ldots\right)\right]$$





Ellipiticity vs Rotations

- Ellipticities have an imaginary component whereas rotations are real. If small they also add up algebraically.

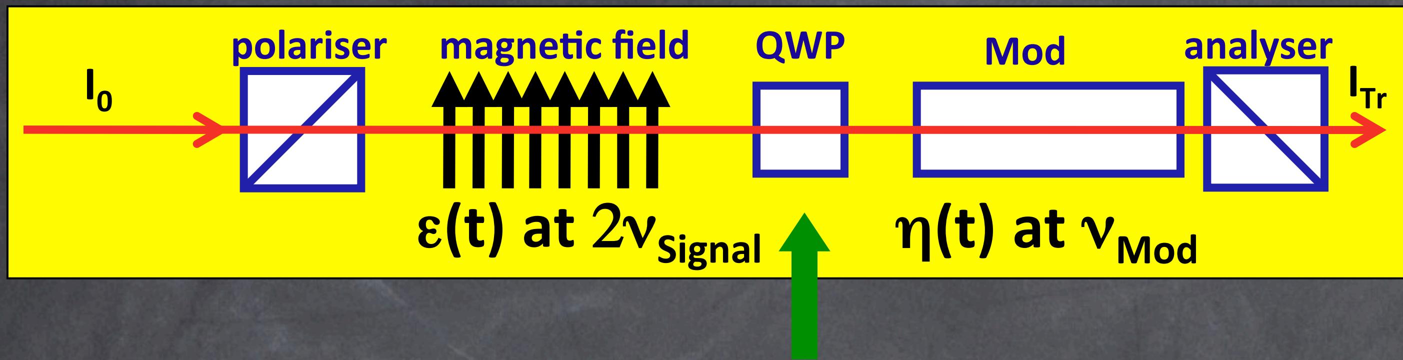
$$\vec{E}_{\rm out} = E_0 \cdot [A] \cdot [MOD] \cdot [ROT] \cdot \begin{pmatrix} 1 \\ 0 \end{pmatrix} = E_0 \begin{pmatrix} 0 \\ \varphi + \imath\eta \end{pmatrix}$$

- After the analyzer the intensity will be

$$\boxed{I_{\rm out} = I_0 |\varphi + \imath\eta|^2 = I_0(\varphi^2 + \eta^2)}$$

- There is no product between φ and η. Rotations do not beat with ellipticities.

Heterodyne detection



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 axis along polarization
QWP axis normal to polarization

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

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

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

Optical path multiplier

Optical path multiplier

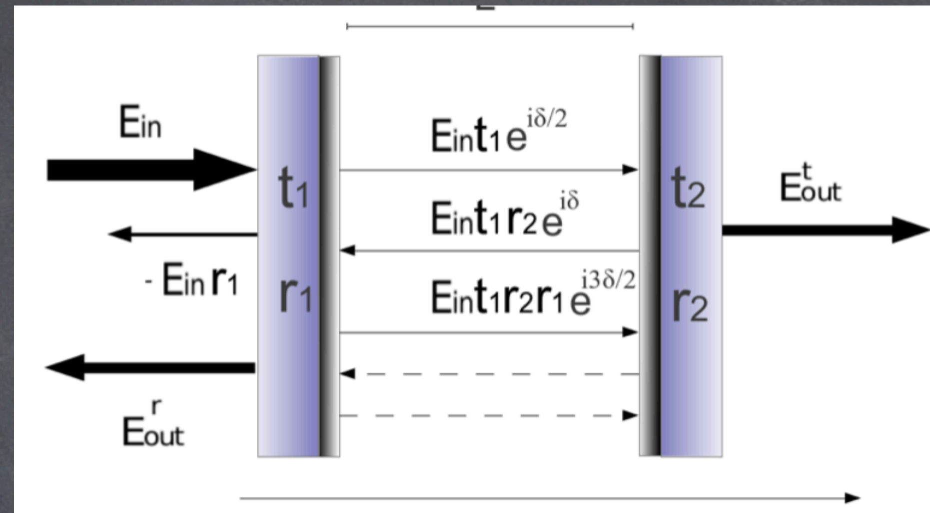
- The ellipticity induced by a birefringence is proportional to the path length in the magnetic region
- A Fabry-Perot interferometer is used to increase the path length by a factor of about 430000. A magnet 1 meter long becomes equivalent to 430 km!
- Very high reflectivity mirrors with very low losses are used
- A standing wave condition is maintained with a feedback system applied to the laser

Fabry-Perot

t and *r* are the reflection coefficients of the electric field

Let us assume $t_1 = t_2$ and $r_1 = r_2$.

Ideally $t^2 + r^2 = 1$



The roundtrip phase of a wave is $\delta = \dfrac{4\pi L}{\lambda}$

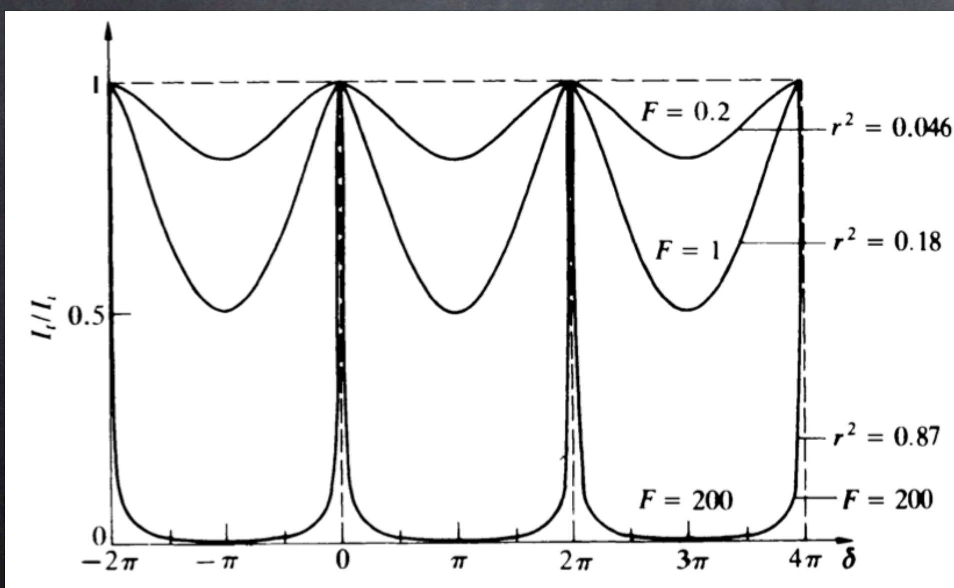
The electric field at the output of the system will be

$$E^t_{\text{out}} = E_{\text{in}} t^2 e^{\imath \frac{\delta}{2}} \sum_{n=0}^{\infty} r^{2n} e^{n\imath\delta} = E_{\text{in}} t^2 \frac{e^{\imath \frac{\delta}{2}}}{1 - r^2 e^{\imath\delta}}$$

Fabry-Perot

- The intensity at the output of the interferometer is

$$I^t_{\mathrm{out}} = \frac{1}{1 + \frac{4r^2}{(1-r^2)^2}\sin^2\frac{\delta}{2}}$$



$\delta = 2\pi$ defines the free spectral range:

$$\nu_{frs} = \frac{c}{2L}$$

The δ corresponding to a FWHM defines the finesse

$$\mathcal{F} = \frac{\nu_{fsr}}{\Delta\nu_{FWHM}} = \frac{\pi\sqrt{r^2}}{1-r^2}$$

Signal amplification

- How much will the Fabry-Perot will increase the effective path length ?
- With the Jones formalism one can also describe the cavity including internal and external birefringences

$$[CAV] = [A] \cdot [SP] \cdot [MOD] \cdot t^2 e^{\imath\delta/2} \sum_{n=0}^{\infty} \left[BRF^2 r^2 e^{\imath\delta}\right]^n \cdot [BRF]$$

- The ellipticity ψ is multiplied by $N = \frac{1+r^2}{1-r^2} = \frac{2\mathcal{F}}{\pi}$

$$\begin{aligned} \vec{E}_{\text{out}} &= E_0 \cdot [CAV] \cdot \begin{pmatrix} 1 \\ 0 \end{pmatrix} \\ &= E_0 \frac{t^2}{t^2 + p} \begin{pmatrix} 0 \\ \imath\alpha(t) + \imath\eta(t) + \imath\frac{1+r^2}{1-r^2}\psi \sin 2\vartheta(t) \end{pmatrix} \end{aligned}$$

Fabry-Perot example

- Given an infrared beam at 1064 nm and a cavity of length L = 3.3 meters with finesse *F* = 670000

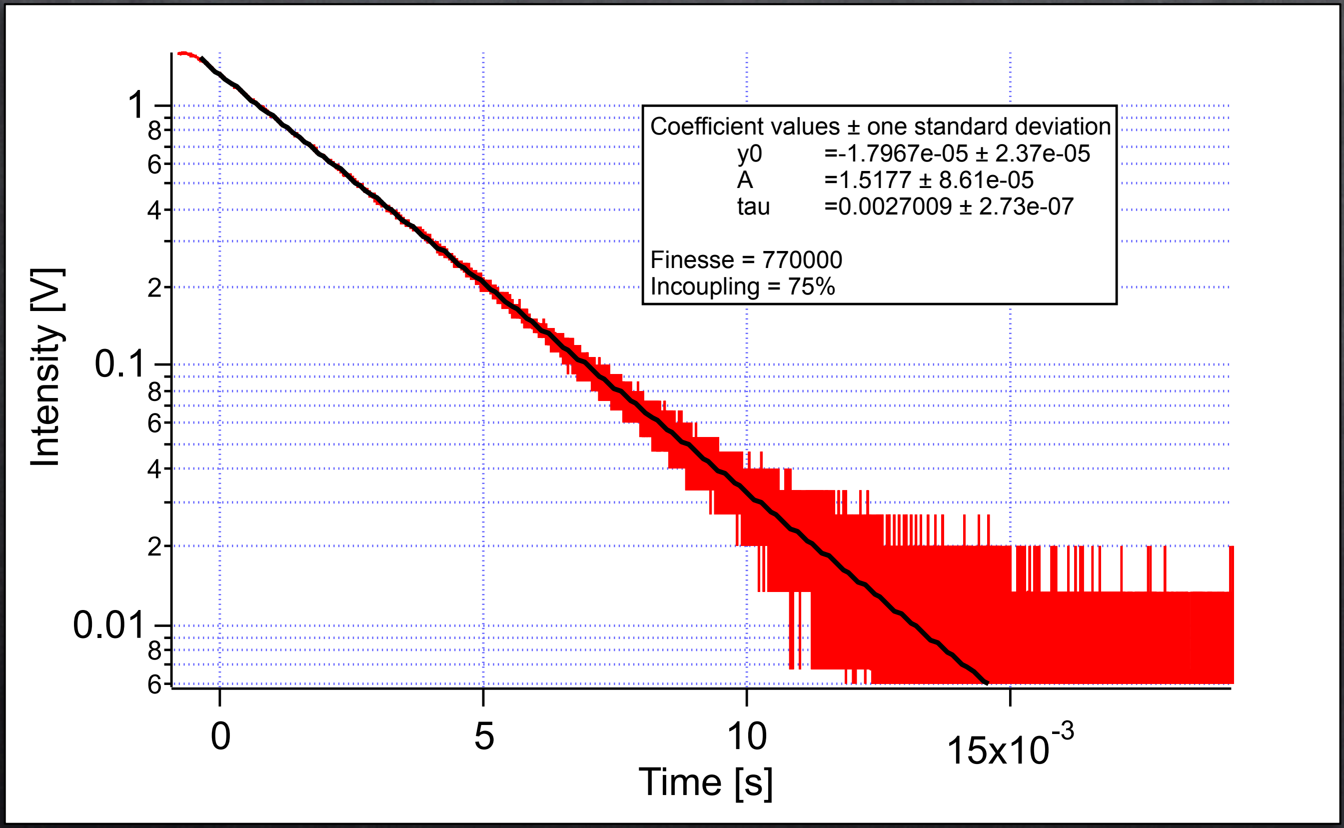
$$\nu_{laser} = \frac{c}{\lambda} = 2.8 \cdot 10^{14}\ \text{Hz} \qquad \nu_{fsr} = \frac{c}{2L} = 45\ \text{MHz}$$

$$\boxed{\Delta\nu_{\text{cavity}} = \frac{\nu_{\text{fsr}}}{\mathcal{F}} = 67\ \text{Hz}}$$

- Very very narrow resonances compared to the frequency of the incoming light.
- Feedback on laser is necessary to maintain resonance: Pound-Drever-Hall
- The cavity has a lifetime $\tau = \frac{\mathcal{F}L}{c\pi} \simeq 2.3\ \text{ms}$

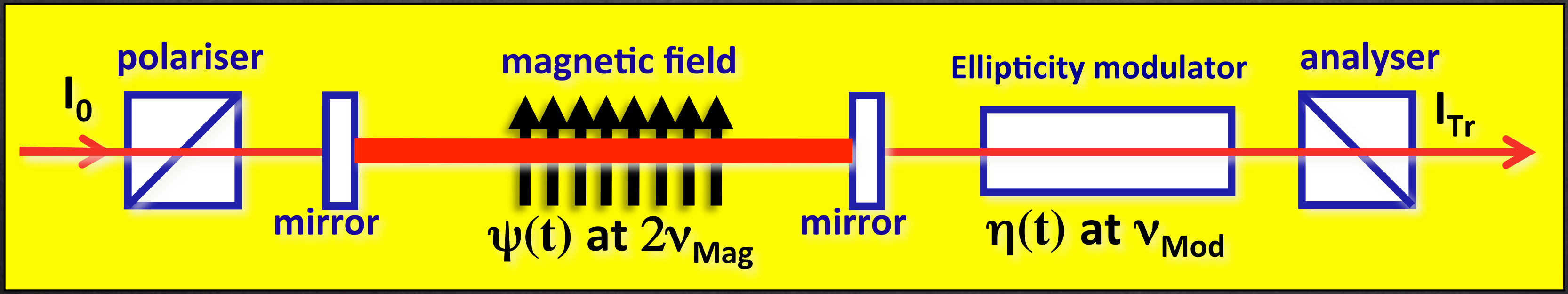
Best measured finesse

- Decay curve of light for our 3.3 m long cavity.
- Record decay time = 2.7 ms



PVLAS scheme

- The cavity will increase the single pass ellipticity by a factor $N = 2\mathcal{F}/\pi$
- The heterodyne detection linearizes the ellipticity ψ to be measured
- The rotating magnetic field will modulate the searched effect



Frequency components

Frequency	Fourier component	Intensity/$I_{\rm out}$	Phase
dc	$I_{\rm dc}$	$\sigma^2 + \alpha_{\rm dc}^2 + \eta_0^2/2$	–
$\nu_{\rm Mod}$	$I_{\nu_{\rm Mod}}$	$2\alpha_{\rm dc}\eta_0$	$\theta_{\rm Mod}$
$\nu_{\rm Mod} \pm 2\nu_{\rm Mag}$	$I_{\nu_{\rm Mod}\pm 2\nu_{\rm Mag}}$	$\eta_0 \dfrac{2\mathcal{F}}{\pi}\psi$	$\theta_{\rm Mod} \pm 2\vartheta_{\rm Mag}$
$2\nu_{\rm Mod}$	$I_{2\nu_{\rm Mod}}$	$\eta_0^2/2$	$2\theta_{\rm Mod}$

The signal amplitude can then be calculated from the two sidebands:

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

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

Shot noise

- The ultimate limit will be the rms shot noise $i_{\rm shot}$ of the current $i_{\rm DC}$ (q = photodiode efficiency ≈ 0.7 A/W, $\Delta\nu$ = bandwidth).

$$i_{\rm shot} = \sqrt{2ei_{\rm DC}\Delta\nu} = \sqrt{2eI_0q\left(\sigma^2 + \frac{\eta_0^2}{2} + \alpha_{\rm DC}^2\right)\Delta\nu}$$

- With $\eta_0 \gg \sigma^2, \alpha_{\rm DC}$ the shot noise spectral sensitivity becomes (I_0 = 16 mW)

$$s_{\rm shot} = \sqrt{\frac{e}{I_0q}} = 3.8\cdot 10^{-9}\ \frac{1}{\sqrt{\rm Hz}}$$

If we were shot noise limited...

- The expected ellipticity for B = 2.5 T, *F* = 6.7·10^5 and L = 1.6 m is

$$\psi_{\rm QED} = 5 \cdot 10^{-11}$$

- The necessary integration time to reach a signal to noise ratio = 1

$$T = \left(\frac{s_{\rm shot}}{\psi_{\rm QED}}\right)^2 = 5800\ {\rm s}$$

Other known noise sources

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

Photodetector noise. Reduce contribution by increasing power or improving detector

$$s_{\rm J} = \sqrt{\frac{4k_{\rm B}T}{G}}\frac{1}{I_{\rm out} q \eta_0}$$

Johnson noise. Reduce contribution by increasing power

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

Laer intensity noise. Reduce contribution by reducing σ^2, stabilize power, increase ν_{Mod}

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

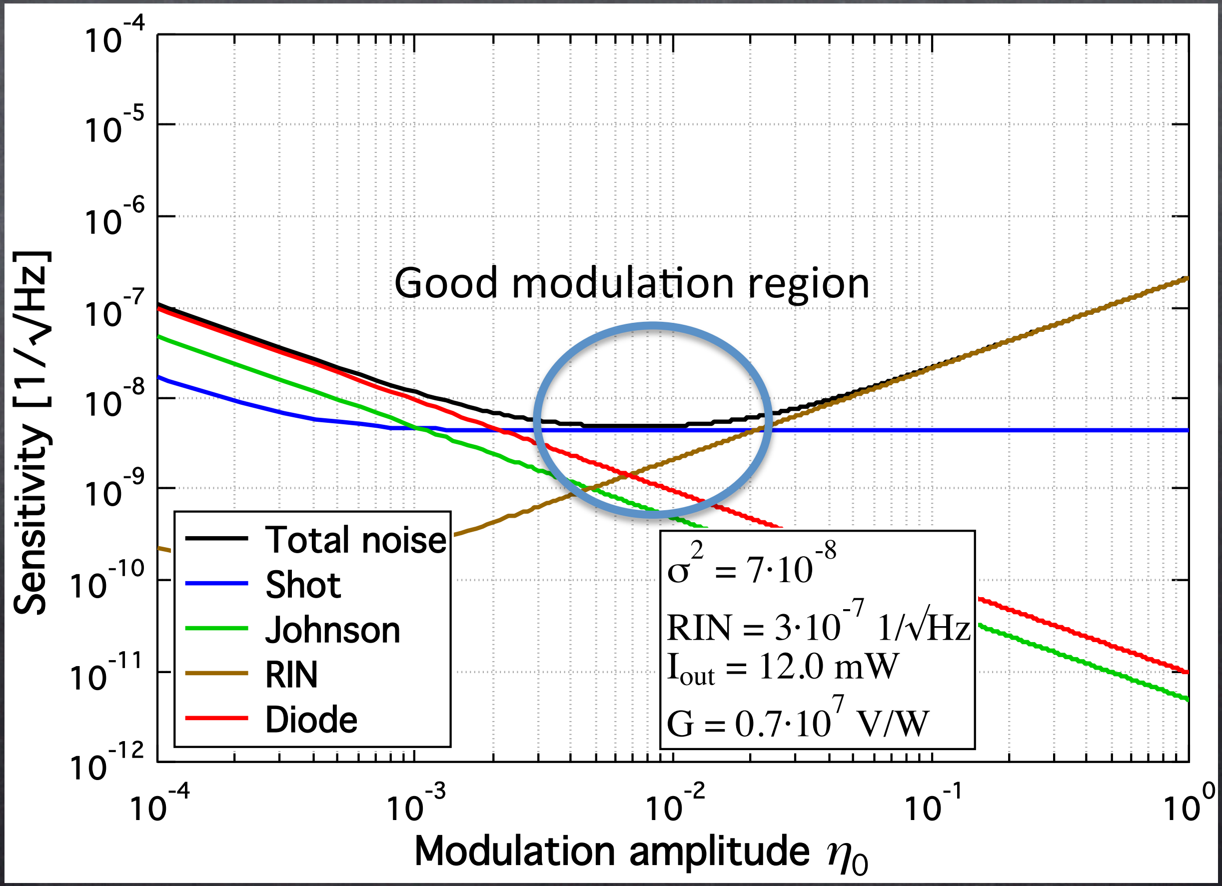
1/f noise: increase ν_{Mag}

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

Calculated noise

- Contribution of the various noises as a function of the modulation amplitude η_0 compared to the measured sensitivity.

$F \approx 670000$



PVLAS in Ferrara

University of Ferrara

Laboratory - clean room

Pro

Clean room class 10000

Temperature stabilization system

Con

Environment with human noise sources during day

Optical bench

Actively isolated granite optical bench

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

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

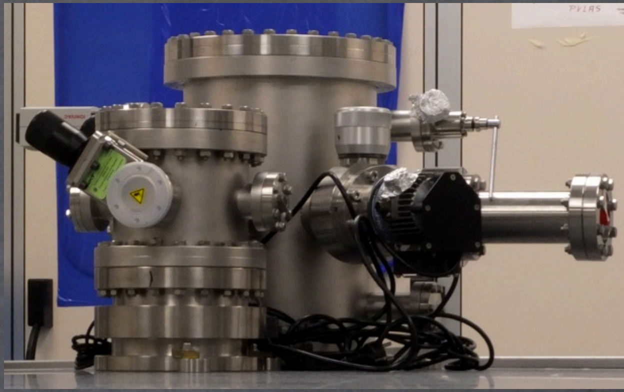
Bench installed

Fortunately survived the May 20 2012 earthquake

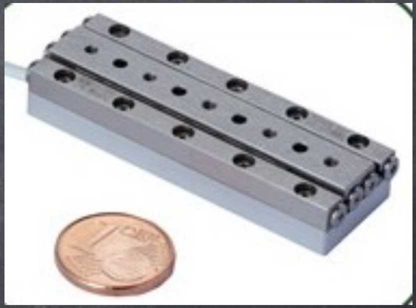
Vacuum and pumping

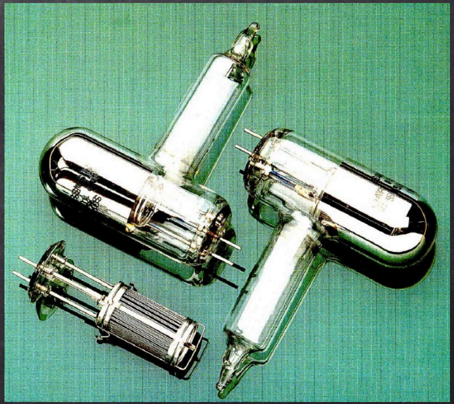
- All components of the vacuum system and optical mounts made with **non magnetic materials** (at best)
- Vacuum pipe through magnet made in **Pyrex** to avoid eddy currents
- Pyrex pipe surrounded by **Carbon fiber tube** to avoid interaction of scattered light with magnets
- Motion of optical components inside vacuum chamber by means of **piezo-motor**
- Low pressure pumping by using getter - NEG pumps – **noise free, magnetic field free**

Vacuum chambers



Linear translator

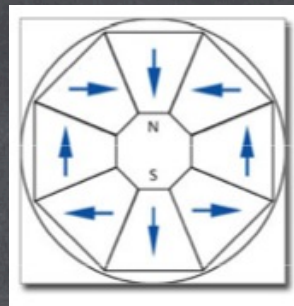


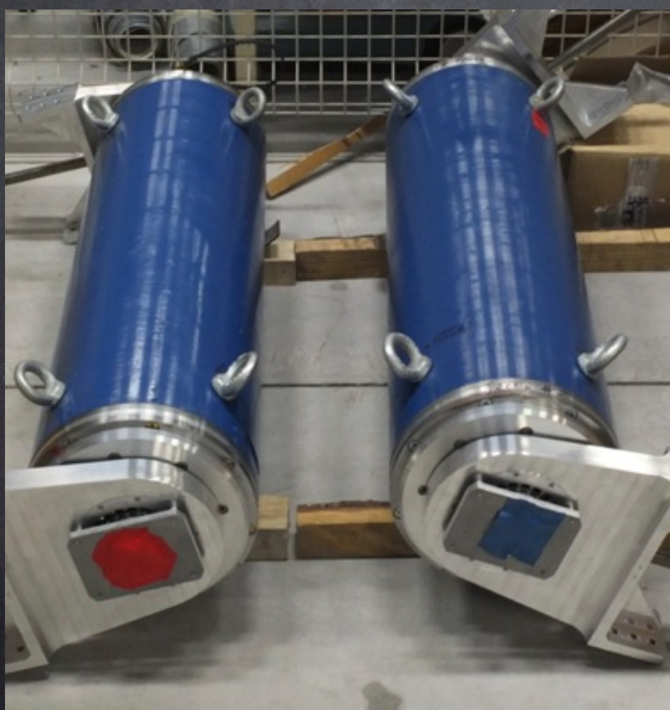


Getter pumps

The magnets

Halbach configuration

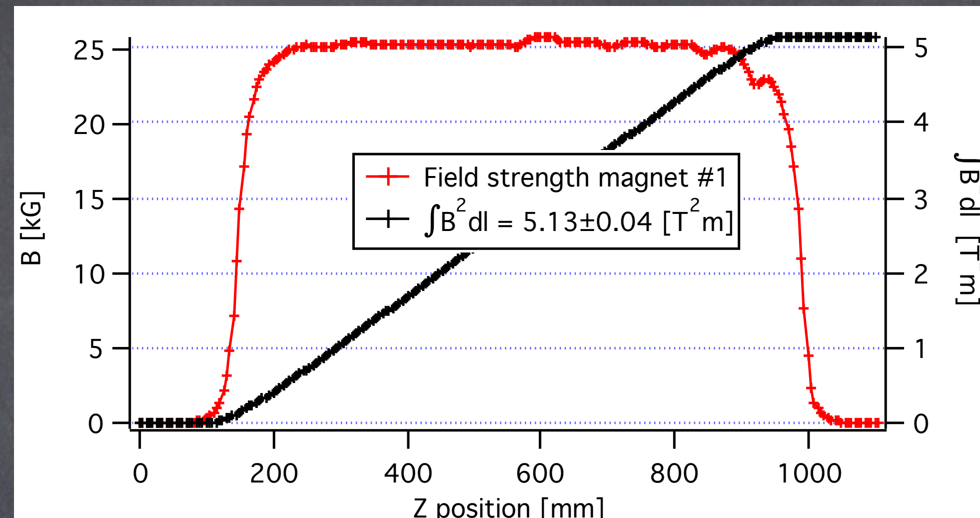


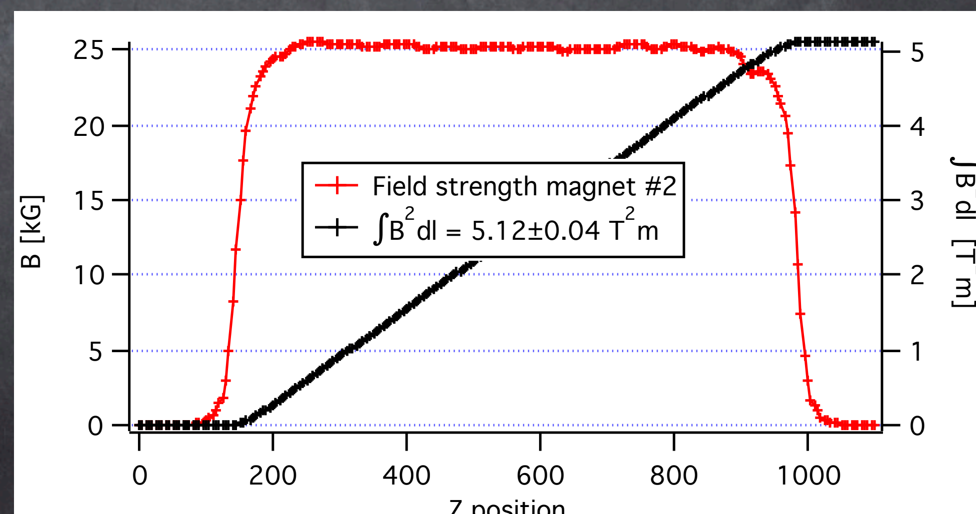


Magnets have built in **magnetic shielding**

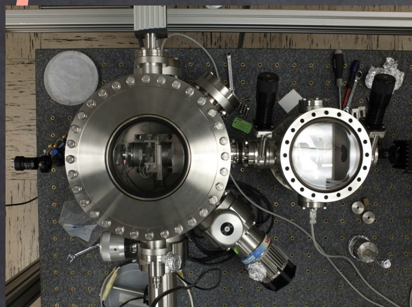
Stray field below 1 Gauss on side

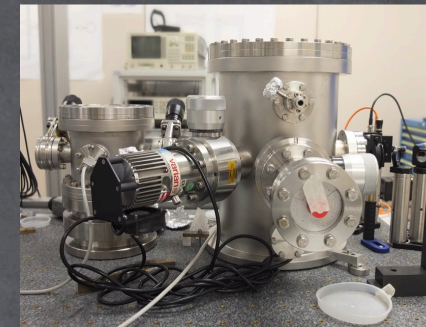
Total field integral = (10.25±0.06) T^2m



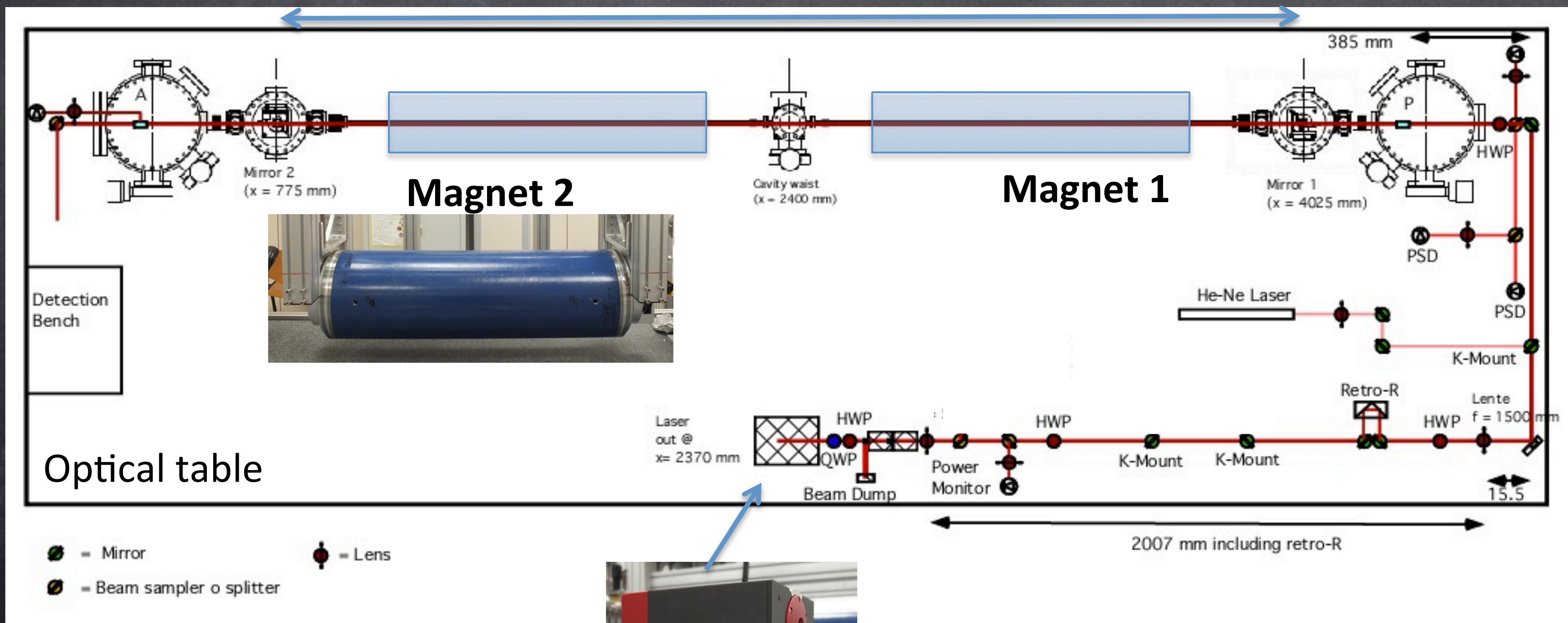


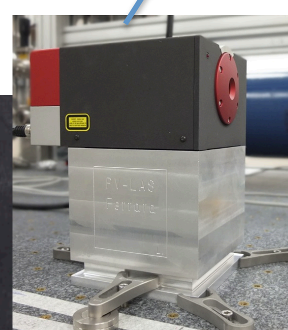
Optics layout





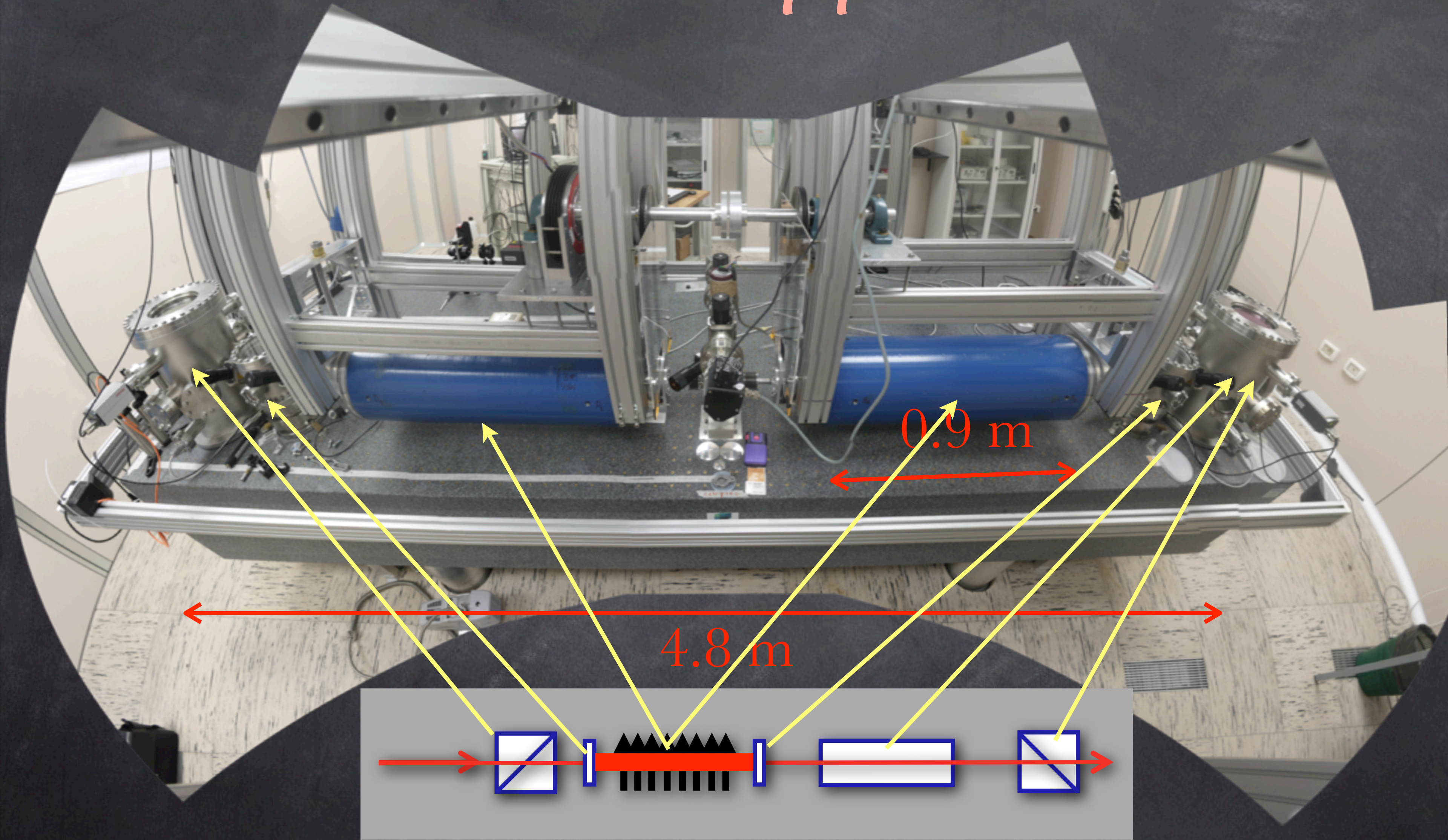
3.3 m long Fabry Perot cavity





2 W NPRO Nd:Yag Laser
λ = 1064 nm

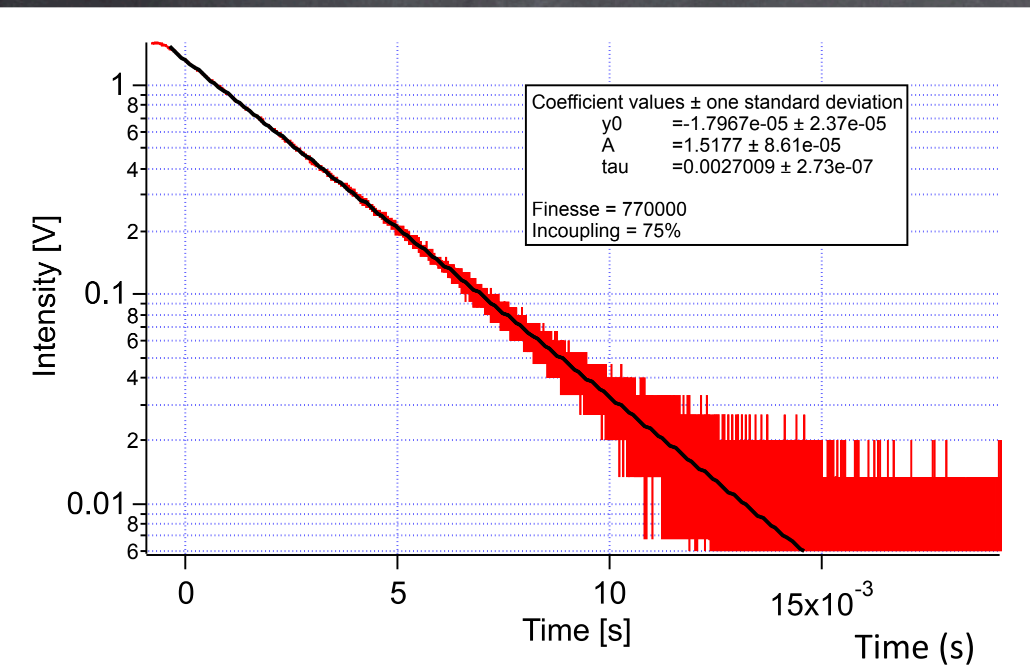
The mounted apparatus

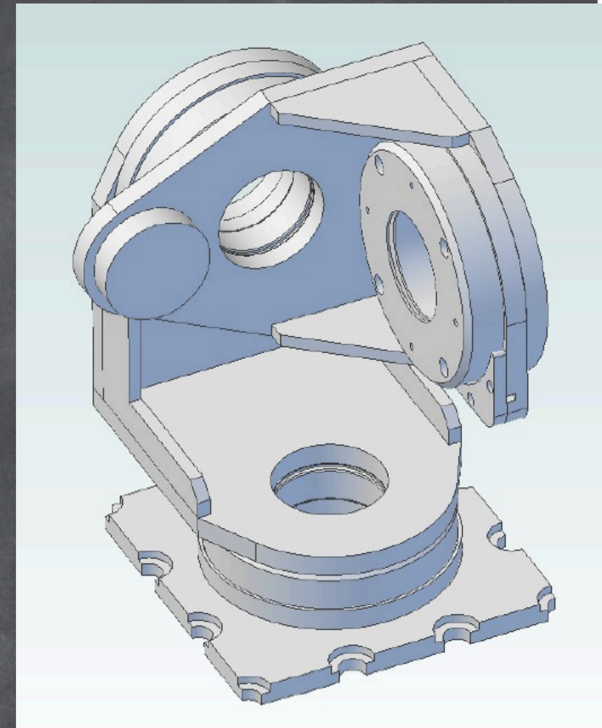


Cavity

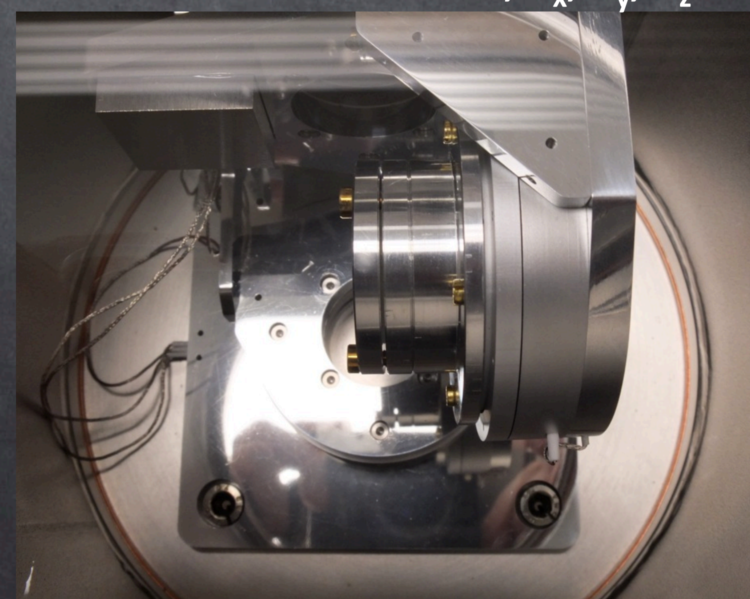
Fabry Perot cavity with low finesse and high finesse mirrors

Spherical mirror with r = − 2 m





3-Motor Mirror tilter, θ_x, θ_y, θ_z



Transmitted power up to 200 mW

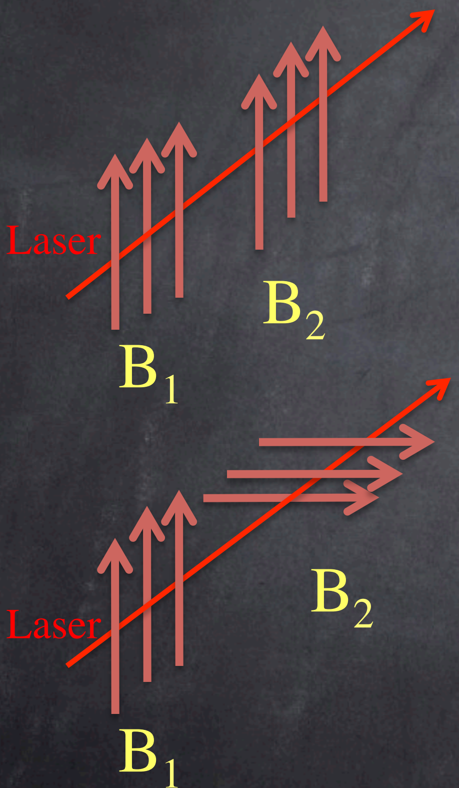
τ = 2.7 ms , d = 3.3 m

Finesse = 770 000 N = 480 000

Circulating power = 500 kW

Two magnets

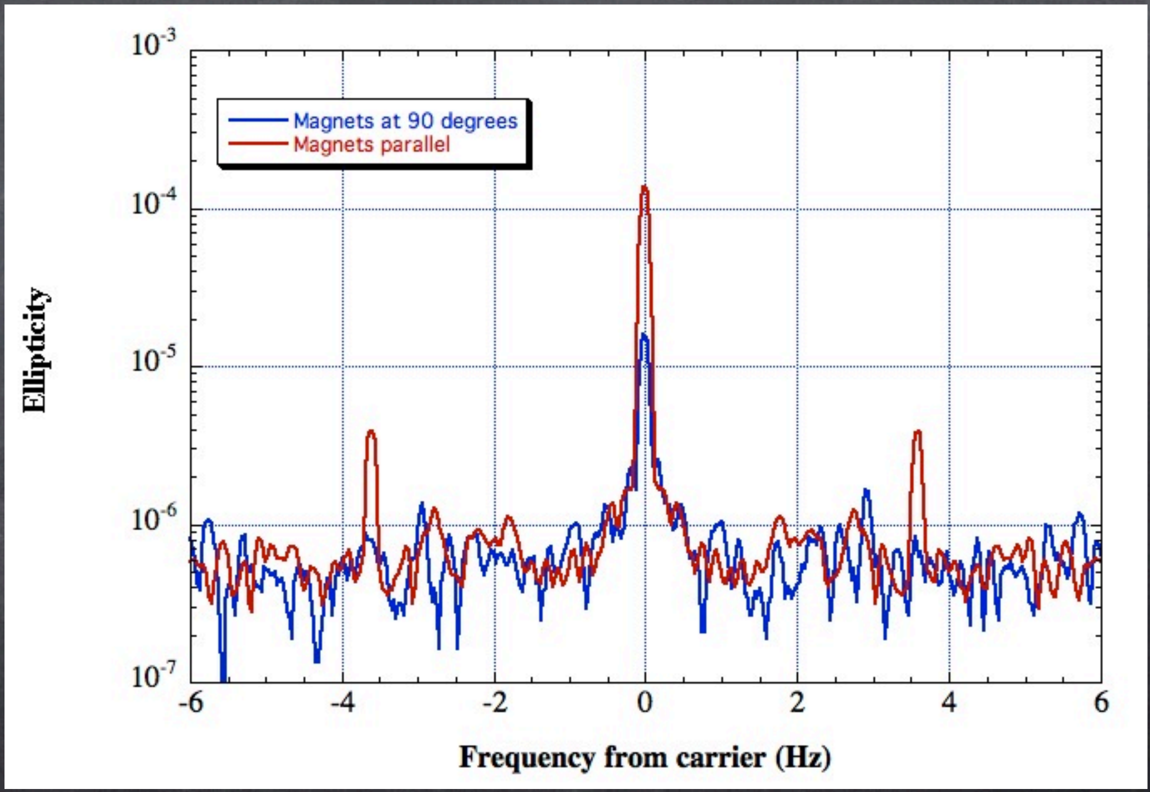
Two magnets system to check that signal is due to magnetic birefringence



$\Psi_{tot} = 2\Psi$

$\Psi_{tot} = 0$

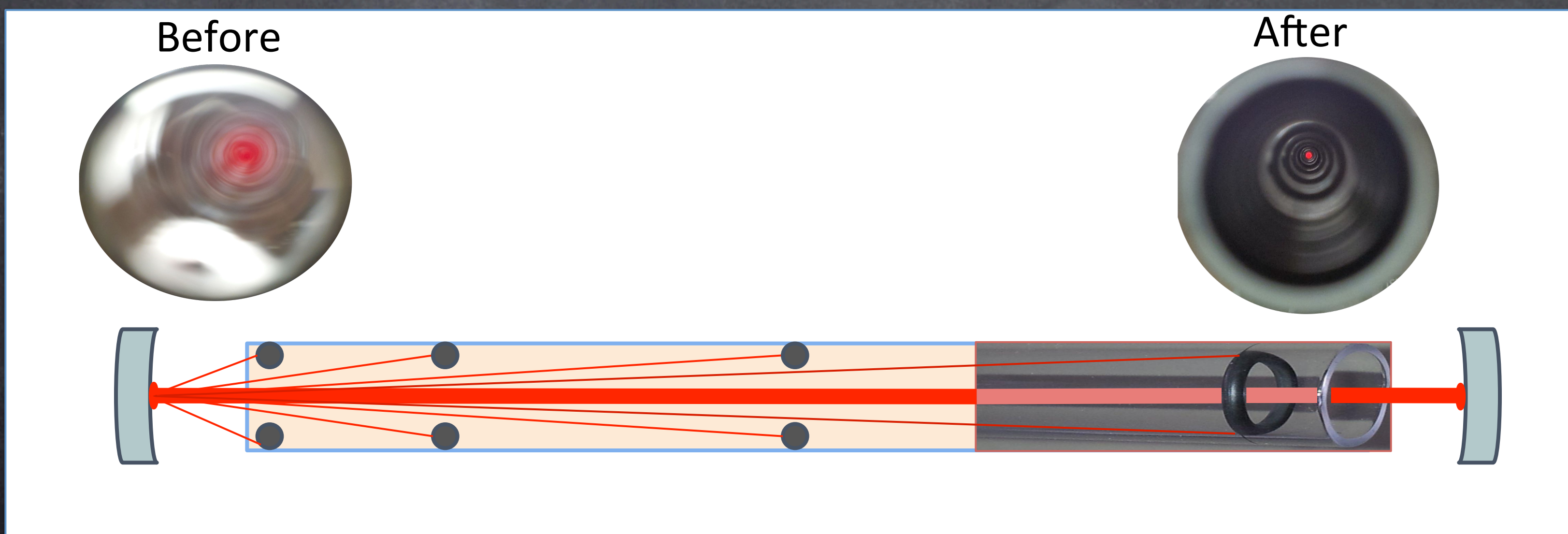
Measurement with 1.3 mbar of air



For a very weak signal this represents a crucial test

Diffused light in tube

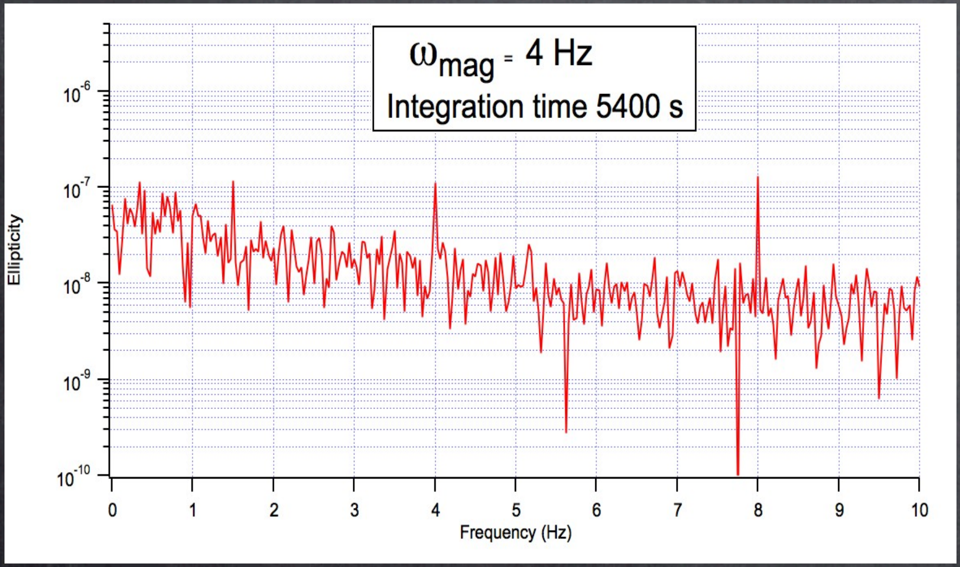
Baffles were mounted in properly spaced positions so that the light scattered from the mirror cannot see the internal surface of the glass tube.

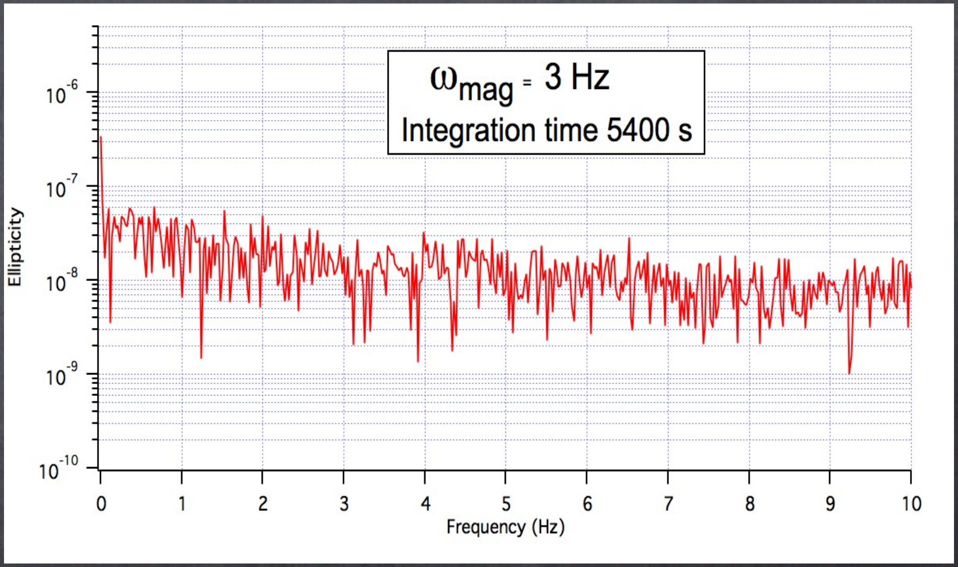


Diffused light in tube

- Glass tube without baffles: spurious peaks were present at ω_{mag} and $2\omega_{mag}$
- The peaks depended on the position of the tube in the magnet

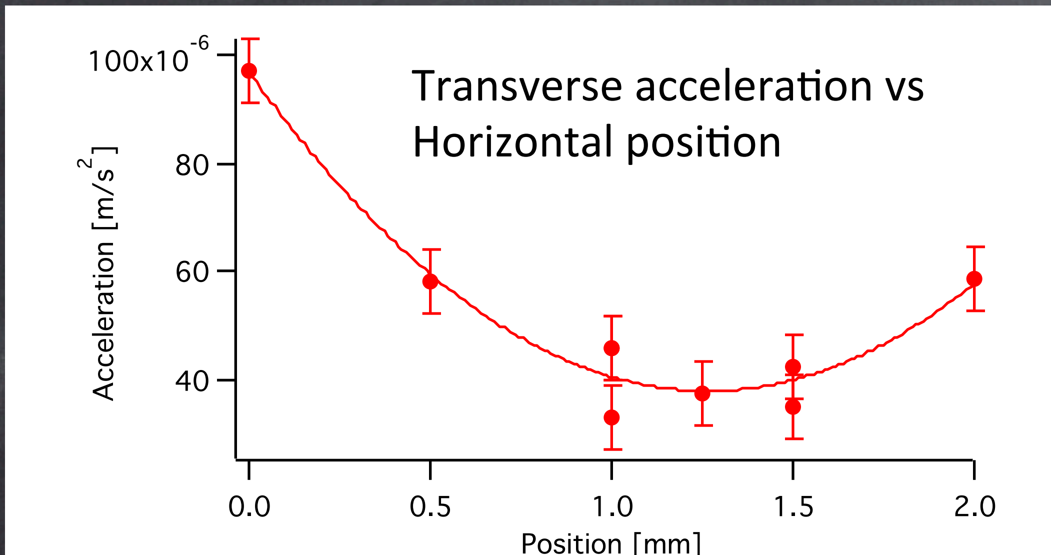
- Glass tube with baffles: spurious peaks are no longer present at ω_{mag} and $2\omega_{mag}$



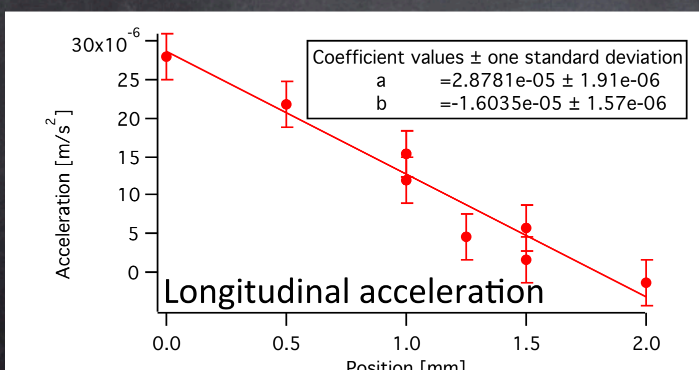


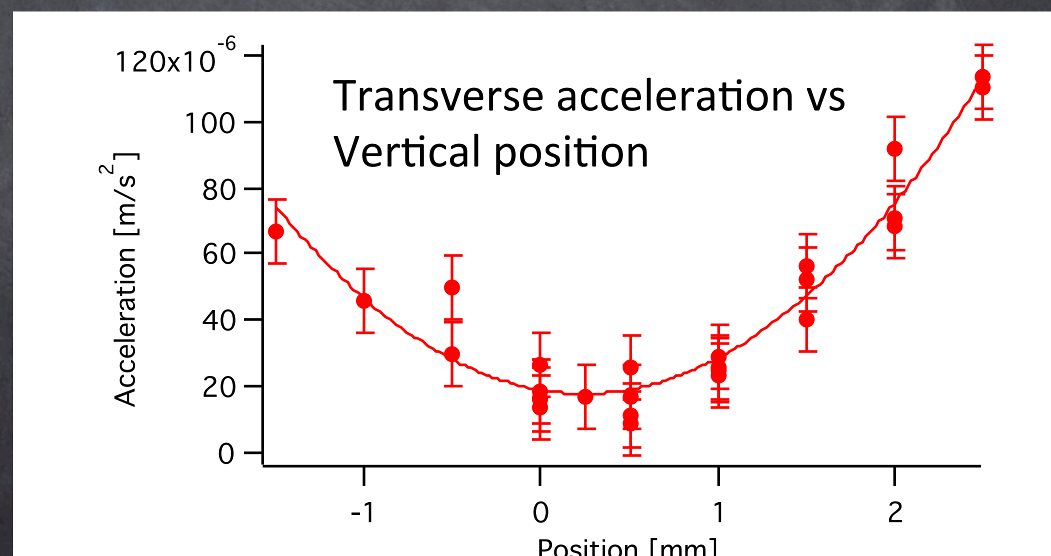
Unfortunately, no improvement in sensitivity

Tube movement



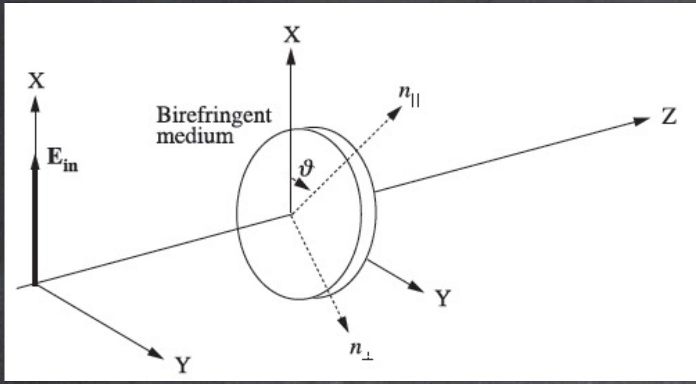
- Placing a 3-axis accelerometer on the glass tube we were able to study its movement as a function of its position
- The glass tube was positioned where the movement was minimum.

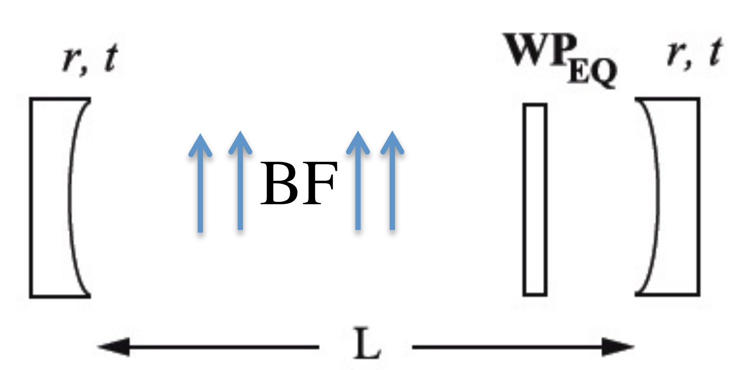




Mirror birefringence

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

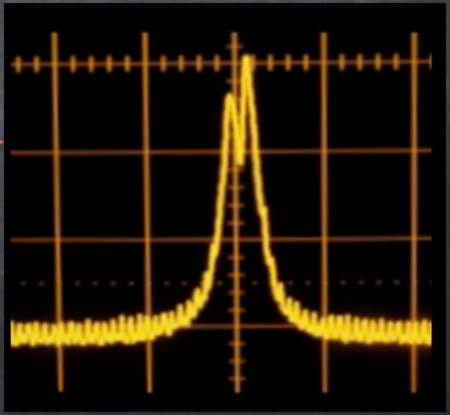




The resulting cavity behaves like a **waveplate.** This results in:

- cavity mode splitting

- increased 1/f noise (?)



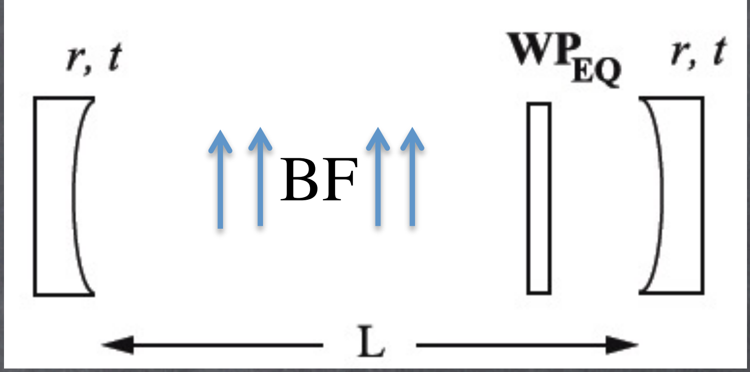
- Cavity mirrors must be rotated to reduce total birefringence
- Polarization must be aligned with one of the equivalent waveplate axes.

Mirror birefringence

[Appl. Phys. B 83, 571-577 (2006)]

$$\mathbf{WP}_{\rm EQ} = \begin{pmatrix} e^{+\imath\delta_{\rm EQ}/2} & 0 \\ 0 & e^{-\imath\delta_{\rm EQ}/2} \end{pmatrix}$$

$$\mathbf{BF} = \begin{pmatrix} 1+\imath\psi\cos 2\vartheta & \imath\psi\sin 2\vartheta \\ \imath\psi\sin 2\vartheta & 1-\imath\psi\cos 2\vartheta \end{pmatrix}$$



$$\mathbf{FP} = t^2 e^{\imath\delta/2} \sum_{n=0}^{\infty} \left[\mathbf{WP}_{\rm EQ}{}^2 \cdot \mathbf{BF}^2 r^2 e^{\imath\delta}\right]^n \cdot \mathbf{WP}_{\rm EQ} \cdot \mathbf{BF}$$

Input beam

$$\vec{E}_{\rm in} = E_0 \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

Locking condition

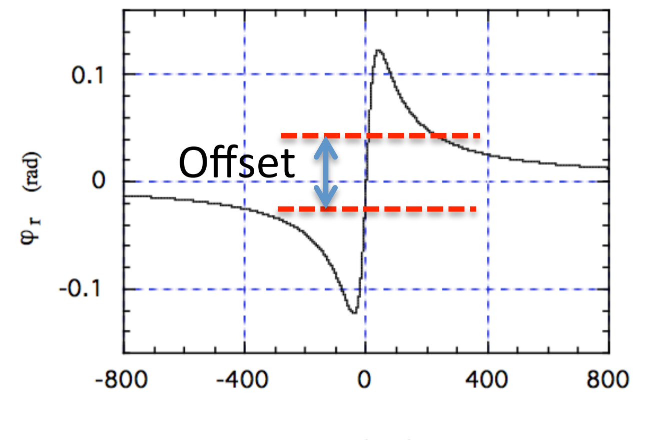
$$\delta + \delta_{\rm EQ} + 2\psi\cos 2\vartheta = 0$$

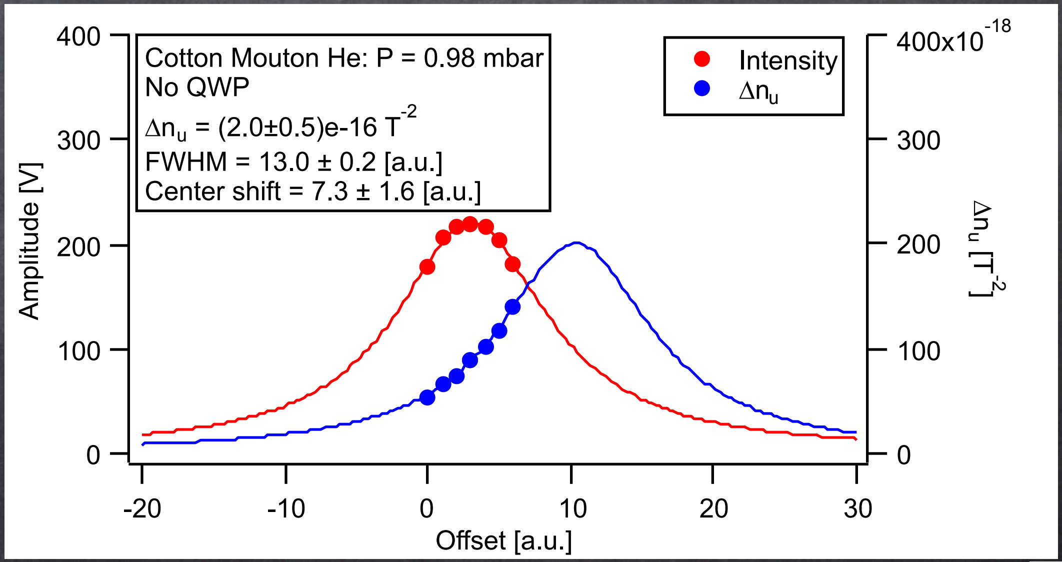
Cavity birefringence

- With He gas at various pressures we measured the ellipticity as a function of feedback offset δ
- The imaginary part of $E(t)$ will beat with the ellipticity of the modulator

$$E(t) = E_0 \left(\frac{2\mathcal{F}}{\pi}\right) i\psi \sin 2\theta \left(1 - i(\delta_{\rm EQ} - \delta)\frac{2\mathcal{F}}{\pi}\right)\left(\frac{1}{1+\frac{4r^2\sin^2(\delta_{\rm EQ}-\delta)}{(1-r^2)^2}}\right)$$

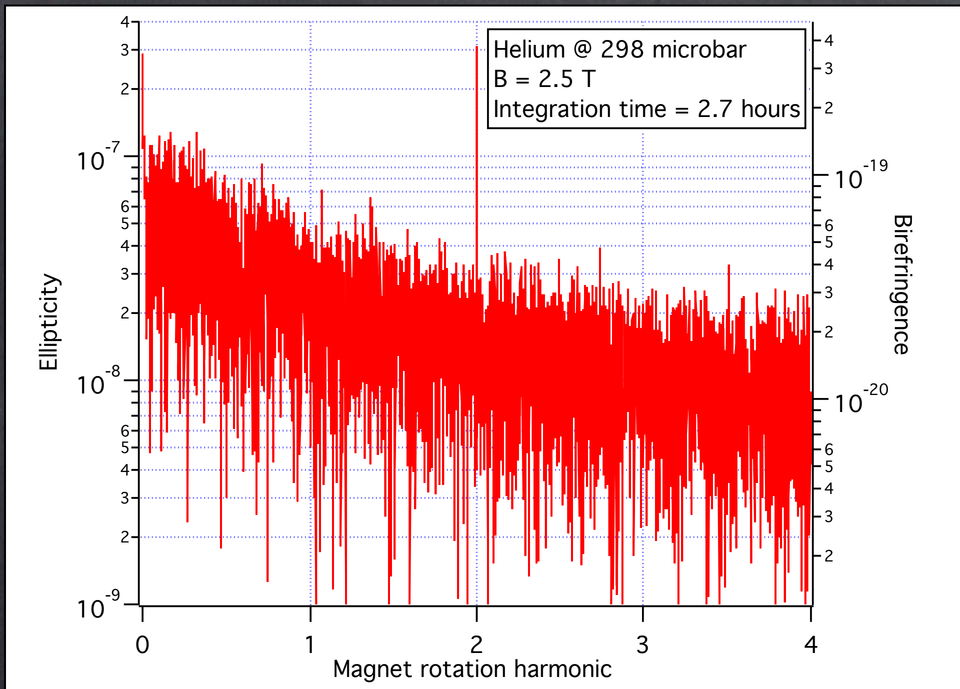
Error signal





Example with P = 0.98 mbar He

Measurement output

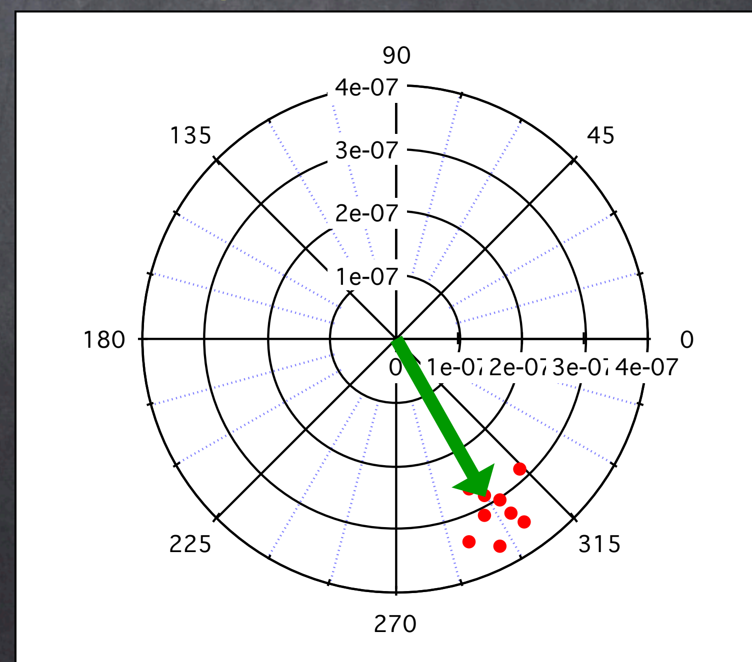


Heterodyne detection technique (Rotating Magnet)

Measured effect given by Fourier amplitude and phase at signal frequency

Vector in the polar plane.

Defines physical axis for any birefringence.

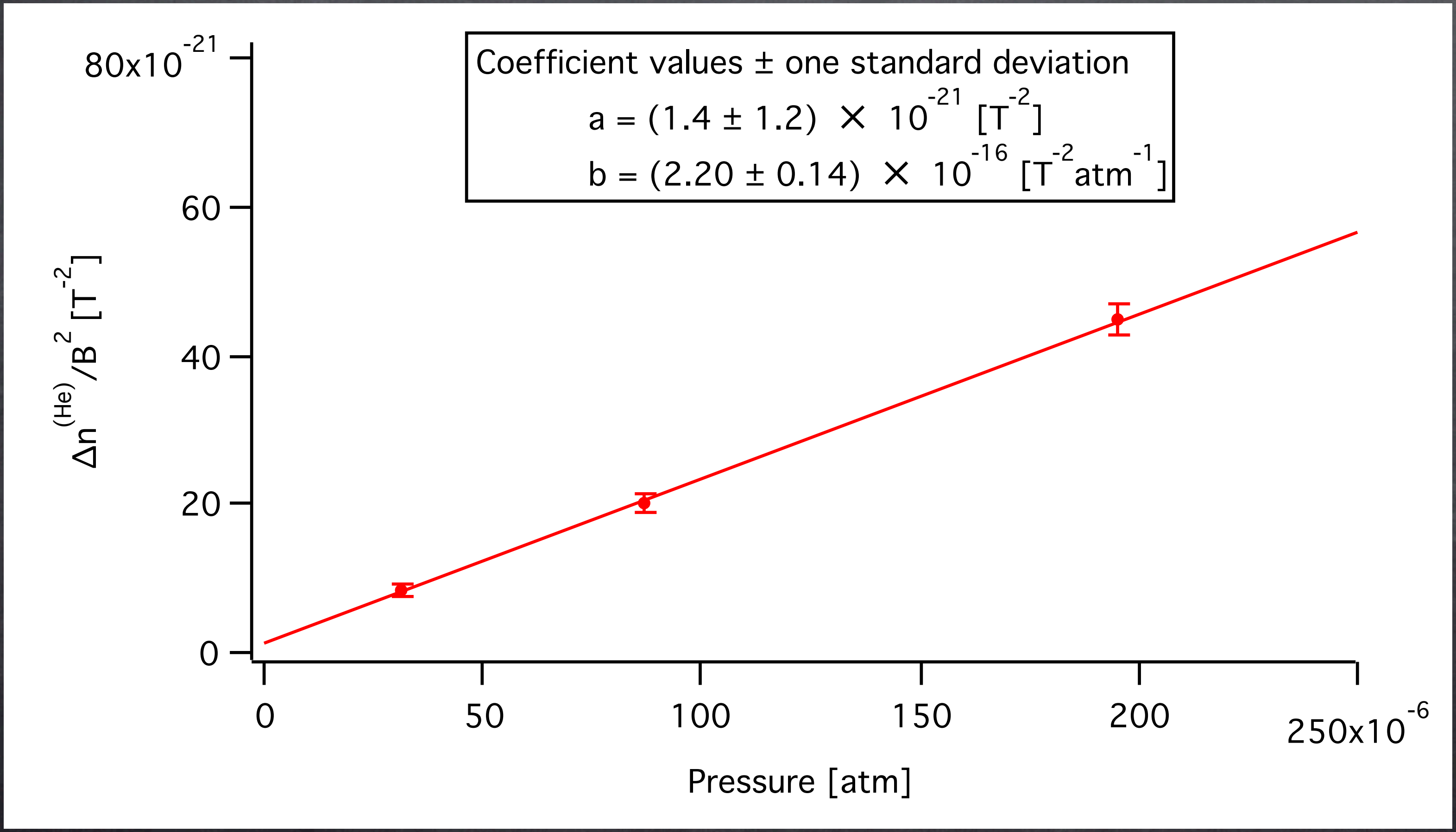


The **amplitude** measures the ellipticity/rotation
The **phase** is related to the triggers position and magnetic field direction. True physical signal must have a definite phase detremined with gases

$$\psi(t) = \psi_0 \sin(2\omega_{\mathrm{Mag}} + \vartheta_0)$$

Calibration with He

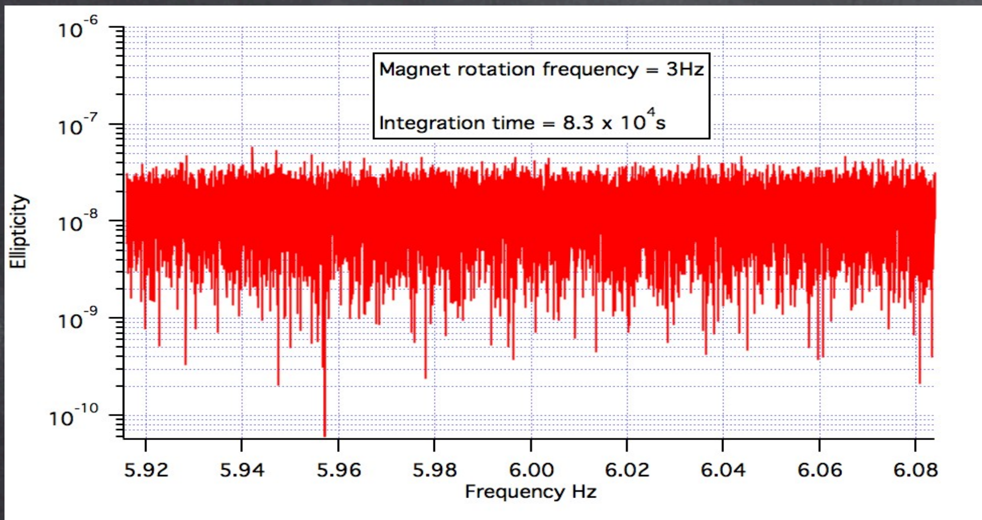
Takes into account the response of the birefringent cavity



The low pressure point took 4 hours integration: apparatus seems stable

Vacuum birefringence results

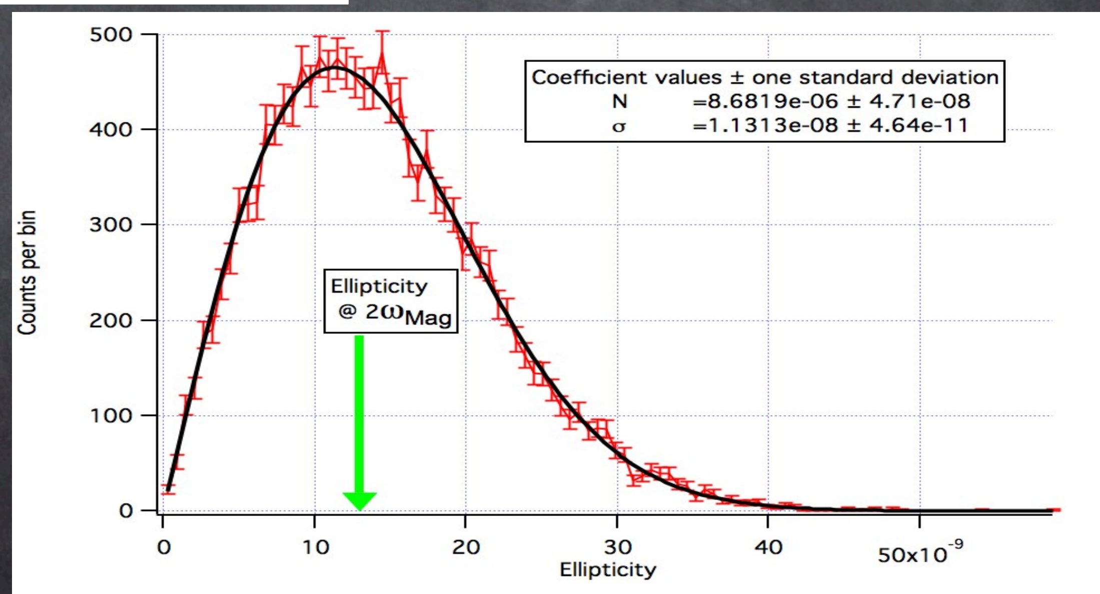
Spectrum of obtained data around signal frequency



Distribution of noise
Rayleigh function

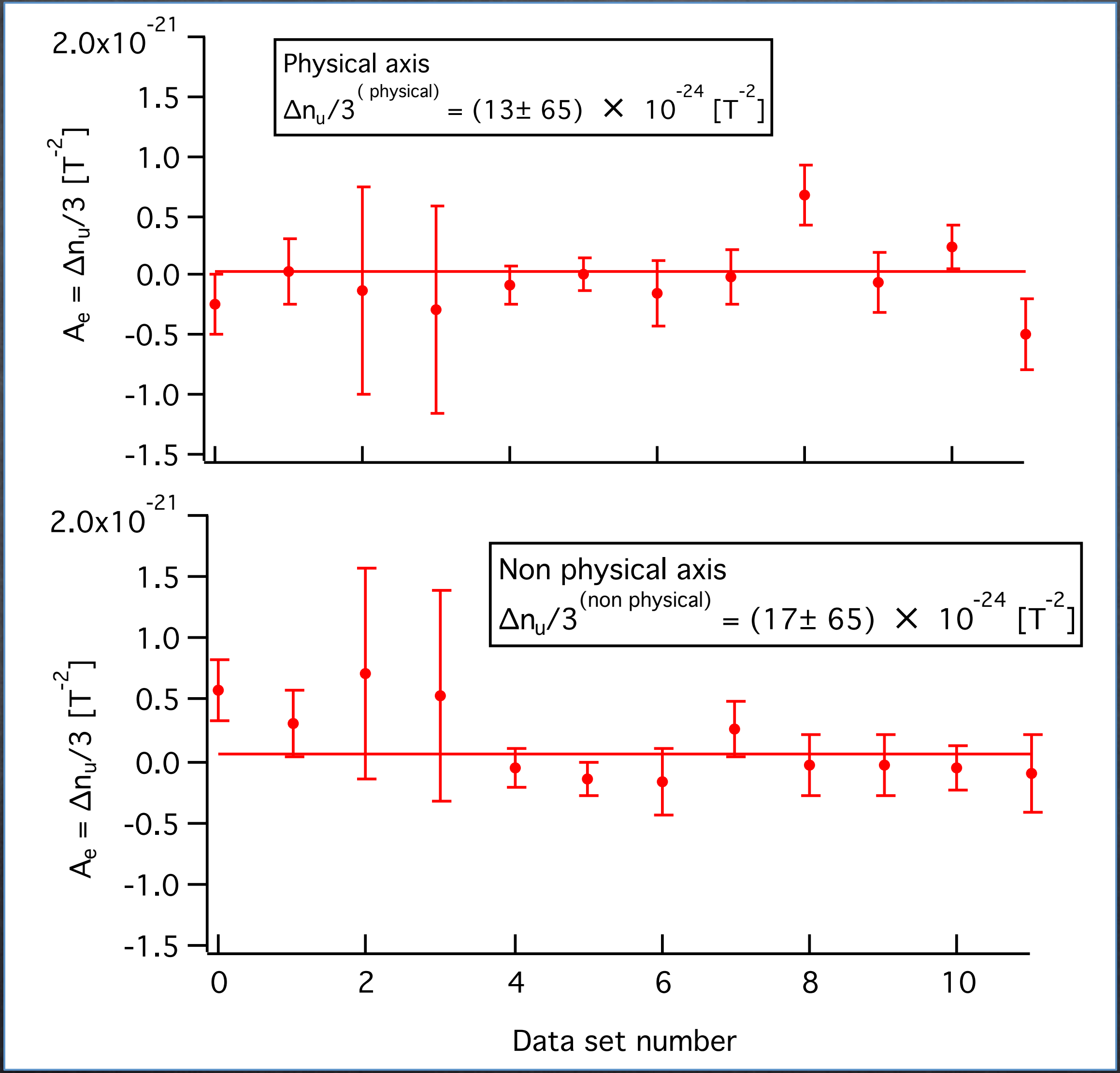
$$P(r) = N\frac{r}{\sigma_\psi^2}e^{-\frac{r^2}{2\sigma_\psi^2}}$$

$\sigma_\psi = 1.1\ 10^{-8}$



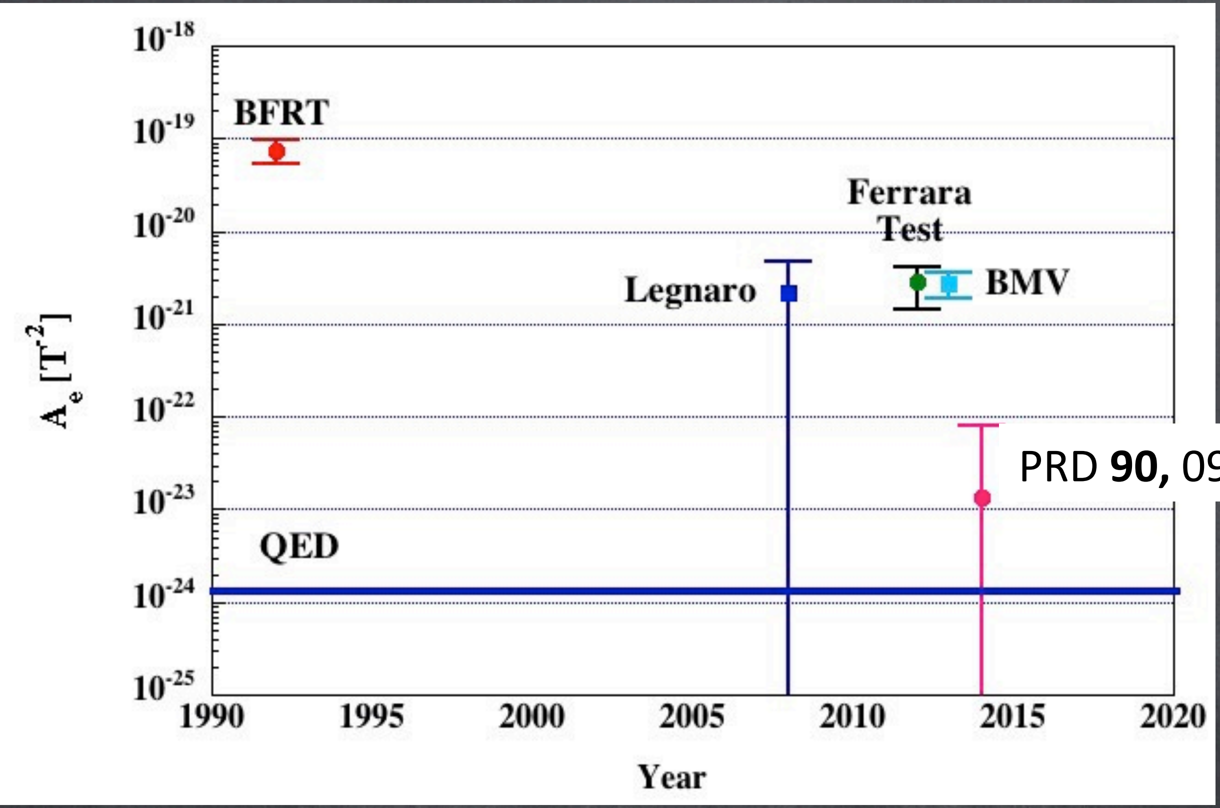
All data

Total integration time = 210 hours



New limits (QED)

Error bars correspond to 1 standard deviation



PRD **90,** 092003 (2014)

$$\Delta n^{(\mathrm{PVLAS})} = (2.5 \pm 12) \times 10^{-22} \ @ \ 2.5\ \mathrm{T}$$

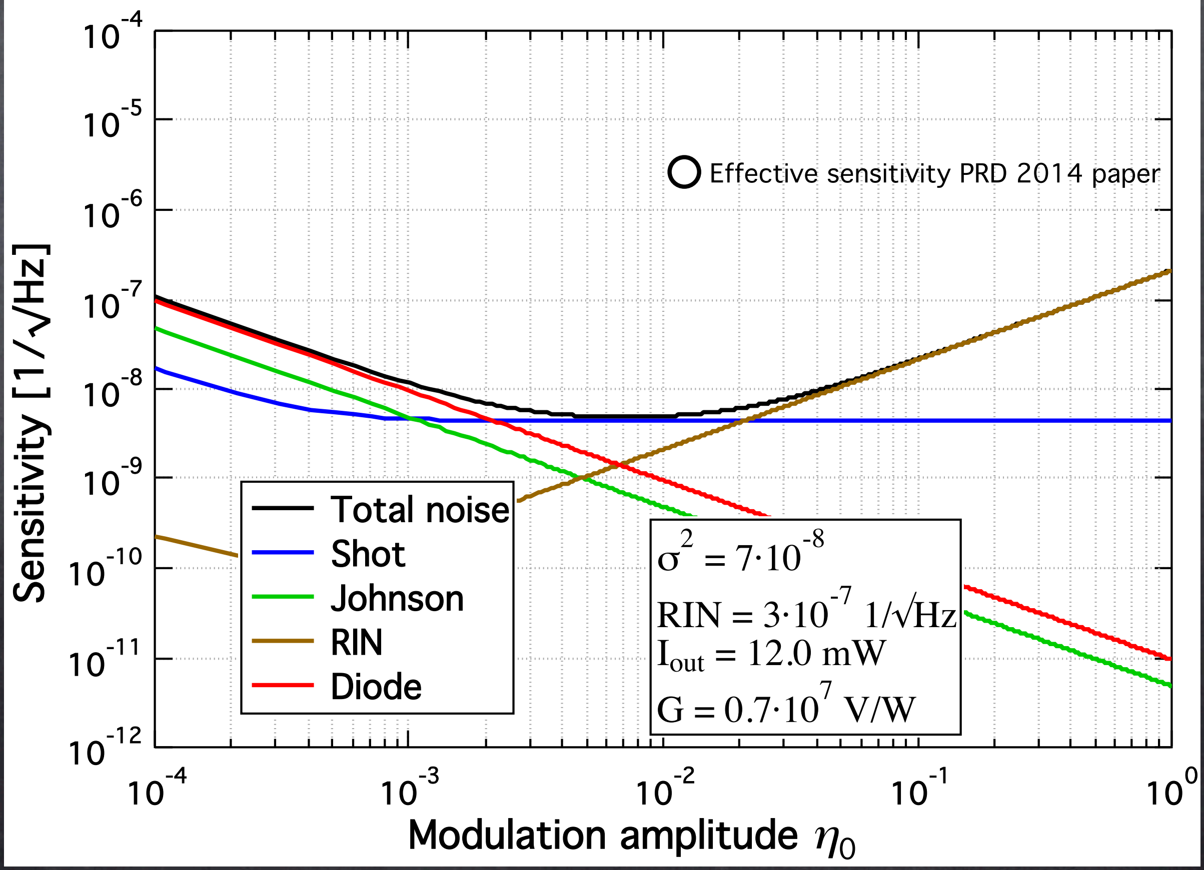
$$\Delta n_u^{(\mathrm{PVLAS})} = 3A_e = (4 \pm 20) \times 10^{-23}\ \mathrm{T}^{-2}$$

Significant improvemt but still far from QED

Calculated and measured noise

- Contribution of the various noises as a function of the modulation amplitude η_0 compared to the measured sensitivity.

F = 670000



Rotation measurements

Mirror birefringence

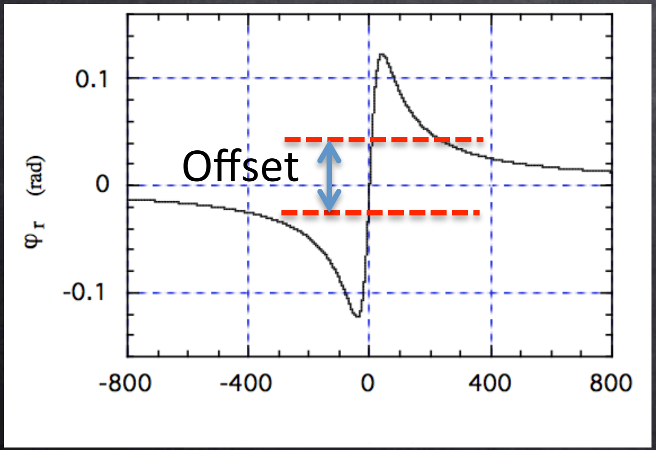
The laser is locked with its polarization along one of the cavity's axis.

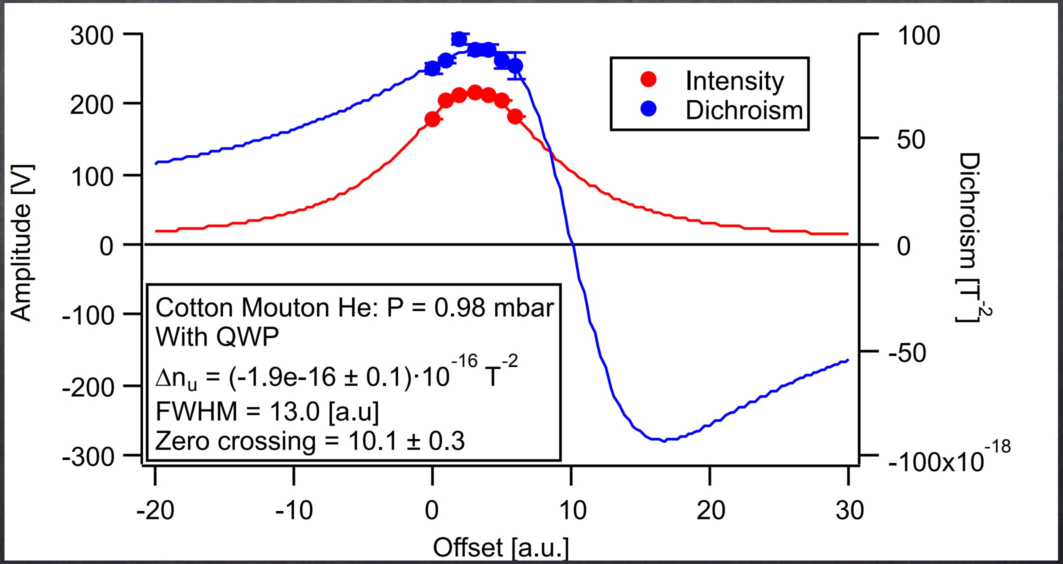
- the perpendicular polarization acquires an extra phase due to the cavity birefringence
- there is also a rotation (real component) [Appl. Phys. B 83, 571-577 (2006)]

$$E(t) = E_0 \left(\frac{2\mathcal{F}}{\pi}\right) i\psi \sin 2\theta \left(1 - i(\delta_{\mathrm{EQ}} - \delta)\frac{2\mathcal{F}}{\pi}\right)\left(\frac{1}{1 + \frac{4r^2 \sin^2(\delta_{\mathrm{EQ}} - \delta)}{(1-r^2)^2}}\right)$$

With a QWP and the ellipticity modulator one can measure the induced rotation.

Error signal





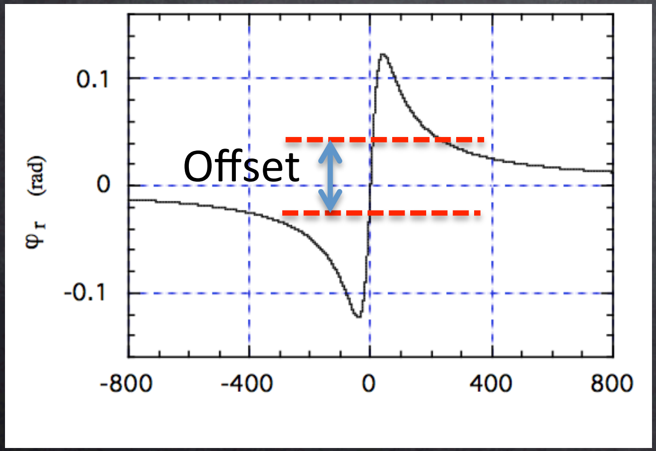
Mirror birefringence

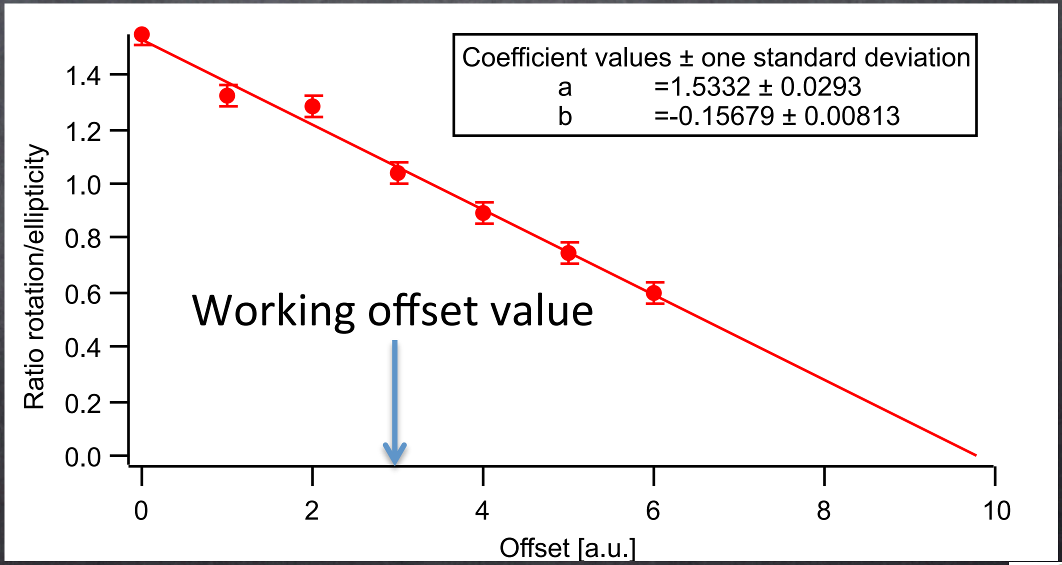
Vice versa if there were a rotation ε induced in the cavity it will partially convert to an ellipticity and beat with the modulator alone

$$E(t) = E_0 \left(\frac{2\mathcal{F}}{\pi}\right) \epsilon \sin 2\theta \left(1 - i(\delta_{\rm EQ} - \delta)\frac{2\mathcal{F}}{\pi}\right)\left(\frac{1}{1+\frac{4r^2\sin^2(\delta_{\rm EQ}-\delta)}{(1-r^2)^2}}\right)$$

Rotation/ellipticity

Error signal



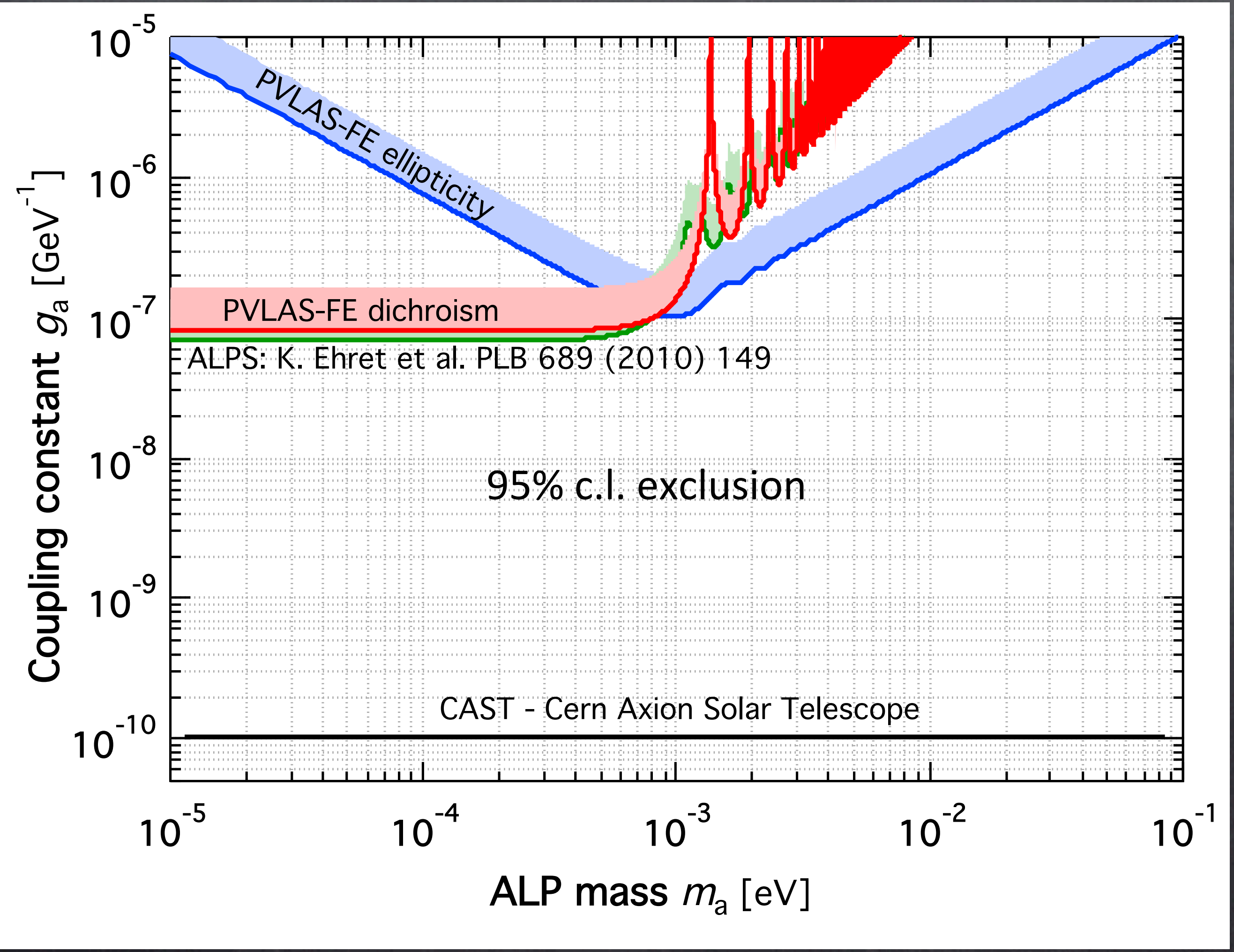


Working offset value = 3.1 → Rotation/ellipticity = 1

Axion-like particles

Total Integration time = 1.15·10^6 s

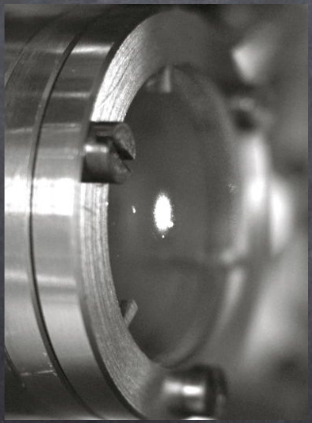
Assuming all the noise is due to ALP rotation: $\epsilon_{\mathrm{vac}} = (2.1 \pm 1.3) \times 10^{-9}$

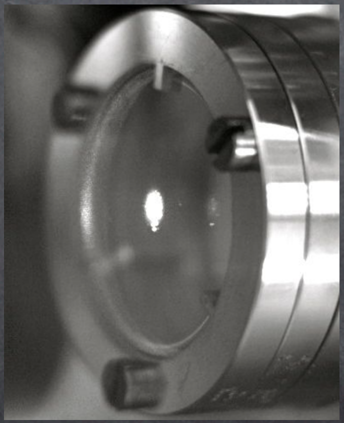


Problems and how to proeed

Sensitivity far from expected

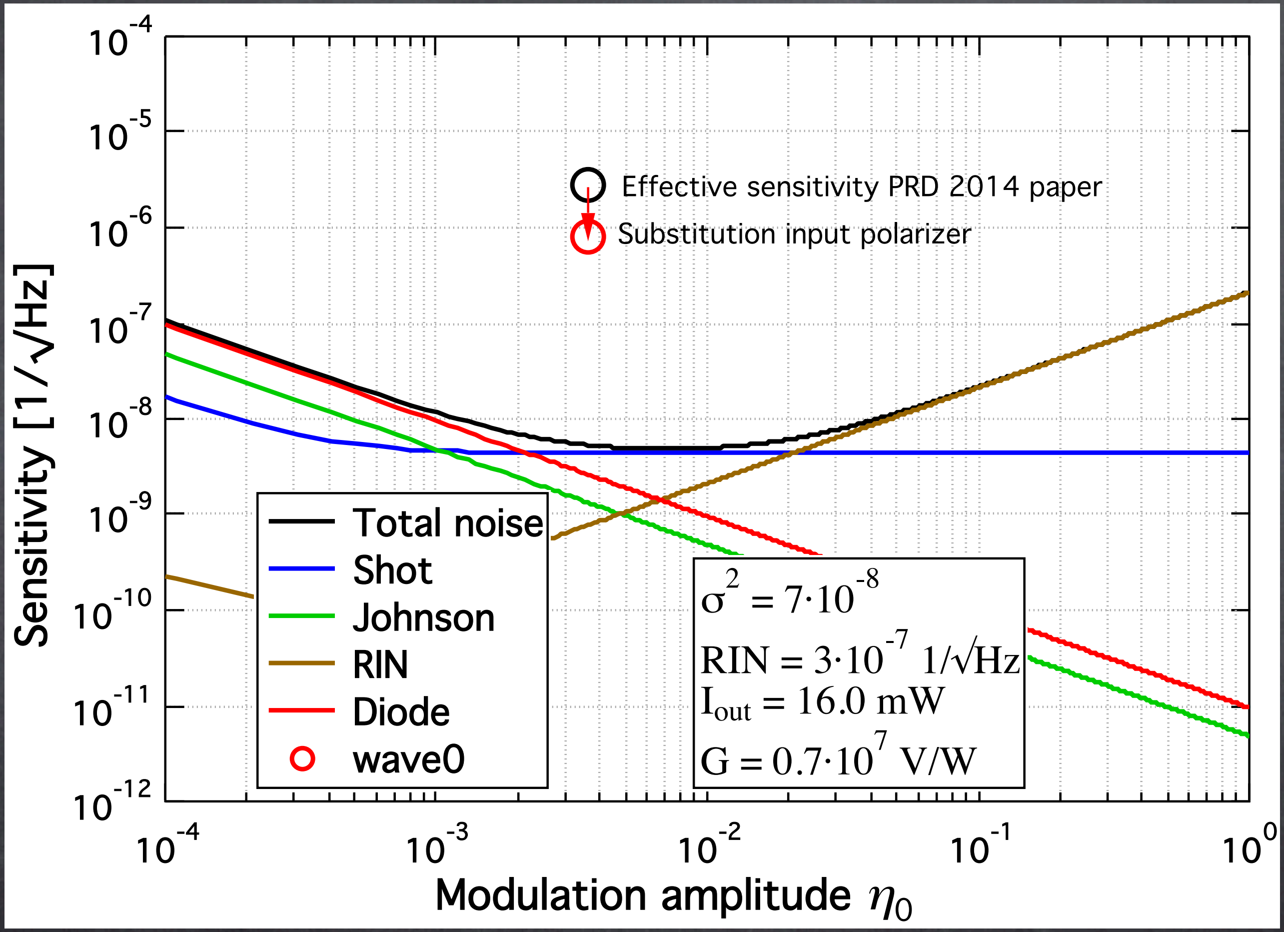
- Diffused light in the chambers due to optical elements and from a few dust speckles on the mirrors
- Substituted input polarizer (fewer surfaces) and noise improved by factor 3 …. Clue?





- Ordered wobble-sticks to try to design a cleaning method
- Ordered absorbing glass to cover inner walls of chambers

Future



- Starting new data taking with new sensitivity
- QED is still out of reach ….