Measuring vacuum magnetic birefringence using an LHC magnet: VMB@CERN

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Summary

- The Superposition Principle
- Vacuum magnetic birefringence
- Present experimental method
- PVLAS results
- Experience from PVLAS
- Polarization modulation scheme
- Possible problems

Superposition Principle

Before relativistic quantum mechanics:

- In vacuum the Superposition Principle holds. Electromagnetism is well described by Maxwell's equations in vacuum which are linear in the fields.
- Everyday experience indicates that light-by-light interaction is not observed.
- The velocity of light is a universal constant *c*. Today *c* is defined to be *c* = 299792458 m/s.

Classical electromagnetism in vacuum

Classical vacuum has no structure

In the absence of free charges and currents

$$\mathrm{div}\,\vec{\mathbf{D}} = 0; \qquad \mathrm{rot}\,\vec{\mathbf{E}} = -\frac{\partial\,\vec{\mathbf{B}}}{\partial t}$$

$$\mathrm{div}\,\vec{\mathbf{B}} = 0; \qquad \mathrm{rot}\,\vec{\mathbf{H}} = \frac{\partial\,\vec{\mathbf{D}}}{\partial t}$$

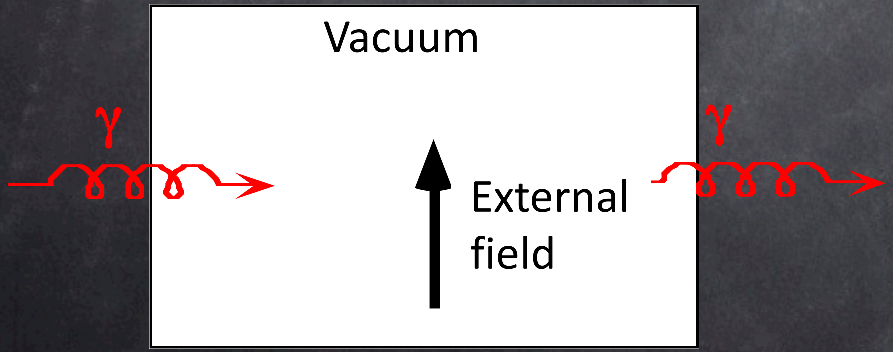
$$\mathcal{L}_{Class} = \frac{1}{2\mu_0}\left(\frac{\mathbf{E}^2}{c^2} - \mathbf{B}^2\right)$$

$$\vec{\mathbf{D}} = \frac{\partial \mathcal{L}_{Class}}{\partial\,\vec{\mathbf{E}}}$$

$$\vec{\mathbf{H}} = -\frac{\partial \mathcal{L}_{Class}}{\partial\,\vec{\mathbf{B}}}$$

$$\vec{\mathbf{D}} = \epsilon_0\,\vec{\mathbf{E}}$$

$$\vec{\mathbf{B}} = \mu_0\,\vec{\mathbf{H}}$$



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

New facts

Three important discoveries changed the scenario:

- Einstein's mass-energy relation (1905)

$$E = mc^2$$

- Heisenberg's Uncertainty Principle (1927)

$$\Delta E \, \Delta t \geq \frac{\hbar}{2}$$

- Dirac's relativistic equation for the electron (1928) predicting negative energy states (discovery anti-matter 1932)

Vacuum can fluctuate

For example, virtual electron-positron pairs may 'exist' for a short time

First intuition of LbL interaction

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

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

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."

Two possible types of phenomena must be considered separately in connection with the foregoing: (1) All incident quanta have the same direction of propagation; (2) The incident quanta have different directions of propagation. Since we are only interested in purely radiation phenomena the frequencies in the second case should lie below mc^2/h so that no permanent formation of electron-positron pairs can occur.

When all incident quanta have the same direction of propagation, the principle of conservation of momentum excludes all scattering processes other than those in the direction of the incident radiation. These scattering processes would be observable if accompanied by a change in frequency. In the language of Dirac's theory of radiation such splitting of the incident quantum occurs in processes of the following type: An electron in a negative energy state passes by absorption of the incident quantum into a state of positive energy; the electron then returns in several steps under emission of $h\nu$ in toto to its original state. At each step total momentum should be conserved.

O. Halpern, Phys. Rev. 44, pp 855, (1933)

H. Euler, B. Kockel (1935)

They wrote an effective Lagrangian density describing electromagnetic interactions in the presence of the virtual electron-positron sea discussed a few years before by Dirac.

$$\boxed{\begin{aligned}\mathcal{L}_{\mathrm{EK}} &= \frac{1}{2\mu_0}\left(\frac{\mathbf{E}^2}{c^2}-\mathbf{B}^2\right)+\\ &+\frac{A_e}{\mu_0}\left[\left(\frac{\mathbf{E}^2}{c^2}-\mathbf{B}^2\right)^2+7\left(\frac{\vec{\mathbf{E}}}{c}\cdot\vec{\mathbf{B}}\right)^2\right]+\ldots\end{aligned}}$$

$$A_e = \frac{2}{45\mu_0}\frac{\alpha^2\lambda\!\!\!^{-}{}_e^3}{m_e c^2} = 1.32\times 10^{-24}\ \mathrm{T}^{-2}$$

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)
J. Schwinger, *Phys. Rev.*, **82,** 664 (1951)

Leads to a non-linear behavior of electromagnetism in vacuum

Index of refraction - 1

Consider linearly polarized light propagating through a transverse magnetic field

By applying the constitutive relations to L_{EK} one finds

$$\vec{\mathbf{D}} = \frac{\partial \mathcal{L}_{EK}}{\partial \vec{\mathbf{E}}} \qquad \vec{\mathbf{H}} = -\frac{\partial \mathcal{L}_{EK}}{\partial \vec{\mathbf{B}}}$$

$$\vec{\mathbf{D}} = \epsilon_0 \vec{\mathbf{E}} + \epsilon_0 A_e \left[4\left(\frac{\mathbf{E}^2}{c^2} - \mathbf{B}^2\right)\vec{\mathbf{E}} + 14\left(\vec{\mathbf{E}}\cdot\vec{\mathbf{B}}\right)\vec{\mathbf{B}}\right]$$

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

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

Index of refraction

$$\begin{cases} \epsilon_\parallel^{(\mathrm{EK})} = 1 + 10 A_e \mathbf{B}_{\mathrm{ext}}^2 \\ \mu_\parallel^{(\mathrm{EK})} = 1 + 4 A_e \mathbf{B}_{\mathrm{ext}}^2 \\ \boxed{n_\parallel^{(\mathrm{EK})} = 1 + 7 A_e \mathbf{B}_{\mathrm{ext}}^2} \end{cases} \qquad \begin{cases} \epsilon_\perp^{(\mathrm{EK})} = 1 - 4 A_e \mathbf{B}_{\mathrm{ext}}^2 \\ \mu_\perp^{(\mathrm{EK})} = 1 + 12 A_e \mathbf{B}_{\mathrm{ext}}^2 \\ \boxed{n_\perp^{(\mathrm{EK})} = 1 + 4 A_e \mathbf{B}_{\mathrm{ext}}^2} \end{cases}$$

Index of refraction - 2

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

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

$v \neq c$

anisotropy

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

$$\Delta n_{(\alpha^2)} = 3A_e \mathbf{B}^2_{\text{ext}}$$

$$\Delta n_{(\alpha^3)} = 3A_e \mathbf{B}^2_{\text{ext}} \left(1 + \frac{25}{4\pi}\alpha\right)$$

$$\Delta n = (4.031699 \pm 0.000002) \times 10^{-24} \left(\frac{\mathbf{B}_{\text{ext}}}{1\,\mathrm{T}}\right)^2$$

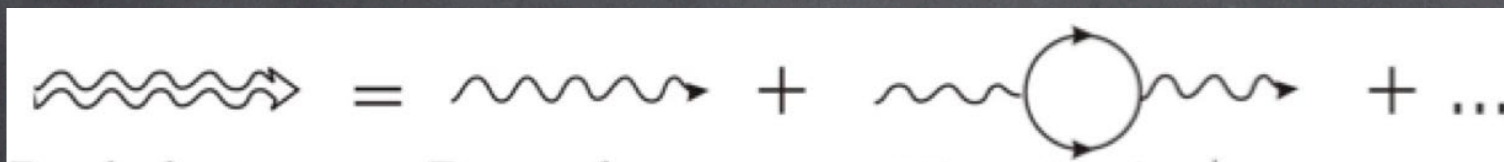
O(α^4), O(α^5) ? Also a theoretical challenge

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

Propagation of light

Photon propagation in vacuum as depicted with Feynman diagrams

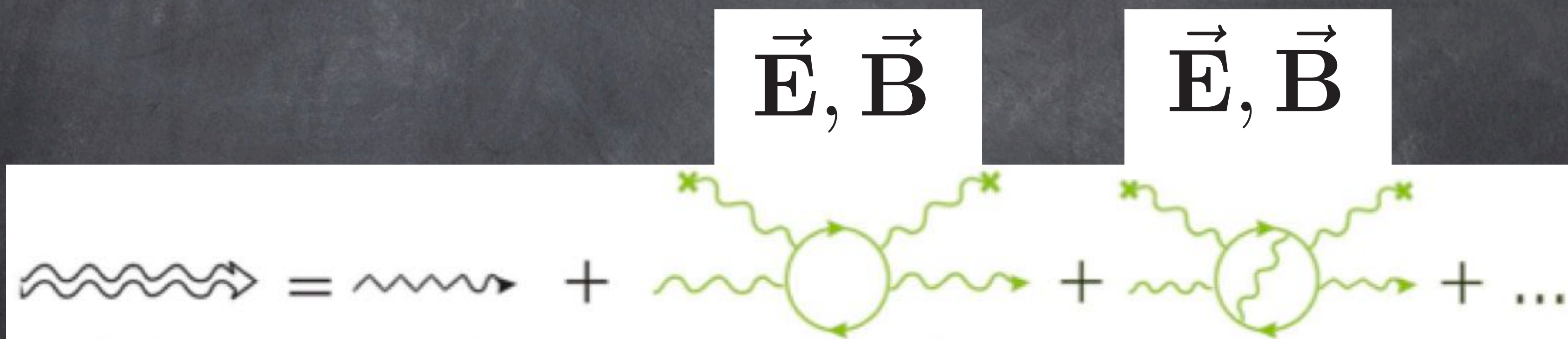
Without external field



$= c$

Real photon Bare photon Virtual pairs

With external field

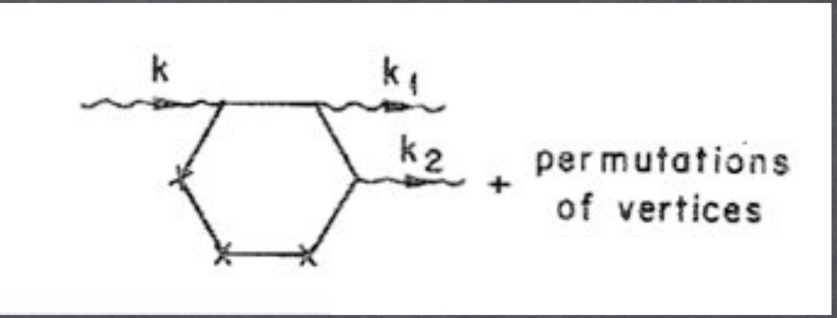


Real photon Bare photon Virtual pairs Radiative corrections

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

Index of refraction - 3

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



$$\mu_{\binom{\perp}{\parallel}} = \frac{4\pi}{\lambda}\kappa_{\binom{\perp}{\parallel}} = \begin{pmatrix}0.51\\0.24\end{pmatrix}\left[\frac{\hbar\omega}{m_e c^2}\right]^5\left[\frac{B\sin\vartheta}{B_{\mathrm{cr}}}\right]^6 \mathrm{cm}^{-1} \quad \left[B_{\mathrm{cr}} = \frac{m_e^2 c^2}{e\hbar} = 4.4\times 10^9\,\mathrm{T}\right]$$

Expected value for n_{vac}

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

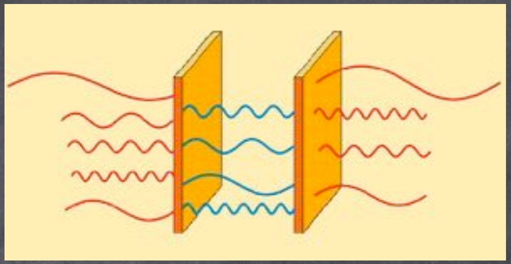
$$n_{\binom{\perp}{\parallel}} = 1 + \begin{pmatrix}4\\7\end{pmatrix}\times \underline{1.32\cdot 10^{-24}}\left(\frac{B}{1\,\mathrm{T}}\right)^2 - i\begin{pmatrix}0.51\\0.24\end{pmatrix}\underline{\times\, 4\cdot 10^{-91}}\left(\frac{\lambda}{1\,\mu\mathrm{m}}\right)\left(\frac{B}{1\,\mathrm{T}}\right)^6\left(\frac{\hbar\omega}{1\,\mathrm{eV}}\right)^6$$

$$A_e = \frac{2}{45\mu_0}\frac{\alpha^2 \lambdabar_e^3}{m_e c^2}$$

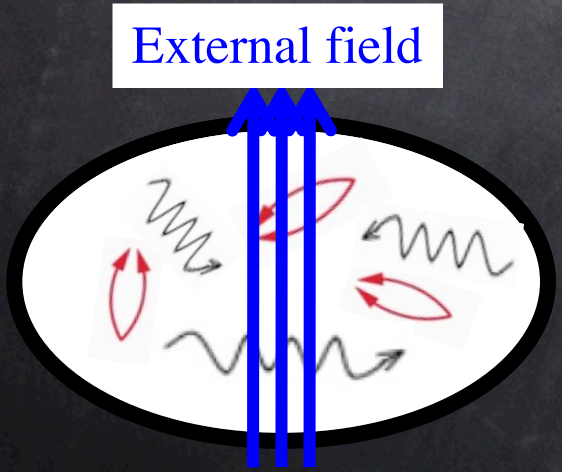
Unmeasurably small

QED Tests

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



- QED tests with only photons in the initial and final states is *still* missing



<u>Macroscopically observable (small) non-linear effects have been predicted since 1935 but have never been directly observed yet.</u>

We will concentrate on the electromagnetic vacuum

Linear birefringence

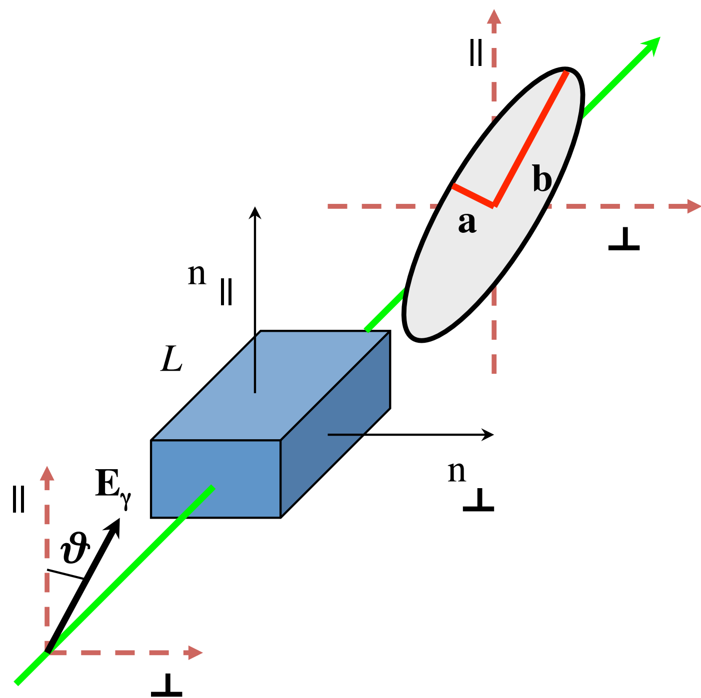
- A birefringent medium has $n_{||} \neq n_{\perp}$
- A linearly polarized light beam propagating through a birefringent medium will acquire an ellipticity ψ

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 $\phi = \frac{2\pi}{\lambda}(n_{\|} - n_{\perp})L$

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

Immaginary



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

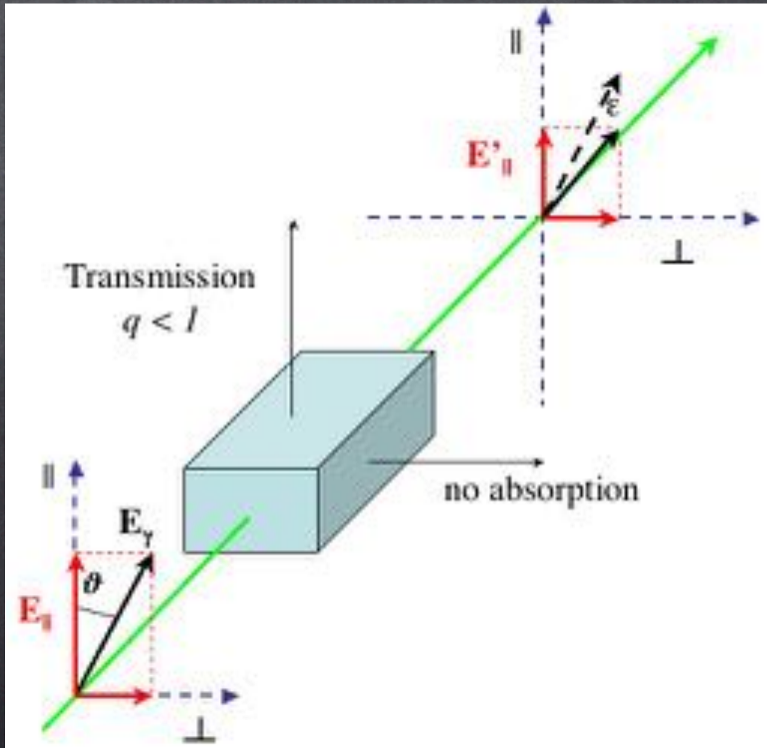
After a reduction of the field component parallel to **B** with respect to the component perpendicular to **B** by $1 - q = \frac{2\pi}{\lambda}(\kappa_{\|} - \kappa_{\perp})L$

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

Real

Apparent rotation

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



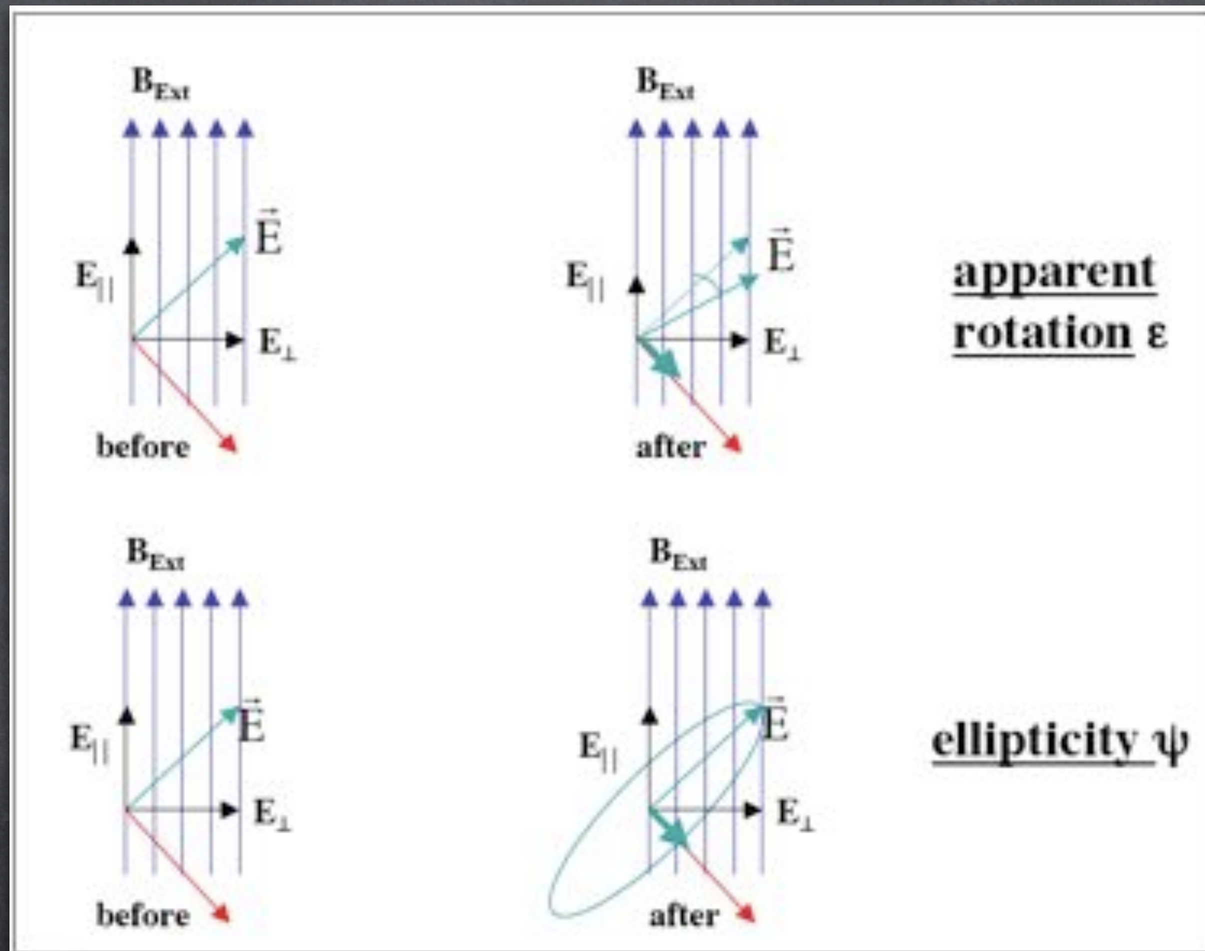
Summing up …

Dichroism $\Delta\kappa$

- (Photon splitting)
- ALPs, MCPs

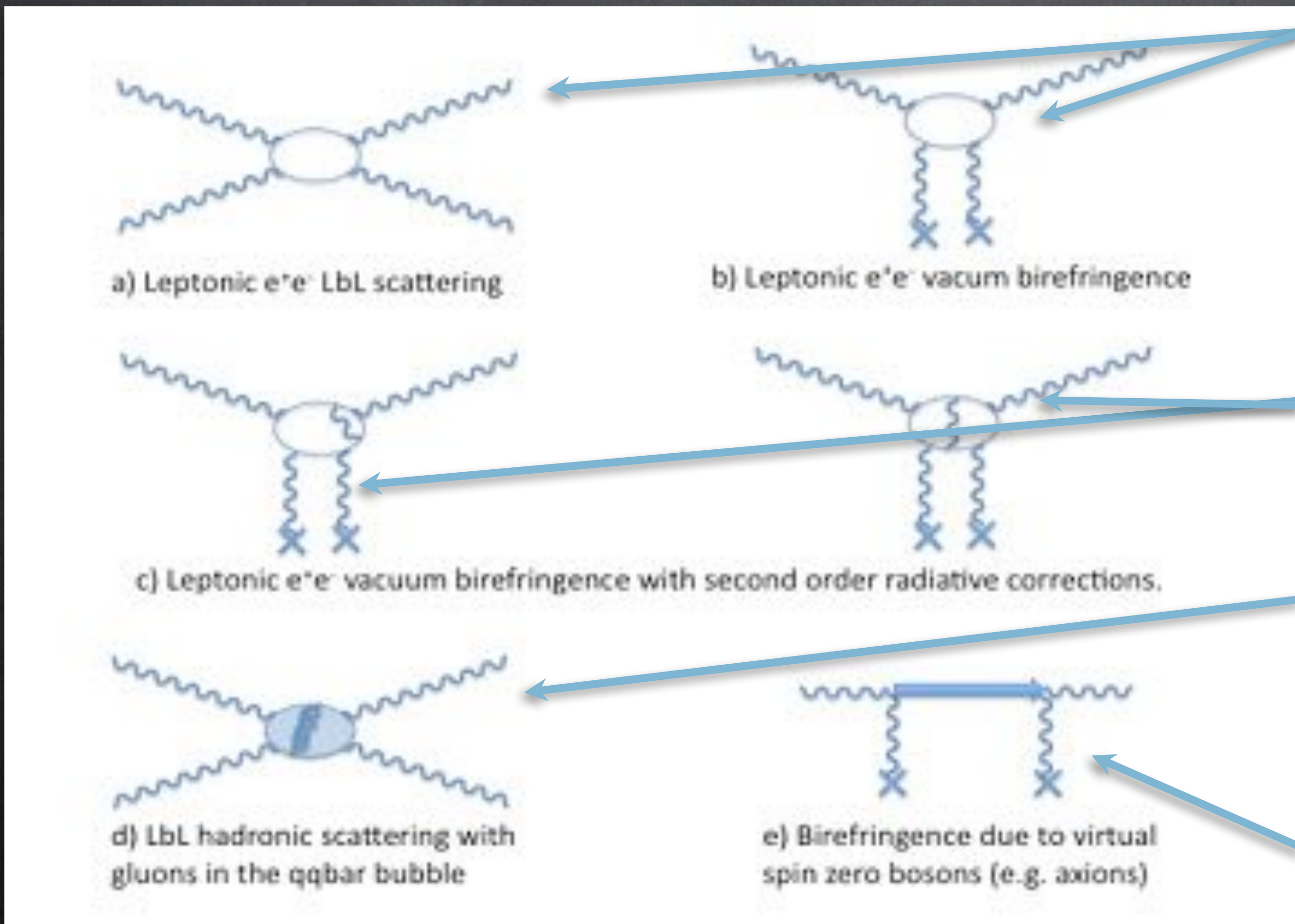
Birefringence Δn

- QED
- ALPs, MCPs



Both Δn and $\Delta\kappa$ are defined with sign

Summary of possible 4 photon processes



Described by the Euler-Heisenberg Lagrangian.

Should be there.

Also includes MCPs

Corrections 1.45%

Hadronic contribution. Difficult to extract from indirect measurements. g-2 open problem.

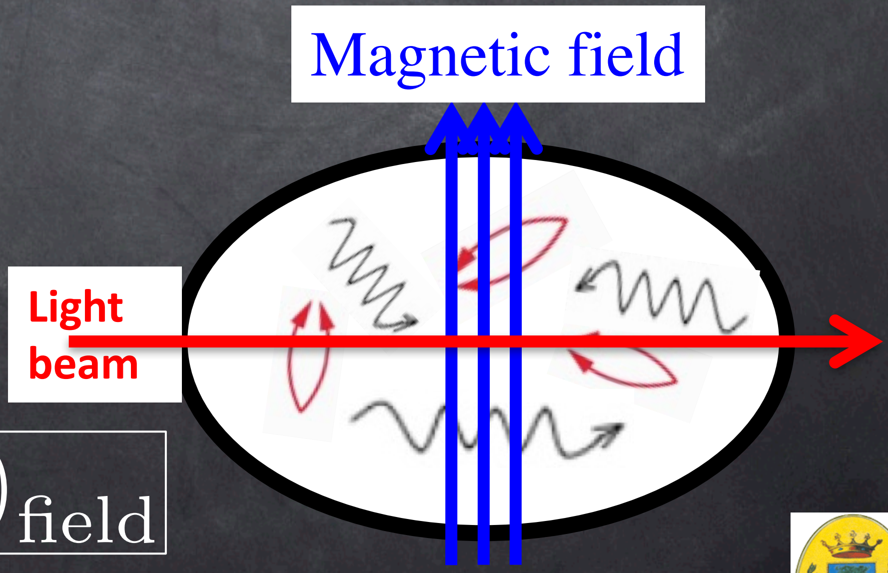
Contribution from hypothetical new particles coupling to two photons.

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

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

$$\boxed{n_{\text{vac}} = 1 + (n_{\text{B}} - i\kappa_{\text{B}})_{\text{field}}}$$



Light propagation in an external field

In particular the interest is to study and hopefully measure

- LINEAR BIREFRINGENCE (polarisation dependent index of refraction)
- LINEAR DICHROISM (polarisation dependent index of absorption)

acquired by vacuum when subject to an external magnetic field

$$\Delta\tilde{n}_{\rm vac} = \Delta n_{\rm B} - i\Delta\kappa_{\rm B}$$

Predicted (QED) Hypothetical (ALPs, MCPs)	Hypothetical (ALPs, MCPs)
birefringence	dichroism
$\Delta n_{\rm B} \propto B^2$	$\Delta\kappa_{\rm B} \propto B^2$
$n_{\rm B,\parallel} \neq n_{\rm B,\perp}$	$\kappa_{\rm B,\parallel} \neq \kappa_{\rm B,\perp}$

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}.

- First proposal to use a polarimeter to measure vacuum magnetic birefringence
- The basic measurement principle is still the same today.

Recent results

- Turolla et al. have indirectly inferred evidence of vacuum magnetic birefringence from optical polarimetry of an isolated neutron star
- ATLAS has indirectly observed $\gamma - \gamma$ interactions at high energies
- These results received lots of interest.
- Low energy non-linear vacuum effects remain a topic of great interest still lacking a direct laboratory confirmation.

- Turolla et al., Monthly Notices of the Royal Astronomical Society, Volume 465, Issue 1, 11 February 2017, Pages 492–500
- ATLAS collaboration, Nature Physics 13, 852–858 (2017)

Experimental method

Key ingredients of PVLAS

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

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

- 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

- $B = 2.5\ \mathrm{T}$
- $L_{\mathrm{eff}} \approx 700\ \mathrm{km}$

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

If we assume a maximum integration time of $10^6\ \mathrm{s}$ (= 12 days)

The necessary ellipticity sensitivity is $S_\psi < 5\cdot 10^{-8}\ 1/\sqrt{\mathrm{Hz}}$
Optical path difference sensitivity is $S_D < 4\cdot 10^{-20}\ \mathrm{m}/\sqrt{\mathrm{Hz}}$

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

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

In principle the effect should be measurable

Numerical values

Main interest of PVLAS is the Euler-Heisenberg birefringence

- $B = 2.5$ T
- $L_{\rm eff} \approx 700$ km

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

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

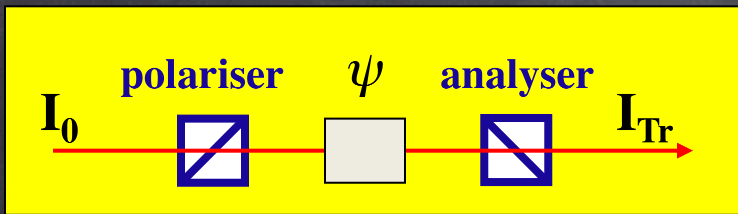
Optical path difference sensitivity is $S_D < 4\cdot 10^{-20}$ m/$\sqrt{\rm Hz}$
Presently our sensitivity is $S_D \approx 3\cdot 10^{-19}$ m/$\sqrt{\rm Hz}$ @ 23 Hz

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

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

In principle the effect should be measurable

Heterodyne detection

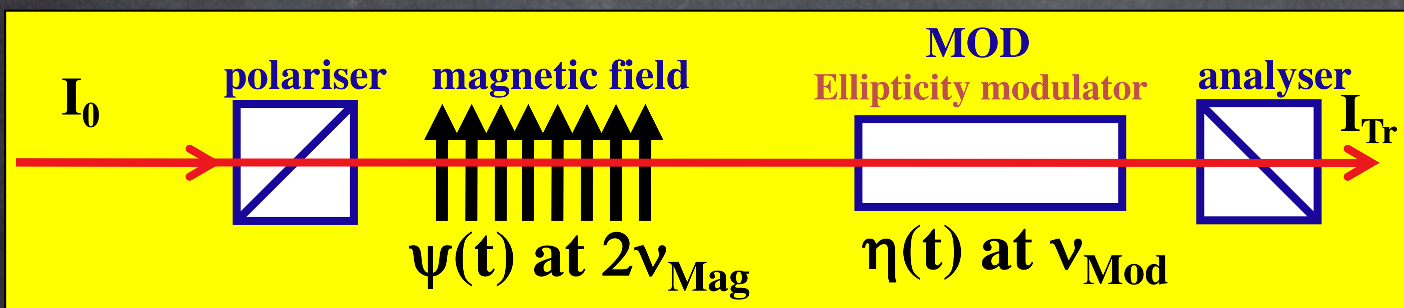


Static detection excluded

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

Extinction ratio $\sigma^2 \approx 10^{-7}$, $\psi \approx 10^{-11}$

Add a know time varying ellipticity $\eta(t)$ to ψ. With η, $\psi << 1$, these add algebraically.



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

The intensity $I_{\rm out}$ is now linear in the ellipticity ψ.

Heterodyne detection

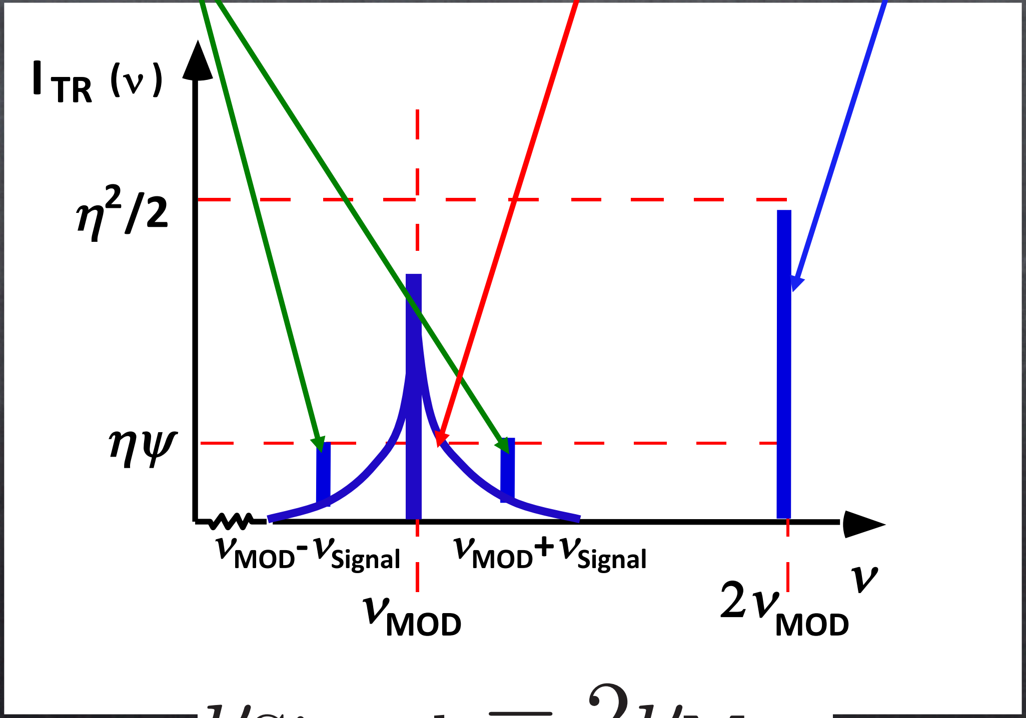
- In practice slowly varying spurious ellipticities $\alpha(t)$ are also present.
- $\psi \sin 2\vartheta$ can also be modulated in time by either rotating the magnetic field or by ramping it. In PVLAS we have permanent magnets and therefore rotate the magnetic field.
- By modulating both η and ϑ the 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

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

Fourier spectrum

With $\eta(t)$ and $\psi(t)$ sinusoidal functions

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



$$\nu_{\text{Signal}} = 2\nu_{\text{Mag}}$$

Ellipiticity vs Rotations

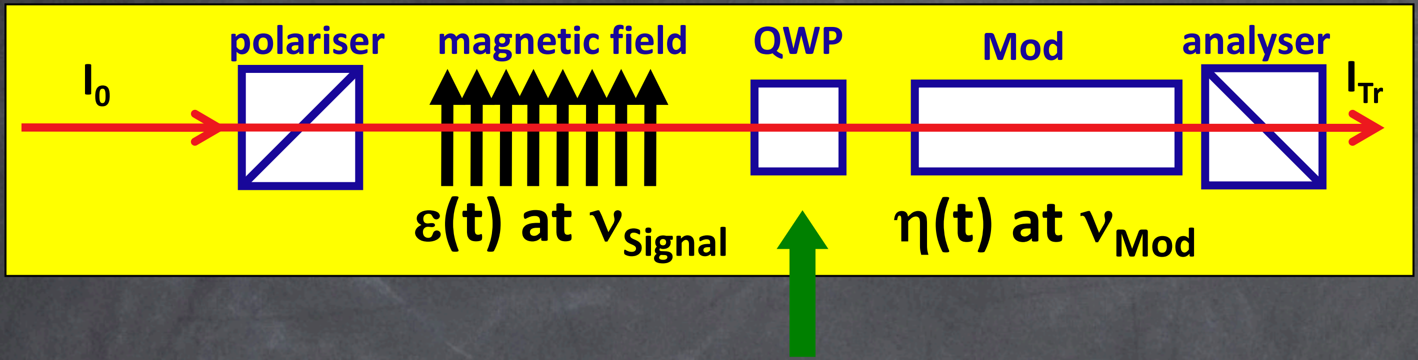
- Ellipticities have an imaginary component whereas rotations are real. If small they also add up algebraically.
- After the analyzer the electric field and the intensity will be

$$\vec{E}_{\text{out}} = E_0 \begin{pmatrix} 0 \\ \varphi + i\eta \end{pmatrix}$$

$$\Rightarrow \quad I_{\text{out}} = I_0 |\varphi + i\eta|^2 = I_0(\varphi^2 + \eta^2)$$

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

Heterodyne rotation detection



QWP can be inserted to transform a rotation $\varepsilon(t)$ into an ellipticity $\psi(t)$ with the same amplitude. It can be oriented in two positions:

QWP axis along polarization

QWP axis normal to polarization

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

$$I_{\text{out}} = I_0\left[\sigma^2 + |i\psi(t) + i\eta(t)|^2\right] =$$
$$= I_0\left[\sigma^2 + \eta^2(t) \pm 2\eta(t)\epsilon(t) + \ldots\right]$$

Optical path multiplier

Optical path multiplier

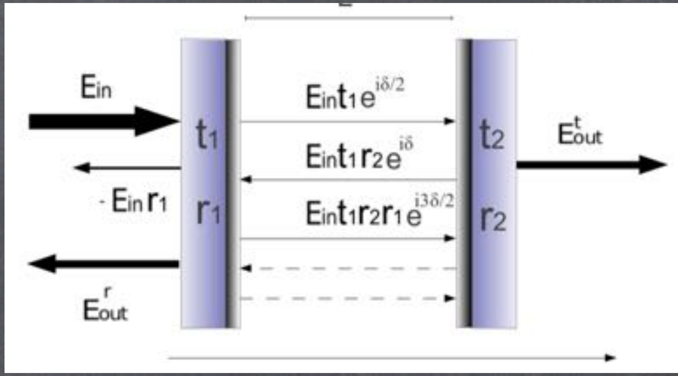
- The ellipticity induced by a birefringence is proportional to the path length in the magnetic region
- A Fabry-Perot interferometer is used to increase the path length by a factor of about 430'000. A magnet 1 meter long becomes equivalent to 430 km!
- Very high reflectivity mirrors with very low losses (≈ ppm) are used
- A critical 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

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

With loses: $t^2 + r^2 + p = 1$

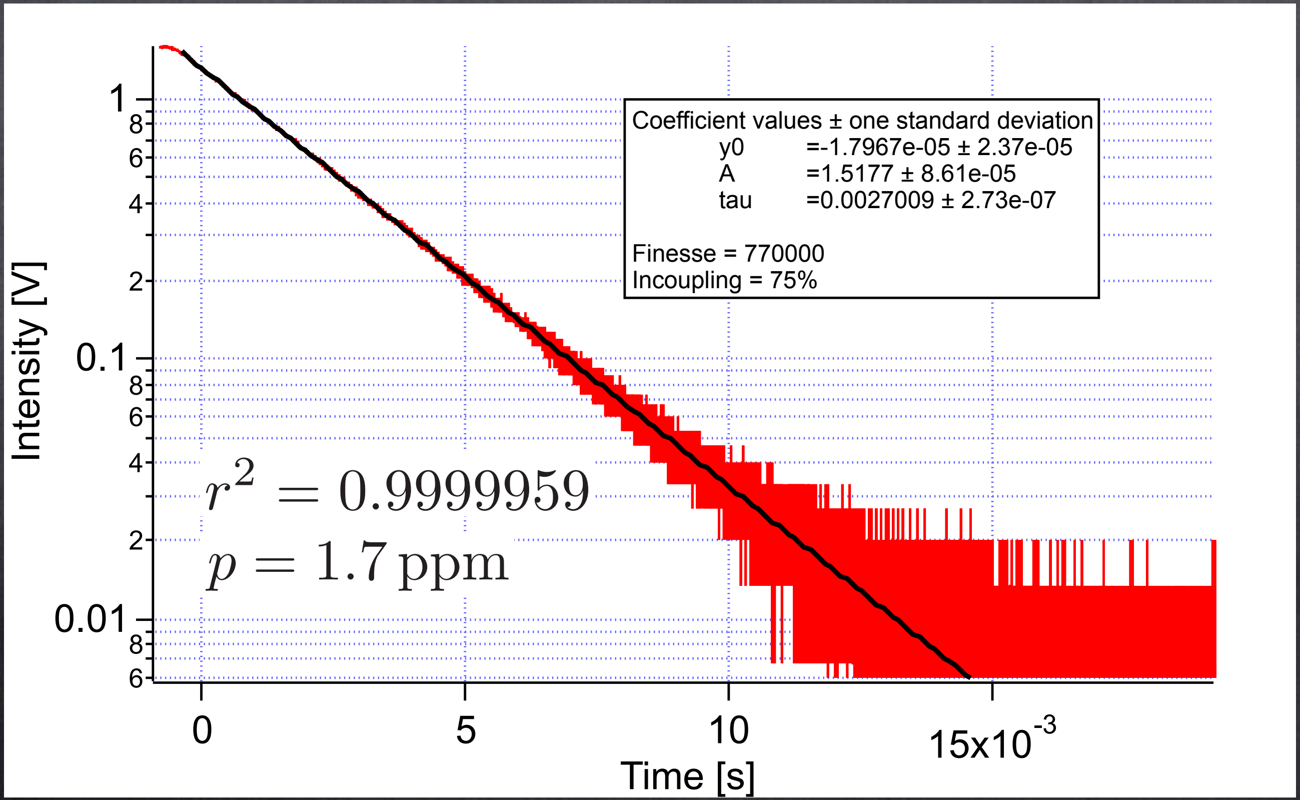
With a birefringent medium the resulting ellipticity is amplified

$$\boxed{\vec{E}_{\text{out}} = E_0 \frac{t^2}{t^2 + p} \begin{pmatrix} 0 \\ i\alpha(t) + i\eta(t) + i\frac{1+r^2}{1-r^2}\psi \sin 2\vartheta(t) \end{pmatrix}}$$

Measuring the finesse

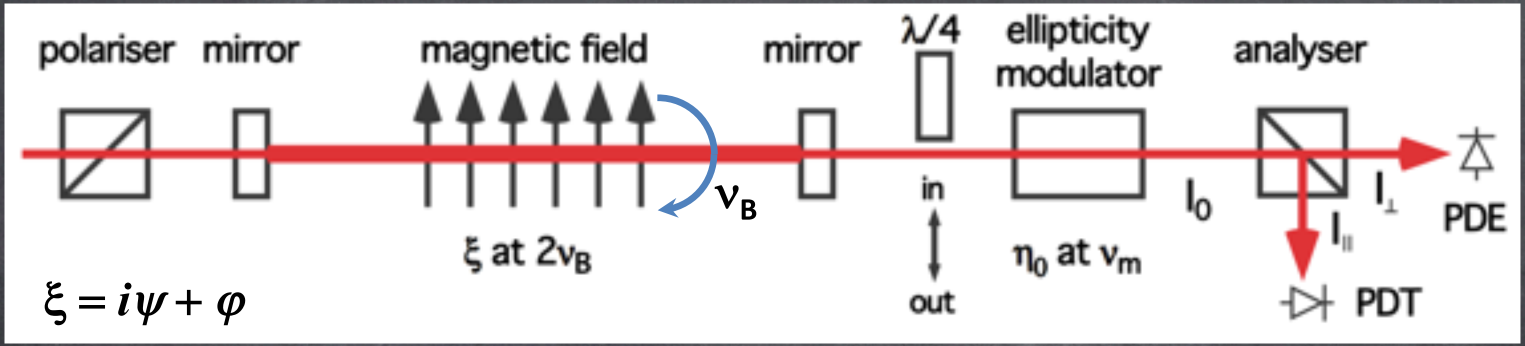
- Decay curve of light for our L = 3.3 m long cavity.
- Record decay time = 2.7 ms

$$\mathcal{F} = \frac{\pi}{1 - r^2} = \frac{\pi c \tau}{L}$$



Summarizing PVLAS scheme

- Single pass ellipticity: $\psi = \dfrac{\pi \Delta n_{\mathrm{B}} L}{\lambda} \sin 2\vartheta(t) = \psi_0 \sin 2\vartheta(t)$
- L is the length of the magnetic field and $\Delta n_{\mathrm{B}} \propto B^2$



F. Della Valle et al. Eur. Phys. J. C (2016) 76:24

- The Fabry-Perot cavity will amplify ψ by a factor $N = 2\mathcal{F}/\pi$ where $\mathcal{F}$ is the finesse of the cavity
- We desire to determine the optical path difference $D_n = \Delta n_{\mathrm{B}} L$ between the two orthogonal polarization states by measuring the induced ellipticity $N\psi$
- Heterodyne detection linearizes the ellipticity ψ to be measured and allows the distinction between a rotation and an ellipticity
- The rotating magnetic field will modulate the desired signal

Summarizing PVLAS scheme

$$I_{\rm out} \simeq I_0 \left| i\eta(t) + iN\psi_0 \sin 2\vartheta(t) + iN\alpha(t) + \varphi(t) + \ldots \right|^2$$

modulator — signal — noise — rotation

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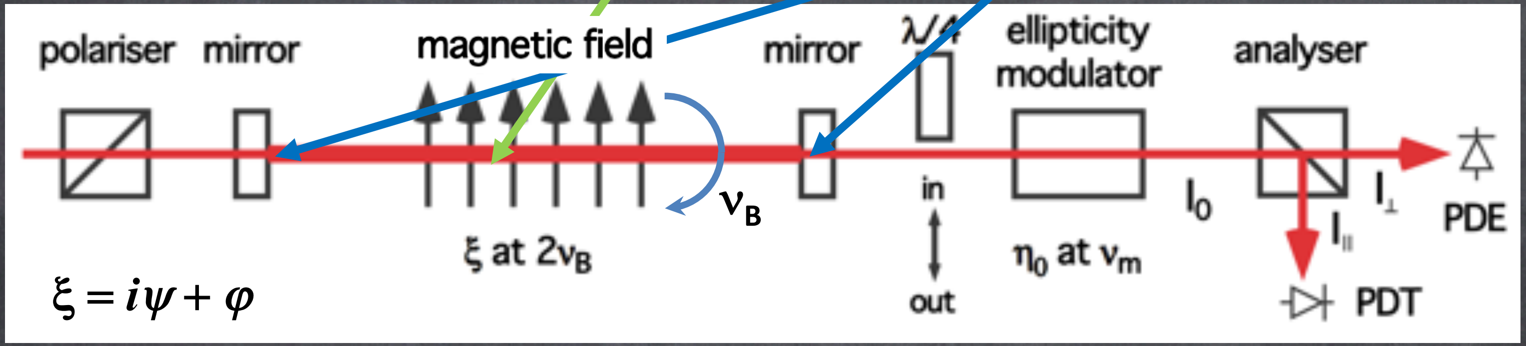
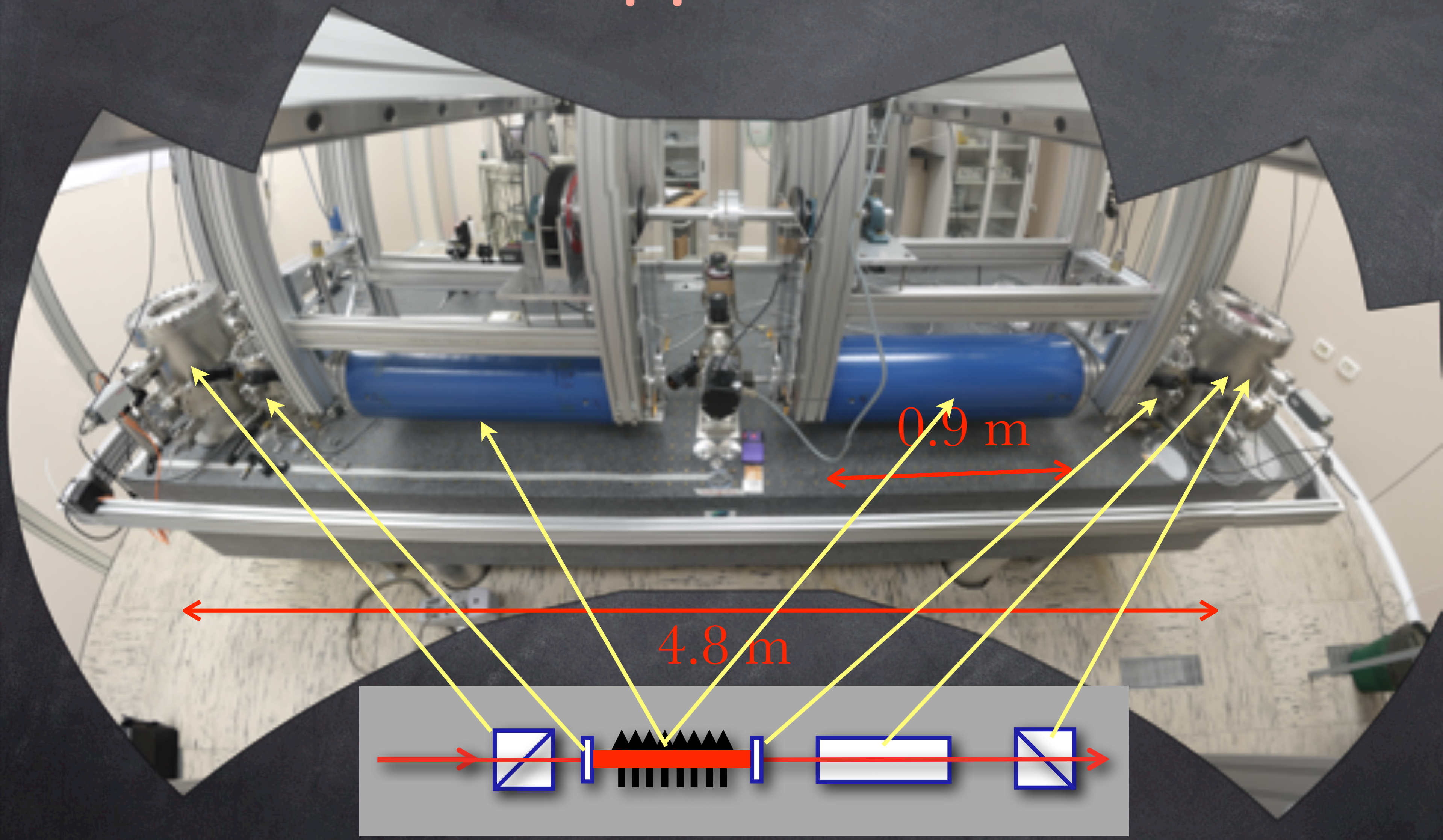


$$I_{\rm out} \simeq I_0 \left\{ \eta^2(t) + 2\eta(t)N\psi_0 \sin 2\vartheta(t) + 2\eta(t)N\alpha(t) + \varphi^2(t) + \ldots \right\}$$

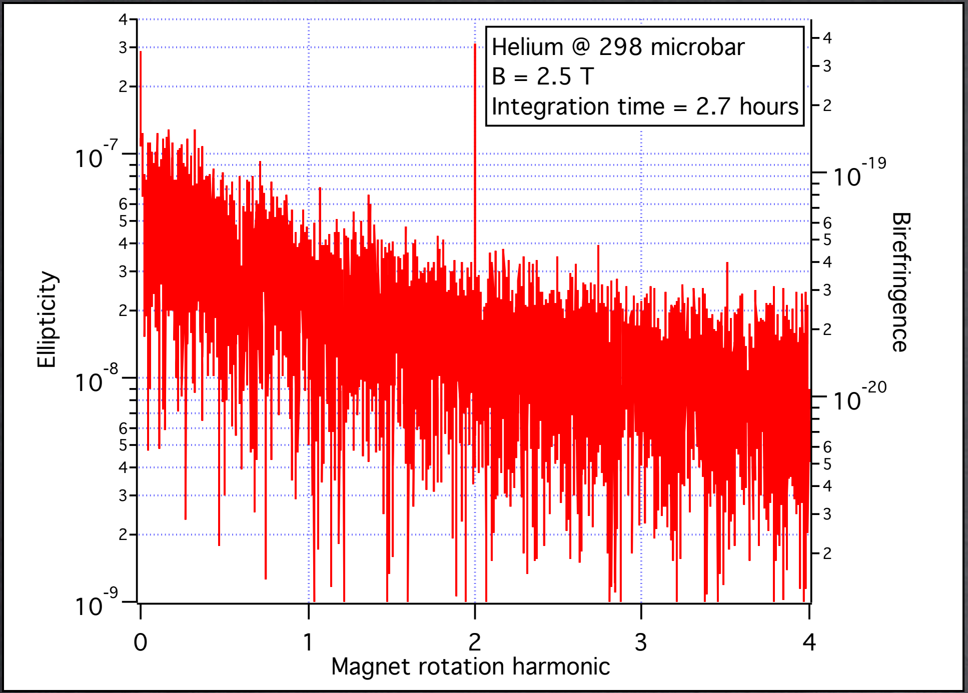
- An ellipticity signal beats with the modulator
- Demodulate the intensity at the frequency of the modulator

A pure sinusoidal signal appears at $2\nu_B$
Need to understand noise contributions at $2\nu_B$
<u>We believe the noise comes from the mirrors</u>

The mounted apparatus



Cotton-Mouton calibration

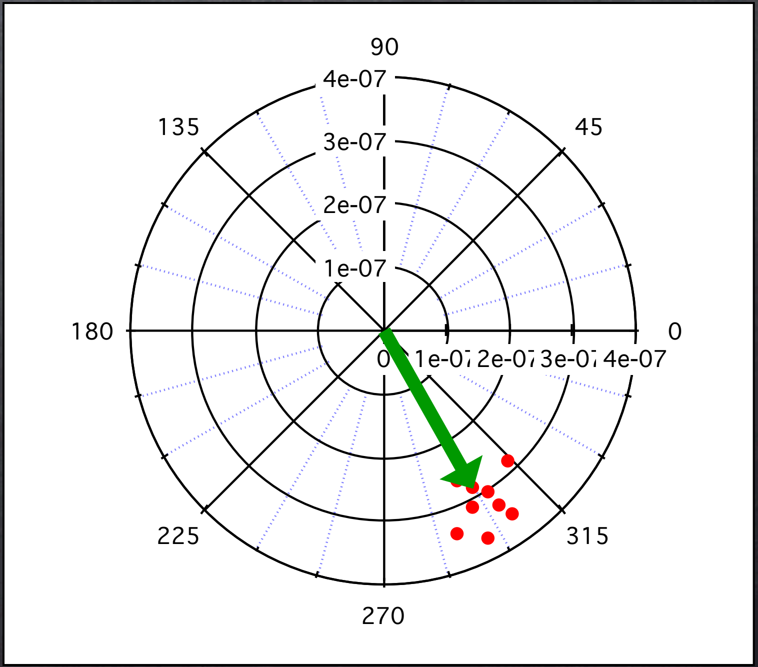


In gasses: $\Delta n_{\mathrm{CM}} \propto B^2$

Measured effect is given by Fourier amplitude and phase at the signal frequency

Vector in the polar plane.

Defines physical axis for any birefringence.



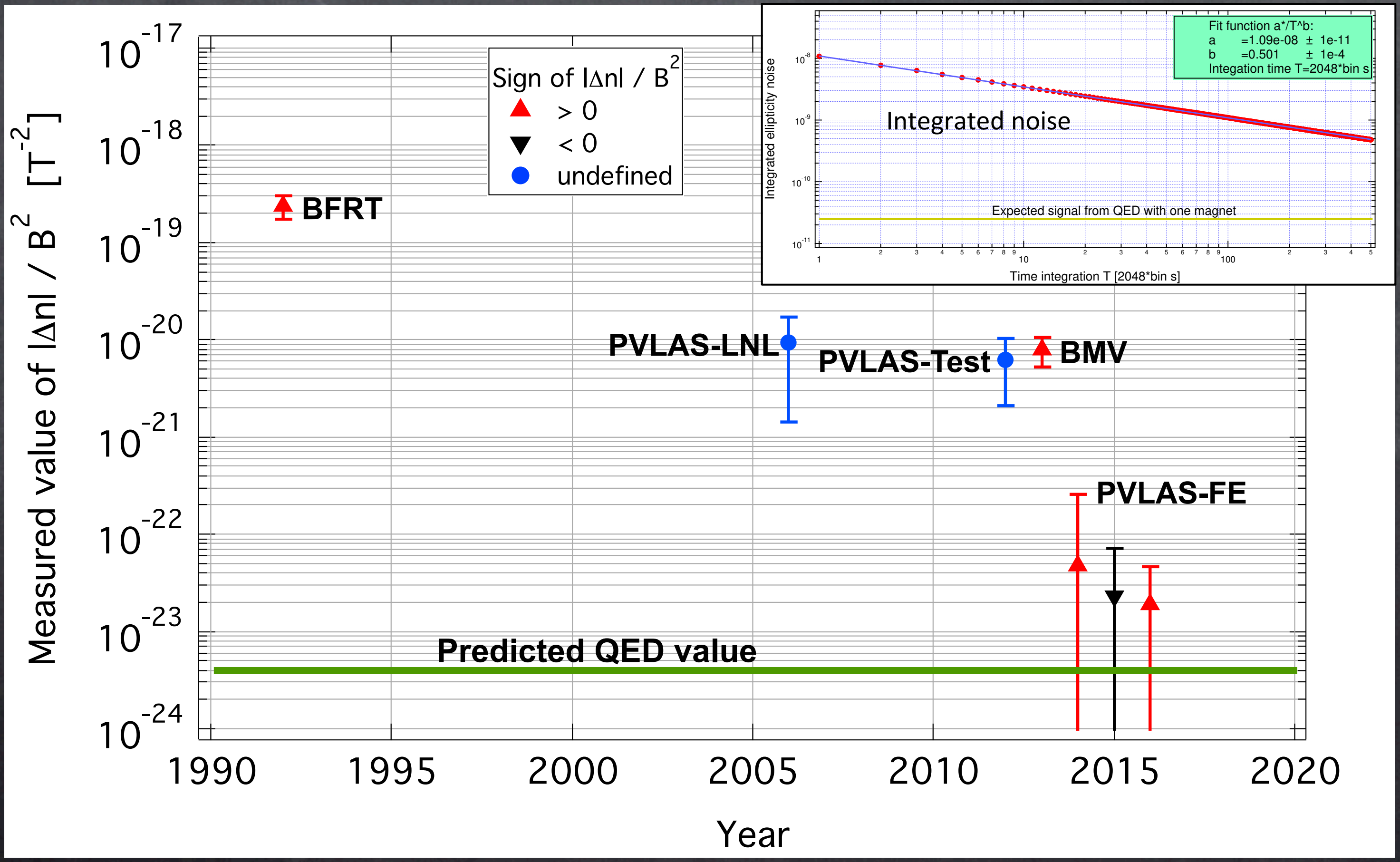
The amplitude measures the ellipticity/rotation. The phase is related to the triggers' positions and magnetic field direction. A true physical signal must have a definite phase determined with gases

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

$$O.P.D = (2.3 \pm 0.1) \times 10^{-19}\ \mathrm{m}$$

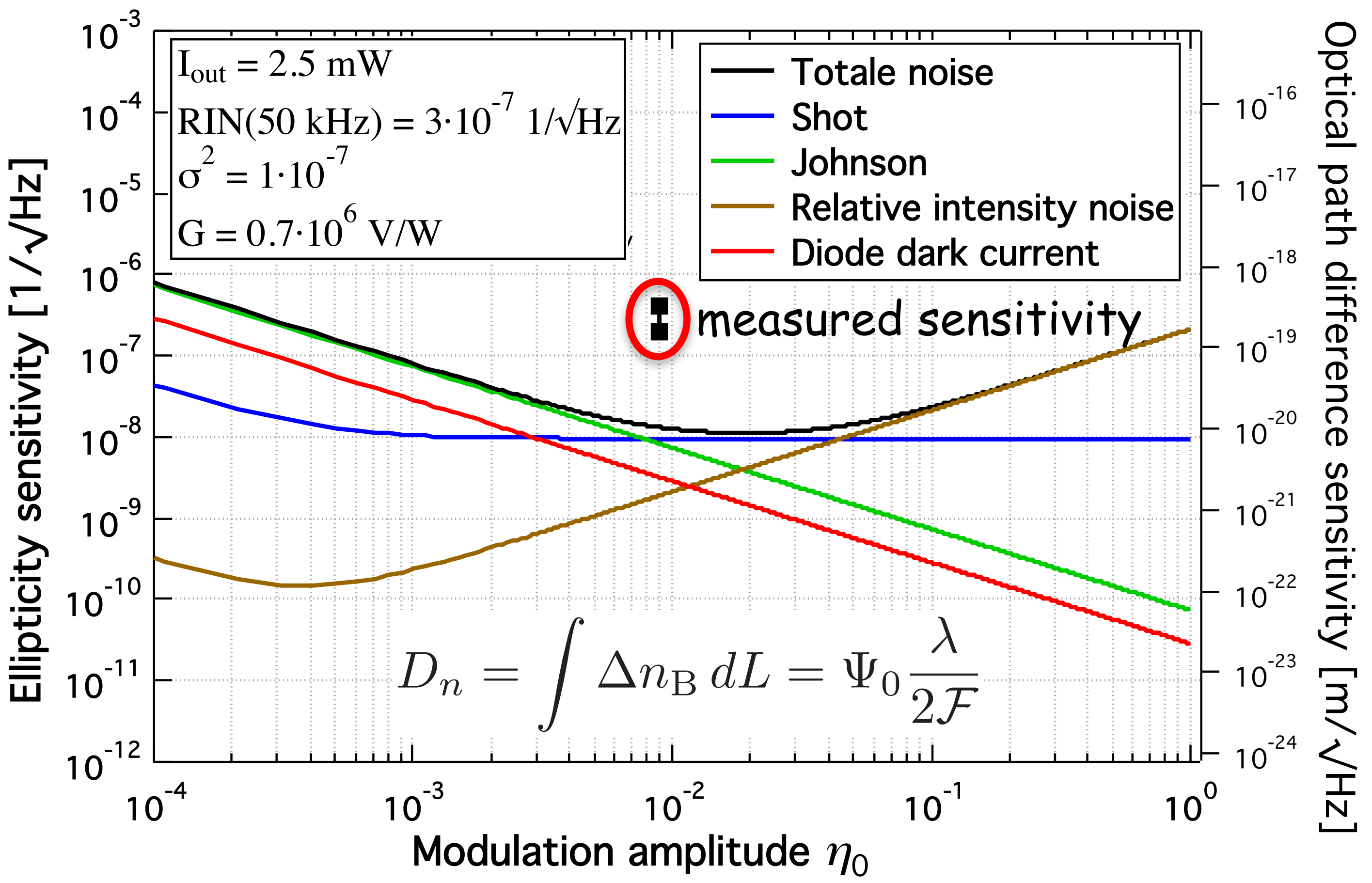
Vacuum magnetic birefringence

- Last PVLAS point corresponds to an integration $T \approx 5 \cdot 10^6$ s.
- Errors correspond to 1σ.
- Cannot overcome the gap by integrating longer
- The use of permanent magnets allowed detailed debugging



Noise budget

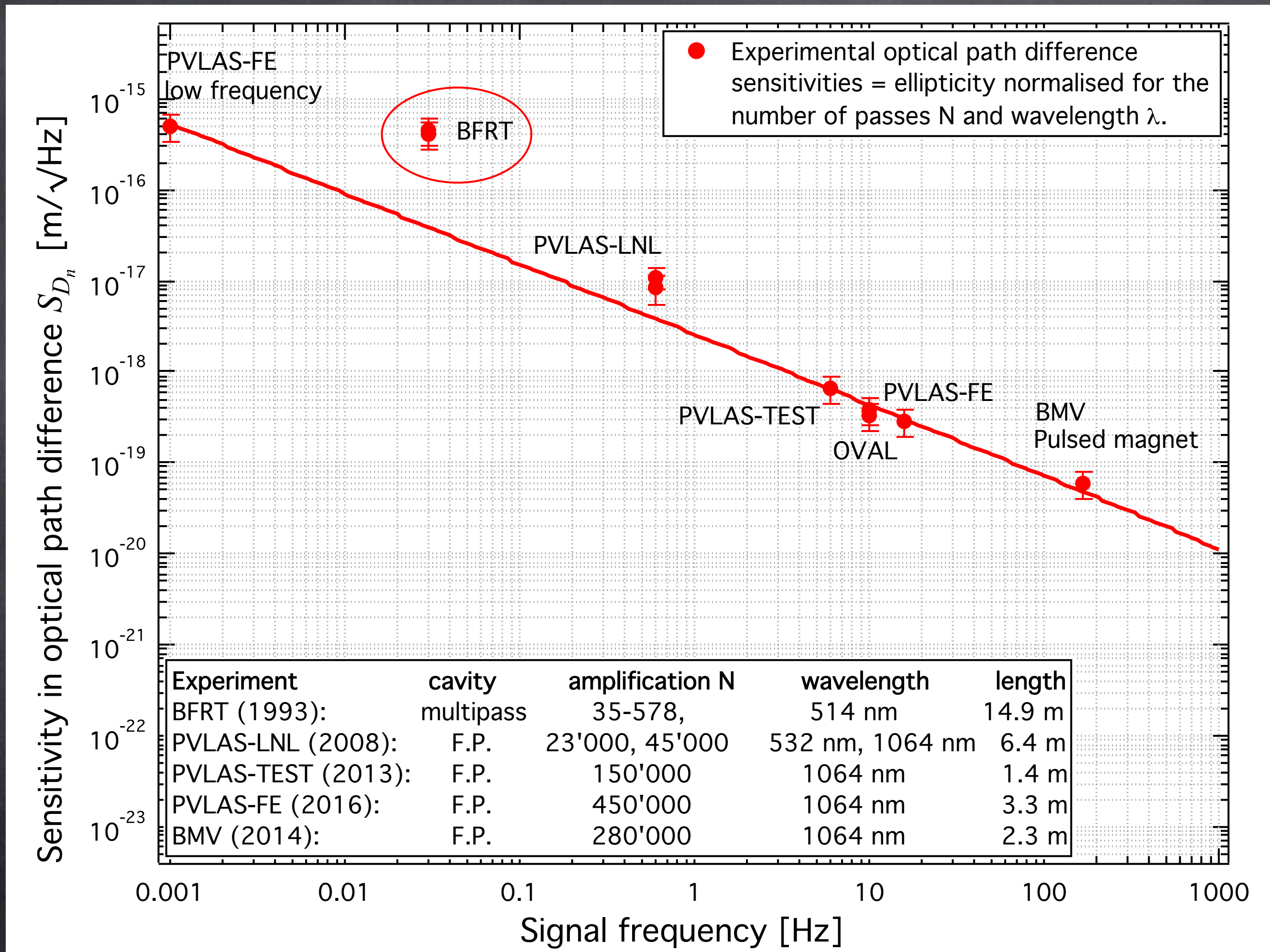
Sensitivity as a function of modulation amplitude
Finesse = 700'000



- Shot noise is reached without the Fabry-Perot cavity
- The extra noise is due to the mirrors of the cavity

Intrinsic noise?

Sensitivity in optical path difference D_n between two perpendicular polarizations



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

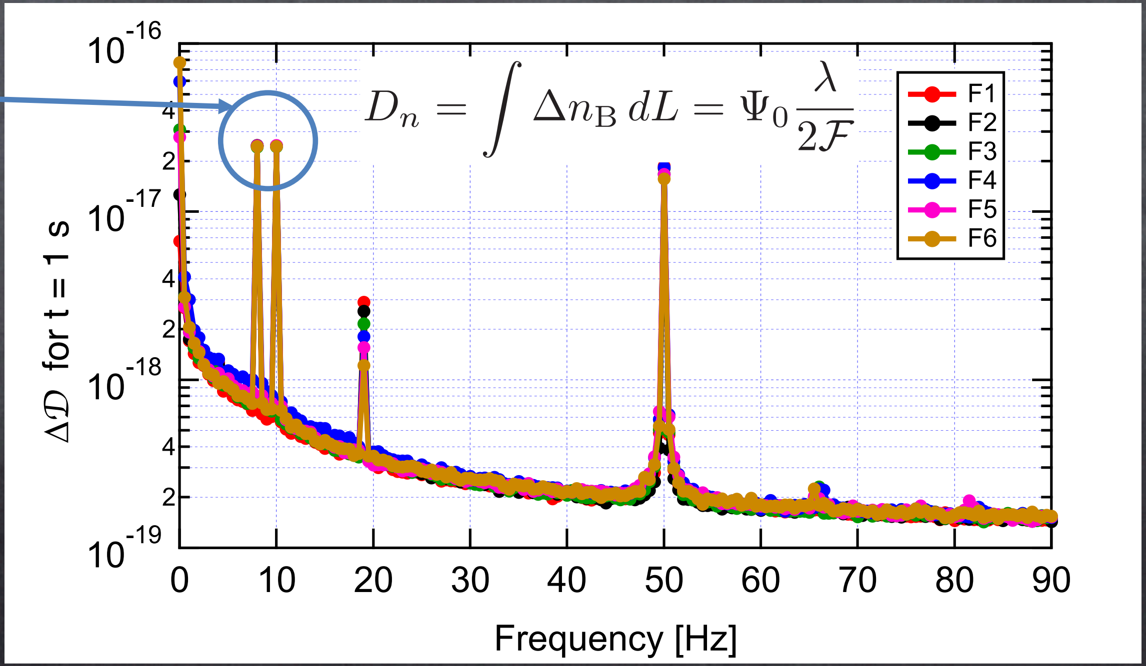
BFRT: R. Cameron et al. PRD, **47** (1993) 3707
PVLAS-LNL: M. Bregant et al. PRD, **78** (2008) 032006
PVLAS-TEST: F. Della Valle et al. NJP, **15** (2013) 053026
PVLAS-FE: F. Della Valle et al. EPJC, **76:24** (2016) 1
BMV: A. Cadène et al. EPJD, **68:16** (2014) 1

Sensitivity in D_n does not depend on finesse

Intrinsic noise

- Measured ellipticity noise and Cotton-Mouton signal as a function of the finesse
- Introduced controlled extra loses p ≈ 10^{-5} in the cavity by clipping the beam
- Finesse range: 250'000 - 690'000

Cotton-Mouton signals



Noise and Cotton-Mouton signals are independent of the finesse

Noise

- Above finesses of ≈ 20.000 this is the dominant noise above ≈ 10 Hz.
  - We believe the noise is of thermal origin. Local temperature fluctuations generate local stress fluctuations. Through the stress optic coefficient this generates birefringence fluctuations: thermo-elastic noise. Estimates indicate that the Ta_5O_2 layers dominate

- The thermo-elastic noise is proportional to the temperature T.
  - To demonstrate the thermal origin of the intrinsic noise we have equipped PVLAS with two dewars and cold fingers for the mirrors. A mirror temperature of 140 K has been reached. If the hypothesis is correct the noise should diminish by a factor ≈ 2. Test are on-going.

- To measure QED we need an improvement in the sensitivity by a factor 30: T = 10 K. This seems very difficult with the present setup

How to beat the noise

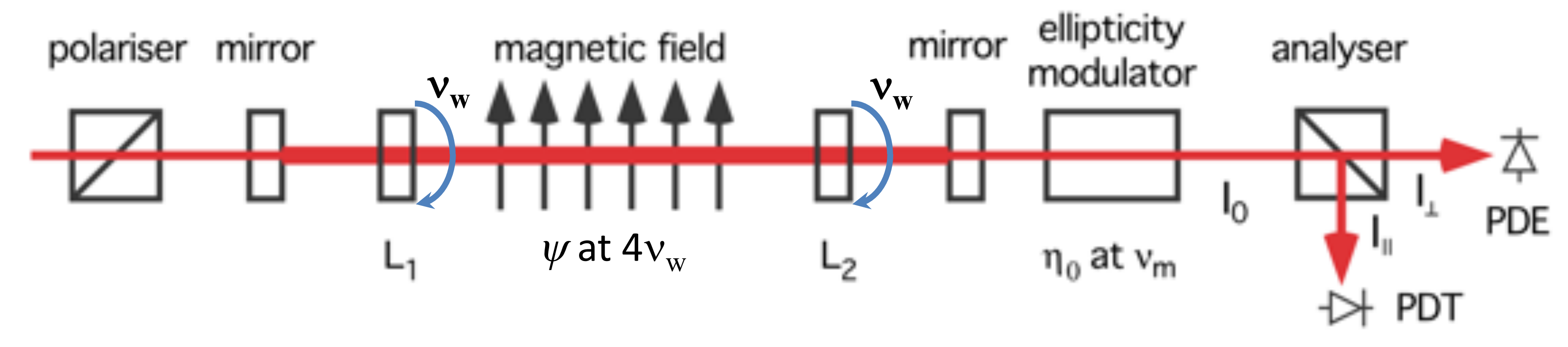
- Increase the frequency of the signal by rotating faster
  - $R \propto \nu^{\alpha}$ with $\alpha \approx -0.7$
  - Maybe improve by a factor 2 with the PVLAS apparatus
- Increase the signal: B^2L of magnet
  - Only real option is to use superconducting static magnets
  - One LHC magnet has B^2L = 1200 T^2m. At present we have 10 T^2m.
  - Superconductor magnets cannot be modulated at ≈ 10 Hz
- Change origin of modulation
  - Rotate the polarization <u>inside the field</u>
  - … <u>But must be kept fixed on the mirrors</u>.

VMB@CERN

Separate magnet from modulation

Polarization modulation scheme

- Rotate polarization inside the magnet
- Fix polarization on mirrors to avoid mirror birefringence signal
- Insert two co-rotating half wave plates @ ν_w with a fixed relative angle $\Delta\phi$
  - Total losses ≤ 0.4% (commercial). Maybe 10 times lower is possible
  - Maximum finesse ≈ 1000 (with ≤ 0.4% losses)



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

Signal and possible problems

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

$$I(t) = I_{\text{out}} \left\{ \eta(t)^2 + 2\eta(t) N \left[\psi_0 \sin 4\phi(t) + \right.\right.$$
$$\left.\left. + \alpha_1 \sin 2\phi(t) + \alpha_2 \sin(2\phi(t) + 2\Delta\phi) \right] \right\}$$

Signal appears a the 4th harmonic of $\nu_{\rm w}$

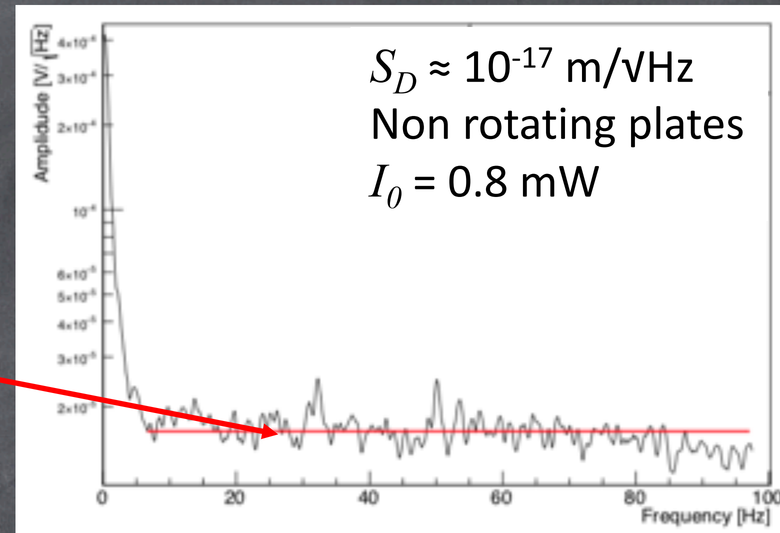
Wave-plate defects $\alpha_{1,2}$

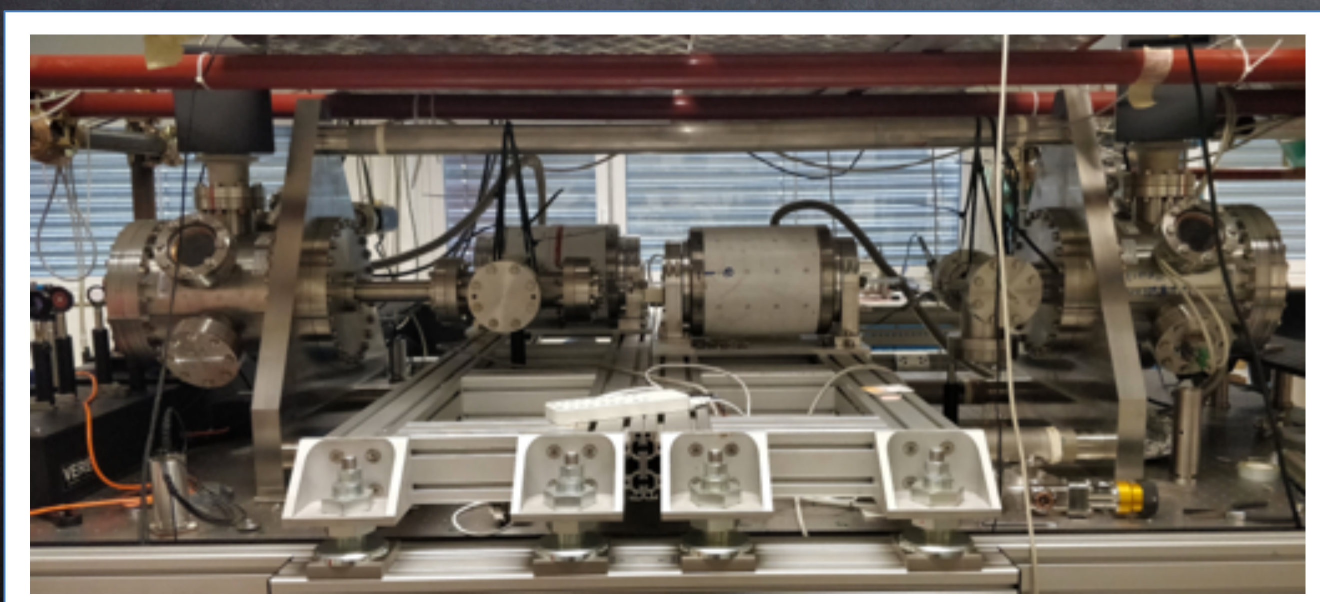
$$\alpha_{1,2}(t) = \alpha_{1,2}^{(0)} + \alpha_{1,2}^{(1)} \cos\phi(t) + \alpha_{1,2}^{(2)} \cos 2\phi(t) + \ldots$$

- $\alpha^{(0)}{}_{1,2} \approx 10^{-3}$ (from manufacturer): appears @ 2nd harmonic
- $\alpha^{(1)}{}_{1,2} \approx 10^{-6}$ (wedge of wave-plate): appears @ 1st and 3rd harmonic
- $\alpha^{(2)}{}_{1,2}$ => appears @ 4th harmonic
- With $\psi_0 = 5\cdot 10^{-12}$ one desires that $\psi_0 > \alpha^{(2)}{}_{1,2}$

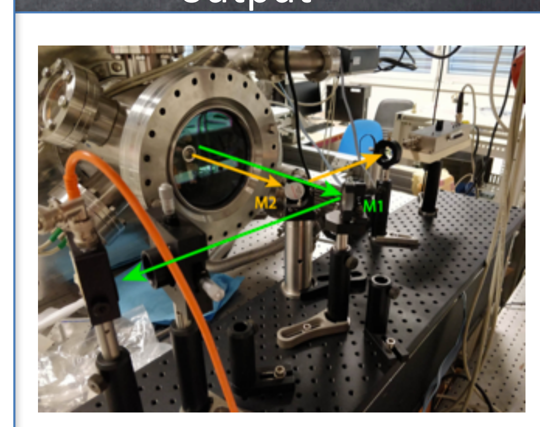
First tests in Ferrara

- Two non rotating HWP were inserted in a Fabry-Perot cavity
- Laser locking worked normally
- Measured a finesse of F = 850
- Noise did not degrade and was compatible with shot-noise





output



VMB@CERN with 1 LHC magnet

- Signal $$D_n = 3A_e B^2 L = 4 \times 10^{-24} B^2 L \text{ m}$$

- Intrinsic noise $$S_{D_n}^{(\text{intrinsic})} = 2.6 \times 10^{-18} \nu^{-0.77} \text{ m}/\sqrt{\text{Hz}}$$

- Shot-noise $$S_{D_n}^{(\text{shot})} = \sqrt{\frac{e}{I_0 q} \frac{\lambda}{\pi N}}$$

- Maximum measurement time $$T = \left(\frac{S_{D_n}}{D_n}\right)^2 \lesssim 10^6 \text{ s}$$

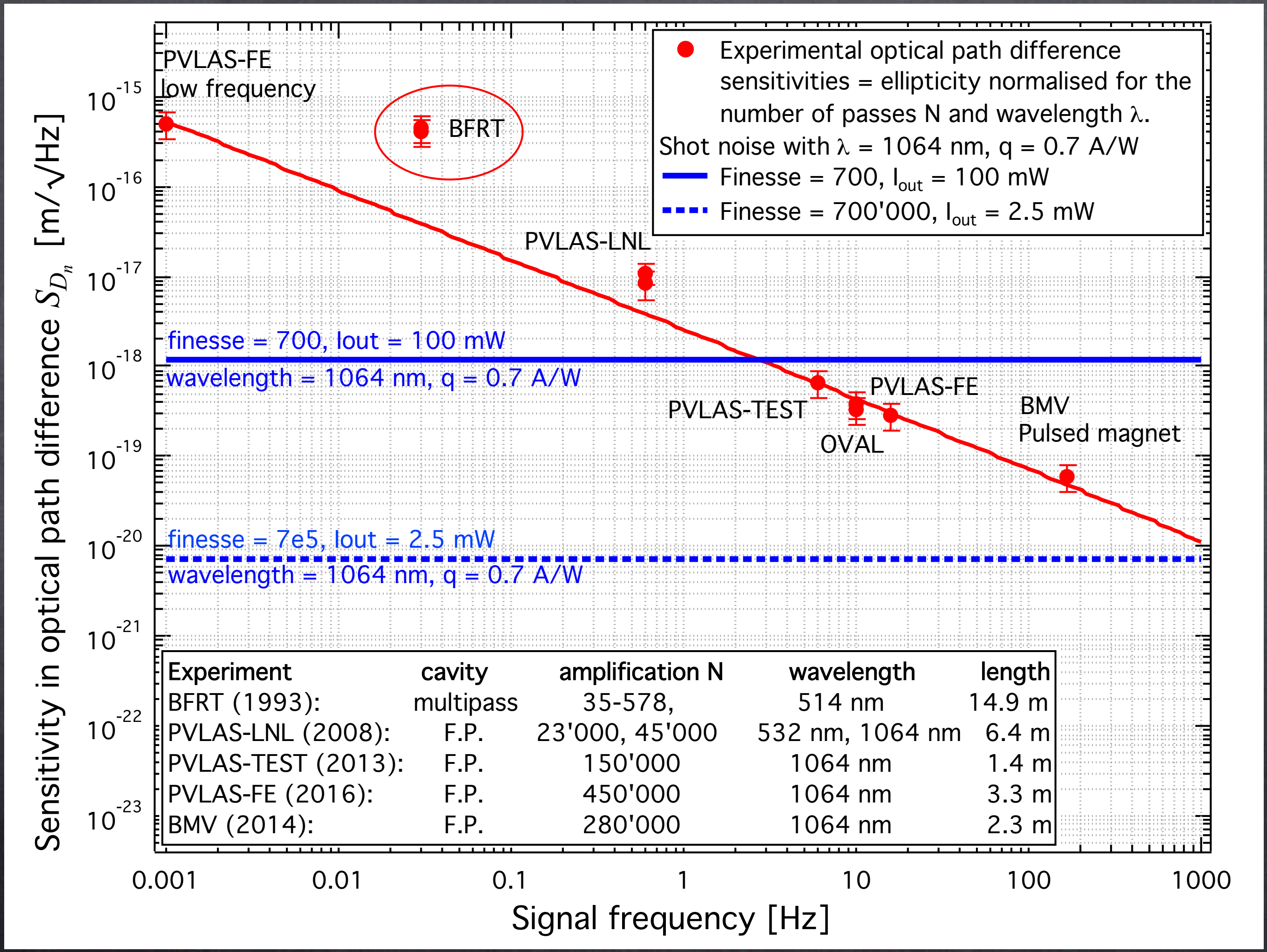
- LHC example: $B^2 L = 1200 \text{ T}^2\text{m}; \quad S_{D_n} = 10^{-18} \text{ m}/\sqrt{\text{Hz}} \text{ @ } 3 \text{ Hz}$

$$\Rightarrow T = 12 \text{ h}$$

What sensitivity could be reached?

Sensitivity in optical path difference D_n between two perpendicular polarizations

$D_n \approx 10^{-18}$ m/$\sqrt{\text{Hz}}$ *goal sensitivity*



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

Conclusions

- Rotating half wave-plates *inside* a Fabry-Perot cavity could be a viable solution to separating the external magnetic field intensity from the modulation frequency
- Technique must be tested
  - Extinction ratio?
  - Extra wide band noise?
  - Maximum finesse? F = 850 achieved; F ≈ 10’000?
- Defects may also be a limit but only at second order: $\alpha^{(2)}_{1,2}$
- With a sensitivity of $D_n \approx 10^{-18}$ m/$\sqrt{\text{Hz}}$ and 1 LHC magnet, vacuum magnetic birefringence could be measured with S/N = 1 in about 1 day.
- LoI has been submitted to CERN: CERN-SPSC-2018-036/SPSC-I-249
- Joint effort between past vacuum magnetic birefringence experiments + LIGO: 16 authors, 7 countries.

Thank you!