University of Ferrara

Recent Results From the PVLAS Experiment and Future Perspectives

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PVLAS Collaboration

(Polarizzazione del Vuoto con LASer)

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Classical Electromagnetism in vacuum

Classical vacuum has no structure. The superposition principle is valid

$$div\vec{D} = 0; \qquad rot\vec{E} = -\frac{1}{c}\frac{\partial\vec{B}}{\partial t}$$

$$div\vec{B} = 0; \qquad rot\vec{H} = \frac{1}{c}\frac{\partial\vec{D}}{\partial t}$$

$$\boxed{L_{EM} = \frac{1}{8\pi}\left(E^2 - B^2\right)}$$

$$\vec{D} = 4\pi\frac{\partial L_{EM}}{\partial\vec{E}}$$

$$\vec{H} = -4\pi\frac{\partial L_{EM}}{\partial\vec{B}}$$

$$\vec{D} = \vec{E}; \qquad \vec{H} = \vec{B}$$

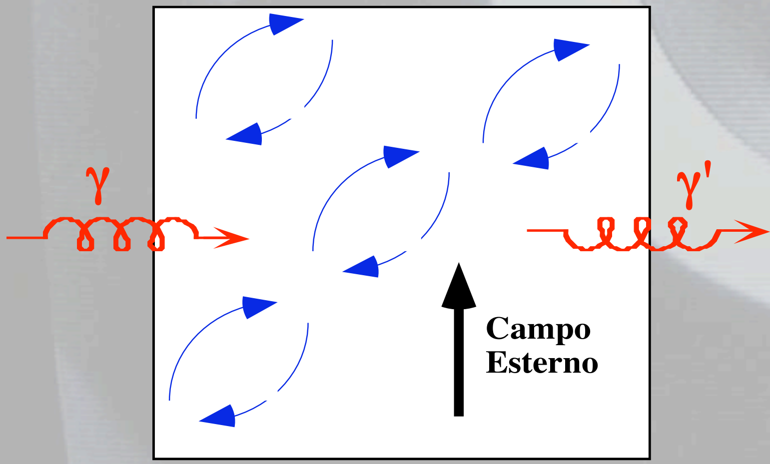
Heisenberg's Uncertainty Principle

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

Vacuum is a minimum energy state and can fluctuate into anything compatible with vacuum

→

Vacuum has a **structure** which can be observed by perturbing it and probing it.



- Evidence of microscopic structure of vacuum is known (Lamb Shift ....)
- Macroscopically observable (small) effects have been predicted since 1936 but have never been directly observed yet.

Aim of PVLAS

PVLAS was designed to obtain experimental information on VACUUM using optical techniques.

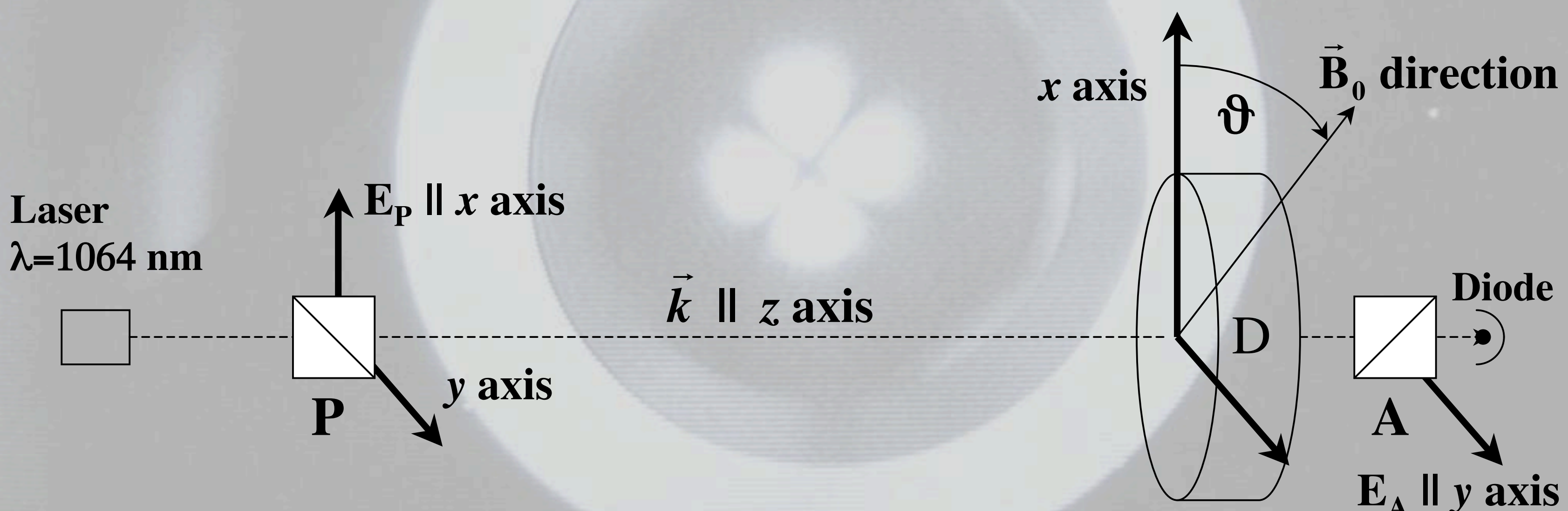
The full experimental program is to detect and measure

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

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

Reference

The polariser P and analyser A define two perpendicular directions which we use as base.



Linear Birefringence

- In coming beam can be expressed as

$$\vec{E}_{in} = E_0 e^{-i\xi} \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

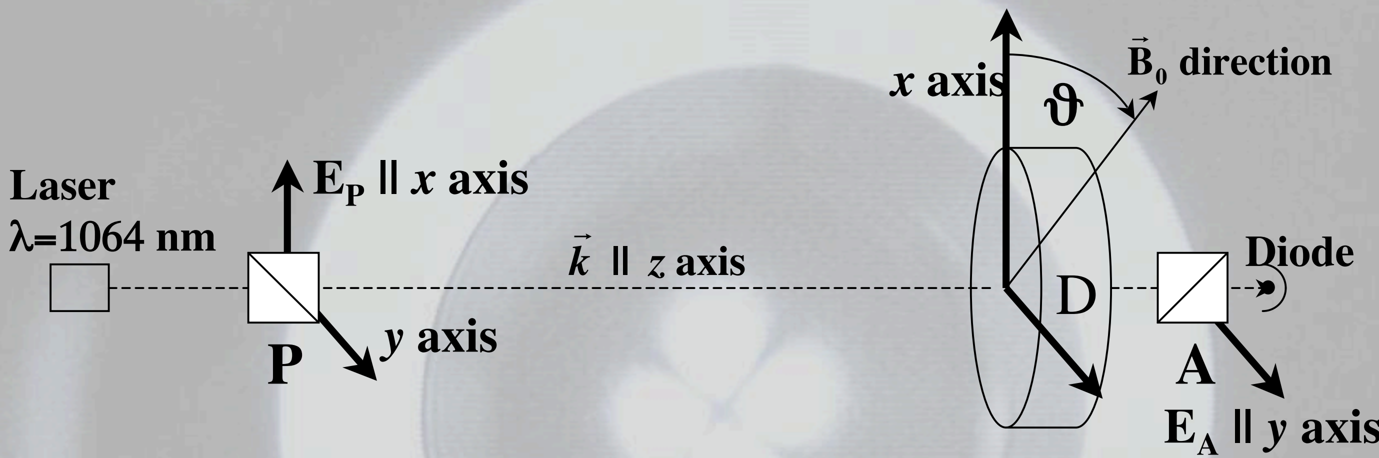
- After a phase delay of the component parallel to **B** by φ

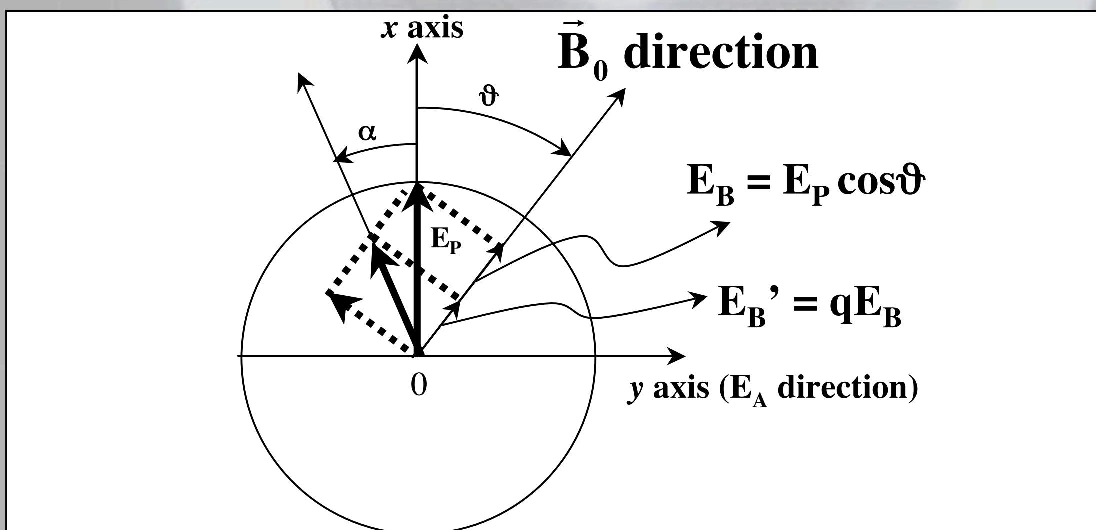
$$\vec{E}_{out} = E_0 e^{-i\xi} \begin{pmatrix} 1 + i\left(\frac{\varphi}{2}\right)\cos 2\vartheta \\ -i\left(\frac{\varphi}{2}\right)\sin 2\vartheta \end{pmatrix}$$

<u>A signal is induced along the direction of the analyser A:</u>

Max. component along A: $\psi = \left(\frac{\varphi}{2}\right)$

Linear Dichroism





Linear Dichroism

- In coming beam can be expressed as

$$\vec{E}_{in} = E_0 e^{-i\xi} \begin{pmatrix} 1 \\ 0 \end{pmatrix}$$

- After reduction of the component parallel to **B** by a factor q (q≤1)

$$\vec{E}_{out} = E_0 e^{-i\xi} \begin{pmatrix} 1 + (q-1)\cos^2\vartheta \\ \left(\frac{q-1}{2}\right)\sin 2\vartheta \end{pmatrix} \approx E_0 e^{-i\xi} \begin{pmatrix} 1 + \left(\frac{q-1}{2}\right)\cos 2\vartheta \\ \left(\frac{q-1}{2}\right)\sin 2\vartheta \end{pmatrix}$$

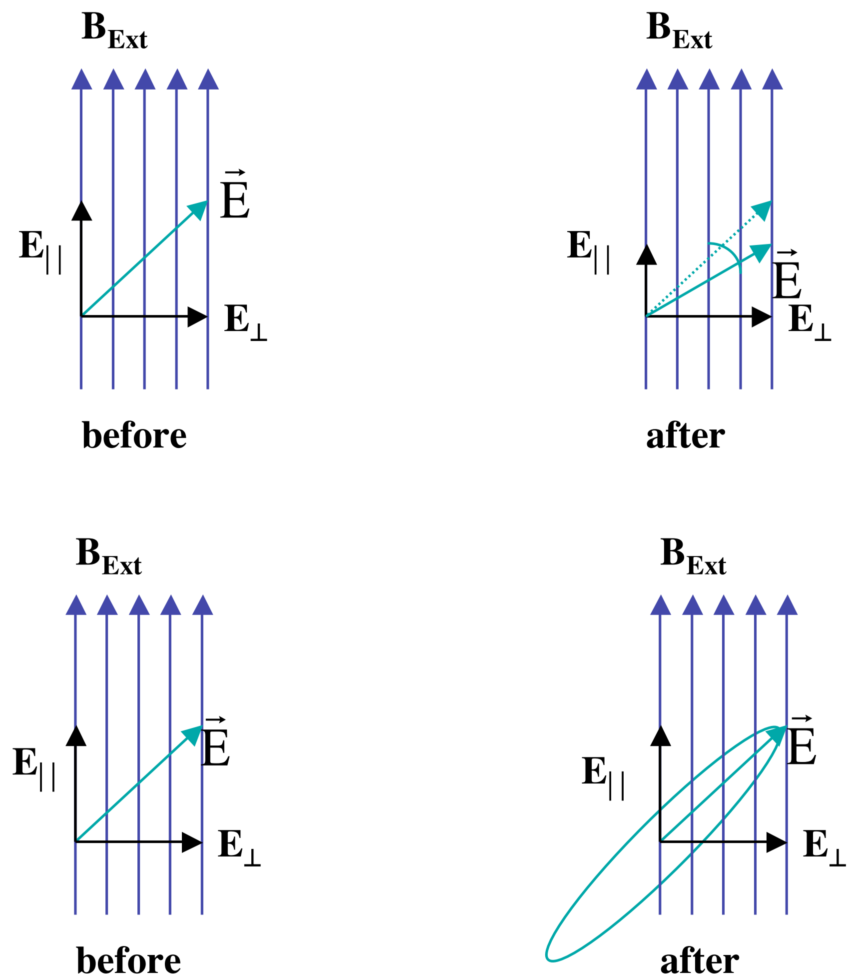
A signal is induced along the direction of the analyser A:

Max. polarization rotation: $\alpha = \left(\frac{1-q}{2}\right)$

Linear dichroism and birefringence

Dichroism

Ellipticity



apparent rotation α

ellipticity ψ

Today's presentation - Dichroism

We have observed consistently a dichroism signal generated by a 1.1 m long, 5.5 T magnet. The beam traverses the region N=52000 times.

$$\text{Total rotation measured} = (2.2 \pm 0.3) \cdot 10^{-7}\text{rad}$$

$$\left(\frac{q-1}{2}\right) = -(3.7 \pm 0.4) \cdot 10^{-12}\text{rad/pass}$$

There is a reduction of the component parallel to **B**.

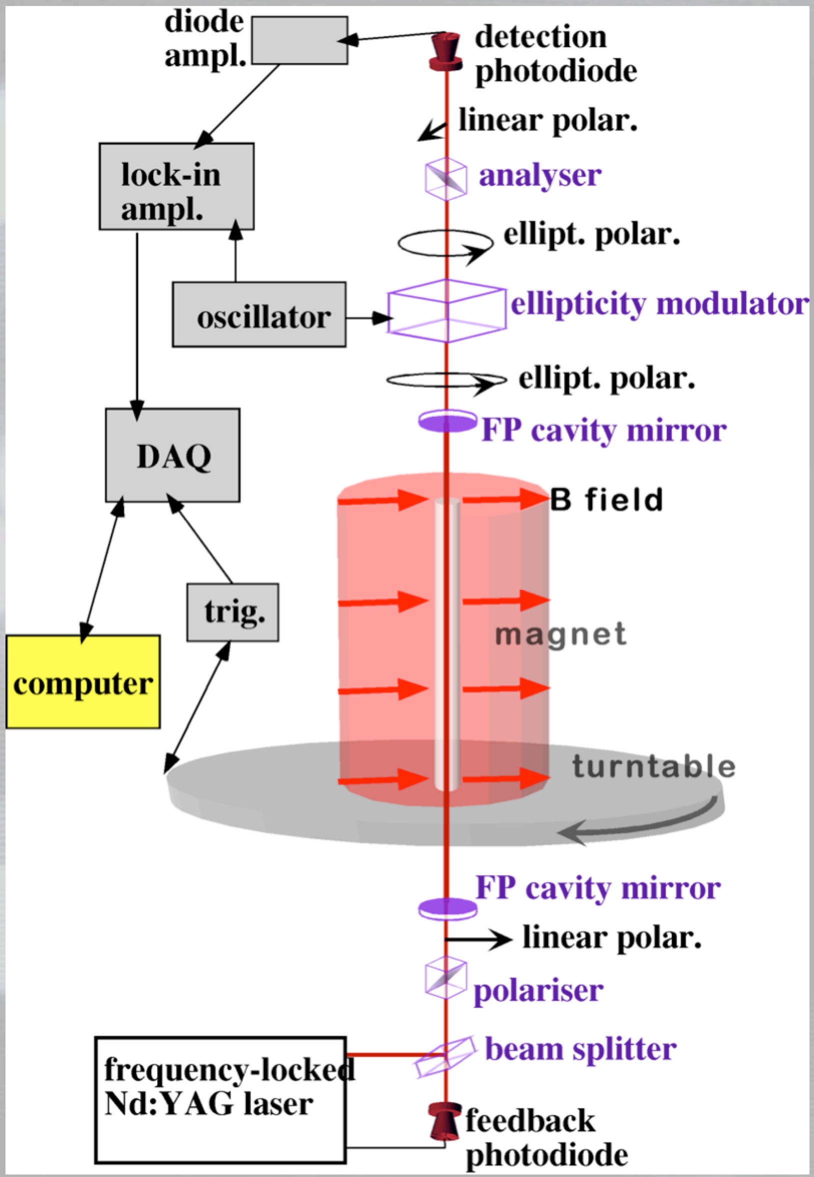
What has happened to the missing part?

- Can we exclude a systematic error?
- Do we have a physical 'handle'?
- What is the comparison of our result with other experiments?
- Future plans.

PVLAS principle

- The optical ellipsometer consists of two crossed polarisers with an ellipticity modulator providing a carrier frequency for heterodyne detection

- The Fabry-Perot increases the optical path in the field region, where the **rotating** magnetic field causes a time-varying ellipticity which then beats with the carrier



Data Acquisition

- Rotating table has 32 ticks equally spaced which trigger ADC + start tick.
- Photodiode signal (I_{Tr}) is demodulated at ω_{SOM}, $2\omega_{SOM}$ with lockin amplifiers.
- Also acquire
  1. light intensity (I_0) (AC and DC coupled)
  2. Position Sensitive photoDiode of output beam
  3. stray magnetic field in 3 positions
  4. laser feedback signal

PVLAS: schematic drawing

- The granite tower (blue in the drawing) supports the upper optical bench and is mechanically isolated from the hall (in green)
- The turntable, holding the magnet, rests on a beam fixed to the floor (green in the drawing)

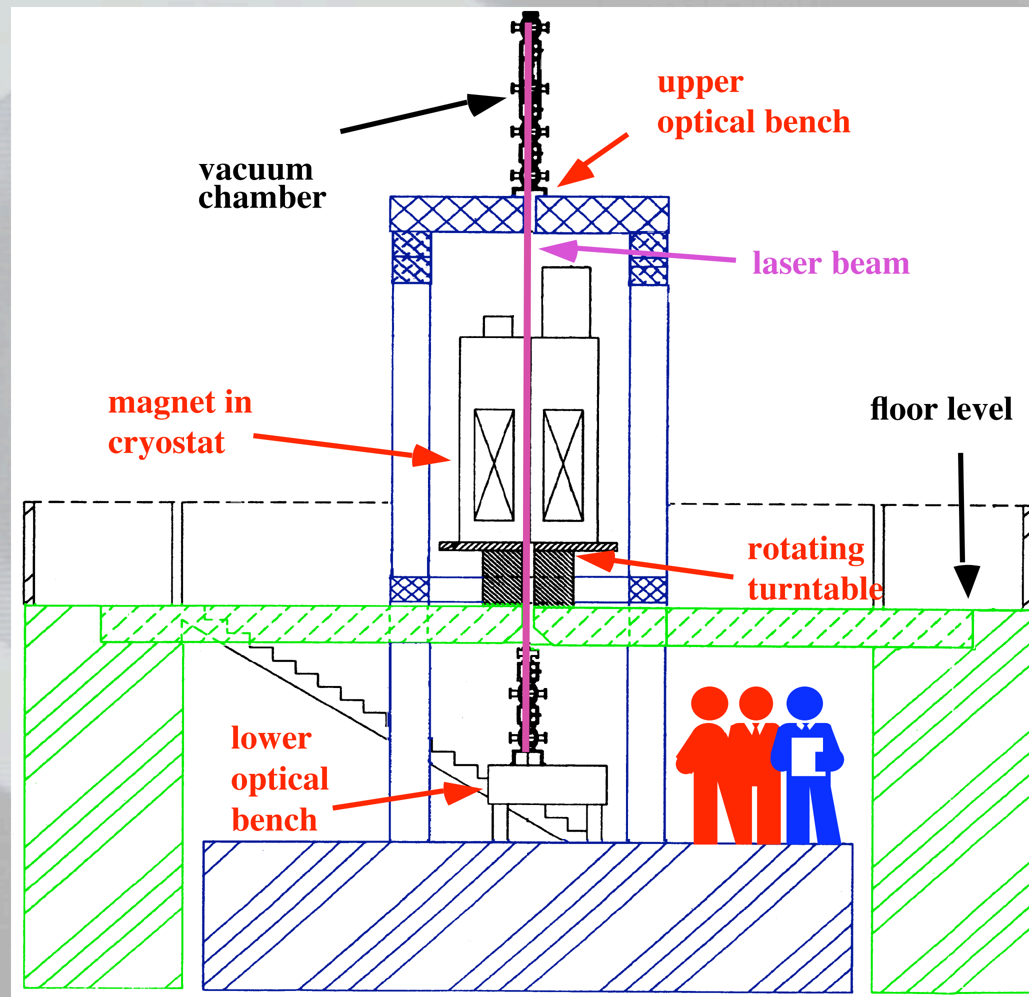
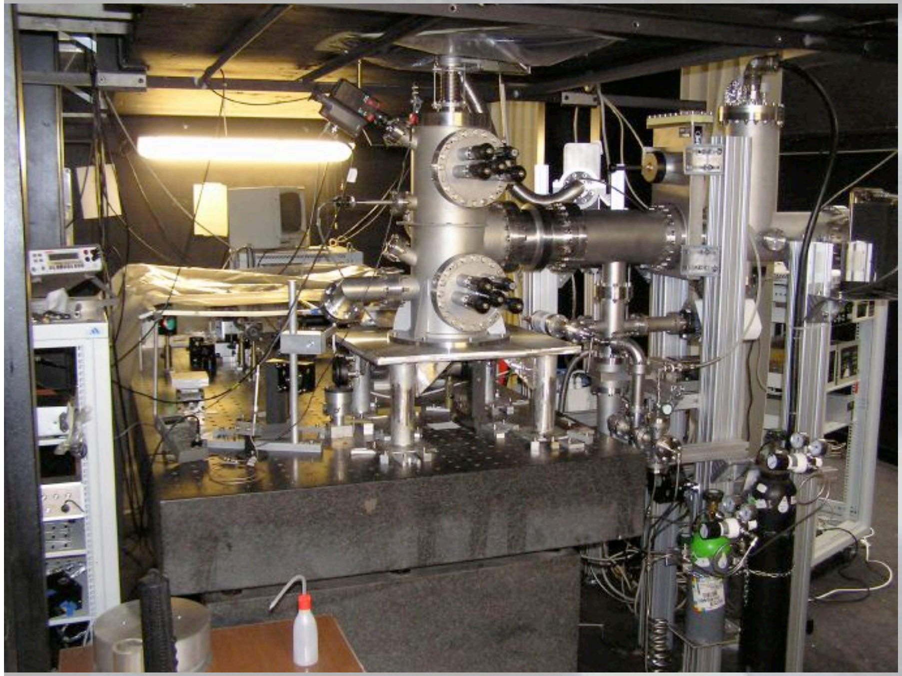
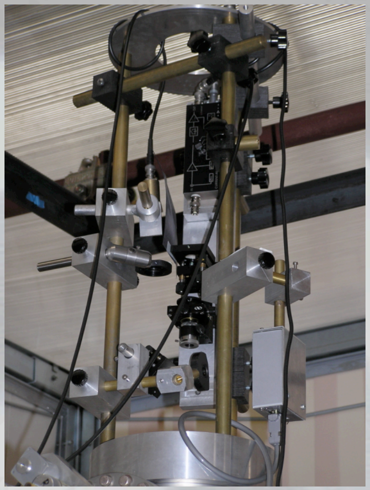


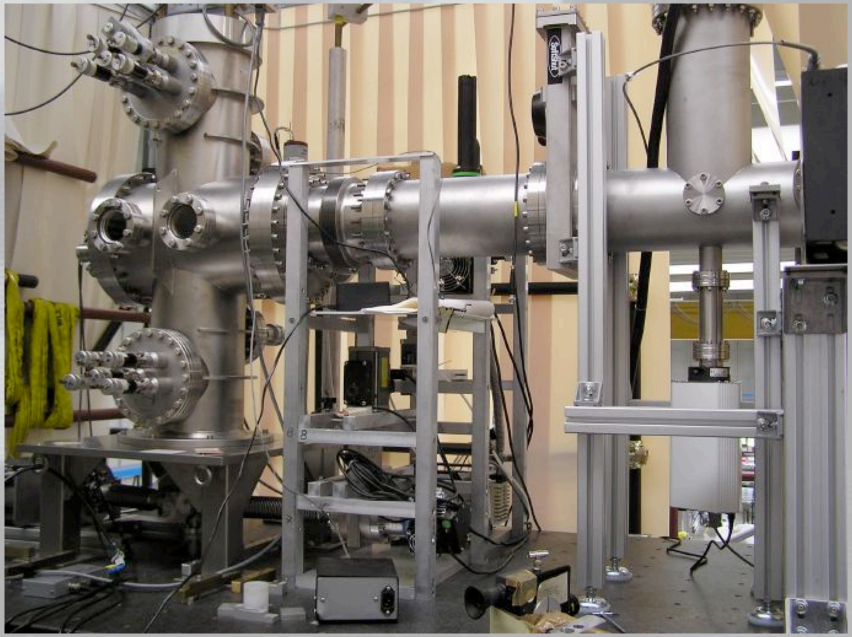
Photo gallery - 1



Lower optical bench



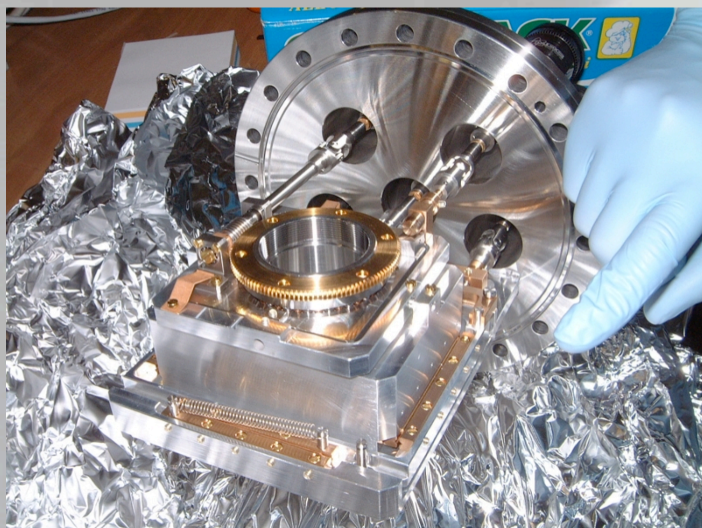
Top photodiode



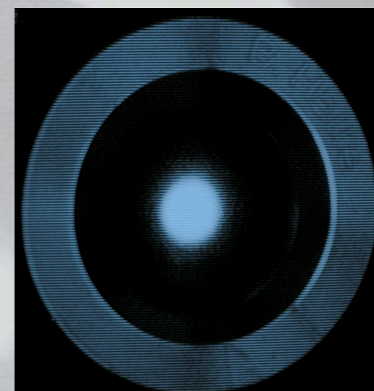
Upper optical bench

Photo gallery - 2

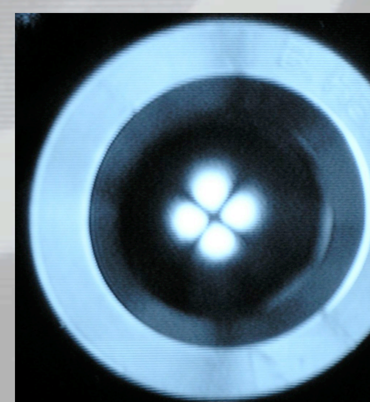
Mirror mount



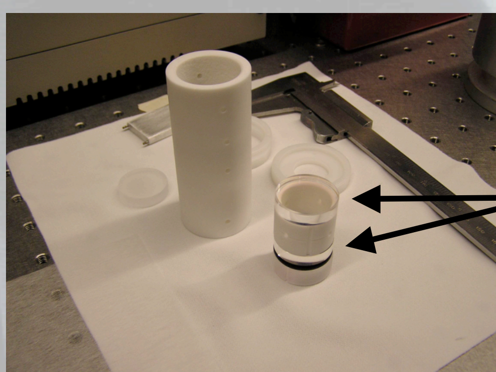
Mode TEM_{00}



Mode TEM_{11}



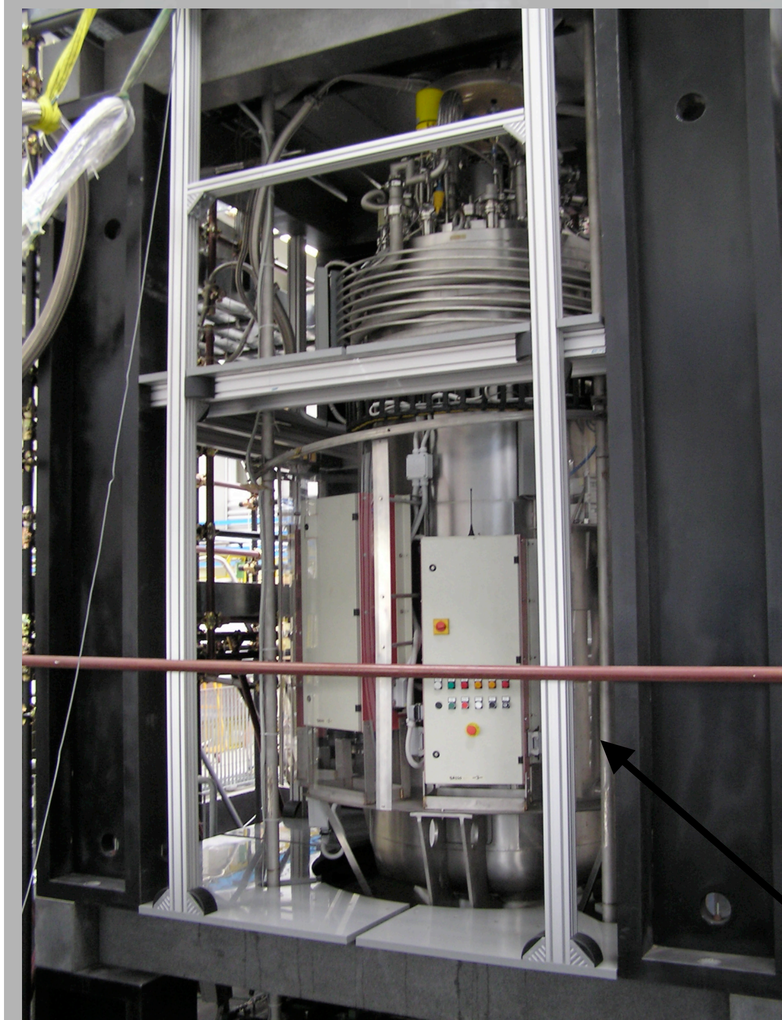
Short test cavity



Mirrors

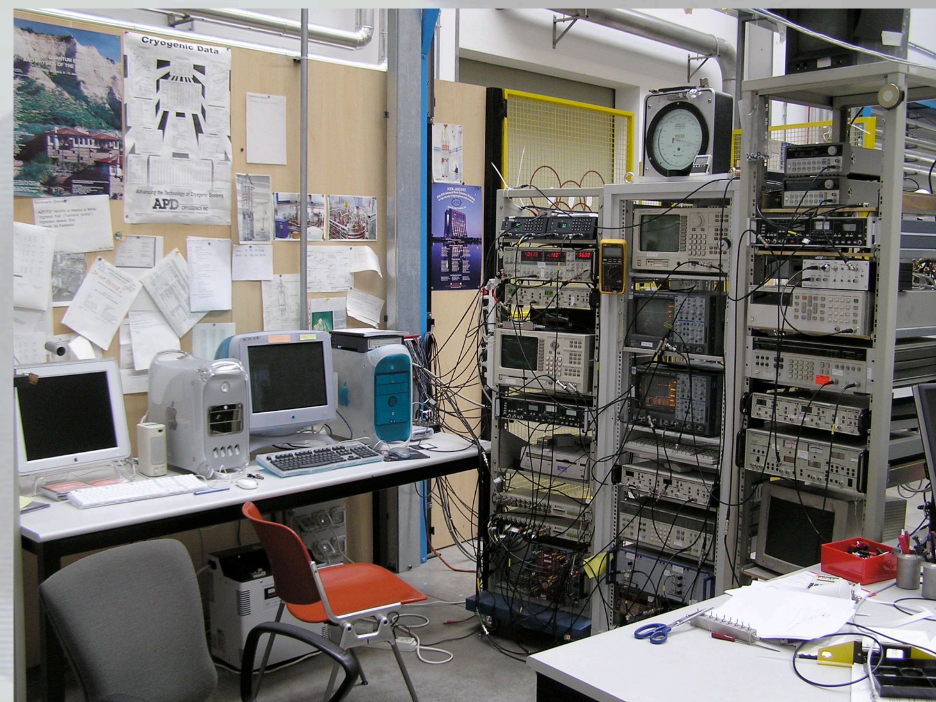
Photo gallery - 3

Cryostat for magnet



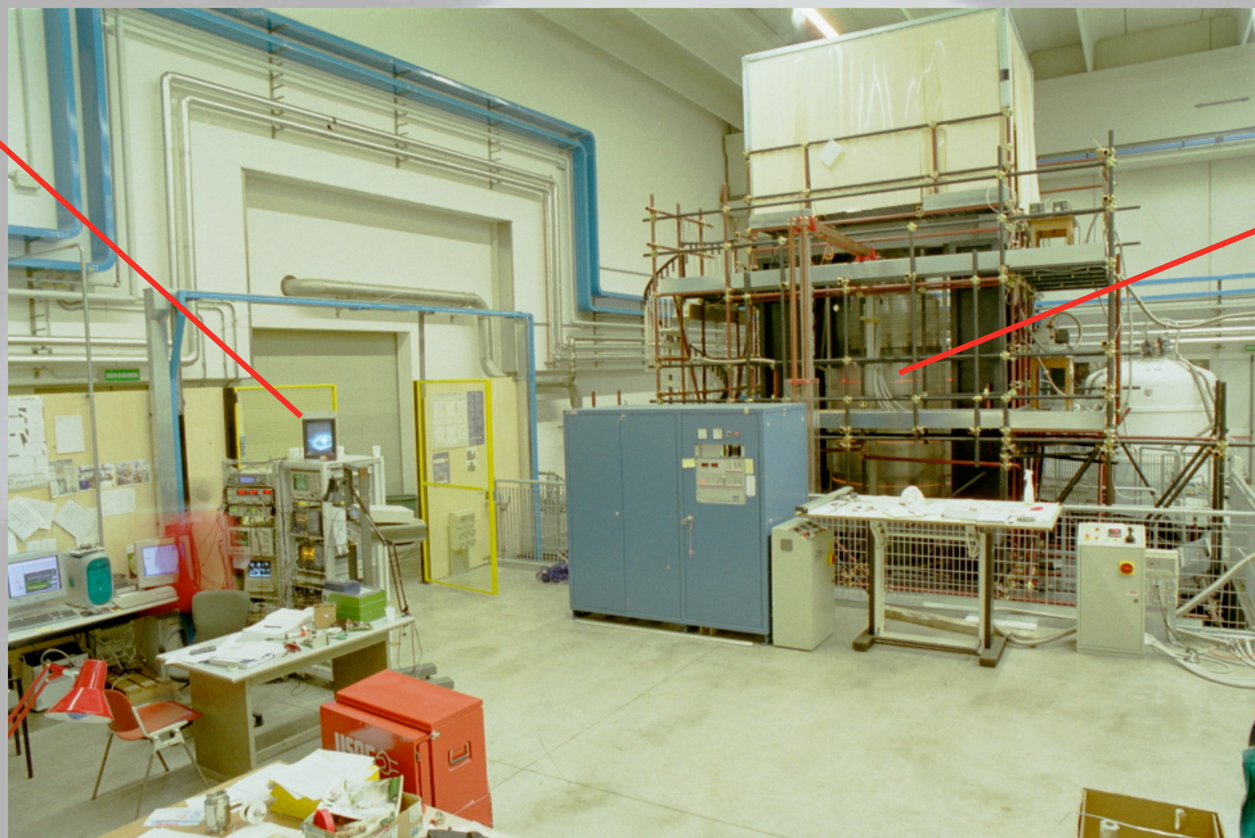
Magnet position

Control room



Running

locked laser during rotation.



Rotating magnet (notice the red streak)

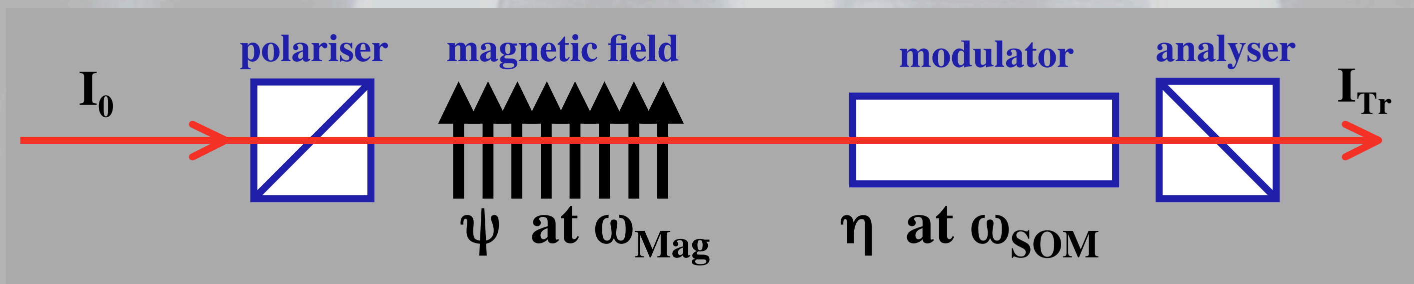
PVLAS Experiment

High sensitivity ellipsometer based on;

- Fabry-Pérot cavity for path length;
- superconducting magnet for high field;
- rotating magnet to reduce 1/f noise;
- heterodyne technique.

Ellipticity measurement principle

- Static measurement is excluded: $I_{Tr} = I_0\left[\sigma^2 + \Psi(t)^2\right]$
- Modulate the effect and add a carrier $\eta(t)$ to signal at ω_{SOM}
- Rotating the field at Ω_{Mag} produces an ellipticity at $2\Omega_{Mag}$



Ideally,

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

Main frequency components at $\omega_{SOM} \pm 2\Omega_{Mag}$ and $2\omega_{SOM}$

In practice, nearly static birefringences $\beta_s(t)$ generate a 1/f noise around ω_{SOM}.

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

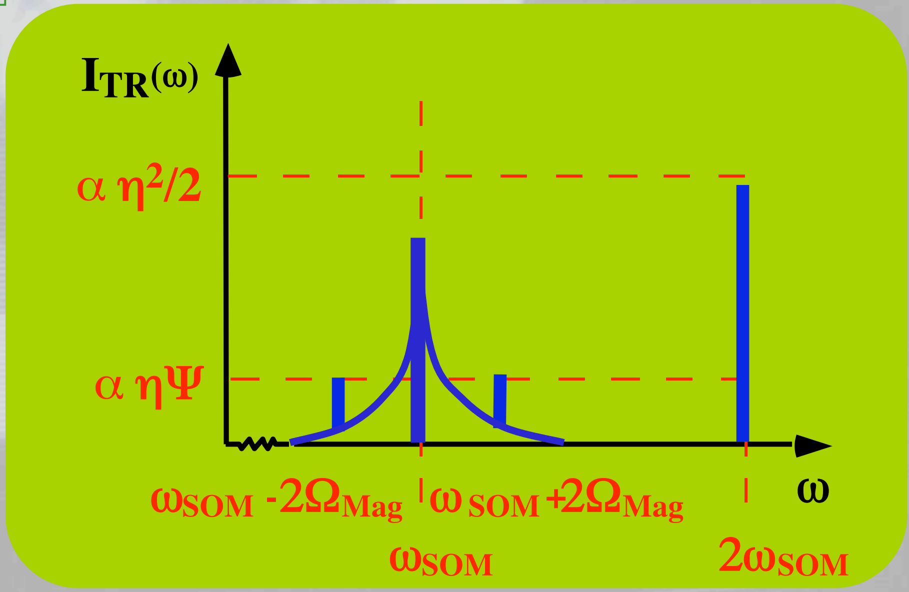
$$= I_0\left[\sigma^2 + \left(\eta(t)^2 + 2\Psi(t)\eta(t) + 2\beta_s(t)\eta(t) + \ldots\right)\right]$$

Normalization

Desired signal

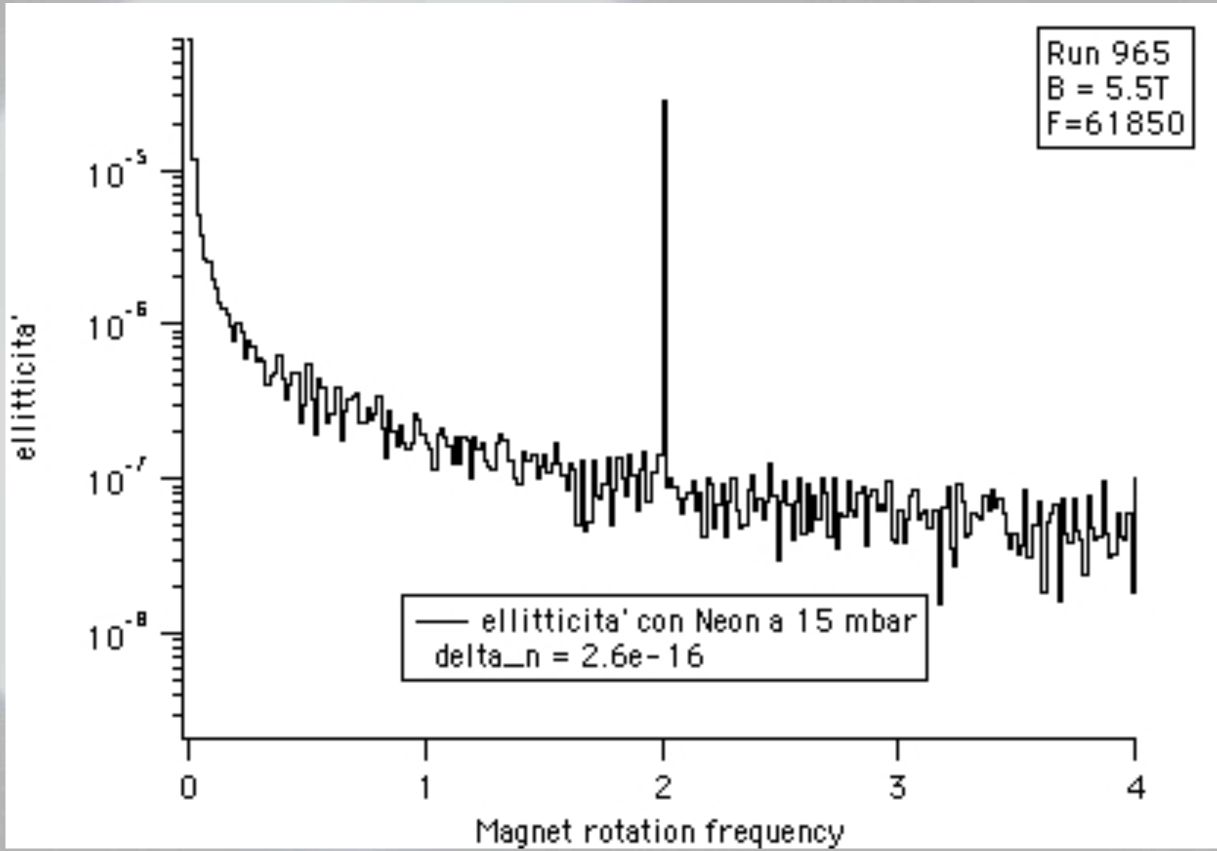
Birefringence noise

- A small, time-varying signal can be extracted from a large noise background with the heterodyne tecnique



Calibration with gases - Cotton Mouton

Spectrum of the signal demodulated at the carrier frequency.
The signal is expected at twice the magnet rotation frequency.



Measurement time

192 s

Sensitivity

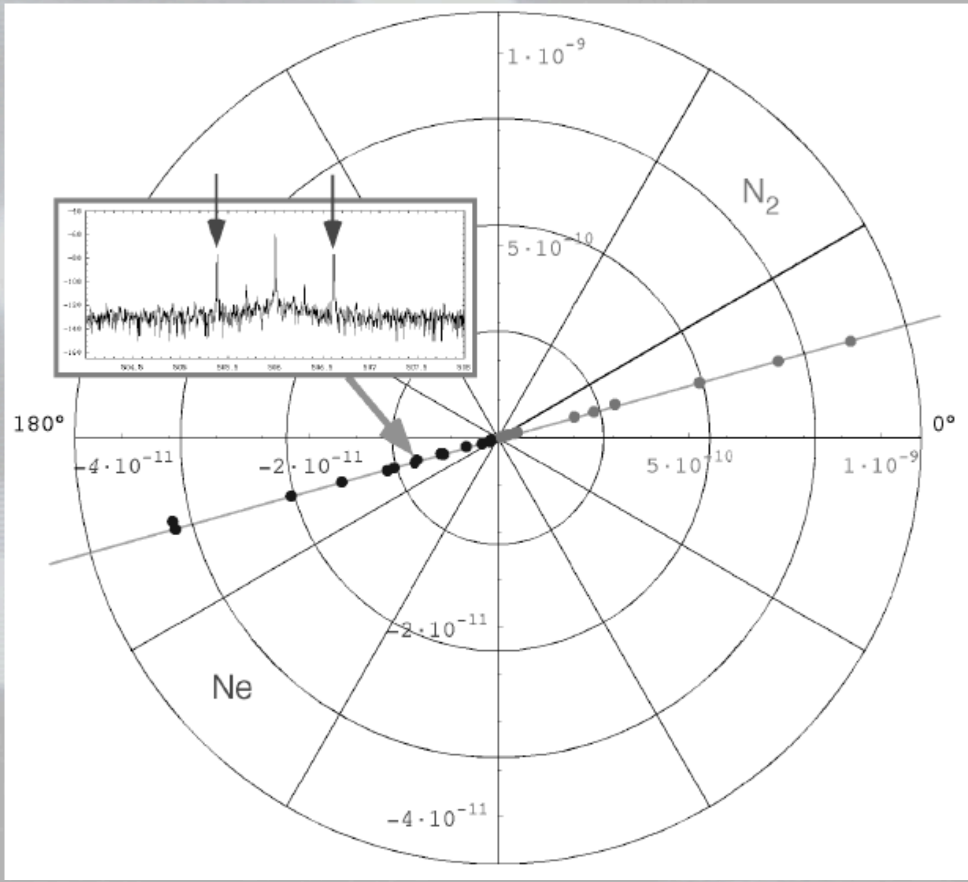
$$\psi^s \approx 6 \cdot 10^{-7} \quad 1/\sqrt{Hz};$$
$$\Delta n^s \approx 2 \cdot 10^{-18} \quad 1/\sqrt{Hz};$$

Corresponds to $\Delta n = 2.6 \cdot 10^{-16}$

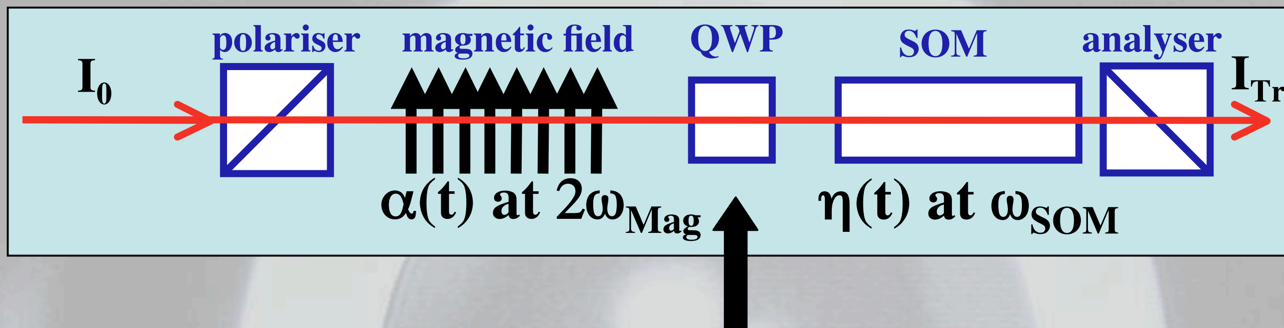
Polar plot of the phase and amplitude of the fourier signal at $2\Omega_{Mag}$ for N_2 and Kr

- **N_2 and Kr have opposite signs**

- Gases define the phase for a 'real' magnetically induce effect.



Dichroism measurements



QWP can be inserted to transform a rotation into an ellipticity with the same amplitude. It can be oriented in two positions: 0° and 90°.

$$\alpha(t) \;\Rightarrow\; \begin{cases} \Psi(t) & \text{for } \vartheta = 0^\circ \\ -\Psi(t) & \text{for } \vartheta = 90^\circ \end{cases}$$

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

Main frequency components at $\omega_{SOM} \pm 2\Omega_{Mag}$ and $2\omega_{SOM}$

Sensitivity and Result

Shot noise sensitivity for PVLAS is

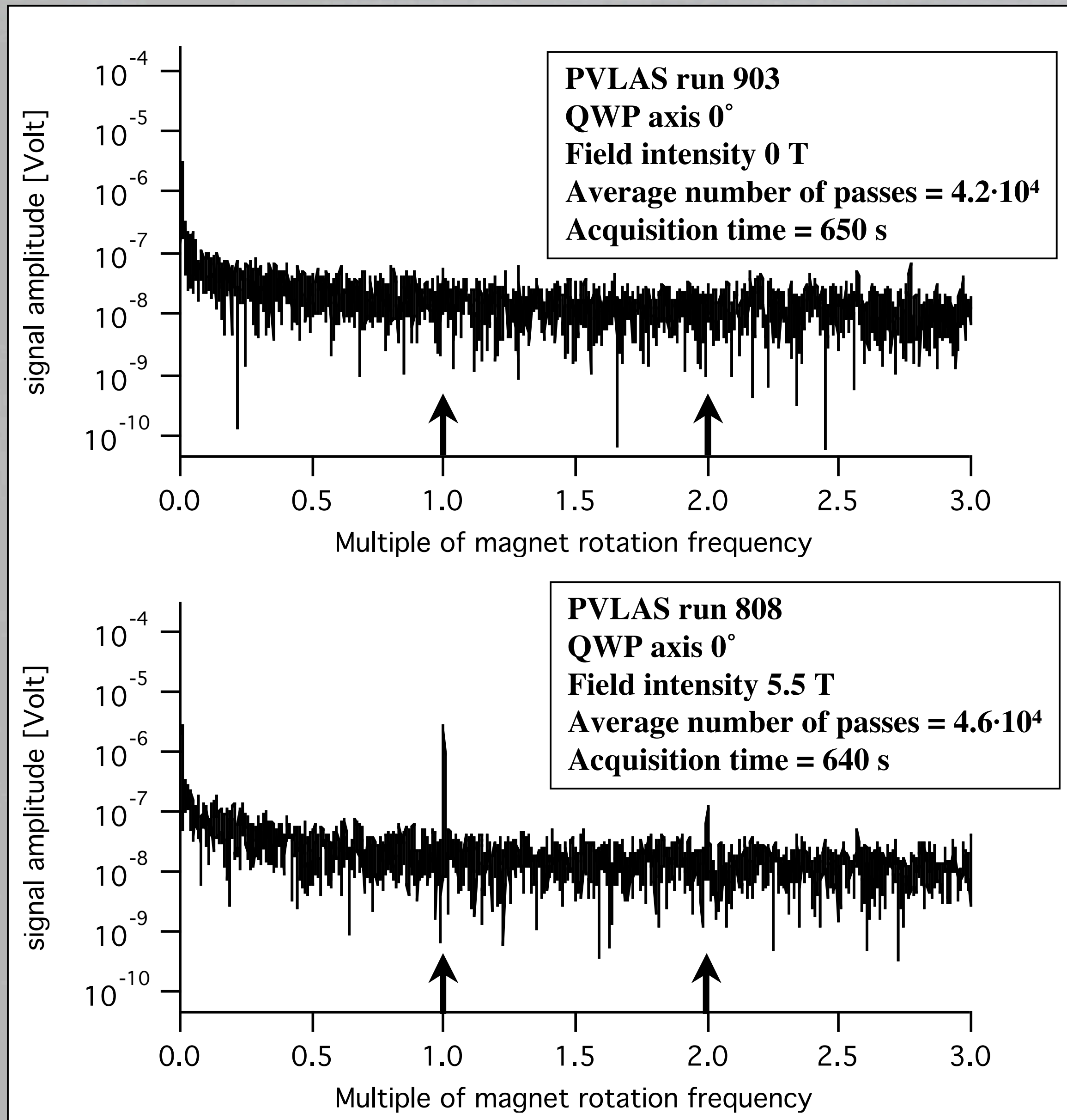
$$\sqrt{\frac{4e}{I_0 q}} = 2 \cdot 10^{-8} / \sqrt{Hz}$$

Present sensitivity for PVLAS is

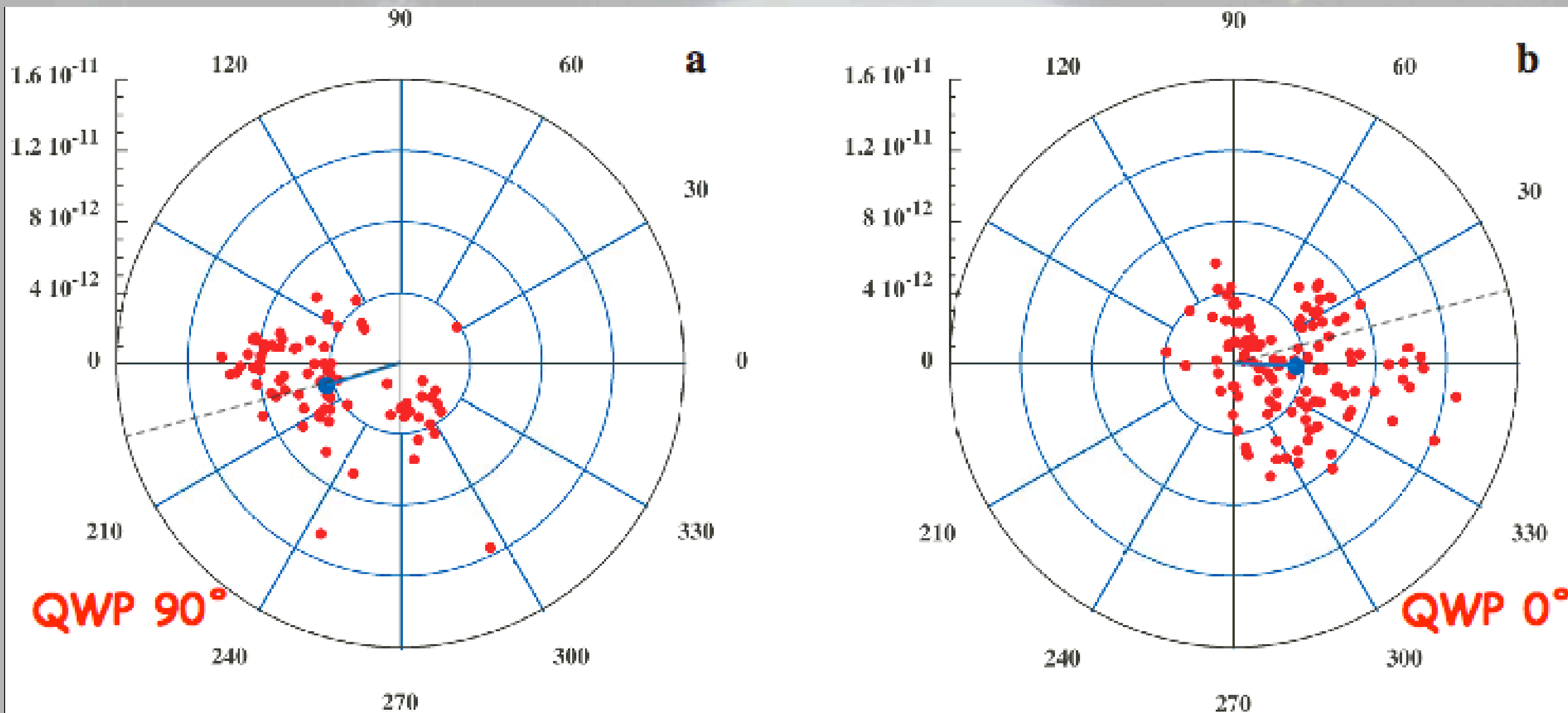
$$\approx 2 \cdot 10^{-7} / \sqrt{Hz}$$

Dichroism signal from PVLAS is

$$= (2.2 \pm 0.3) \cdot 10^{-7} \text{ rad}$$


PVLAS run 903
QWP axis 0°
Field intensity 0 T
Average number of passes = 4.2·10⁴
Acquisition time = 650 s
signal amplitude [Volt]
Multiple of magnet rotation frequency
PVLAS run 808
QWP axis 0°
Field intensity 5.5 T
Average number of passes = 4.6·10⁴
Acquisition time = 640 s
signal amplitude [Volt]
Multiple of magnet rotation frequency

Results for the measured dichroism in vacuum



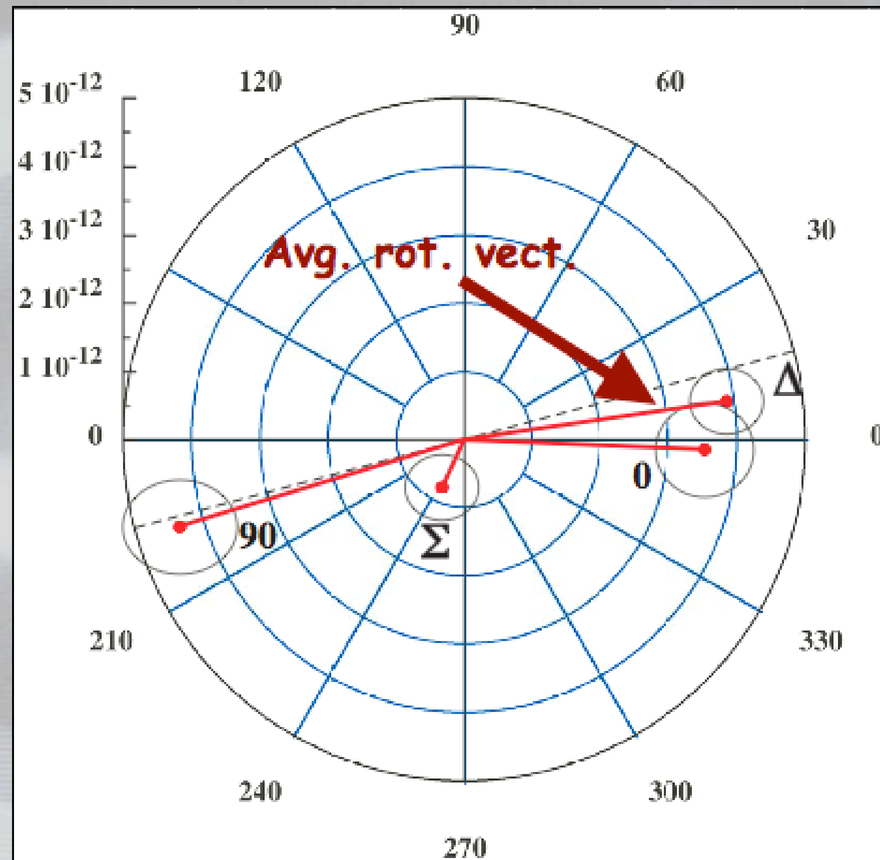
- Observed signal in vacuum with B≠ 0 and cavity present
- The data distribution changes sign when rotating the QWP
- The average vectors lie along the physical axis

Results for the measured dichroism in vacuum

– – QWP 90°: Result of weighted average with the quarter wave plate at 90°

– – QWP 0°: Result of weighted average with the quarter wave plate at 0°

……. N_2: Physical axis defined by measuring the Cotton-Mouton effect in Nitrogen



Dichroism signal = $(2.2 \pm 0.3) \cdot 10^{-7}$ rad

—— HalfDifference Δ: $\dfrac{\overrightarrow{QWP0} - \overrightarrow{QWP90}}{2}$ = Dichroism

—— HalfSum Σ: $\dfrac{\overrightarrow{QWP0} + \overrightarrow{QWP90}}{2}$ = Spurious signal

Error or physical signal?

Candidate	*Test*	*Comment*
residual gas	pressure measurement	excluded
mirror coating birefringence	direct measurement	excluded
electrical pick-up	measurement without the cavity	excluded
beam pointing instability	correlation with measured position signal	possibility.
polarizer movement	measurement without the cavity	excluded
diffusion from magnetised surfaces	pinhole insertion	excluded
physical signal	must satisfy signal conditions	NOT excluded

Final Vacuum Result

$$\text{Total rotation measured} = (2.2 \pm 0.3) \cdot 10^{-7}\,\text{rad}$$

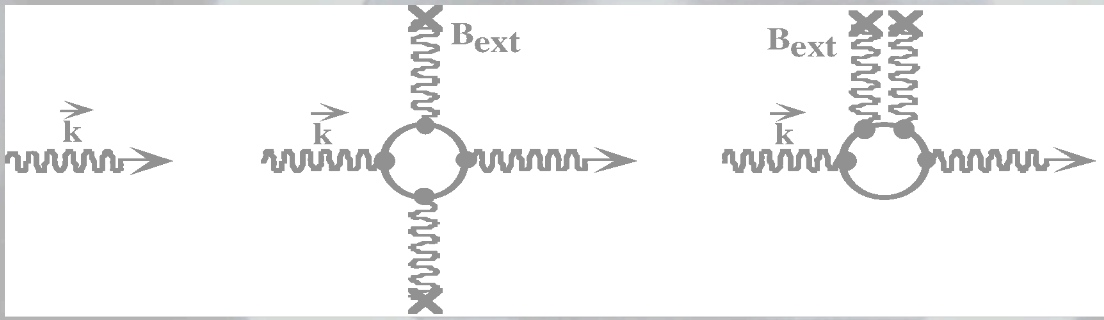
$$\left(\frac{q-1}{2}\right) = -(3.7 \pm 0.4) \cdot 10^{-12}\,\text{rad/pass}$$

<u>Questions</u>: What is the origin of this dichroism?

1. Possible systematic error.
2. If it is physical, is it an absorption or a mixing?
3. QED-QCD interference leading to photon splitting?
4. ....?

Vacuum as a Medium - QED

- Scheme:
  - **perturb** the vacuum state with an external field
  - **probe** the **perturbed** vacuum state with a polarized laser beam
  - **deduce** information on the structure of the vacuum state



The propagation of light will be affected by the polarized vacuum fluctuations.

•It seems that the leading term is due to e^+e^- pairs.
•This effect can be calculated by the leading term in the Euler-Heisenberg effective lagrangian.

Euler-Heisenberg Effective Lagrangian

$$L_{EH} = \frac{1}{8\pi}\left(\mathrm{E}^2 - \mathrm{B}^2\right) - \frac{\alpha}{8\pi^2}\int_0^\infty d\eta \frac{e^{-\eta}}{\eta}\left[\vec{\mathrm{E}}\cdot\vec{\mathrm{B}}\frac{\Re\cosh\left(\eta\sqrt{\left(\mathrm{E}^2-\mathrm{B}^2\right)+2i\left(\vec{\mathrm{E}}\cdot\vec{\mathrm{B}}\right)}/F_c\right)}{\Im\cosh\left(\eta\sqrt{\left(\mathrm{E}^2-\mathrm{B}^2\right)+2i\left(\vec{\mathrm{E}}\cdot\vec{\mathrm{B}}\right)}/F_c\right)} - \frac{F_c^2}{\eta^2} - \frac{\mathrm{E}^2-\mathrm{B}^2}{3}\right]$$

$$F_c = \frac{m_e^2 c^3}{e\hbar} = \text{critical field;}$$

For fields much smaller than the critical field ($B << 4.4\cdot 10^{13}$ gauss $E << 4.4\cdot 10^{13}$ statvolt/cm) one can write

$$L_{EH} = L_{EM} + L_{QED}$$

$$L_{EM} = \frac{1}{8\pi}\left(\mathrm{E}^2 - \mathrm{B}^2\right)$$

$$L_{QED} = \frac{A_e}{4\pi}\left[\left(\mathrm{E}^2 - \mathrm{B}^2\right)^2 + 7\left(\vec{\mathrm{E}}\cdot\vec{\mathrm{B}}\right)^2\right]$$

$$A_e = \frac{1}{90\pi}\left(\frac{\alpha^2 \lambda\!\!\!^{-}{}_e^3}{m_e c^2}\right) = 4/3\cdot 10^{-32}\ \mathrm{cm}^3/\mathrm{erg}$$

- Higher order terms are neglected
- virtual pairs other than e^+e^- are neglected

Induced Magnetic Birefringence of Vacuum

•Light propagation is still described by Maxwell's equations in media. They no longer are linear due to E-H correction.

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

$$\vec{\mathbf{D}} = 4\pi \frac{\partial L_{EH}}{\partial \vec{\mathbf{E}}}$$

$$\vec{\mathbf{H}} = -4\pi \frac{\partial L_{EH}}{\partial \vec{\mathbf{B}}}$$

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

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

Linearly polarized light passing through a transverse external magnetic field.

$$\begin{cases} \varepsilon_{||} = 1 + 10A_eB_0^2 \\ \mu_{||} = 1 + 4A_eB_0^2 \\ n_{||} = 1 + 7A_eB_0^2 \end{cases} \qquad \begin{cases} \varepsilon_{\perp} = 1 - 4A_eB_0^2 \\ \mu_{\perp} = 1 + 12A_eB_0^2 \\ n_{\perp} = 1 + 4A_eB_0^2 \end{cases}$$

$$\Delta n = 3A_eB_0^2 \approx 4 \cdot 10^{-32}B_0^2 \quad (B_0 \text{ in gauss})$$

- $v \neq c$
- anisotropy

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

Numbers

$$\Psi_{1pass} = \frac{\varphi}{2} = \frac{\pi L}{\lambda}\Delta n \sin 2\vartheta$$

High field
B = 6T → $\Delta n = 3A_e B_0^2 = 1.2 \cdot 10^{-22}$

Long optical path length in field → High finesse optical cavity
$F \approx 10^5$; $L = 1.1$ m

$$\Psi_{Cavity} = \left(\frac{2F}{\pi}\right)\frac{\pi L}{\lambda}\Delta n \sin 2\theta$$

With these numbers $\Psi \approx 3 \cdot 10^{-11}$

What else?

QED

•Photon splitting? Much smaller than birefringence.

•Higher order corrections are ~ 1%

OTHER

•quark-gluon contribution: QED-QCD interference?

•*low mass, neutral particle search: axion-like*

Axion-like contribution

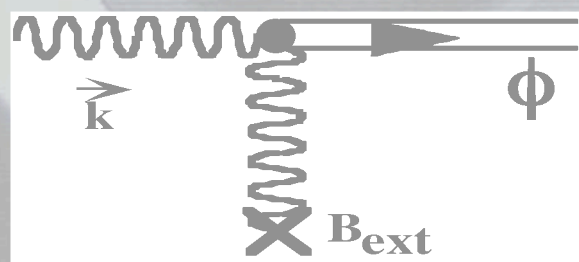
- One can add extra terms [*] to the E-H lagrangian to include contributions from hypothetical <u>neutral light particles interacting weakly with two photons</u>

$$L_\phi = \frac{1}{4M}\phi\left(\vec{E}_\gamma \cdot \vec{B}_{ext}\right)$$

pseudoscalar case

$$L_\sigma = \frac{1}{4M_s}\sigma\left(E_\gamma^2 - B_{ext}^2\right)$$

scalar case



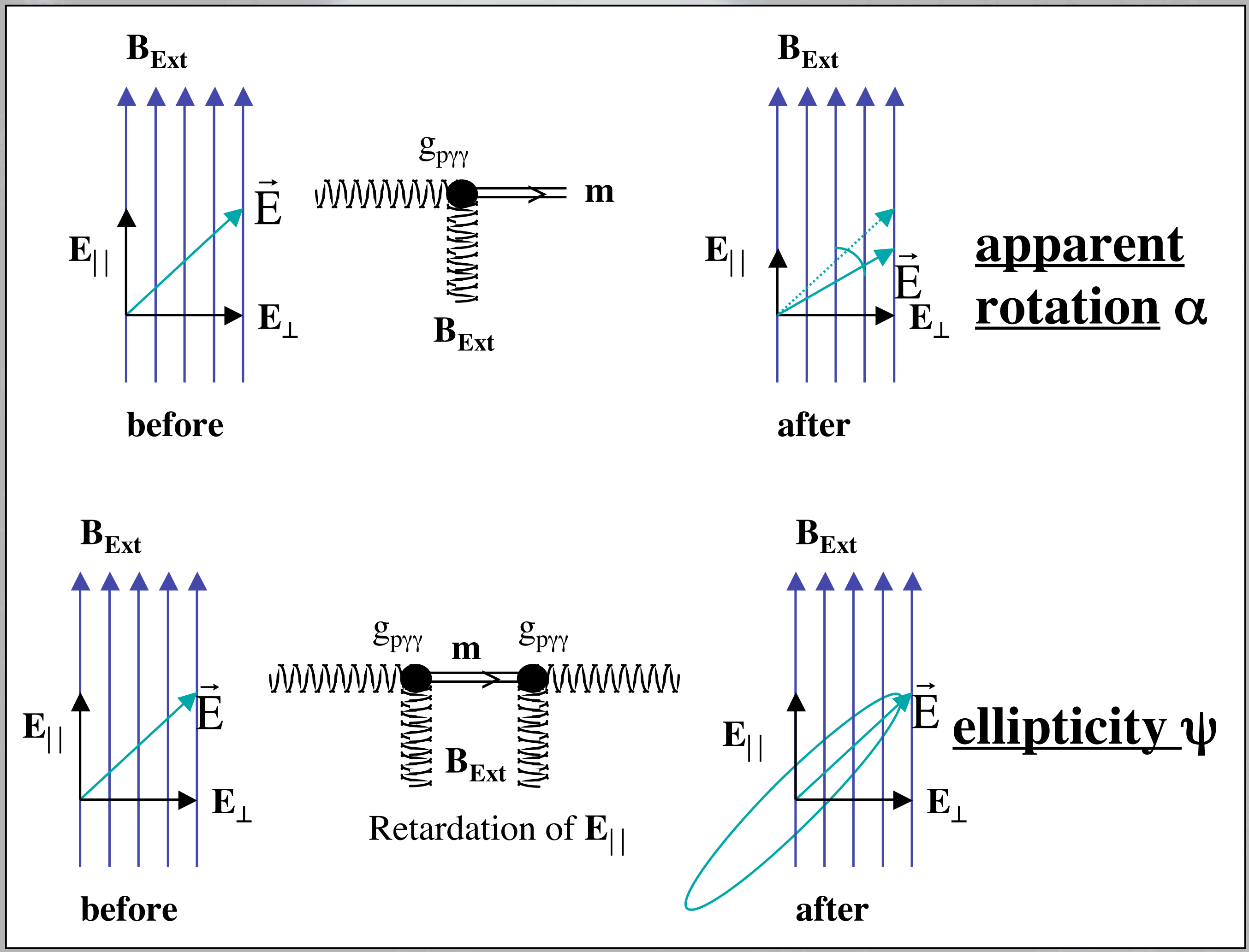
M, M_s are inverse coupling constants

[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]

Effect of Axion-like particle

Dichroism

Ellipticity



Induced linear birefringence and dichroism

Dichroism

$$\alpha = -\sin 2\vartheta \left(\frac{BL}{4M}\right)^2 N \left(\frac{\sin x}{x}\right)^2$$

Ellipticity

$$\psi = \sin 2\vartheta \frac{kB^2L}{4M^2 k_m{}^2} N \left(1 - \frac{\sin 2x}{2x}\right)$$

$$x = \frac{L}{2}\left[\frac{k_m{}^2}{2k} + (n-1)k\right]$$

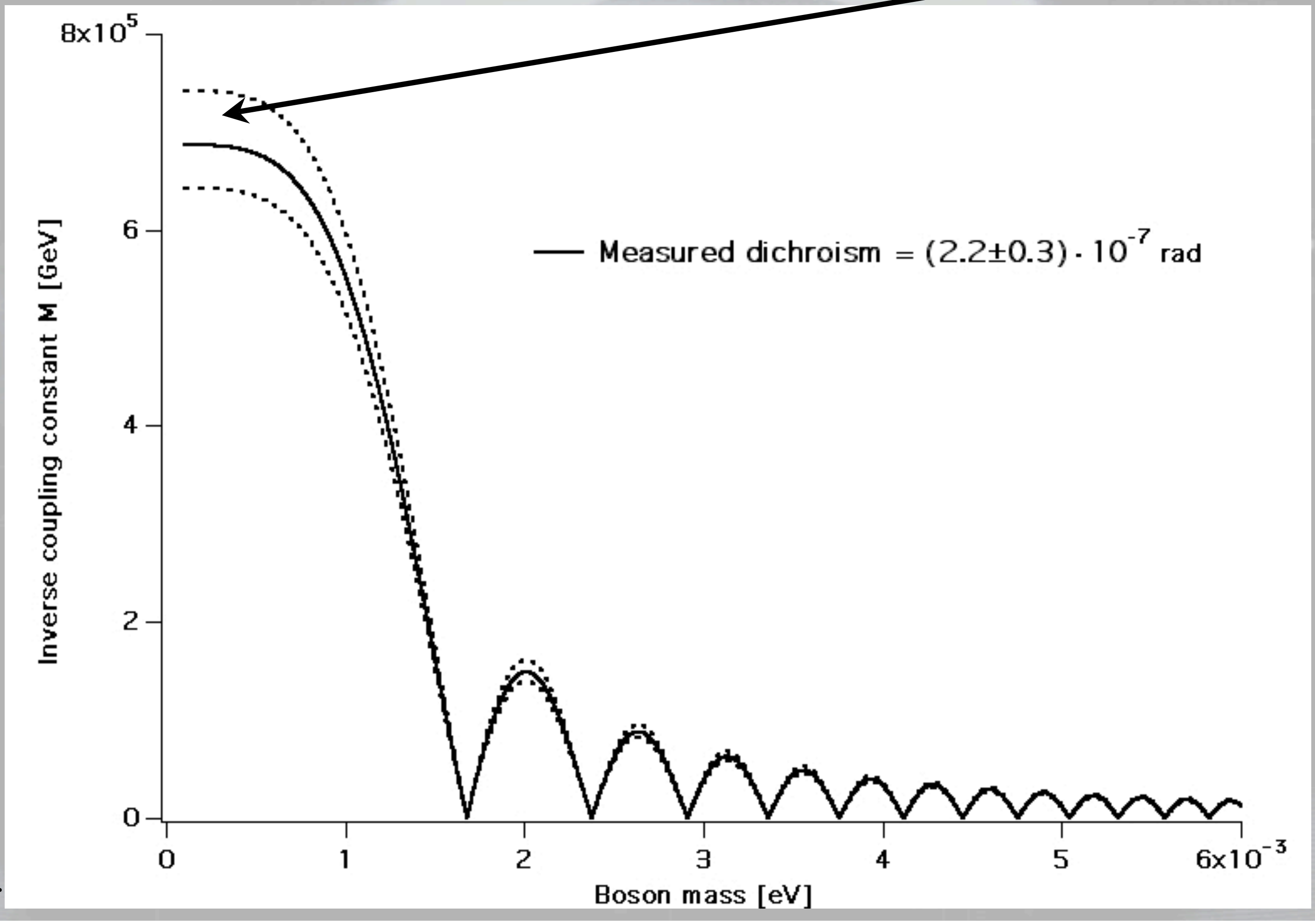
$$k = \frac{2\pi}{\lambda}; \qquad N = \frac{2F}{\pi}; \qquad k_m = \frac{mc}{\hbar}$$

- Both α and ψ are proportional to N
- Both α and ψ are proportional to B^2
- α depends only on *M* for small x
- **the ratio ψ / α depends only on $k_m{}^2$**

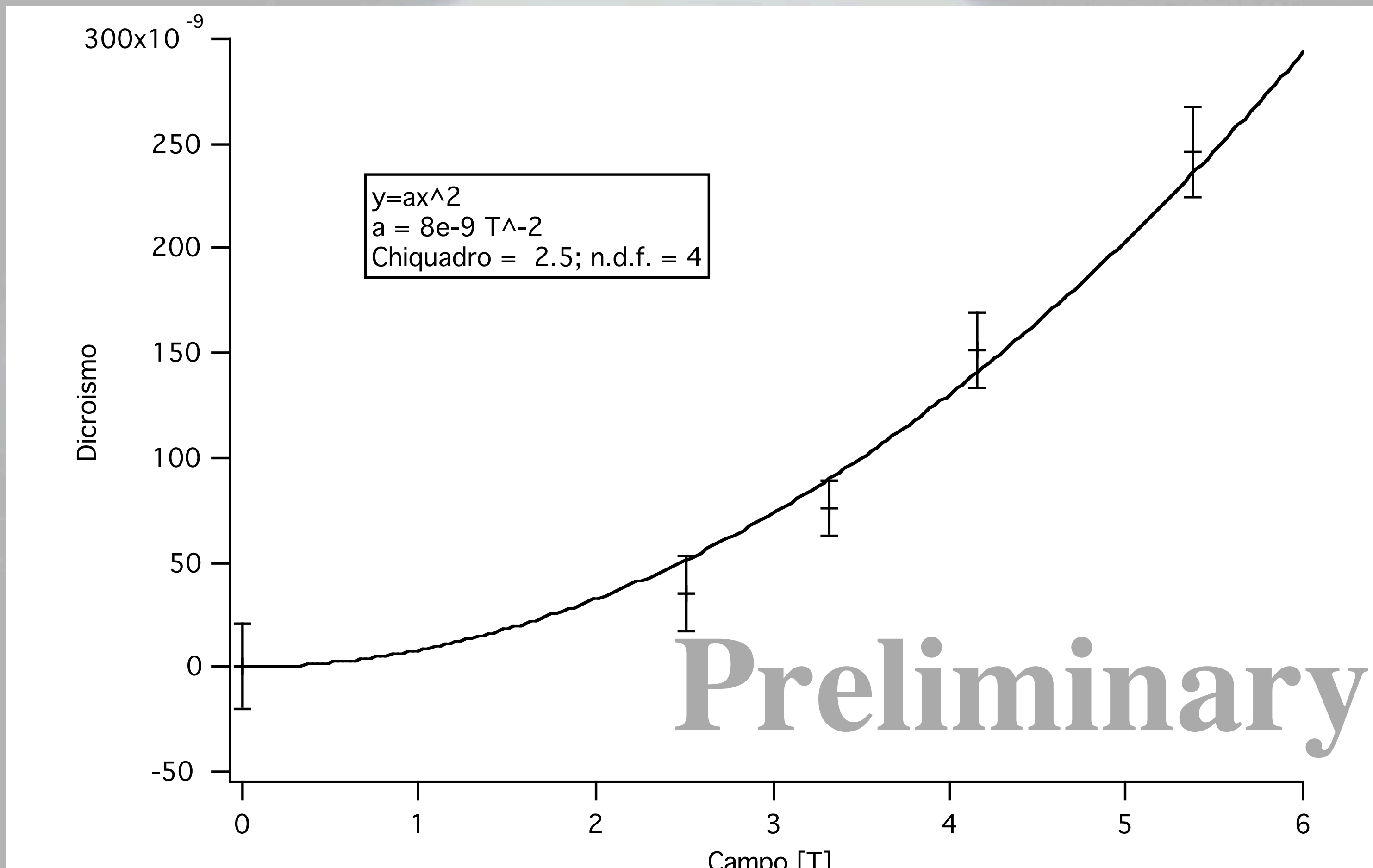
Both *M* and k_m can be disentangled

M Vs. m for Dichroism

With very small x, M must be greater than $7 \cdot 10^5$GeV



Field dependence



Using gases as physical 'handle' in axion search

If we assume that the effect is due to a light neutral particle we can use a gas to change its effective mass causing oscillations of the signal as a function of pressure.

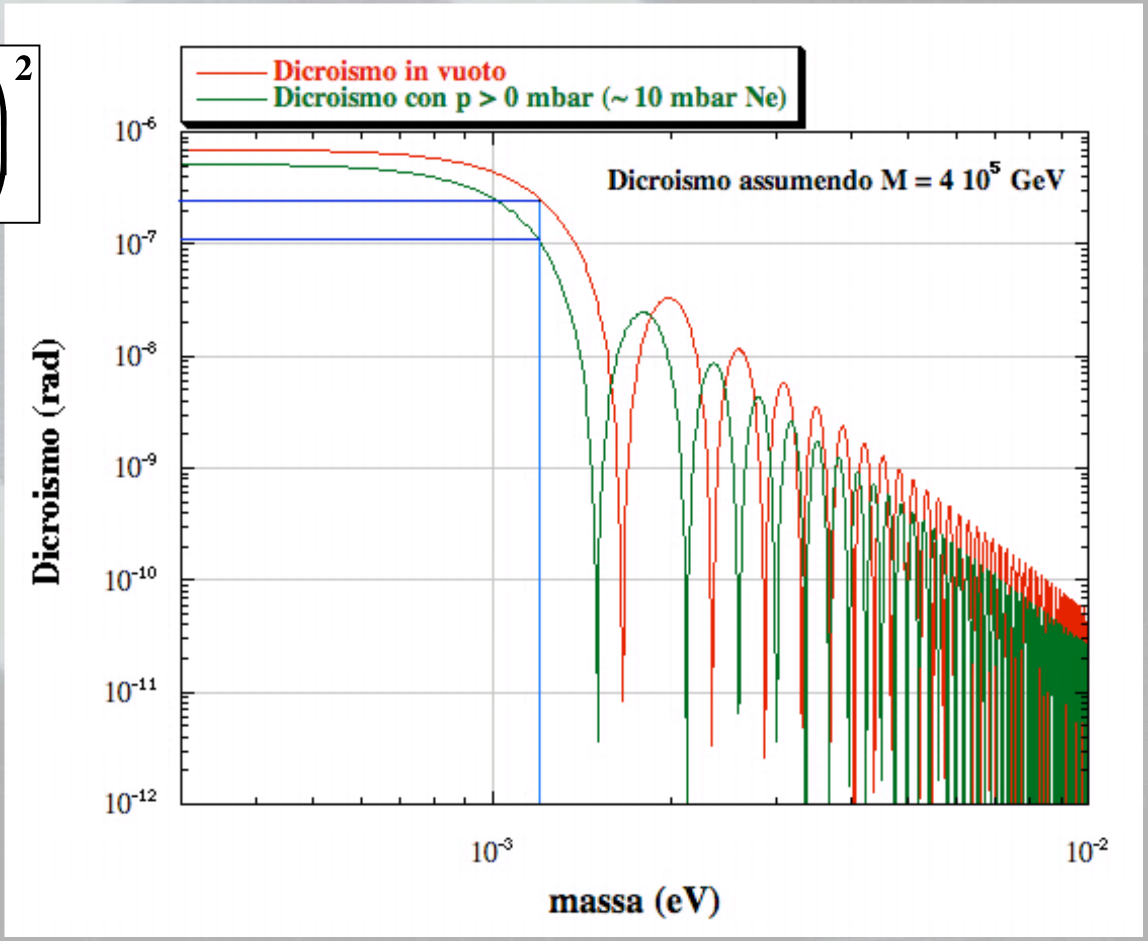
$$\alpha = -\sin 2\vartheta \left(\frac{BL}{4M}\right)^2 N \left(\frac{\sin x}{x}\right)^2$$

$$x = \frac{L}{2}\left[\frac{k_m^{\ 2}}{2k} + (n-1)k\right]$$

$$k = \frac{2\pi}{\lambda};$$

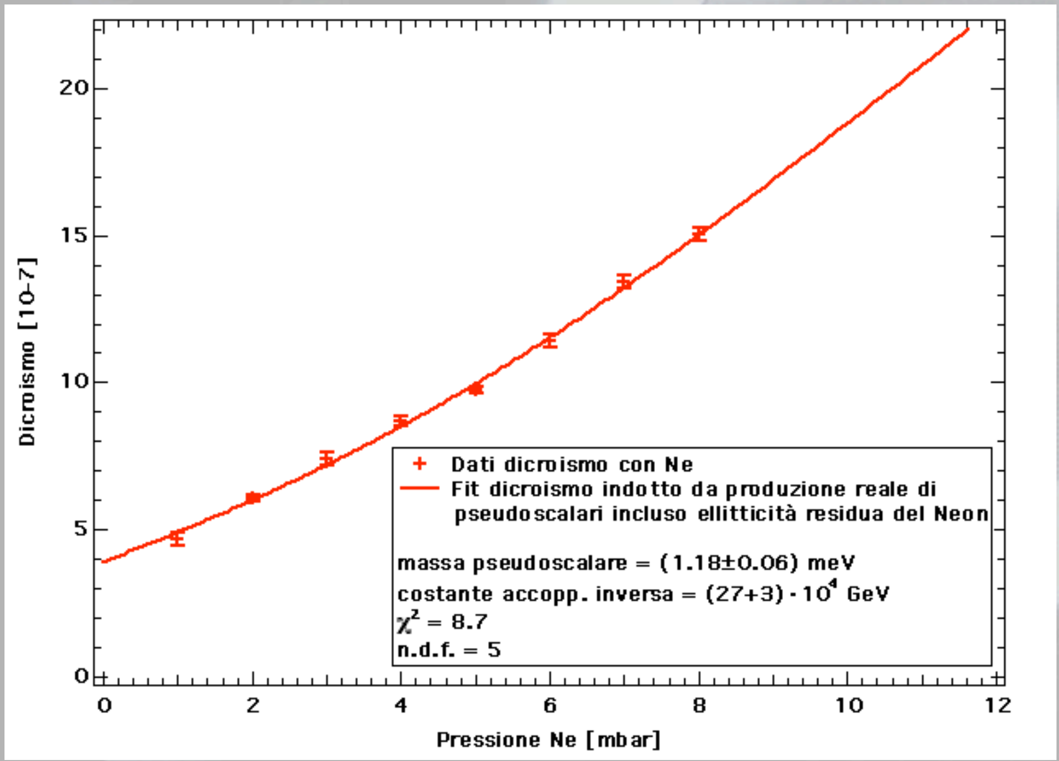
$$N = \frac{2F}{\pi};$$

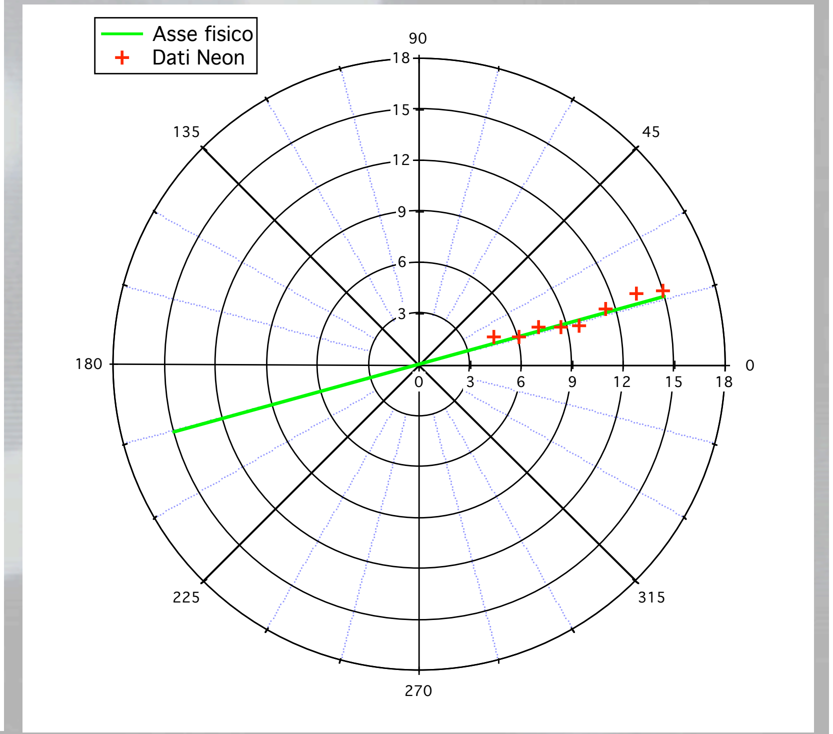
$$k_m = \frac{mc}{\hbar}$$



Dichroism Vs. Neon gas pressure

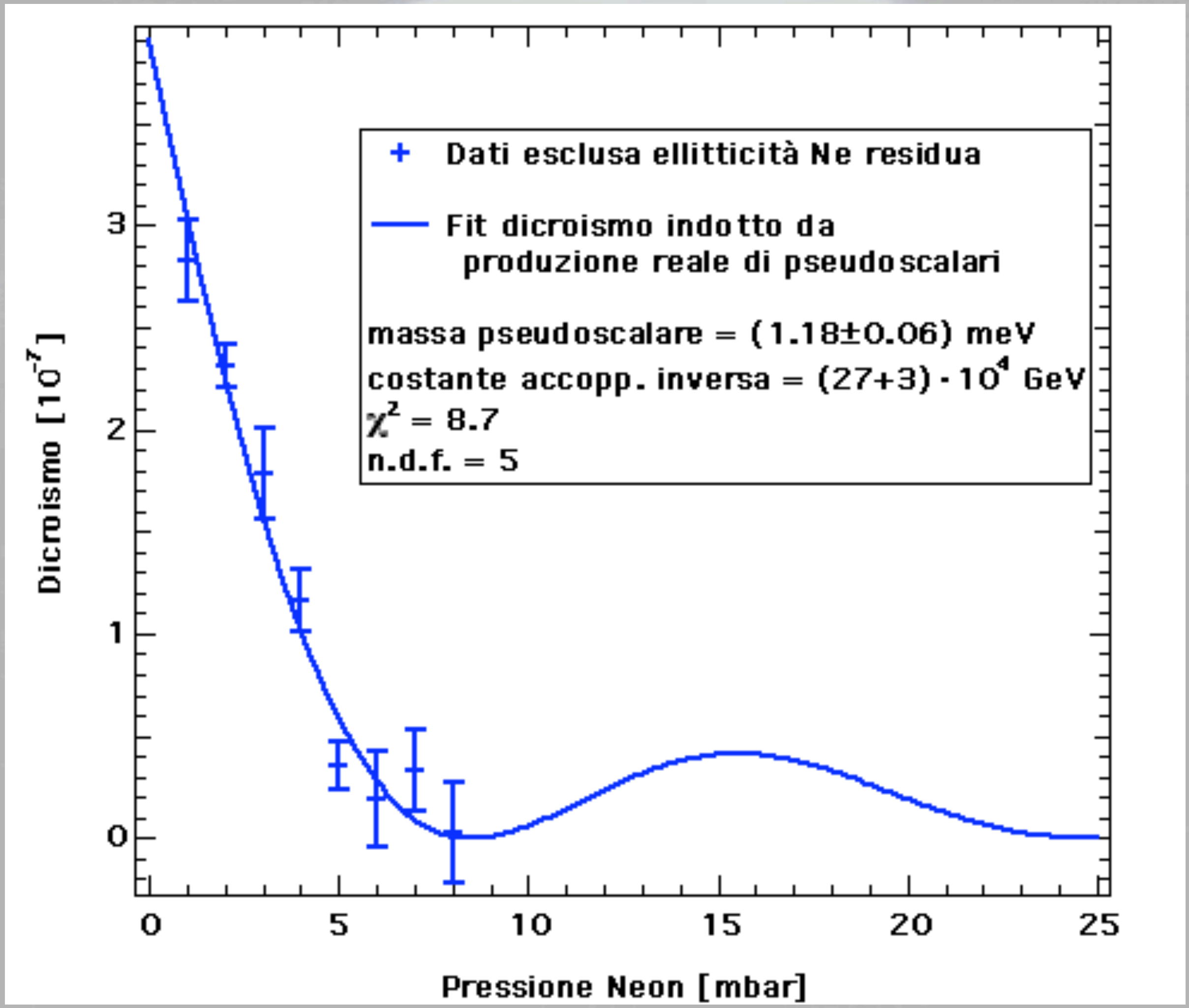
- Gasses do not generate dichroism
- Small dichroism proportional to pressure due to Cotton Mouton effect, cavity transfer function and mirror birefringence - understood



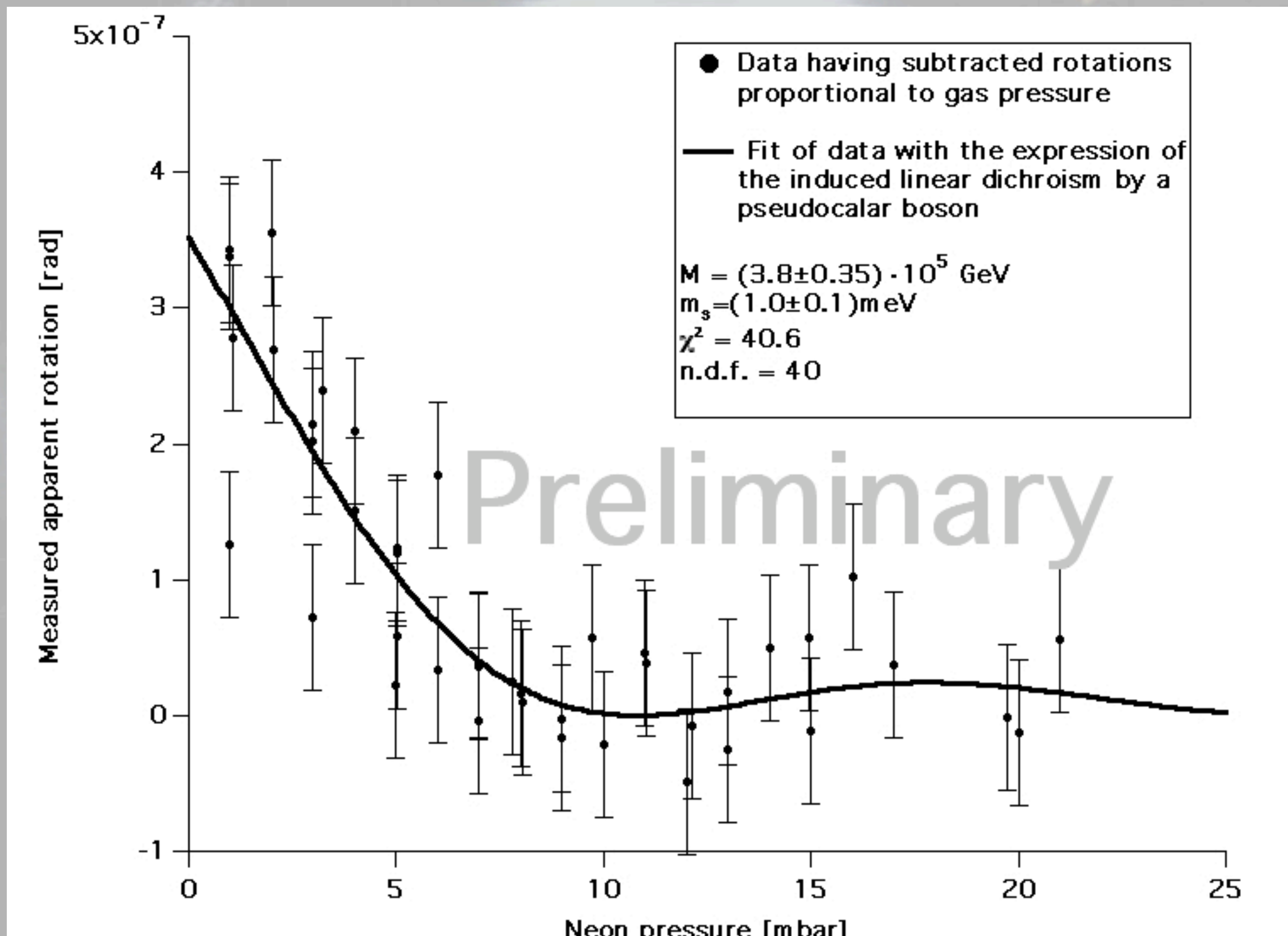


Dichroism Vs. Neon gas pressure

First Neon gas data



More Ne gas measurements



Ellipticity?

- Everthing is birefringent. Furthermore birefringences are not uniform
- Small movements will cause variable signal
- The physical ‘handle’ available for dichroism does not work here
  - Cotton Mouton effect
  - Dependence of boson induced ellipticity is small and does not have a strong dependence on index of refraction

What I can say is that here too we always have a signal at twice the magnet rotation frequency. Variability is greater than dichroism signal. Analysis is still on going.

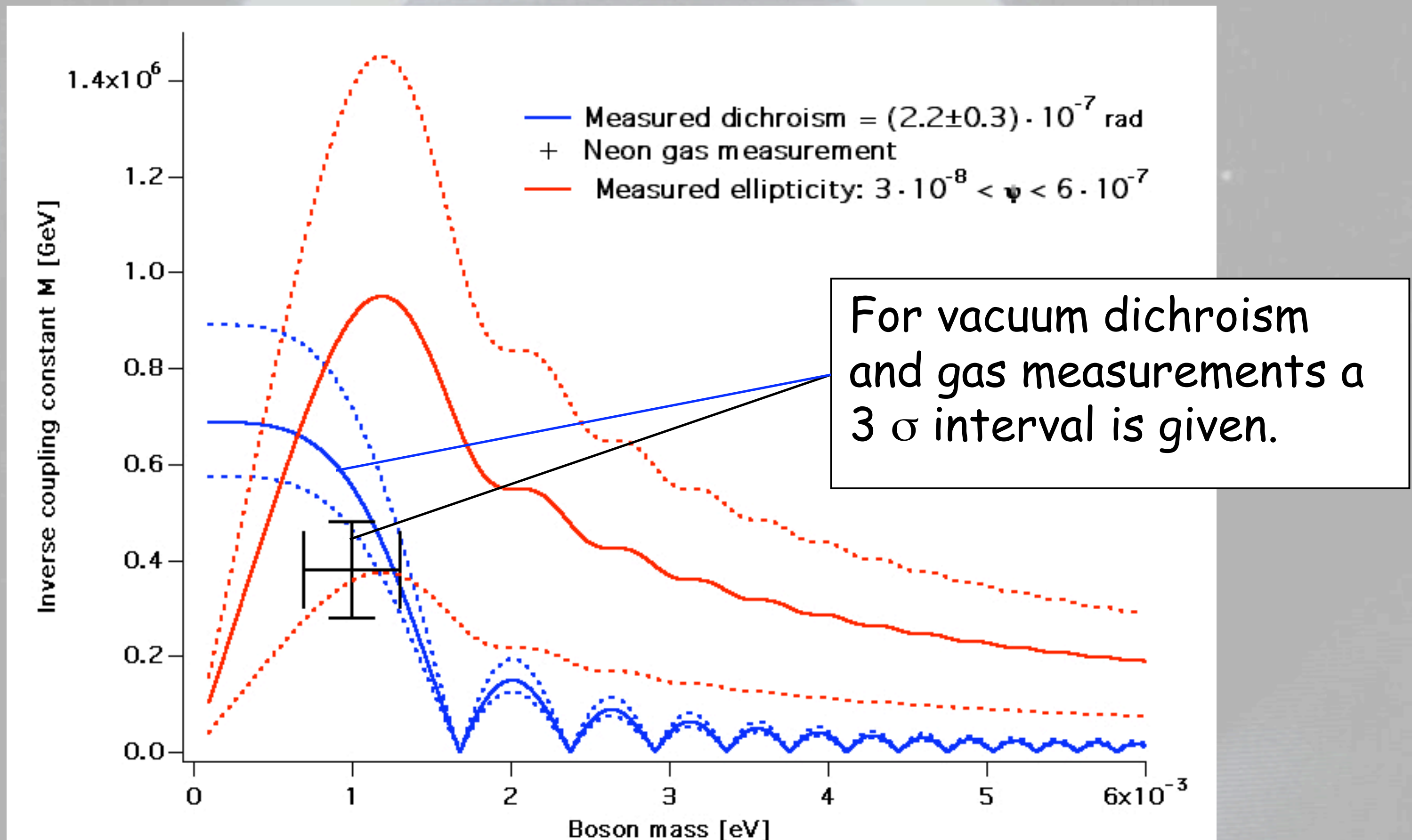
Per pass we have $1.4 \cdot 10^{-12} < \psi < 9 \cdot 10^{-12}$ (Preliminary)

Speculation

If we believe in the signals in vacuum seen by PVLAS (B = 5.5T; N = 52000)

$3 \cdot 10^{-8}$ < ellipticity < $6 \cdot 10^{-7}$; dichroism = $(2.2 \pm 0.3) \cdot 10^{-7}$ rad

and we interpret the signals as due to a pseudoscalar particle of mass *m* and inverse coupling constant *M* to two photons

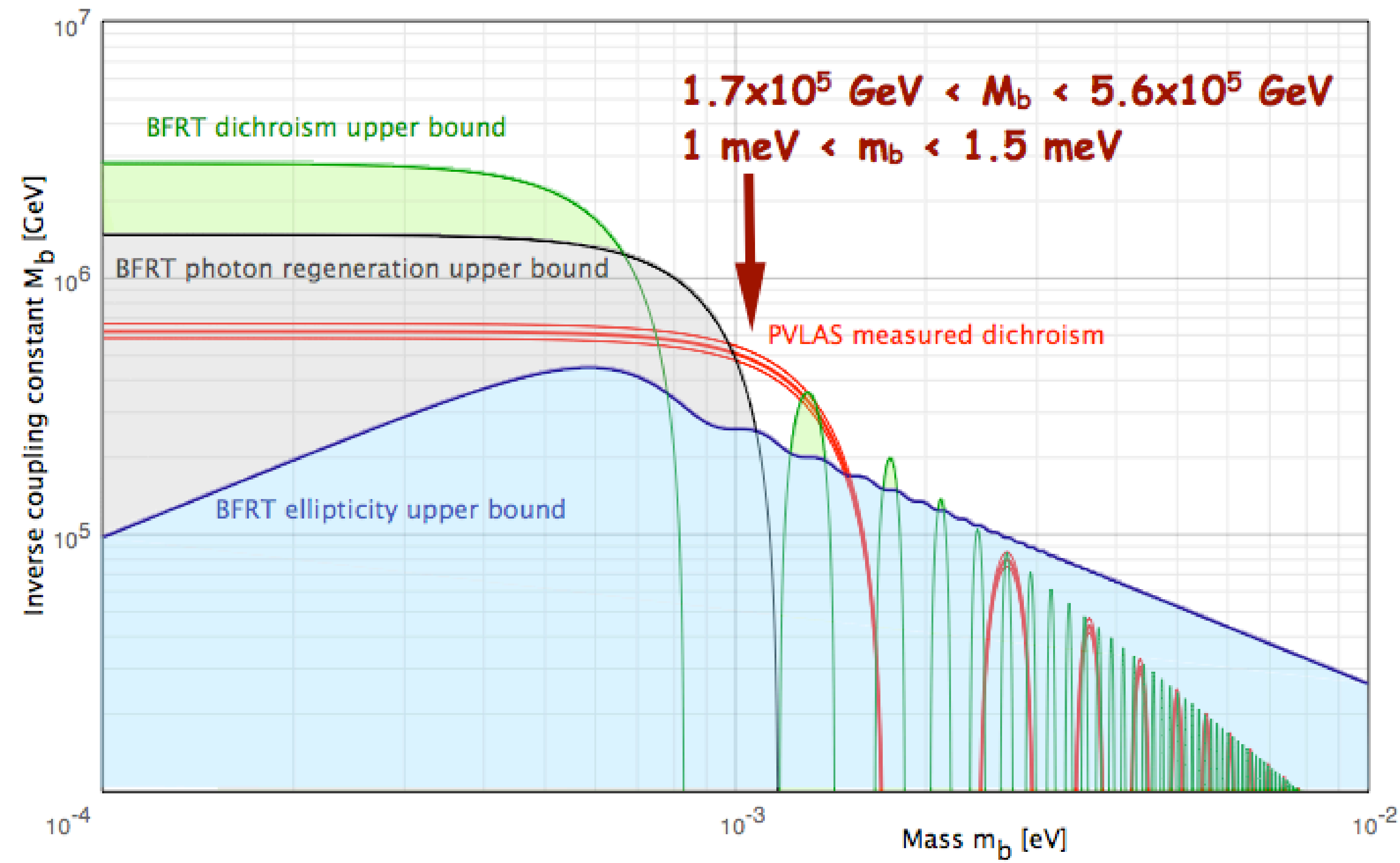


Other experiments

- Two types of limits
  - <u>model dependent</u>
    - "microwave cavity expt."(BNL-Rochester-Fermilab) based on the existence of galactic halo axions. Very low masses and very narrow bands
    - "solar axion expt." (BNL-Rochester-Trieste-Fermilab) based on the conversion of solar axions in a magnetic field
    - CAST solar axion experiment: $M > 8.6 \cdot 10^9$ GeV for $m < 20$ meV
  - <u>model independent</u>
    - "laser expt." (BNL-Rochester-Trieste-Fermilab) PVLAS precursor
    - PVLAS

E. Massò proposes solution by introducing boson form factor which suppresses solar (high energy) production.
hep-ph/0504202 v2 31 May 2005

BFRT - PVLAS

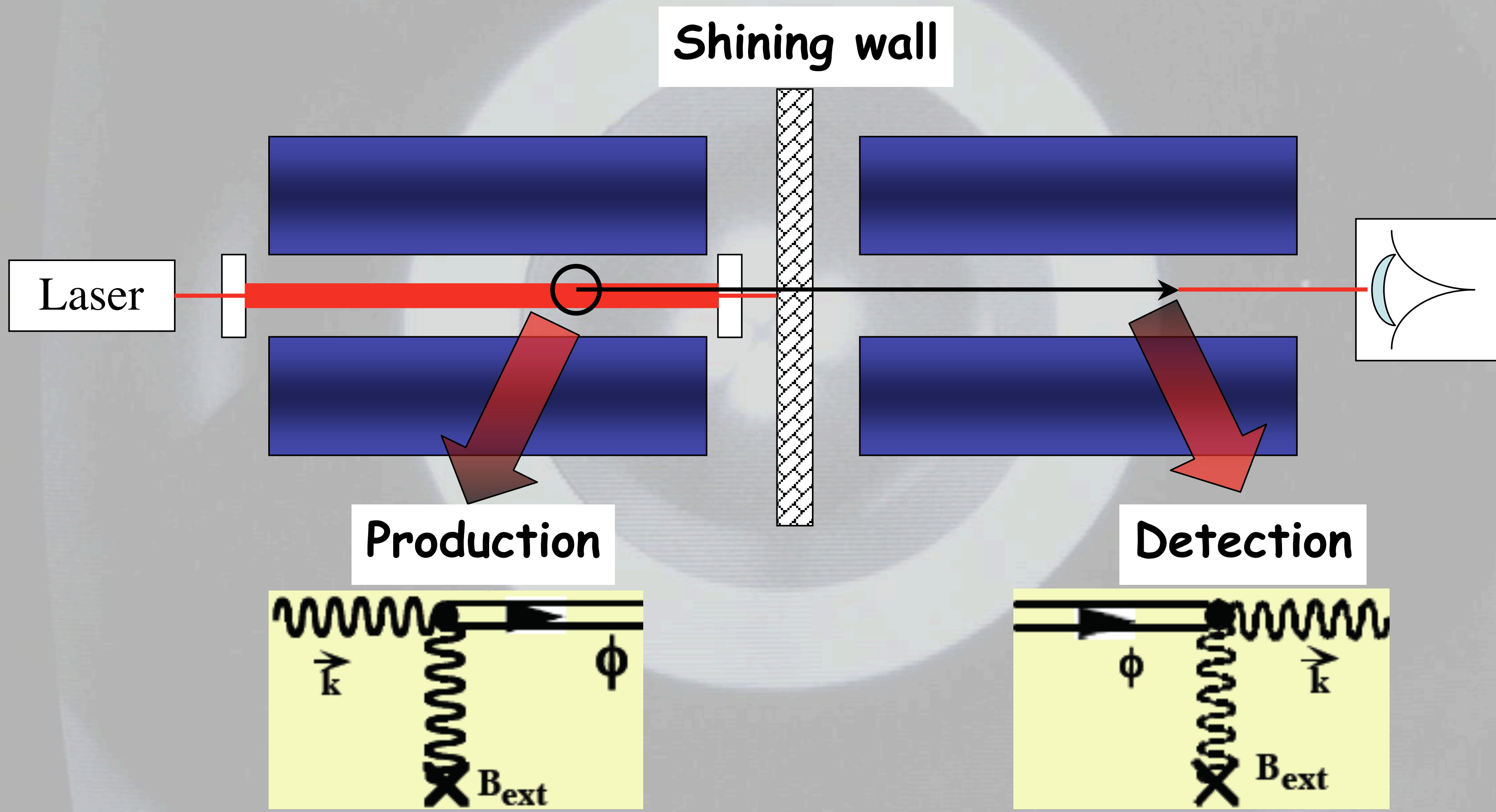


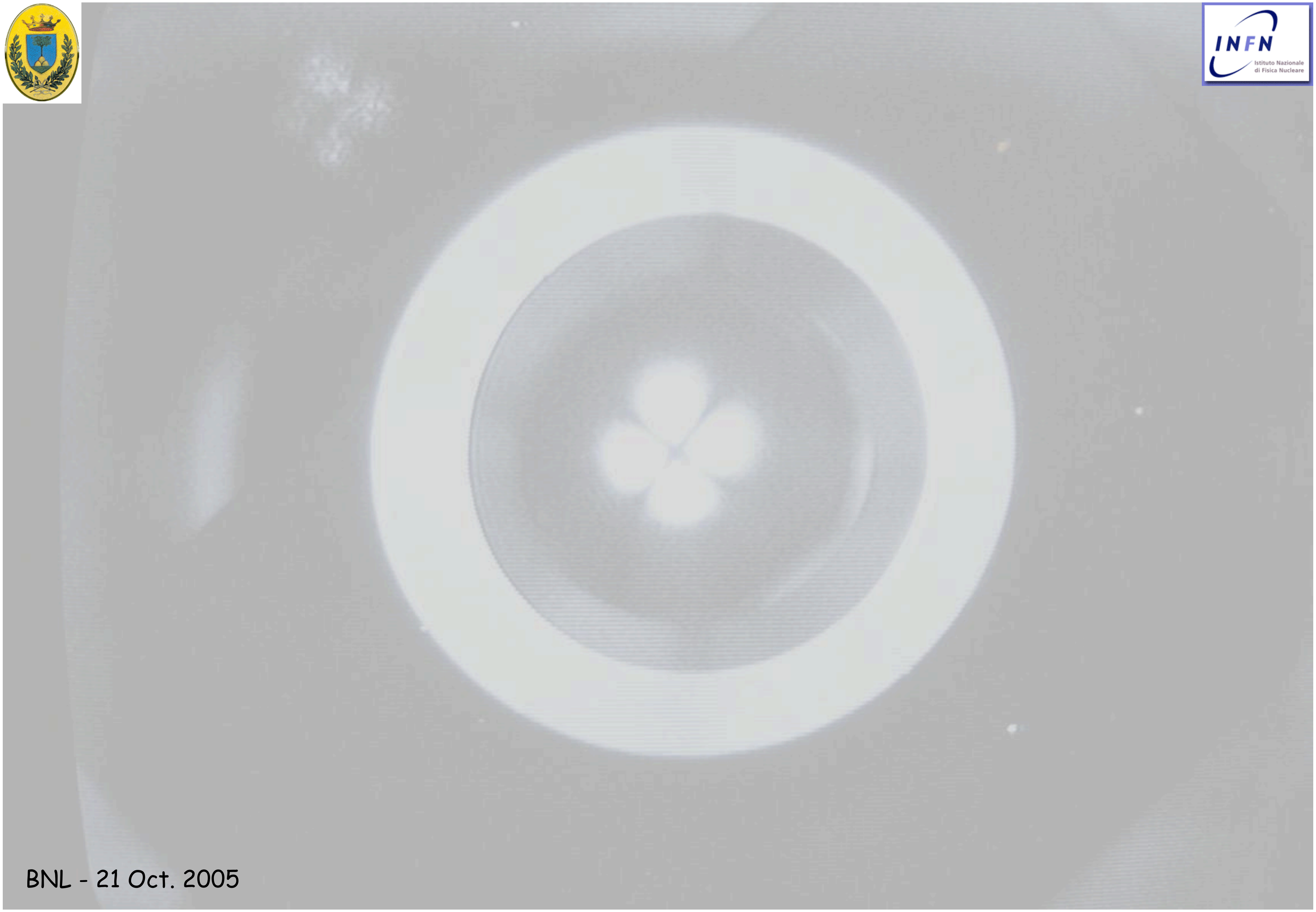
BFRT dichroism upper bound
BFRT photon regeneration upper bound
BFRT ellipticity upper bound
PVLAS measured dichroism
1.7x10^5 GeV < M_b < 5.6x10^5 GeV
1 meV < m_b < 1.5 meV
Inverse coupling constant M_b [GeV]
Mass m_b [eV]
10^7
10^6
10^5
10^-4
10^-3
10^-2

Near future and on going activities

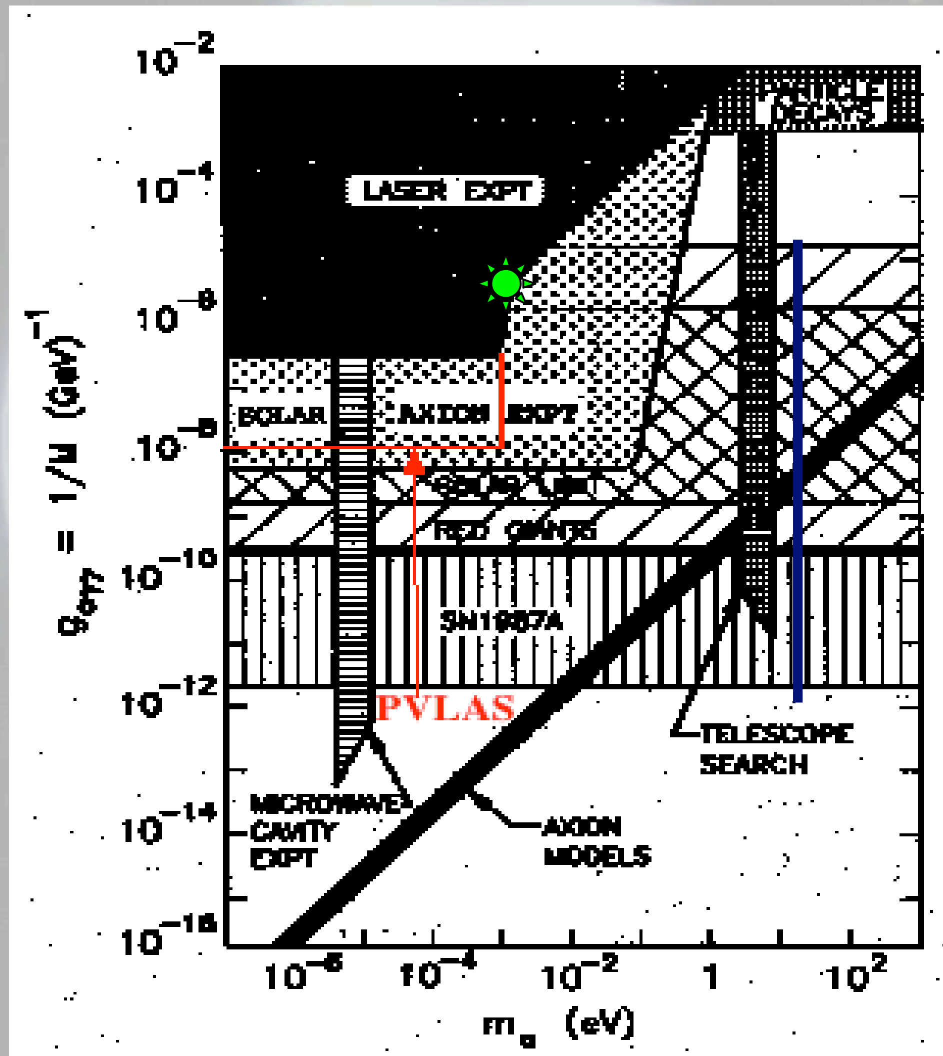
- Continue with different wavelength: λ = 532 nm
  - First measurements have already been performed. Apparatus is functioning. Next run in October.
- Change gas: Measured with He and 532 nm. Will repeat in October
- Input beam has been stabilized. Cavity will also be stabilized
- Search for unexpected photon splitting
- <u>Regeneration experiment</u>

Regeneration



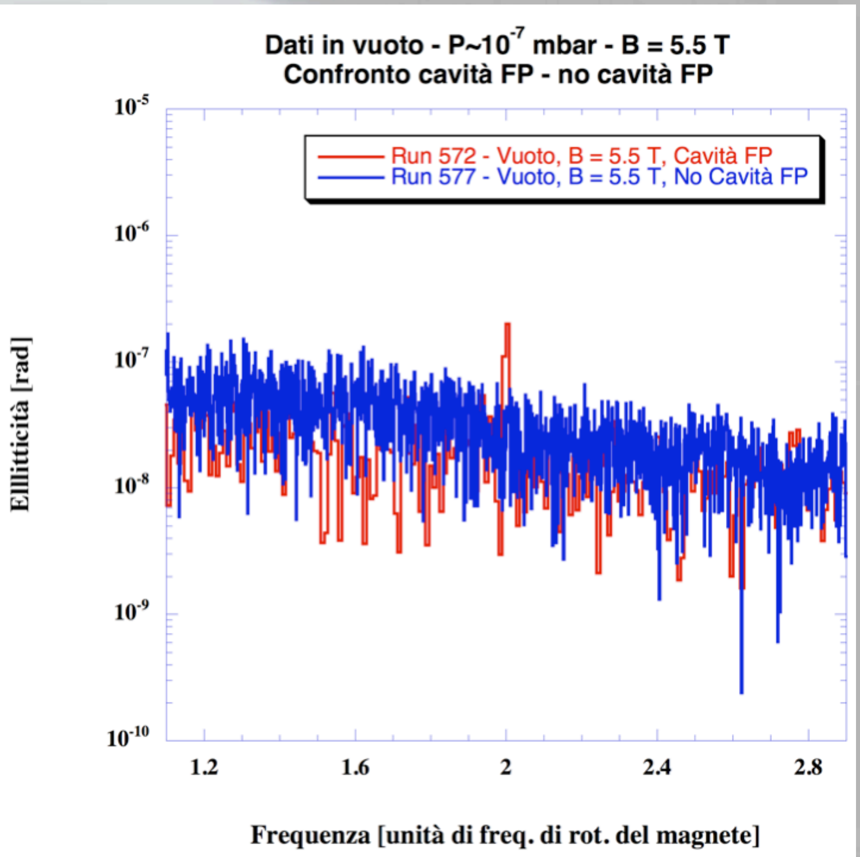


Current axion limits



Localization of the effect

By removing the F.P. the **signal** disapears.



Other property

Moreover by substituting one of the mirrors with a short cavity the signal disappears.
By introducing the QWP before the modulator the signal diminishes

The signal is generated within the cavity

Outline

- Experimental aim of PVLAS
- Method and experimental setup
- Present results
- Possible interpretation and future plans