Experimental study of the "vacuum element" with PVLAS

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Collaborazione PVLAS

Domenico Cantatore - "Cielo di sera"

Summary

- the "vacuum element": macroscopic properties
- experimental technique
- recent results
- discussion
  - speculations
  - future prospects

PVLAS collaboration

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- A. Zanetti (TS)

A closer look ...

The “vacuum element”

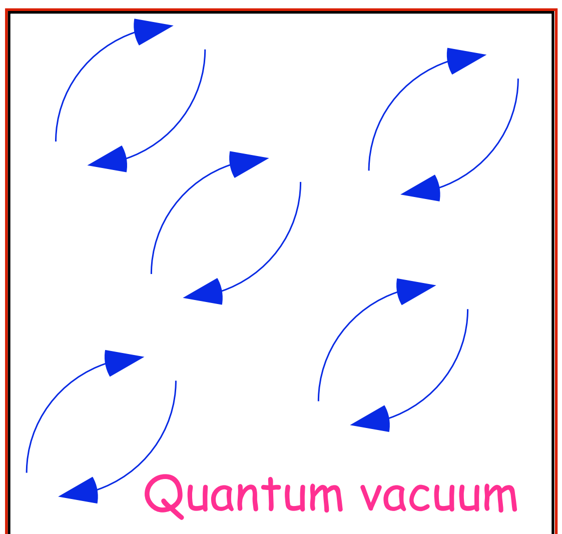
- “Intuitive” picture of the quantum vacuum
  - quantum vs. “Torricellian” vacuum
  - seeing the quantum vacuum
- Particle point of view
  - photon-photon scattering in QED
  - Heisenberg-Euler effective lagrangian
- Main theme of the PVLAS experiment
  - practical case (...leading to the experimental technique)
  - vacuum as a medium

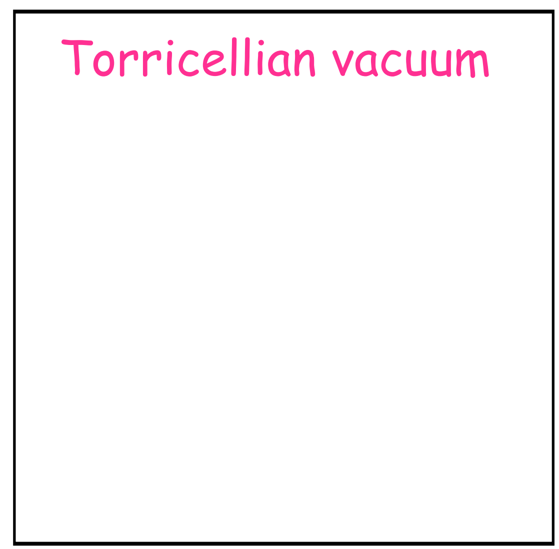
Quantum vs. Torricellian vacuum

- Torricellian vacuum
  - "empty": all matter removed
- Quantum vacuum
  - NOT "empty": contains the zero-point energy of fields
    - Intuitive picture: apply the uncertainty principle for short time intervals

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

($\Delta t \sim 10^{-21}$ s)
"full" of virtual particle-antiparticle pairs

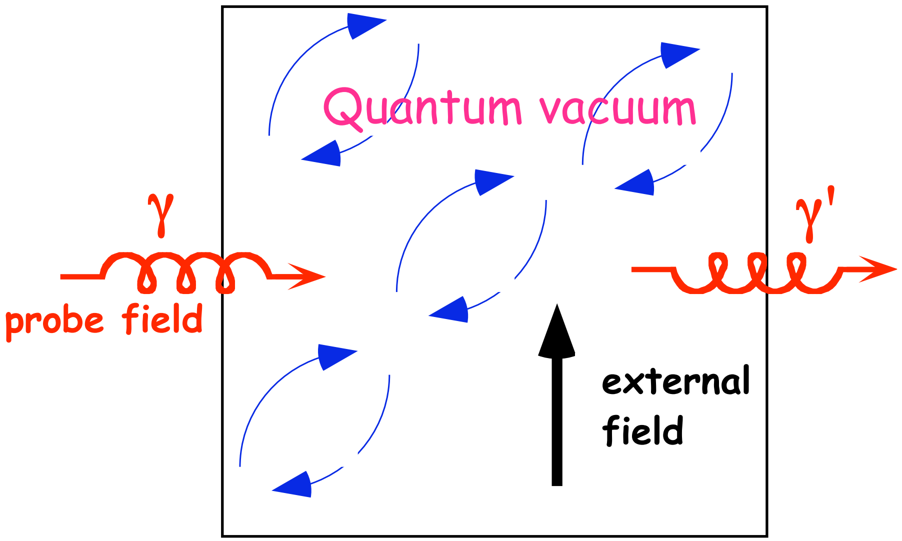




"empty"
($\Delta t \sim \infty$)

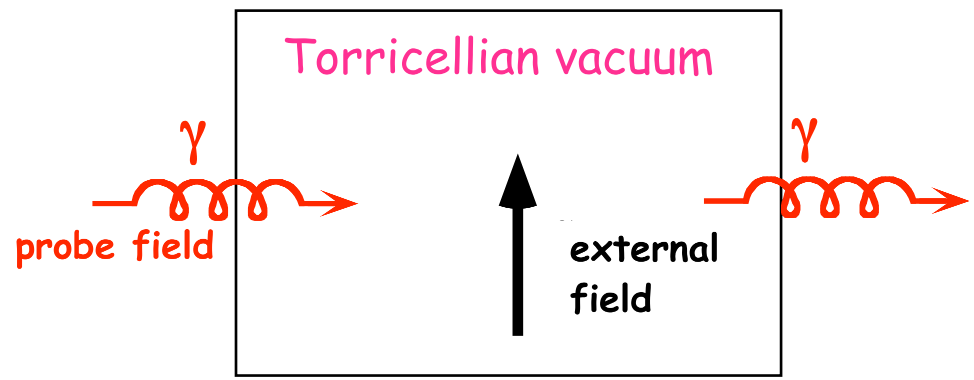
Seeing the quantum vacuum

- Treat vacuum as a material medium
  - gas/vacuum analogy: atomic currents/virtual currents
- Perturb the vacuum element with an external field
- Use an electromagnetic "probe" to measure macroscopic properties of the vacuum element resulting from microscopic interactions



The superposition principle no longer holds: probe and external fields interact (photon-photon scattering)

Exiting light carries information on the interaction, hence on the structure of the vacuum element



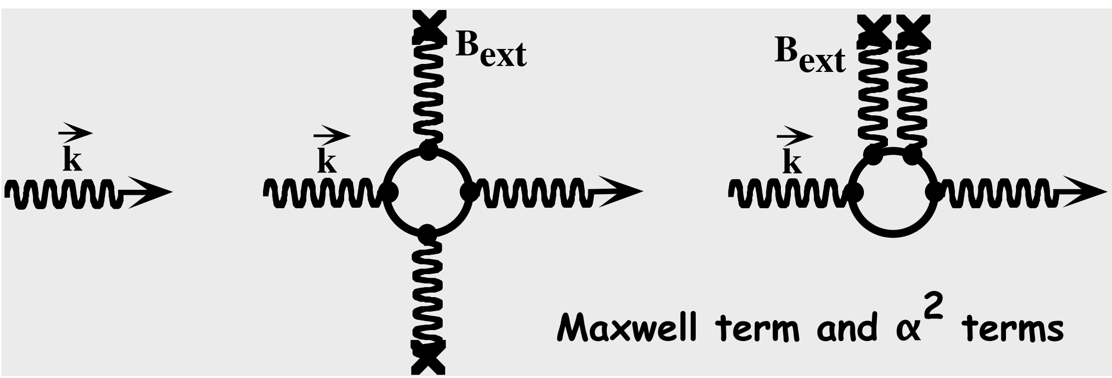
No effect on the probe field: the superposition principle holds and external and probe fields do not interact (Maxwell's equations are linear)

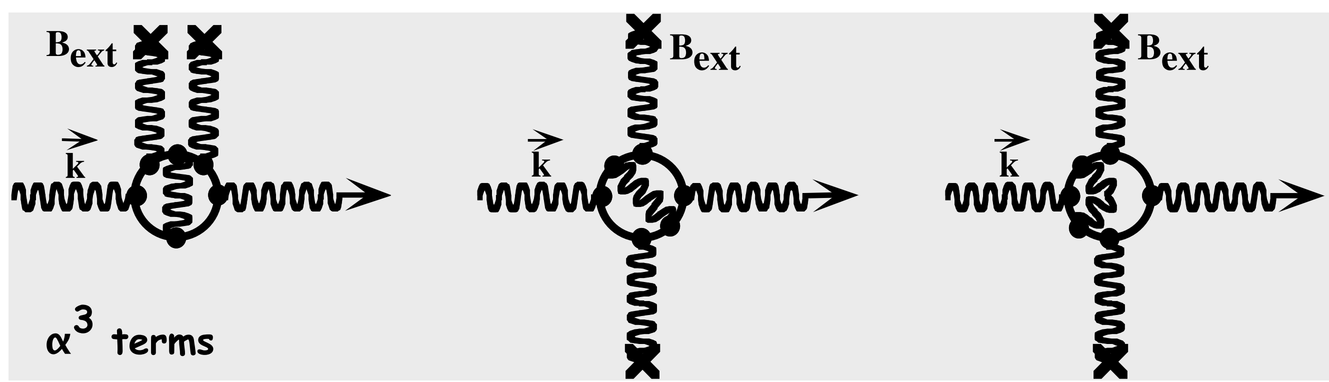
Particle point of view

- Photon-photon scattering can be described in QED by the Heisenberg-Euler effective lagrangian (Adler, Ann. Phys. vol. 67, p. 599, 1971)
  - in gaussian units
  -
  - α is the fine structure constant, fields are subcritical and slowly varying

$$L = L_{em} + L_{HE} = \frac{1}{8\pi}\left(\vec{E}^2 - \vec{B}^2\right) + \frac{2\alpha^2}{720\pi^2}\frac{\left(\hbar/m_e c\right)^3}{m_e c^2}\left[\left(\vec{E}^2 - \vec{B}^2\right)^2 + 7\left(\vec{E}\cdot\vec{B}\right)^2\right] + \mathrm{o}\left(\alpha^2\right)$$

Corresponding Feynman diagrams

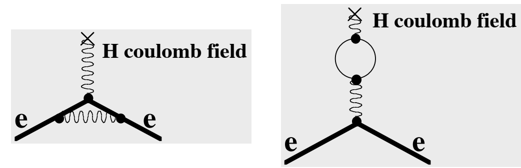




Experiments on microscopic QED interactions

- Lamb-shift in hydrogen

Vacuum polarisation

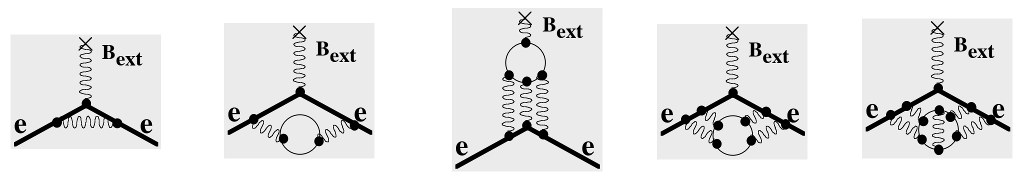


correction of order α α ~ 2 % of the measured effect

- (g-2)

Vacuum polarisation

Photon-Photon scattering

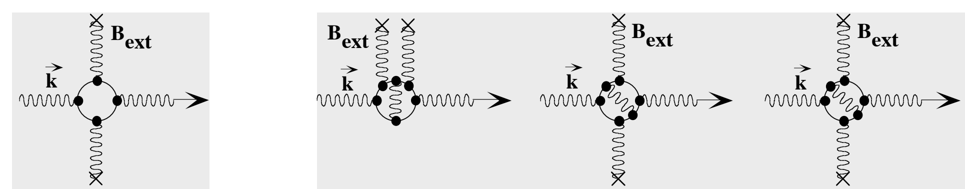


correction of order α α^2 α^3 α^4 α^5

~5 % of the measured effect

- PVLAS

Photon-Photon scattering



correction of order α^2 entire measured effect α^3 ~ 1 % of the measured effect

A practical case

- Vacuum is perturbed by a uniform magnetic field
- Probe field is a linearly polarised light beam

Insert in the H-E lagrangian:

$$\vec{E} = \vec{E}_{wave} \quad ; \quad \vec{B} = \vec{B}_{ext} + \vec{B}_{wave}$$
$$\left|\vec{B}_{ext}\right| >> \left|\vec{B}_{wave}\right|$$

Two cases follow

$$\vec{E}_{wave} \parallel \vec{B}_{ext}$$

$$\varepsilon_{\parallel} = 1 + 10AB_{ext}^2 \quad ; \quad \mu_{\parallel} = 1 + 4AB_{ext}^2$$
$$\Rightarrow \quad n_{\parallel} = \sqrt{\varepsilon_{\parallel}\mu_{\parallel}} \approx 1 + 7AB_{ext}^2$$

$$\vec{E}_{wave} \perp \vec{B}_{ext}$$

$$\varepsilon_{\perp} = 1 - 4AB_{ext}^2 \quad ; \quad \mu_{\perp} = 1 + 12AB_{ext}^2$$
$$\Rightarrow \quad n_{\perp} = \sqrt{\varepsilon\perp\mu_{\perp}} \approx 1 + 4AB_{ext}^2$$

An <u>anisotropy</u> results leading to a difference in refractive indices (known in optics as **birefringence**)

$$\Delta n_{QED} = n_{\parallel} - n_{\perp} = 3AB_{ext}^2 \quad \left(\approx 4 \times 10^{-32} B_{ext}^2[Gauss]\right)$$

$$A = \frac{\alpha^2}{90\pi}\frac{(\hbar/m_e c)^3}{m_e c^2} \approx 1.32 \cdot 10^{-32} \quad cm^3/erg$$

... macroscopic consequences

- Vacuum in the presence of an external magnetic field becomes a birefringent medium, and the difference of the refractive indices for photons polarised parallel and normal to the field is

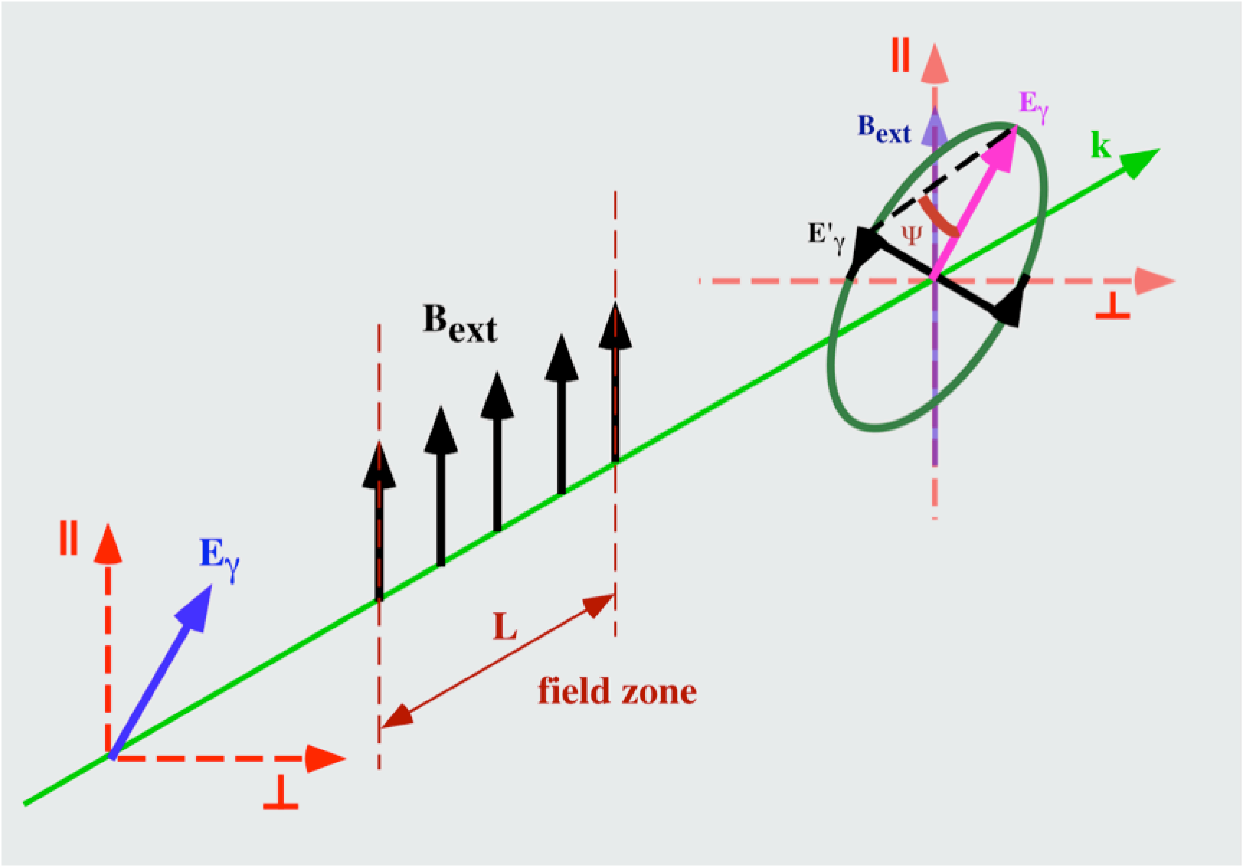
$$\Delta n_{QED} = n_{\parallel} - n_{\perp} = 3AB_{ext}^2$$

- A linearly polarised light beam propagating through a field region will emerge with an elliptical polarisation, characterised by a given ratio of the semi-minor to the semi-major axis of the polarisation ellipse: this quantity is called in optics ellipticity
- The experimental challenge is then measuring the ellipticity, for a given field intensity and a given length of the interaction zone, to determine the vacuum magnetic birefringence

$$\Psi = \left(\frac{\pi L}{\lambda}\sin 2\theta\right)\Delta n_{QED}$$

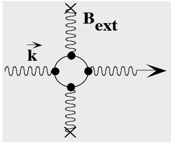
$$\Delta n_{QED} \approx 1.2\cdot 10^{-22} \qquad B = 5.5\ T$$

$$\psi \approx 2.1\cdot 10^{-11} \qquad L_{eff} = 60\ km$$



"Theme" of the PVLAS experiment

- Measure the magneto-optical activity of the vacuum element (in practice a gas in the zero-pressure limit)
  - possible contributions
    - QED interactions



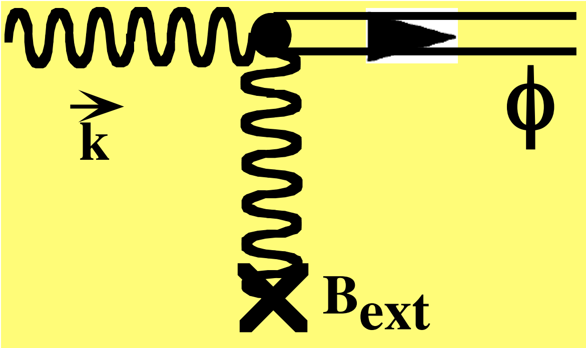
+ diagrams of order higher than α^2

    - QCD (quark loops)
    - other processes involving two photons
- Treat vacuum as a "target" (photon-photon collider)
  - production of yet unobserved vacuum "states"
    - dark matter particles
    - ...

Additional vacuum "states"

- Further terms[*] can be added to the H-E lagrangian to take into account the possible contibution of neutral, light, scalar/ pseudoscalar particles coupled to two photons (Primakoff effect)
  - the axion, introduced to solve the strong CP problem, is an example of this type of particle

Primakoff effect



Extra lagrangian terms

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

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

M, M_σ - inverse coupling constants

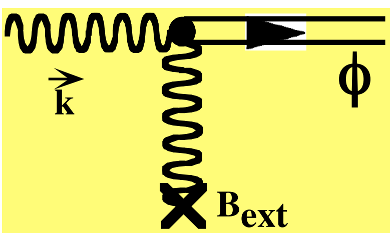
[*] [L.Maiani, R. Petronzio, E. Zavattini, Phys. Lett B, Vol. 173, no.3 1986]
[E. Massò and R. Toldrà, Phys. Rev. D, Vol. 52, no. 4, 1995]

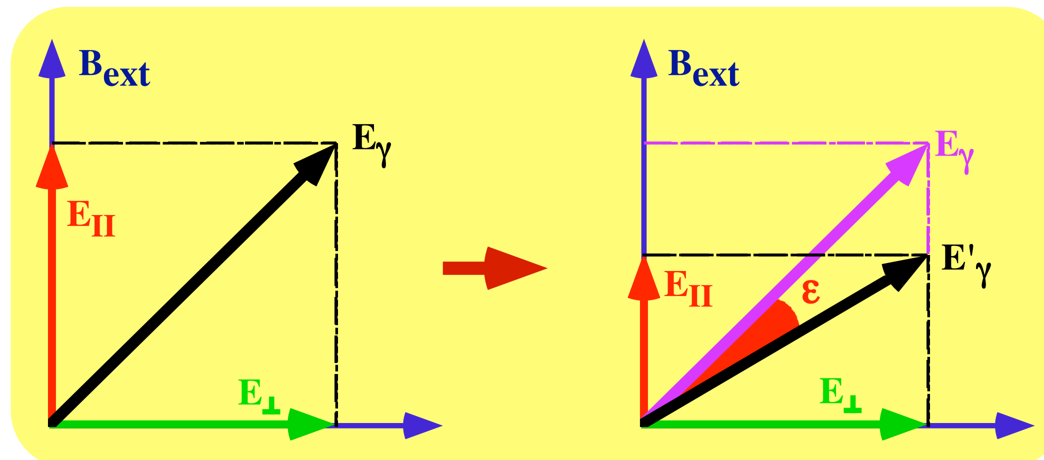
... resulting macroscopic effect

- Two processes can take place simultaneously: <u>real and virtual production</u>
- These processes lead to different modifications of the polarisation state of a probe light beam

dichroism ε

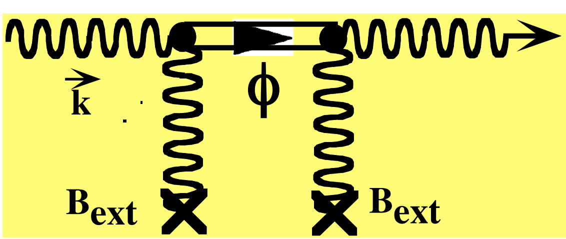
real production

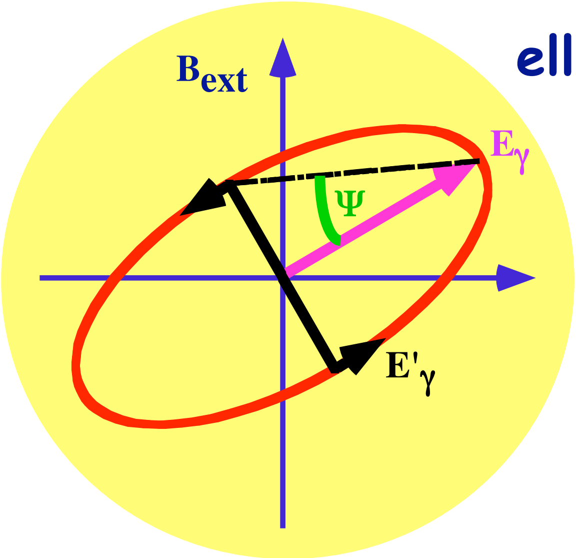




ellipticity ψ

virtual production





Particle identification

Using the H-E lagrangian including the extra terms, induced dichroism and ellipticity can be linked to the particle characteristic parameters: mass and inverse coupling to two photons

Dichroism and ellipticity are measured independently leading to a direct identification of the particle through its parameters (equations in Heaviside-Lorentz units):

$$\varepsilon = \frac{1}{M^2}\frac{2FB_{ext}^2\omega^2}{\pi m_a^4}\left[\sin\left(\frac{m_a^2 l}{2\omega}\right)\right]^2$$

Dichroism (optical rotation)

$$\psi = \frac{1}{M^2}\frac{FB_{ext}^2\omega^2}{\pi m_a^4}\left[\frac{m_a^2 l}{2\omega} - \sin\left(\frac{m_a^2 l}{2\omega}\right)\right]$$

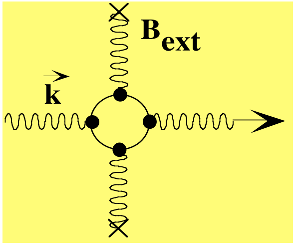
Ellipticity

m_a = particle mass
M = inverse coupling constant
F =amplification factor
ω = energy of the probe beam
l = length of the interaction region

Notice that particles are both produced and detected in an earthbound laboratory, resulting in a model-independent identification (no astrophysics!)

Summarising...

- Nature and structure of the vacuum fluctuations are studied experimentally
- Key idea:
  - treat vacuum as a material medium and perturb it with an external field
  - use a polarised light beam as a probe to evidence the effect of the field on the vacuum structure
  - quantitative information on the vacuum structure is extracted from the measured effect
- Particle point of view -> study processes such as:



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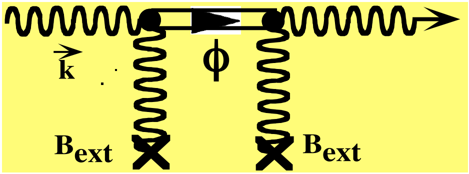

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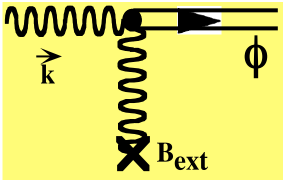
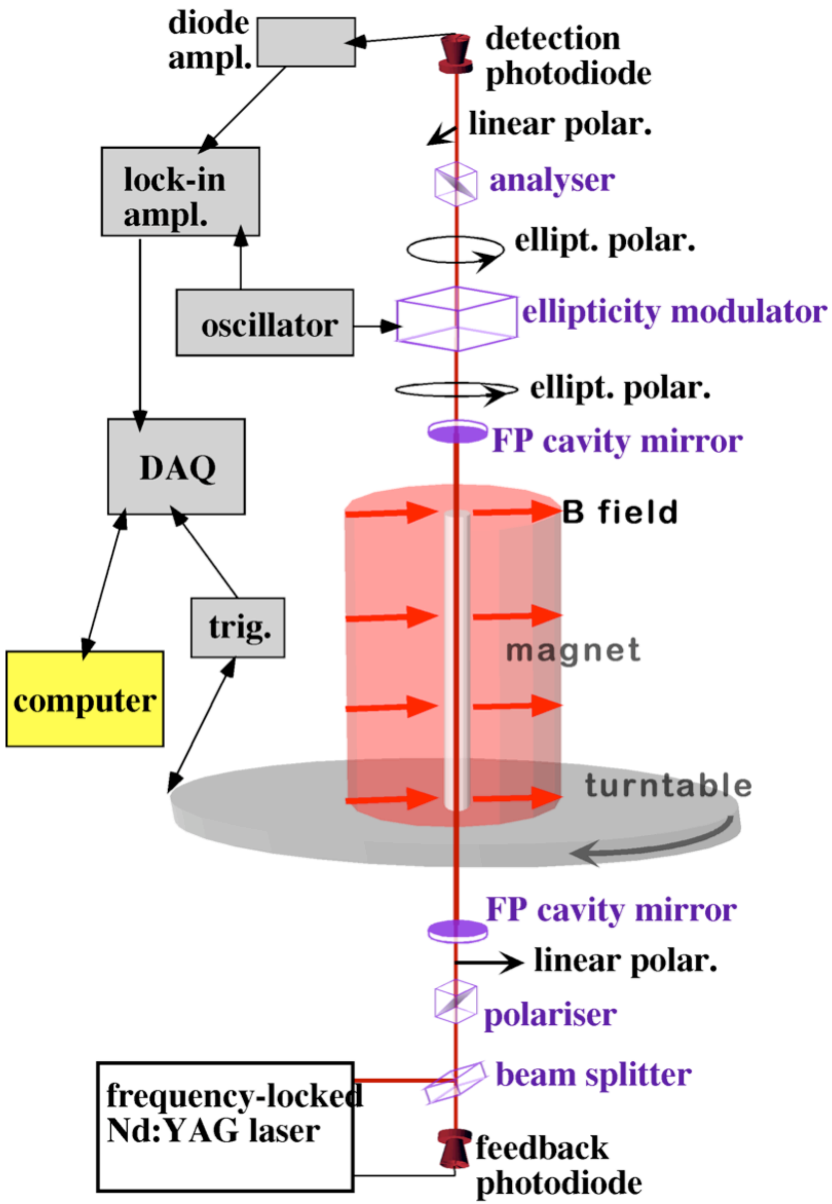


, ...

Experimental strategy

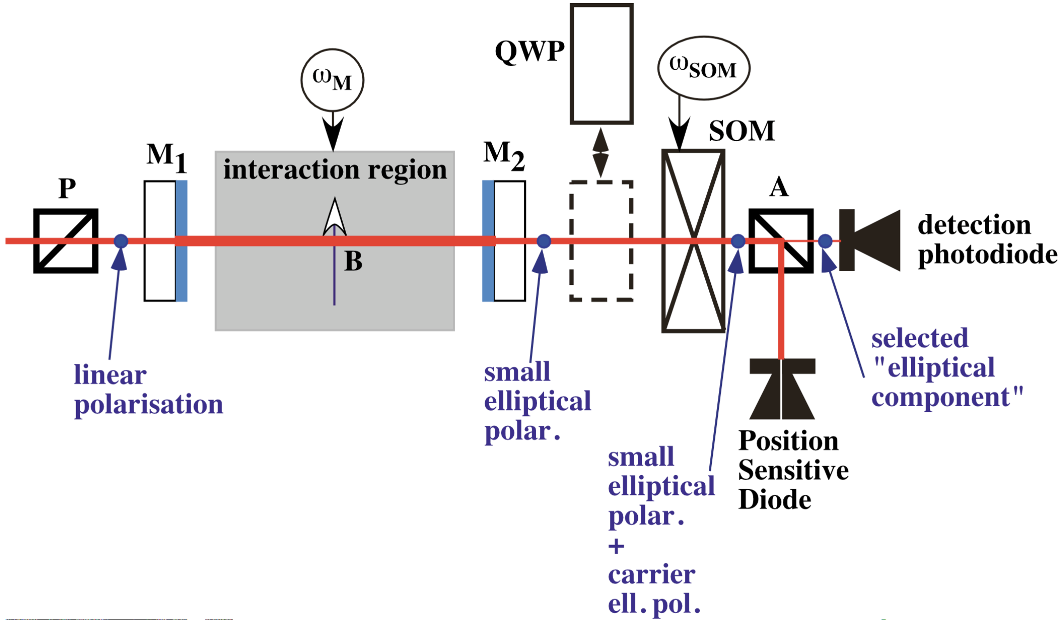
- Build a high-sensitivity ellipsometer
- Three synergic approaches and three corresponding (met!) technical challenges
  - high intensity magnetic field
    - superconducting dipole magnet
  - as long as possible optical path
    - high Q Fabry-Perot optical resonator
  - heterodyne detection
    - magnet housed in a rotating cryostat
    - granite tower-like structure to hold the optics and isolate it mechanically

PVLAS - Schematic



- Main parameters of the apparatus
  - magnet
    - dipole, 6 T, temp. 4.2 K, 1 m field zone
  - cryostat
    - rotation frequency ~300 mHz, sliding contacts, warm bore to allow light propagation in the interaction zone
  - laser
    - 1064 nm, 100 mW, frequency-locked to the F.-P. cavity
  - Fabry-Perot optical cavity
    - 6.4 m length, finesse ~100000, optical path in the interaction region ~ 60 km
  - heterodyne ellipsometer
    - ellipticity modulator (SOM) and high extinction (~10^{-7}) crossed polarisers
    - time-modulation of the effect
  - detection chain
    - photodiode with low-noise amplifier
  - DAQ
    - demodulated at low frequency and phase-locked to the magnetic field instantaneous direction
    - high sampling frequency direct acquisition

Detection method

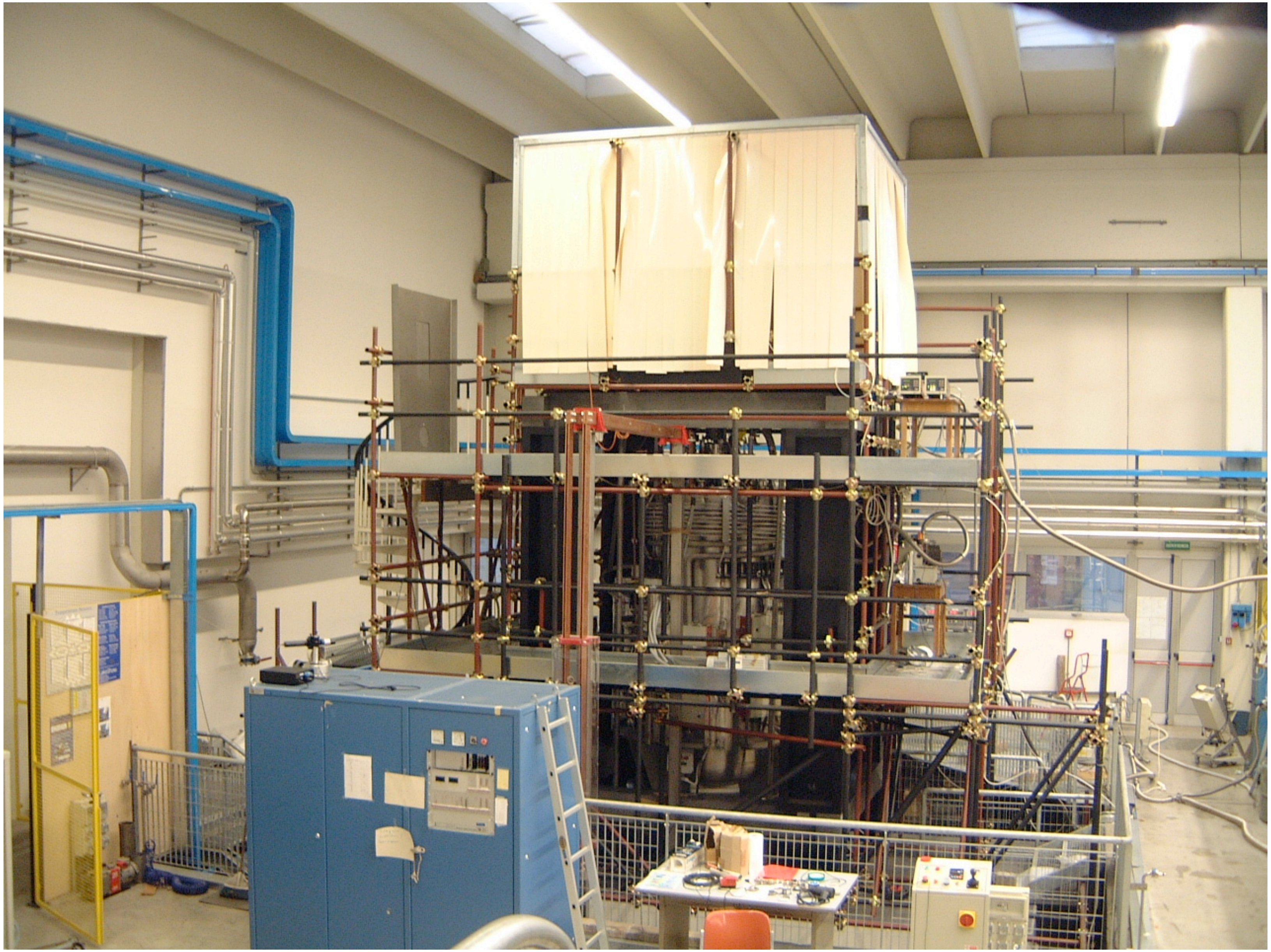


- A pair of crossed polarisers (P, A) detects variations in the polarisation state
- a ~10^5 finesse Fabry-Perot (mirrors M1 and M2) increases the optical path
- A transverse magnetic field (B~ 6 T) is generated by a superconducting dipole
- A quarter-wave-plate (QWP) can be inserted in order to measure rotations
- Signals are extracted using the heterodyne technique
  - the interaction is time-modulated by the magnet rotation (the rotation itself provides the synchronisation necessary for absolute signal phase determination)
  - the necessary carrier ellipticity signal is provided by an in-house developed ellipticity modulator (SOM)
- The light intensity transmitted through the analyser A is detected by a photodiode and Fourier-analysed: the resulting (complex) spectrum contains the physical information

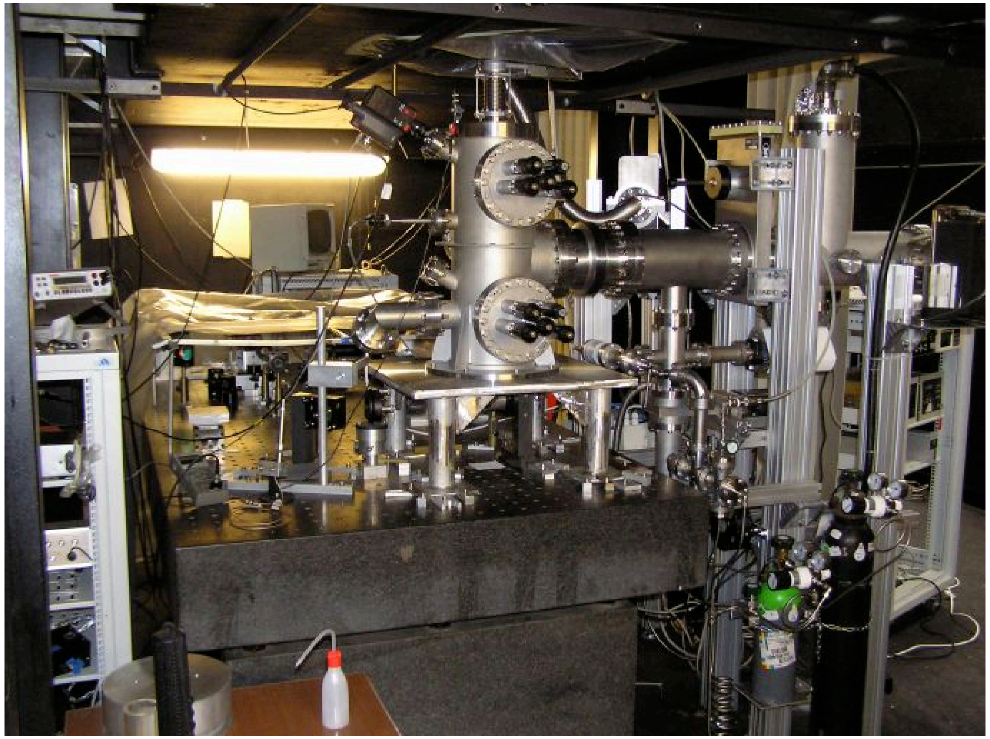
In brief ...

- In the PVLAS apparatus two independent determinations can be carried out
  - without quarter-wave-plate
    - Ellipticity acquired in the optical path between the two crossed polarisers
  - with quarter-wave-plate
    - Rotations (dichroisms) of the polarisation plane induced in the optical path before the QWP

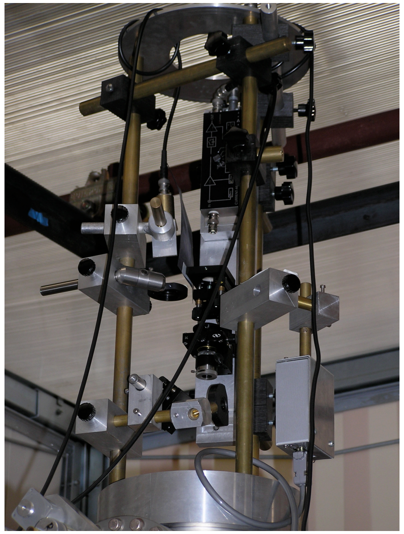
PVLAS hall at LNL



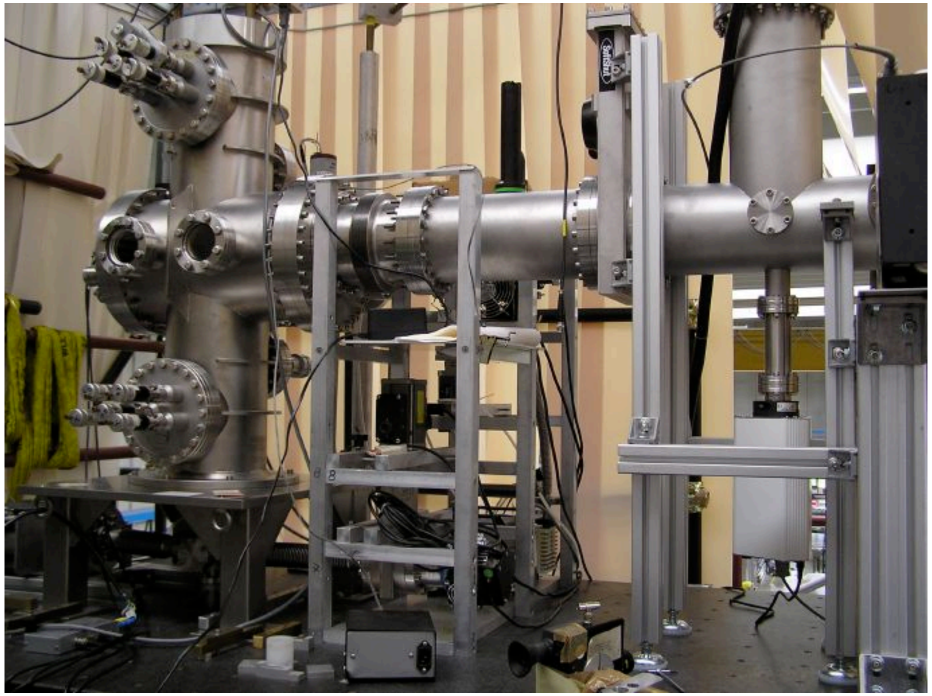
Gallery (I)



Lower optical bench with laser and vacuum chamber holding part of the optics



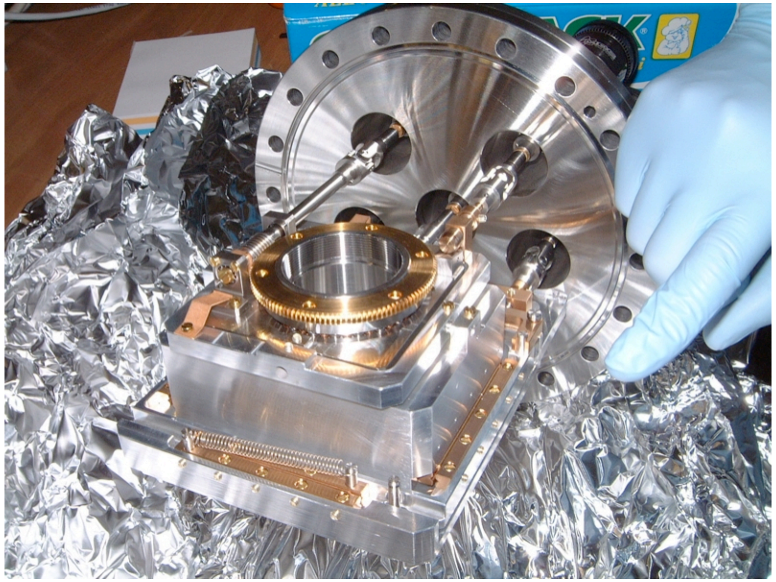
Detection photodiodes



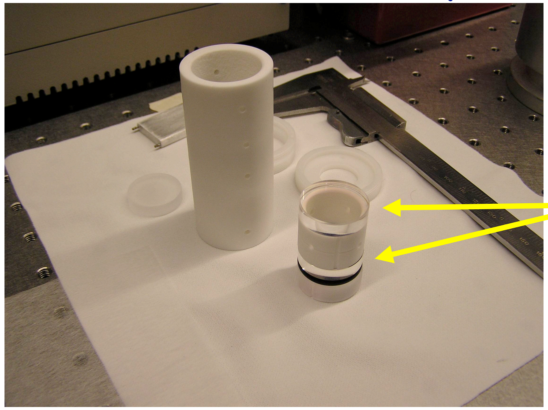
Upper optical bench with vacuum chamber

Gallery (II)

Vacuum movement stage

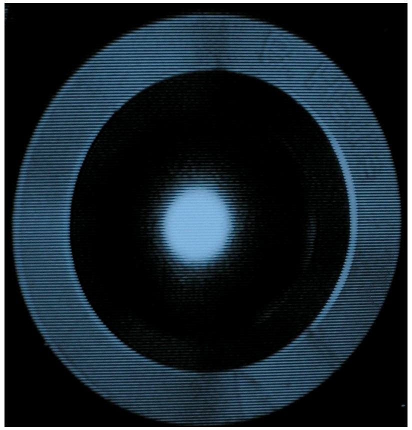


17 mm test cavity

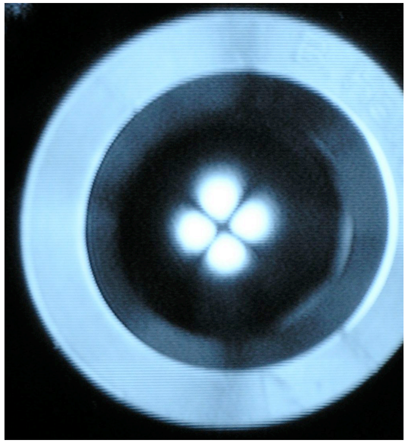


Mirrors

6.4 m cavity TEM00 mode

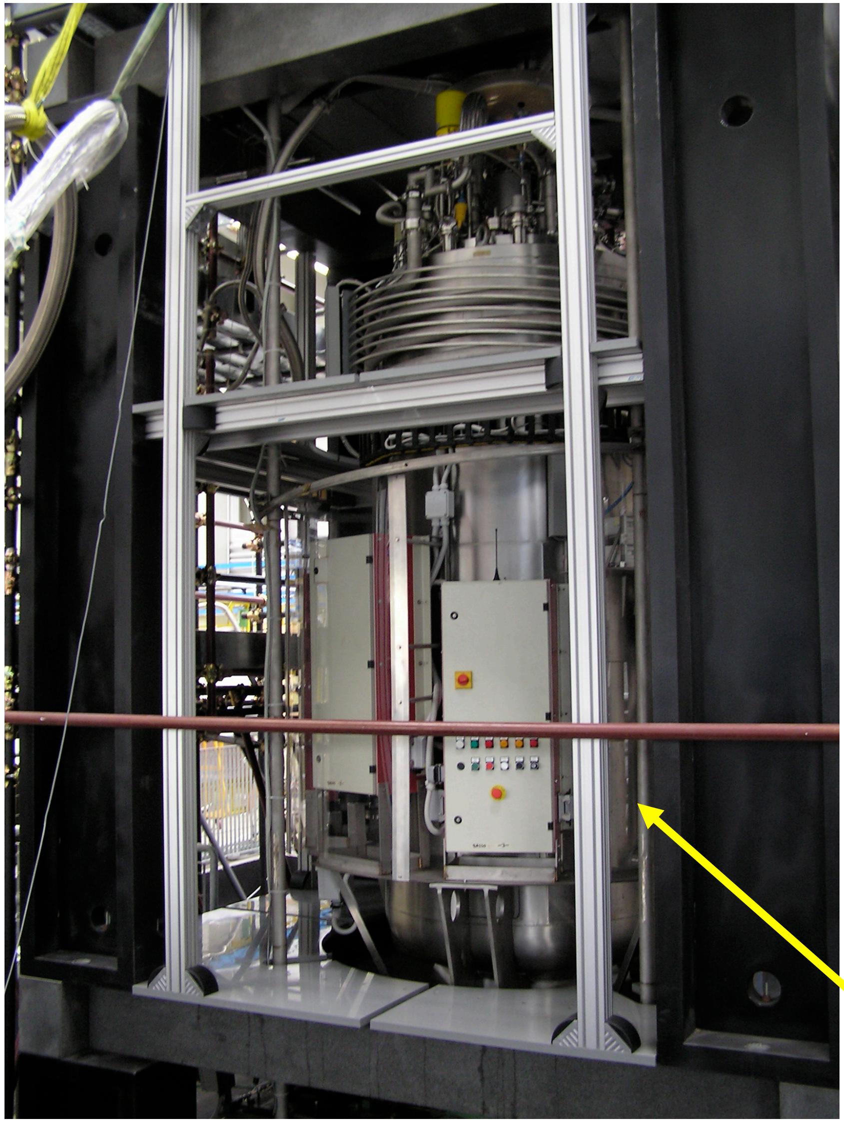


6.4 m cavity TEM11 mode



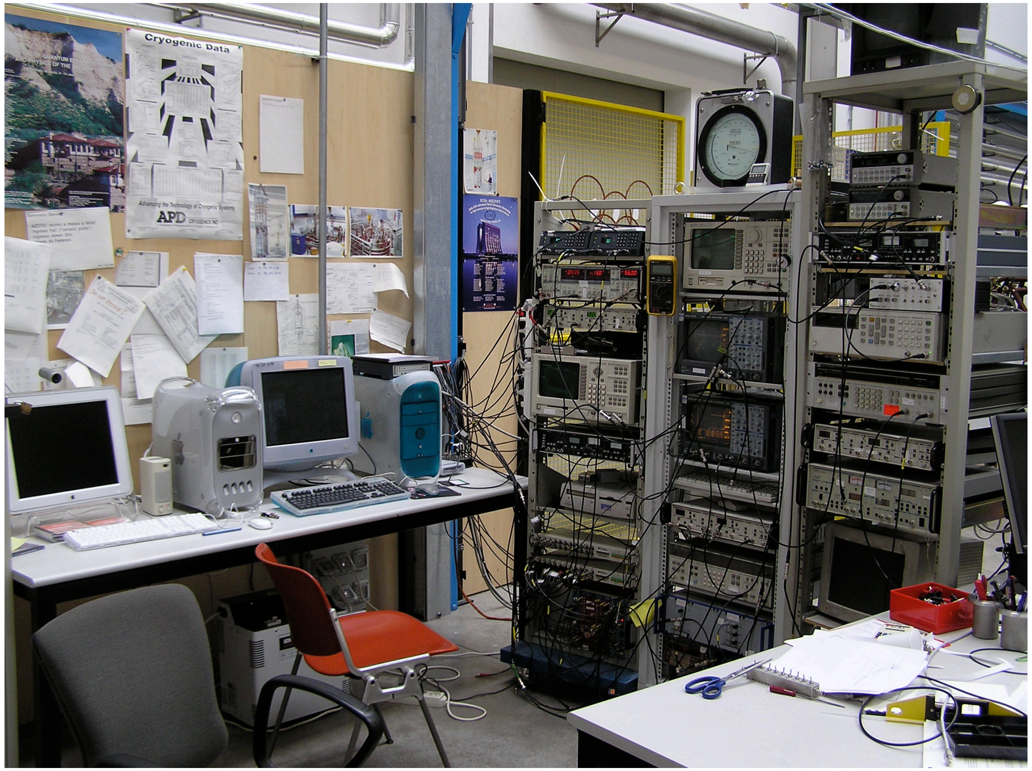
Gallery (III)

Rotating cryostat



magnet position

Counting room



Logistics of a measurement run

- Operations necessary for a data taking run
  - Preliminarly
    - cool magnet to Liquid He temperature and fill the cryostat with cryogenic fluid
  - Measurement cycle
    - magnet is energised when the cryostat is full (2000 A typical current)
    - a multiblade switch immersed in Liquid He shorts the magnet coils
    - the power supply is disconnected and the cryostat is brought up to rotating speed
    - data taking can be activated until LHe level in the cryostat falls below a critical value
    - rotation is stopped and LHe level is replenished
    - cycle restarts

What is actually measured?

- The data acquisition system records, as a function of time, the current generated by a photodiode detecting light intensity transmitted through the ellipsometer, plus several control signals
- The Fourier analysis of this current yields phase and amplitude of the interesting frequency components
- In particular, the <u>physically significant signal appears at twice the magnet rotation frequency</u> (due to heterodyne)
- Since data acquisition is triggered by magnet rotation, the instantaneous direction of the magnetic field vector is always known and the absolute phases of all acquired signals are determined

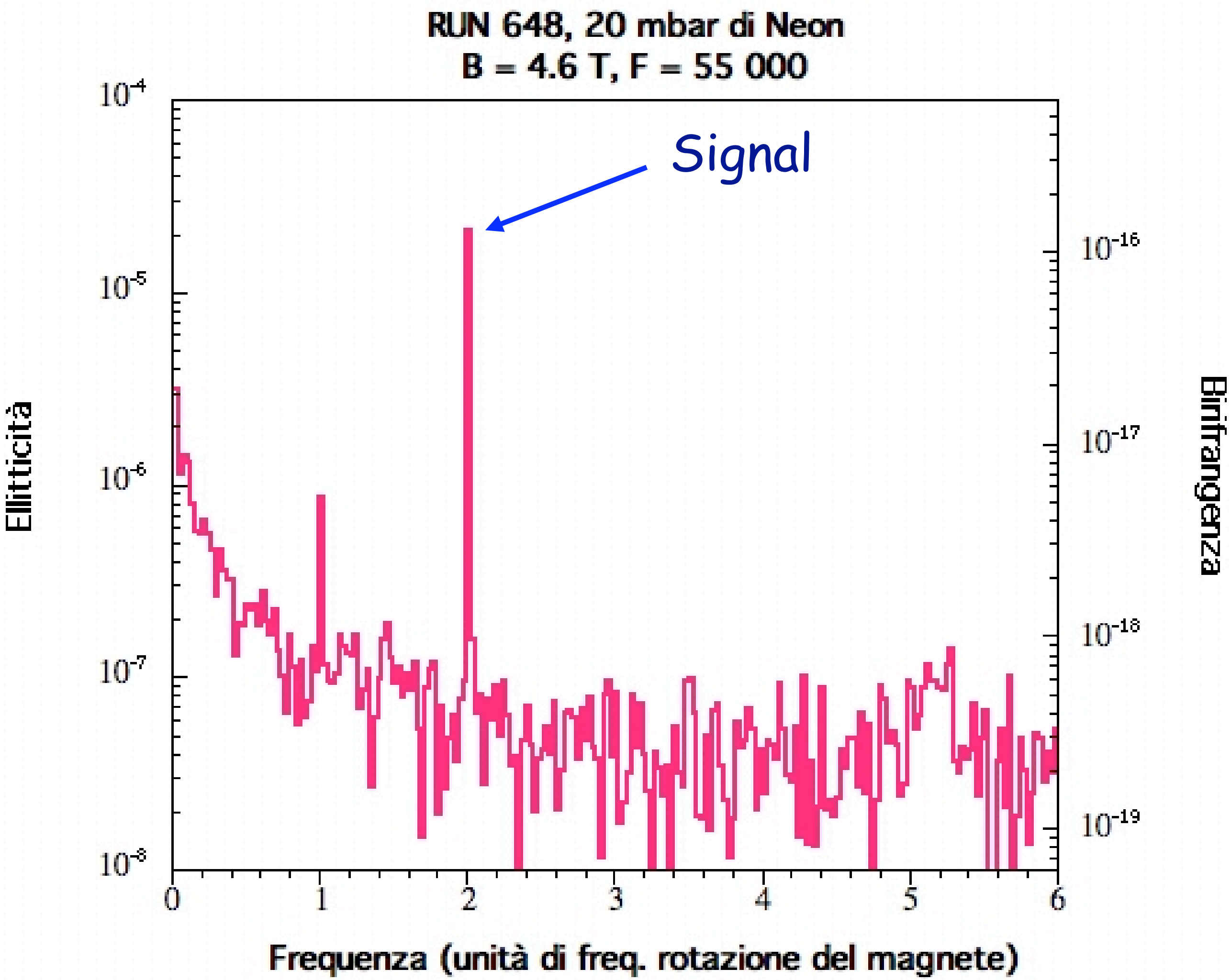
Measurements and results

- 2001-2003 (15 groups of data runs)
  - commissioning
  - ellipsometer calibration (phase and amplitude) by measuring the magneting birefringence (Cotton-Mouton effect) of test gases
  - measurement of magneto-optical activity of the vacuum element
    - ellipticity
    - dichroism
  - diagnostic tests on the observed signal

Gas calibration spectrum

Amplitude spectrum demodulated at the carrier frequency (506 Hz) of the ellipticity modulator

The expected birefringence signal appears at twice the magnet rotation frequency (0.6 Hz in this case)



Measurement time 130 s

Sensitivity

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

Cotton-Mouton effect in gases

A gaseous medium becomes birefringent in the presence of a transverse magnetic field.
The reference quantity is the specific birefringence $\Delta n_u [T^{-2}\ atm^{-1}]$

$$\psi_{gas} = \pi \frac{L}{\lambda} \Delta n_u B^2 p$$

We take advantage of this phenomenon to calibrate the apparatus

Some values of specific birefringence

$\Delta n_u(N_2) = -\ 2.5\ 10^{-13}\ \ T^{-2}\ atm^{-1}$

$\Delta n_u(O_2) = -\ 2.5\ 10^{-12}\ \ T^{-2}\ atm^{-1}$

$\Delta n_u(He) = 1.8\ 10^{-16}\ \ T^{-2}\ atm^{-1}$

$\Delta n_u(Ne) = 6.3\ 10^{-16}\ \ T^{-2}\ atm^{-1}$

These translate into a constraint on the residual gas pressure in the PVLAS vacuum chambers.

For instance $p(O_2) < 10^{-8}$ mbar

Polar plot of gas data

Gas birefringence data taken at several pressure values

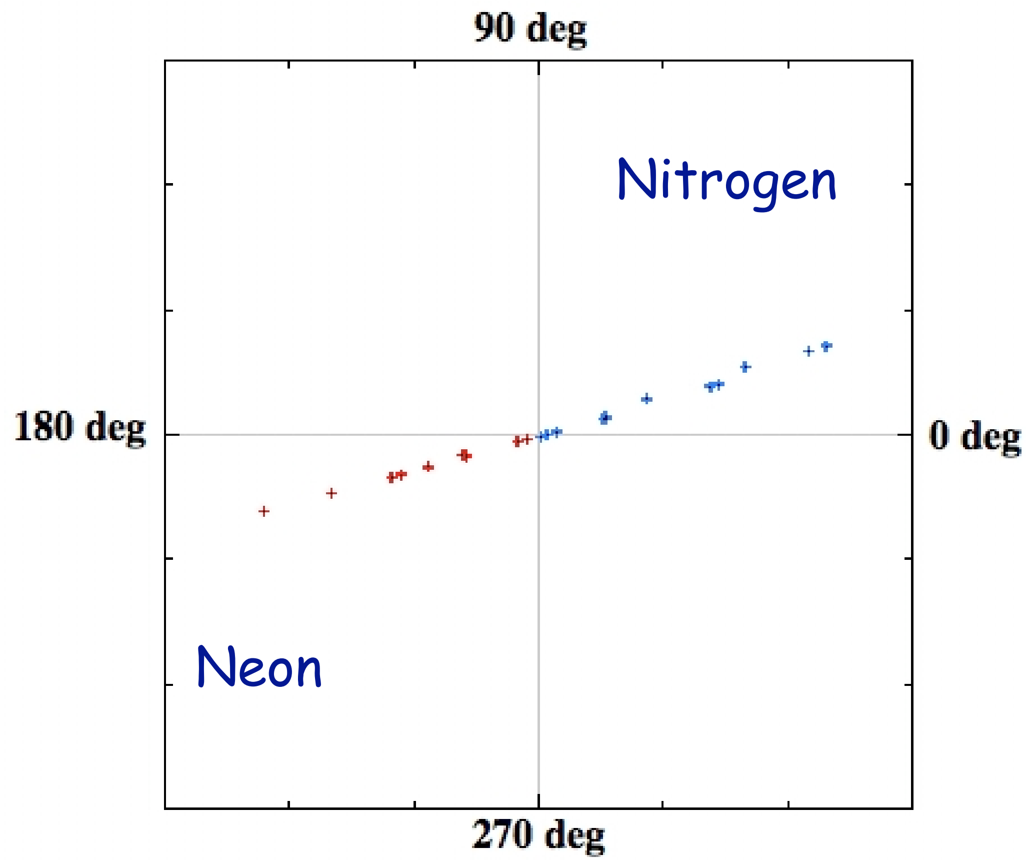
Phases of signals at twice the magnet rotation frequency

Distance from origin is proportional to ellipticity (in A.U.)

Data points lie on straight line representing the "physical axis"

This axis is the direction corresponding to a 45° angle between the magnetic field and the (fixed) initial linear polarisation

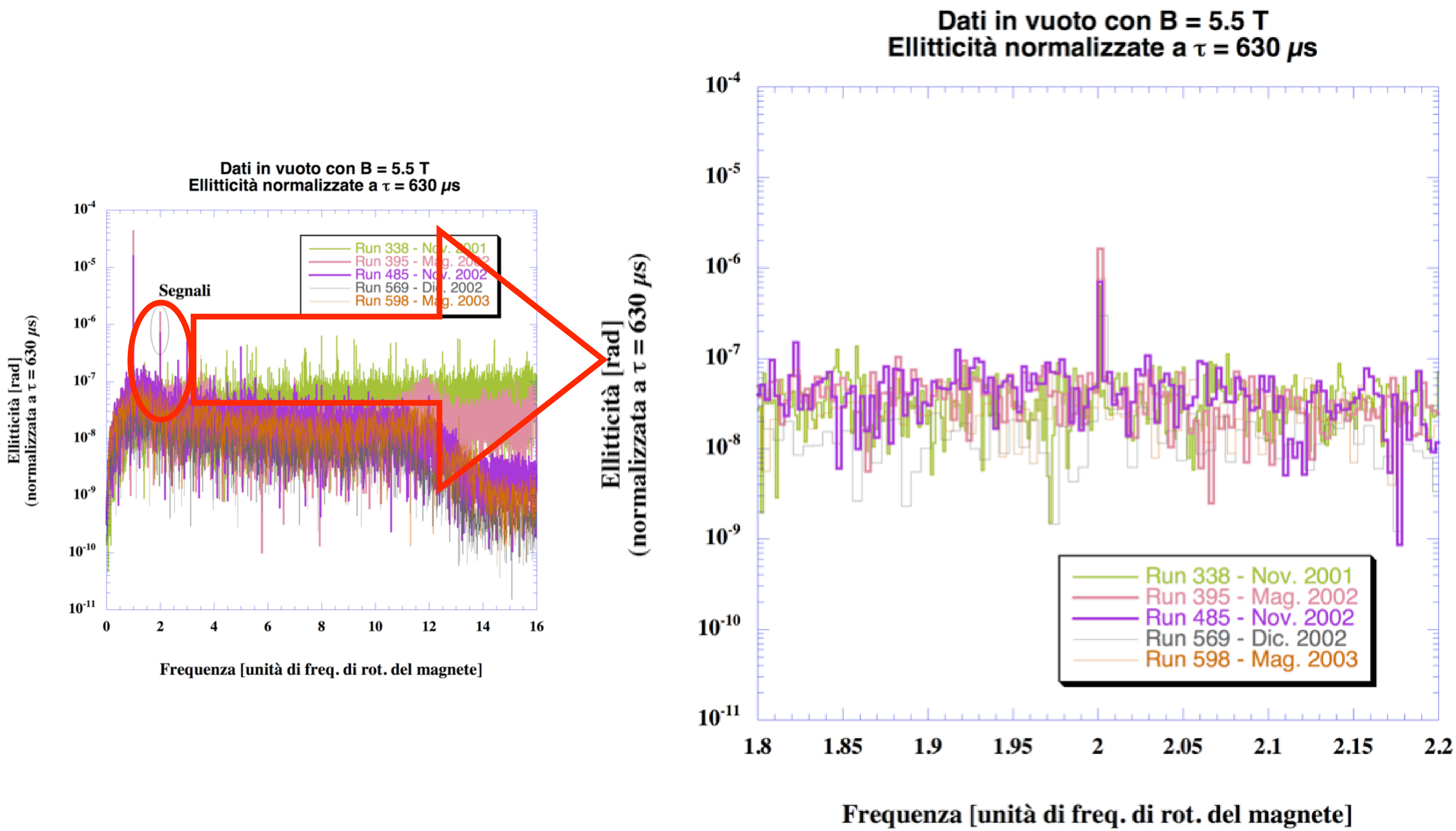
Notice that Nitrogen and Neon have opposite sign birefringences



Vacuum measurements results

- Always observed a signal in vacuum at the expected frequency when $B \neq 0$
  - ellipticity
  - dichroism
- For the ellipticity signal
  - excluded spurious signals of "trivial" origin
  - a series of tests shows that
    - the observed signal is a "true" ellipticity
    - the observed signal is generated inside the interaction region (F-P cavity including mirrors and the space in between)

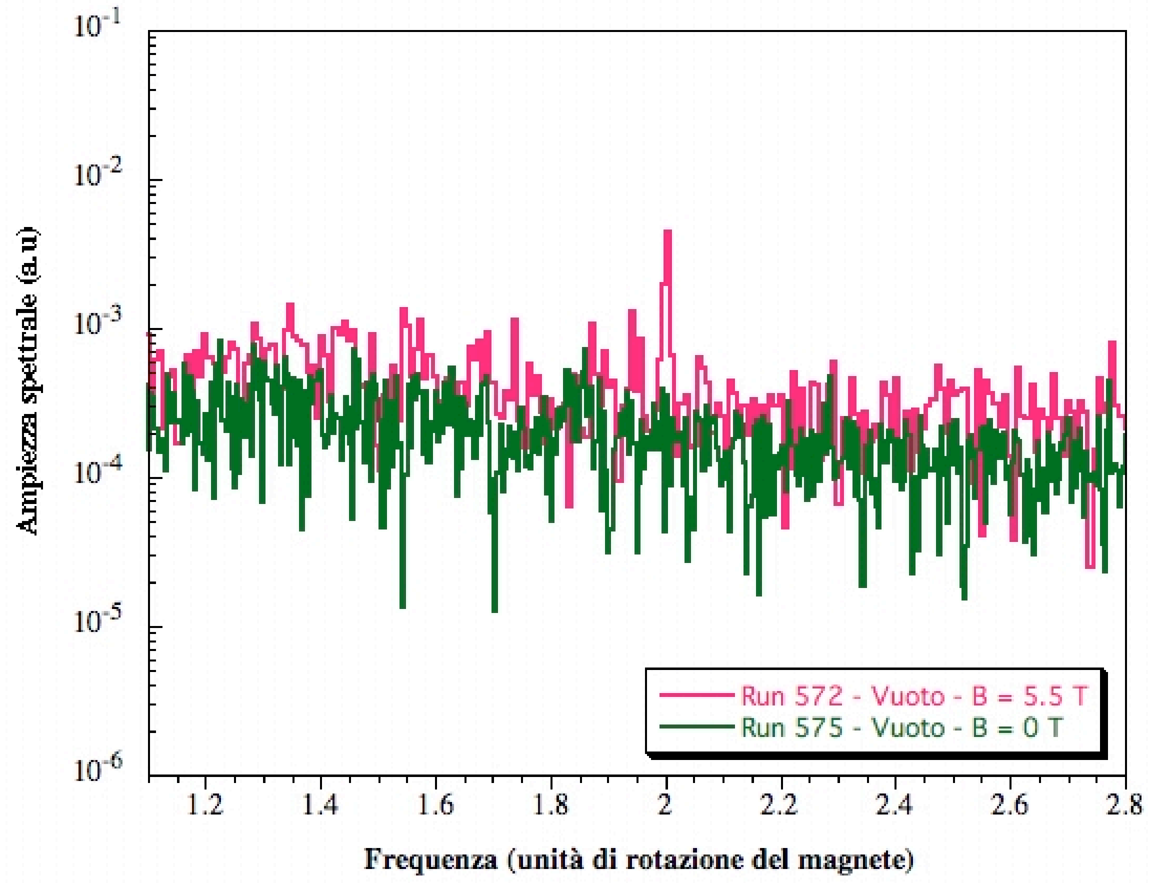
Vacuum ellipticity: a brief history



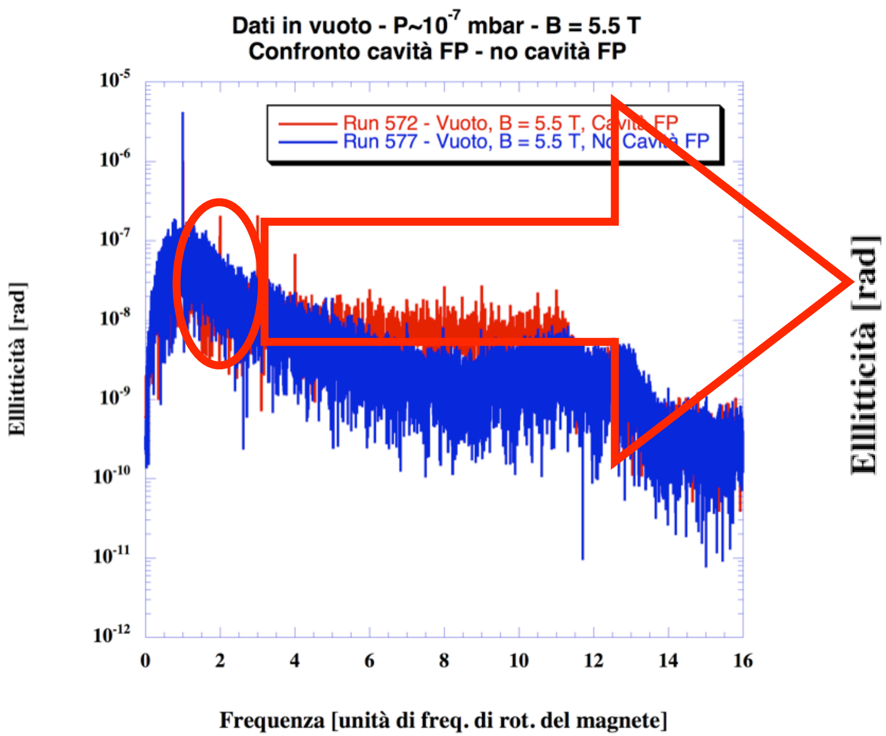
Eliminating trivia ...

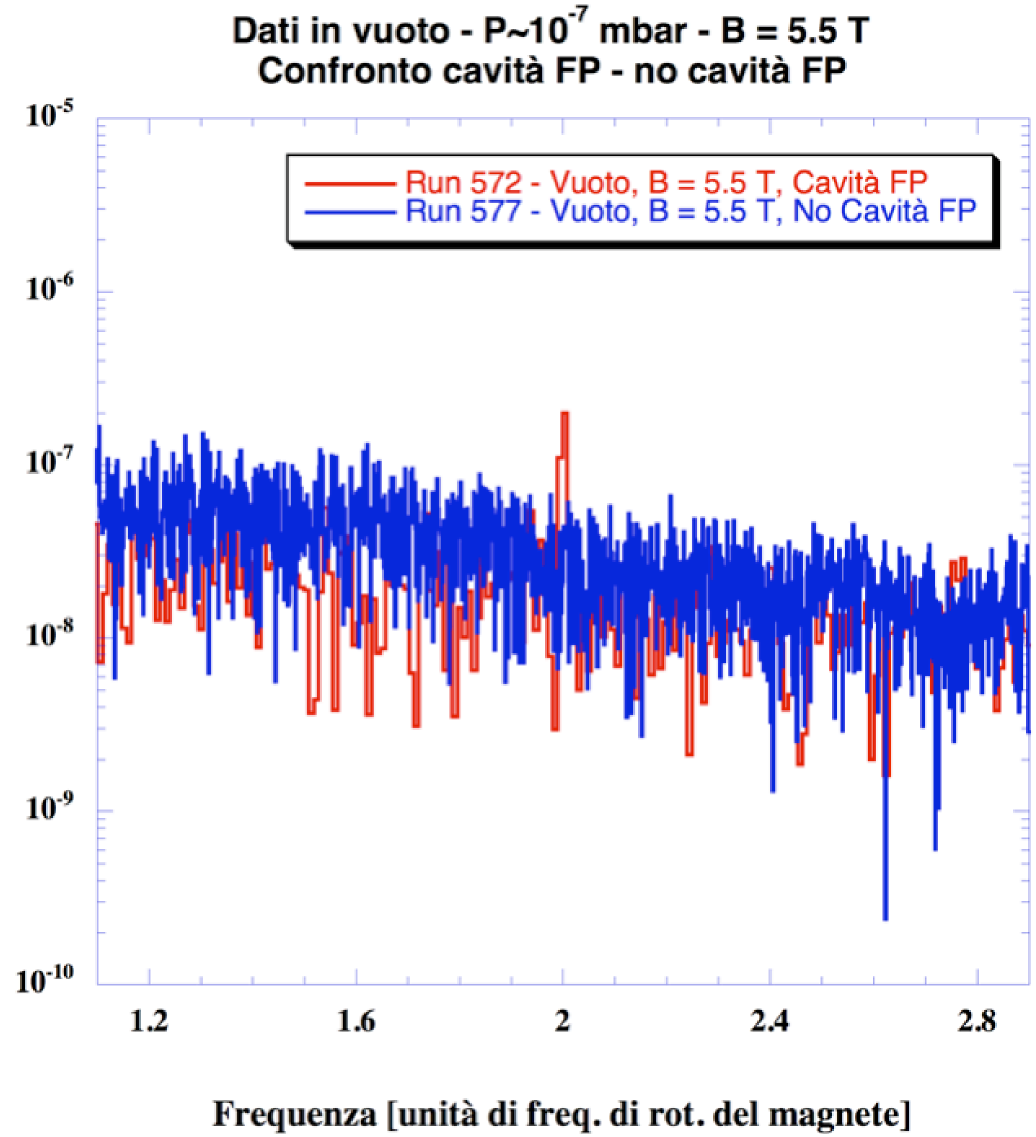
- Spurious ellipticity induced by the SOM modulator or electromagnetic pick-up
  - excluded by comparing
    - data with and without Fabry-Perot cavity
    - data with and without QWP
- Magnetic birefringence of the residual gas
  - excluded by checks on pneumatic vacuum
- Diffusion off magnetised surfaces
  - excluded by data taken with several different-size spatial filters

Comparison field On-Off



Comparison FP- no FP

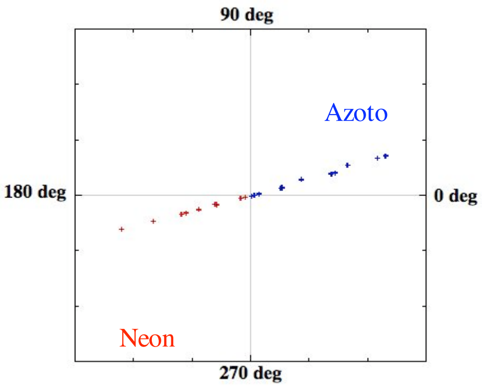




Characteristics of the observed signal

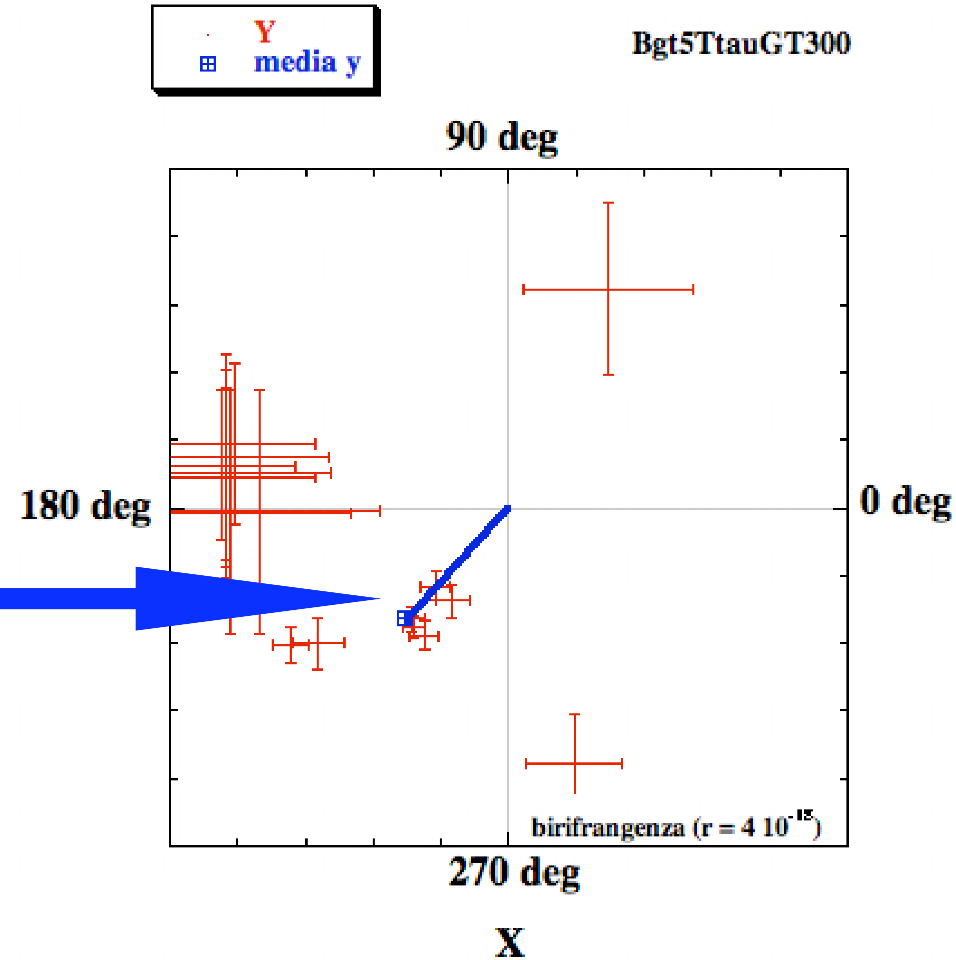
- The observed signal is caused by a "true" ellipticity generated inside the Fabry-Perot cavity (interaction region)
  - measured vacuum phases "group" in the neighbourhood of the physical axis defined by the gas calibration
  - the magnetic birefringence of nitrogen, measured at low pressure values for a fixed field, shows an "anomalous" behaviour
  - signal amplitude changes (by about a factor of 3) when inserting the QWP

Global polar plot of vacuum ellipticity data



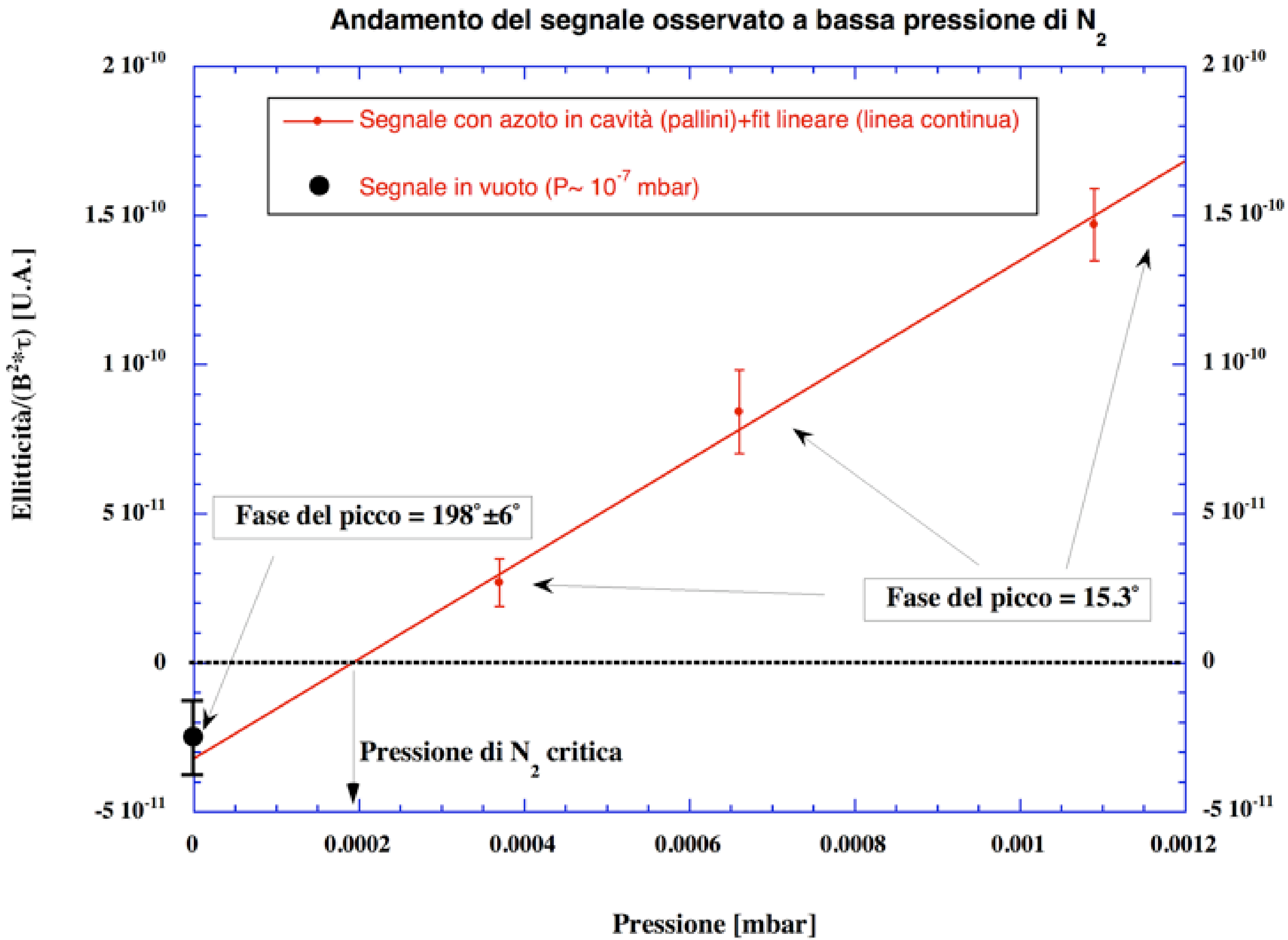
physical axis: 15.3°

Vacuum data with B ~ 5.5 T and finesse> 40 000



The average vector corresponds to $\Delta n = (2.3 \pm 0.1)\ 10^{-18}$, with a phase = (225±3)°

Nitrogen birefringence vs. pressure



Possible candidates

Birefringence induced on the FP mirrors by the stray magnetic field (Cotton-Mouton effect)	Excluded Cotton-Mouton effect on mirrors has been measured and found negligible a test run using a 17 mm long FP cavity immersed in the stray field does not show signals
Birefringence induced by beam movements	NOT excluded, however - no correlation has been found so far between the beam movements and the signal observed at twice the magnet rotation frequency
Birefringence of unknown origin	NOT excluded
Vacuum magnetic birefringence	NOT excluded, however - signal amplitude much larger than expected from "pure QED" calculations
Birefringence due to virtual particle production	NOT excluded

Discussion

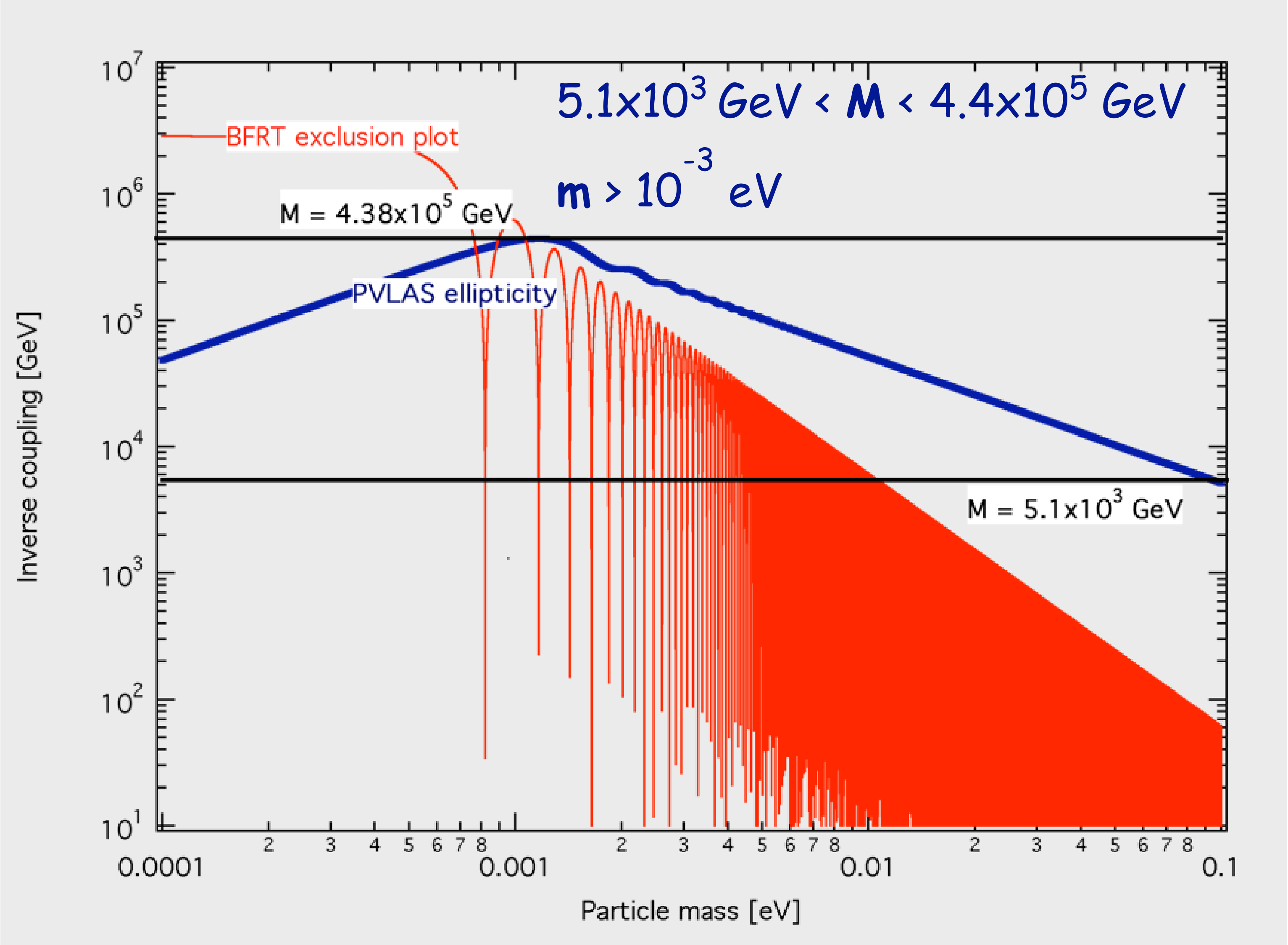
- PVLAS is active both taking and analysing data
- Results obtained up to now show
  - a signal observed in vacuum when $B \neq 0$ compatibile with an ellipticity generated in the interaction region
  - the physical interpretation of this signal is still open
- Ongoing and short-term activities
  - complete dichroism signal analysis
  - upcoming measurement runs
    - gas studies at low pressure
    - increase statistics
    - change wavelength (532 nm)

Speculations (I)

- Considering the average vector from vacuum data taken at 5.5. T one finds
  - $\Delta n_{exp} = 2.1\text{x}10^{-18}$
- QED calculations give, for B = 5.5 T,
  - $\Delta n_{QED} = 1.21\text{x}10^{-22}$
  - it follows
    - $(\Delta n_{exp}/\Delta n_{QED}) \sim 1.7\text{x}10^{4}$
- "Pure QED" is not then the sole contribution to the vacuum magnetic birefringence:
  - production of pseudoscalars (since phase matches Nitrogen phase)?
  - QCD contribution?

Speculations (II)

- Believing in the PVLAS observed ellipticity signal (4.32×10^{-7} rad at B = 5.5 T, finesse = 97000) and taking into account the published BFRT(*) exclusion plot, one can immediately constrain **M** (inverse coupling to two photons of produced particles) and particle mass **m**



(*) BFRT Brookhaven-Rochester-Fermilab-Trieste collaboration

Conclusions and future prospects

- In both cases (“good” signal or “smart” spurious):
  - PVLAS must extract every possible information from the present apparatus and experimental technique
    - planned steps
      - new amagnetic access structure
      - green laser (532 nm)
    - medium term extensions
      - permanent magnets
  - it is necessary to plan and prepare new lines of research in order to make full use of the available free parameters
    - photon energy
    - magnetic field source
    - length of the interaction region

$$\Psi_{QED} = N \frac{3\alpha^2}{45 m_e^2} B_0^2 (\omega L)$$

photon-photon scattering

$$\Psi_P \approx N \frac{B_0^2}{96} \frac{m_P^2}{M^2} \left(\frac{L^3}{\omega^2} \right)$$

virtual production

$$\varepsilon_P \approx N \frac{B_0^2}{8 M^2} L^2$$

real production

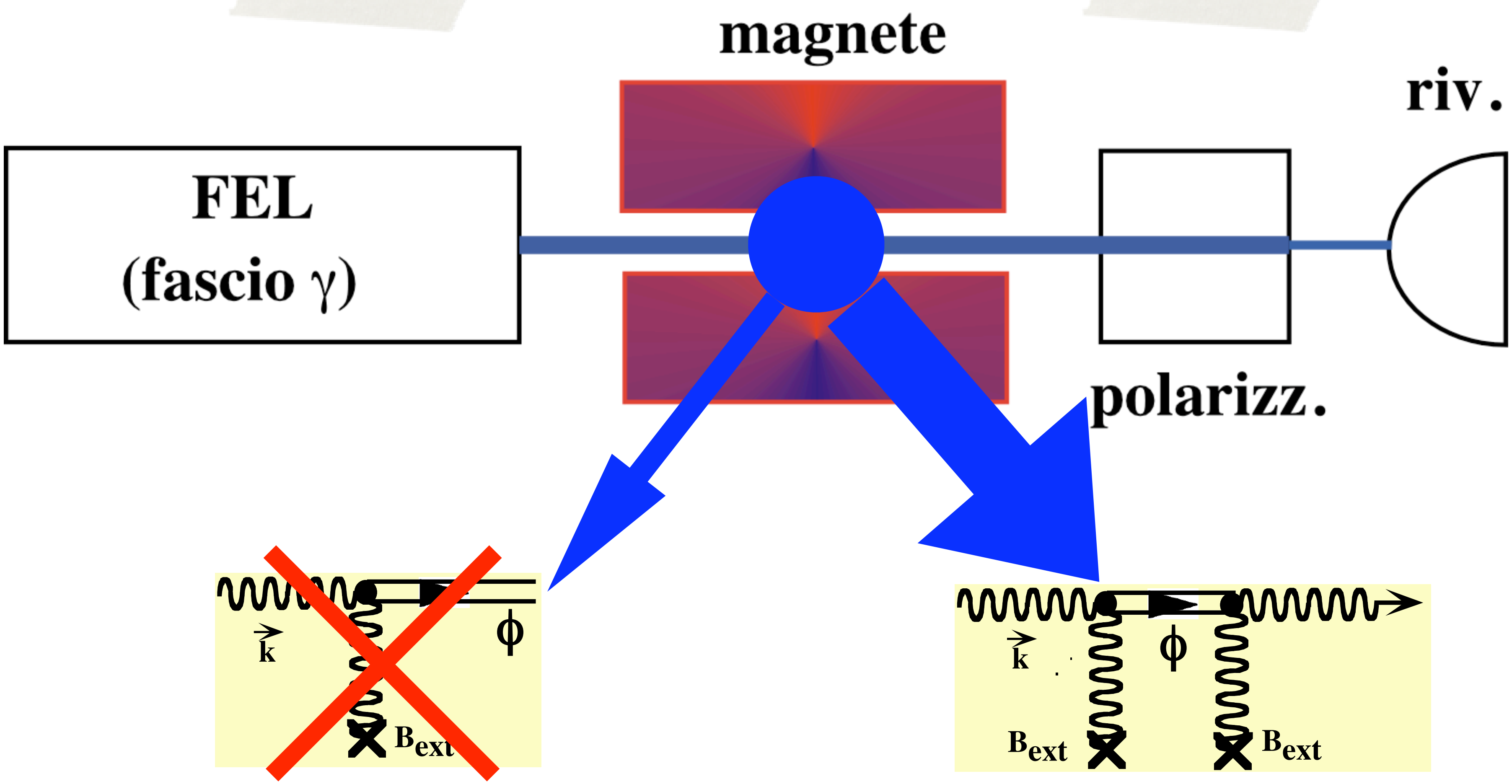
$$\frac{\Psi_{QED}}{\Psi_P} = \frac{96 \alpha^2 M^2}{15 m_e^4 m_P^2} \left(\frac{\omega^3}{L^2} \right)$$

$$\frac{\Psi_P}{\varepsilon_P} = \frac{m_P^2}{6} \left(\frac{L}{\omega} \right)$$

Long term ideas

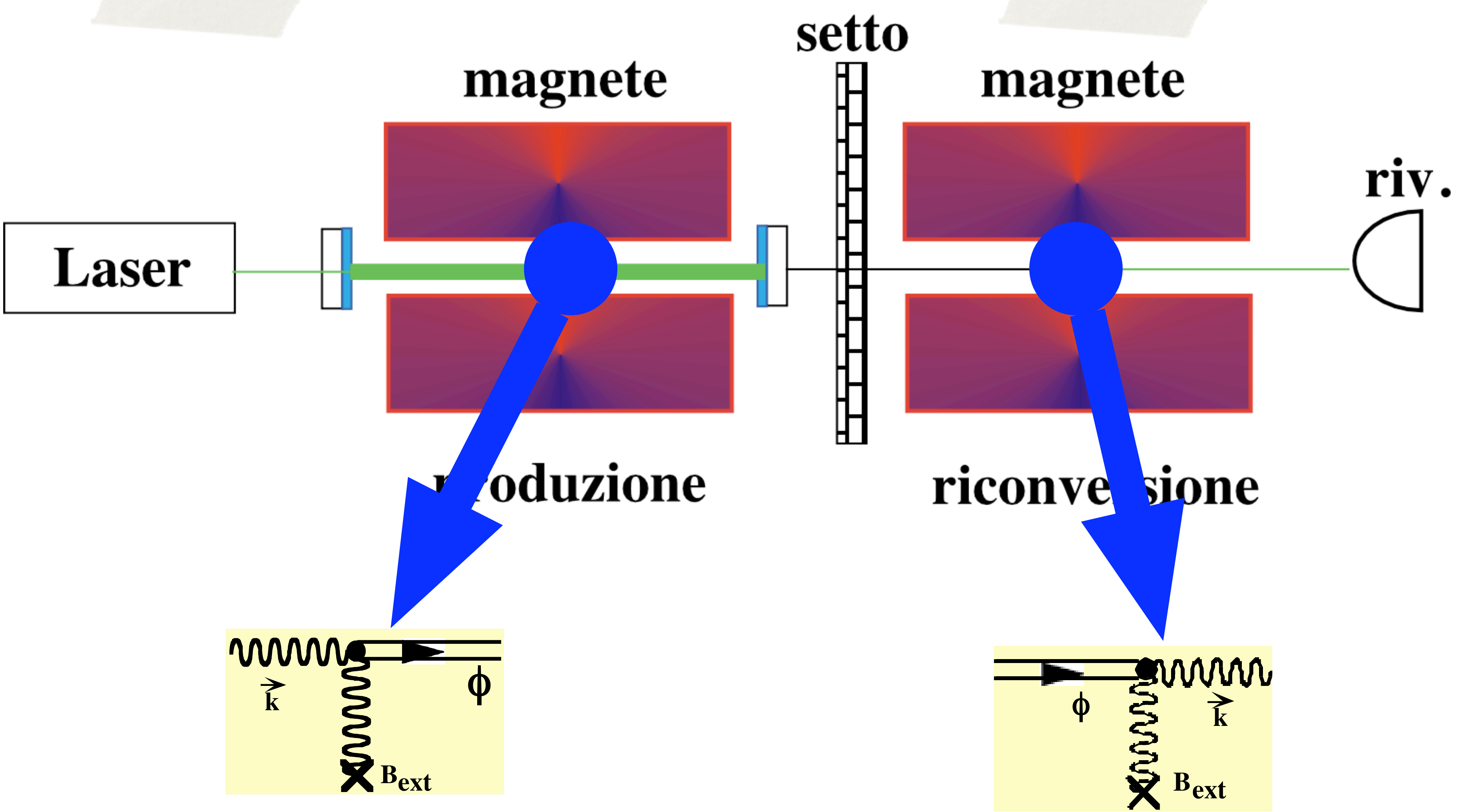
- Higher energy sources
  - FEL
  - backscattered polarised γ rays
- Photon regeneration

FEL source (or high energy photon beam)



Suppressed by beam energy

Photon regeneration



Upcoming ...

- PVLAS
  - proceed with extensions
- New ideas
  - workshop on FEL-related opportunities
  - R&D on
    - precision polarisation measurements for photons with Energy > visibile photons
    - feasibility study on a photon regeneration experiment