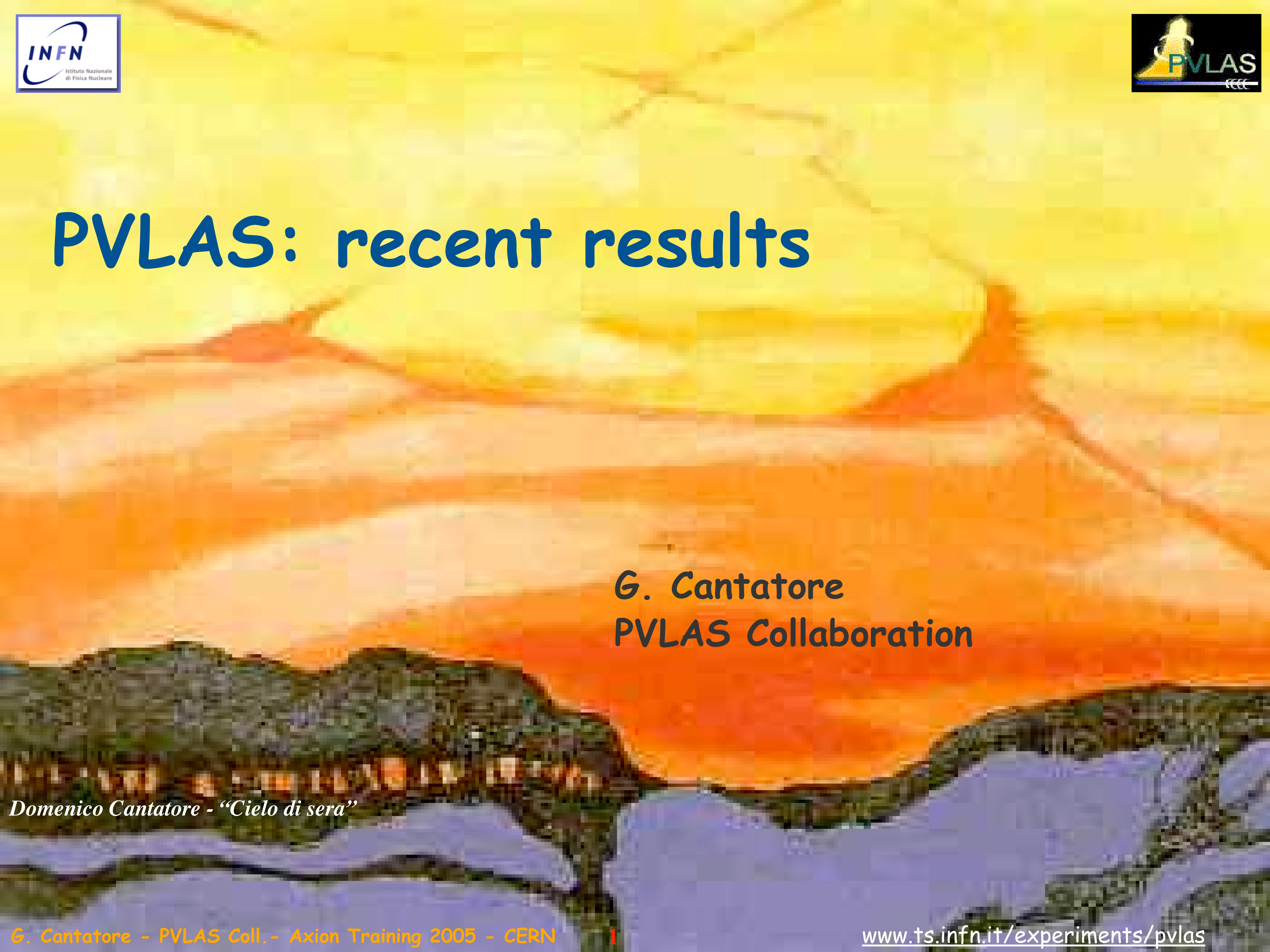
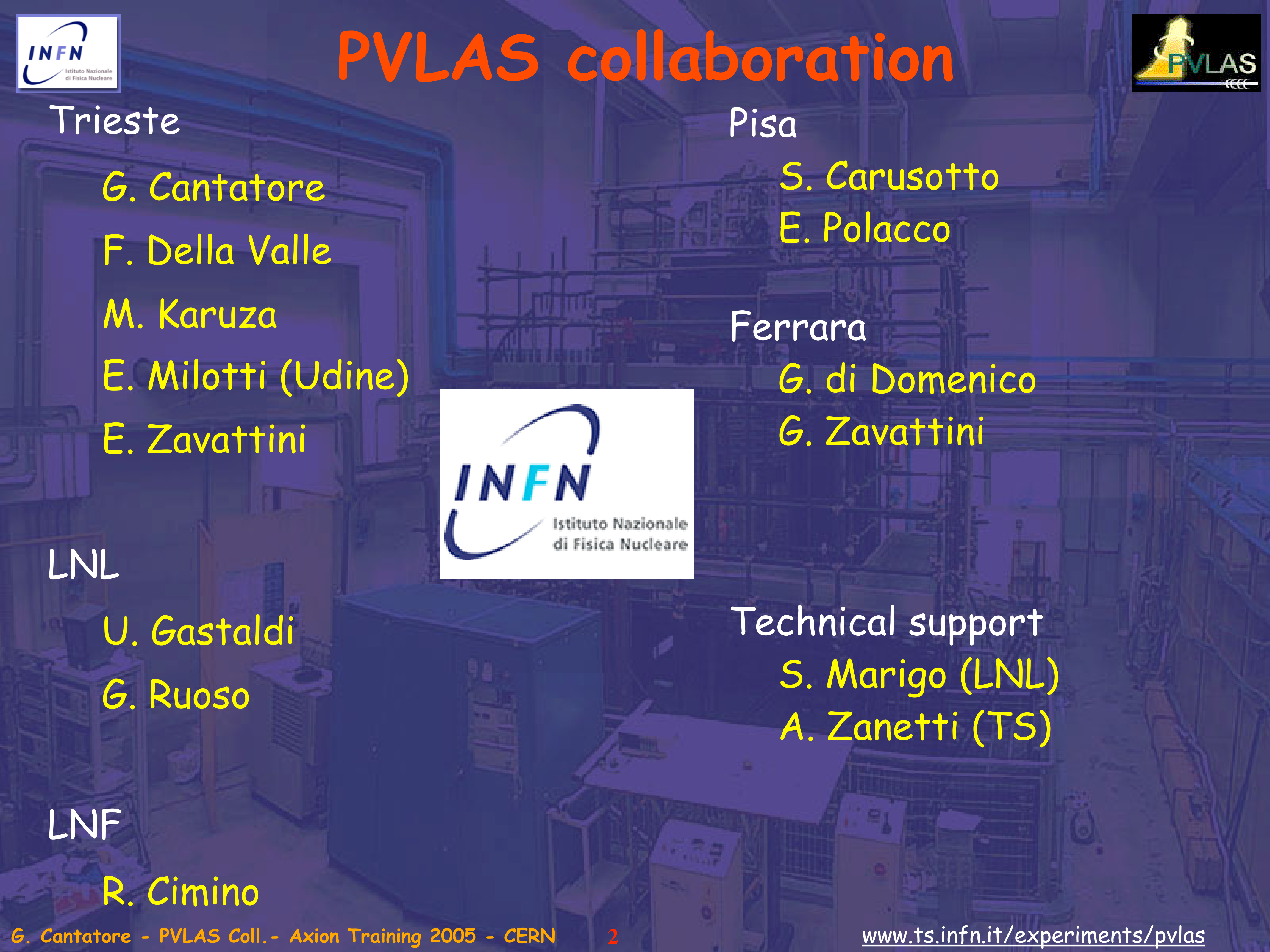
PVLAS: recent results

G. Cantatore
PVLAS Collaboration



Domenico Cantatore - “Cielo di sera”

PVLAS collaboration



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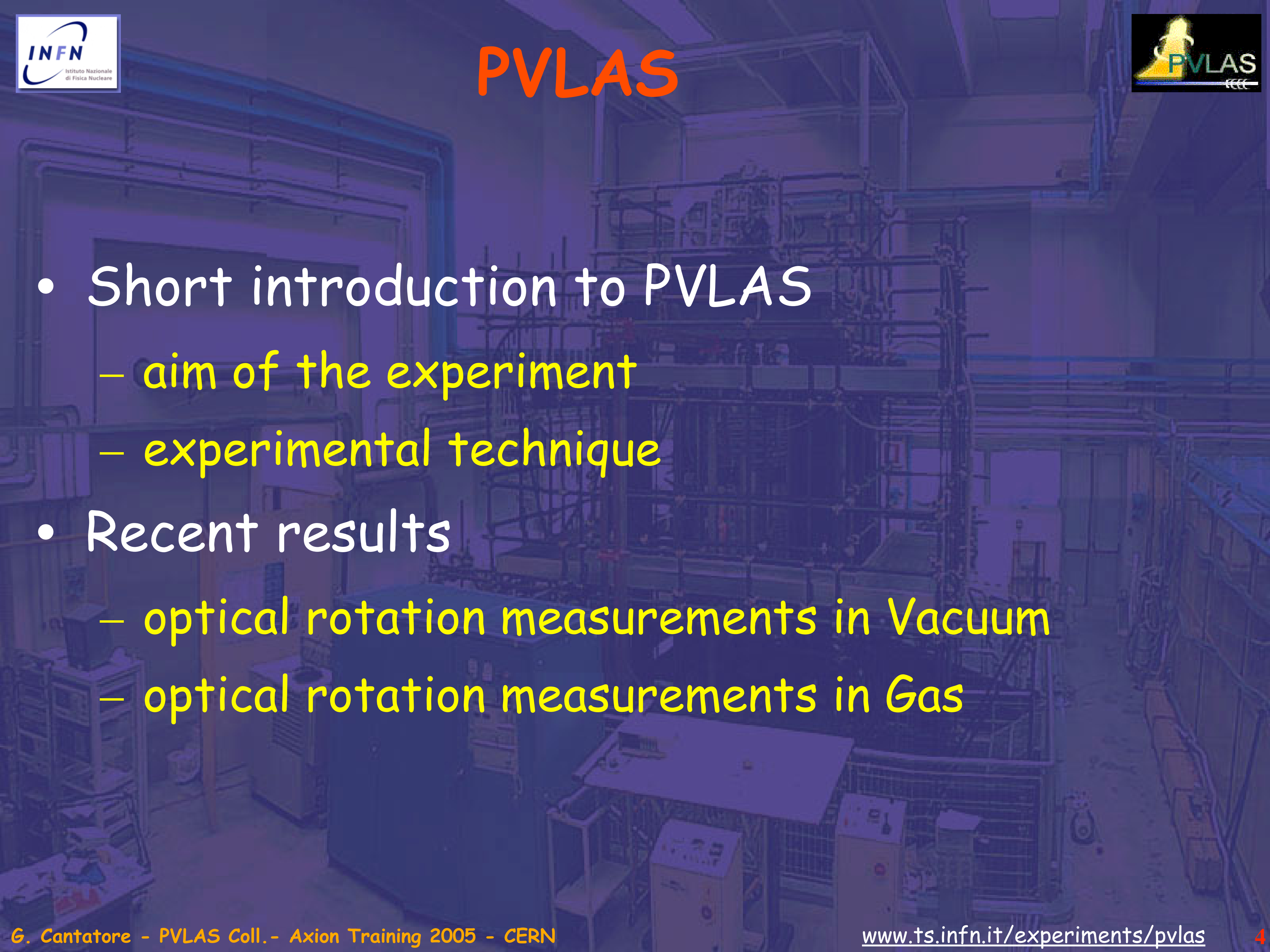
A closer look ...

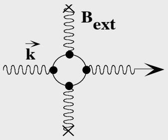
PVLAS



- Short introduction to PVLAS
  - aim of the experiment
  - experimental technique
- Recent results
  - optical rotation measurements in Vacuum
  - optical rotation measurements in Gas

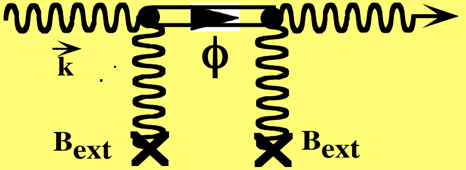
Theme and aim of the PVLAS experiment

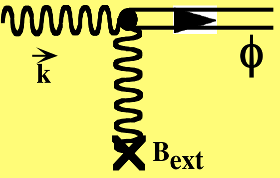
- Theme
  - Vacuum as a "target": low energy photon-photon collider
    - QED interactions
    - other interactions?
- Aim
  - Measure the magnetically induced linear birefringence and linear dichroism (optical rotation) of the Vacuum element (in practice a gas in the zero-pressure limit)
  - Possible contributions to macroscopic properties
    - photon-photon scattering →



+ diagrams of order higher than α^2

    - production of:
      - neutral bosons
      - ...





PVLAS
(Polarizzazione del Vuoto con LASer)

PVLAS was originally designed to obtain experimental information on quantum Vacuum using optical ellipsometric techniques.

The present full experimental program is to detect and measure

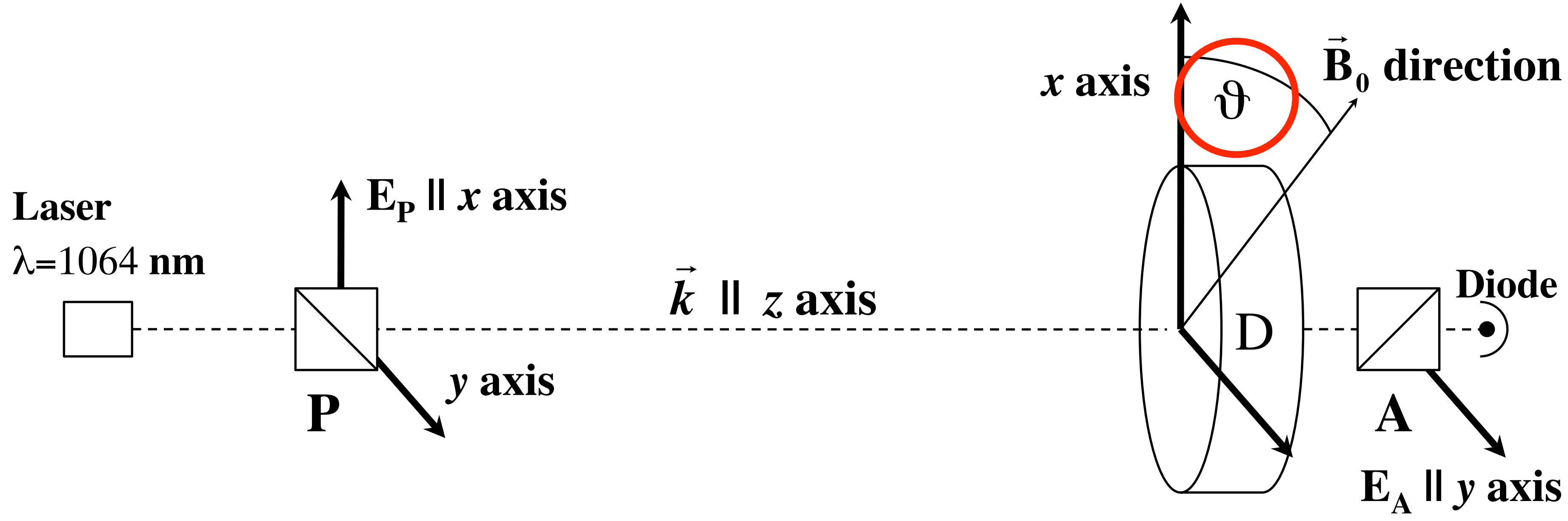
LINEAR BIREFRINGENCE

LINEAR DICHROISM

acquired by a polarised light beam propagating in Vacuo in the presence of an external transverse magnetic field B

Reference coordinates

The apparatus contains a polariser P and an analyser A defining two perpendicular directions which we use as a base.



Linear Birefringence

The electric field of the incoming beam can be expressed as

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

- Propagation through a magnetic field zone introduces a phase delay of the component parallel to **B** by φ (is ϑ the angle between **B** and the polariser axis)

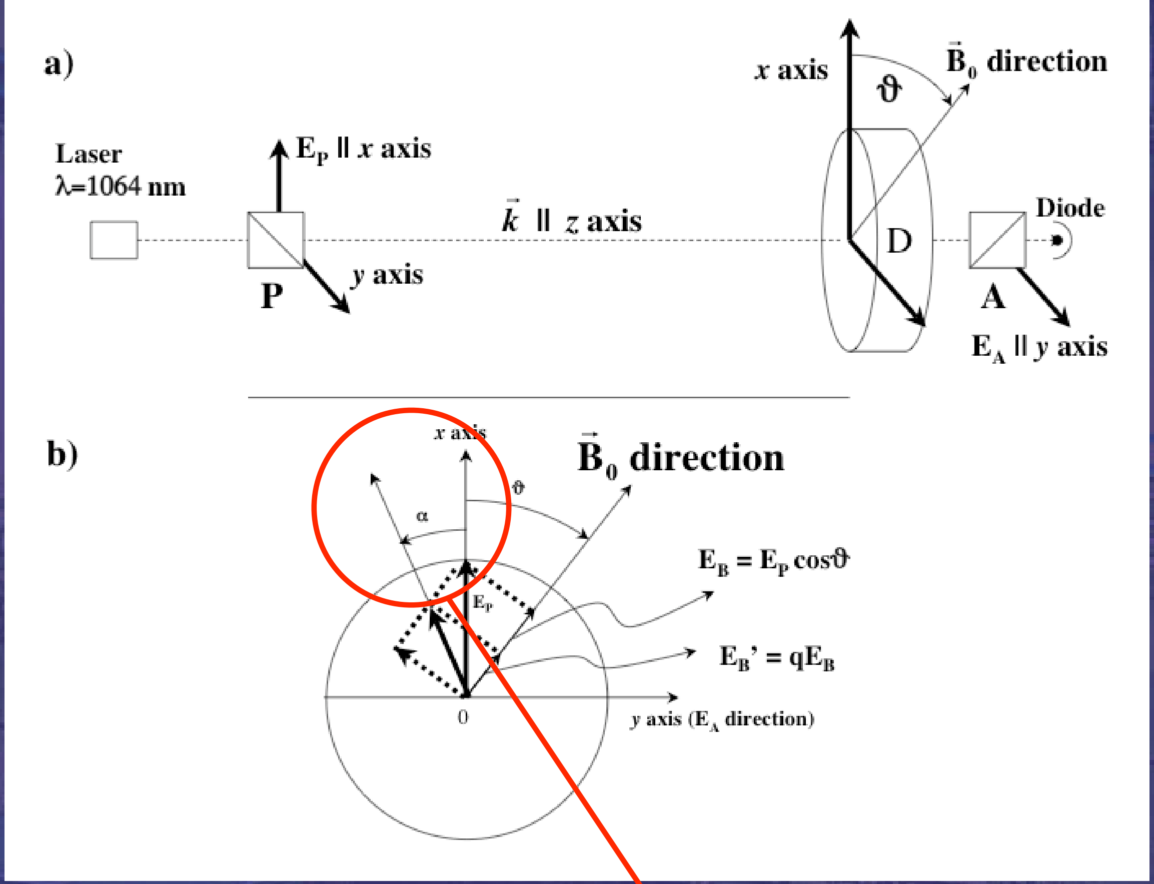
$$\vec{E}_{out} = E_0 e^{-i\xi} \begin{pmatrix} 1 + i\left(\frac{\varphi}{2}\right)\cos 2\vartheta \\ -i\left(\frac{\varphi}{2}\right)\sin 2\vartheta \end{pmatrix}$$

A signal is induced along the direction of the analyser A with maximum amplitude:

$$\psi = \left(\frac{\varphi}{2}\right)$$

Linear dichroism

- The rotation of the polarisation plane of linearly polarised light is useful to mesasure the effect of a dichroic medium
- In the case shown here one measures the <u>selective absorption q</u> in the presence of the magnetic field B

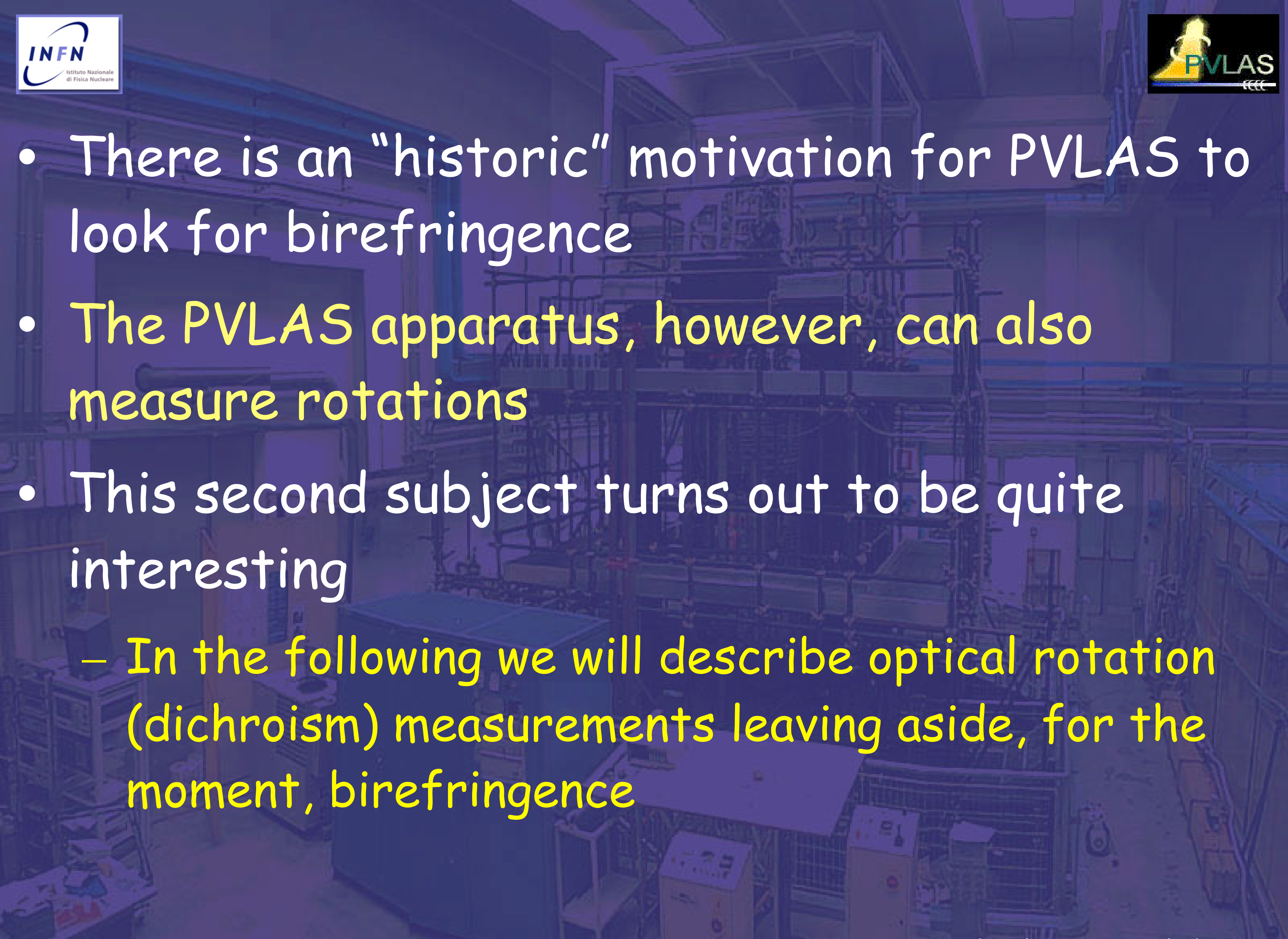


$$\vec{E}_{in} = E_0 e^{-i\xi}\begin{pmatrix}1\\0\end{pmatrix} \Rightarrow$$

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

Max amplitude of the signal along the analyser direction corresponding to a rotation of the polarisation plane →

$$\alpha = \left(\frac{q-1}{2}\right)$$



- There is an "historic" motivation for PVLAS to look for birefringence
- The PVLAS apparatus, however, can also measure rotations
- This second subject turns out to be quite interesting
  - In the following we will describe optical rotation (dichroism) measurements leaving aside, for the moment, birefringence

Experimental result on dichroism in Vacuo

We have consistently observed a dichroism signal generated by a 1.1 m long, 5.5 T magnet. The beam (at $\lambda = 1064$ nm) traverses the magnetic region N ~ 50000 times.

Total measured rotation = $(2.0\pm0.3)\cdot 10^{-7}$ rad corresponding to

$$\left(\frac{q-1}{2}\right) = -(3.9\pm0.5)\cdot 10^{-12}\ \text{rad/pass}$$

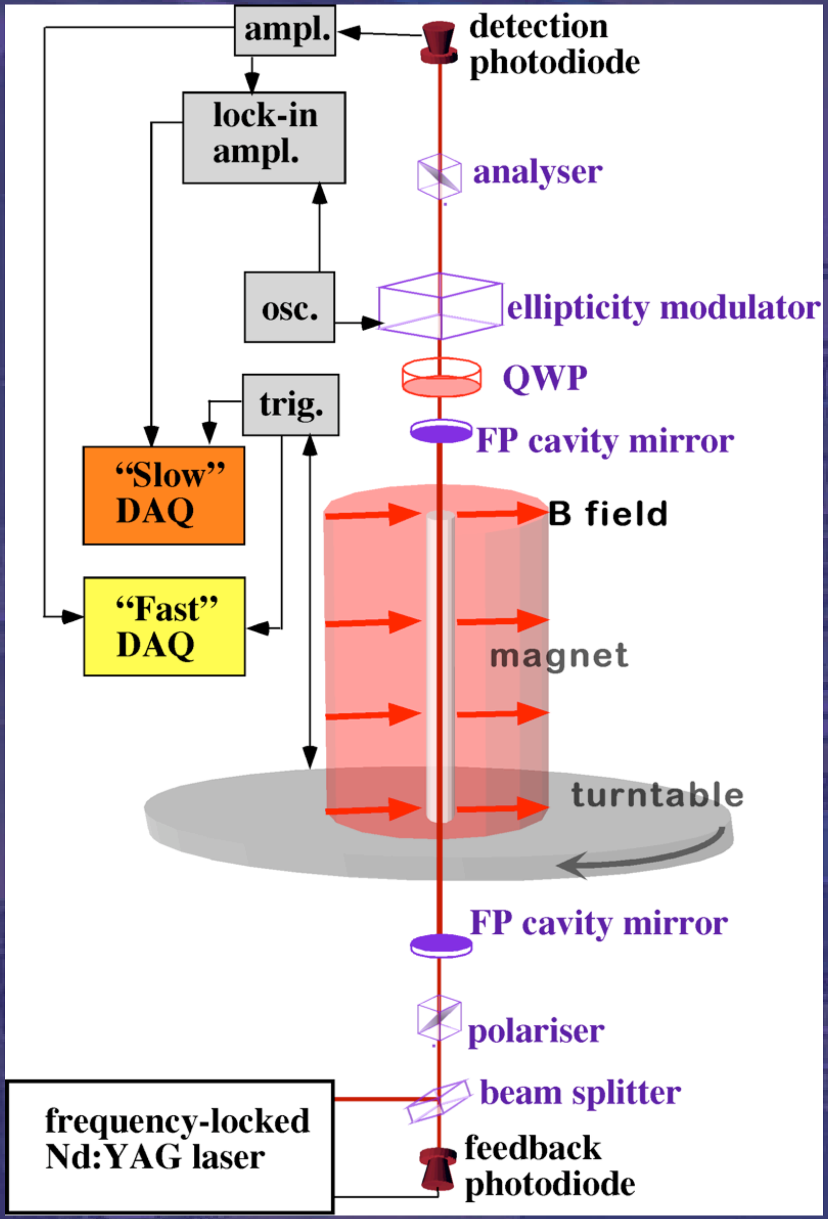
Empirical fact: there is a reduction of the electric field component parallel to B.

Key Question: what has happened to the missing part?

Further questions:

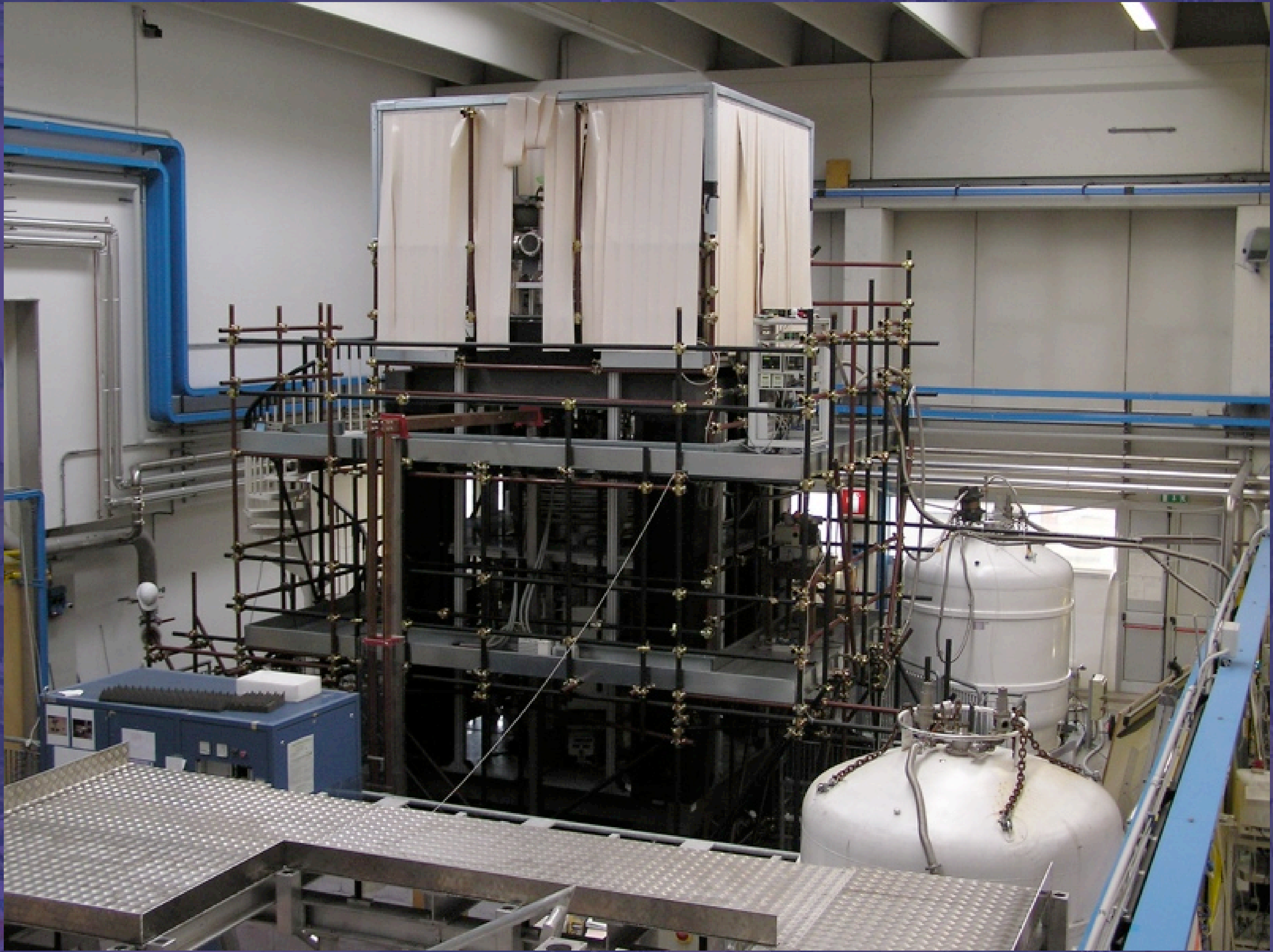
- Can we exclude a systematic error?
- Do we have a physics test we can perform?
- What is the comparison of our result with other experiments?

PVLAS - Schematic

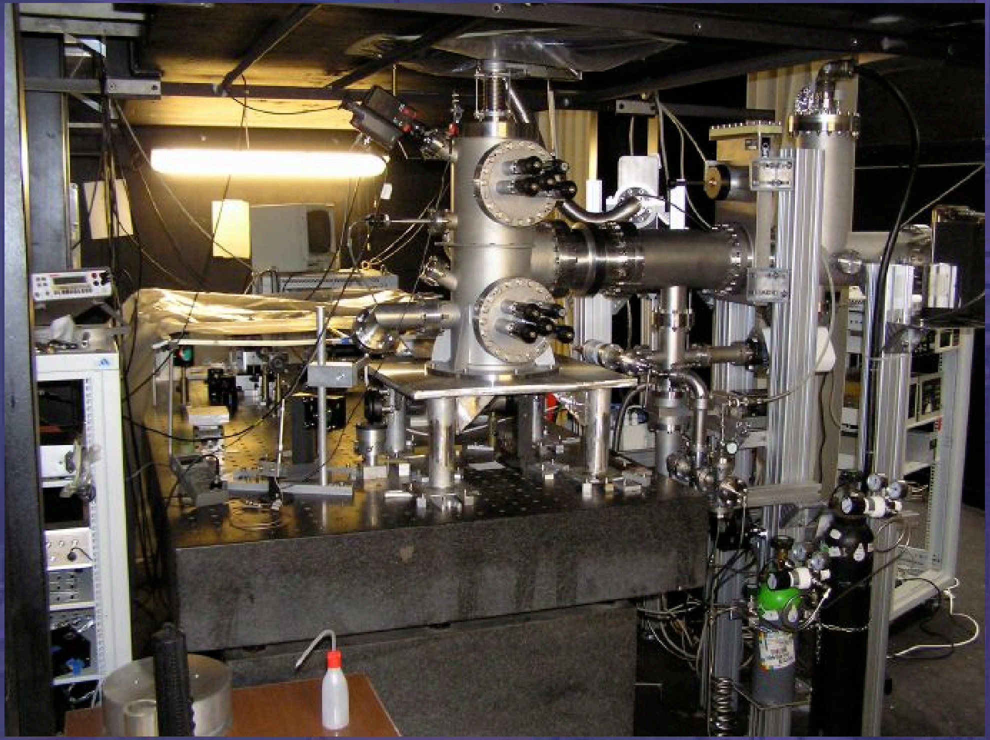


- Main parameters of the apparatus
  - magnet
    - dipole, 6 T, temp. 4.2 K, 1 m field zone
  - cryostat
    - rotation frequency ~300 mHz, sliding contacts, warm bore to allow light propagation in the interaction zone
  - laser
    - 1064 nm, 100 mW, frequency-locked to the F.-P. cavity
  - Fabry-Perot 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 + Quarter Wave Plate (QWP)
    - time-modulation of the effect
  - detection chain
    - photodiode with low-noise amplifier
  - DAQ
    - Slow: demodulated at low frequency and phase-locked to the magnetic field instantaneous direction
    - Fast: high sampling frequency direct acquisition

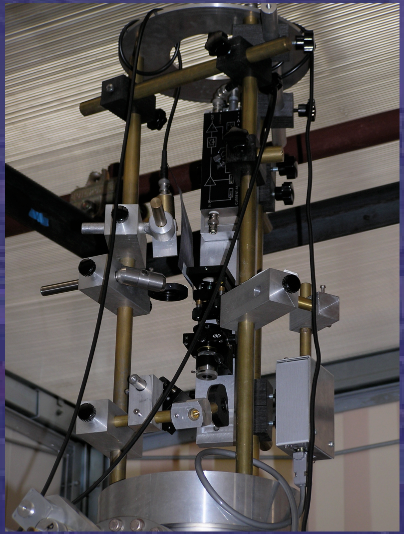
PVLAS hall at LNL



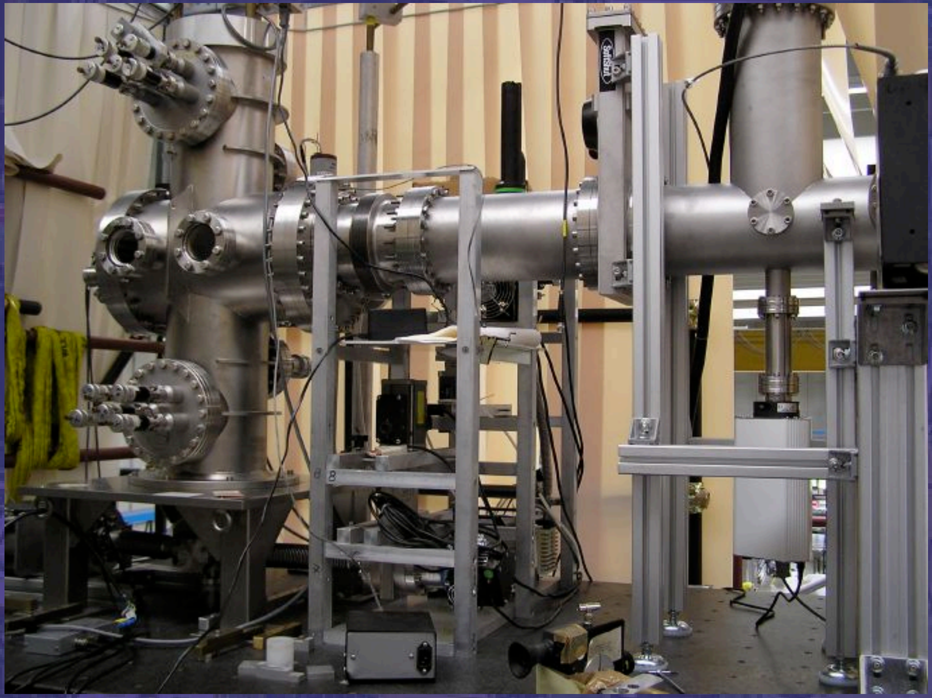
Gallery (I)



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



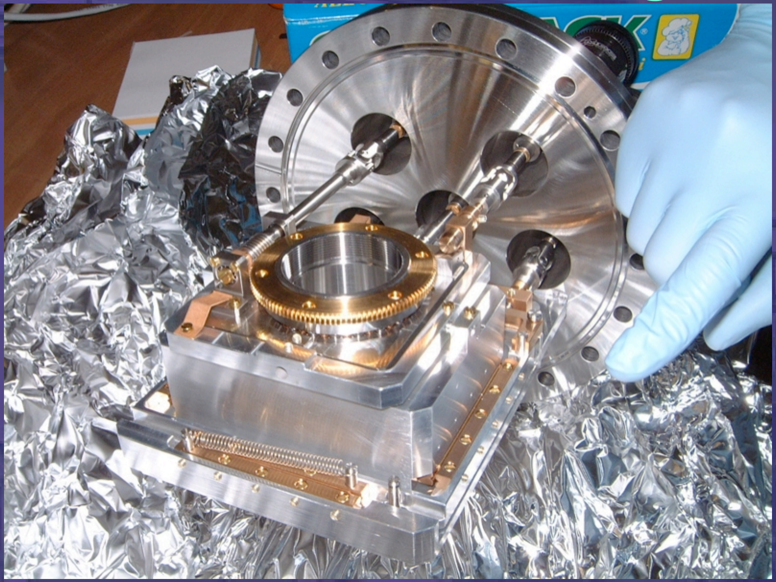
Detection photodiodes



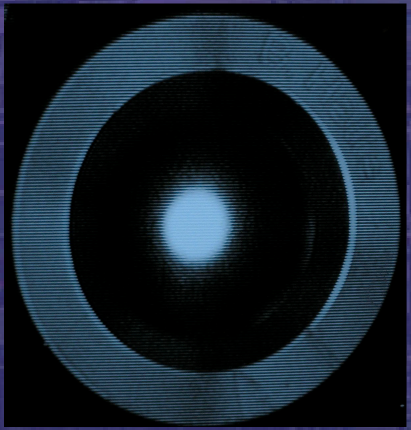
Upper optical bench with vacuum chamber

Gallery (II)

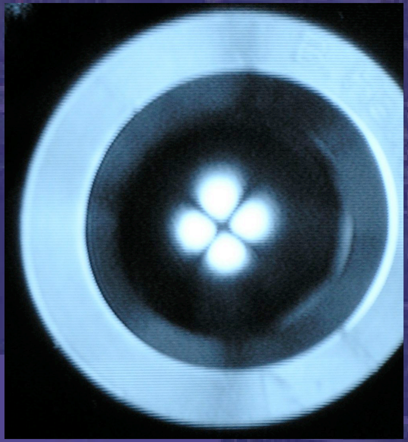
Vacuum movement stage



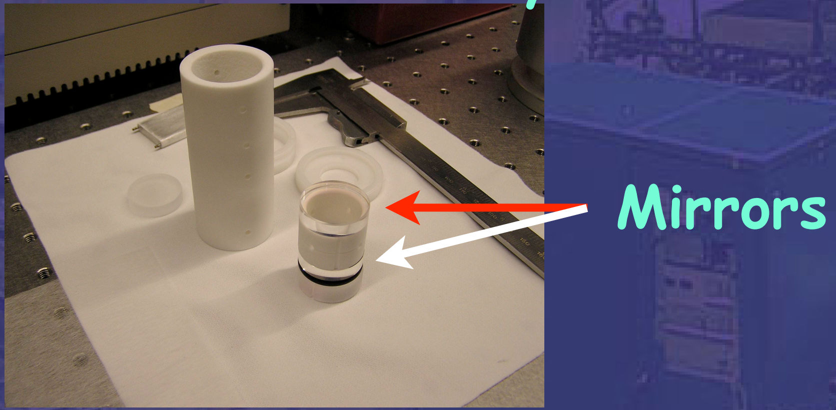
6.4 m cavity TEM00 mode



6.4 m cavity TEM11 mode



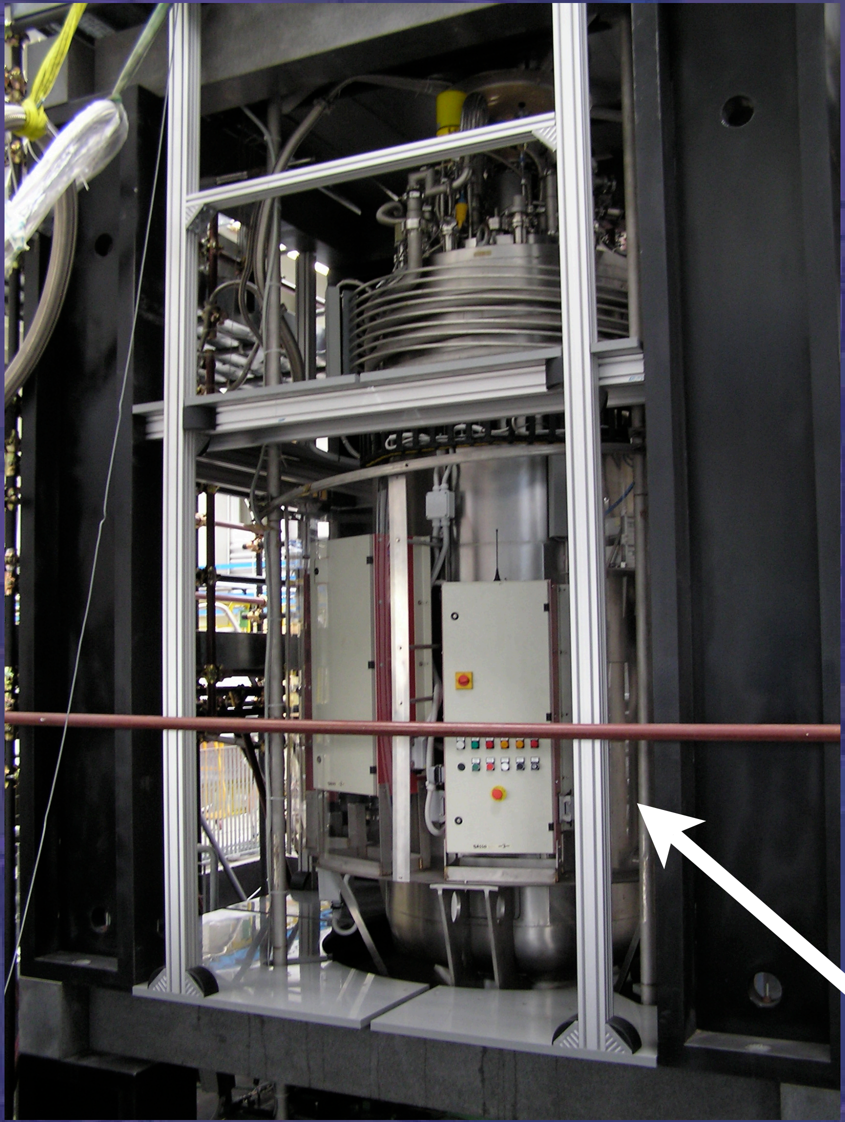
17 mm test cavity



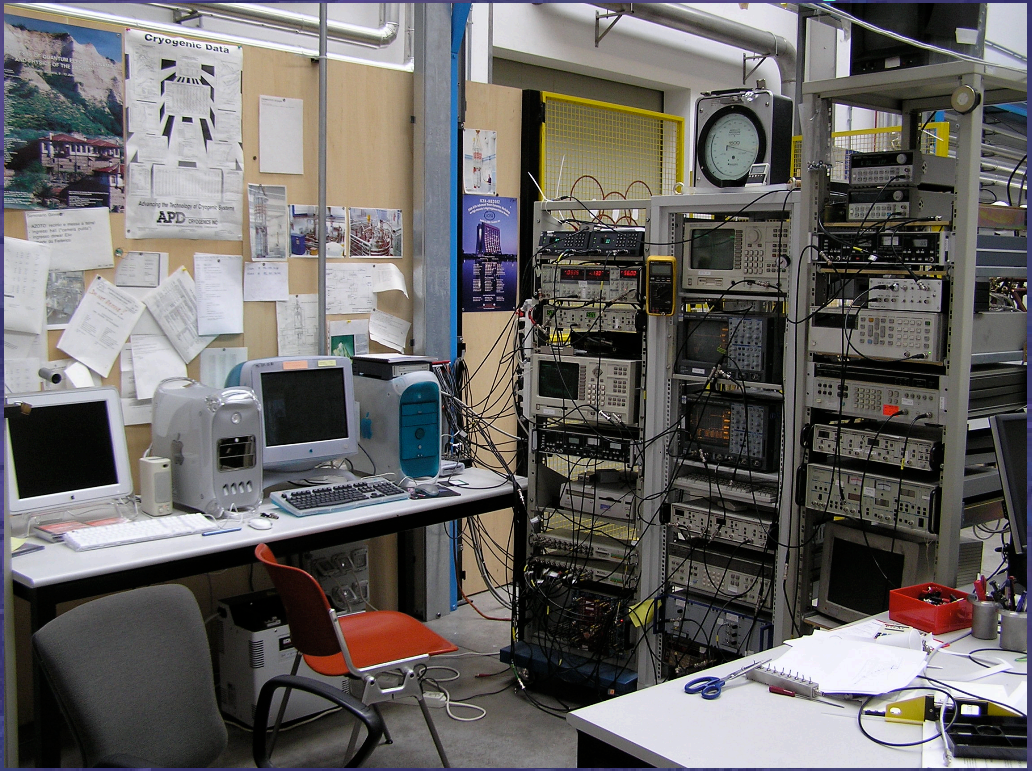
Mirrors

Gallery (III)

Rotating cryostat

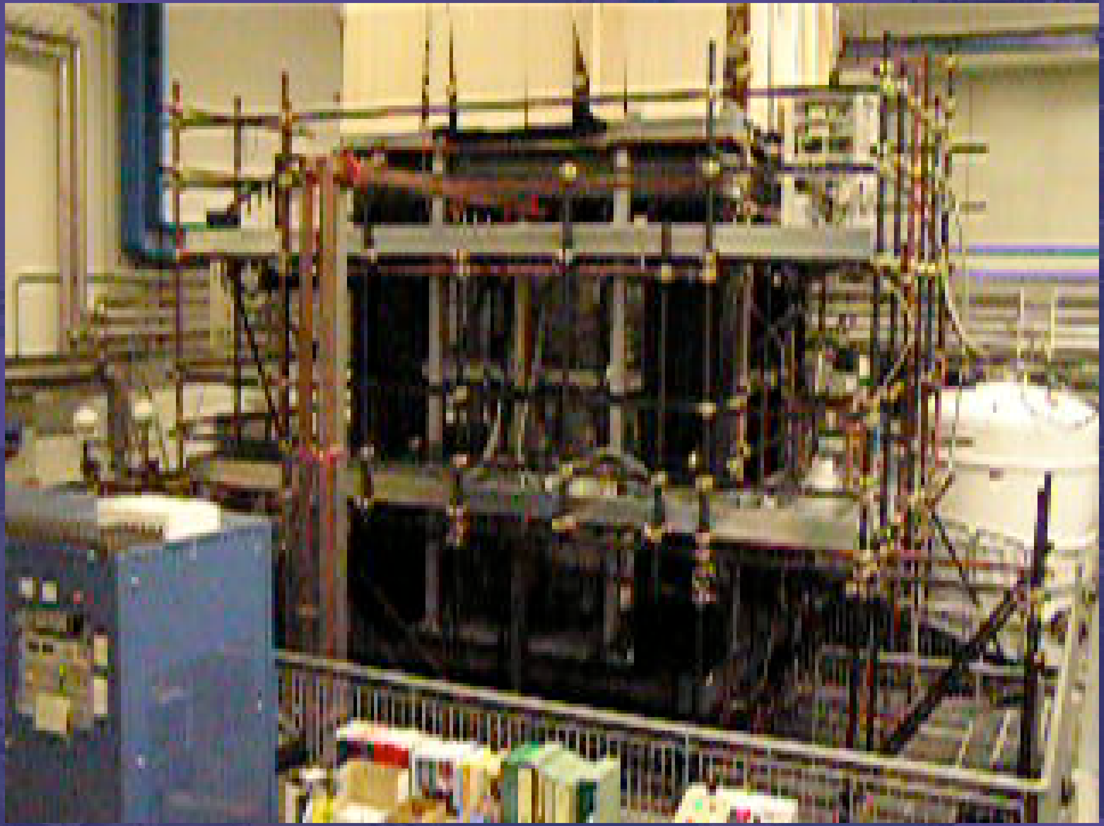


Counting room

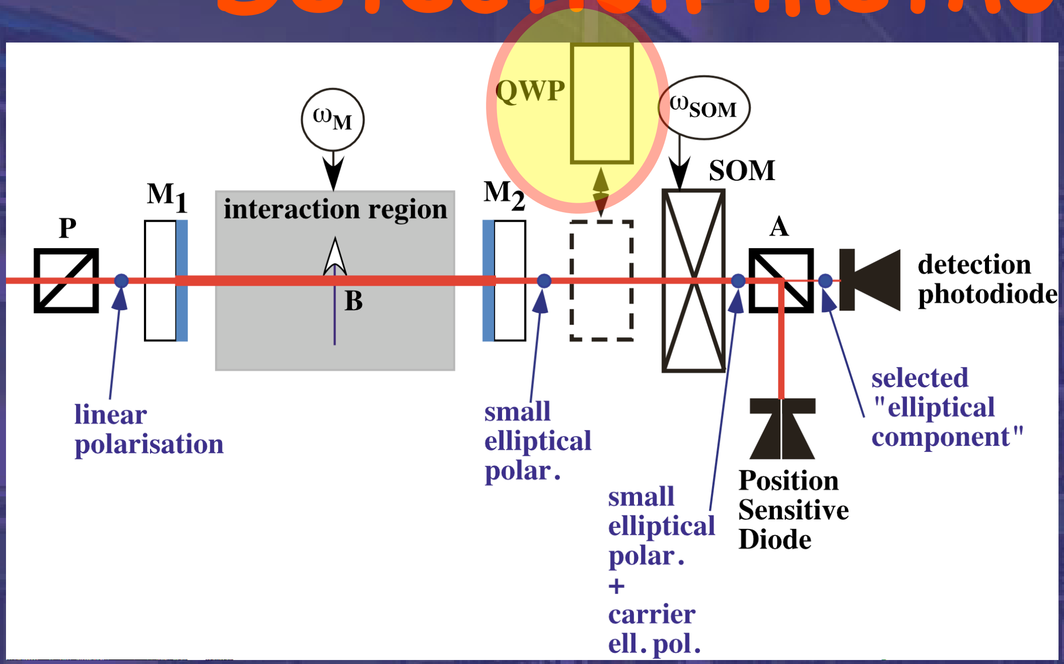


magnet position

PVLAS Videos



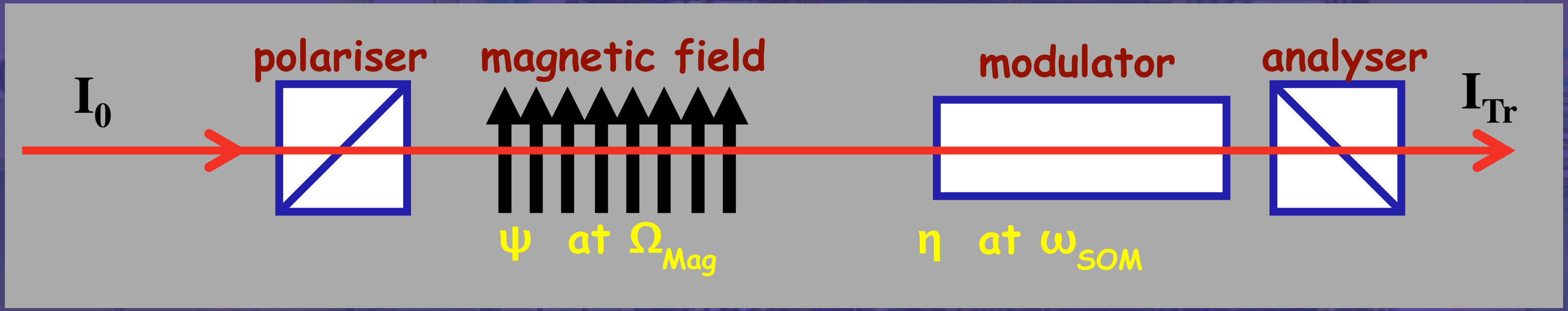
Detection method



- 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

Ellipticity measurement principle

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



Ideally the transmitted intensity is given by,

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

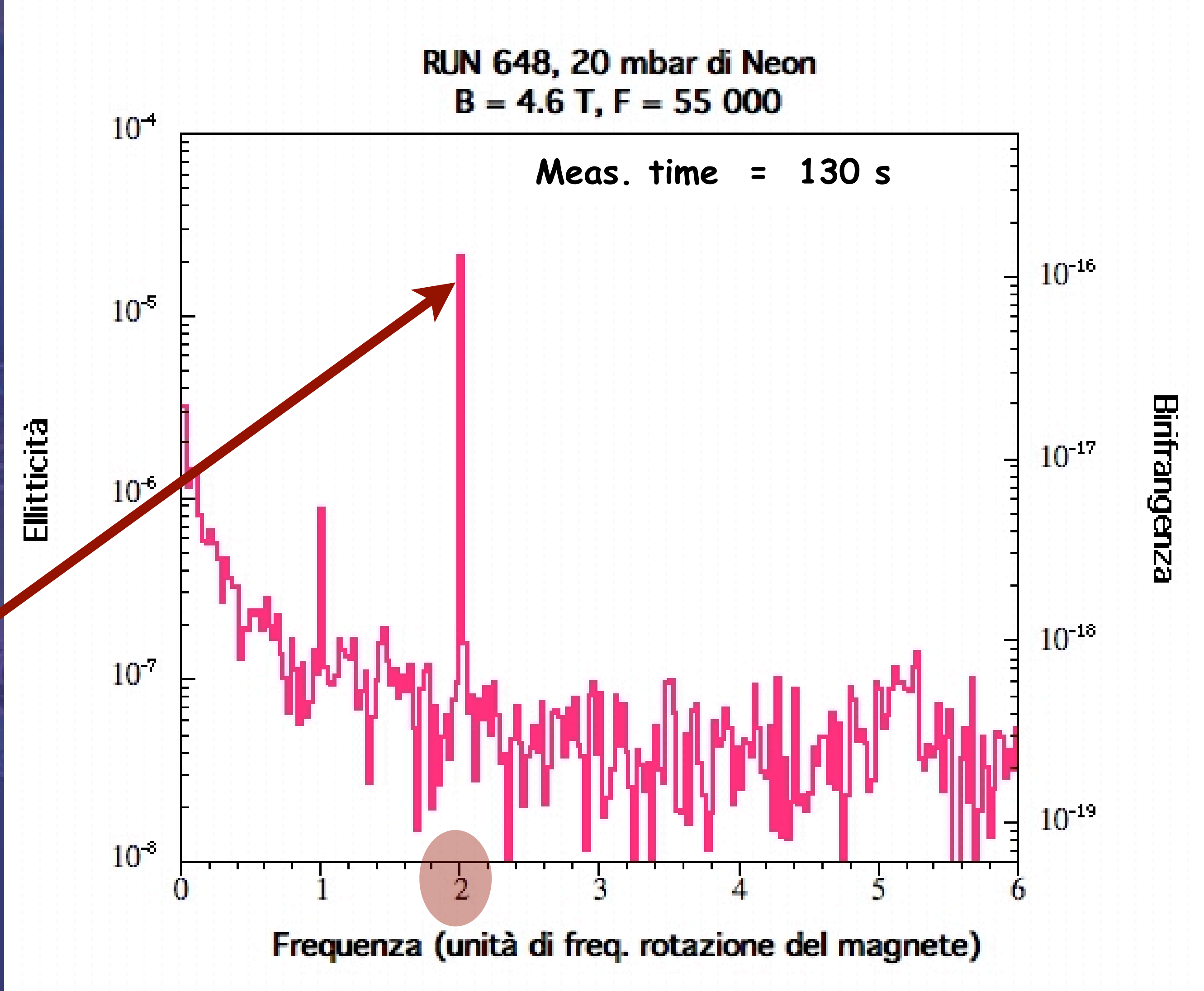
The main frequency components appear at $\omega_{SOM} \pm 2\Omega_{Mag}$ and $2\omega_{SOM}$

Performance tests with gases

Measurements of the Cotton-Mouton effect in gases (done without the QWP)

The slow DAQ gives an amplitude spectrum demodulated at the carrier frequency of the ellipticity modulator (506 Hz)

The expected signal (magnetic birefringence of a gas in this case) appears at twice the magnet rotation frequency (here 0.6 Hz)


RUN 648, 20 mbar di Neon
B = 4.6 T, F = 55 000

Meas. time = 130 s

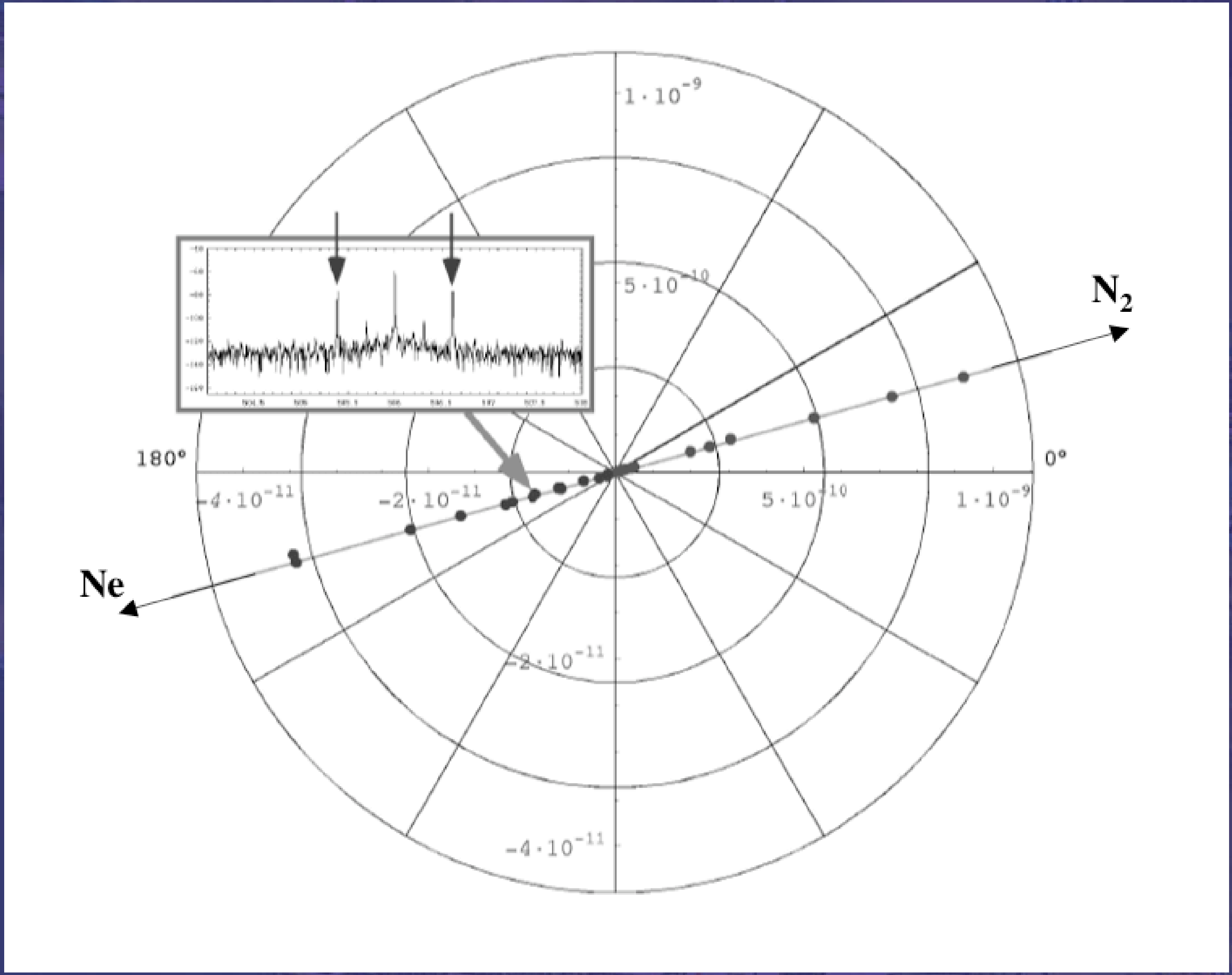
Sensitivity

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

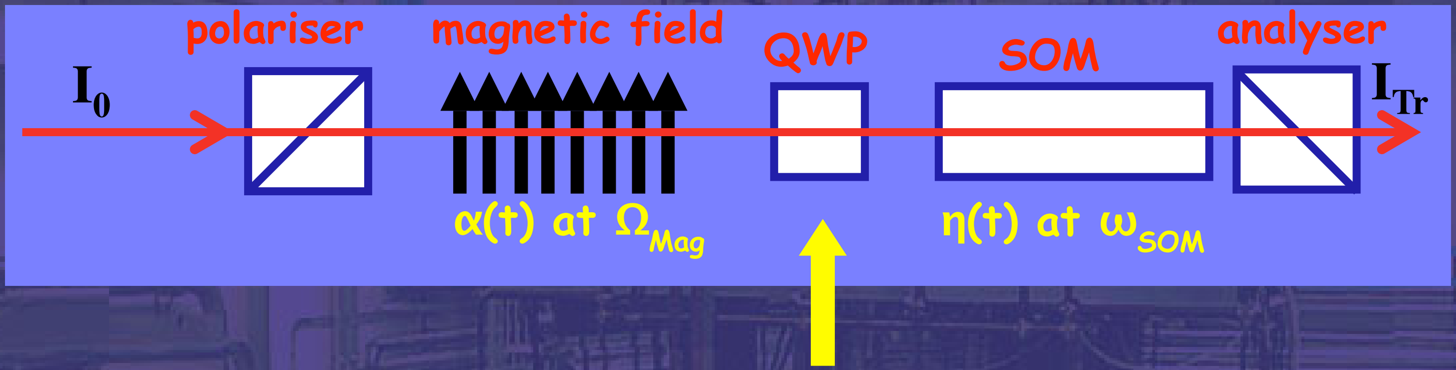
$$\Delta n^s \approx 2 \cdot 10^{-18} \quad 1/\sqrt{Hz}\,;$$

Signal phase check

- Polar plot of amplitude and phase of the signal peaks obtained from the Cotton-Mouton Effect of Ne and N_2. Data points were taken at several pressure values (<mbar for N_2; 1-20 mbar for Ne)
- Points align along a straight line determined by the apparatus geometry and by the position of the initial polarisation



Dichroism measurement principle



A QWP can be inserted to transform a rotation into an ellipticity with the same amplitude. Two positions for the QWP slow axis: 0° and 90°.

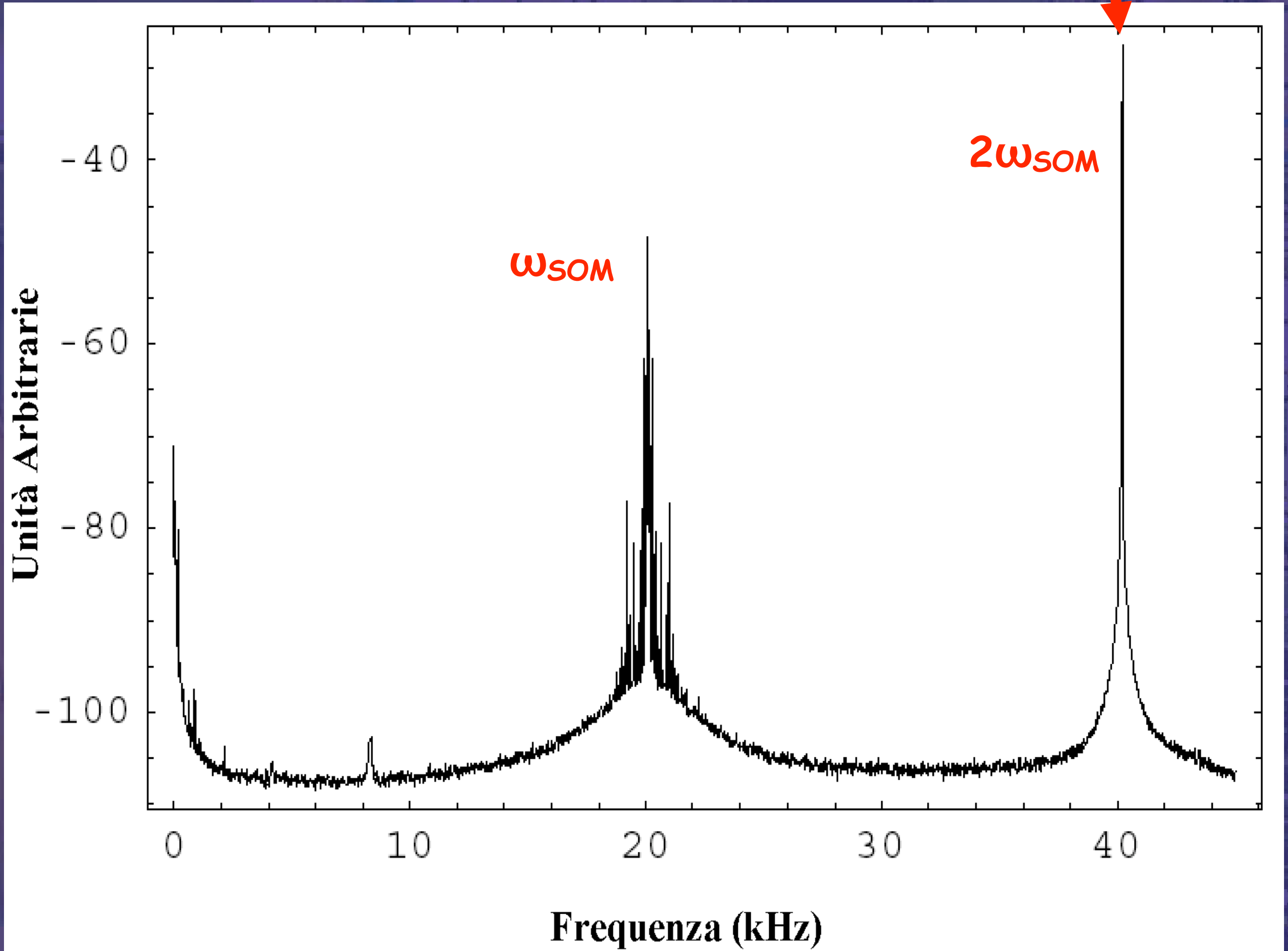
$$\alpha(t) \Rightarrow \begin{cases} \Psi(t) & \text{for } \vartheta = 0^\circ \\ -\Psi(t) & \text{for } \vartheta = 90^\circ \end{cases}$$

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

The main frequency components appear at $\omega_{SOM} \pm 2\Omega_{Mag}$ and $2\omega_{SOM}$

Experimentally

Normalization peak

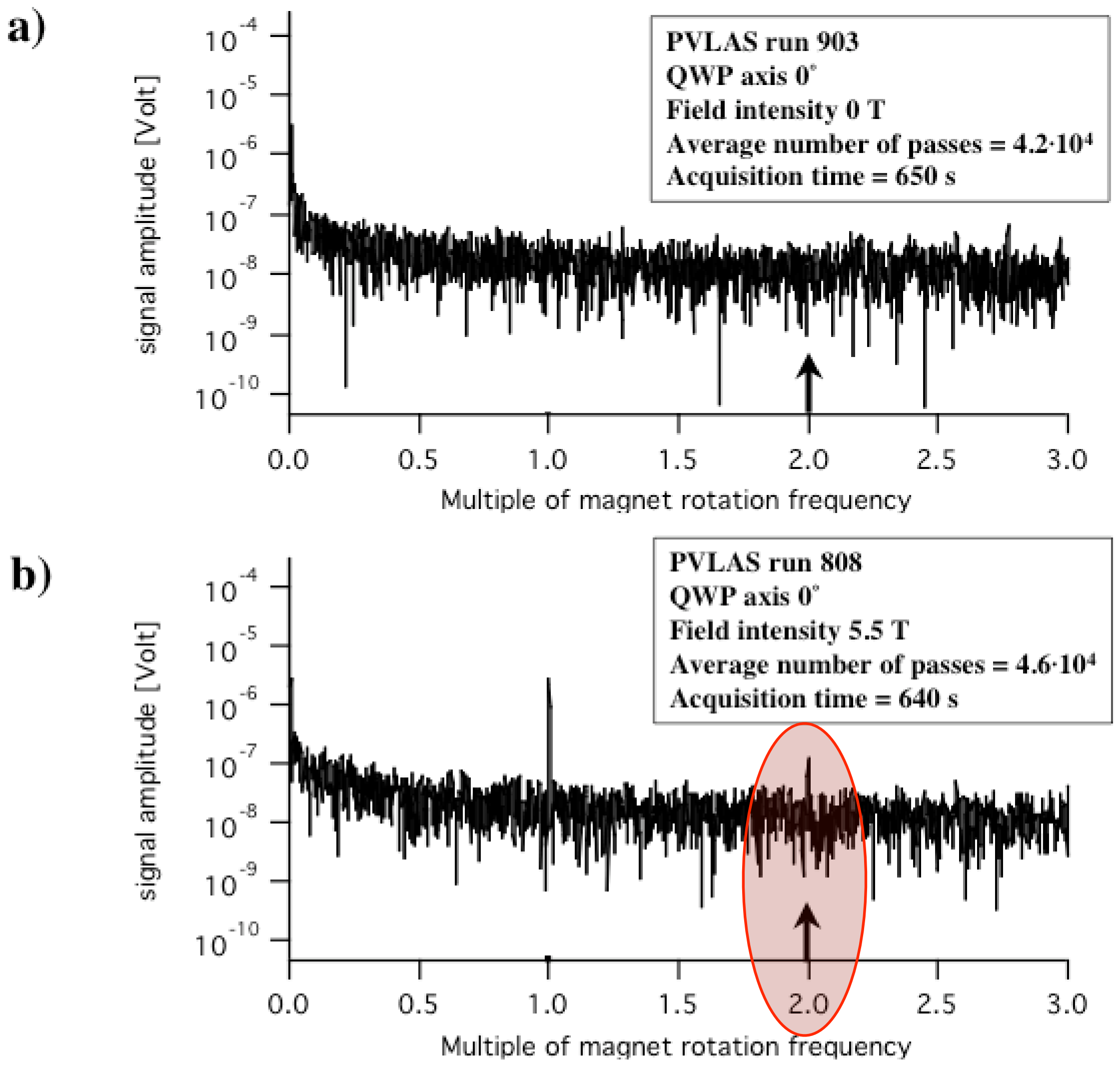


Recent results on optical rotation (dichroism) measurements in Vacuo

- Summarising
  - sensitivity of $\sim 2\cdot 10^{-7}$ rad/√Hz (shot-noise limit is $2\cdot 10^{-8}$ rad/√Hz)
  - observed a rotation of the polarisation plane of light at 1064 nm propagating in Vacuum in presence of a transverse magnetic field (with the above sensitivity the signal is seen above background in a matter of seconds with SNR~5-10
  - with 5.5 T and ~50000 passes in the Fabry–Perot cavity the weighted average amplitude of the effect is $(2.0\pm0.3)\times 10^{-7}$ rad
  - the rotation is generated within the FP
  - the signal (on average) has the phase expected for a physical signal

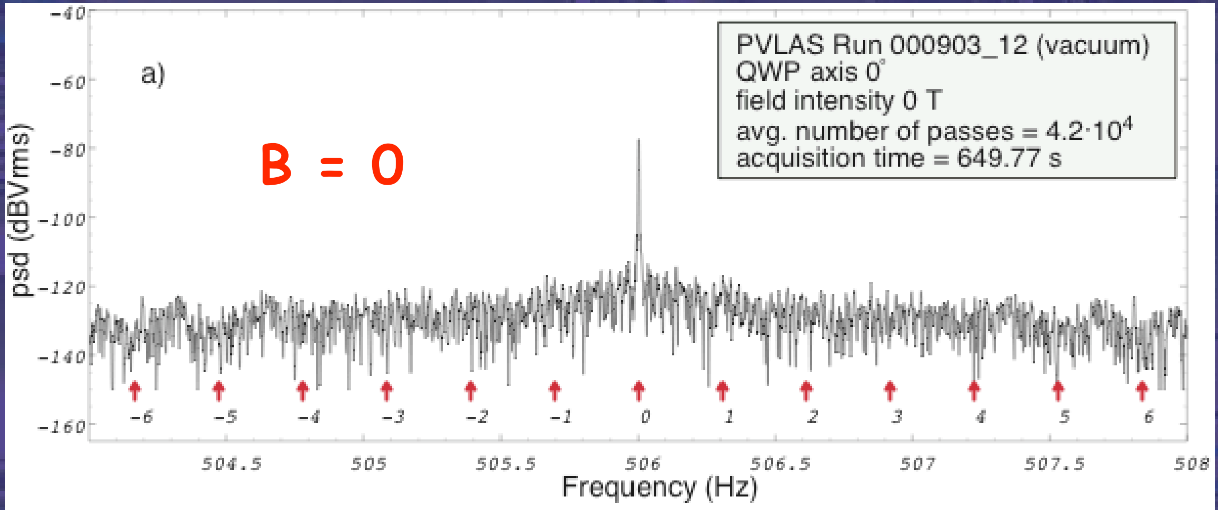
Vacuum rotation measurements (amplitude) I

- Vacuum spectra ($P < 10^{-7}$ mbar, cavity with 50000 passes)
- Rotation measurements
  - a) field B = 0
  - b) field B = 5.5 T
- The peak at frequency 2.0 (in units of the magnet rotation frequency) corresponds to an <u>observed rotation in vacuum ~2×10^{-7} rad</u>

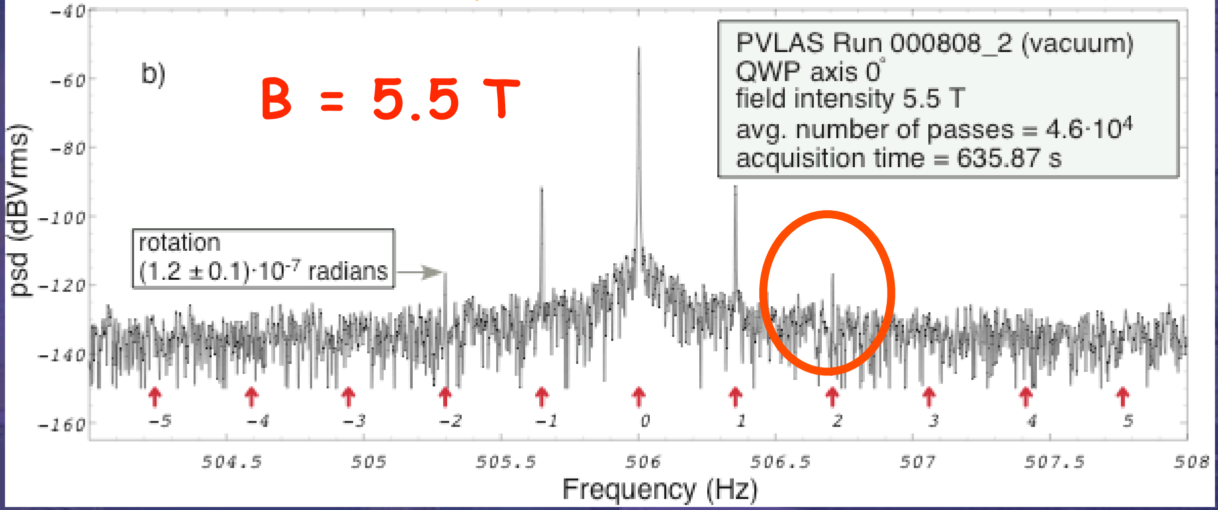


"Slow" DAQ - demodulated spectra: SOM freq. → 0 Hz

Vacuum rotation measurements (amplitude) II



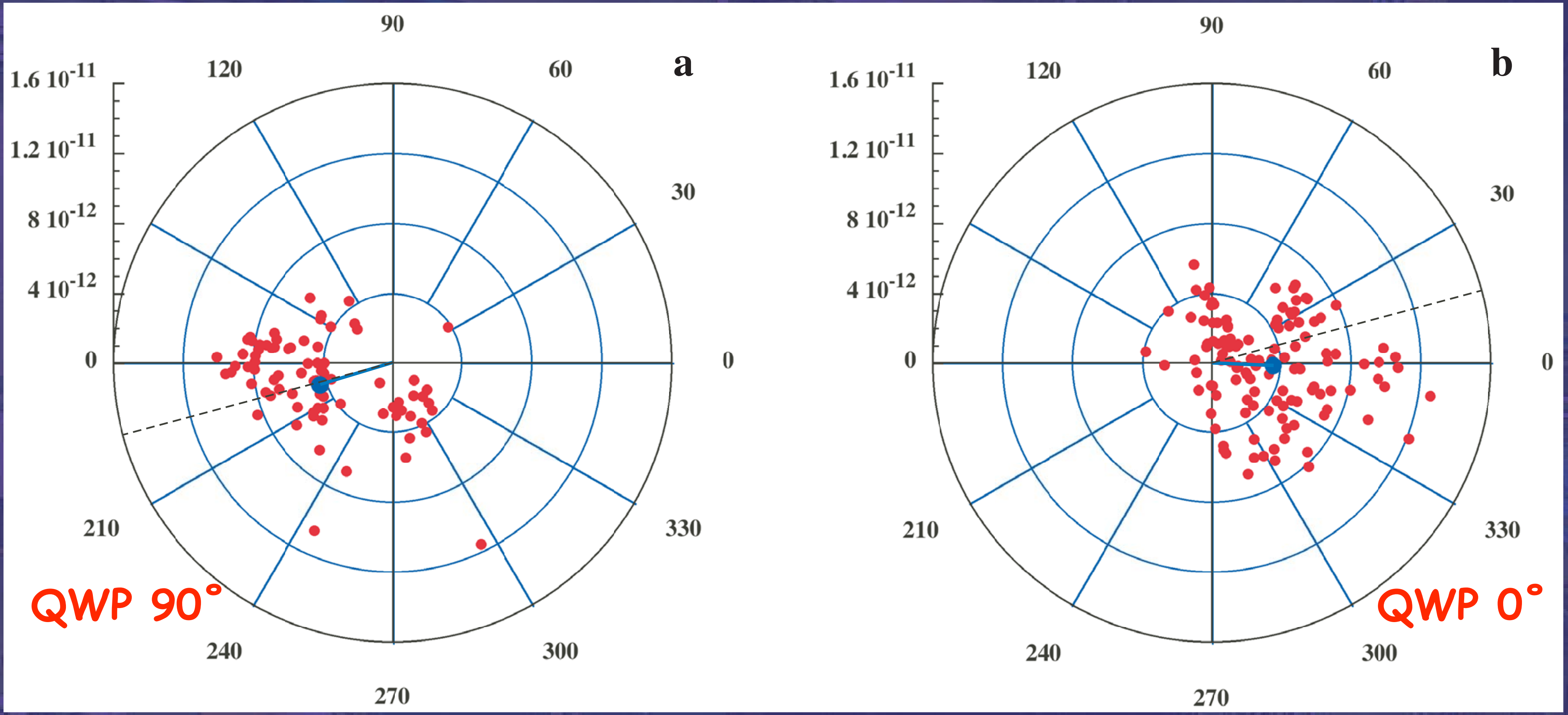
“Fast” DAQ - spectra around 506 Hz = SOM freq.



- Signal observed in Vacuo with B ≠ 0 and cavity present
- Data clusters in polar plane change sign under a QWP axis exchange
- The average rotation vector lies along the physical axis

The signal corresponds to a “true” rotation (dichroism) with amplitude $(3.9 \pm 0.5) \times 10^{-12}$ rad/pass

Vacuum rotation measurements - phase



- Plots are referred to the two possible orientations of the slow axis of the QWP
- Physical axis is at 15°
- Data points correspond to 100 s time records taken in Vacuo at 5.5 T and N ~ 50000 passes in the cavity

Note the sign change of the distribution under a QWP axis exchange

Vacuum rotation measurements - Summary Vectors

- Amplitude and phase of the rotation peak are obtained from a fit for each one of 250 100 s long records
- The set of 250 records has a large internal dispersion. Under the assumption that this is due to a 1/f type gaussian noise it is possible to treat this dispersion as an additional uncertainty and to sum it to the statistical uncertainty. The total uncertainty thus obtained is used in the weighted averages
- The plot shows

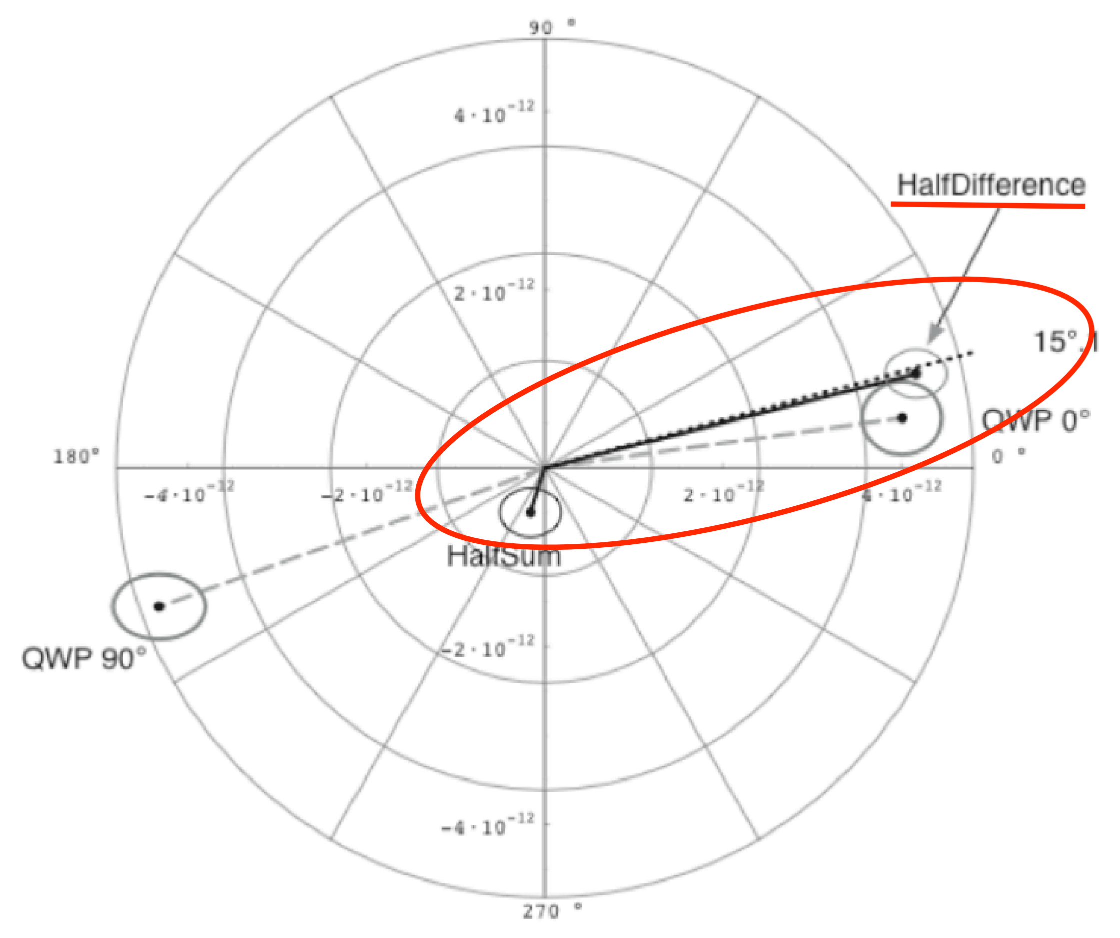
  QWP 0° = weighted average vector with the QWP axis at 0°

  QWP 90° = weighted average vector with the QWP axis at 90°

  HalfDifference = part changing sign under exchange of the QWP axes

  HalfSum = spurious part

  - ellipses at vector tips give an estimate of the 1 σ uncertainty



The HalfDifference vector, corresponding to a true rotation, has the expected phase

Preliminary conclusions with IR laser

- In Vacuo selective absorption of photons
  - experimental observation
  - selection along the magnetic field direction
- Possible mechanisms (speculations!!!)
  - photon splitting
  - photon->light neutral boson oscillation
- Publication
  - hep-ex/0507107 -> Phys. Rev. Lett.

“Fu vera gloria? . . .”

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

Discussion

I. instrumental artifact

- ongoing measurements at 532 nm should give a few answers
- think very hard ....

II. physical origin of the signal

Fact: selective absorption of photons

Compatible with what? Two (or more?) possibilities

1. photon splitting
2. photon-boson oscillation
3. ....

Model of photon-boson oscillation

Induced rotation (and induced ellipticity) can be expressed as functions of particle mass and inverse coupling constant to two photons.

Rotation and ellipticity can be measured independently yielding a direct particle identification through its parameters (equations in Heaviside-Lorentz units):

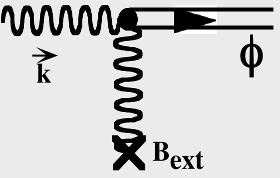
[L.Maiani, R. Petronzio, E. Zavattini, Phys. Lett B, Vol. 173, no.3 1986]
[E. Massò and R. Toldrà, Phys. Rev. D, Vol. 52, no. 4, 1995]

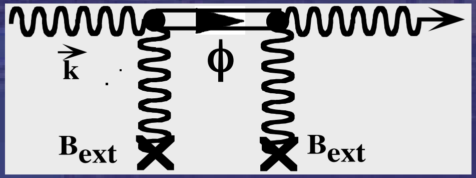
$$\varepsilon = \frac{1}{M^2}\frac{2FB_{ext}^2\omega^2}{\pi m_a^4}\left[\sin\left(\frac{m_a^2 l}{2\omega}\right)\right]^2$$

Rotation (linear dichroism)

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

Ellipticity (linear birefringence)





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

Note that particles would be both produced and detected in the laboratory
No astrophysics!

Dichroism from γ→boson oscillations

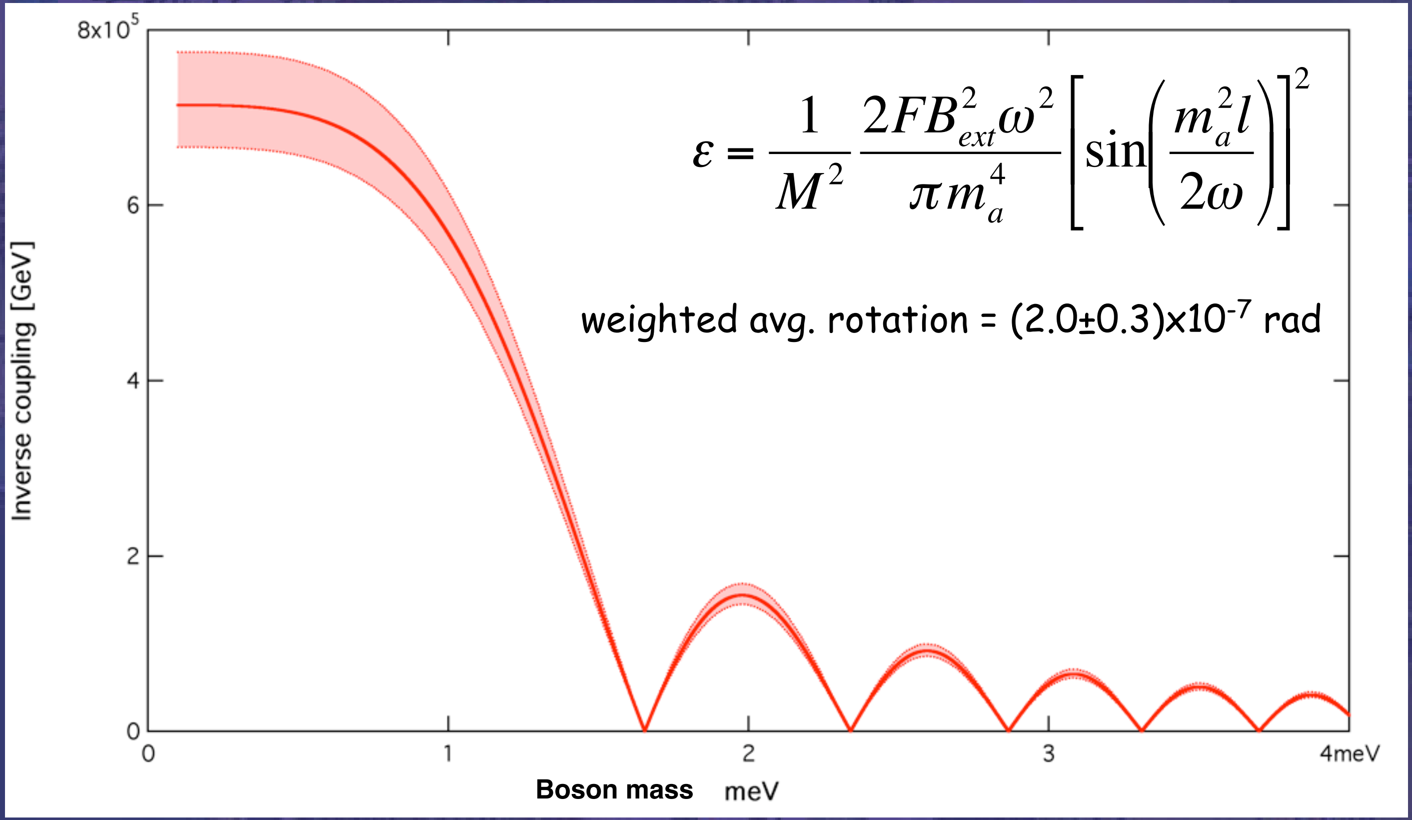
- In the model the observed dichroism is given by

$$\varepsilon = -\sin 2\theta \left(\frac{BL}{4M_b}\right)^2 N \left[\frac{\sin\left(m_b^2 L/4\omega\right)}{m_b^2 L/4\omega}\right]^2$$

- The amplitude of the observed dichroism signal $(3.9 \pm 0.5) \times 10^{-12}$ rad/pass, selects a curve in the m_b-M_b (mass-inverse coupling) plane
- One can compare this result with limits derived from pioneer measurements done at BNL by the BFRT collaboration (see PRD 47, 3707 (1993))

Photon-boson oscillations in Vacuo

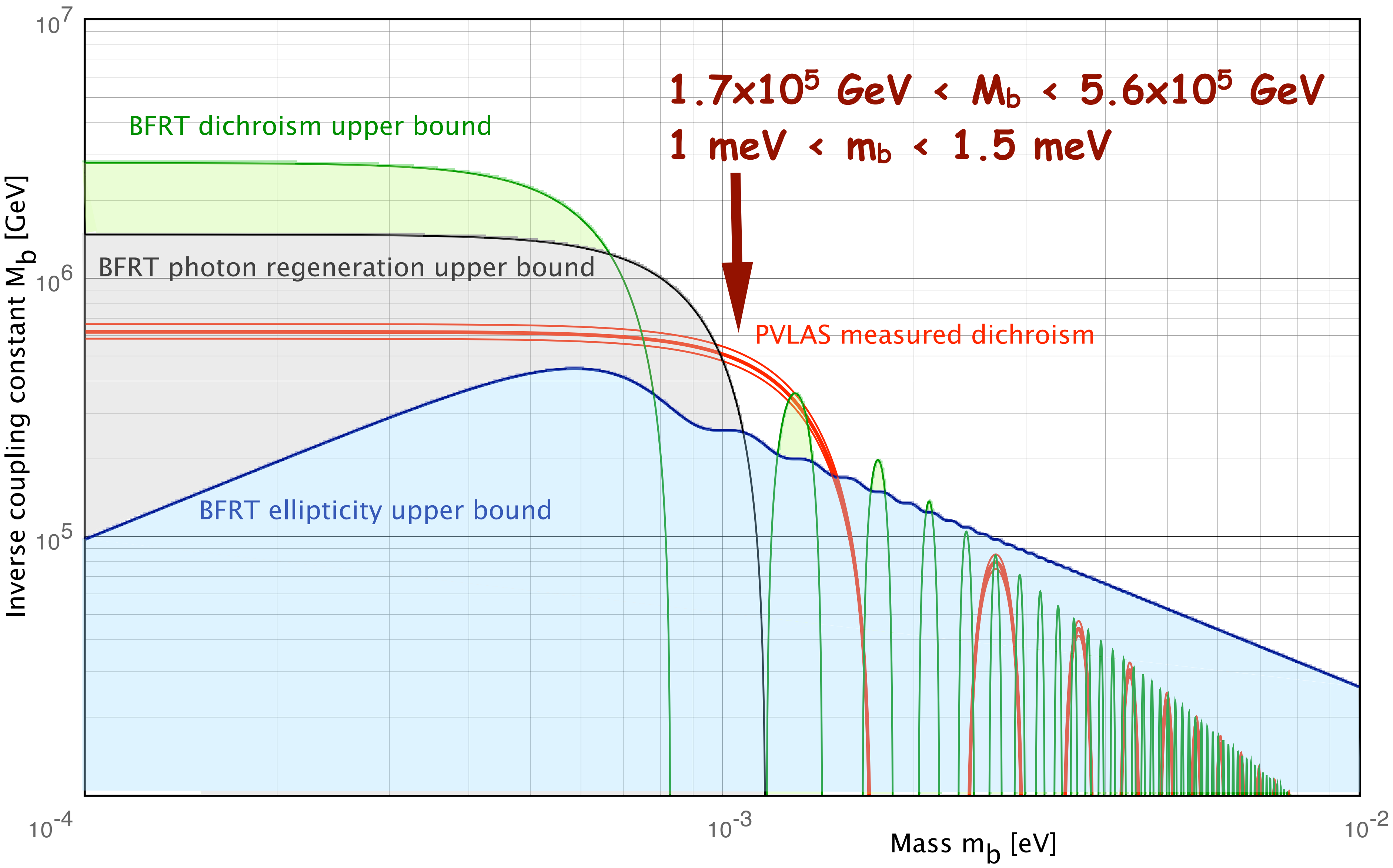
- Curve in the m_b-M_b plane corresponding to the measured rotation
- The allowed (m,M) pairs must lie on the curve



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

weighted avg. rotation = $(2.0\pm0.3)\times10^{-7}$ rad

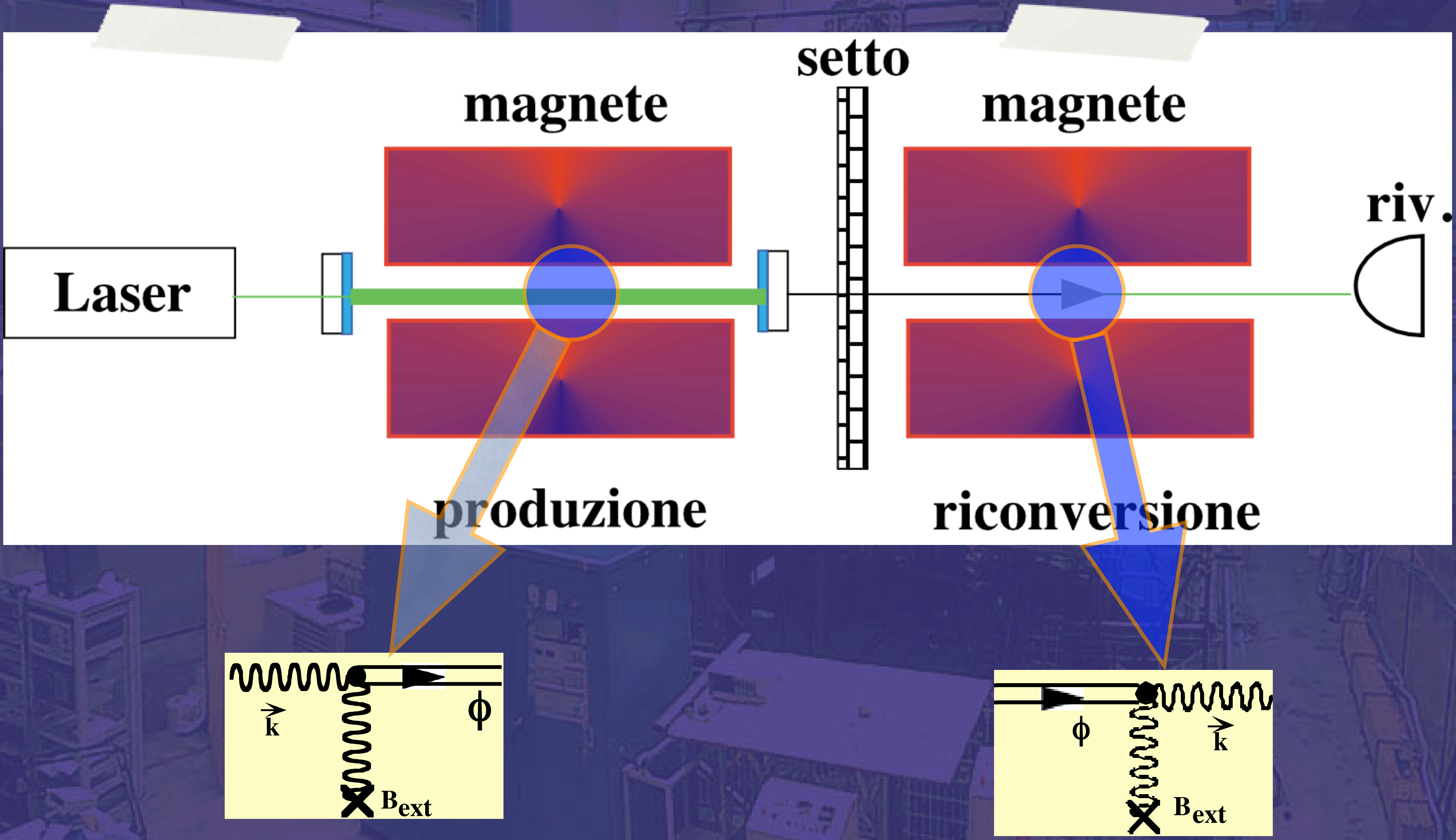
BFRT and PVLAS results on the m_b-M_b plane



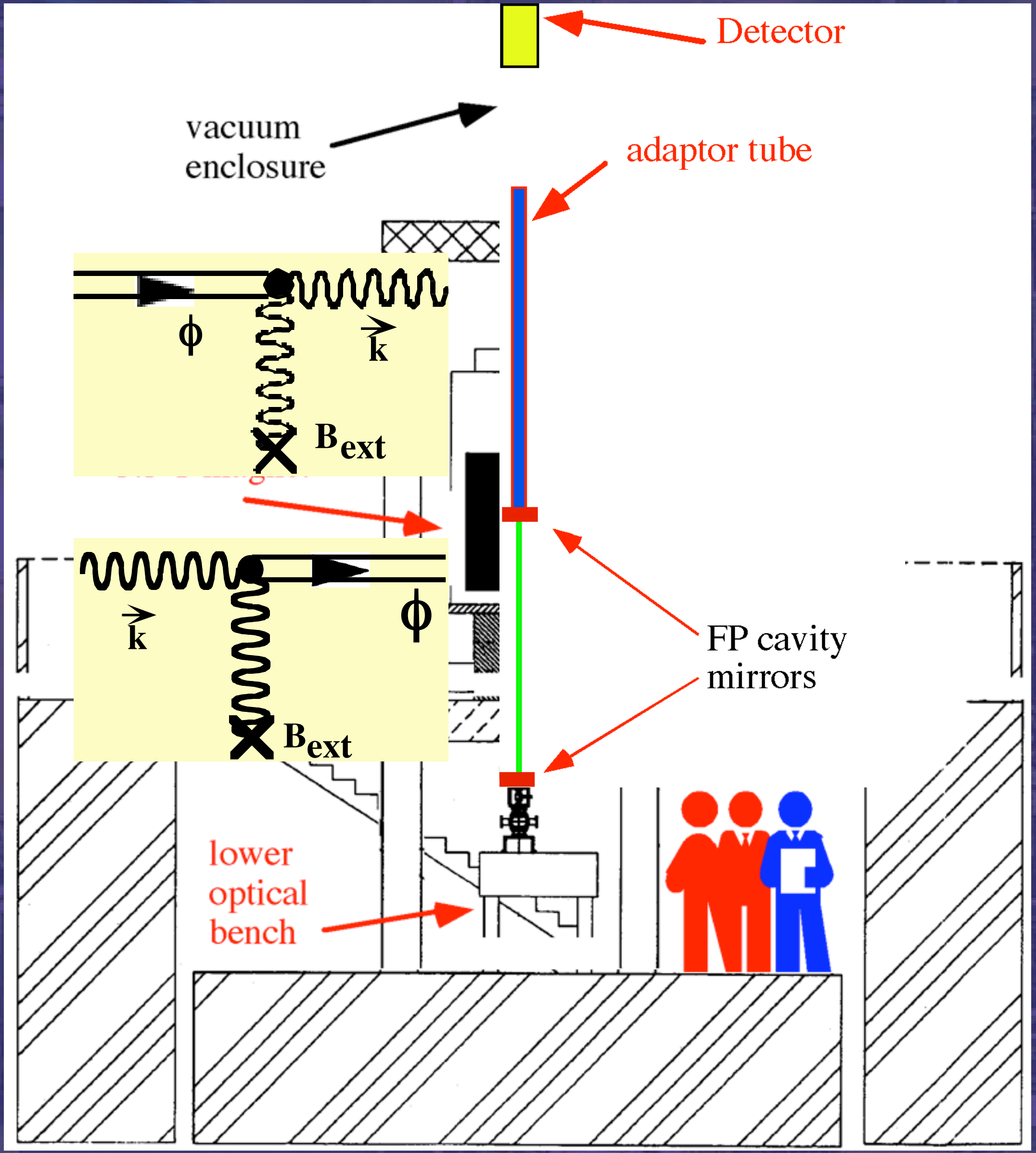
1.7×10^5 GeV < M_b < 5.6×10^5 GeV

1 meV < m_b < 1.5 meV

Photon regeneration scheme

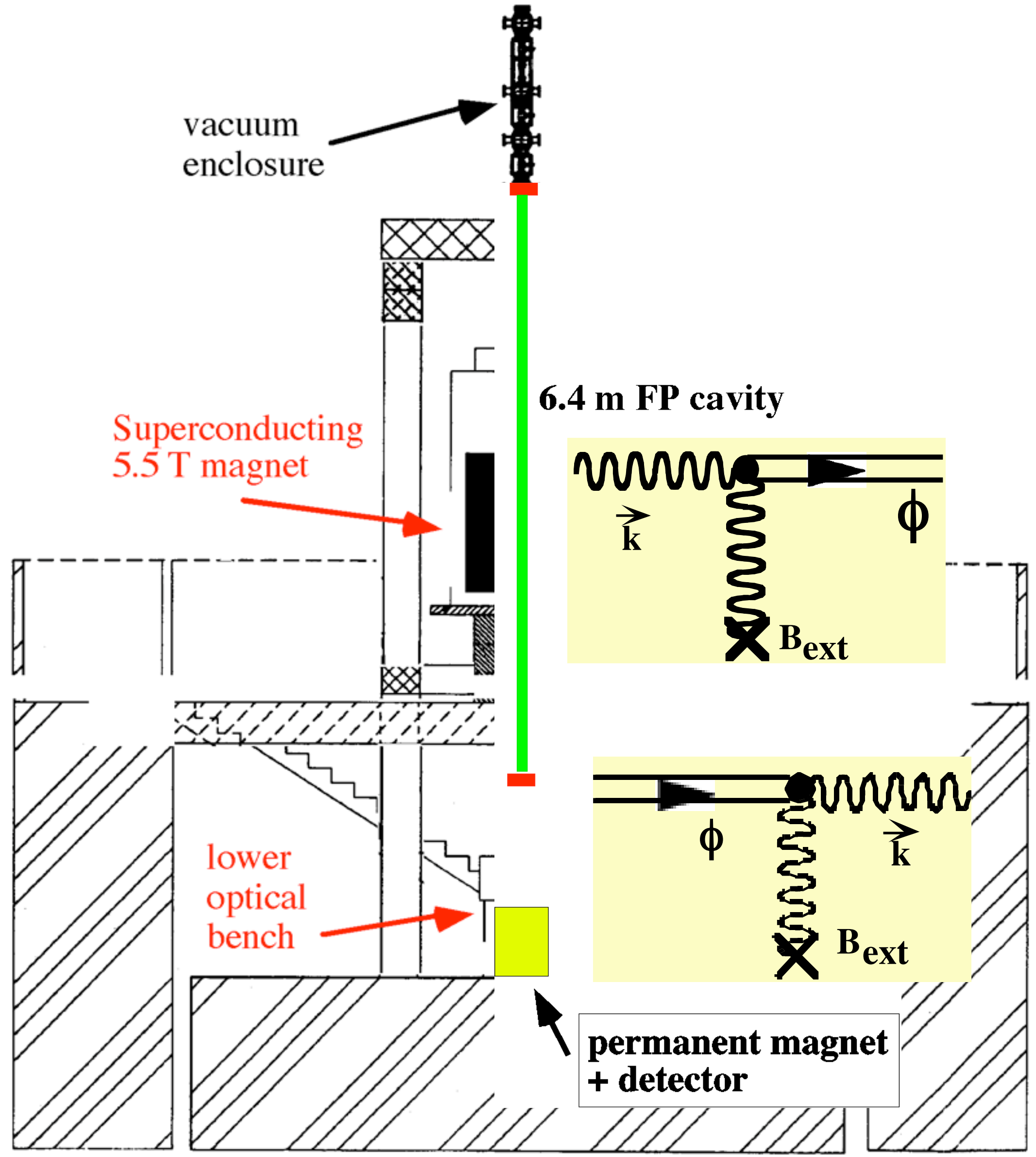


Photon regeneration test at PVLAS
"half magnet"



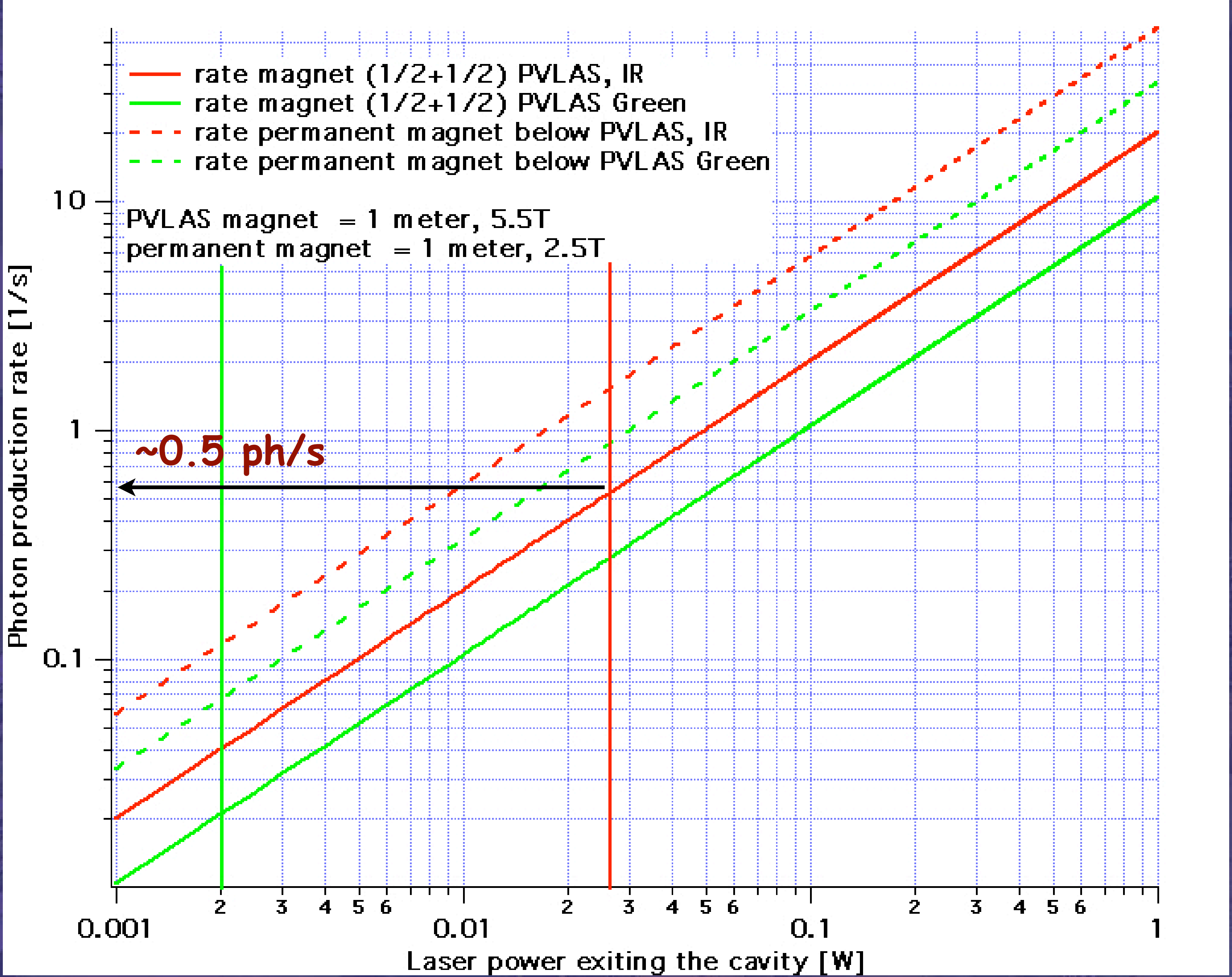
Upward propagating particles

Photon regeneration test at PVLAS permanent magnet

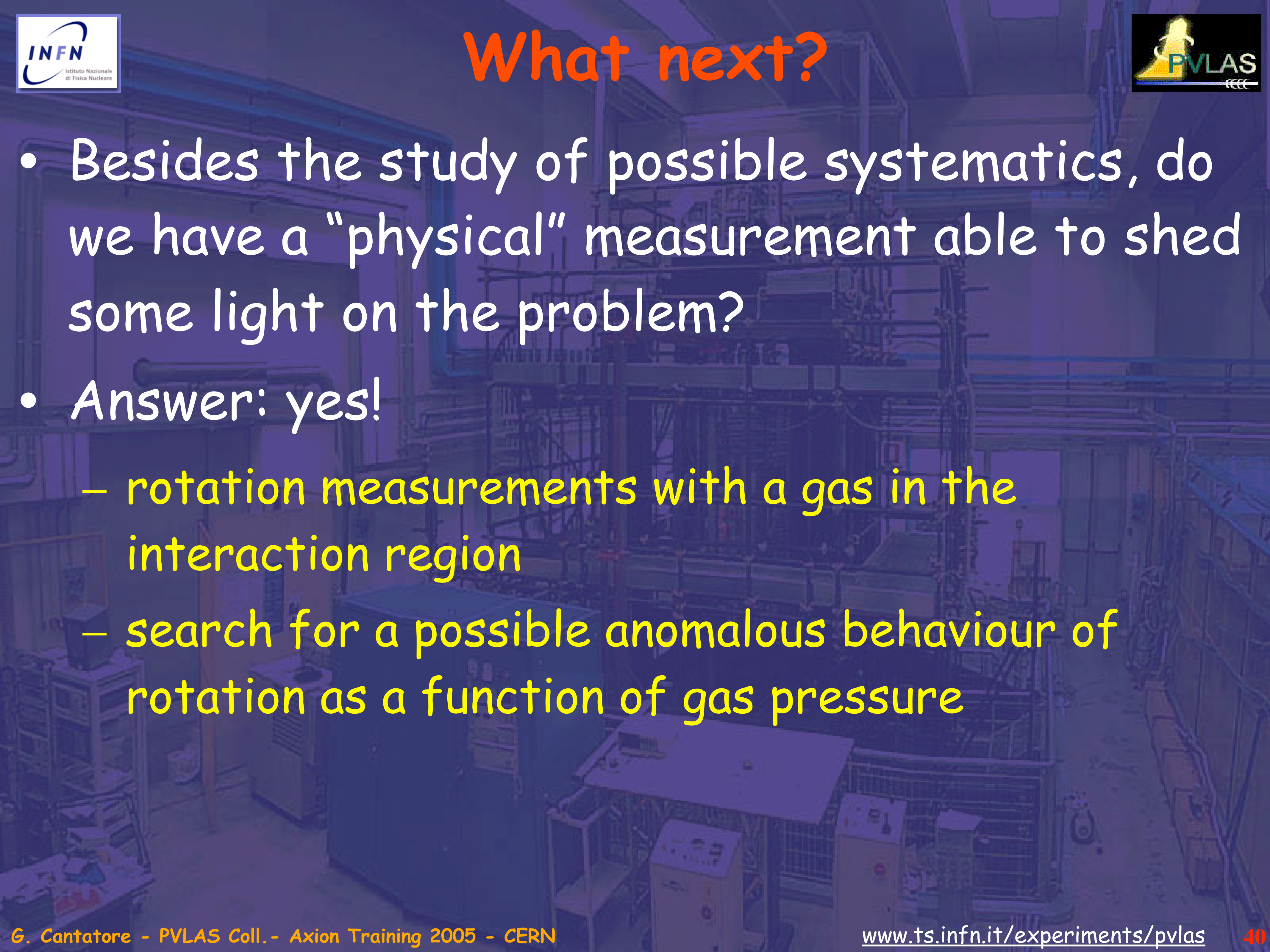


Downward propagating particles

Photon regeneration at PVLAS: rates



What next?



- Besides the study of possible systematics, do we have a "physical" measurement able to shed some light on the problem?
- Answer: yes!
  - rotation measurements with a gas in the interaction region
  - search for a possible anomalous behaviour of rotation as a function of gas pressure

Photon boson oscillation in a gaseous medium

The dichroism induced by real particle production is given here, where n_{gas} is the refractive index of the medium where the production takes place

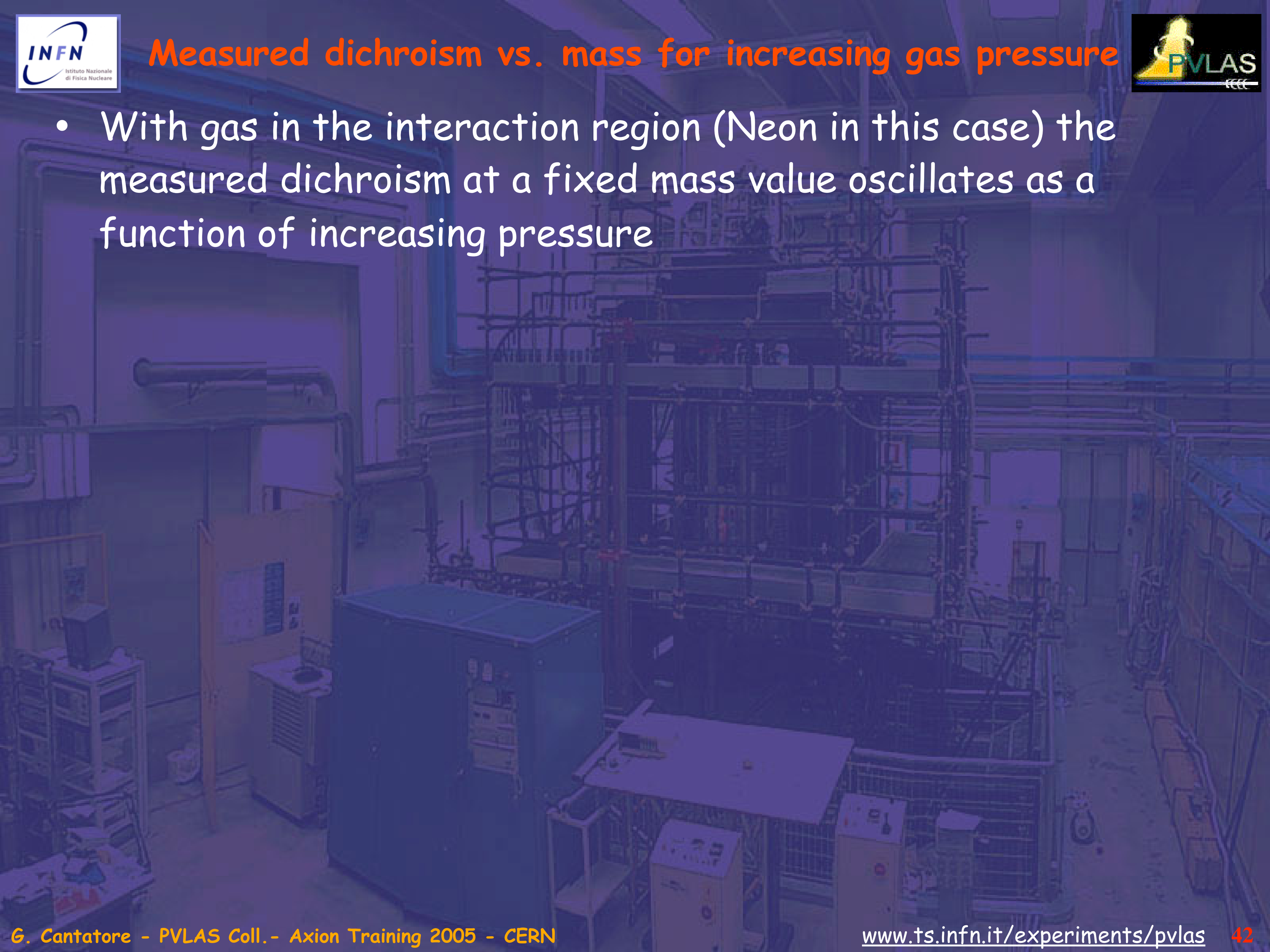
$$f_{mix}(p,M,m)=\frac{1}{4}\left(\frac{BL}{2M}\right)^2\left(\frac{\sin\left(\frac{\left(\frac{2p_{gas}\left(\boxed{n_{gas}}-1\right)\omega^2}{p_{atm}}+m^2\right)L}{4\omega}\right)}{\frac{\left(\frac{2p_{gas}\left(\boxed{n_{gas}}-1\right)\omega^2}{p_{atm}}+m^2\right)L}{4\omega}}\right)^2$$

In practice, one changes the optical path length along which the bosons and photons oscillate into one another

- For fixed parameters (including M), when a gas with increasing pressure is inserted in the interaction zone **the zeroes of the curve giving dichroism as a function of particle mass move towards smaller mass values**

- The observed dichroism shows a characteristic oscillation as a function of pressure

Measured dichroism vs. mass for increasing gas pressure



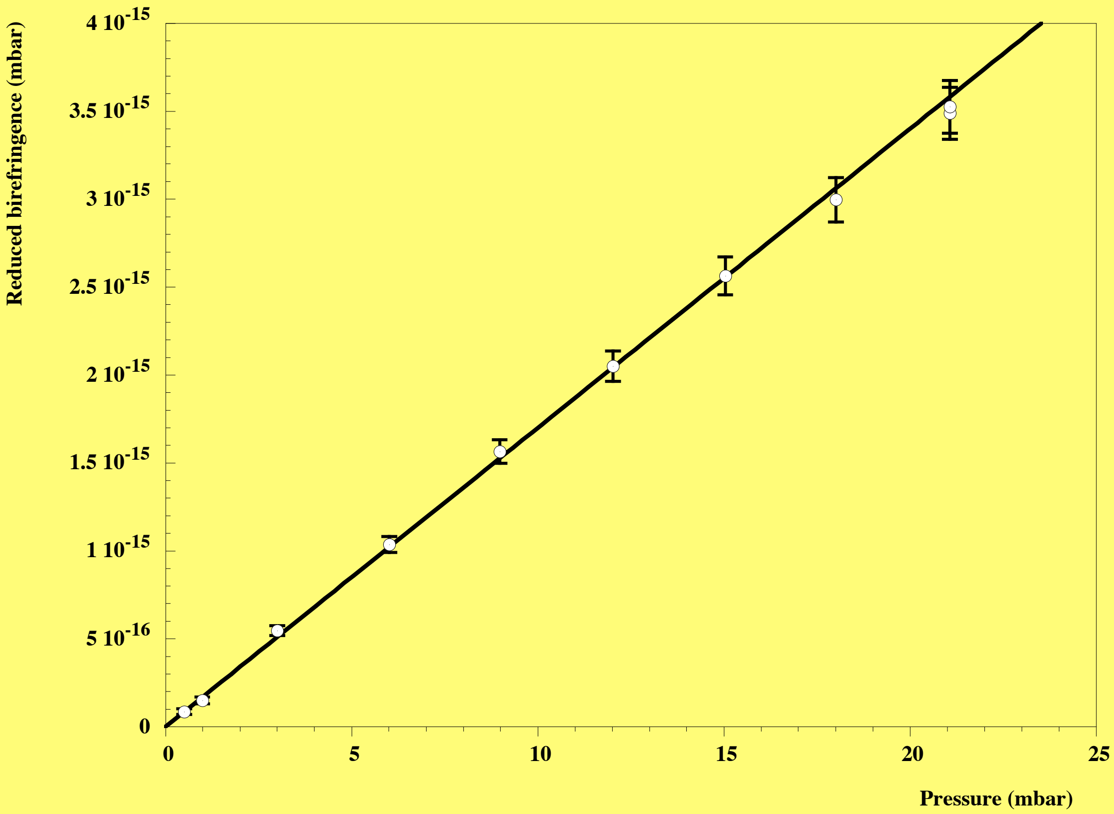
- With gas in the interaction region (Neon in this case) the measured dichroism at a fixed mass value oscillates as a function of increasing pressure

Gas measurement results (at 1064 nm)

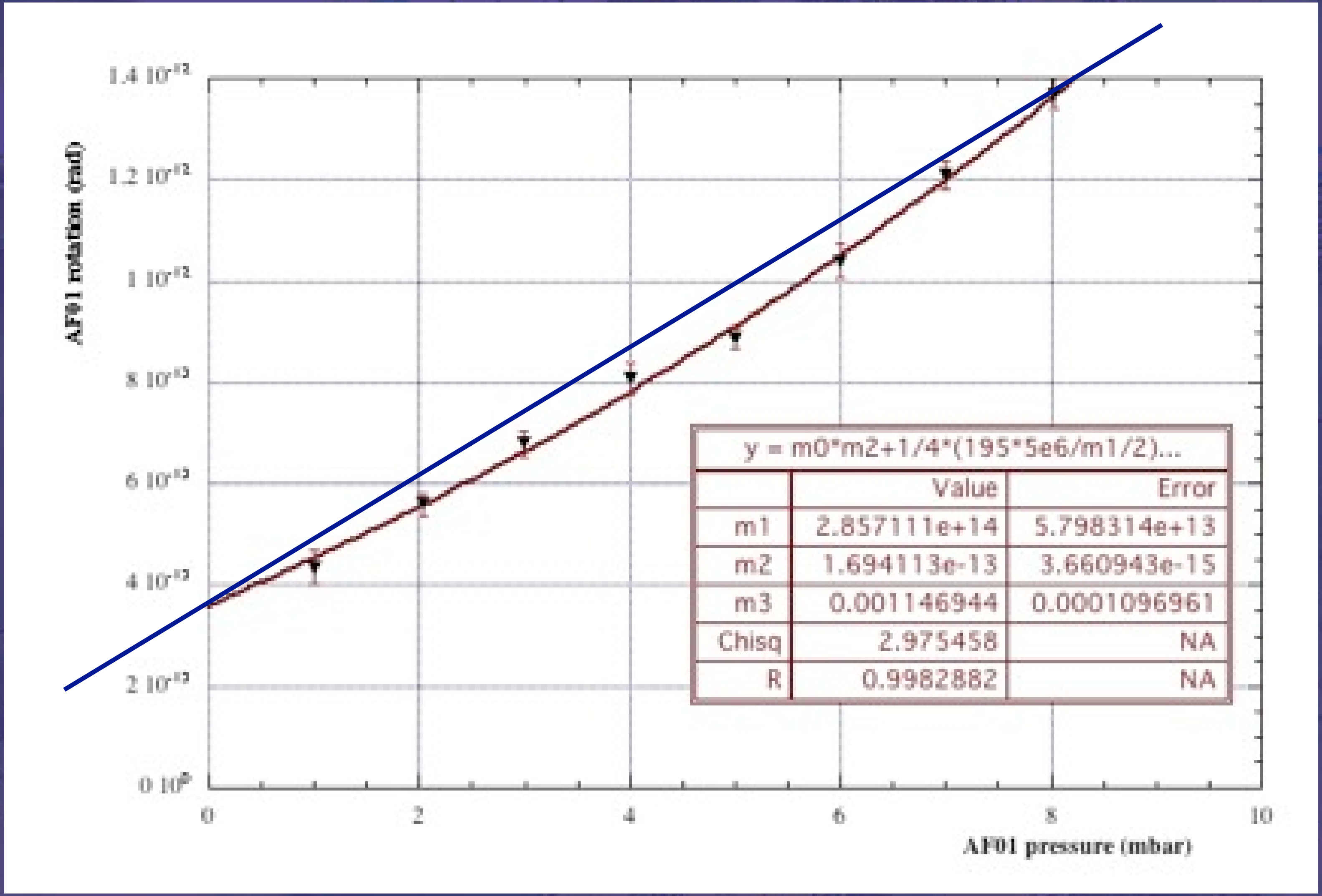
- Ellipticity vs. pressure for Ne and He
  - Cotton-Mouton effect (-> publication)
  - operation check of the apparatus
- Dichroism vs. pressure for Ne and He
  - observed anomalous behaviour as a function of pressure
    - extract oscillating part
    - compare with vacuum results

Cotton-Mouton effect in Ne

- Ellipticity is a linear function of pressure -> OK



Dichroism in Ne vs. pressure at 1064 nm



y = m0*m2+1/4*(195*5e6/m1/2)...

	Value	Error
m1	2.857111e+14	5.798314e+13
m2	1.694113e-13	3.660943e-15
m3	0.001146944	0.0001096961
Chisq	2.975458	NA
R	0.9982882	NA

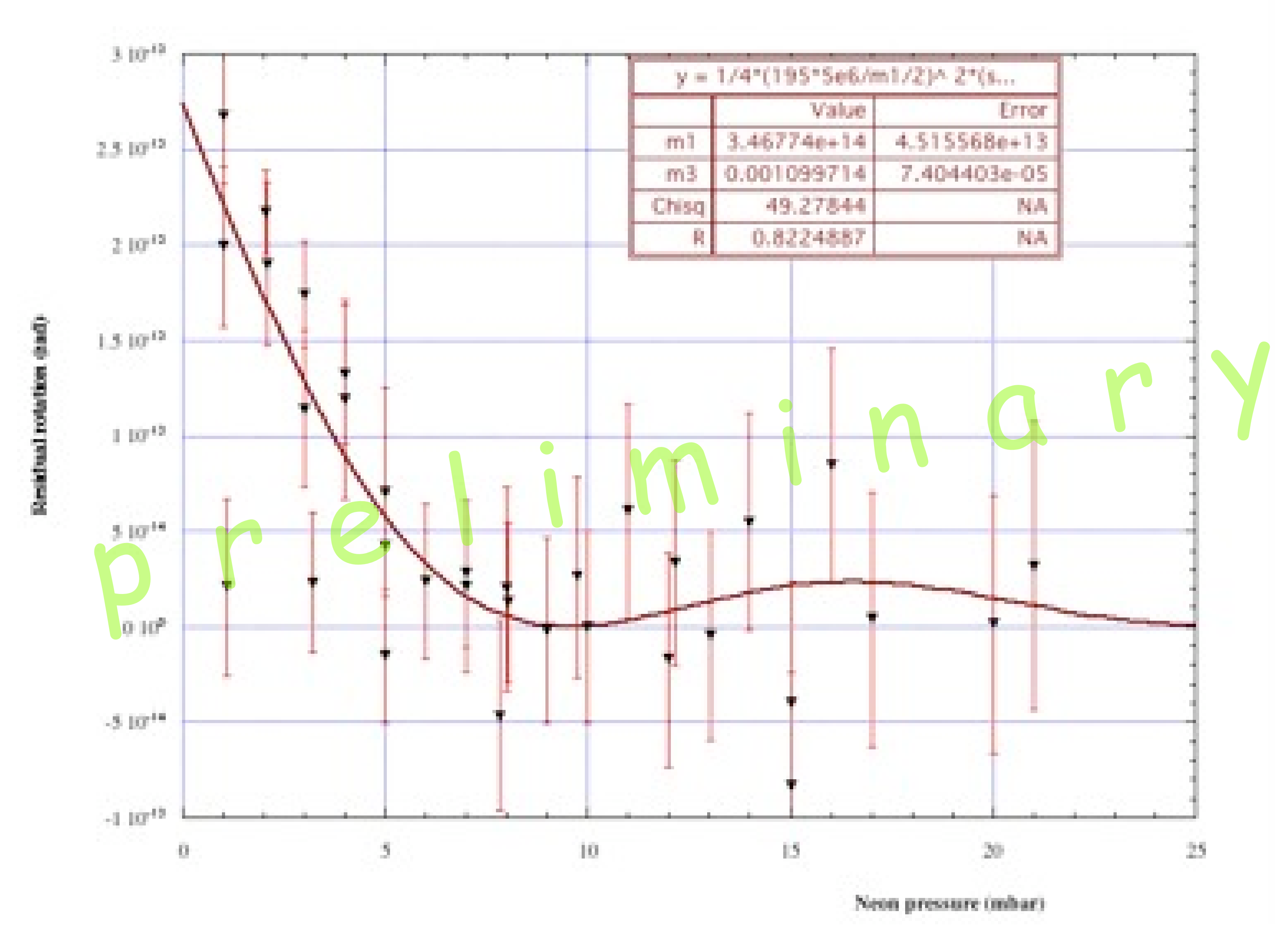
Anomalos dichroism in gas

- One observes a linear dependence on pressure plus a deviation (la “pancia”)
  - Linear part
    - gases do not exhibit an intrinsic magnetic rotation analogous to the Cotton-Mouton effect
    - the linear part is due to the magnetic birefringence of the gas which is transformed into a rotation by the cavity due to mirror intrinsic birefringence (calucaltions by G. Zavattini)
  - Deviation fron linear behaviour (la “pancia”)
    - data are fitted with the following function

$$f_{tot} = a + bp_{gas} + f_{mix}(p,M,m)$$

  - Values for m_b ed M_b are given by the fit. One can subtract the linear part to evidence the oscillation

Dichroism in Ne at 1064 nm - oscillating part



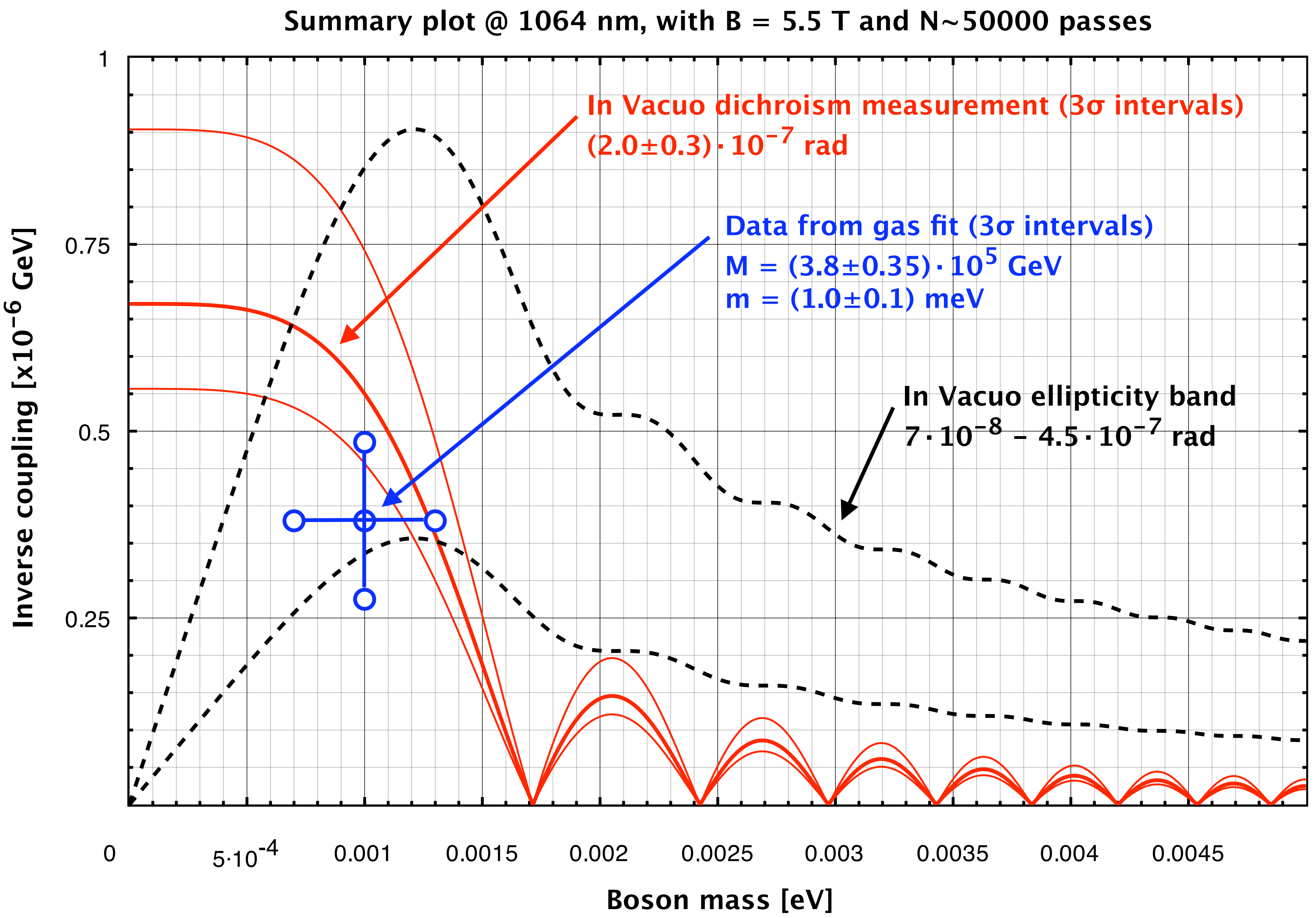
	Value	Error
m1	3.46774e+14	4.515568e+13
m3	0.001099714	7.404403e-05
Chisq	49.27844	NA
R	0.8224887	NA

What about ellipticity in Vacuo?

- Ellipticity measurements are more difficult than dichroism ones
  - almost everything is birefringent (but not dichroic)
  - birefringencies are never uniform
  - small beam movements induce variable birefringence
  - The "pysical" test available for dichroism, although present in principle, does not work
    - large "background" due to Cotton-Mouton effect
    - pressure dependence of boson induced ellitpicity is not as strong
- We consistently observe, however, an ellipticity signal in Vacuo with the magnetic field present. Phase and amplitude vary more than in the dichroism case and there is an ongoing analisys/measurement effort in order to undestand it
- As a very preliminary interval we can take (in rad/pass)

$$1.4\cdot10^{-12} < \psi < 9\cdot10^{-12}$$

Speculative global view



Conclusions

- PVLAS is attempting to directly measure the magneto-optical properties of the Vacuum element and is opening a new path in this field of physics
- Some of the processes accessible with these low-energy measurements (at the moment…)
  - photon-photon scattering
  - real or virtual particle production …
- <u>After years of efforts there are interesting results</u>:
  - observed a rotation signal in vacuum in the presence of a magnetic field
  - more to come ……