University of Ferrara

Esperimento PVLAS per la misura della birifrangenza magnetica del vuoto

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per la collaborazione PVLAS

"Hands holding the void"
Alberto Giacometti

PVLAS collaboration

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Summary

- Introduction:
  - Aim of the PVLAS experiment
  - Experimental technique
- PVLAS
  - Overview of published results
- Development phases
  - Improvements with respect to PVLAS-LNL
  - Ferrara Test apparatus
  - Final experiment

Classical Electromagnetism in vacuum

Classical vacuum has no structure.

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

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

$$L_{EM} = \frac{1}{2\mu_0}\left(\frac{\mathbf{E}^2}{c^2} - \mathbf{B}^2\right)$$

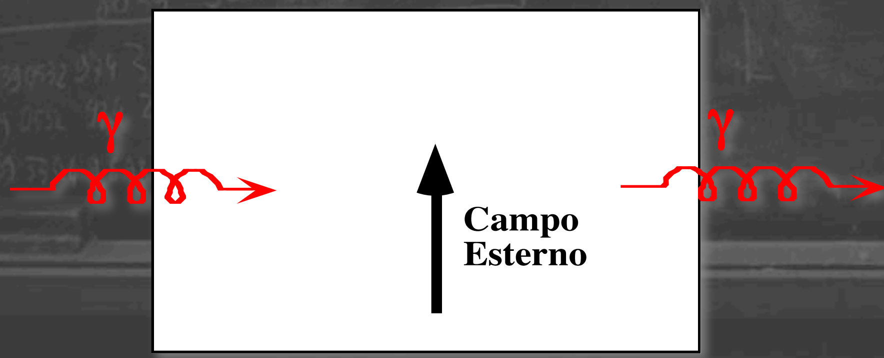
$$\vec{\mathbf{D}} = \frac{\partial L_{EM}}{\partial \vec{\mathbf{E}}}$$

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

$$\vec{\mathbf{D}} = \varepsilon_0 \vec{\mathbf{E}}; \qquad \mu_0 \vec{\mathbf{H}} = \vec{\mathbf{B}}$$

The superposition principle is valid

with $c = 1/\sqrt{(\varepsilon_0 \mu_0)}$

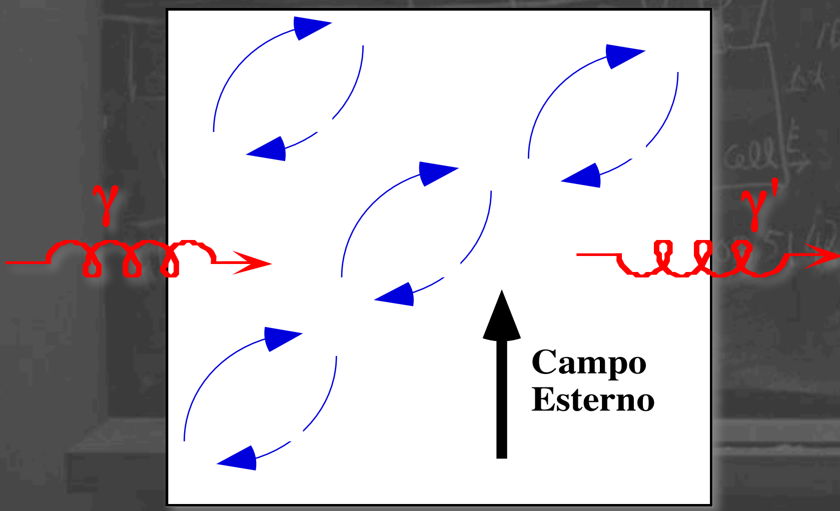


Heisenberg's Uncertainty Principle

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

Vacuum is the 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.

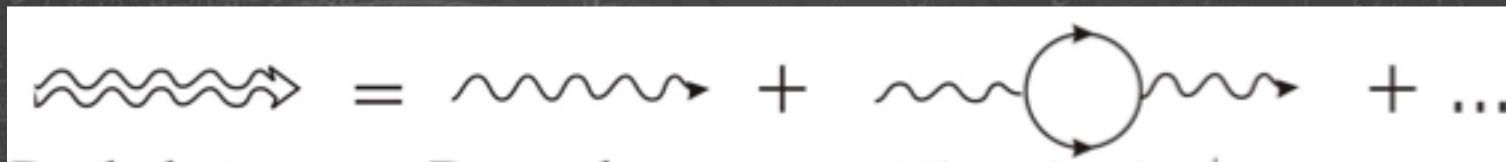


- QED tests in bound systems – Lamb shift
- QED tests in charged particles – (g-2)
- QED tests with photons is missing
- Macroscopically observable (small) non linear effects have been predicted since 1936 but have never been directly observed yet.

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 **polarization** and **external field**!

Euler-Heisenberg Effective Lagrangian

For fields much smaller than the critical field ($B \ll 4.4\cdot10^{9}$ T; $E \ll 1.3\cdot10^{18}$ V/m) one can write

W Heisenberg and H Euler, *Z. Phys.* **98**, 714 (1936)
H Euler, *Ann. Phys.* **26**, 398 (1936)

$$L = L_{em} + L_{HE} = \frac{1}{2\mu_0}\left(\frac{E^2}{c^2} - B^2\right) + \frac{A_e}{\mu_0}\left[\left(\frac{E^2}{c^2} - B^2\right)^2 + 7\left(\frac{\vec{E}}{c}\cdot\vec{B}\right)^2\right] + \dots$$

$$A_e = \frac{2}{45\mu_0}\left(\frac{\alpha^2 \lambda\!\!\!^{-}{}_e^3}{m_e c^2}\right) = 1.32\cdot10^{-24}\ \mathrm{T}^{-2}$$

CPT and Lorentz invariant => Coefficients determined by theory

Are neglected:

- α^3 and higher order terms
- virtual pairs with particles different from $e^+ e^-$

Induced Magnetic Birefringence of Vacuum

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

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

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

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

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

Index of refraction

Linearly polarized light passing through a transverse external magnetic field perpendicular to $\vec{k}$.

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

- $v \neq c$
- anisotropy

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

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

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

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

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

$\Delta n = 2.5\cdot 10^{-23}$ for $B = 2.5$ T

Cotton-Mouton Effect

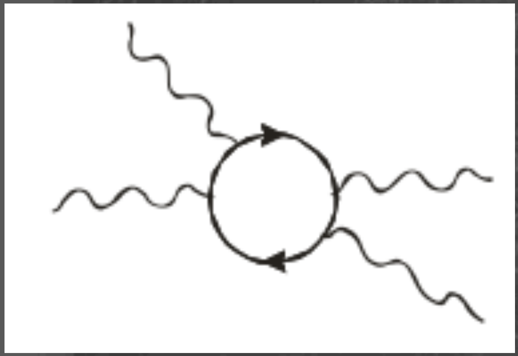
Vacuum behaves like a gas: Cotton-Mouton effect

Gas	CM constant (atm Tesla^{-2})	vacuum equiv. pressure (mbar)
N_2	$-2.45 \cdot 10^{-13}$	$1.6 \cdot 10^{-8}$
Ar	$6.8 \cdot 10^{-15}$	$5.8 \cdot 10^{-7}$
Kr	$9.9 \cdot 10^{-15}$	$4 \cdot 10^{-7}$
Ne	$2.8 \cdot 10^{-16}$	$1.4 \cdot 10^{-5}$
He	$1.8 \cdot 10^{-16}$	$2.2 \cdot 10^{-5}$
H_2	$8.5 \cdot 10^{-15}$	$4.7 \cdot 10^{-7}$

$$\Delta n_{CM} = \mathrm{CM} \frac{P}{P_{atm}} B_0^2$$

For He:
Vacuum is 'equivalent' to $5.8 \cdot 10^{11}$ He atoms/cm^3

Light-Light scattering



Very low energy photon-photon scattering is proportional to A_e^2.

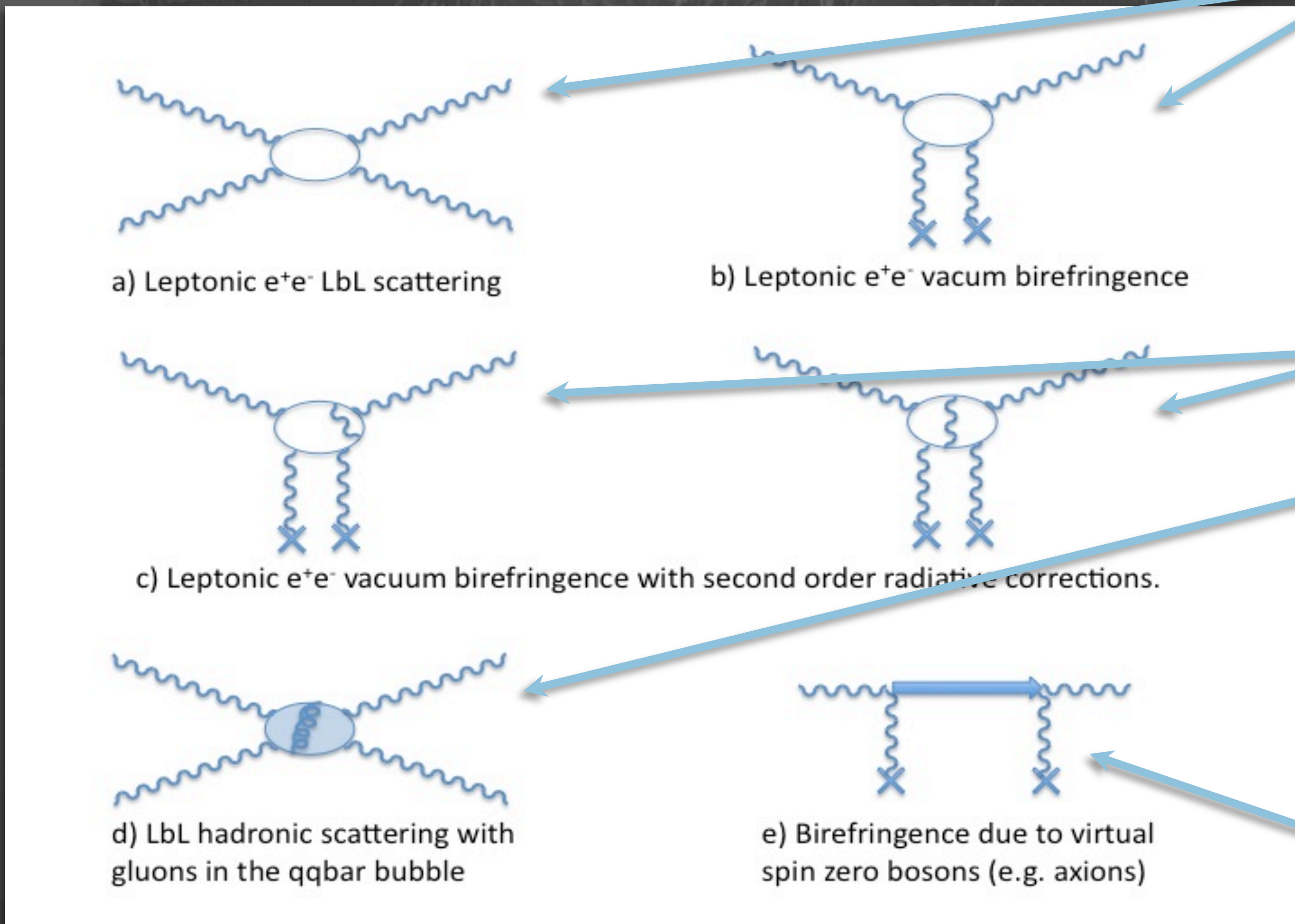
For non polarized light: $$\sigma_{\gamma\gamma}^{[*]} = \frac{973\mu_0^2}{20\pi}\frac{E_\gamma^6}{\hbar^4 c^4}A_e^2$$

From Euler-Heisenberg Lagrangian (S.I. units)

- For light at 1064 nm this predicts a value of $\sigma_{\gamma\gamma}$ = **1.8·10^{-65} cm^2**
- Experimentally Bernard et al.[**] have published $\sigma_{\gamma\gamma}$ < **1.5·10^{-48} cm^2**

*Duane et al., Phys Rev. D, vol 57 p. 2443 (1998)
**Bernard D. et al., The European Physical Journal D, vol 10, p. 141 (1999)

Summary of possibile 4 photon processes



- Described by the Euler-Heisenberg Lagrangian.

  Should be there.

  Also includes MCPs
- Radiatie correction 1.45%
- Hadronic contribution. Difficult to extract from indirect measurements. g-2 open problem.
- Contribution from hypothetical new particles coupling to two photons.

Aim of PVLAS

- We want to study the speed of light in the perturbed vacuum and therefore study changes in the refractive index

$$n_{vacuum} = 1 + \left(\delta n_r - i\kappa\right)_{field}$$

- Absolute changes of n_{vacuum} are too difficult to measure so we study anisotropies due to the perturbing field.
- Linear birefringence and linear dichroism
- Linear dichroism (photon splitting) results to be exceedingly small

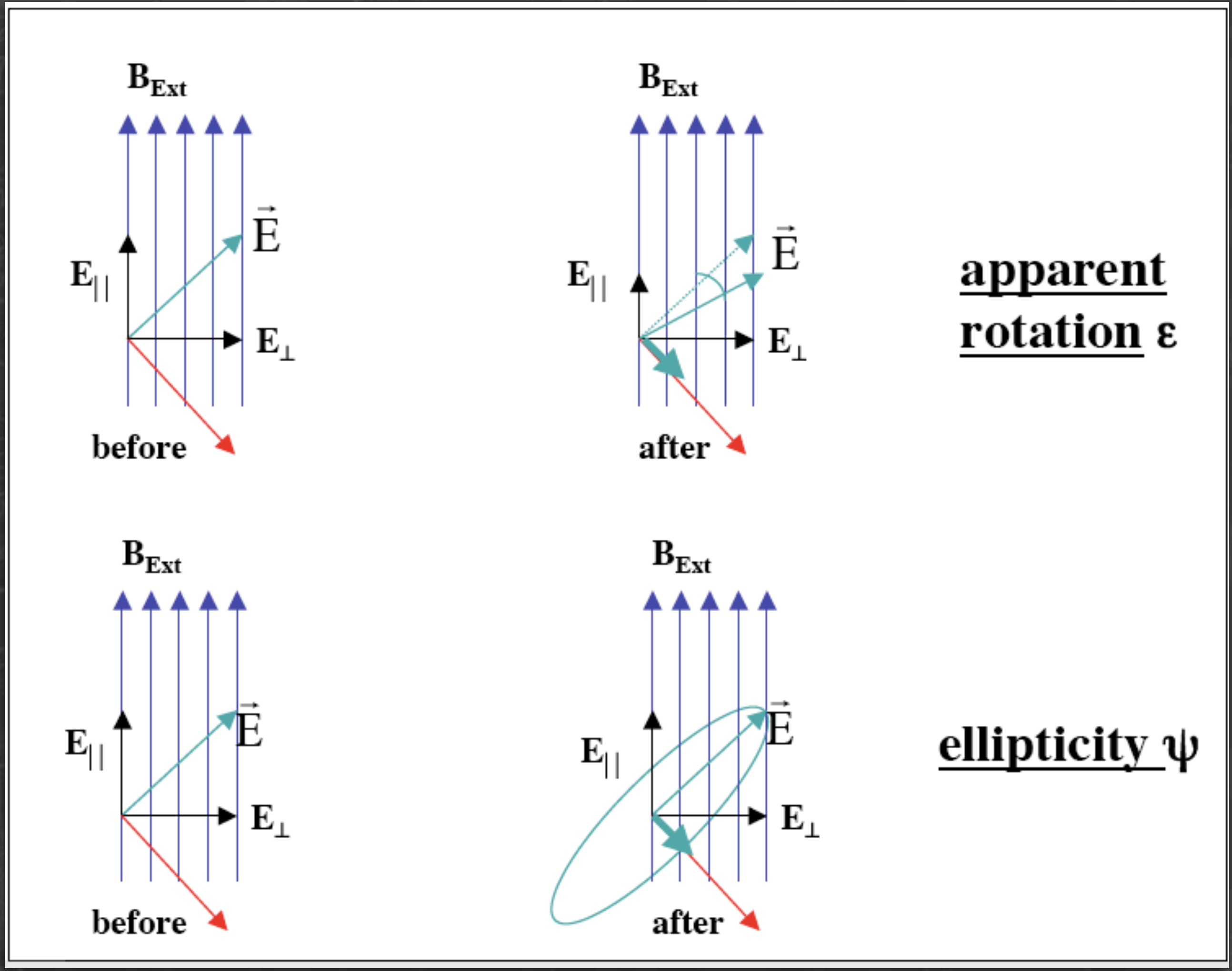
Propagation of the photon in an external field

Dichroism ΔK

• (Photon splitting)
• Real particle production

Birefringence Δn

• QED dispersion
• Virtual particle production
• MCPs
• Hadrons



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

Summing up

Experimental study of the quantum vacuum with:

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

Ellipticity

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

Key Ingredients

- high magnetic field
  superconducting dipole magnet or high field permanent magnet
- long optical path
  delay line cavity or very-high Q Fabry-Perot resonator
- ellipsometer with heterodyne detection for best sensitivity
  periodic change of field amplitude/direction for signal modulation

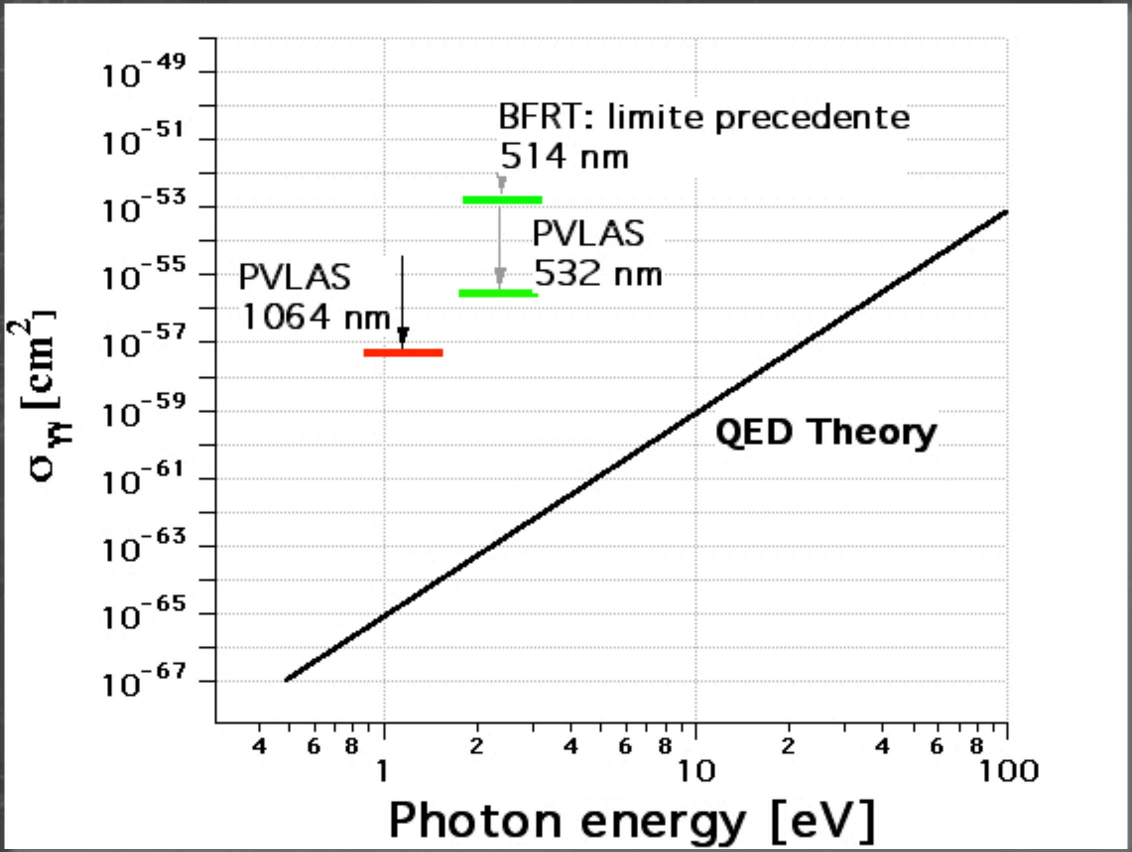
Present published results - QED

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

$\Delta n_{1064} < 4.6\ 10^{-20}$ @ 1064 nm

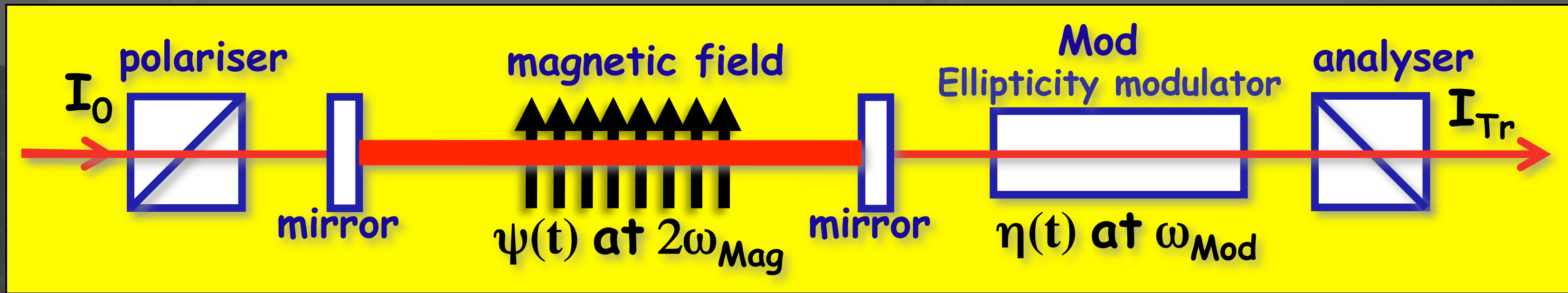
$\Delta n_{532} < 1.0\ 10^{-19}$ @ 532 nm

$A_e^{(FE)} < 2.9\ 10^{-21}\ T^{-2}$
$A_e^{(QED)} = 1.3\ 10^{-24}\ T^{-2}$



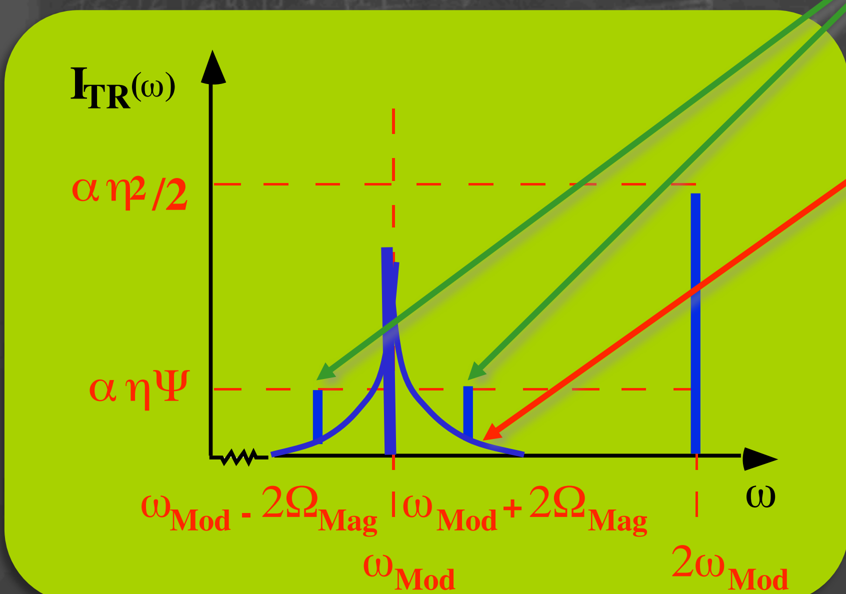
Bregant et al, PRD 78, 032006 (2008)

$\sigma_{\gamma\gamma} < 9.5\ 10^{-59}\ cm^2$ @ 1064 nm
$\sigma_{\gamma\gamma} < 2.7\ 10^{-56}\ cm^2$ @ 532 nm



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

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



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

Limitations of the LNL apparatus

- Superconducting magnets produce **stray field** when operated at high fields (saturated iron)

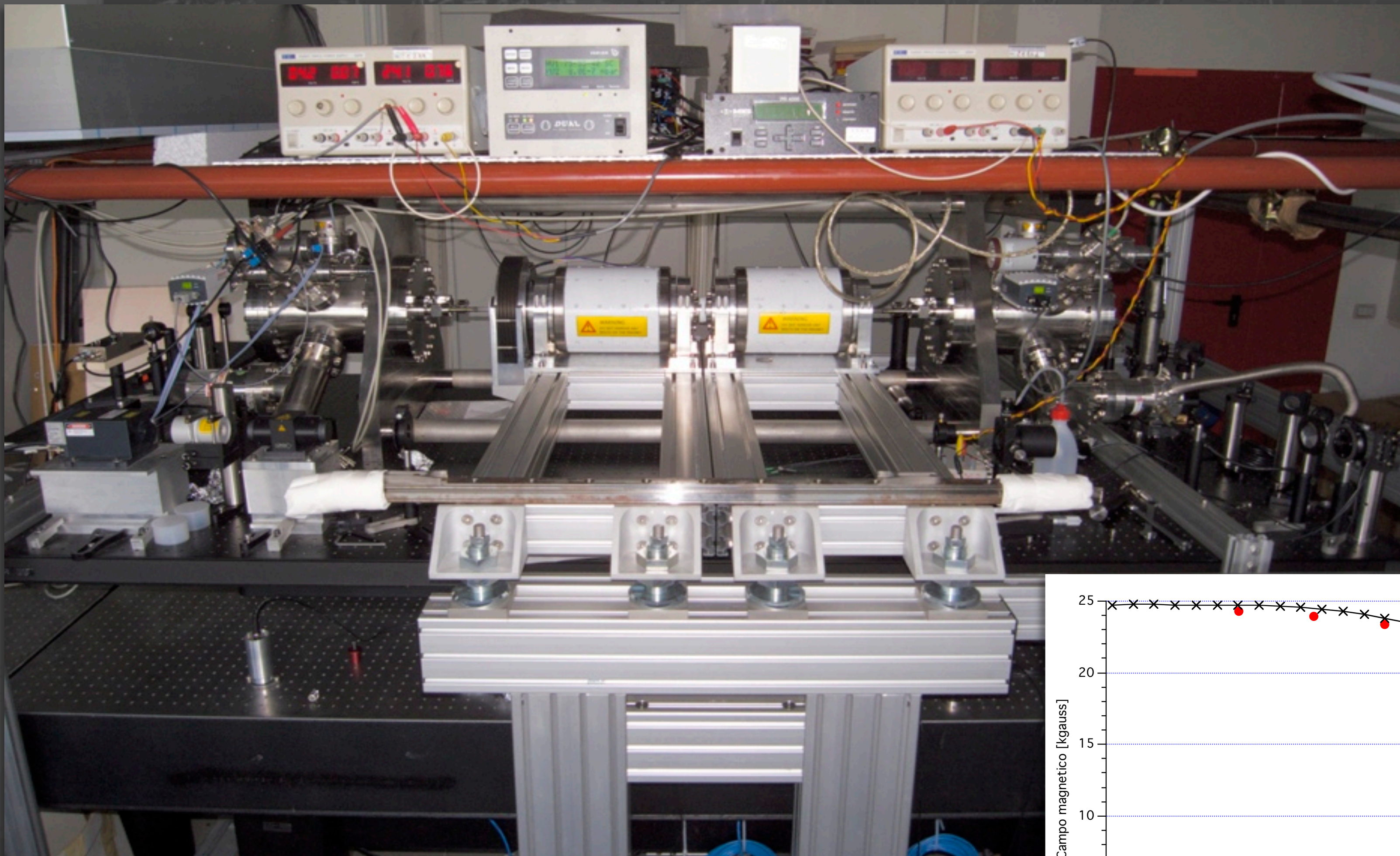
- **Running time limited** due to liquid helium consuption

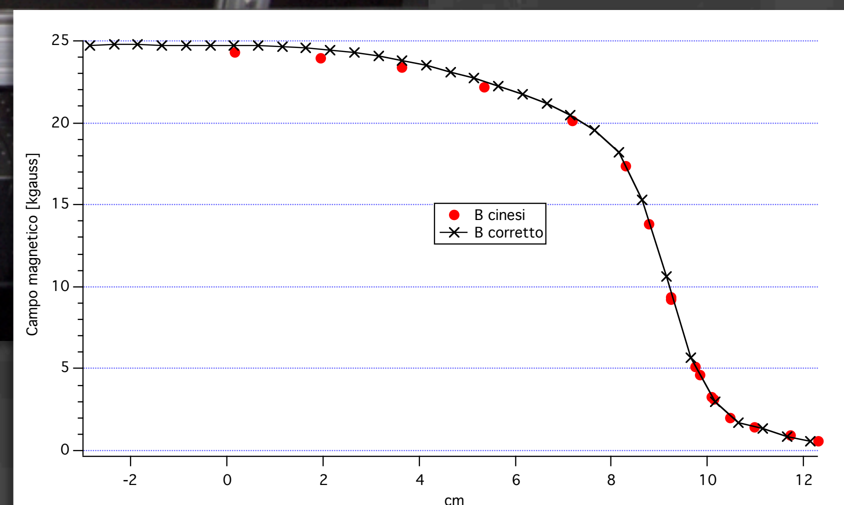
- Observed **correlation between seismic noise and ellipticity noise.** The Legnaro apparatus is large and therefore difficult to isolate seismically.

- **No zero measurement possibile** with field turned ON.

Test apparatus in Ferrara

Two permanent magnets allow a zero measurement





Fabry Perot

Ferrara test apparatus - High finesse successful

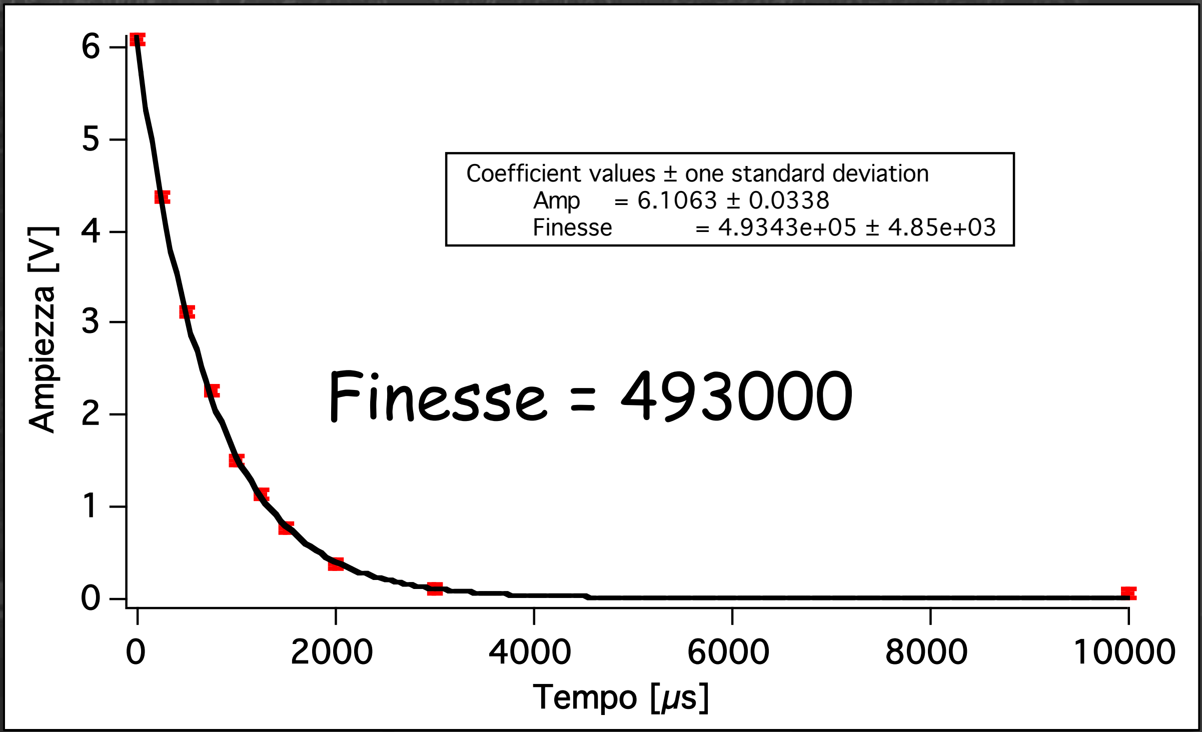
The **Fabry-Perot cavity** is a resonant optical cavity that **increases the effective optical path**. It is composed of **two mirrors placed at a separation *d*** which is an integer multiple of the light half wavelength. To obtain this condition a laser is phase locked to the cavity using a feedback circuit.

Amplification factor

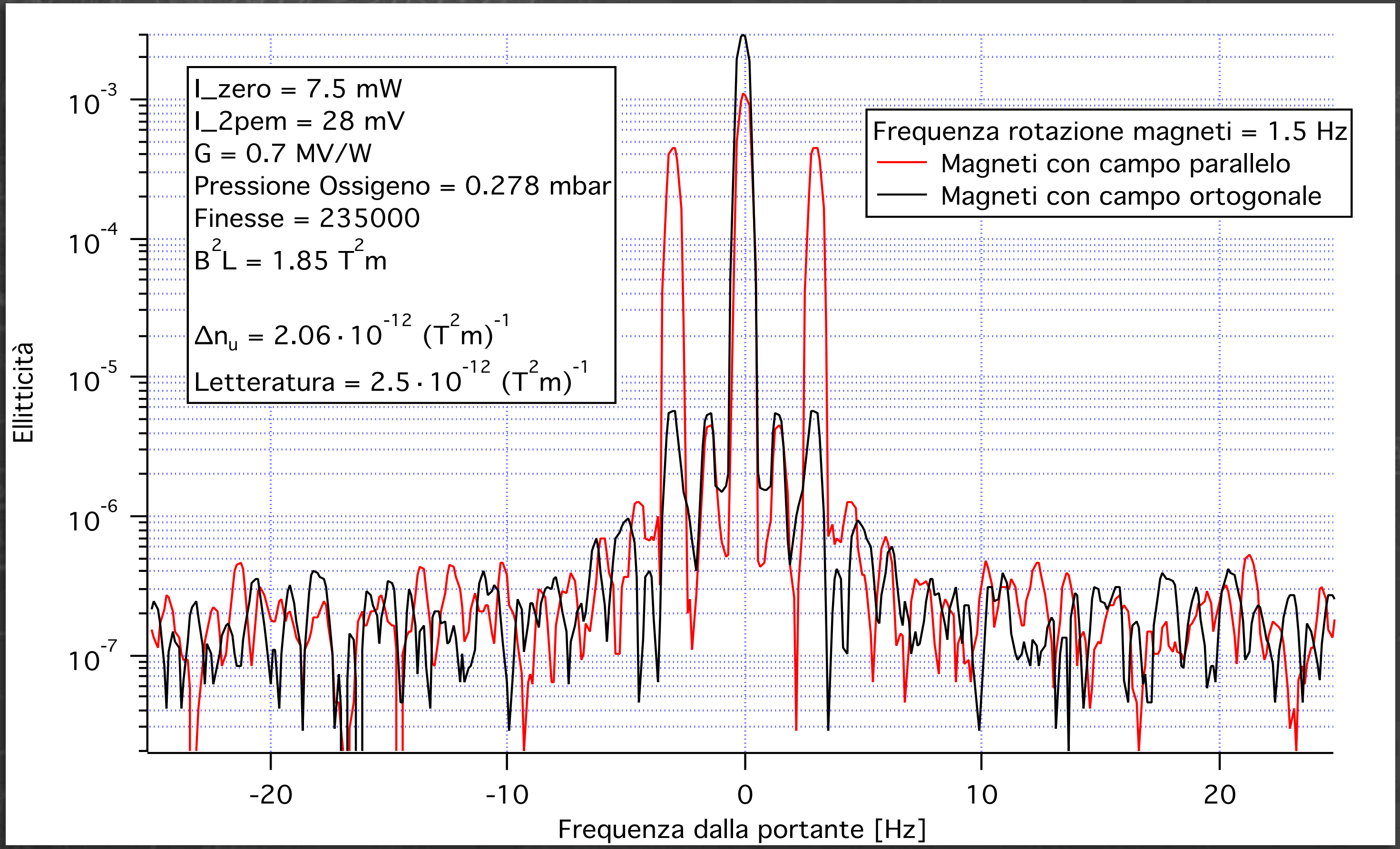
$$N = \frac{2F}{\pi}$$

Finesse

$$F = \frac{\pi c \tau}{d}$$



Two magnet configuration



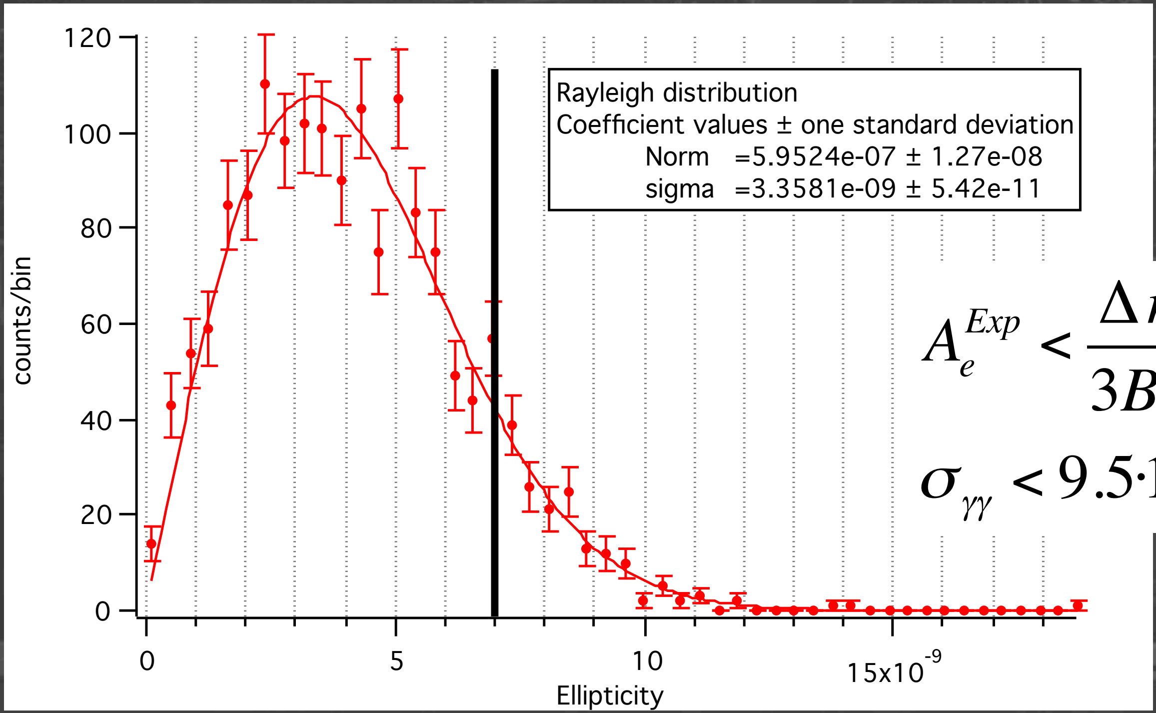
In red, magnets at 0 degrees
In black, magnets at 90 degrees

With a finesse = 245000 and with the magnets perpendicular to each other we demonstrated a reduction of more than a factor 80 of the Cotton Mouton signal

Rotating vs non rotating magnets

Rotating Magnets
No peak
Sensitivity = $3.0\cdot10^{-7}$ 1/√Hz
Δn sensitivity = $1.8\cdot10^{-18}$ 1/√Hz
T = 2.3 hours

Non rotating Magnets
No peak
Sensitivity = $3.3\cdot10^{-7}$ 1/√Hz
Δn sensitivity = $1.8\cdot10^{-18}$ 1/√Hz
T = 4.8 hours



$$A_e^{Exp} < \frac{\Delta n}{3B^2} = \frac{\sigma\lambda}{2FL3B^2} = 2.9\cdot10^{-21}\ \mathrm{T}^{-2}$$

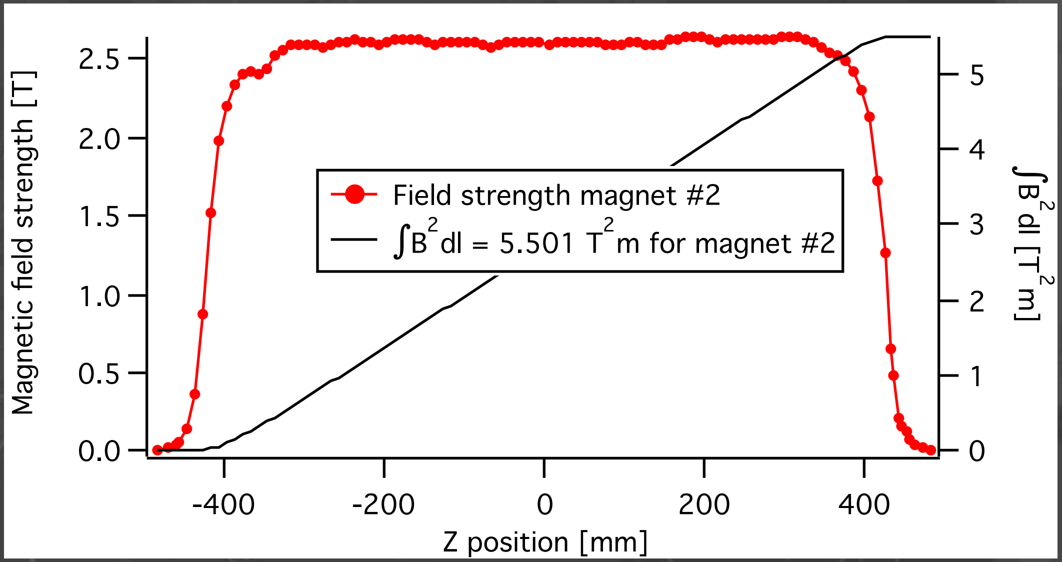
$$\sigma_{\gamma\gamma} < 9.5\cdot10^{-59}\ \mathrm{cm}^2\ @\ 1064\ \mathrm{nm}$$

Ellipticity histograms around 2 Ω_{Mag}

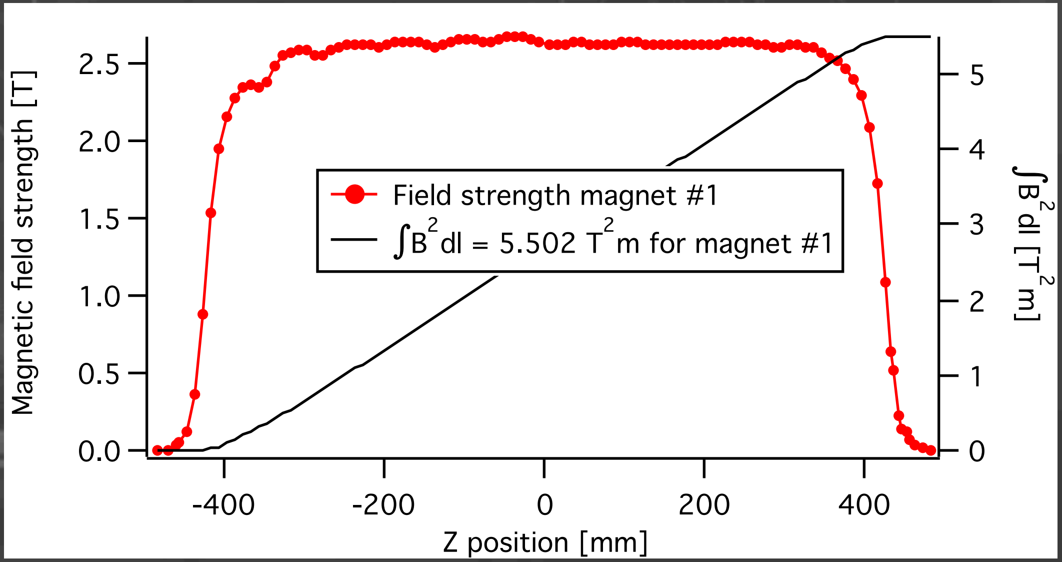
New granite optical bench

Installation in Ferrara clean room

Magnets

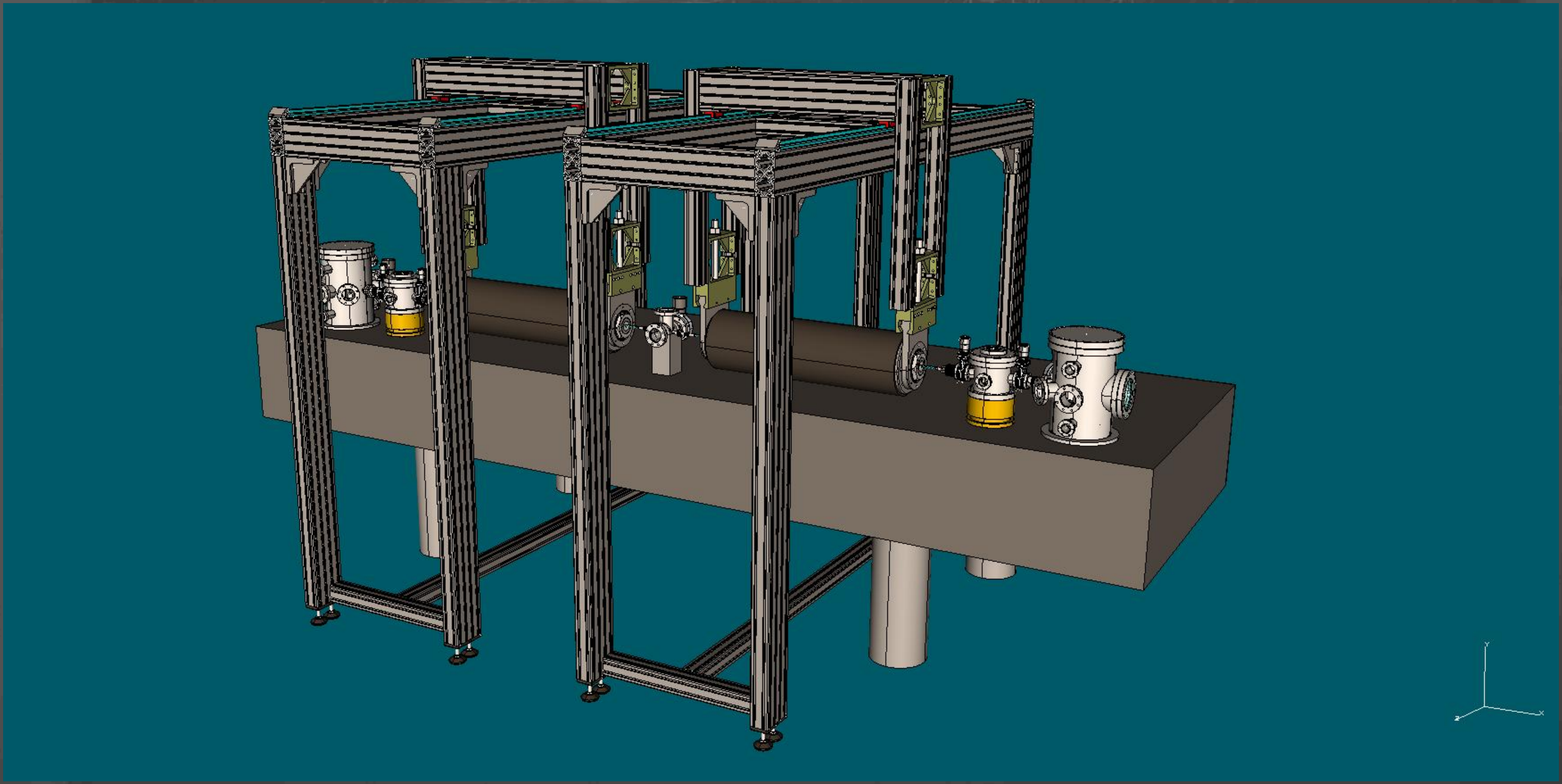


Field strength magnet #2
∫B²dl = 5.501 T²m for magnet #2
Magnetic field strength [T]
∫B²dl [T²m]
Z position [mm]
2.5
2.0
1.5
1.0
0.5
0.0
-400
-200
0
200
400
5
4
3
2
1
0

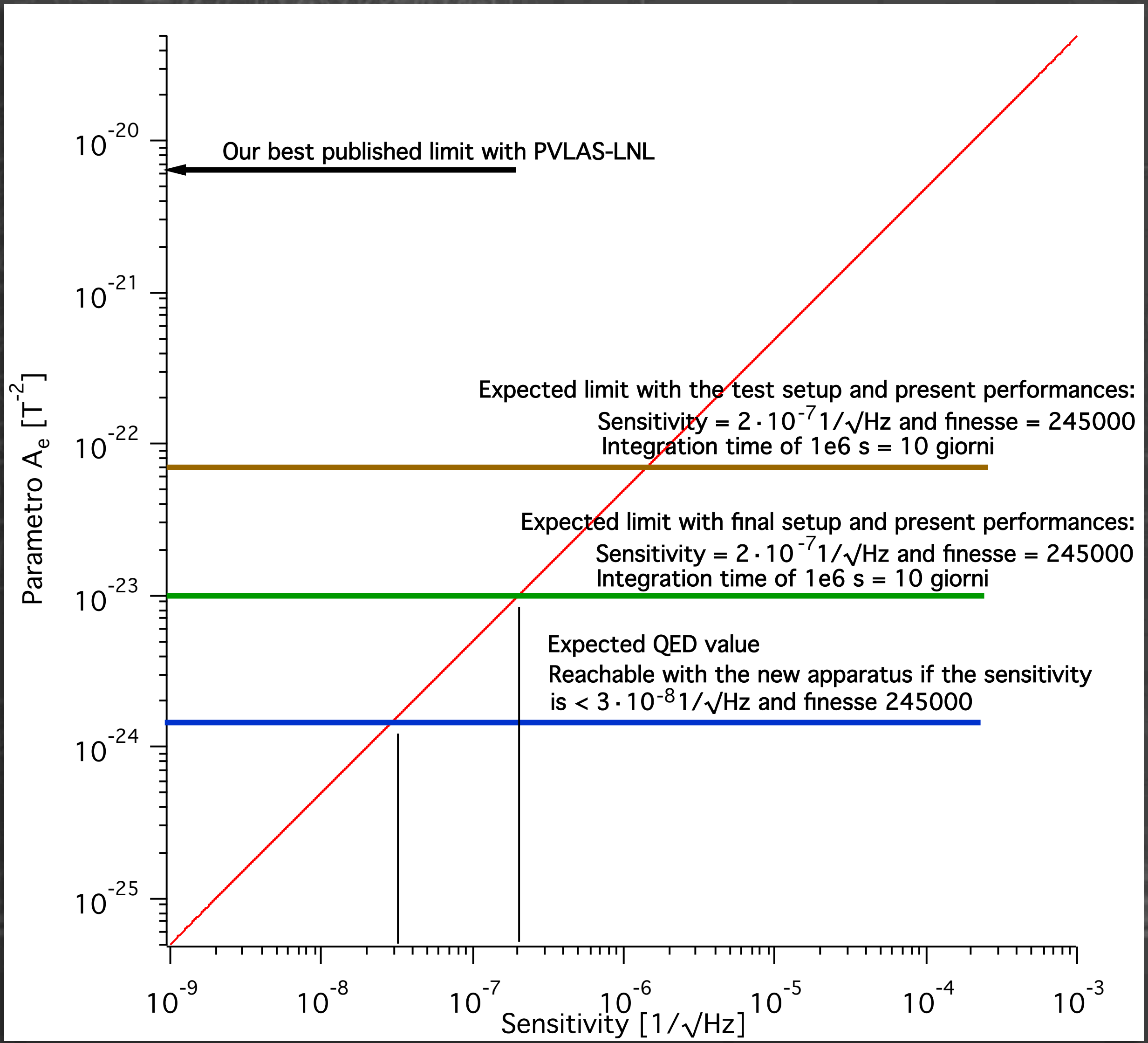


Field strength magnet #1
∫B²dl = 5.502 T²m for magnet #1
Magnetic field strength [T]
∫B²dl [T²m]
Z position [mm]
2.5
2.0
1.5
1.0
0.5
0.0
-400
-200
0
200
400
5
4
3
2
1
0

Mechanical Design



Parameter space



Other world efforts

Q&A experiment - Taiwan

Sensibilità 10^{-6} $1/\sqrt{Hz}$, con F = 30000, campo 2.3 T, L = 180 cm, 1 magnete. Banchi ottici separati. Ellitticità = $2 \cdot 10^{-12}$.

$T_{QED} = 2 \cdot 10^{11}$ s = 6500 anni

BMV experiment - Toulouse

Sensibilità in $\Delta n \approx 5 \cdot 10^{-20}$ $1/\sqrt{Hz}$ con F = 529000, campo impulsato qualche ≈ 3 ms, 115 T^2m, 1 colpo/12 min => sensibilità efficace = $1.7 \cdot 10^{-17}$ $1/\sqrt{Hz}$. Ellitticità = $1 \cdot 10^{-10}$

$T_{QED} = 1.8 \cdot 10^{13}$ s = $5 \cdot 10^{5}$ anni

OSQAR experiment - CERN

Sensibilità = ??? Magnete di LHC lungo 15 m, 10 T, Finesse ≈ 1000, banchi ottici separati. Magnete non modulabile. Ellitticità = $1 \cdot 10^{-11}$. Assumendo sensibilità = 10^{-7} $1/\sqrt{Hz}$. A che frequenza? Presumibilmente mHz .... Difficilmente ottenibile

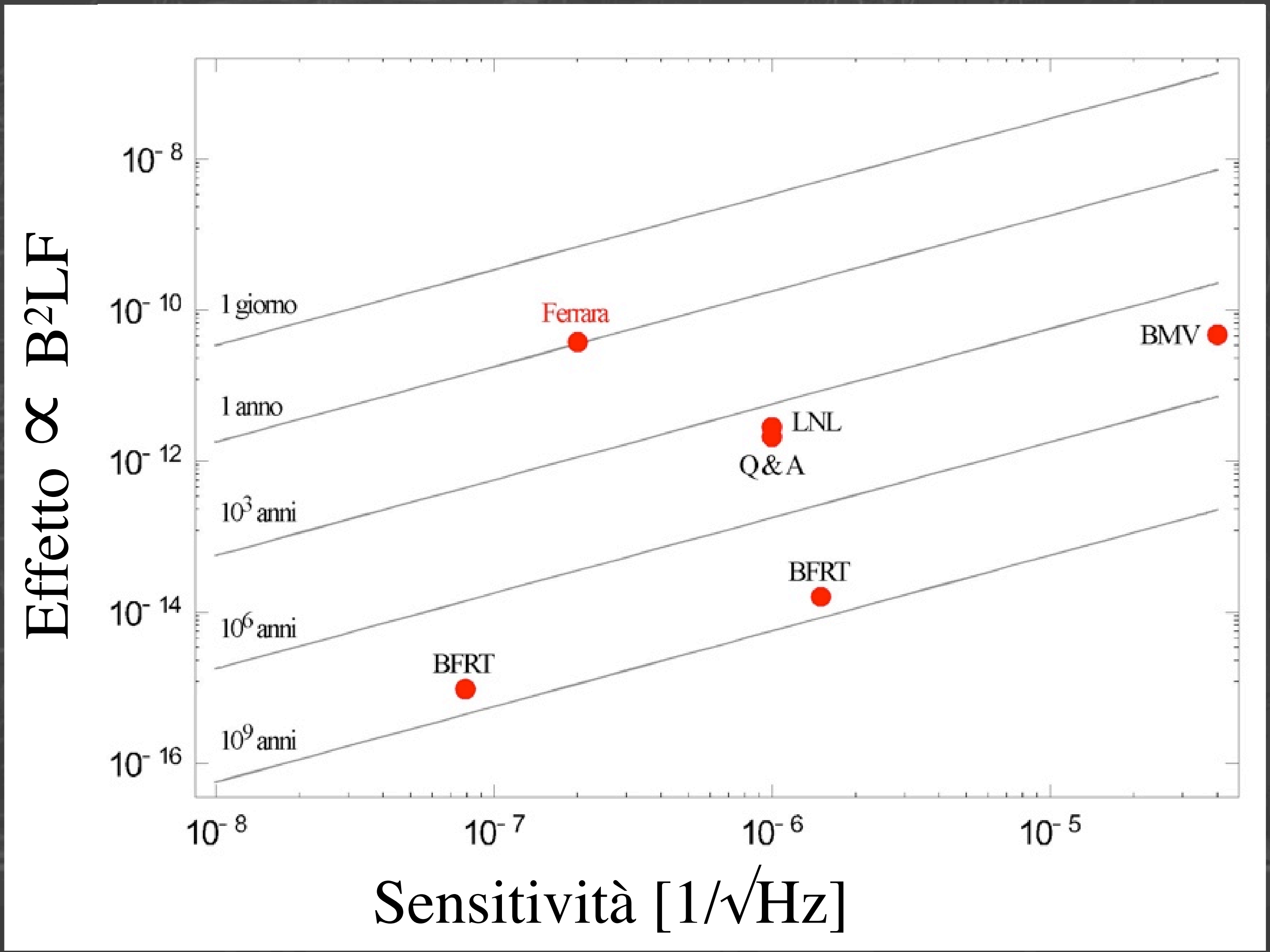
$T_{QED} = 10^{8}$ s = 3.2 anni ???

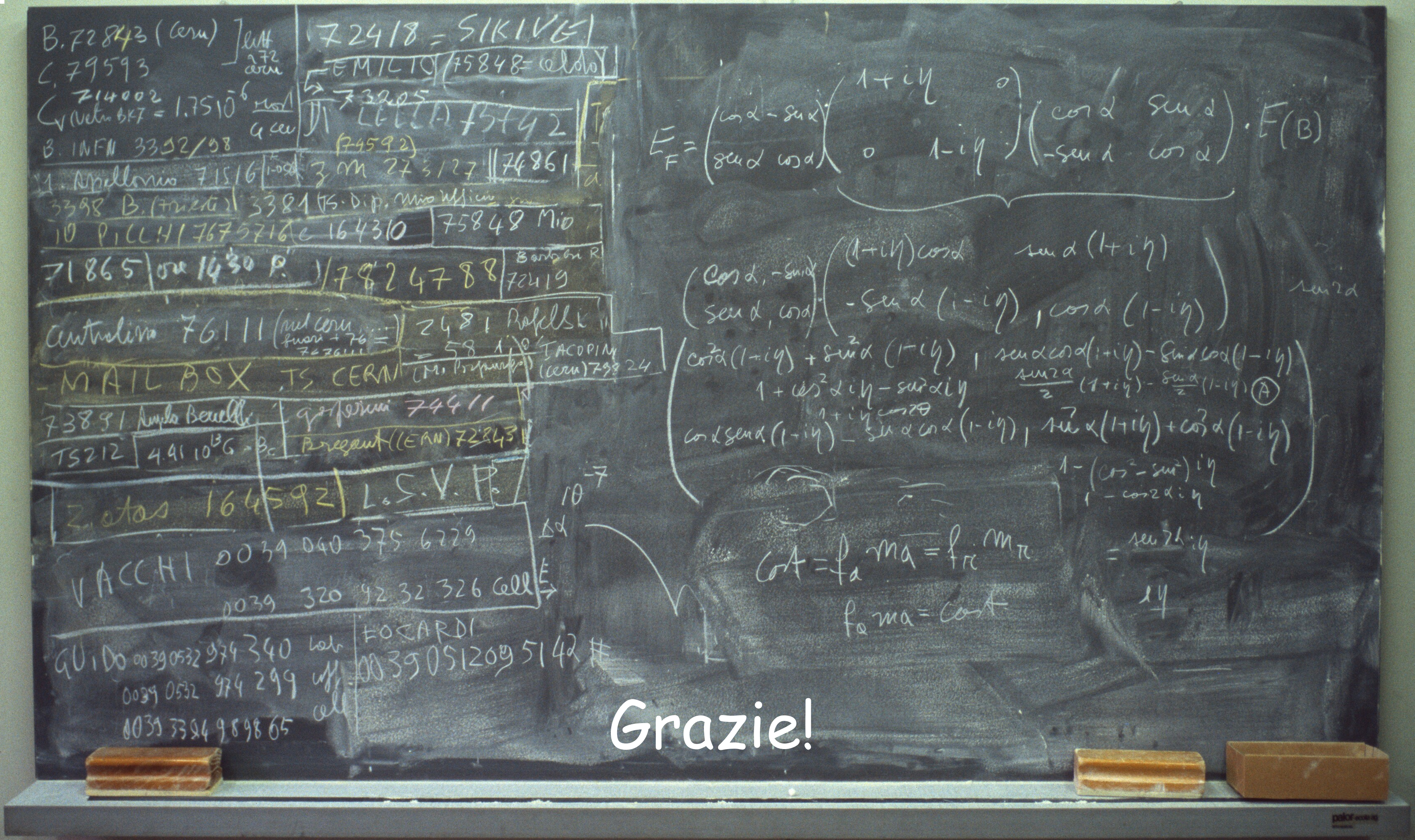
PVLAS - Ferrara

Sensibilità $2 \cdot 10^{-7}$ $1/\sqrt{Hz}$, con F = 285000, campo 2.6 T, L = 1.8 m, 2 magneti, 11 T^2m Banco unico ottico. Ellitticità = $2.4 \cdot 10^{-11}$

$T_{QED} = 7.2 \cdot 10^{7}$ s = 2.2 anni

Measurement time





Grazie!

Post-Maxwellian models - 3

For $\vartheta \neq 0$ $\begin{cases} f_{\parallel}^{(\mathrm{pM})}\left(\vartheta, E_\gamma\right) \propto \eta_1 E_\gamma^3 \\ f_{\perp}^{(\mathrm{pM})}\left(\vartheta, E_\gamma\right) \propto \left(a\eta_1 + b\eta_2\right) E_\gamma^3 \end{cases} \Rightarrow$ Always $\neq 0$

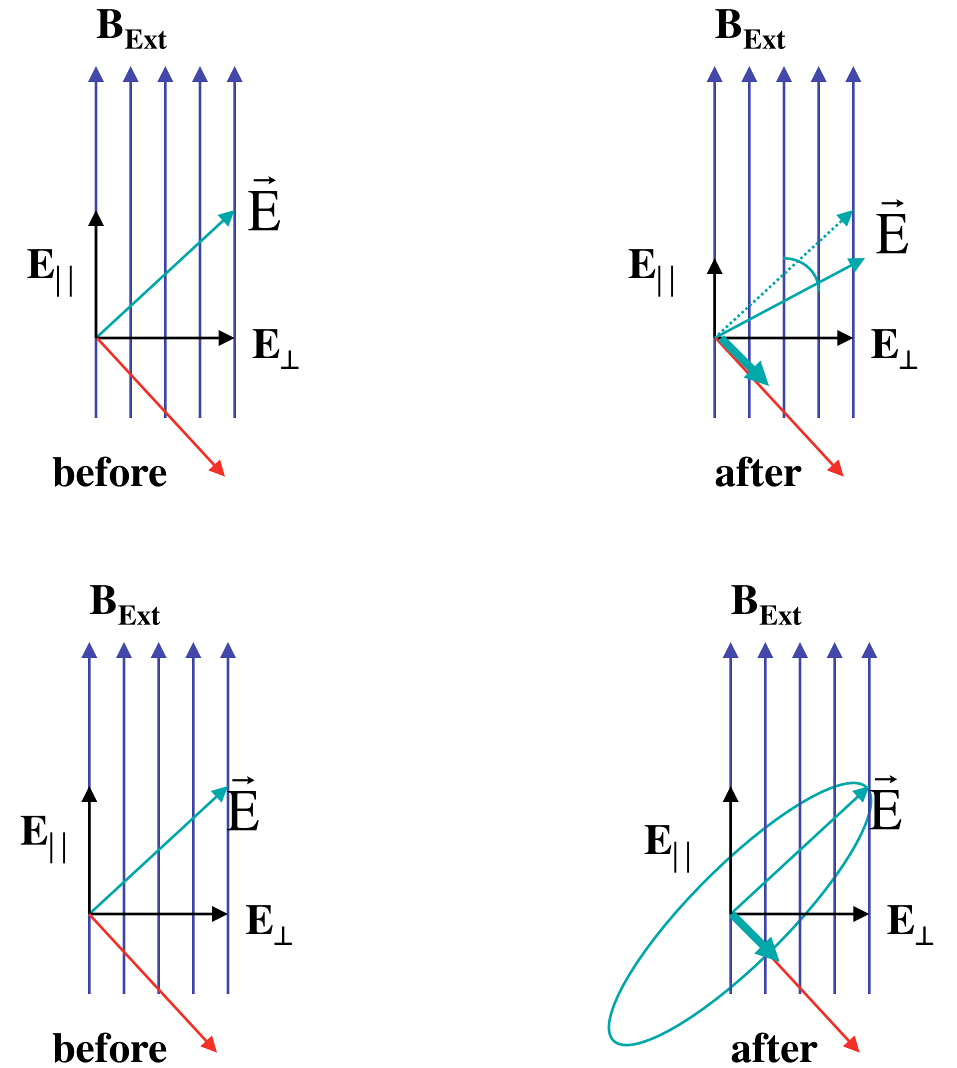
$$\Delta n^{(pM)} = 2\xi\left(\eta_2 - \eta_1\right) B_{Ext}^2$$

If $\eta_1 = \eta_2 \Rightarrow \Delta n^{(pM)} = 0$
e.g. Born - Infeld

Linear dichroism and birefringence

Dichroism

Ellipticity



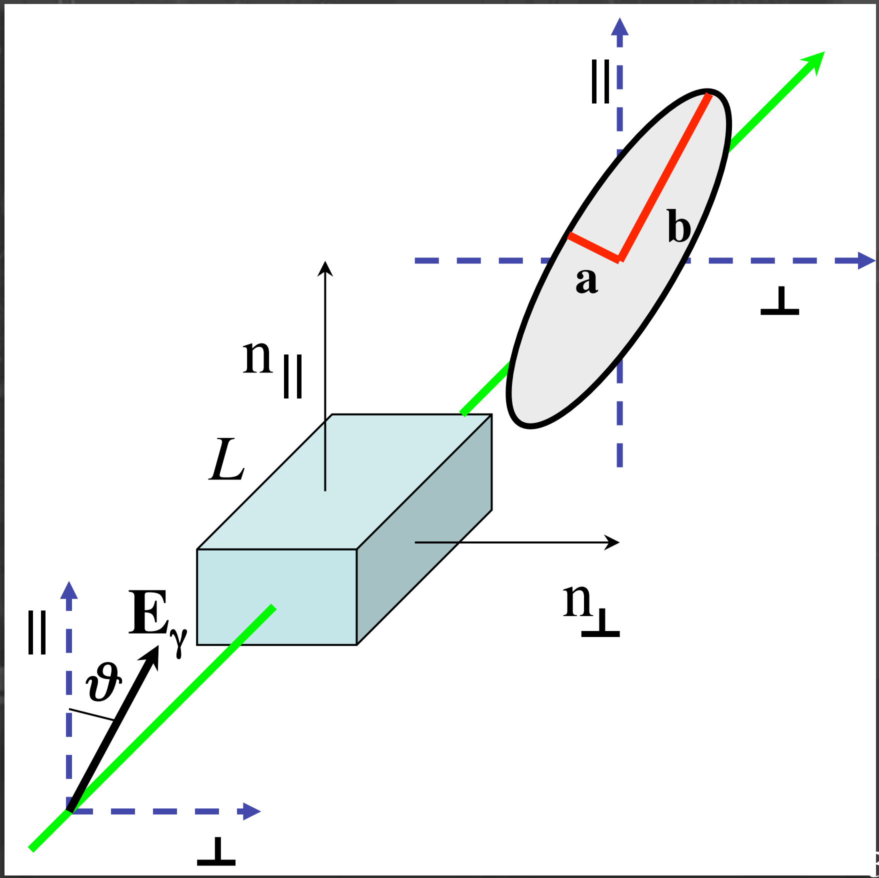
apparent rotation ε

ellipticity ψ

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

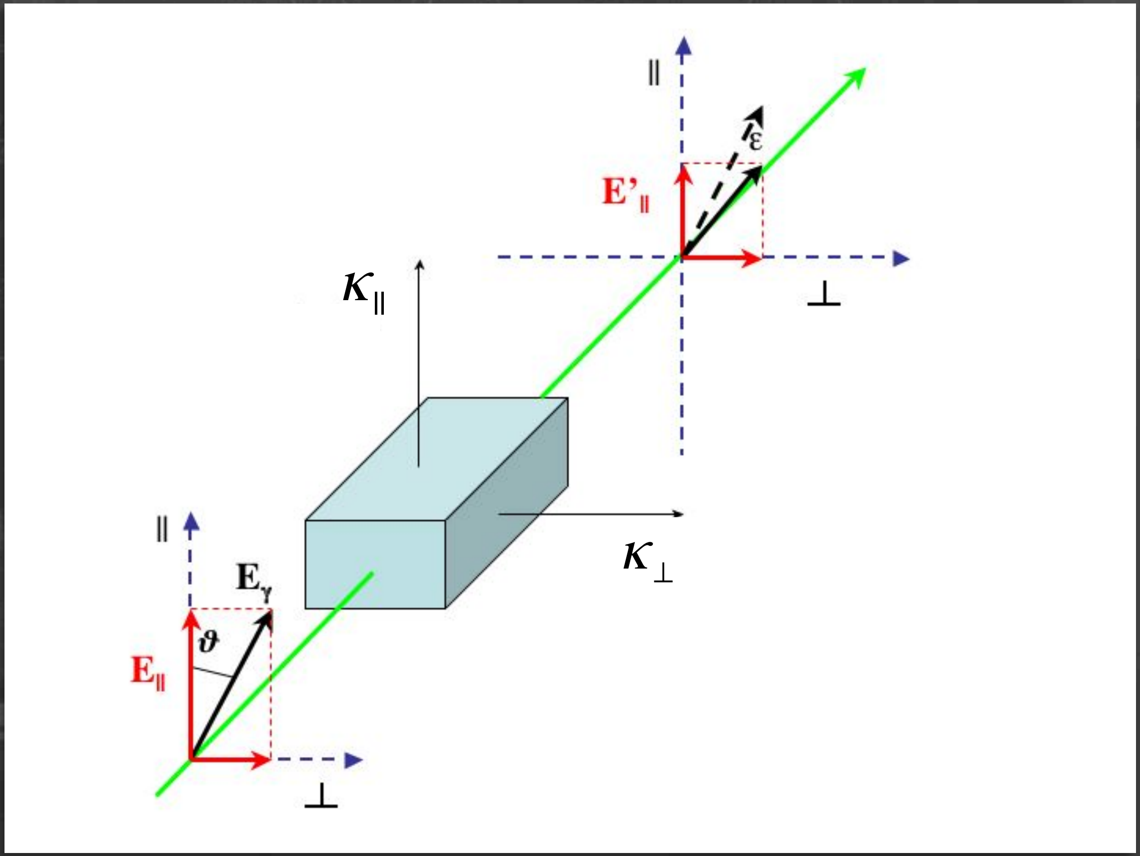
$$\psi = \frac{a}{b} = \frac{\pi L(n_{||} - n_\perp)}{\lambda}\sin 2\vartheta$$



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

$$\varepsilon = \frac{\pi L(\kappa_{\|} - \kappa_{\perp})}{\lambda} \sin 2\vartheta$$



Absorption coefficient $= \dfrac{2\pi}{\lambda}\kappa$

Axion-like contribution

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

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

pseudoscalar case

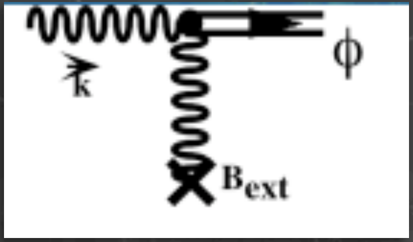
M, M_s are inverse coupling constants

$$L_\sigma = \frac{1}{M_s}\sigma\left(\vec{B}_\gamma \cdot \vec{B}_{ext}\right)$$

scalar case

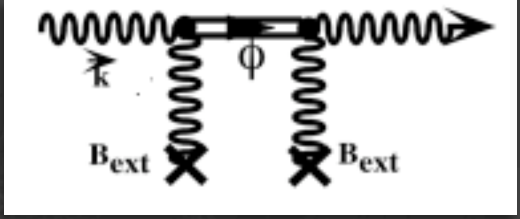
Effects on photon propagation

Absorption



DICHROISM

Dispersion



BIREFRINGENCE

[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]

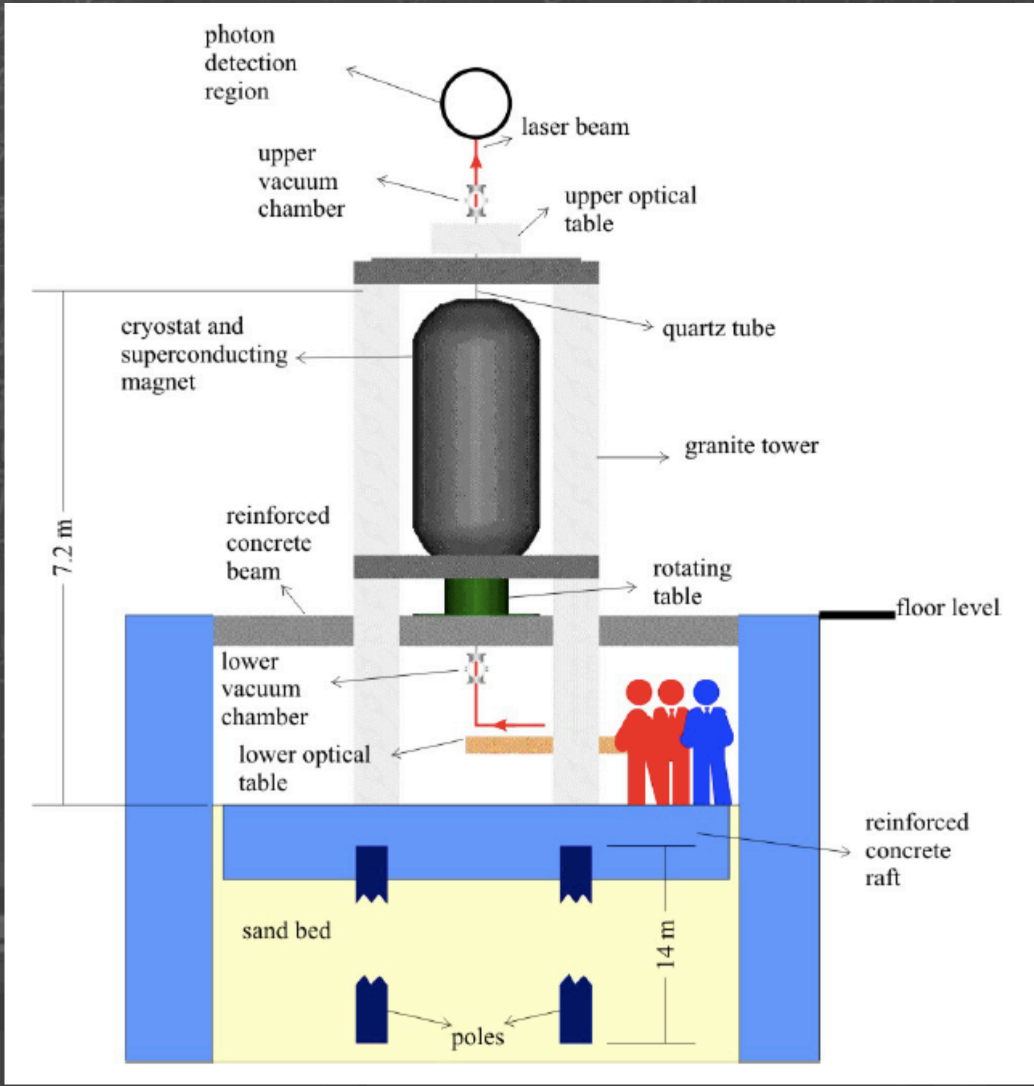
Past - PVLAS at Lab. Nazionali Legnaro

Focused on a general study of the vacuum in the presence of a magnetic field

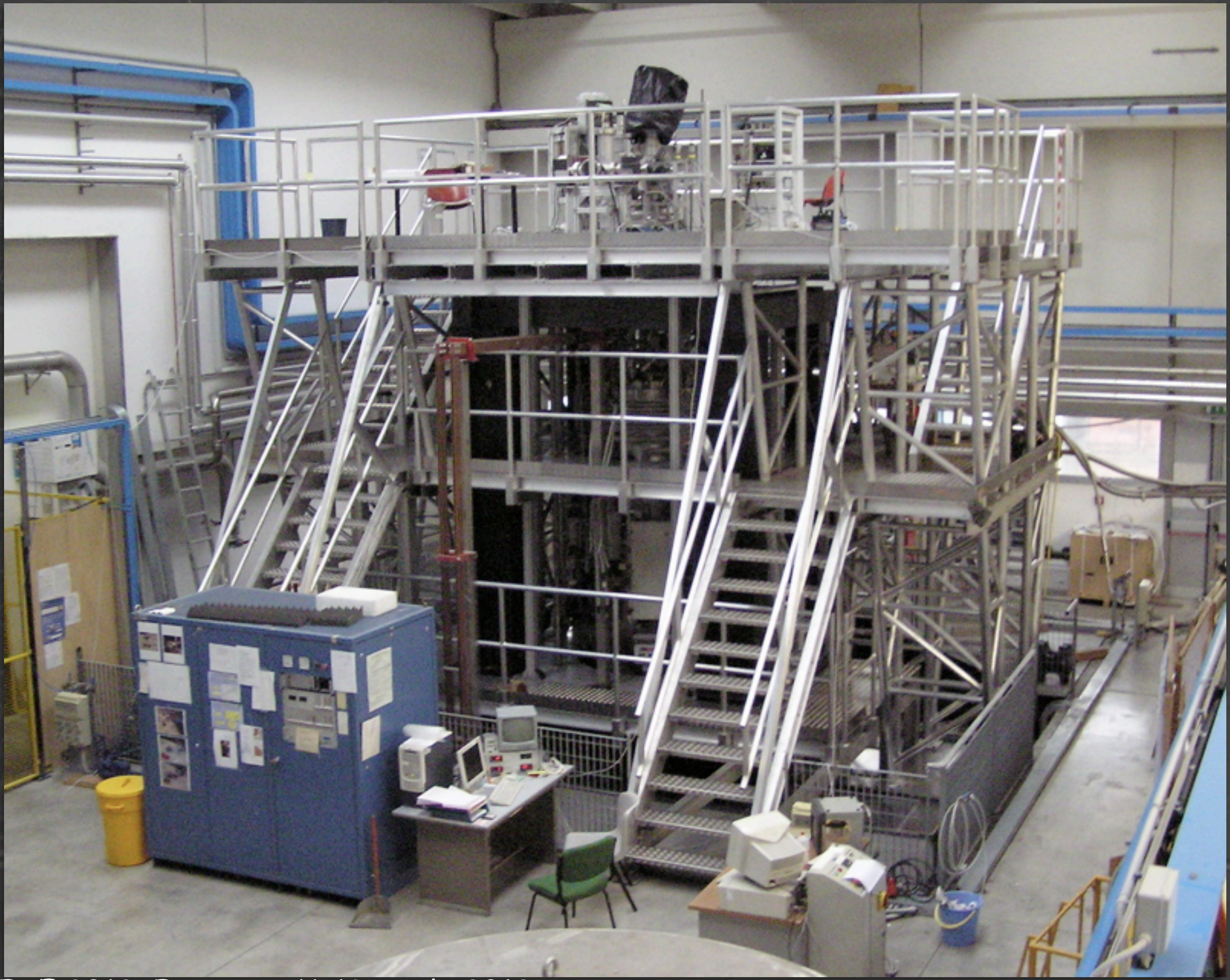
Polarizzazione del
Vuoto con **LAS**er

Major improvements compared to previous efforts:

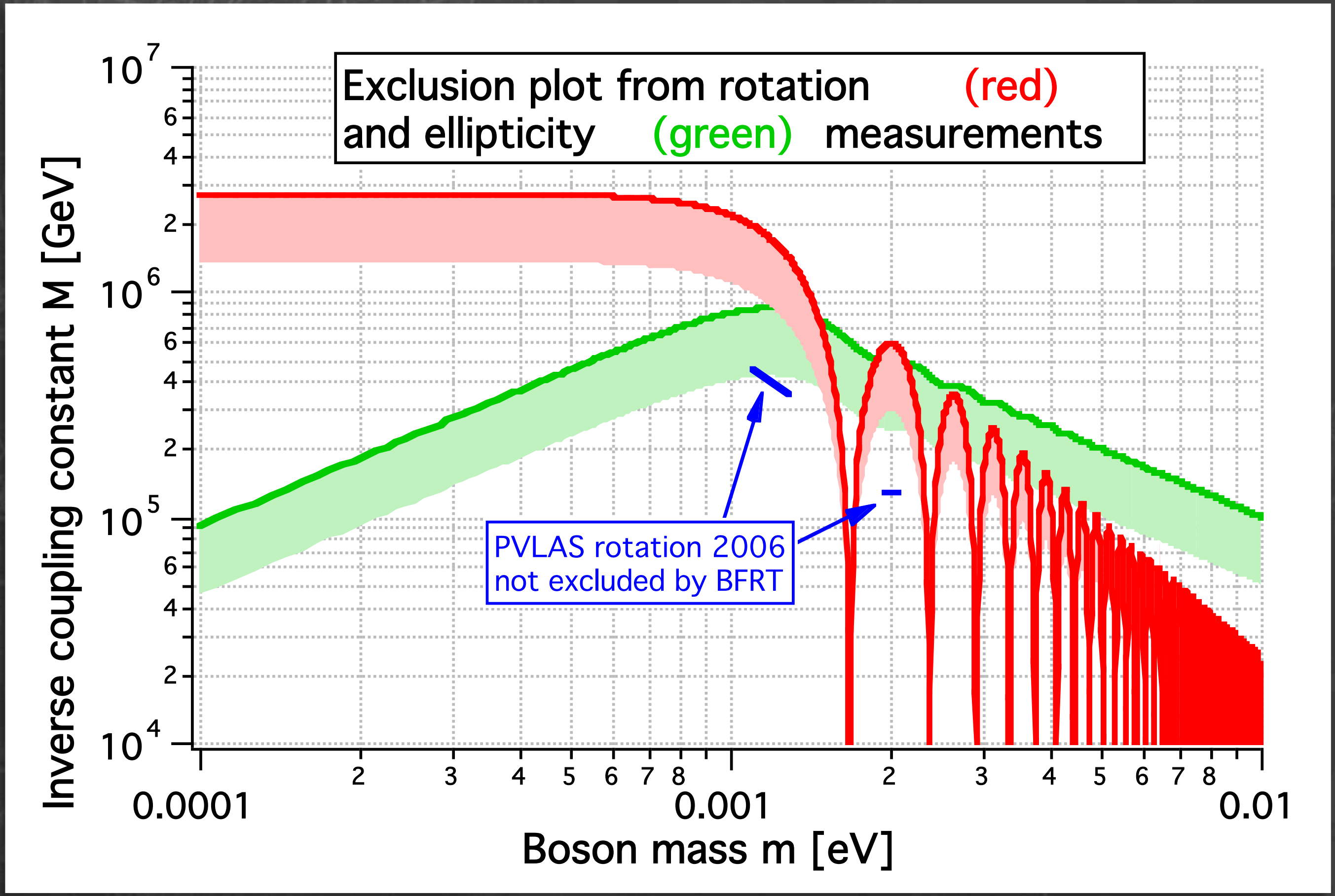
- Resonant **FP cavity (6.4 m)** for large amplification factor ($> 5\ 10^4$)
- Rotating cryostat allows high modulation frequency (up to 0.4 Hz)
- Large magnetic field (magnet tested up to 7 T)
- Magnetic system mechanically decoupled from optical system



Past - PVLAS at Lab. Nazionali Legnaro



Present published results - ALP

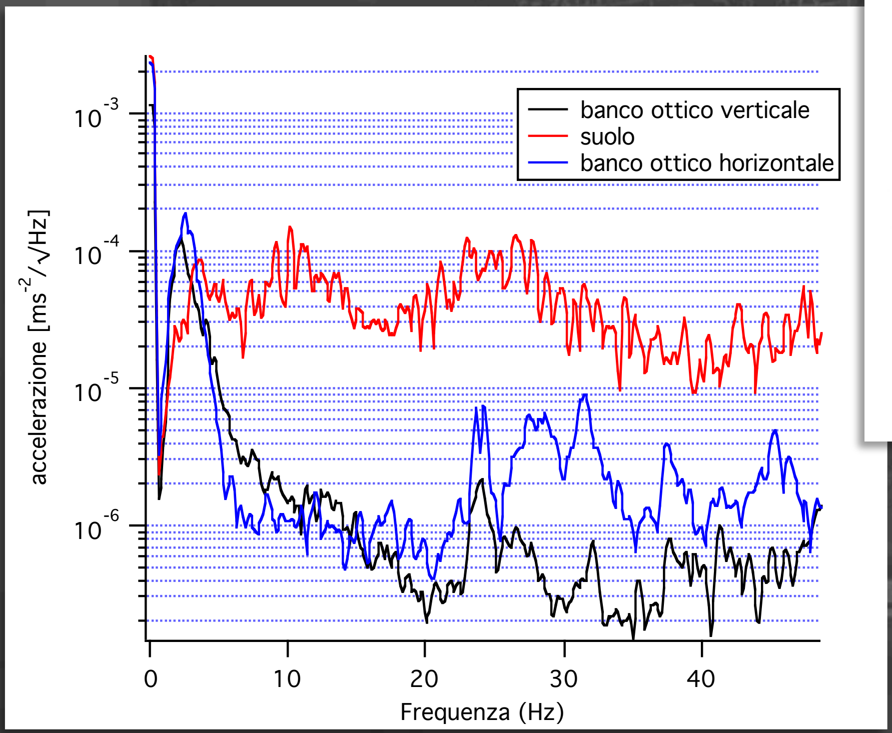


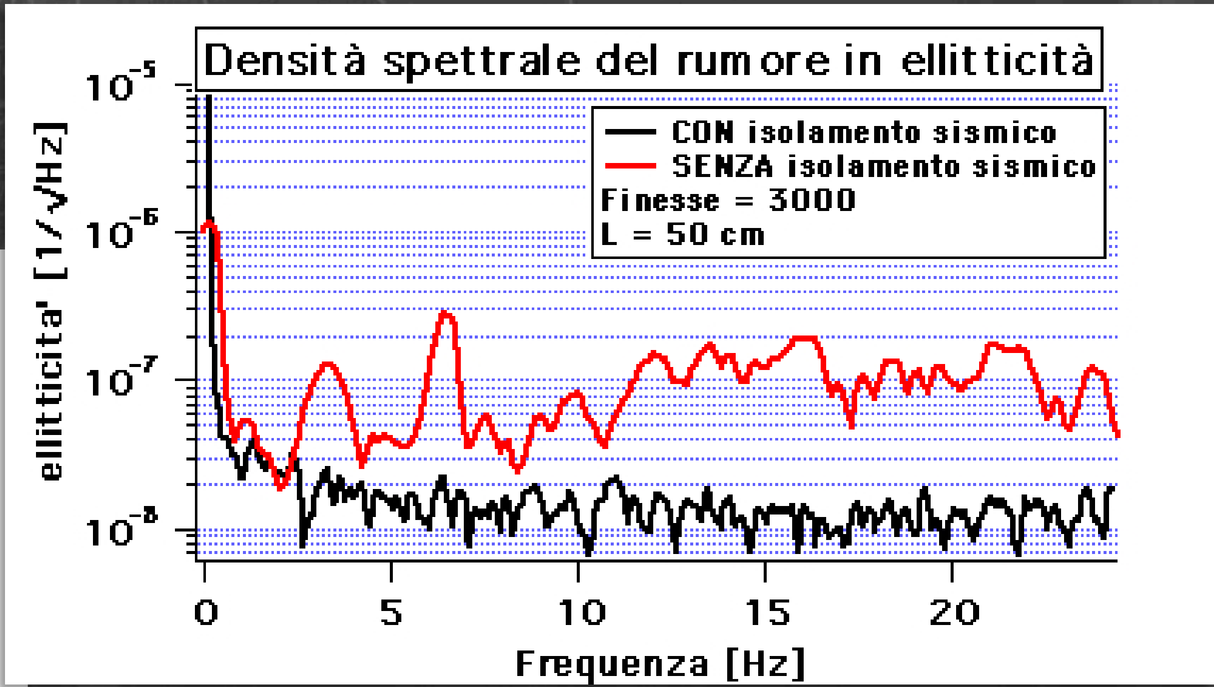
The CAST experiment at CERN has excluded values of M < 10^{10} GeV

<u>Unreachable with present lab techniques</u>

Low finesse - seismic isolation

Compact 50 cm long ellipsometer without magnetic field





Flat noise spectrum above ≈ 5 Hz

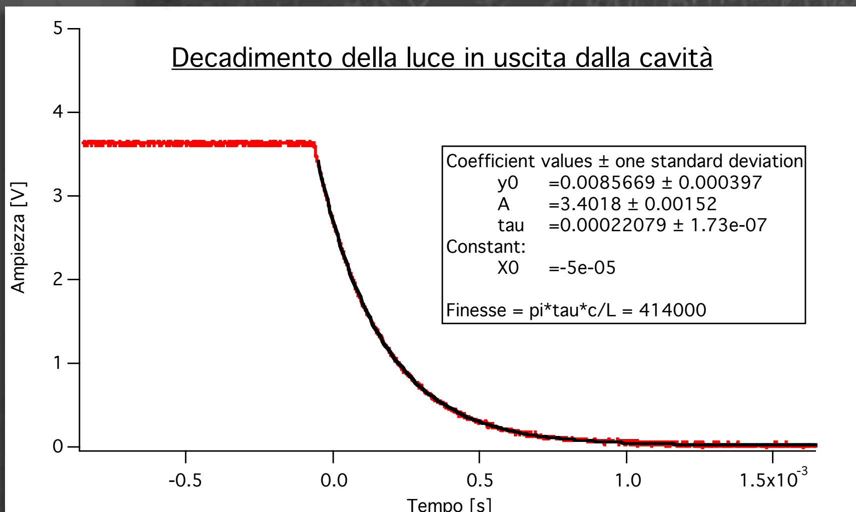
High finesse - seismic isolation

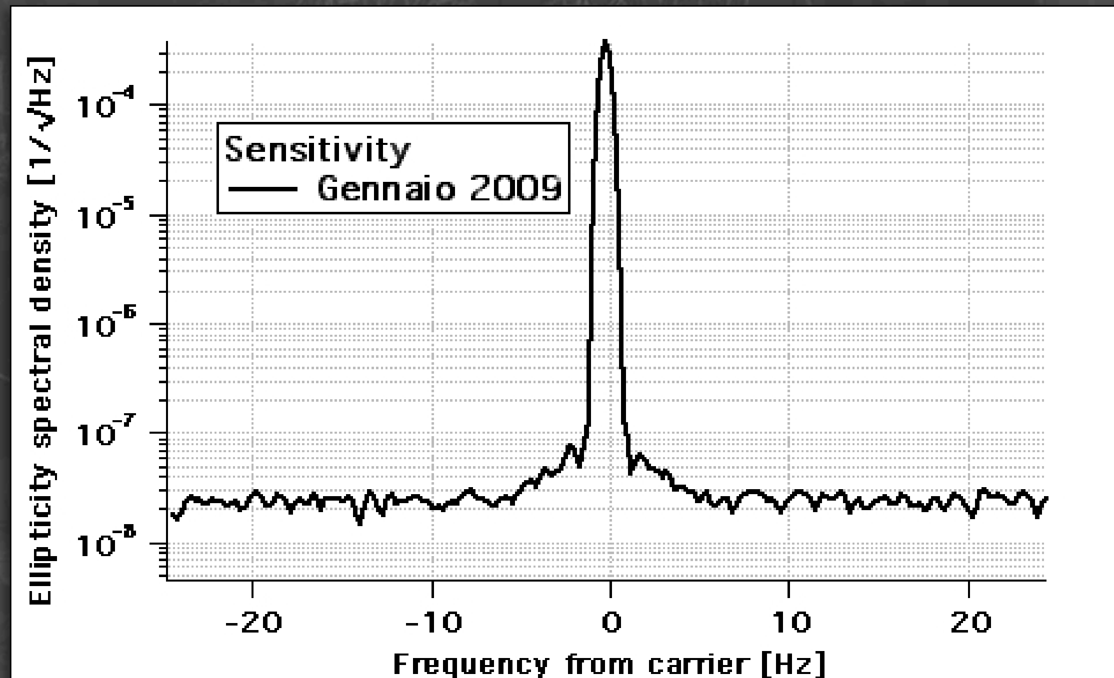
High finesse: F = 414000

$L_{eff} = (2F/\pi)L = 130$ km

Compact 50 cm long ellipsometer without magnetic field

Cavity output power = 25 mW
Laser-cavity coupling = 75%
Cavity transimission = 25%

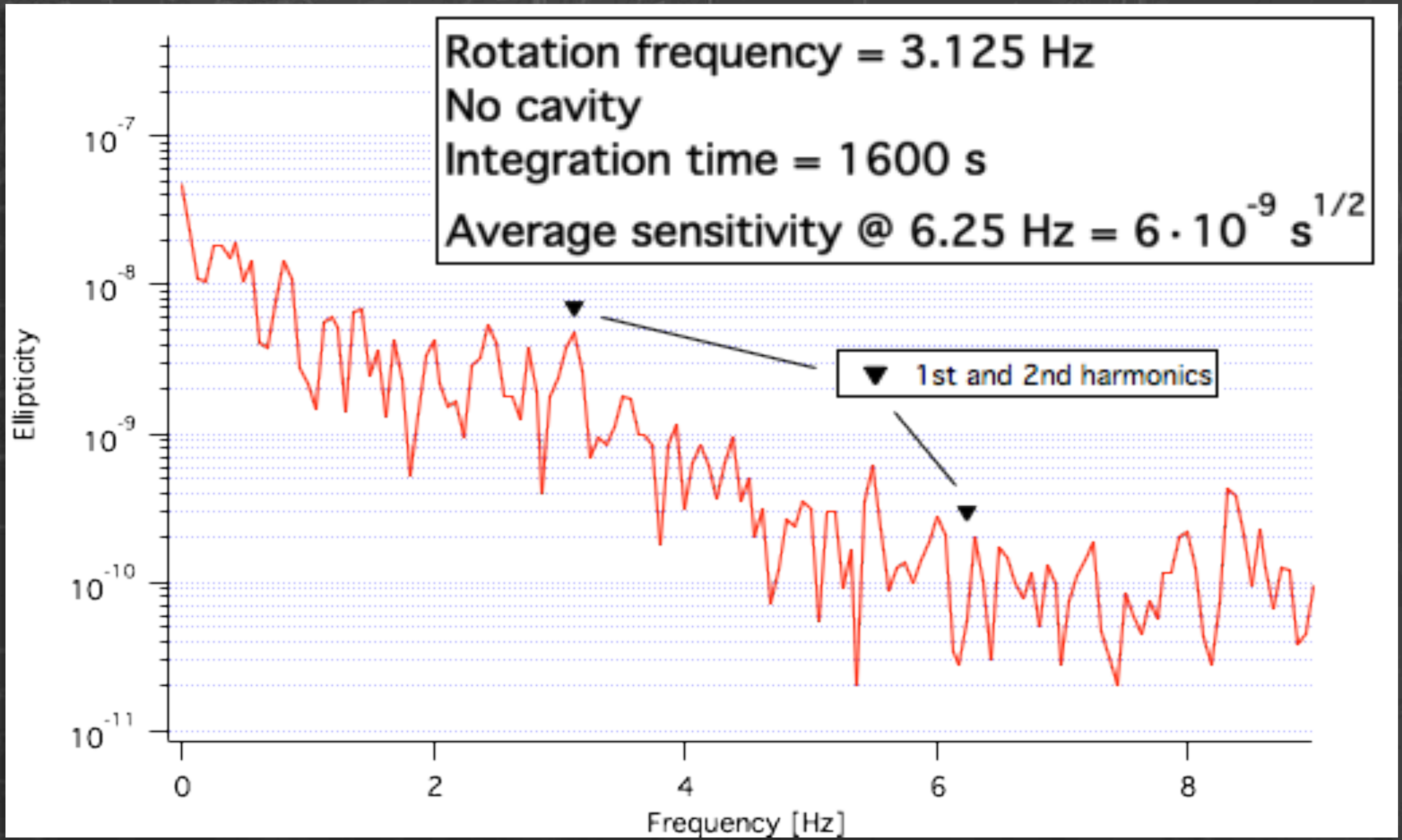




Record sensitivity with a cavity $\Psi = 3\cdot10^{-8}$ 1/√Hz
Assuming B = 2.3 T: Sensitivity in $\Delta n/B^2 = 1.5\cdot10^{-20}$ T^{-2} 1/√Hz

Ferrara test apparatus - sensitivity

No cavity - reached expected noise level with rotating magnets

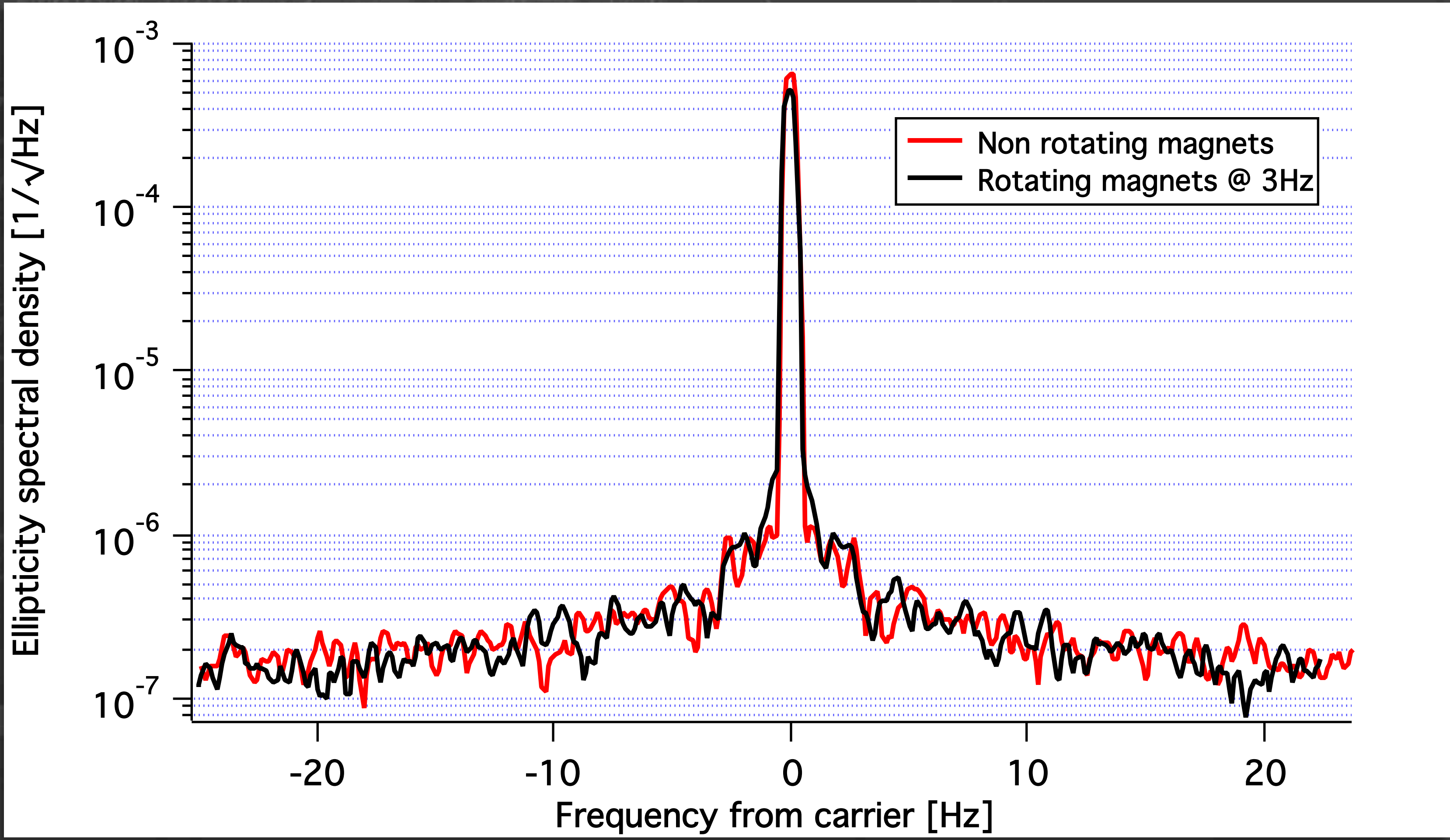


No electronically induced signals in the readout system

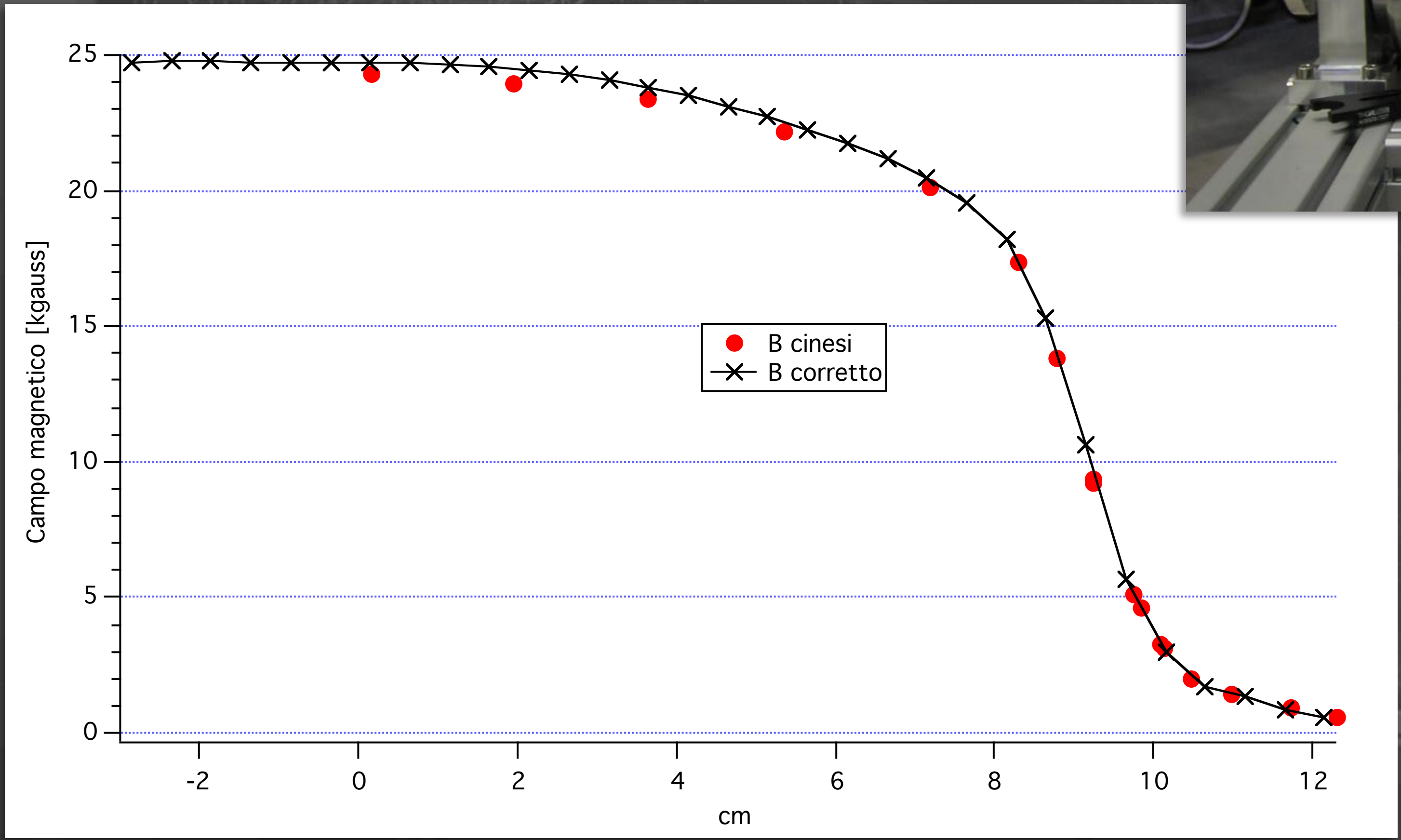
Ferrara test apparatus - sensitivity

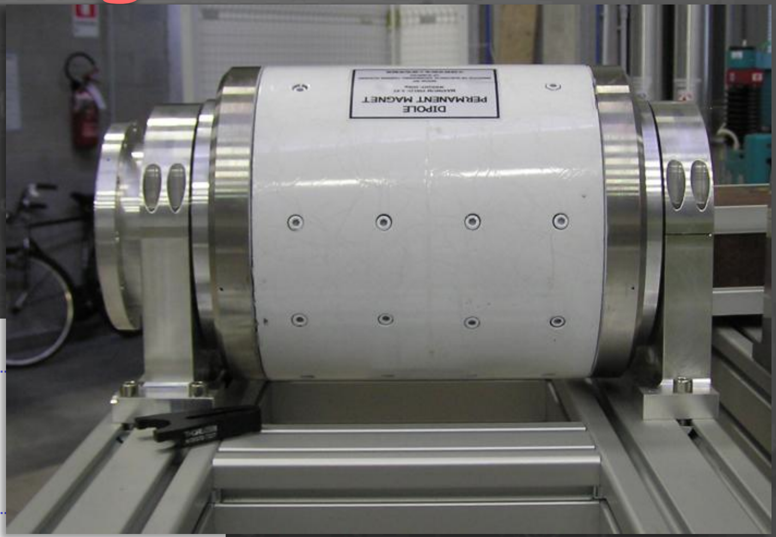
With high-finesse cavity > 400000

Sensitivity worsened - still under study



Permanent Test Magnets





New granite optical bench

Installation in Ferrara clean room

Present - Future

Currently building final apparatus in clean room in Ferrara.

- Magnetic field: 2 x 1 m long magnets with 2.5 T (arrived)
- Magnet support structure (arrived)
- Magnet support mechanics + motor (ordered)
- Optical bench with isolation system (installed)
- Optical enclosures (arriving)
- New laser (2 Watts, 1064 nm) (arrived)
- All optical elements, supports and movements will be non magnetic (arrived)
- Getters will be used as vacuum pumps (arrived)

Some numerical values

Main interest is the Euler-Heisenberg birefringence

- $B = 2.5$ T
- $F = 4\cdot10^5$ → $\Delta n = 2.5\cdot10^{-23}$ → $\boxed{\psi = 3.7\cdot10^{-11}}$
- $L = 2$ m

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

Ellipticity sensitivity of < $3.7\cdot10^{-8}$ $1/\sqrt{\text{Hz}}$
Birefringence sensitivity < $2.5\cdot10^{-20}$ $1/\sqrt{\text{Hz}}$

Present sensitivity in $\Delta n = 1.8\cdot10^{-18}$ $1/\sqrt{\text{Hz}}$

Shot noise limit = $\sqrt{\dfrac{e}{2I_0 q}} = 1\cdot10^{-9}\dfrac{1}{\sqrt{\text{Hz}}}$ for $I_0 = 100$ mW

(I_0 = output intensity reaching the analyzer)