The BMV project :

(Biréfringence Magnétique du Vide)

Optical detection of axions ?

Carlo RIZZO

LCAR-IRSAMC

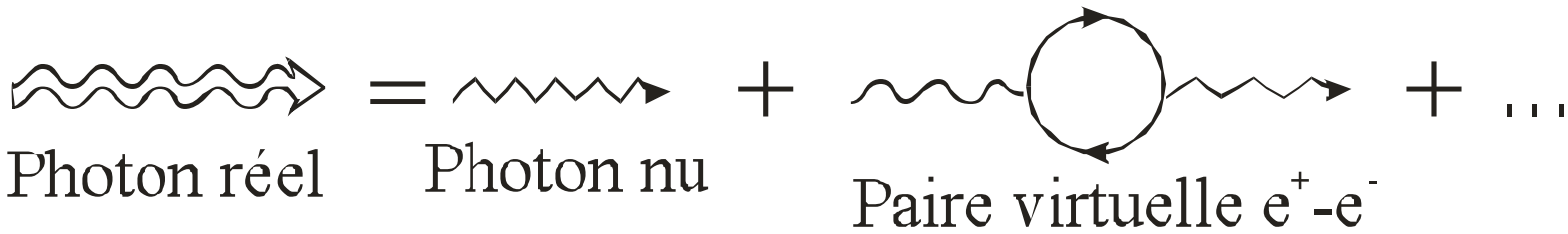
Université Paul Sabatier et CNRS

Toulouse

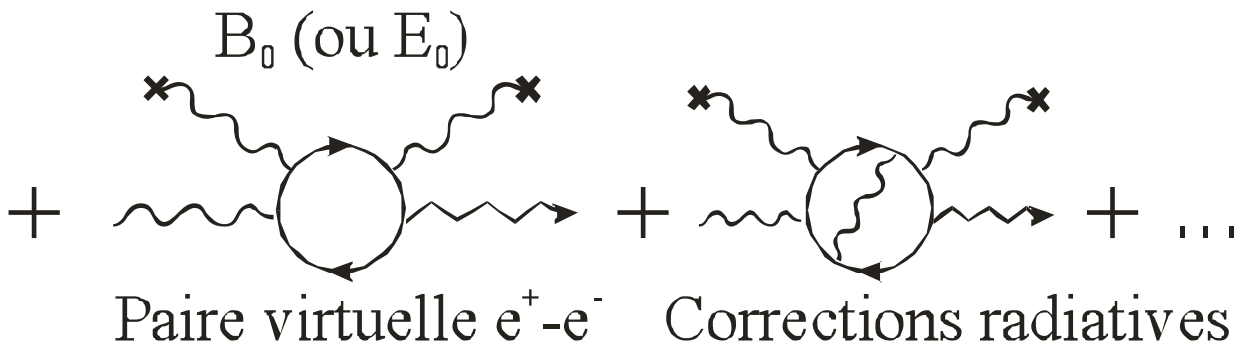
Outline

- Introduction
- Historical overview
- Recent results
- Future projects
- The BMV project
- Conclusions

Propagation in a vacuum: c



Propagation in a vacuum in the presence of a magnetic field



O(α^2)

O(α^3)

1,5 % du terme d'O(α^2)

V.I.Ritus, *Sov. Phys. JETP* **42**, 774 (1975)

$$L = \frac{1}{2}F + aF^2 + bG^2 + \ldots \qquad F = \left(\varepsilon_0 E^2 - \mu_0^{-1} B^2\right); \quad G = \sqrt{\varepsilon_0 \mu_0^{-1}}\left(\vec{E} \bullet \vec{B}\right)$$

1935-1936 Kochel, Euler, Heisenberg $\frac{b}{a} = 7$

H.Euler et K.Kochel, *Naturwiss*. **23** (1935); W.Heisenberg et H.Euler, *Z. Phys.* **38** (1936) 714

… in the presence of B_0 : $npar \neq nper$

Cotton-Mouton effect

$$\Delta n = \left(b - 4a\right)\mu_0^{-1} B_0^2$$

$$\Delta n = 4 \text{ x } 10^{-24}\ B_0^2$$

with B_0 in Tesla

$$\Delta n = npar - nper$$

Z.Bialynicka-Birula et I.Bialynicki-Birula, *Phys. Rev. D* **2** (1970) 2341

experimental challenge

Ellipticity $\propto B_0^2 \text{x} L$

low mass *m*, chargeless, spinless boson Φ

Pseudoscalar particle *(like axions of Peccei et Quinn)*

R. Peccei et H.R.Quinn, *Phys. Rev. Lett.* **38** (1977) 1440

$$L_{ps} = 1/M \; \Phi \; G$$

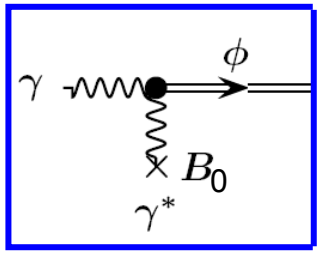
Scalar particle

$$L_s = 1/M \; \Phi \; F$$

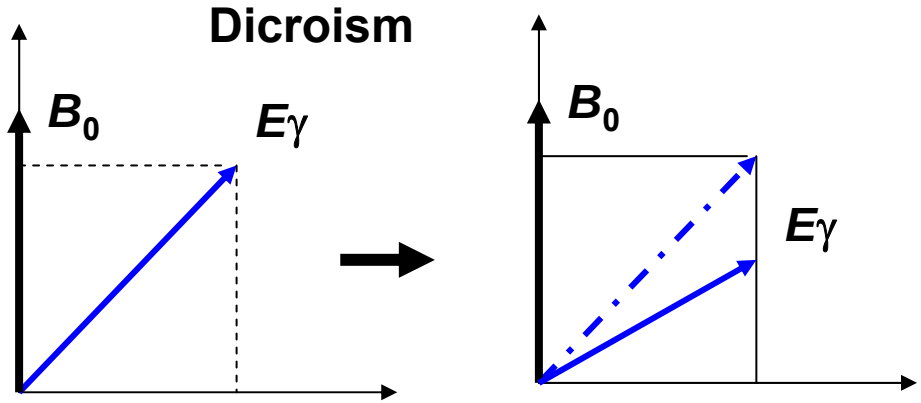
(Coupling constant $g = 1/M$)

Φ dark matter ? *It depends.*

Real particle

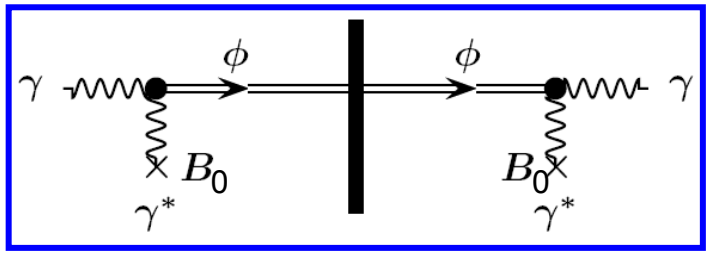


Dicroism



« Pseudoscalar »

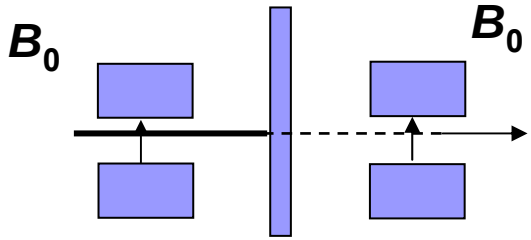
« B_0L » effects



wall

L.Maiani, R.Petronzio et E.Zavattini, *Phys. Lett. B* **175** (1986) 359

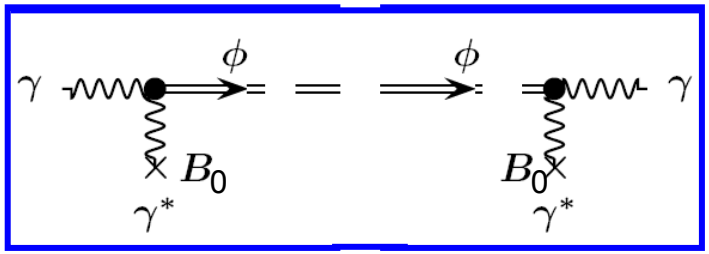
Photoregeneration



wall

K. Van Bibber *et al.*, *Phys. Rev. Lett.* **59** (1987) 759

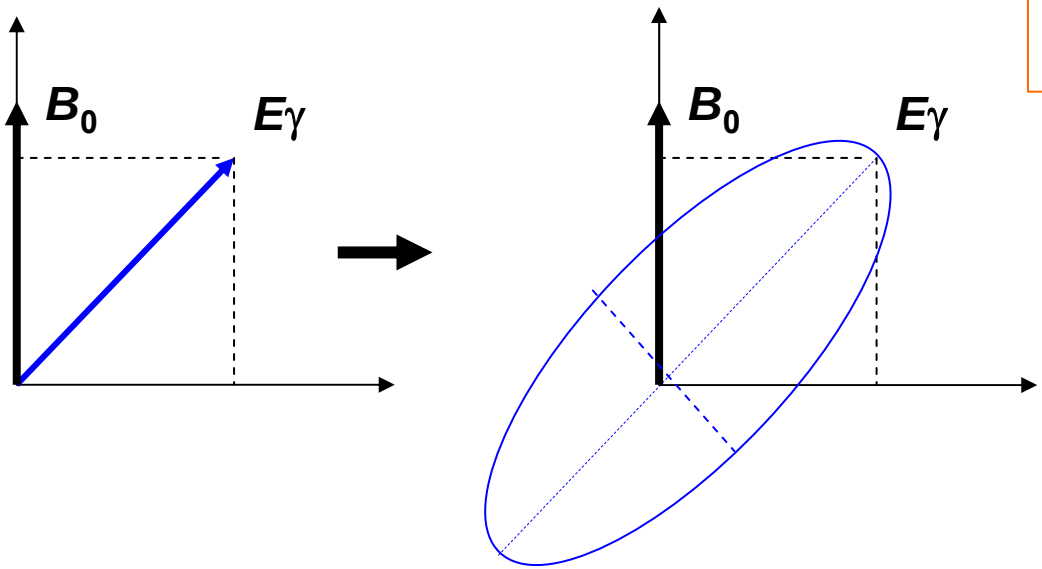
Virtual particle



$\Delta n > 0 \Longrightarrow$ **Pseudoscalar**

$\Delta n < 0 \Longrightarrow$ **Scalar**

Ellipticity



L.Maiani, R.Petronzio et E.Zavattini, *Phys. Lett. B* **175** (1986) 359

Outline

- Introduction
- Historical overview
- Recent results
- Future projects
- The BMV project
- Conclusions

EXPERIMENTAL METHOD TO DETECT THE VACUUM BIREFRINGENCE INDUCED BY A MAGNETIC FIELD

E. IACOPINI and E. ZAVATTINI
CERN, Geneva, Switzerland

Volume 85B, number 1 PHYSICS LETTERS 30 July 1979

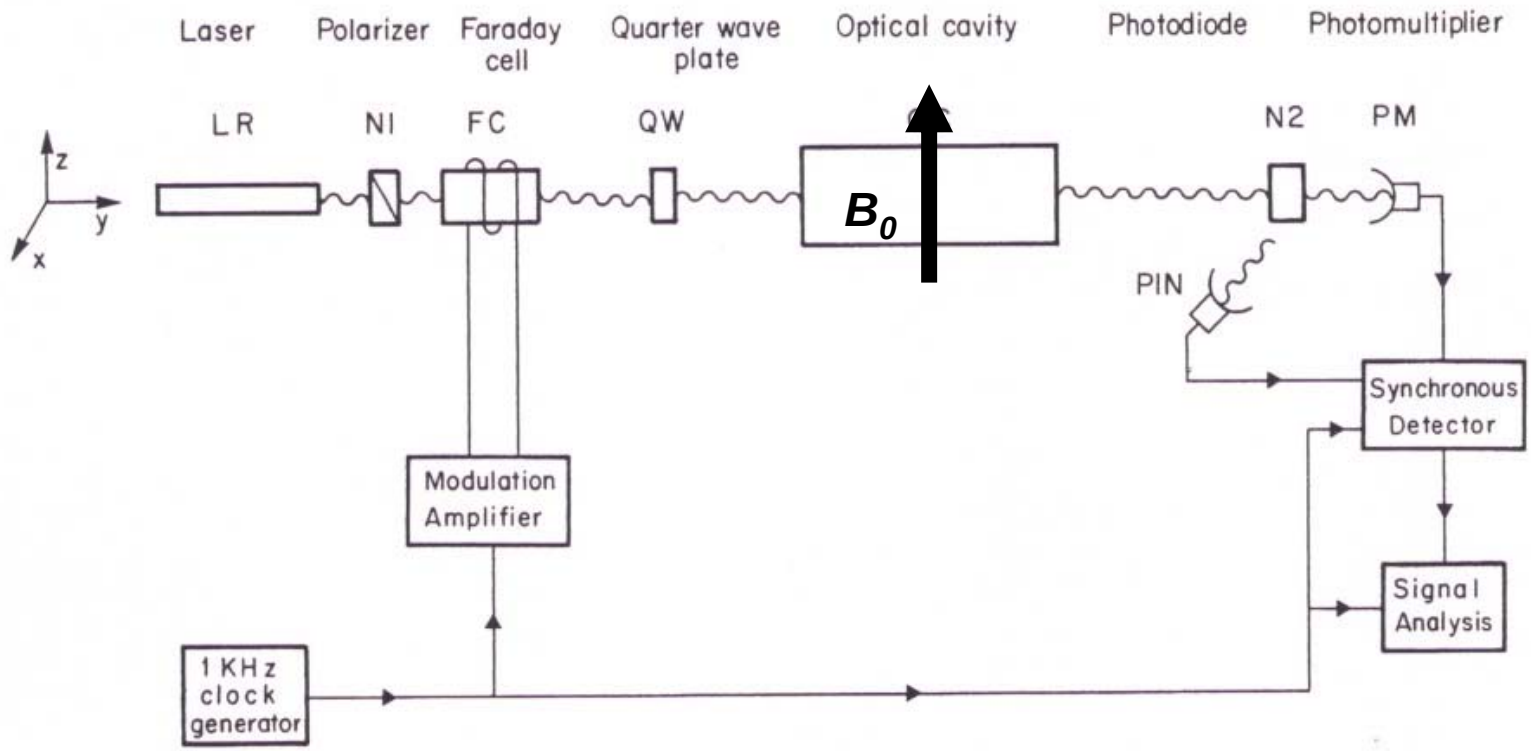


Fig. 3. Principle elements of the experimental apparatus.

Brookhaven-Rochester-Fermilab-Trieste collaboration : 1988-1993

A.C.Melissinos, E.Zavattini *et al.*

Brookhaven National Laboratories
Upton, NY, USA

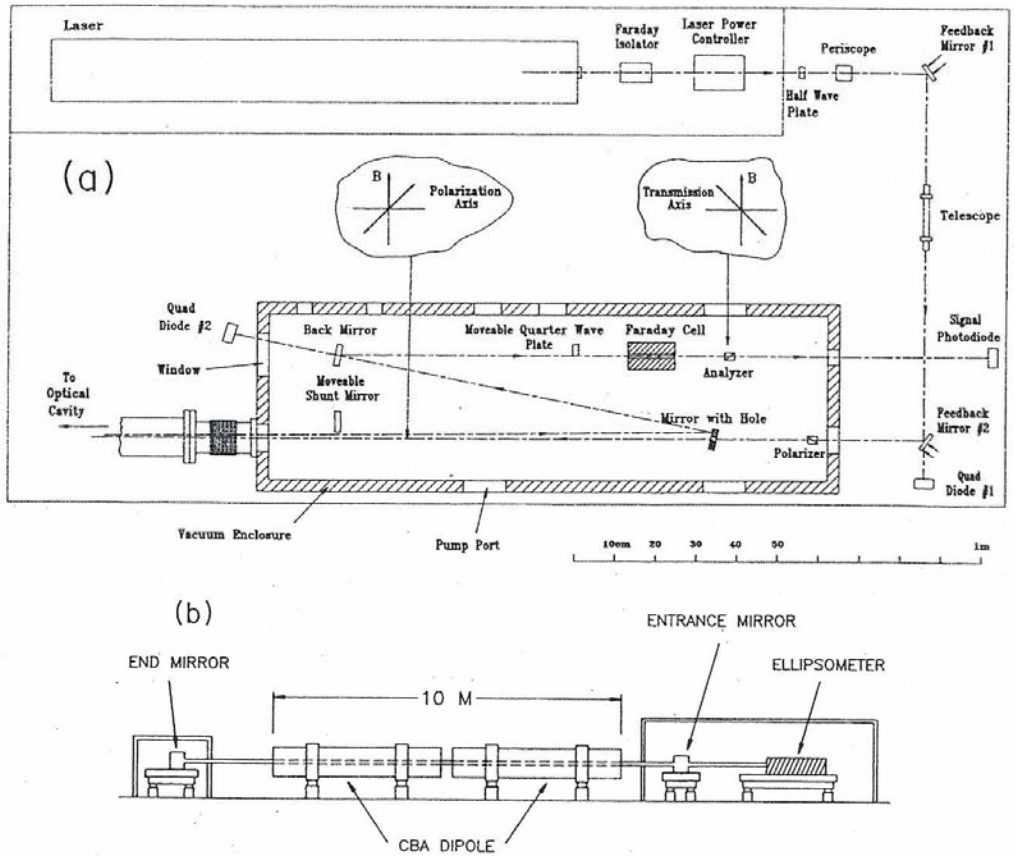


FIG. 4. (a) Schematic view of the ellipsometer; the volume inside the hatched area is evacuated. (b) Layout of the experiment and of the superconducting magnets.

Multipass optical cavity
500 passages in the field

$B_0L \approx 16$ Tm
$B_0^2L \approx 35$ T^{2}m

R.Cameron, et al., *Phys. Rev. D* **47** (1993) 3707

TABLE II. Best sensitivites achieved with the feedback system operating.

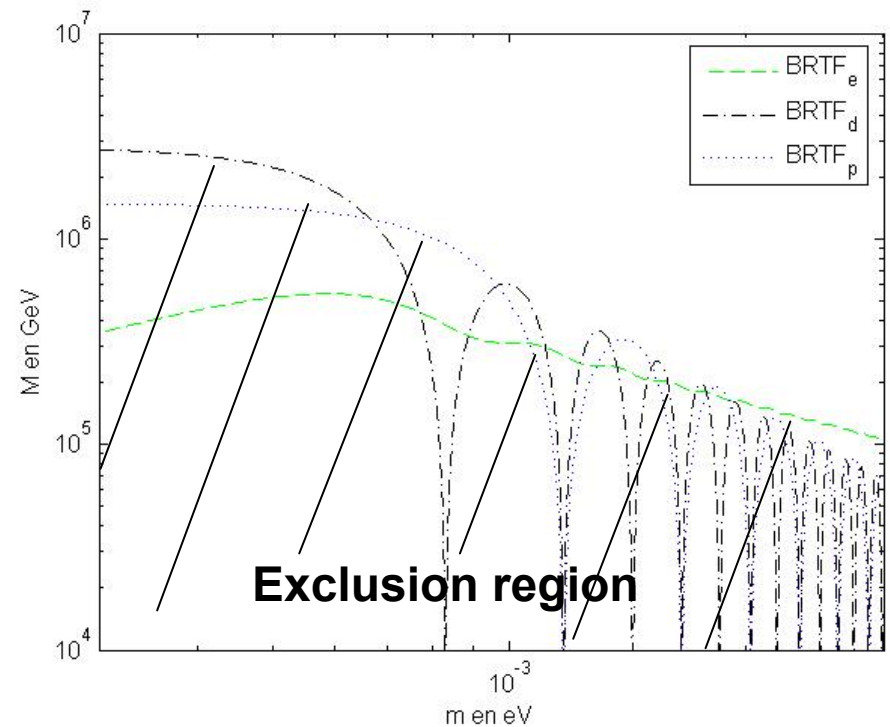
Number of reflections	Rotation or ellipticity	Number of averages	Measured rms noise level (rad)	Achieved sensitivity (rad/$\sqrt{\text{Hz}}$)
Shunt	Rotation	48	4.3×10^{-11}	7.6×10^{-9}
Shunt	Ellipticity	25	2.0×10^{-10}	2.6×10^{-8}
34	Rotation	66	1.6×10^{-10}	3.3×10^{-8}
34	Ellipticity	25	2.0×10^{-9}	
254	Rotation	40	4.2×10^{-10}	6.7×10^{-8}
578	Ellipticity	13	5.1×10^{-8}	1.5×10^{-6}

Ellipticity < 2.0x10^{-9}

$\Delta n < 2{,}8\ 10^{-19}\ T^{-2}$

Measurements :

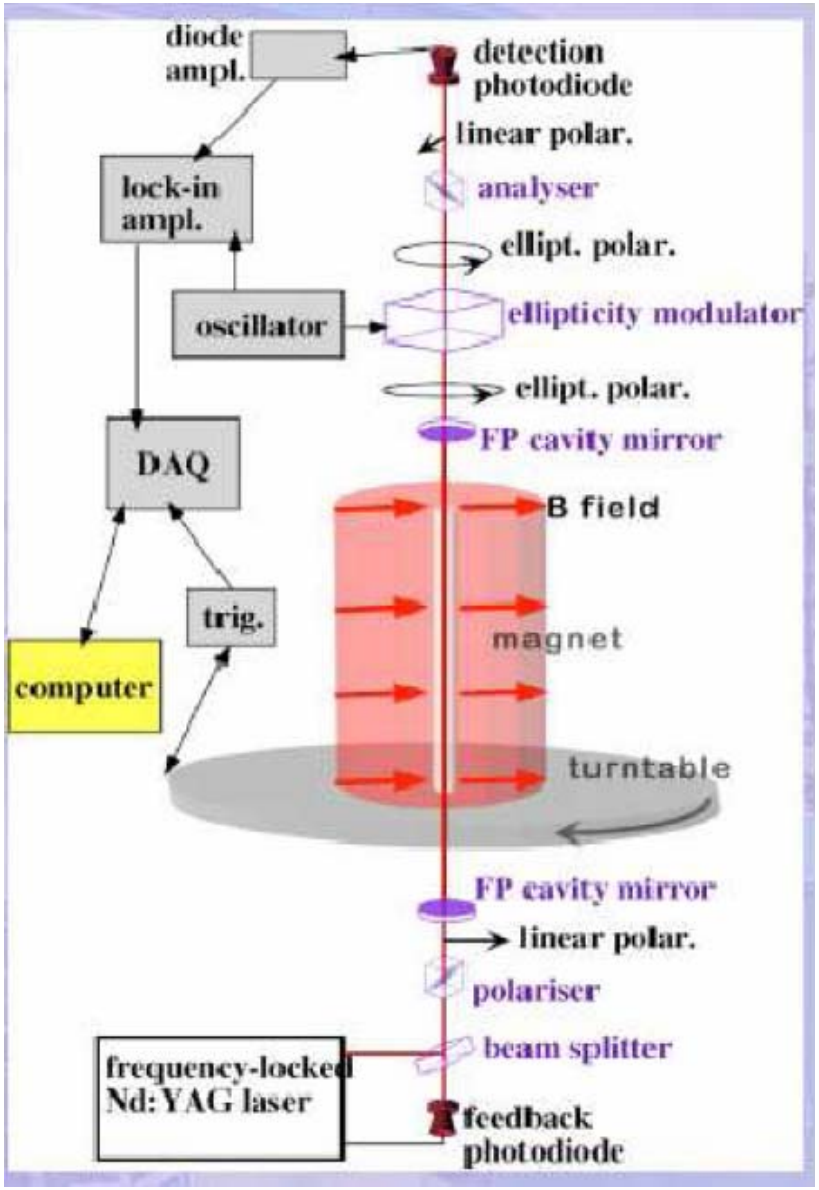
Ellipticity
Dicroism
Photoregeneration



R.Cameron, et al., *Phys. Rev. D* **47** (1993) 3707

Outline

- Introduction
- Historical overview
- Recent results
- Future projects
- The BMV project
- Conclusions



Since 1992,

Polarizzazione del Vuoto con LASer (PVLAS)

E.Zavattini *et al.*

B_0^2L = 25 T²m
B_0L = 5 Tm
Cavity finesse = 70 000
Modulation frequency = 0.6 Hz
Sensitivity = 10^{-7} $1/\sqrt{Hz}$

Laboratori Nazionali di Legnaro, INFN, Italy

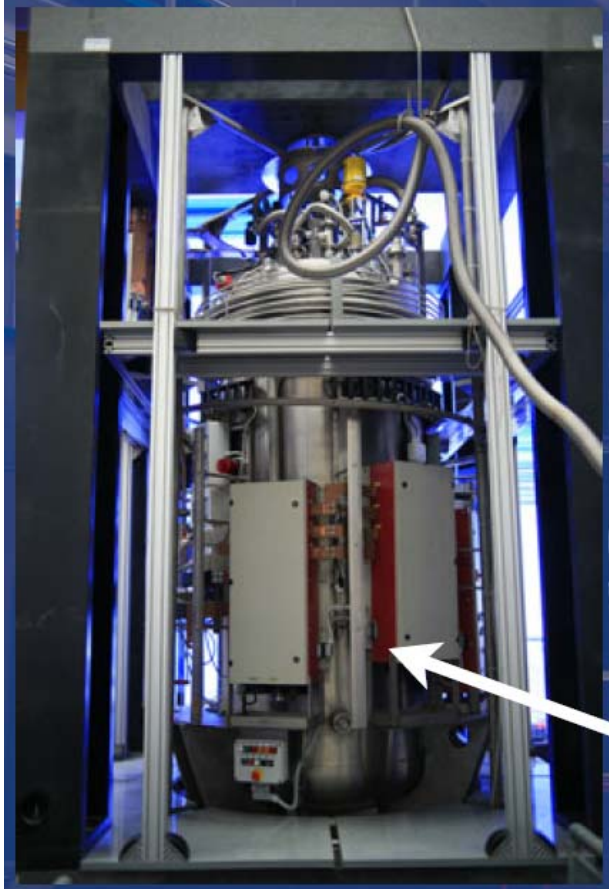
D.Bakalov, et al., *Quantum Semiclass. Opt.* **10** (1998) 239

PVLAS hall at LNL
INFN
PVLAS
G. Cantatore - PVLAS Coll.- Axion Training 2005 - CERN
www.ts.infn.it/experiments/pvlas
13

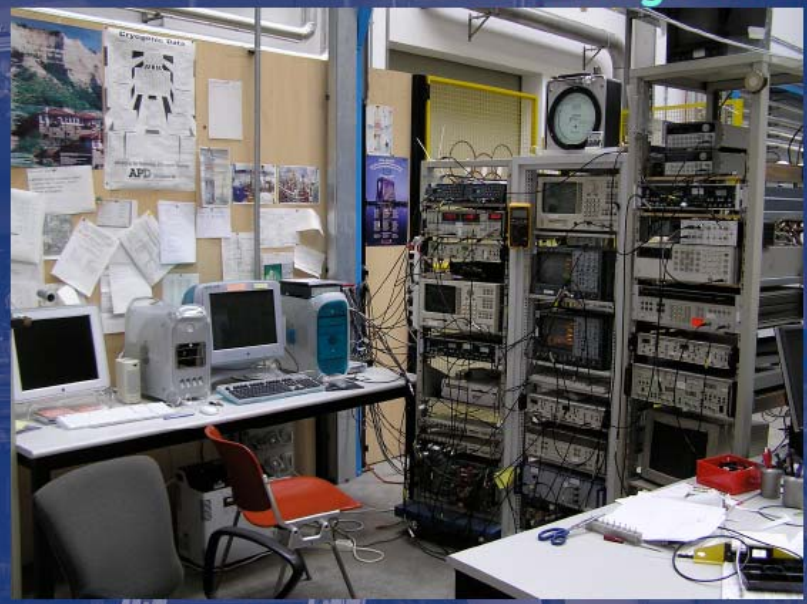
A nudo ...

Gallery (III)

Rotating cryostat

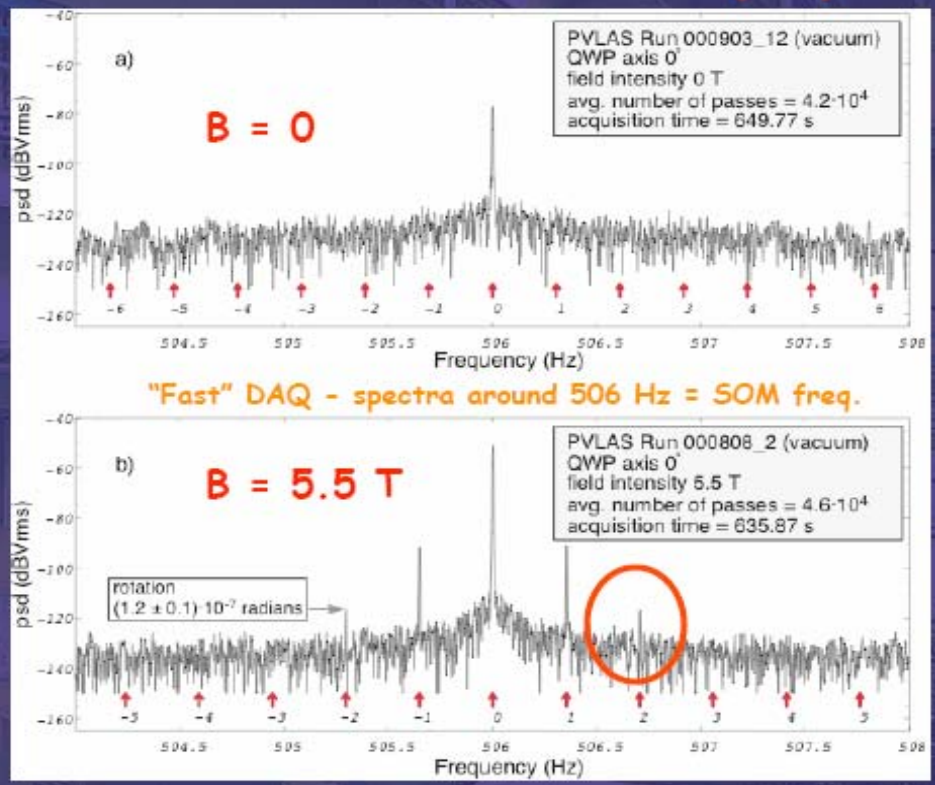


Counting room



magnet position

Vacuum rotation measurements (amplitude) II



- 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 $(3.9\pm0.5)\times10^{-12}$ rad/pass

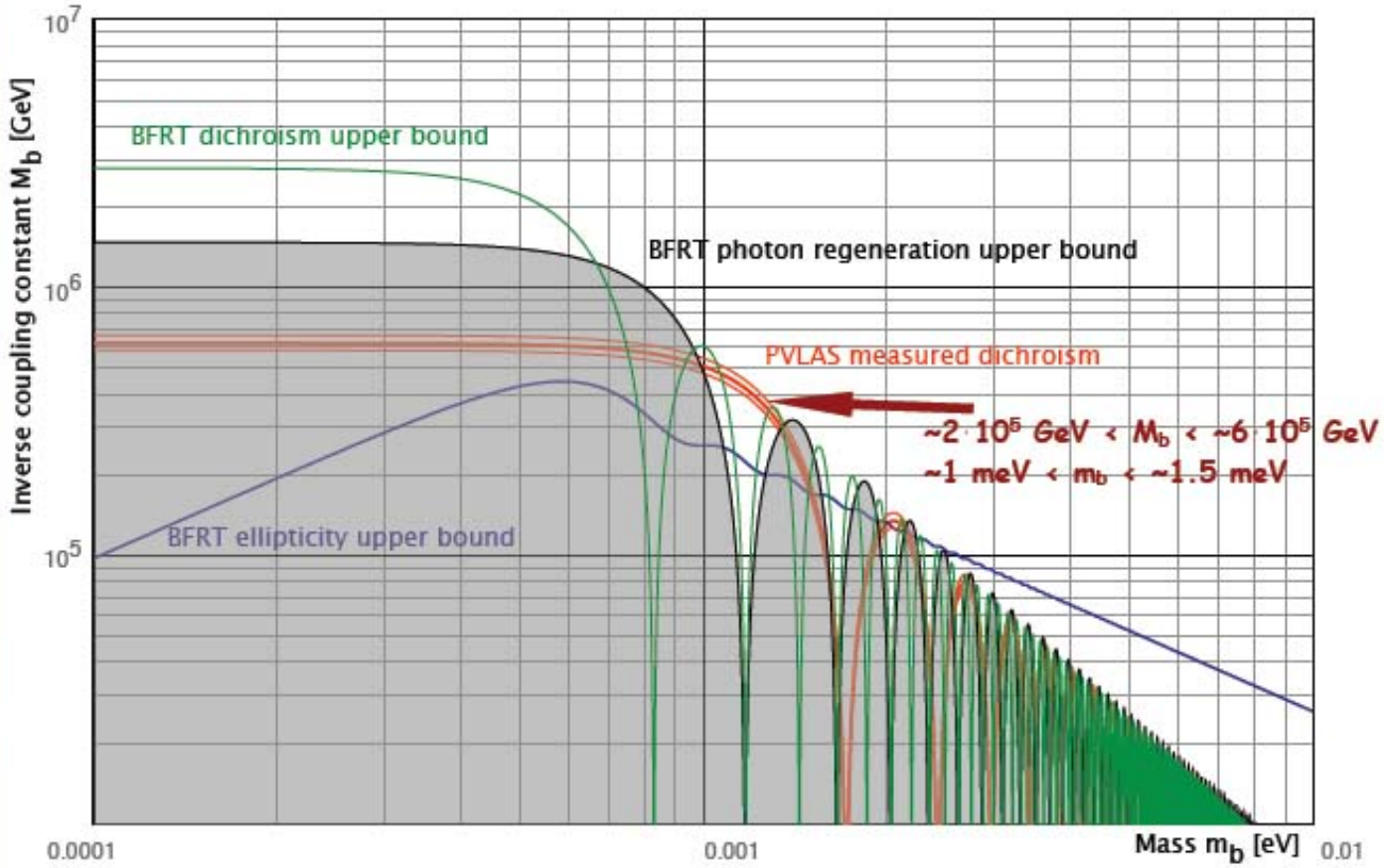
G. Cantatore - PVLAS Coll.- Axion Training 2005 - CERN

www.ts.infn.it/experiments/pvlas

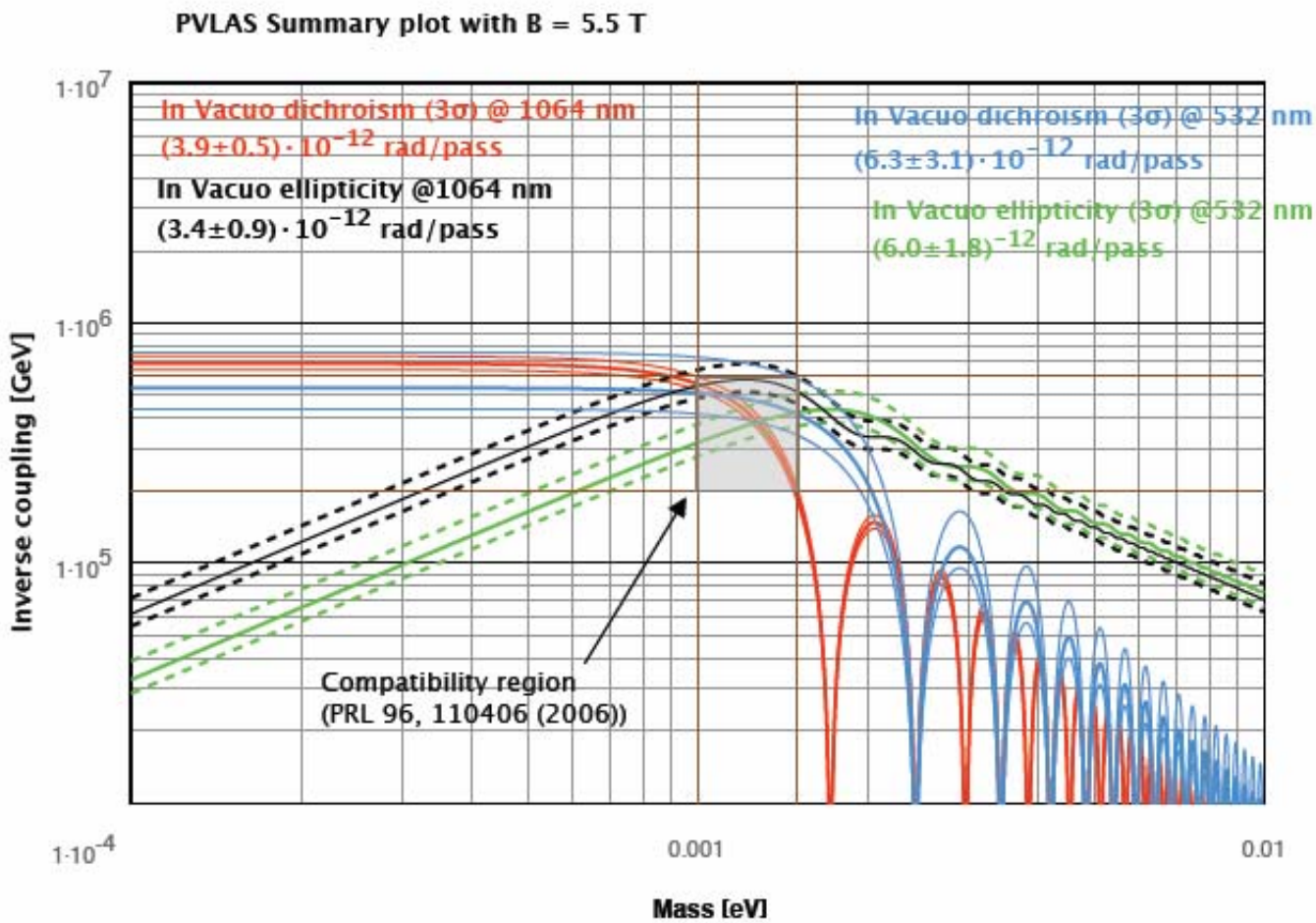
E.Zavattini, et al., *Phys. Rev. Lett.* **96** (2006) 110406

BFRT and PVLAS results on the $m_b - M_b$ plane

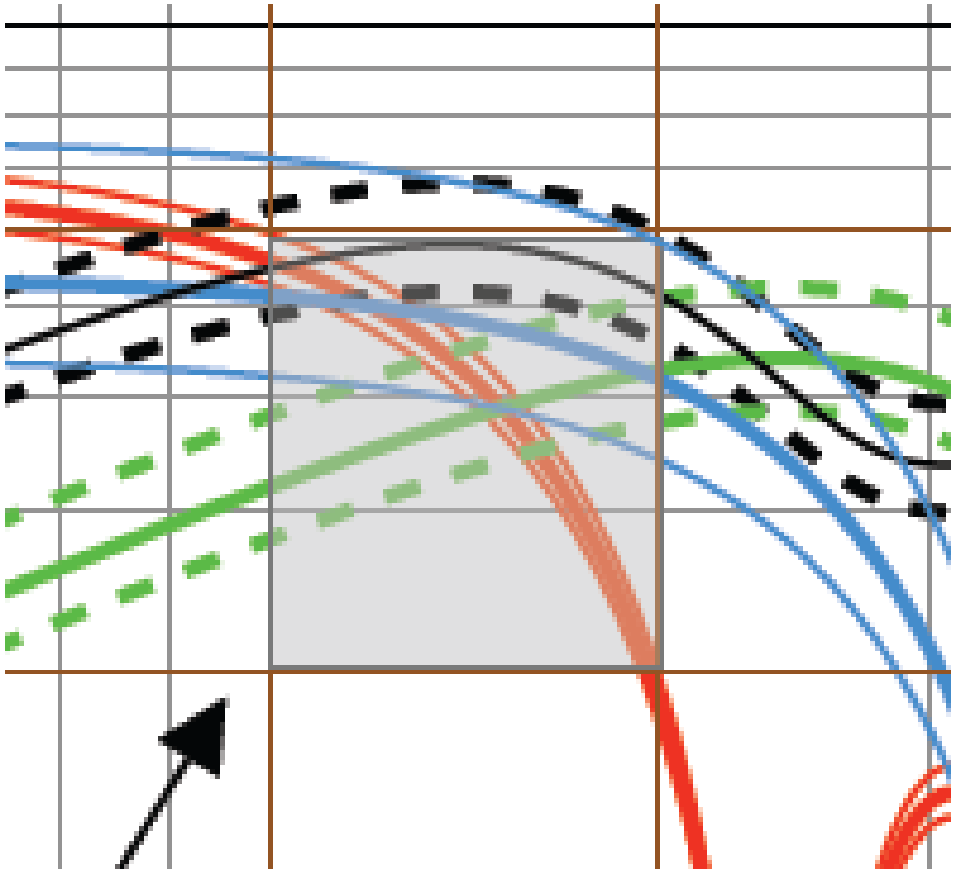
E.Zavattini, et al., *Phys. Rev. Lett.* **96** (2006) 110406



Global view


PVLAS Summary plot with B = 5.5 T
In Vacuo dichroism (3σ) @ 1064 nm
(3.9±0.5)·10^-12 rad/pass
In Vacuo ellipticity @1064 nm
(3.4±0.9)·10^-12 rad/pass
In Vacuo dichroism (3σ) @ 532 nm
(6.3±3.1)·10^-12 rad/pass
In Vacuo ellipticity (3σ) @532 nm
(6.0±1.8)^-12 rad/pass
Compatibility region
(PRL 96, 110406 (2006))
Inverse coupling [GeV]
1·10^7
1·10^6
1·10^5
1·10^-4
0.001
0.01
Mass [eV]

Zoom



Scalar or Pseudoscalar ?

Dicroism > 0

Pseudoscalar !?

Birefringence : $\Delta n < 0$

Scalar !?

M. Karuza, PhD Thesis (2007)

Vol 441| 4 May 2006

nature

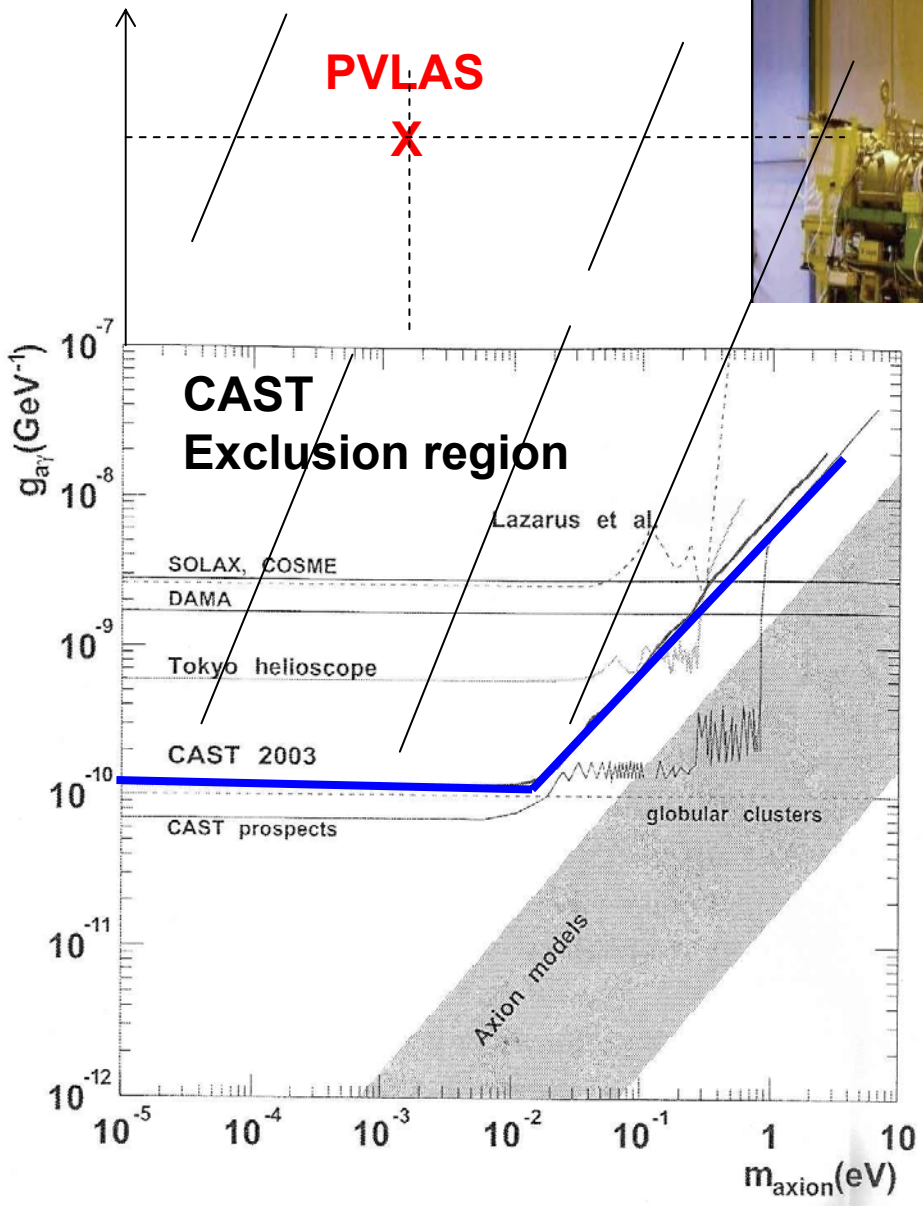
NEWS & VIEWS

PARTICLE PHYSICS

The first axion?

Steve Lamoreaux

For almost 30 years, the hunt has been on for a ghostly particle proposed to plug a gap in the standard model of particle physics. The detection of a tiny optical effect might be the first positive sighting.

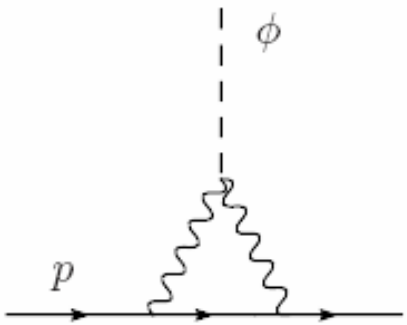


CAST

Cern Axion Solar Telescope

K.Zioutas, et al., *Phys. Rev. Lett.* **94** (2005) 121301

Scalar ?



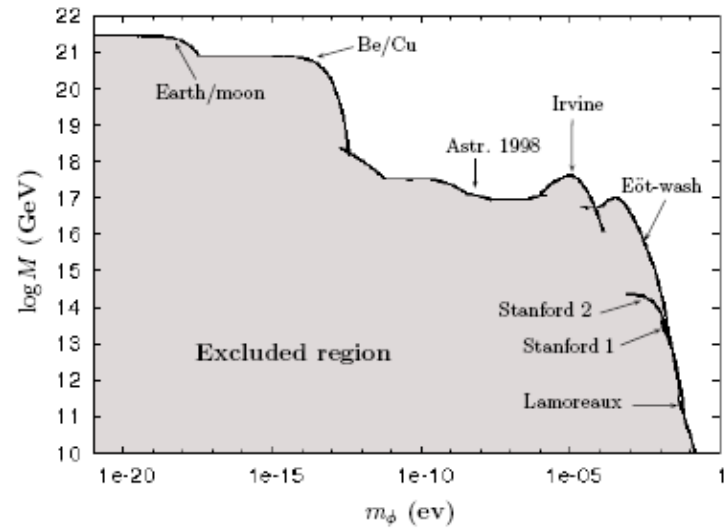
$$y = 4\,\frac{\alpha}{\pi}\,\frac{m_p}{M}\,\log\frac{\Lambda}{m_p}$$

$$\mathcal{L}_2 = y\,\phi\bar{\Psi}\Psi$$

Ψ is the proton field and y the Yukawa coupling

$$V(r) \simeq G\frac{m_1 m_2}{r}\left[1 + \frac{1}{G m_p^2}\,y^2\left(\frac{Z}{A}\right)_1\left(\frac{Z}{A}\right)_2 e^{-m_\phi r}\right]$$

Non newtonian force !



Light scalars coupled to photons and non-newtonian forces

Arnaud Dupays
INAF-IASF, Via E. Bassini 15, I-20133 Milano, Italy

Eduard Massó and Javier Redondo
Grup de Física Teòrica and Institut de Física d'Altes Energies, Universitat Autònoma de Barcelona, 08193 Bellaterra, Spain

Carlo Rizzo
Laboratoire Collision Agrégats et Réactivité, IRSAMC, Université Paul Sabatier et CNRS, 31062 Toulouse, France

PRL in press

New theories ? : ~~AXION~~ ~~SCALAR~~

The existence of a massive paraphoton which would couple with the standard photon and with the axionlike particle

E.Masso et J.Redondo, J. of Cosmology and Astroparticle Physics, **9** (2005) 015

The photon-initiated real or virtual production of pairs of low mass millicharged particles

H. Gies, J. Jaeckel and A. Ringwald, Phys. Rev. Lett., **97** (2006) 140402

The existence of an ultralight pseudo-scalar particle interacting with two photons and a scalar boson together with the existence of a low scale phase transition in the theory

R. N. Mohapatra and Salah Nasri, Phys. Rev. Lett., **98** (2007) 050402

…

What next ?? ⇨ **New experiments !!**

Outline

- Introduction
- Historical overview
- Recent results ⇨ Very recent results
- Future projects
- The BMV project
- Conclusions

Since 1994 **Q&A** (Quantum electrodynamics test & search for Axion)

Pr. Ni (University of Taiwan)

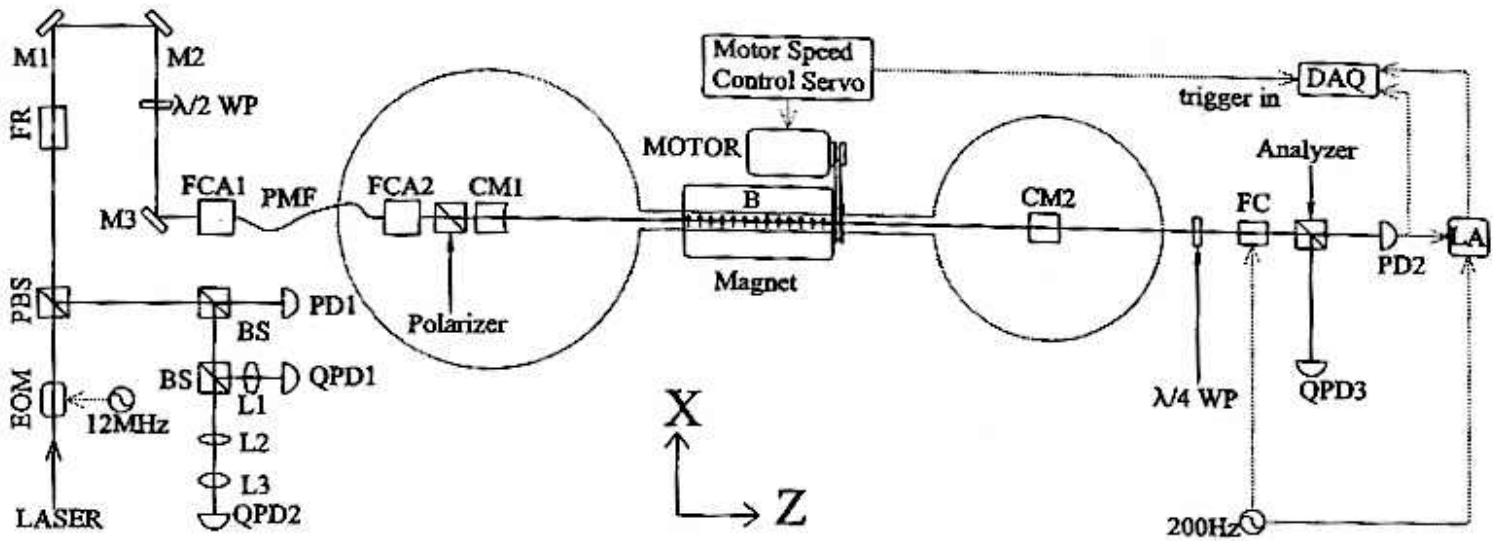


Figure 1. Experimental Setup. EOM electro-optical modulator; λ/2 WP half-wave plate; λ/4 WP quarter-wave plate; L1, L2, L3 lenses; M1, M2, M3 reflection mirrors; PBS polarizing beam splitter; BS beam spiltter; FR Faraday rotator; FCA1, FCA2 fibre coupler assemblies; PMF polarization maintaining fibre; CM1, CM2 cavity mirrors; B magnetic field; PD1, PD2 phtodetectors; QPD1, QPD2, QPD3 quadrant photodiodes ; FC Faraday cell; DAQ data acquisition system; LA lock-in amplifier.

Preliminary results on arXiv ⟹ **"Almost" disproved PVLAS**

hep-ex/0611050

Confidence level of their limits ? ≈ 1 σ

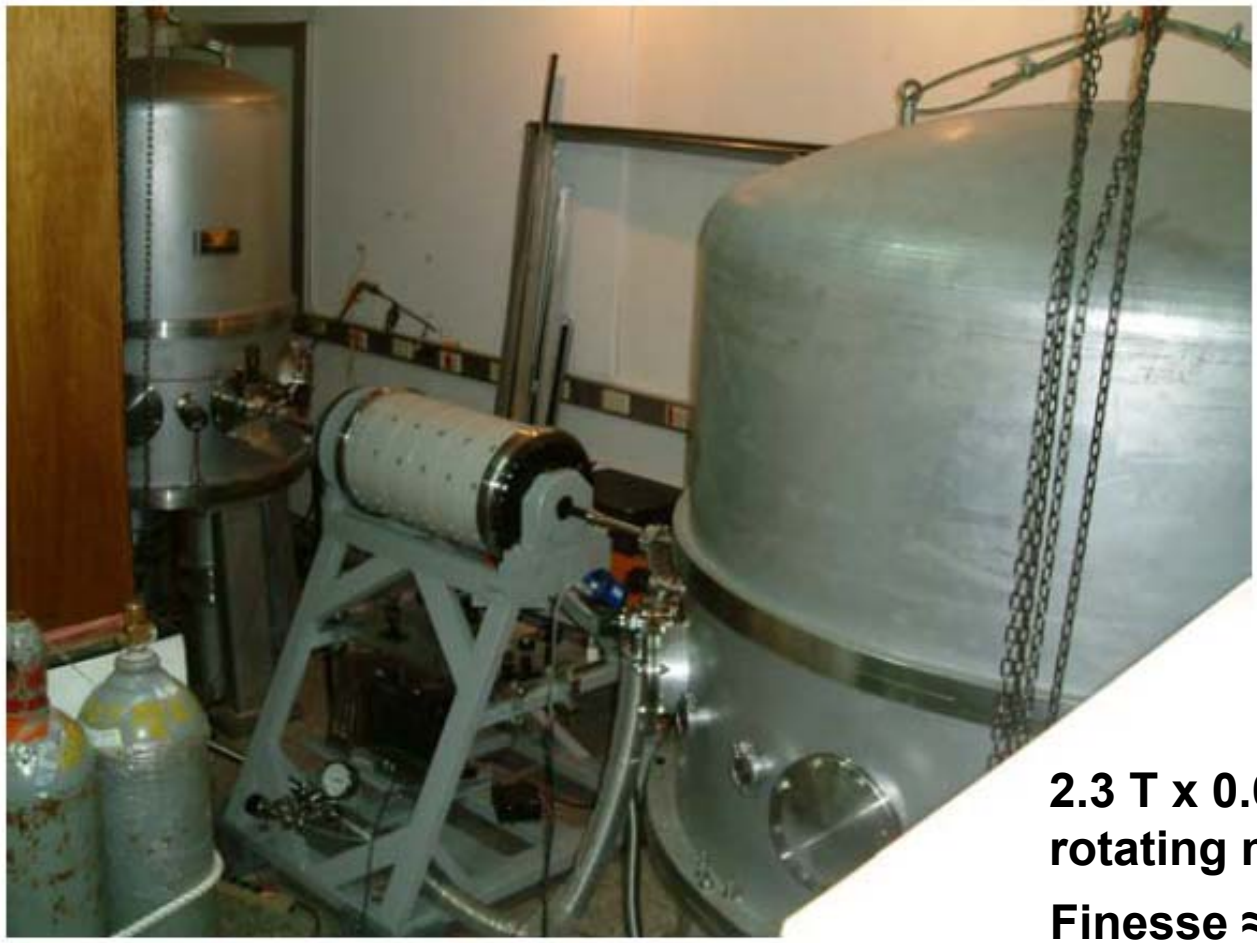


Fig. 3. A picture of experimental apparatus.

2.3 T x 0.6 m permanent rotating magnet

Finesse ≈ 30 000

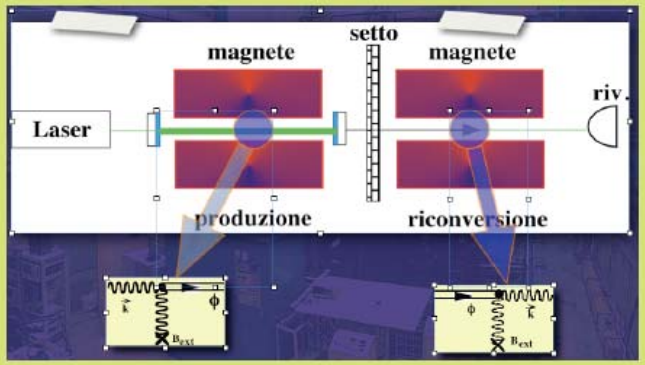
Sensitivity = 10^{-6} $1/\sqrt{Hz}$

Outline

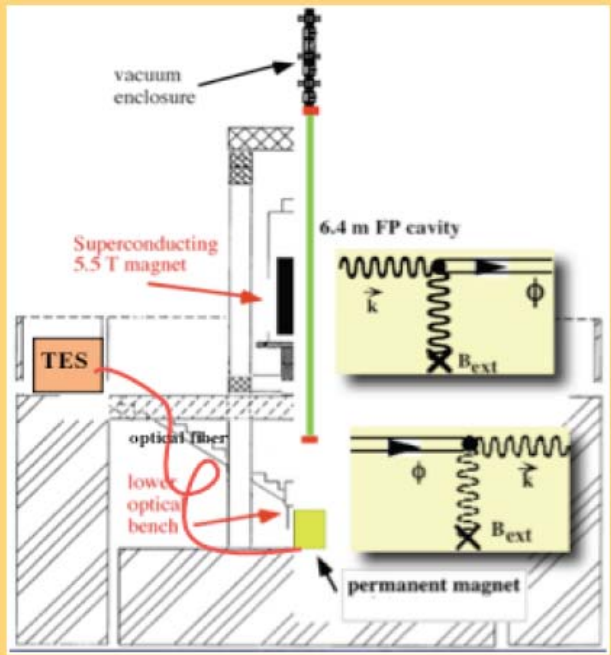
- Introduction
- Historical overview
- Recent results
- Future projects
- The BMV project
- Conclusions

Photon regeneration test at PVLAS

- Principle of a photon regeneration experiment



- Implementation at PVLAS with
  - 50 cm 2.2 T permanent magnet
  - TES detector



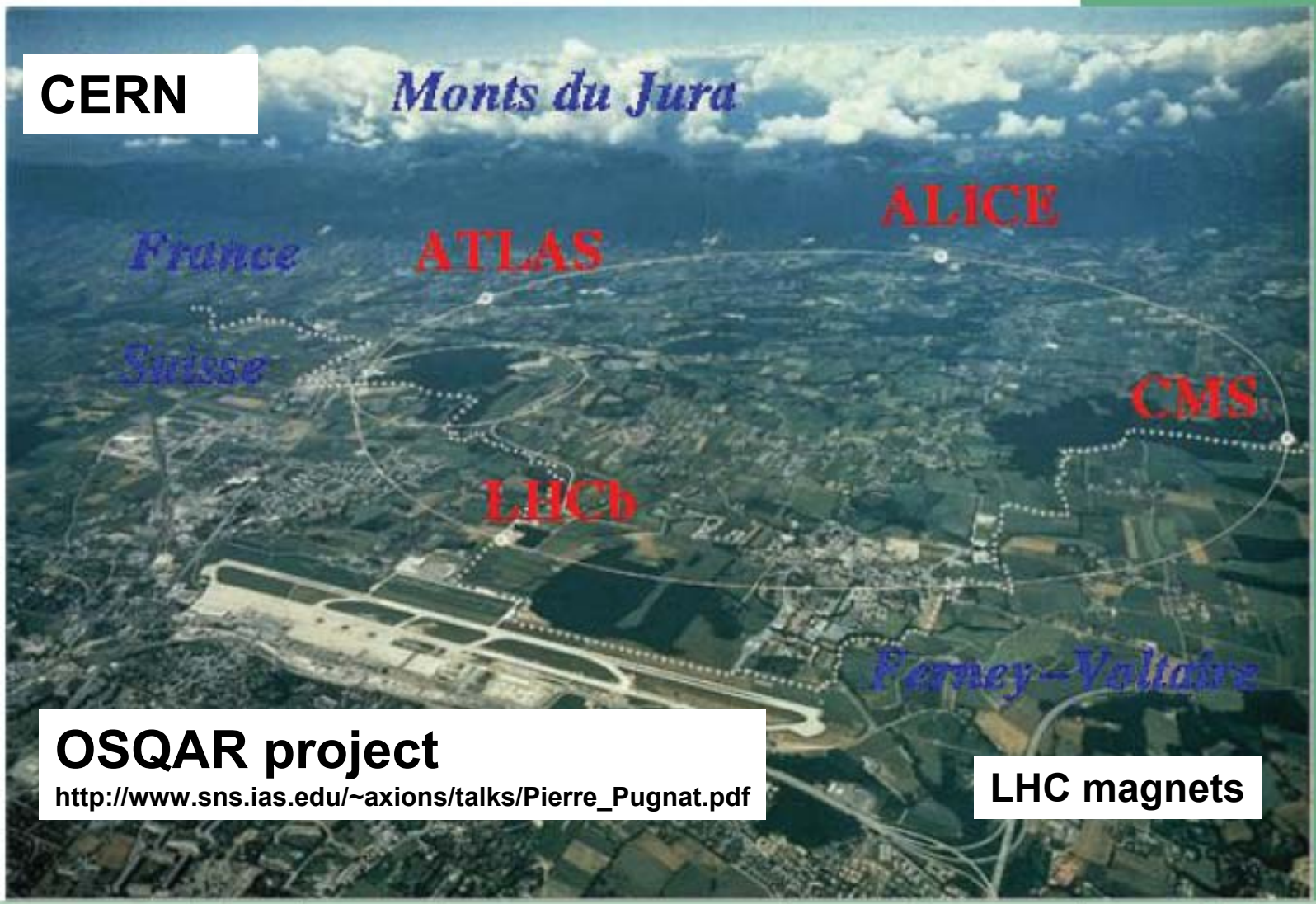
Axion-Like Particle Search at DESY

The ALPS Project (Proposal)

DESY, Laser Zentrum Hannover, Sternwarte Bergedorf

http://www.sns.ias.edu/~axions/talks/Axel_Lindner.pdf

HERA magnets



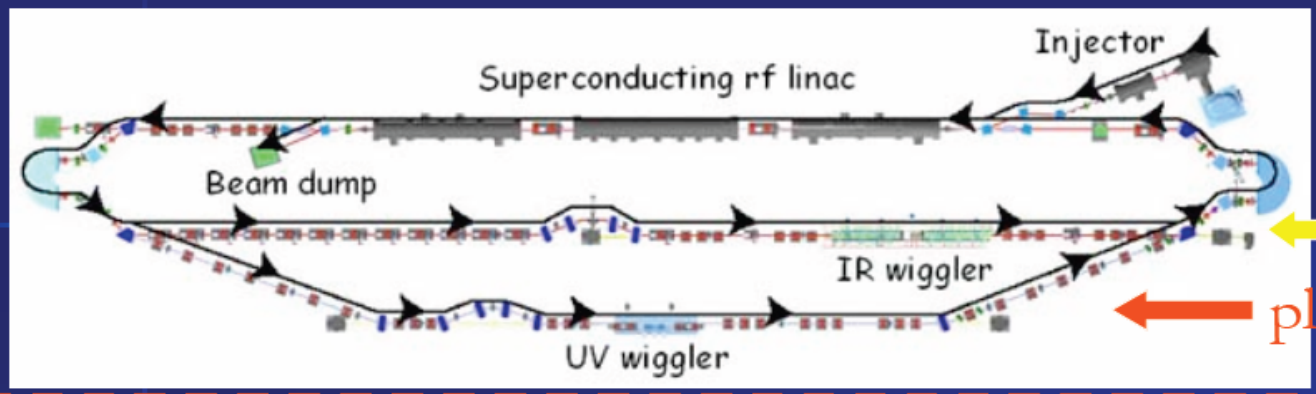
OSQAR project

http://www.sns.ias.edu/~axions/talks/Pierre_Pugnat.pdf

LHC magnets

figure 1 : Vue générale du site du CERN où le LHC est en construction. La ligne pointillée représente le passage de la frontière entre la France et la Suisse. En arrière plan, se devinent les monts du Jura ; au premier plan, on voit l'aéroport de Genève-Cointrin. Le cercle indique l'emplacement du tunnel dans lequel est installé l'accélérateur de particules.

JLAB FEL: regeneration experiment



current

planned; 2007

LIPSS Project: A Search for Photon Regeneration at Optical Frequencies

http://www.sns.ias.edu/~axions/talks/Andrei_Afanasev.pdf

Data early 2007 ?

Outline

- Introduction
- Historical overview
- Recent results
- Future projects
- The BMV project
- Conclusions

The *Biréfringence Magnétique du Vide* project

Laboratoire Collisions Agrégats Réactivité, Toulouse, France :

B.Pinto da Souza (Ph-D), M.Fouché, C.Robilliard, J.Vigué, C.Rizzo.

Laboratoire National Champs Magnétiques Pulsés, Toulouse, France :

S.Batut (Ph-D), G.Rikken, R.Battesti.

and **≈ 10 Engineers et Technicians**

In collaboration with

LMA-VIRGO, Lyon, France :

LULI, Ecole Polytechnique, France.

LNCMP :
European record of magnetic field

Power supply
24 kV, 14 MJ
65 kA

77.3 T

Campus of the Toulouse III University

The BMV project :

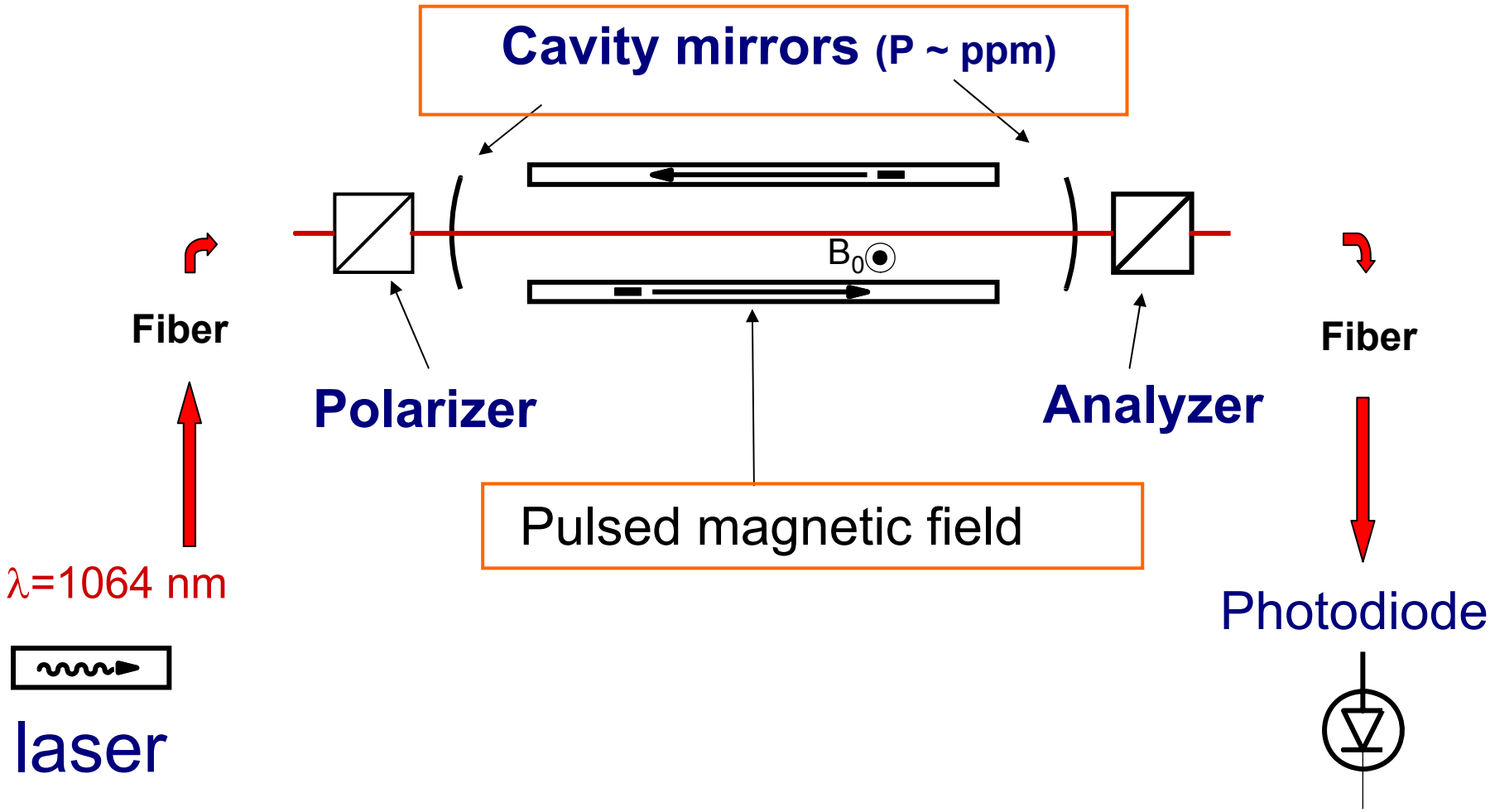
BMV at the LNCMP

Funded since 2001
Motivated by the QED

Regeneration of photons at the LULI

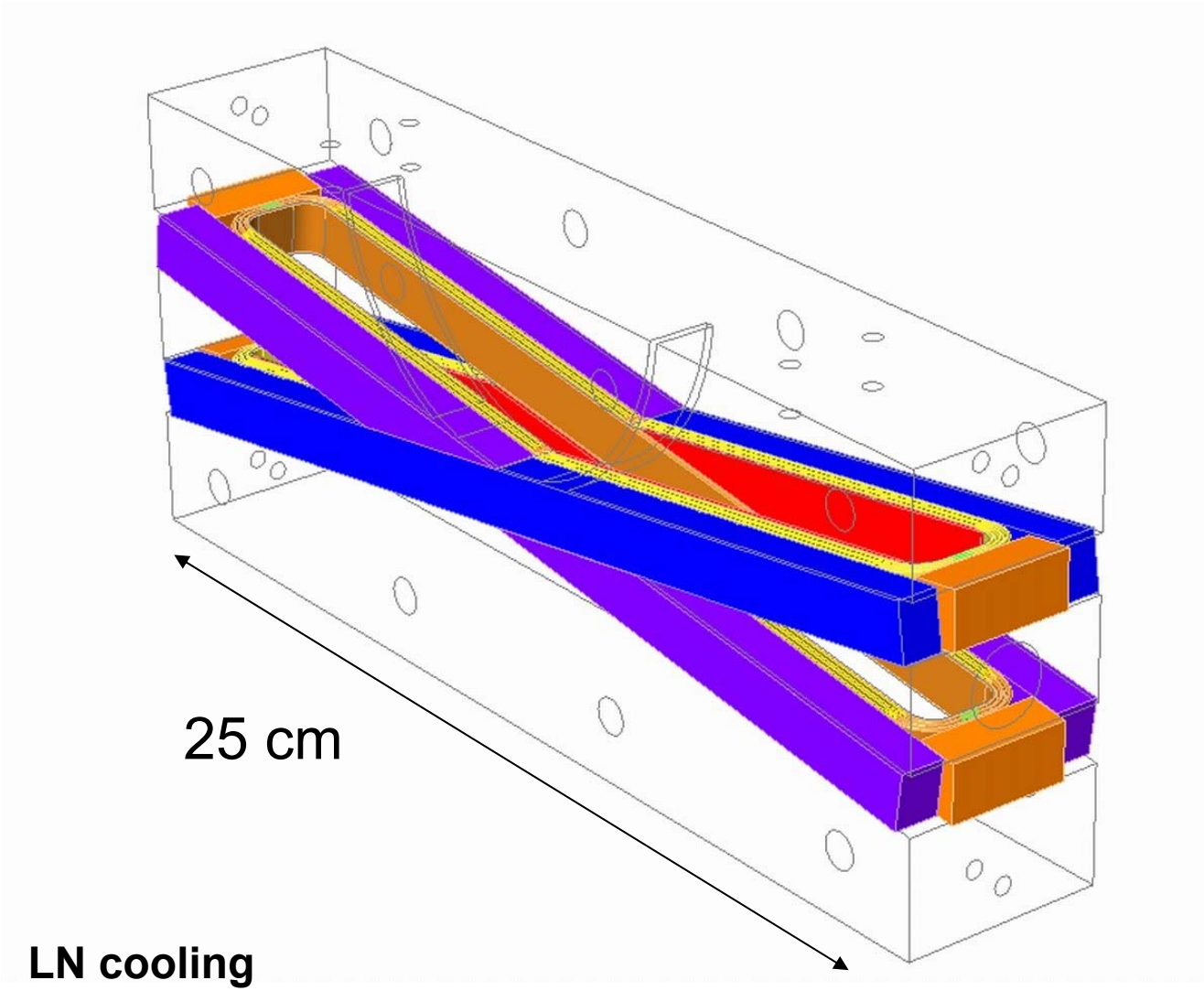
Funded in 2006
Motivated by PVLAS results
i.e. axionlike particle search

Experimental scheme : based on Iacopini and Zavattini's paper (1979)



S.Askenazy, *et al.*, CP564, *Quantum Electrodynamics and Physics of the Vacuum,* edited by G.Cantatore (2001) AIP

Xcoil



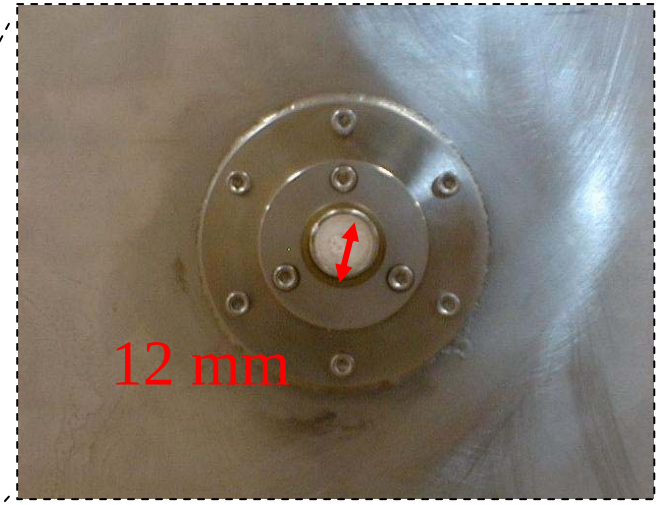
LN cooling

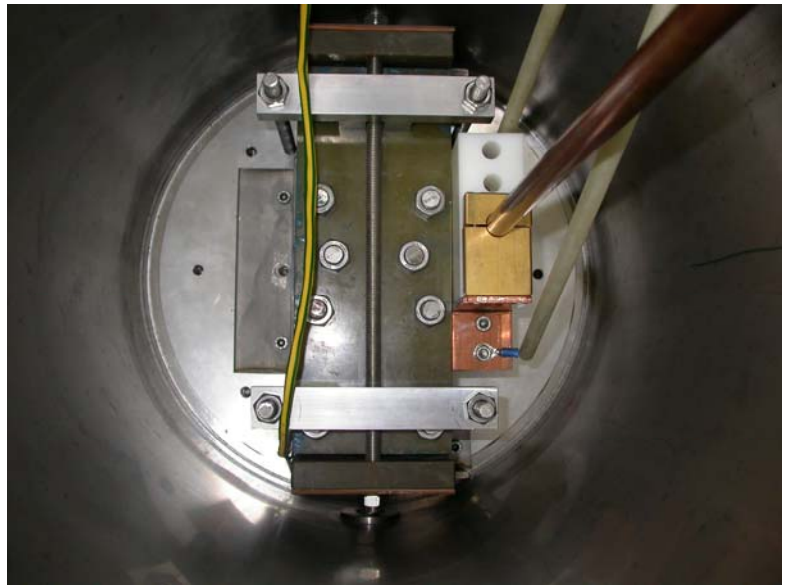
X coil

Winding

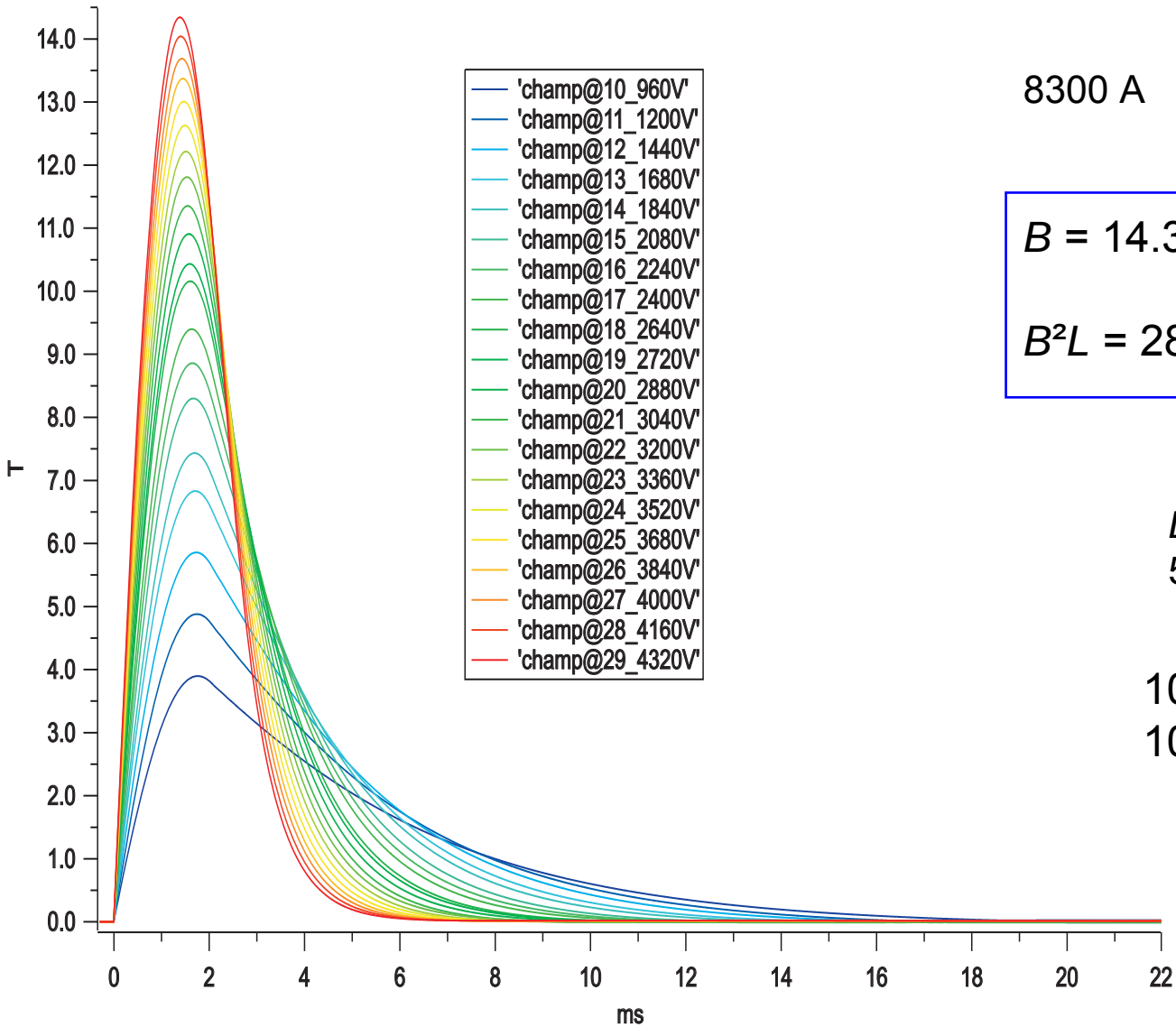
Test at liquid nitrogen temperature

LN cryostat





The coil in its cryostat



8300 A

B = 14.3 T;

B^2L = 28 T²m; BL = 2.6 Tm

Duty cycle :
5 pulses per hours

100 pulses at 11.5 T
100 pulses at 12.5 T

Fabry-Perot cavity

- Ellipticity x $2F/\pi$.
- Mirrors birefringence
- Pound-Drever-Hall locking

Finesse F > 200 000
Mirrors made at the LMA-VIRGO of Lyon → Clean room

Mirrors for the Fabry-Perot : 4 ready in Toulouse

LABORATOIRE MATÉRIAUX AVANCÉS

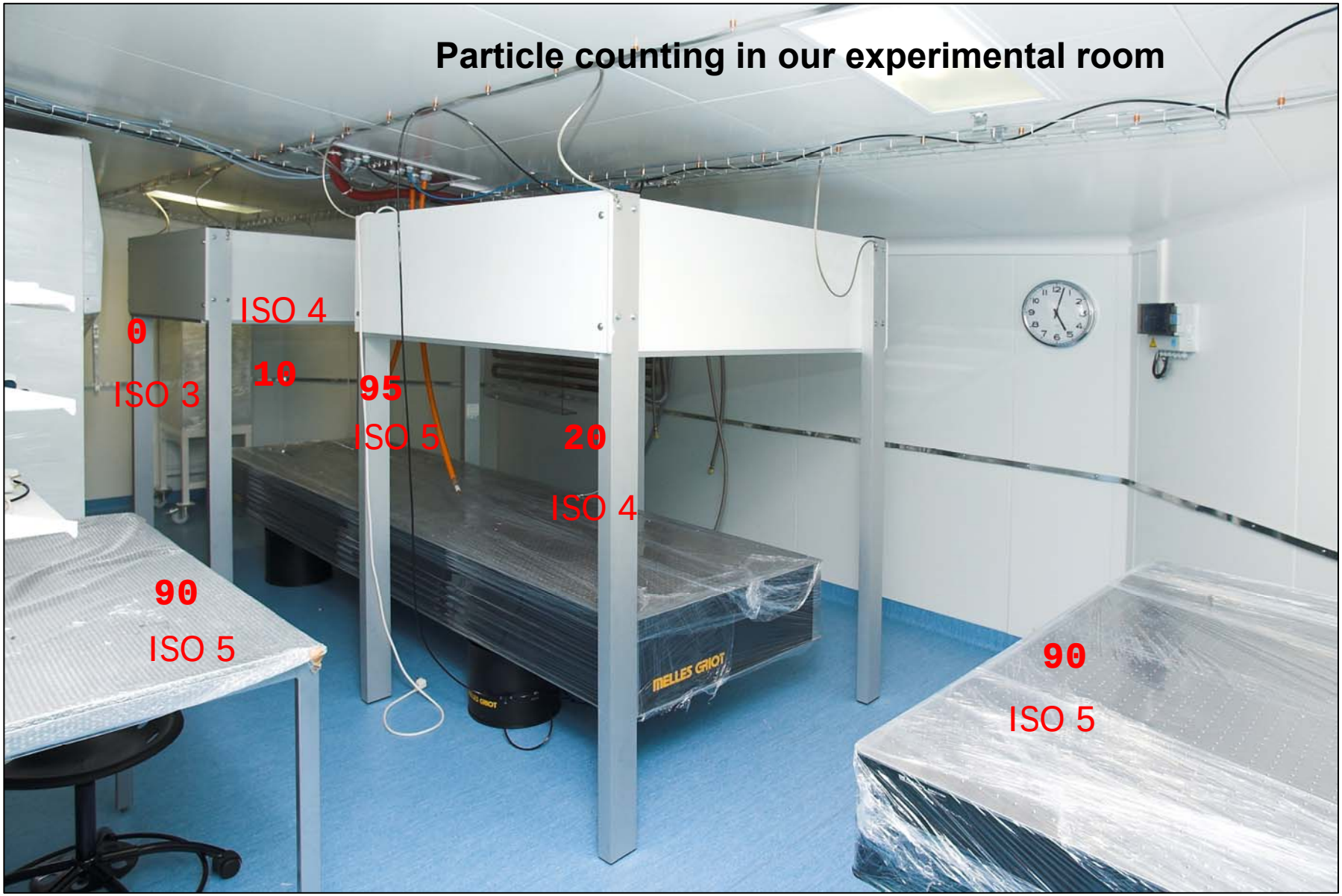
Miroirs (HB)22 HBB haute réflectivité pour cavités BMV

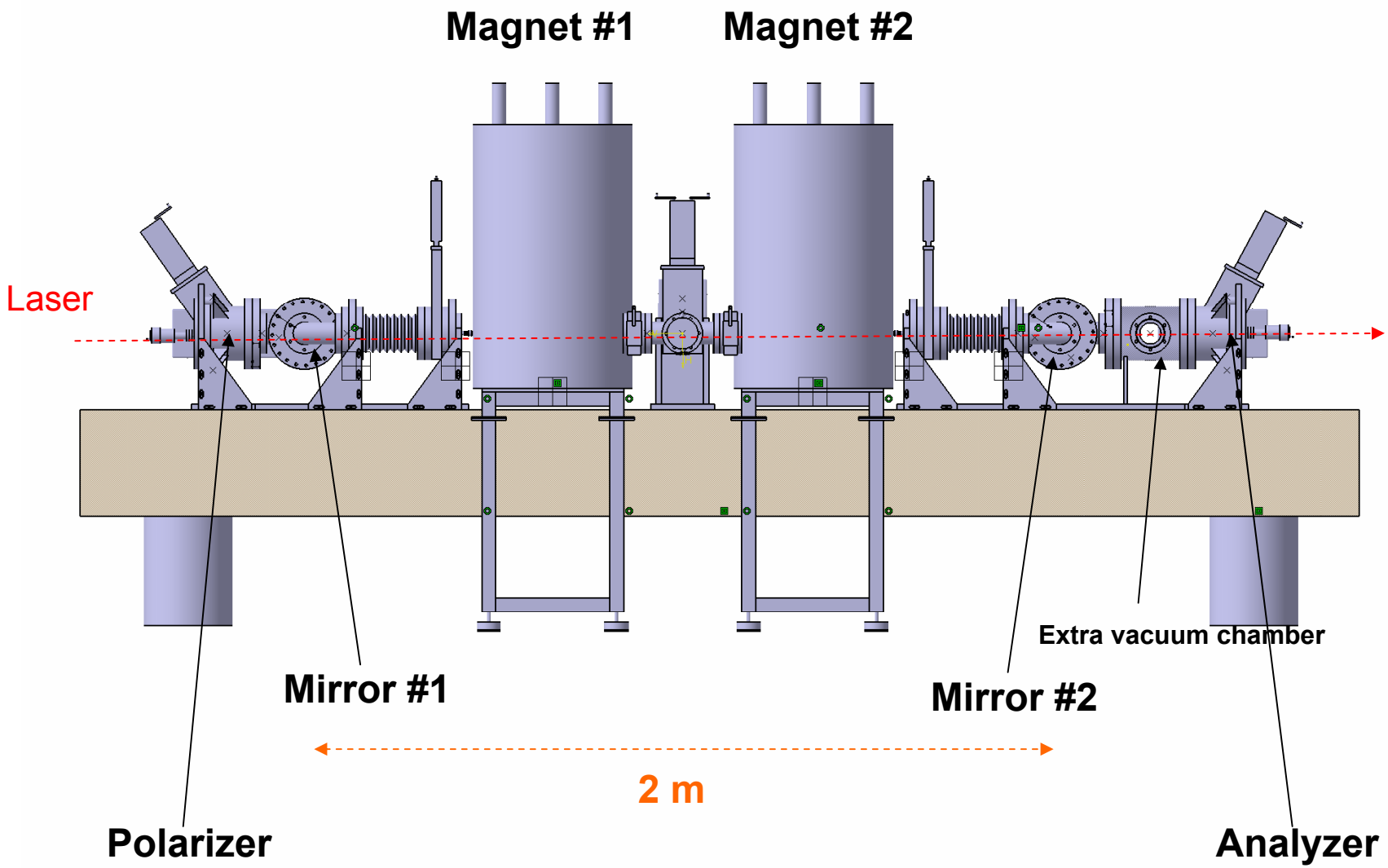
Référence	Diffusion (ppm) @ 1064 nm		Absorption @ 1064 nm (ppm)	Transmission @ 1064 nm (ppm)
	Sur ∅ 16 mm	Au centre (P_D)	(P_A)	(T)
06033/11 concave 8 m, incidence 0°	9	2,4	0,8	1,7 incidence 1°
06033/12 concave 8 m, incidence 0°	8	8	0,8	1,9 incidence 1°
06033/13 concave 8 m, incidence 0°	9	7	0,8	1,5 incidence 1°
06033/14 concave 8 m, incidence 0°	11	2,4	0,8	1,6 incidence 1°

$$650\,000 \geq F = \frac{\pi}{T + P_D + P_A} \geq 290\,000$$

LMA
22, Bd Niels Bohr
69622 – Villeurbanne Cedex

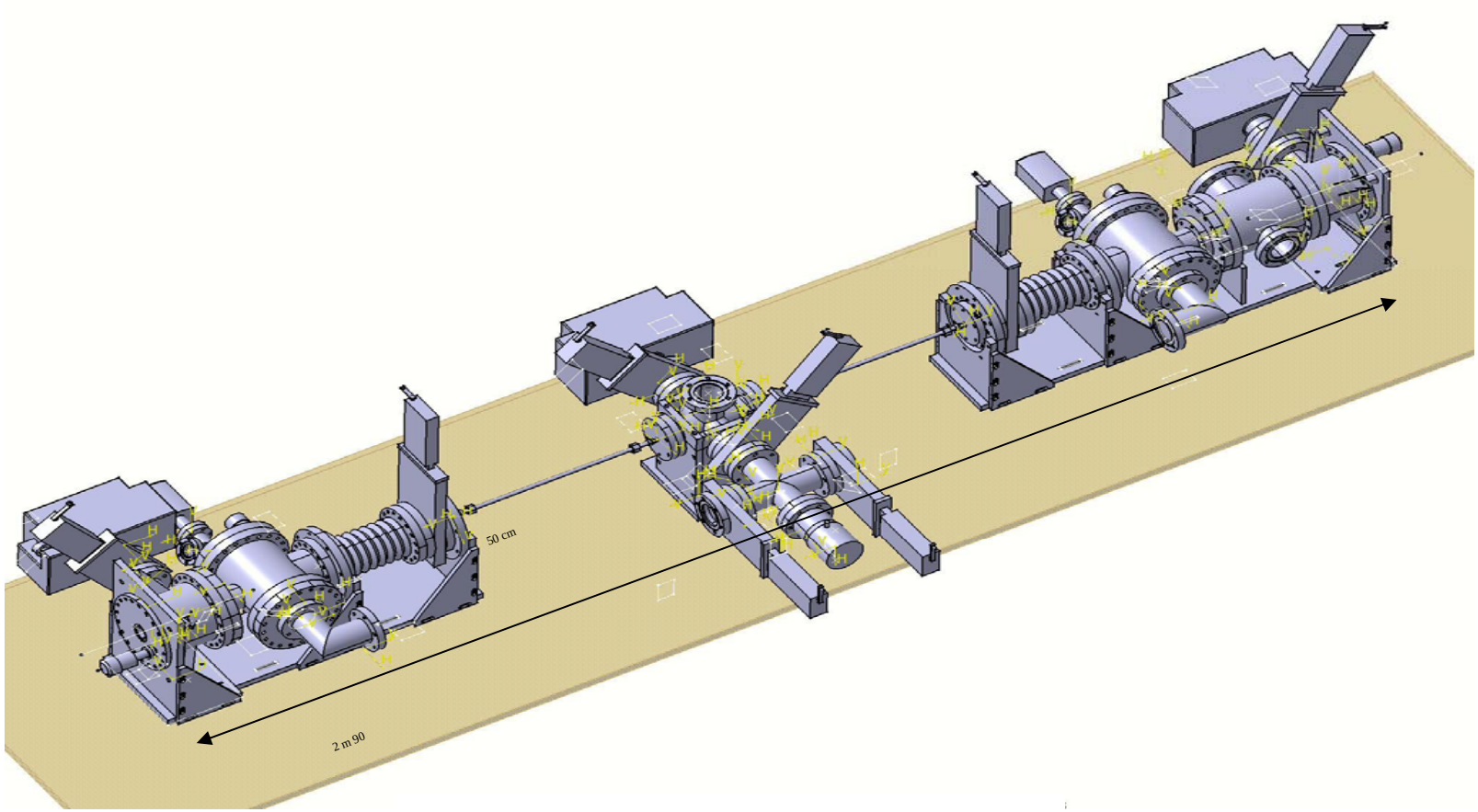
Mai 2006


Particle counting in our experimental room
ISO 4
0
ISO 3
10
95
ISO 5
20
ISO 4
90
ISO 5
90
ISO 5
MELLES GRIOT


Magnet #1
Magnet #2
Laser
Extra vacuum chamber
Mirror #1
Mirror #2
2 m
Polarizer
Analyzer

Set-up

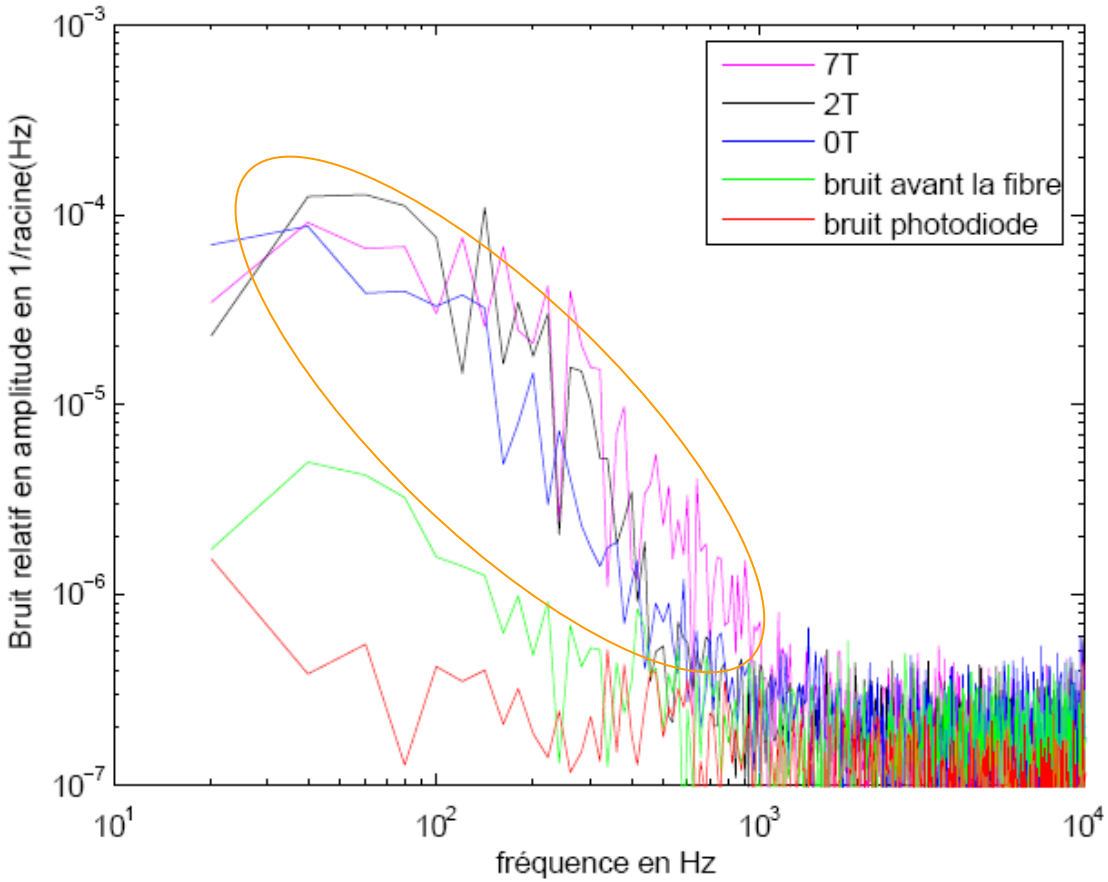
BMV



Optical set-up completed july 2006

Optical fiber injection

Noise measurements with field up to 7 T



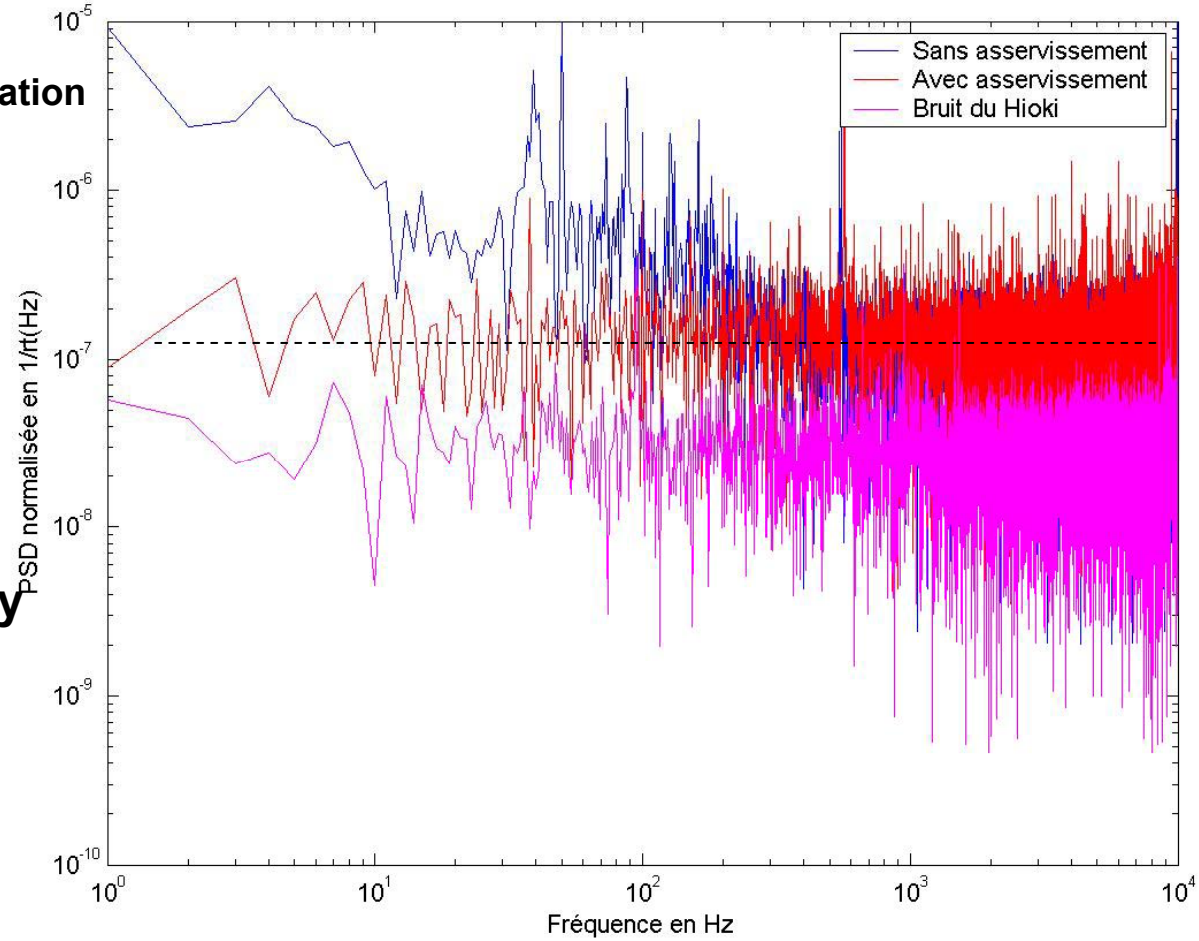
Polarisation noise

Thanks to a polarisation stabilisation of the laser light after the fiber,

10^{-7} Hz$^{-1/2}$

Corresponding sensitivity

≈ 10^{-9} Hz$^{-1/2}$!!



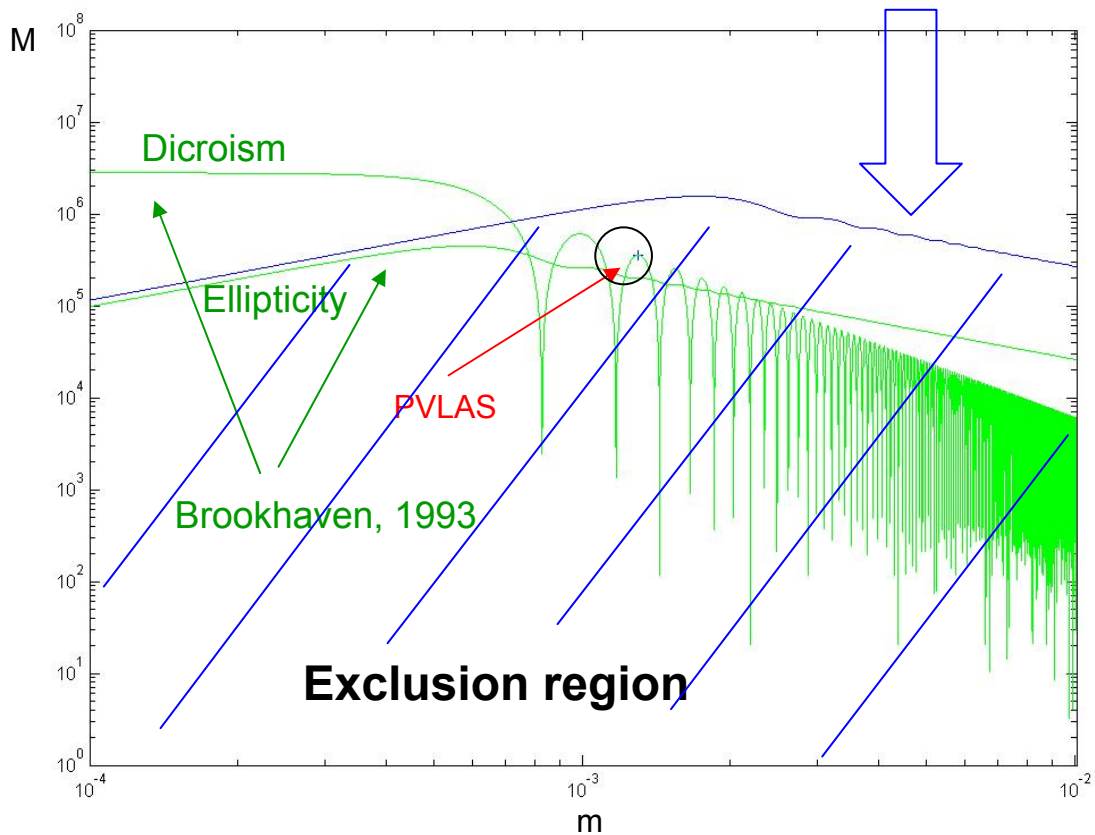
PVLAS : qq 10^{-7} Hz$^{-1/2}$
Q&A : qq 10-6 Hz-1/2
Expected for BMV : 10^{-8} Hz$^{-1/2}$

expected :

- BL = (2x)2.3 Tm; B^2L = (2x)21 T²m
- finesse ≥ 200 000
- Sensitivity = $10^{-8}/Hz^{1/2}$

BMV, **30 pulses,** 1 day

Test of PVLAS results in 2007

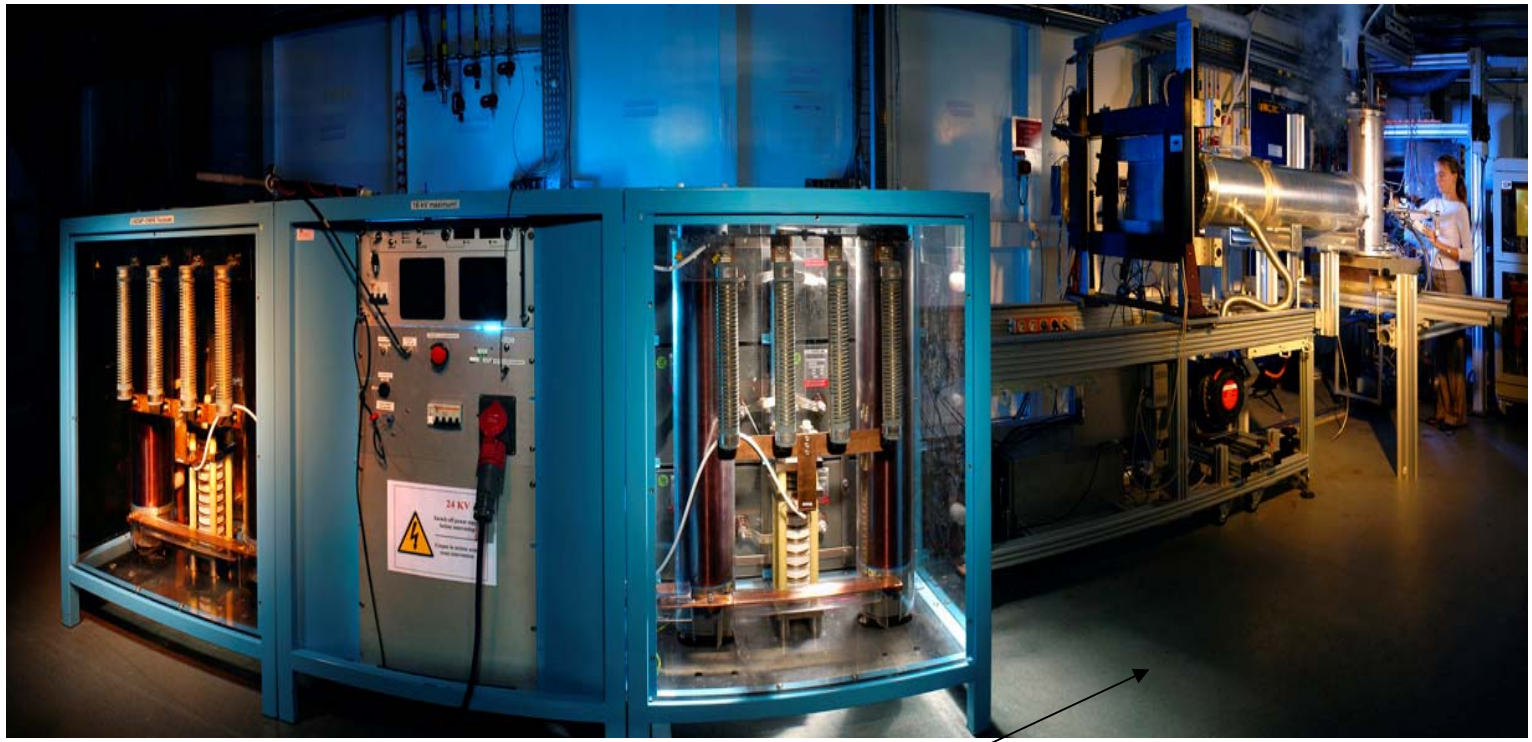


Photon regeneration at LULI

(*L*aboratoire pour l'*U*tilisation des *L*asers *I*ntenses)

Campus of the *École Polytechnique*
Outside Paris

Thanks to the pulsed coils of BMV



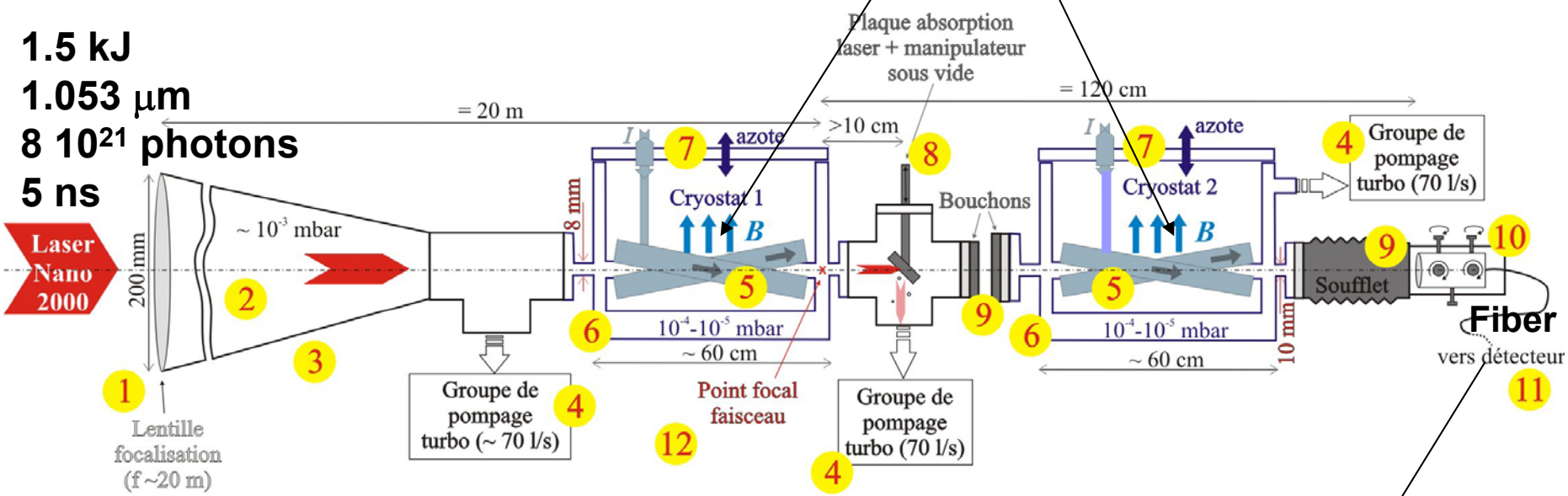
24 kV; 3x(1,2)^3 m^3

Transportable power supply (here at the ESRF, Grenoble)

Experimental scheme

10 T over 0.4 m

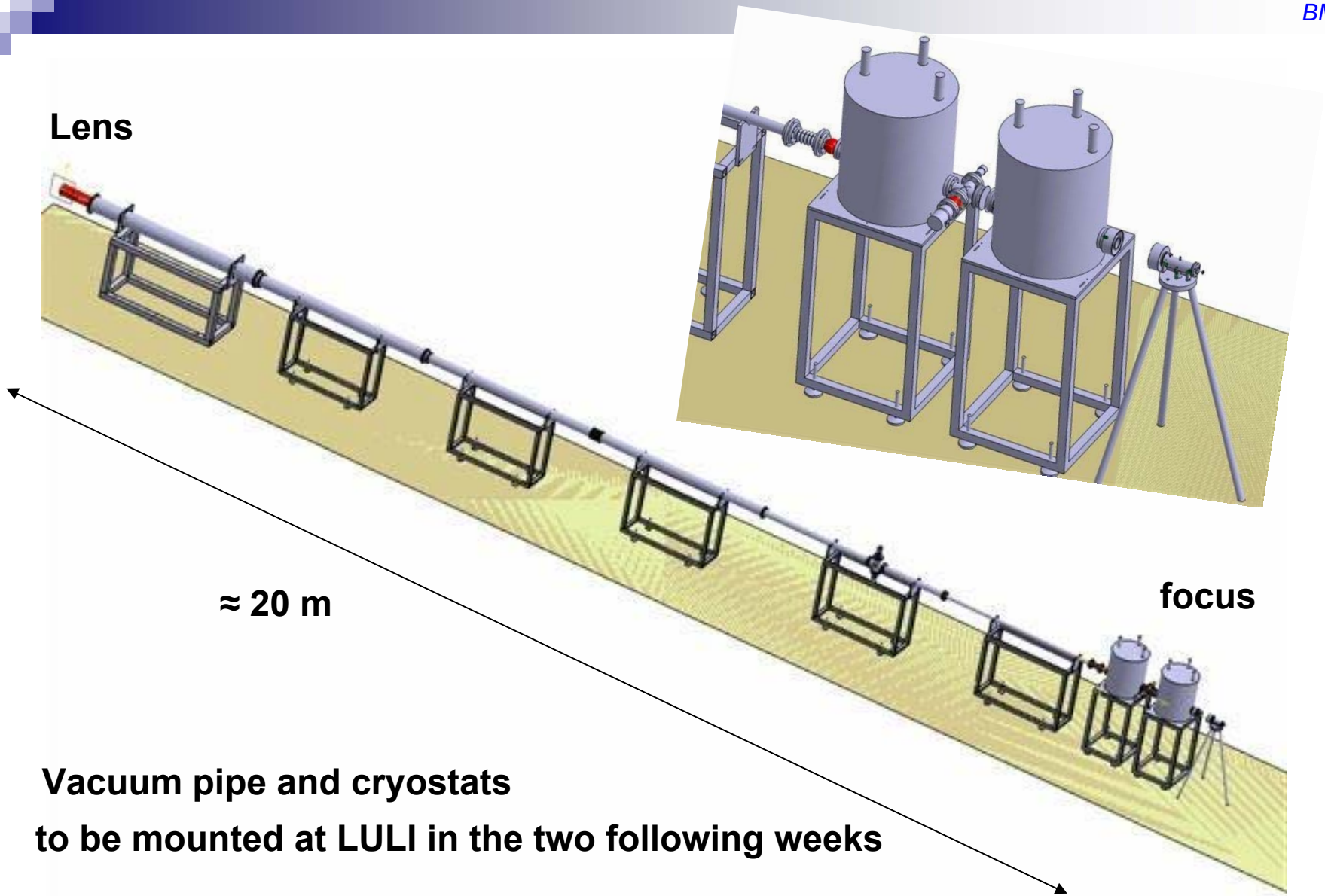
1.5 kJ
1.053 μm
8 10^{21} photons
5 ns



13 Synchronisation
14 Passage de câbles, installation
15 Mise à la terre parties métalliques
16 Prise de données
17 Protocoles d'alignement et de tir
18 19

Single photon counter,
0.4 detection efficiency,
Noise : 5 10^{-5} counts/ns

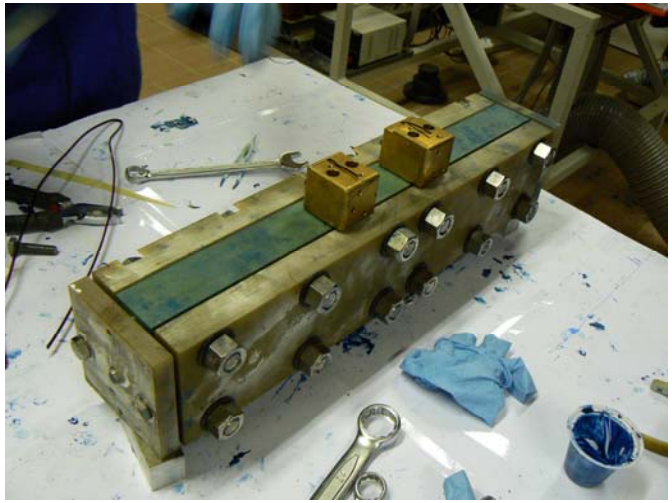
BMV



Vacuum pipe and cryostats

to be mounted at LULI in the two following weeks

Laser room at LULI



- **Pulsed coils**
  - Xcoil
  - 10 T * 0,45 m

    ⇒ **B.L = 4,5 T.m for 5 ms**

Tested up to 5,15 T.m
(Bmax = 14,15 T / 58 T^2.m)

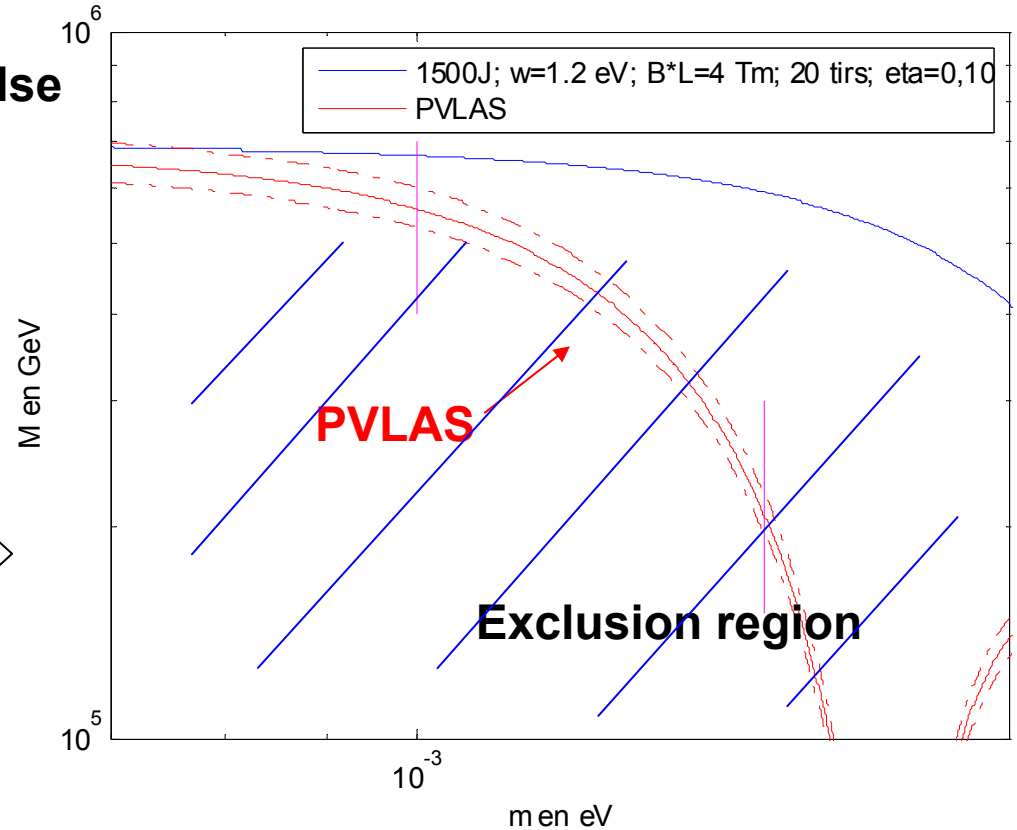
- **Single photon counter**
  - detection efficiency = 0.4
  - Low noise
  - Injected by fiber

Under final test

Beam time : one week in May, July and September 07

More than 1 photon for laser pulse following PVLAS !

Limits after 20 laser pulses (5 days)



- Conclusions : A new discovery ?

the answer in 2007 !

If not … QED vacuum birefringence measurement coming soon

… soon after upgrade to 4 magnets of 25 T.

The BMV project

(Biréfringence Magnétique du Vide)

Carlo RIZZO

LCAR-IRSAMC

Université Paul Sabatier et CNRS

Toulouse

carlo.rizzo@irsamc.ups-tlse.fr

CNRS PostDoc position open starting 9/07 !!!!!