Magnéto-optique du vide quantique

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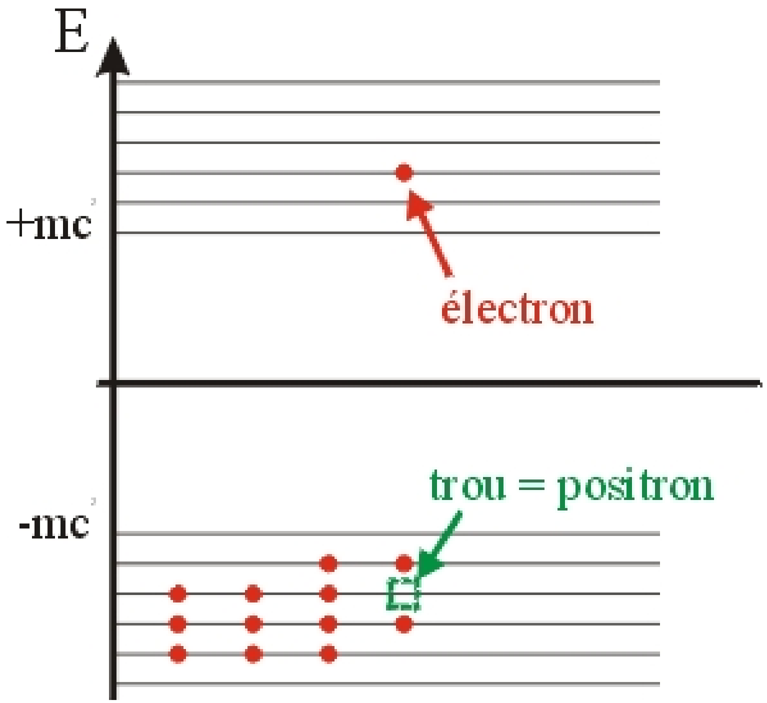
Plan

- Introduction
- Historique
- Résultats récents
- Les projets futurs
- Le projet BMV de Toulouse :
  premiers résultats
- Conclusions

Le modèle de Dirac du Vide Quantique : 1934

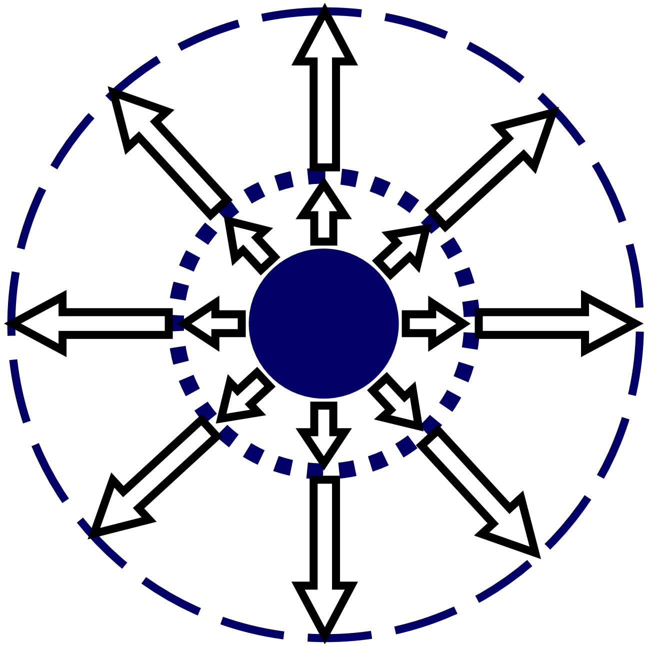


« Previously, people have thought of the vacuum as a region of space that is completely empty, a region of space that does not contain anything at all. Now we must adopt a new picture. We may say that the vacuum is a region of space where we have the lowest possible energy. Now, to get the lowest energy we must fill up all the states of negative energy […]Thus we must set up a new picture of the vacuum in which all the negative energy states are occupied and all the positive energy states are unoccupied.»

P.A.M. Dirac

P.A.M. Dirac, *Rapport du 7ᵉ Conseil Solvay de physique, structure et propriétés des noyaux atomiques*, (1934) 203

L'expansion de l'univers s'accélère !!!



L'existence de la densité d'énergie du vide pourrait expliquer ce phénomène

mais

sa valeur est au moins 10^{50} fois trop grande !

Propagation de la lumière dans le vide quantique

Le vide est invariant par Lorentz et CPT, donc

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

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

… en présence de B_0 : $n_{par} \neq n_{per}$

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

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

avec B_0 en Tesla

$$\Delta n = n_{par} - n_{per}$$

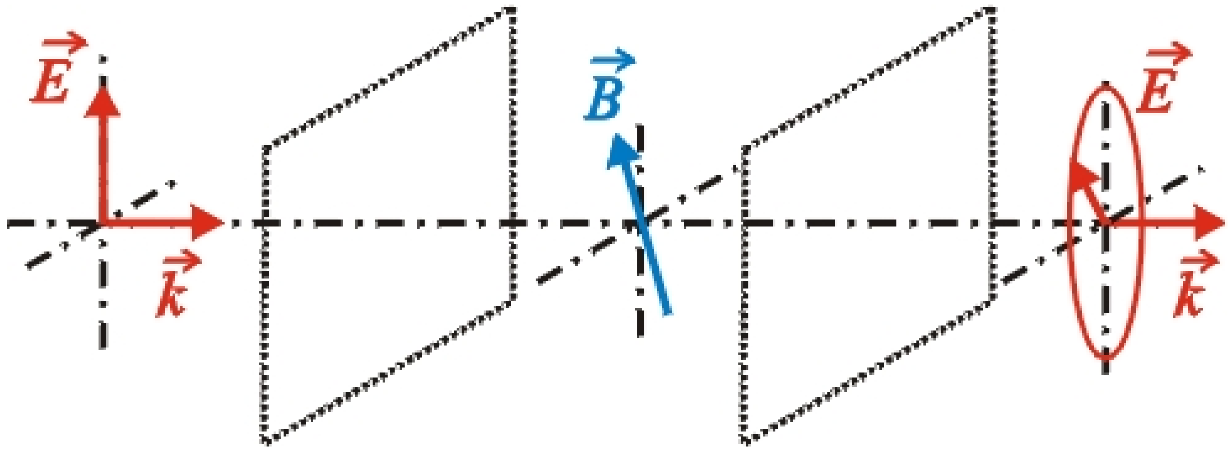
Z.Bialynicka-Birula et I.Bialynicki-Birula, *Phys. Rev. D* **2** (1970) 2341

Le vide quantique est un milieu optique non linéaire

Biréfringence magnétique du vide

ou *effet Cotton-Mouton* : connu depuis 1901 dans les milieux standards

J.Kerr, *Br. Assoc. Rep.* (1901) 568;
A.Cotton et H.Mouton, *Ct. R. hebd. Séanc Acad. Sci. Paris* **141** (1905) 317, 349; ibid. **142** (1906) 203; Ibid. **145** (1907) 229

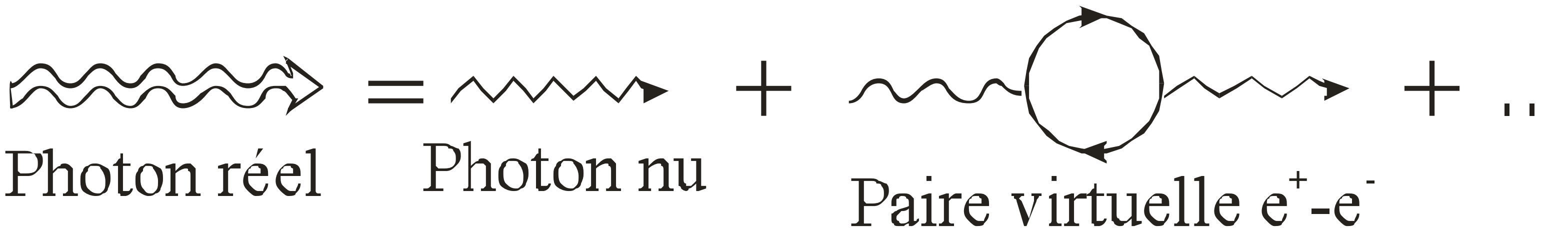


$$\Delta n\ (\text{vide}) \approx 10^{-8}\ \Delta n\ (\text{hélium STP})$$

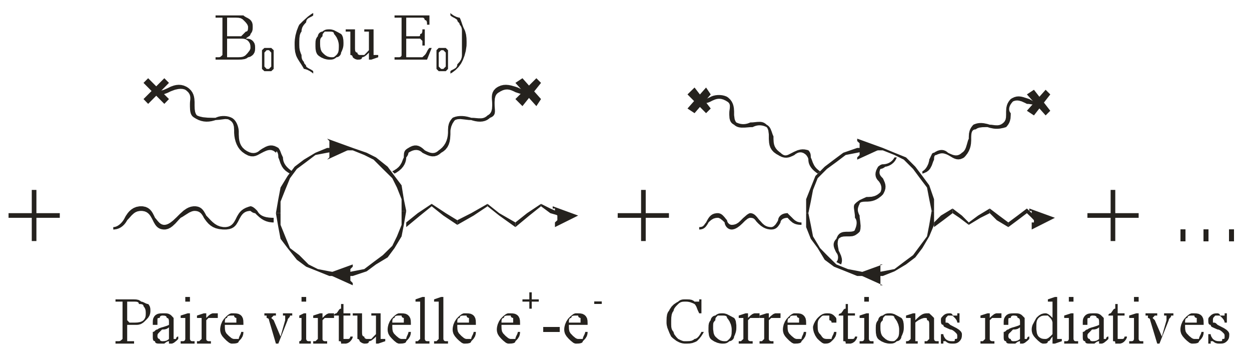
C.Rizzo, A.Rizzo, D.M.Bishop, *Int. Rev. Phys. Chem.* **16** (1997) 81

Propagation dans le vide :

c



Propagation dans le vide en présence d’un champ



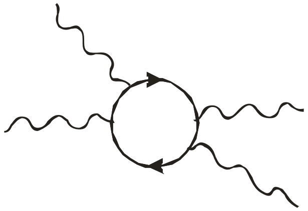
O(α^2)

O(α^3)

1,5 % du terme d’O(α^2)

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

O(α²)



Collisions photon-photon

A.L.Hughes et G.E.M.Jauncey, *Phys. Rev.* **36** (1930) 773

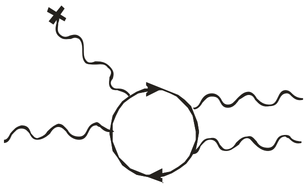
R.Karplus et M.Neuman, *Phys. Rev.* **83** (1951) 776

Mélange à quatre ondes

D.Bernard *et al*, *Eur. Phys. J. D* **10** (2000) 141 => Expérience au LULI, École Polytechnique

O(α²)

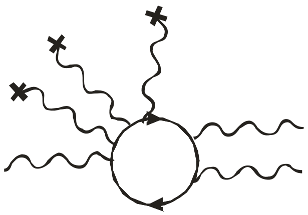
O(α³)



Photon splitting

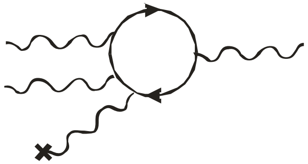
= 0 !

⇒



Génération de subharmoniques

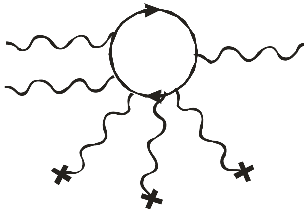
S.L.Adler *et al*., *Phys. Rev. Lett.* **25** (1970) 1061



Génération d'harmoniques

= 0 !

⇒



Y.I.Ding et A.E.Kaplan, *Int. J. Nonlin. Opt. Phys.* **1** (1992) 51

A.M.Fedotov, N.B.Narozhny, « Generation of harmonics by a focused laser beam in vacuum », *arXix:hep-ph/0604258v1* 27 Apr 2006

Φ Particule bosonique de faible masse *m*, neutre, sans spin

Φ matière noire ? Ça depend !

S'il y a un couplage avec deux photons, *L* peut s'écrire :

(Constante de couplage $g = 1/M$)

Particule pseudoscalaire *(comme les axions de Peccei et Quinn)*

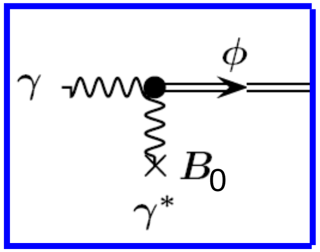
R. Peccei et H.R.Quinn, *Phys. Rev. Lett.* **38** (1977) 1440

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

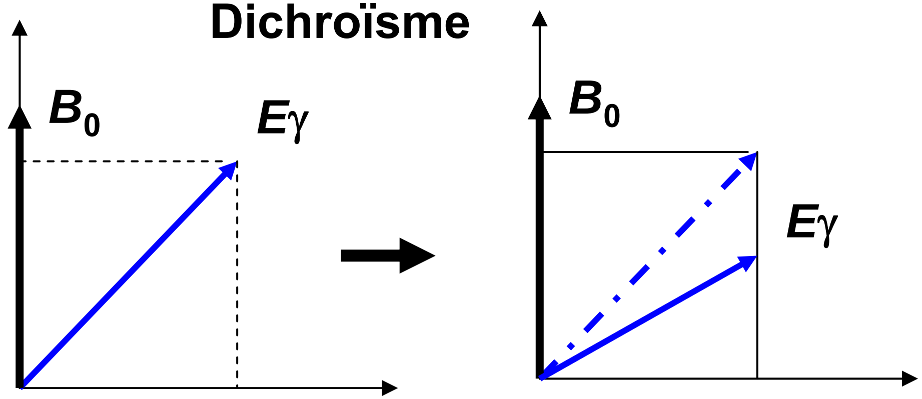
Particule scalaire

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

Particule réelle



Dichroïsme

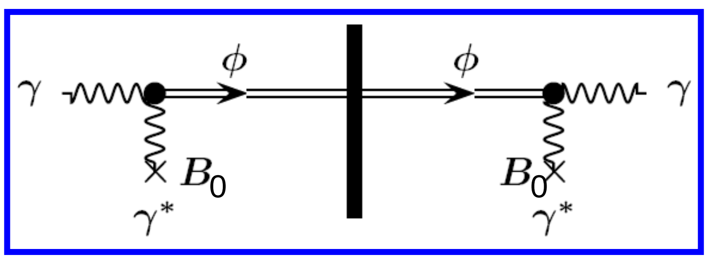


Cas « Pseudoscalaire »

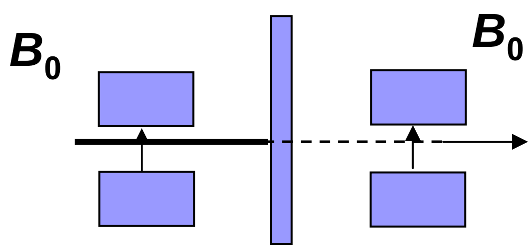
Effets « B_0L »

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

Photorégénération



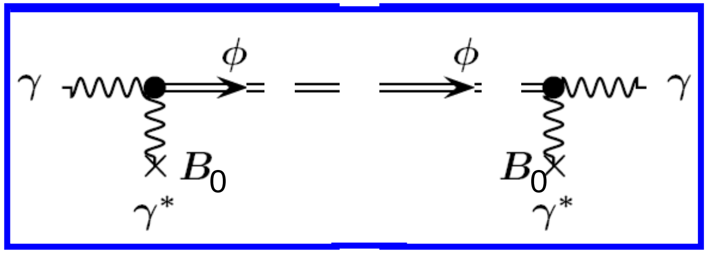
mur



mur

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

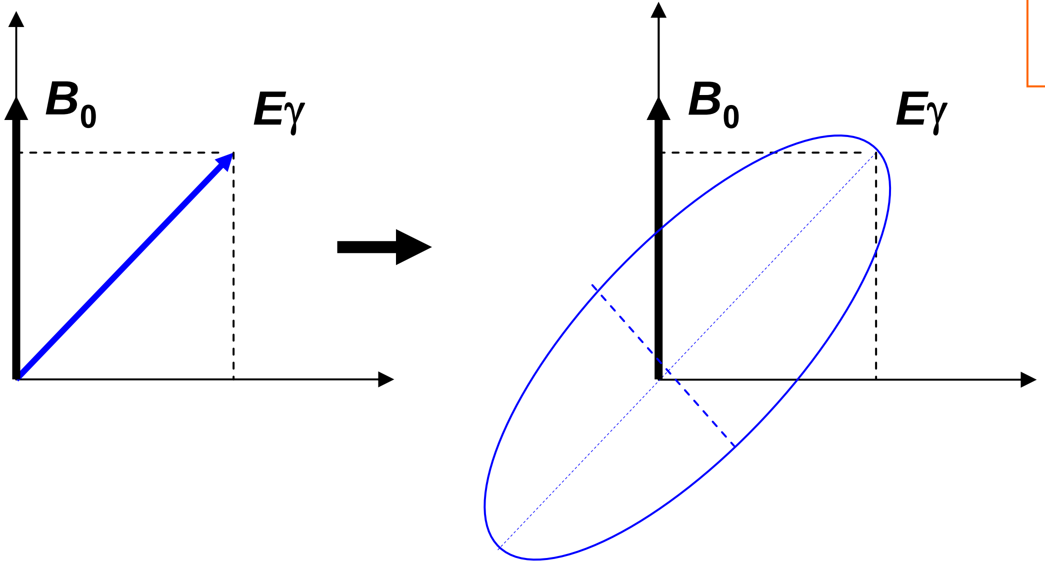
Particule virtuelle



$\Delta n > 0 \Rightarrow$ **Pseudoscalaire**

$\Delta n < 0 \Rightarrow$ **Scalaire**

Ellipticité



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

Plan

- Introduction : **Biréfringence magnétique du Vide; Dichroïsme et ellipticité dus aux PBFM, Photorégénération des PBFM.**
- Historique
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Expériences avec un **interféromètre de Michelson-Morley**

•1889 – 1898 : Morley, Boston, USA,
B_0 = 0,165 T, **$\Delta n < 10^{-8}$**

•1930-1940 : Farr et Banwell, Nouvelle Zelande,
B_0 = 2 T, **$\Delta n < 10^{-9}$**

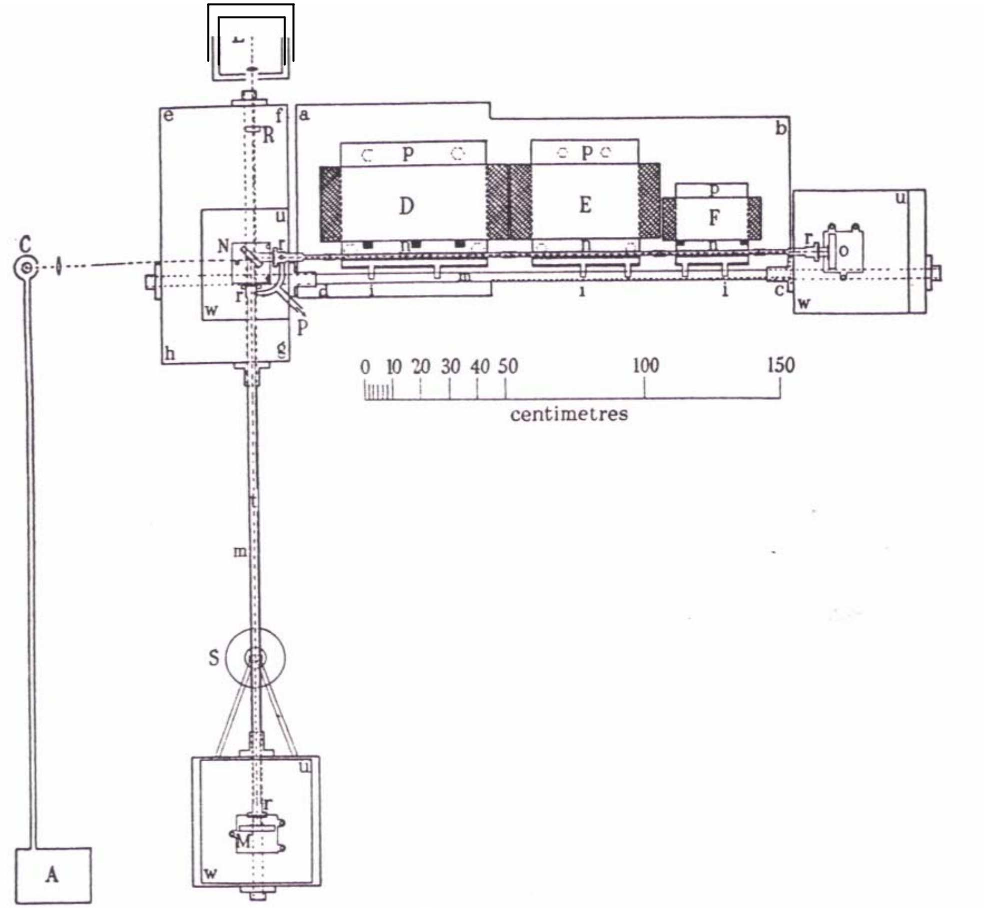


FIGURE 1

E.Morley, H.Eddy et D.C.Miller, *Bul. Western Reserve U.* **1** (1898) 50

C.C.Farr et C.J.Banwell, *Proc. Roy. Soc. London A.*137 (1932) 275

C.J.Banwell et C.C.Farr, *Proc. Roy. Soc. London A.*175 (1940) 1

In modern physics there have been developed two complementary – and apparently mutually contradictory – modes of description of radiation processes and of the motion of molecules, atoms, electrons and protons. How far can the parallelism in description of photons (light quanta) and members of the second group of entities be carried ?

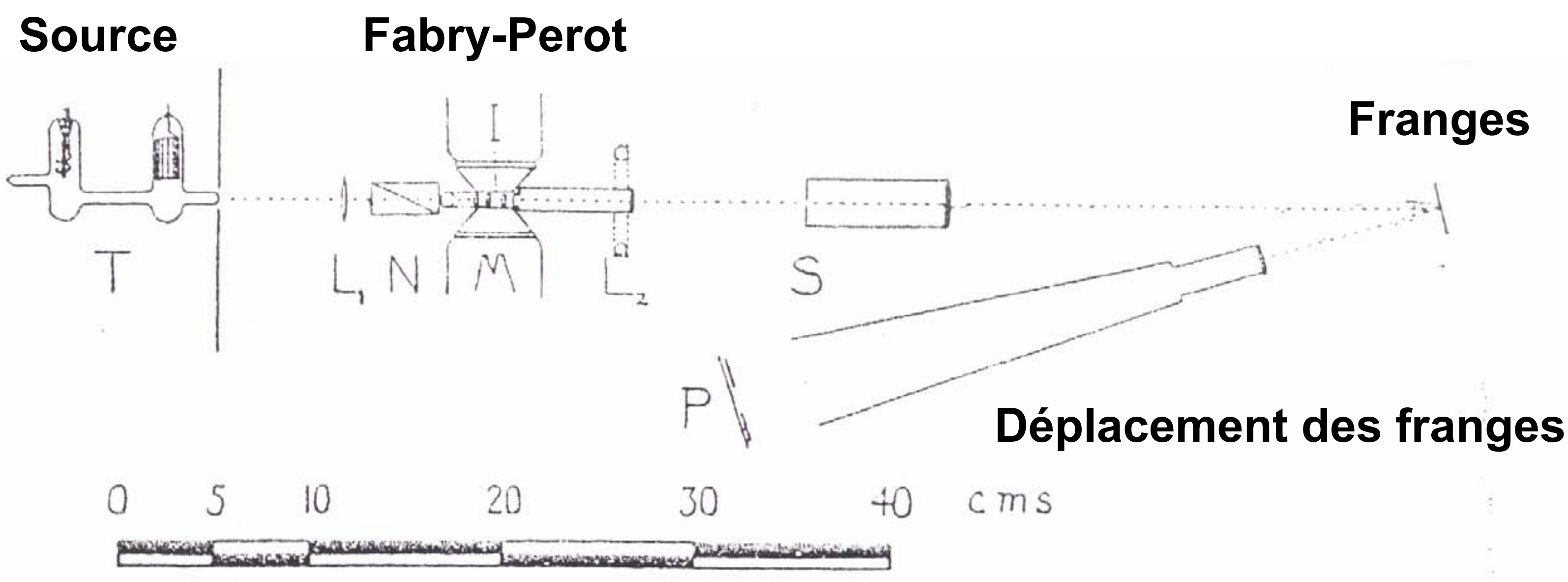


FIG. 1.

W.H.Watson, Roy. Soc. Proc. London A **125**, 345 (1929)

Lumière

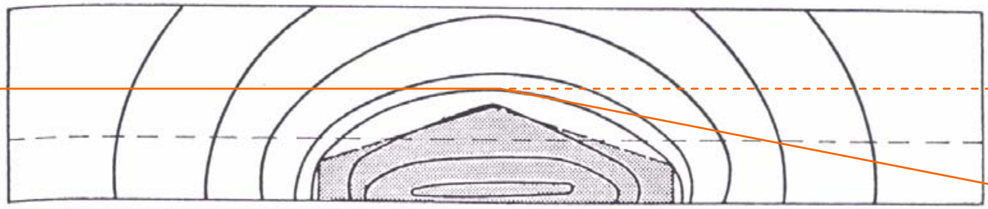


FIGURE 5. Plot of magnetic field in central vertical plane of 30 mm gap; lines of force normal to plane of diagram. Contours of constant strength (in succession, starting with outermost) at 900, 2000, 3700, 5700, 6500, 7500, 8500 and 9000 Oe. Shaded area indicates to scale the shape of the pole-faces, which are 10 cm long. Broken line indicates mean light path.

Angle de déviation

$< 5\ 10^{-13}$ rad

R.V. Jones
Proc. Roy. Soc. London A **260**, 47 (1961)

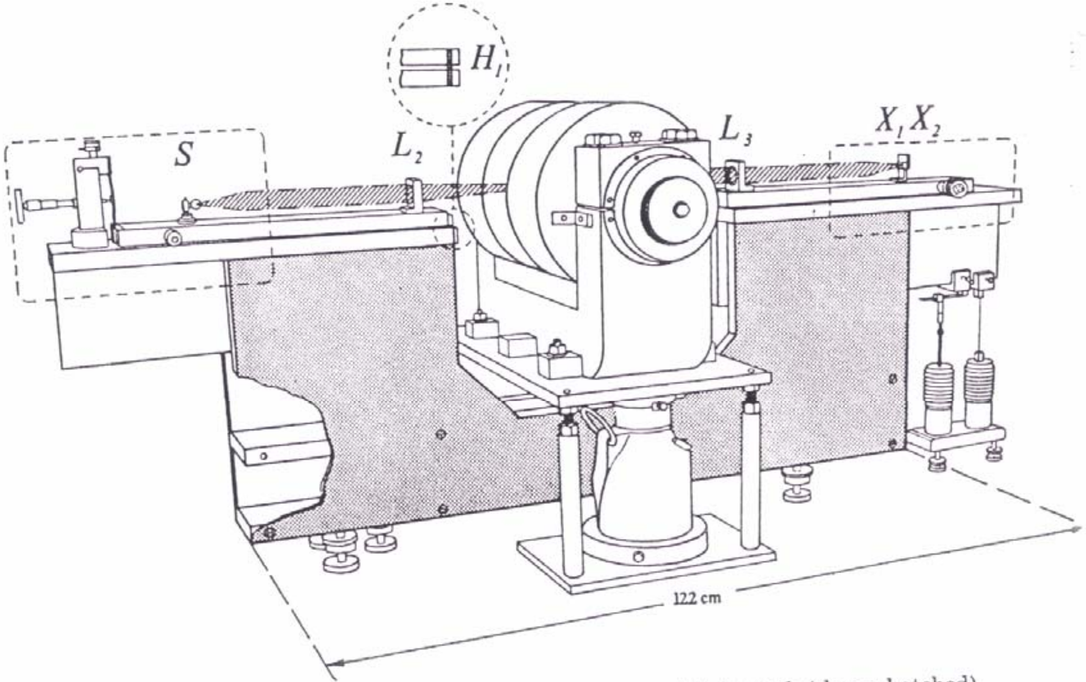


FIGURE 2. General disposition of base, magnet, and light path (shown hatched). Details in cartouches shown in figures 3 and 4.

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

Schéma de principe

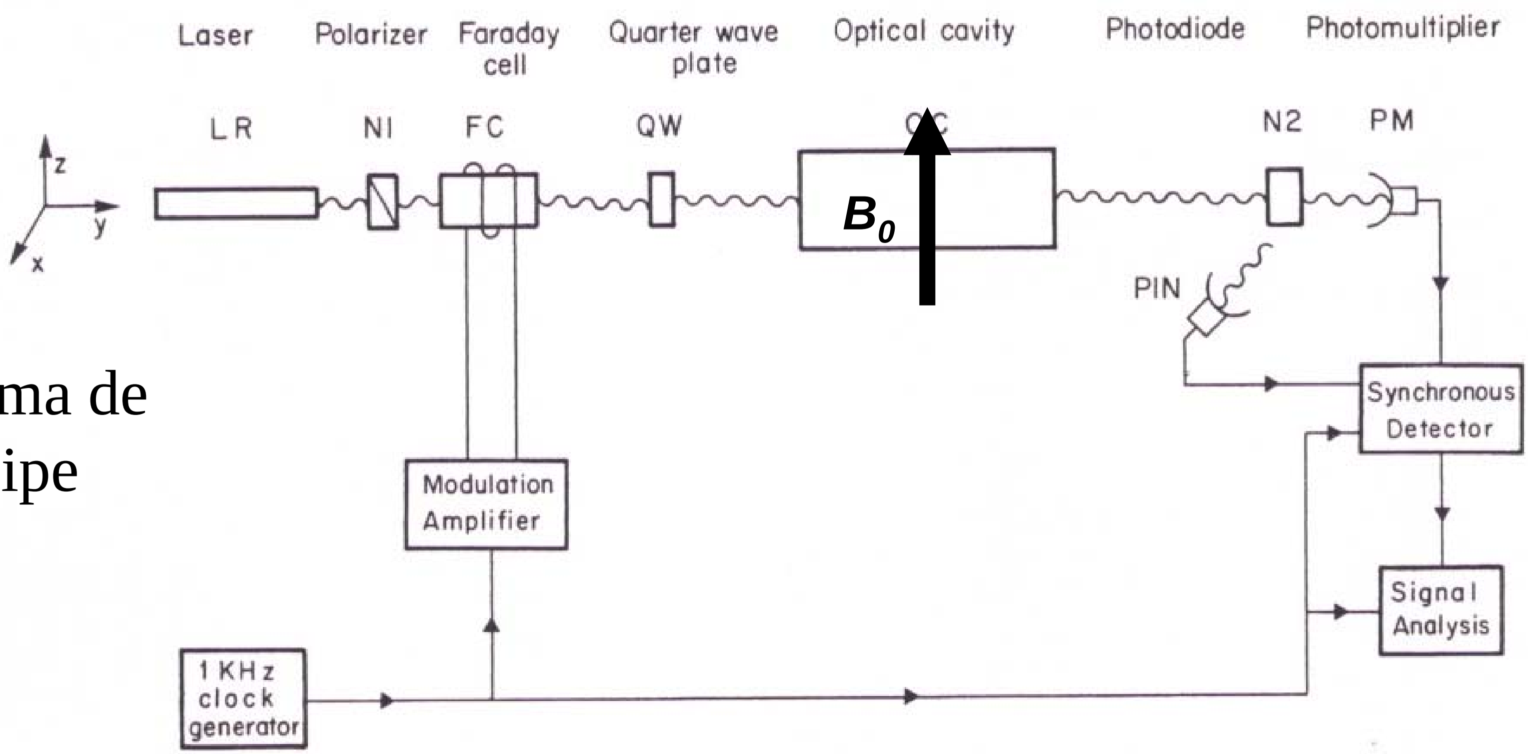


Fig. 3. Principle elements of the experimental apparatus.

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

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

Expérience montée aux
Brookhaven National Laboratories
Upton, NY, USA

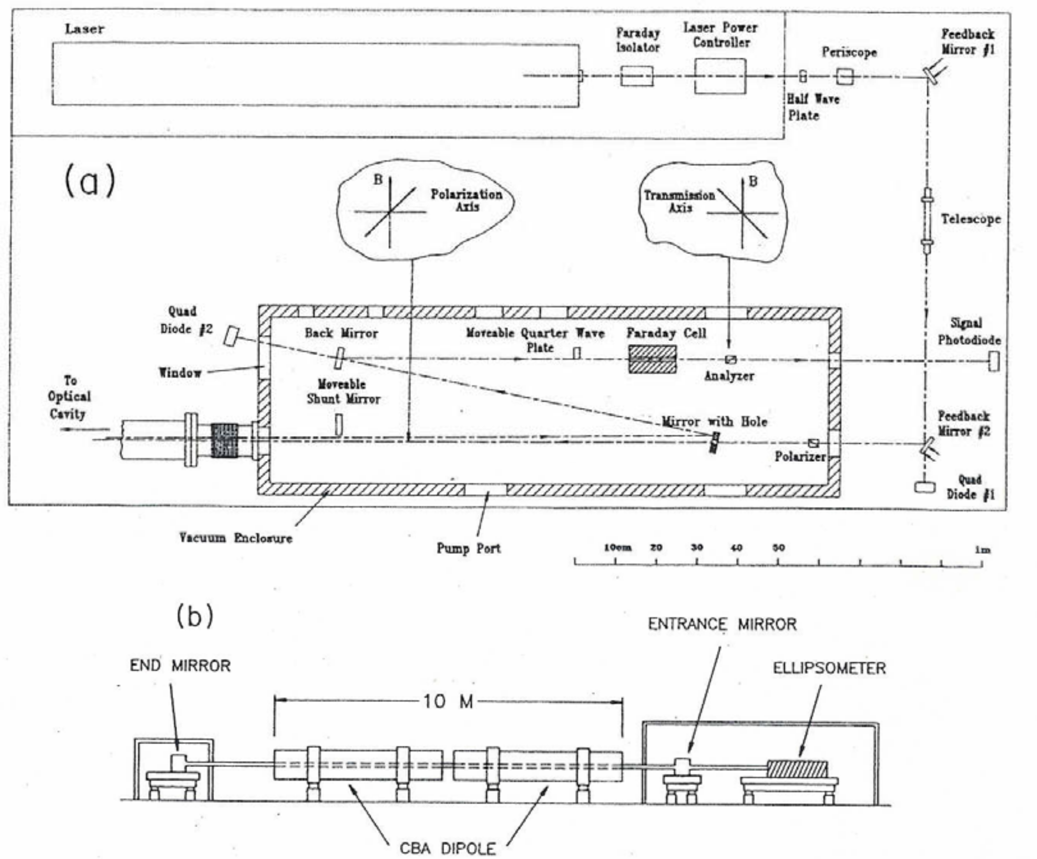


FIG. 4. (a) Schematic view of the ellipsometer; the volume inside the hatched area is evacuated. (b) Layout of the experiment and of the superconducting magnets.

**Cavité optique « multipass » :
500 passages dans le champ**

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

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

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

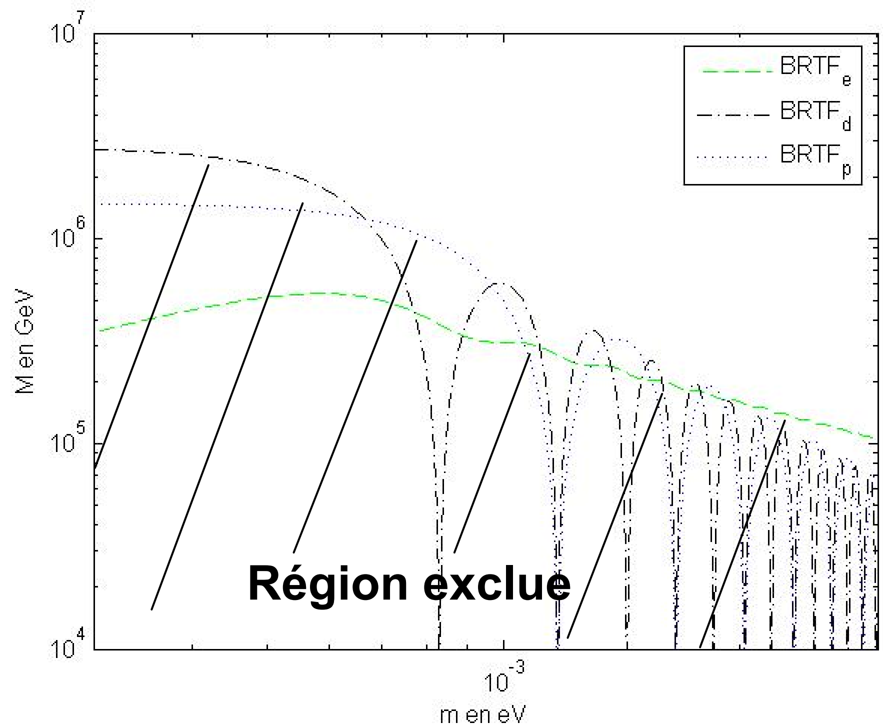
Number of reflections	Rotation or ellipticity	Number of averages	Measured rms noise level (rad)	Achieved sensitivity (rad/$\sqrt{\text{Hz}}$)
Shunt	Rotation	48	4.3×10^{-11}	7.6×10^{-9}
Shunt	Ellipticity	25	2.0×10^{-10}	2.6×10^{-8}
34	Rotation	66	1.6×10^{-10}	3.3×10^{-8}
34	Ellipticity	25	2.0×10^{-9}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

Ellipticité < 2.0×10^{-9}

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

Mesures de :

Ellipticité
Dichroïsme
Photorégénération



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

Proposition d’expérience au FERMILAB (Chicago, USA) :

Pas acceptée !

Proposal

Measurement of the Magnetically-Induced QED Birefringence of the Vacuum and An Improved Laboratory Search for Axions

Siu Au Lee, William M. Fairbank, Jr. and Walter H. Toki
Department of Physics, Colorado State University
Fort Collins, Colorado 80523

John L. Hall
Joint Institute for Laboratory Astrophysics
University of Colorado and The National Institute of Standards and Technology
Boulder, Colorado 80309

Tariq S. Jaffery
Superconducting Super Collider Laboratory
Waxahachie, Texas 75165

Patrick Colestock, Vernon Cupps, Hans Kautzky, Moyses Kuchnir and Frank Nezri
Fermi National Accelerator Laboratory
Batavia, Illinois 60510

Submitted to
Fermi National Accelerator Laboratory

March 28, 1995

Spokesperson:
Siu Au Lee
Phone: (303) 491-6389
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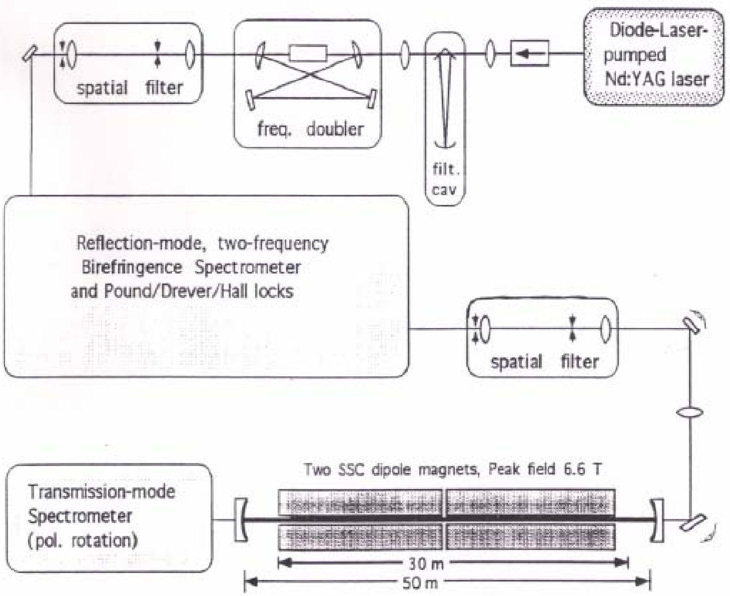
Deputy Spokesperson:
Frank Nezrick
Phone: (708) 840-4604
FAX: (708) 840-3867
Email: frank_nezrick@qmgate.fnal.gov



Aimant du SSC

J.L.Hall, J.Ye, L-S.Ma, *Phys. Rev. A* **62** (2000) 013815

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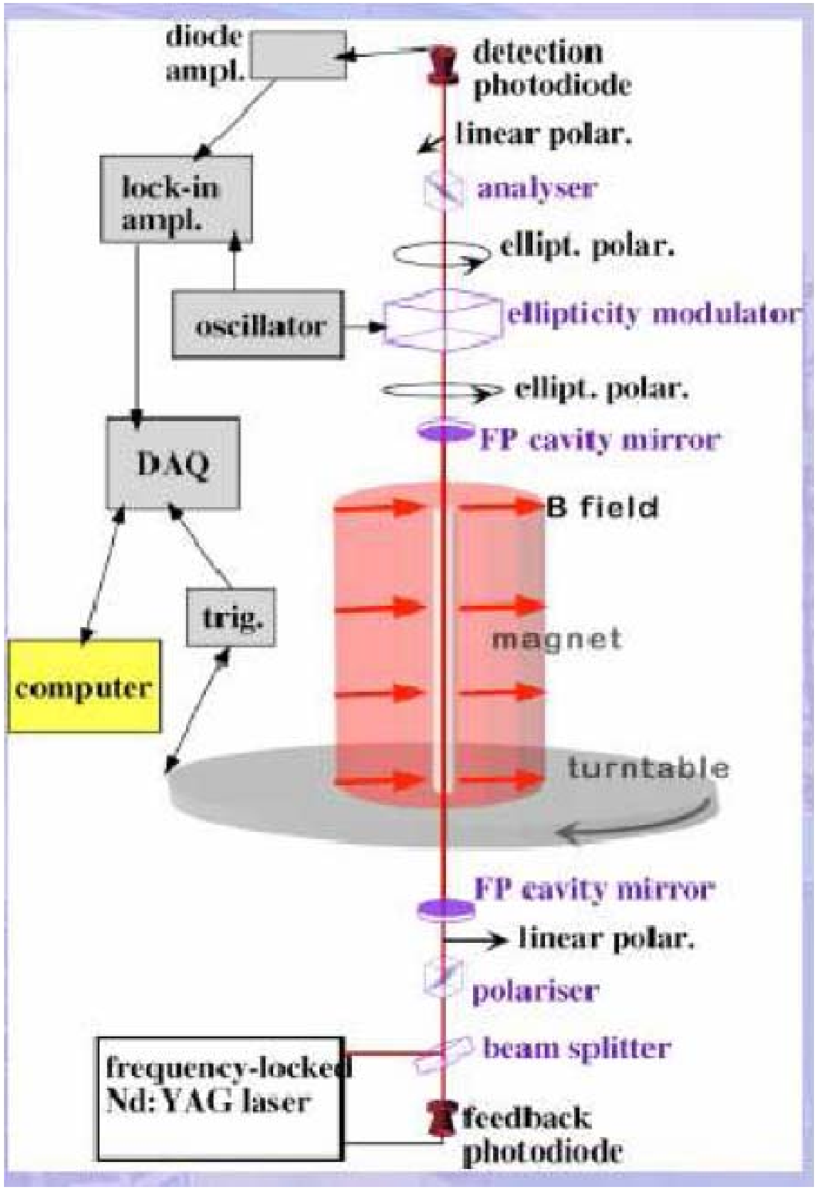


Expérience *Polarizzazione del Vuoto con LASer* (PVLAS) : 1992 – en cours

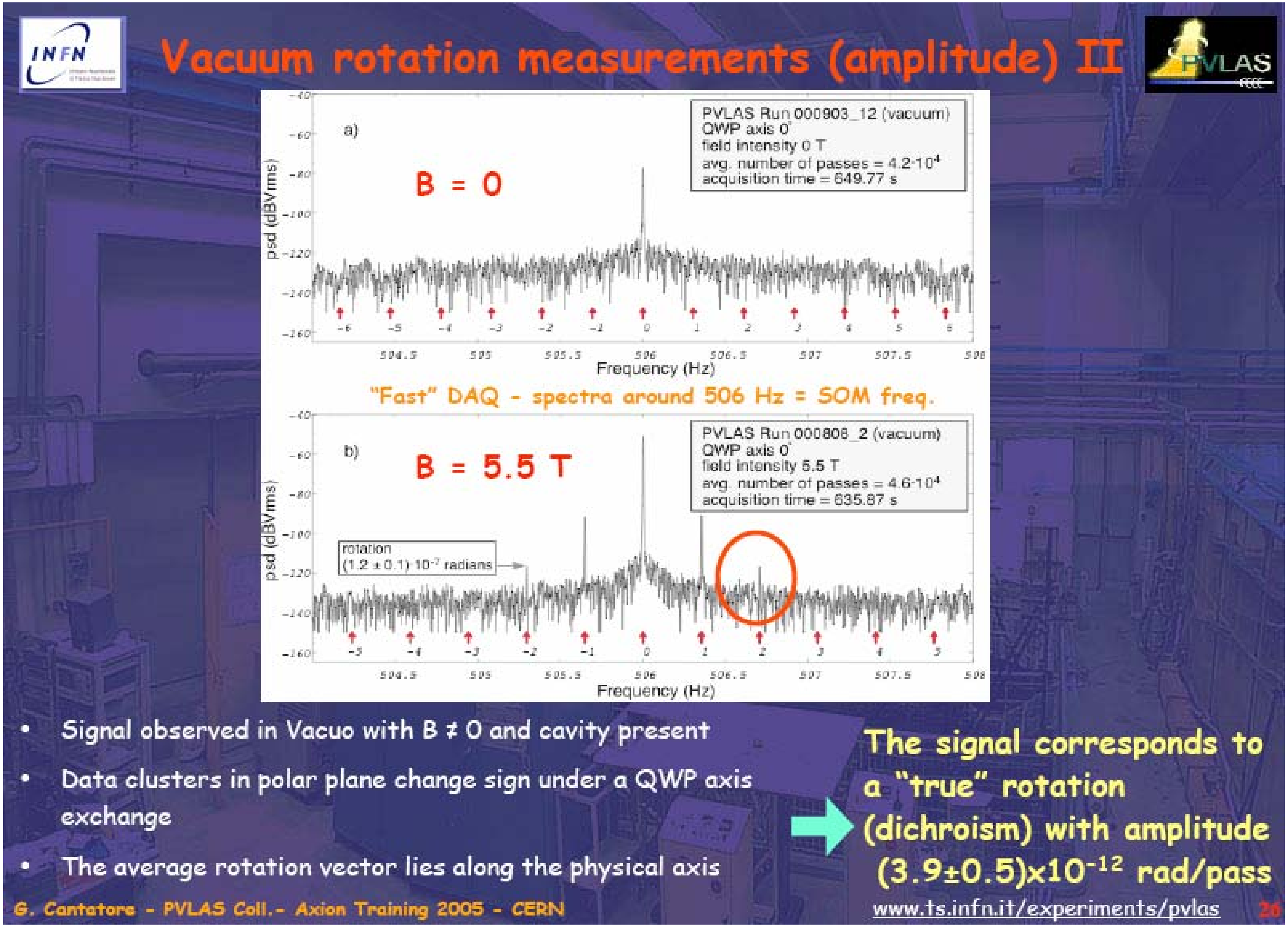
E.Zavattini *et al.*

B_0^2L = 25 T²m
B_0L = 5 Tm
Finesse de la cavité = 70 000
fréquence de modulation 0.6 Hz
Sensibilité = 10^{-7} $1/\sqrt{\text{Hz}}$

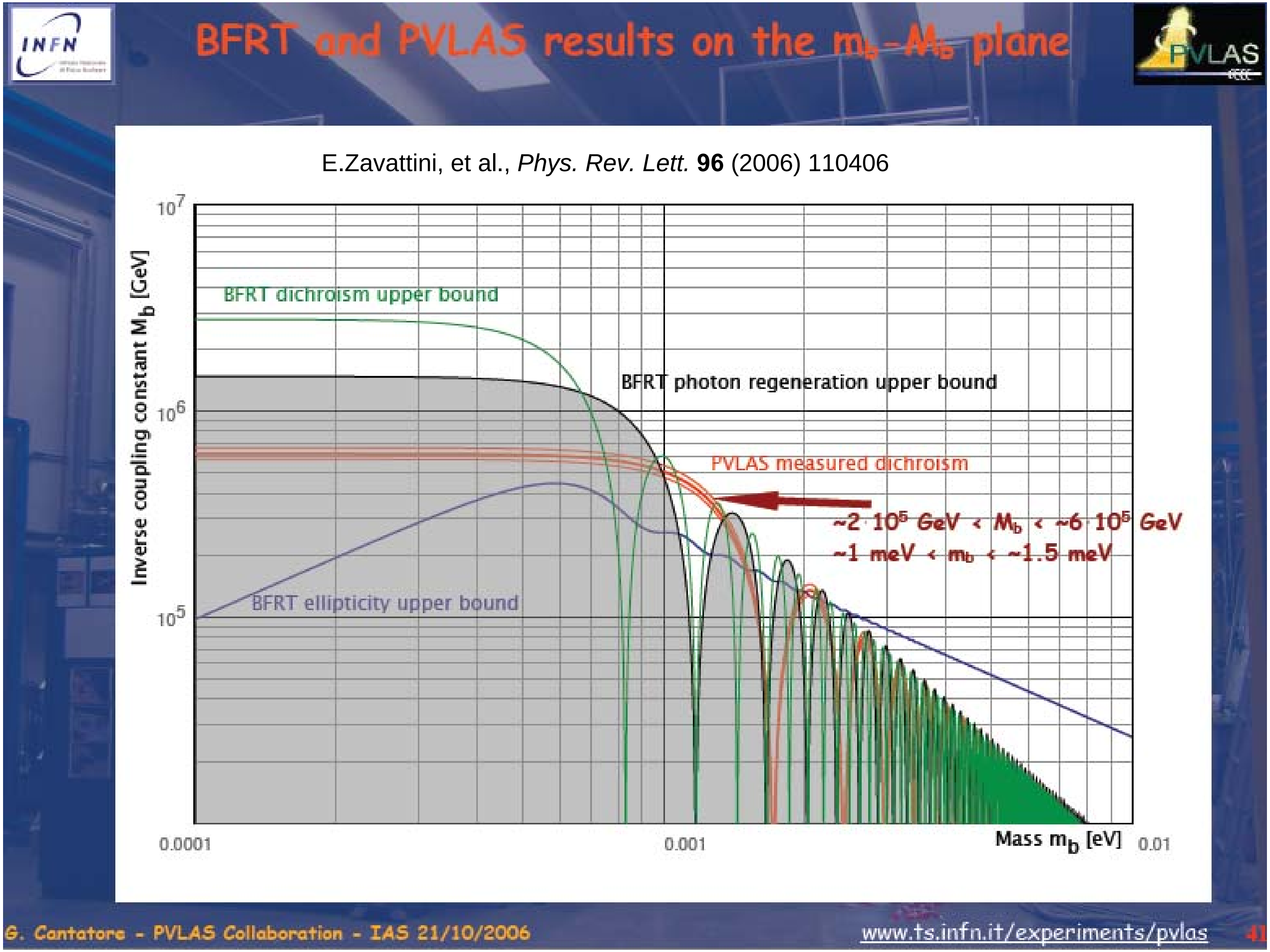
Laboratori Nazionali di Legnaro, INFN, Vénétie, Italie

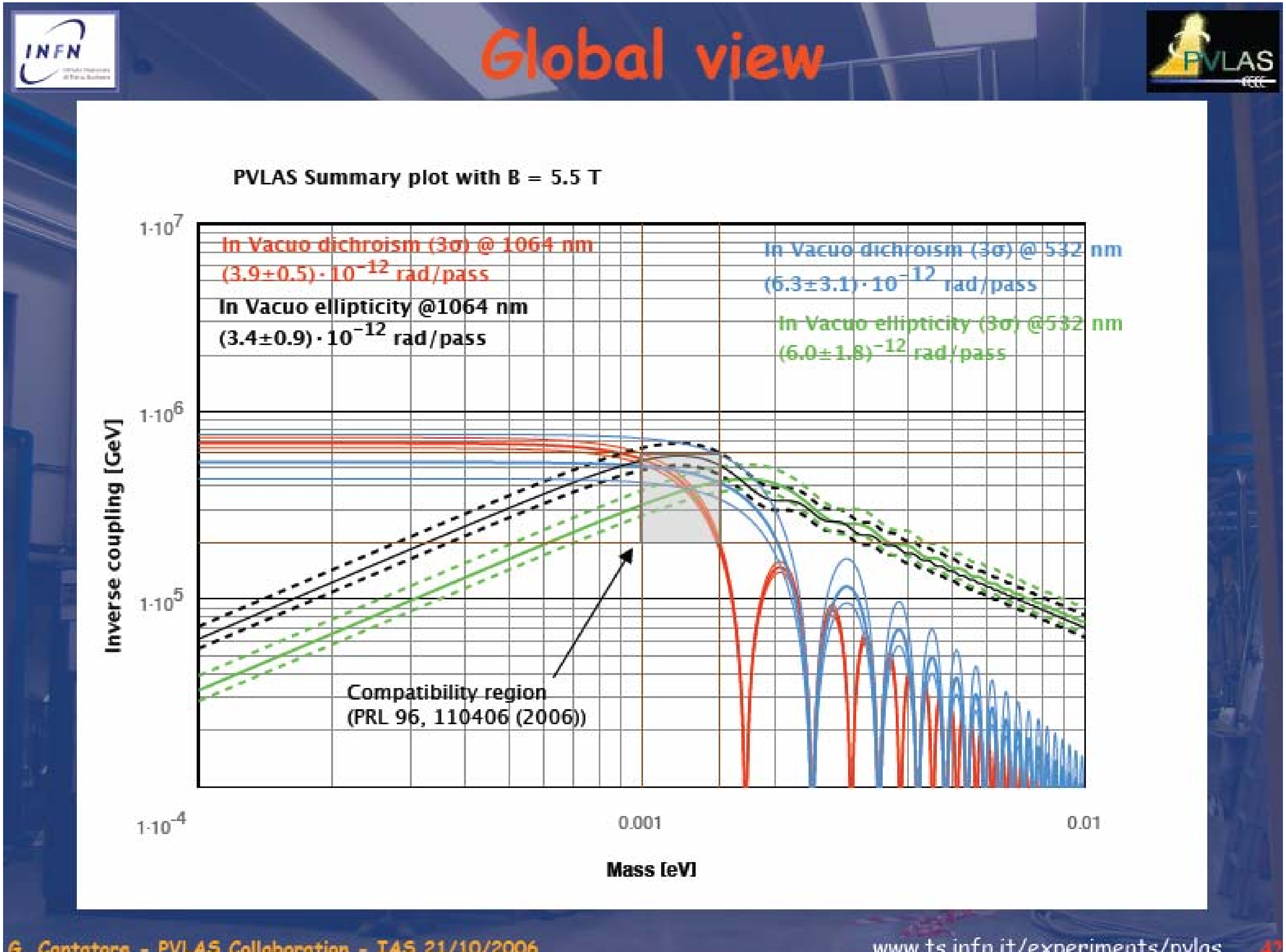
D.Bakalov, et al., *Quantum Semiclass. Opt.* **10** (1998) 239


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

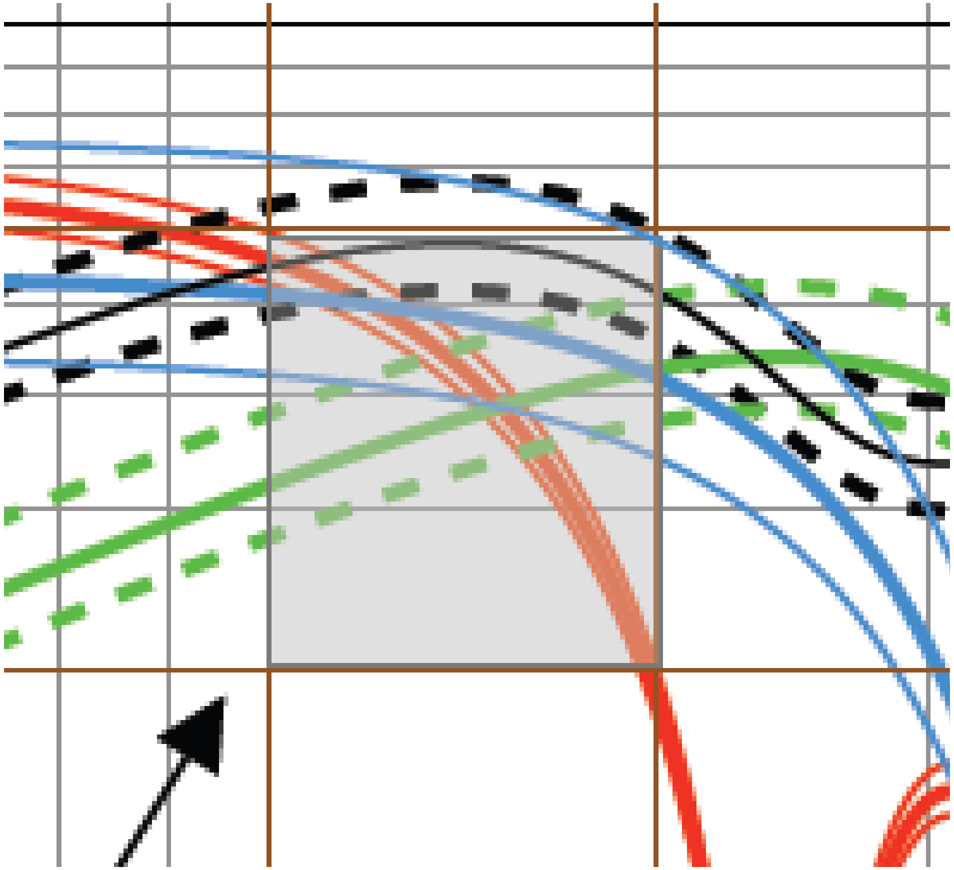


E.Zavattini, et al., *Phys. Rev. Lett.* **96** (2006) 110406


INFN
BFRT and PVLAS results on the m_b–M_b plane
PVLAS
E.Zavattini, et al., Phys. Rev. Lett. 96 (2006) 110406
Inverse coupling constant M_b [GeV]
10^7
10^6
10^5
BFRT dichroism upper bound
BFRT photon regeneration upper bound
PVLAS measured dichroism
~2·10^5 GeV < M_b < ~6·10^5 GeV
~1 meV < m_b < ~1.5 meV
BFRT ellipticity upper bound
0.0001
0.001
Mass m_b [eV]
0.01
G. Cantatore - PVLAS Collaboration - IAS 21/10/2006
www.ts.infn.it/experiments/pvlas
41


INFN
Global view
PVLAS
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]
G. Cantatore - PVLAS Collaboration - IAS 21/10/2006
www.ts.infn.it/experiments/pvlas

Zoom : quatre mesures indépendantes → **Même région du plan m-M**



Scalaire or Pseudoscalaire ?

Dichroïsme > 0

Pseudoscalaire !?

Biréfringence : $\Delta n < 0$

Scalaire !?

M. Karuza, PhD Thesis (2007)

Vol 441| 4 May 2006 nature

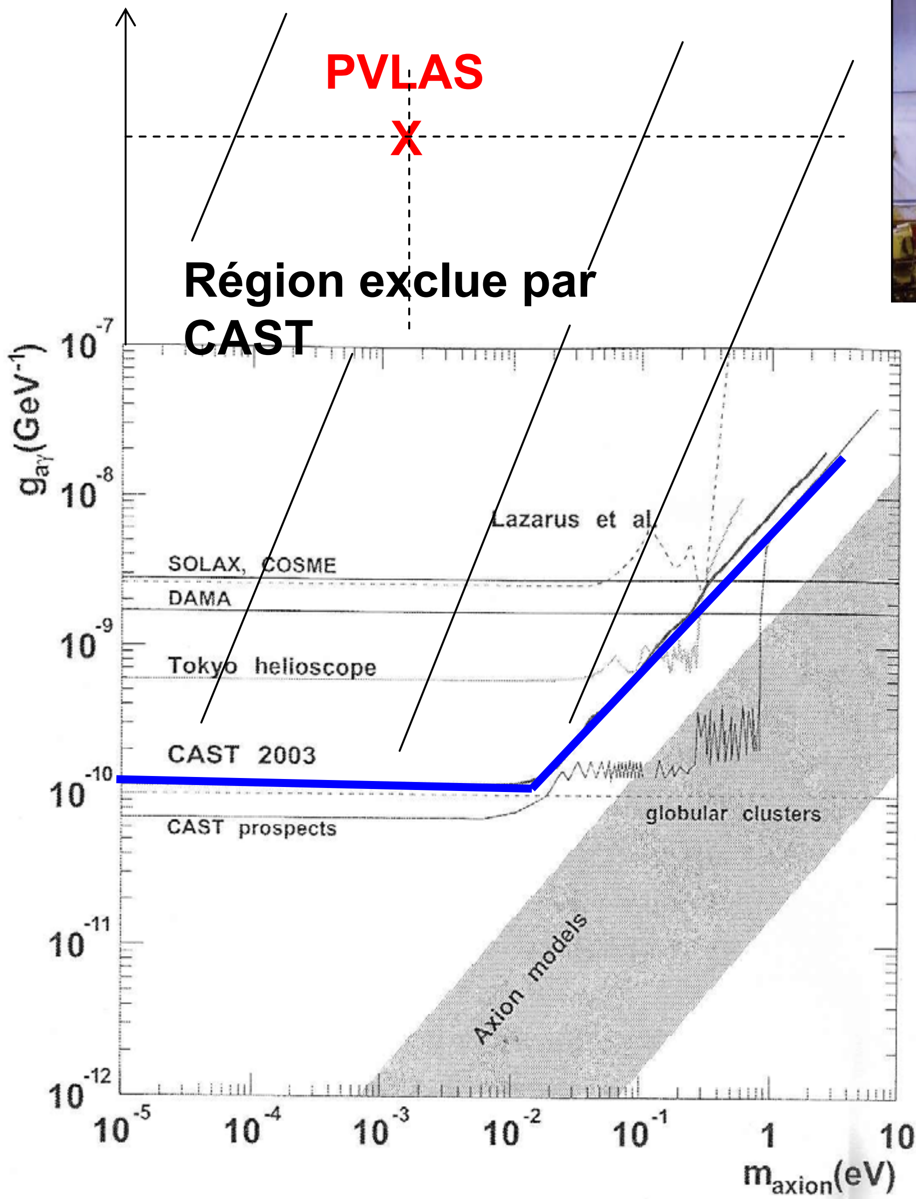
NEWS & VIEWS

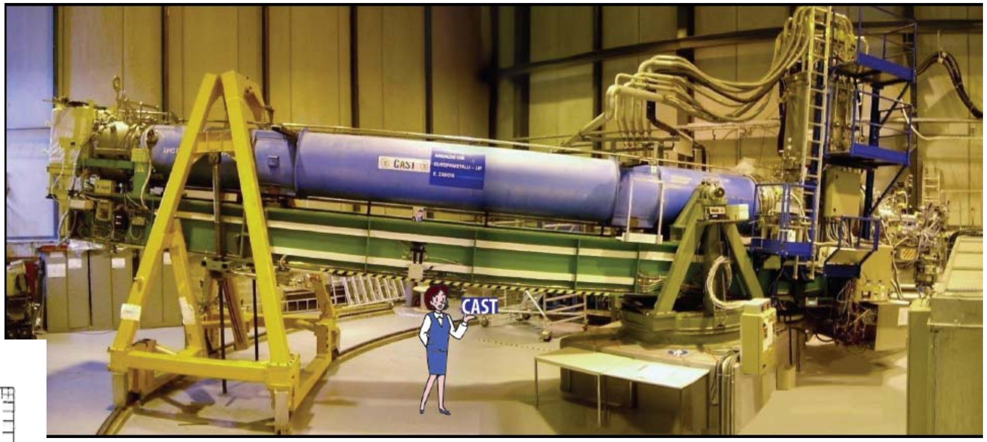
PARTICLE PHYSICS

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.



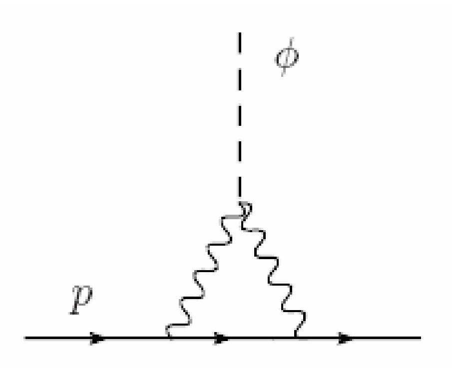


CAST

Cern Axion Solar Telescope

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

Scalar ?



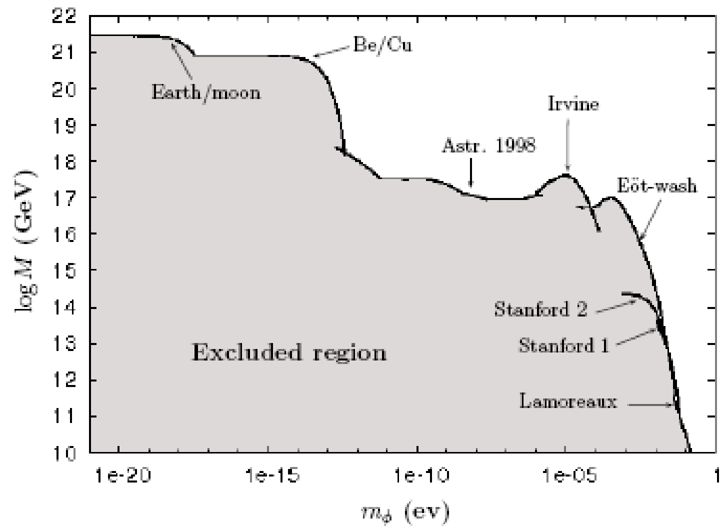
$$y = 4\,\frac{\alpha}{\pi}\,\frac{m_p}{M}\,\log\frac{\Lambda}{m_p}$$

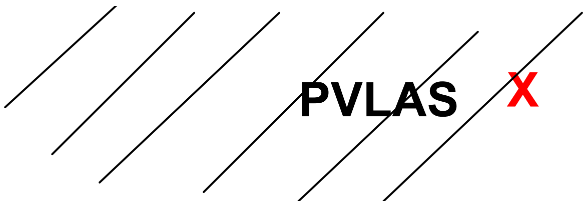
$$\mathcal{L}_2 = y\,\phi\bar{\Psi}\Psi$$

Ψ is the proton field and y the Yukawa coupling

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

Force non newtonienne !





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

Phys. Rev. Lett. 98, 131802 (2007)

Nouvelles théories ? : ~~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

…

Nouvelles expériences !!

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- Introduction
- Historique
- Résultats récents ⇨ Résultats très récents
- Les futurs projets
- Le projet BMV de Toulouse
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Depuis 1994 **Q&A** (Quantum electrodynamics test & search for Axion)

Pr. Ni (University of Taiwan)

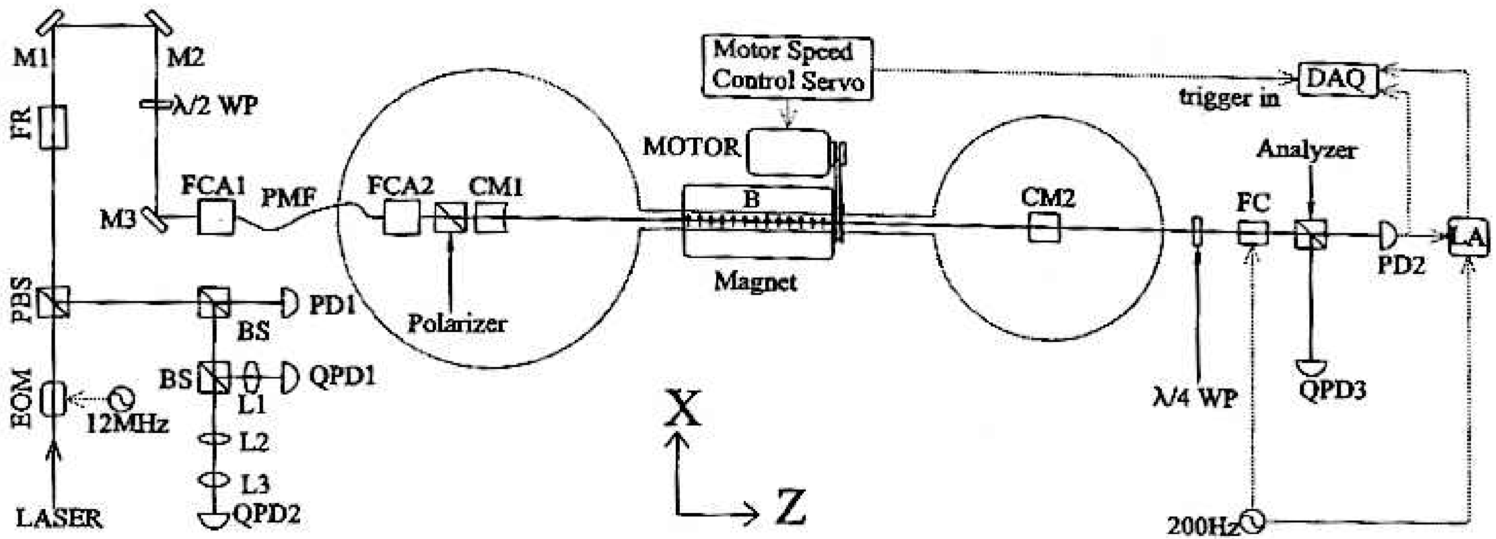

Figure 1. Experimental Setup. EOM electro-optical modulator; λ/2 WP half-wave plate; λ/4 WP quarter-wave plate; L1, L2, L3 lenses; M1, M2, M3 reflection mirrors; PBS polarizing beam splitter; BS beam spiltter; FR Faraday rotator; FCA1, FCA2 fibre coupler assemblies; PMF polarization maintaining fibre; 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.

Résultats préliminaires sur arXiv ⇒ **"Presque" en contradiction avec PVLAS**

hep-ex/0611050

Niveau de confiance ? ≈ 1 σ

Fig. 3. A picture of experimental apparatus.

2.3 T x 0.6 m aimant Permanent tournant

Finesse ≈ 30 000

Sensibilité = 10^{-6} $1/\sqrt{Hz}$

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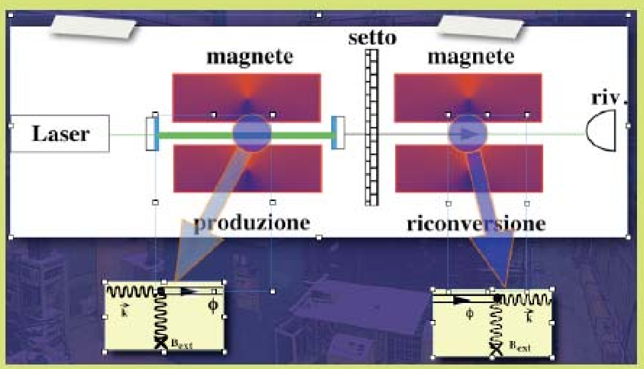
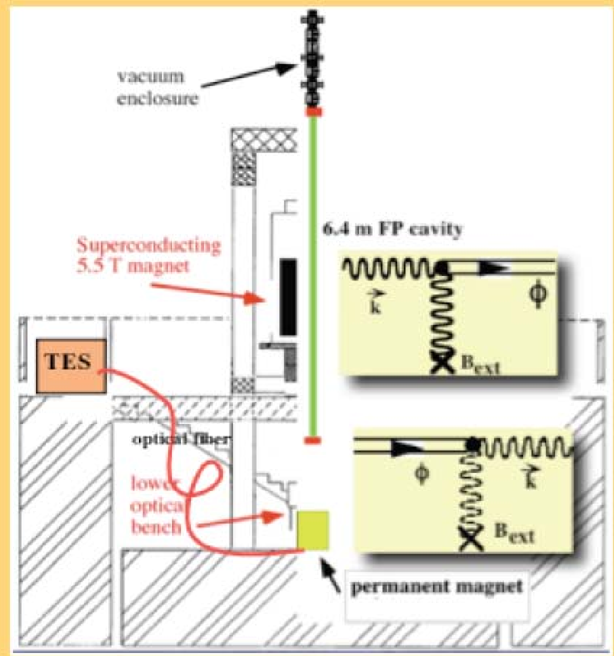
Photon regeneration test at PVLAS

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

- Principle of a photon regeneration experiment





G. Cantatore - PVLAS Collaboration - IAS 21/10/2006

www.ts.infn.it/experiments/pvlas


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

Aimants de HERA

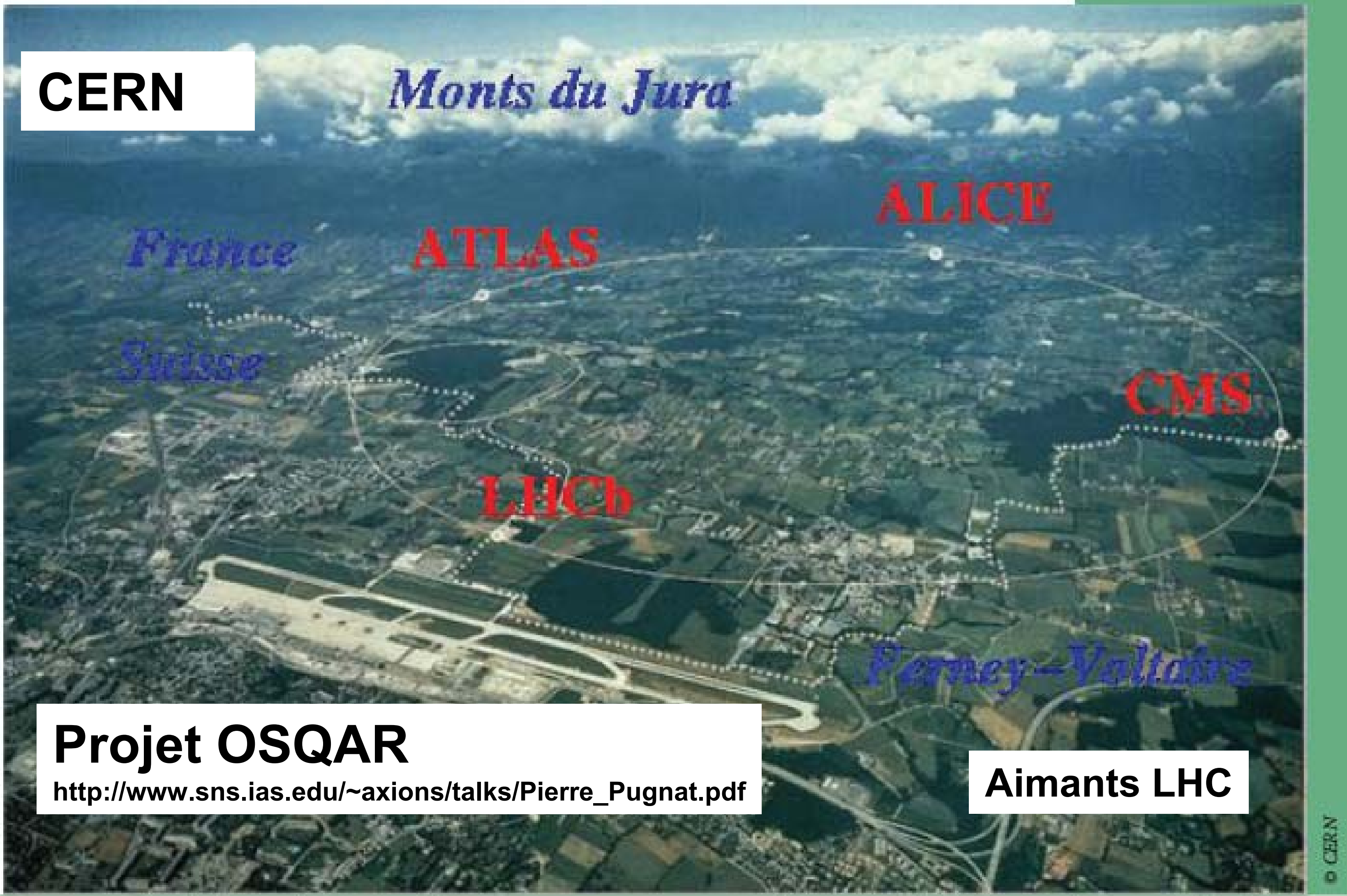
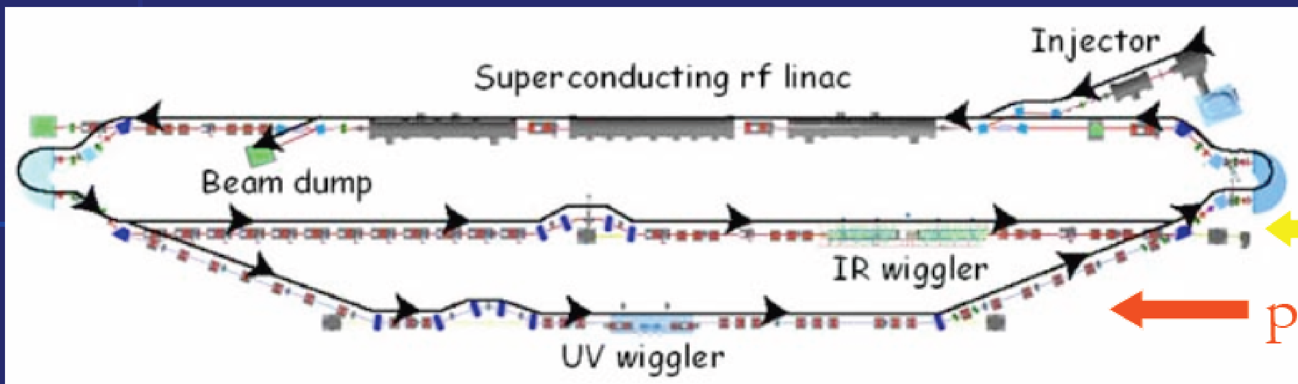


figure 1 : Vue générale du site du CERN où le LHC est en construction. La ligne pointillée représente le passage de la frontière entre la France et la Suisse. En arrière plan, se devinent les monts du Jura ; au premier plan, on voit l'aéroport de Genève-Cointrin. Le cercle indique l'emplacement du tunnel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

Données en 2007 ?!

Collisions photon-photon au Rutheford Appleton Laboratory

arXiv:hep-ph/0510076 v1 6 Oct 2005

Using high-power lasers for detection of elastic photon-photon scattering

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Rutherford Appleton Laboratory, Chilton, Didcot OX11 0QX, Oxfordshire, UK

(Dated: October 7, 2005)

The properties of four-wave interaction via the nonlinear quantum vacuum is investigated. The effect of the quantum vacuum is to generate photons with new frequencies and wave vectors, due to elastic photon–photon scattering. An expression for the number of generated photons is derived and using state-of-the-art laser data it is found that the number of photons can reach detectable levels. In particular, the prospect of using the high repetition Astra Gemini system at the Rutherford Appleton Laboratory is discussed. The problem of noise sources is reviewed, and it is found that the noise level can be reduced well below the signal level. Thus, detection of elastic photon–photon scattering may for the first time be achieved.

PACS numbers: 12.20.Fv, 42.65.-k, 42.50.Xa

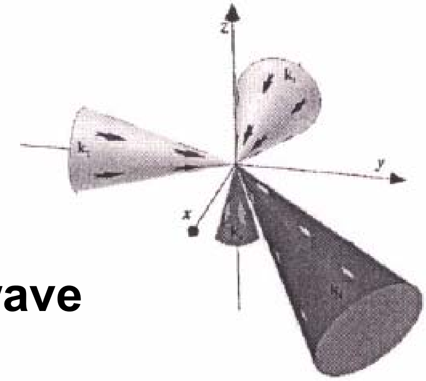

FIG. 1: Configuration of the incoming laser beams and the direction of the scattered wave for the suggested three-dimensional configuration of wave vectors, which satisfies the matching conditions (5).

Light diffraction by a strong standing electromagnetic wave

arXiv:hep-ph/0602039v1 3 Feb 2006

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Nouveau schéma avec des lasers *femto*

PHYSICAL REVIEW A **70**, 033801 (2004)

Ultrafast resonant polarization interferometry: Towards the first direct detection of vacuum polarization

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(Received 25 February 2004; published 2 September 2004)

Vacuum polarization, an effect originally predicted nearly 70 years ago, is still yet to be directly detected despite significant experimental effort. Previous attempts have made use of large liquid-helium cooled electromagnets which inadvertently generate spurious signals that mask the desired signal. We present an approach for the ultrasensitive detection of optical birefringence that can be usefully applied to a laboratory detection of vacuum polarization. The technique has a predicted birefringence measurement sensitivity of $\Delta n \sim 10^{-20}$ in a 1 s measurement. When combined with the extreme polarizing fields achievable in this design we predict that a vacuum polarization signal will be seen in a measurement of just a few days in duration.

DOI: 10.1103/PhysRevA.70.033801 PACS number(s): 42.50.Xa, 12.20.Fv, 42.62.Eh, 42.25.Lc

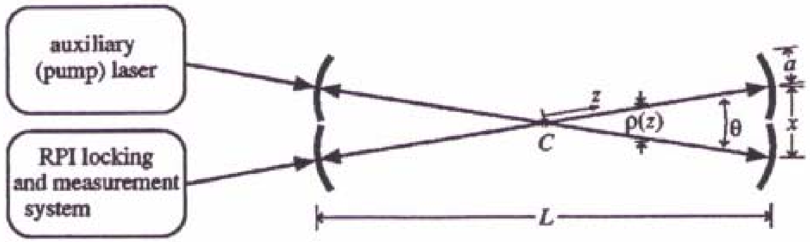

FIG. 2. Measurement scheme for optically induced birefringence.

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