The BMV experiment

(Biréfringence Magnétique du Vide)

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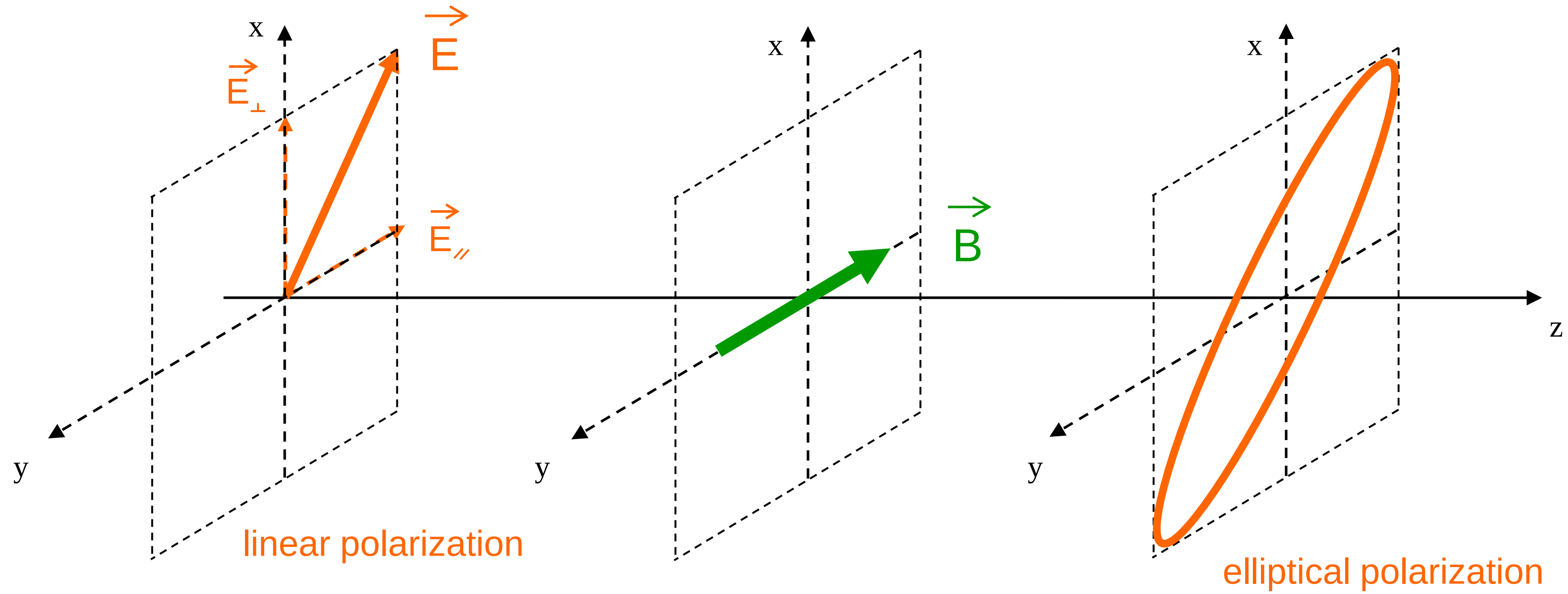
18/11/2013

LABORATOIRE NATIONAL DES CHAMPS MAGNETIQUES INTENSES
CNRS UPR 3228

Magnetic birefringence : Cotton-Mouton effect



Induced magnetic birefringence :

$$\Delta n = (n_{//} - n_{\perp}) \; \alpha \; \boldsymbol{B^2}$$

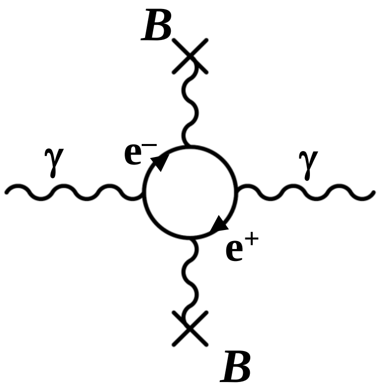
- This effect exists in **any** medium, even in **vacuum**

Vacuum magnetic birefringence: predicted by QED

- Vacuum polarization

  $\rightarrow$ *nonlinear interaction between electromagnetic fields*

- Calculated in the 70's :



$$\Delta n = \frac{2}{15}\frac{\alpha^2\hbar^3}{m_e^4 c^5}\frac{B^2}{\mu_0}$$

$$\Delta n = k_{CM}\, B^2 \qquad \text{with} \qquad k_{CM} \approx 4.10^{-24}\,\mathrm{T}^{-2}$$

Never observed !
QED test

- The BMV project : development of a very sensitive ellipsometer in order to be able to observe for the first time the QED prediction

W. Heinsenberg et al., Z. Phys. **38,** 714 (1936)
Z. Bialynicka-Birula and I. Bialynicki-Birula, *Phys. Rev. D* **2**, 2.34 (1970)
R. Battesti and C. Rizzo, *Rep. Prog. Phys.* **76**, 016401 (2013)

Outline

- The LNCMI
- Experimental setup
- Signal analysis
- Cotton-Mouton effect of helium gas
- Cotton-Mouton effect of vacuum
- Axions
- Conclusions and perspectives

Biréfringence Magnétique du Vide

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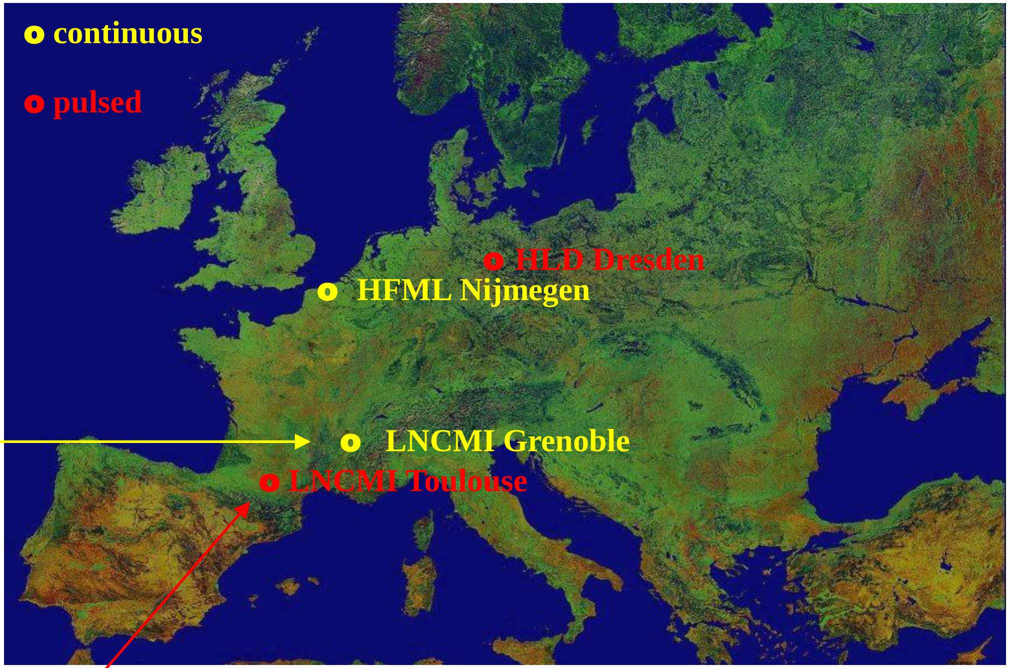
LNCMI

Laboratoire
National des
Champs
Magnétiques
Intenses



Member of the EMFL

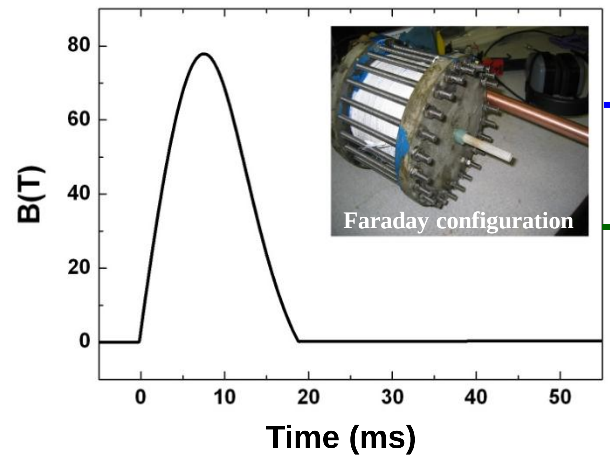
European **M**agnetic **F**ield **L**aboratory
with the HFML of Nijmegen
and the HLD of Dresden.

Generation of intenses pulsed magnetic fields ?

one method : having a strong current circulating into a coil

two problems :

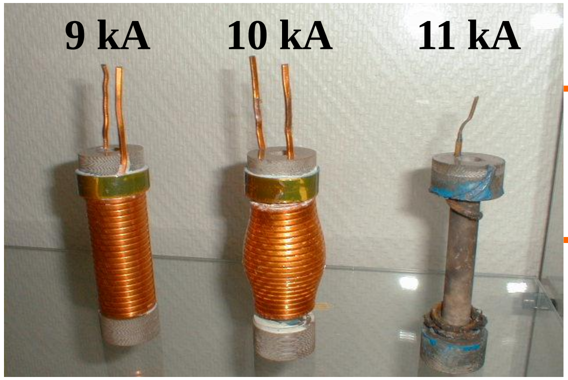
- heating



→ cooling

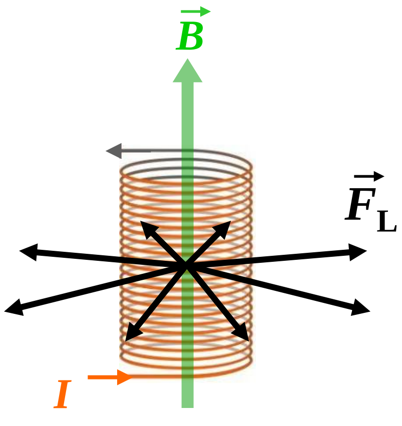
→ pulsed regime

- magnetic pressure



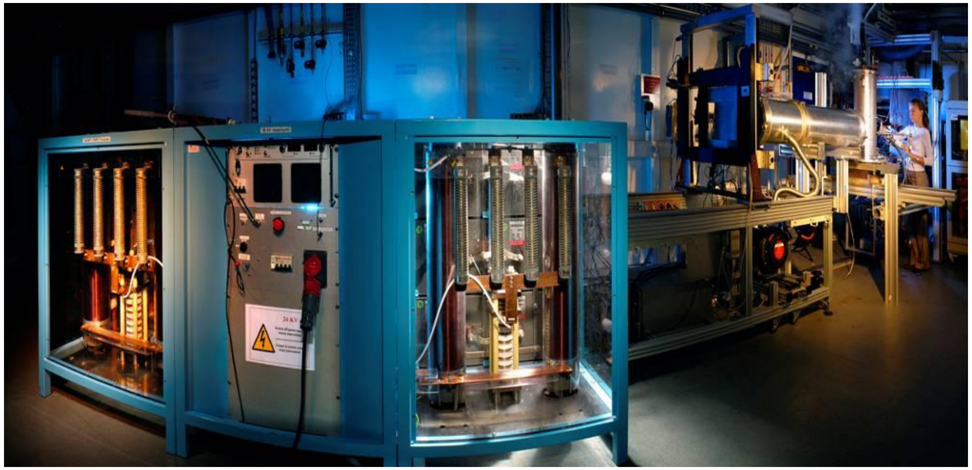
→ ultra strong conductors

→ external reinforcement



The pulsed field facility in Toulouse
with its 6 capacitors banks from 10 kJ to 14 MJ

3 are mobile



To perform experiments in other facilities and combine magnetic field with intense lasers, X-rays, or neutrons (LULI, ESRF, ILL, CLIO…)

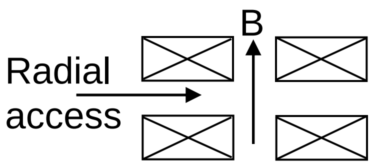
Coil development for pulsed magnetic field

standard solenoids : high field, long pulse,
suited to many types of experiments

specific magnets : magnetic field is not the only parameter

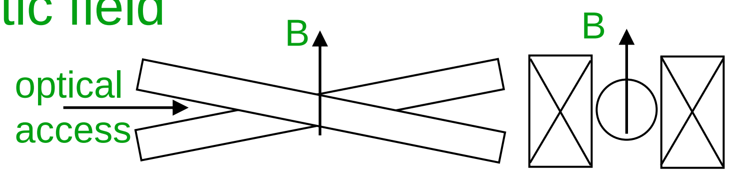
- access perpendicular to magnetic field

30 T split-pair coil for X-rays diffraction at ESRF
40 T for plasma physics at LULI



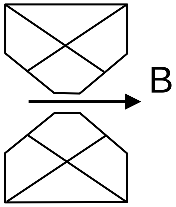
- long optical path with transverse magnetic field

30 T XXL coil for vacuum magnetic birefringence



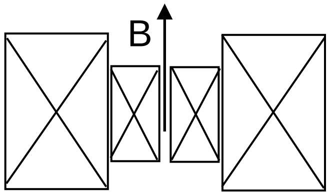
- conical access in the magnet bore

30 T coils with axial access and conical bore for X-ray diffraction
40 T wide angle conical access solenoid with a high duty-cycle for neutron scattering



- high field nested-coils

85 T long pulse dual coil system



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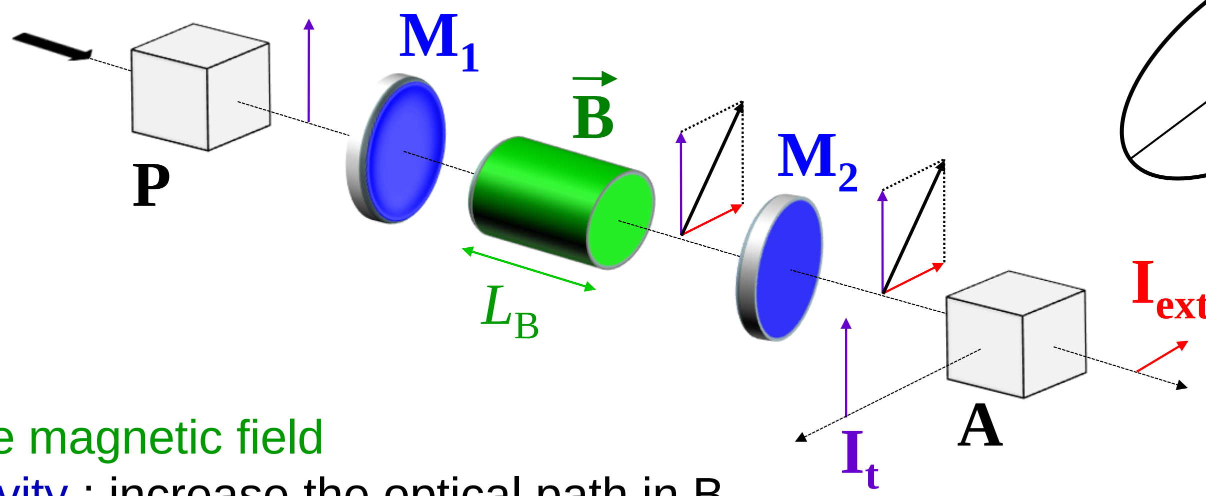
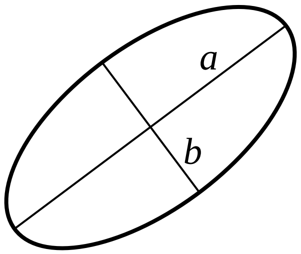
The ellipsometer

Laser
λ = 1064 nm





- High transverse magnetic field
- Fabry-Pérot cavity : increase the optical path in B
- P and A : polarizers crossed at maximum extinction
- B at 45° compared to polarizers' direction

Ellipticity measurement : $$\Psi = \frac{\pi}{\lambda} k_{\mathrm{CM}} \left(\frac{2F}{\pi} \right) B^2 L_{\mathrm{B}}$$

As high as possible

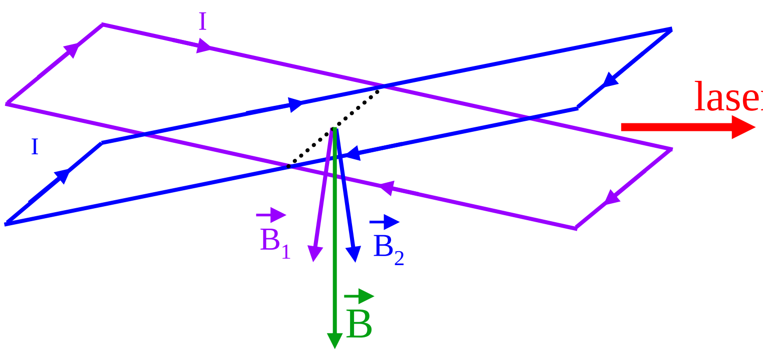
Cavity finesse as high as possible

As high as possible

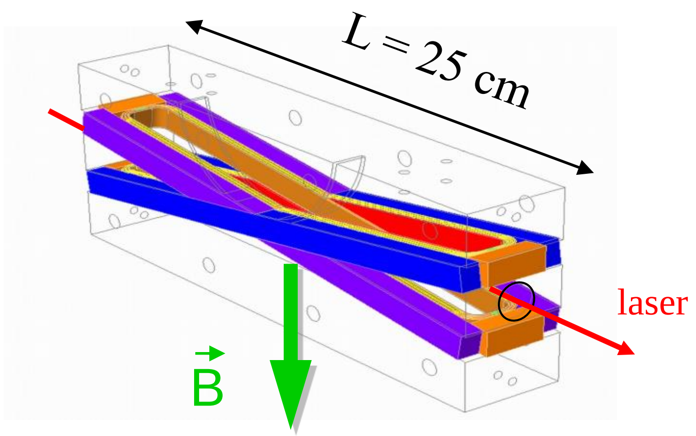
Pulsed transverse magnetic field

X-coil geometry $\Rightarrow$ high transverse magnetic field

Unconventional pulsed magnets developed at LNCMI



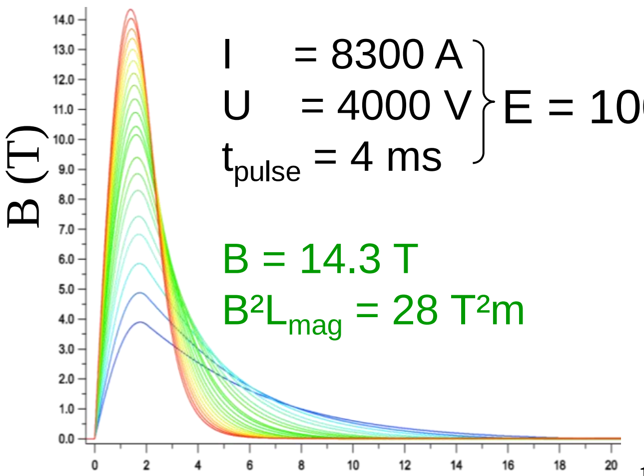
Voigt configuration



R. Battesti *et al.*, *EPJD* ***46****, 323 (2008)*

Pulsed transverse magnetic field

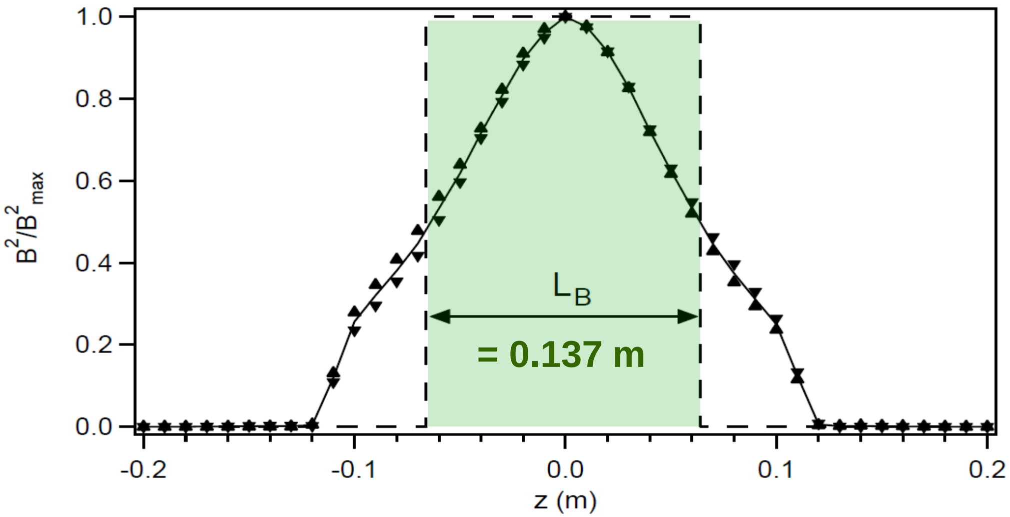
- Time evolution :



$I = 8300$ A
$U = 4000$ V
$t_{pulse} = 4$ ms
E = 100 kJ

B = 14.3 T
$B^2 L_{mag} = 28\ T^2m$

- Longitudinal profile :

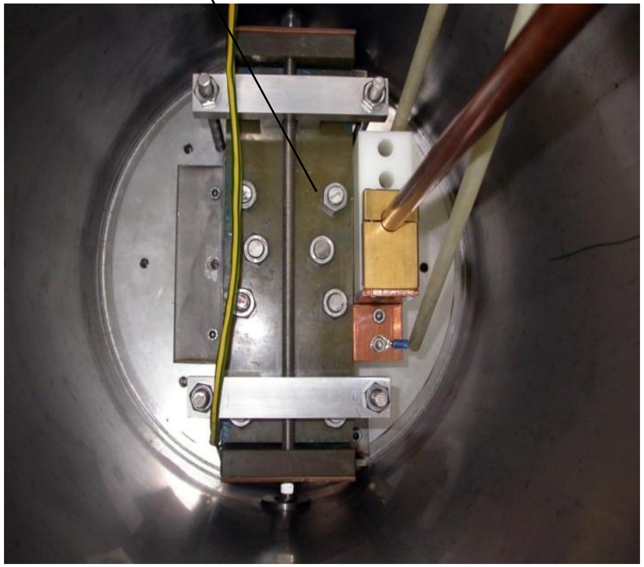


Currently :

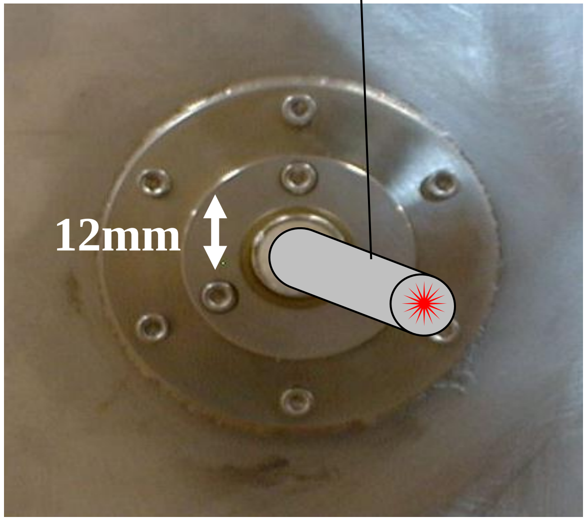
$$B_{max} = 6.5\ \mathrm{T}$$
$$B^2_{max} L_B = 5.7\ \mathrm{T}^2\mathrm{m}$$

Pulsed transverse magnetic field

External reinforcement to contain the magnetic pressure



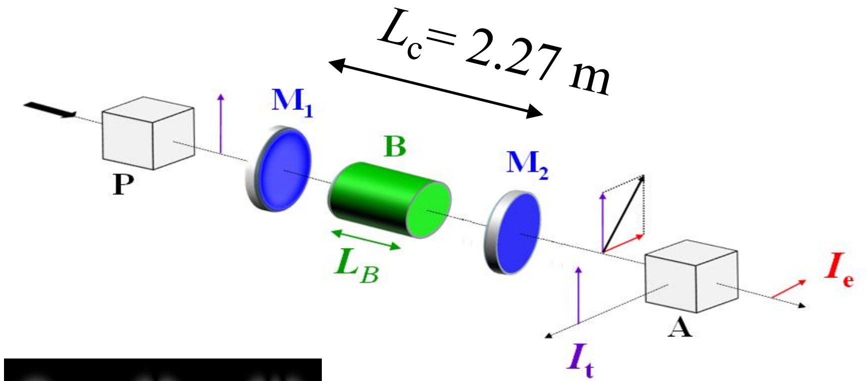
Hole to let the laser in

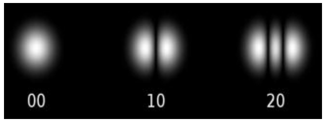


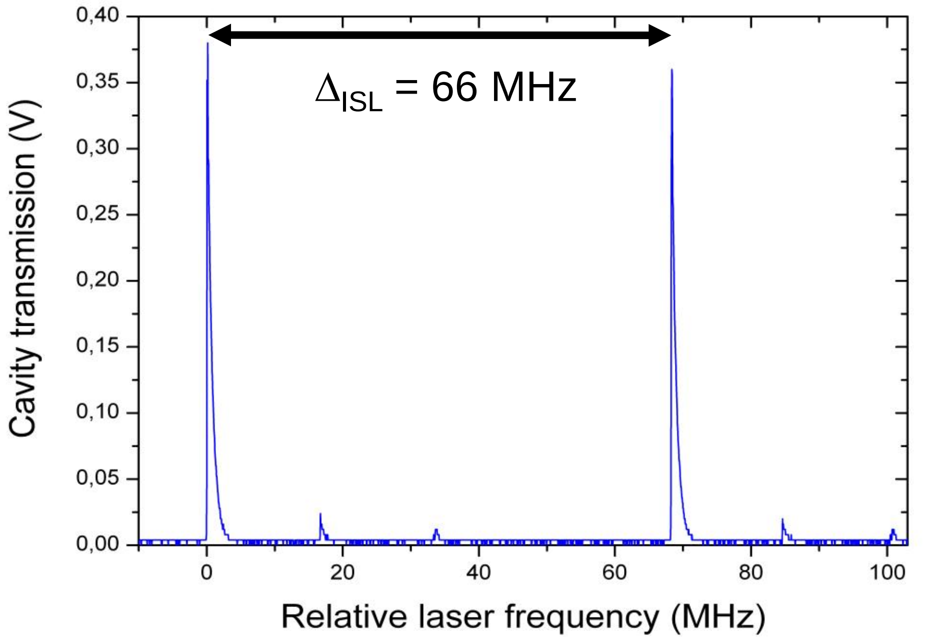
Immersion in liquid nitrogen to avoid consequences of heating

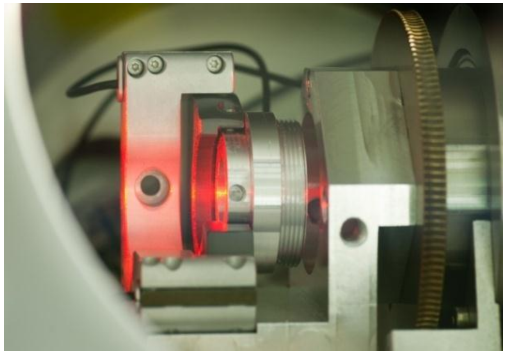
The Fabry-Pérot cavity

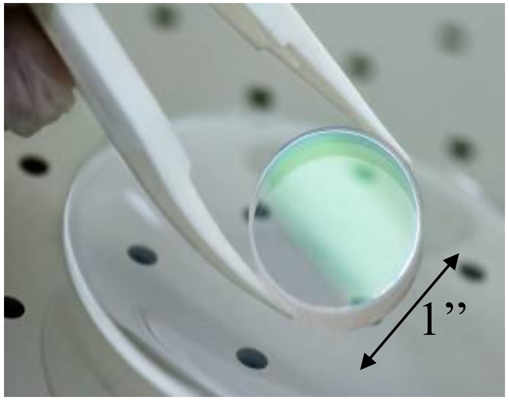
$$\Psi = \frac{\pi}{\lambda} k_{\mathrm{CM}} \left(\frac{2F}{\pi} \right) B^2 L_{\mathrm{B}}$$







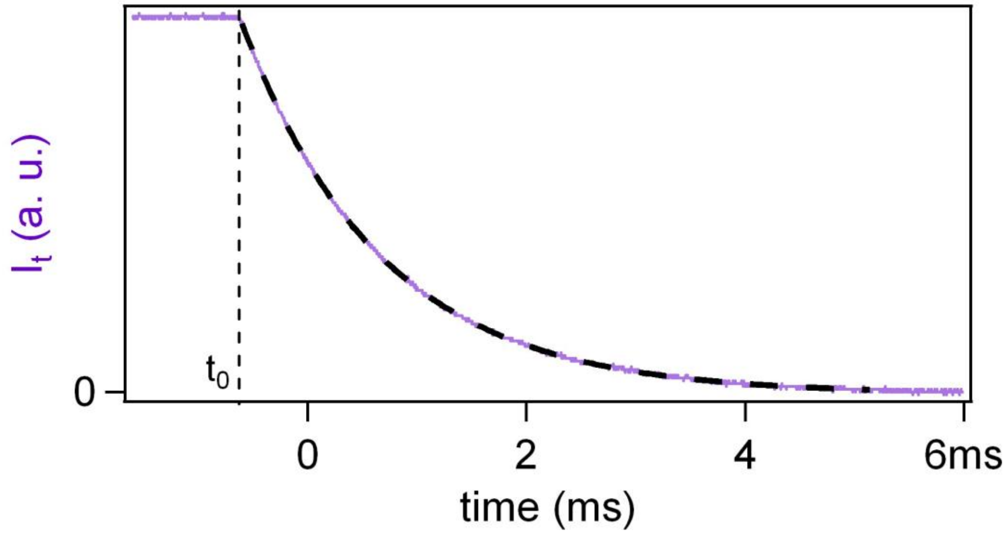




ATFilms Precision Optics, Technical Solutions

The Fabry-Pérot cavity

Finesse :



- photon lifetime in the cavity (L_c = 2.27 m long) :
  τ = 1.08 ms

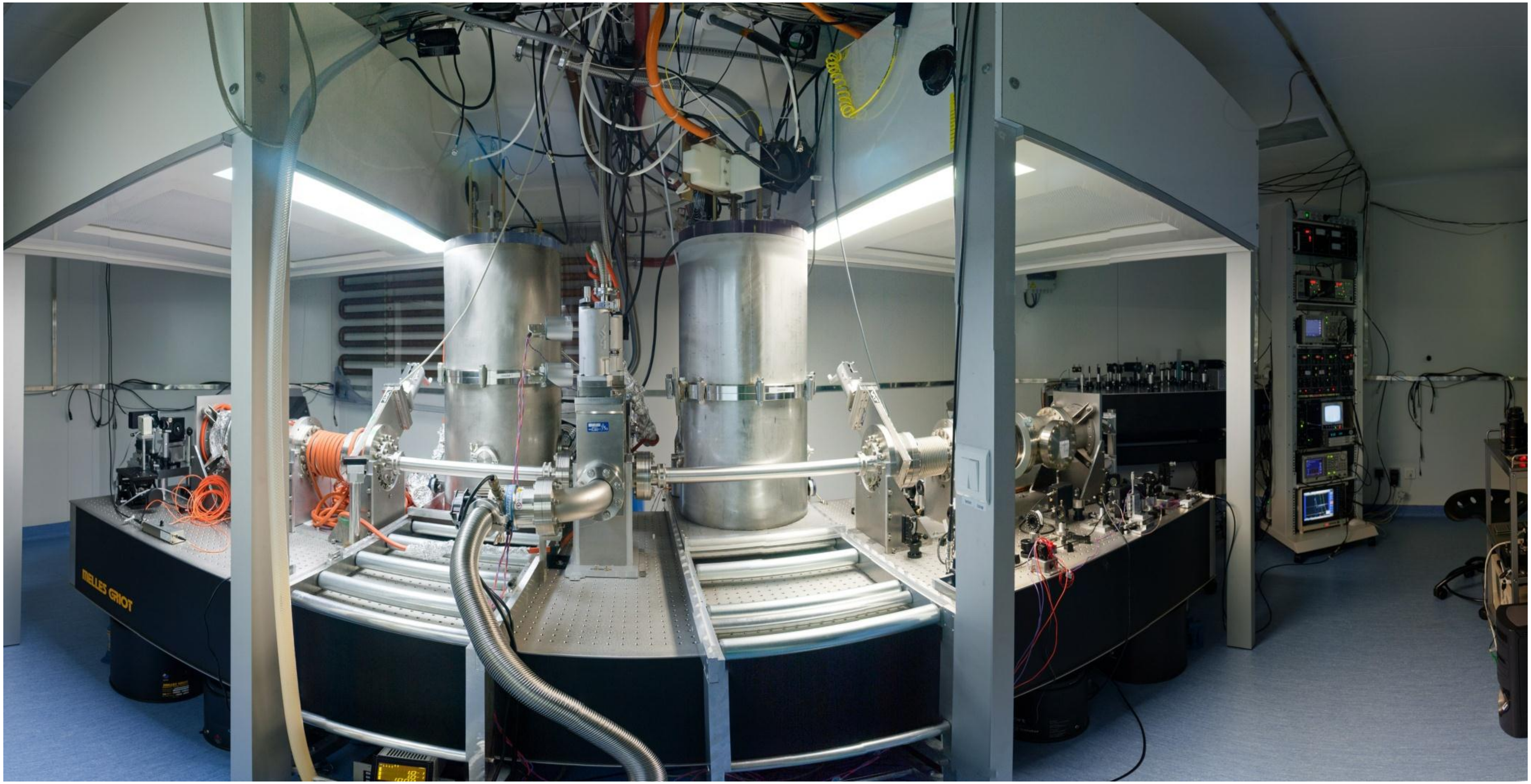
- flight distance in the cavity = 325 km

$$\boxed{F = \frac{\pi c \tau}{L_c} = 450\,000}$$

Other cavities around the world

	VIRGO	PVLAS	aLIGO	BMV (Biréfringence Magnétique du Vide)
L_c	3 km	6.4 m	4 km	2.27 m
τ	159 ms	442 ms	970 ms	1.08 ms
$F = \dfrac{\pi c \tau}{L_c}$	50	70 000	230	450 000
$\Delta\nu = \dfrac{c}{2L_c F}$	1 kHz	360 Hz	164 Hz	147 Hz

➡ One of the **sharpest** cavities of the world high reflectivity mirrors → experiment mounted in a **clean room**

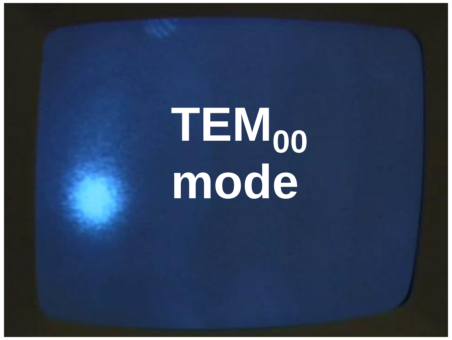


NB: Magnets removed from light path

Data acquisition

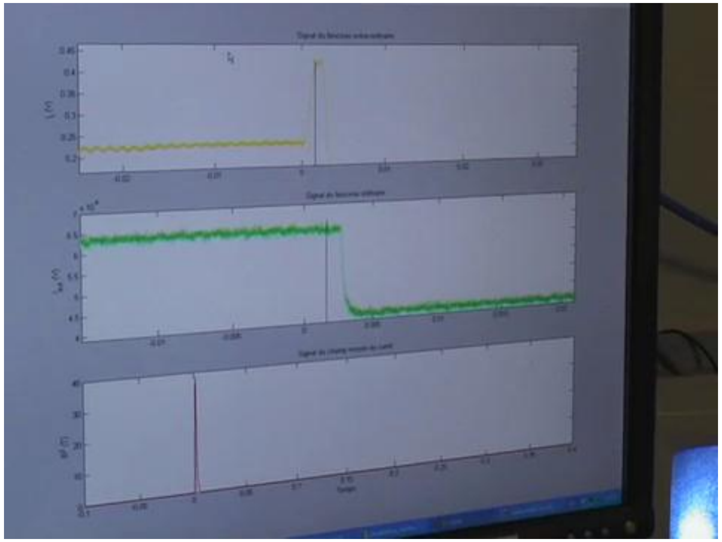
Alignment of the cavity mirrors

Laser locked on the cavity



Shot

Data analysis



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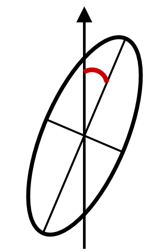
Signal analysis

Γ : cavity static ellipticity, adjusted with mirrors' orientation and measured before each shot

ε : angle between the polarizer axis and the major axis of the ellipse, proportionnal to Γ



$$\frac{I_{\text{ext}}(t)}{I_{\text{t,f}}(t)} = \sigma^2 + [\Gamma + \Psi(t)]^2 + [\varepsilon + \theta_{\text{F}}(t)]^2$$

σ^2 : polarizers extinction ratio, measured before each shot

$$\sigma^2 = \left(\frac{I_{\text{ext}}}{I_{\text{t}}}\right)_{\Gamma=0,\varepsilon=0} \approx 4\times10^{-7}$$

$\Psi(t)$: ellipticity to be measured, proportional to $B^2(t)$

θ_{F} : Faraday effect of the gas or the mirrors, propotionnal to $B(t)$

Signal analysis

$$\frac{I_{\mathrm{ext}}(t)}{I_{\mathrm{t,f}}(t)} = \sigma^2 + [\Gamma + \Psi(t)]^2 + [\varepsilon + \theta_{\mathrm{F}}(t)]^2$$

$$= \underbrace{\sigma^2 + \Gamma^2 + \varepsilon^2}_{\mathrm{DC}} + 2\Gamma\Psi(t) + 2\varepsilon\theta_{\mathrm{F}}(t) + \Psi^2(t) + \theta_{\mathrm{F}}{}^2(t)$$

- We calculate :

$$Y(t) = \frac{I_{\mathrm{ext}}(t)/I_{\mathrm{t,f}}(t) - \mathrm{DC}}{2|\Gamma|} = \gamma\,\Psi(t) + \gamma\,\frac{|\varepsilon|\theta_{\mathrm{F}}(t)}{|\Gamma|} + \frac{\Psi^2(t)}{2|\Gamma|} + \frac{\theta_{\mathrm{F}}{}^2(t)}{2|\Gamma|}$$

γ = +1 si $\Gamma>0$

γ = -1 si $\Gamma<0$

Signal analysis

$$\frac{I_{\mathrm{ext}}(t)}{I_{\mathrm{t,f}}(t)} = \sigma^2 + [\Gamma + \Psi(t)]^2 + [\varepsilon + \theta_{\mathrm{F}}(t)]^2$$

$$= \underbrace{\sigma^2 + \Gamma^2 + \varepsilon^2}_{\mathrm{DC}} + 2\Gamma\Psi(t) + 2\varepsilon\theta_{\mathrm{F}}(t) + \Psi^2(t) + \theta_{\mathrm{F}}^{\ 2}(t)$$

B^2

B^4

- We calculate :

$$Y(t) = \frac{I_{\mathrm{ext}}(t)/I_{\mathrm{t,f}}(t) - \mathrm{DC}}{2|\Gamma|} = \gamma\,\Psi(t) + \gamma\,\frac{|\varepsilon|\theta_{\mathrm{F}}(t)}{|\Gamma|} + \frac{\Psi^2(t)}{2|\Gamma|} + \frac{\theta_{\mathrm{F}}^{\ 2}(t)}{2|\Gamma|}$$

Measured
before the shot

B

$\gamma = +1$ si $\Gamma > 0$

$\gamma = -1$ si $\Gamma < 0$

Signal analysis

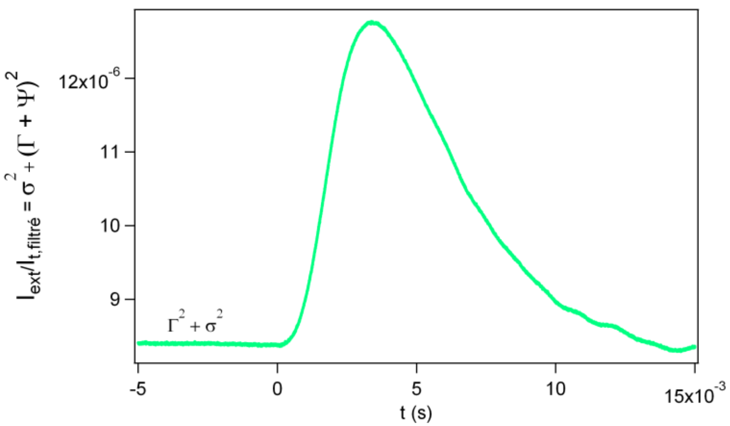
- Variable parameters :

  - sign of Γ : can be switched by rotating the mirrors

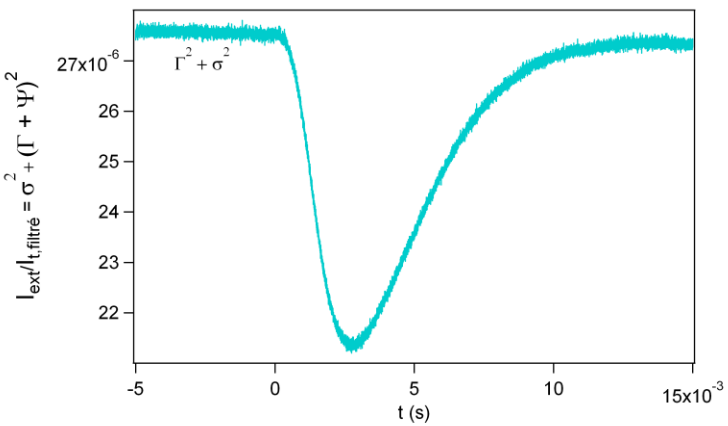
Validation : Cotton-Mouton mesurements of N_2

$\rightarrow k_{CM} = -2.00\times10^{-13}\ \mathrm{T}^{-2}.\ \mathrm{atm}^{-1}$

Magnetic pulses with P = 6 mbar, and B = 3 T



Increasing signal → Γ < 0



Decreasing signal → Γ > 0

Signal analysis

- Variable parameters :

  - sign of Γ : can be switched by rotating the mirrors

  - direction of $\vec{B}$

- 4 series of shots : $Y_{>>}$, $Y_{><}$, $Y_{<<}$, $Y_{<>}$

Sign of Γ Direction of $\vec{B}$

- *Y* signals are linear combination of different effects :

$$
\begin{aligned}
Y_{>>}(t) &= a_{>>}S_{++}(t) + b_{>>}S_{+-}(t) + c_{>>}S_{--}(t) + d_{>>}S_{-+}(t) \\
Y_{><}(t) &= a_{><}S_{++}(t) - b_{><}S_{+-}(t) - c_{><}S_{--}(t) + d_{><}S_{-+}(t) \\
Y_{<<}(t) &= a_{<<}S_{++}(t) - b_{<<}S_{+-}(t) + c_{<<}S_{--}(t) - d_{<<}S_{-+}(t) \\
Y_{<>}(t) &= a_{<>}S_{++}(t) + b_{<>}S_{+-}(t) - c_{<>}S_{--}(t) - d_{<>}S_{-+}(t)
\end{aligned}
$$

Parity with respect to the sign of Γ

Parity with respect to the direction of $\vec{B}$

Signal analysis

- <u>Variable parameters :</u>

  - sign of Γ : can be switched by rotating the mirrors

  - direction of $\vec{B}$

- 4 series of shots : $Y_{>>}$, $Y_{><}$, $Y_{<<}$, $Y_{<>}$

Sign of Γ — Direction of $\vec{B}$

- *Y* signals are linear combination of different effects :

$$Y_{>>}(t) = a_{>>}S_{++}(t) + b_{>>}S_{+-}(t) + c_{>>}S_{--}(t) + d_{>>}S_{-+}(t)$$

$$Y_{><}(t) = a_{><}S_{++}(t) - b_{><}S_{+-}(t) - c_{><}S_{--}(t) + d_{><}S_{-+}(t)$$

$$Y_{<<}(t) = a_{<<}S_{++}(t) - b_{<<}S_{+-}(t) + c_{<<}S_{--}(t) - d_{<<}S_{-+}(t)$$

$$Y_{<>}(t) = a_{<>}S_{++}(t) + b_{<>}S_{+-}(t) - c_{<>}S_{--}(t) - d_{<>}S_{-+}(t)$$

- $a_{>>} \approx a_{><} \approx a_{<<} \approx a_{<>} \ldots$, depending on experimental conditions

Signal analysis

Signal	Physical effect
$S_{++}(t)$	$\theta_F^{\,2}(t)$, $\Psi^2(t)$
$S_{+-}(t)$	Effect outside the cavity
$S_{--}(t)$	$\gamma\theta_F(t)$
$S_{-+}(t)$	$\gamma\Psi(t)$

To isolate $S_{-+}(t)$: linear combinations of $Y(t)$

$$J_1(t) = \frac{1}{4}\left[Y_{>>} + Y_{><} + Y_{<<} + Y_{<>}\right] = \bar{a}S_{++} + \Delta b_1 S_{+-} + \Delta c_1 S_{--} + \Delta d_1 S_{-+} \approx \bar{a}S_{++}$$

$$J_2(t) = \frac{1}{4}\left[Y_{>>} - Y_{><} - Y_{<<} + Y_{<>}\right] = \bar{b}S_{+-} + \Delta a_2 S_{++} + \Delta c_2 S_{--} + \Delta d_2 S_{-+} \approx \bar{b}S_{+-}$$

$$J_3(t) = \frac{1}{4}\left[Y_{>>} - Y_{><} + Y_{<<} - Y_{<>}\right] = \bar{c}S_{--} + \Delta a_3 S_{++} + \Delta b_3 S_{+-} + \Delta d_3 S_{-+} \approx \bar{c}S_{--}$$

$$J_4(t) = \frac{1}{4}\left[Y_{>>} + Y_{><} - Y_{<<} - Y_{<>}\right] = \bar{d}S_{-+} + \Delta a_4 S_{++} + \Delta b_4 S_{+-} + \Delta c_4 S_{--}$$

Signal analysis

- Ellipticity signal :

$$J_4(t)=\frac{1}{4}\left[Y_{>>}+Y_{><}-Y_{<<}-Y_{<>}\right]=\underbrace{\bar{d}S_{-+}}_{\Psi(t)\,=\,\alpha\, B^2_{\mathrm{f}}(t)}+\overbrace{\Delta a_4 S_{++}}^{\Delta a/\bar{a}\, J_1(t)}+\overbrace{\Delta b_4 S_{+-}}^{\Delta b/\bar{b}\, J_2(t)}+\overbrace{\Delta c_4 S_{--}}^{\Delta c/\bar{c}\, J_3(t)}$$

$$\boxed{k_{CM}=\frac{\alpha\lambda}{2FL_{\mathrm{B}}}}$$

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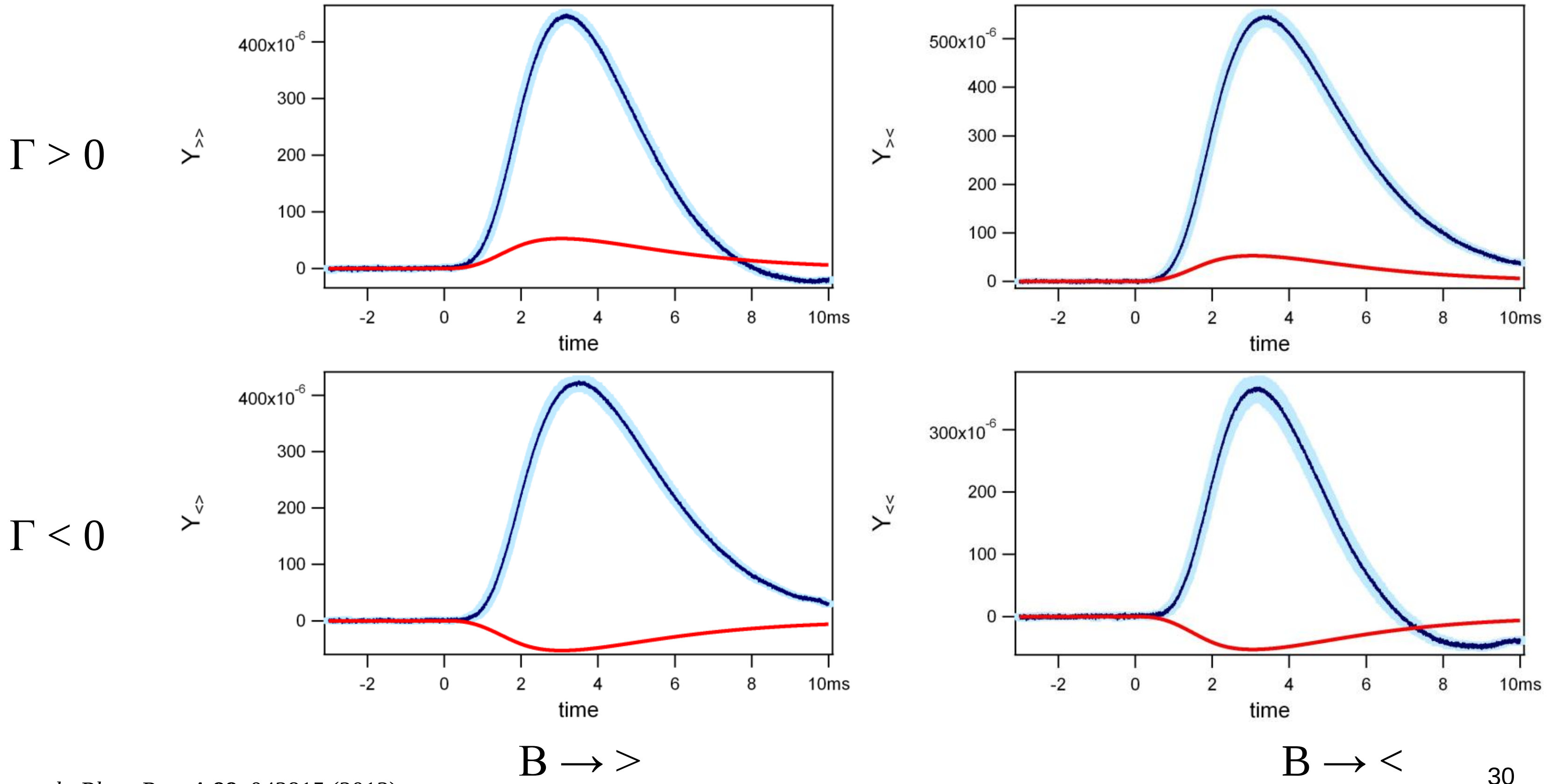
Cotton-Mouton effect of helium gas

- Theoretical prediction : k_{CM} = $(2.237 \pm 0.009)\times10^{-16}$ $T^{-2}.atm^{-1}$ at 293K
- Smallest effect after vacuum

P = 450 matm

$Y(t)$ signals → linear combination of different signals



A. Cadène *et al.*, *Phys. Rev. A* **88**, 043815 (2013)

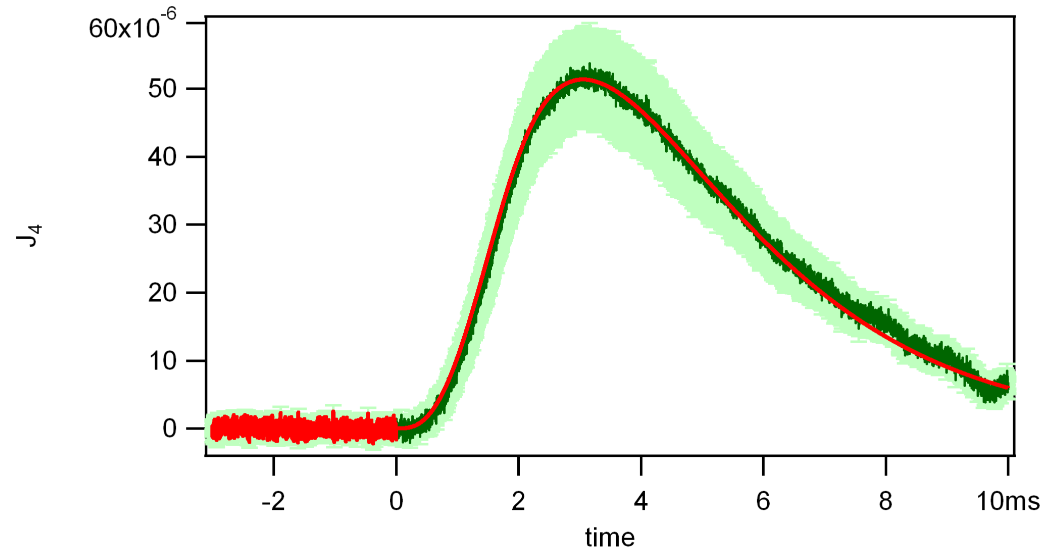
Cotton-Mouton effect of helium gas

P = 450 matm

$$J_4(t) = \bar{d}S_{-+} + \overbrace{\Delta a_4 S_{++}}^{\Delta a/\bar{a}\, J_1(t)} + \overbrace{\Delta b_4 S_{+-}}^{\Delta b/\bar{b}\, J_2(t)} + \overbrace{\Delta c_4 S_{--}}^{\Delta c/\bar{c}\, J_3(t)}$$

$$\bar{d}S_{-+} >> \Delta a_4 S_{++}, \Delta b_4 S_{+-}, \Delta c_4 S_{--} \longrightarrow J_4(t) \approx \underbrace{\bar{d}S_{-+}}_{\Psi(t) = \alpha B^2_f(t)}$$

- J_4 fitted by $\alpha B^2{}_f$:



$\rightarrow k_{CM} = 9.7 \times 10^{-17}\ \mathrm{T}^{-2}$

A. Cadène *et al.*, *Phys. Rev. A* **88**, 043815 (2013)

Cotton-Mouton effect of helium gas

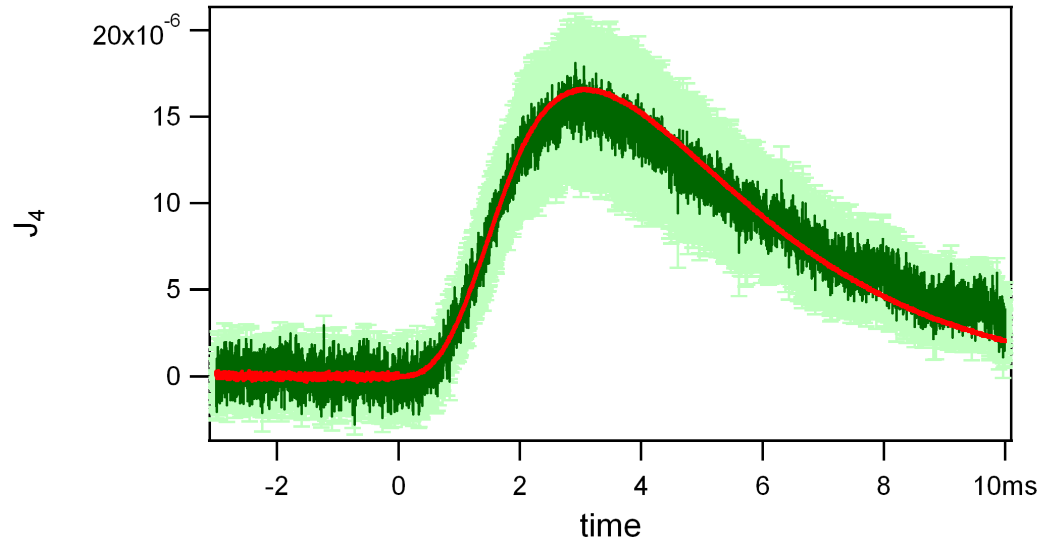
P = 162 matm

- J_4 fitted by $\alpha B^2{}_{\mathrm{f}}$:

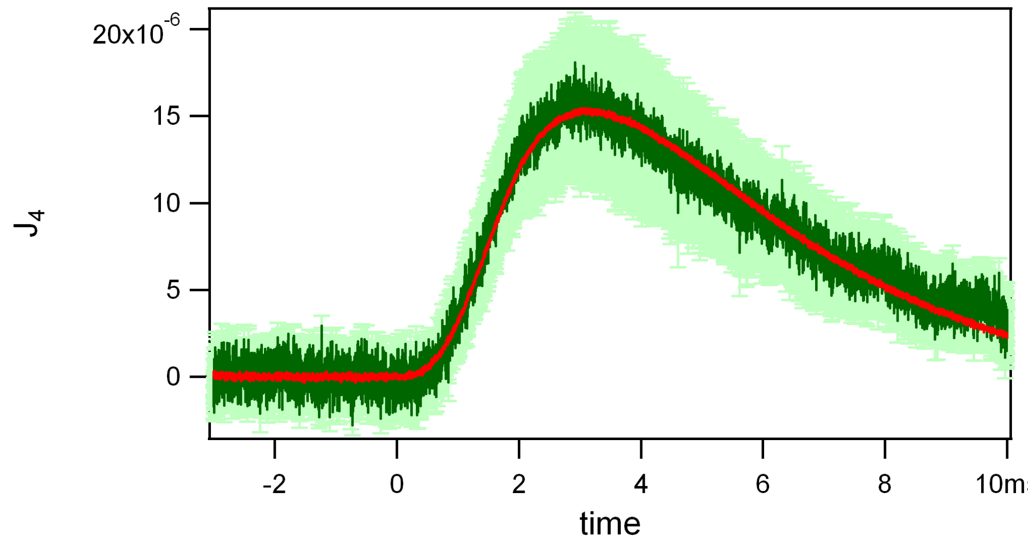
$\rightarrow k_{\mathrm{CM}} = 3.2\times 10^{-17}\ \mathrm{T}^{-2}$

$$\bar{d}S_{-+} \cancel{\gg} \Delta a_4 S_{++}, \Delta b_4 S_{+-}, \Delta c_4 S_{--}$$

$$J_4(t) \approx \bar{d}S_{-+} + \ldots$$



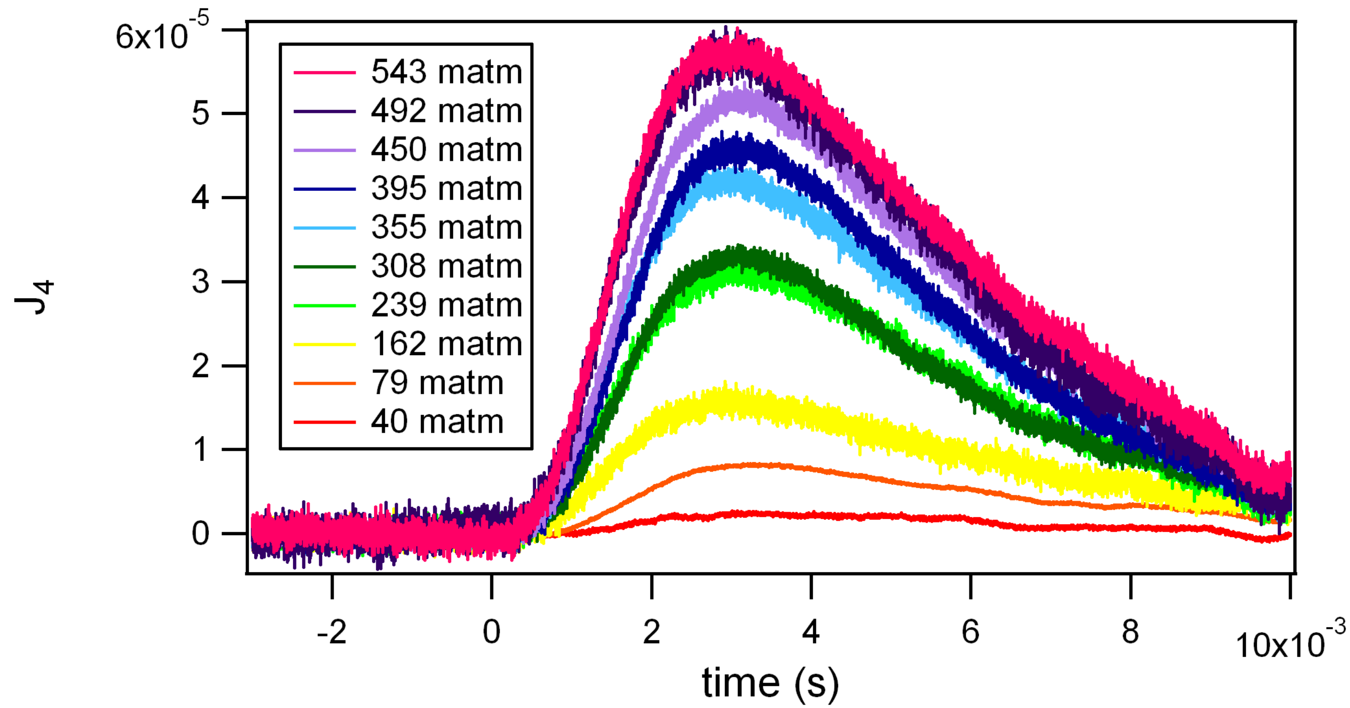
- J_4 fitted by $\alpha B^2{}_{\mathrm{f}} + \alpha_1 J_1 + \alpha_3 J_3$



A. Cadène *et al.*, *Phys. Rev. A* **88**, 043815 (2013)

Cotton-Mouton effect of helium gas

- Measurements between 40 matm and 550 matm, B = 3T



A. Cadène *et al.*, *Phys. Rev. A* **88**, 043815 (2013)

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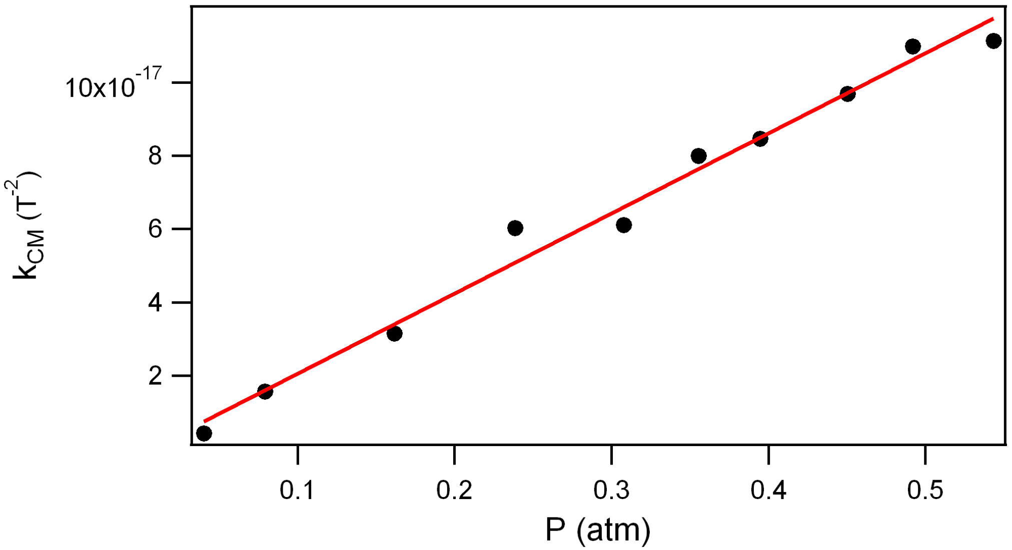


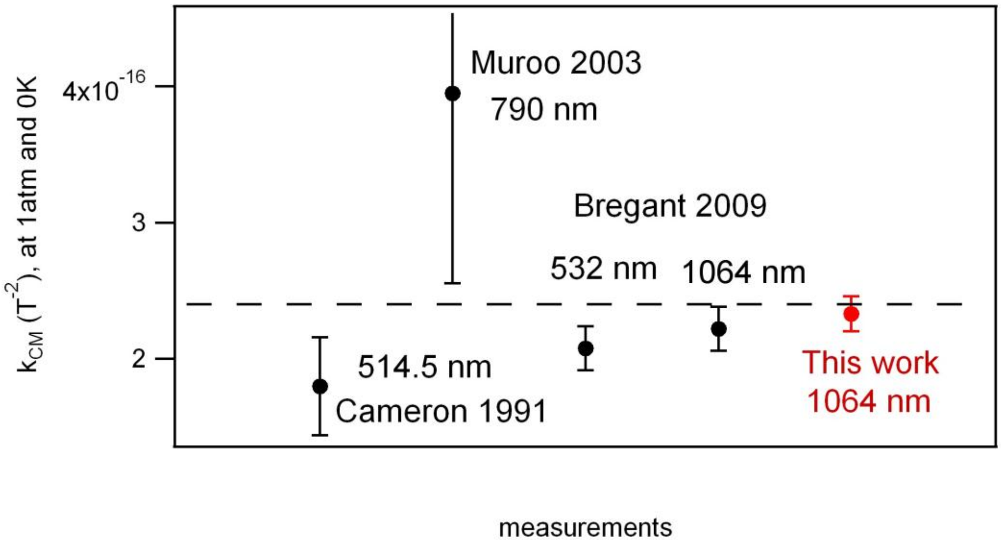
- Cotton-Mouton effect of helium : k_{CM} = (2.19 ± 0.12)×10^{-16} T^{-2}.atm^{-1} at 293K
- Theoretical prediction : k_{CM} = (2.237 ± 0.009)×10^{-16} T^{-2}.atm^{-1}

→ Validation of the analysis method

A. Cadène *et al.*, *Phys. Rev. A* **88**, 043815 (2013)

Cotton-Mouton effect of helium gas

- <u>Comparison</u>



Cameron 1991 : R. Cameron *et al.*, *Phys. Rev. A* **157**, 125 (1991)

Muroo 2003 : K. Muroo *et al.*, *J. Opt. Soc. Am. B* **20**, 2249 (2003)

Bregant 2009 : M. Bregant *et al.*, *Chem. Phys. Lett.* **471**, 322 (2009)

This work : A. Cadène *et al.*, *Phys. Rev. A* **88**, 043815 (2013)

Outline

- The LNCMI
- Experimental setup
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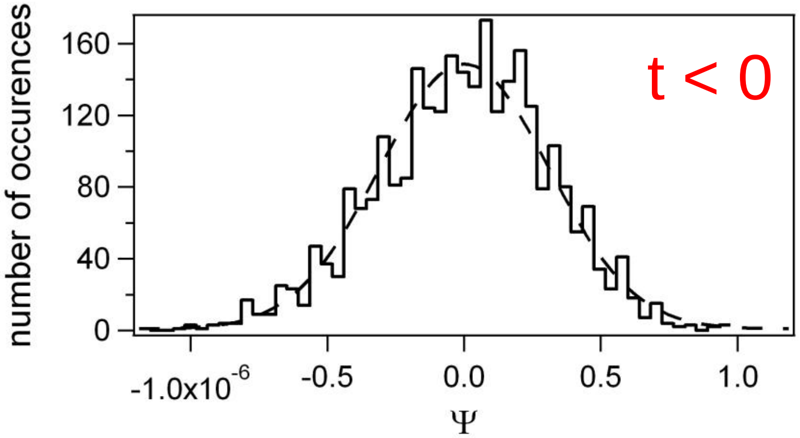
- Cotton-Mouton effect of helium gas
- **Cotton-Mouton effect of vacuum**
- Axions
- Conclusions and perspectives

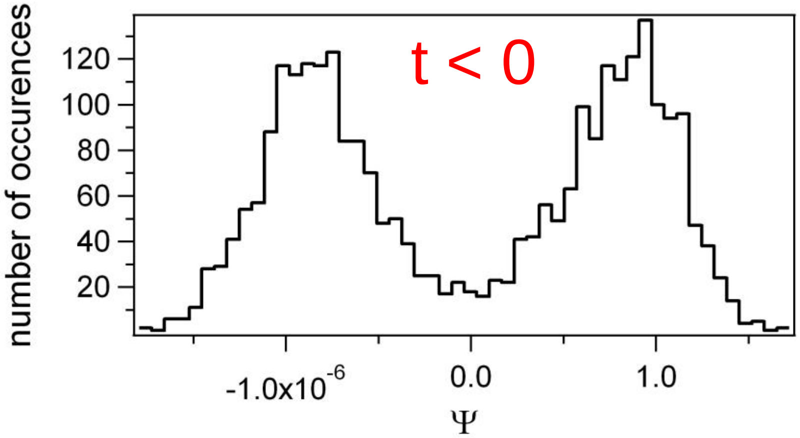
Biréfringence Magnétique du Vide

Vacuum magnetic birefringence

- Around than 200 shots, P ≈ 10^{-7} mbar, B = 6.5T
- Selection of the shots : 101 shots selected



Selected shot

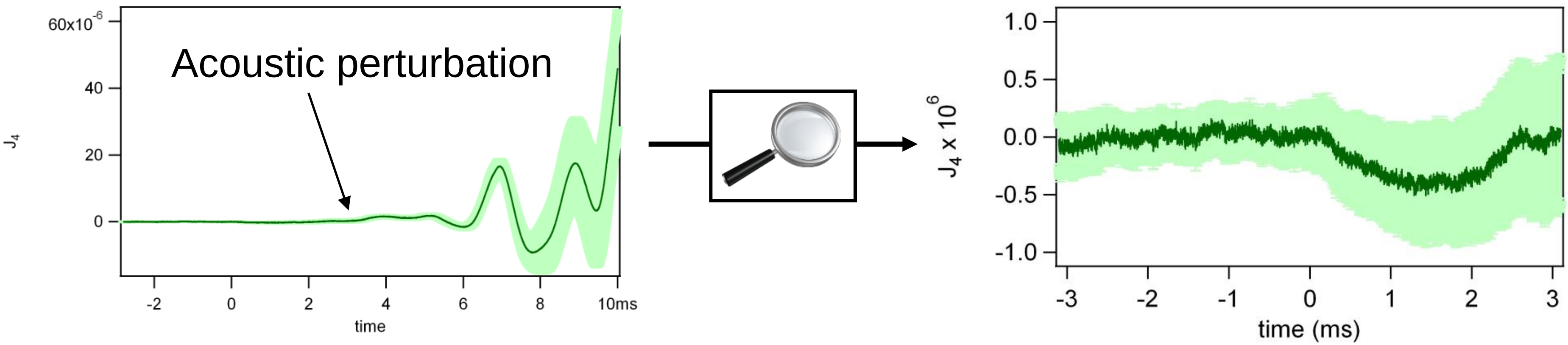


Rejected shot

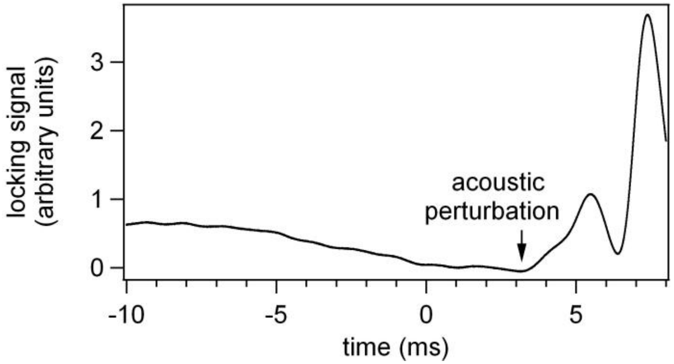
A. Cadène et al., arXiv:1302.5389v2 (2013)

Vacuum magnetic birefringence

- Around than 200 shots, P ≈ 10^{-7} mbar, B = 6.5T
- Selection of the shots : 101 shots selected
- Calculation of J_4



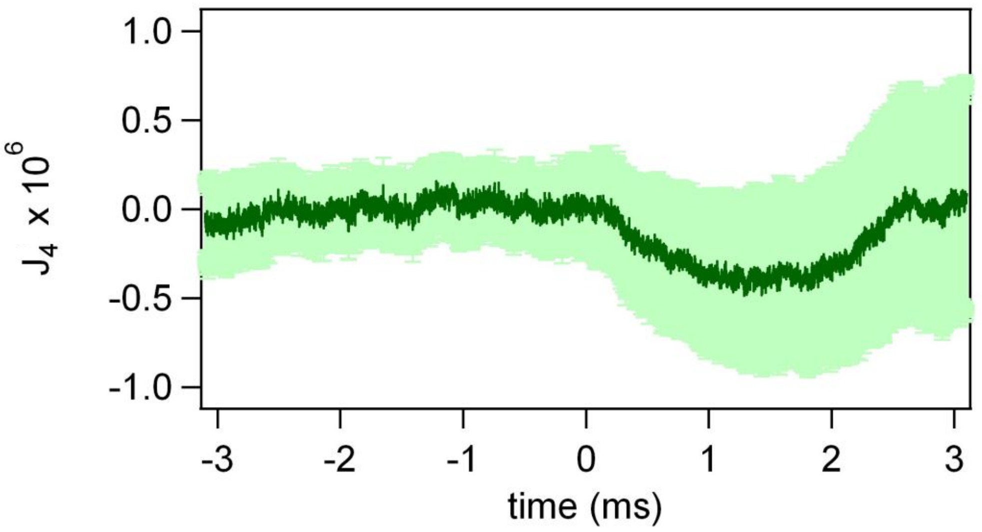
- Acoustic perturbation also observed on the locking signal



A. Cadène et al., arXiv:1302.5389v2 (2013)

Vacuum magnetic birefringence

$$J_4(t) \approx \underbrace{\bar{d}S_{-+}}_{\Psi(t)}$$



A. Cadène et al., arXiv:1302.5389v2 (2013)

Vacuum magnetic birefringence

Contribution to $\Psi(t)$:

- Cotton-Mouton effect of **vacuum** :

$$\Rightarrow \ k_{\mathrm{CM}} = 4 \times 10^{-24}\ \mathrm{T}^{-2}$$

- Cotton-Mouton effect of **residual gaz** :

$P \approx 10^{-7}$ mbar, most important contributions come from N_2 and O_2

$$\Rightarrow \ k_{\mathrm{CM}} = 5 \times 10^{-23}\ \mathrm{T}^{-2}$$

- Cotton-Mouton effect of the **mirrors** :

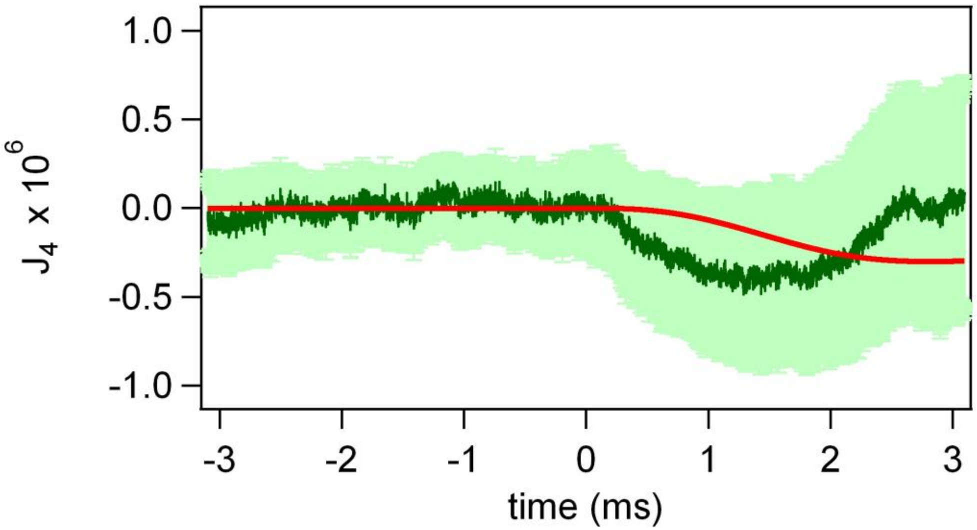
$B_{\mathrm{mirror}} \approx 150\ \mu\mathrm{T}$

$$\Rightarrow \ k_{\mathrm{CM}} = 1 \times 10^{-24}\ \mathrm{T}^{-2}$$

A. Cadène et al., arXiv:1302.5389v2 (2013)

Vacuum magnetic birefringence

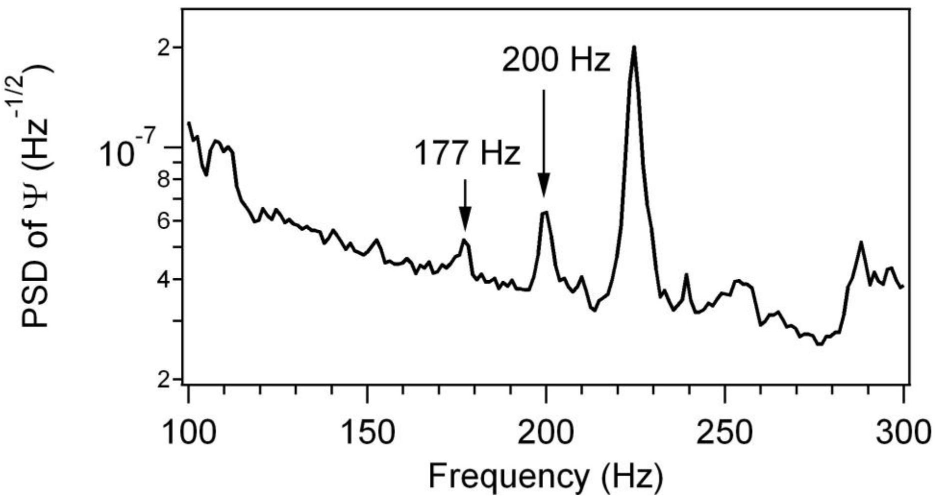
$$J_4(t) \approx \underbrace{\bar{d}S_{-+}}_{\Psi(t)}$$



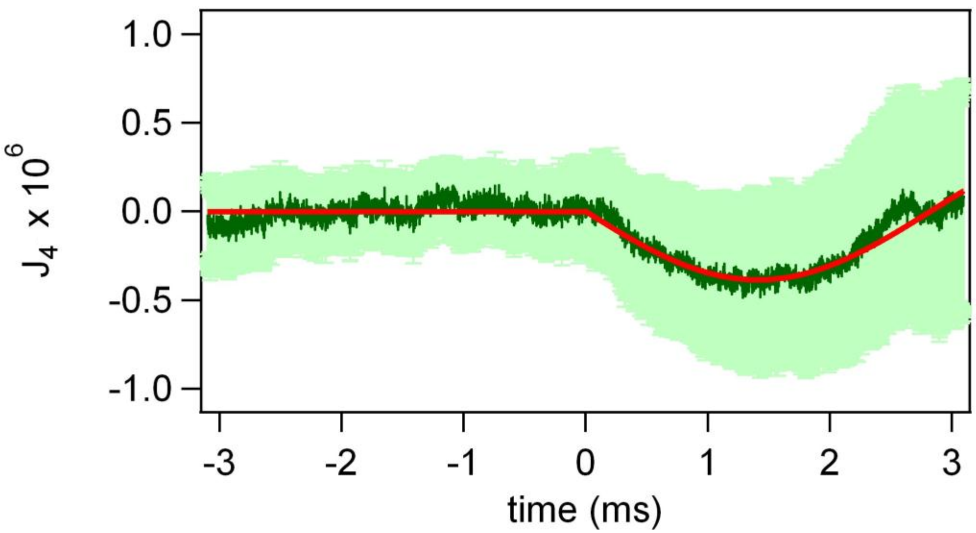
$B^2{}_f$ function superimposed to guide the eyes

A. Cadène et al., arXiv:1302.5389v2 (2013)

Vacuum magnetic birefringence

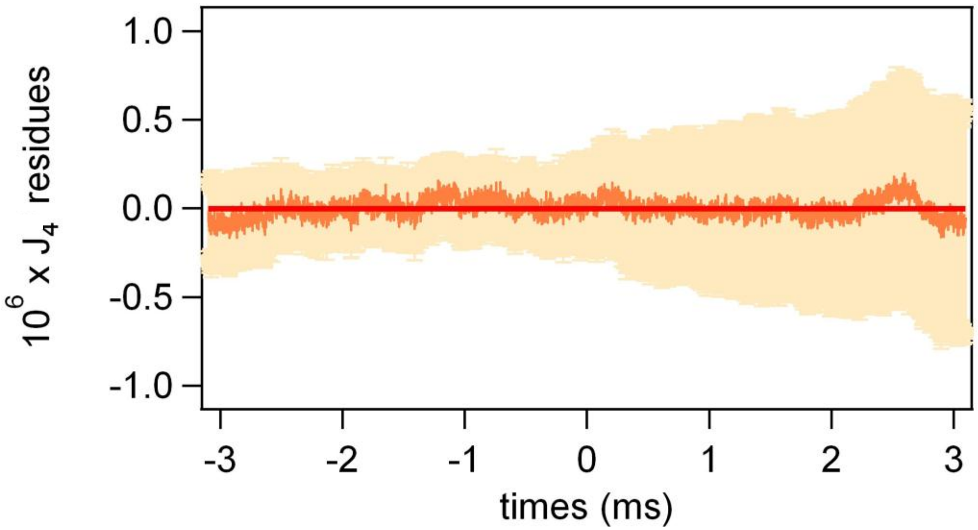


Fit by a sine, f =177 Hz



A. Cadène et al., arXiv:1302.5389v2 (2013)

Vacuum magnetic birefringence



$$\boxed{k_{CM} = (5.1 \pm 6.2) \times 10^{-21}\ \mathrm{T}^{-2}}$$

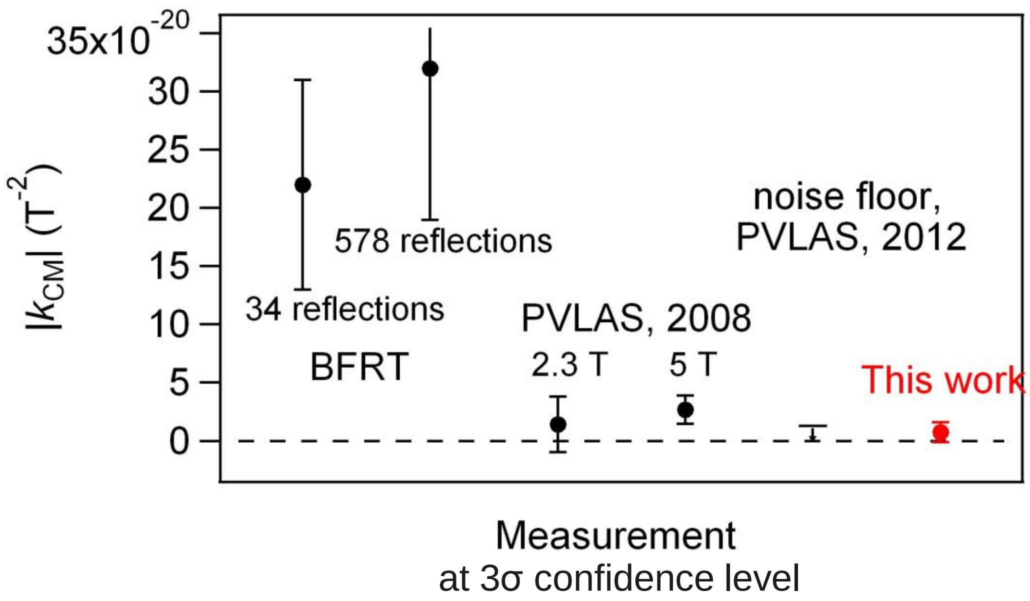
at 3σ confidence level

→ 3 orders of magnitude from the QED measurement

A. Cadène et al., arXiv:1302.5389v2 (2013)

Vacuum magnetic birefringence

- <u>Comparison</u>



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

PVLAS, 2008 : E. Zavattini *et al.*, *Phys. Rev. D* **77**, 032006 (2008)

PVLAS, 2012 : G. Zavattini *et al.*, *Int. J. of Mod. Phys. A* **27**, 1260017 (2012)

This work : *A. Cadène et al., arXiv:1302.5389v2 (2013)*, submitted to PRD

Outline

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Biréfringence Magnétique du Vide

Axions

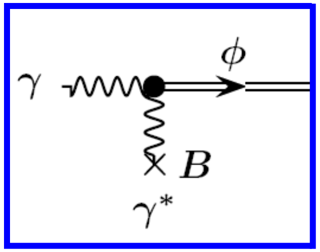
By product : beyond Standard Model

Example :   axion physics

- Axion : pseudoscalar, spinless, chargeless particle coupling with two photons
- Two free parameter theory : g coupling constant and m_a mass of the axion
- Axion can be detected in an experiment like the BMV one !

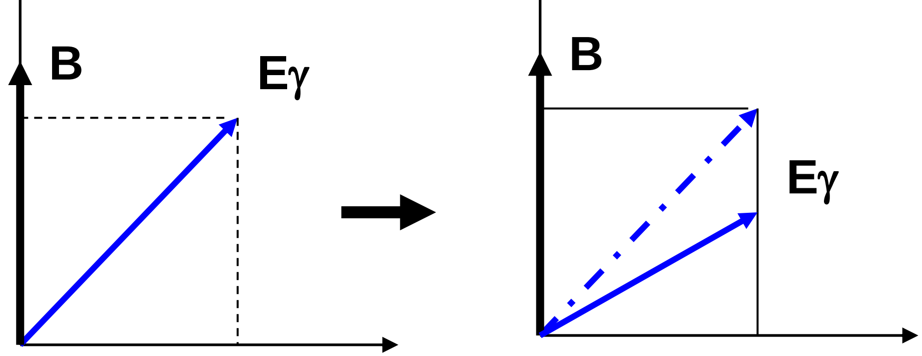
Axions

Real particle



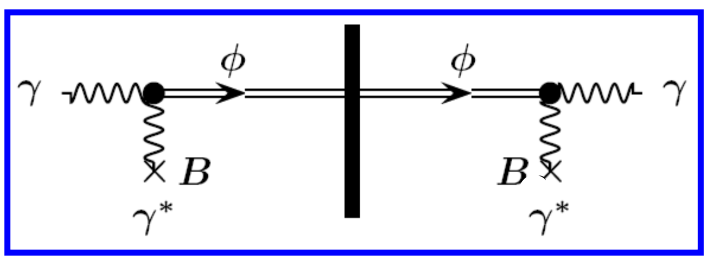
« BL » effects

Dicroism



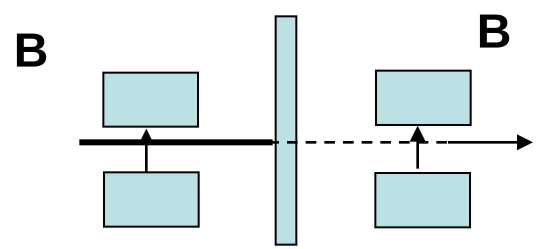
« Pseudoscalar case »

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



wall

Photon regeneration

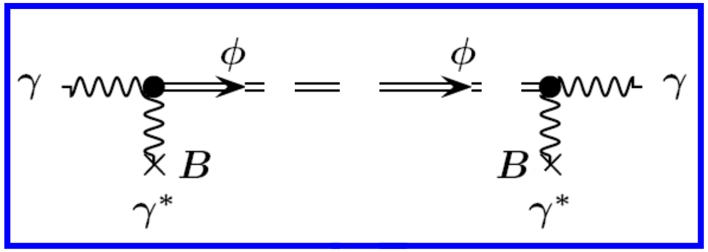


wall

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

Axions

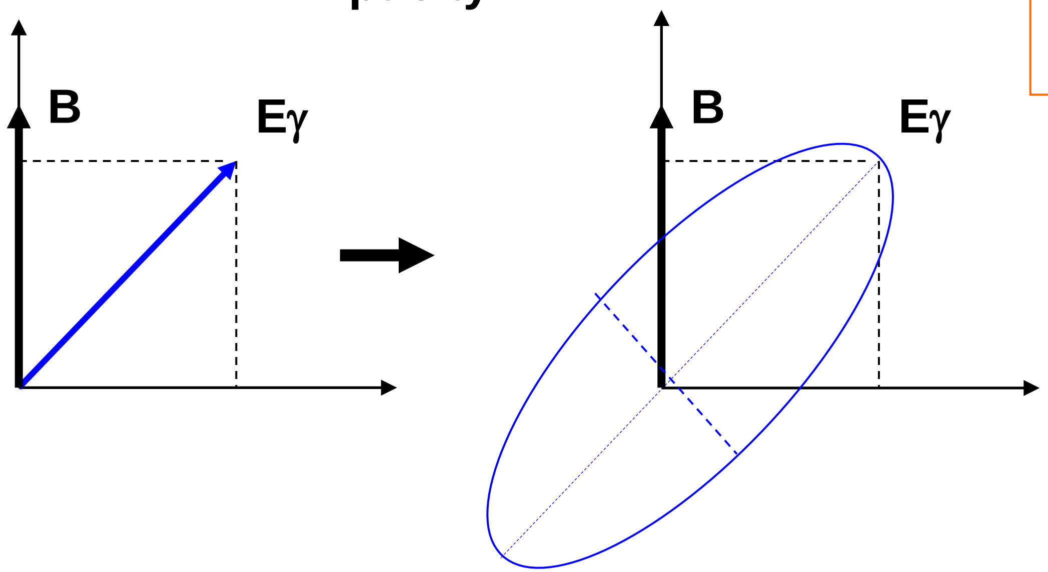
Virtual particle



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

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

Ellipticity



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

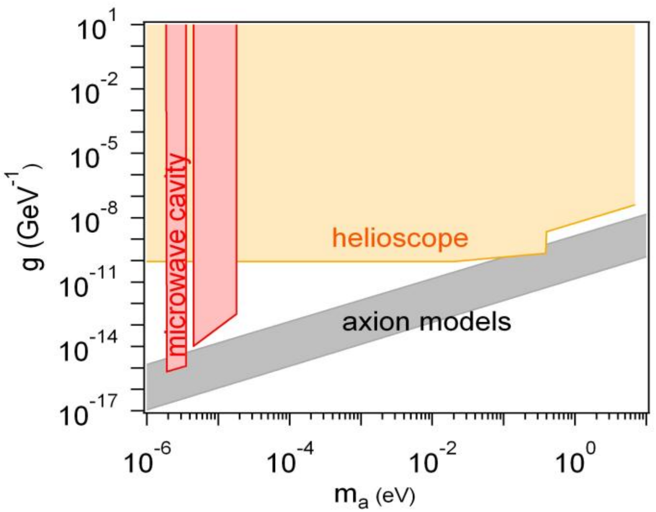
Axions

- <u>Axion source :</u>

  - solar origin : CAST

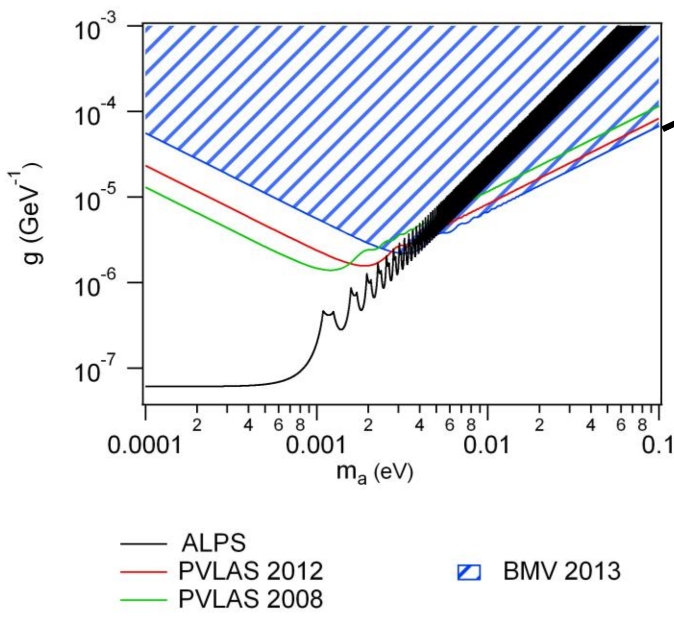
  - cosmic origin : ADMX

- <u>Detection on earth</u>



- <u>Axion source and detection on earth :</u>

  - light shining through the wall : ALPS



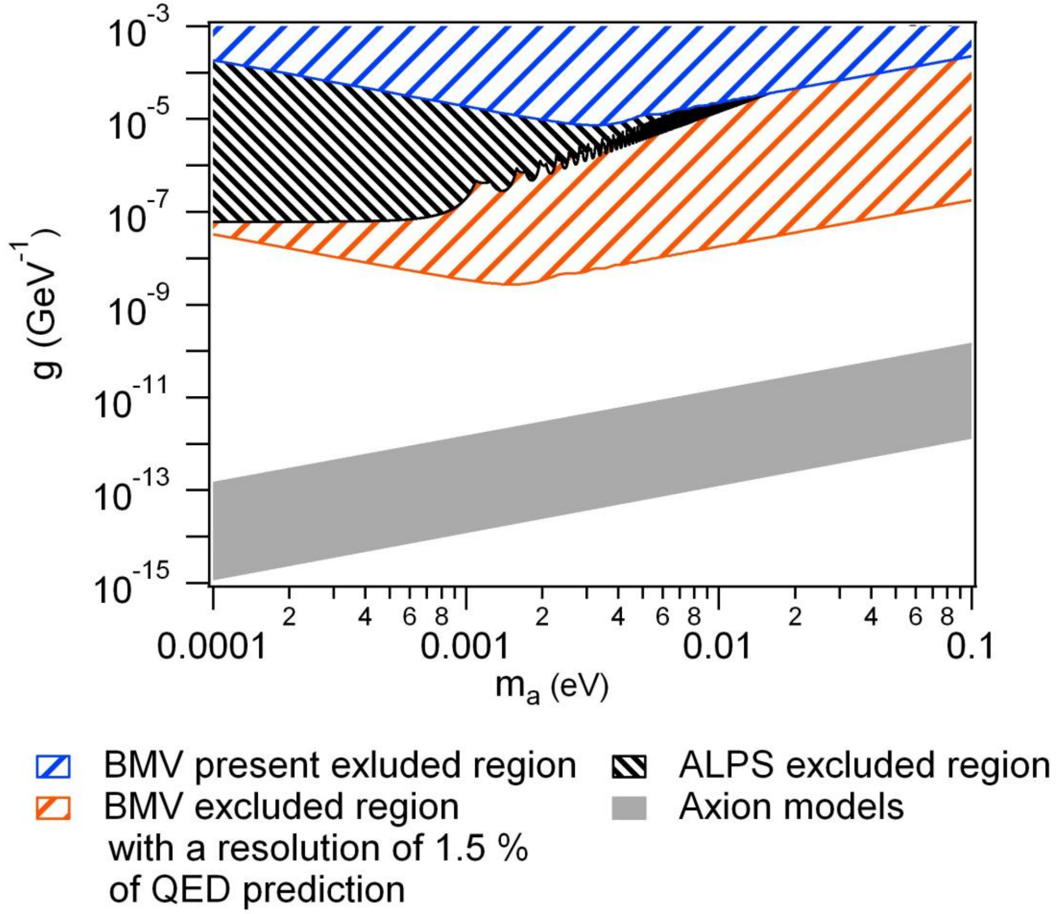
Limits also apply to large masses

CAST :E. Arik et al, J. Cosm. Astropart. Phys. **02**, 8 (2009)
ADMX : S. J. Asztalos et al., Phys. Rev. Lett. **104**, 041301 (2010)

ALPS : K. Ehret et al., Phys. Lett. B **689**, 149 (2010)
PVLAS, 2008 : E. Zavattini *et al.*, *Phys. Rev. D* **77**, 032006 (2008)
PVLAS, 2012 : G. Zavattini *et al.*, *Int. J. of Mod. Phys. A* **27**, 1260017 (2012)

Axions

- Axion source and detection on earth :



ALPS : K. Ehret et al., Phys. Lett. B **689**, 149 (2010)

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Biréfringence Magnétique du Vide

Where we are :

- Coupling high magnetic field and one of the best Fabry-Pérot cavity
- Measurements performed in gases and vacuum
- Sensitivity ≈ 10^{-20} T^{-2}/ pulse

Perspectives : → Goal : 10^{-22} T^{-2}/pulse

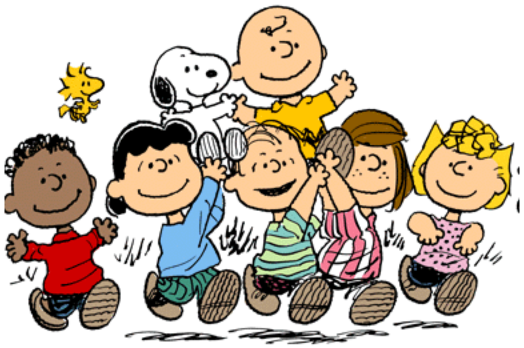
Vacuum QED measurement : 1000 pulses (3 months)

- Increase the transverse magnetic field : 2 XXL-coil, operational before the end of the year

$B^2L_B > 300\ T^2m$

- Improvement of the finesse, collaboration with LMA (Lyon)
- Improvement of the optical sensitivity : new setup

Biréfringence Magnétique du Vide



Thanks to the whole laboratory staff and to all the colleagues involved in the project.

- Rémy Battesti
- Paul Berceau
- Agathe Cadène
- Mathilde Fouché
- Carlo Rizzo

Thank you

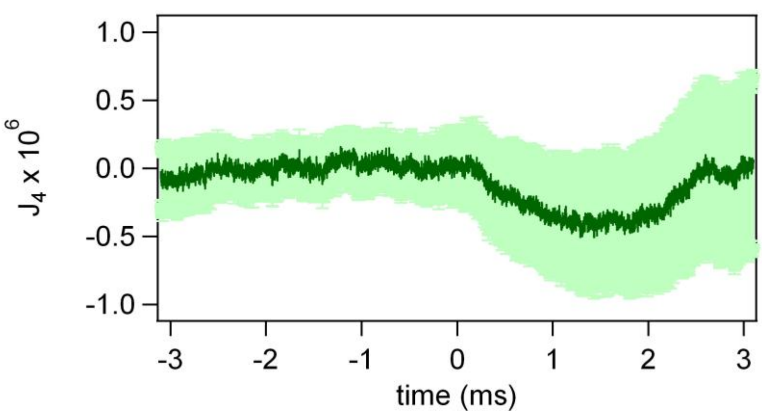
for your attention

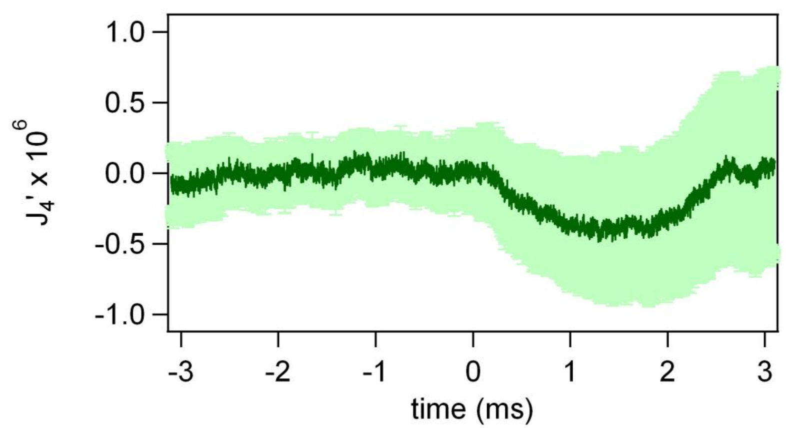
Vacuum magnetic birefringence

$$J_4(t) = \underbrace{\bar{d}S_{-+}}_{\Psi(t)} + \underbrace{\Delta a_4 S_{++}}_{\Delta a/\bar{a}\, J_1(t)} + \underbrace{\Delta b_4 S_{+-}}_{\Delta b/\bar{b}\, J_2(t)} + \underbrace{\Delta c_4 S_{--}}_{\Delta c/\bar{c}\, J_3(t)}$$

$$\left.\begin{array}{l} \Delta a/\bar{a} \\ \Delta b/\bar{b} \\ \Delta c/\bar{c} \end{array}\right\}$$ Depend on experimental parameters, in particular on the value of Γ, lower than 8%

→ Can be calculated and subtracted to obtain : $J_4^{'}(t) = \bar{d}S_{-+} = \Psi(t)$

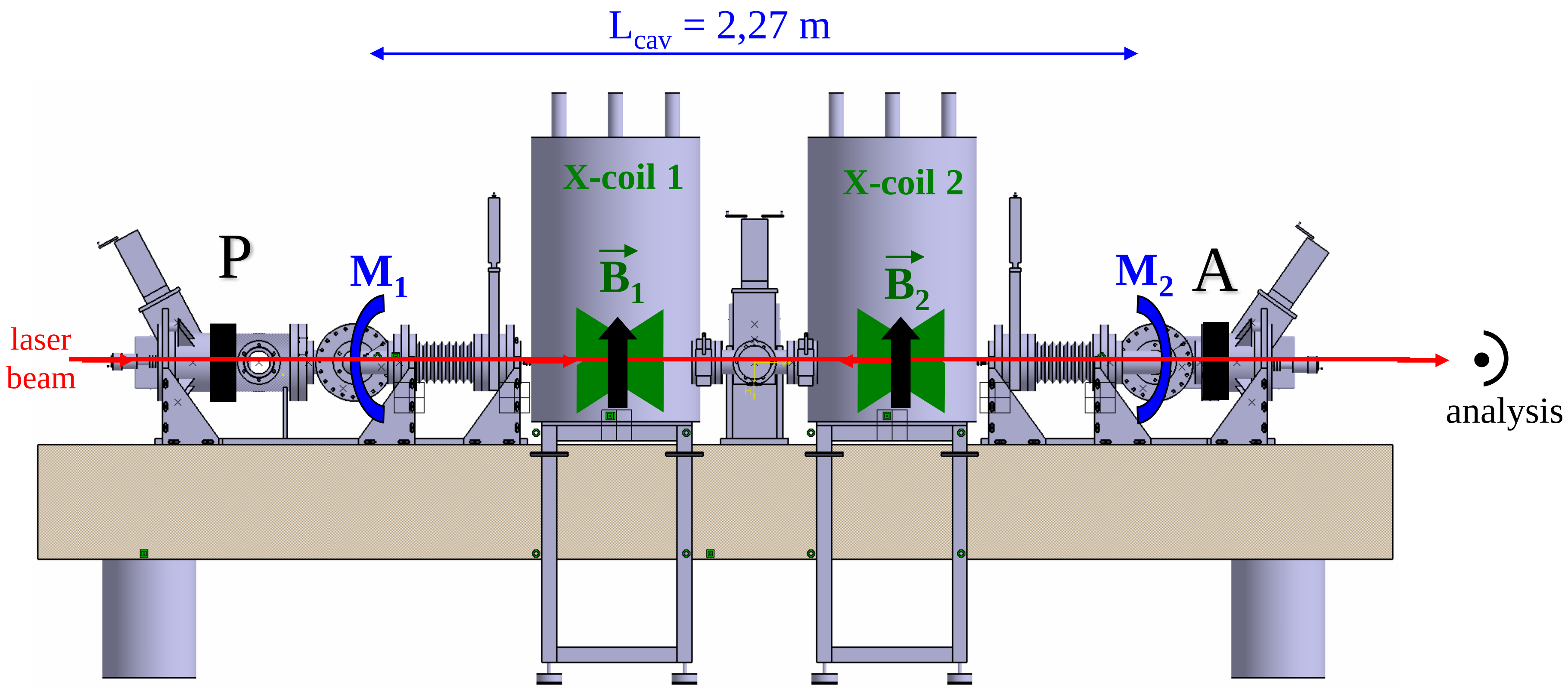




A. Cadène et al., arXiv:1302.5389v2 (2013)

BMV experimental setup

- Pulsed transverse magnetic field **B** as high as possible
- Increase of the path of light in the medium : Fabry-Perot cavity



Acoustic perturbations

- Sensitivity limitations
  - optical detection

    - PSD of powers I_t and I_e (in locked regime)

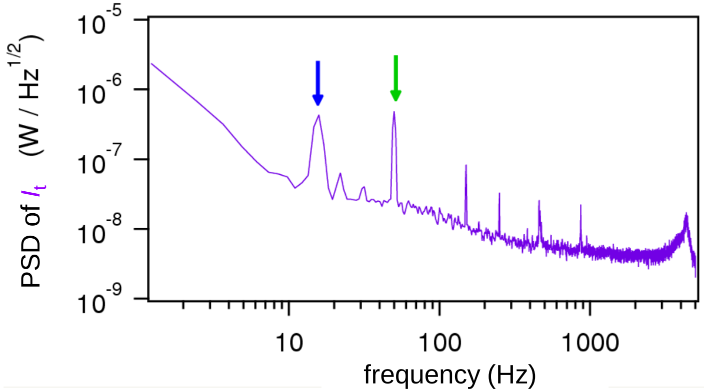
    cavity ⇔ **low pass filter**

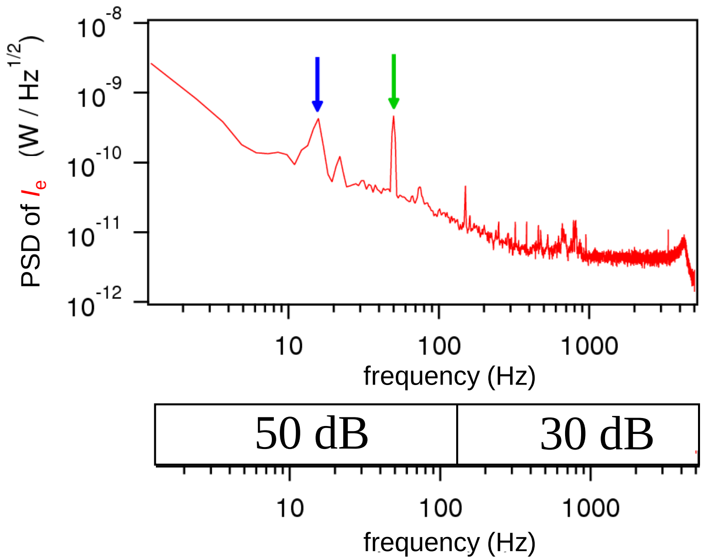
    cutoff frequency: $\nu_c = \dfrac{1}{4\pi\tau} \approx 75\ \text{Hz}$

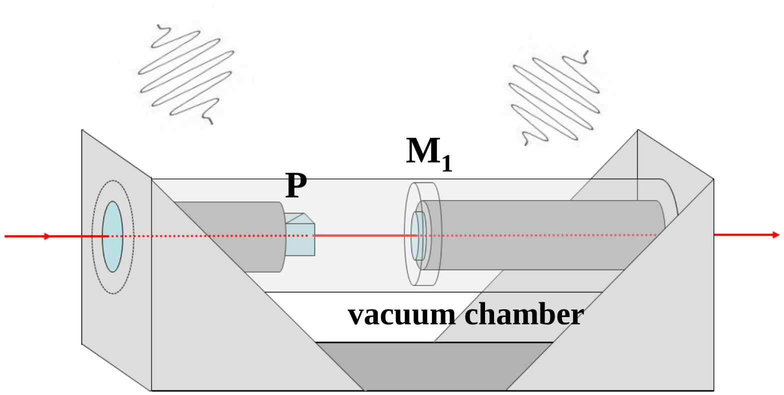
    - resonance frequencies: **16 Hz** and **49 Hz**

    ⇔ **stationary acoustic waves**

➡ **need an acoustic insulation**







BMV run in the world

expérience	BFRT	PVLAS	Q&A	BMV
état	arrêtée	en fonction	en fonction	en fonction
régime du champ	continu	continu	continu	pulsé
F	34 réflexions (cavité multi-passage)	245 000	30 000	460 000
$B^2 L_\mathrm{B}$ ($\mathrm{T}^2\mathrm{m}$)	13.5	2.1	3.2	3.0
sensibilité actuelle en Ψ	7.9×10^{-8} rad/$\sqrt{\mathrm{Hz}}$	3.1×10^{-7} rad/$\sqrt{\mathrm{Hz}}$	1.0×10^{-6} rad/$\sqrt{\mathrm{Hz}}$	2.4×10^{-7} rad par tir
limite Δn_b (T^{-2})	2.2×10^{-19}	4.4×10^{-21}	.	9×10^{-20}
intégration	16 375 s	8192 s	2×10^6 s	1 tir (4 ms)
signal attendu en Ψ (rad)	.	3.9×10^{-12}	4.7×10^{-13}	2.1×10^{-11}
intégration nécessaire	.	6.3×10^9 s	4.5×10^{12} s	1.3×10^8 tirs

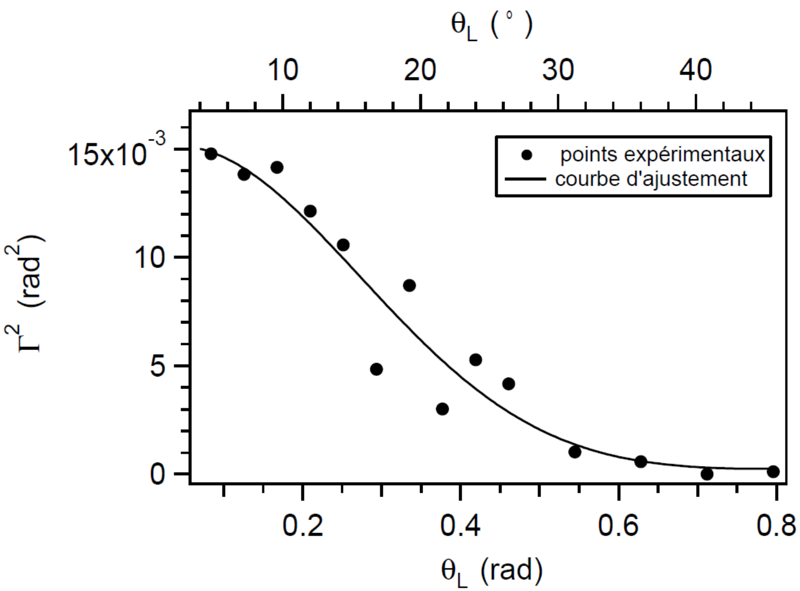
Cavité Fabry-Perot

- Biréfringence intrinsèque
  - ellipticité statique induite par les couches diélectriques

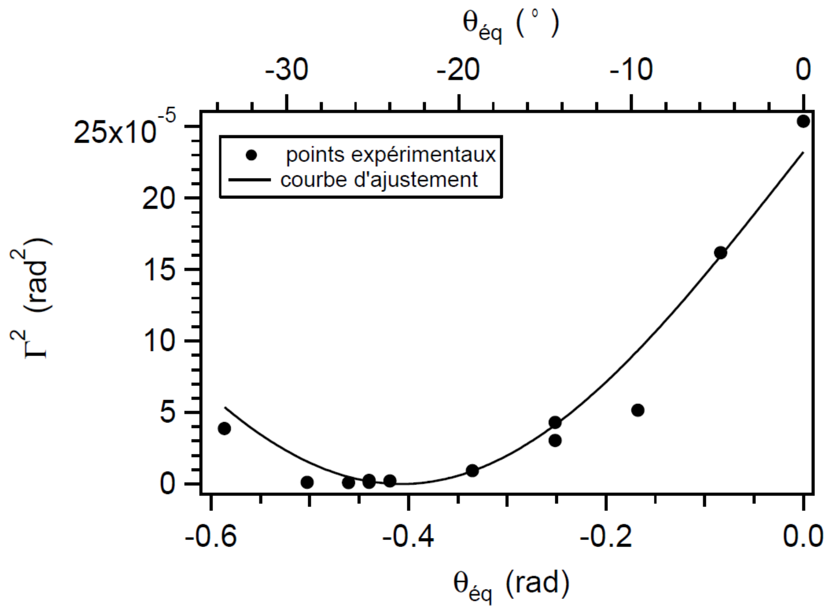
$$\Gamma = \frac{F}{\pi}\,\delta_{\acute{e}q}\,\sin 2\left(\theta_{\acute{e}q} - \theta_p\right)$$

  - diminution nécessaire de Γ

- par rotation du miroir M_1 seul (θ_L) :



- par rotation simultanée des miroirs M_1 et M_2 $(\theta_{\acute{e}q})$:



typiquement, $\Gamma \sim 1$ à 3×10^{-3} rad

PVLAS

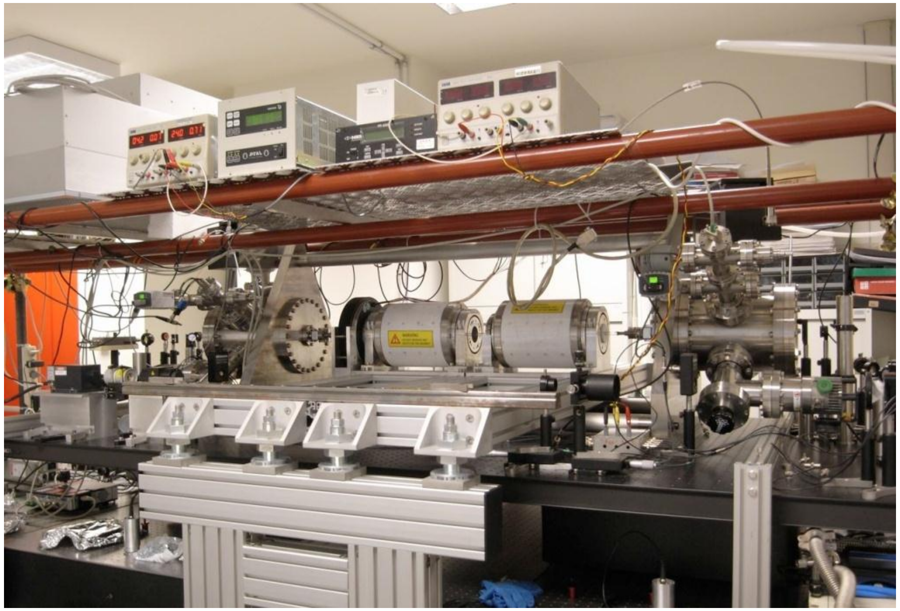
(**P**olarizzazione del **V**uoto con **LAS**er)

Ferrara Laboratory, Italy

$$\Psi = \frac{2F}{\lambda} \Delta n_{\mathrm{b}} \, B^2 \, L_B \sin(2\theta)$$

since 1992

→ Effect modulation by **rotation** of the whole superconducting **magnet**



- Laser : λ = 1064 nm
- Permanent magnet : $B^2 L_B$ = 2.1 T^2m
- Fabry-Perot cavity : F ~ 245000

G. Zavattini *et al*, *arXiv:1201.2309v1 (2012)*

Expected QED ellipticity:

$$\Psi_{\mathrm{PVLAS}} = 4 \times 10^{-12} \mathrm{rad}$$

Q&A
(**Q**uantum electrodynamics test **&** search for **A**xion)

Center for gravitation and cosmology, Taiwan

$$\Psi = \frac{2F}{\lambda} \Delta n_{\mathrm{b}}\, B^2\, L_B \sin(2\theta)$$

since 1996

→ Effect modulation
by **rotation** of the whole
superconducting **magnet**

- Laser : λ = 1064 nm
- Permanent magnet : B^2L_B = 3.2 T^2m
- Fabry-Perot cavity : F ~ 30000

H.H. Mei *et al*, *Mod. Phys. Lett. A* ***25****, 983 (2010)*

Expected QED ellipticity:

$$\Psi_{\mathrm{Q\&A}} = 4.7 \times 10^{-13} \mathrm{rad}$$

OSQAR

(**O**ptical **S**earch for **Q**ED vacuum magnetic birefringence, **A**xions and photon **R**egeneration)

CERN, Geneva Switzerland

$$\Psi = \frac{2F}{\lambda} \Delta n_{\mathrm{b}}\, B^2\, L_B \sin(2\theta)$$

proposal

→ Effect modulation by **rotation** of the **polarization** of light

- Laser : λ = 1064 nm
- Permanent magnet : $B^2 L_B$ = 1000 T^2m
- Fabry-Perot cavity : F ~ 2000

Expected QED ellipticity:

$$\Psi_{\mathrm{OSCAR}} = 1.5\times 10^{-11}\,\mathrm{rad}$$

P. Pugnat *et al.*, *Phys. Rev. D* ***78****, 092003 (2008)*