Vacuum magnetic birefringence

Terrestrial experiments

Rémy Battesti

Université de Toulouse

LABORATOIRE NATIONAL DES CHAMPS MAGNETIQUES INTENSES - TOULOUSE

Does light interact with electromagnetic fields ?

Does the velocity of light change in the presence of electromagnetic fields ?

1934-35 Heisenberg-Euler effective Lagrangian

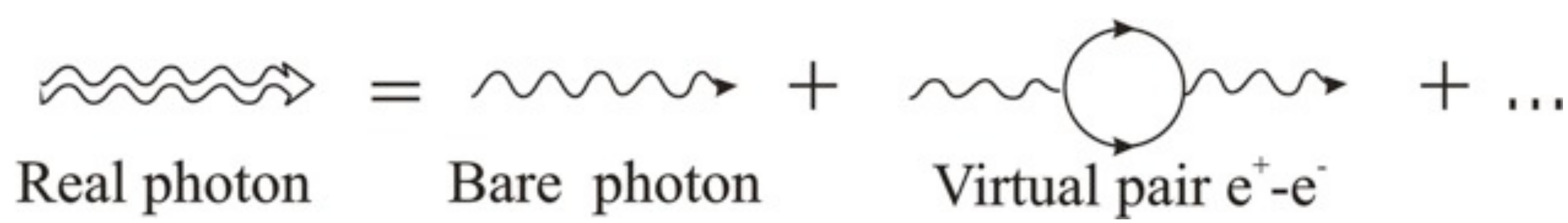
Vacuum is **Lorentz** and **CPT invariant**

$$L = \frac{1}{2}F + aF^2 + 7aG^2 + \ldots$$

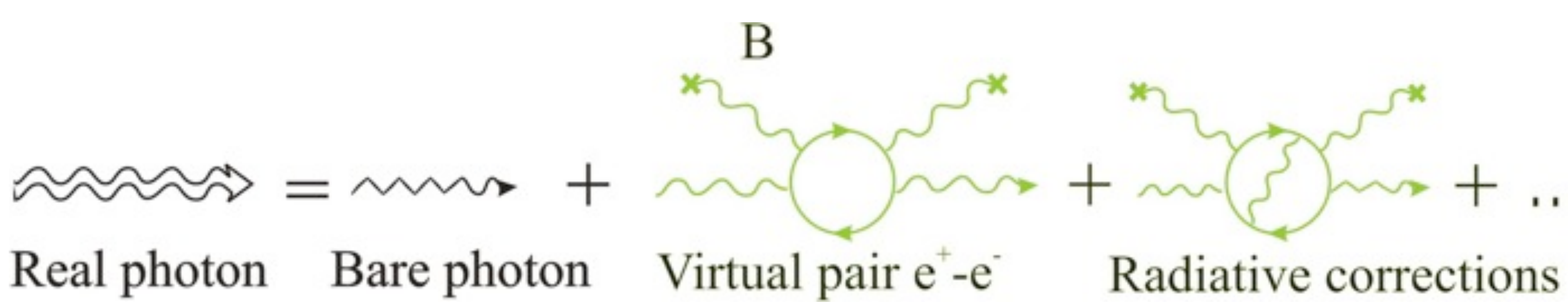
where $F = \left(\epsilon_0 E^2 - \frac{B^2}{\mu_0}\right)$ and $G = \sqrt{\frac{\epsilon_0}{\mu_0}}\left(\vec{E}.\vec{B}\right)$

1950 … **Pictorial representation based on Feynman's diagrams**

Without external field:



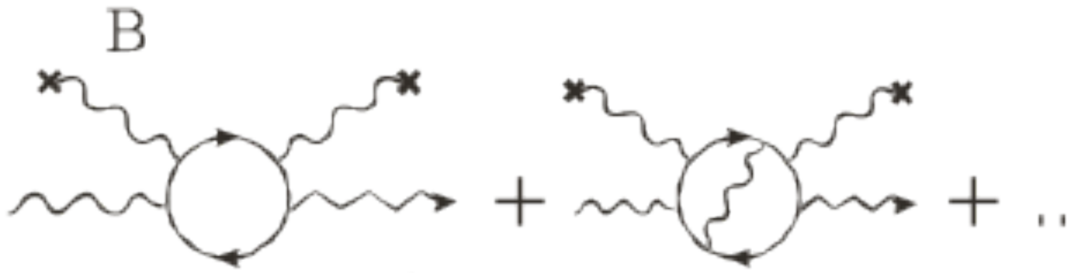
With external field B:



1970 : C depends on light polarization !

The BMV project : Final goal

Experimental challenge :



Radiative corrections

Δn (vide) = 4. 10^{-24} B^2 (B en Tesla)

→ **Δn (vide) ≈ 10^{-8} Δn (hélium CNTP)**

Fundamental constants : 2006 codata

$$\Delta n = \frac{2}{15}\frac{\alpha^2 h^3}{m_e^4 c^5}\left(1+\frac{4050}{648\pi}\alpha\right)\frac{B^2}{\mu_0}$$

$$\Delta n = \left[(4,031699 \pm 0,000005)\times 10^{-24}\right]\left(\frac{B}{1T}\right)^2$$

V.I.Ritus, *Sov. Phys. JETP* **42**, 774 (1975) **O(α^3)**

O(α^4) **?**

O(α^5) **?**

Theoretical challenge !

QED tests

S.S. Schweber, *QED and the men who made it*, Princeton;
T.Kinoshita, *Quantum Electrodynamics*, World Scientific

Bound states : Hydrogène, Muonium, Positronium …. **Lamb shift**

$\mu^+ - e^-$ $e^+ - e^-$

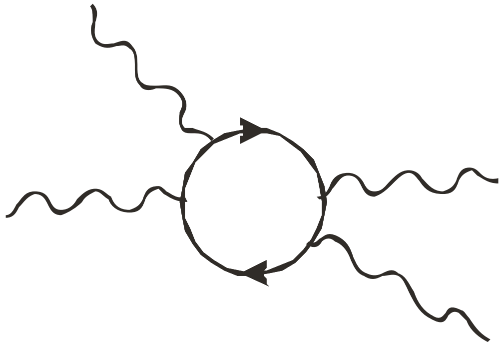
α **Mesurement of the fine structure constant**

Charged particle : anomalous magnetic moment of electron and muon **g-2**

Photon : ?

Propagation in external fields (VMB)

Photon-photon collisions



Photon-photon collisions

Four wave mixing

A.L.Hughes et G.E.M.Jauncey, *Phys. Rev.* **36** (1930) 773
R.Karplus et M.Neuman, *Phys. Rev.* **83** (1951) 776

O(α^2)

D.Bernard *et al*, *Eur. Phys. J. D* **10** (2000) 141

$\sigma_{\gamma\gamma} \sim 10^{-69}\ \mathrm{m}^2$ **No signal !**

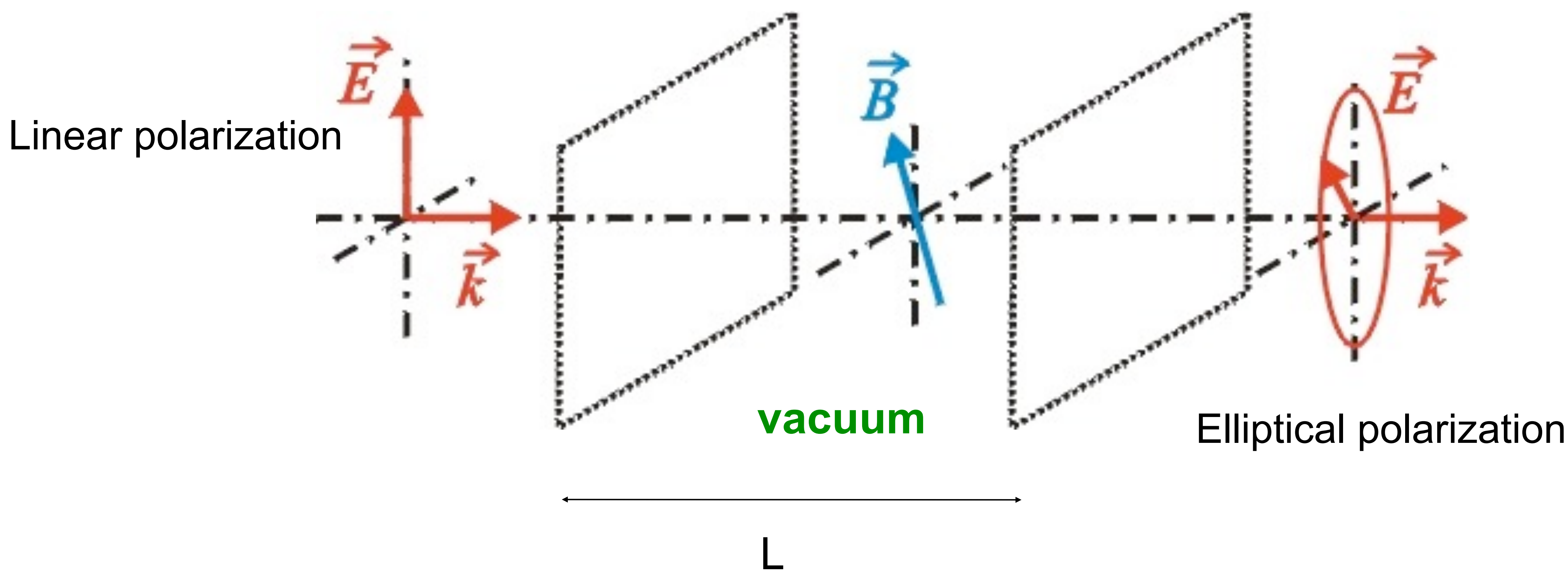
1934 : Vacuum is a non linear optical medium

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

1970 : The value of the Vacuum magnetic birefringence is published

Vacuum Cotton-Mouton effect

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

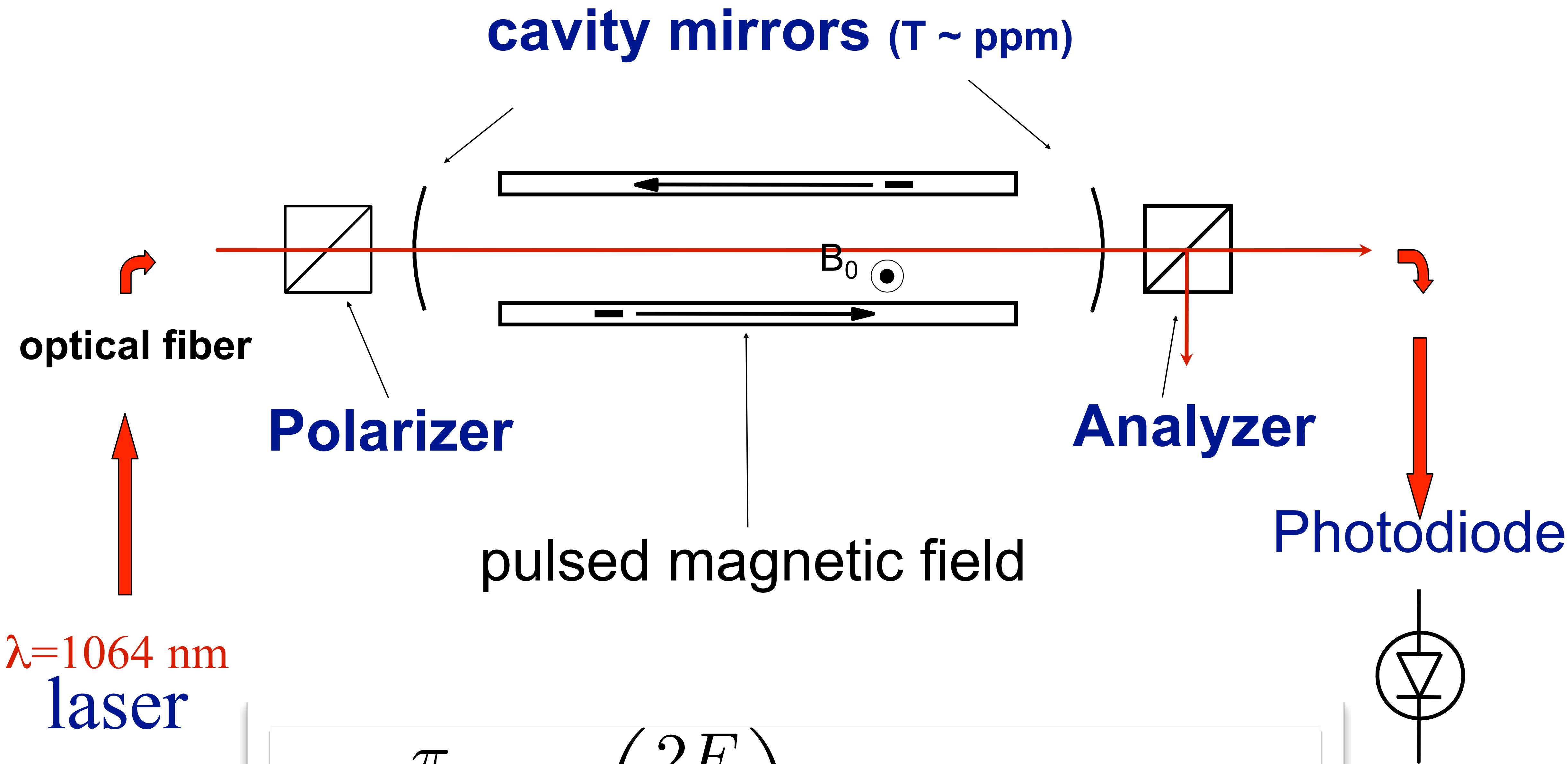


From **QED theory** : $\Delta n = 4\times10^{-24}\,\mathbf{B}^2 = \Delta n_u \times \mathbf{B}^2$

Cotton Mouton effect has been discovered in 1901, studied in details since 1904, and it exists in all media.

Δn for helium gas (1 atm, 1 T, 0 °C) is about 2 10^{-16}.

experimental set up based on Iacopini and Zavattini idea (1979)



$$\psi = \frac{\pi}{\lambda}\Delta n_u \left(\frac{2F}{\pi}\right)\left(B^2 L_{mag}\right) sin(2\theta)$$

Experimental final goals

Table top experiment

- **cavity finesse** : F ~ 1 000 000
  LMA (Lyon – IN2P3) mirrors
- **magnetic field** : $B^2 L_{mag} > 600\ T^2\ m$
  (short $L_{mag} \Rightarrow$ high B)
- **Nd:Yag laser** : λ = 1064 nm

$\Rightarrow$ **expected ellipticity to be measured :**

$$\Psi_{QED} = 5 \times 10^{-9}$$

Battesti et al., *Eur. Phys. J. D,* vol. **46**, pp. 323 (2008)

Other experiments around the world

Q&A (Quantum electrodynamics test & search for Axion)

Center for gravitation and cosmology, National Tsing Hua University of Taiwan

$$\psi = \frac{\pi}{\lambda}\Delta n_u \left(\frac{2F}{\pi}\right)\left(B^2 L_{mag}\right) sin(2\theta)$$

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

- Laser : λ = 1064 nm
- Permanent magnet : B = 2.3 T
  L_{mag} = 1.8 m
- Fabry-Perot cavity : F ~ 100 000
  L_{cav} = 5 m

W-T Ni

H.H. Mei et al, arXiv:1001.4325v1 [Mod. Phys. Lett. A (2010)]

Expected ellipticity : $\Psi_{Q\&A} = 7 \times 10^{-12}$

OSQAR Project at CERN

QED Test & Axion Search using decommissioned LHC superconducting dipole magnet(s)

- Ideal integration are within a superconducting dipole magnet use in accelerator for HEP
- With this respect, LHC superconducting dipoles *are within the most powerful at present:*
  - $B_{max} \approx 9.76$ T @ 1.9 K
  - Magnetic Length: 14.3 m
    i.e. $B^2 L \approx 1360\ T^2\,m$

  ⇒ *Big interest in using LHC decommissioned prototypes*

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

CERN, Geneva Switzerland

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

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

- Laser : λ = 1064 nm
- Permanent magnet : B = 9.5 T
  L_{mag} = 14.3 m
- Fabry-Perot cavity : F ~ 2 000
  L_{cav} = 20 m

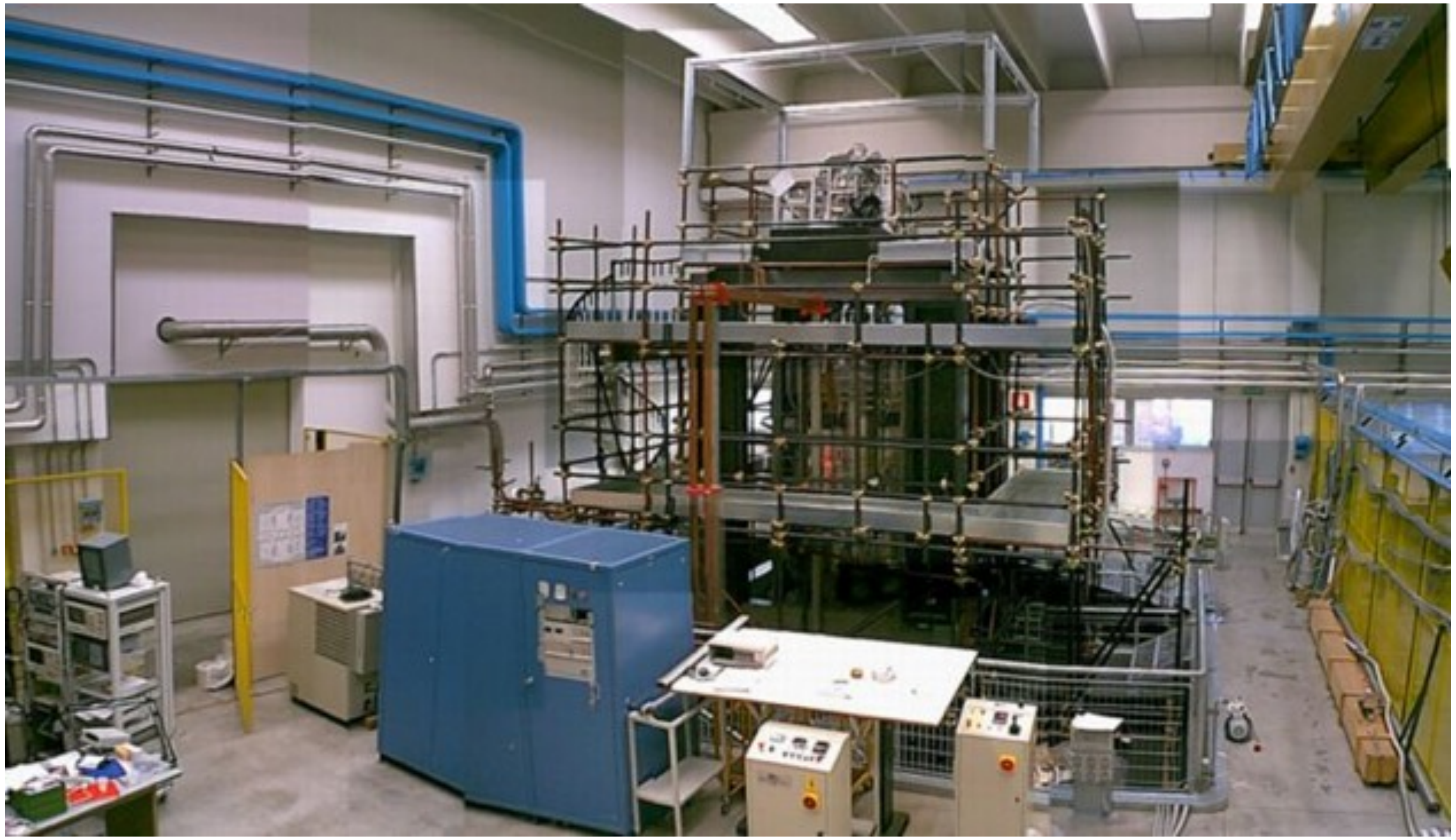
Expected ellipticity : $\Psi_{OSCAR} = 2 \times 10^{-12}$

PVLAS (Polarizzazione del Vuoto con LASer) experiment

E. Zavattini

1992 – 2010 ?

- Superconducting magnet : 5 T - 1 m.
- Laser λ = 1064 ou 532 nm.
- Fabry-Perot cavity F ~ 10^5, L ~ 6 m.



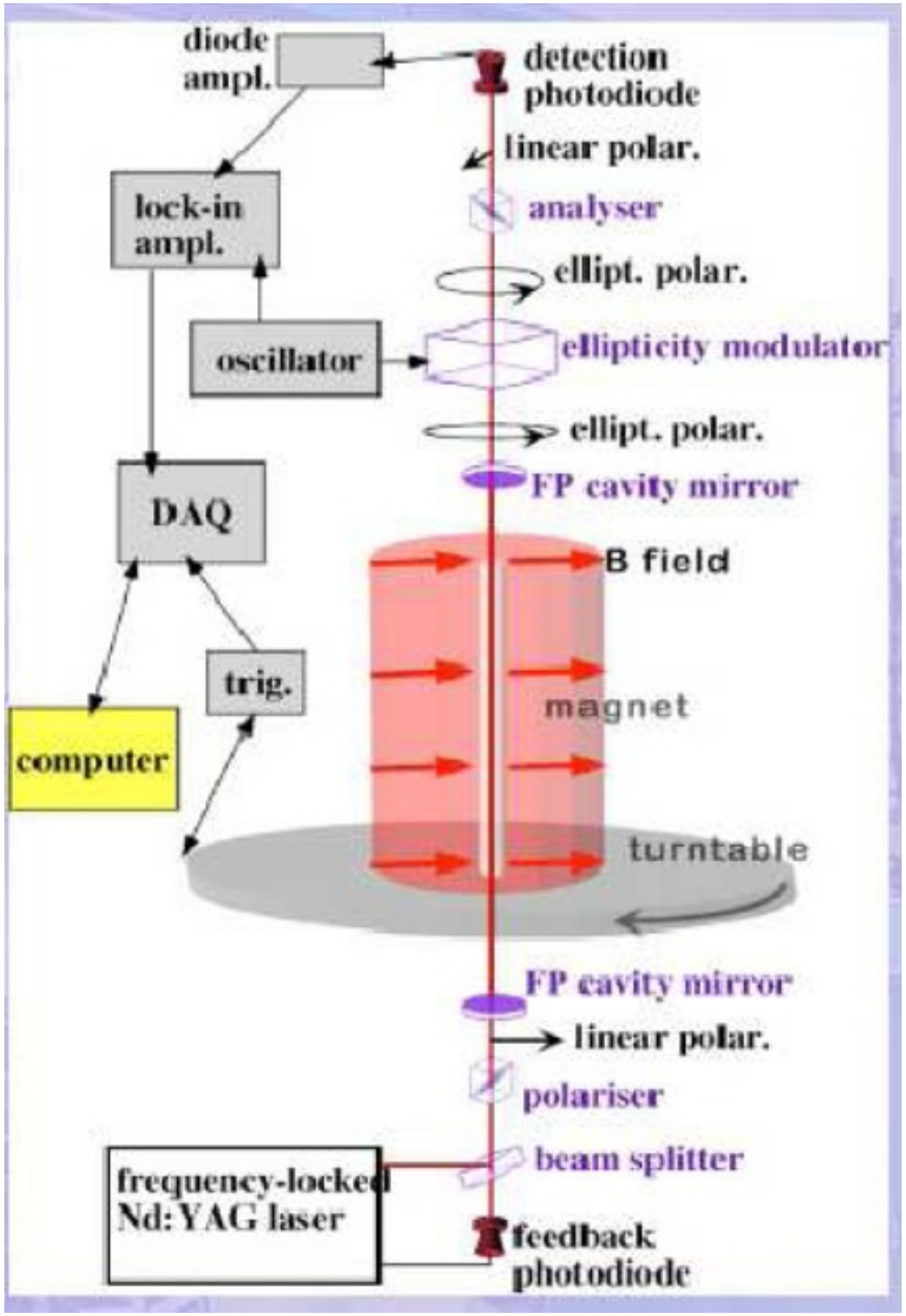
Effect modulation by rotation of the whole superconducting magnet

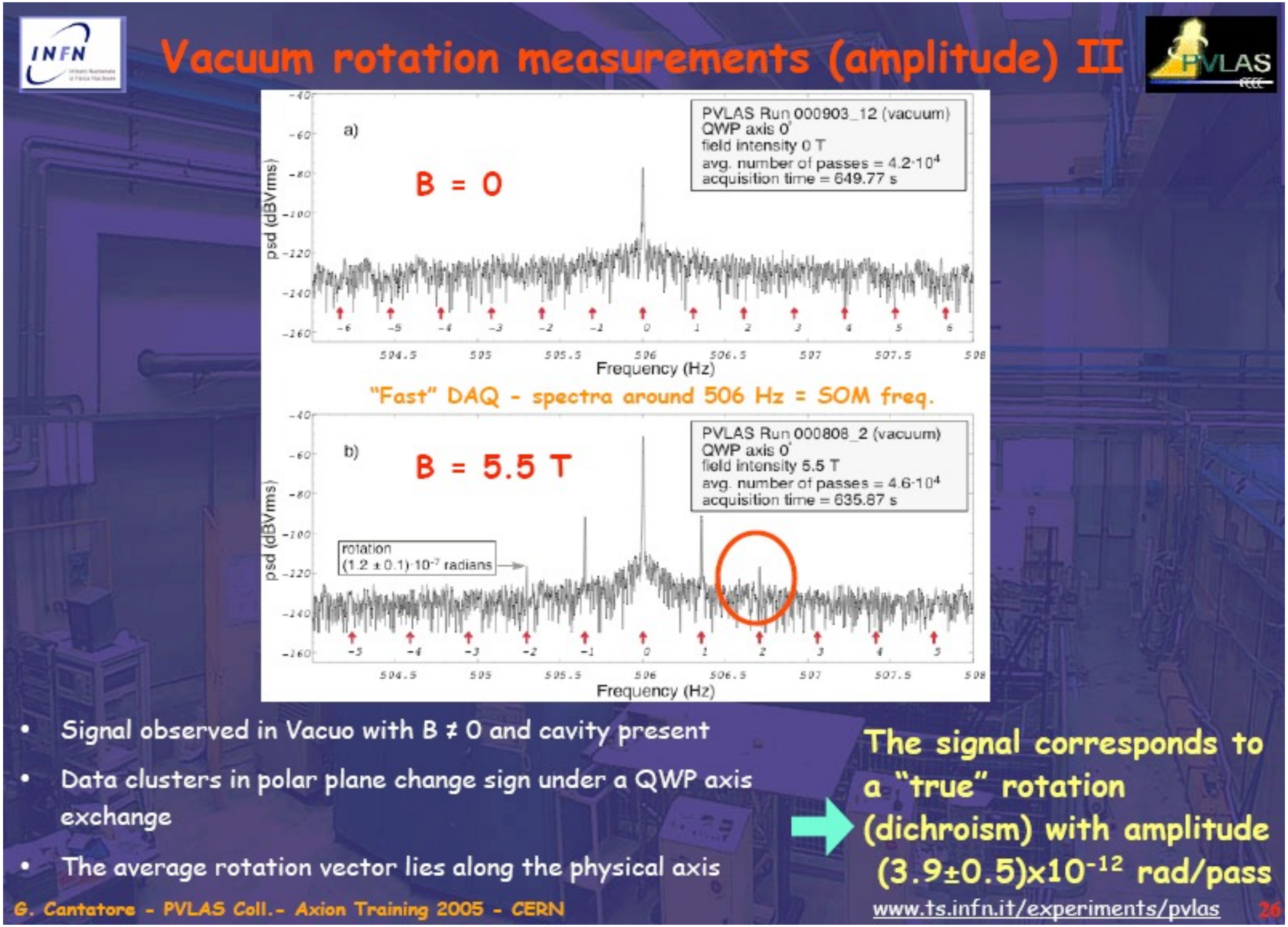
Expected ellipticity :

5×10^{-11}

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

Legnaro Lab, Italy


diode ampl.
detection photodiode
linear polar.
lock-in ampl.
analyser
ellipt. polar.
oscillator
ellipticity modulator
ellipt. polar.
DAQ
FP cavity mirror
B field
trig.
magnet
computer
turntable
FP cavity mirror
linear polar.
polariser
beam splitter
frequency-locked Nd:YAG laser
feedback photodiode



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

Vol 441| 4 May 2006 nature

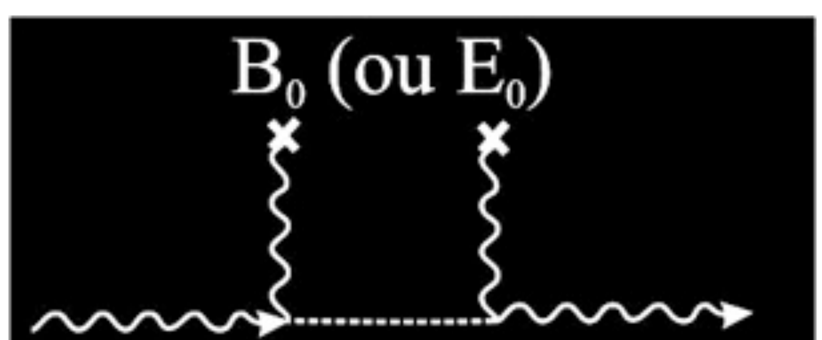
NEWS & VIEWS

PARTICLE PHYSICS

The first axion?

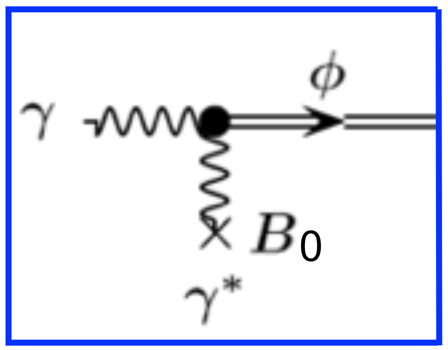
Steve Lamoreaux

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.

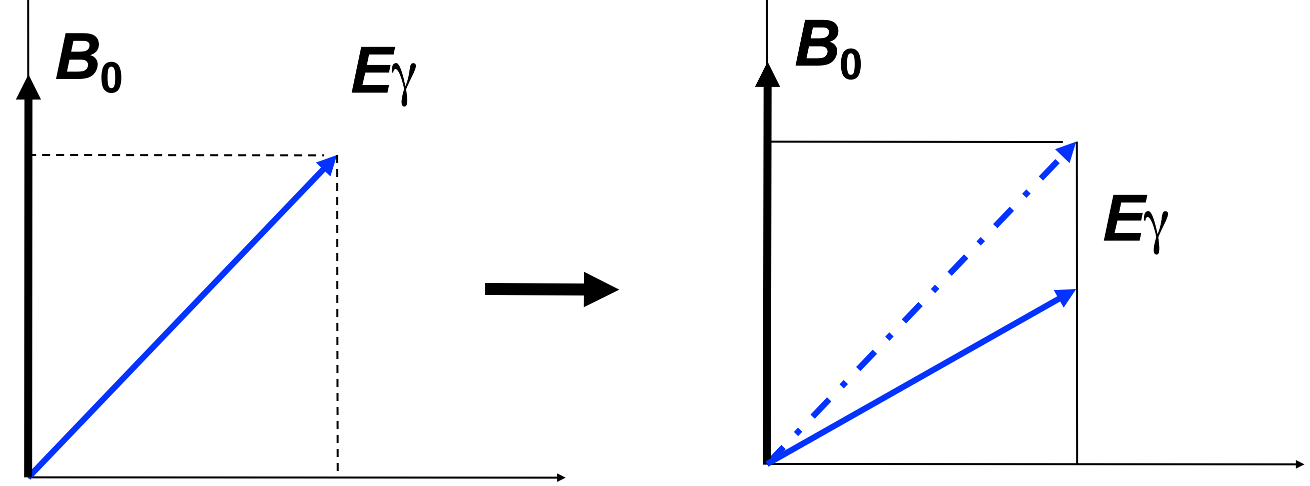


bosonic, low mass m, neutral, spinless particle

Real particle

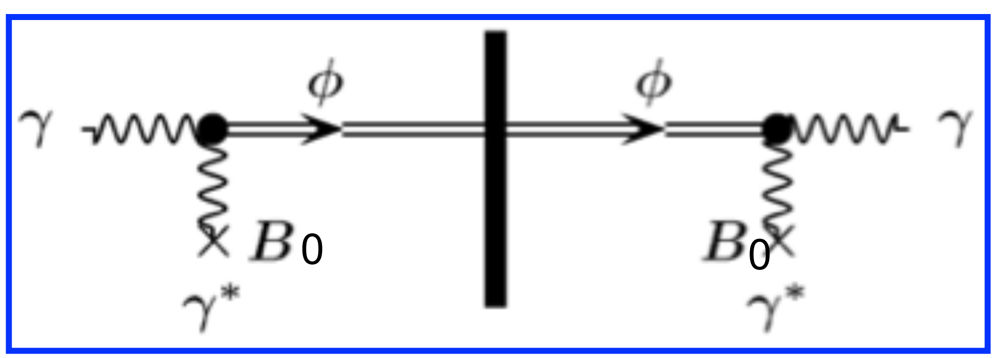


Dicroism



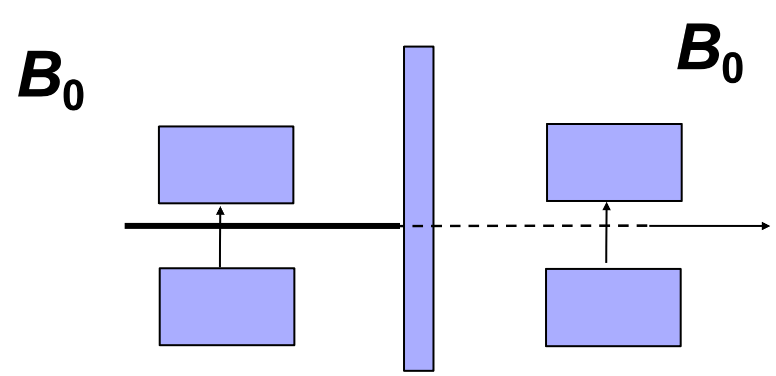
« Pseudoscalar »

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



wall

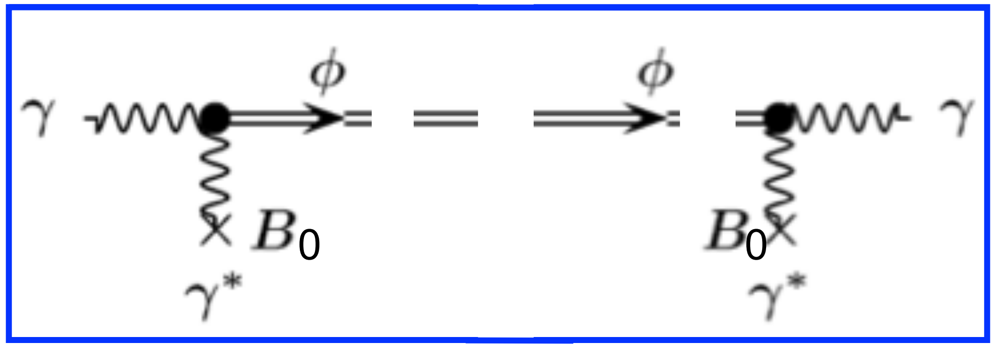
Photoregeneration



wall

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

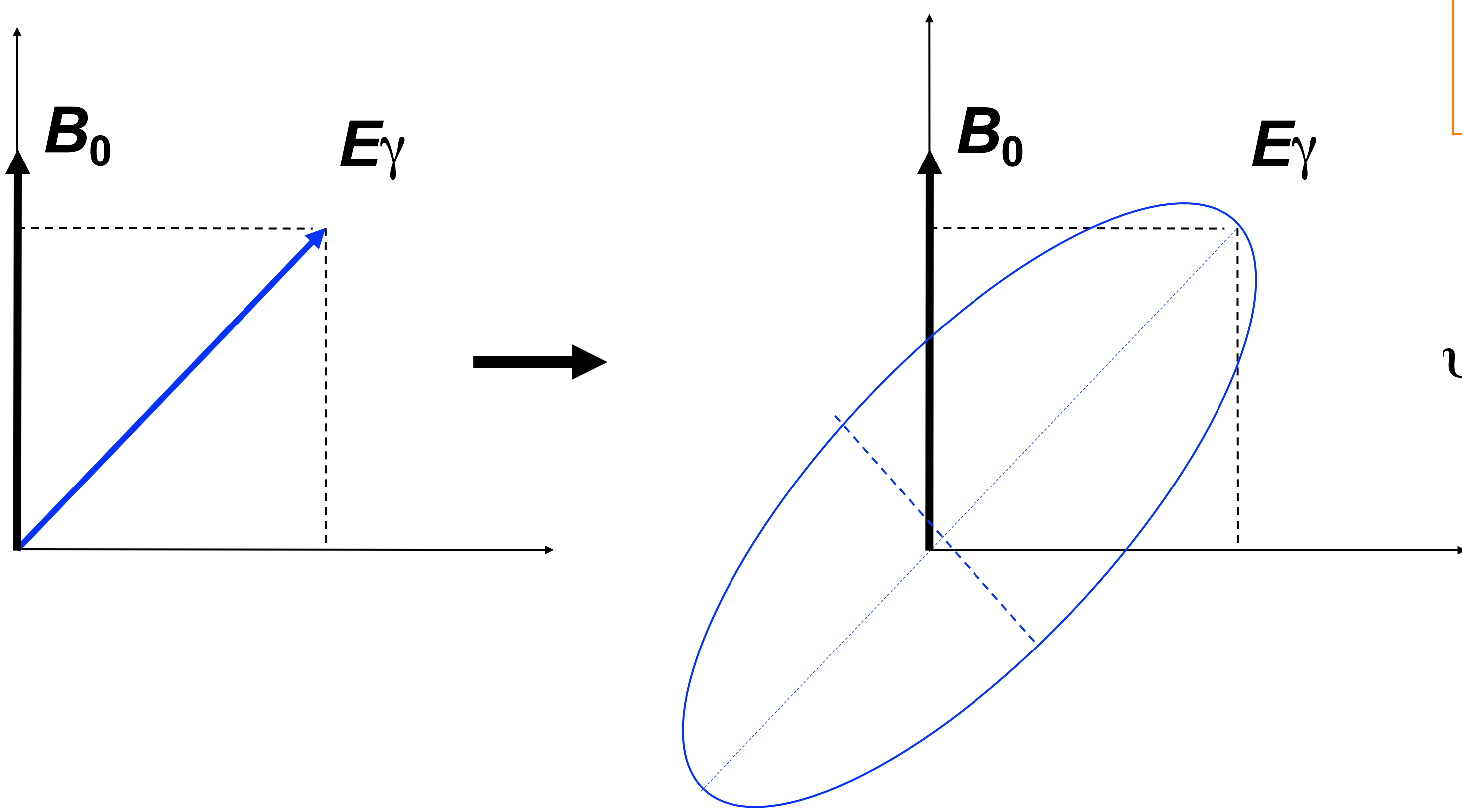
Virtual particle



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

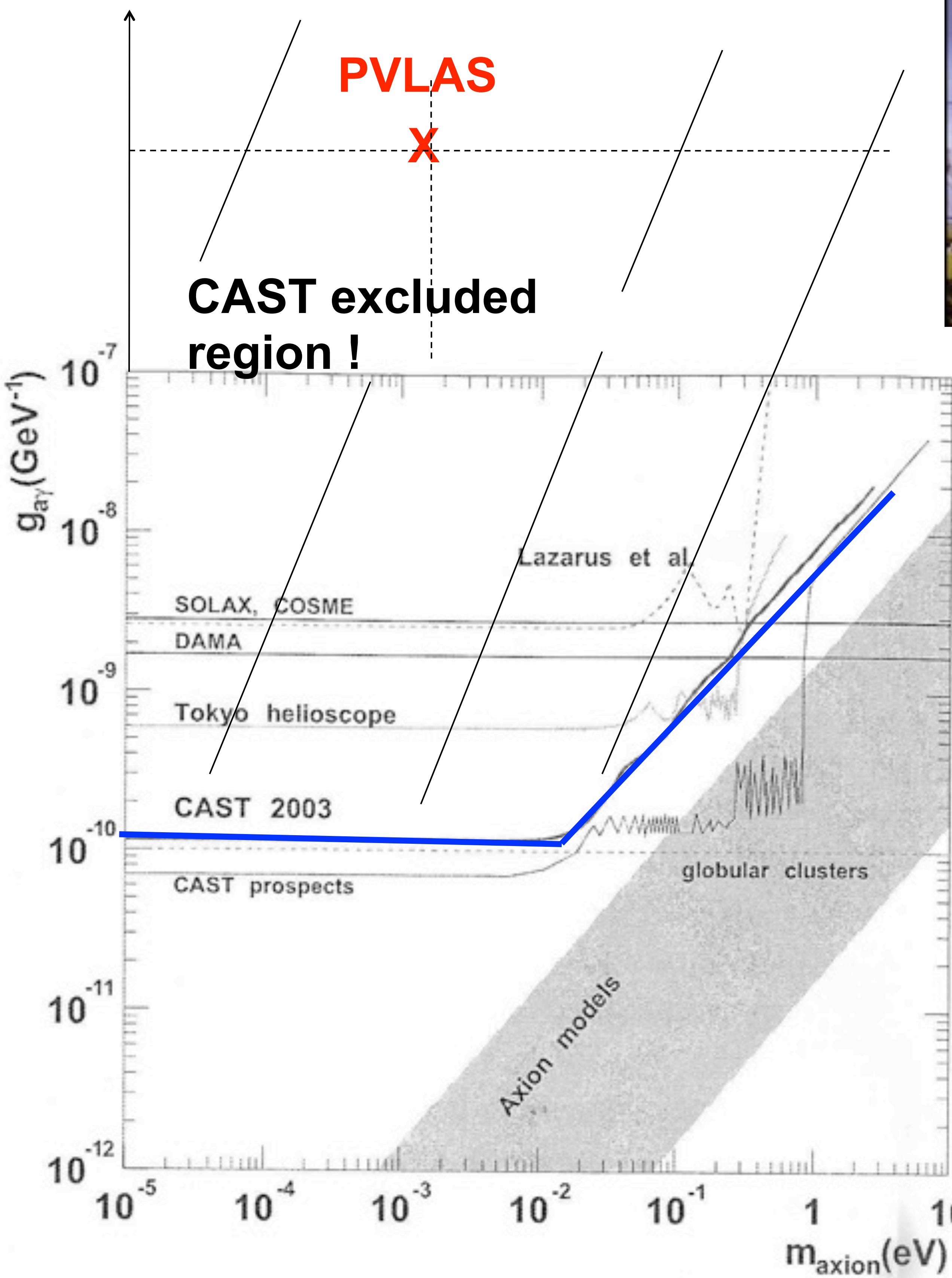
$\Delta n < 0 \Longrightarrow$ **Scalar**

Ellipticity



$$\psi = \frac{1}{2}\left[\frac{B^2\omega^2}{M^2 m_a^4}\right]\left[\frac{m_a^2 L_{mag}}{2\omega} - \sin\left(\frac{m_a^2 L_{mag}}{2\omega}\right)\right]$$

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



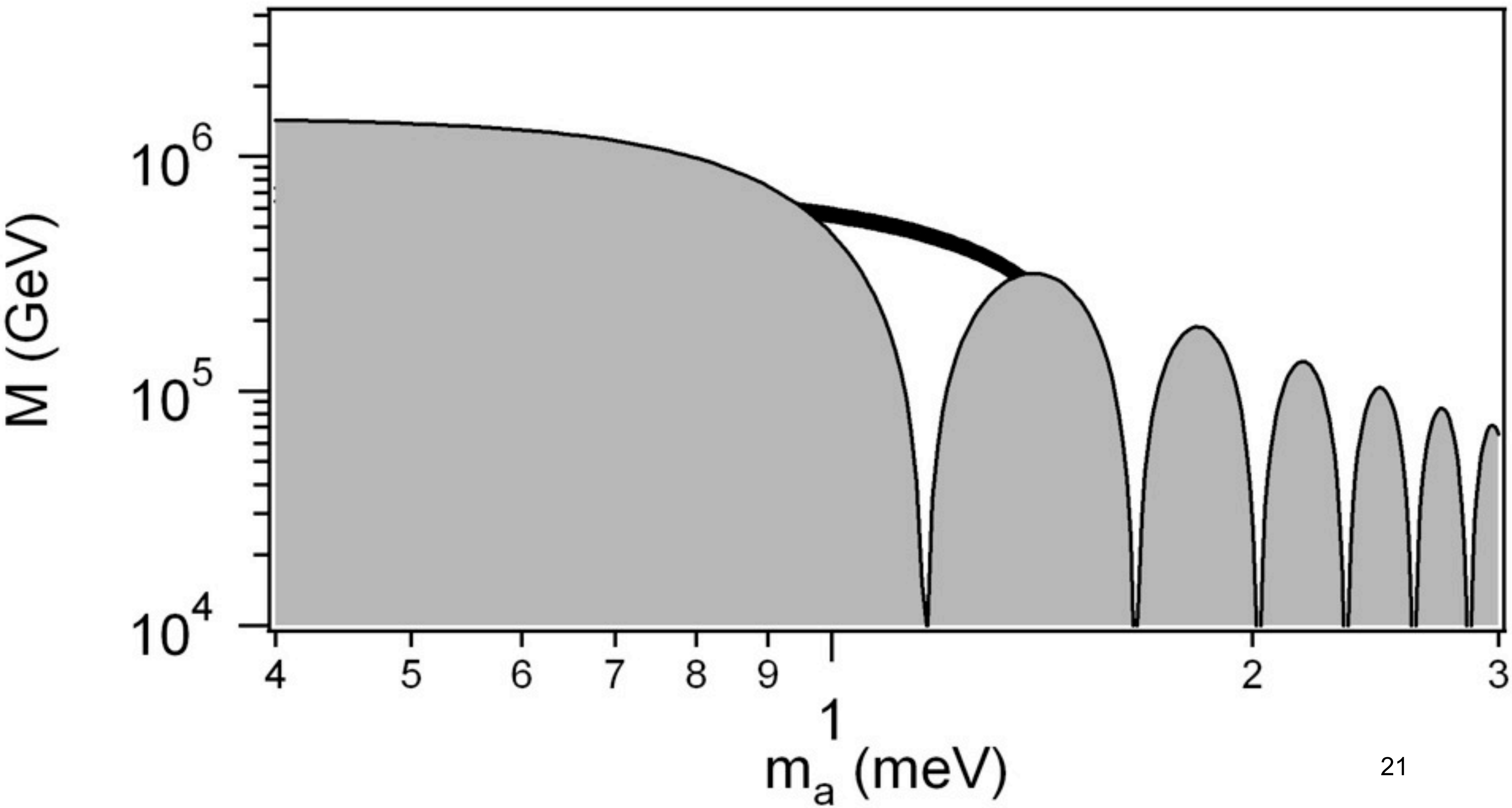
CAST

Cern Axion Solar Telescope

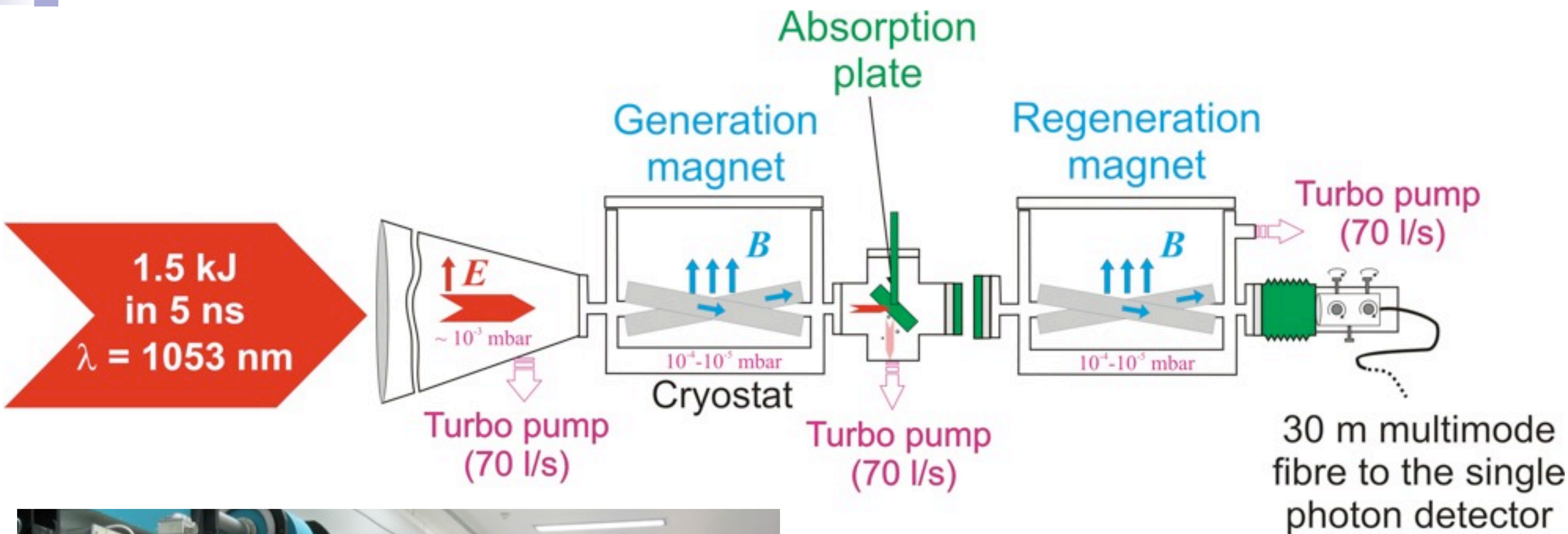
K.Zioutas, et al., *Phys. Rev. Lett.* **94** (2005) 121301

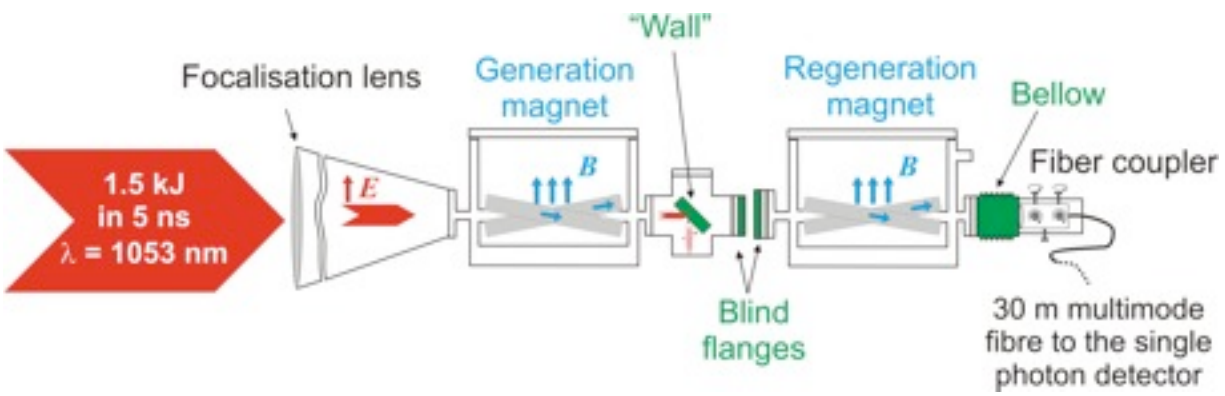
BFRT 3σ R.Cameron, et al., *Phys. Rev. D* **47** (1993) 3707

PVLAS 3σ 2006 E.Zavattini, et al., *Phys. Rev. Lett.* **96** (2006) 110406

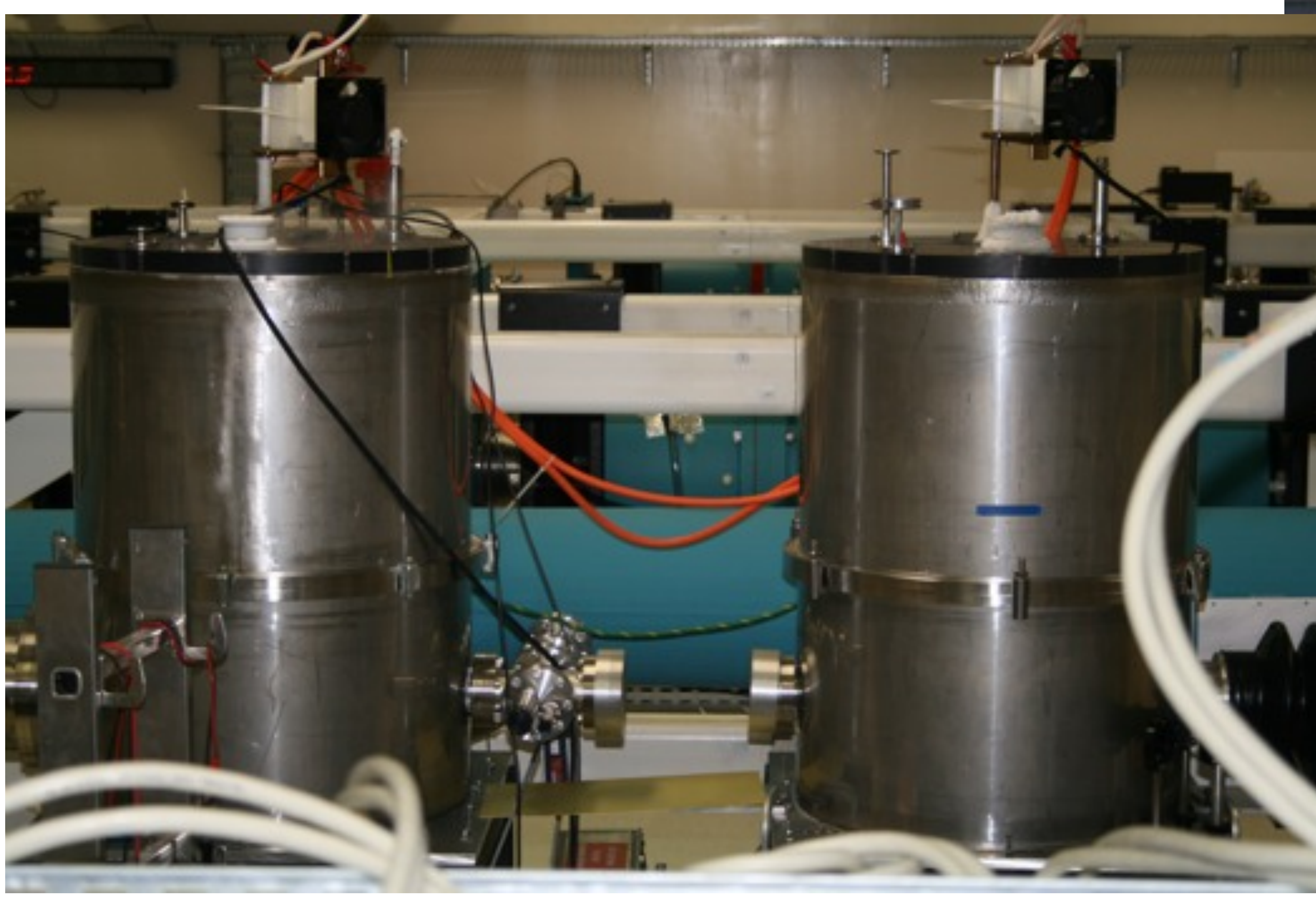


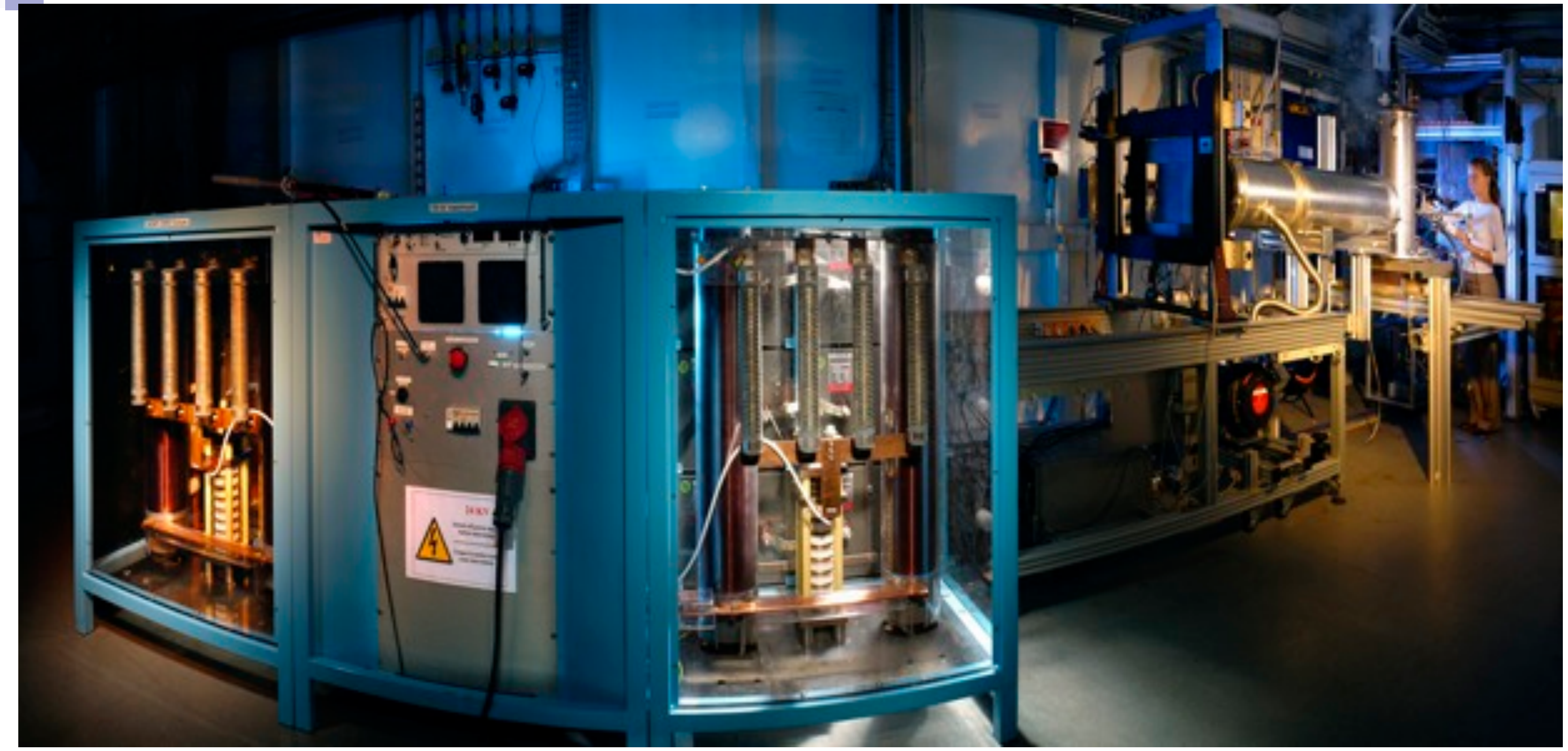
Photon regeneration experiment at LULI





Coils and their cryostats

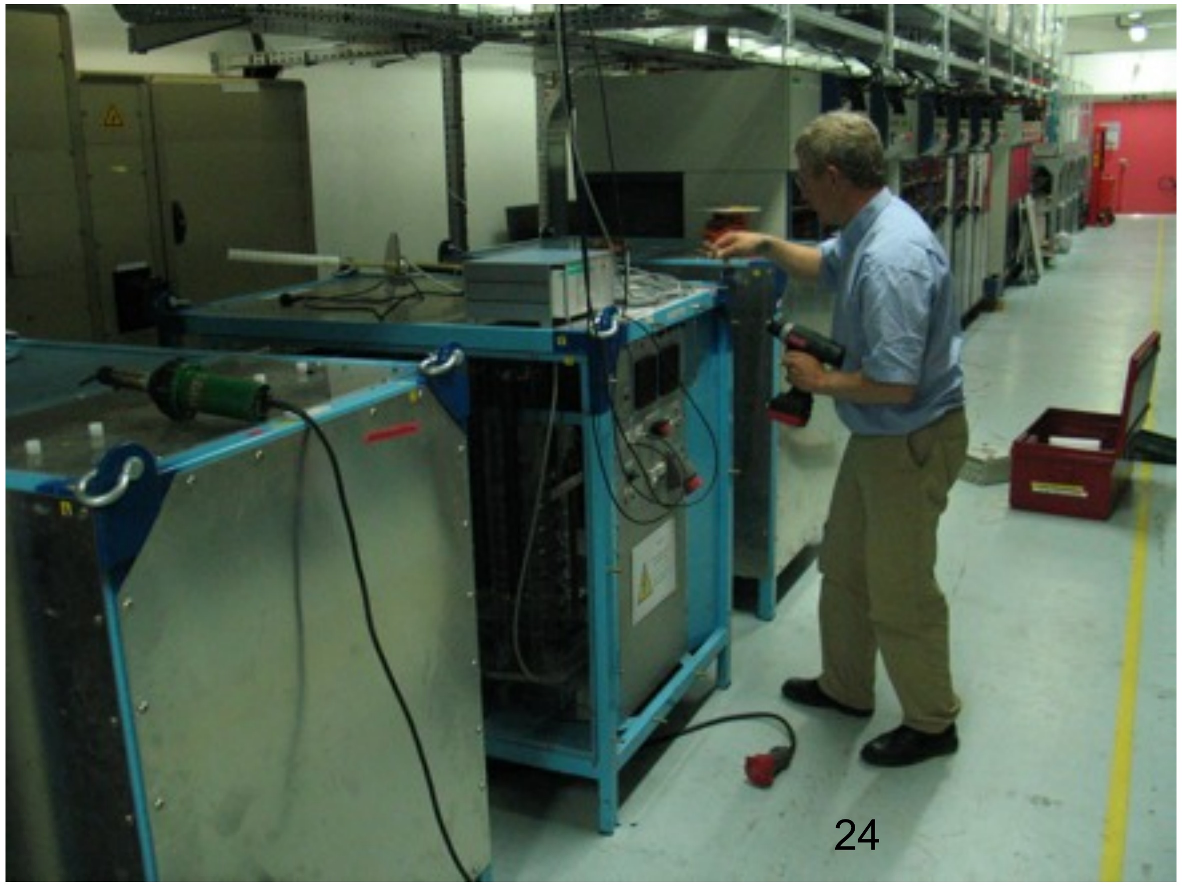




For the Pulsed magnetic field :

Transportable generator

V_{max} = 16 kV
3 x 1 m^3
~ 3 tons



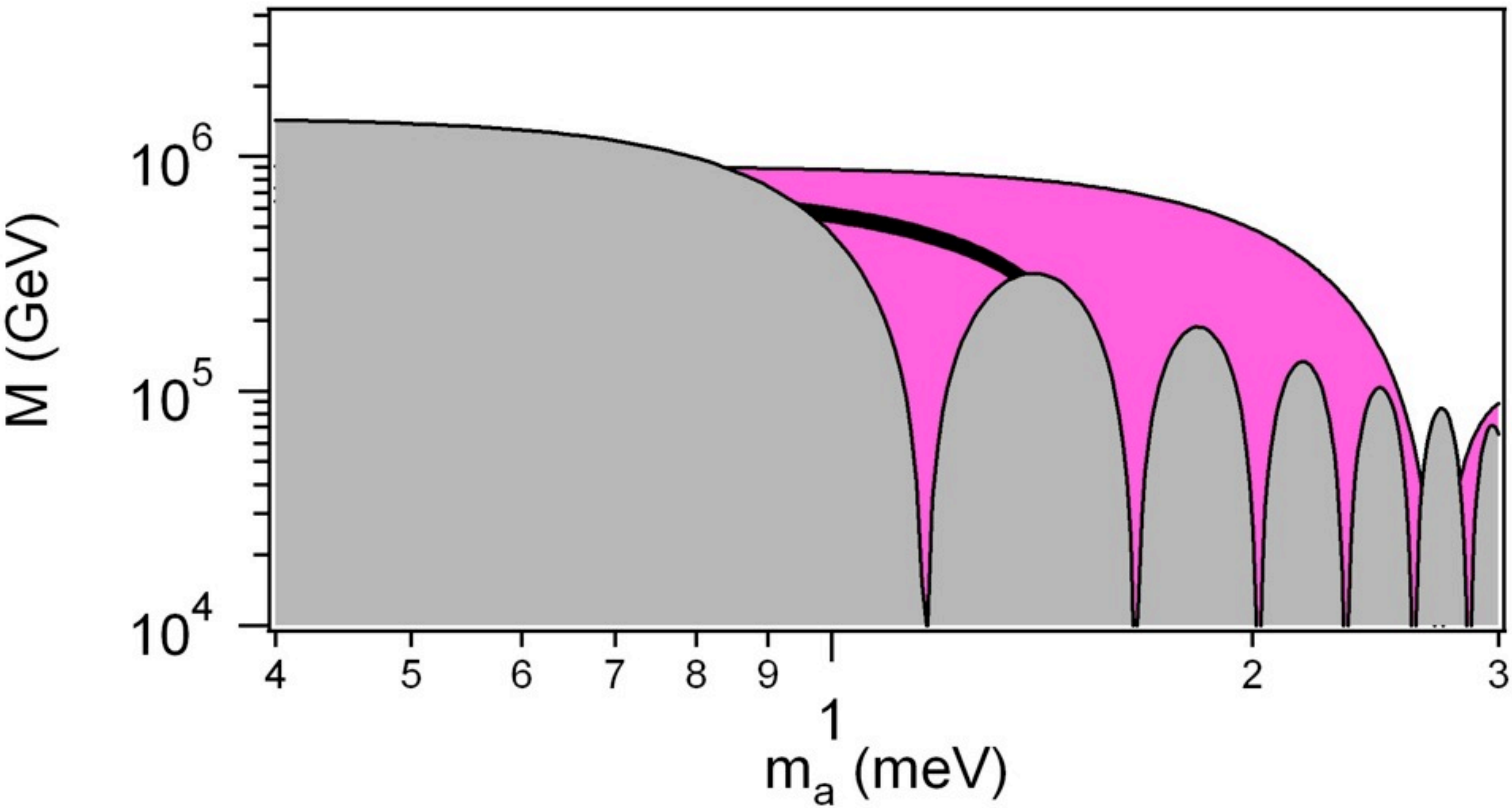
PVLAS excluded

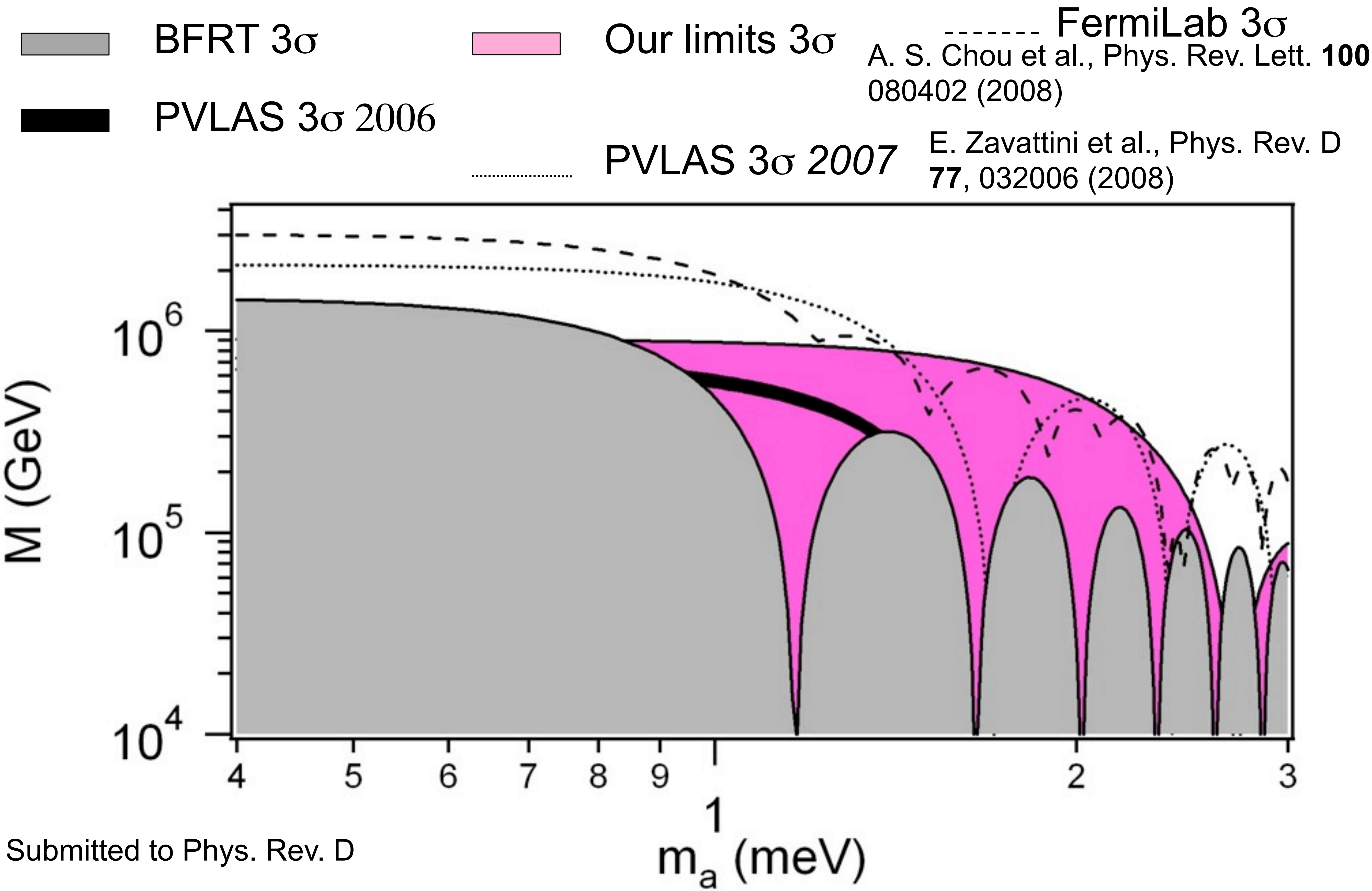
BFRT 3σ

BMV limits 3σ

PVLAS 3σ 2006

C. Robilliard et al., Phys. Rev. Lett. **99**, 190403 (2007)
Fouche et al, Phys. Rev. D **78**, 032013, (2008).





Submitted to Phys. Rev. D

Compared to other experiments

BFRT 3σ

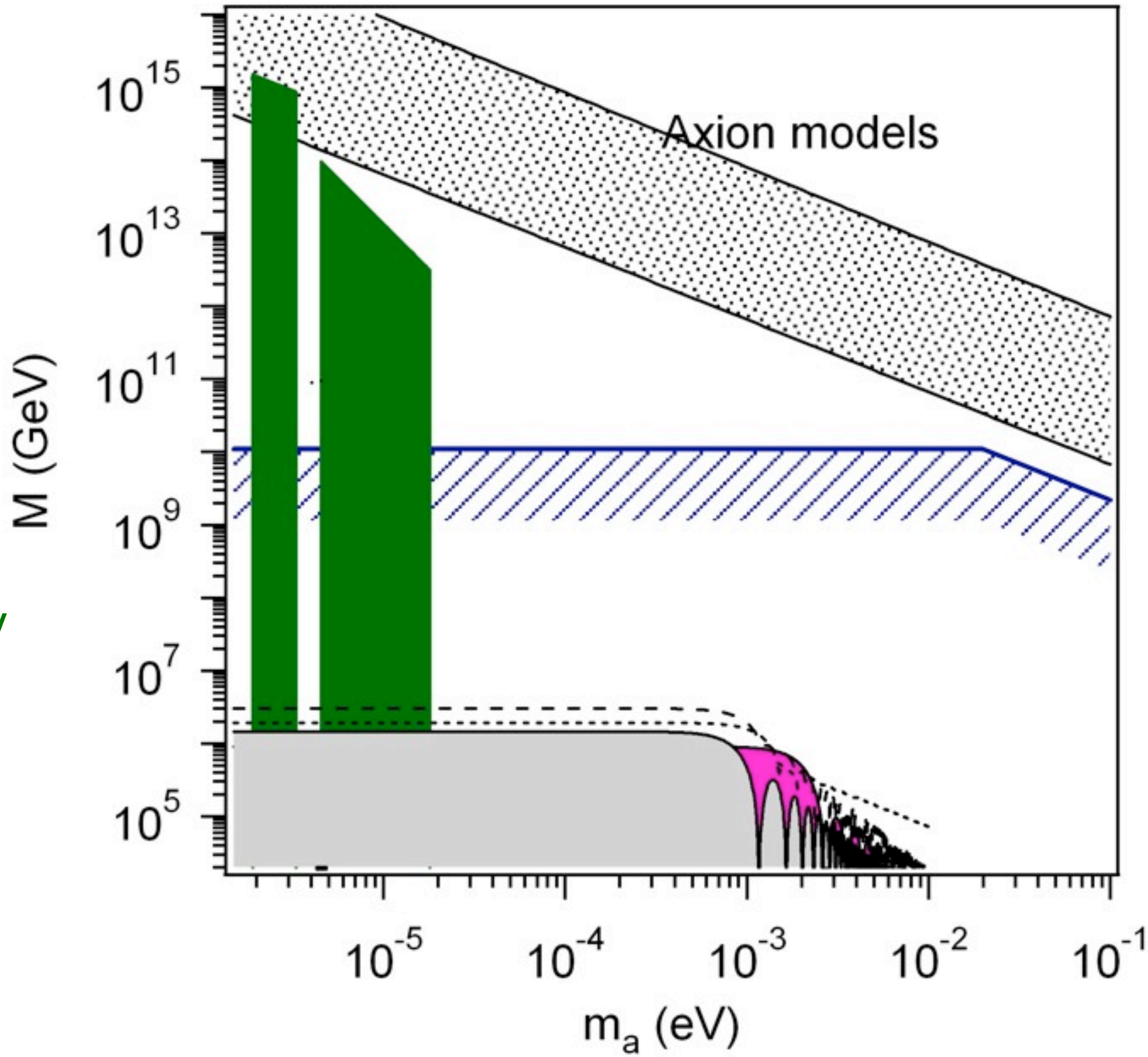
Our limits 3σ

FermiLab 3σ

PVLAS 3σ
2007

Microwave cavity experiments

CAST



Vol 441 | 4 May 2006 nature

NEWS & VIEWS

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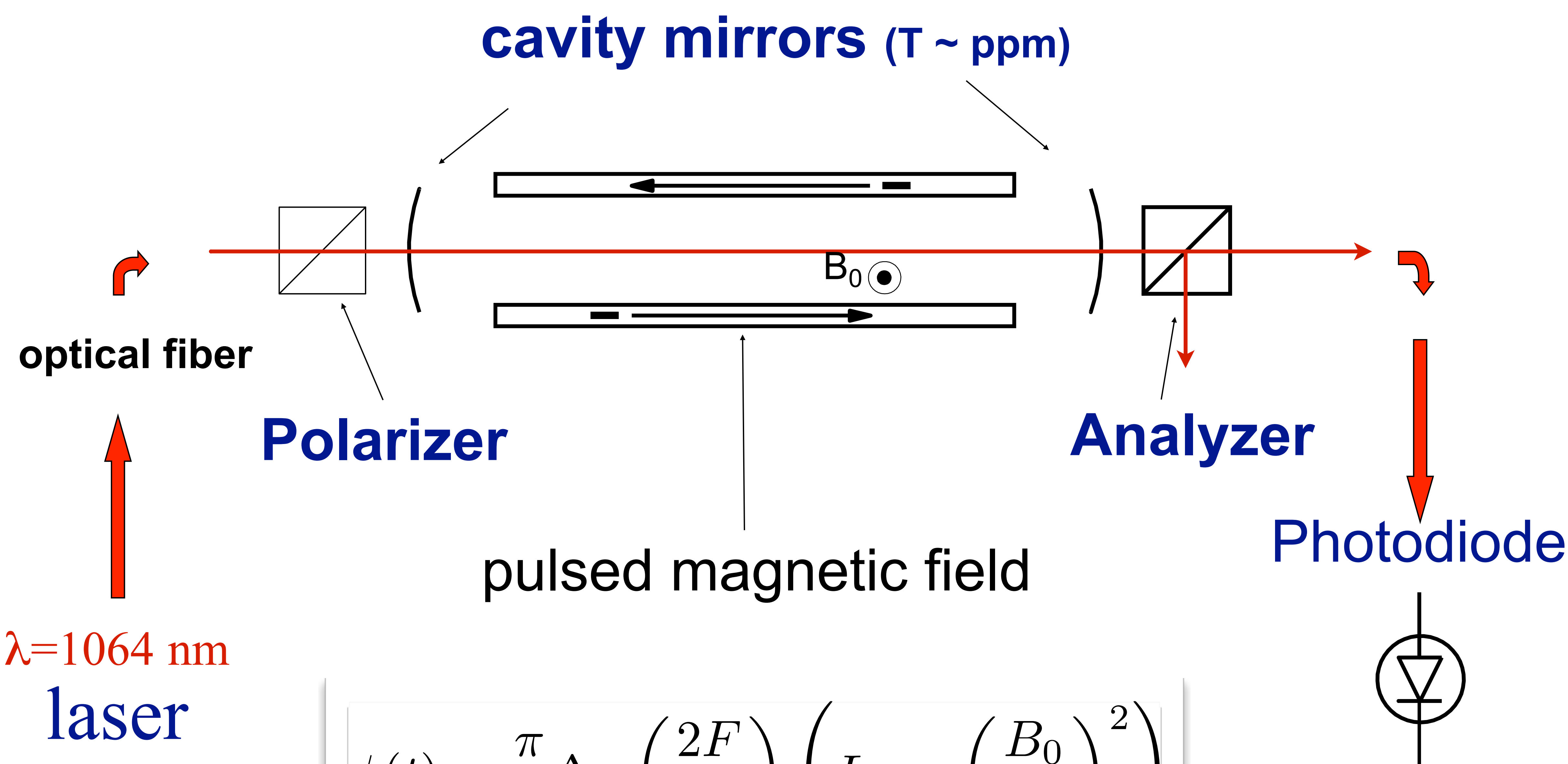
For almost 30 years, the hunt has been on for a ghostly particle proposed to plug a gap in the standard model of particle physics. The detection of a tiny optical effect might be the first positive sighting.

NO !

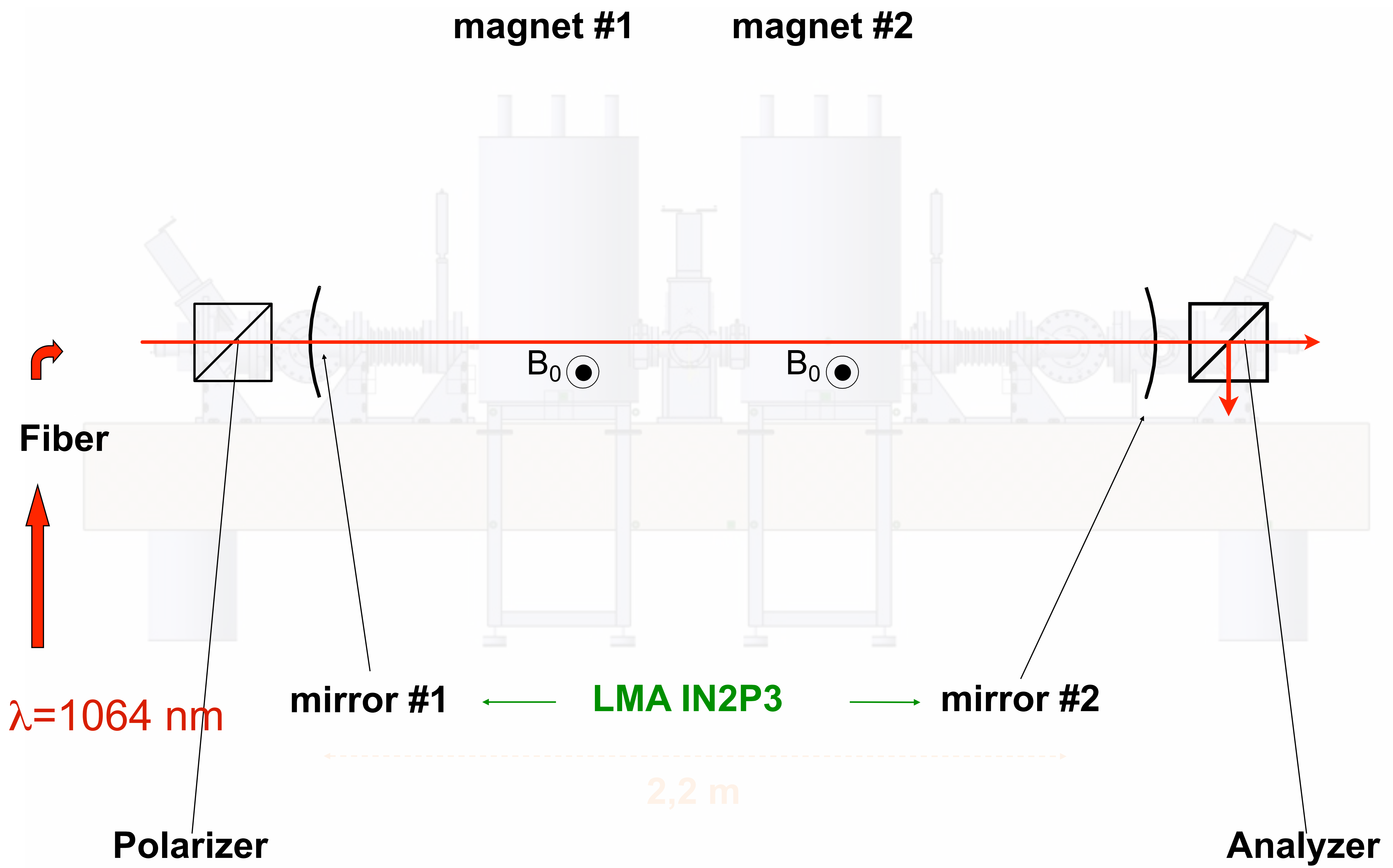
The BMV experiment

Biréfringence Magnétique du Vide

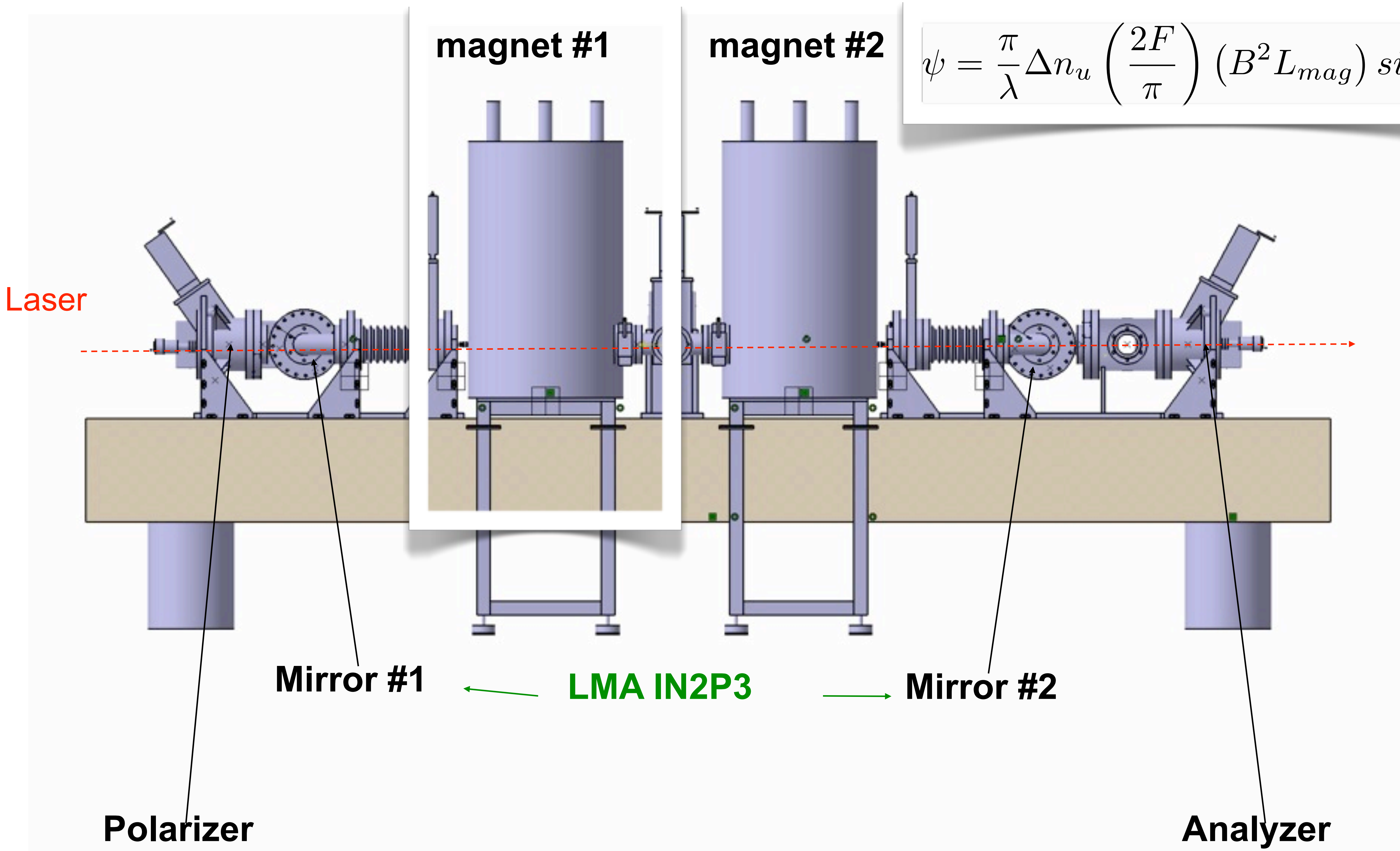


$$\psi(t) = \frac{\pi}{\lambda}\Delta n \left(\frac{2F}{\pi}\right)\left(L_{mag}\left(\frac{B_0}{1T}\right)^2\right)$$

Experimental set up



$$\psi = \frac{\pi}{\lambda}\Delta n_u \left(\frac{2F}{\pi}\right) (B^2 L_{mag})\, sin(2\theta)$$



Since 1/1/09

LNCMP Toulouse

LCMI Grenoble

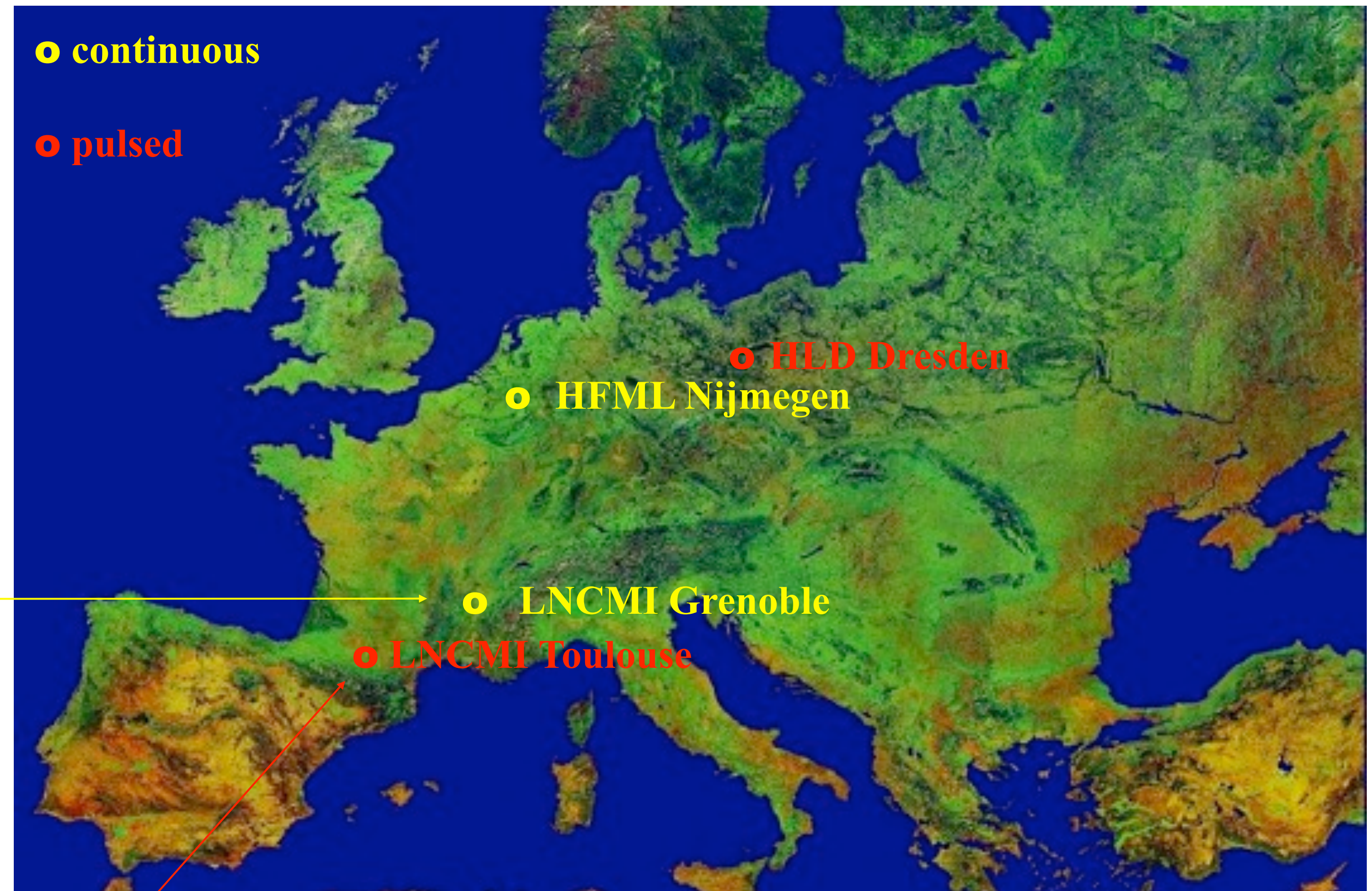
Laboratoire National des Champs Magnétiques Intenses

LNCMI

The laboratory

Since 01/01/09 :

Laboratoire
National des
Champs
Magnétiques
Intenses



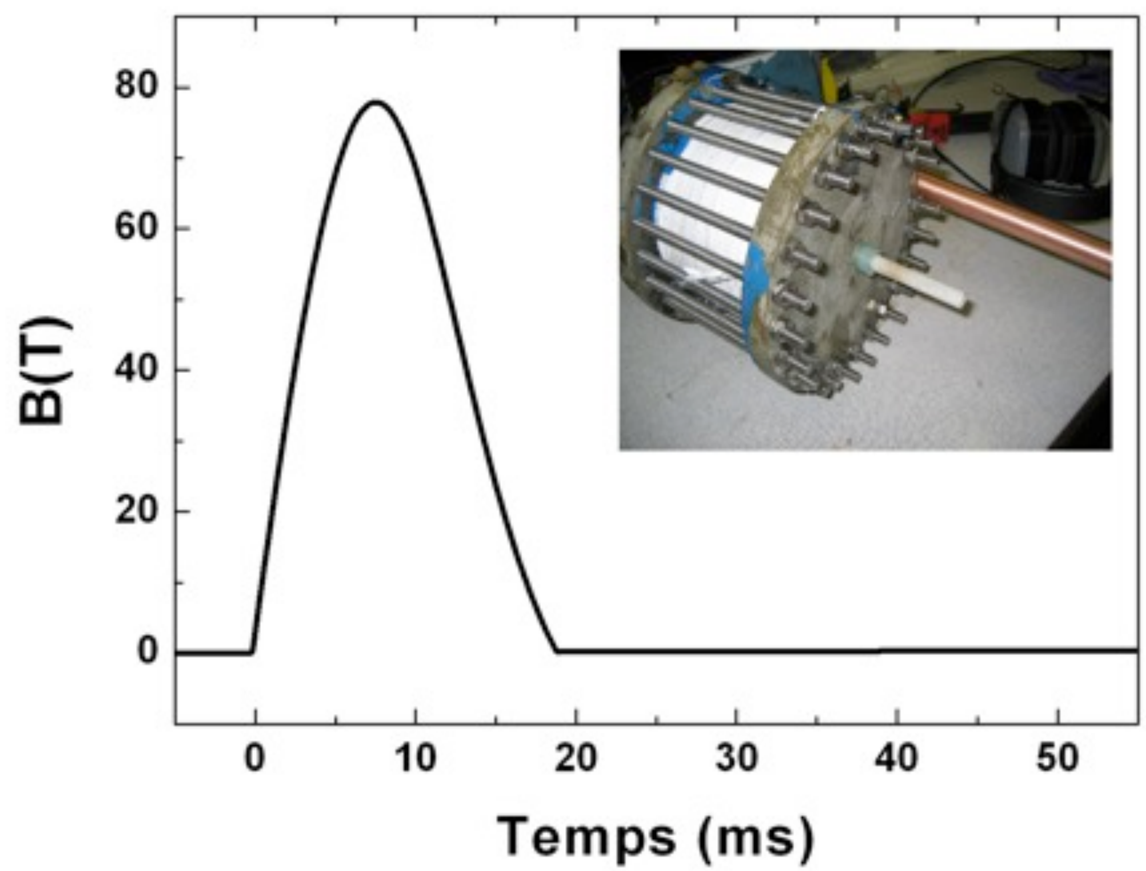
Future plans :

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

LNCMI Toulouse bank of capacitors

14 MJ, 1 GW

Faraday configuration



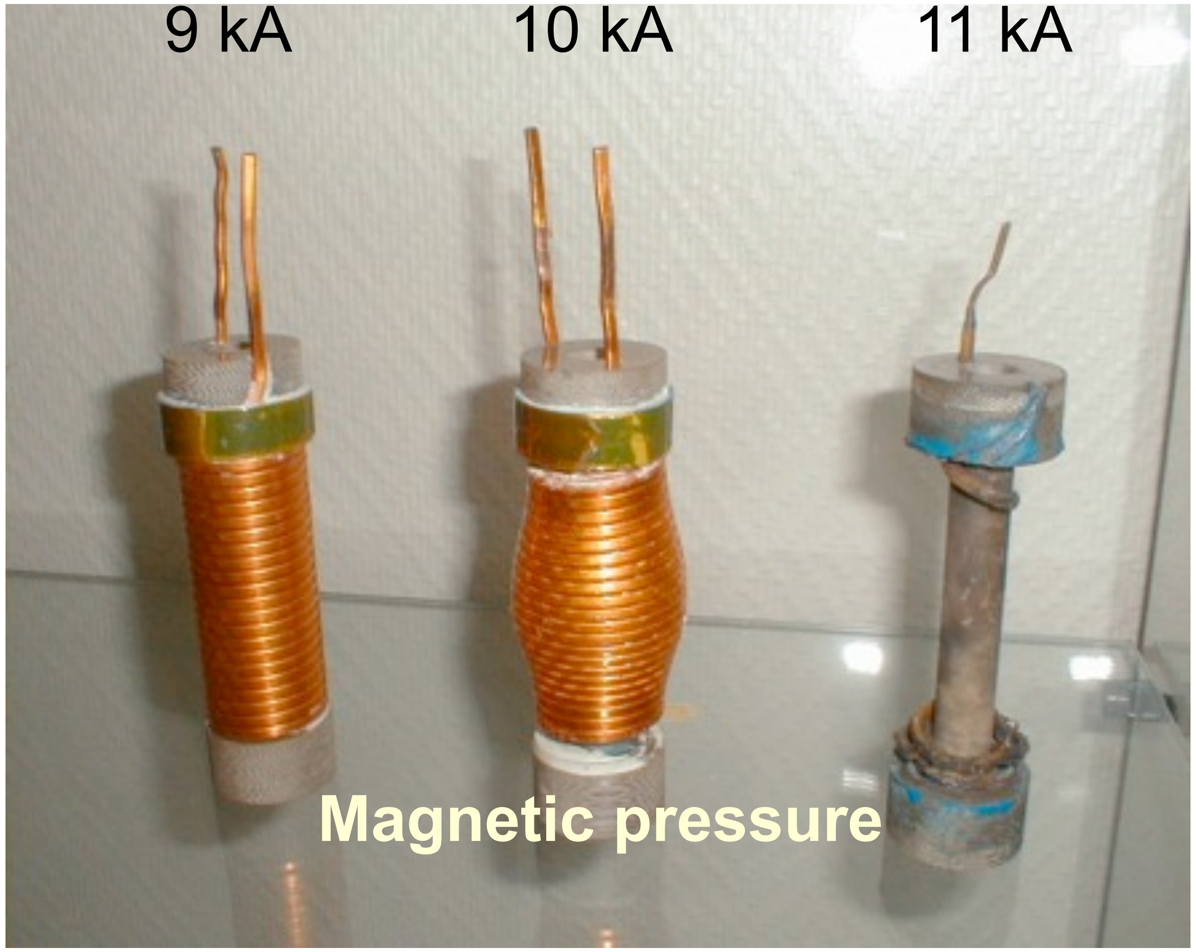
Future plans : **EMFL**
(European Magnetic Field Laboratory)
with the HFML de Nijmegen
and the HLD de Dresden.

Intense magnetic fields ?

The only method : having a strong current circulating into a coil

Two problems :

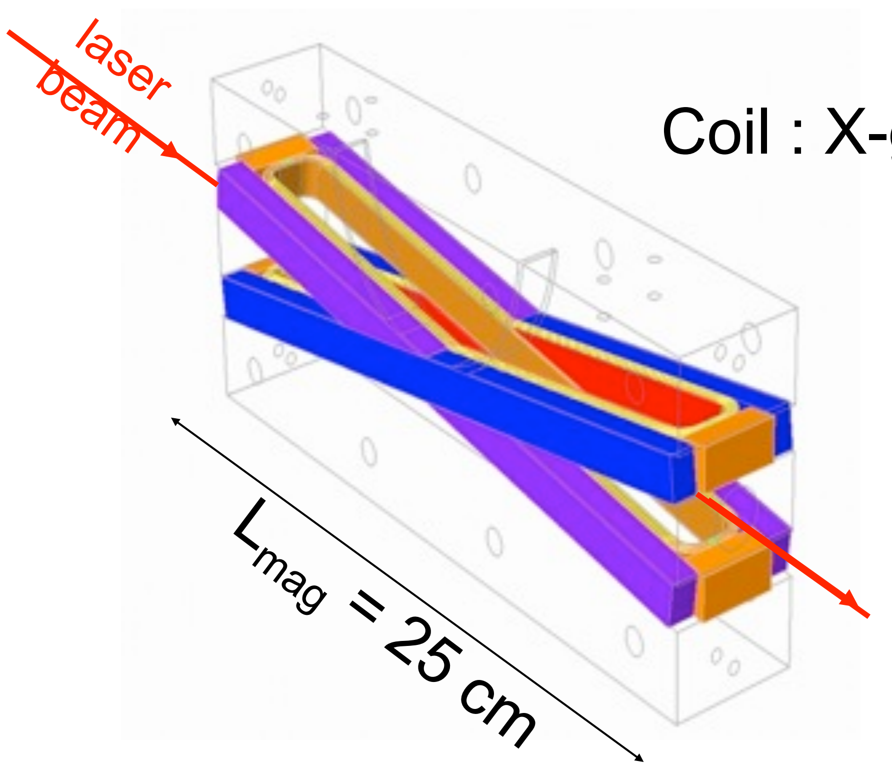
Heating ! → Superconductor (limited by B_{crit}) / Cooling / Pulsed field



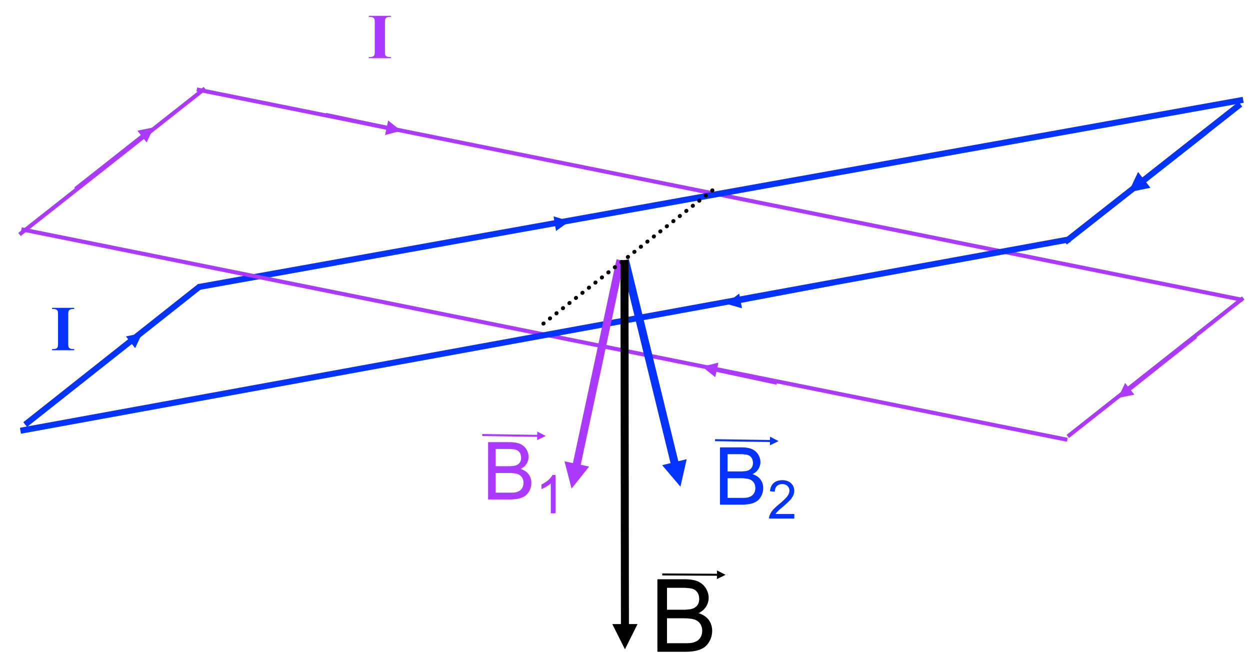
Magnetic pressure ! B^2/μ_0

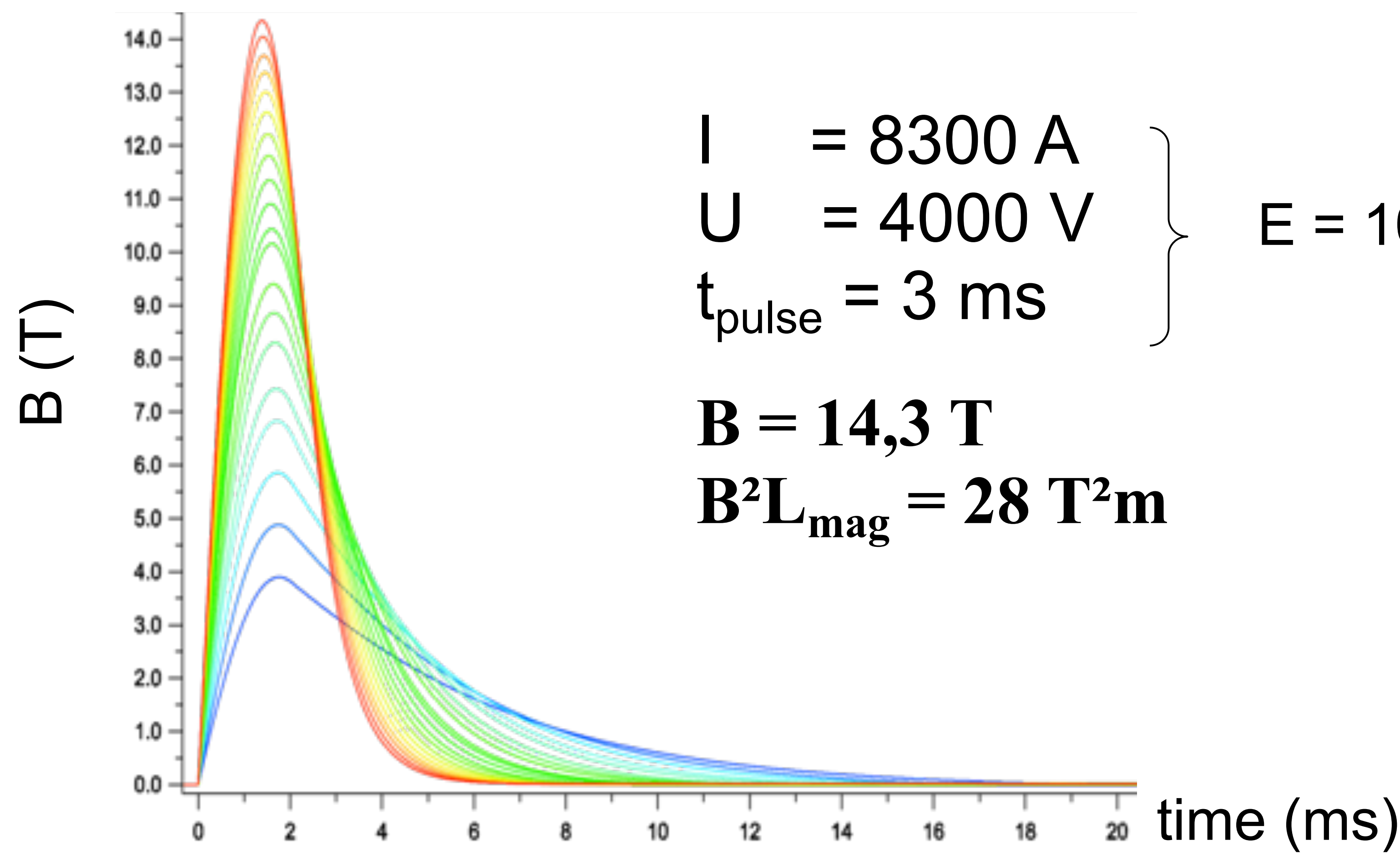
→ Ultra strong conductors
→ External reinforcement

Pulsed transverse magnetic field



Coil : X-geometry





$I = 8300$ A
$U = 4000$ V
$t_{pulse} = 3$ ms

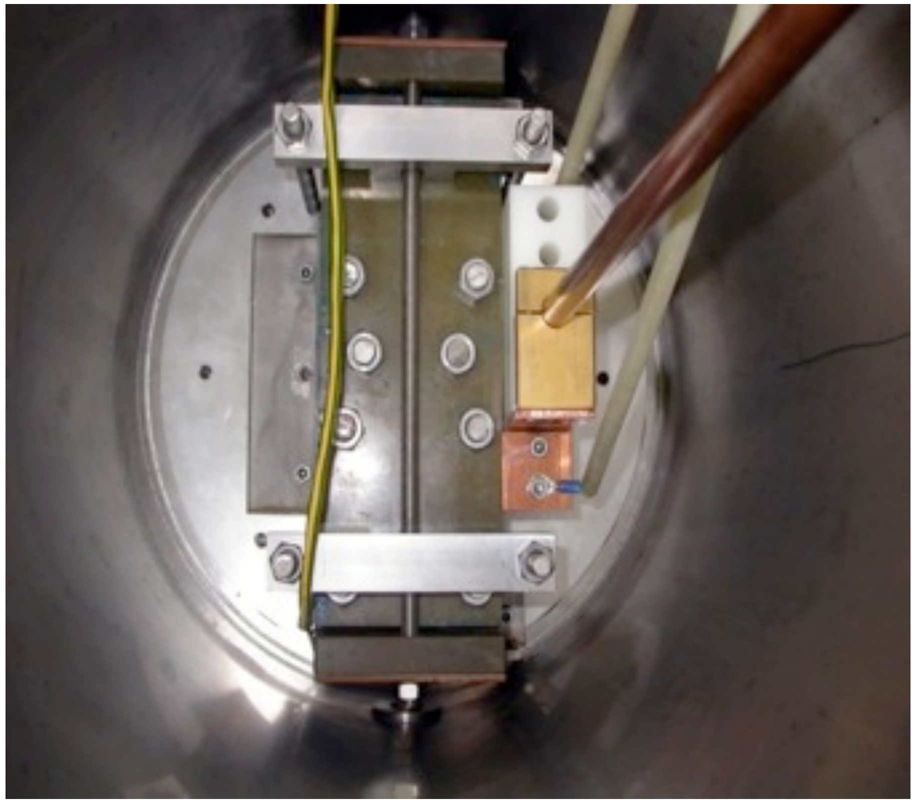
} E = 100 kJ

B = 14,3 T

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

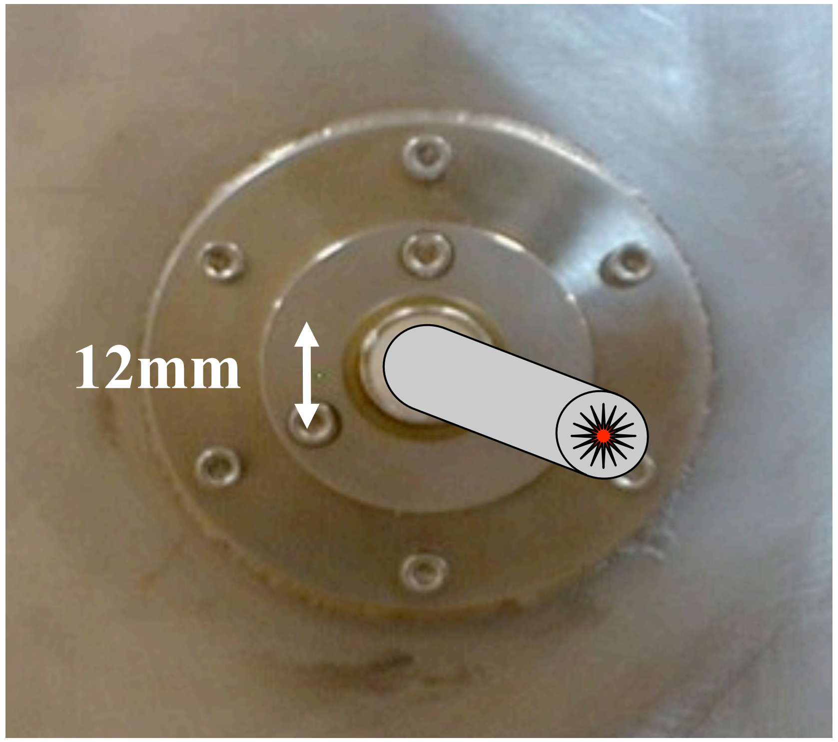
➡ **Unconventional** magnets developed at LNCMI

Pulsed transverse magnetic field

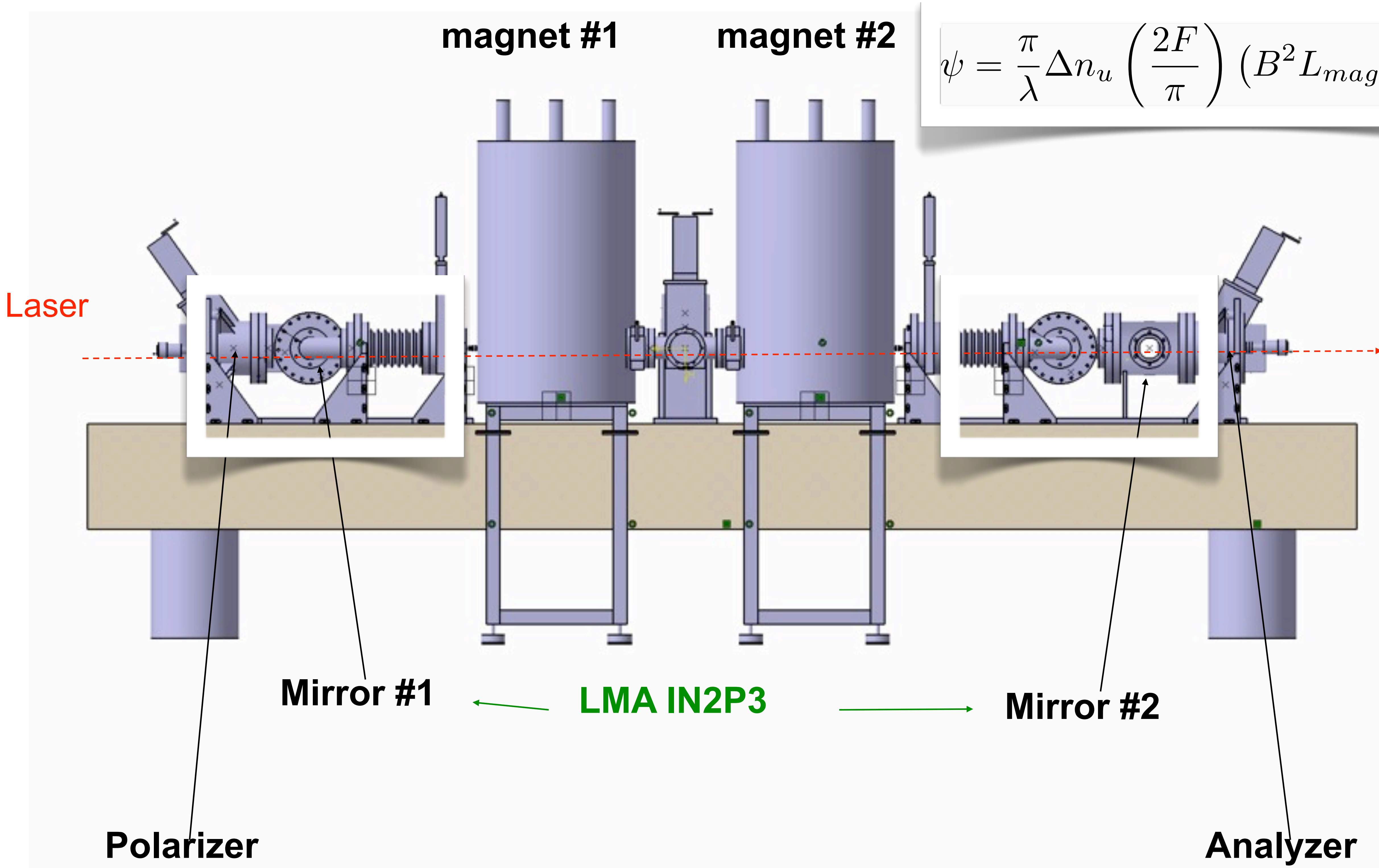


X-coil in its N_2(liq) cryostat

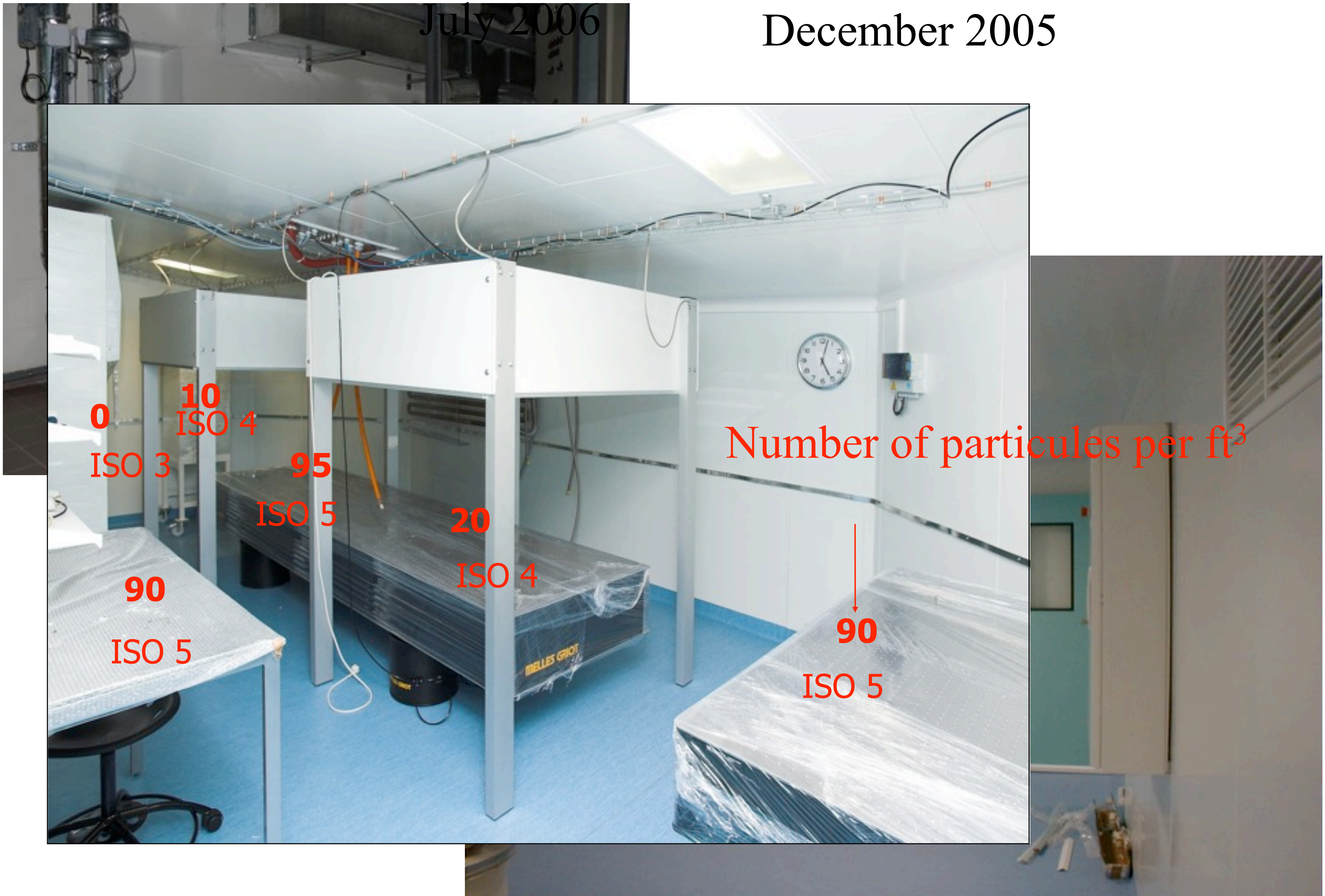
Cryostat with a thin hole made by the cryogenic team



$$\psi = \frac{\pi}{\lambda}\Delta n_u \left(\frac{2F}{\pi}\right)(B^2 L_{mag})\, sin(2\theta)$$



December 2005



Clean room

Magnet #1 Magnet #2

Mirror #2 Mirror #1

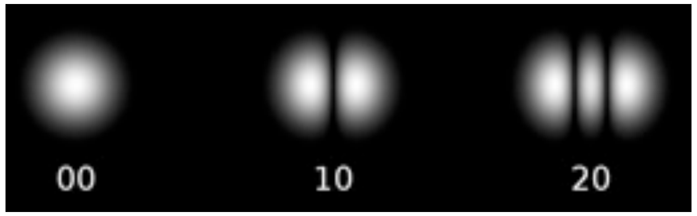
Analyzer Polarizer

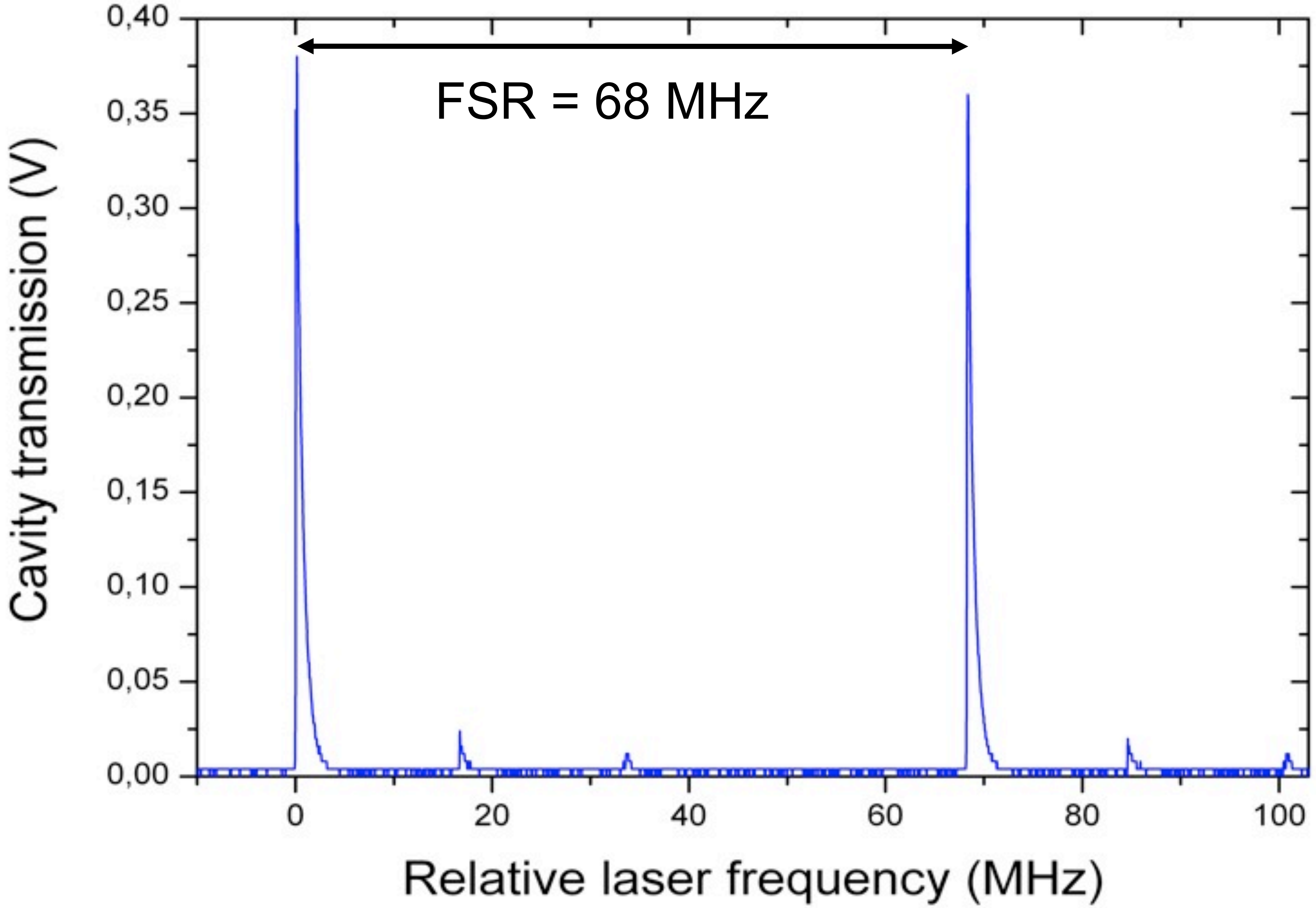
3.6 m table top experiment

The experimental setup in the clean room at LNCMI

FP cavity

- Cavity length : 2.28 m
- Waist : 1.1 mm

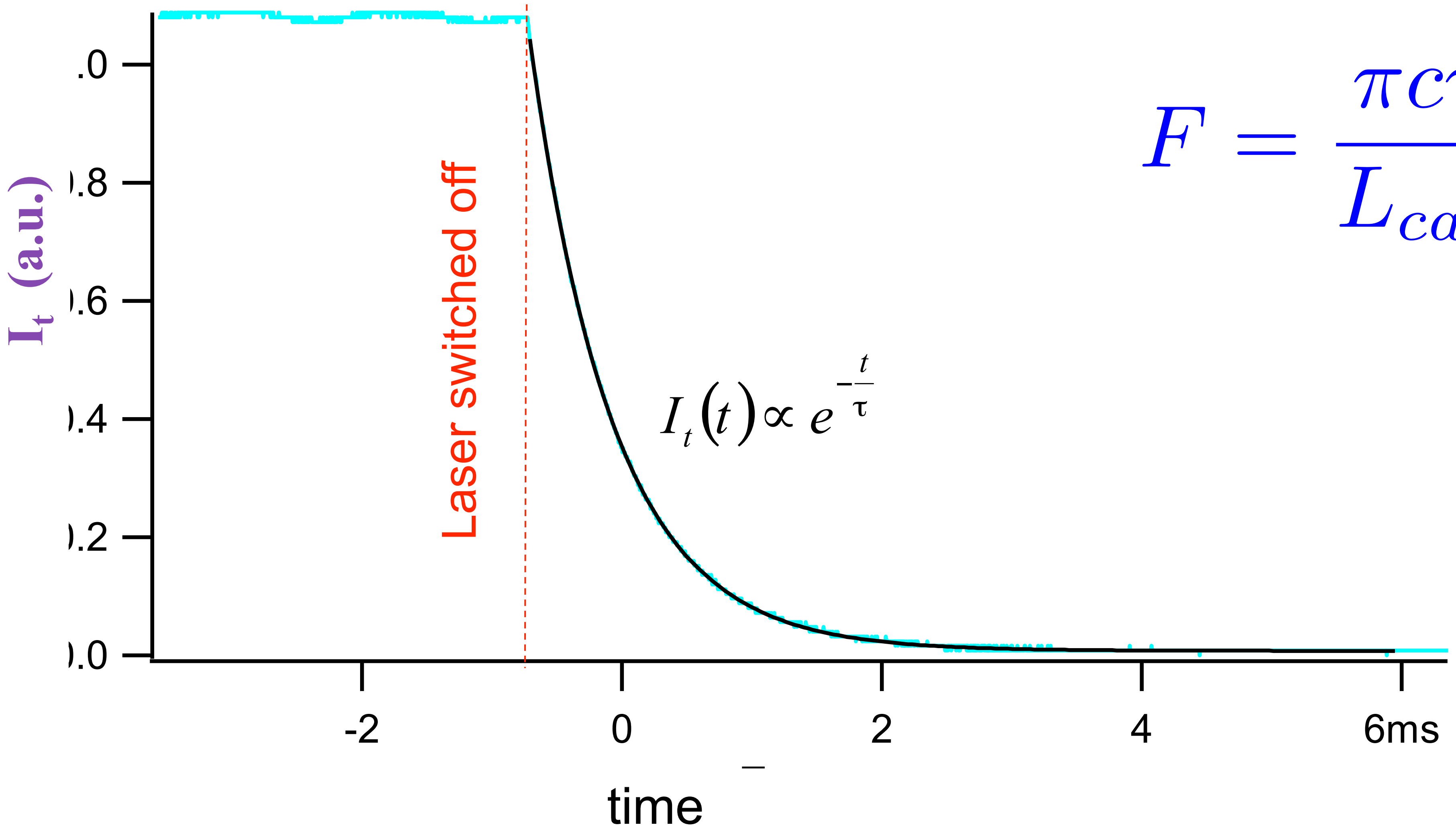




Fabry-Perot cavity

photon lifetime : $\tau = 650\mu s$

flight distance in the cavity = 200 km !



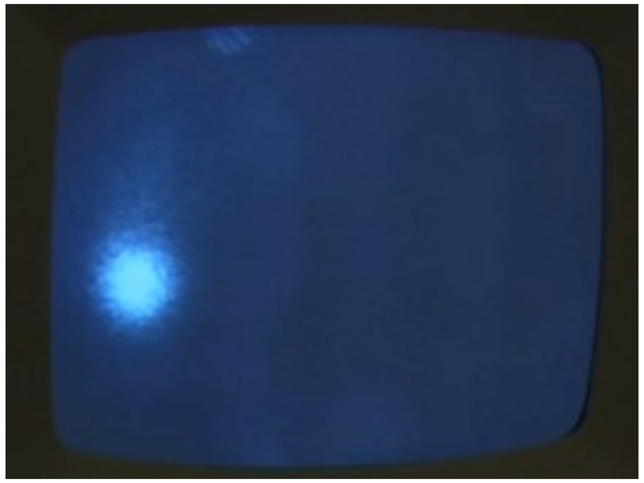
$$F = \frac{\pi c \tau}{L_{cav}} = 270000$$

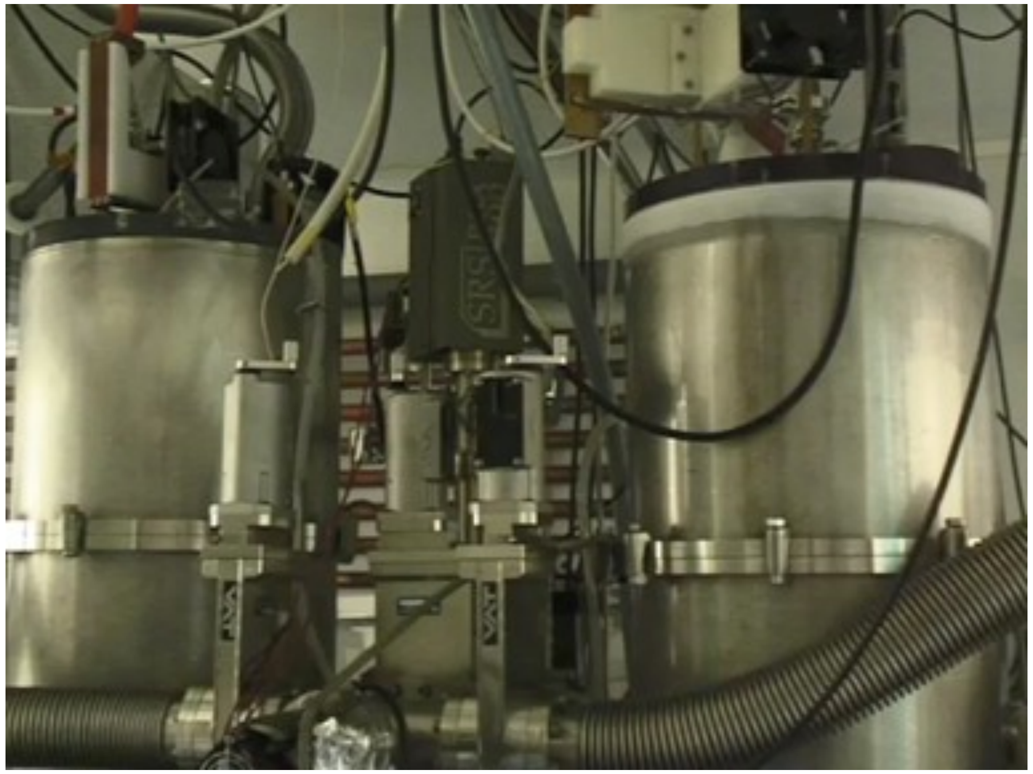
Interferometers in the world

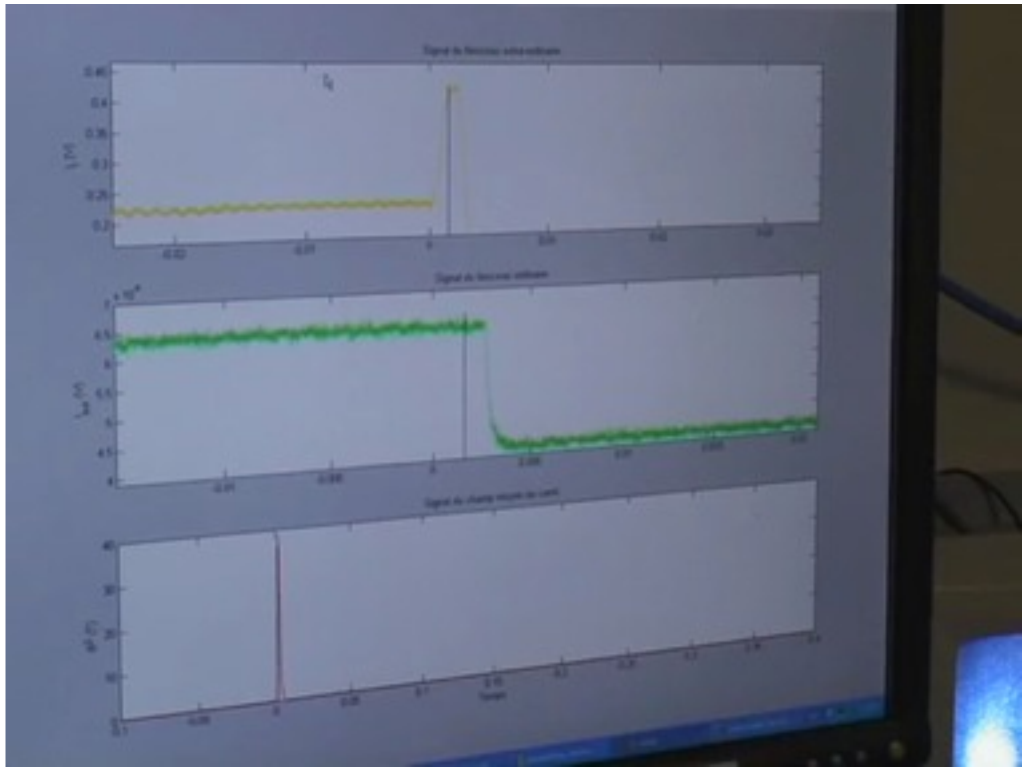
	Adv. LIGO	BMV	PVLAS	VIRGO
L_{cav}	4 km	2.3 m	6.4 m	3 km
F	230	270	70 000	50
$\Delta\nu$	164 Hz	250 Hz	360 Hz	1 kHz

→ One of the **sharpest** cavities of the world

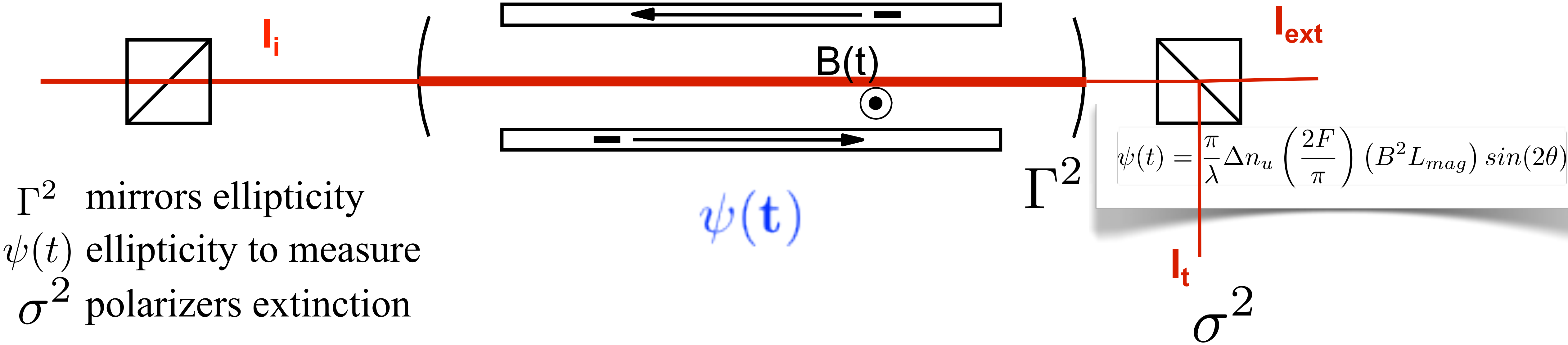
The BMV project : Data taking







Images from a movie realized for the IYA2009



$$I_{ext} = I_t\sigma^2 + I_t(\Gamma + \psi(t))^2$$

$$\psi(t) = \Gamma\sqrt{1 + \frac{I_{ext} - I_t(\sigma^2 + \Gamma^2)}{I_t\Gamma^2}} - \Gamma \qquad = \alpha B(t)^2$$

Correlation between the pulsed field $B(t)^2$ and the measured ellipticity $\psi(t)$:

en T^{-2}

$$\alpha = \frac{\int_0^T \psi(t)B(t)^2 dt}{\int_0^T B(t)^4 dt} = \frac{2FL_{mag}}{\lambda}\Delta n_u$$

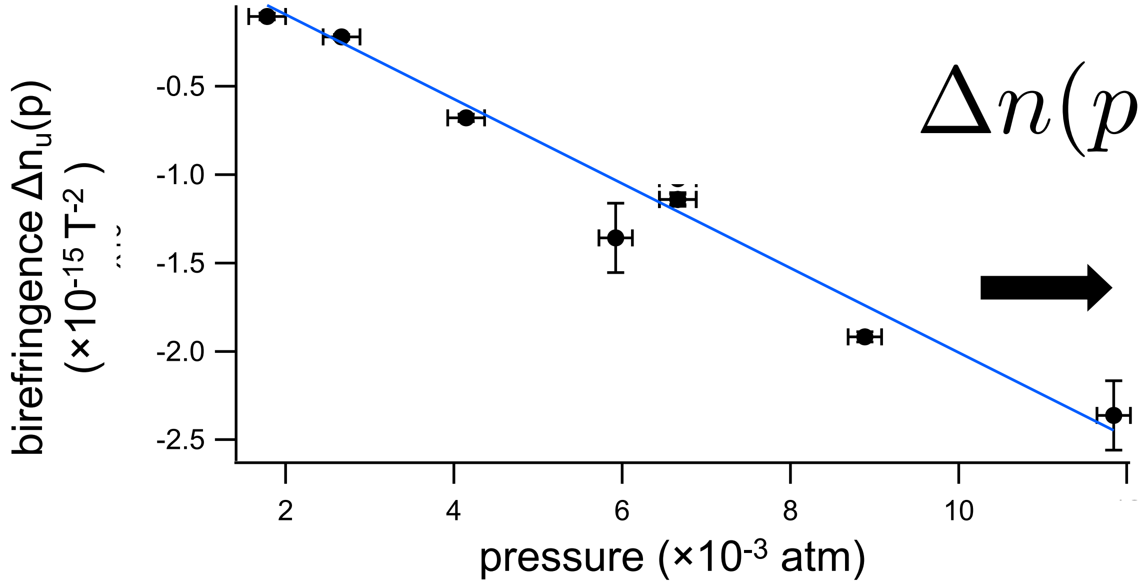
α gives the value of the birefringence Δn_u of the considered medium

First measurements

Biréfringence Magnétique du Vide

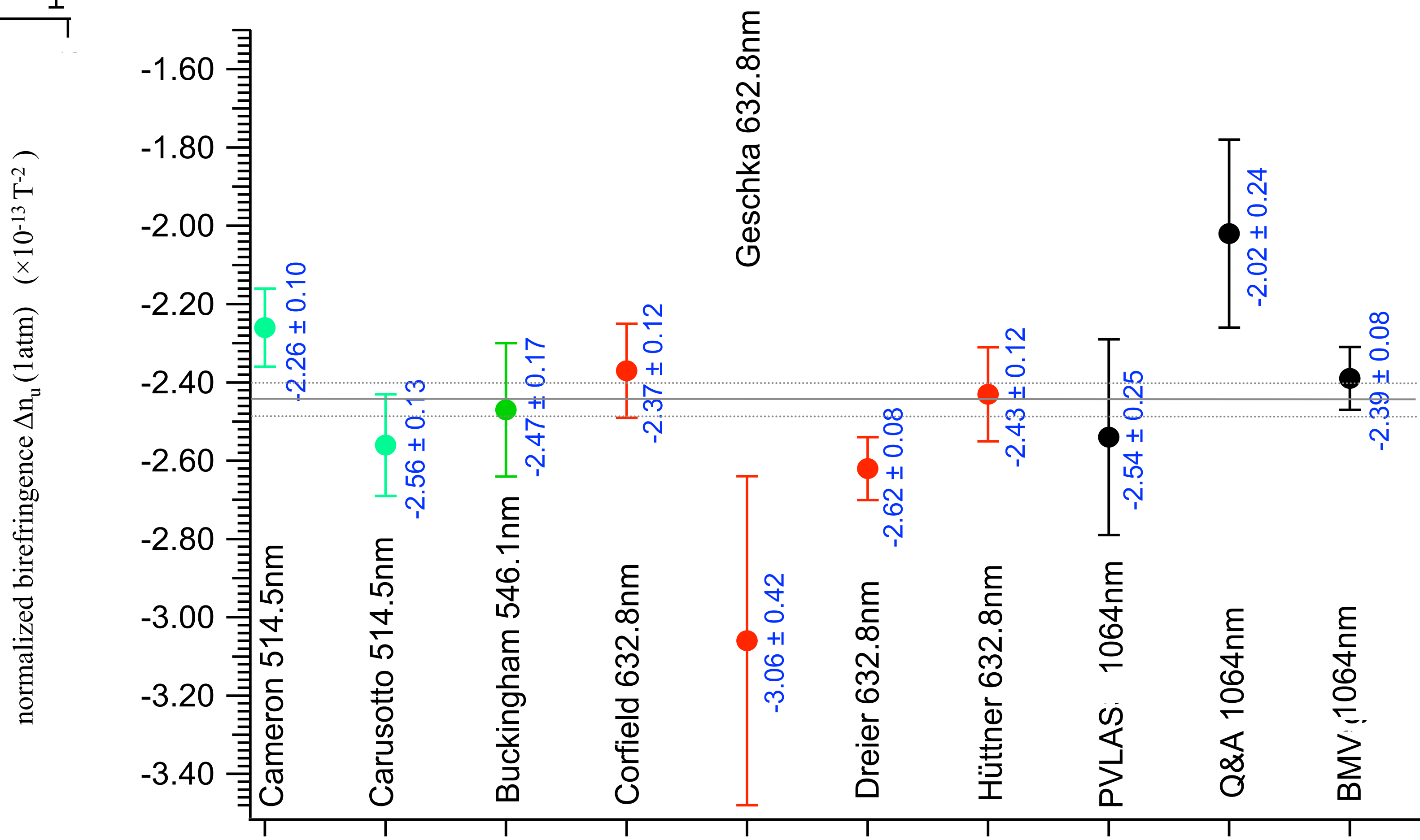
Results

- Magnetic birefringence of **nitrogen *vs* pressure**



$$\Delta n(p) = p(atm) \times \Delta n_u(1atm)$$

$$\Delta n_u(1atm) = (-2.39 \pm 0.08) \times 10^{-13} T^{-2}$$

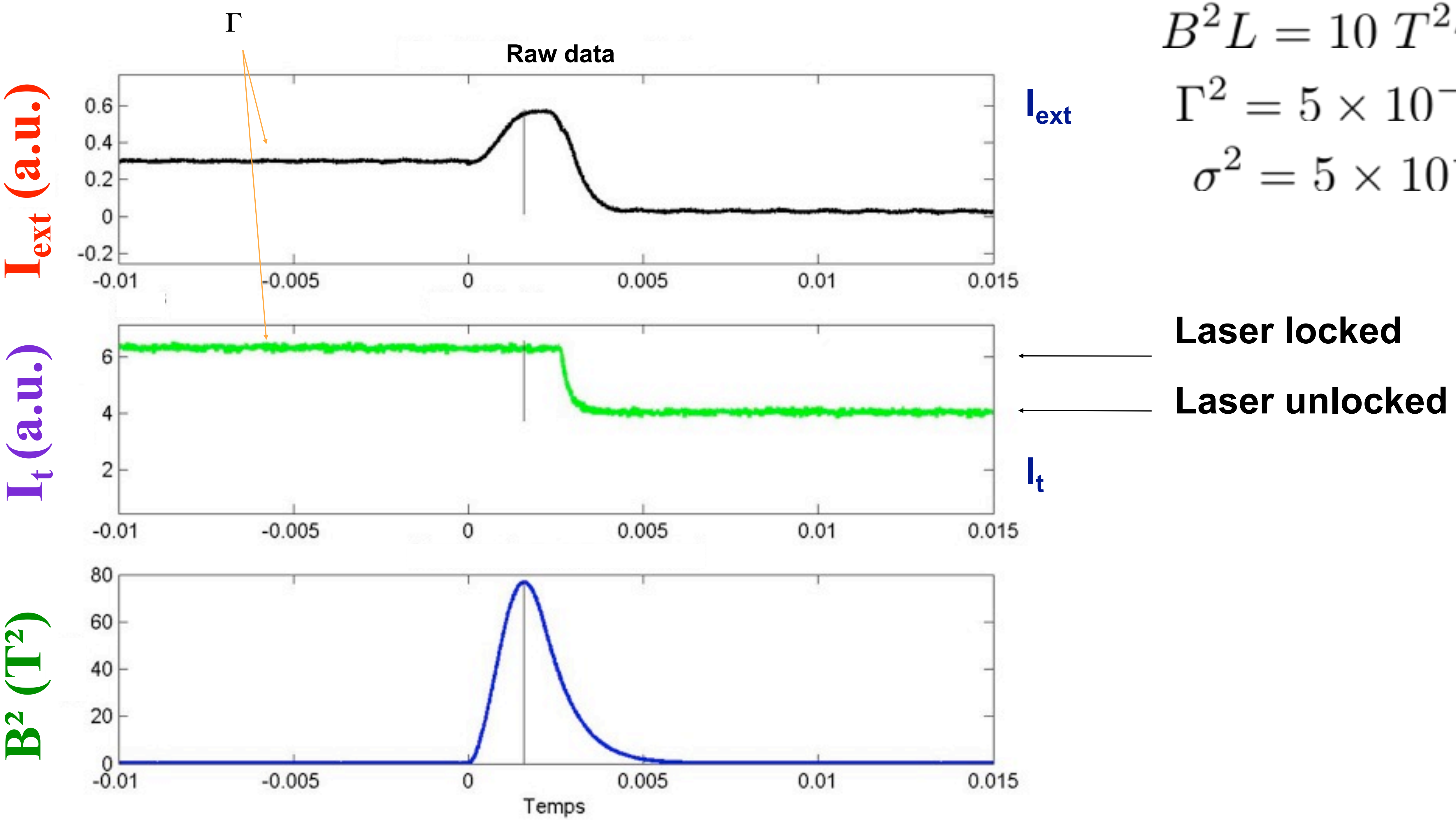


→ value **in agreement**
with the existing measurements
and with theoretical calculations

$$B^2 L = 10\ T^2 m$$

$$\Gamma^2 = 5 \times 10^{-6}$$

$$\sigma^2 = 5 \times 10^{-7}$$

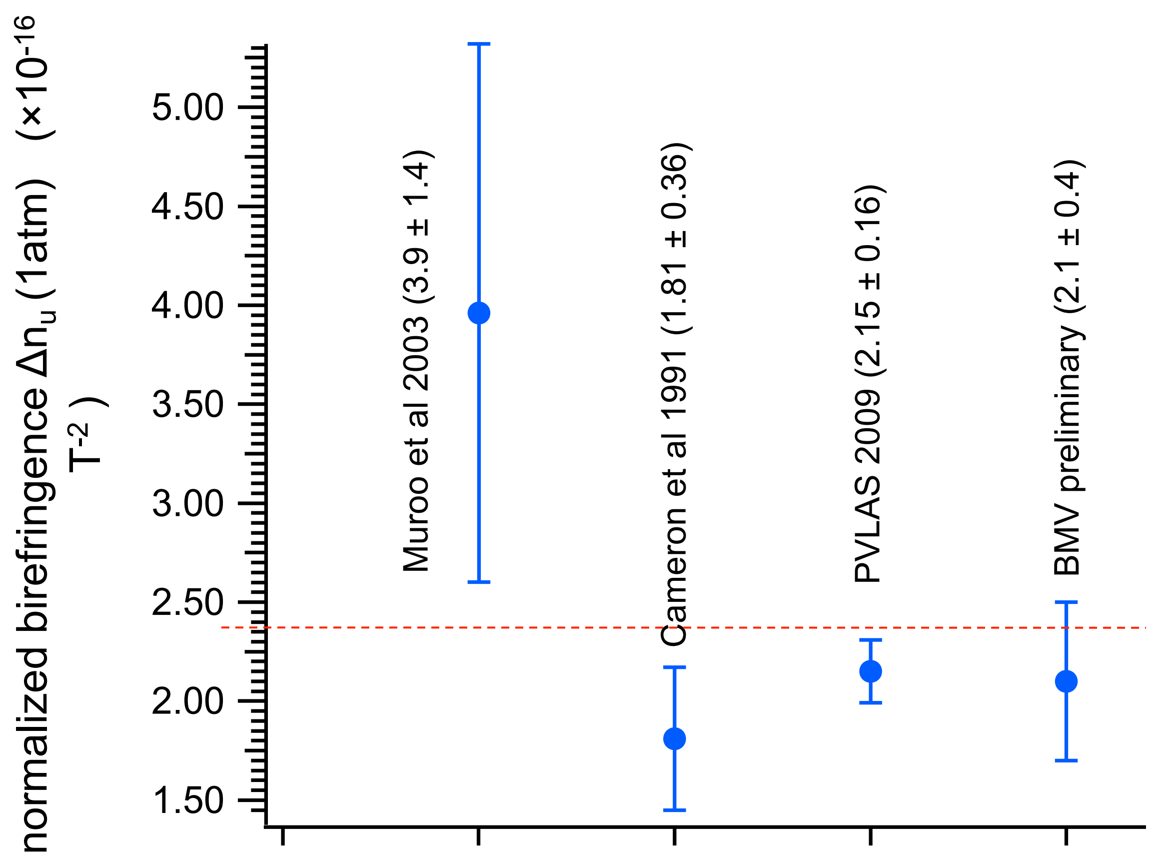


Preliminary value of magnetic birefringence of **helium** :

At 1 atm :

Theory : $\Delta n_u(1atm) = (2.400 \pm 0.005) \times 10^{-16} T^{-2}$

Our preliminary measurement : $\Delta n_u(1atm) = (2.1 \pm 0.4) \times 10^{-16} T^{-2}$



➡ good **agreement**

➡ **calibration** of our ellipsometer

Conclusions

and perspectives

Conclusion

Laser locked on a 2.3 m Fabry Perot cavity ($\Delta\nu$=500 Hz)

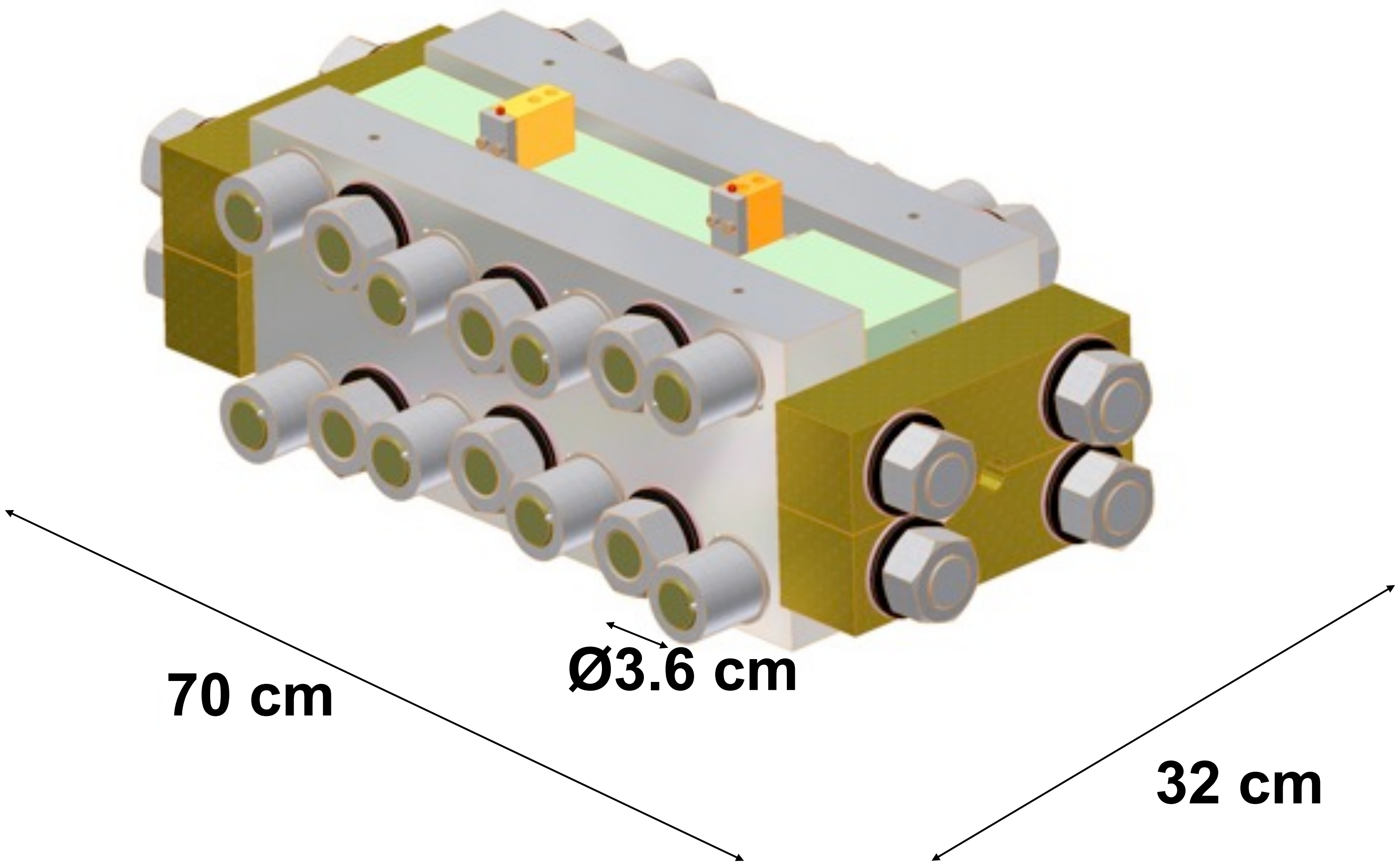
All components are working together especially the **high magnetic field** and the **Fabry Perot cavity**

We are able to measure the smallest Cotton mouton effect in gases

What else ?...

XXL Coil

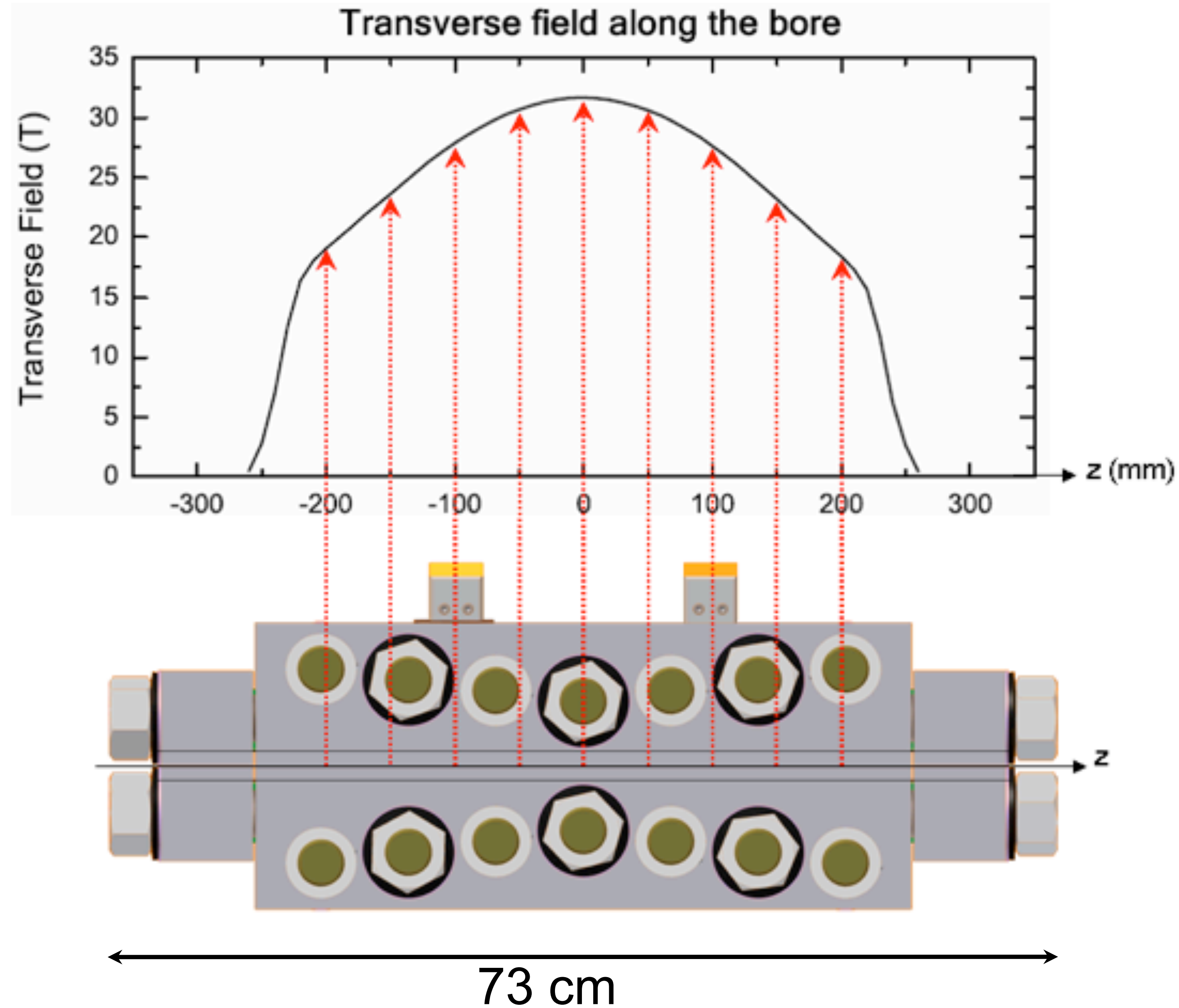
Designed at LNCMI

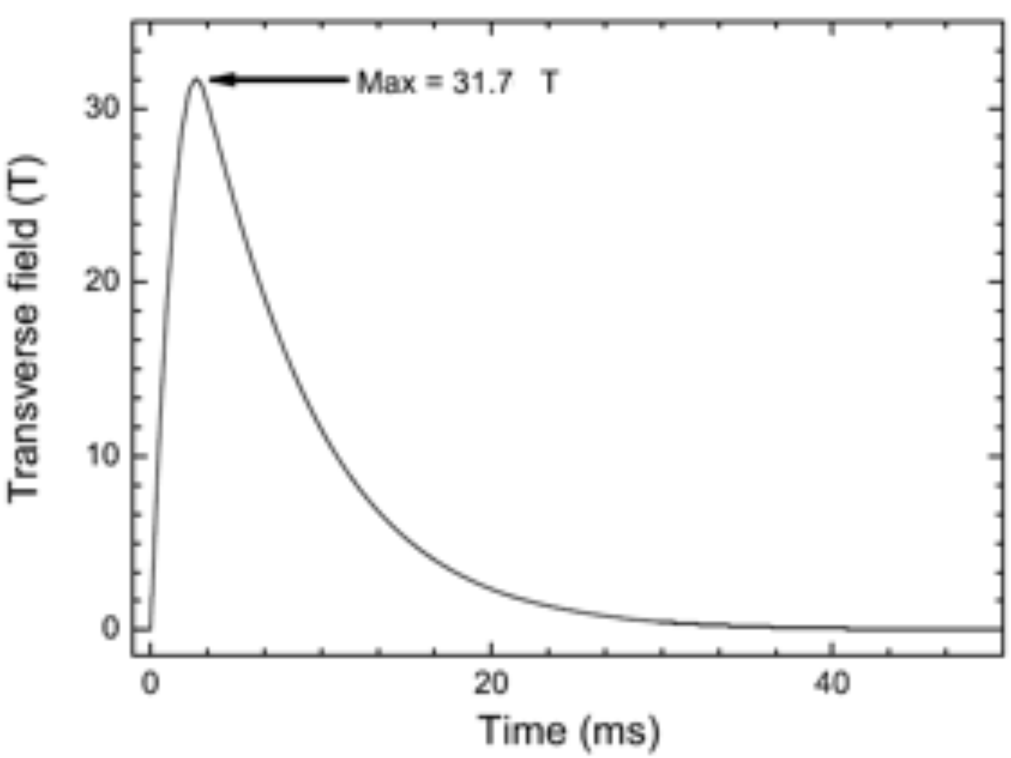


250 Kg

Magnetic pressure: 700 t on the screws !!

$B^2L > 200\ T^2m$ → **3 magnets !** → **Final set up**





$$I = 36\ 000 A$$

$$B^2 L = 300\ T^2 m$$

Can we reach the QED limit ?

we have		**we need**
Vacuum shots performed		New vacuum shots to be performed
Experimental parameters :		New experimental parameters :
↗ $F = 100\,000$	× 10 →	$F = 1\,000\,000$
↗ $B^2 L_{mag} = 26\ T^2m$	× 20 →	$B^2 L_{mag} = 600\ T^2m$
↘ $\sigma^2 = 10^{-7}$	/ 10 →	$\sigma^2 = 10^{-8}$
↘ $\Gamma^2 = 10^{-6}$	/ 10 →	$\Gamma^2 = 10^{-7}$

F and $B^2 L_{mag}$ } $\Psi_{QED} = 4.5 \times 10^{-9}$

+ ↗ stability of locking system

Sensibility reached in ellipticity :

$$\varnothing_{\text{sensibility}} = 2\times10^{-7}/\sqrt{Hz}$$

corresponding to :

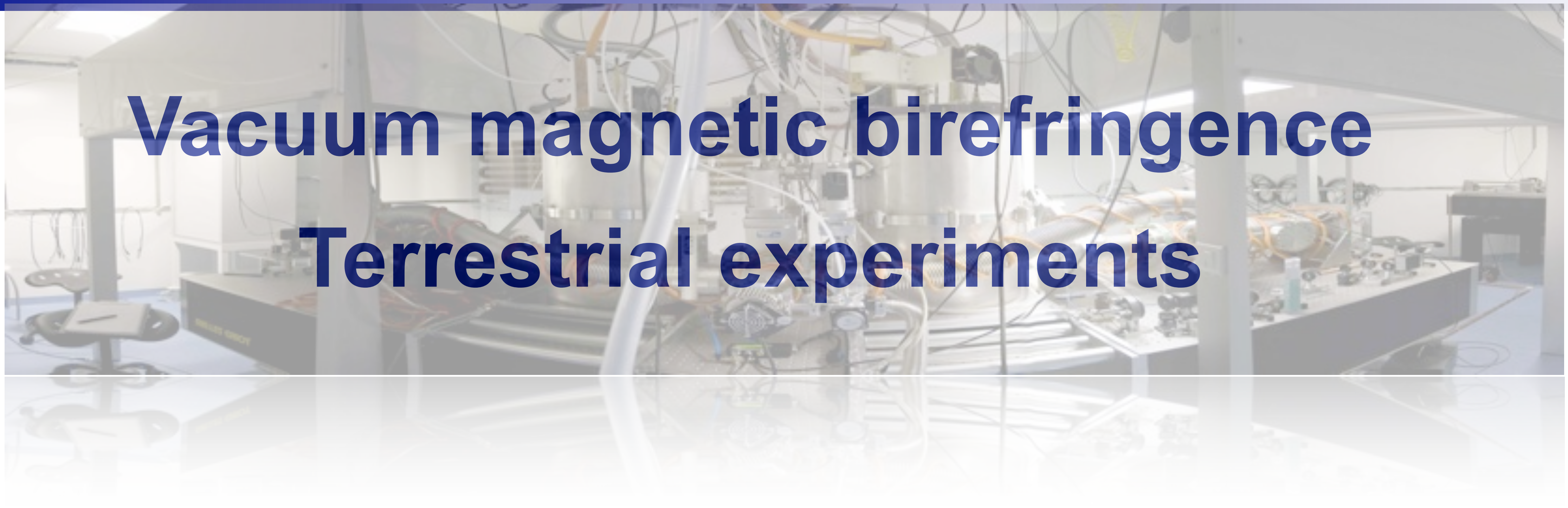
$$\mathbf{\Delta n_u = 2 \times 10^{-18}\ T^{-2}\ /\ shot}$$

corresponding to a sensibility of :

$$\mathbf{\Delta n_u = 8\times10^{-23}\ T^{-2}\ /\ shot}$$

So, the number of shots is :

$$\left(\frac{8 \times 10^{-23}}{4 \times 10^{-24}}\right)^2 = \mathbf{400\ shots}$$



Vacuum magnetic birefringence

Terrestrial experiments

Rémy Battesti

remy.battesti@lncmi.cnrs.fr

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