Le vide quantique en laboratoire

…par l'électrodynamique non linéaire

Laboratory tests of a quantum vacuum

… by the non linear electrodynamics

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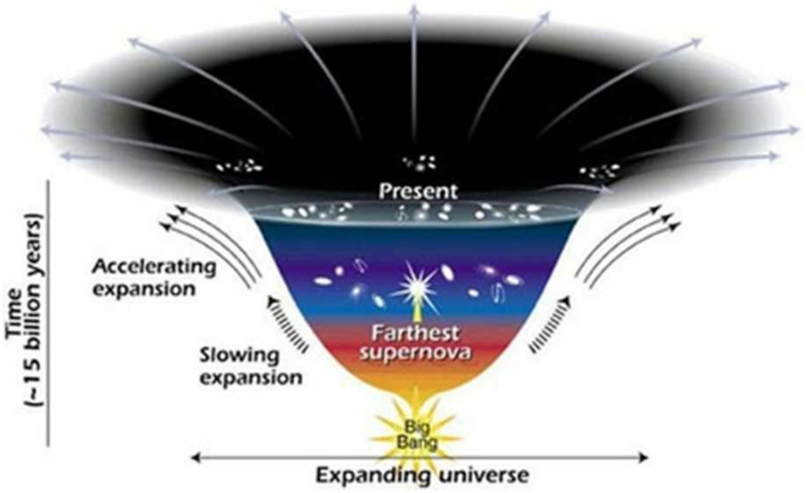
What does «vacuum» mean ?

- **Aristotle : *«The investigation of similar questions about the void, also, must be held to belong to the physicist - namely whether it exists or not, and how it exists or what it is »*** **(Physics, part VI-IX, book IV, ~350 B.C.)**

Vacuum energy could be the cause of the universe expansion acceleration !

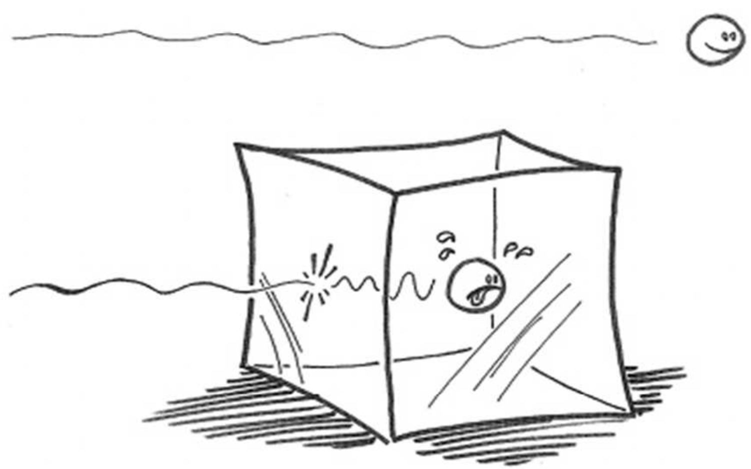
Dark energy !

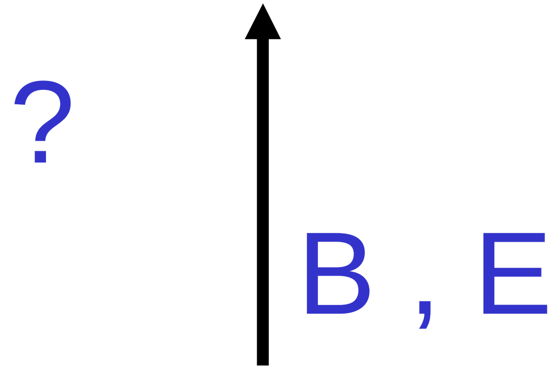


A vacuum has macroscopic properties !

Magnetic and electric properties of a quantum vacuum, R. Battesti and C. Rizzo, Rep. Prog. Phys. **76**, 016401 (2013)
Limits on nonlinear electrodynamics, M. Fouché, R. Battesti and C. Rizzo, PHYSICAL REVIEW D **93**, 093020 (2016)

- **For physicists, a vacuum is a place where the speed of light is equal to c,   with c= 299 792 458 m/s**





Credit : B. Mollier

- **In a vacuum, the light travels at c. But, in a medium (like water, glass etc..), its speed is reduced … and viceversa.**

What about light propagating in vacuum in the presence of electromagnetic fields ?

More in general, what about interactions between electromagnetic fields ?

Non linear electrodynamics : photon-photon interactions

$$\mathcal{L} = \sum_{i=0}^{\infty} \sum_{j=0}^{\infty} c_{i,j} \mathcal{F}^i \mathcal{G}^j$$

$$\mathcal{F} = \epsilon_0 E^2 - \frac{B^2}{\mu_0},$$

$$\mathcal{G} = \sqrt{\frac{\epsilon_0}{\mu_0}} \mathbf{E} \cdot \mathbf{B},$$

Lorentz invariants

$$\mathcal{L} = \mathcal{L}_0 + \mathcal{L}_{\mathrm{NL}},$$

$$\text{with} \quad \mathcal{L}_0 = \frac{1}{2} \mathcal{F},$$

$$\text{and} \quad \mathcal{L}_{\mathrm{NL}} \simeq c_{0,1} \mathcal{G} + c_{2,0} \mathcal{F}^2 + c_{0,2} \mathcal{G}^2 + c_{1,1} \mathcal{F} \mathcal{G}.$$

Low field limit

Constutive equations

$$\mathbf{P} = \frac{\partial \mathcal{L}}{\partial \mathbf{E}} - \epsilon_0 \mathbf{E}$$

$$\mathbf{M} = \frac{\partial \mathcal{L}}{\partial \mathbf{B}} - \frac{\mathbf{B}}{\mu_0}.$$

$$\mathbf{P} = c_{0,1}\sqrt{\frac{\epsilon_0}{\mu_0}}\mathbf{B} + 4c_{2,0}\epsilon_0\mathcal{F}\mathbf{E} + 2c_{0,2}\sqrt{\frac{\epsilon_0}{\mu_0}}\mathcal{G}\mathbf{B} + c_{1,1}\left(2\epsilon_0\mathcal{G}\mathbf{E} + \sqrt{\frac{\epsilon_0}{\mu_0}}\mathcal{F}\mathbf{B}\right),$$

$$\mathbf{M} = c_{0,1}\sqrt{\frac{\epsilon_0}{\mu_0}}\mathbf{E} - 4c_{2,0}\mathcal{F}\frac{\mathbf{B}}{\mu_0} + 2c_{0,2}\sqrt{\frac{\epsilon_0}{\mu_0}}\mathcal{G}\mathbf{E} - c_{1,1}\left(2\mathcal{G}\frac{\mathbf{B}}{\mu_0} - \sqrt{\frac{\epsilon_0}{\mu_0}}\mathcal{F}\mathbf{E}\right).$$

Point charged particle with a magnetic moment : apparent magnetic monopole …

Light propagating in the presence of light : photon – photon scattering …

Light propagating in the presence of an external field : vacuum magnetic linear birefringence

also known as Vacuum Cotton-Mouton effect

…

A. Heisenberg and Euler effective Lagrangian

1935 - 1936

$$\mathcal{L}_{\rm NL} = \frac{\alpha}{90\pi}\frac{1}{\epsilon_0 E_{cr}^2}[\mathcal{F}^2 + 7\mathcal{G}^2]$$

Based on Dirac’s model of a vacuum

$$E_{\rm cr} = 1.3 \times 10^{18}\ {\rm V/m}$$
$$B_{\rm cr} = E_{\rm cr}/c = m_e^2 c^2/e\hbar = 4.4 \times 10^9\ {\rm T}$$

$$c_{2,0} = \frac{2\alpha^2\hbar^3}{45 m_e^4 c^5} = \frac{\alpha}{90\pi}\frac{1}{\epsilon_0 E_{\rm cr}^2} = \frac{\alpha}{90\pi}\frac{\mu_0}{B_{\rm cr}^2} \simeq 1.66 \times 10^{-30}\left[\frac{m^3}{J}\right],$$

$$c_{0,2} = 7c_{2,0},$$

B. Born-Infeld effective Lagrangian

1934

$$\mathcal{L} \simeq \frac{1}{2}\mathcal{F} + \frac{1}{8\epsilon_0 E_{\rm abs}^2}\mathcal{F}^2 + \frac{1}{2\epsilon_0 E_{\rm abs}^2}\mathcal{G}^2$$

$$c_{2,0} = \frac{1}{8\epsilon_0 E_{\rm abs}^2},$$

$$c_{0,2} = \frac{1}{2\epsilon_0 E_{\rm abs}^2} = 4c_{2,0}.$$

An attempt to solve the problem of the infinite energy of a charged point particle

C. Lagrangian in the string theory framework

Nowadays

$$\mathcal{L} = \frac{1}{2}\mathcal{F} + \frac{\gamma}{4}[(1-b)\mathcal{F}^2 + 6\mathcal{G}^2]$$

$$c_{2,0} = \frac{\gamma}{4}(1-b),$$

$$c_{0,2} = \frac{3}{2}\gamma.$$

It contains the previous two as a particular case

Test of
non linear electrodynamics

Test of
long range electromagnetic
interactions

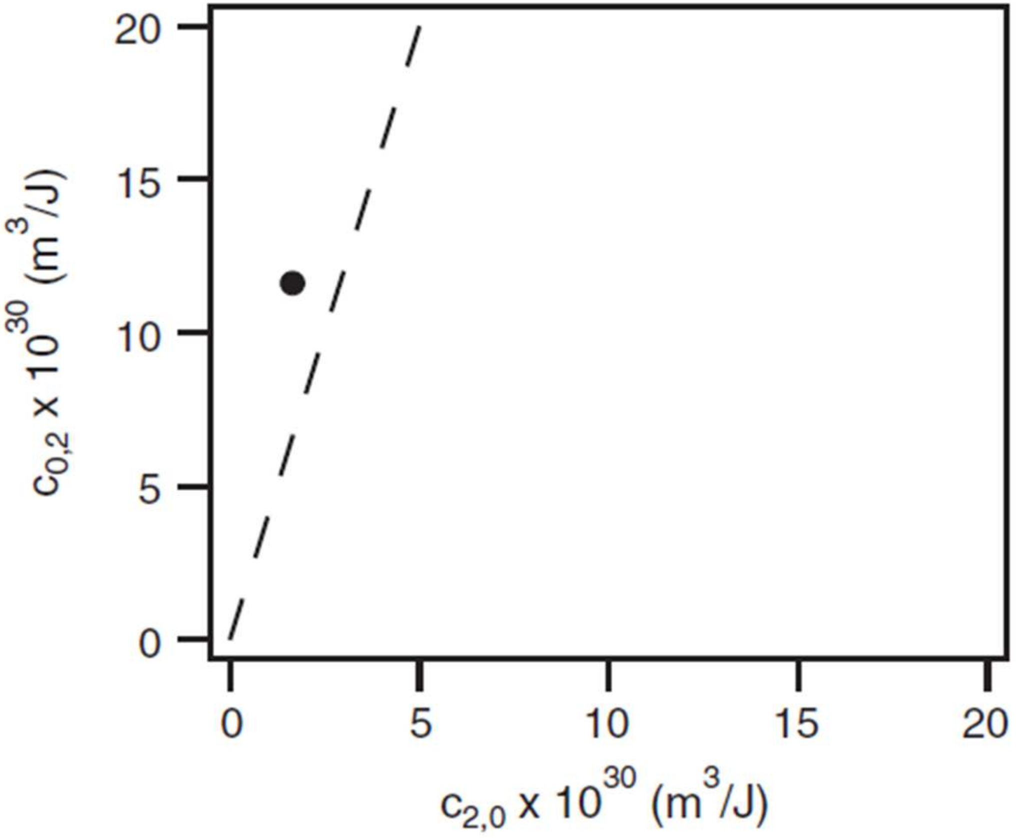
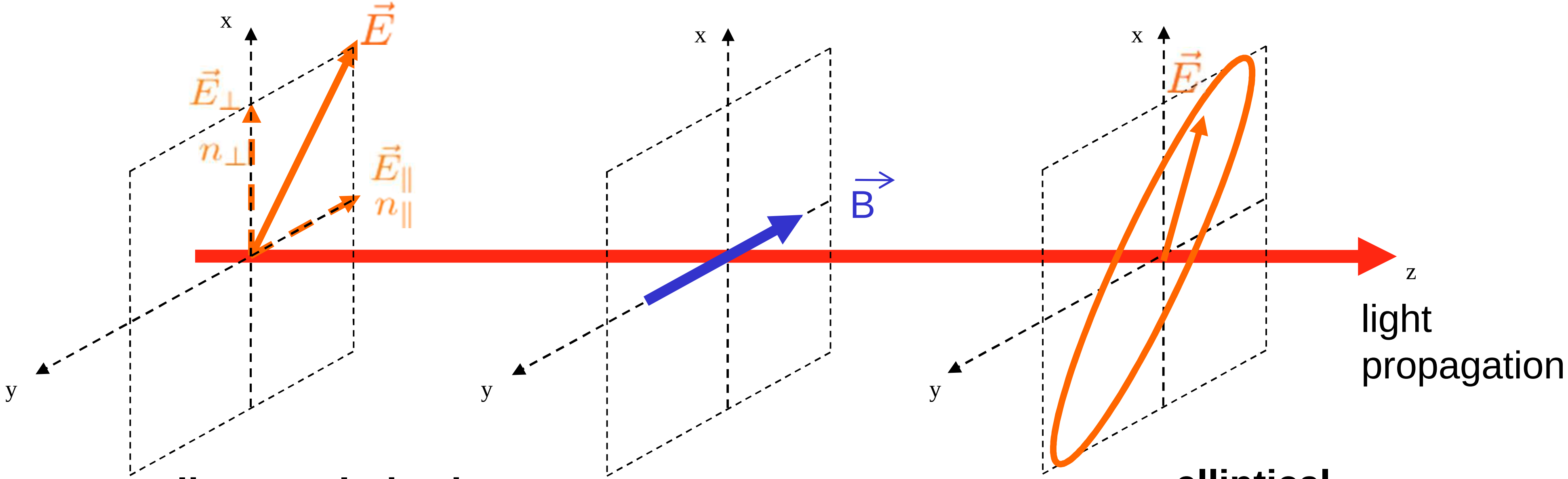


FIG. 1. Born-Infeld prediction and Heisenberg-Euler prediction in the $(c_{2,0}, c_{0,2})$ parameter space. The Born-Infeld prediction is represented by a straight line, while the Heisenberg-Euler one is a point.

Vacuum magnetic linear birefringence



linear polarization

elliptical polarization

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

Effect as old as 1935,

but still not observed in a laboratory

H. Euler and B. Kochel, Naturwissenschaften **23** 246 (1935)
W. Heinsenberg and H. Euler, Z. Phys. **38,** 714 (1936)

Z. Bialynika-Birula et al., Phys. Rev. D **2,** 2341 (1970)

❑ Vacuum magnetic linear birefringence

Heisenberg – Euler prediction

$$\Delta n = \left(\frac{2\alpha^2\hbar^3}{15 m_e^4 c^5} + \frac{5}{6}\frac{\alpha^3\hbar^3}{\pi m_e^4 c^5}\right)\frac{B_0^2}{\mu_0} = \frac{2\alpha^2\hbar^3}{15 m_e^4 c^5}\left(1 + \frac{25\alpha}{4\pi}\right)\frac{B_0^2}{\mu_0}$$

$$\Delta n = k_{CM}\ B^2$$

CODATA 2012

$$k_{CM} = (4.0317 \pm 0.0009) \times 10^{-24}\ \mathrm{T}^{-2}$$

a very challenging task !

❑ Vacuum magnetic linear birefringence

Born - Infeld prediction

$$\Delta n = 0$$

because $c_{0,2} = 4\ c_{2,0}$!

BMV group

Permanent staff :

that signed the original proposal

Rémy Battesti

Jérôme Béard

Julien Billette

Mathilde Fouché (INLN Nice)

Paul Frings

Laurent Pinard (LMA Lyon)

Carlo Rizzo

carlo.rizzo@lncmi.cnrs.fr

PhD students :

Alice Rivère (2014- 2017)

+ 2 years of PostDoc contract thanks to ANR

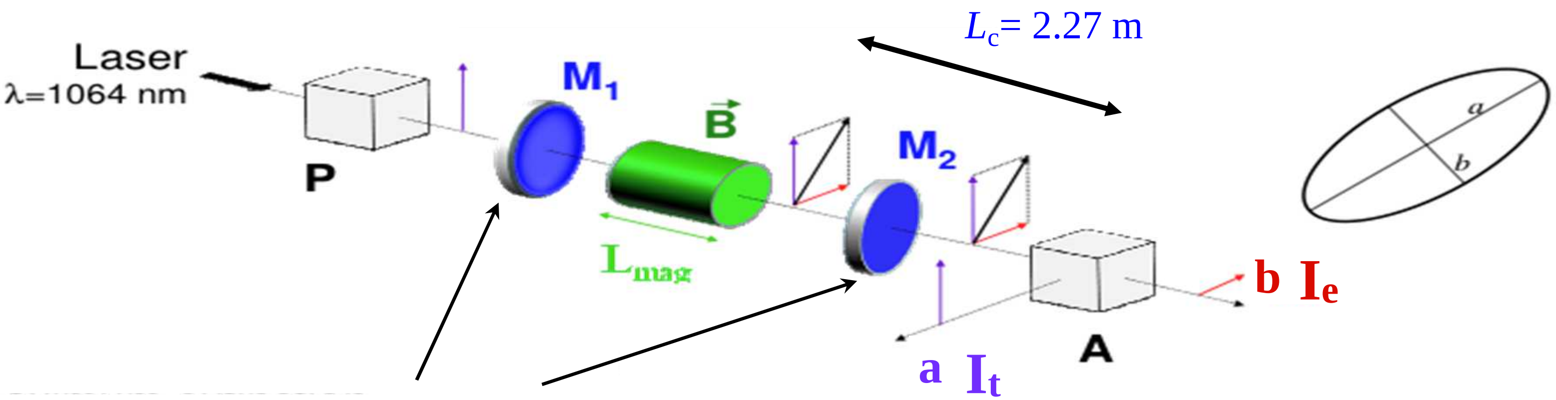
Michael Hartman

(past LIGO member)

+

Technical staff of LNCMI and LMA (cryogenics, mechanics, electronics, coils, generator, mirror fabrication)

❑ Ellipticity measurement : BMV experiment



Fabry Perot cavity

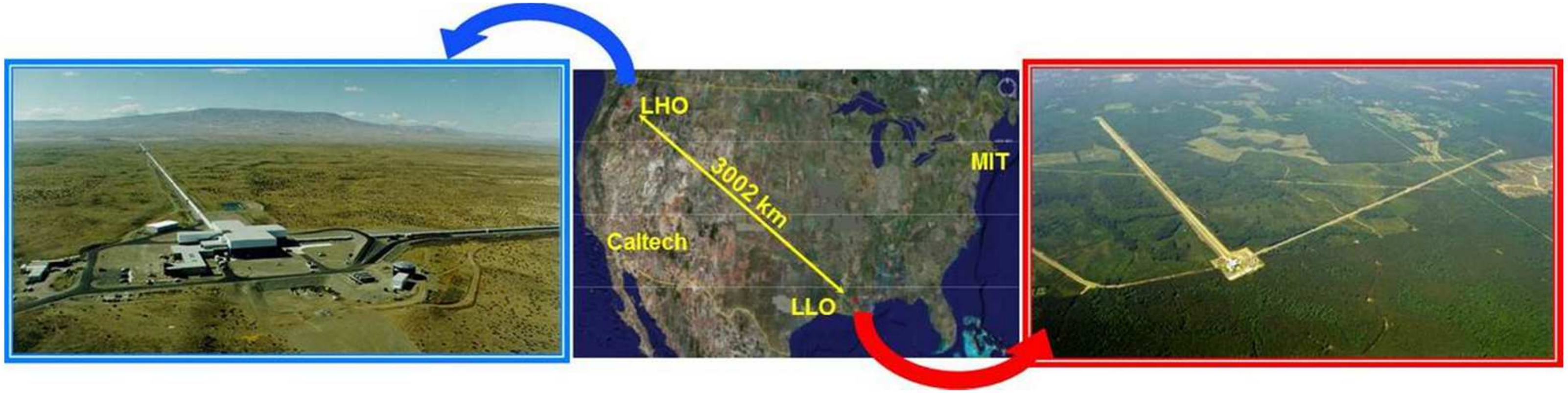
Very high magnetic field
+
Very precise optical measurements

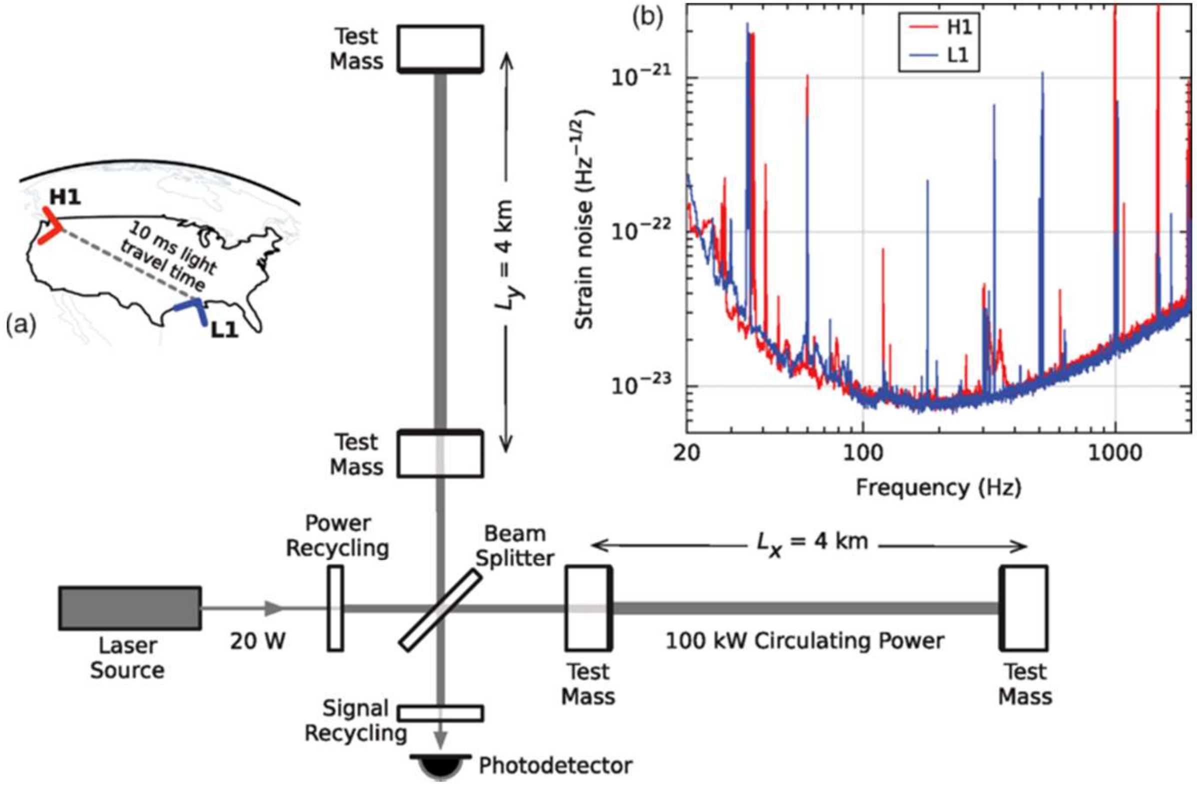
- Ellipticity to be measured :

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

$F \simeq 450\ 000$ $\longrightarrow$ light trapped for ~ 300 Km in the magnetic field !

LIGO





10^{-24} ?!

Same order of magnitude of G.W. dephasing !

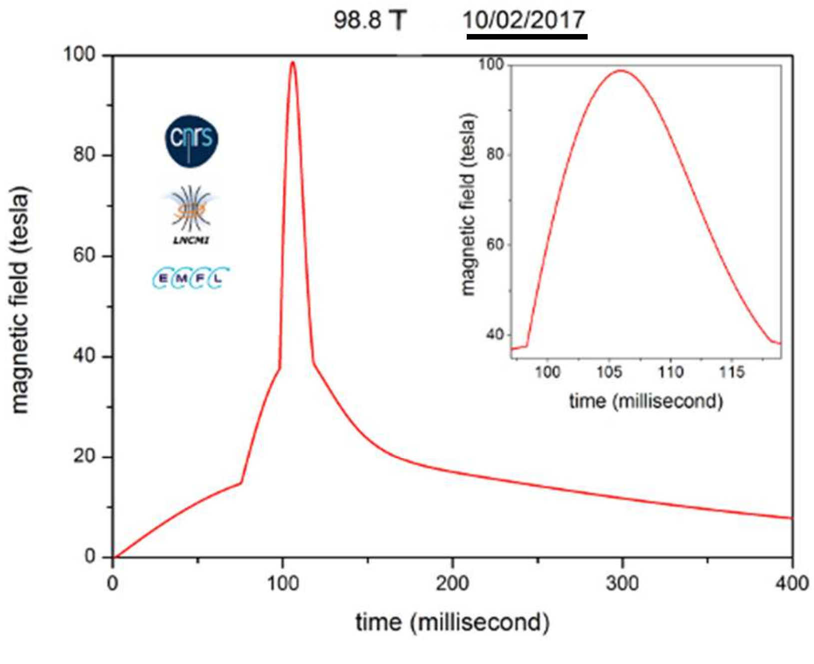
Same kind of optical Instrument !

G.W. : separate arm interferometer
BMV : polarization interferometer

Laboratoire National des Champs Magnétiques Intenses - Toulouse

LNCMI breaks the European record of non destructive pulsed magnetic field

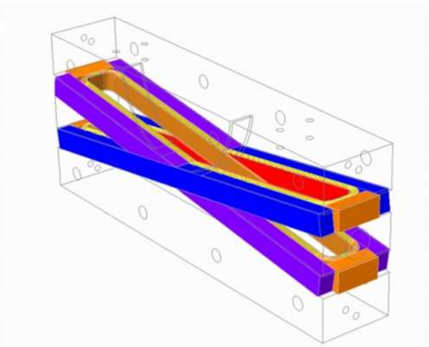
New european record of magnetic pulse 98.8 T

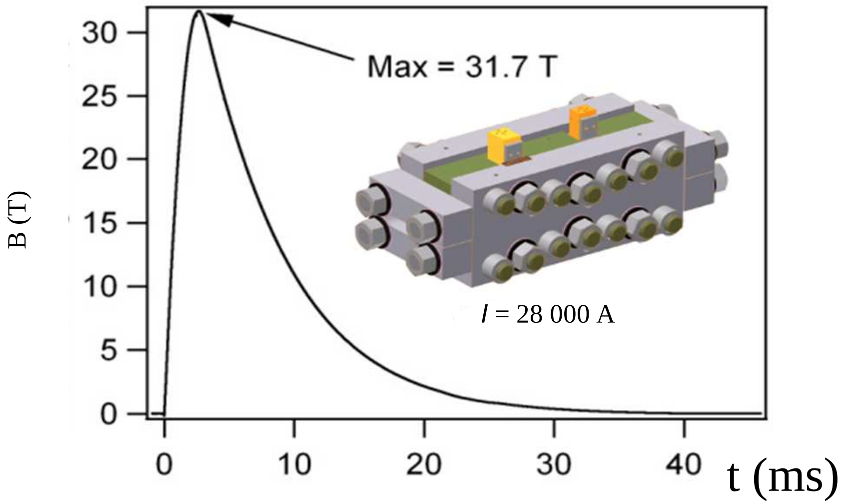


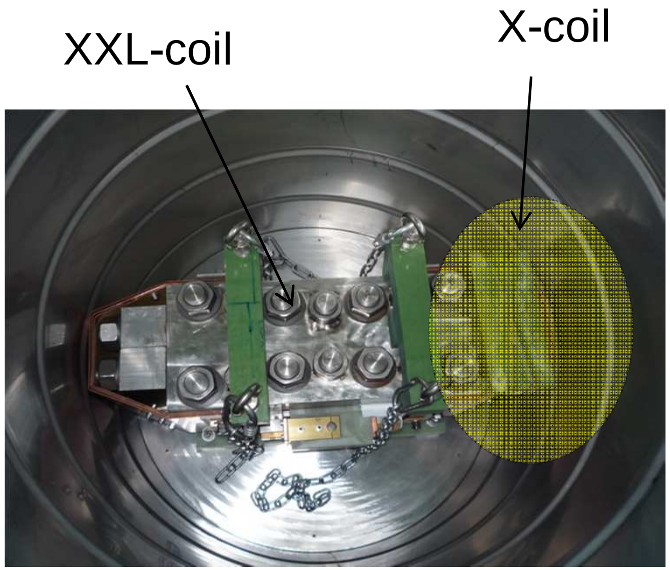
Faraday configuration : B field parallel to the axis

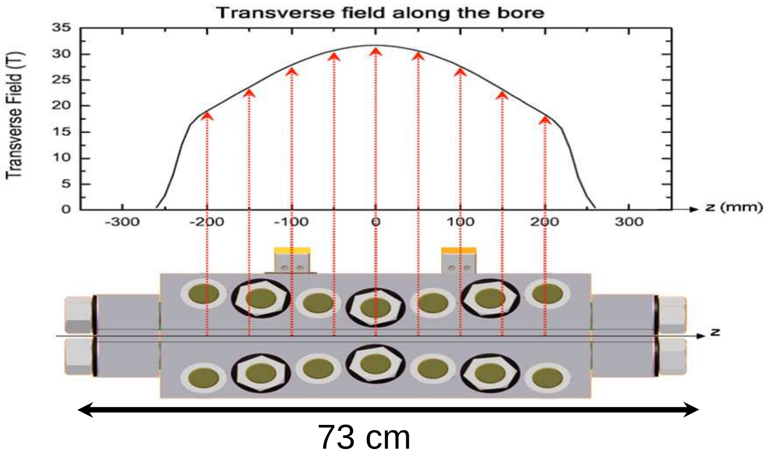
Magnetic field : XXL-Coils

❑ Higher B^2L (300 T^2m)



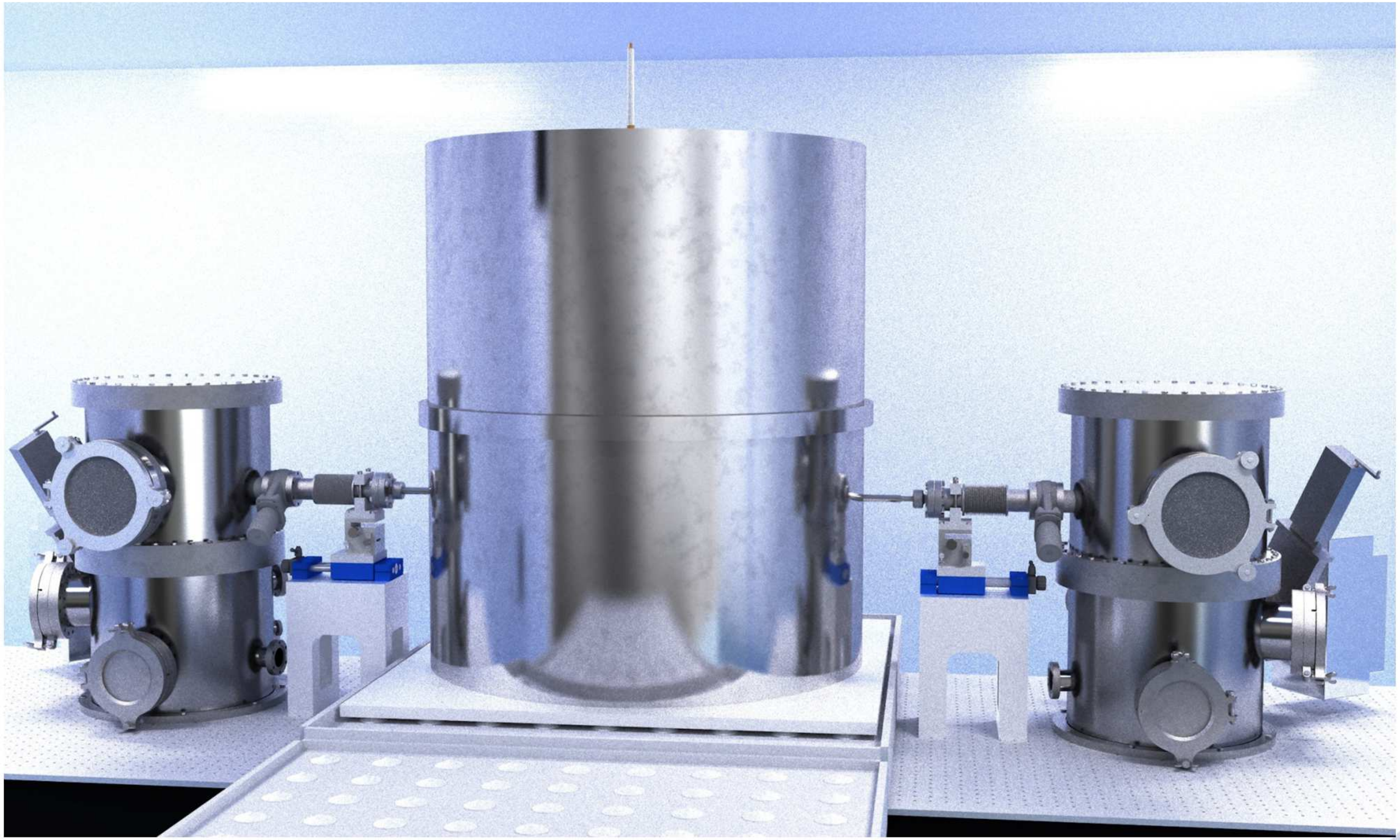






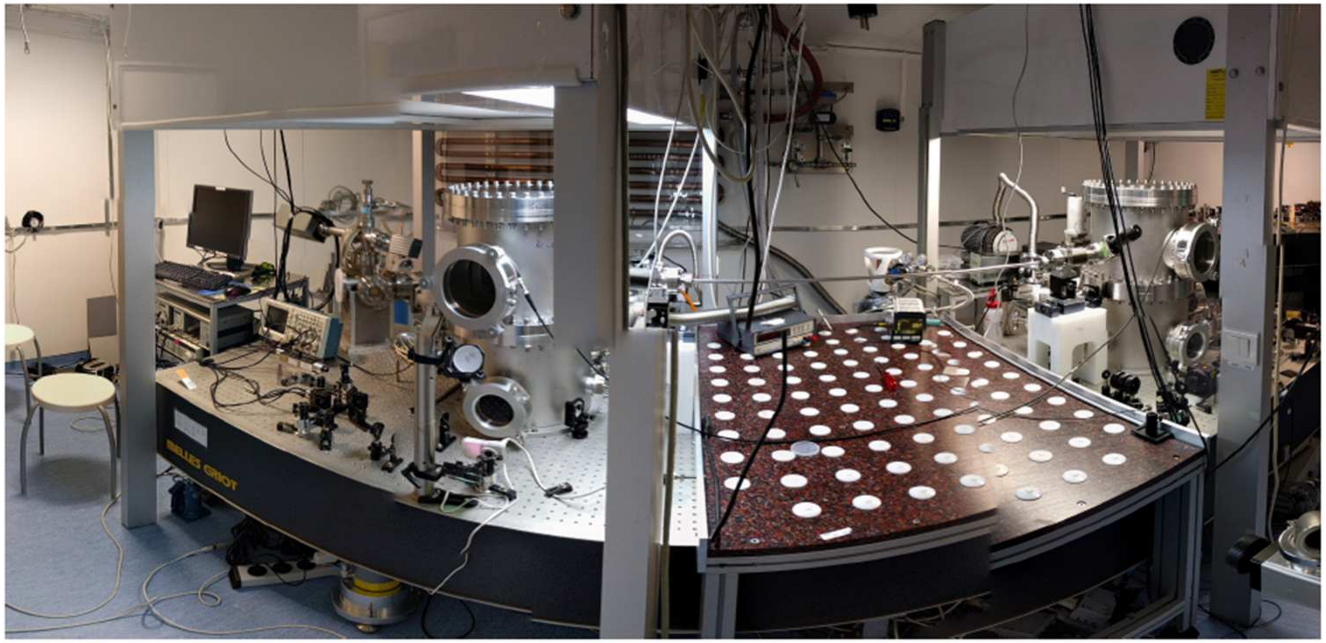
$I = 36\ 000A$

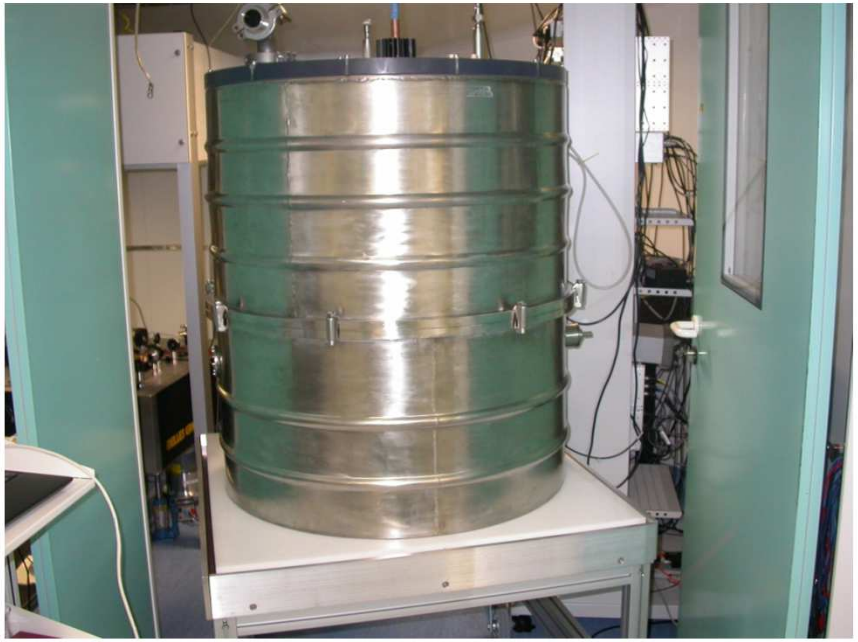
BMV.II



3D view

The real thing !



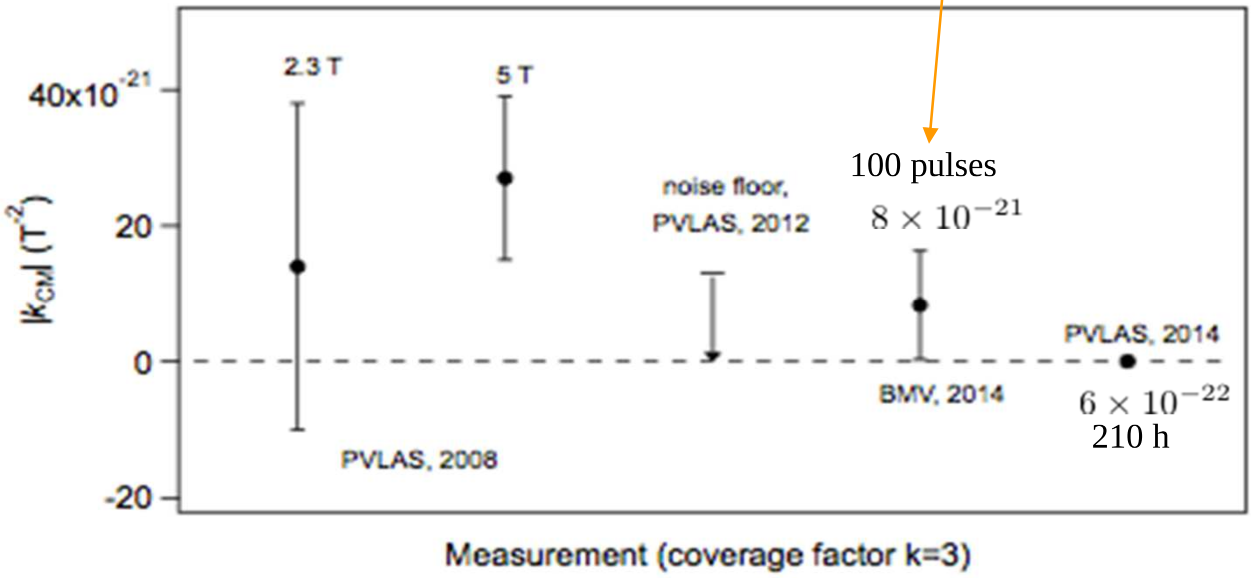


The cryostat entering in the clean room

The race for the Cotton Mouton effect in vacuum

$$k_{CM} = (8.3 \pm 8.0) \times 10^{-21}\ \mathrm{T}^{-2}$$

BMV last result



Last results (2016):
PVLAS is heading again !
A factor 20 from goal !

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)

BMV 2014 : A. Cadène *et al*, Eur. Phys. J. D, **68**, number 1 (2014)

PVLAS 2014 : F. Della Valle *et al*, Phys. Rev. D 90, 092003 (2014).

+ OVAL Tokyo
+ Q&A Taiwan
+ OSQAR CERN
+ Very intense laser sources …

Astrophysical evidence !?

Maybe, if you assume the values of the star parameters.

Evidence for vacuum birefringence from the first optical polarimetry measurement of the isolated neutron star RX J1856.5−3754*

R. P. Mignani[1,2]†, V. Testa[3], D. González Caniulef[4], R. Taverna[5], R. Turolla[5,4], S. Zane[4], K. Wu[4]

[1] INAF - Istituto di Astrofisica Spaziale e Fisica Cosmica Milano, via E. Bassini 15, 20133, Milano, Italy
[2] Janusz Gil Institute of Astronomy, University of Zielona Góra, Lubuska 2, 65-265, Zielona Góra, Poland
[3] INAF - Osservatorio Astronomico di Roma, via Frascati 33, 00040, Monteporzio, Italy
[4] Mullard Space Science Laboratory, University College London, Holmbury St. Mary, Dorking, Surrey, RH5 6NT, UK
[5] Dipartimento di Fisica e Astronomia, Universitá di Padova, via Marzolo 8, 35131 Padova, Italy

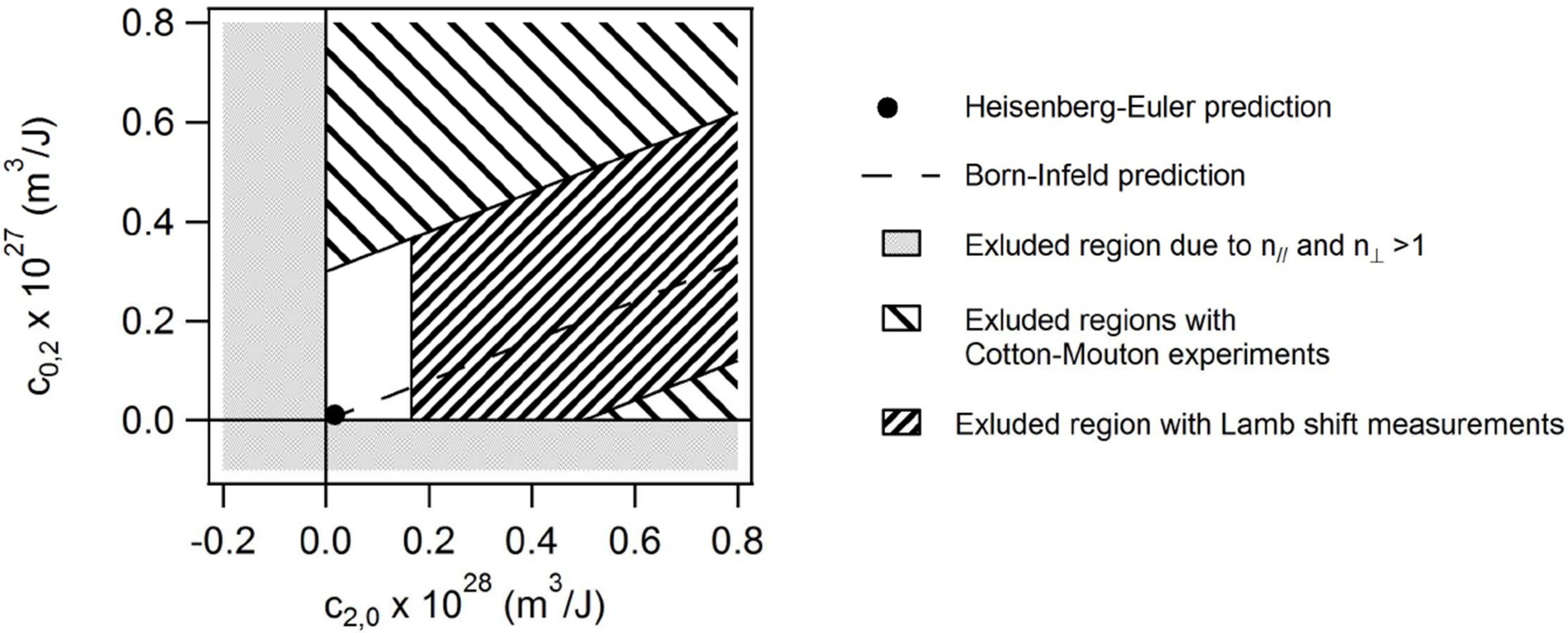
Mignani *et al.*, MNRAS, **465**, 492 (2016)

Pour Carlo Rizzo, il s'agit d'une belle association entre physique et astrophysique. « *L'inconvénient des observations astrophysiques et que nous ne maîtrisons pas les conditions comme en laboratoire.* » Il tente donc avec son équipe de détecter cet effet sur Terre à l'aide d'aimants pulsés dont l'intensité atteint quelques dizaines de teslas. Cela permettrait de comparer finement théorie et expérience. **Sylvain Guilbaud**

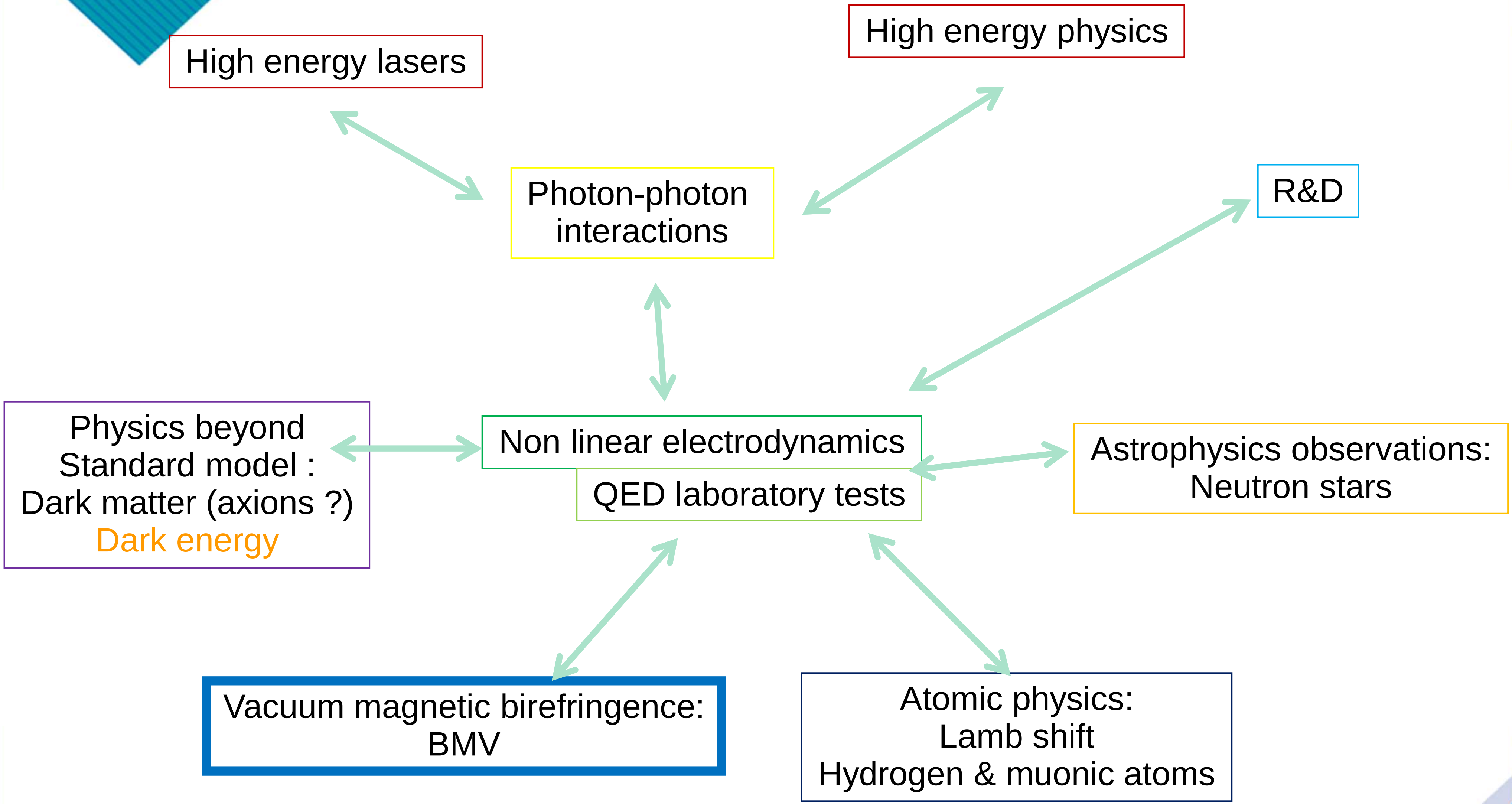
24 · La Recherche | Février 2017 · N°520

The press is getting interested !

Looking to all that with a wider approach than Heisenberg – Euler QED :

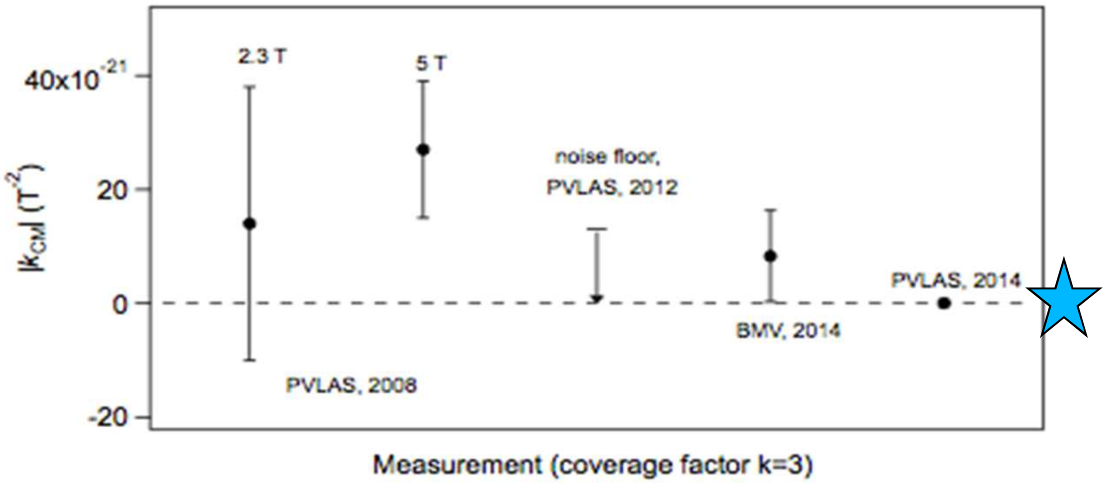


General CONCLUSION



BMV CONCLUSION

We are in the race !



BMV 2018 ?

We are working hard for that

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EUROPEAN ORGANISATION FOR NUCLEAR RESEARCH (CERN)

Submitted to: Nature Physics

CERN-EP-2016-316
February 7, 2017

Evidence for light-by-light scattering in heavy-ion collisions with the ATLAS detector at the LHC

The ATLAS Collaboration

Light-by-light scattering ($\gamma\gamma \rightarrow \gamma\gamma$) is a quantum-mechanical process that is forbidden in the classical theory of electrodynamics. This reaction is accessible at the Large Hadron Collider thanks to the large electromagnetic field strengths generated by ultra-relativistic colliding lead (Pb) ions. Using 480 μb^{-1} of Pb+Pb collision data recorded at a centre-of-mass energy per nucleon pair of 5.02 TeV by the ATLAS detector, the ATLAS Collaboration reports evidence for the $\gamma\gamma \rightarrow \gamma\gamma$ reaction. A total of 13 candidate events are observed with an expected background of 2.6 ± 0.7 events. After background subtraction and analysis corrections, the fiducial cross section of the process Pb+Pb ($\gamma\gamma$) $\rightarrow$ Pb$^{(*)}$+Pb$^{(*)}$ $\gamma\gamma$, for photon transverse energy $E_T > 3$ GeV, photon absolute pseudorapidity $|\eta| < 2.4$, diphoton invariant mass greater than 6 GeV, diphoton transverse momentum lower than 2 GeV and diphoton acoplanarity below 0.01, is measured to be 70 ± 24 (stat.) $\pm$ 17 (syst.) nb, which is in agreement with Standard Model predictions.

Light by light scattering also observed for the first time ?!

In competitions with experiment at high power lasers