Optical Polarimetry for the Magnetic Birefringence of Vacuum

Federico Della Valle
Dip. di Scienze Fisiche, della Terra e dell'Ambiente – Università di Siena (Italy)
INFN – Sezione di Pisa (Italy)

Orosei – 30 Aprile 2019

Summary

- Physics case
- Opto-polarimetric detection scheme
- PVLAS experimental set-up
- Latest results
- Prospects: the VMB@CERN proposal
- Conclusions

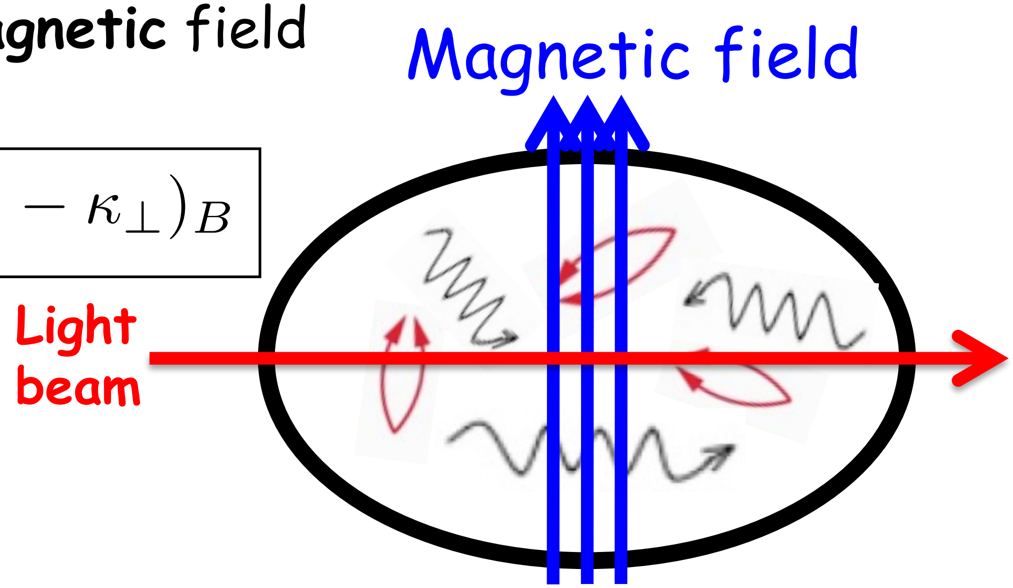
Light propagation in an external field

- **Experimental study of the structure and the nature of the quantum vacuum**
- General method:
  - **Perturb** the vacuum with an **external field**
  - **Probe** the perturbed vacuum with a **polarized light beam**

Anisotropy of the index of refraction of vacuum induced by an external **magnetic** field

$$\Delta\tilde{n}_{\text{vacuum}} = (n_{\parallel} - n_{\perp})_B + i(\kappa_{\parallel} - \kappa_{\perp})_B$$

$$n_{\text{media}} = \frac{c}{v_{\text{light}}}$$



Light by light scattering

H. Euler and B. Kockel (1935): an effective Lagrangian density describing electromagnetic interactions in the presence of the virtual electron-positron sea discussed a few years before by Dirac:

$$\mathcal{L}_{EK} = \frac{1}{2\mu_0}\left(\frac{E^2}{c^2} - B^2\right) + \\ + \frac{A_e}{\mu_0}\left[\left(\frac{E^2}{c^2} - B^2\right)^2 + 7\left(\frac{\mathbf{E}}{c}\cdot\mathbf{B}\right)^2\right] + \ldots$$

$$A_e = \frac{2}{45\mu_0}\frac{\alpha^2\hbar^3}{m_e^4 c^5} = 1.32 \times 10^{-24}\ \mathrm{T}^{-2}$$

H Euler and B Kockel, *Naturwissenschaften* **23**, 246 (1935)
W Heisenberg and H Euler, *Z. Phys.* **98**, 714 (1936)
H Euler, *Ann. Phys.* **26**, 398 (1936)
V Weisskopf, *Mat.-Fis. Med. Dan. Vidensk. Selsk.* **14**. 6 (1936)
See also: J. Schwinger, *Phys. Rev.*, **82**, 664 (1951)

Non-linear behaviour of Electromagnetism in vacuum

Index of refraction

Linearly polarized light propagating through a transverse magnetic field

$$\mathbf{D} = \frac{\partial \mathcal{L}_{\mathrm{EK}}}{\partial \mathbf{E}} \qquad \mathbf{H} = \frac{\partial \mathcal{L}_{\mathrm{EK}}}{\partial \mathbf{B}}$$

$$\mathbf{D} = \epsilon_0 \mathbf{E} + \epsilon_0 A_e \left[4\left(\frac{E^2}{c^2} - B^2\right)\mathbf{E} + 14\,(\mathbf{E}\cdot\mathbf{B})\,\mathbf{B} \right]$$

$$\mathbf{H} = \epsilon_0 \frac{\mathbf{B}}{\mu_0} + \frac{A_e}{\mu_0}\left[4\left(\frac{E^2}{c^2} - B^2\right)\mathbf{B} + 14\left(\frac{\mathbf{E}}{c}\cdot\mathbf{B}\right)\frac{\mathbf{E}}{c} \right]$$

Light propagation is still described by Maxwell's equations in media but these are no longer linear due to Euler-Kockel correction.

The superposition principle no longer holds.

$$\epsilon_{\|}^{(\mathrm{EK})} = 1 + 10 A_e B_{\mathrm{ext}}^2 \qquad \epsilon_{\perp}^{(\mathrm{EK})} = 1 - 4 A_e B_{\mathrm{ext}}^2$$

$$\mu_{\|}^{(\mathrm{EK})} = 1 + 4 A_e B_{\mathrm{ext}}^2 \qquad \mu_{\perp}^{(\mathrm{EK})} = 1 + 12 A_e B_{\mathrm{ext}}^2$$

$$n_{\|}^{(\mathrm{EK})} = 1 + 7 A_e B_{\mathrm{ext}}^2 \qquad n_{\perp}^{(\mathrm{EK})} = 1 + 4 A_e B_{\mathrm{ext}}^2$$

Vacuum magnetic birefringence

$n_{\parallel,\perp} > 1$

$n_{\parallel} \neq n_{\perp}$

→ $v \neq c$

anisotropy

→ A_e can be determined by measuring the magnetic birefringence of vacuum.

$$\mathrm{O}\left(\alpha^2\right): \qquad \Delta n_B = 3A_e B_{\mathrm{ext}}^2$$

$$\mathrm{O}\left(\alpha^3\right): \qquad \Delta n_B = 3A_e B_{\mathrm{ext}}^2 \left(1 + \frac{25}{4\pi}\alpha\right)$$

1.5%

$$\Delta n_B = (4.031699 \pm 0.000002) \times 10^{-24} \left(\frac{B_{\mathrm{ext}}}{1\ \mathrm{T}}\right)^2$$

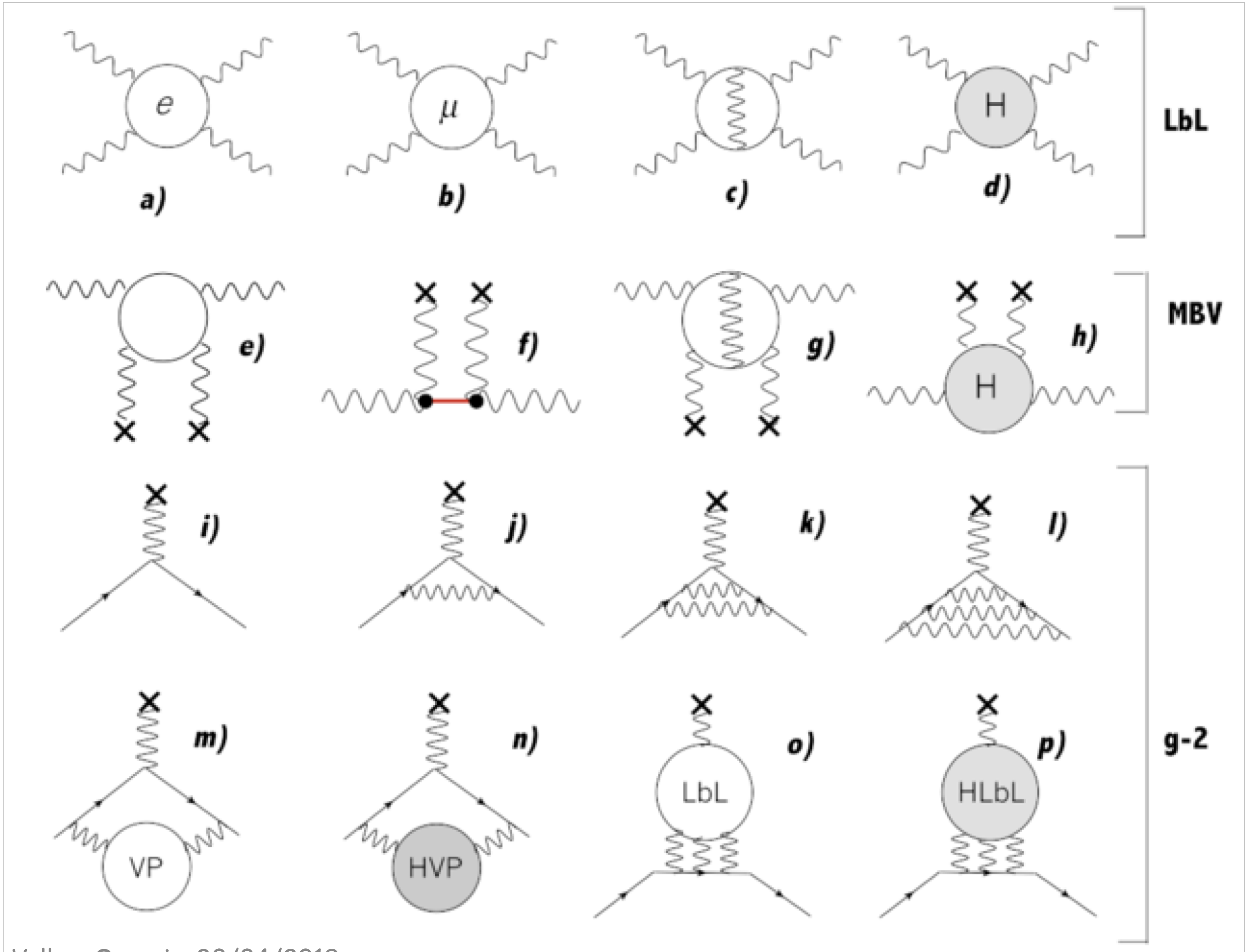
O(α^4), O(α^5) ? Also a theoretical challenge

$$\Delta n_B = 2.5 \times 10^{-23} \quad @ \quad 2.5\ \mathrm{T}$$

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

The QED bestiary

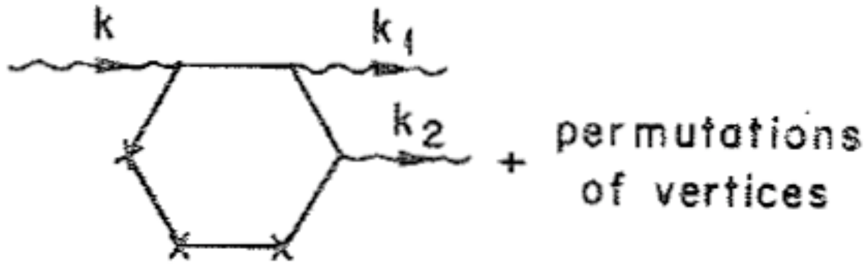
Feynman, Schwinger, Tomonaga 1946-1951



Index of refraction: imaginary part

$$\tilde{n}_{\text{vacuum}} = n_B + i\kappa_B$$

S. Adler (1971) calculated the QED absorption related to photon splitting



$$\alpha_{\perp,\parallel} = \frac{4\pi}{\lambda}\kappa_{\perp,\parallel} = (0.51, 0.24)\left(\frac{\hbar\omega}{m_e c^2}\right)^5 \left(\frac{B}{B_{\text{cr}}}\right)^6 \ \text{cm}^{-1}$$

$$B_{\text{cr}} = \frac{m_e^2 c^2}{e\hbar} = 4.41 \times 10^9\ \text{T}$$

$$\Delta\kappa_B = -2.5 \times 10^{-92} \left(\frac{1\ \mu\text{m}}{\lambda}\right)^4 \left(\frac{B}{1\ \text{T}}\right)^6$$

Unmeasurably small

Other QED tests:

- Microscopic tests
  - QED tests in bound systems – Lamb shift, Delbrück scattering
  - QED tests with charged particles – (g-2)
  - High energy light-by-light scattering (**ATLAS**, this workshop)

⋮

- Macroscopic tests
  - Casimir effect (photon zero point fluctuations)
  - MBV of magnetars (**Mignani et al**, this workshop)
  - Recent proposals:
  - Refraction of light by light (**Sarazin et al**, this workshop)
  - Direct light-by-light scattering (**King and Heinzl**, this workshop)

⋮

D Bernard et al, EPJD **10**, 141 (2000)
Lündstrom, Tommasini…

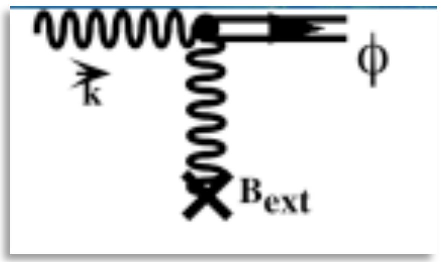
QED laboratory tests with only photons in the initial and final states are still missing

Axion-like particles (ALP)

Extra Lagrangian density terms to include contributions from hypothetical **neutral light particles weakly interacting with two photons**

	pseudoscalar	scalar (e.g. chameleon)
g_a, g_s coupling constants	$L_a = g_a \phi_a \left(\vec{E}_\gamma \cdot \vec{B}_{ext} \right)$	$L_s = g_s \phi_s \left(\vec{B}_\gamma \cdot \vec{B}_{ext} \right)$

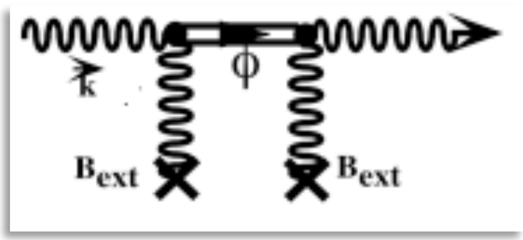
both interactions are polarization dependent



Absorption → rotation

$$x = \frac{L m_{a,s}^2}{4\omega}$$

$$|\Delta\kappa^{(\mathrm{ALP})}| = \kappa_{\parallel}^{a} = \kappa_{\perp}^{s} = \frac{2}{\omega L} \left(\frac{g_{a,s} B_{\mathrm{ext}} L}{4} \right)^2 \left(\frac{\sin x}{x} \right)^2$$



Dispersion → ellipticity

$$|\Delta n^{(\mathrm{ALP})}| = n_{\parallel}^{a} - 1 = n_{\perp}^{s} - 1 = \frac{g_{a,s}^2 B_{\mathrm{ext}}^2}{2 m_{a,s}^2} \left(1 - \frac{\sin 2x}{2x} \right)$$

Maiani L, Petronzio R, Zavattini E, Phys. Lett B **173**, 359 (1986)
Raffelt G and Stodolsky L Phys. Rev. D **37**, 1237 (1988)

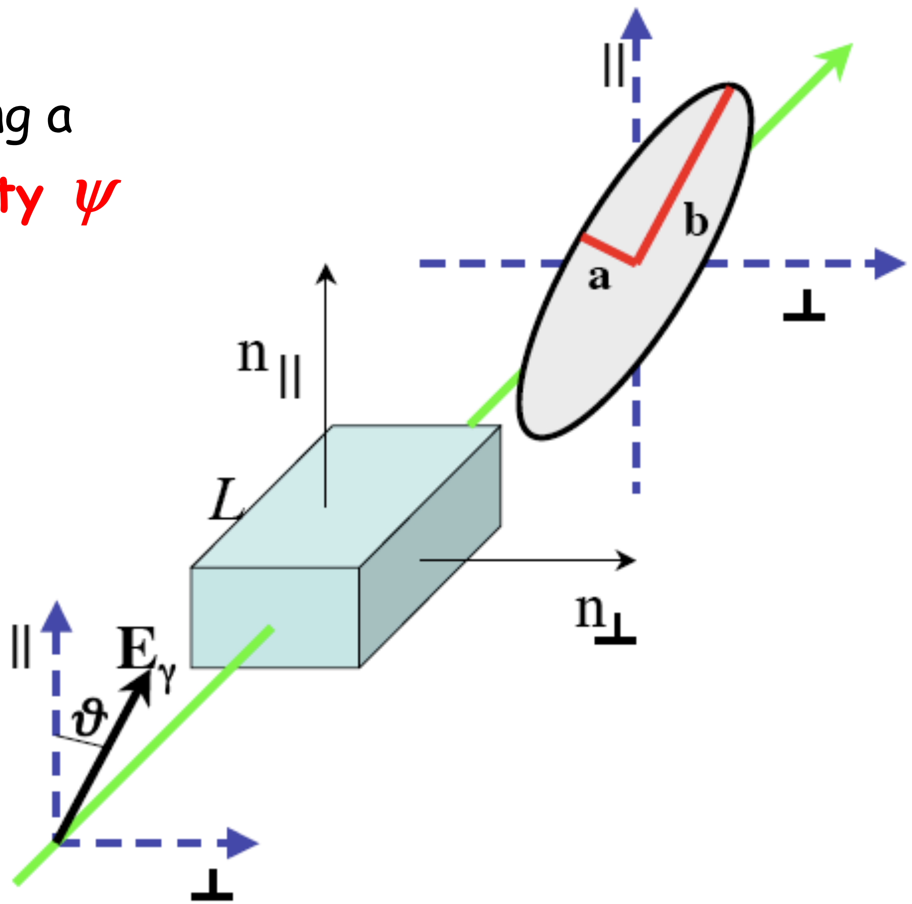
Linear birefringence

- The index of refraction (real part) is different for two orthogonal directions

$$\Delta n = n_{\parallel} - n_{\perp} \neq 0$$

- A linearly polarized light beam traversing a birefringent medium **acquires an ellipticity ψ**

$$\psi = \pm\frac{a}{b} = \pi\frac{L}{\lambda}\Delta n \sin 2\vartheta$$



QED vacuum magnetic birefringence
L = 1.64 m, λ = 1064 nm, B = 2.5 T

$$\Delta n_{QED} = 2.5\times10^{-23}$$

$$\psi_{QED} = 1.2\times10^{-16}$$

Linear dichroism

- The **extinction coefficient** is different for two orthogonal directions

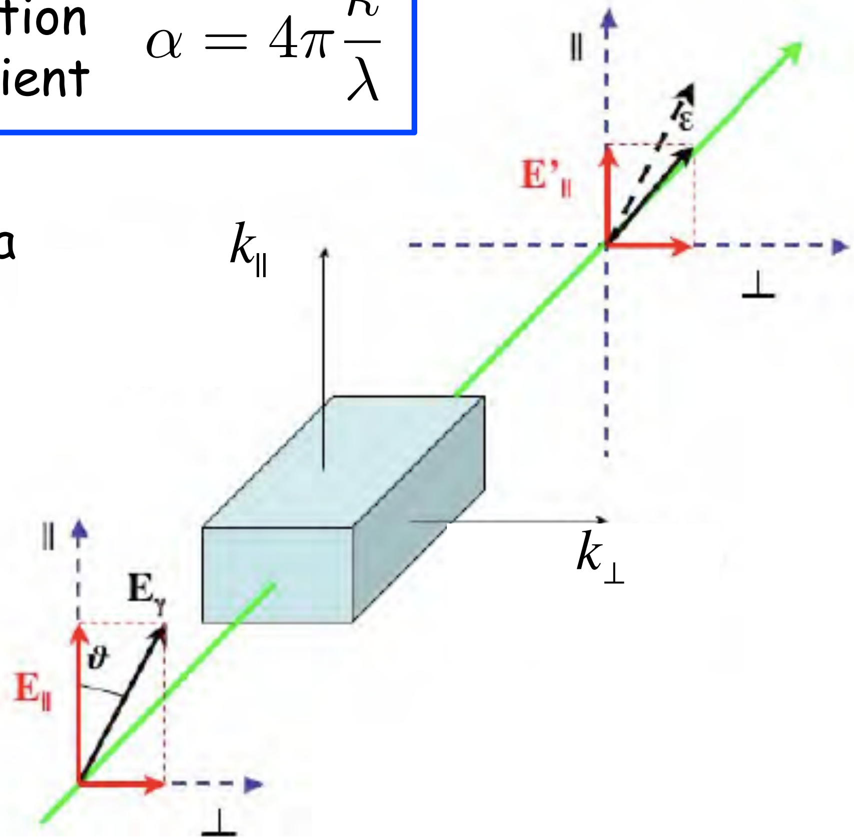
$$\tilde{n} = n + i\kappa$$

$$\Delta\kappa = \kappa_{\parallel} - \kappa_{\perp} \neq 0$$

Absorption coefficient $\alpha = 4\pi \frac{\kappa}{\lambda}$

A linearly polarised light beam traversing a dichroic medium **is rotated by an angle ε**

$$\varepsilon = \pi \frac{L}{\lambda} \Delta\kappa \sin 2\vartheta$$



QED vacuum magnetic photon splitting

L = 1.64 m, λ = 1064 nm, B = 2.5 T

Δk_{QED} = -5×10^{-91}

ε_{QED} = -2×10^{-83}

Larger effects might come from axion-like particles

Sensitive magnetic polarimetry

Volume 85B, number 1 PHYSICS LETTERS 30 July 1979

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

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

In this letter a method of measuring the birefringence induced in vacuum by a magnetic field is described: this effect is evaluated using the non-linear Euler–Heisenberg–Weisskopf lagrangian. The optical apparatus discussed here may detect an induced ellipticity on a laser beam down to 10^{-11}.

Emilio Zavattini
(1927 -2007)

- signal modulation; beat with a known effect for linearization
- high magnetic field *B*
- longest possible optical path *L*

Experimental strategies

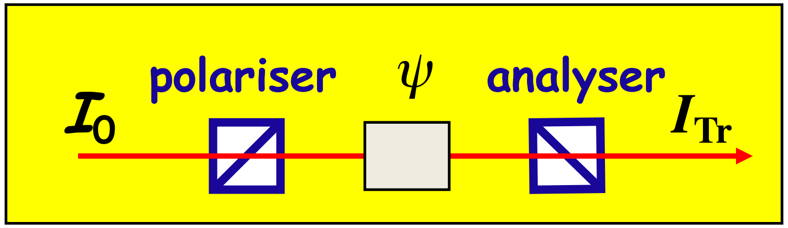
- **Signal modulation**
  Periodic change of the effect: modulate either field **intensity** (BFRT) or field **direction** (PVLAS, Q & A).
  Add a modulated ellipticity: **heterodyne detection**
  Pulsed magnets: (BMV, OVAL)
  Beat with a static effect: **homodyne detection**

- **High magnetic field *B***
  Superconductive magnets: (BFRT, PVLAS LNL)
  Electromagnets: (BMV, OVAL)
  Dipole permanent magnets: (PVLAS Ferrara, Q & A)
  long duty cycle; high frequency rotation (PVLAS reached 23 Hz)

- **Longest possible optical path *L***
  Multi-pass cavity: (BFRT)
  High-Q Fabry-Perot resonator: (BMV, OVAL, PVLAS, Q & A) largest optical path-length multiplication factor $\approx 5\times10^5$ (PVLAS Ferrara)

BFRT: R Cameron et al, PRD **47**, 3707 (1993)
PVLAS LNL: E Zavattini et al, PRD **77**, 032006 (2008)
M Bregant et al, PRD **78**, 032006 (2008)
Q & A: H-H Mei et al, MPLA **25**, 983 (2010)
BMV: A Cadène et al, EPJD **68**, 16 (2014)
OVAL: X Fan et al, EPJD **71**, 308 (2017)
PVLAS Ferrara: F Della Valle et al, EPJC **76**, 24 (2016)
G Zavattini et al, EPJC **78**, 585 (2018)

Heterodyne detection - ellipticity



$$I_{tr} = I_0\left[\sigma^2 + \psi^2\right]$$

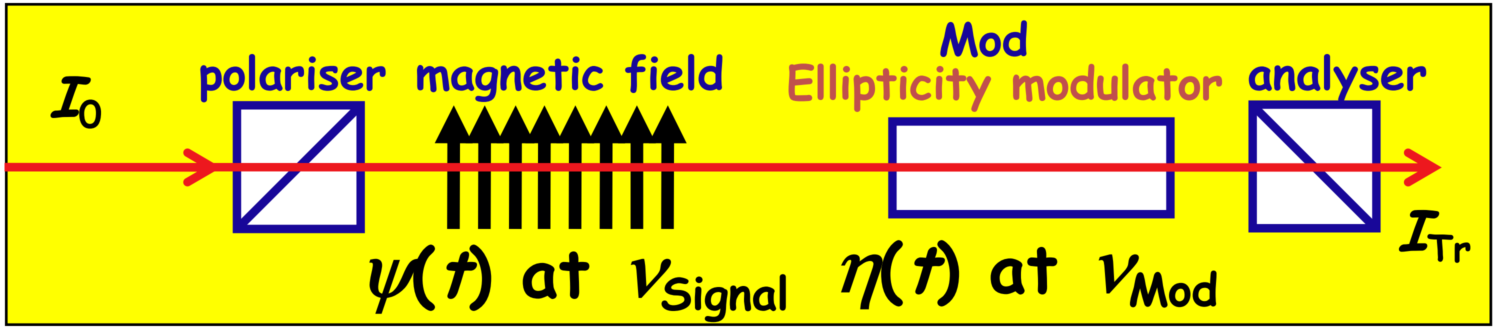
$\psi_{QED} = 1.2\times10^{-16}$

$\sigma^2 \approx 10^{-7}$–10^{-8}

static detection excluded

Signal modulated in time. Beat with a calibrated effect

- Signal linear in the ellipticity
- Smaller $1/f$ noise



$$I_{Tr} = I_0\left[\sigma^2 + \left(\psi(t) + \eta(t)\right)^2\right] = I_0\left[\sigma^2 + \left(\psi(t)^2 + \eta(t)^2 + 2\psi(t)\eta(t)\right)\right]$$

Main frequency components at $\nu_{Mod} \pm \nu_{Signal}$ (and $2\,\nu_{Mod}$)

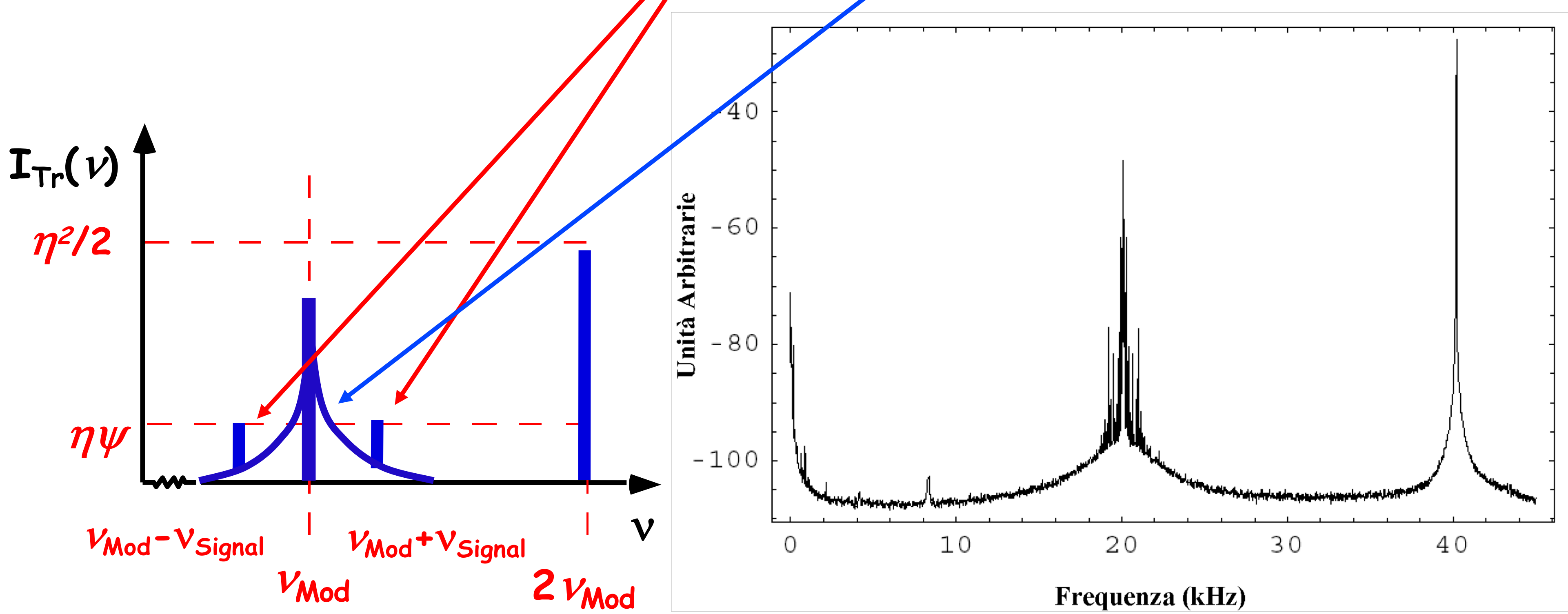
Signal frequency layout

Nearly static birefringences $\alpha_s(t)$ generate a $1/f$ noise centred at the carrier modulation frequency ν_{Mod}

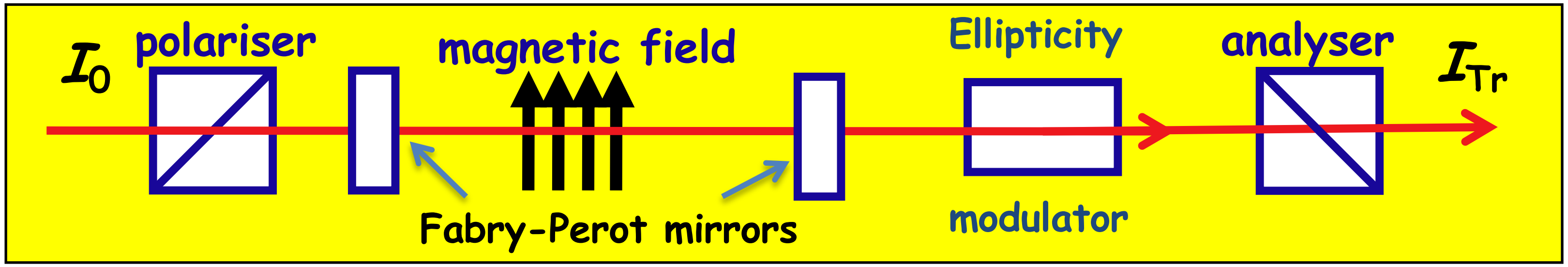
$$I_{Tr} = I_0\left[\sigma^2 + \left(\psi(t) + \eta(t) + \alpha_s(t)\right)^2\right]$$

$$= I_0\left[\sigma^2 + \left(\eta(t)^2 + 2\psi(t)\eta(t) + 2\alpha_s(t)\eta(t) + \ldots\right)\right]$$

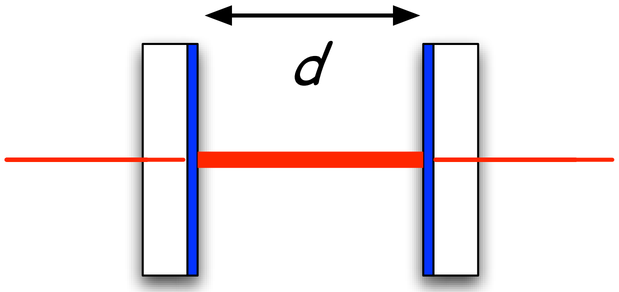
signal noise



Signal amplification: Fabry Perot cavity



Fabry-Perot: **resonant optical cavity** increasing the effective optical path.
Made of two mirror placed at a separation *d* which is an integer multiple of $\lambda/2$.
The laser is frequency-locked to the cavity using a feedback circuit.



cavity decay time

τ = 2.7 ms

Finesse

$$\mathcal{F} = \frac{\pi c \tau}{d}$$

Amplification

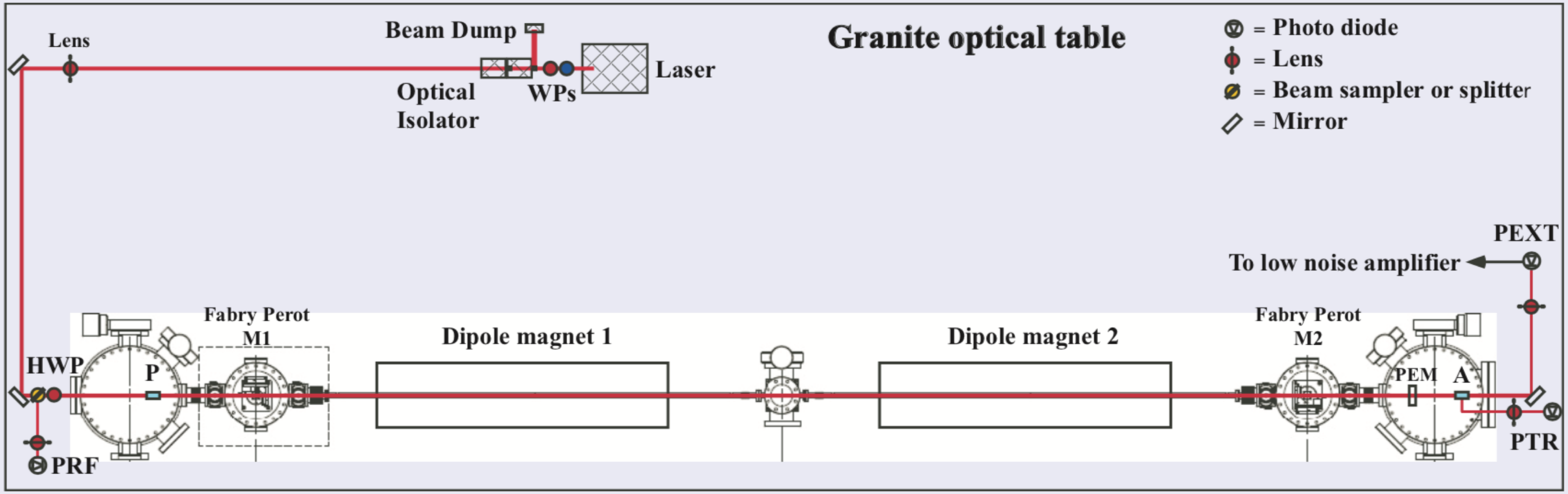
$$N = \frac{2\mathcal{F}}{\pi} \approx 5 \times 10^5$$

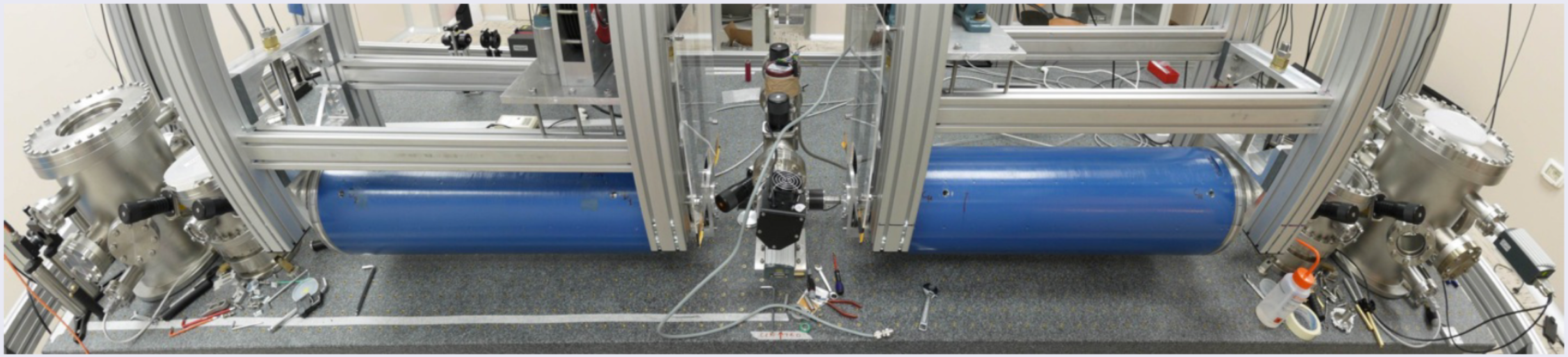
Vacuum magnetic birefringence:
L = 1.64 m, λ = 1064 nm, B = 2.5 T
N = 445000

$\Delta n_{QED} = 2.5 \times 10^{-23}$

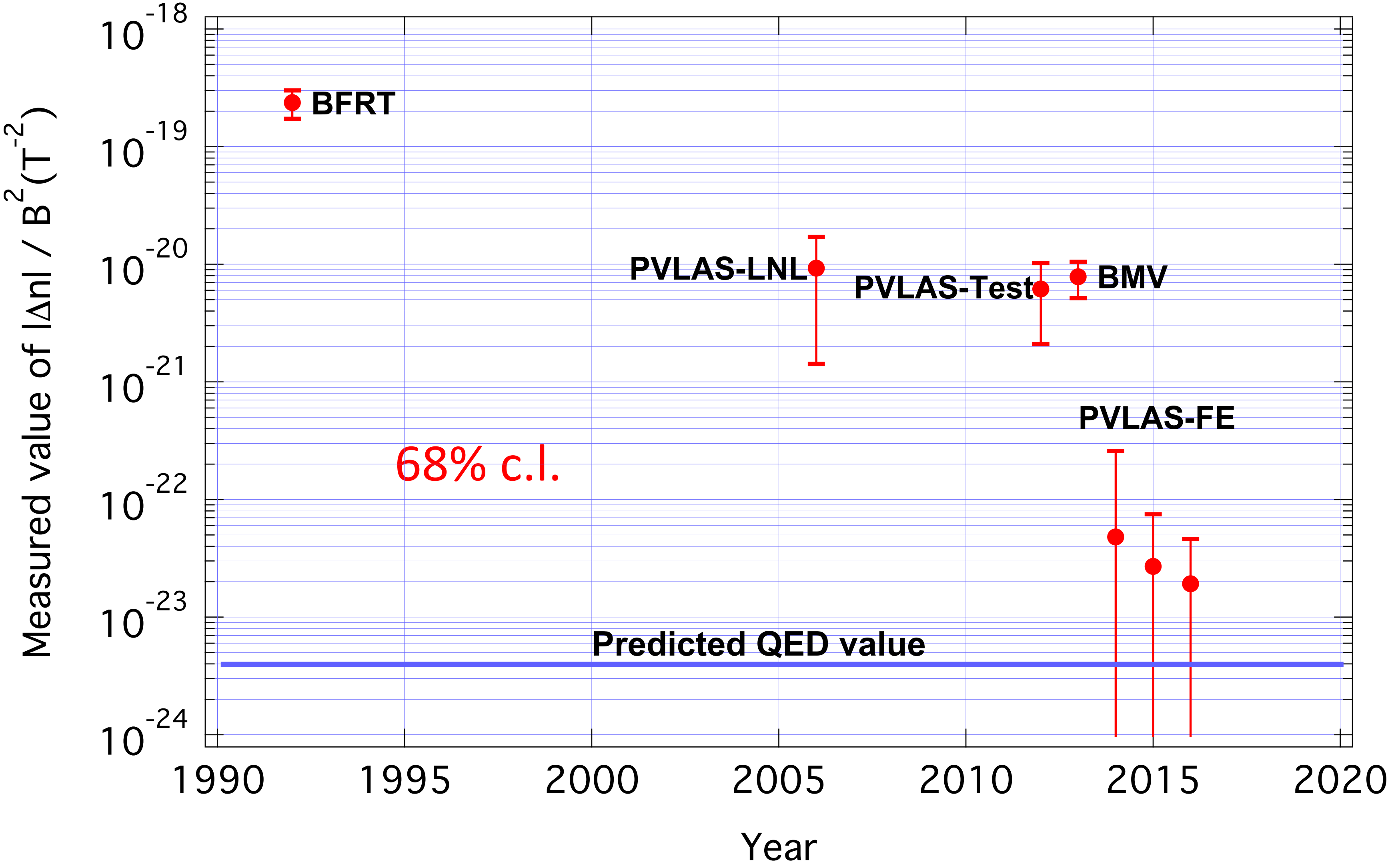
$N\psi_{QED} = 5.4 \times 10^{-11}$

The PVLAS apparatus





Timeline of vacuum birefringence



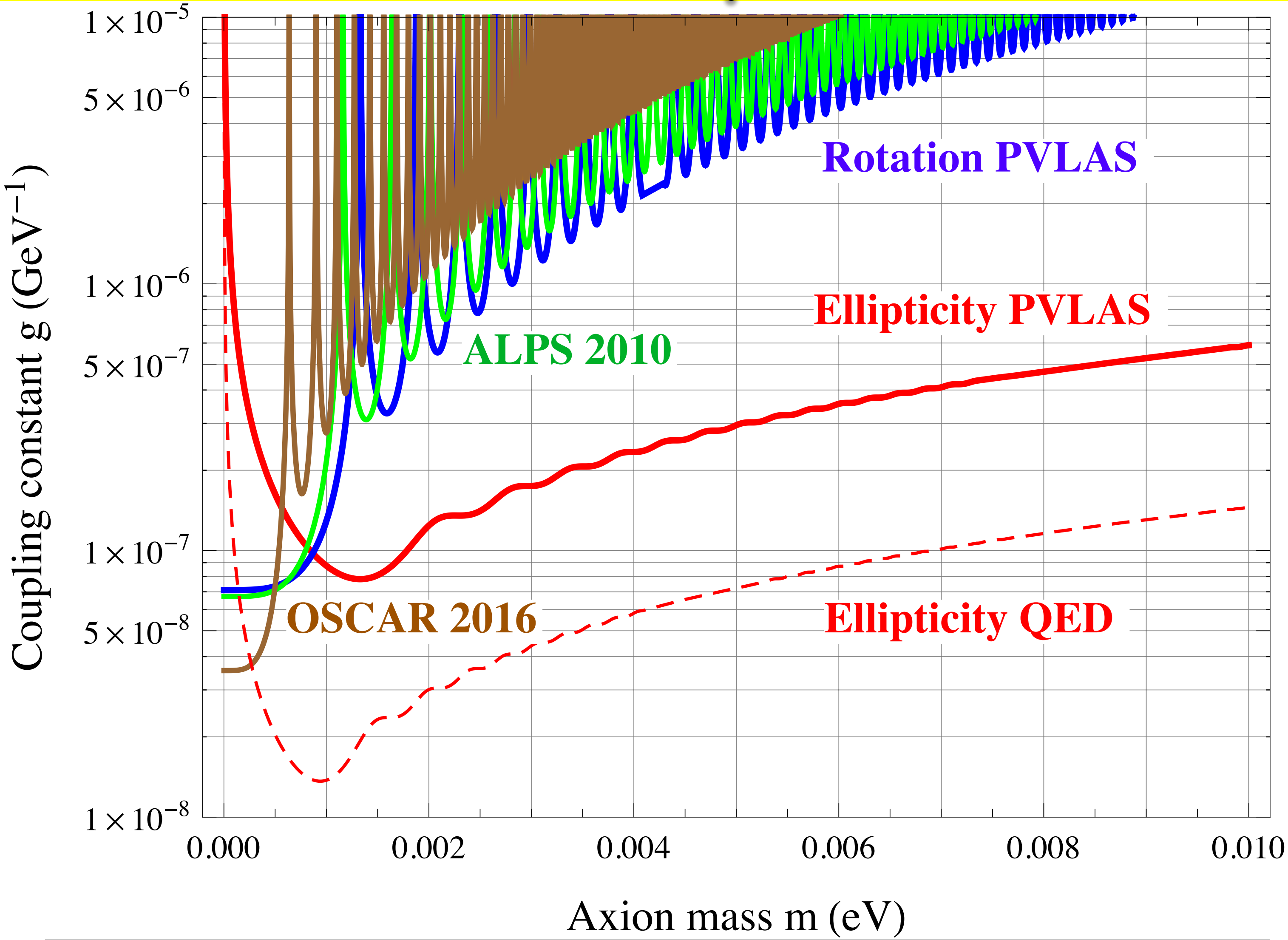
BFRT: R Cameron et al, PRD **47**, 3707 (1993)
PVLAS-LNL: E Zavattini et al, PRD **77**, 032006 (2008)
M Bregant et al, PRD **78**, 032006 (2008)
PVLAS-TEST: F Della Valle et al, NJP **15**, 053026 (2013)
BMV: A Cadène et al, EPJD **68**, 16 (2014)

$\Delta n_{PVLAS\text{-}2014} = \quad 4.0 \pm 20 \times 10^{-23}\ T^{-2}$ $\quad T_{2014} \approx 1 \times 10^6$ s $\quad$ F Della Valle et al, PRD **90**, 092003 (2014)

$\Delta n_{PVLAS\text{-}2015} = -\,2.4 \pm 4.8 \times 10^{-23}\ T^{-2}$ $\quad T_{2015} \approx 3 \times 10^6$ s $\quad$ F Della Valle et al, EPJC **76**, 24 (2016)

$\Delta n_{PVLAS\text{-}2016} = \quad 3.8 \pm 3.2 \times 10^{-23}\ T^{-2}$ $\quad T_{2016} \approx 5 \times 10^6$ s $\quad$ A Ejlli, PhD Thesis, 2017, unpublished

Axion-like particles

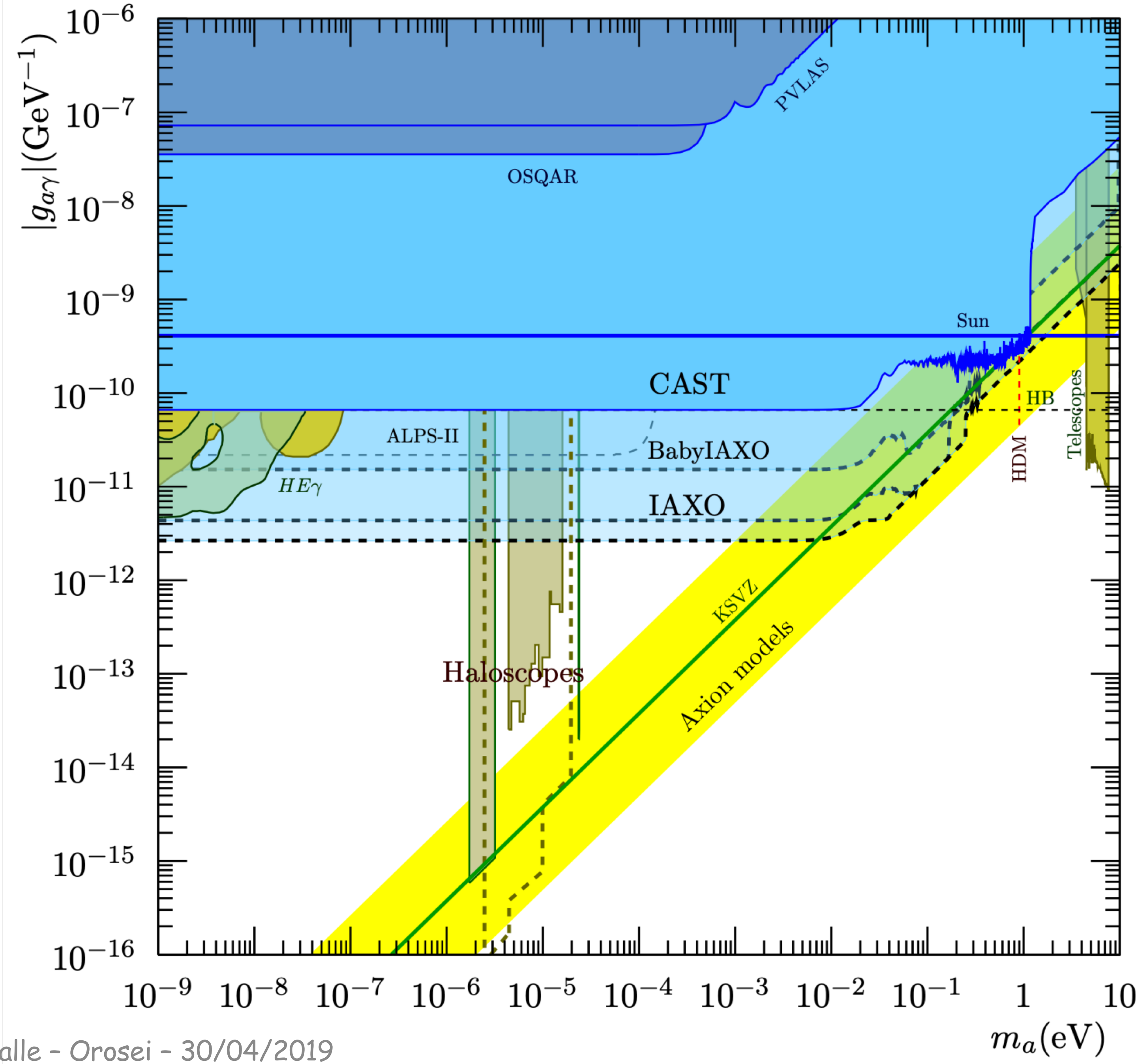


$$\Delta n^{(\mathrm{PVLAS})} = (-19 \pm 20) \times 10^{-23} \qquad @\ B = 2.5\ \mathrm{T}.$$

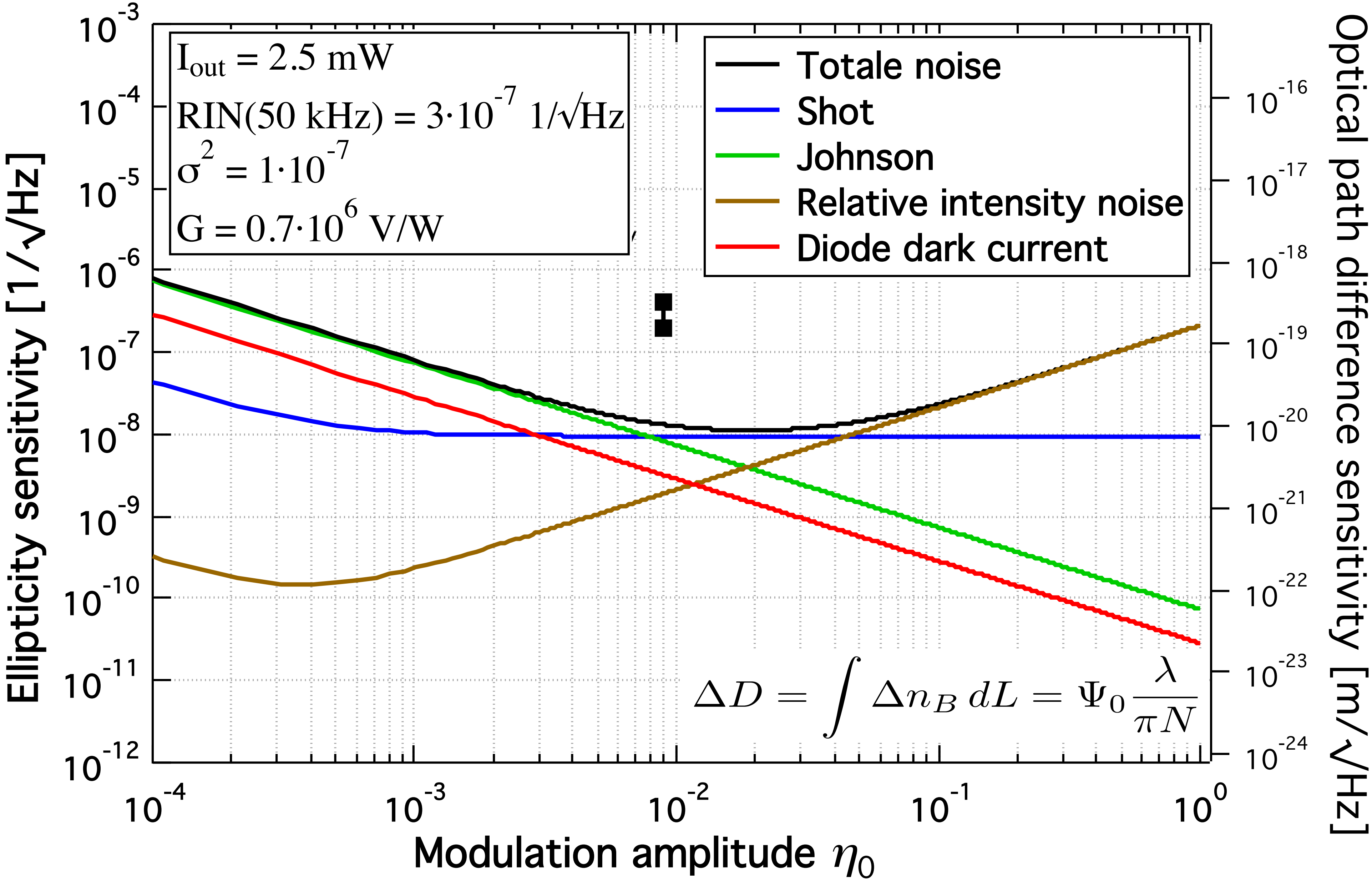
$$\Delta \kappa^{(\mathrm{PVLAS})} = (-24 \pm 30) \times 10^{-23} \qquad @\ B = 2.5\ \mathrm{T}$$

PVLAS is model independent

Armengaud et al, arXiv:1904.09155v1

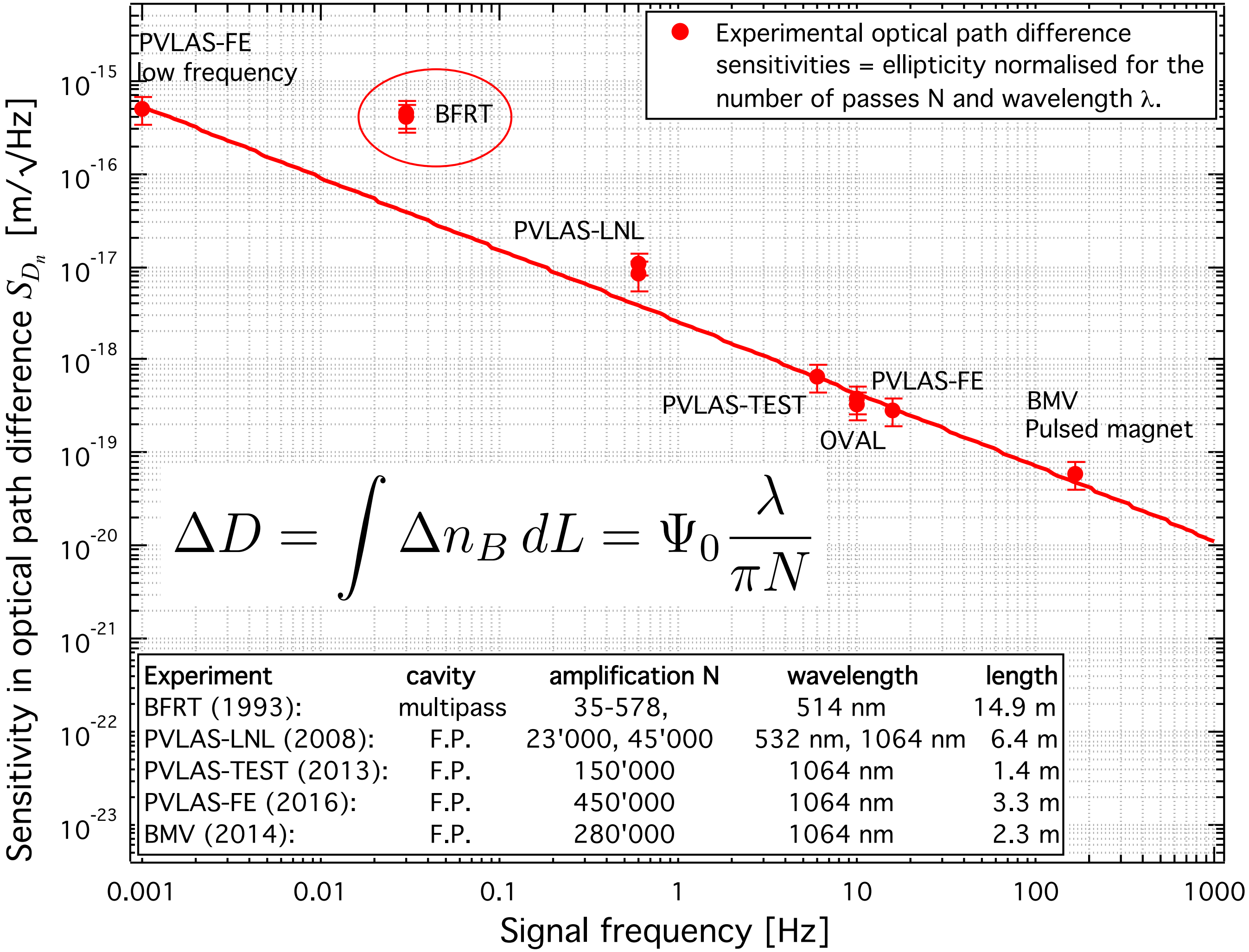


The sensitivity problem



Intrinsic noise?

Sensitivity in optical path difference ΔD between two perpendicular polarizations



$$\Delta D = \int \Delta n_B \, dL = \Psi_0 \frac{\lambda}{\pi N}$$

Experiment	cavity	amplification N	wavelength	length
BFRT (1993):	multipass	35-578,	514 nm	14.9 m
PVLAS-LNL (2008):	F.P.	23'000, 45'000	532 nm, 1064 nm	6.4 m
PVLAS-TEST (2013):	F.P.	150'000	1064 nm	1.4 m
PVLAS-FE (2016):	F.P.	450'000	1064 nm	3.3 m
BMV (2014):	F.P.	280'000	1064 nm	2.3 m

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PVLAS-FE: F Della Valle et al, EPJC **76**, 24 (2016)
G Zavattini et al, EPJC **78**, 585 (2018)

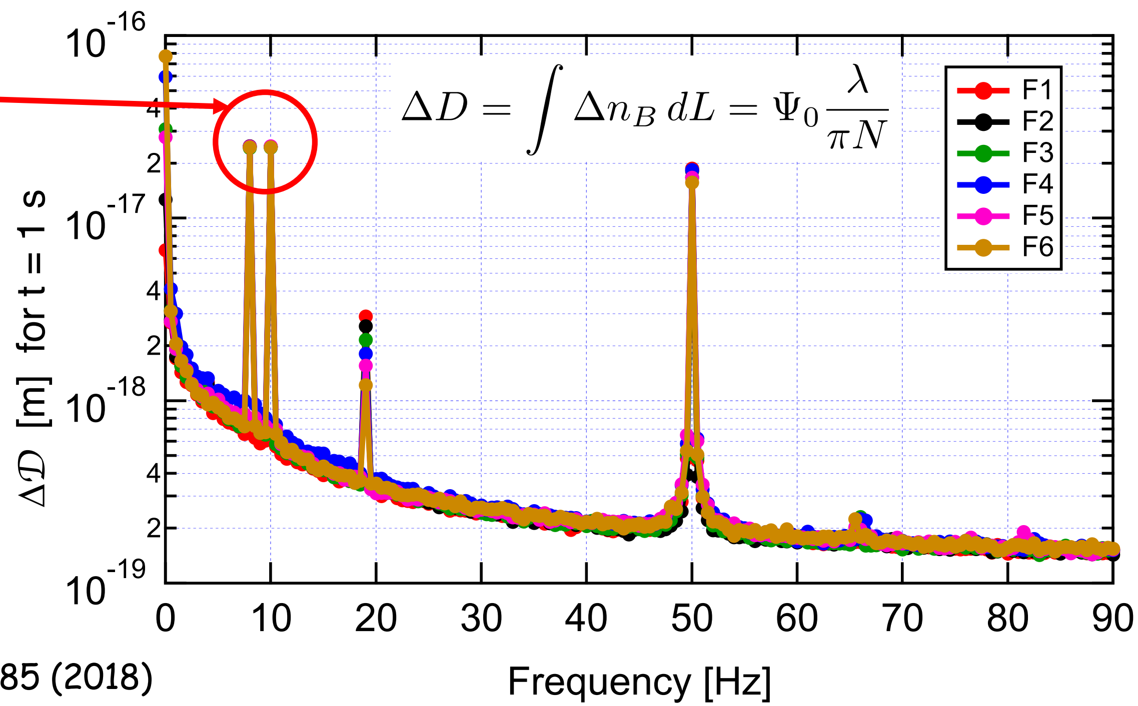
Updated graph from G. Zavattini et al. EPJC **76**, 294 (2016)

<u>Sensitivity in ΔD does not depend on finesse</u>

Intrinsic noise

- Measured ellipticity noise and Cotton-Mouton signal as a function of the finesse
- Introduced controlled extra losses p ≈ 10^{-5} in the cavity by clipping the beam
- Finesse range (F1 – F6): 250'000 – 690'000

Cotton-Mouton signals



G Zavattini et al, EPJC **78**, 585 (2018)

Noise and Cotton-Mouton ΔD signals are independent of the finesse

How to beat the noise

- Increase the frequency of the signal by rotating faster
  - $S_{\Delta D} \propto \nu^{\alpha}$ with $\alpha \approx -0.8$
  - Maybe improve by a factor 2 with the PVLAS apparatus

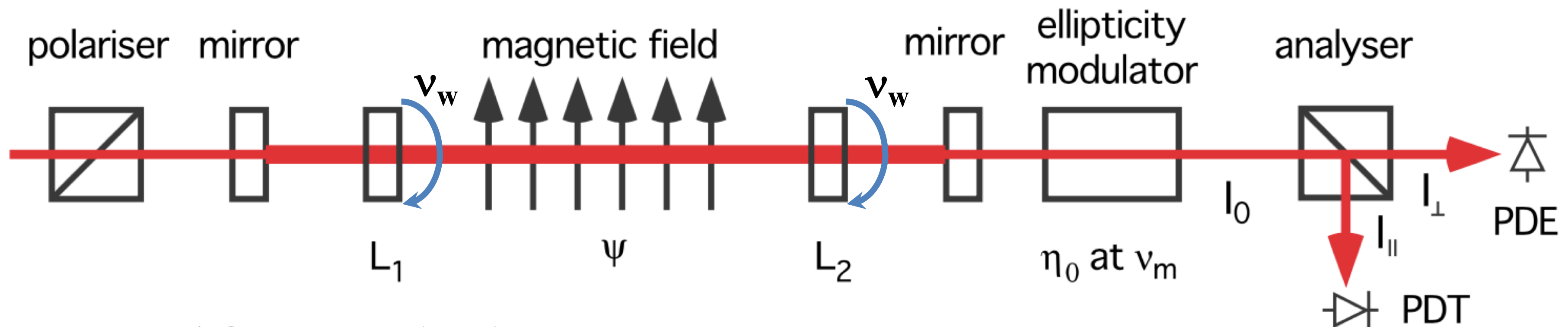
- Increase the signal: B^2L of magnet
  - Only real option is to use superconducting static magnets
  - One LHC magnet has B^2L = 1200 T^2m. At present we have 10 T^2m.
  - Superconductor magnets cannot be modulated at ≈ 10 Hz

- Change origin of modulation G Zavattini et al, EPJC **76**, 294 (2016)
  - Rotate the polarization inside the field
  - … But must be kept fixed on the mirrors.

Separate magnet from modulation

Polarization modulation scheme

- Insert two half wave plates co-rotating @ ν_W with a fixed relative angle $\Delta\phi$
- Rotate polarization inside the magnetic field
- Fix polarization on mirrors to avoid mirror birefringence signal
  - Total losses ≲ 0.4% (commercial). Maybe 10 times lower is possible
  - Maximum finesse ≈ 10000 (with ≲ 0.04% losses)



G Zavattini et al, EPJC **76**, 294 (2016)

Signal and possible problems

$$I(t) = I_{\rm out}\left\{\eta(t)^2 + 2\eta(t)N\left[\psi_0 \sin 4\phi(t) + \right.\right.$$
$$\left.\left. +\alpha_1 \sin 2\phi(t) + \alpha_2 \sin\left(2\phi(t) + 2\Delta\phi\right)\right]\right\}$$

Signal appears a the 4th harmonic of $\nu_{\rm waveplate}$

Wave-plate defects $\alpha_{1,2}$

$$\alpha_{1,2} = \alpha_{1,2}^{(0)} + \alpha_{1,2}^{(1)} \cos\phi + \alpha_{1,2}^{(2)} \cos 2\phi + \ldots$$

- $\alpha^{(0)}{}_{1,2} \approx 10^{-3}$ (from manufacturer): appears @ 2nd harmonic
- $\alpha^{(1)}{}_{1,2} \approx 10^{-6}$ (wedge of wave-plate): appears @ 1st and 3rd harmonic
- $\alpha^{(2)}{}_{1,2}$ => appears @ 4th harmonic
- Condition is that $\alpha^{(2)}{}_{1,2} < \psi_0$ with $\psi_0 \approx 10^{-14}$. Must be tested.

G Zavattini et al, EPJC **76**, 294 (2016)

VMB@CERN with 1 LHC magnet

- Signal $$\Delta D = 3A_e B^2 L = 4 \times 10^{-24} \left(\frac{B}{1\ \mathrm{T}}\right)^2 \left(\frac{L}{1\ \mathrm{m}}\right)\ \mathrm{m}$$

- Intrinsic noise $$S_{\Delta D}^{(\mathrm{intrinsic})} = 2.6 \times 10^{-18} \left(\frac{\nu}{1\ \mathrm{Hz}}\right)^{-0.77} \frac{\mathrm{m}}{\sqrt{\mathrm{Hz}}}$$

- Shot-noise $$S_{\Delta D}^{(\mathrm{shot})} = \sqrt{\frac{e}{I_0 q}} \frac{\lambda}{\pi N} \frac{\mathrm{m}}{\sqrt{\mathrm{Hz}}}$$

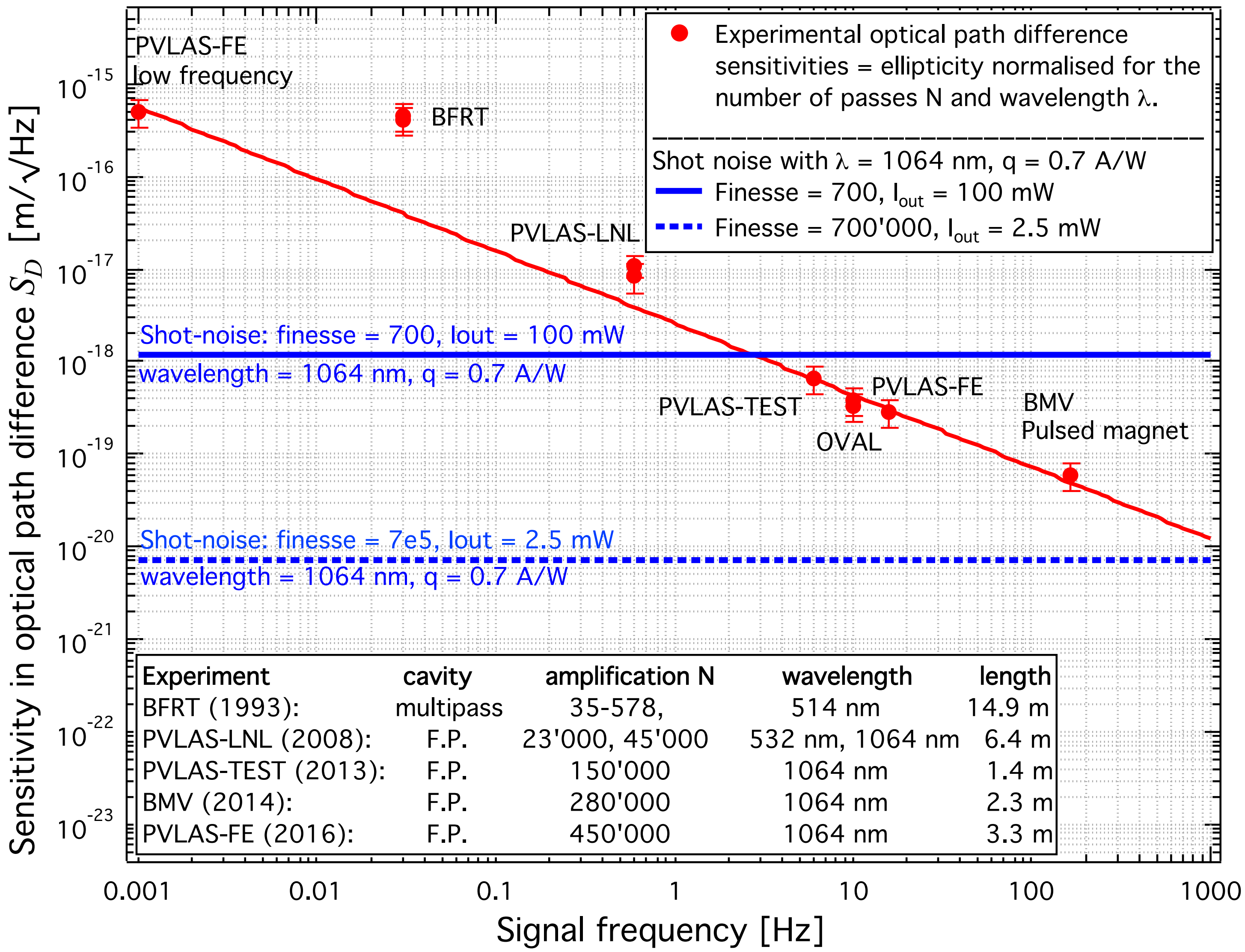
- Maximum measurement time $$T = \left(\frac{S_{\Delta D}}{\Delta D}\right)^2 \lesssim 10^6\ \mathrm{s}$$

- LHC example: $$B^2 L = 1200\ \mathrm{T}^2\mathrm{m}$$ $$S_{\Delta D} = 10^{-18} \frac{\mathrm{m}}{\sqrt{\mathrm{Hz}}} \quad @ \quad 3\ \mathrm{Hz}$$ $$\Longrightarrow \boxed{T = 12\ \mathrm{h}}$$

R Ballou at al, CERN-SPSC-2018-036 / SPSC-I-249

What sensitivity could be reached?

Sensitivity in optical path difference ΔD between two perpendicular polarizations



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Updated graph from G. Zavattini et al. EPJC **76**, 294 (2016)

$S_{\Delta D} \approx 10^{-18}$ m/√Hz goal sensitivity

Conclusions

- I have presented a brief updated report of the **opto-polarimetric method** to measure **vacuum magnetic birefringence**
- **PVLAS**, the most advanced experimental effort in this field is unable to reach the goal due to insufficient sensitivity. PVLAS achievements:
  - integrated signal is less than one order of magnitude from the QED signal
  - best laboratory limits for axion-like particles with $m > 1$ meV
- **New idea: separate magnet and modulation**
  - employ a **LHC magnet** ($B^2L = 1200\ T^2m$)
  - modulate the effect by **inserting two co-rotating half-wave plates inside the optical cavity** (polarization fixed on the surface of the mirrors)

Optical Polarimetry for the Magnetic Birefringence of Vacuum

Federico Della Valle
Dip. di Scienze Fisiche, della Terra e dell'Ambiente – Università di Siena (Italy)
INFN – Sezione di Pisa (Italy)

Orosei – 30 Aprile 2019