Birefringence noise in VMB experiments

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Euler-Heisenberg-Weisskopf Lagrangian

Lagrangian of the electromagnetic field in QED. Maxwell's equations are still valid but they are no longer linear. At lowest order:

$$L = L_{em} + L_{EH} = \frac{1}{2\mu_0}\left(\frac{E^2}{c^2} - B^2\right) + \frac{A_e}{\mu_0}\left[\left(\frac{E^2}{c^2} - B^2\right)^2 + 7\left(\frac{\vec{E}}{c}\cdot\vec{B}\right)^2\right]$$

$$A_e = \frac{2}{45\mu_0}\left(\frac{\alpha^2 \lambda_e^3}{m_e c^2}\right) = 1.32 \cdot 10^{-24}\ \mathrm{T}^{-2}$$

[W Heisenberg and H Euler, *Z. Phys.* **98**, 714 (1936)]
[H Euler, *Ann. Phys.* **26**, 398 (1936)]

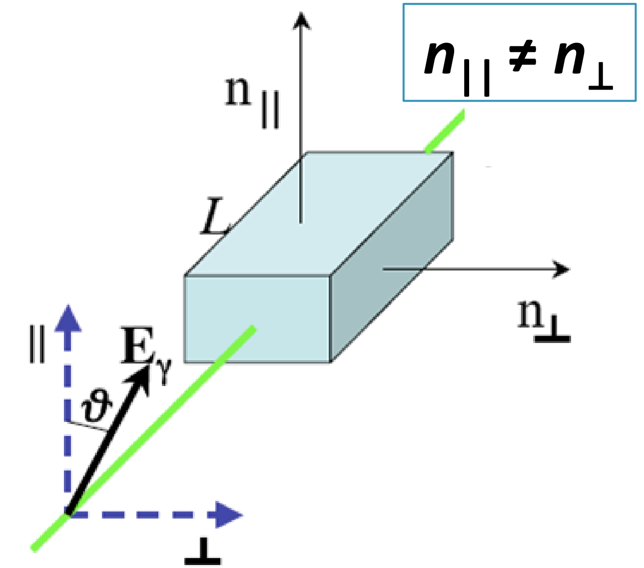
for fields much smaller than the critical field (B << $4.4\cdot10^{9}$ T; E << $1.3\cdot10^{18}$ V/m)

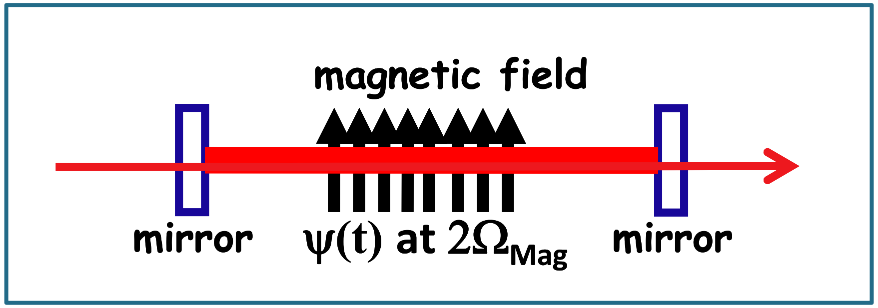
$$\Delta n_{QED} = 3A_e B^2 = 4\times10^{-24}\ B^2$$

Polarimetry

A linearly polarized light beam propagating through a birefringent medium will acquire an **<u>ellipticity</u>** ψ

$$\psi = \frac{\pi}{\lambda} \cdot \Delta n \cdot L \cdot \sin(2\theta)$$





Key ingredients

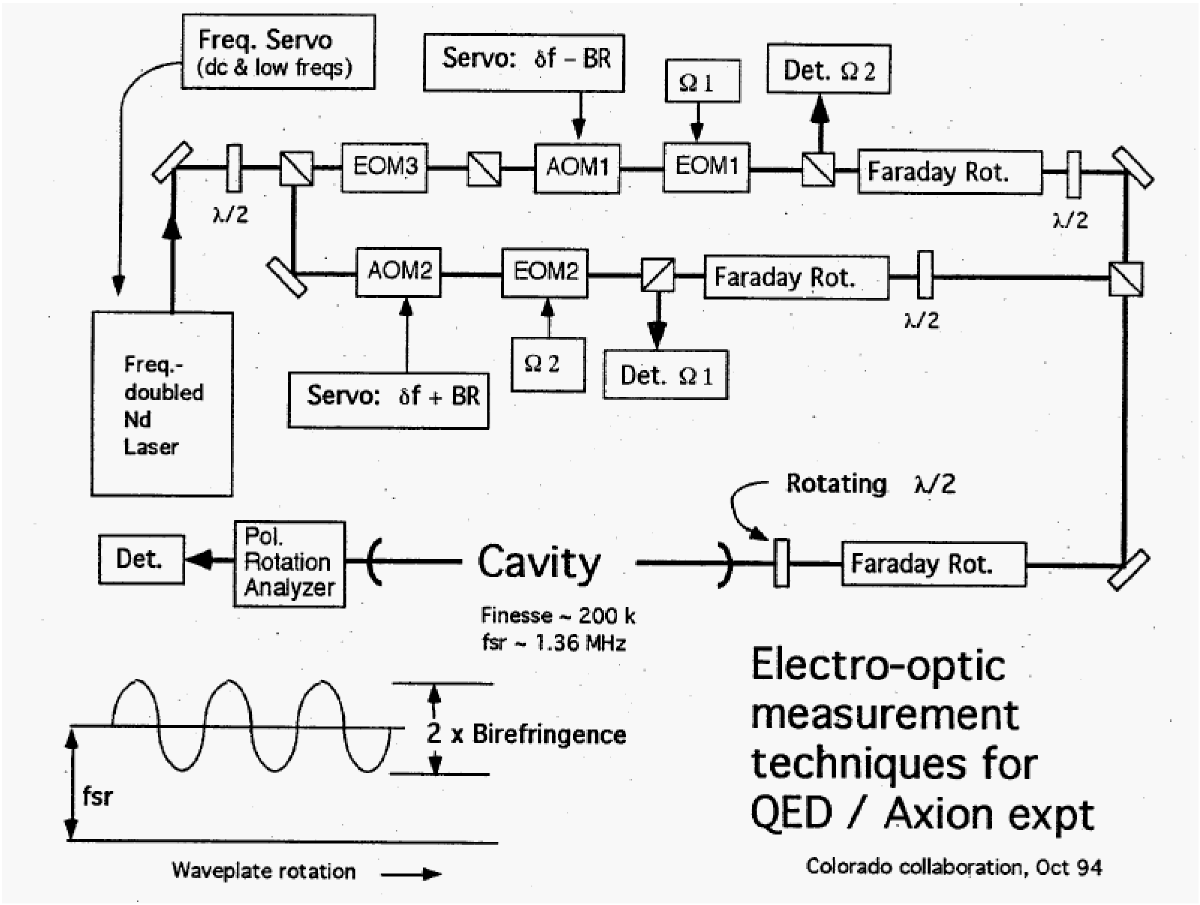
- **High finesse optical cavity**
  large path length in magnetic field
- **Modulation of the signal**
  decouple from static effects

Frequency metrology

Polarization-dependent optical length of the cavity (and so is the res. frequency)

$$\Delta L = \Delta n \cdot L$$

Two linearly polarized beams are independently locked to the two orthogonal states of the cavity.
From the frequency difference of these beams one can recover the birefringence of the medium inside the cavity.



[Fermilab TDR]

Noise types

- <u>Peaks:</u> mechanical vibrations, coupling to the magnetic field, ecc

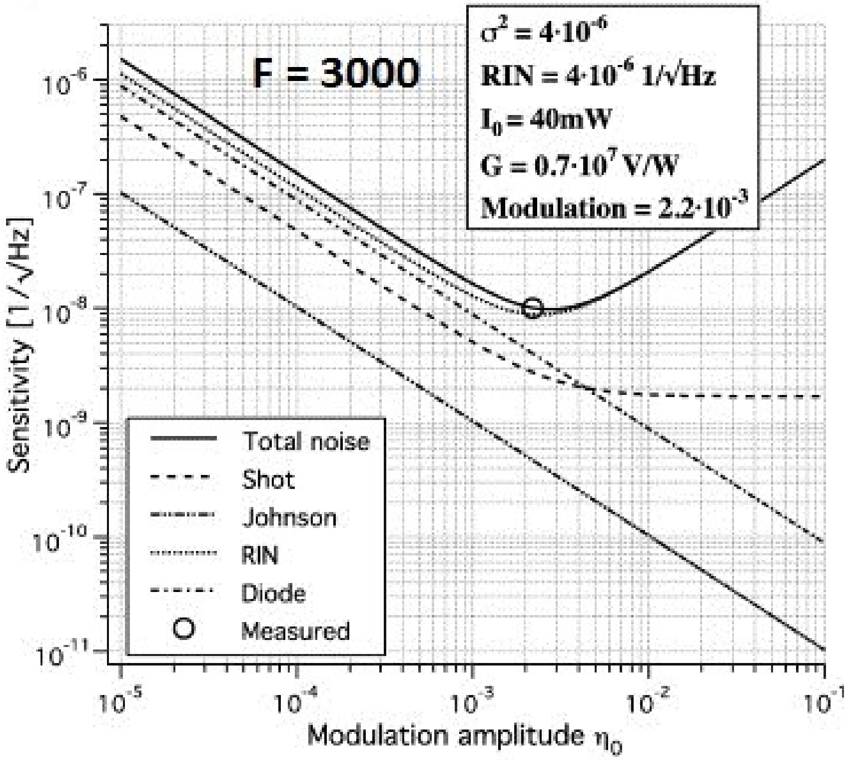
SPURIOUS SIGNALS
NO GAIN FROM INTEGRATION

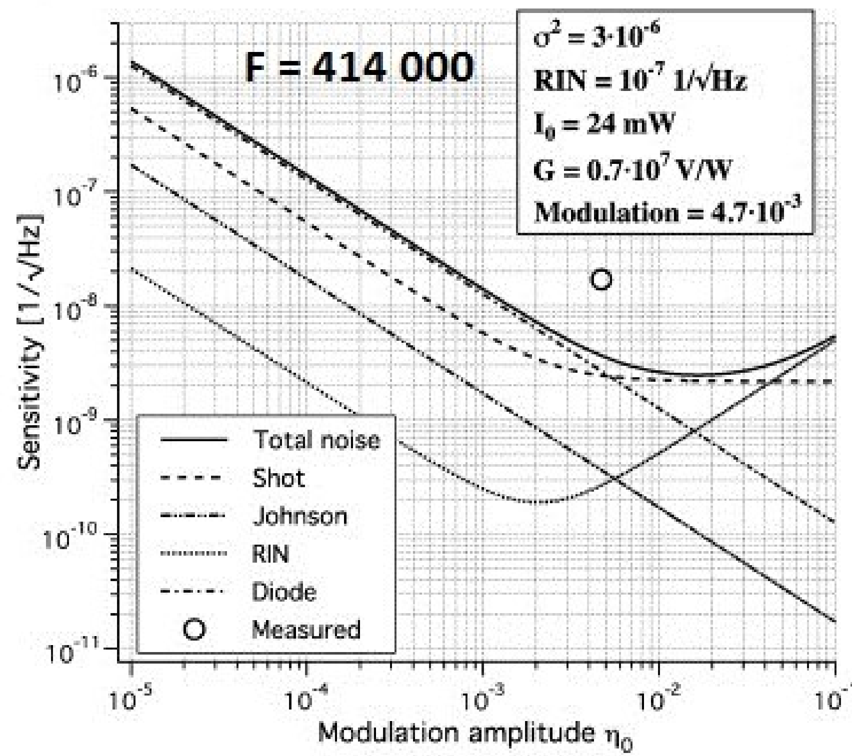
- <u>Broadband noise:</u> currently limit in sensitivity that is far from shot noise limited performance

REDUCES IF INTEGRATED IN TIME

(still there even if one removes completely the magnets.)

Sensitivity

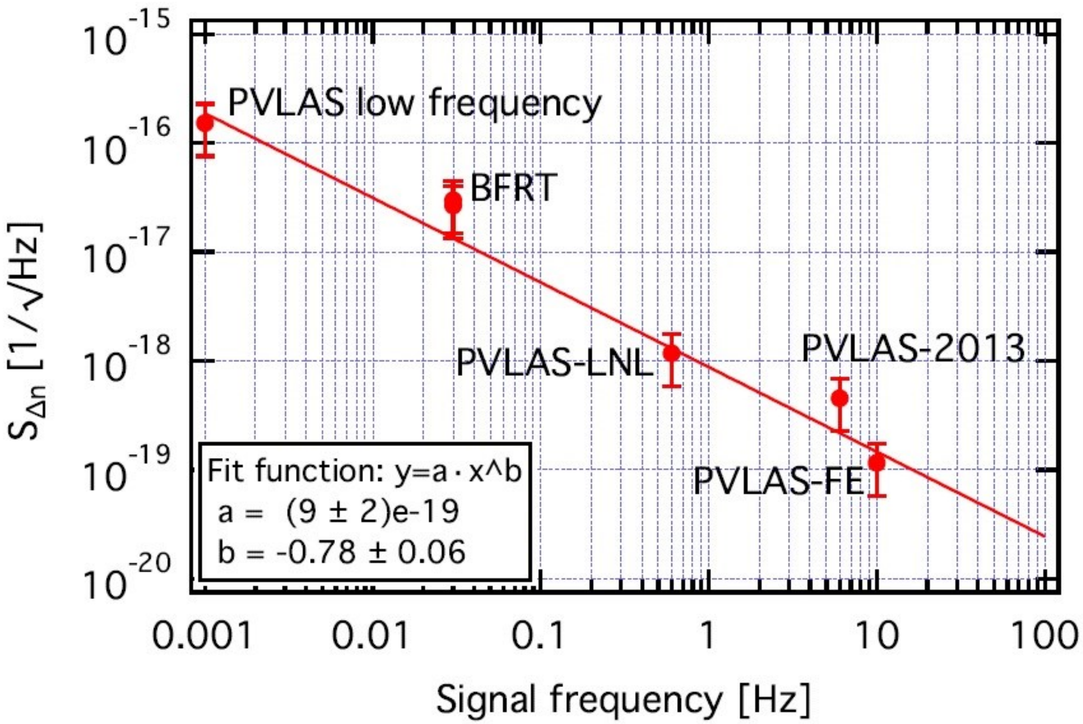




Noise budget OK. L = 50 cm Sensitivity worsened!!

[F. Della Valle et al., Optics Communications **283**, 4194 (2010)]

Sensitivity in birefringence



[G. Zavattini et al., EPJ C **76**, 294 (2016)]

$$S_{\Delta n} = S_\psi \frac{\lambda}{\pi\left(\frac{2\mathscr{F}}{\pi}\right)d}$$

(d = length of the FP cavity)

- 1/f dependence
- scaling with length and finesse

<u>Needs to be studied further with a systematic approach!</u>

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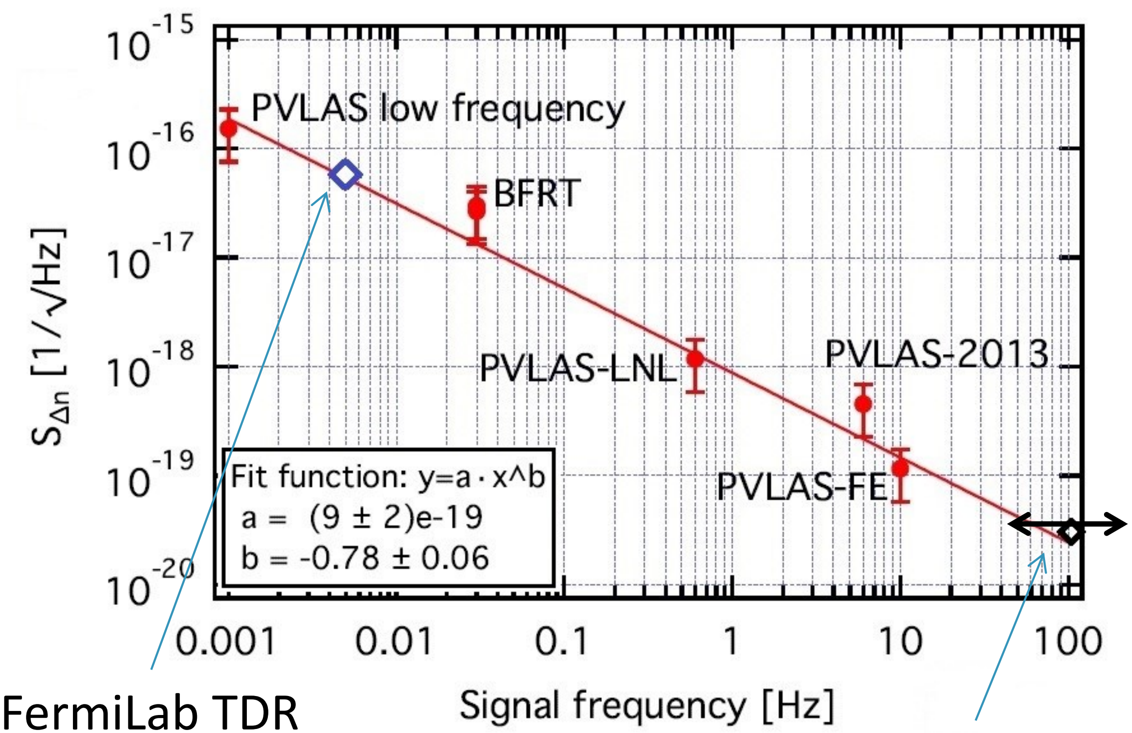
Sensitivity in birefringence



$$S_{\Delta n} = S_{\psi} \frac{\lambda}{\pi \left(\frac{2\mathscr{F}}{\pi}\right) d}$$

One would expect a constant S_{ψ} (given by the polarimeter), so:

larger finesses and longer cavities

↓

larger the induced ψ with a given Δn

↓

better birefringence sensitivity

FermiLab TDR
$6.5 \times 10^{-17}/\sqrt{Hz}$
@ ~ 5 mHz

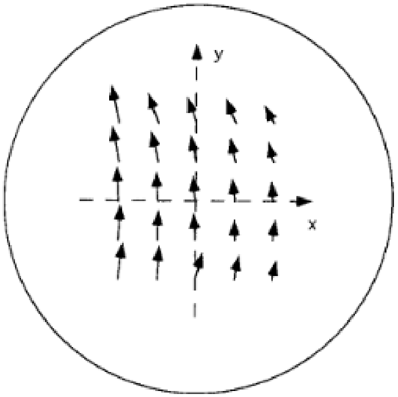
← NEED TO BE CHECKED!! →

BMV EPJ D 2013
$2.7 \times 10^{-20}\ /\sqrt{Hz}$
@ ~ 100Hz

Most-likely source: cavity mirrors

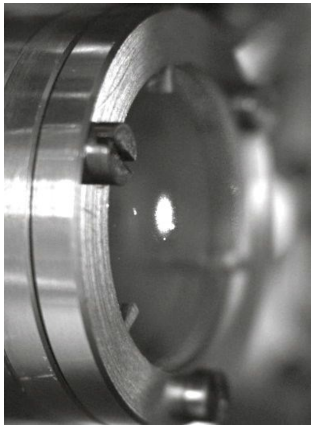
TWO MECHANISMS UNDER CONSIDERATION:

1. Non-uniform birefringence on the surface of the mirror ("birefringence map")



[P. Micossi et al., Appl. Phys. B **57**, 95 (1993)]

2. Scattered light from point defects that is collinear with the cavity eigenmode



Birefringence noise: $\mathfrak{I}$ and d

$$S_{\Delta n} = S_{\psi} \frac{\lambda}{\pi \left(\frac{2\mathscr{F}}{\pi}\right) d}$$

N = roundtrip number

cavity length (α beam area)

- larger beams probe larger areas on the mirror (proportionality to cavity length)
- number of reflections (proportionality to finesse)

but:

1/f dependence?? <u>DON'T KNOW…</u>
(movement of the beam on the mirror surface?)