OSQAR ***STATUS REPORT***

Progress in ultra-fine birefringence measurements

Mathieu Durand[1], **Jérôme Morville**[1], **Daniélé Romanini**[2]

(1)Laboratoire de Spectrométrie Ionique et Moléculaire (**LASIM**)
UMR CNRS 5579, Université Claude Bernard-Lyon1

(2)Laboratoire de Spectrométrie Physique (**LSP**)
UMR CNRS 5588, Université Joseph Fourier - Grenoble

NEW collaborator

the 94th Meeting of the SPSC – CERN – 2009-November 24

The OSQAR Collaboration *at present*

▸ *24 Members from 10 Institutes (Cz, Fr, Po & CERN)*

CERN, Geneva, Switzerland
P. Pugnat (now at LNCMI-CNRS), M. Schott, A. Siemko

Charles University, Faculty of Mathematics & Physics, Prague, Czech Republic
M. Finger Jr., M. Finger

Czech Technical University, Faculty of Mechanical Engineering, Prague, Czech Republic
J. Hošek, M. Kràl, J. Zicha, M. Virius

ISI, ASCR, Brno, Czech Republic
A. Srnka

IMEP/LAHC - INPG, 38016 Grenoble Cédex-1, France
L. Duvillaret, G. Vitrant, J.M. Duchamp

IN, CNRS – UJF & INPG, BP 166, 38042 Grenoble Cédex-9, France
B. Barbara, R. Ballou, Y. Souche

LASIM , UCB Lyon1 & CNRS, 69622 Villeurbannes, France
M. Durand, J. Morville

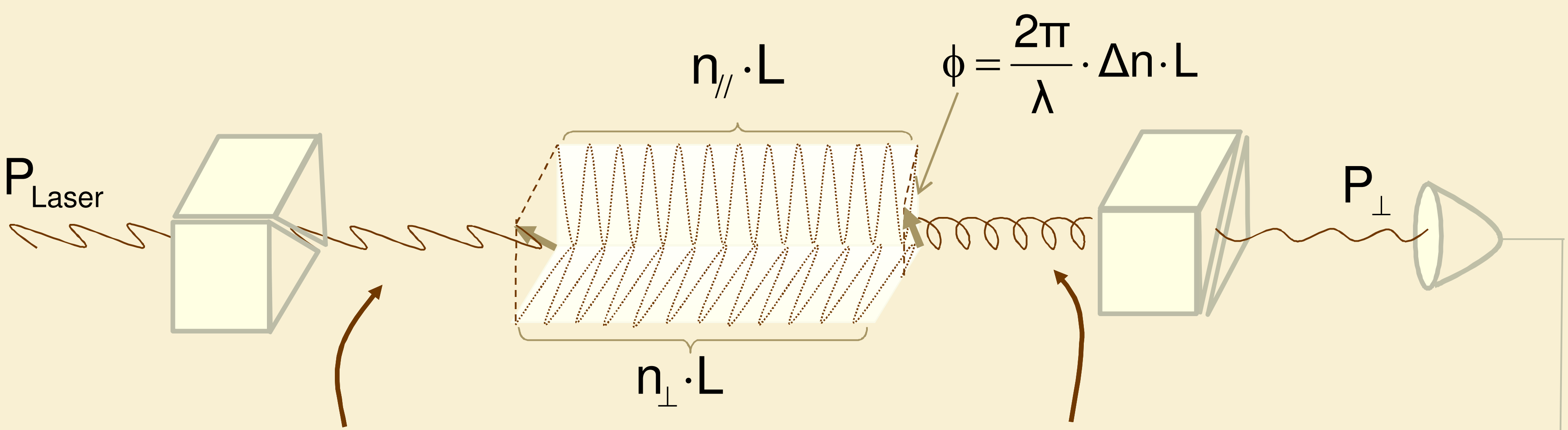
LSP, UJF & CNRS, 38402 Saint-Martin d'Hères, France
R. Jost, S. Kassi, D. Romanini

TUL, Czech Republic
M. Šulc

Warsaw University, Physics Department, Poland
A. Hryczuk, K. A. Meissner

What is birefringence ?

Matter anisotropy induces different answer with the electric field vector orientation



Entering linearly polarized

Light exits elliptically polarized

Malus law for small dephasing $P_{\perp} = \left(\frac{\phi}{2}\right)^2 \cdot P_{Laser}$

The vacuum embedded in a magnetic field should also be anisotropic

$$\Delta n = 4 \cdot 10^{-24} \cdot B_0^{\,2}$$

giving $\Delta n \approx 3{,}6 \cdot 10^{-22}$ If $B_0 \approx 9{,}5\mathrm{T}$

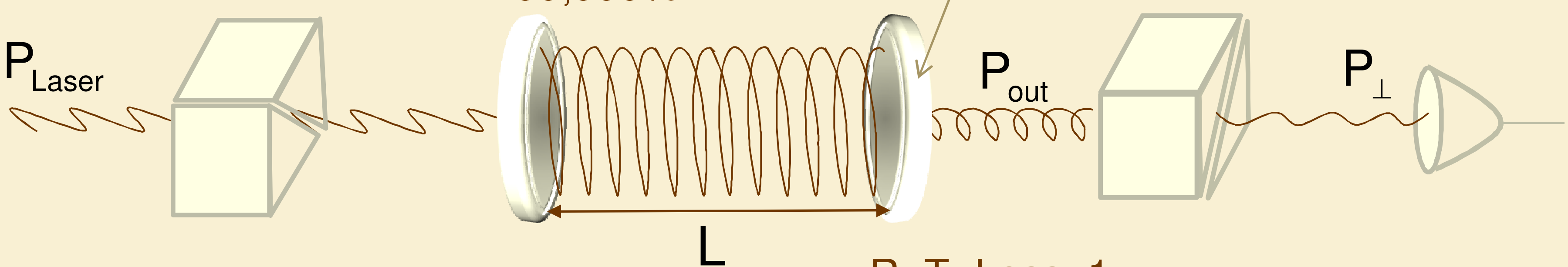
$$\phi = 0{,}7 \cdot 10^{-13}\,\mathrm{rad}$$

Is predicted @ λ=500 nm with **the CERN dipole magnets**

$$(L = 15\mathrm{m})$$

Using High Finesse Optical Cavity

The medium is contained between two high reflective and low losses dielectric mirrors

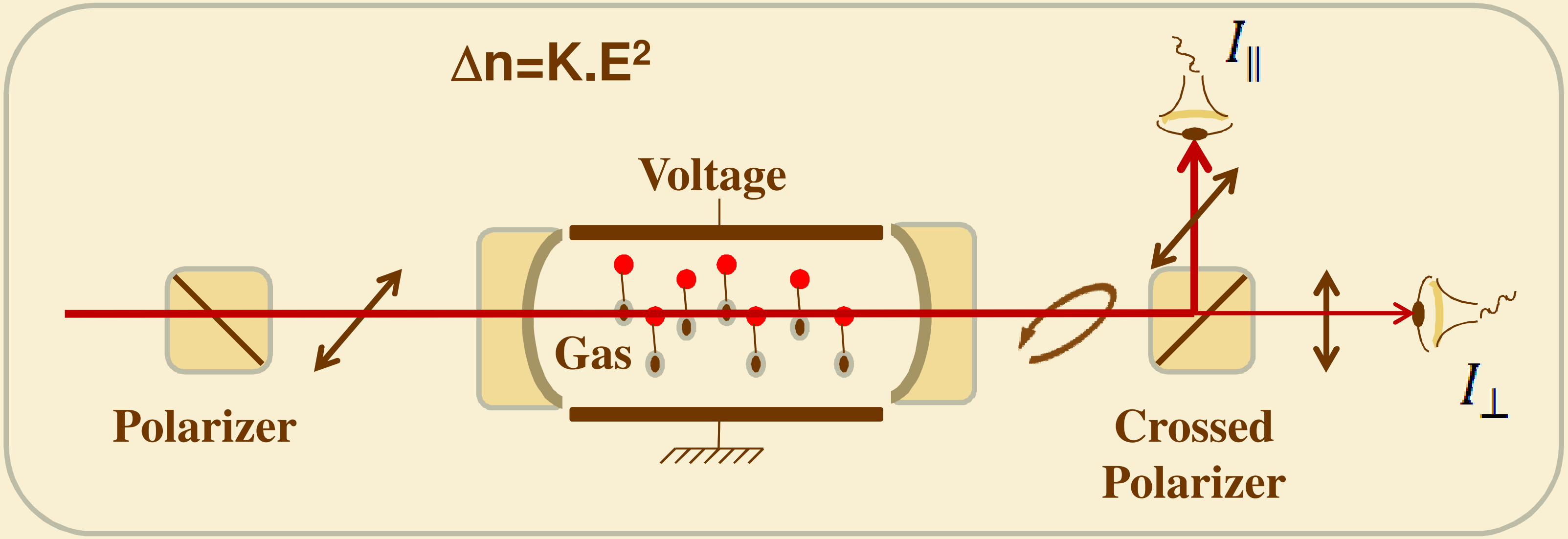


$$\phi = \frac{2\pi}{\lambda} \cdot \Delta n \cdot L_{eff}$$

If light resonates inside the cavity (constructive interference at each round trip), Light transmitted trough the exit mirror has an effective optical pathlength of

$$L_{eff} = \frac{2F}{\pi} \cdot L$$ with the **finesse** $$F = \frac{\pi}{1-R} \geq 10^5$$

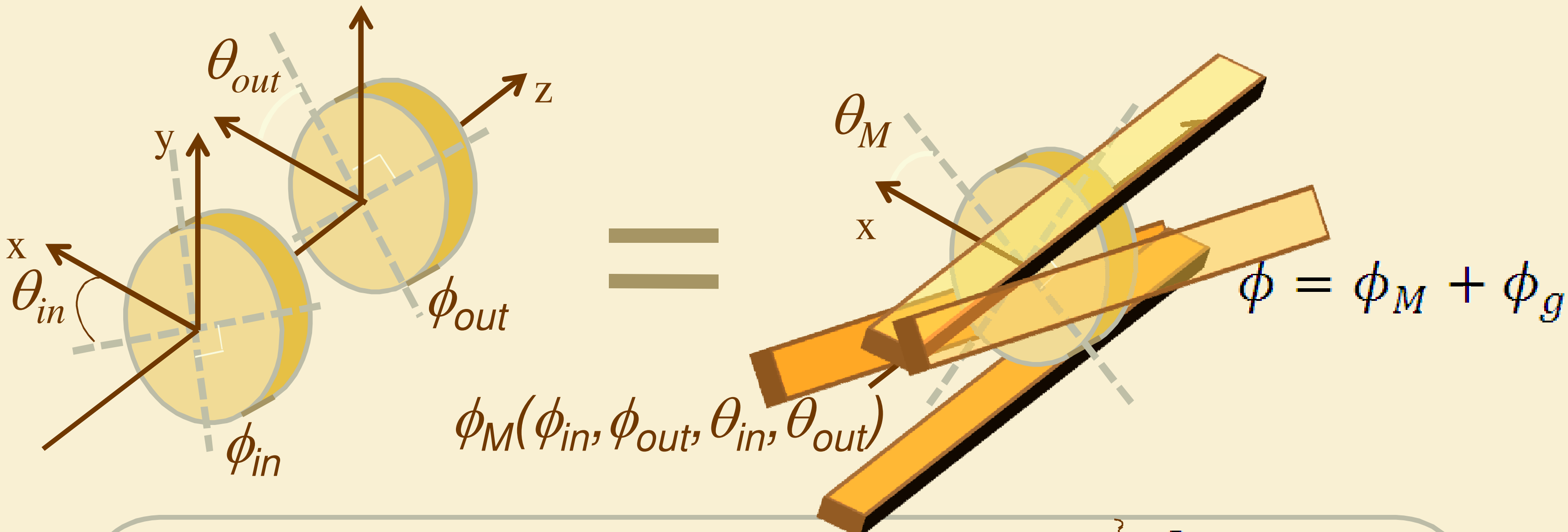
Recent Kerr anisotropy measurements
PhD thesis : Mathieu Durand (07/23/2009)

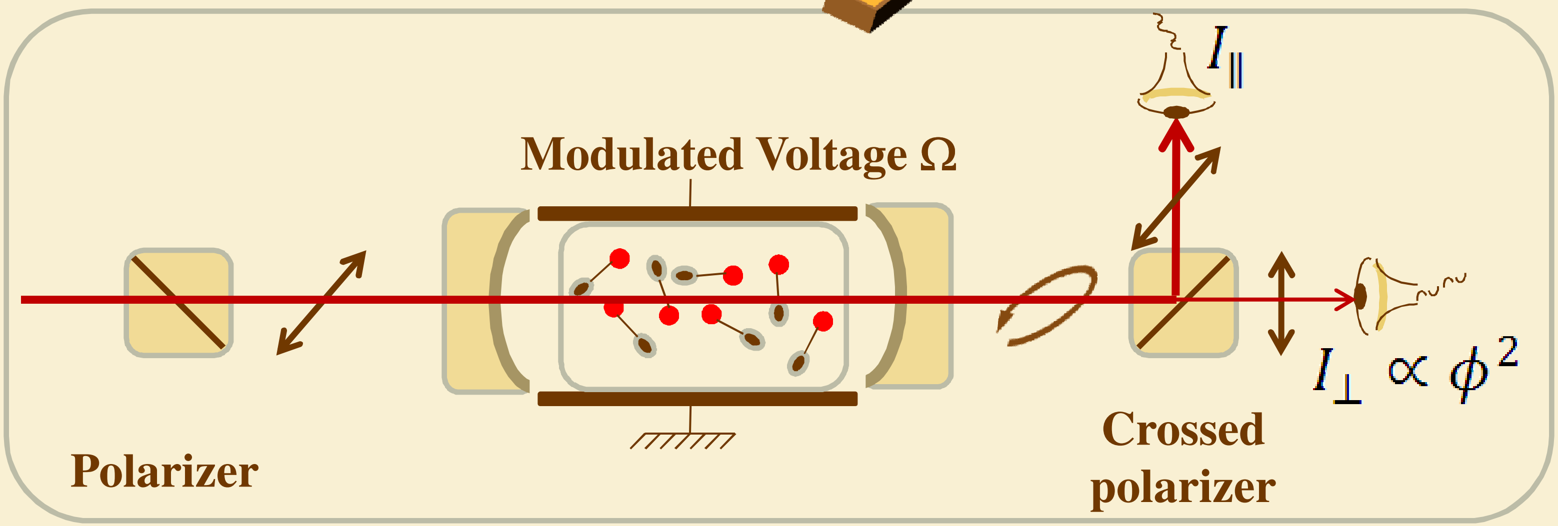


$$\frac{I_{\perp}}{I_{\parallel}} = \left(\frac{2\,F}{\pi}\right)^2 \cdot \left(\frac{\phi}{2}\right)^2$$

At this level of sensitivity, residual mirrors birefringence entirely conceals the effect of gas birefringence

Using residual mirrors birefringence as an optical bias for homodyne detection





$$\frac{I_\perp}{I_\parallel} = \underbrace{\left(\frac{2F}{\pi}\right)^2 \cdot \left(\frac{\phi_M}{2}\right)^2}_{\text{DC}} + \underbrace{\left(\frac{2F}{\pi}\right)^2 \cdot \phi_M \phi_y \cdot \cos(\Omega t)}_{\Omega \text{ component}} + \underbrace{\cdots}_{\text{negligible high order terms}}$$

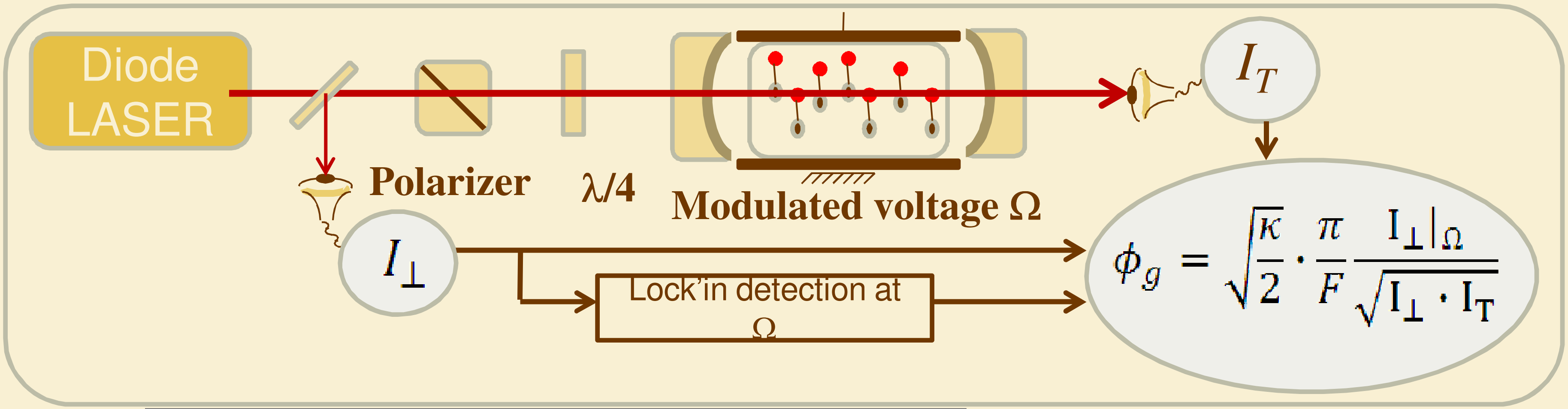
The lowest gas dephasing measurable : σ_{ϕ_g}

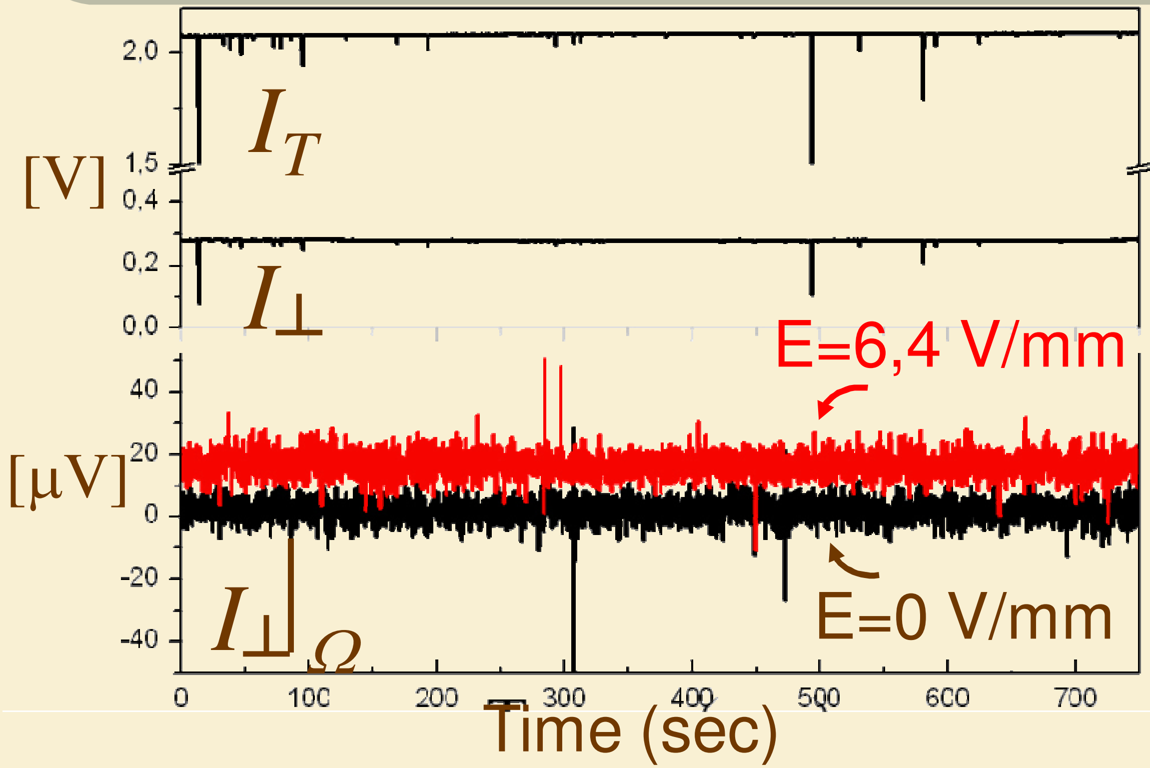
⇔ Sensitivity given by :

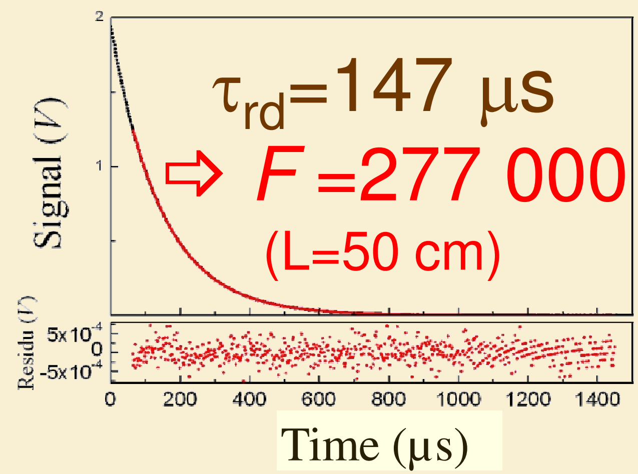
$$noise\left(\left.\frac{I_\perp}{I_{//}}\right|_{\Omega}\right) = \left(\frac{2F}{\pi}\right)^2 \cdot \phi_M \cdot \sigma_{\phi_g}$$

Gain induced by the optical bias : $G = \phi_M / \phi_g >> 10^4$

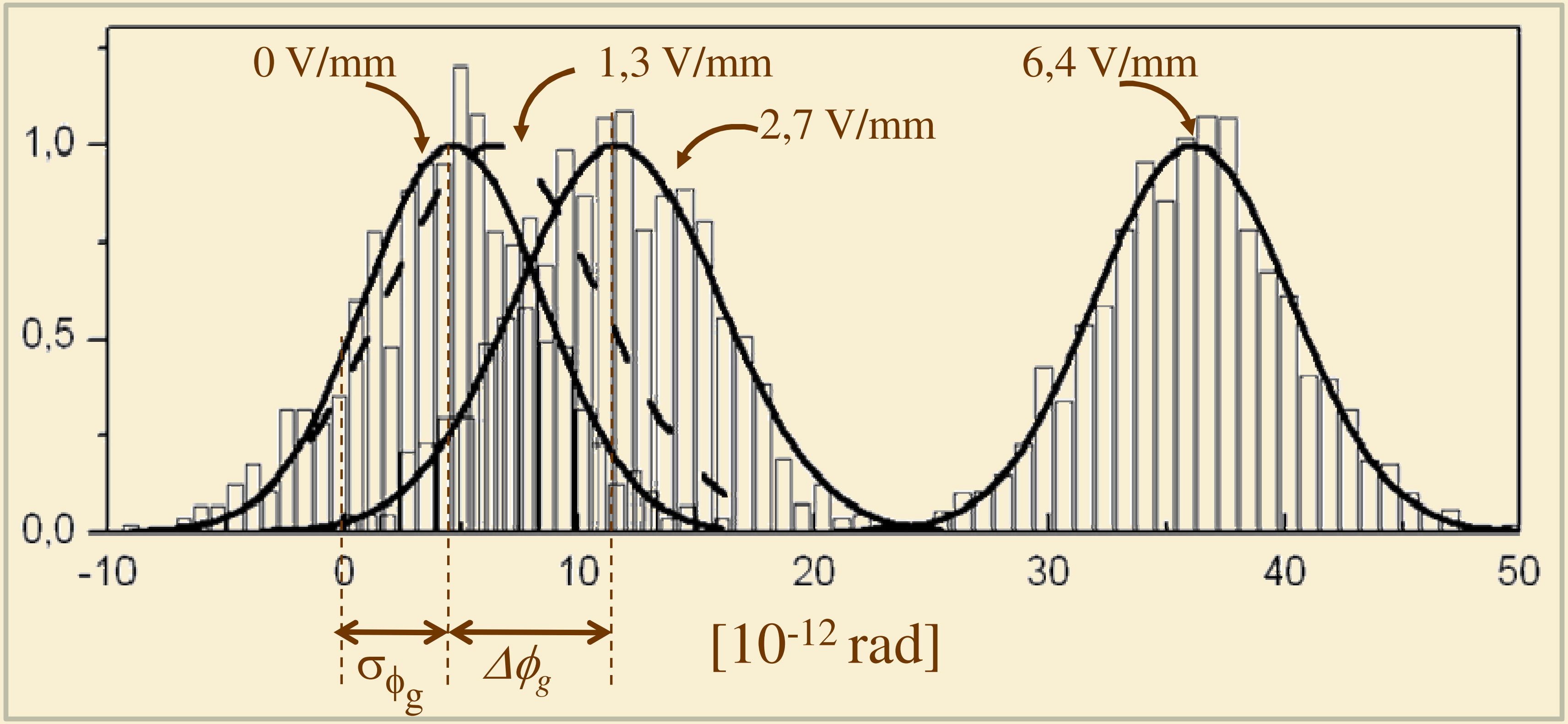
Experimental set-up with N_2 as a gas test







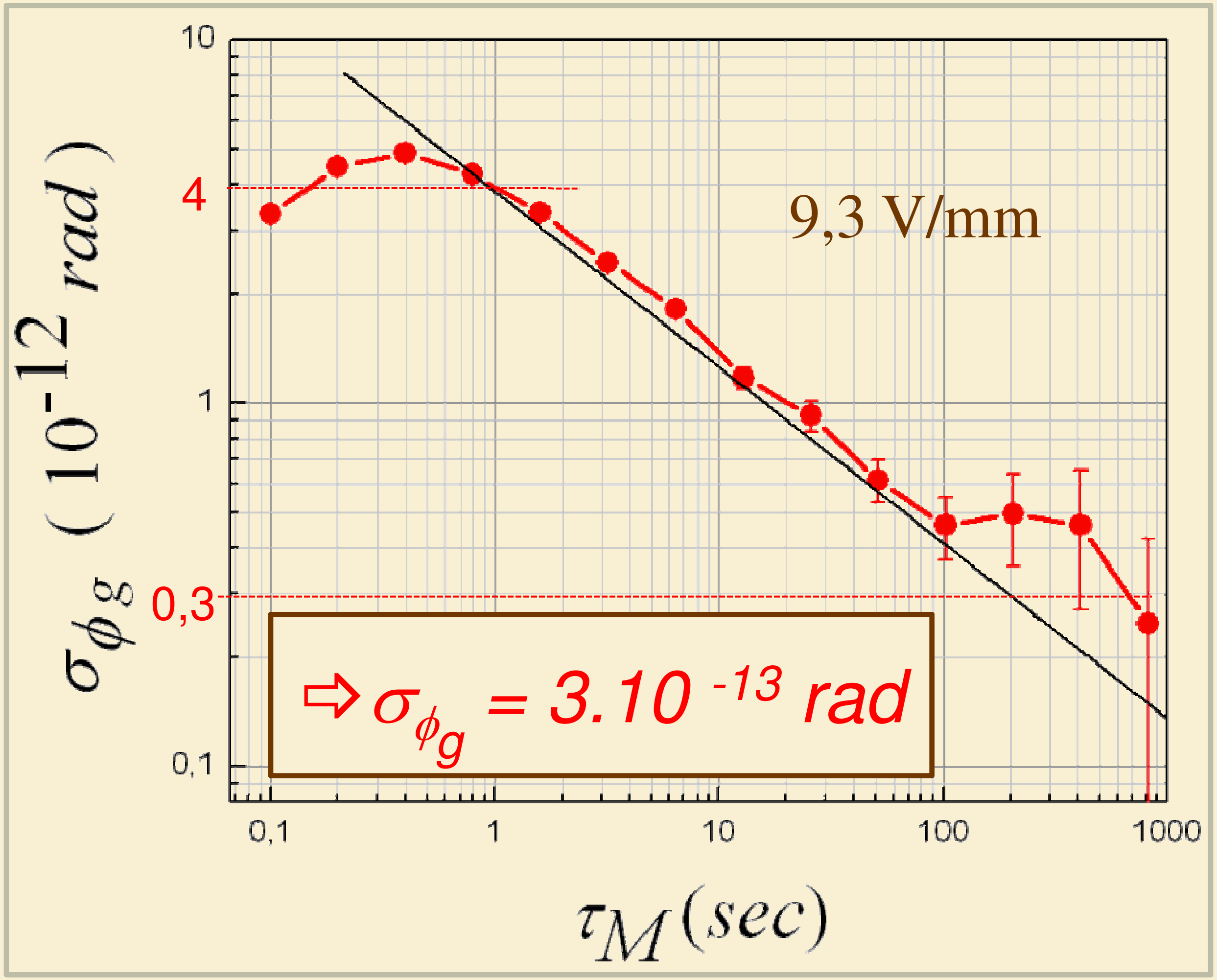
Measured sensitivity with N_2 as a gas test



$\Rightarrow \sigma_{\phi_g} = 4.10^{-12}\ rad/Hz^{1/2}$

Measured sensitivity with N_2 as a gas test as a function of integration time

Allan variance plot :



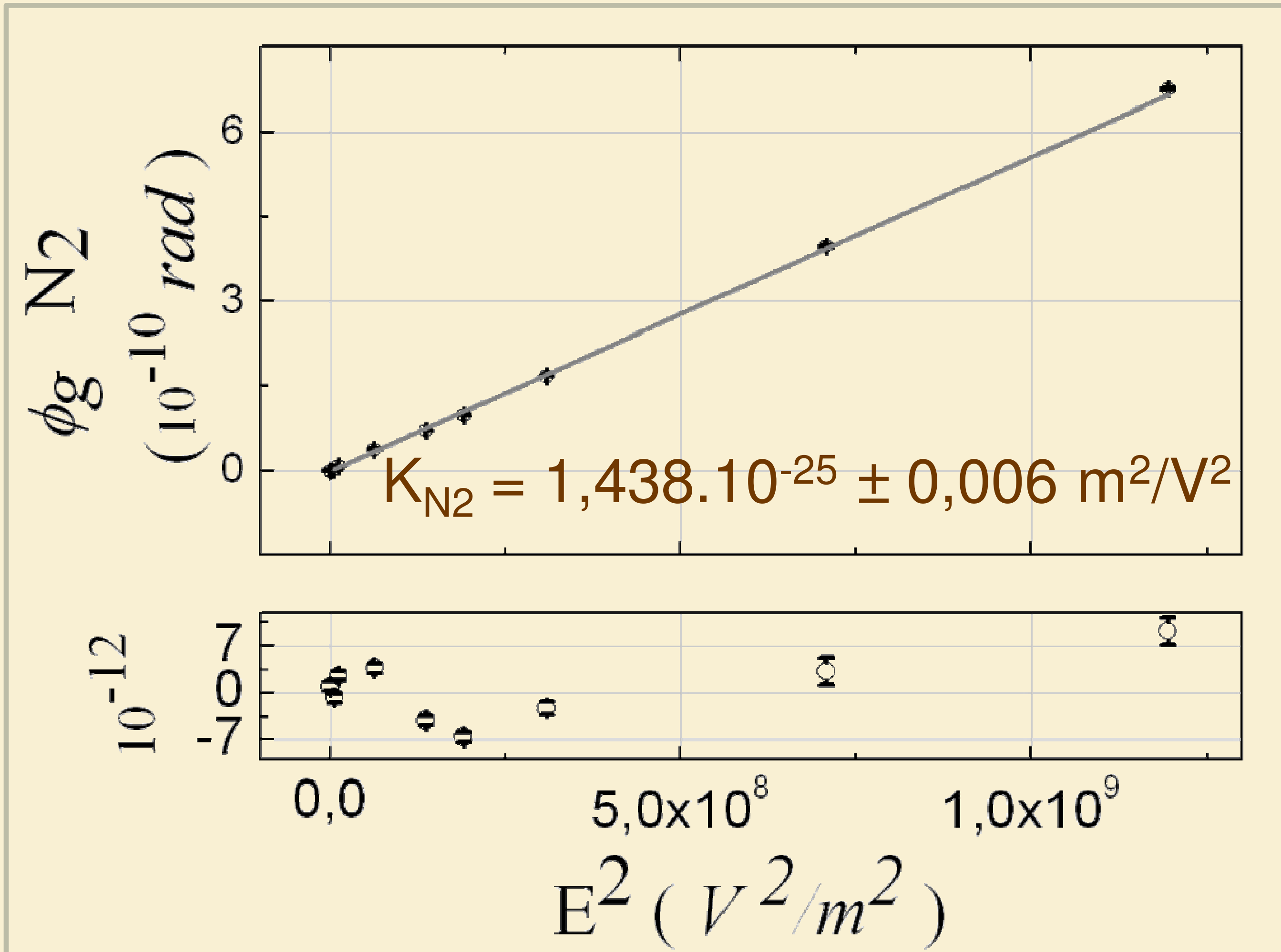
Measurement of Kerr constants

-Kerr constant *K*:

$$\phi_g = \frac{2\,\pi \cdot L}{\lambda} \cdot K \cdot \mathrm{E}^2$$

L = 50 cm

λ = 810 nm



Kerr constants of several gases

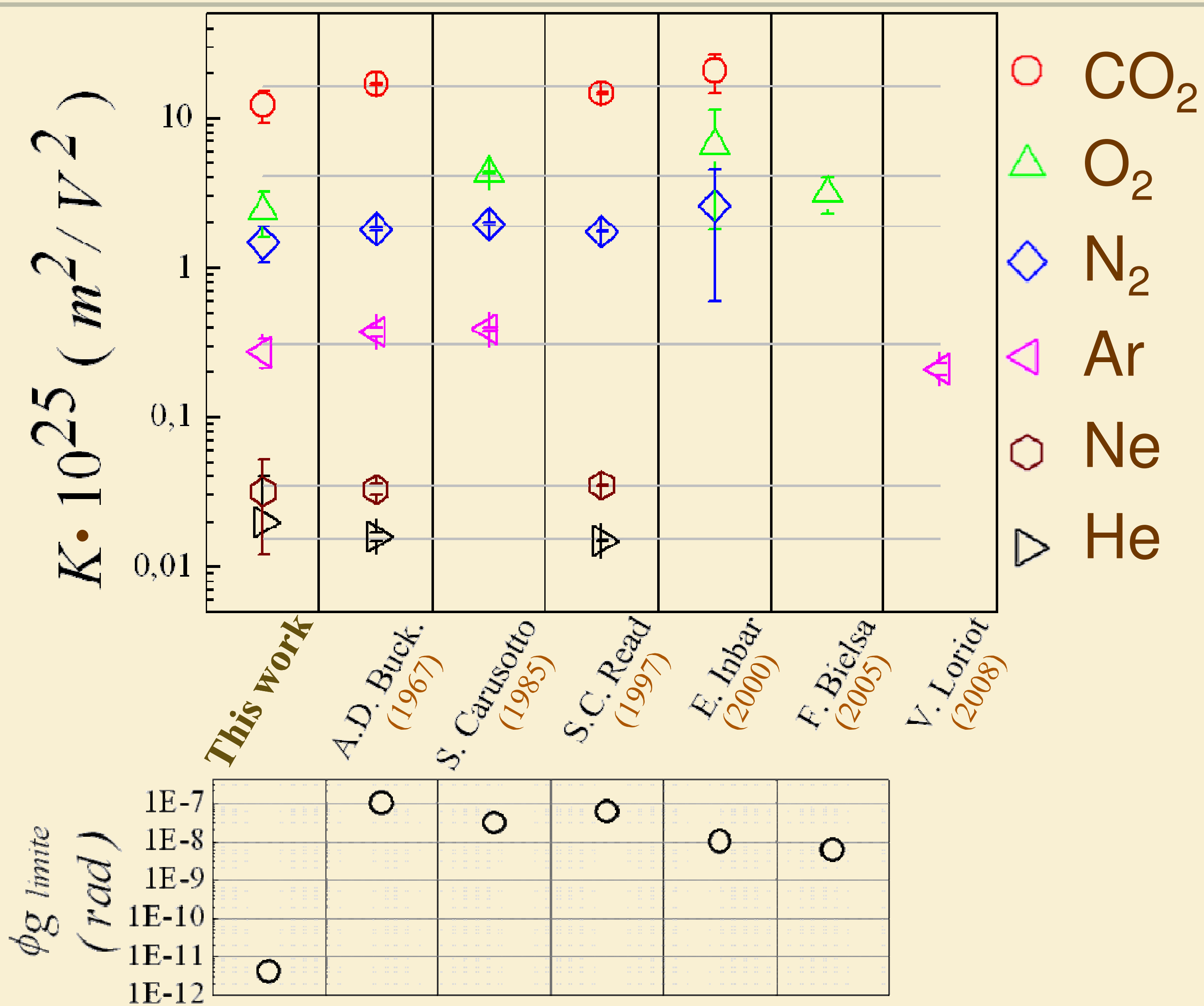
Molecular gases → alignment
Atomic gases → distortion of electronic wavefunction

20% (O$_2$) → $1{,}64 \pm 0{,}04$ ← 80% (N$_2$)

	CO_2	O_2	Air sec	N_2
$K \cdot 10^{25}\ (m^2/V^2)$	$12,11 \pm 0,03$	$2,46 \pm 0,03$	$1,573 \pm 0,006$	$1,438 \pm 0,006$

	Ar	Ne	He
$K \cdot 10^{25}\ (m^2/V^2)$	$0,249 \pm 0,006$	$0,036 \pm 0,008$	$0,02 \pm 0,01$

Comparison with published results



Achievement

⇨ a table top optical system for Kerr birefringence measurement in gas phase is demonstrated

⇨ $\sigma_{\phi_g} = 4.10^{-12}\ rad/Hz^{1/2}$	a factor two above the **shot noise level with 3 mW** incident laser power
⇨ $\sigma_{\phi_g} = 3.10^{-13}\ rad$	By averaging over 800 s, **limited by the laser-cavity servo-lock system**

⇨ Only the PVLAS system reaches comparable performance, based on noise analysis (4-times better, in development since 1994)

⇨ Our result constitutes the present **state-of-the-art validated on a physical signal**.

outlooks

Accommodation to the OSQAR experiment

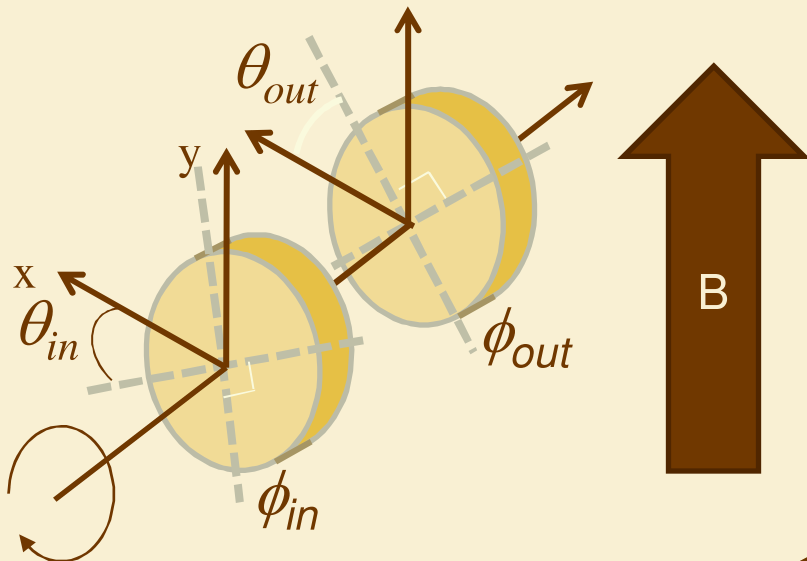
Recall : $$\phi = 0{,}7 \cdot 10^{-13}\,\mathrm{rad}$$ With B_0=9,5T and L=15m

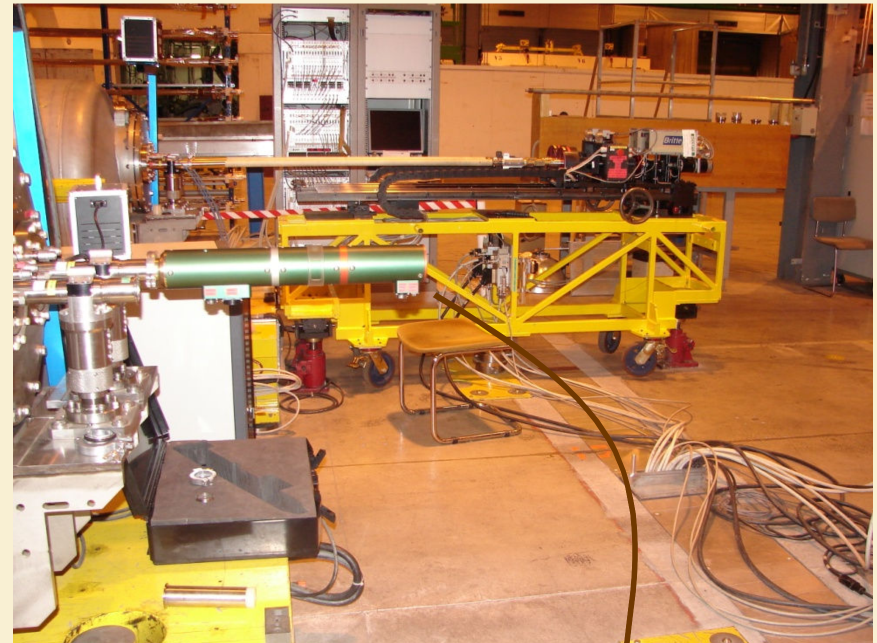
- Detection at the shot noise level $\sigma_{\phi_g} \rightarrow \sigma_{\phi_g}/2$
- Measuring in transmission (instead of reflection) : $\sigma_{\phi_g} \rightarrow \sigma_{\phi_g}/5$
- An increase of the laser beam transverse dimension (a factor 40 with a confocal cavity of 20 m length) increases the maximal incident power and thus the shot noise level $\sigma_{\phi_g} \rightarrow \sigma_{\phi_g}/6$
- Integration time of 1 hour : $\sigma_{\phi_g} \rightarrow \sigma_{\phi_g}/\sqrt{3600}$

All taken into account $\sigma_{\phi_g} \rightarrow$ $$\sigma_{\phi_g}/60^2 = 1{,}1 \cdot 10^{-15}\,\mathrm{rad}$$

outlooks

Magnetic field and homodyne detection scheme





All the setup rotates

8 Hz demonstrated with the new version

Two possibilities

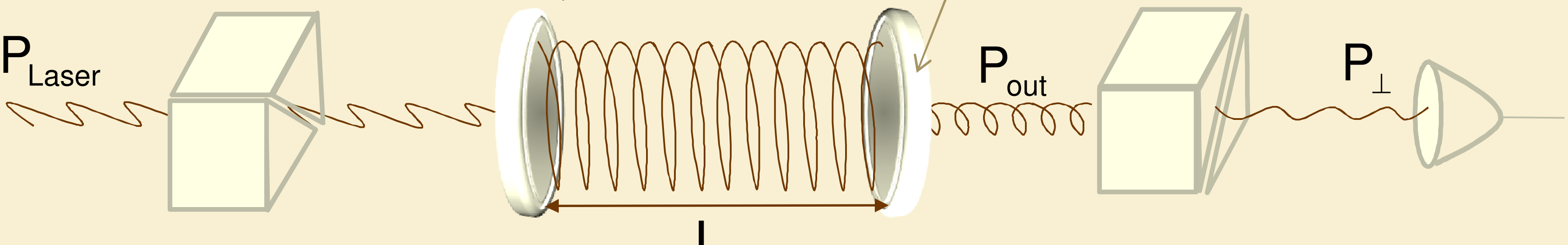
Only mirrors rotates around their optical axis

maintaining high finesse properties

The cavity more in detailed

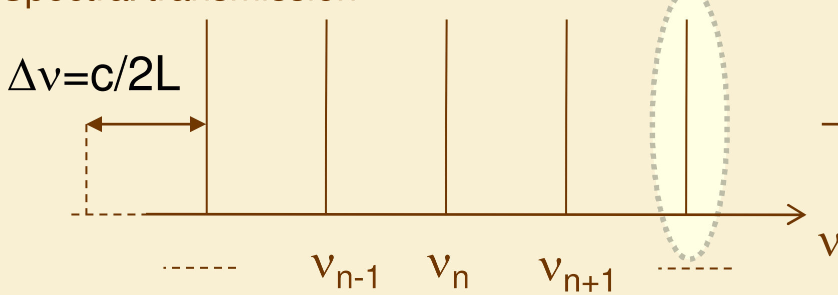
$$\phi = \frac{2\pi}{\lambda}\cdot\Delta n\cdot L_{eff}$$

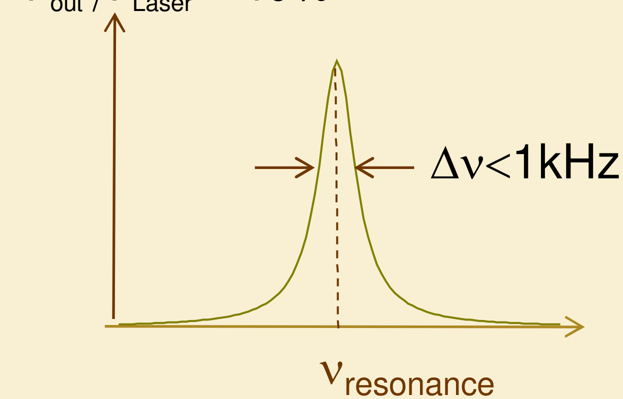
R~99,999%



R+T+Loss=1
(Loss~few ppm)

Spectral transmission





Constructive interferences => frequency comb

The finesse is defined as :

Cavity lifetime

$$F = \frac{\Delta\nu}{\delta\nu} = \frac{2\pi\cdot\tau_{ringdown}}{\tau_{roundtrip}} = \frac{\pi}{1-R} \geq 10^5$$

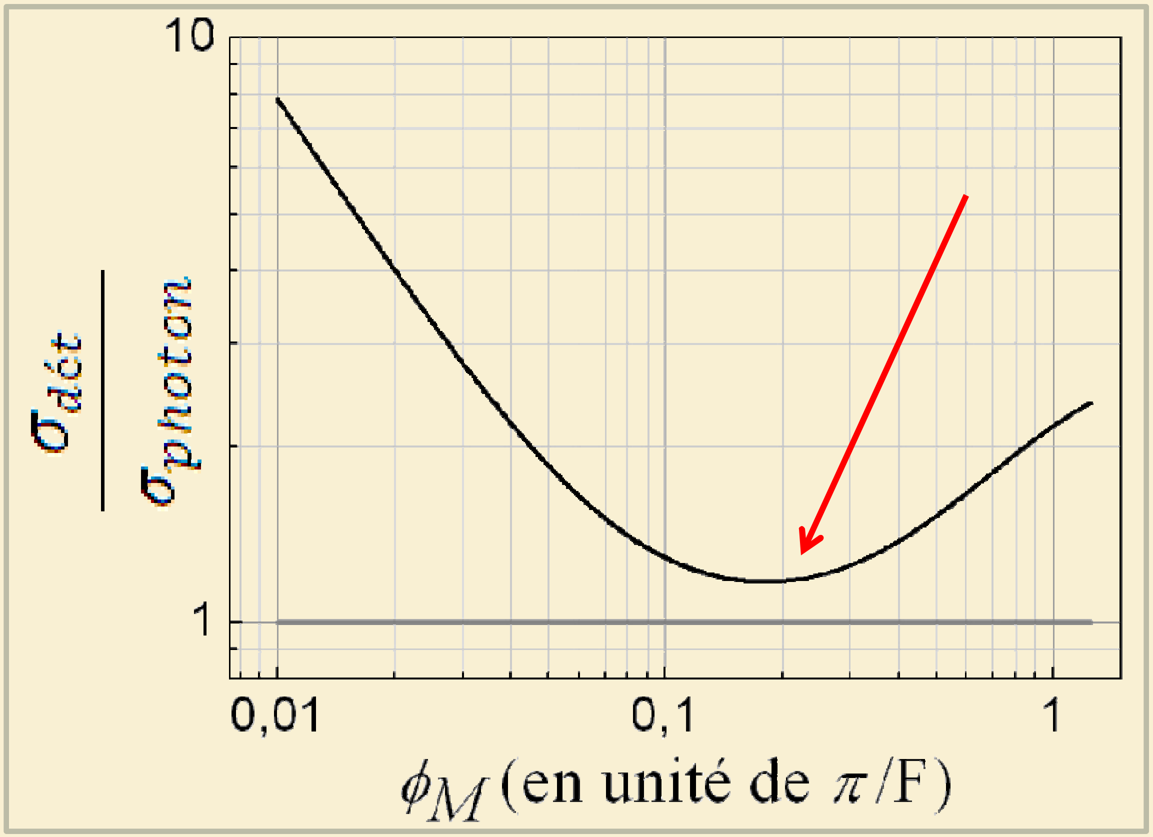
$$L_{eff} = \frac{2F}{\pi}\cdot L$$

Mirror birefringence as optical bias and noise analysis

Optical detection

$$\left(\frac{\sigma_{dét}}{\sigma_{photon}}\right)^2 = 1 + \frac{1}{2\,e \cdot S \cdot I_\perp(\phi_M)} \cdot \left[i^2 + \frac{4\,k_B\,T}{G} + \frac{b_q}{G^2}\right] + \frac{\Delta^2}{2\,e} \cdot S \cdot I_\perp(\phi_M)$$

Laser-cavity locking residual instability



⇨ Optimum : $\phi_M \sim 0{,}1 \cdot \pi/F$