# DeLLight
# *(Deflection of Light by Light)*
# with LASERIX @ LAL

Modification of the vacuum refractive index (i.e. the light velocity)
when vacuum is stressed by intense electromagnetic fields

***ANR Project (2019-2021)***

**LAL**: *F. Couchot, X. Sarazin, M. Urban, S. Robertson (post-doc LAL, theory)*

***LASERIX** (@LAL): E. Baynard, J. Demailly, O. Guilbaud, S. Kazamias, B. Lucas, M. Pittman,*

***APC**: A. Djannati-Ataï*

*Xavier Sarazin (LAL)*

*Séminaire LPNHE 9 Décembre 2019*

# The DeLLight group @ LAL

François Couchot

Aurélie Maillet (starting PhD)

Scott Robertson (post-doc ANR)

Xavier Sarazin

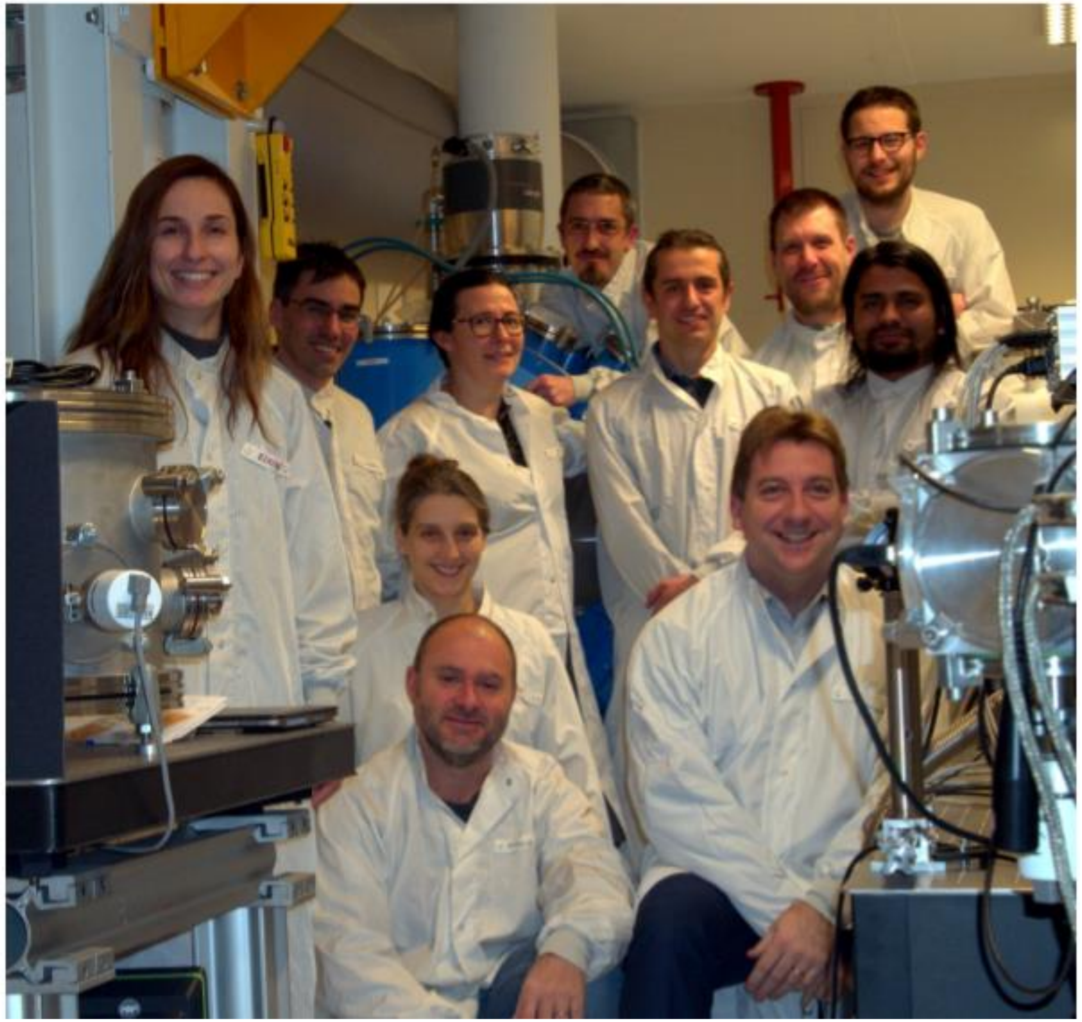
+ Marcel Urban (émerite)

# Thanks to LASERIX

- Installed at LAL since a few years
- 30 fs, 2.5 J pulses @ 10 Hz
- $\lambda \sim 800$ nm

- Dedicated to
  - X-ray laser pulses production
  - Laser-plasma acceleration tests
  - Others…

- http://hebergement.u-psud.fr/laserix/en/



# Is the vacuum optical index constant ?

- Maxwell's equations are « linear » in vacuum

$$\begin{cases} \mathbf{D} = \varepsilon_0 \mathbf{E} \\ \mathbf{B} = \mu_0 \mathbf{H} \end{cases} \qquad c = \frac{1}{\sqrt{\varepsilon_0 \mu_0}}$$

➡ **$\varepsilon_0$ and $\mu_0$ are CONSTANT**

**Optical index (*n*=1) is constant**

Do not depend on external fields

- Maxwell's equations are not linear in dielectric media

$$\begin{cases} \mathbf{D} = \varepsilon_0 \mathbf{E} + \mathbf{P}(\mathbf{E},\mathbf{B}) = \varepsilon(\mathbf{E},\mathbf{B}).\mathbf{E} \\ \mathbf{B} = \mu_0 \mathbf{H} + \mu_0 \mathbf{M}(\mathbf{E},\mathbf{B}) = \mu(\mathbf{E},\mathbf{B}).\mathbf{H} \end{cases} \qquad v = \frac{1}{\sqrt{\varepsilon(E,B)\mu(E,B)}}$$

➡ Optical index depends on external fields E,B $\Rightarrow$ ***n*(E,B)**

There is a non linear interaction between the electromagnetic fields, through the medium

*n*(B) : Birefringence induced by an external magnetic field, first measured by **Faraday** (1845)

*n*(E) : Refractive index increased by an electric field, first measured by **Kerr** (1875)

# Is the vacuum optical index constant ?

A well known nonlinear optical phenomenon in dielectric media is the **Kerr effect**:

$\Rightarrow$ Modification of the refractive index proportional to the intensity $I$ (W/cm$^2$) of the electric field in the electromagnetic wave

$$n = n_0 + n_2 \times I(\mathrm{W/cm^2})$$

$$\begin{cases} n_2(Silica) \cong 10^{-16}\ \mathrm{cm^2/W} \\ n_2(Air) \cong 10^{-19}\ \mathrm{cm^2/W} \end{cases}$$

# Is the vacuum optical index constant ?

Is the vacuum a non linear optical medium
as other material mediums ?

Can the vacuum optical index (i.e. the light velocity)
be modified by an external field ?

*This latter question has been studied for the first time in 1907 by A. Einstein in the case of gravitaion…*

# Is the vacuum optical index modified by gravitation ?

- Einstein first used the notion of vacuum refractive index and noticed that the **speed of light *c* is modified in accelerated frames and gravitation fields**

« *On the relativity principle and the conclusions drawn from it* », A. Einstein, Jahrbuch der Radioktivität une Elektronik 4 (1907) 411-462

(https://einsteinpapers.press.princeton.edu/vol2-trans/266)

V. PRINCIPLE OF RELATIVITY AND GRAVITATION

§17. *Accelerated reference system and gravitational field*

So far we have applied the principle of relativity, i.e., the assumption that the physical laws are independent of the state of motion of the reference system, only to *nonaccelerated* reference systems. Is it conceivable that the principle of relativity also applies to systems that are accelerated relative to each other?

[...]

These equations too have the same form as the corresponding equations of the nonaccelerated or gravitation-free space; however, $c$ is here replaced by the value

$$c\left[1+\frac{\gamma\xi}{c^2}\right]=c\left[1+\frac{\Phi}{c^2}\right].$$

$$\Delta n(vacuum) \propto \frac{GM}{rc^2}$$

See also:

- Einstein, A., "Über den Einfluss der Schwerkraft auf die Ausbreitung des Lichtes“, Annalen der Physik 35, 898-908 (1911)
- *Einstein A., Ann. Physik 38 (1912) 1059: “The constancy of the velocity of light can be maintained only insofar as one restricts oneself to spatio-temporal regions of constant gravitational potential”*

# Is the vacuum optical index modified by gravitation ?

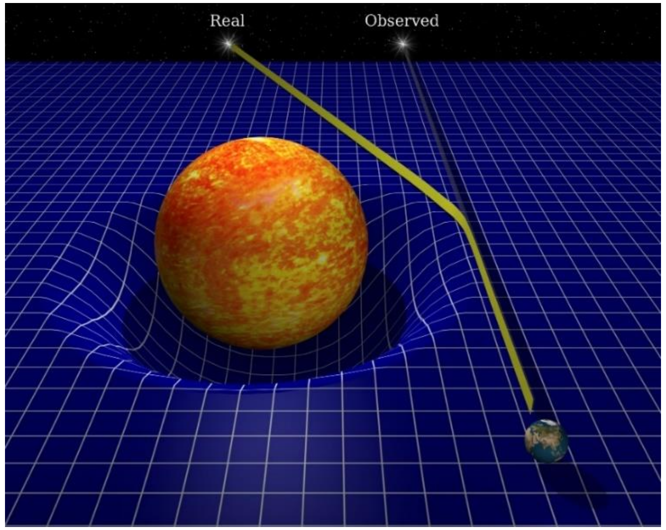
- Einstein first used the notion of vacuum refractive index and noticed that the **speed of light *c* is modified in accelerated frames and gravitation fields**

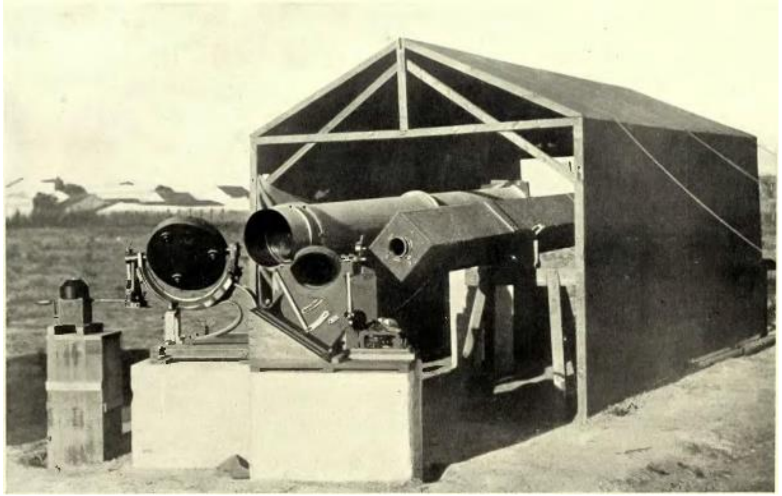
- Einstein generalized the « $\boldsymbol{c = \text{constante}}$ » relativity principle thanks to the introduction of a ***curved spacetime metric***

$\Rightarrow$ The General Relativity is a « *geo-metric* » theory

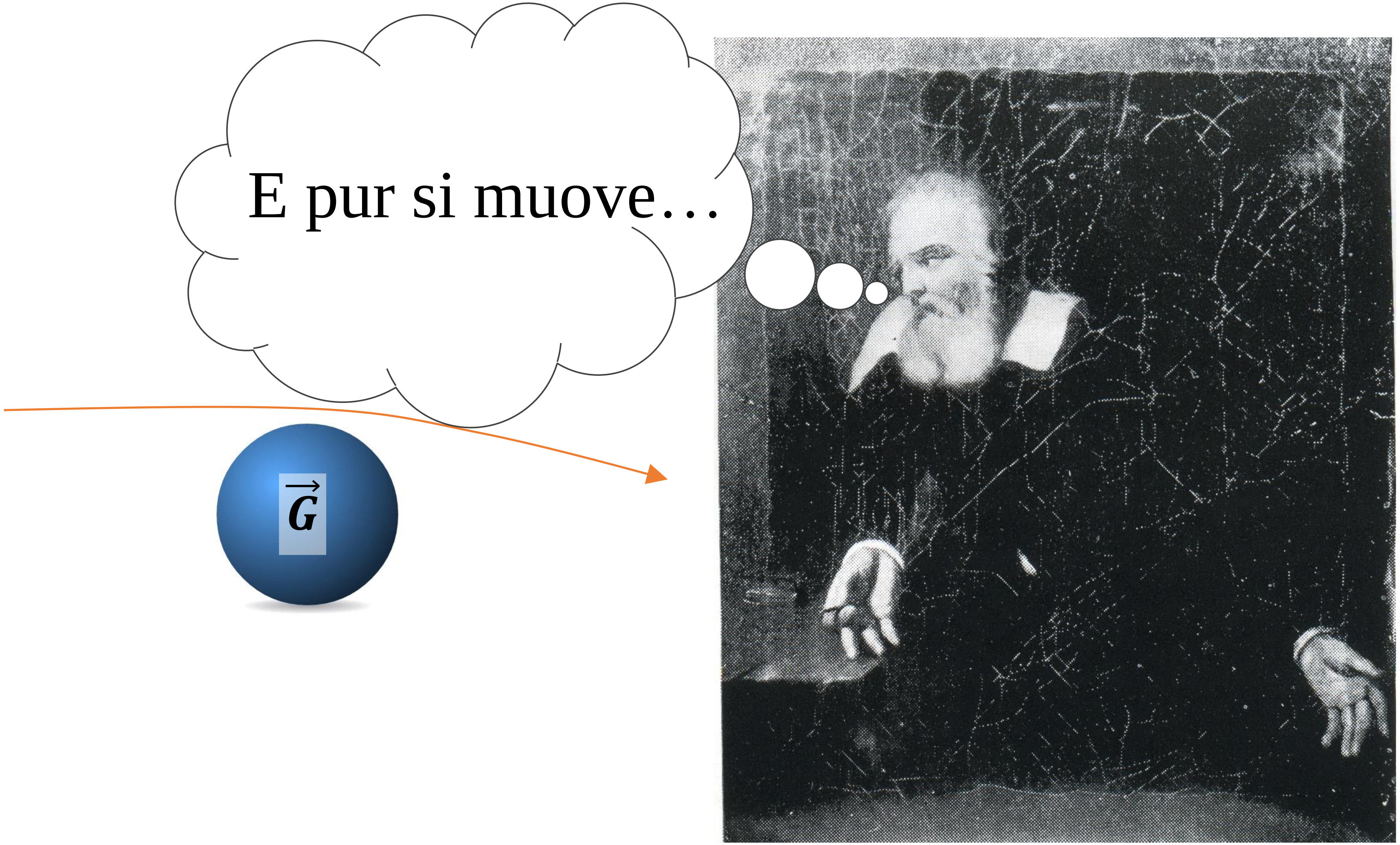
$\Rightarrow$ Vacuum has no physical role anymore

Deflection of light first observed by Eddington in 1919



# Is the vacuum optical index modified by gravitation ?



# Is the vacuum optical index modified by gravitation ?

- **Another empirical approach initially proposed by Wilson (1921) and Dicke (1957)**

*Wilson, Phys. Rev.* ***17****, 54 (1921)*
*Dicke, Rev. Mod. Phys.* ***29****, 363 (1957)*

  - ✓ **Euclidean flat metric**
  - ✓ **Spatial change of $\varepsilon_0$ and $\mu_0$** by the gravitational potential

$\Rightarrow$ Modification of the vacuum optical index $n(r)$ and the inertial masses $m(r)$

- **Vacuum refractive index $n(r)$ formally identical to $g_{00}$ in General Relativity for Maxwell equations**

$\Rightarrow$ *See Landau & Lifshitz (1975) : "A static gravitational field plays the role of a medium with electric and magnetic permeabilities* $\varepsilon_0 = \mu_0 = 1/\sqrt{g_{00}}$*"*

- **Exemple : Static spherical gravitational field** *(Wilson-Dicke Analogy)*

$$\begin{cases} n(r) = \left(1 - \dfrac{2GM}{rc_\infty^2}\right)^{-1} \\ m(r) = m_\infty \times n^{3/2}(r) \end{cases}$$

(to preserve the equivalence principle)

➡ For instance, gravitational redshift is induced by a radial change of both the vacuum optical index and the atomic energy levels

# Cosmology with a vacuum index increasing with time

$$n(r) \cong 1 + \frac{2GM}{rc_\infty^2}$$

? Dicke's idea: $1 = n(t=0) = \int \frac{2G(r)4\pi\rho r^2}{rc^2(r)} dr$

**$n(t)$ increases with time, uniformly in space**

Hubble cosmological redshift due to a time variation of both $n(t)$ and the atomic energy levels

**SN-Ia data are well fitted by an exponantial variation of the vacuum refractive index in a static Euclidean metric:**

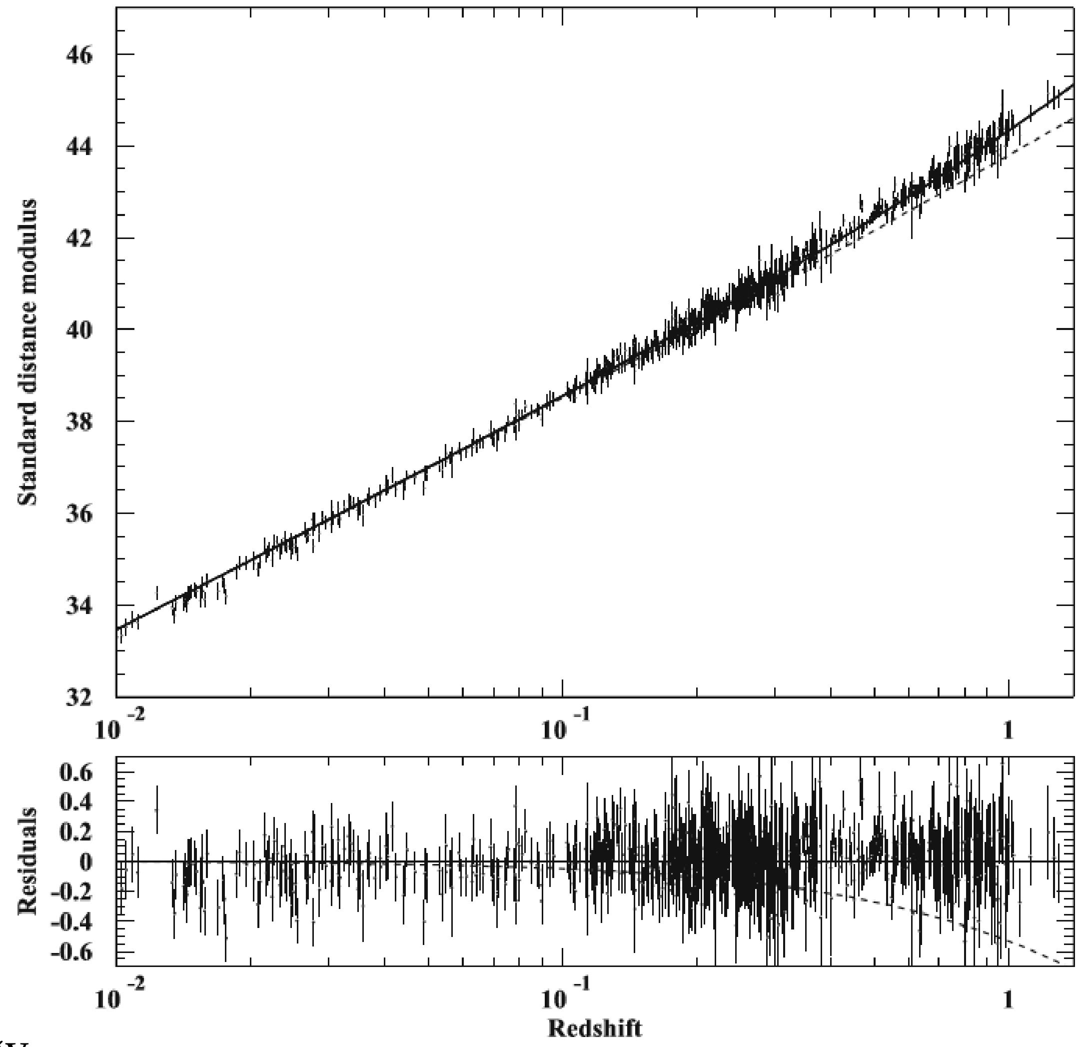
$$n(t) = e^{t/\tau_0}$$

$$\tau_0 = 8.0^{+0.2}_{-0.8} \text{ Gyr}$$

*XS et al. Eur. Phys. J. C 78, 444 (2018); arXiv:1805.03503*

Also shown in this article:

- ✓ Time dilatation of the SN-Ia
- ✓ Evolution of the CMB consistent with standard cosmology



Is the vacuum optical index modified by electromagnetic fields ?

# « Born-Infeld » non linear electrodynamics

**A crucial problem in physics**:

Electromagnetic mass of the electron = self-energy of a point charge… which is infinite !

*(By the way, this problem is still unsolved in quantum field theory !…)*

➡ **How to regularize an electromagnetic field ?**

Born and Infeld, in 1934, proposed to introduce non linear interactions between electromagnetic fields by assuming an absolute field $E_{abs}$

*Born and Infeld, Proc. R. Soc. A 144, 425 (1934)*
*Fouché et al., Phys. Rev. D 93, 093020 (2016)*

$$\mathcal{L}_{Born} = \epsilon_0 E_{abs}^2 \left( -\sqrt{1 - \frac{\epsilon_0 E^2 - B^2/\mu_0}{\epsilon_0 E_{abs}^2} - \frac{(\mathbf{E}\cdot\mathbf{B})^2}{\mu_0 E_{abs}^2}} + 1 \right)$$

$$\mathcal{L}_{Born} \cong \mathcal{L}_{Maxwell} + \delta\mathcal{L}_{NL} \quad \begin{cases} \mathcal{L}_{Maxwell} = \frac{1}{2}\left(\epsilon_0 E^2 - \frac{1}{\mu_0} B^2\right) \\ \delta\mathcal{L}_{NL} = \frac{1}{8\epsilon_0 E_{abs}^2}\left(\epsilon_0 E^2 - \frac{1}{\mu_0} B^2\right)^2 + \frac{1}{2\epsilon_0 E_{abs}^2}(\mathbf{E}\cdot\mathbf{B})^2 \end{cases}$$

➡ $E_{abs}$ is a free parameter of the Born-Infeld theory

⚠ **Born-Infeld theory predicts no birefringence** ⚠

# « Euler-Heisenberg Lagrangian » & non linear QED

Euler-Heisenberg (1935) : nonlinearity induced by the coupling of the field with the $e^+/e^-$ virtual pairs in vacuum

*Heisenberg and Euler, Z. Phys. 98, 714 (1936)*

$$\begin{cases} \boldsymbol{D} = \varepsilon_0 \boldsymbol{E} + \boldsymbol{P}(\boldsymbol{E},\boldsymbol{B}) \\ \boldsymbol{B} = \mu_0 \boldsymbol{H} + \mu_0 \boldsymbol{M}(\boldsymbol{E},\boldsymbol{B}) \end{cases} \qquad \begin{cases} \boldsymbol{P} = \xi \varepsilon_0^2 [2(E^2 - c^2B^2)\boldsymbol{E} + 7c^2(\boldsymbol{E}.\boldsymbol{B})\boldsymbol{B}] \\ \boldsymbol{M} = -\xi \varepsilon_0^2 [2(E^2 - c^2B^2)\boldsymbol{B} - 7(\boldsymbol{E}.\boldsymbol{B})\boldsymbol{E}] \end{cases} \qquad \xi^{-1} = \frac{45 m_e^4 c^5}{4\alpha^2 \hbar^3} \approx 3\ 10^{29}\ \mathrm{J/m^3}$$

⇒ Modification of the Maxwell's equations in vacuum ⇒ Vacuum is a non linear medium

**The vacuum refractive index is not an absolute constant** $n \neq 1$

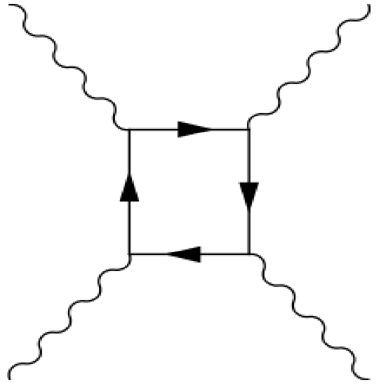
It can be **modified on large scale** (low energy) when it is stressed by intense e.m. fields

This result has been derived later by Schwinger within the QED frame

*J. Schwinger, Phys. Rev. 82, 664 (1951)*

Schwinger critical field :

$$\begin{cases} E_{cr} = \dfrac{m_e^2 c^3}{e\hbar} = 1.3 \times 10^{18}\ \mathrm{V/m} \\ B_{cr} = E_{cr}/c = 4.4 \times 10^9\ \mathrm{T} \end{cases}$$

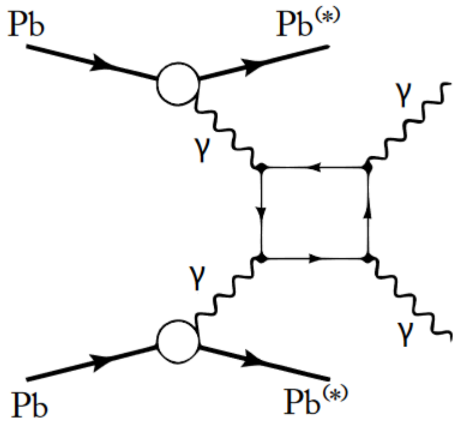


# Two-photons scattering v.s. Intense fields

Coherence effect @ macroscopic scale
in intense Field intensity

$E_{cr} = 1.3 \times 10^{18}$ V/m

$\boldsymbol{E_{LASERIX} \approx 3 \times 10^{13}}$ **V/m**




Pb+Pb(γγ)
→ Pb(*)+Pb(*) γγ

Two-photons scattering
Perturbative QED

Atlas,CMS@LHC

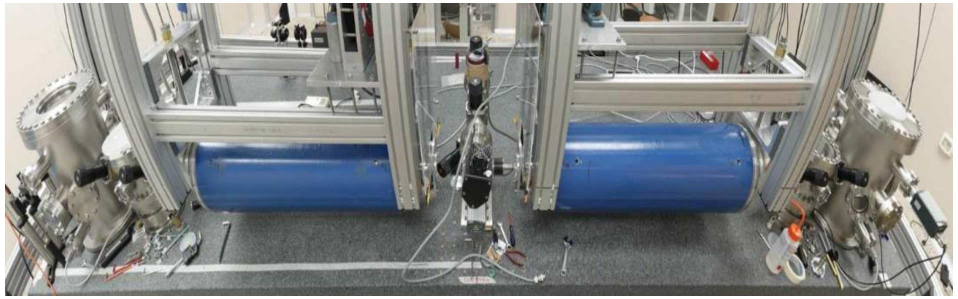
*arXiv:1702.01625*
*arXiv:1810.04602*

# Current experimental tests: Vacuum Magnetic Birefringence

➢ Search for birefringence with the PVLAS + BMV experiments

$$\Delta n_{QED} = 4 \times 10^{-24}\ T^{-2}$$

Fabry-Perrot laser cavity with an external B field



PVLAS: Rotating field B=2.5 T *Eur. Phys. J. C (2016) 76:2*

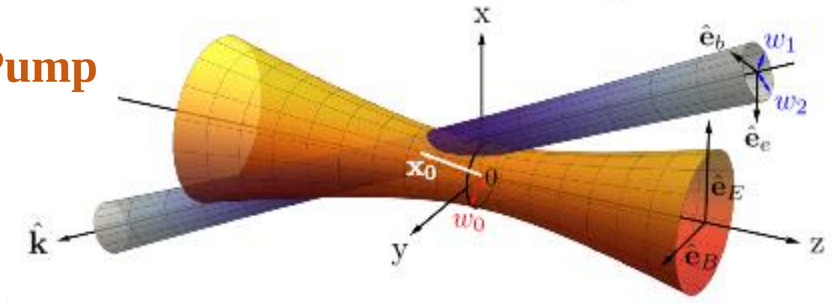
BMV: Pulsed field B=6.5 T *Eur. Phys. J. D (2014) 68: 16*

**0.1 σ sensitivity after ~100 days of measurement**

⇒ Letter of intent submitted end 2018 for a VMB experiment @ CERN *(CERN-SPSC-2018-036/SPSC-I-249)*

➢ Project @ XFEL using x-ray free electron and intense PW laser *Phys. Rev. D 94,013004 (2016)*

**Laser Pump**

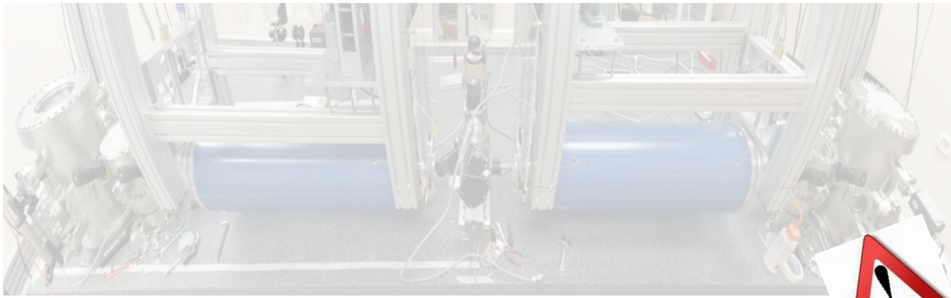


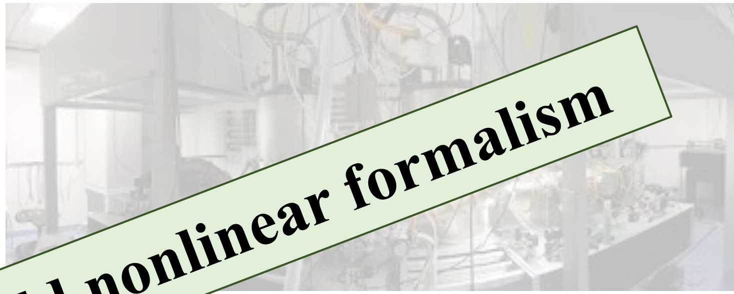

**X-ray Probe**

# Current experimental tests: Vacuum Magnetic Birefringence

- Search for birefringence with the PVLAS + BMV experiments $\Delta n_{\mathrm{QED}} = 4 \times 10^{-24}\ \mathrm{T}^{-2}$

Fabry-Perrot laser cavity with an external B field





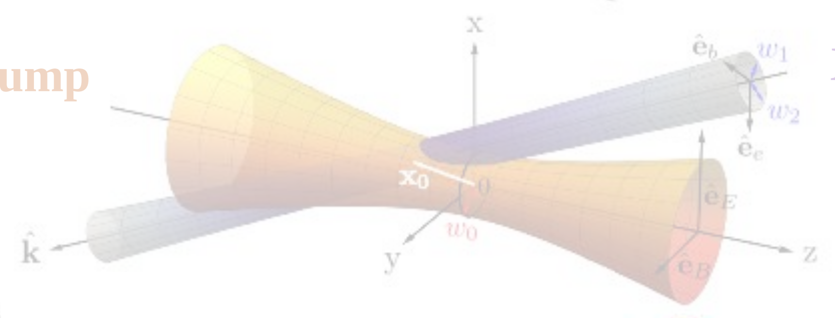
PVLAS: Rotating field B=2.5 T *Eur. Phys. J. C ...16) 76:2...* ...V: Pulsed field B=6.5 T *Eur. Phys. J. D (2014) 68: 16*

**0.1 σ sensitivity after ~1... ...measurement**

**Birefringence null with Born-Infeld nonlinear formalism**

⇒ Letter of intent s... 2018 for a VMB experiment @ CERN *(CERN-SPSC-2018-036/SPSC-I-249)*

- Project @ XF... using x-ray free electron and intense PW laser *Phys. Rev. D 94,013004 (2016)*



# Jone’s experiment in 1960…

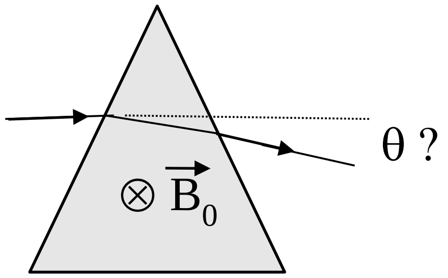
- Variation of the vacuum refractive index, independentely of the polarization, has been tested only once, by R.V. Jones in 1960

- **Jones’s experiment (1960)** : Magnetic prism in vacuum with a static external field **B = 1 Tesla**

  Theoretical expected signal $\Delta\theta_{\mathrm{QED}} \cong 10^{-23}$ rad

  Sensitivity ≅ 0.5 picorad (!)

  $\Delta\theta_{\mathrm{QED}} \propto B^2$




**DeLLight with intense laser field produced by LASERIX**

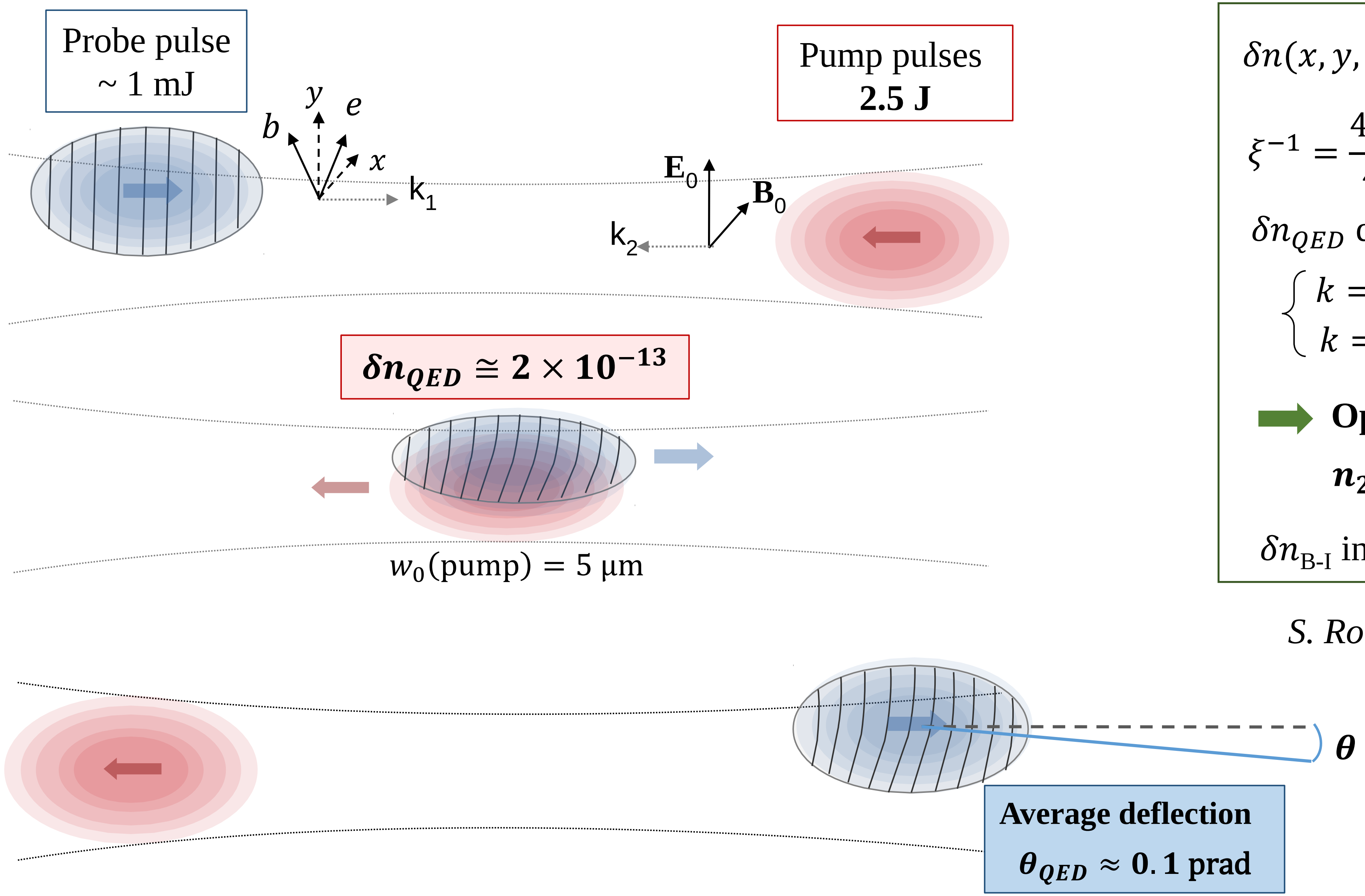
2.5 J, 30 fs, $w_0$=5μm ⇒ ~ $3 \times 10^{20}$ W/cm$^2$ ⇒ $\boldsymbol{E} \sim \mathbf{3 \times 10^{13} V/m}$, $\boldsymbol{B} \sim \mathbf{10^5}$ **T**

# The DeLLight experiment

- ✓ Principle published in 2016
  X. Sarazin et al., *Refraction of light by light in vacuum*, Eur. Phys. J. D, 70 1 (2016) 13

- ✓ Recently consolidated by Scott J. Robertson's theory work
  *arXiv:1908.00896*, accepted for publication in Phys. Rev.

# Pump-Probe interaction




$$\delta n(x,y,z,t) = k \times \xi 4\varepsilon_0 E_0^2$$

$$\xi^{-1} = \frac{45 m_e^4 c^5}{4\alpha^2 \hbar^3} \approx 3 \times 10^{29}\ \text{J/m}^3$$

$\delta n_{QED}$ depends on the polarisation

$$\begin{cases} k = 7/4 & \text{when } e_y = 0 \\ k = 1 & \text{when } e_x = 0 \end{cases}$$

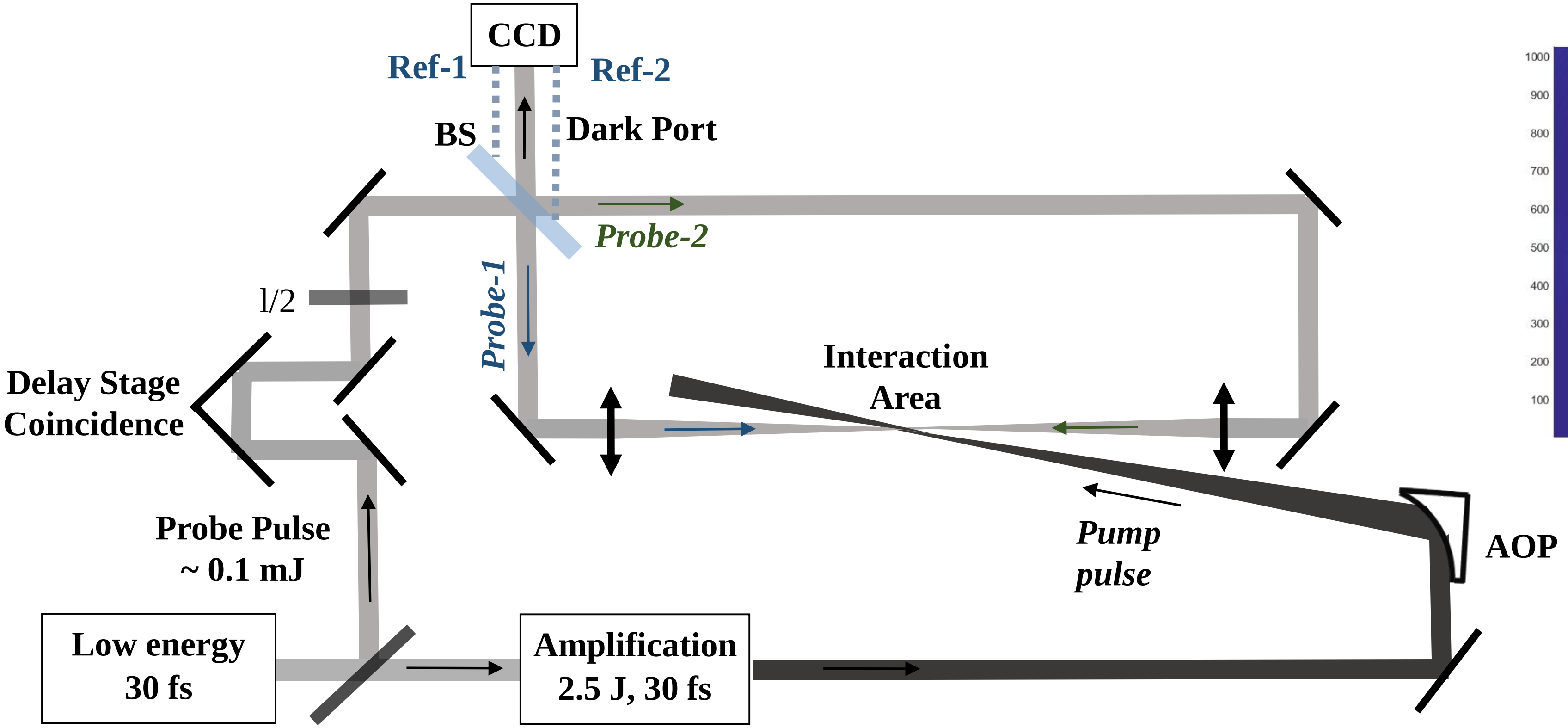
➡ **Optical Kerr index**

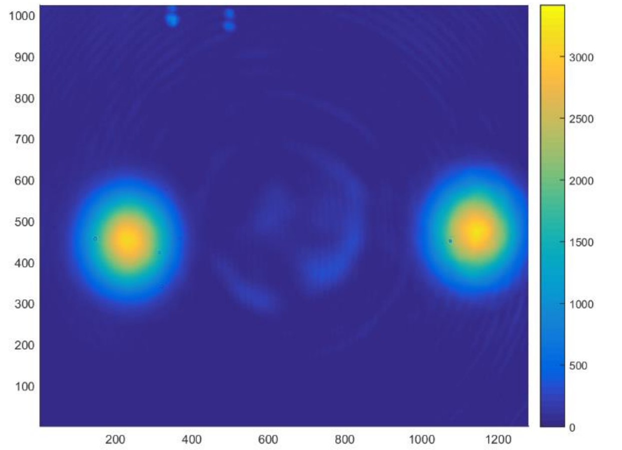
$$\boldsymbol{n_2 = 1.6 \times 10^{-33}\ \text{W/cm}^2}$$

$\delta n_{\text{B-I}}$ independent of the polarisation

*S. Robertson, arXiv:1908.00896*
*(Phys. Rev. A 2019)*

# Refraction measured with a Sagnac Interferometer



- **Refraction** of the probe pulse $\Rightarrow$ **Transversal shift $\boldsymbol{\Delta x}$** of the interference intensity profile
- **Amplification factor $\boldsymbol{\mathcal{F}}$** compared to standard pointing method: $\mathcal{F} = \dfrac{1}{2\sqrt{Extinction}} = 250$ for Extincton $= 0.4 \times 10^{-5}$
- Extinction independent of the beam pointing fluctuations
- The **beam pointing fluctuations** are measured and suppressed thanks to the back-reflexions on the beam splitter

# Numerical Simulations

## 3-d (x,y,z) numerical simulations:

- **Two pulses** (30 fs, 800 nm) with ortogonal polarisation are counter-propagating (along z) and focused
- Transversal profiles of the beams are **gaussian**
- Energy pump pulse **E=2.5 J**

  (Energy probe pulse is negligible ~100 μJ)
- Minimum waist at focus: $\boldsymbol{W_o}$**(pump)** $=$ $\boldsymbol{w_o}$**(probe) = 5 μm**
- Pump beam is shifted transversely by a distance $\boldsymbol{\delta}_{\textbf{shift}}$
- Vacuum refractive index is calculated in the interaction : $\delta n_{QED}(x,z,t) = 7\xi\varepsilon_0 c^2 E^2(x,z,t)$

  $\Rightarrow$ After interaction, the probe pulse is refracted by a phase $\varphi_{QED}(x,z) = \int \frac{2\pi c}{\lambda}\delta n_{QED}(x,z,t)dt$
- Gaussian propagation of the refracted and unrefracted probe pulses to the **focal distance** $\boldsymbol{f}$
- Finaly they interfer in the dark output with an **extinction** $\boldsymbol{\mathcal{F} = 4\epsilon^2} = 0.4 \times 10^{-5}$

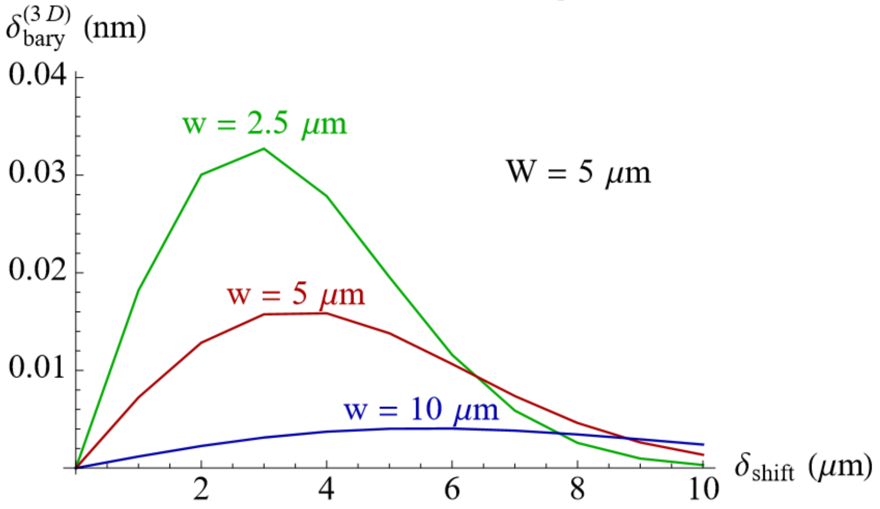
  ($\epsilon$ = assymetry of the beam splitter)

# Numerical Simulations

- E = 2.5 J,
- Extinction = 0.4 $10^{-5}$ ($\epsilon = 10^{-3}$)
- f = 50 cm *(limited by the beam divergence)*
- $W_0$(pump) = $w_0$(probe) = 5 µm

$$\boldsymbol{\Delta y = 0.015\ nm}$$

Signal depends on $\delta_p$




Signal $\Delta x$ reduced by ~20% if jitter pump ±2.5µm

$$\Delta y = 2.7\ \text{nm}\ \times \frac{E(Joule) \times f(m)}{\left(w_0^2 + W_0^2\ (\mu\text{m})\right)^{3/2} \times \sqrt{\mathcal{F}/10^{-5}}}$$

# Expected sensitivity

- Switch ON & OFF alternatively the pump beam (laser repetition rate = 10 Hz):

  ⇒ Barycenters of the intensity profile : $\bar{y}_k^{ON}$ and $\bar{y}_k^{OFF}$

  ⇒ Signal (ON-OFF) for the measurement $k$ : $\Delta y_k = \bar{y}_k^{ON} - \bar{y}_k^{OFF}$

- With $N_{mes}$ measurements collected, the average signal is $\overline{\Delta y} \pm \sigma_y/\sqrt{N_{mes}}$

  where **$\boldsymbol{\sigma_y}$ is the ON-OFF spatial resolution, including systematics**

- The sensitivity (number of standard deviations $N_{sig}$) is :

$$\boldsymbol{N_{sig}} = \frac{\overline{\Delta y}}{\sigma_y/\sqrt{N_{mes}}} = 1.8 \times 10^3 \times \frac{E(Joule) \times f(m) \times \sqrt{T_{obs}(\text{days})}}{\left(w_0^2 + W_0^2\ (\mu\text{m})\right)^{3/2} \times \sqrt{\mathcal{F}/10^{-5}} \times \boldsymbol{\sigma_y}(\text{nm})}$$

$$\begin{cases} E = 2.5\ \text{J},\ f = 0.5\ \text{m} \\ \text{Extinction}\ \ \mathcal{F} = 10^{-5} \\ \sigma_x = 10\ \text{nm} \\ w_0\ \text{(pump, probe)} = 5\ \mu\text{m} \end{cases}$$

⇒ $N_{sig} \cong 0.6 \times \sqrt{T_{obs}(\text{days})}$ ⇒ **3 sigma in ~20 days**

With $w_0(probe) = 20\ \mu\text{m}$ ⇒ $N_{sig} \cong 0.1$ (same as PVLAS birefringence sensitivity) with 16 days of collected data

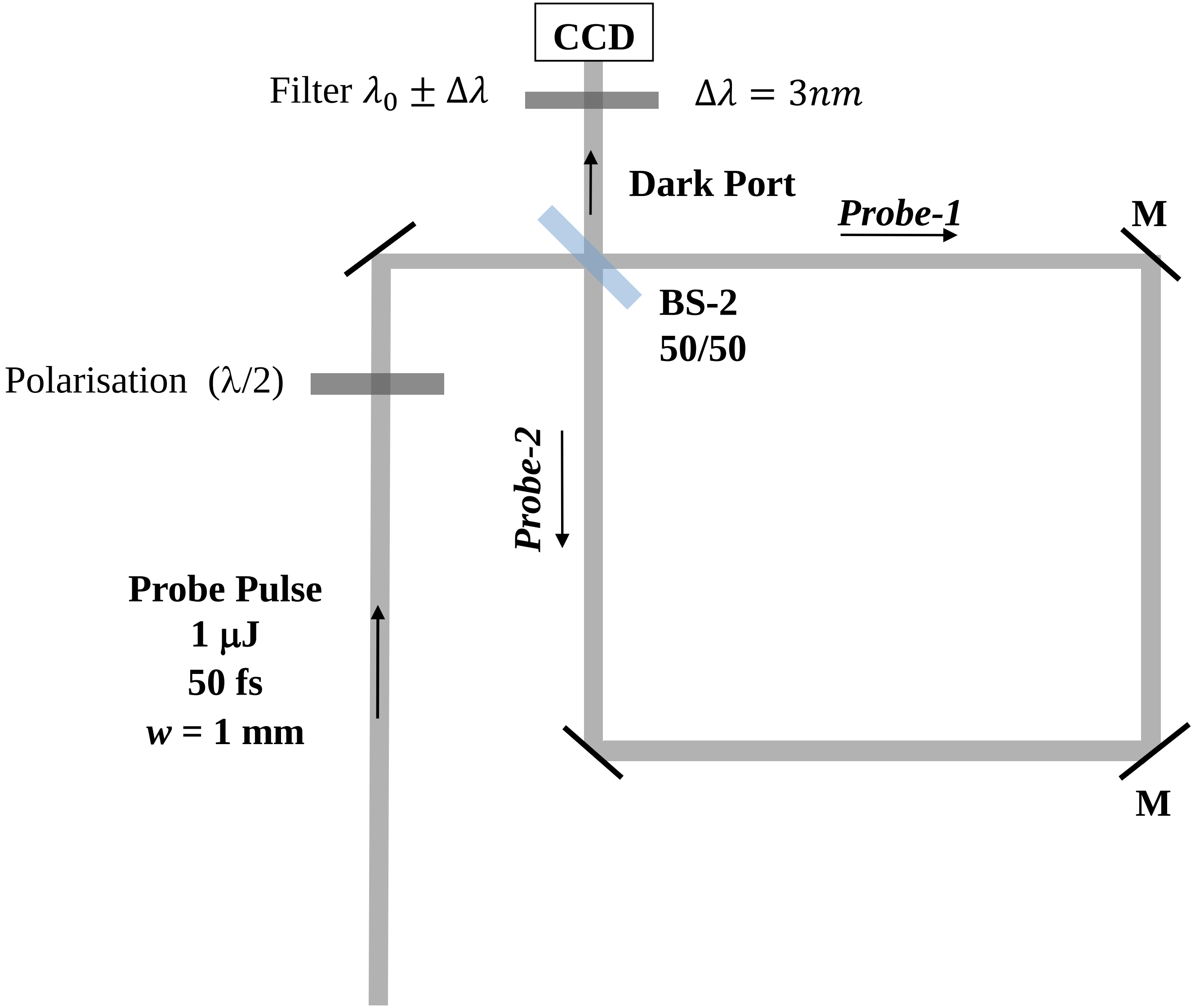
# Experimental challenges

- ✓ Extinction: $\mathcal{F} = 10^{-5}$
- ✓ Spatial resolution: $\sigma_x = 10$ nm
- ✓ Waist at focus as low as possible

  + stability of the pump-probe overlap

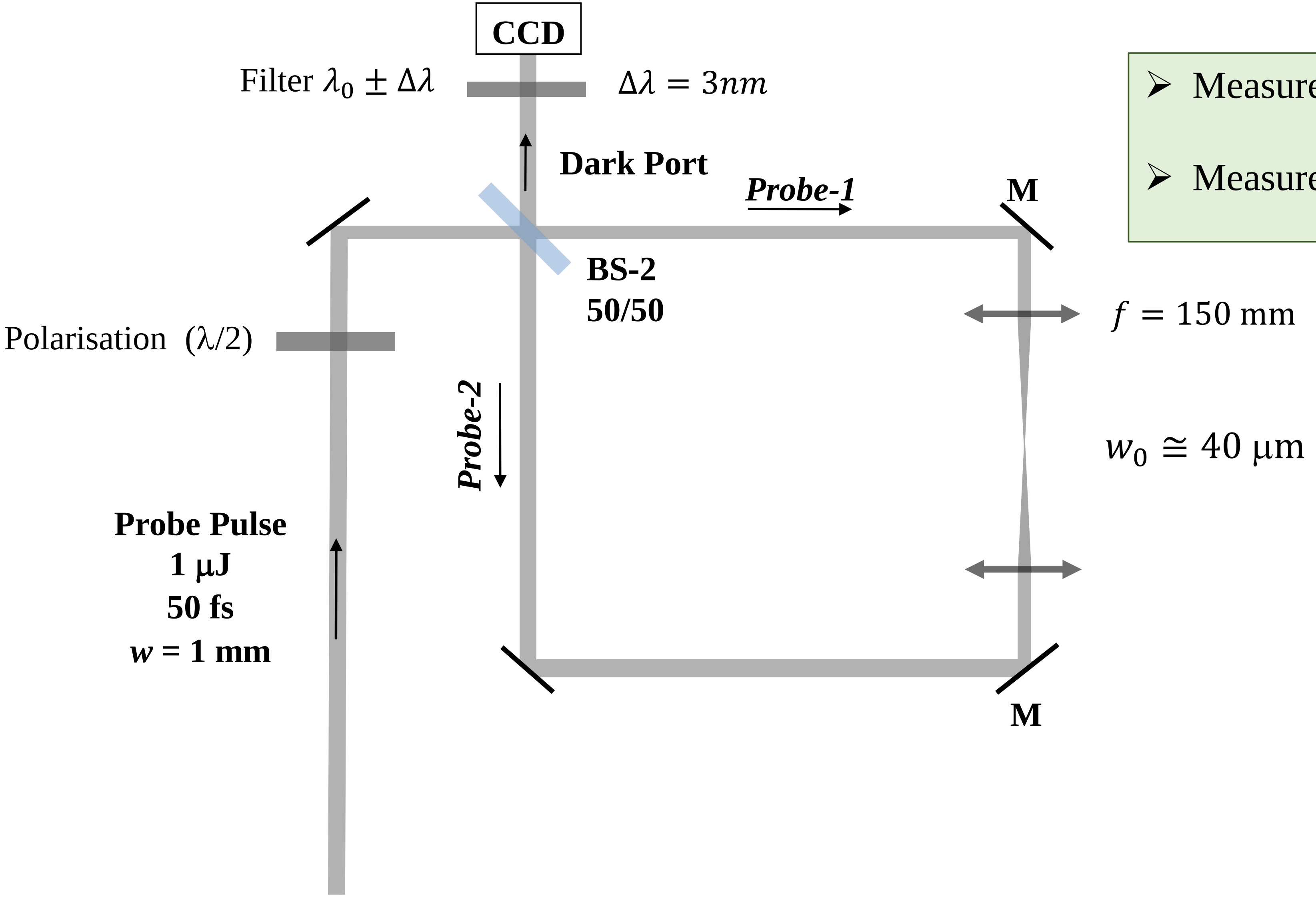
DeLLight prototypes

# DeLLight prototypes



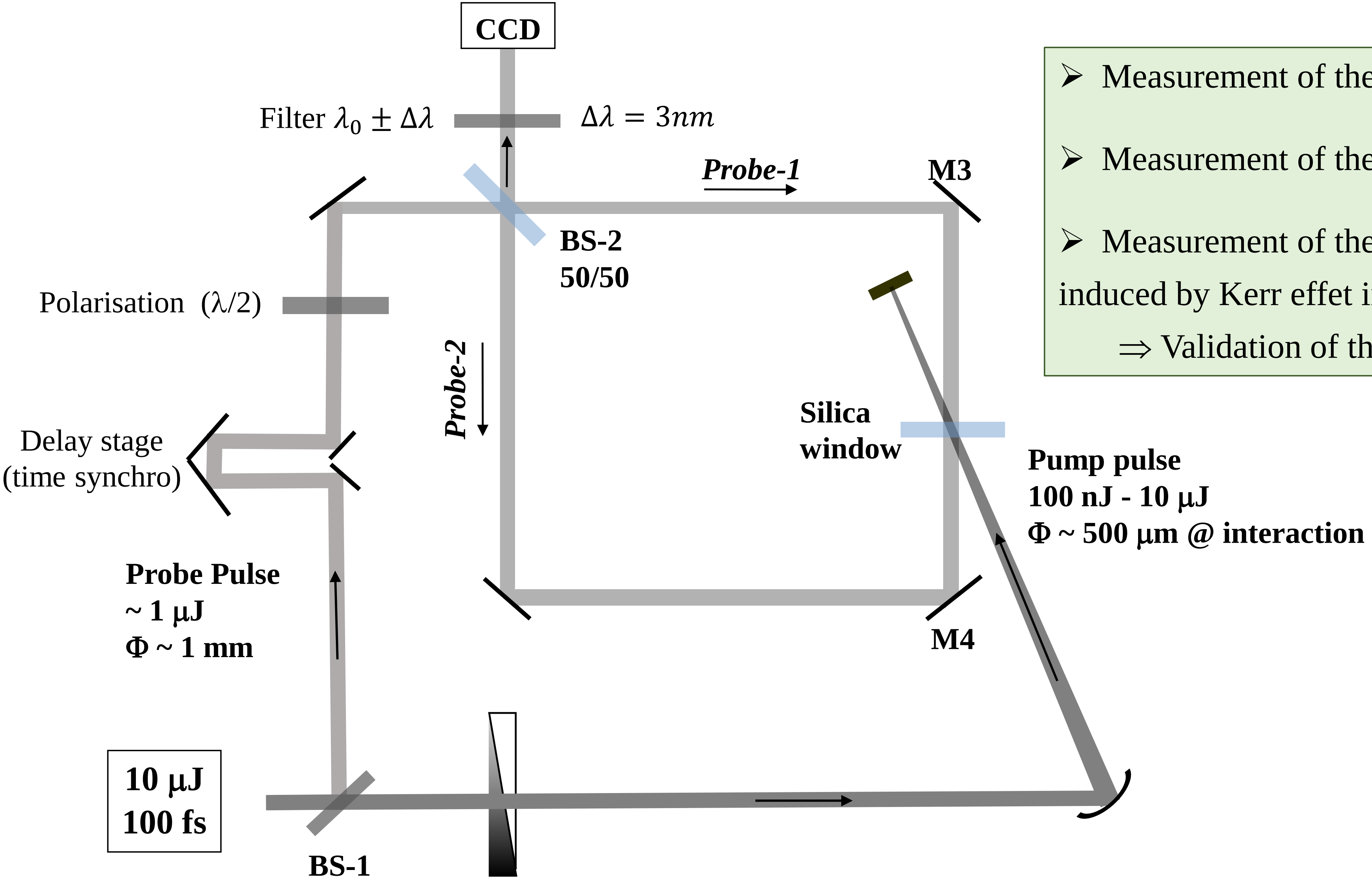

- Measurement of the extinction factor
- Measurement of the spatial resolution

# DeLLight prototypes




- Measurement of the extinction factor
- Measurement of the spatial resolution

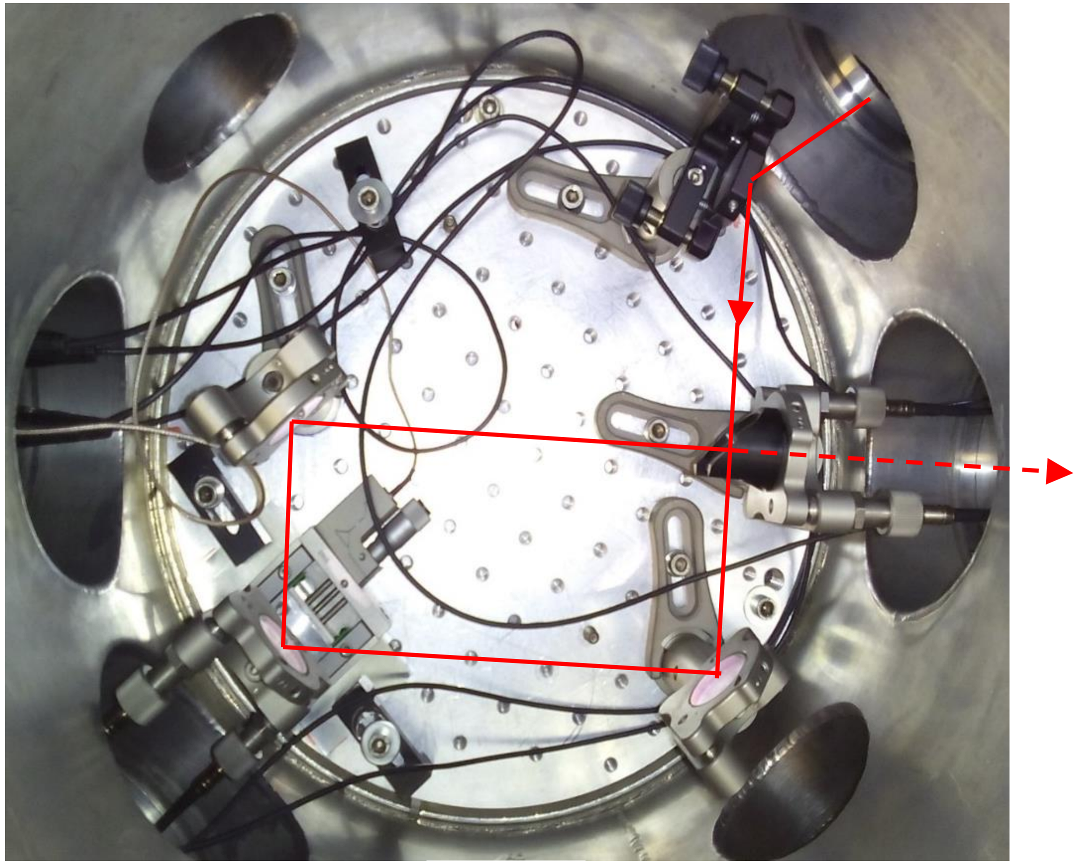
# DeLLight prototypes




- Measurement of the extinction factor
- Measurement of the spatial resolution
- Measurement of the index gradient induced by Kerr effet in silica window and in gas

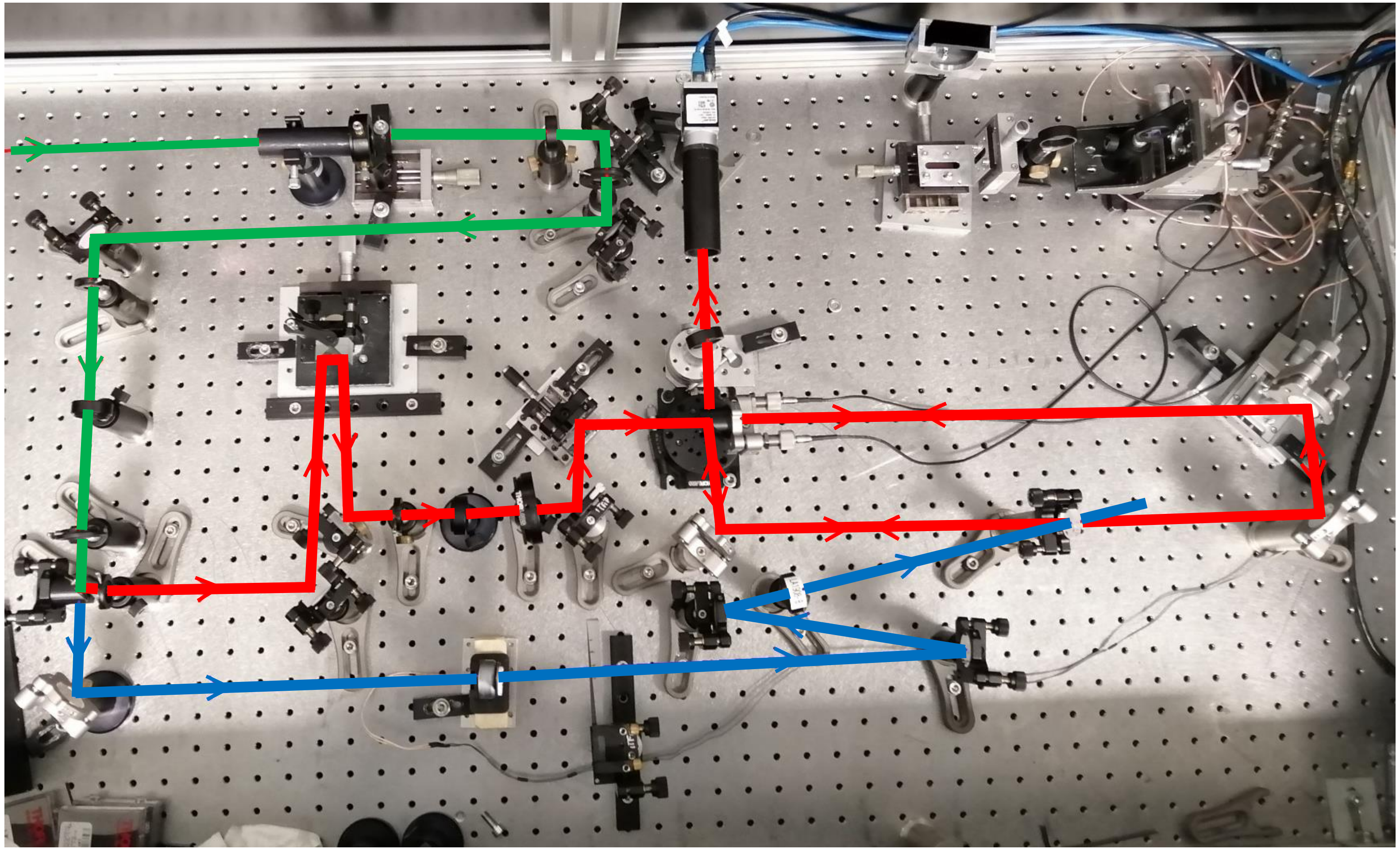
  ⇒ Validation of the methode

# Sagnac interferometer in vacuum



⟵ 20 cm ⟶

# DeLLight current prototype



- ✓ Beam Splitter 50/50 *Semrock™* (thickness=3mm)
- ✓ Flat silver mirror standard (λ/10)
- ✓ BS and opposite mirror controled with piezo *POLARIS® K1S2P* 5 nrad/mV
- ✓ Filter $\Delta\lambda = 3$ nm @ 800 nm in the dark output
- ✓ CCD camera *BASLER™* *acA1300-60gm*
  1260x1080 pixels
  pixel size = 5.3 μm
  saturation ≅ $10^4$ electrons/pixel

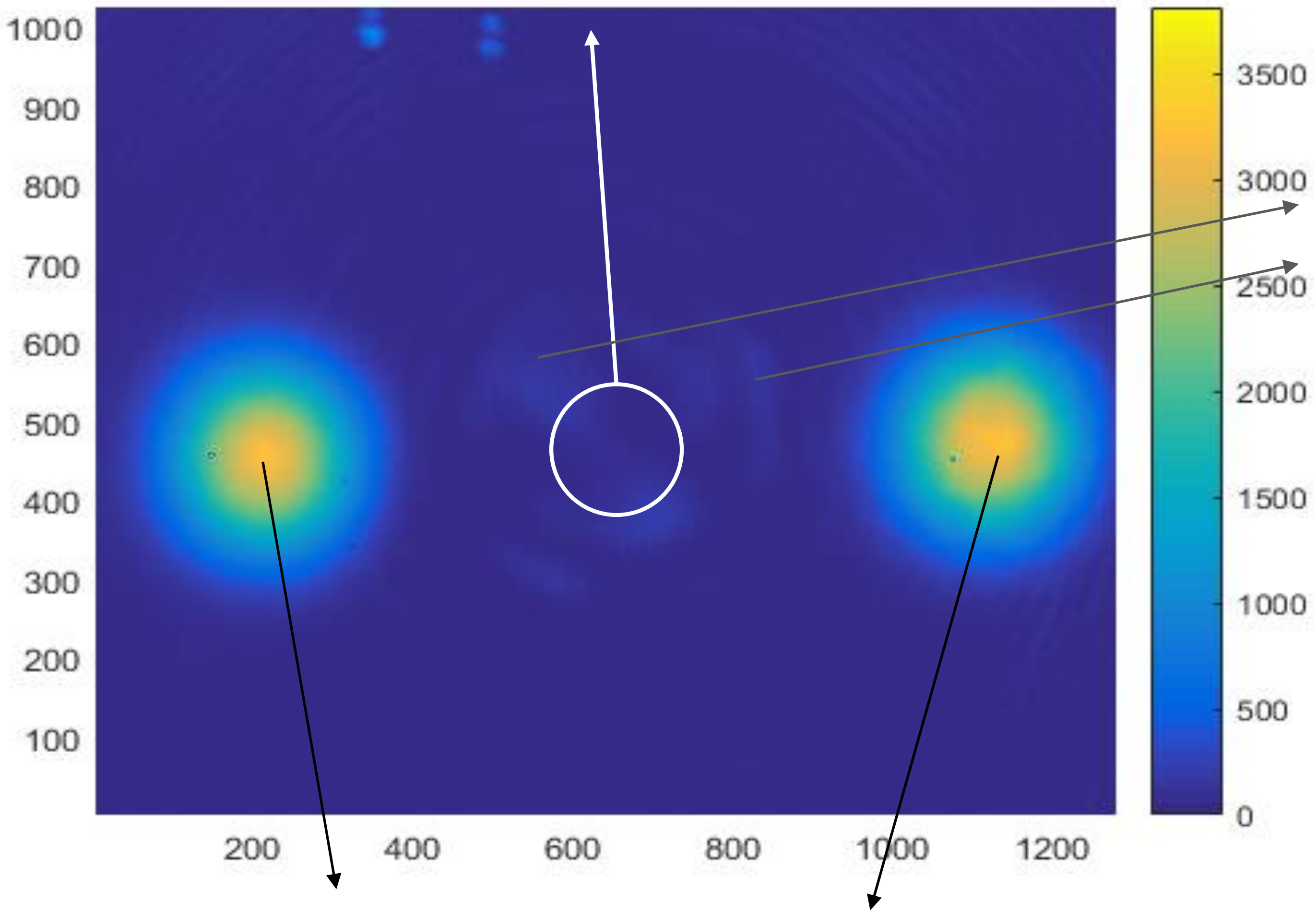
# Extinction of the interferometer

Signal : Extinction ~ $10^{-5}$

Extinction = $4\varepsilon^2$

$\varepsilon = I_t/I_r$ = Asymetry (intensity) of the beam splitter

$\varepsilon$ depends upon the polarization




Hot spots :

Surface defects on mirors inside the Sagnac

Back reflection (~ $5\times10^{-4}$)

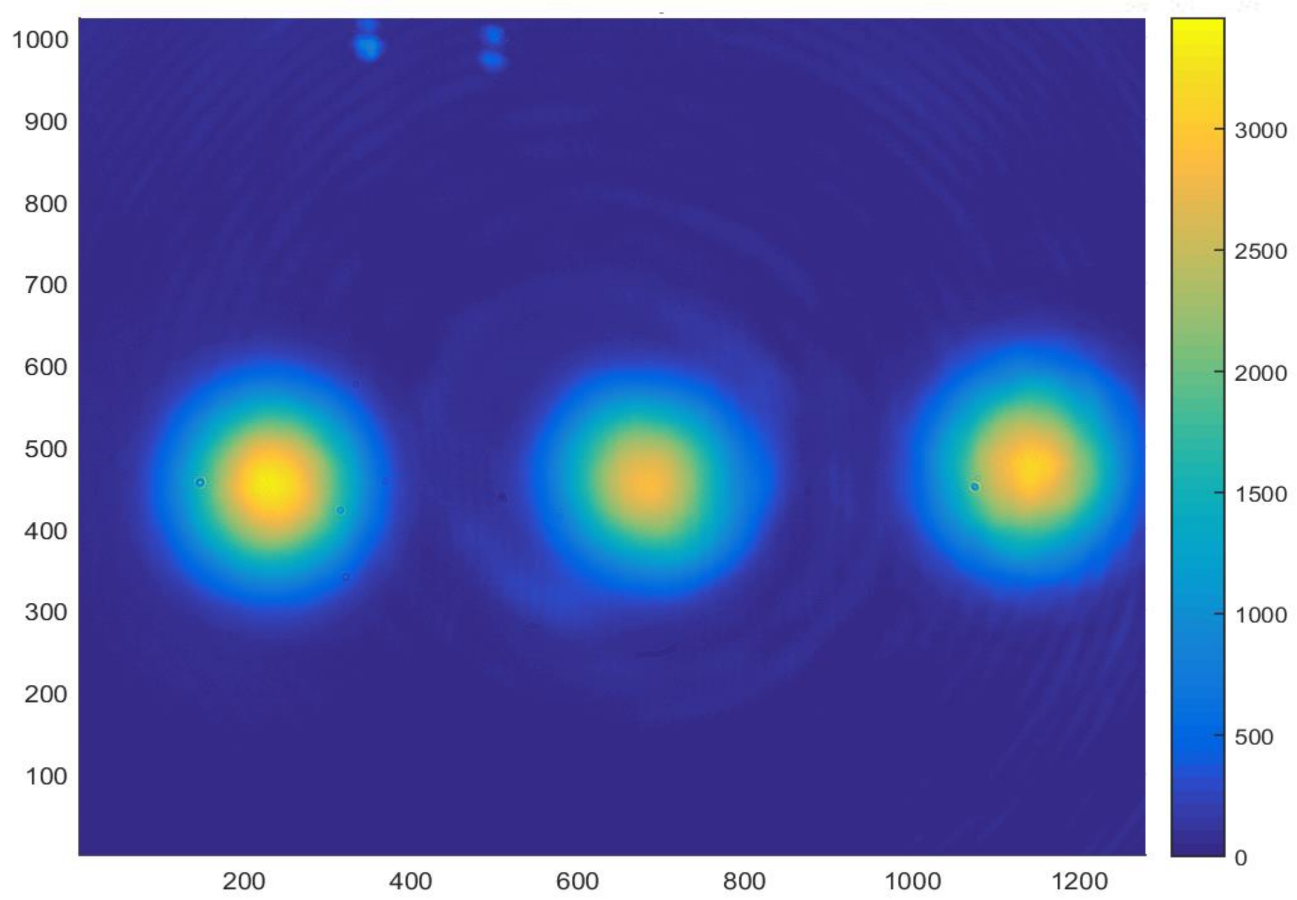
# Extinction of the interferometer

Rotation of the polarization ⇒ Extinction ~ $5\times10^{-4}$

Extinction = $4\varepsilon^2$

$\varepsilon = I_t/I_r =$ Asymetry (intensity) of the beam splitter

$\varepsilon$ depends upon the polarization



# Experimental challenges

- ✓ Extinction: $\mathcal{F} = 4\epsilon^2 \cong 10^{-5}$
- ✓ Spatial resolution: $\sigma_x$
- ✓ Waist at focus as low as possible

  + stability of the pump-probe overlap

# Spatial resolution

**Expected resolution limited by the photon statistic:**

$$\Rightarrow \sigma_x \propto \frac{d_{pix}}{\sqrt{N_{e-}^{max}}}$$

- Monte-Carlo: CCD (*BASLER™ acA1300-60gm)*
  - Pixel size $d_{pix}$: 5.4×5.4 μm$^2$
  - Charge saturation $N_{e-}^{max} \cong 10^4$ e$^-$/pixel

$$\Rightarrow \boldsymbol{\sigma_x} \cong \mathbf{33\ nm}$$

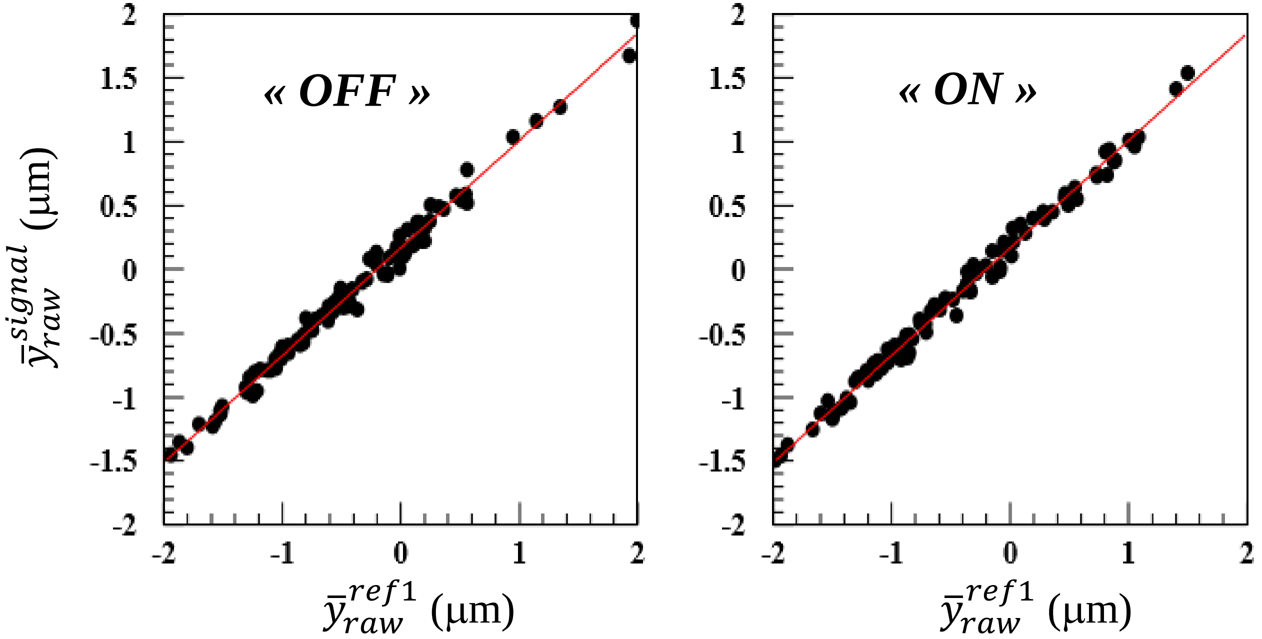
- With better CCD *BASLER™* (*acA4024-29um* ):
  - Pixel size $d_{pix}$: 1.8×1.8 μm$^2$
  - Charge saturation $N_{e-}^{max} \cong 10^4$ e$^-$/pixel

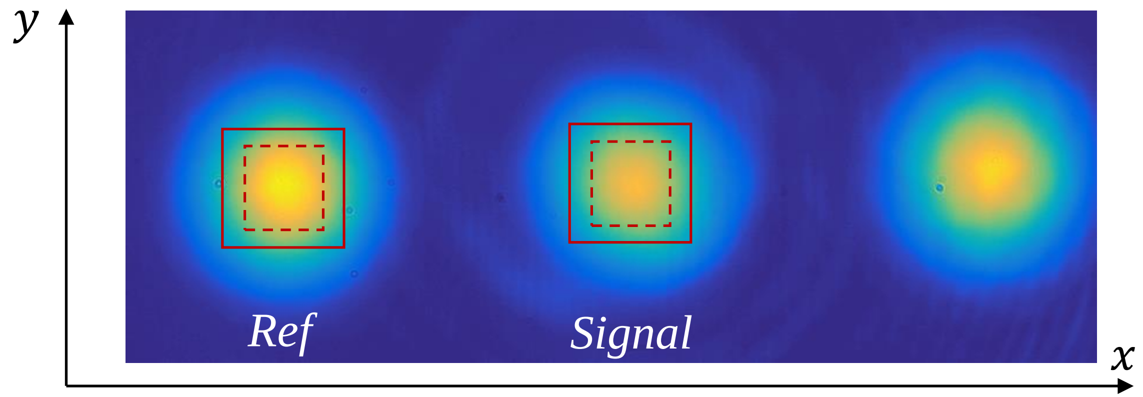
$$\Rightarrow \boldsymbol{\sigma_x} \cong \mathbf{10\ nm}$$

# Spatial resolution

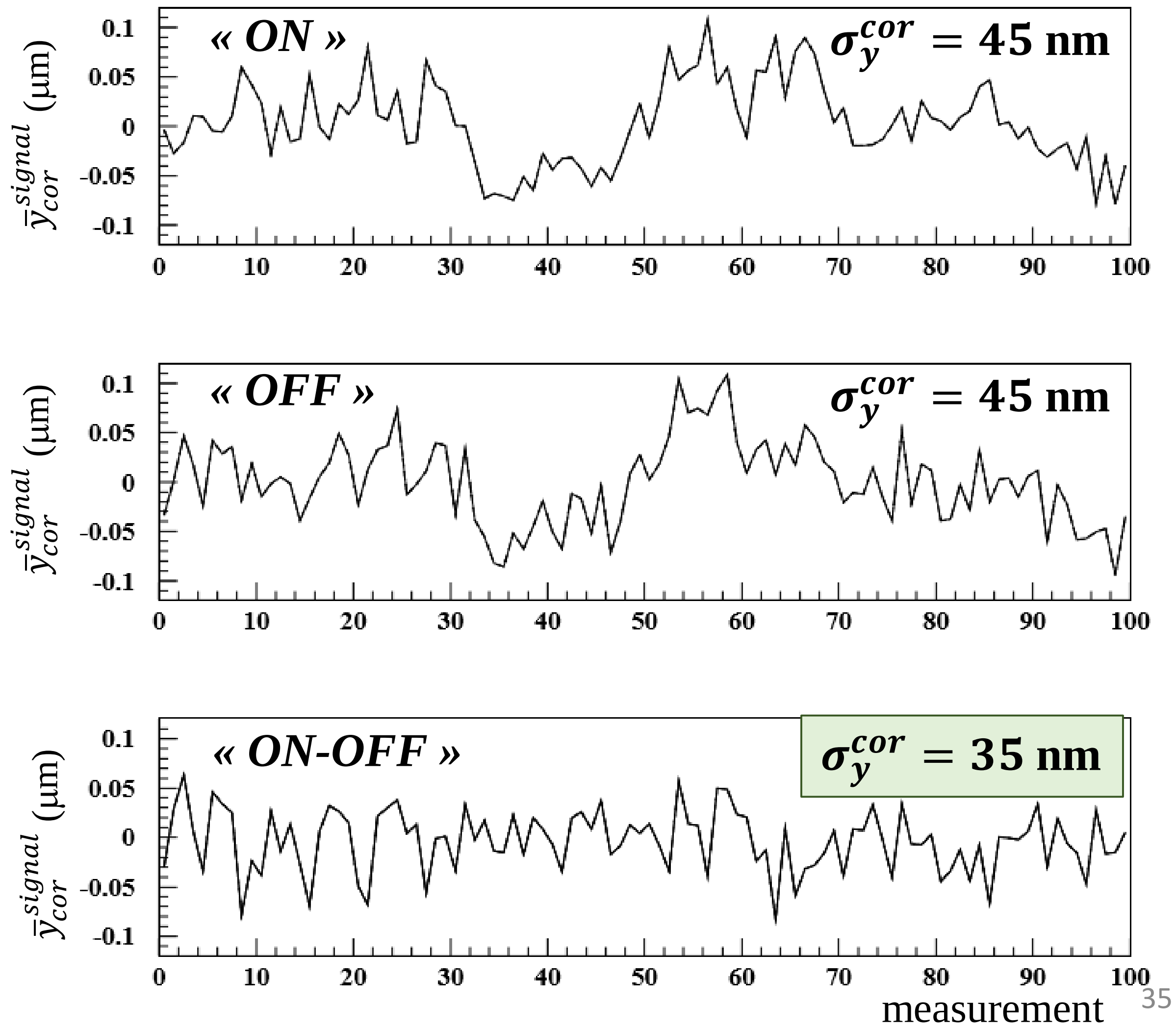
Analysis based on a barycenter calculation in a simple square analysis window (RoI) : $\mathbf{ROI = 1.5 \times \sigma_{beam}}$

**Beam pointing fluctuations are well measured by the back-reflections on BS**

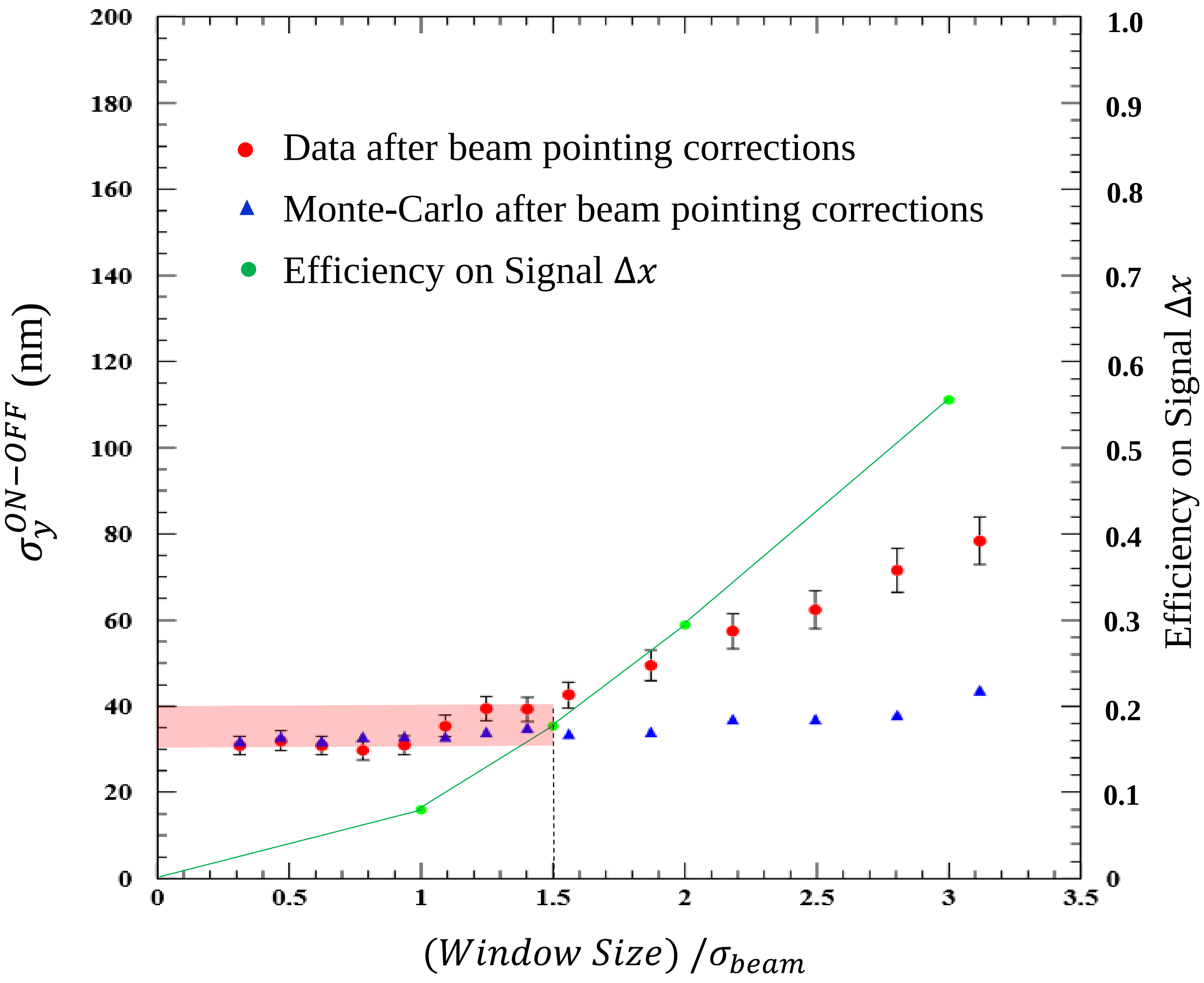



**After beam pointing correction**
**⇒ low frequency drift supressed by ON-OFF subtraction**



# Spatial resolution




- RoI $\lesssim 1.5 \times \sigma_{beam}$

  $\Rightarrow$ Data $\boldsymbol{\sigma_x} \cong$ **30 – 40 nm**

- RoI $\gtrsim 1.5 \times \sigma_{beam}$

  $\Rightarrow$ Fluctuations of the interference profile (induced by the hot spots)

Work in progress to reduce them:

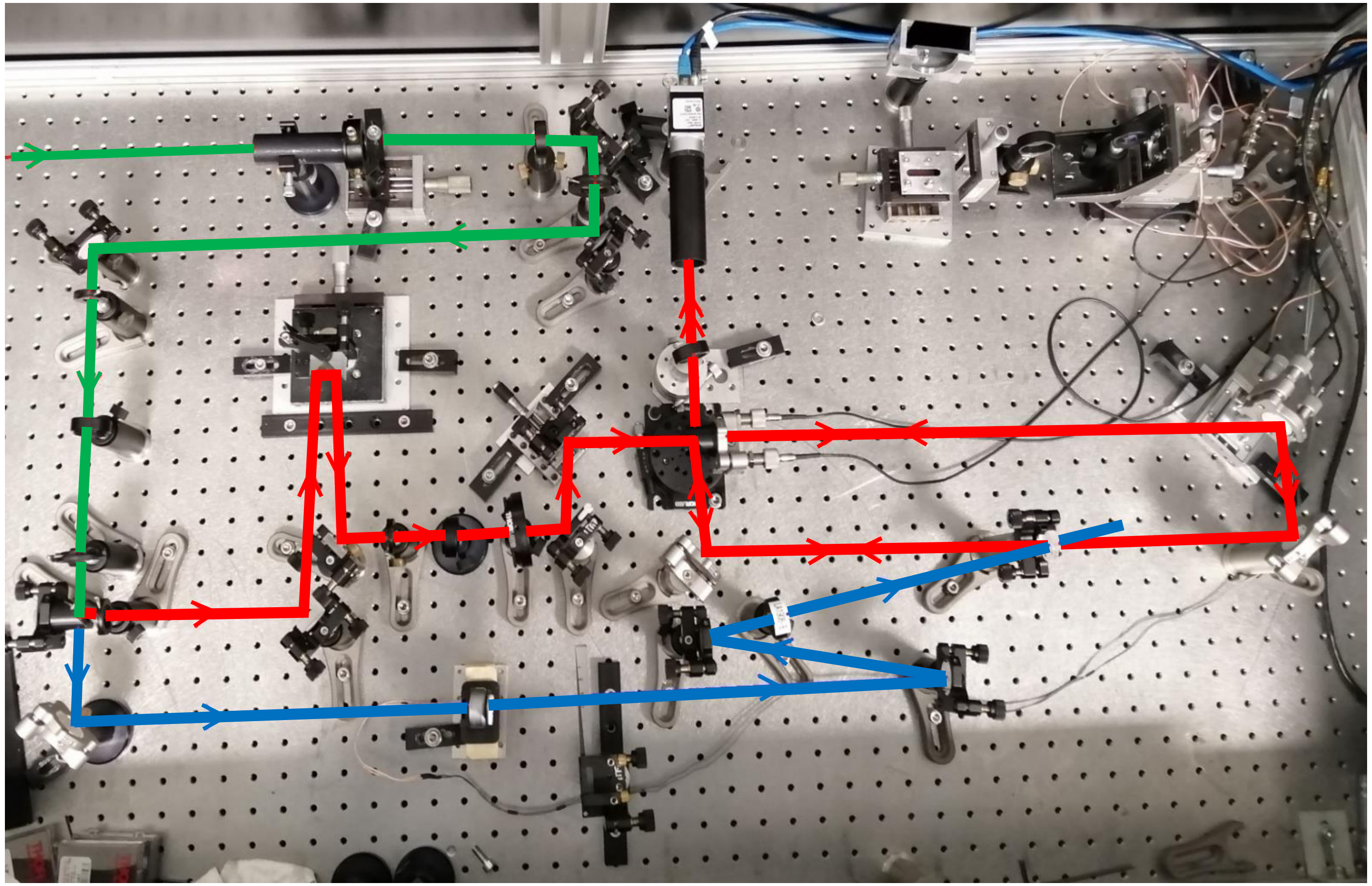
- Background mapping & substraction
- Fit of the profiles
- Surface quality of the optics
- CCD uniformity
- Etc…

# Experimental challenges

- ✓ Extinction: $\mathcal{F} = 4\epsilon^2 \cong 10^{-5}$
- ✓ Spatial resolution: $\sigma_x$
- ✓ Demonstration of the method by observing the non linear Kerr effect

# Observation of the non linear Kerr effect

Kerr effect induced in a fused silica window (5 mm thick)



$n(I) = n_0 + n_2 \times I(\mathrm{W/cm^2})$

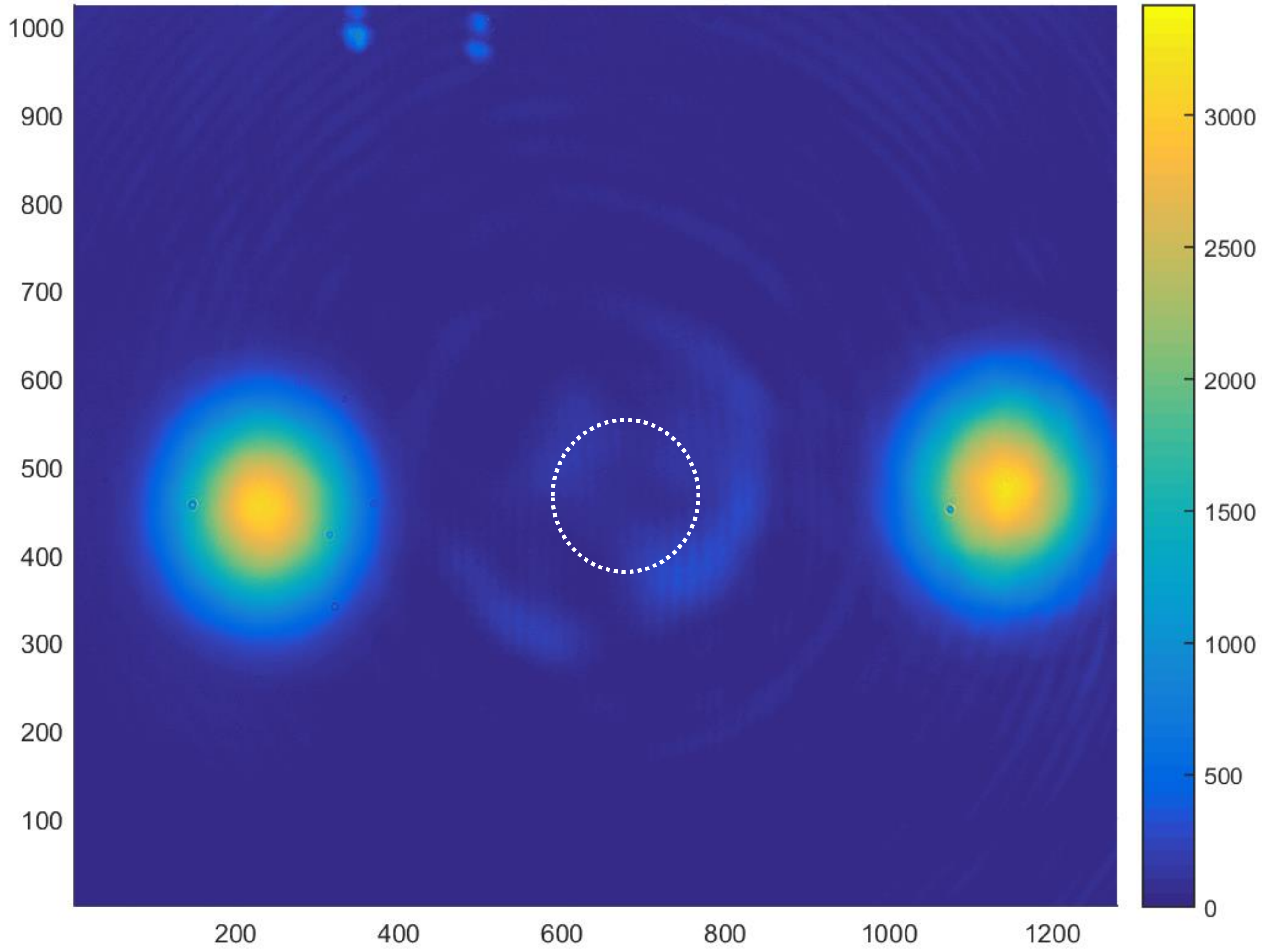
$n_2(\mathrm{Silica}) \approx 10^{-16}\ \mathrm{cm^2/W}$

- $\Phi$(probe) ≅ 1 mm (fwhm)
- $\Phi$(pump) ≅ 500 µm (fwhm)
- Duration of the pulses $\Delta t$ ~ 50 fs
- Energy Pump varies from ~12 µJ down to ~300 nJ

# Measurement of the Kerr signal in $SiO_2$

Maximal extinction

Without pump



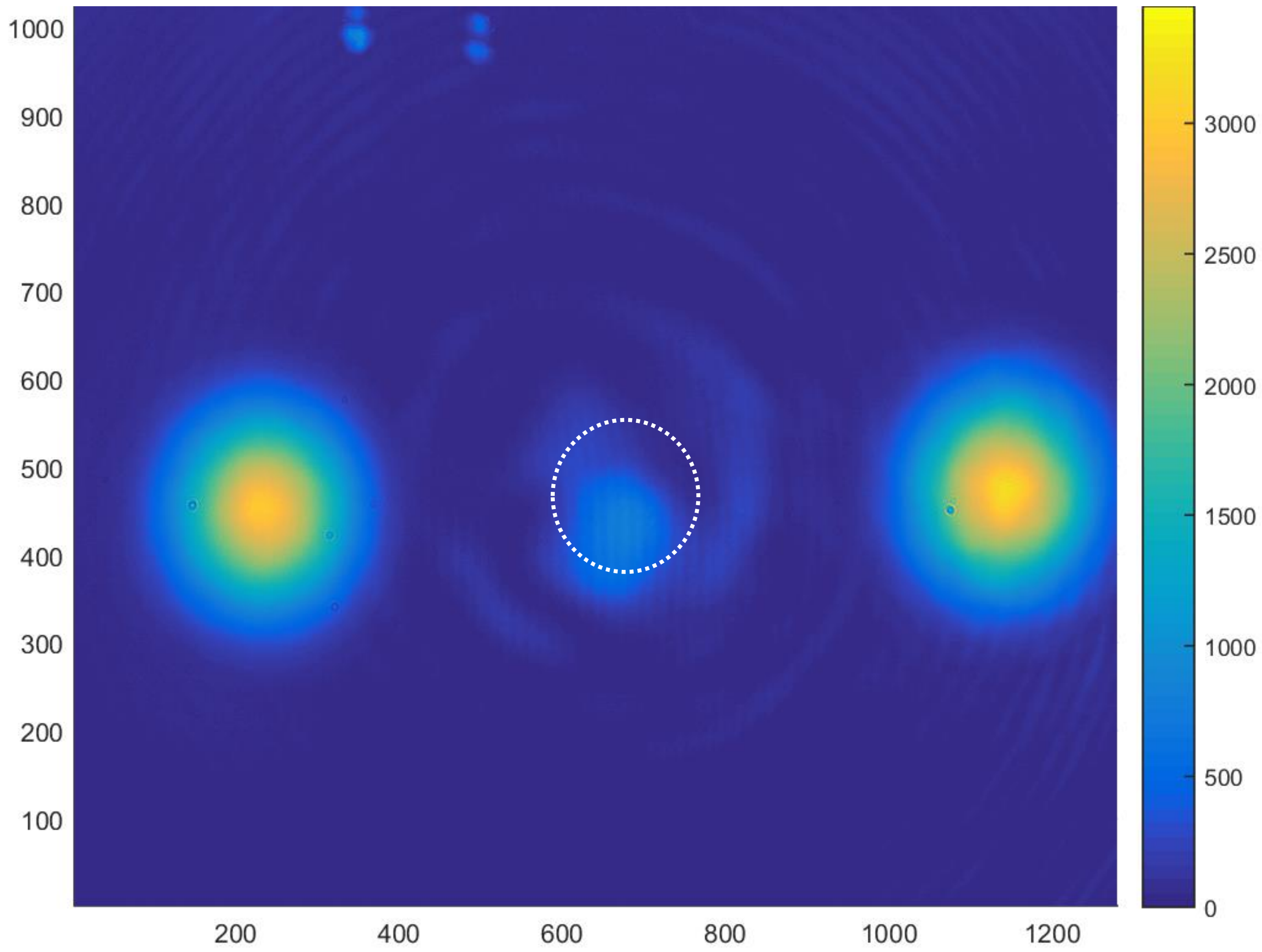

Intensity profiles in the dark output
of the Sagnac interferometer

# Measurement of the Kerr signal in $SiO_2$

Maximal extinction

With pump I ~ $10^{10}$ W/cm$^2$

Energy pump ~ 10 μJ



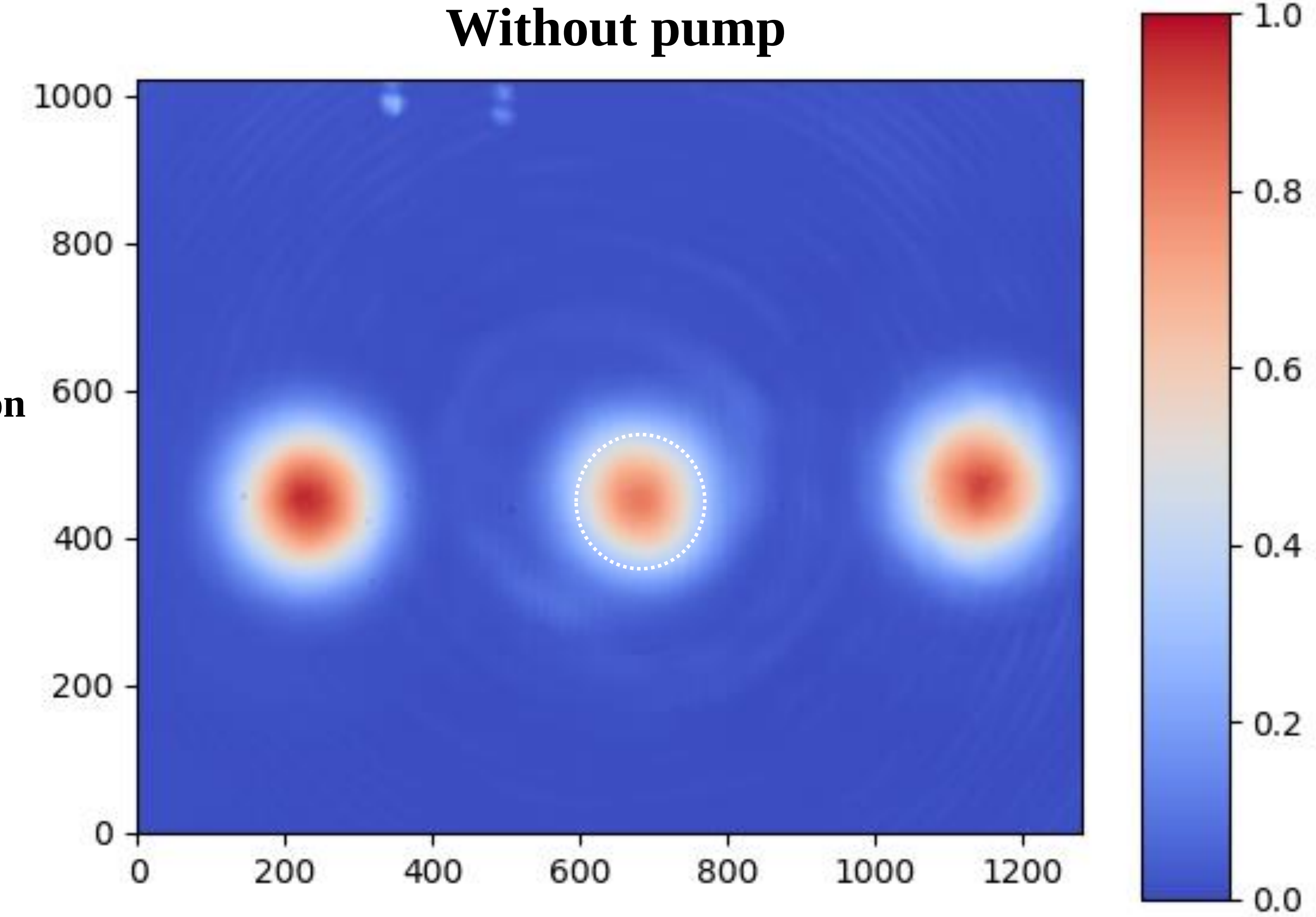

Intensity profiles in the dark output
of the Sagnac interferometer

# Measurement of the Kerr signal in $SiO_2$

**Without pump**

**With rotated polarization**

$\mathcal{F} = 5 \times 10^{-4}$




Intensity profiles in the dark output
of the Sagnac interferometer

# Measurement of the Kerr signal in $SiO_2$

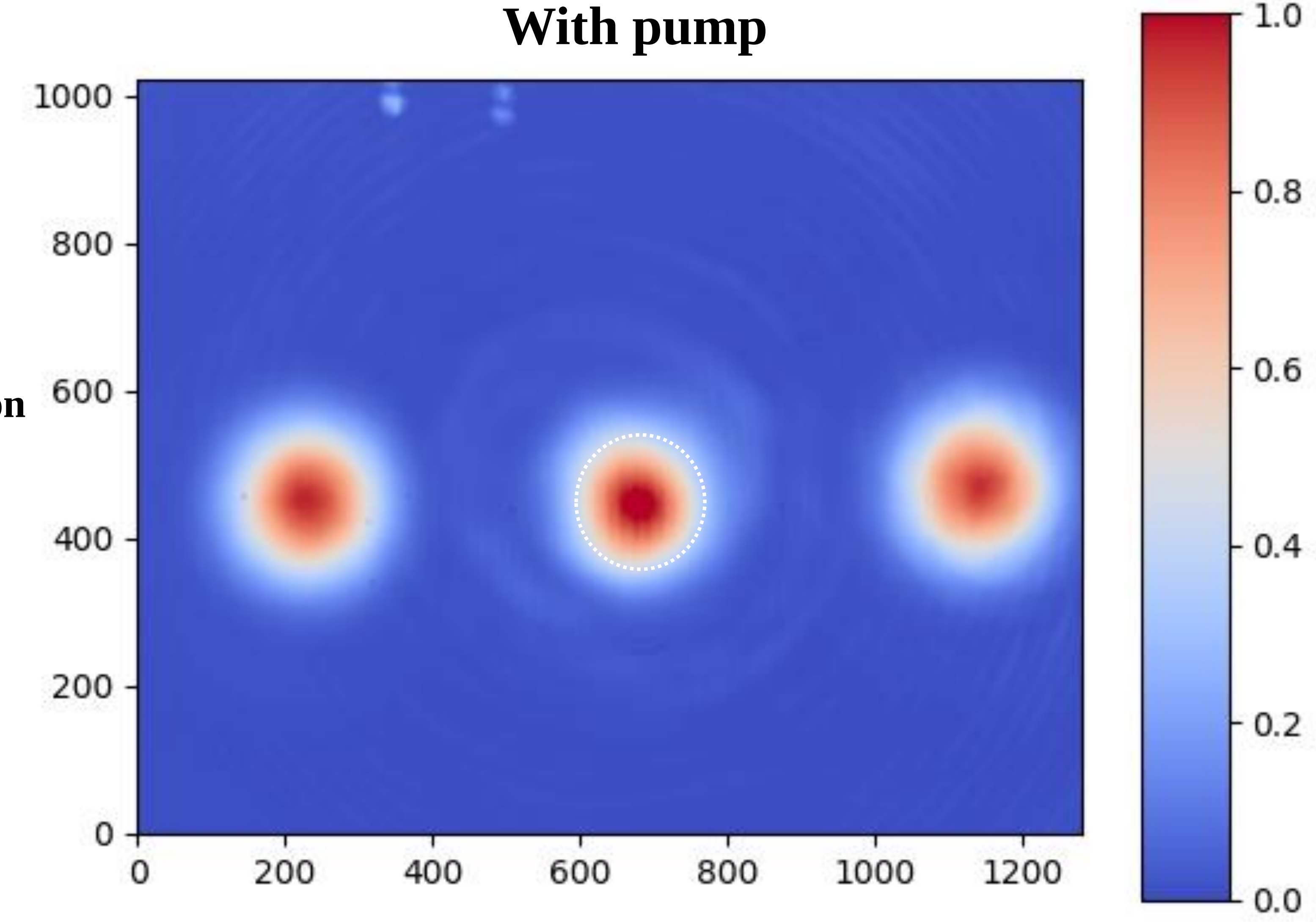
**With pump**

$I \sim 10^{11}$ W/cm$^2$

Energy pump ~ 10 μJ

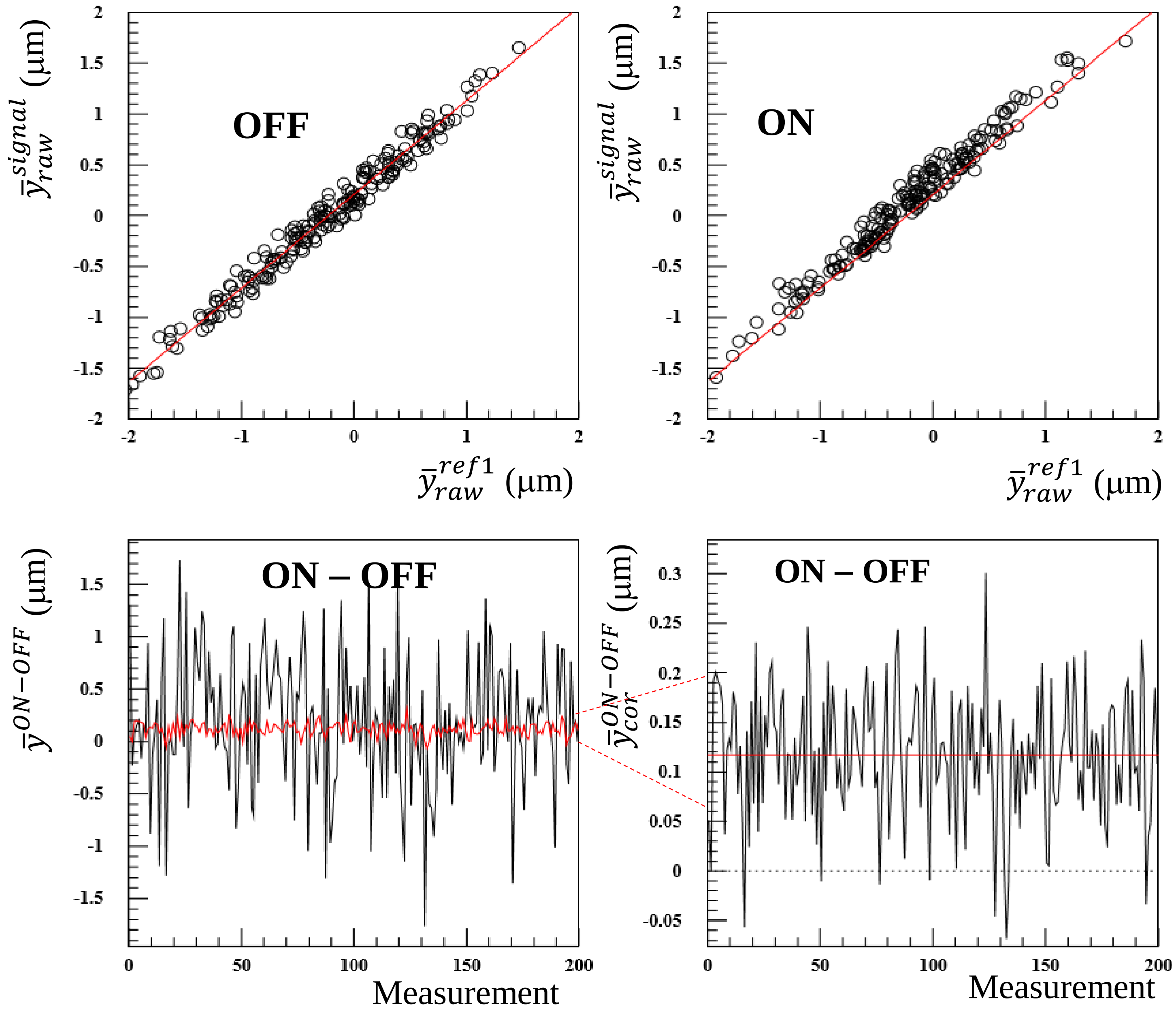
**With rotated polarization**

$\boldsymbol{\mathcal{F} = 5 \times 10^{-4}}$




Intensity profiles in the dark output
of the Sagnac interferometer

# Measurement of the Kerr signal in $SiO_2$




Energy pump ~ 300 nJ

Δt ~ 100 fs

Φ(pump) ~ 500 μm

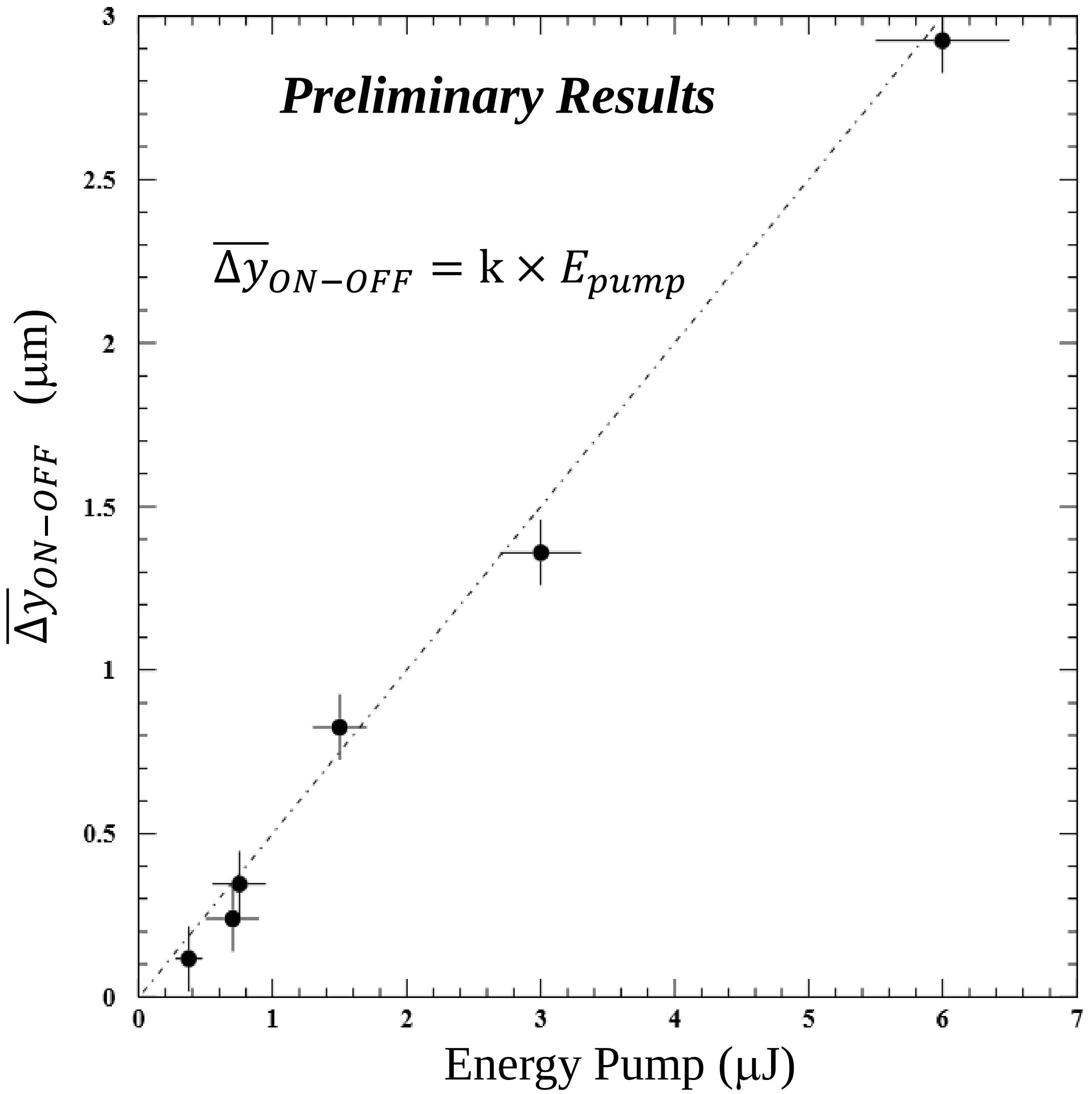
→ I ~ $10^9$ W/cm$^2$

→ $\boldsymbol{\Delta n \approx 10^{-7}}$

$\boldsymbol{\Delta y = 117.0 \pm 4.5}$ **nm**

(200 meas. ON-OFF; $T_{obs}$ = 40 sec.)

# Measurement of the Kerr signal in $SiO_2$




- ✓ Signal $\overline{\Delta y}_{ON-OFF}$ is proportional to the energy of the pump, as expected for the Kerr effect
- ✓ Preliminary results, work in progress...
  - Simulations of the Kerr effect
  - Influence of the polarization
  - measure Kerr effect in gas
  - ….

# DeLLight for the next 3 years

**Funded** (~310 keuros) by **ANR** for 3 years 2019 – 2021

2/3 Equipement

1/3 2-years post-doc (Scott Robertson)

**Partners**: LAL, LPGP, LUMAT, APC

**Program**:

1. DeLLight-0 (2019-2020):
   - Kerr effect inside Silica window ⇒ $\delta n \approx 10^{-8}$
   - Kerr effect & plasma inside low pressure gas ⇒ $\delta n \approx 10^{-11}$
2. DeLLight Phase 1 (2020-2021): Measure in vacuum with 2 Joules & focus $w_0$ = 20 μm
3. DeLLight Phase 2 (2021): Measure in vacuum with focus $w_0$ = 5μm ⇒ $\delta n \approx 2 \times 10^{-13}$

# DeLLight and other intense laser facilities

- **LASERIX** (LAL, Orsay):
  running 2J, 30fs ⇒ ~**70 TW @ 10 Hz** ⇒ $\boldsymbol{\Delta x_{LASERIX} \approx 0.01}$ **nm**

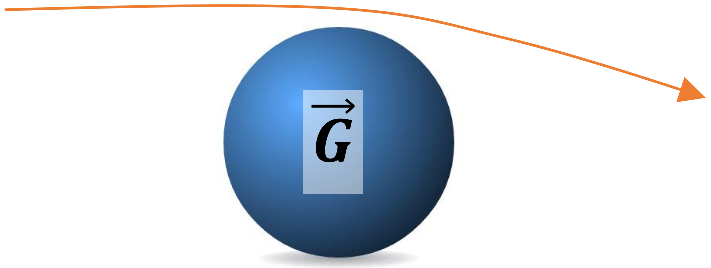
- **BELLA** laser (Berkeley LBNL):
  running with 40J, 30fs ⇒ ~**1 PW @ 1 Hz**

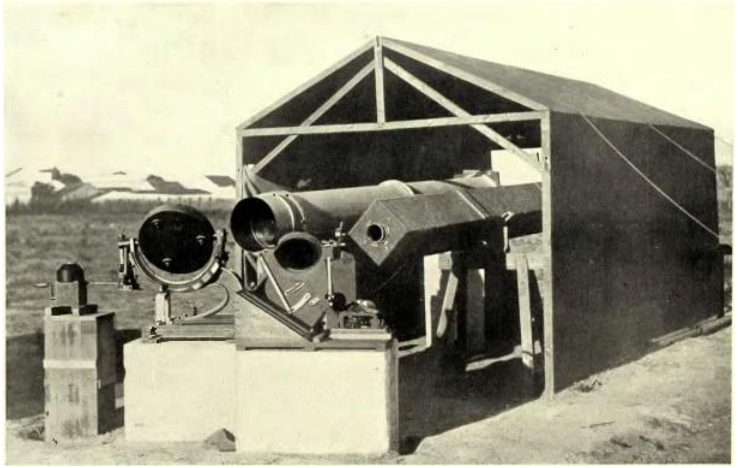
- **APOLLON** laser (Saclay):
  2019: 30 J, 30 fs ⇒ ~1 PW @ 0.1 Hz
  Target: 100 J, 20 fs ⇒ ~5 PW @ 0.1 Hz

- **HAPLS** laser (developed by LLNL and running @ ELI Beamlines Research Center, Czech Republic)
  Diode-pumped petawatt laser in order to reach 10 Hz repetition rate
  June 2018: 16 joules, 27 femtosecond pulse duration (0.5 PW) @ 3.3Hz
  2020 : 30 J, 30 fs ⇒ **1 PW @ 10 Hz** ⇒ $\boldsymbol{\Delta x_{HAPLS} \approx 0.1}$ **nm**
  Target: ~200 Joules, 30 fs ⇒ ~ 6 PW @ 10 Hz ⇒ $\boldsymbol{\Delta x_{HAPLS} \approx 0.6}$ **nm**

# Conclusions

- In May 29, 1919 Eddington measured the deflection of light by a gravitational field

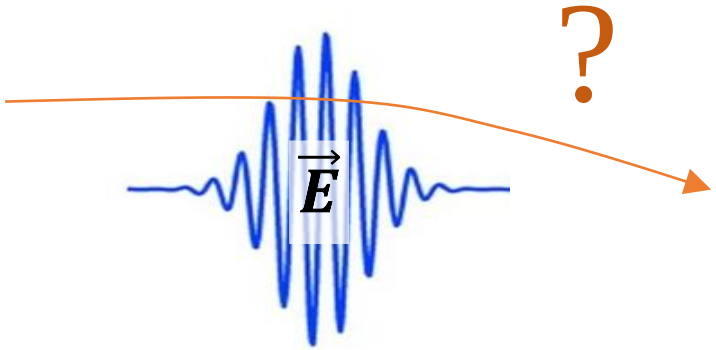


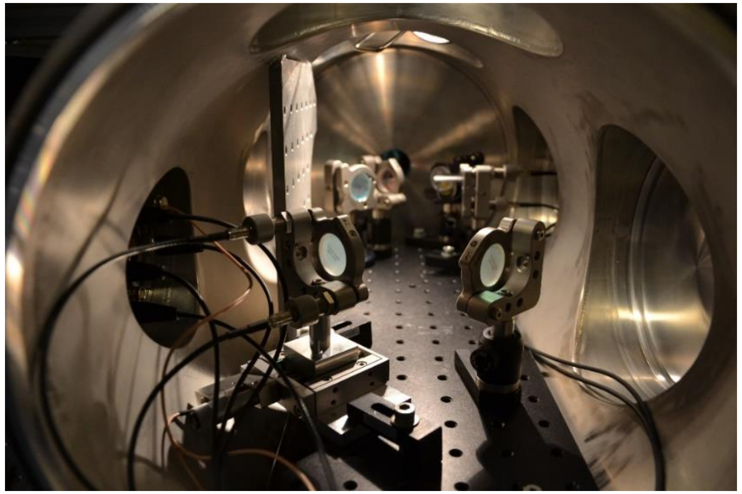



***Deflection already observed***

***But no physical model for vacuum…***

- In May 29, 20XX…. DeLLight will measure the deflection of light by an electromagnetic field ?



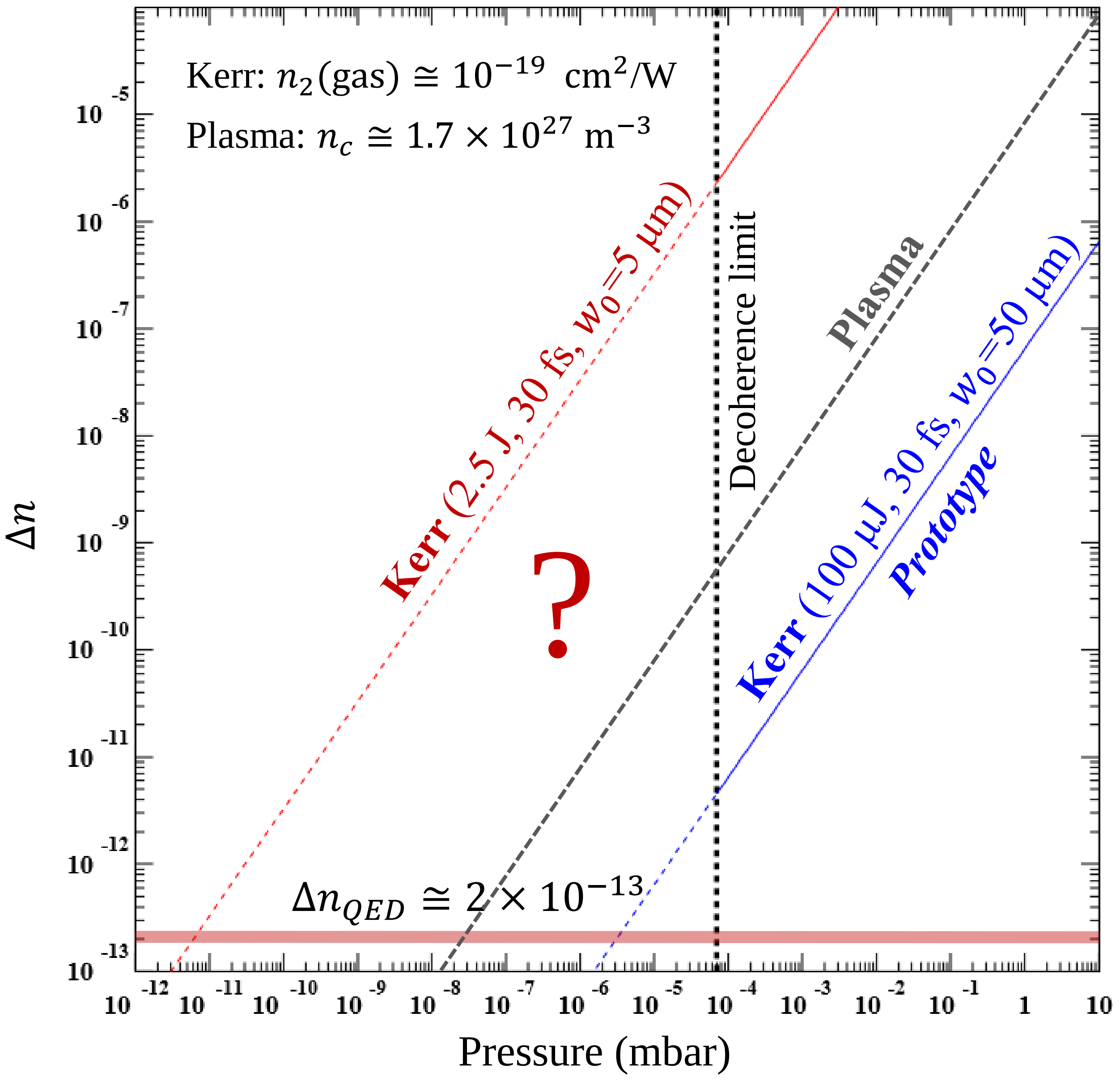



***Vacuum QED exists***

***But deflection never observed !…***

# Backup

# Kerr effect and plasma in residual gas

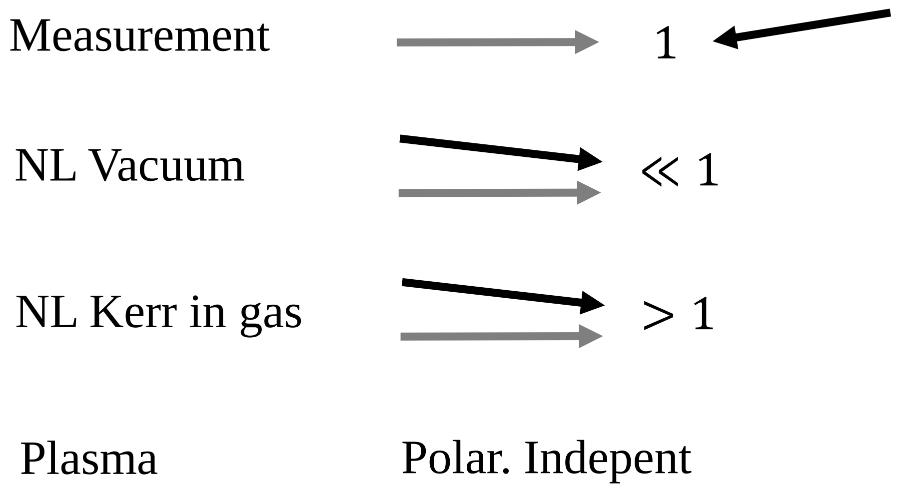



- **Kerr effect in gas: Decoherence limit ?**

$p \cong 7 \times 10^{-5}$ mbar $\Rightarrow$ distance between atoms $\cong \lambda_{laser}$

- **Plasma**: $\Delta n_{plasma} \cong \Delta n_{QED}$ for $p = 2 \times 10^{-8}$ mbar

- Beam polarisation & orientation used to distinguish the processes

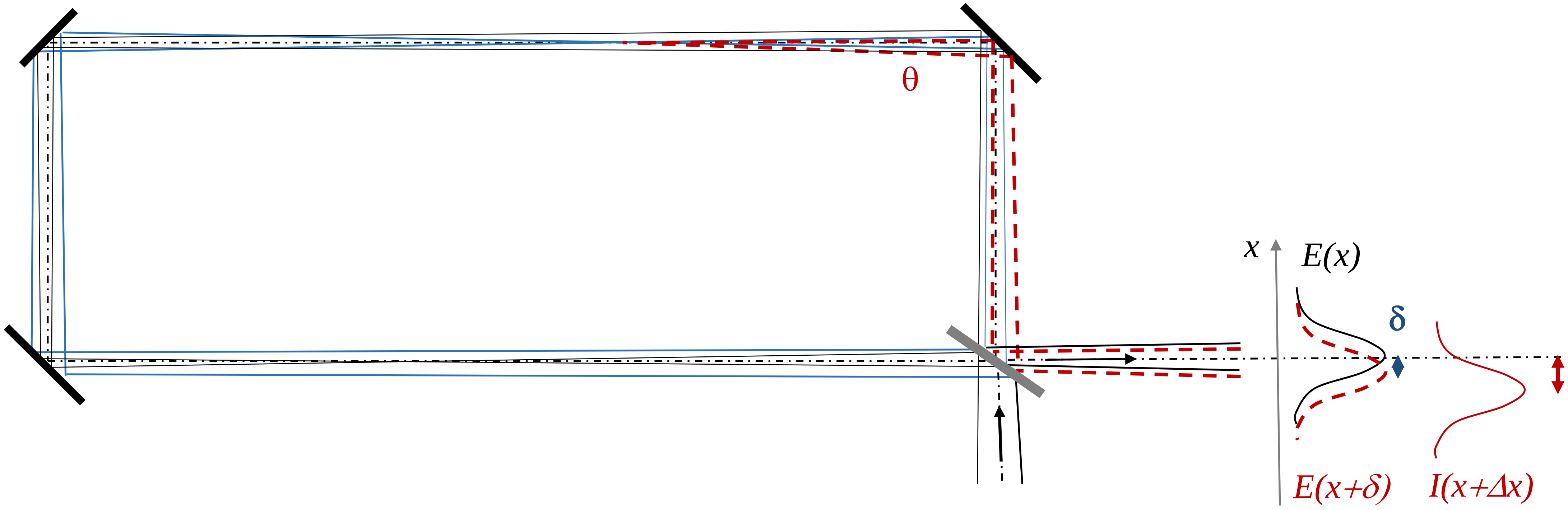


# Amplification with a Sagnac Interferometer

$$I(x) = I_0\left(\left(\frac{1}{2}+\epsilon\right)E(x+\delta) - \left(\frac{1}{2}-\epsilon\right)E(x)\right)^2 \cong 2\delta\epsilon\frac{\partial E}{\partial x} + 4\epsilon^2 E^2(x) \quad (\delta \ll 1)$$

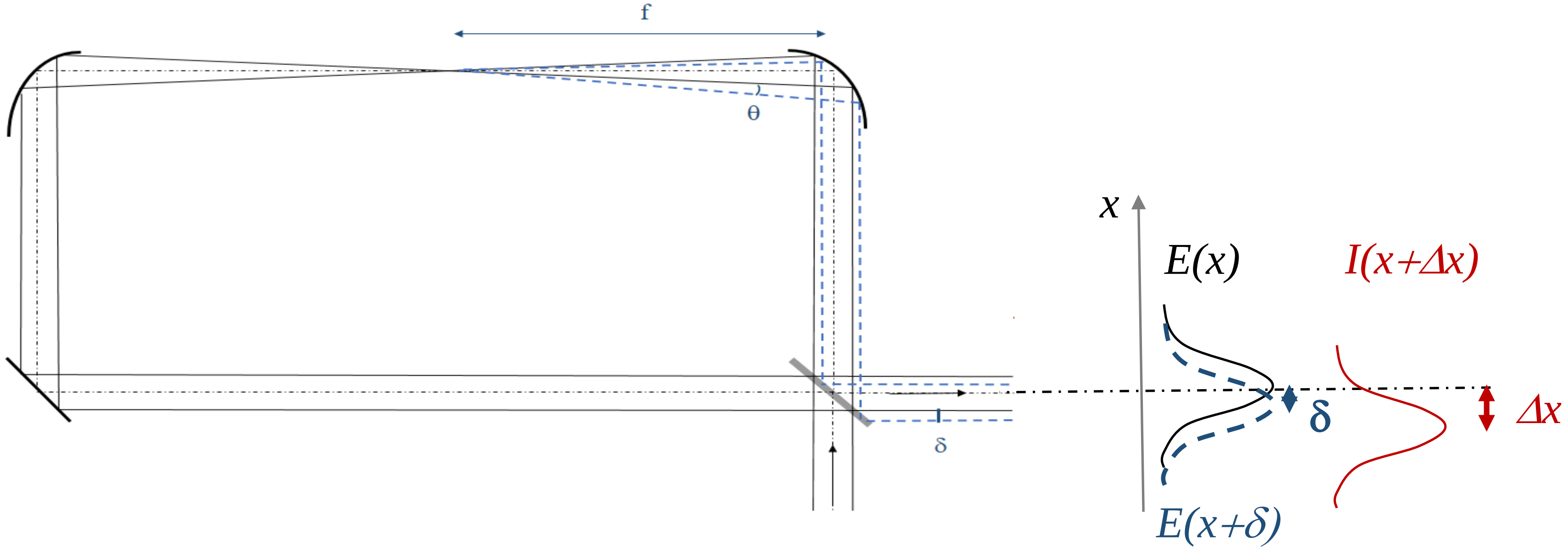
$$E(x) = exp\left(-\frac{x^2}{2\sigma^2}\right) \Rightarrow I(x) = \left(\frac{2\epsilon\delta}{\sigma^2}x + 4\epsilon^2\right)\exp\left(-\frac{x^2}{\sigma^2}\right) \Rightarrow \Delta x = \frac{\int_{-\infty}^{+\infty} xI(x)dx}{\int_{-\infty}^{+\infty} I(x)dx} = \frac{\delta}{4\epsilon}$$

Extinction factor : $\mathcal{F} = \frac{I_{out}}{I_{in}} = 4\epsilon^2$ ➡ Amplification $= \frac{\Delta x}{\delta} = \frac{1}{2\sqrt{\mathcal{F}}}$



# Refraction measured with a Sagnac Interferometer

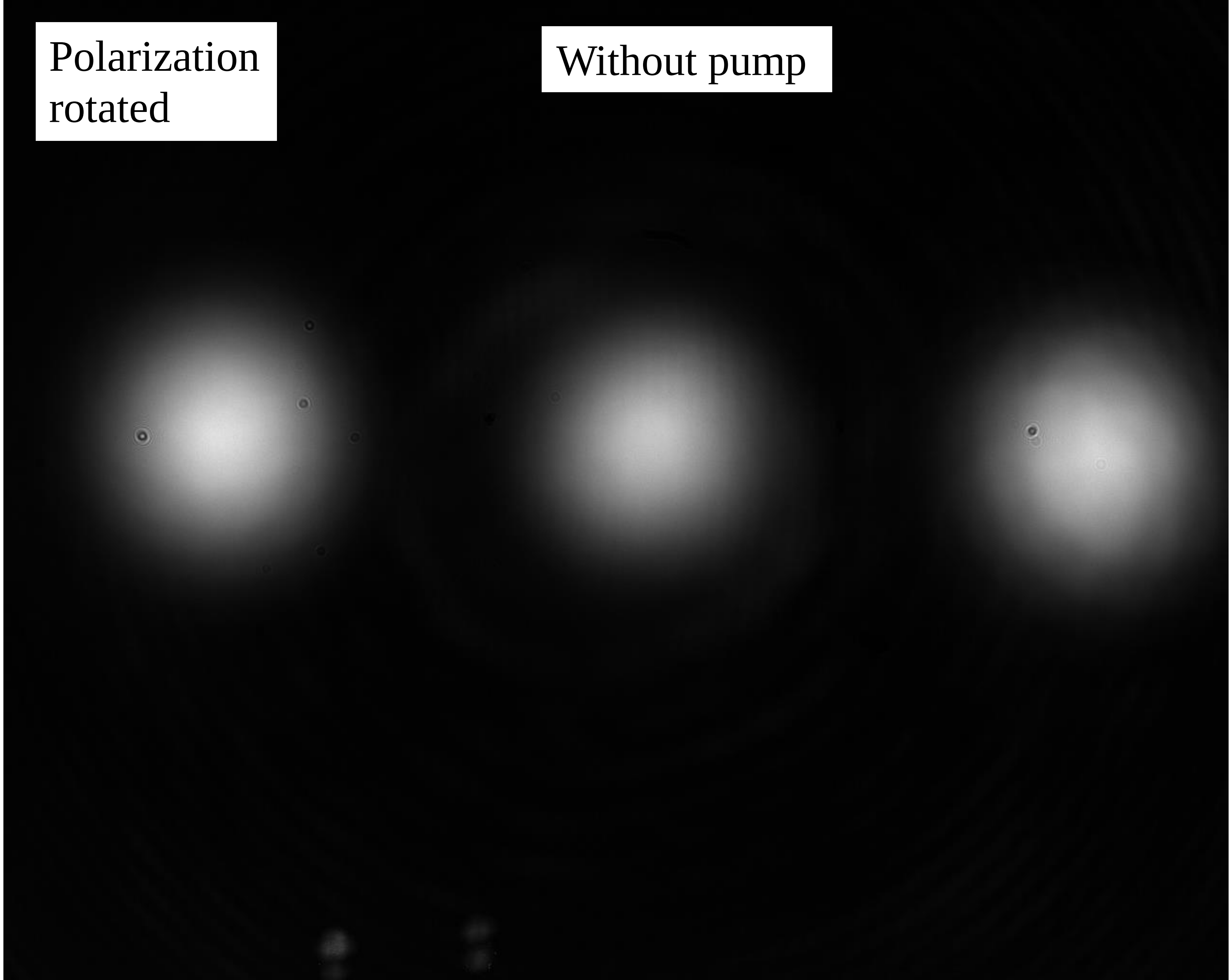
- Refraction of the probe pulse $\Rightarrow$ **Transversal shift $\Delta x$ of the interference intensity profile**

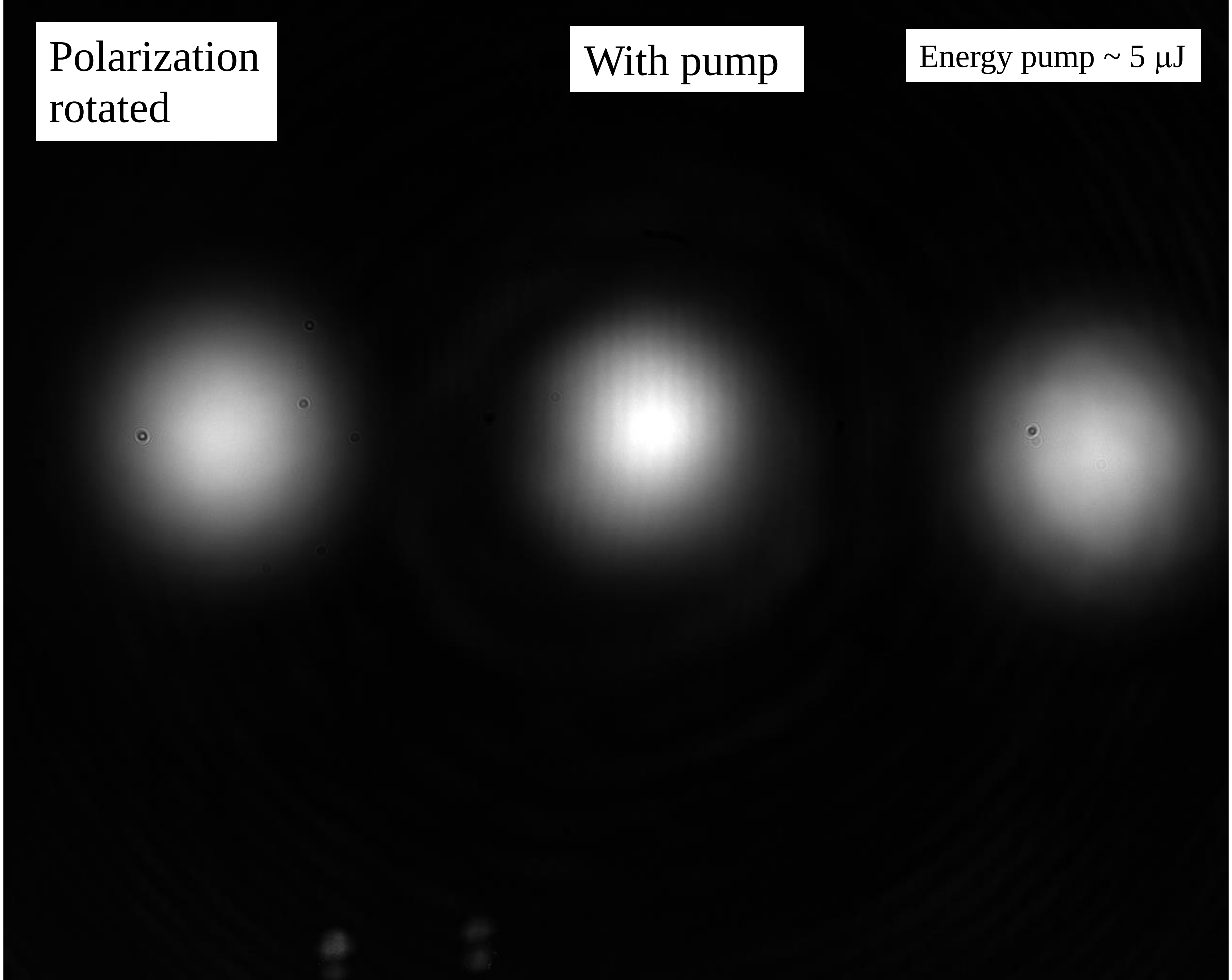



- Interference $\Rightarrow$ **Amplification factor $\mathcal{F}$** compared to standard pointing method (with transversal shift $\delta$)

$$\mathcal{F} = \frac{\Delta x}{\delta} = \frac{1}{2\sqrt{Extinction}}$$ where $Extinction = \frac{I_{out}}{I_{in}} = 4\epsilon^2$ and $\epsilon$ = asymetry in intensity of the beam splitter)

$$\boldsymbol{\epsilon = 10^{-3} \Rightarrow Extinction = 0.4\ 10^{-5} \Rightarrow \mathcal{F} = 250}$$


Polarization
rotated
Without pump


Polarization rotated
With pump
Energy pump ~ 5 μJ

# Pressure in the interaction area

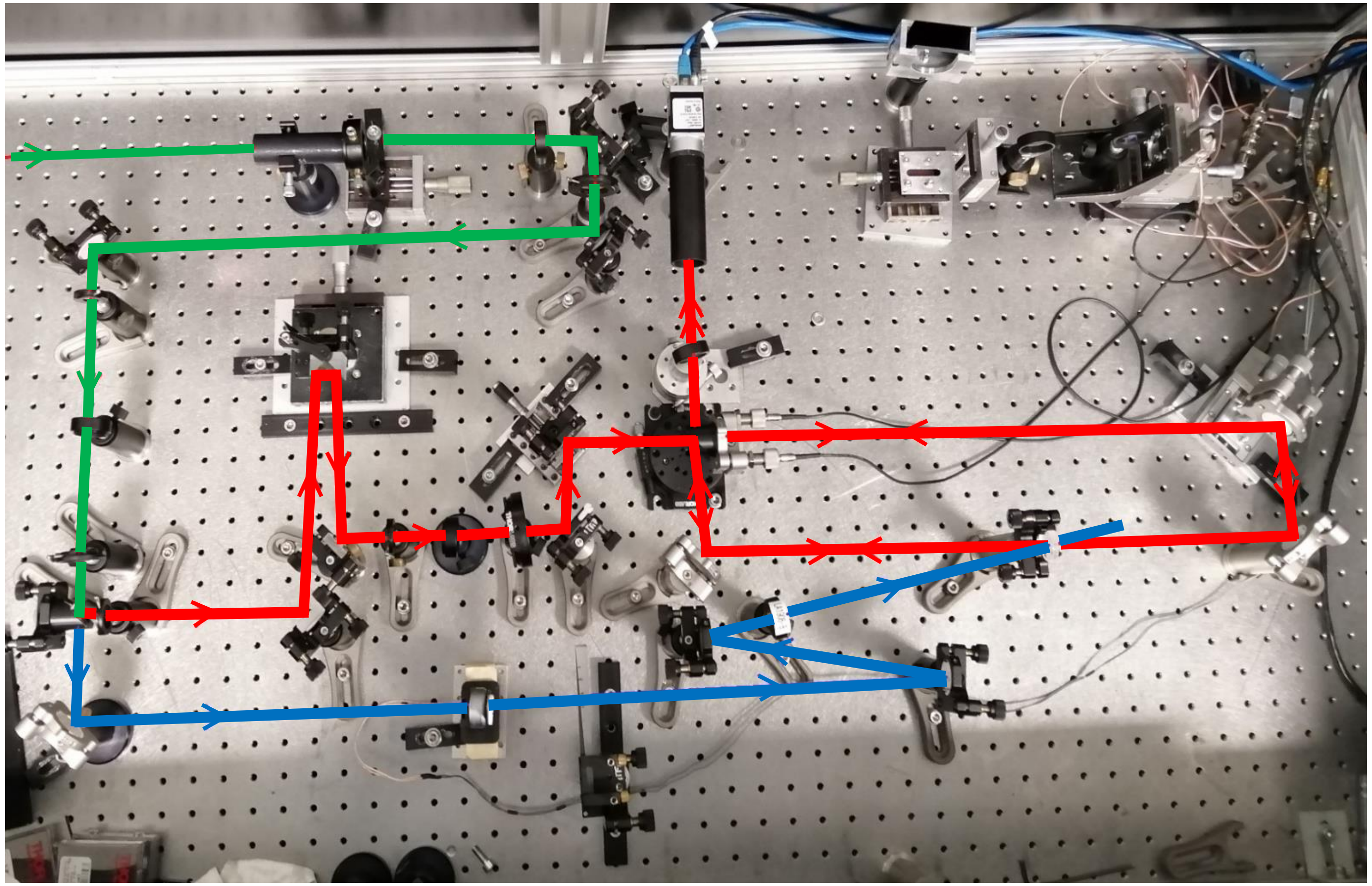
Phase-1 ($w_0 \cong 10 - 15$ μm) P=$10^{-6}$ mbar

$\Rightarrow$ ~ 10 molecules in the volume $V = w_0^2 \times \Delta t \times c$ $(\Delta t \times c = 10\mu s)$

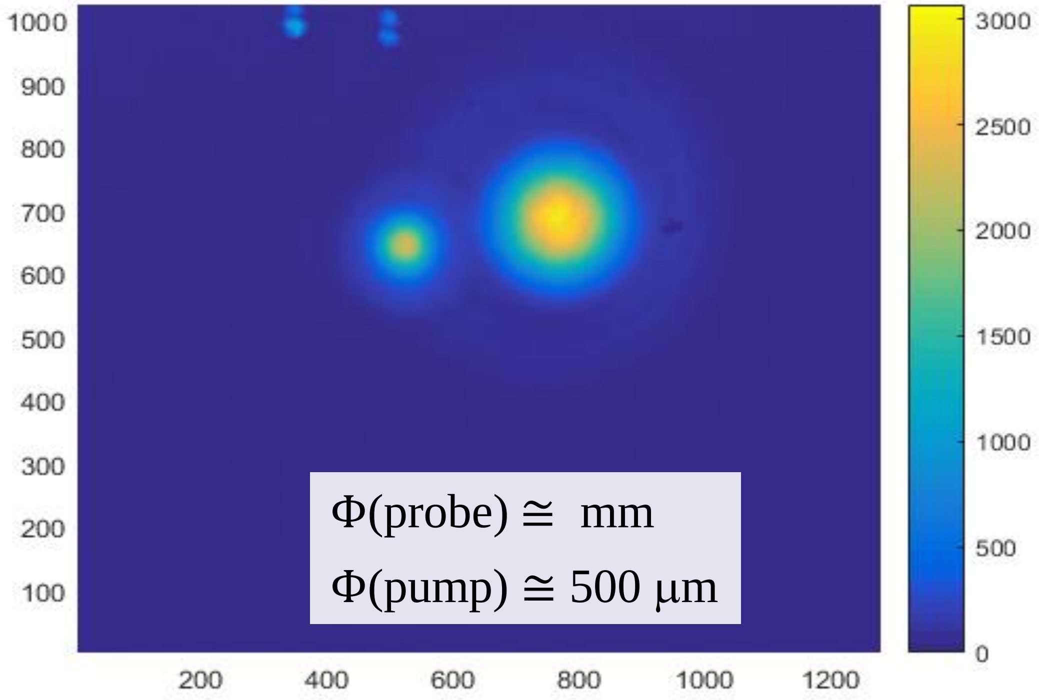
Phase-2 ($w_0 \cong 5$ μm) P=$10^{-9}$ mbar

$\Rightarrow$ ~ 1 molecule in the volume $V = (20\ \mu m)^2 \times 10 \times \Delta t \times c$

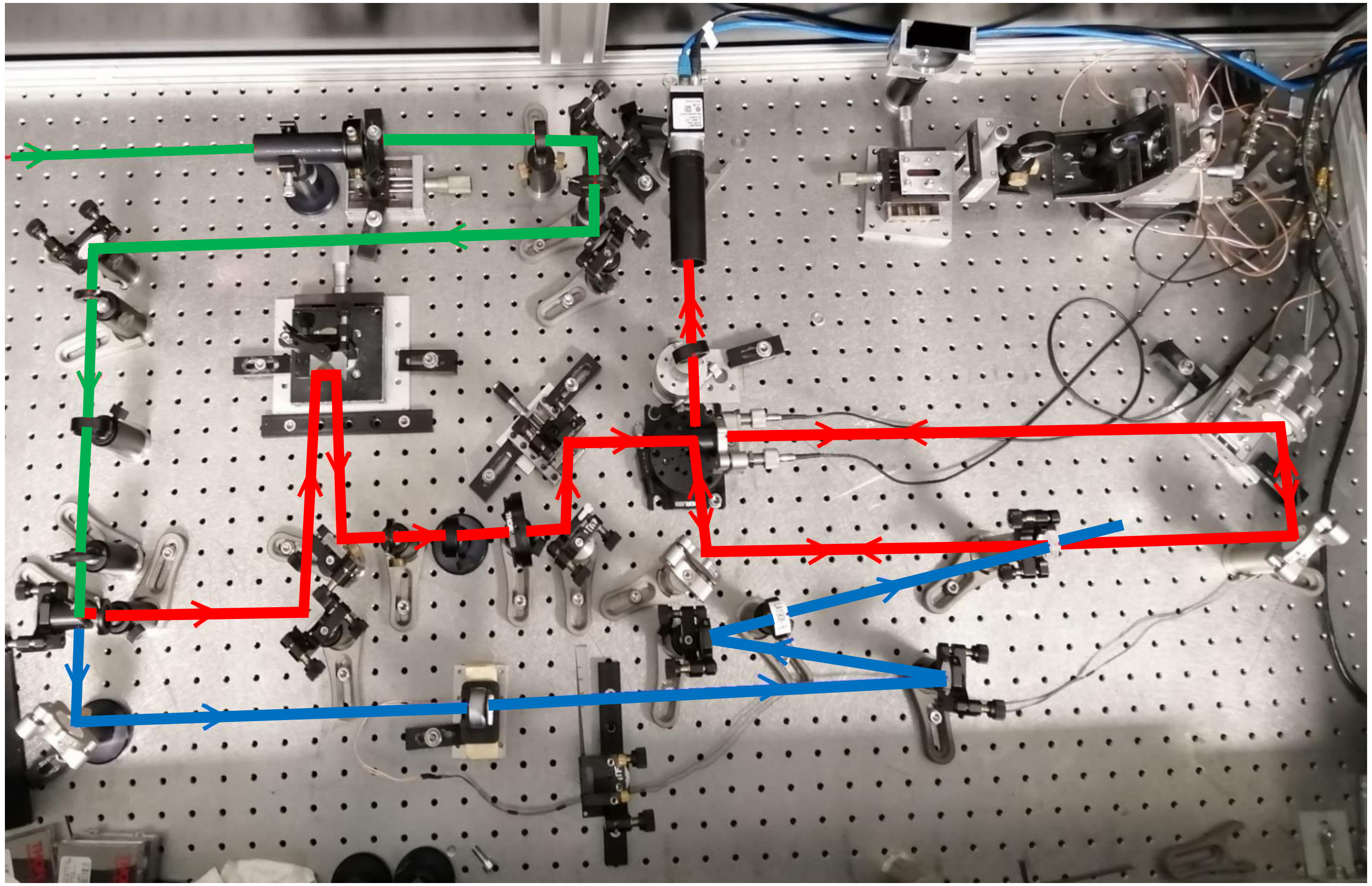
# Observation of the non linear Kerr effect



Intensity profiles of the Pump & Probe in the interaction area



# Observation of the non linear Kerr effect



Intensity profiles of the Pump & Probe in the interaction area