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

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

ANR Project (2019-2021)

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The DeLLight group @ LAL

DEL LIGHT

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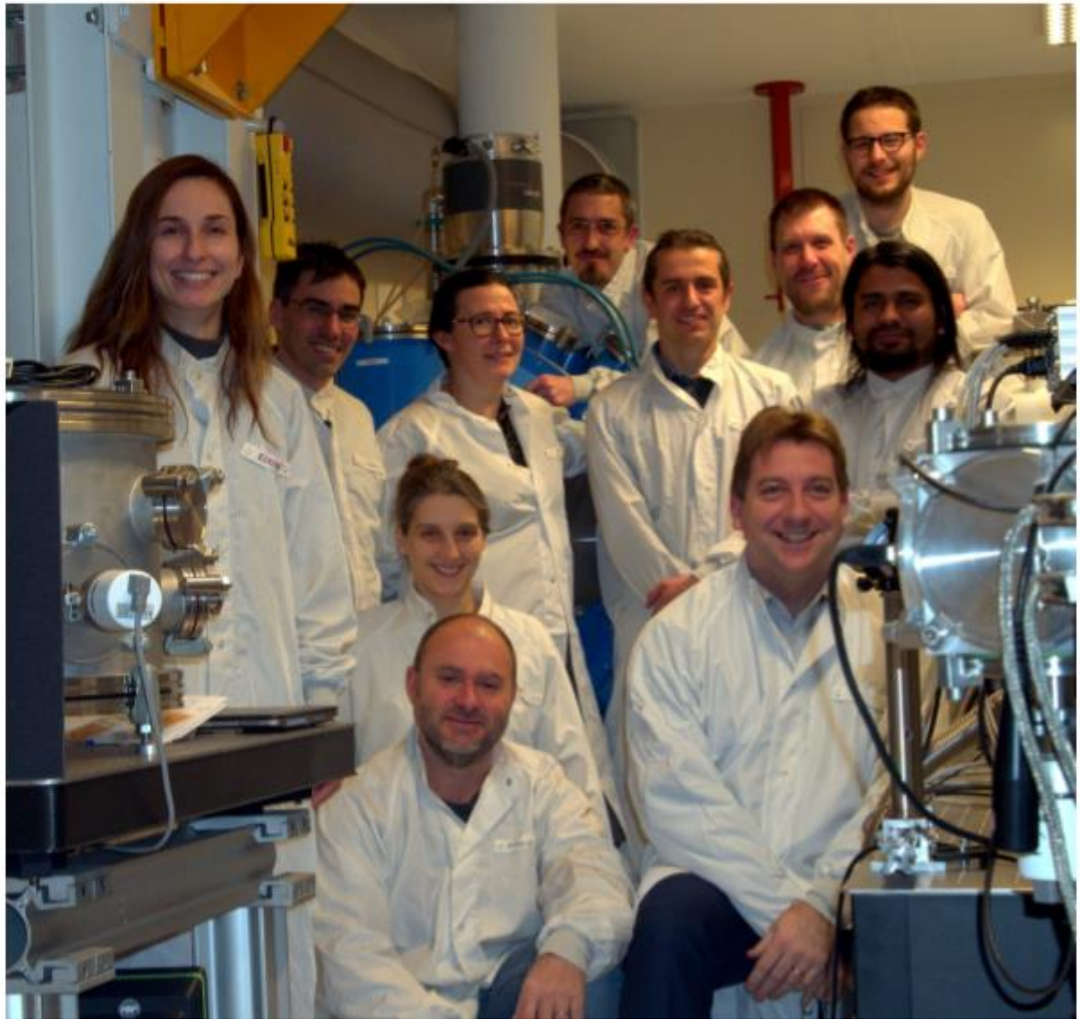
Thanks to LASERIX

- Installed at LAL since a few years
- 30 fs, 2.5 J pulses @ 10 Hz
- $\lambda \sim 800$ nm
- ~ 1μm position jitter at focus
- 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

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

→

ε_0 and μ_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 nonlinear optical phenomenon in dielectric media is the **Kerr effect**:

⇒ 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 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 ?

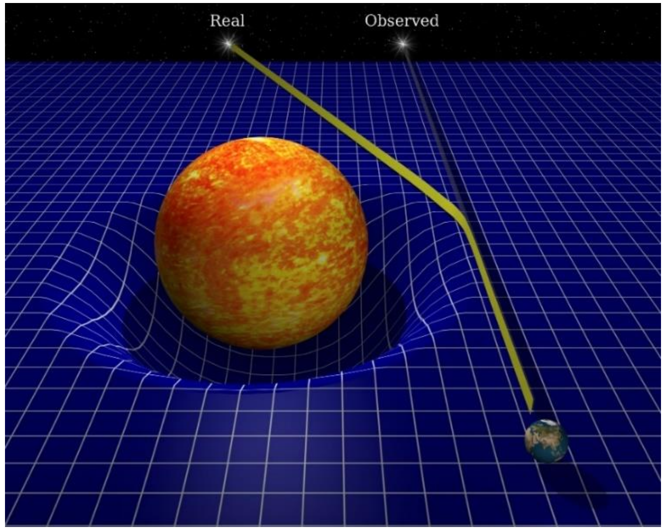
- Einstein first used the notion of vacuum refractive index and noticed that the **speed of light *c* is modified in accelerated frames and gravitation fields**

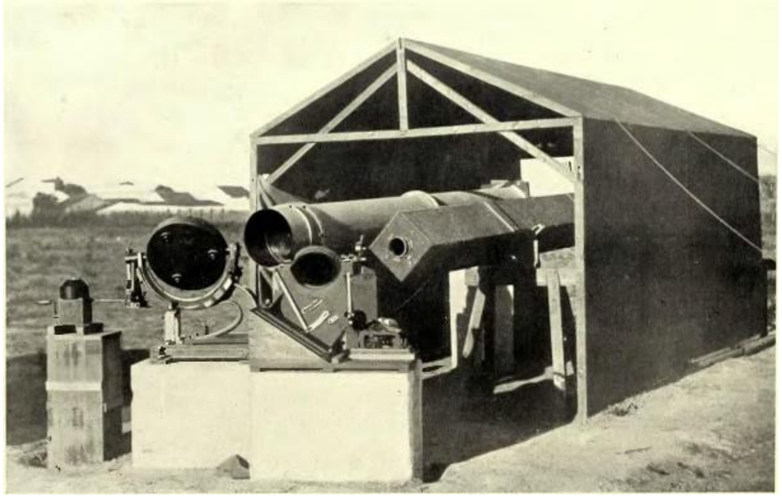
- Einstein generalized the « $\boldsymbol{c = \mathrm{constante}}$ » relativity principle thanks to the introduction of a ***curved spacetime metric***

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

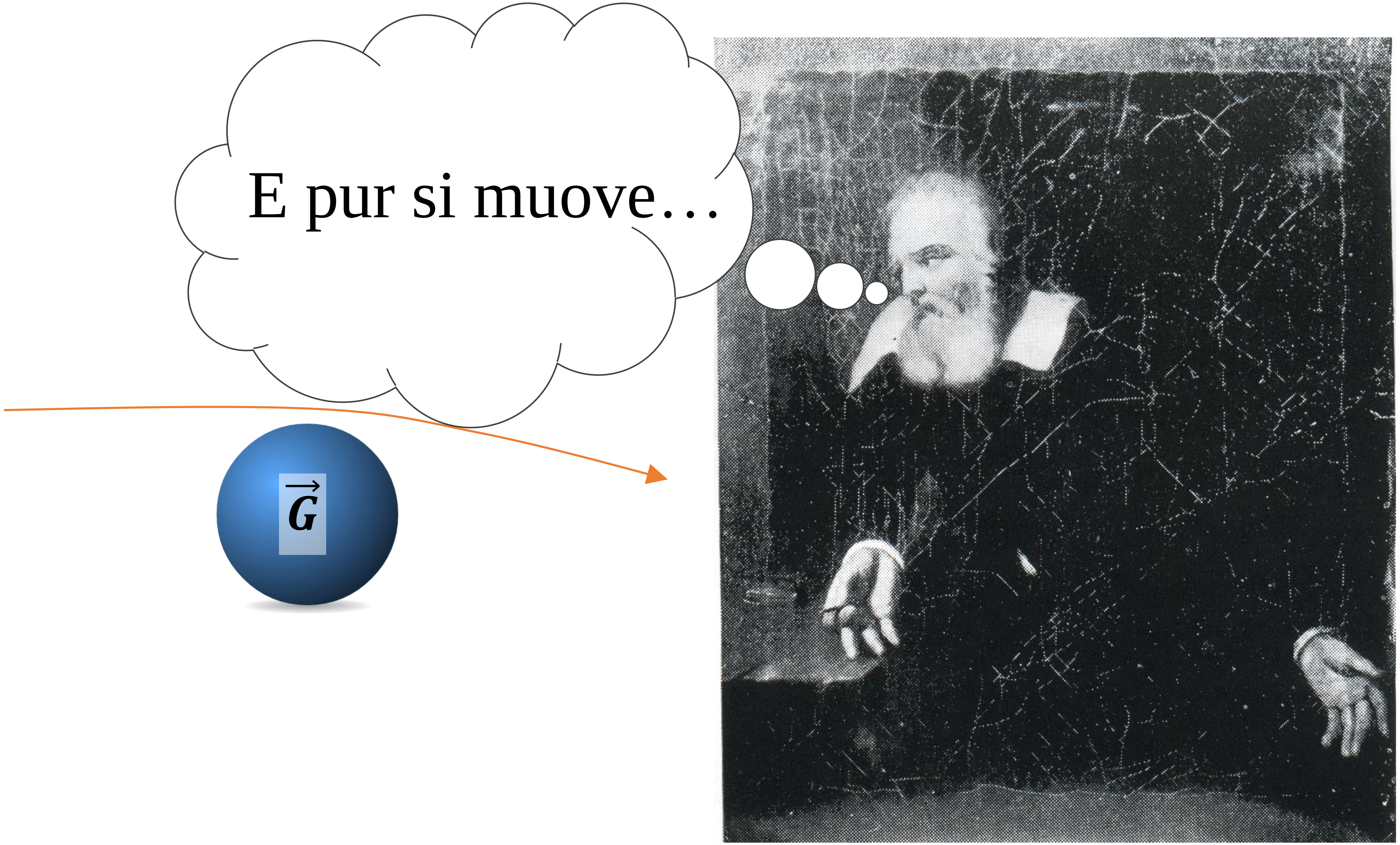
  $\Rightarrow$ Vacuum has no physical role anymore

➡ 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 ε_0 and μ_0** by the gravitational potential

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

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

$\Rightarrow$ *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

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

? 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

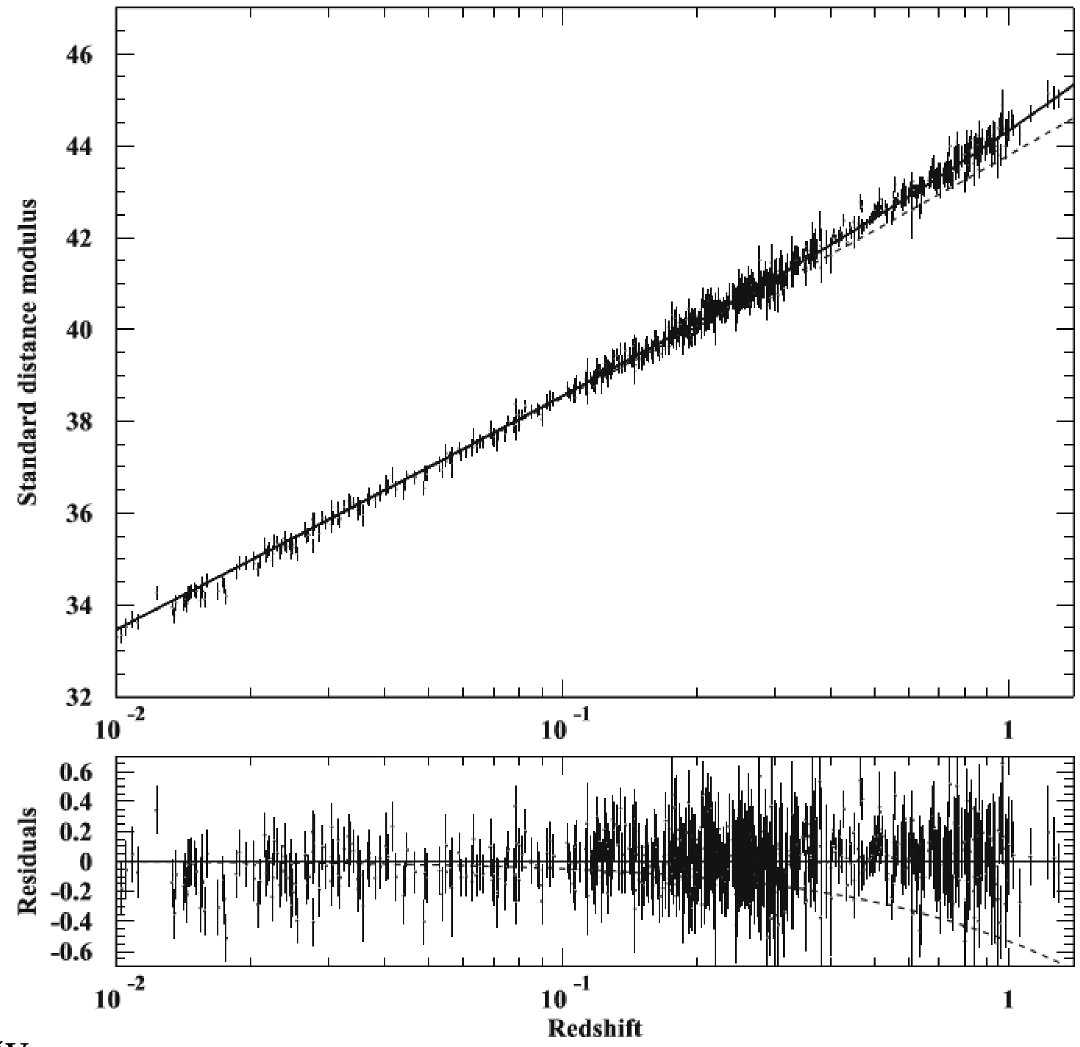
Hubble cosmological redshift due to a time variation of both $n(t)$ and the atomic energy levels

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}

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

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

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

➡ 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)

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

$\Rightarrow$ Modification of the Maxwell's equations in vacuum $\Rightarrow$ Vacuum is a non linear medium

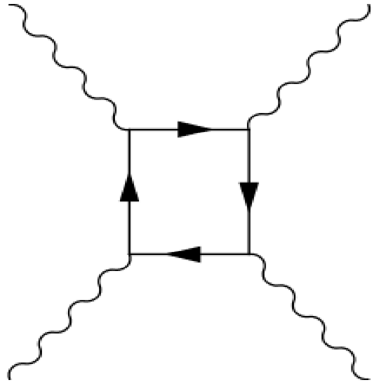
The vacuum refractive index is not an absolute constant $n \neq 1$

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

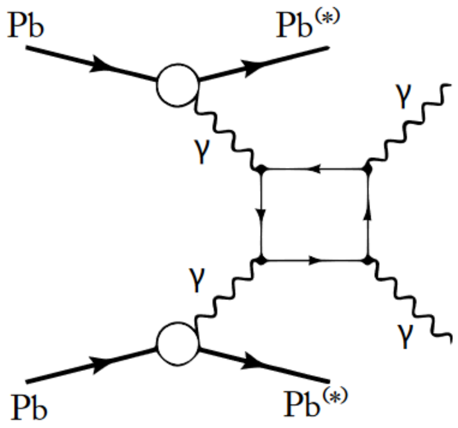


Two-photons scattering v.s. Intense fields

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

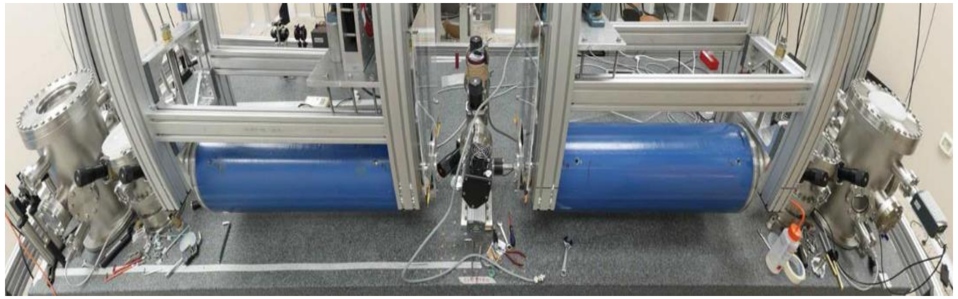
arXiv:1702.01625
arXiv:1810.04602

Current experimental tests: Vacuum Magnetic Birefringence

- Search for birefringence with the PVLAS + BMV experiments

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

Fabry-Perrot laser cavity with an external B field



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

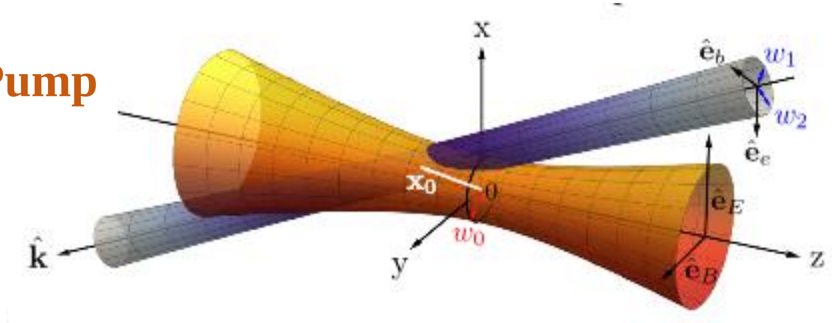
BMV: Pulsed field B=6.5 T *Eur. Phys. J. D (2014) 68: 16*

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

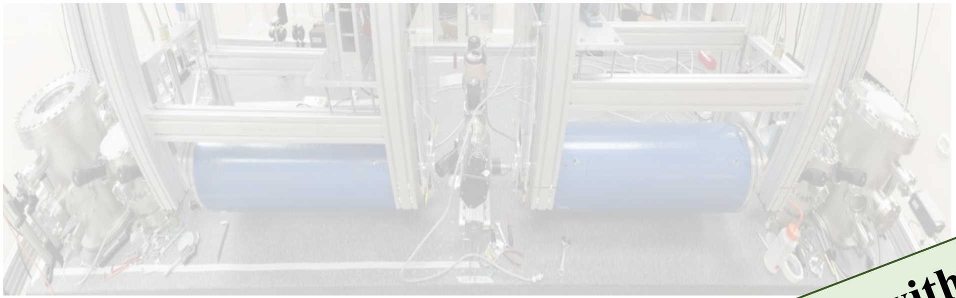


X-ray Probe

Current experimental tests

- 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



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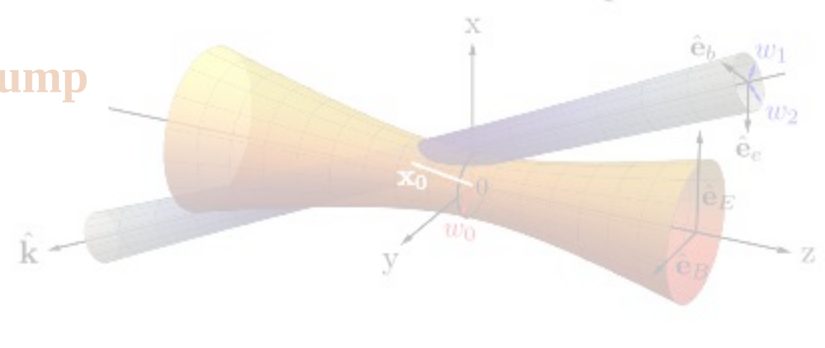
BMV: Pulsed field B=6.5 T *Eur. Phys. J. D (2014) 68: 16*

0.1 σ ... after ~100 days of measurement

Birefringence null with Born-Infeld nonlinear formalism

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

Laser Pump



X-ray Probe

Jone's experiment in 1960…

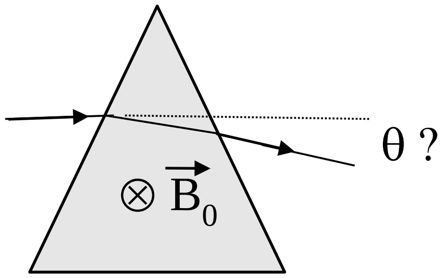
- Variation of the vacuum refractive index, independentely of the polarization, has been tested only once, by R.V. Jones in 1960

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

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

  Sensitivity ≅ 0.5 picorad (!)

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



DeLLight with intense laser field produced by LASERIX

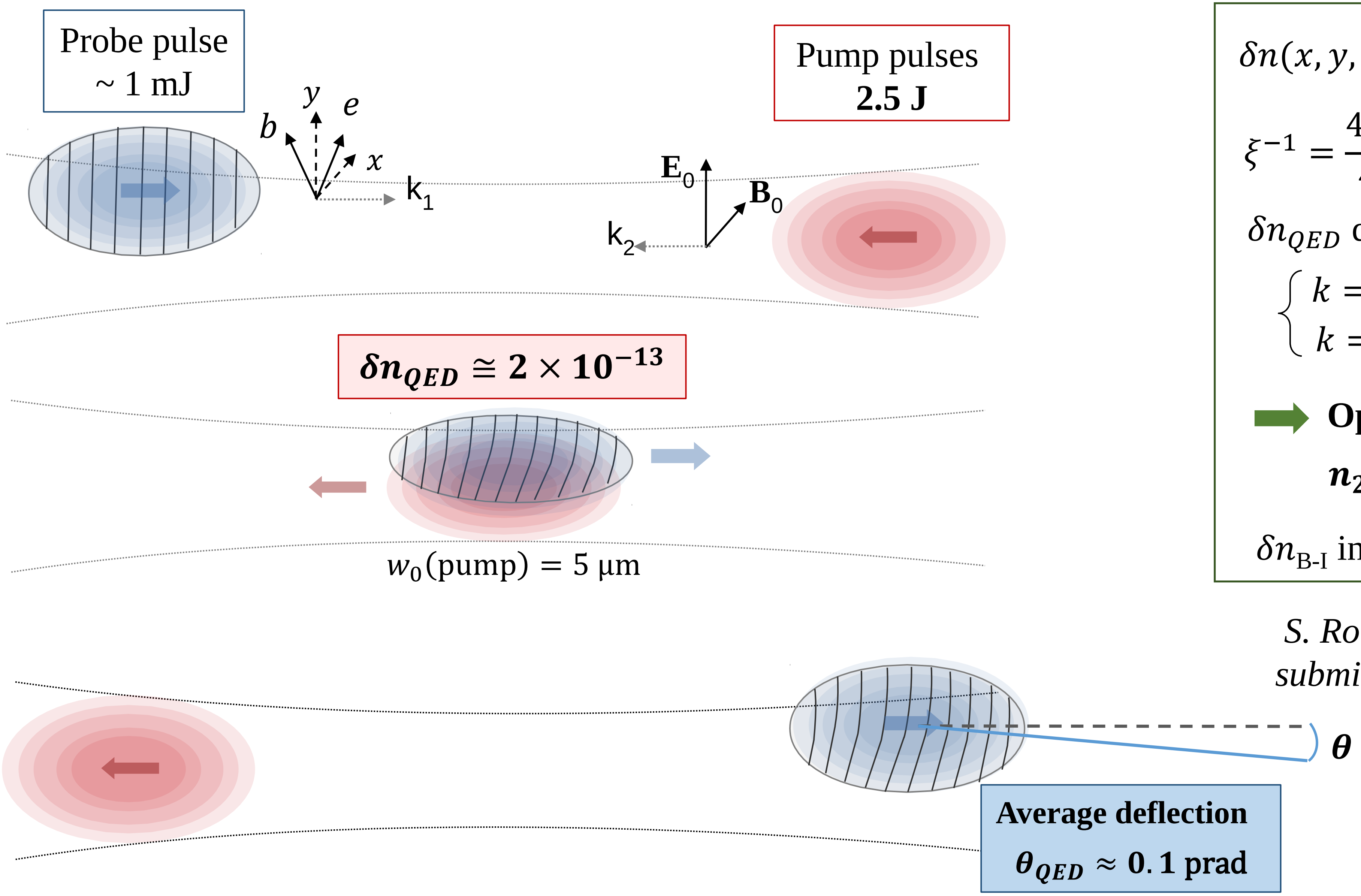
2.5 J, 30 fs, w_0=5µm ⇒ ~ 3×10^{20} W/cm^2 ⇒ $\boldsymbol{E} \sim \mathbf{3 \times 10^{13} V/m}$, $\boldsymbol{B} \sim \mathbf{10^5}$ **T**

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, submitted to Phys. Rev.

Pump-Probe interaction



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

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

δn_{QED} depends on the polarisation

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

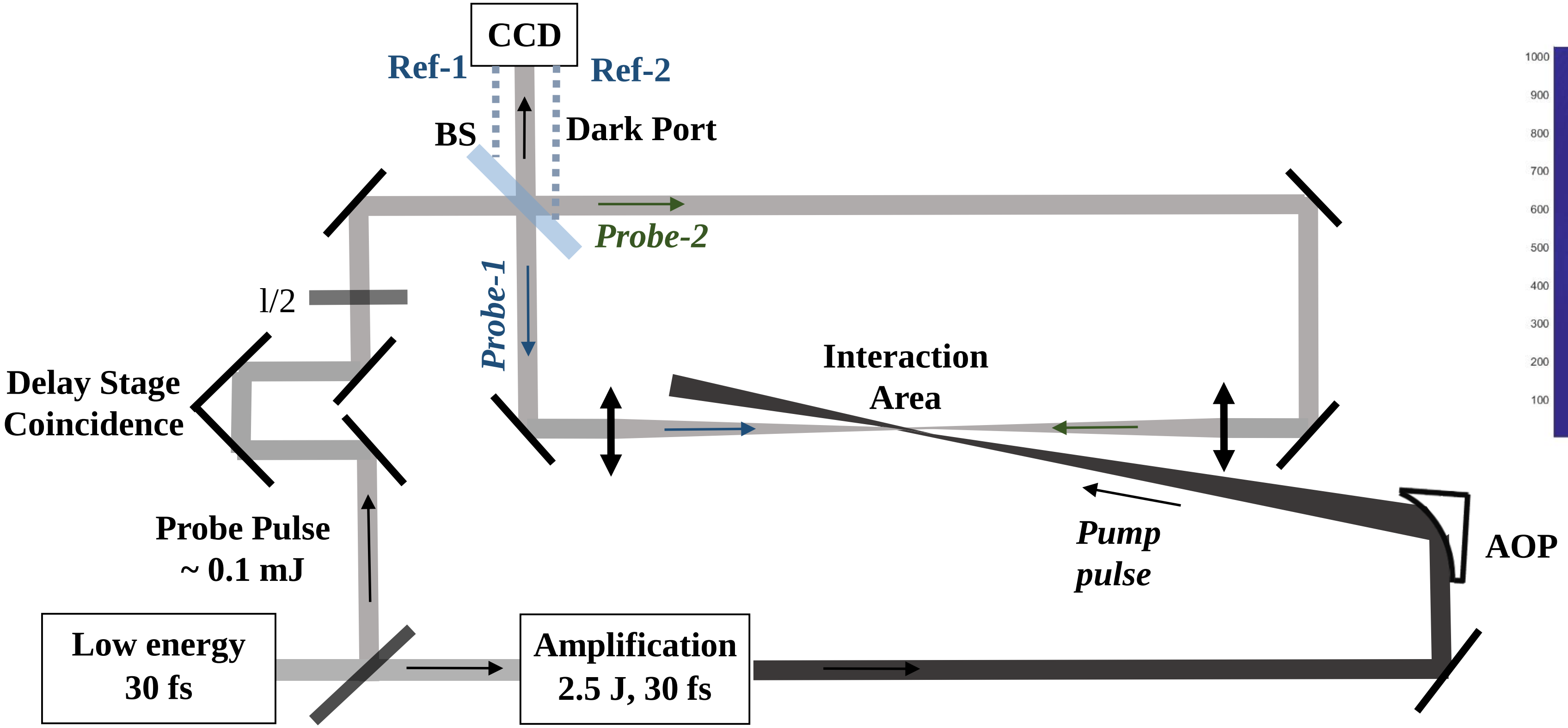
Optical Kerr index

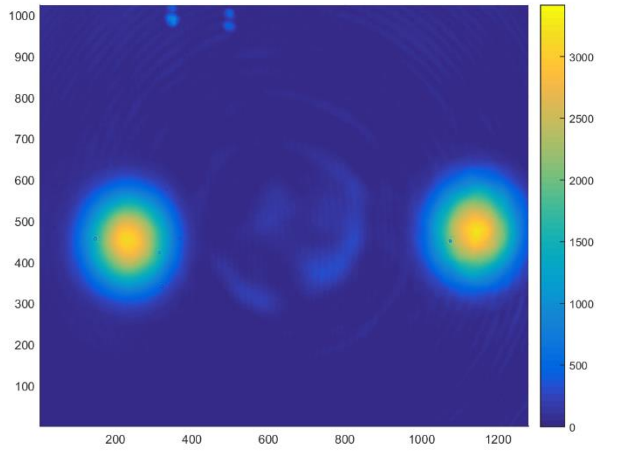
$$\boldsymbol{n_2 = 1.6 \times 10^{-33}\ \text{W/cm}^2}$$

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

S. Robertson, arXiv:1908.00896 submitted to Phys. Rev.

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 $\boldsymbol{\delta_{\text{shift}}}$
- 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 *f***
- Finaly they interfer in the dark output with an **extinction** $\boldsymbol{\mathcal{F} = 4\epsilon^2} = 0.4 \times 10^{-5}$

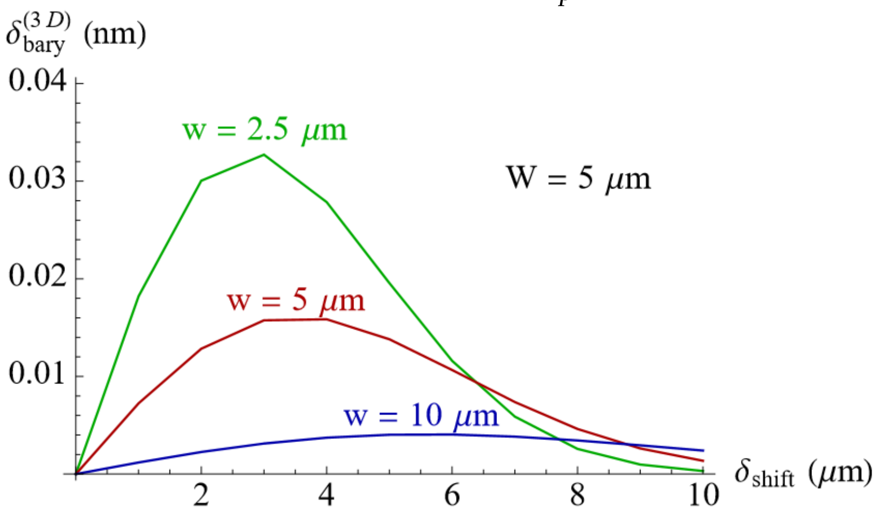
  (ϵ = assymetry of the beam splitter)

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 δ_p



Signal Δx 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

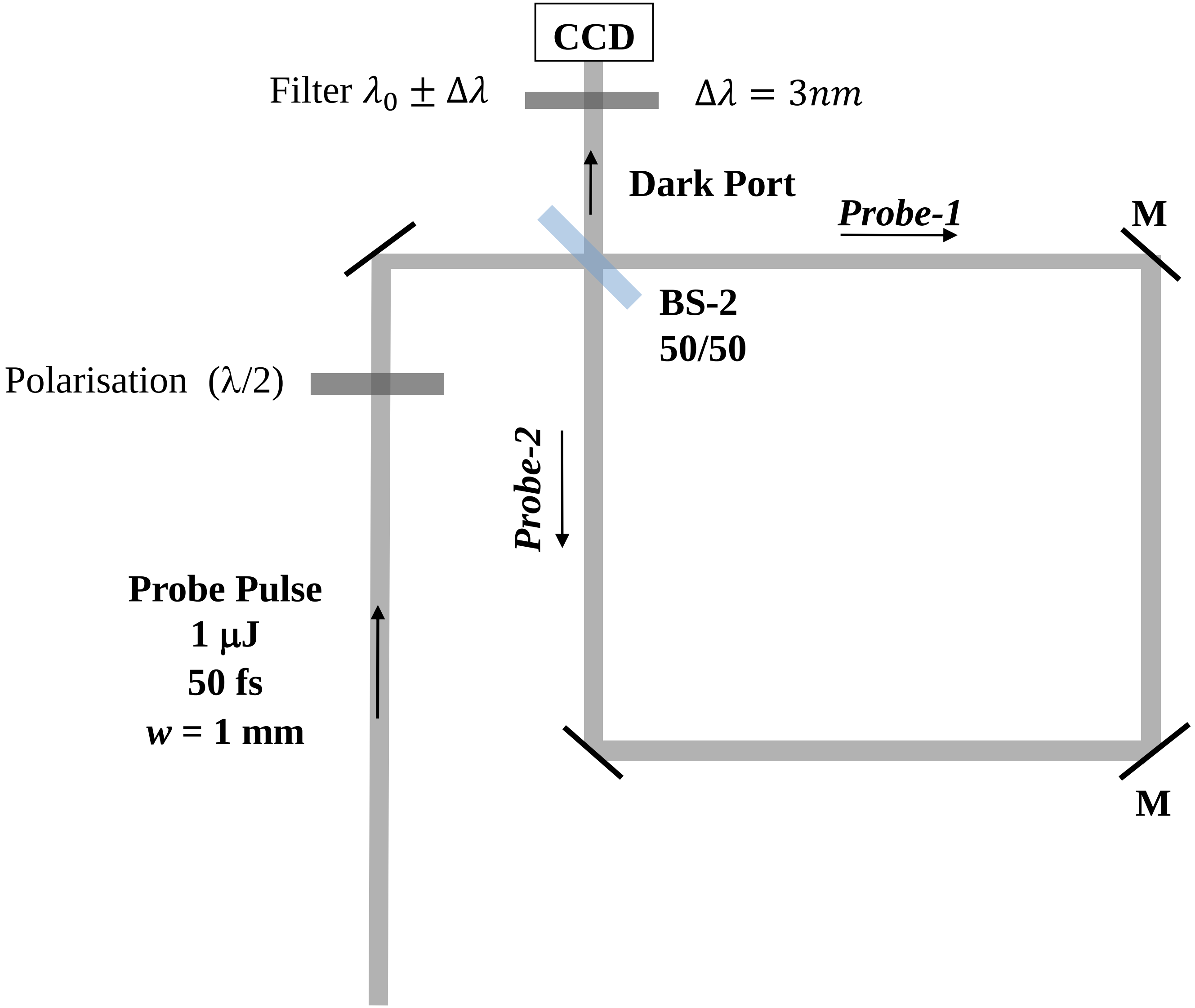
Experimental challenges

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

  + stability of the pump-probe overlap

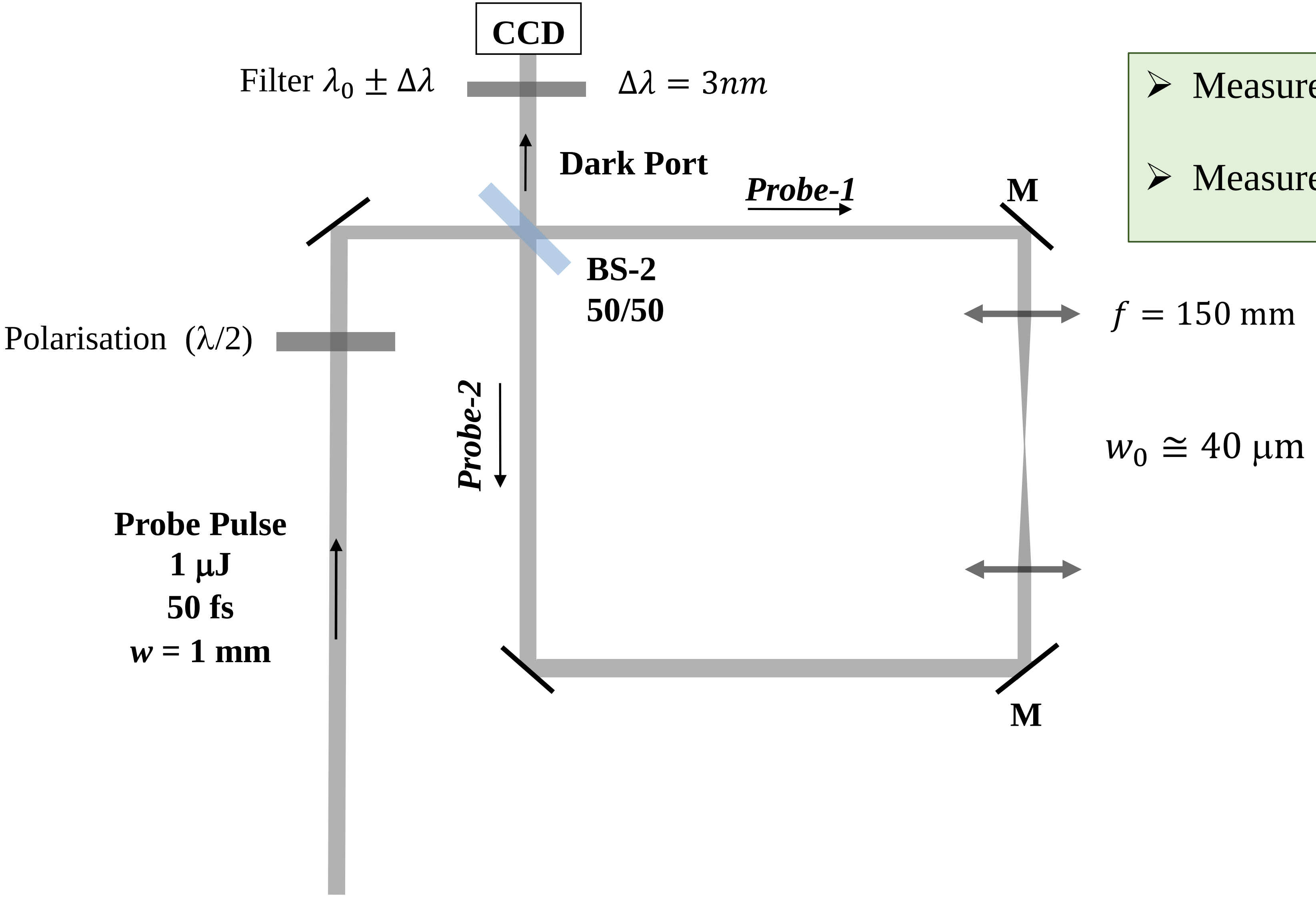
DeLLight prototypes

DeLLight prototypes



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

DeLLight prototypes



- Measurement of the extinction factor
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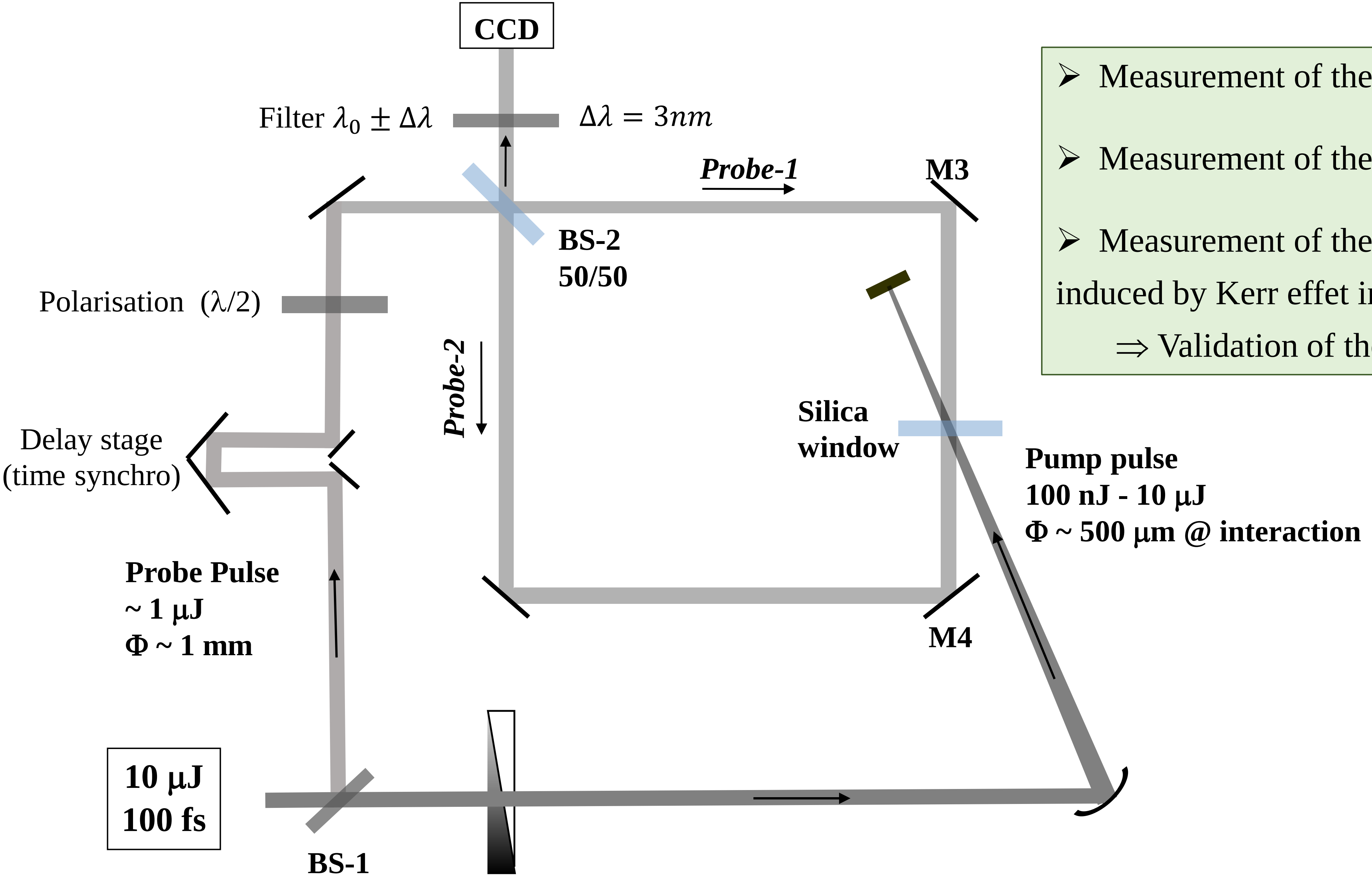
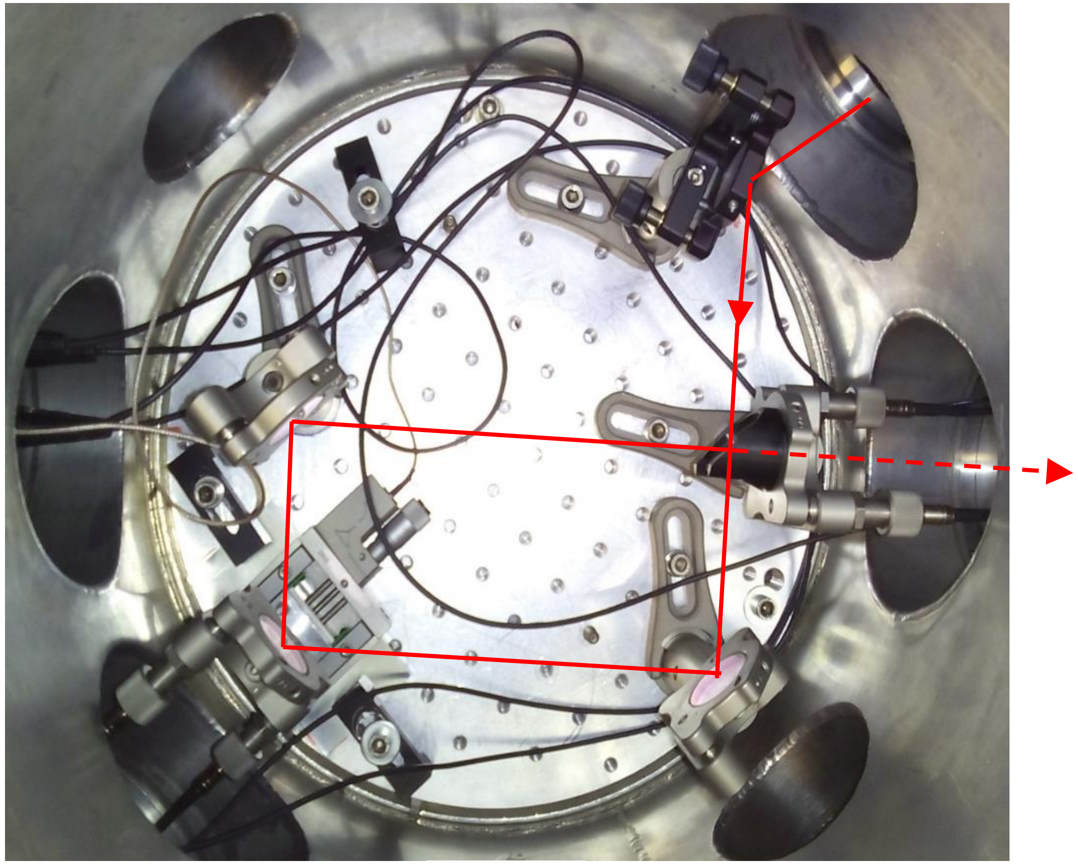
DeLLight prototypes



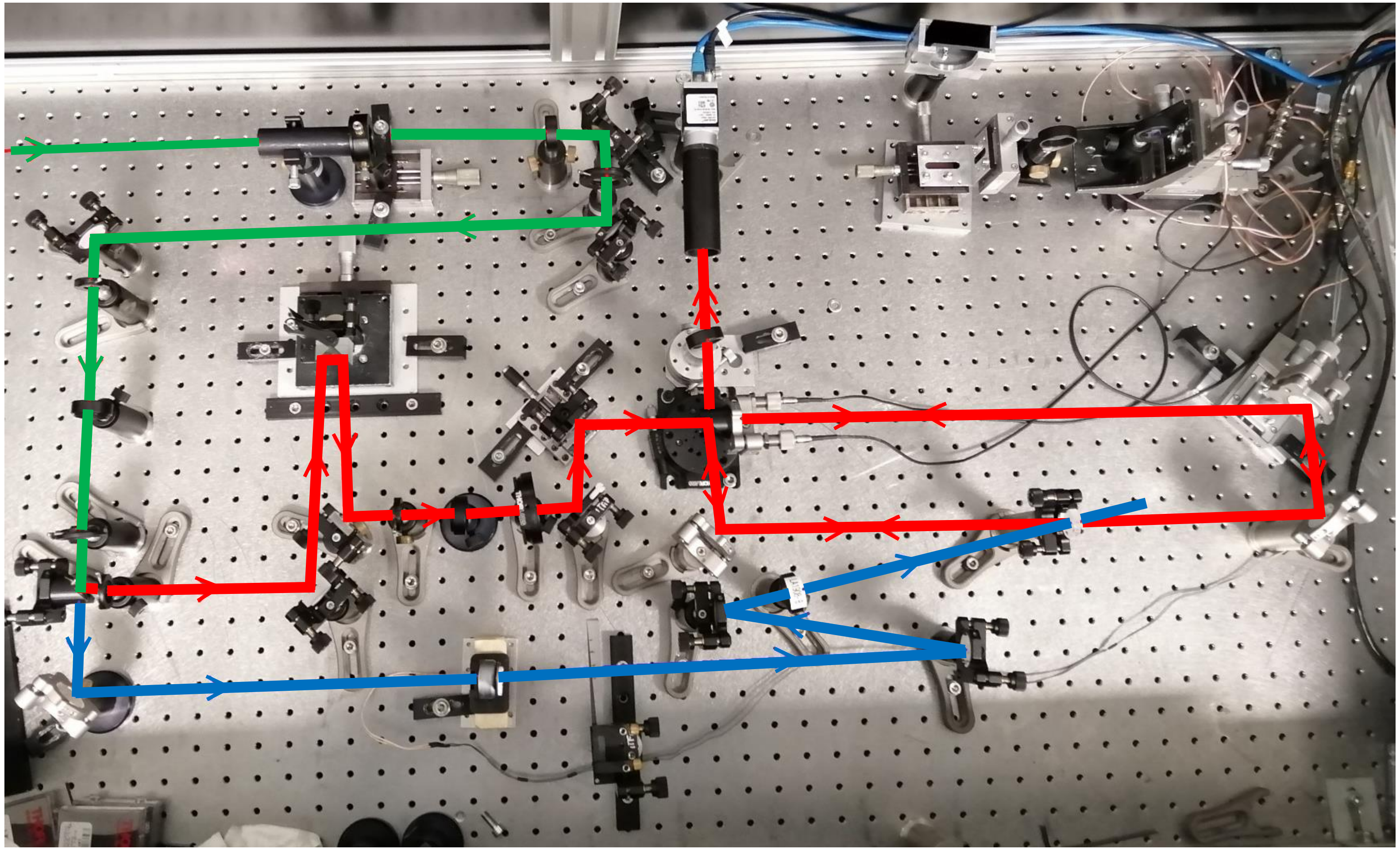
- Measurement of the extinction factor
- Measurement of the spatial resolution
- Measurement of the index gradient induced by Kerr effet in silica window and in gas

  ⇒ Validation of the methode

Sagnac interferometer in vacuum



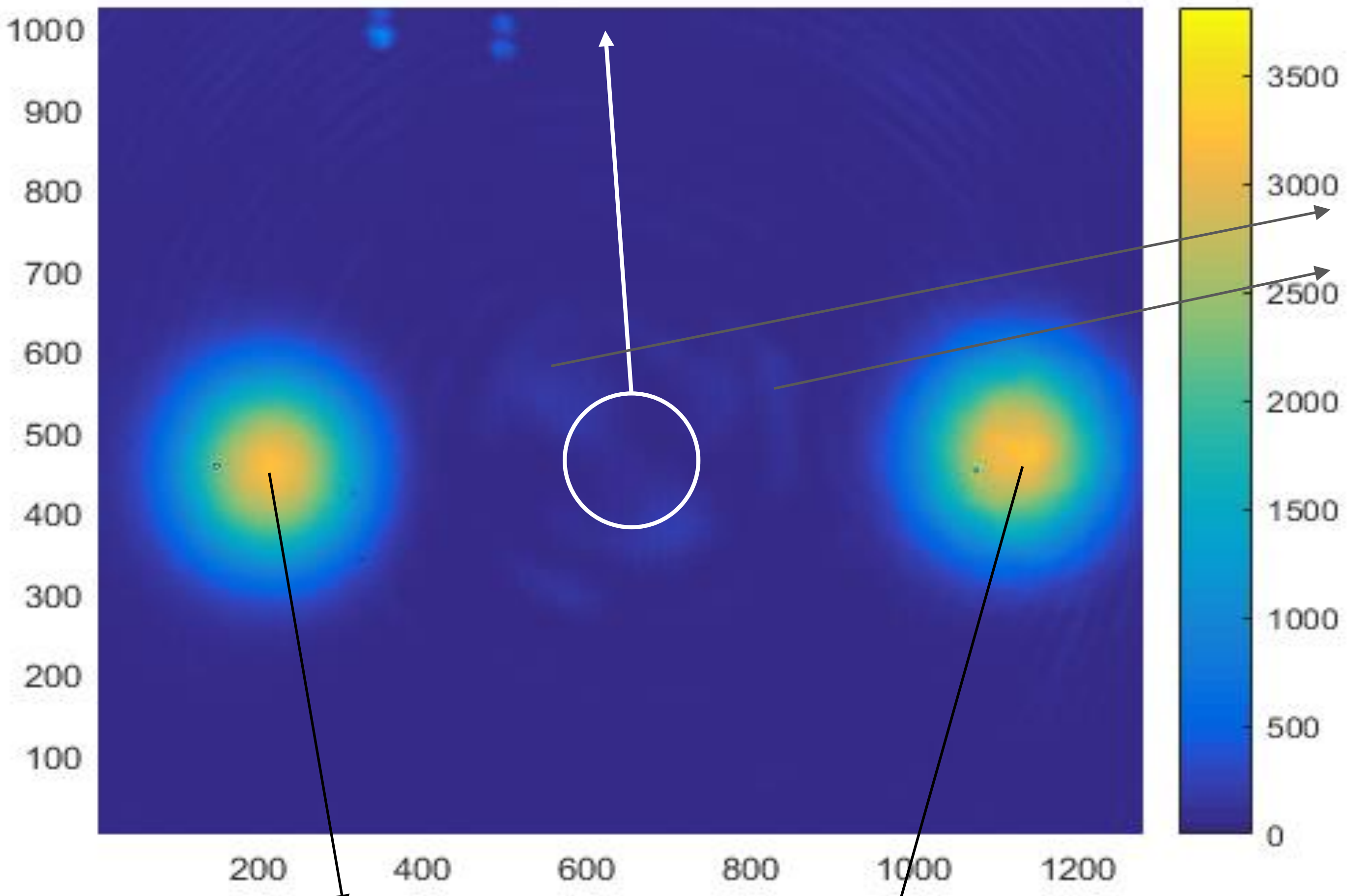
DeLLight current prototype



- ✓ 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 Δλ = 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}



Hot spots :

Surface defects on mirors inside the Sagnac

Back reflection (~ 10^{-3})

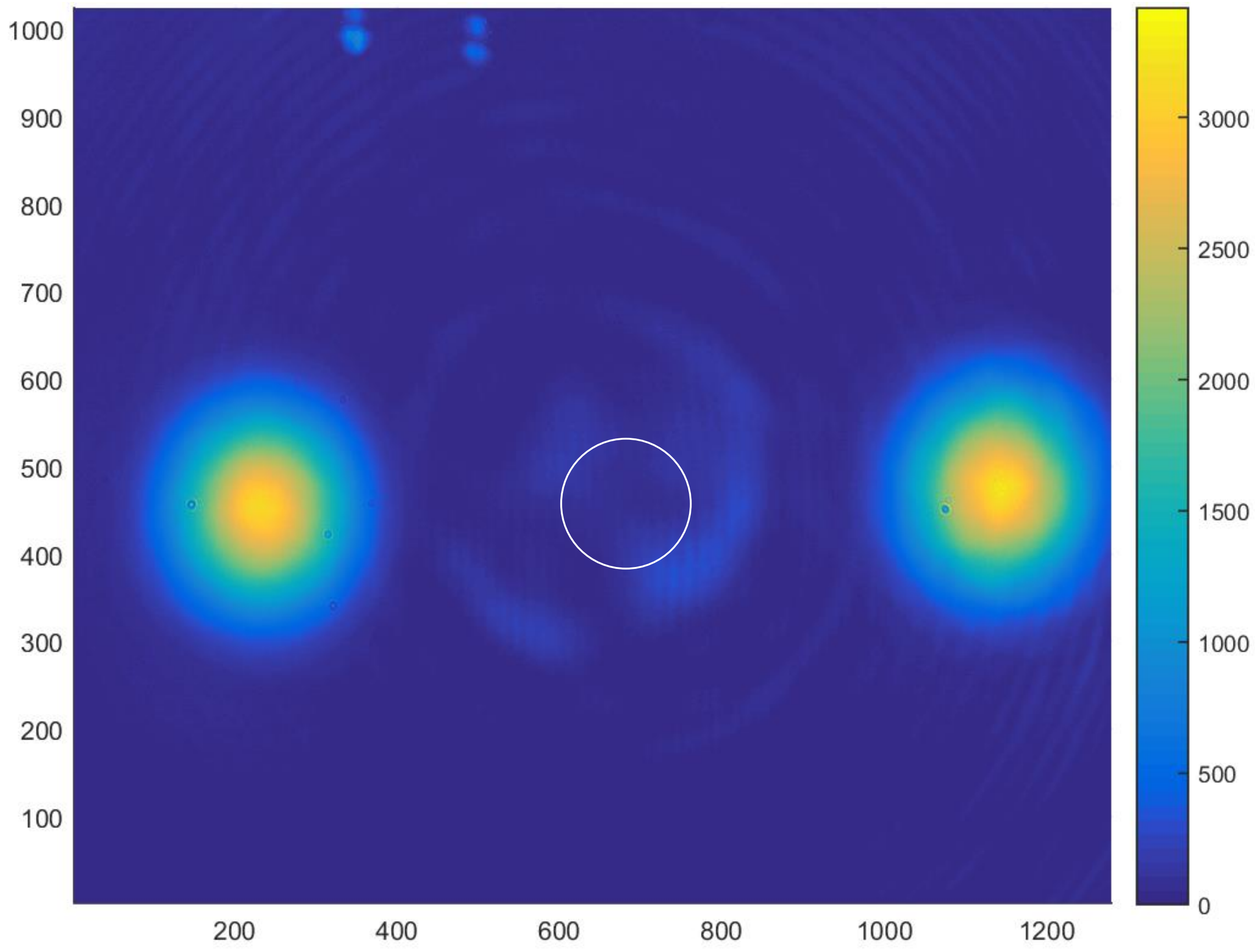
Extinction of the interferometer

Polarization of the probe beam

Extinction = $4\varepsilon^2$

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

ε depends upon the polarization



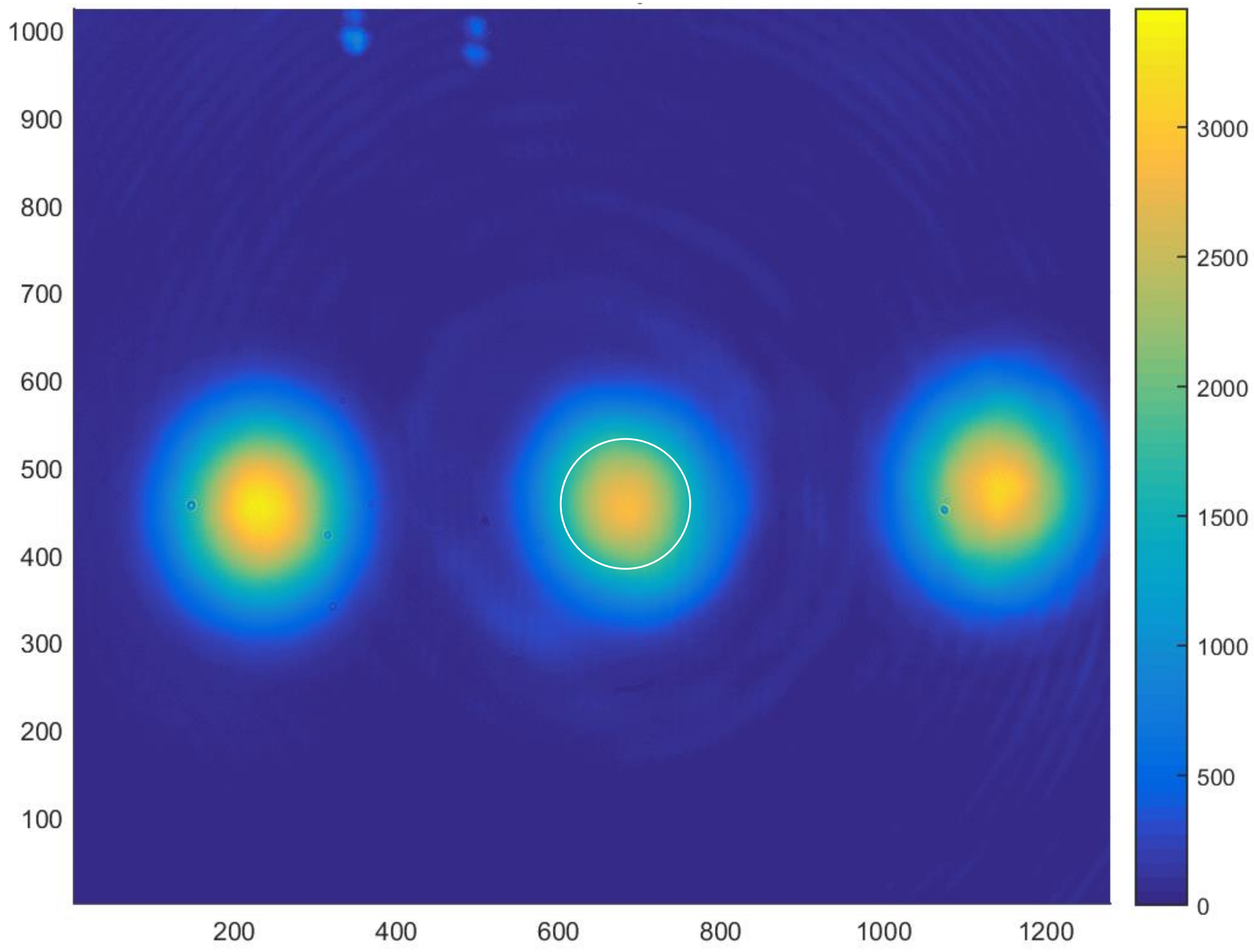
Extinction of the interferometer

Rotation of the polarization ⇒ Extinction ~ 10^{-3}

Extinction = $4\varepsilon^2$

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

ε depends upon the polarization



Experimental challenges

- ✓ Extinction: $\mathcal{F} = 4\epsilon^2 \cong 10^{-5}$
- ✓ Spatial resolution: σ_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

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

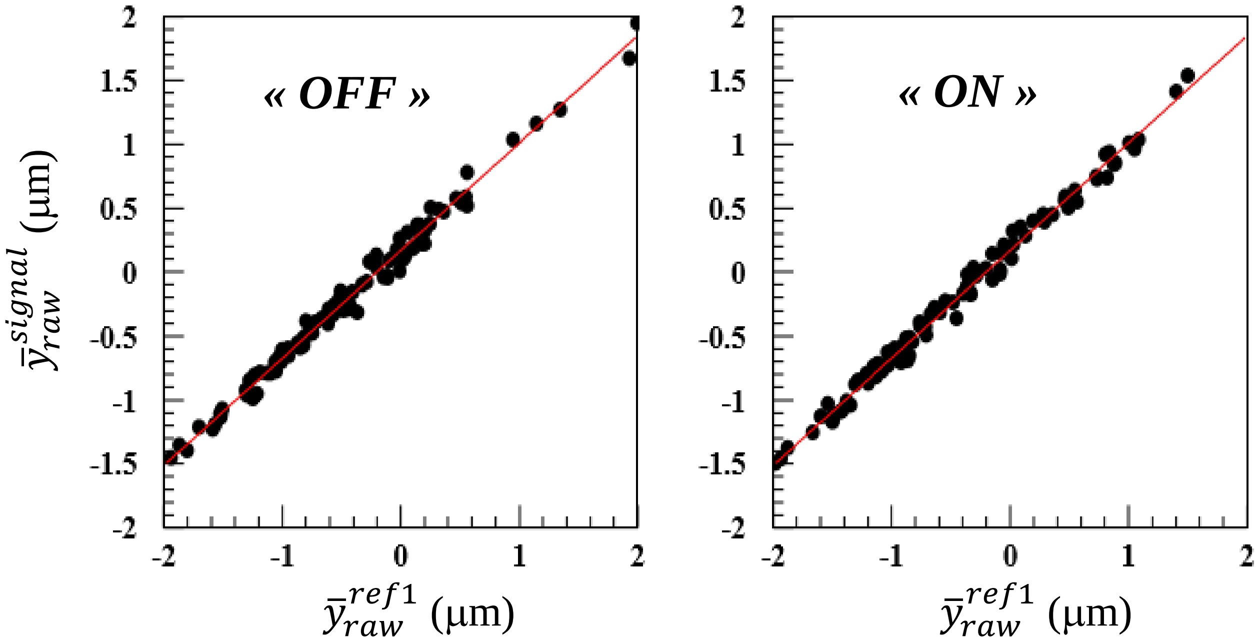
- With better CCD *BASLER™* (*acA4024-29um*):
  - Pixel size d_{pix}: 1.8×1.8 μm^2
  - Charge saturation $N_{e-}^{max} \cong 10^4$ e$^-$/pixel

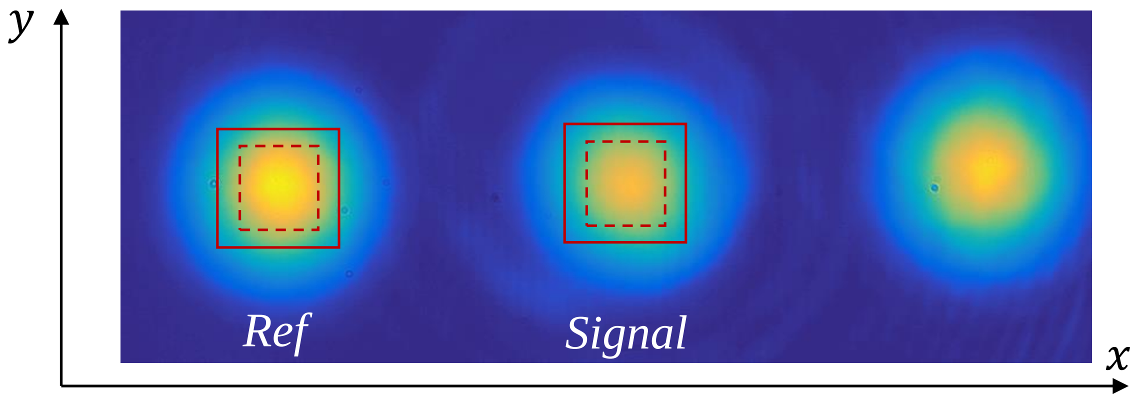
$\Rightarrow$ $\boldsymbol{\sigma_x} \cong$ **10 nm**

Spatial resolution

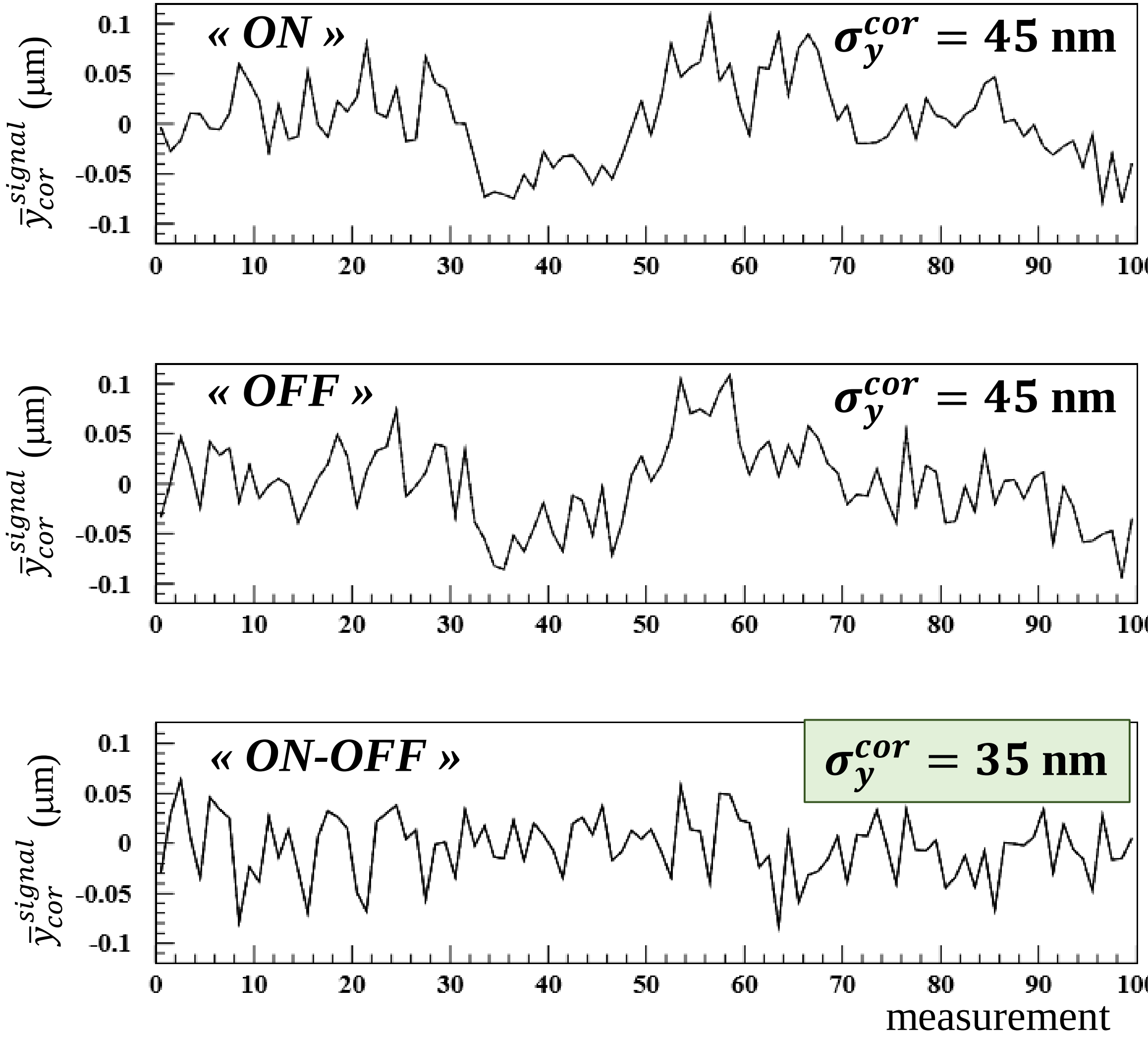
Analysis based on a barycenter calculation in a simple square analysis window (RoI) : $\mathbf{ROI = 1.5 \times \sigma_{beam}}$

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

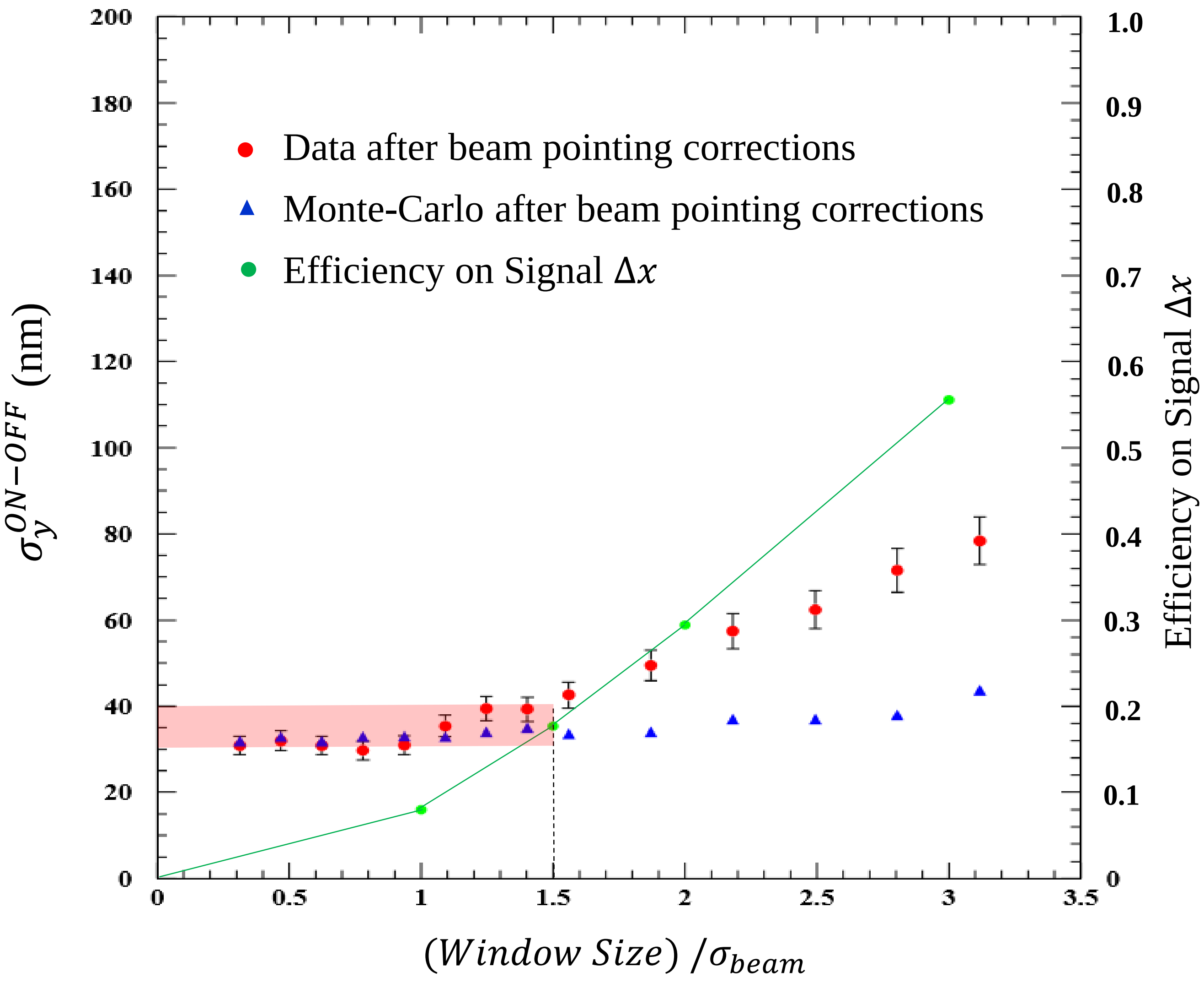




After beam pointing correction
⇒ low frequency drift supressed by ON-OFF subtraction



Spatial resolution



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

  $\Rightarrow$ Data $\boldsymbol{\sigma_x} \cong \mathbf{30 - 40}$ **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:

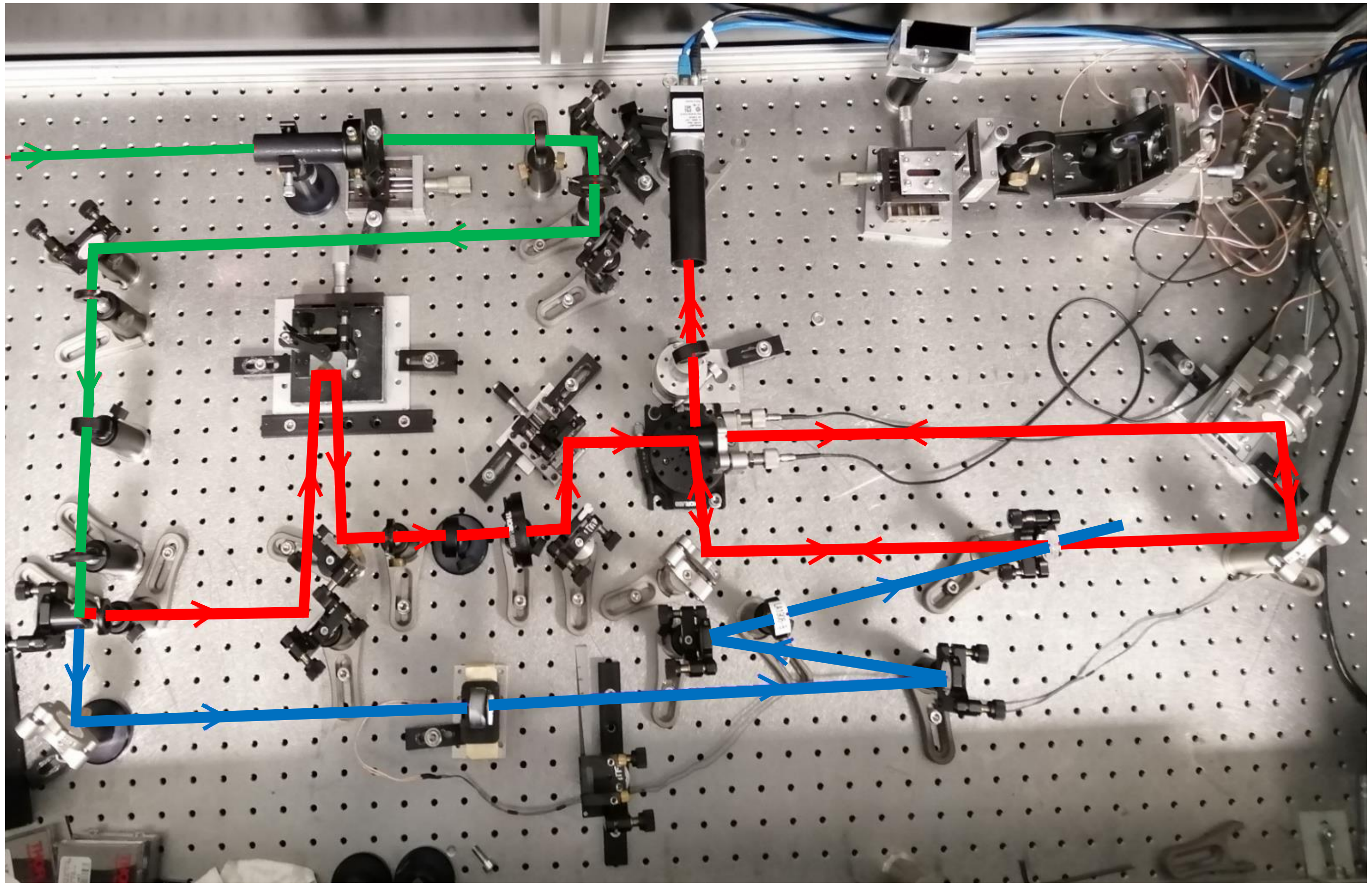
- Background mapping & substraction
- Fit of the profiles
- Surface quality of the optics
- CCD uniformity
- Etc…

Experimental challenges

- ✓ Extinction: $\mathcal{F} = 4\epsilon^2 \cong 10^{-5}$
- ✓ Spatial resolution: σ_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)

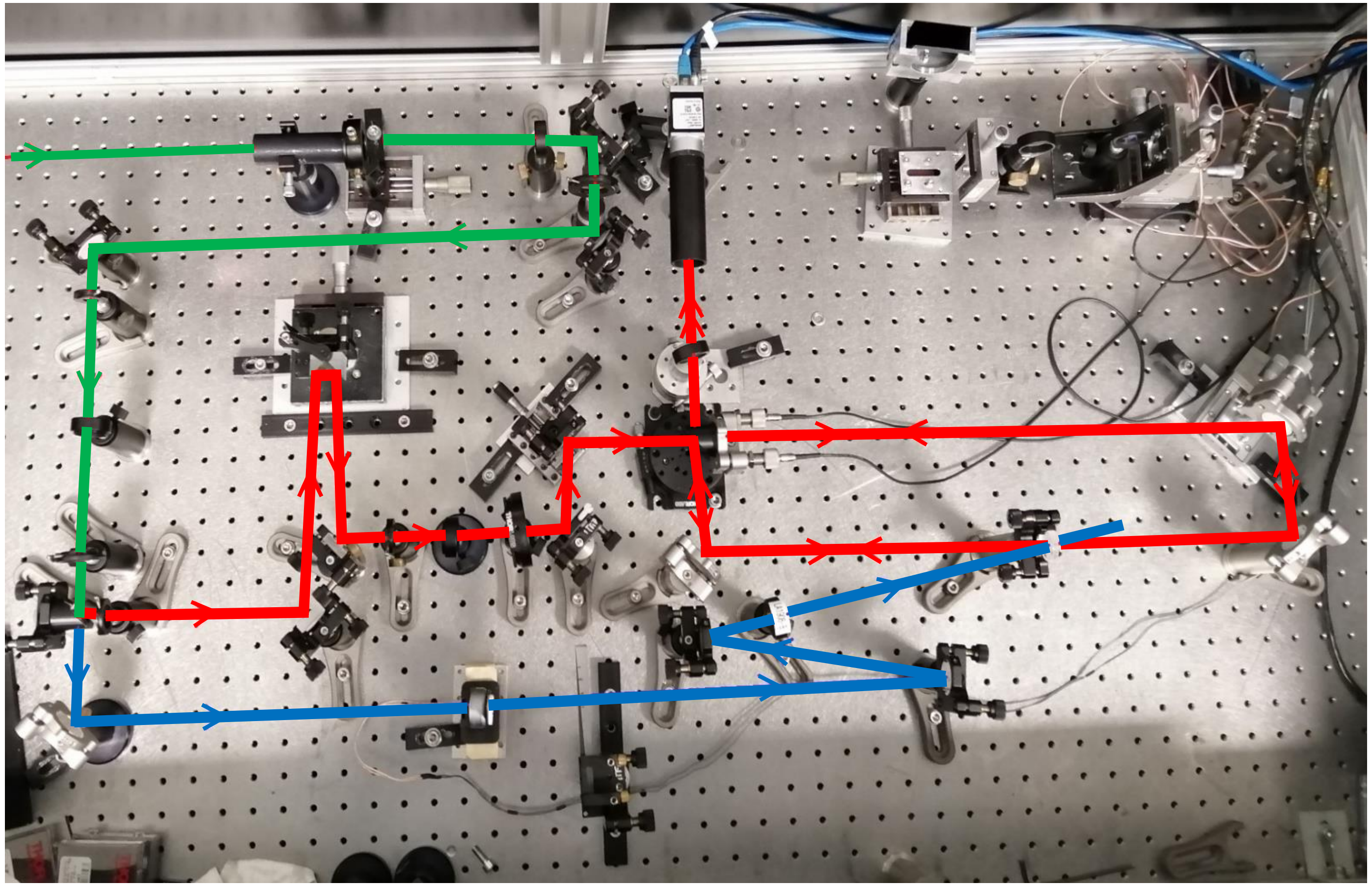


$n(I) = n_0 + n_2 \times I(\mathrm{W/cm^2})$

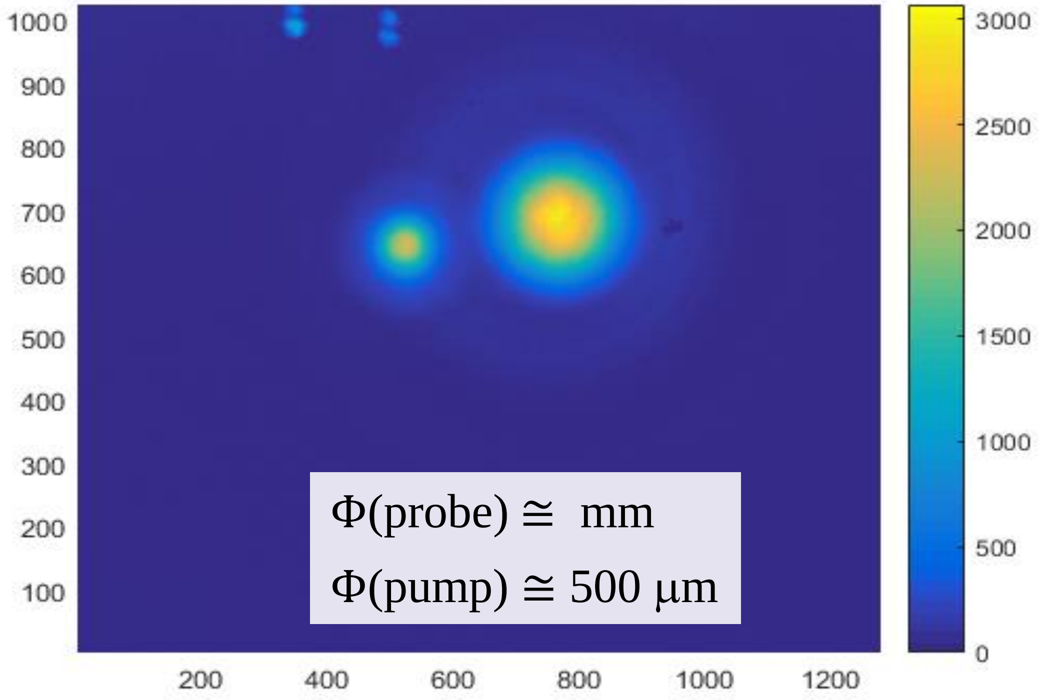
$n_2(\mathrm{Silica}) \approx 10^{-16}\ \mathrm{cm^2/W}$

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

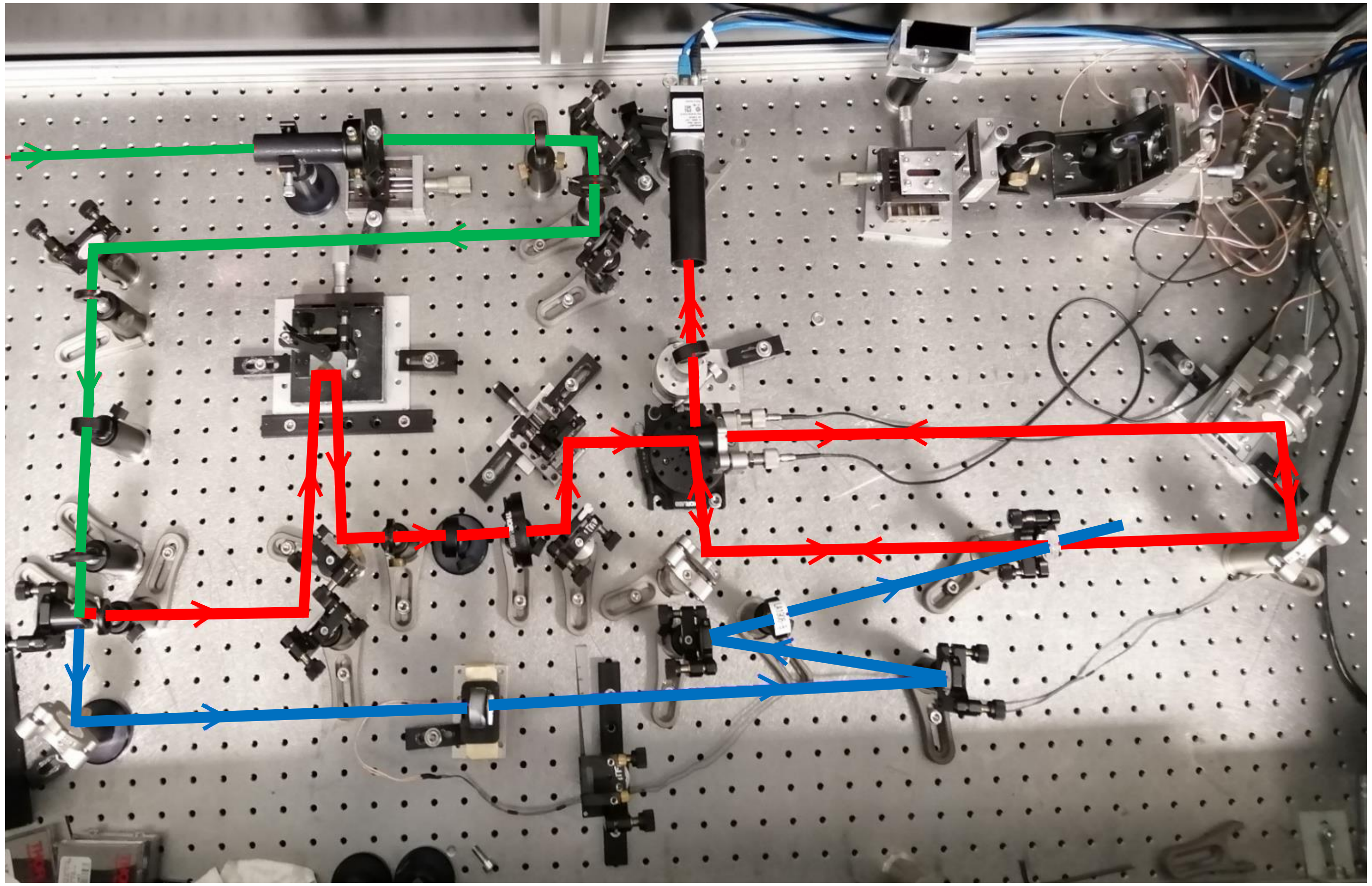
Observation of the non linear Kerr effect



Intensity profiles of the Pump & Probe
in the interaction area



Observation of the non linear Kerr effect



Intensity profiles of the Pump & Probe
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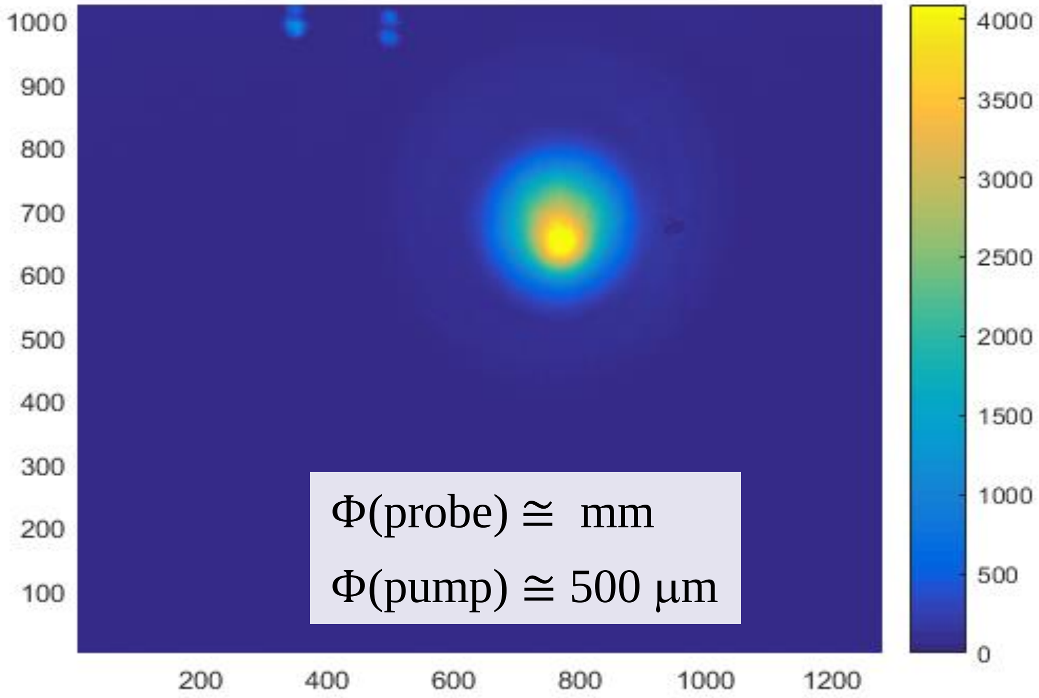
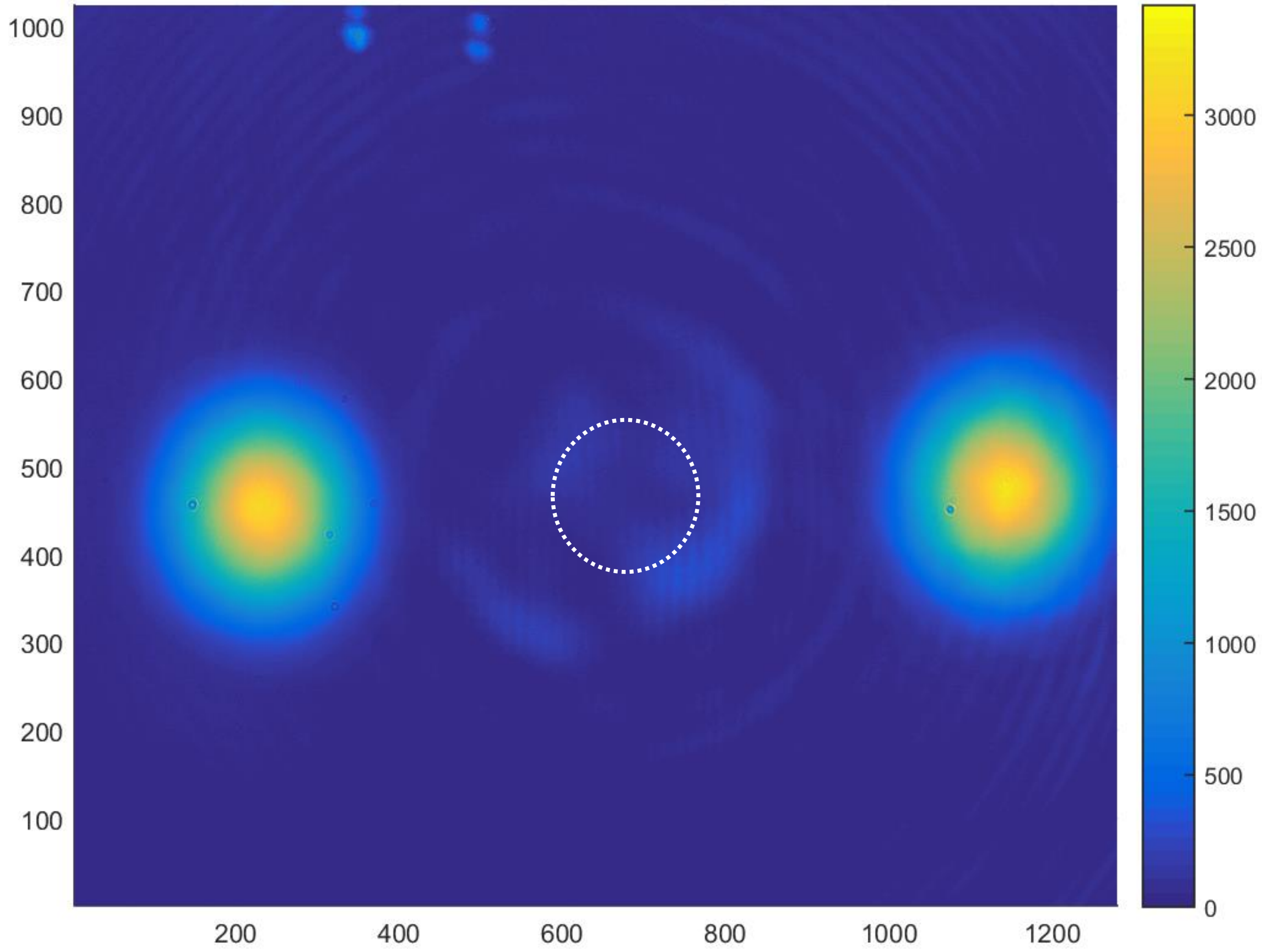


Measurement of the Kerr signal in SiO_2

Maximal extinction

Without pump



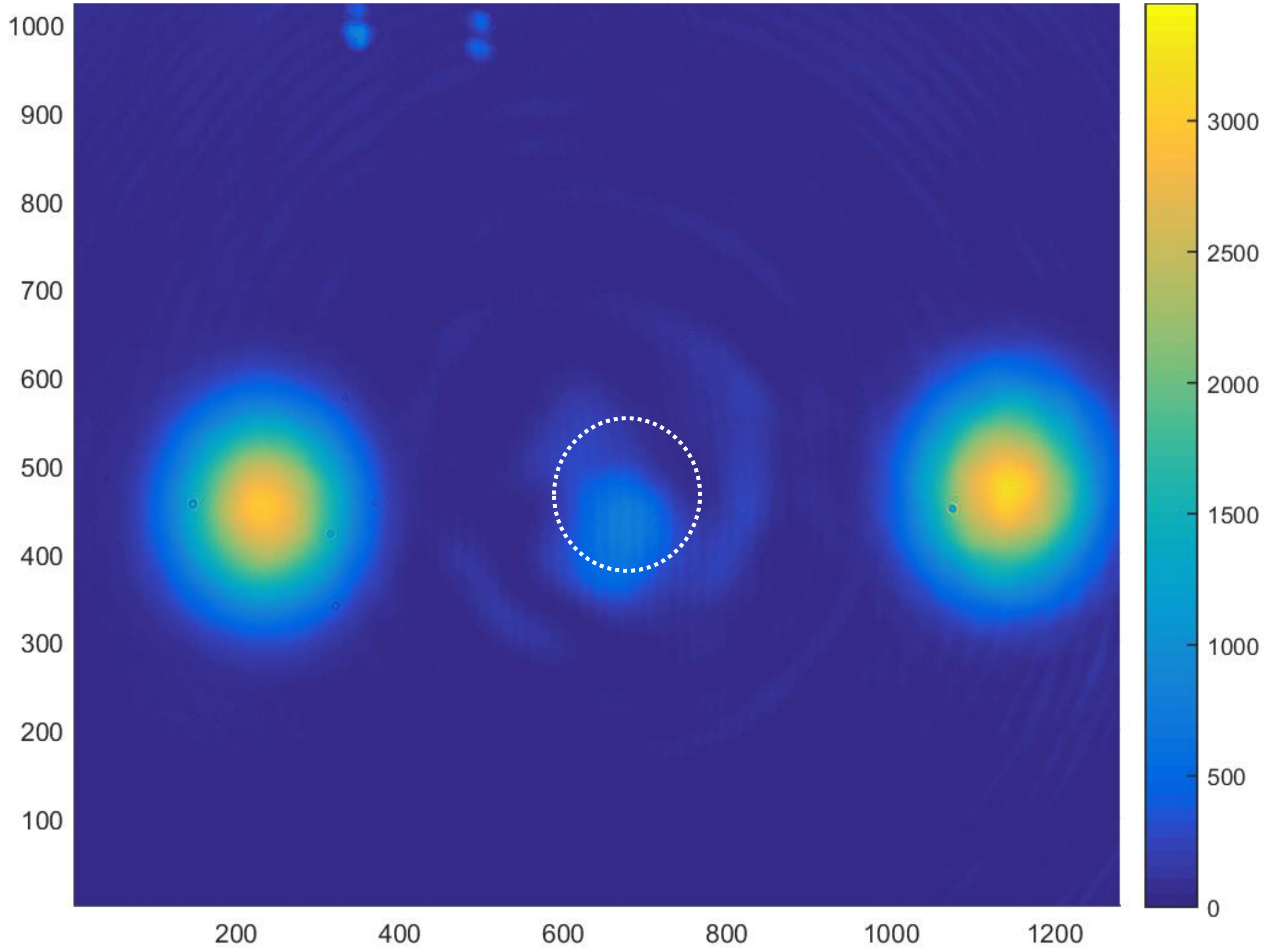
Intensity profiles in the dark output
of the Sagnac interferometer

Measurement of the Kerr signal in SiO_2

Maximal extinction

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

Energy pump ~ 10 μJ



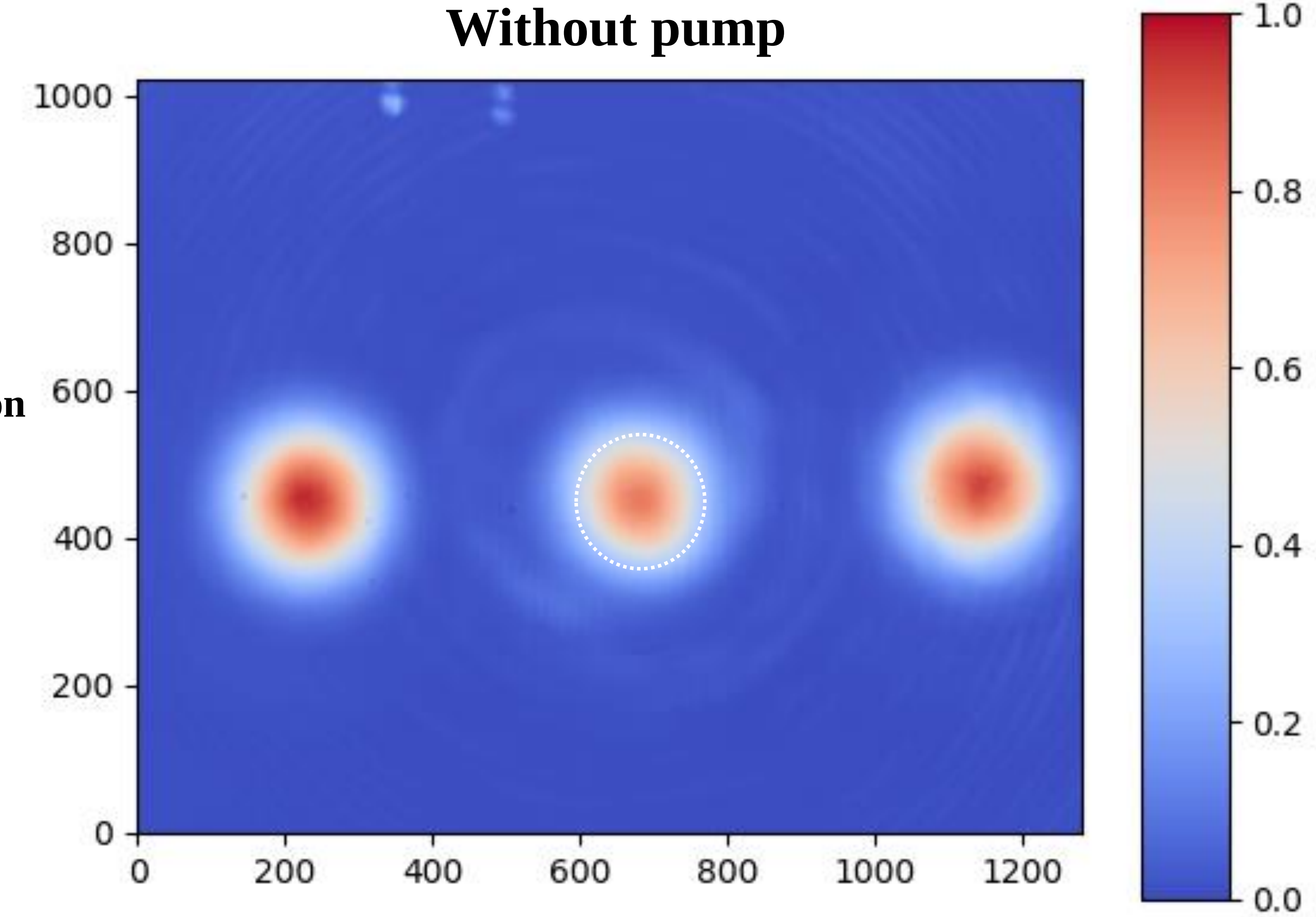
Intensity profiles in the dark output
of the Sagnac interferometer

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

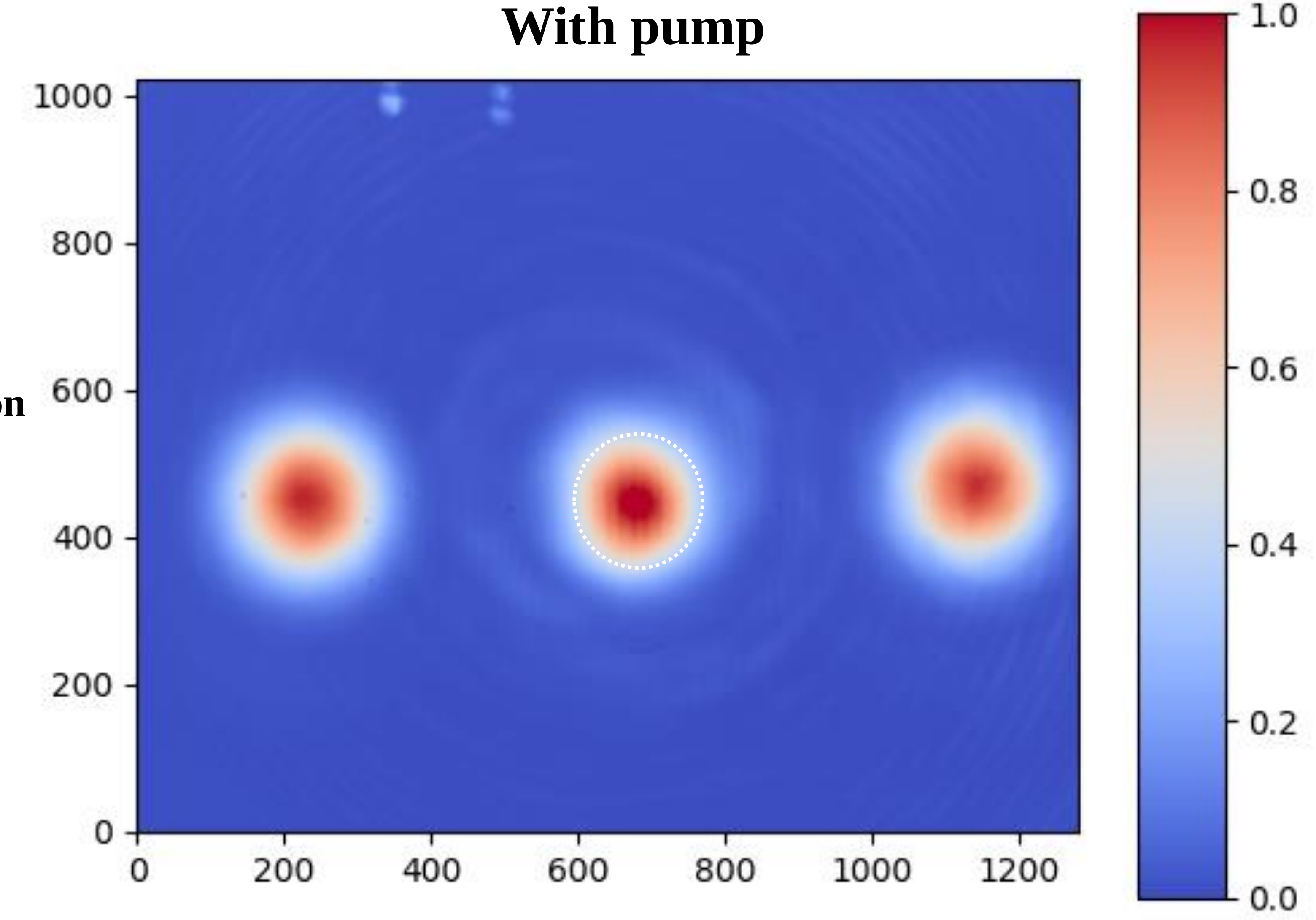
With pump

I ~ 10^{11} W/cm^2

Energy pump ~ 10 μJ

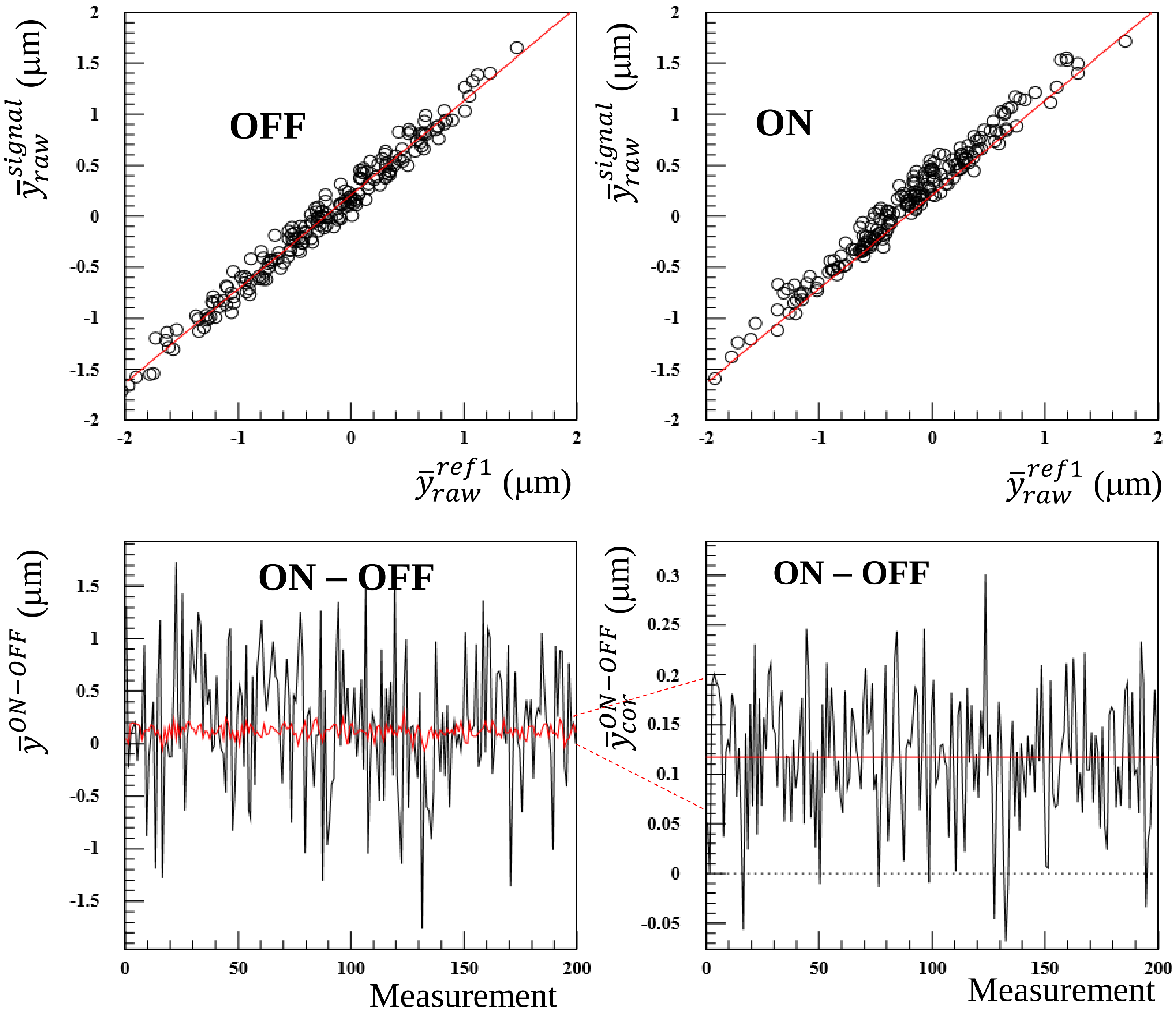
With rotated polarization

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



Intensity profiles in the dark output
of the Sagnac interferometer

Measurement of the Kerr signal in SiO_2



Energy pump ~ 300 nJ

Δt ~ 100 fs

Φ(pump) ~ 500 μm

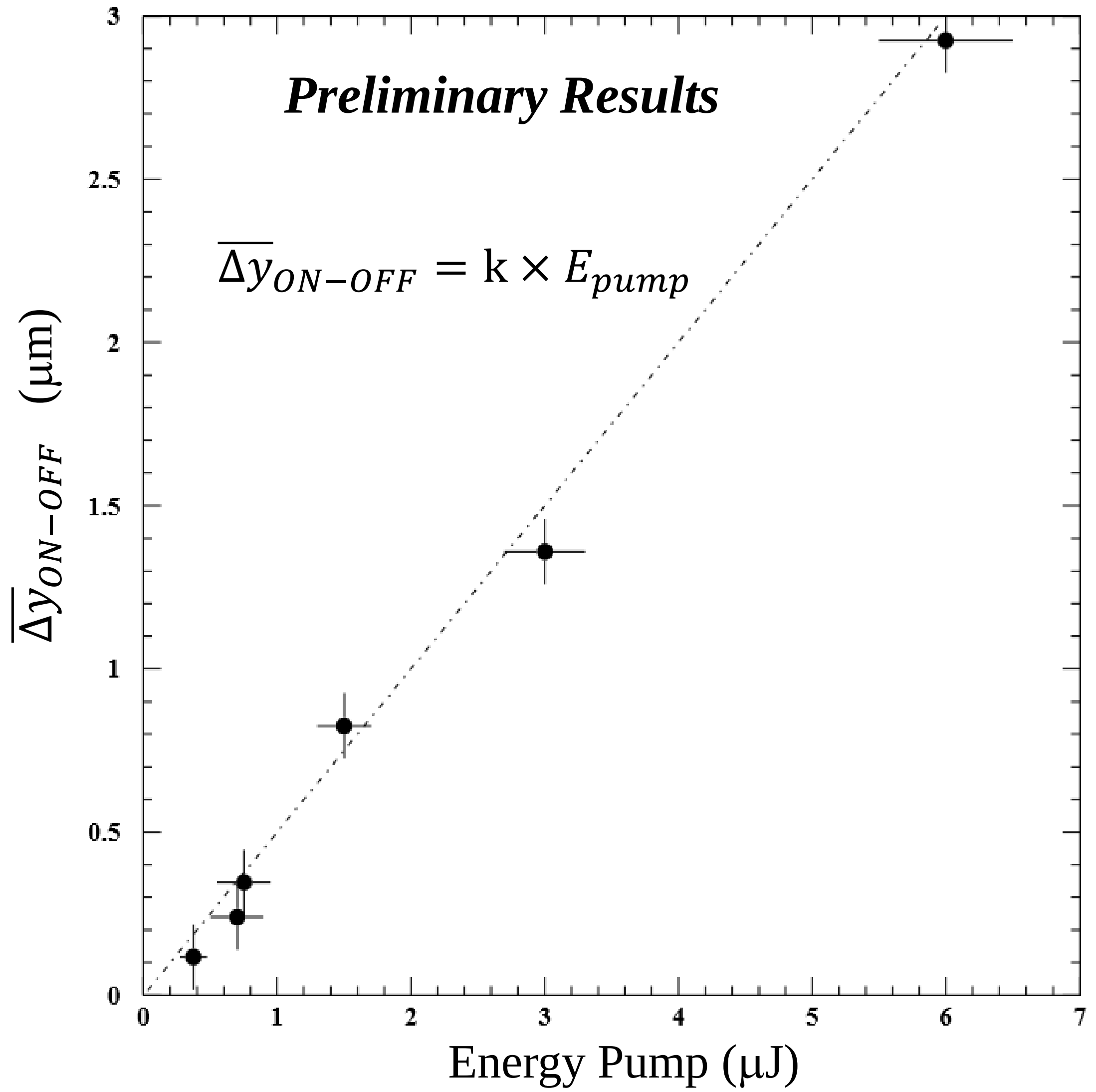
→ I ~ 10^9 W/cm^2

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

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

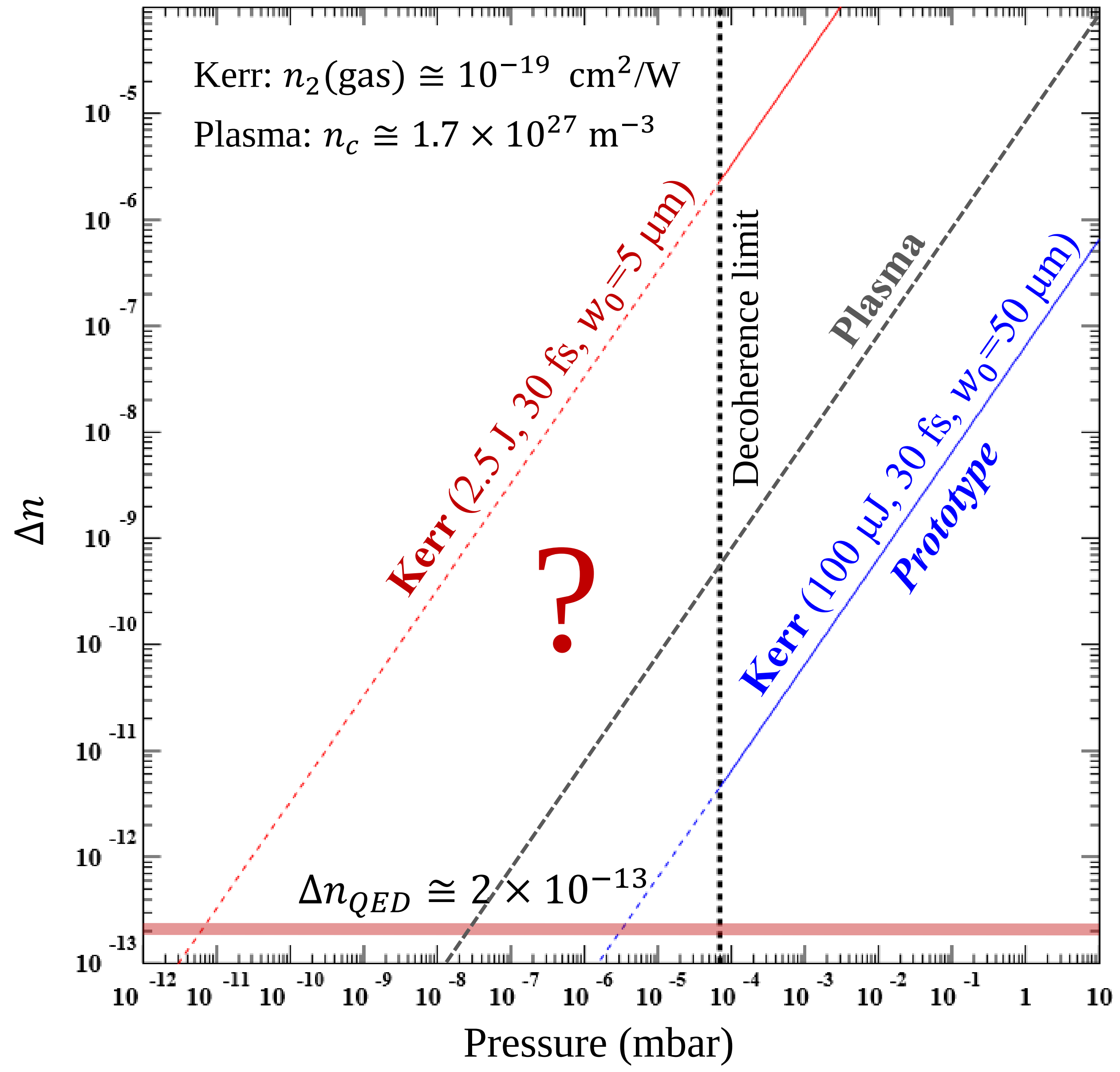
(200 meas. ON-OFF; T_{obs} = 40 sec.)

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
  - ….
- ✓ Next step: measure Kerr effect in gas

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

Measurement → 1

NL Vacuum → $\ll 1$

NL Kerr in gas → > 1

Plasma — Polar. Indepent

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 $w_0 = 20\ \mu m$
3. DeLLight Phase 2 (2021): Measure in vacuum with focus $w_0 = 5 \mu m \Rightarrow \delta n \approx 2 \times 10^{-13}$

DeLLight and other intense laser facilities

- **LASERIX** (LAL, Orsay):

  running 2J, 30fs $\Rightarrow$ ~**70 TW @ 10 Hz** $\Rightarrow$ $\boldsymbol{\Delta x_{LASERIX} \approx 0.01}$ **nm**

- **BELLA** laser (Berkeley LBNL):

  running with 40J, 30fs $\Rightarrow$ ~**1 PW @ 1 Hz**

- **APOLLON** laser (Saclay):

  2019: 30 J, 30 fs $\Rightarrow$ ~1 PW @ 0.1 Hz

  Target: 100 J, 20 fs $\Rightarrow$ ~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

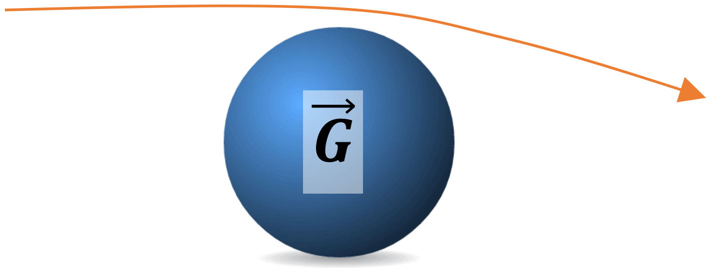
  June 2018: 16 joules, 27 femtosecond pulse duration (0.5 PW) @ 3.3Hz

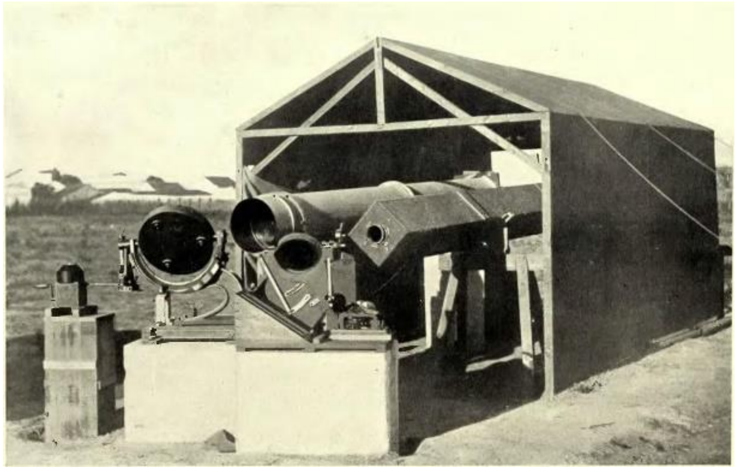
  2020 : 30 J, 30 fs $\Rightarrow$ **1 PW @ 10 Hz** $\Rightarrow$ $\boldsymbol{\Delta x_{HAPLS} \approx}$ **0.1 nm**

  Target: ~200 Joules, 30 fs $\Rightarrow$ ~ 6 PW @ 10 Hz $\Rightarrow$ $\boldsymbol{\Delta x_{HAPLS} \approx}$ **0.6 nm**

Conclusions

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

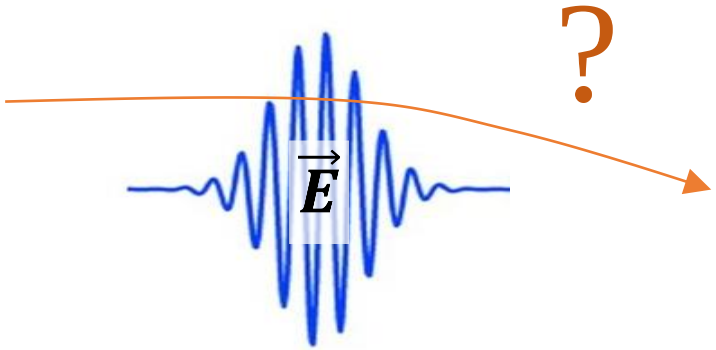


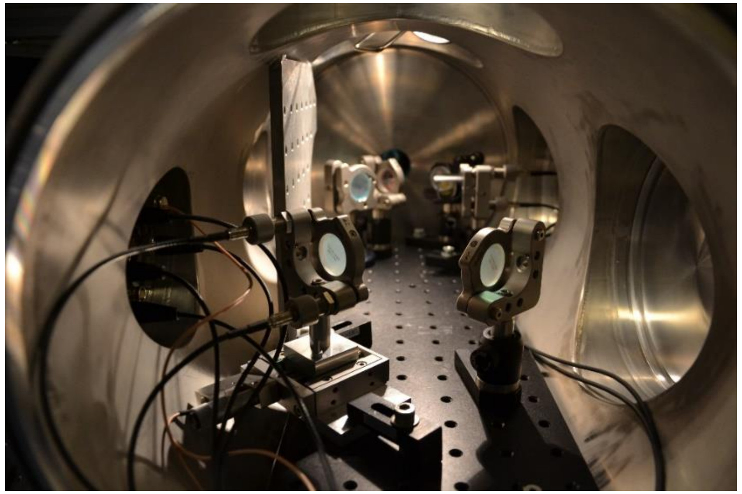


Deflection already observed

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 !…

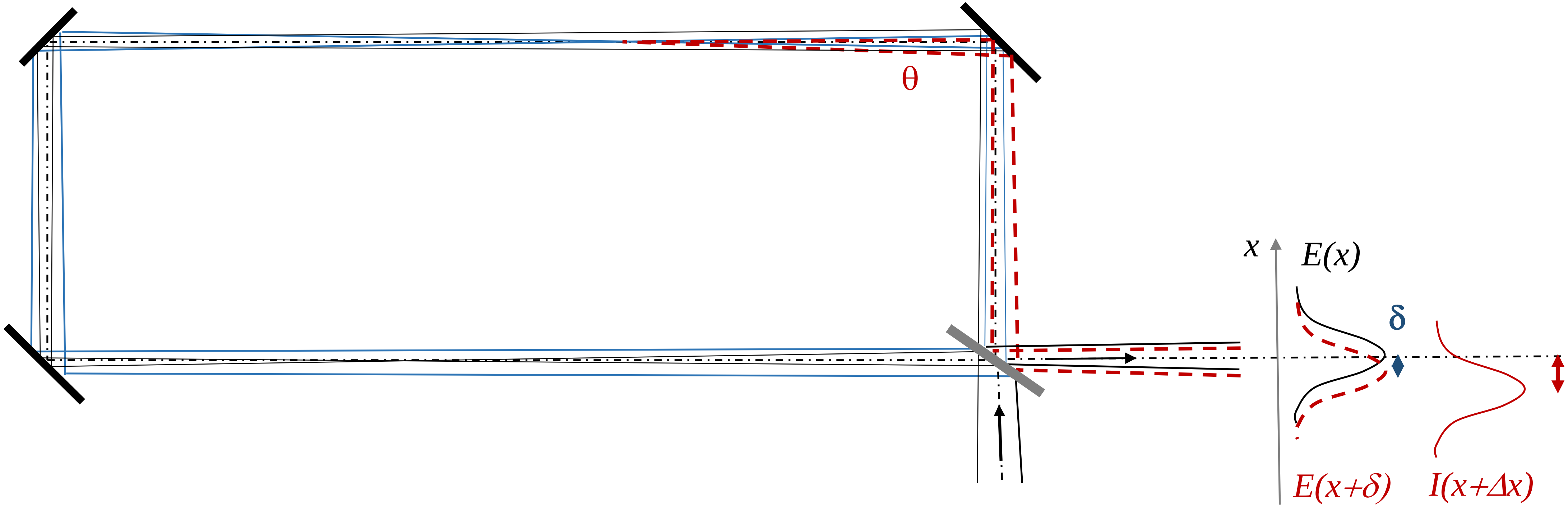
Backup

Amplification with a Sagnac Interferometer

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

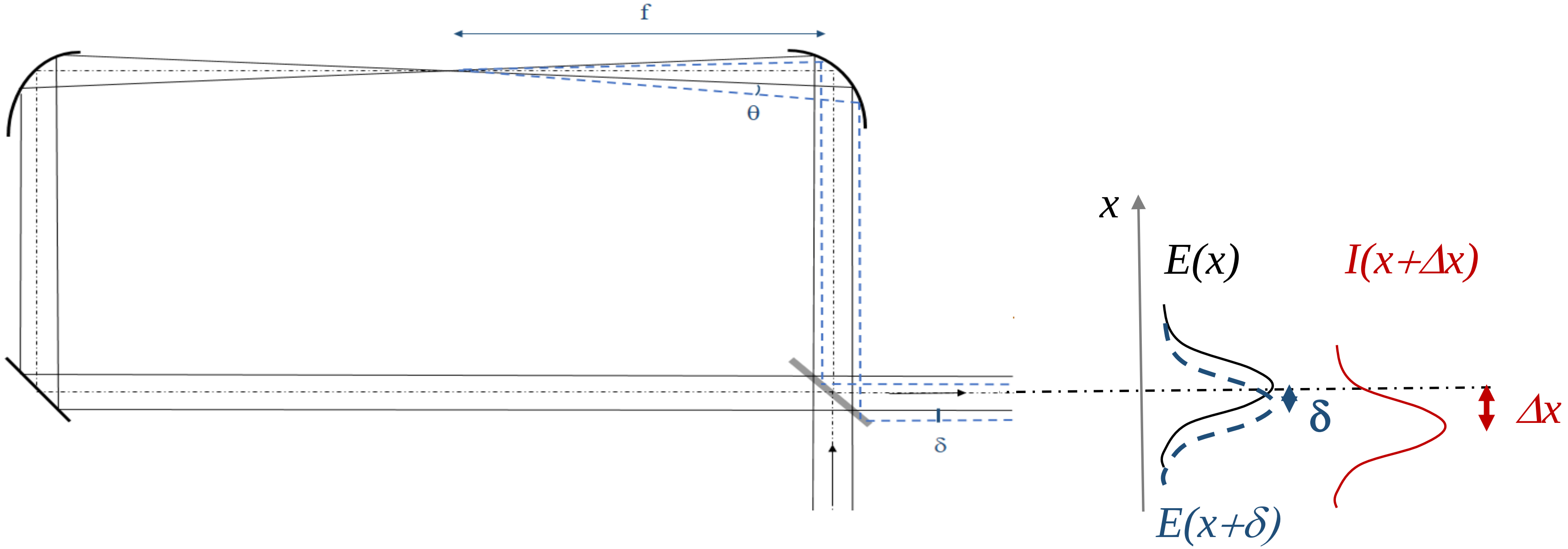
$$E(x) = exp\left(-\frac{x^2}{2\sigma^2}\right) \Rightarrow I(x) = \left(\frac{2\epsilon\delta}{\sigma^2}x + 4\epsilon^2\right)\exp\left(-\frac{x^2}{\sigma^2}\right) \Rightarrow \Delta x = \frac{\int_{-\infty}^{+\infty} xI(x)dx}{\int_{-\infty}^{+\infty} I(x)dx} = \frac{\delta}{4\epsilon}$$

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

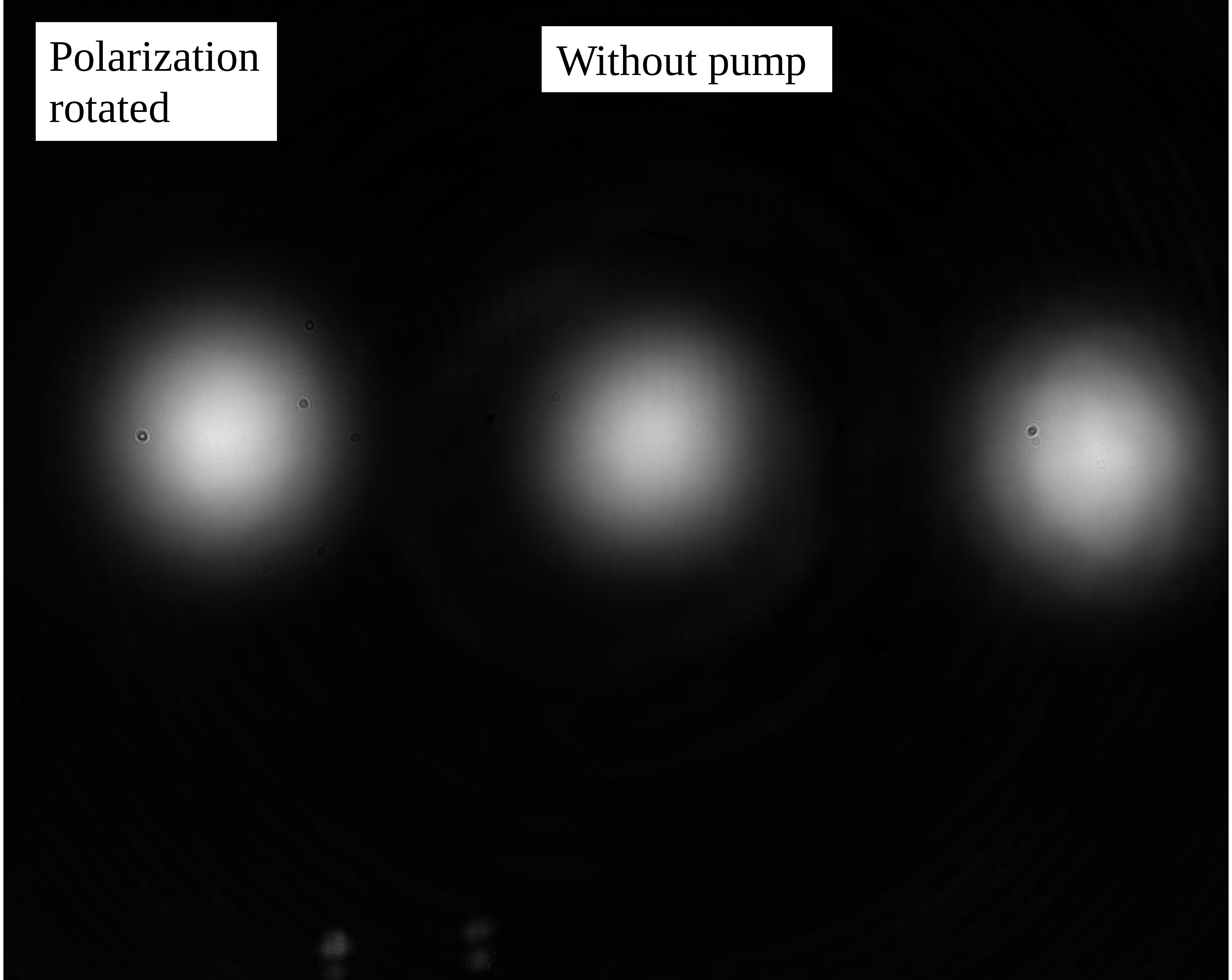
- Refraction of the probe pulse $\Rightarrow$ **Transversal shift Δx of the interference intensity profile**

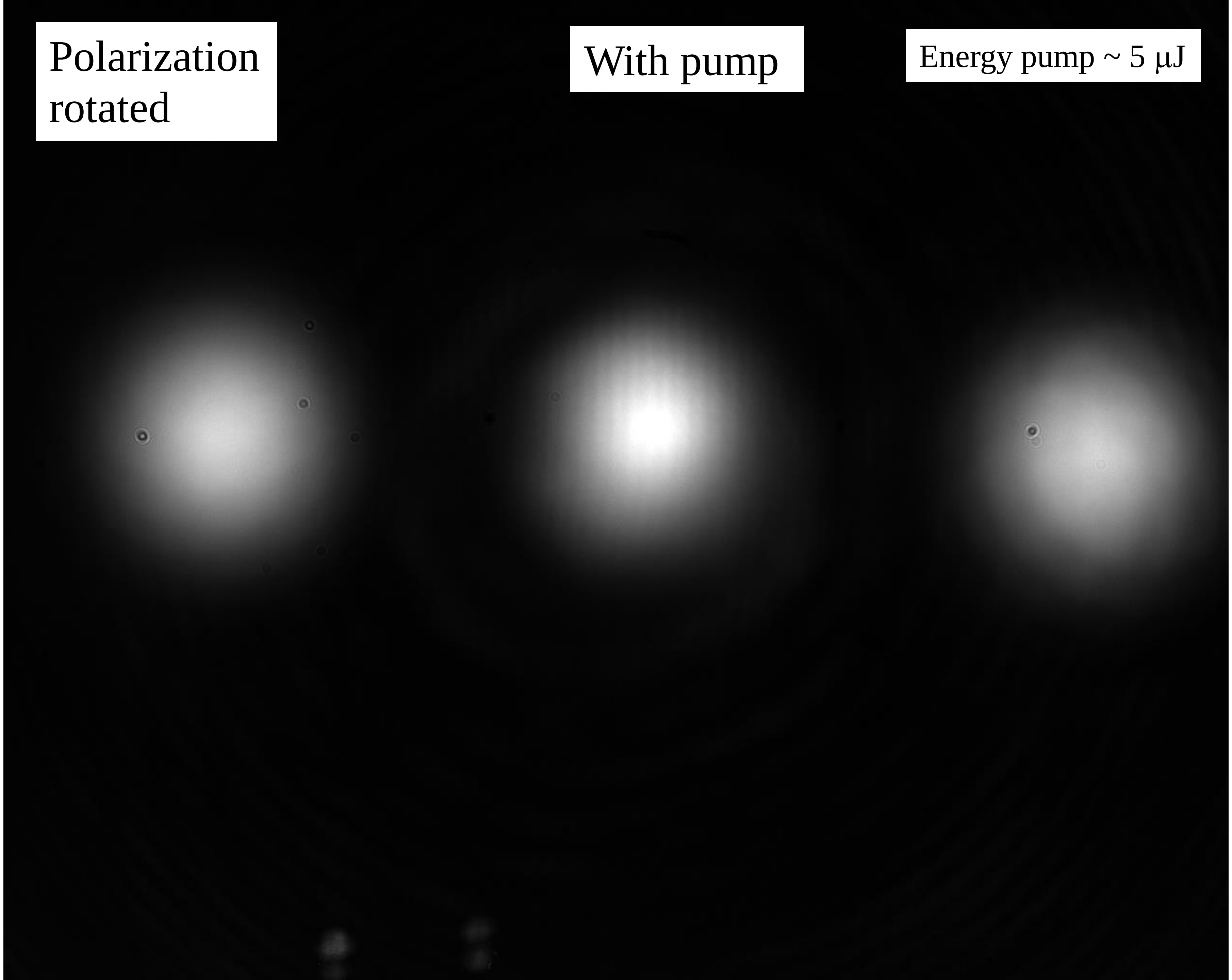


- Interference $\Rightarrow$ **Amplification factor $\mathcal{F}$** compared to standard pointing method (with transversal shift δ)

$$\mathcal{F} = \frac{\Delta x}{\delta} = \frac{1}{2\sqrt{Extinction}}$$ where $Extinction = \frac{I_{out}}{I_{in}} = 4\epsilon^2$ and ϵ = 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 $V = (20\ \mu m)^2 \times 10 \times \Delta t \times c$