DeLLight
(Deflection of Light by Light)
with LASERIX

Modification of the vacuum refractive index in intense electromagnetic fields

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Xavier Sarazin (LAL) *Séminaire IRFU 19 Novembre 2018*

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 medium

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

➡ Optical index is not constant but 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 ?

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

Can the vacuum optical index be modified by an external field ?

This question has been studied for the first time in 1911
in the case of gravitaion…

Is the vacuum optical index modified by gravitation ?

Einstein is the first one to note that n and c are affected by the gravitation:

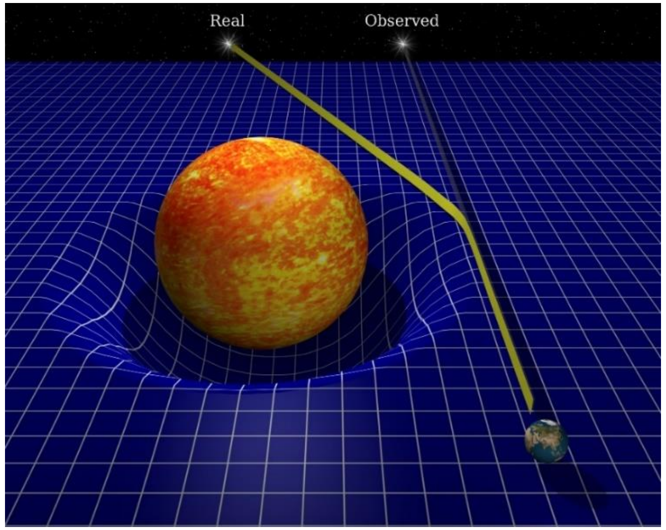
- ✓ Einstein, A. 'Über den Einfluss der Schwerkraft auf die Ausbreitung des Lichtes', Annalen der Physik 35, 898-908 (1911)
- ✓ *"The constancy of the velocity of light can be maintained only insofar as one restricts oneself to spatio-temporal regions of constant gravitational potential"* *(Einstein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

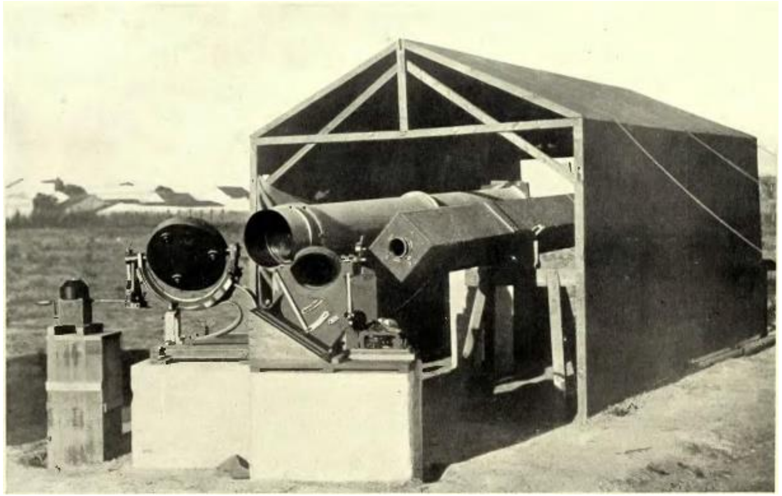
Einstein generalized the « c = **constante** » relativity principle thanks to the introduction of a ***curved spacetime metric***

$\Rightarrow$ 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 ?

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 and the inertial masses

$\boldsymbol{n(r)}$ 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)*

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

(to preserve the equivalence principle)

Cosmology with a vacuum index increasing with time

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

?

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

$\Rightarrow n(t)$ increases with time

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

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

✓ Euclidean static metric

✓ Relative variation $dn(t)/n(t)$ is time invariant:

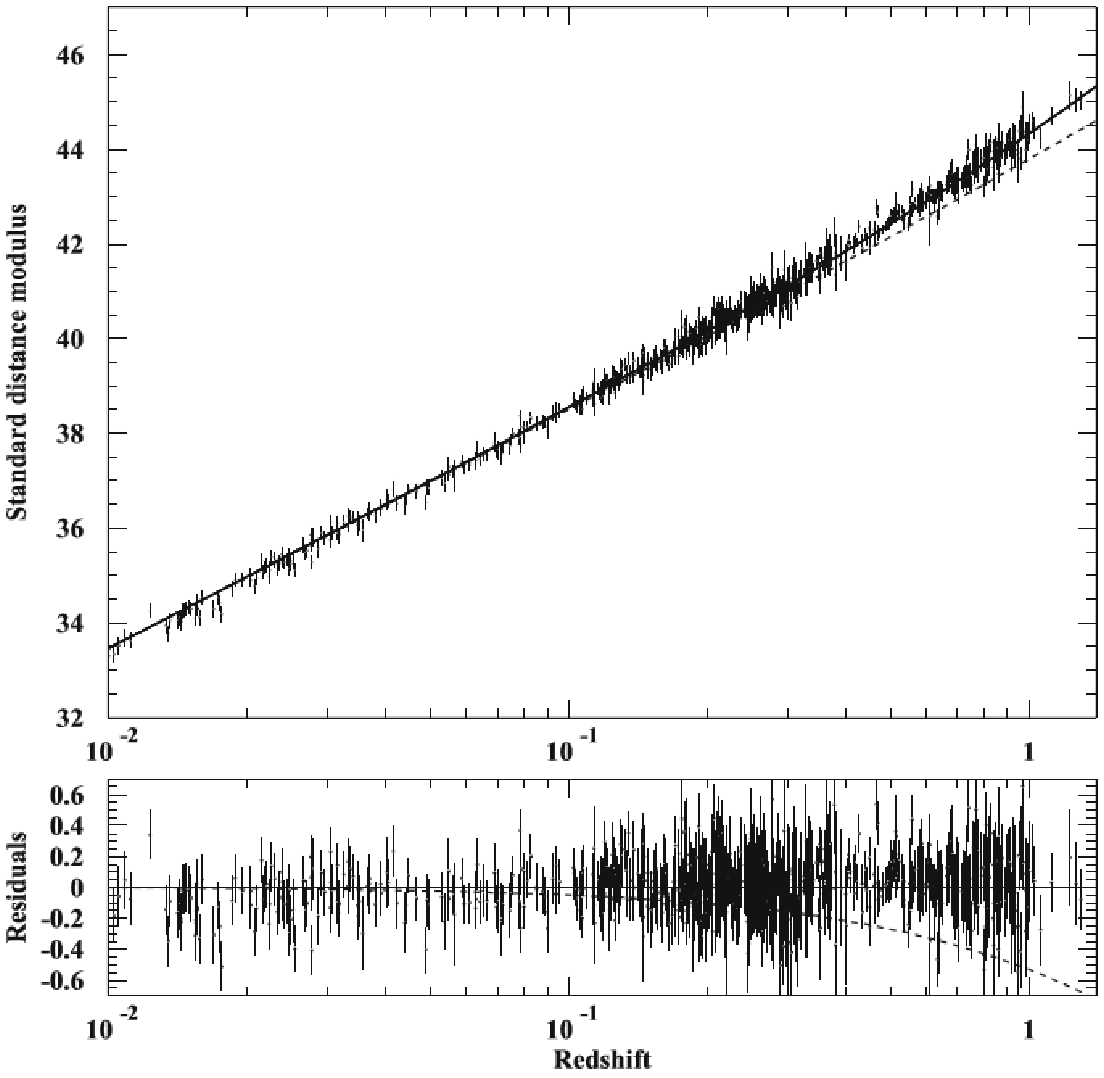
$$n(t) = e^{t/\tau_0}$$

$\Rightarrow$ Cosmological redshift SN-Ia well fitted (without Λ)

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

$\Rightarrow$ Time dilatation of the SN-Ia

$\Rightarrow$ 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)

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

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

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)

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

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

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

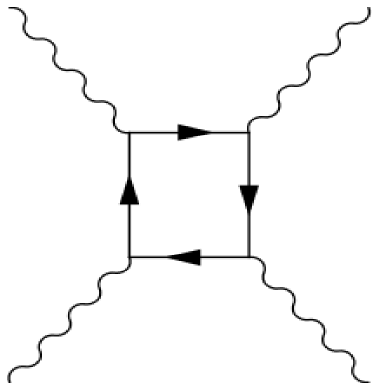
It can be **modified on large scale** (low energy) when it is stressed by intense e.m. fields

This result has been derived later by Schwinger with 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

Fundamental level (stationary system)
in intense Field intensity

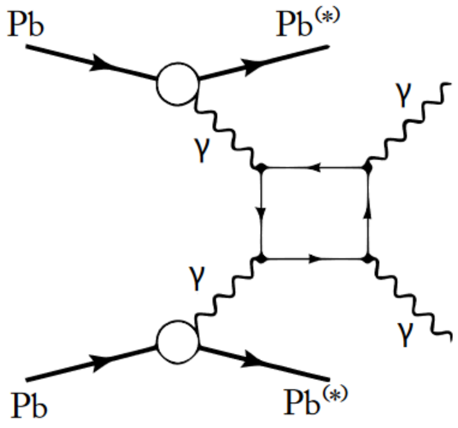
$E_{cr} = 1.3 \times 10^{18}$ V/m

$E_{H-\mu} \approx 4 \times 10^{15}$ V/m

μ–hydrogen spectrocopy

$E_{H-e} \approx 10^{11}$ V/m

e–hydrogen spectrocopy



Pb+Pb(γγ)
$\rightarrow$ Pb$^{(*)}$+Pb$^{(*)}$ γγ

Two-photons scattering
Perturbative QED

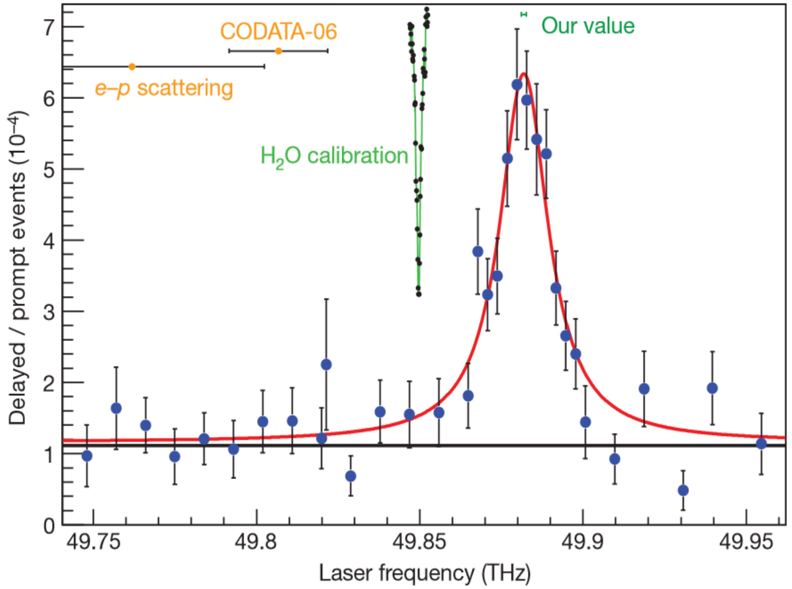
Atlas,CMS@LHC

arXiv:1702.01625
arXiv:1810.04602

Two-photons scattering v.s. Intense fields

Fundamental level (stationary system) in intense Field intensity

$\Delta E/E \approx 2 \times 10^{-3}$



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$E_{H-e} \approx 10^{11}$ V/m

μ–hydrogen spectrocopy

e–hydrogen spectrocopy

R_∞ is modified ?
QED effects are unsufficient ?

Pohl et al. Nature 2010
Antognini et al. Science 2013

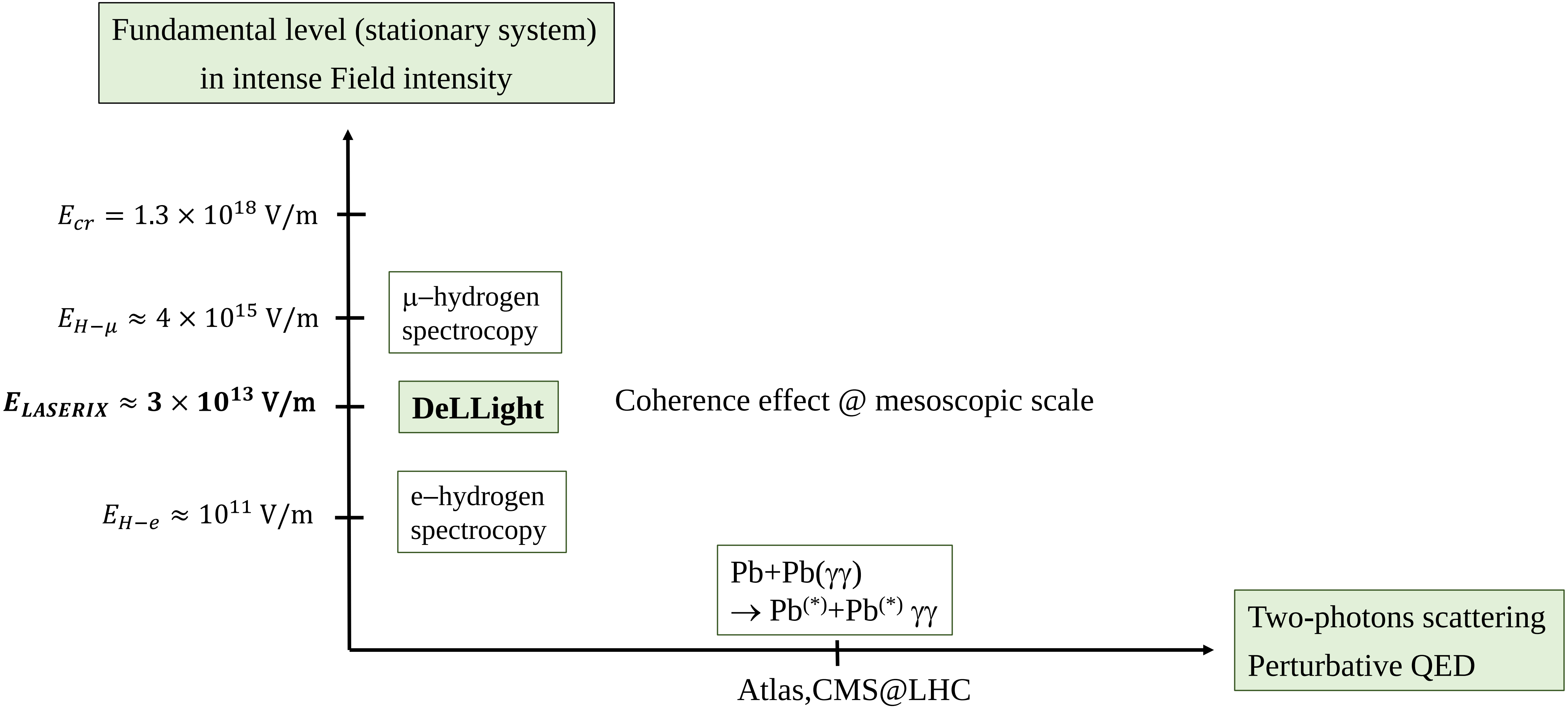
Pb+Pb(γγ) → Pb$^{(*)}$+Pb$^{(*)}$ γγ

Atlas,CMS@LHC

arXiv:1702.01625
arXiv:1810.04602

Two-photons scattering
Perturbative QED

Two-photons scattering v.s. Intense fields

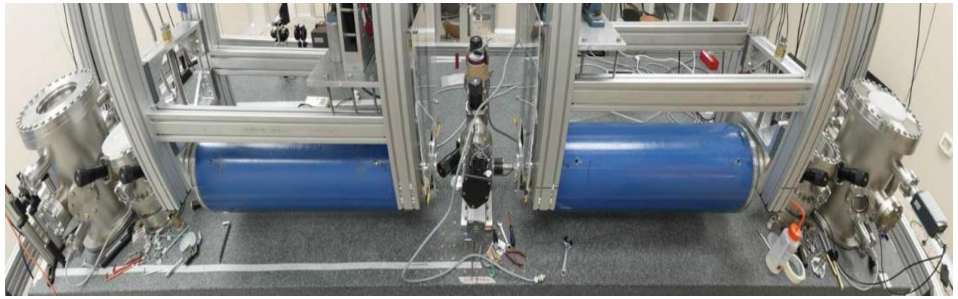


arXiv:1702.01625
arXiv:1810.04602

Current experimental tests

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

Fabry-Perrot laser cavity with an external B field



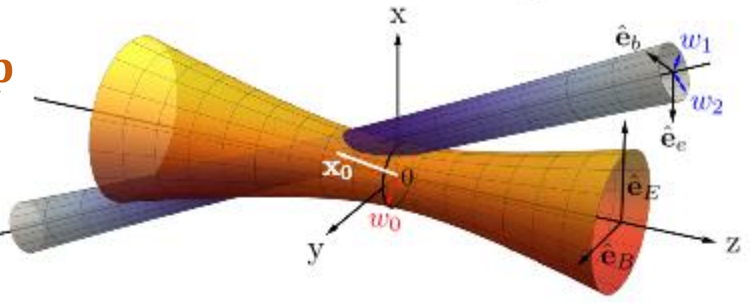
PVLAS: Rotating field B=2.5 T *Eur. Phys. J. C (2016) 76:2*

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

0.1 σ sensitivity after ~100 days of measurement

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

Laser Pump

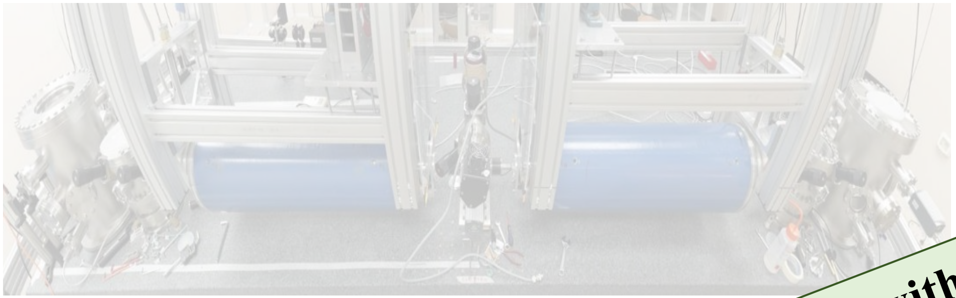


X-ray Probe

Current experimental tests

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

Fabry-Perrot laser cavity with an external B field



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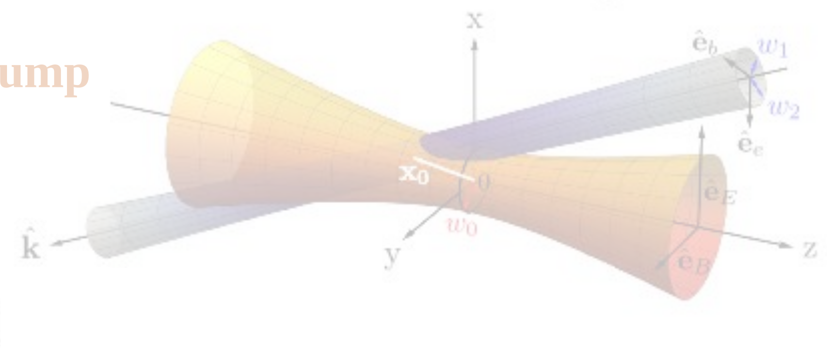
BMV: Pulsed field B=6.5 T *Eur. Phys. J. D (2014) 68: 16*

0.1 σ ... fter ~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

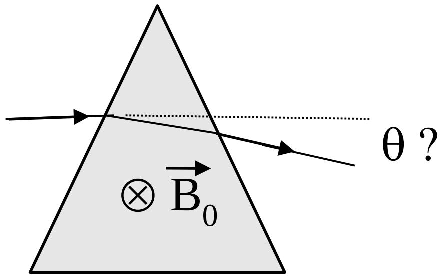
Jone's experiment in 1960…

- 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 (!)



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

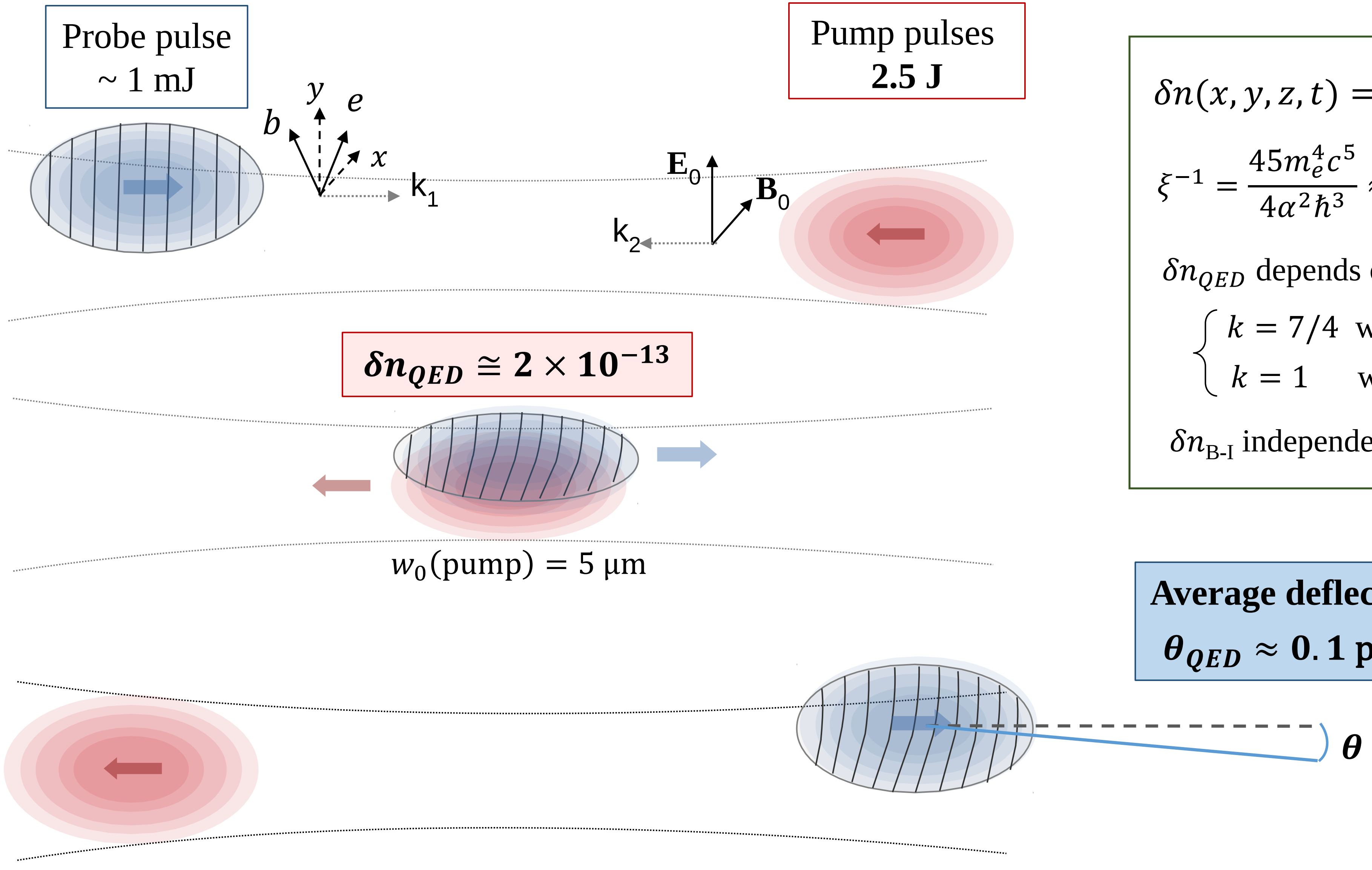
DeLLight with intense laser field produced by LASERIX

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

The DeLLight experiment

Pump-Probe interaction

Recent calculations done by Scott Robertson, post-doc LAL & LPT (R. Parentani)



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

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

δn_{QED} depends on the polarisation

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

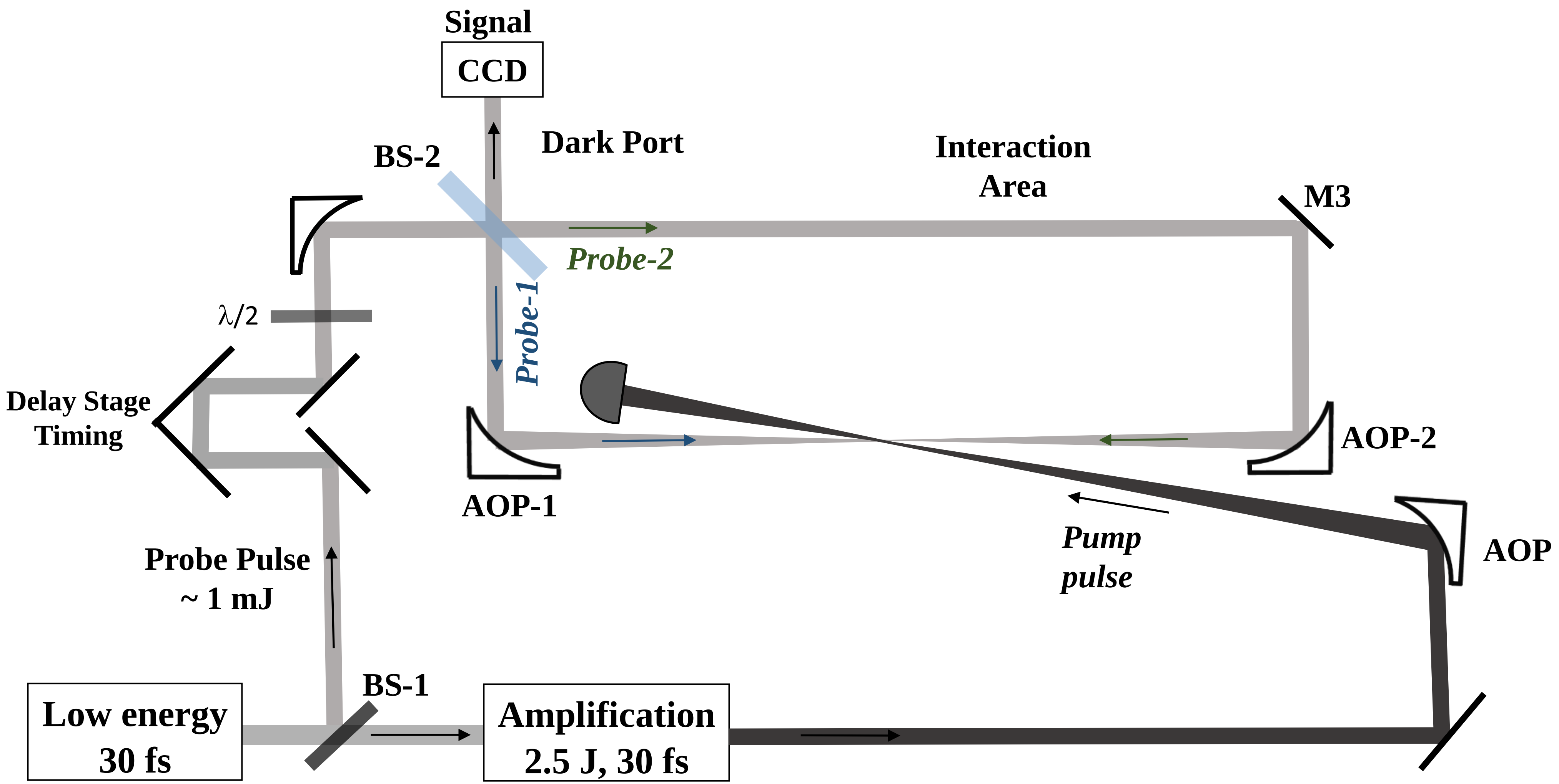
$\delta n_{\text{B-I}}$ independent of the polarisation

Average deflection

$\boldsymbol{\theta_{QED} \approx 0.1}$ **prad**

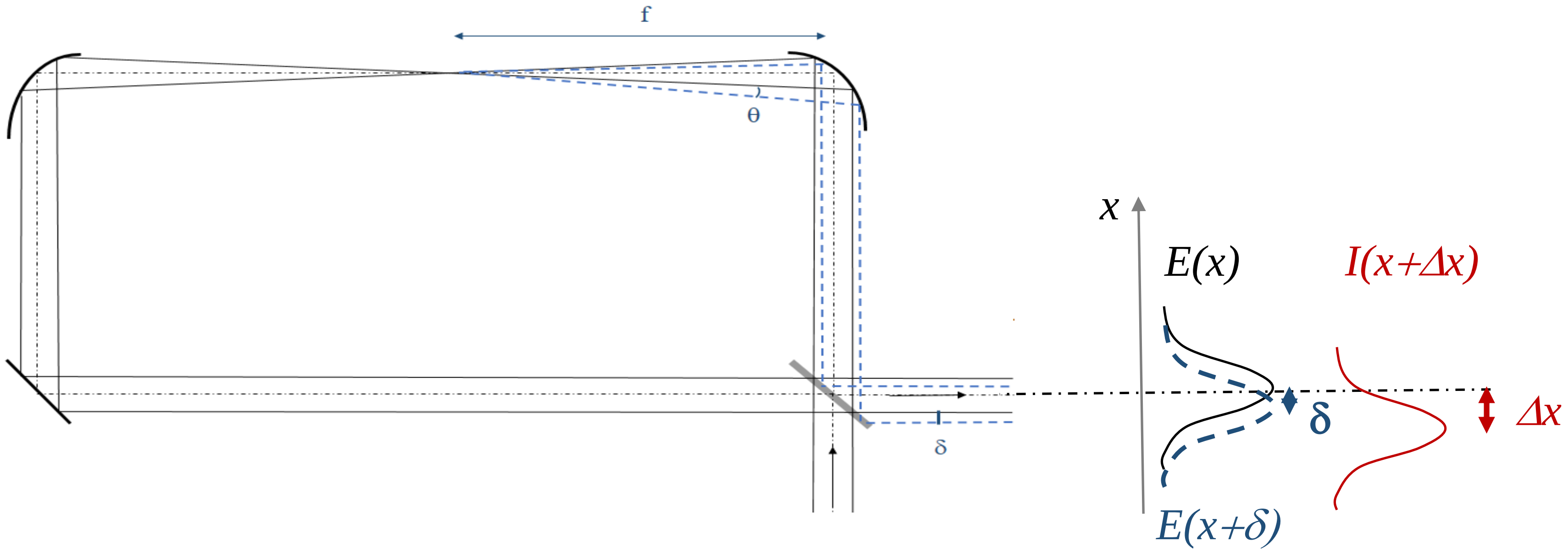
Refraction measured with a Sagnac Interferometer

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



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)

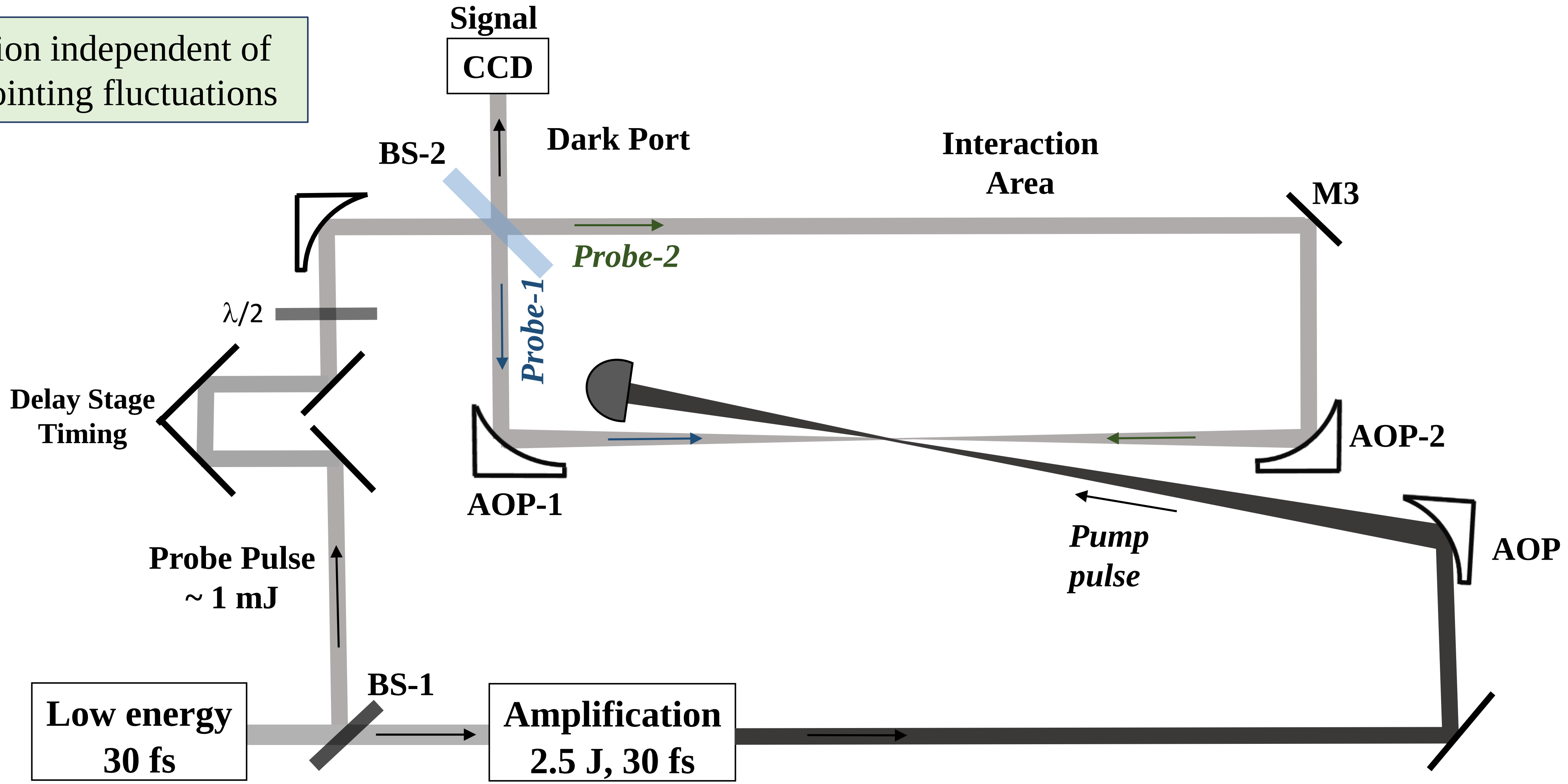
$$\boxed{\epsilon = 10^{-3} \Rightarrow Extinction = 0.4\ 10^{-5} \Rightarrow \mathcal{F} = 250}$$

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 $\boldsymbol{\mathcal{F}} = \frac{\mathbf{1}}{\mathbf{2}\sqrt{\boldsymbol{Extinction}}} = \mathbf{250}$ when $Extinction = 0.4\ 10^{-5}$

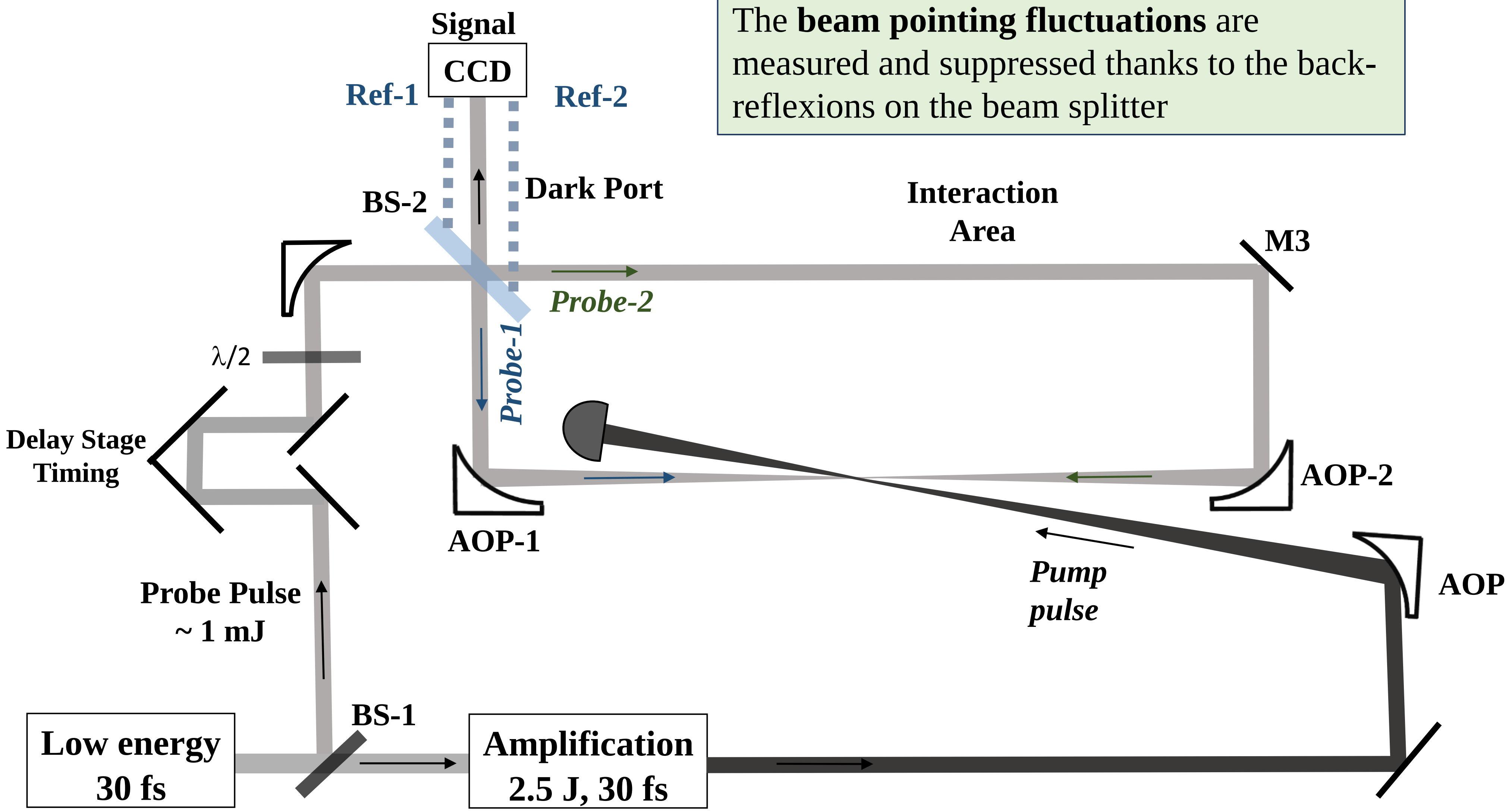
Extinction independent of beam pointing fluctuations



Refraction measured with a Sagnac Interferometer

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

The **beam pointing fluctuations** are measured and suppressed thanks to the back-reflexions on the beam splitter



Numerical Simulations

Preliminary 2-d (x,z) numerical simulation:

- **Two pulses** (30 fs, 800 nm) with ortogonal polarisation are counter-propagating (along z) and focused
- **Transversal profiles of the beams are gaussian:** $\boldsymbol{\mathcal{E}(x,z) = A_0 e^{(-x^2/w_0^2)}}$
- Energy pump pulse **E=2.5 J**; Energy probe pulse is negligible (1 mJ)
- Minimum waist at focus: $\boldsymbol{w_o(\text{probe}) = 2 \times w_o(\text{pump})}$
- Probe beam is shifted transversally by a distance $\boldsymbol{\delta_p}$
- 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 a **distance D**, where they interfer

$\Rightarrow$ Interference with an **extinction** $\boldsymbol{\mathcal{F} = 4\epsilon^2}$ (ϵ = assymetry of the beam splitter)

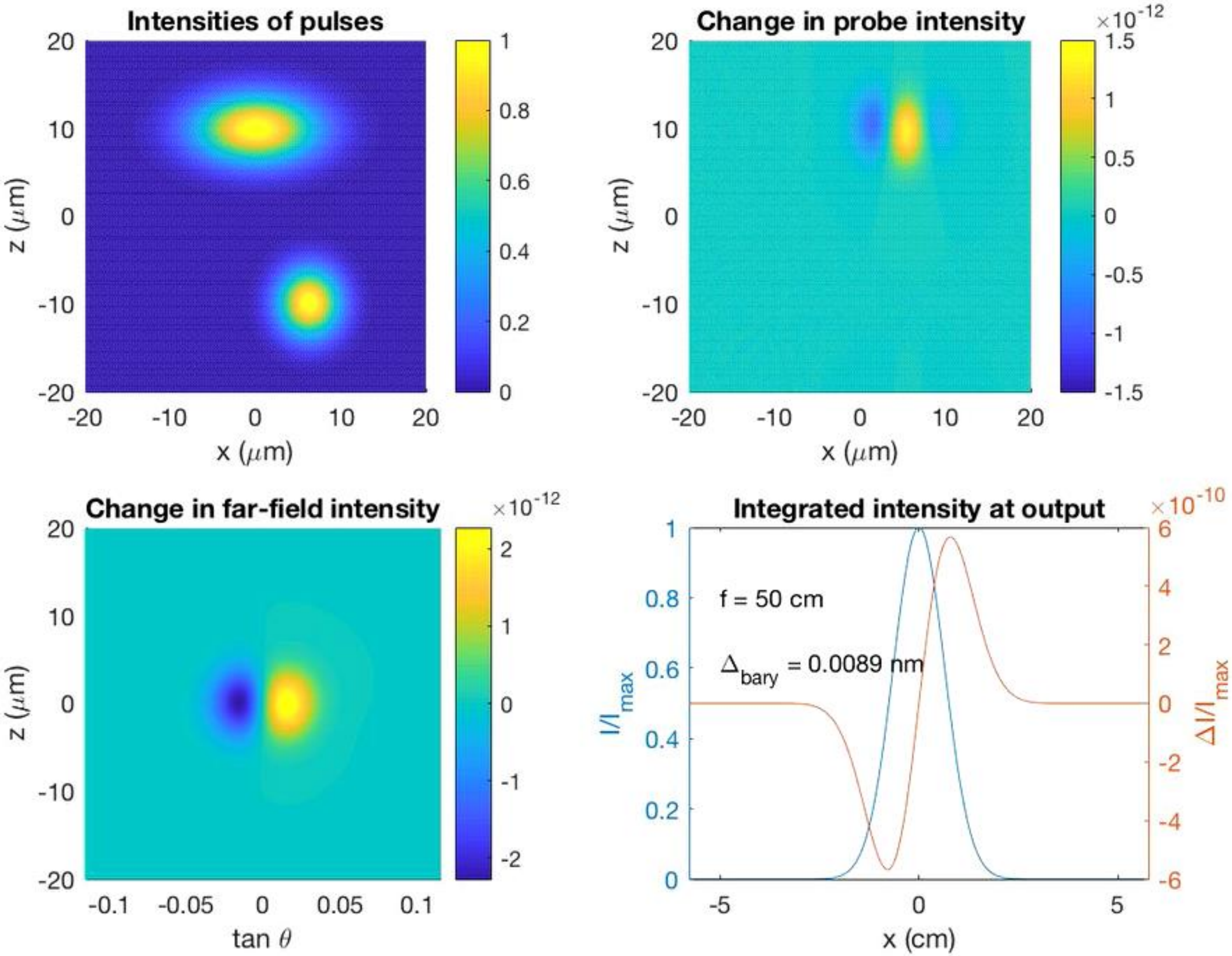
Numerical Simulations

- $E = 2.5$ J,
- Extinction = $0.4\ 10^{-5}$ $(\epsilon = 10^{-3})$
- D = 50 cm *(limited by the beam divergence)*
- w_0(pump) = 5 µm, w_0(probe) = 10 µm
- $\delta_p = w_0/2$

$\boxed{\boldsymbol{\Delta x \approx 0.01\, nm}}$

Signal Δx reduced by ~20% if jitter pump ±2.5µm

$$\boxed{\Delta x \cong 6.10^{-10}\ \mathrm{m}\ \times \frac{E(Joule) \times D(m)}{\left(w_0(\mu\mathrm{m})\right)^3 \times \sqrt{\mathcal{F}/10^{-5}}}}$$



Expected sensitivity

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

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

  $\Rightarrow$ Signal (ON-OFF) for the measurement k : $\Delta x_k = \bar{x}_k^{ON} - \bar{x}_k^{OFF}$

- N_{mes} measurements collected $\Rightarrow$ Average signal = $\overline{\Delta x} \pm \sigma_x / \sqrt{N_{mes}}$

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

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

$$\boldsymbol{N_{sig}} = \frac{\overline{\Delta x}}{\sigma_x / \sqrt{N_{mes}}} \cong 500 \times \frac{\sqrt{\boldsymbol{T_{obs}}(\text{days})}}{\left(\boldsymbol{w_{0,pump}}(\mu\text{m})\right)^3 \times \sqrt{\boldsymbol{\mathcal{F}}/10^{-5}} \times \boldsymbol{\sigma_x}(\text{nm})}$$

$$\begin{cases} \text{Extinction } \mathcal{F} = 0.4\ 10^{-5} \ (\epsilon = 10^{-3}) \\ \sigma_x = 10 \text{ nm} \\ w_0 \text{ (pump)} = 5\ \mu\text{m} \end{cases} \Rightarrow N_{sig} \cong 0.6\sqrt{T_{obs}(\text{days})} \Rightarrow$$ 3 sigma discovery in 25 days

$$\begin{cases} T_{obs} \propto w_{0,pump}^6 \\ T_{obs} \propto \sigma_x^2 \end{cases}$$

With w_0 (pump) = 20 µm $\Rightarrow N_{sig} \cong 0.1$ with 100 days of collected data

(same as PVLAS birefringence sensitivity)

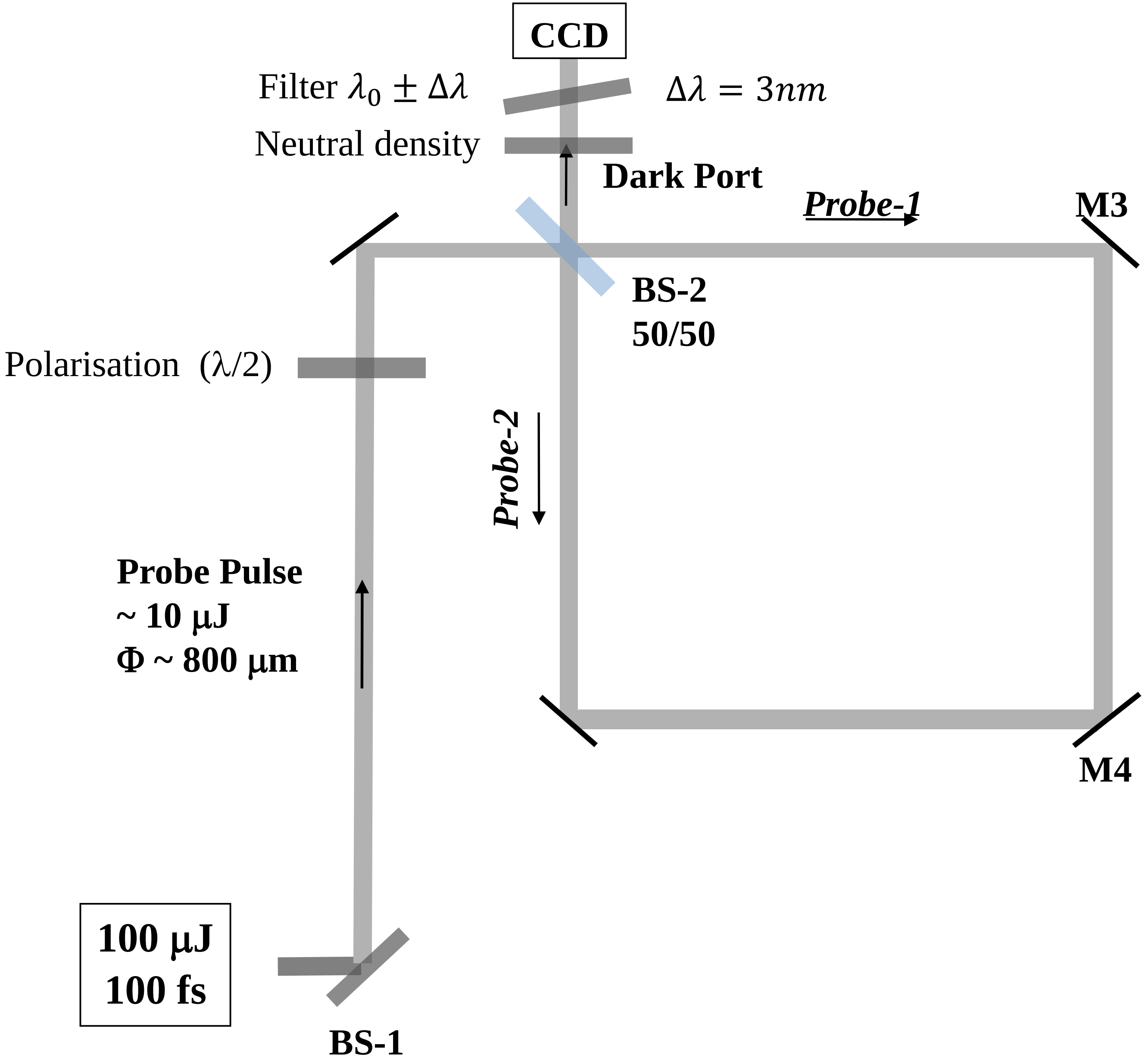
Experimental challenges

- ✓ Extinction: $\mathcal{F} = 0.4\ \ 10^{-5}\ \ (\epsilon = 10^{-3})$
- ✓ Spatial resolution: $\sigma_x = 10$ nm
- ✓ Waist at focus as low as possible

  \+ stability of the pump-probe overlap

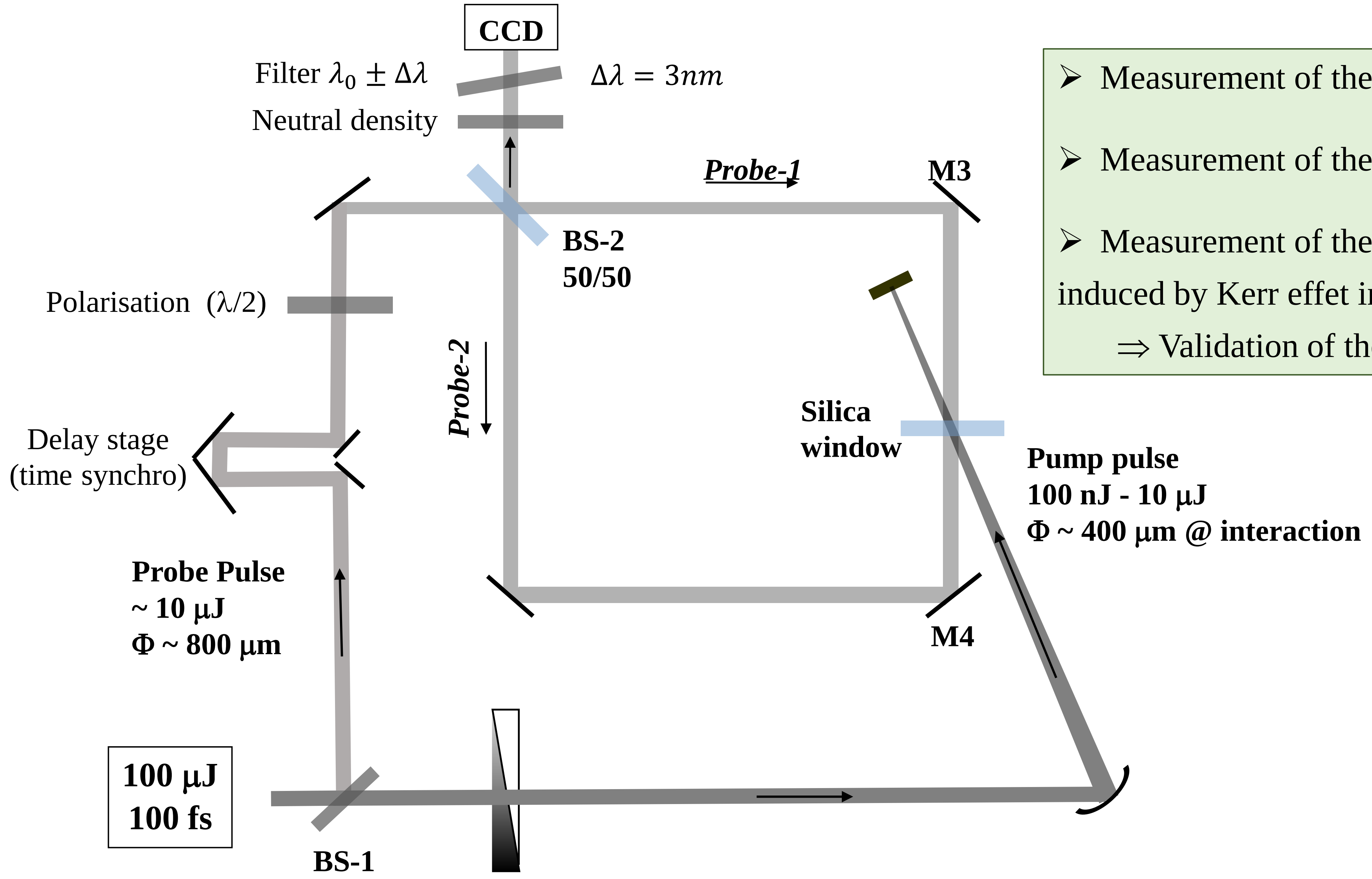
DeLLight-0 prototype

DeLLight-0 prototype



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

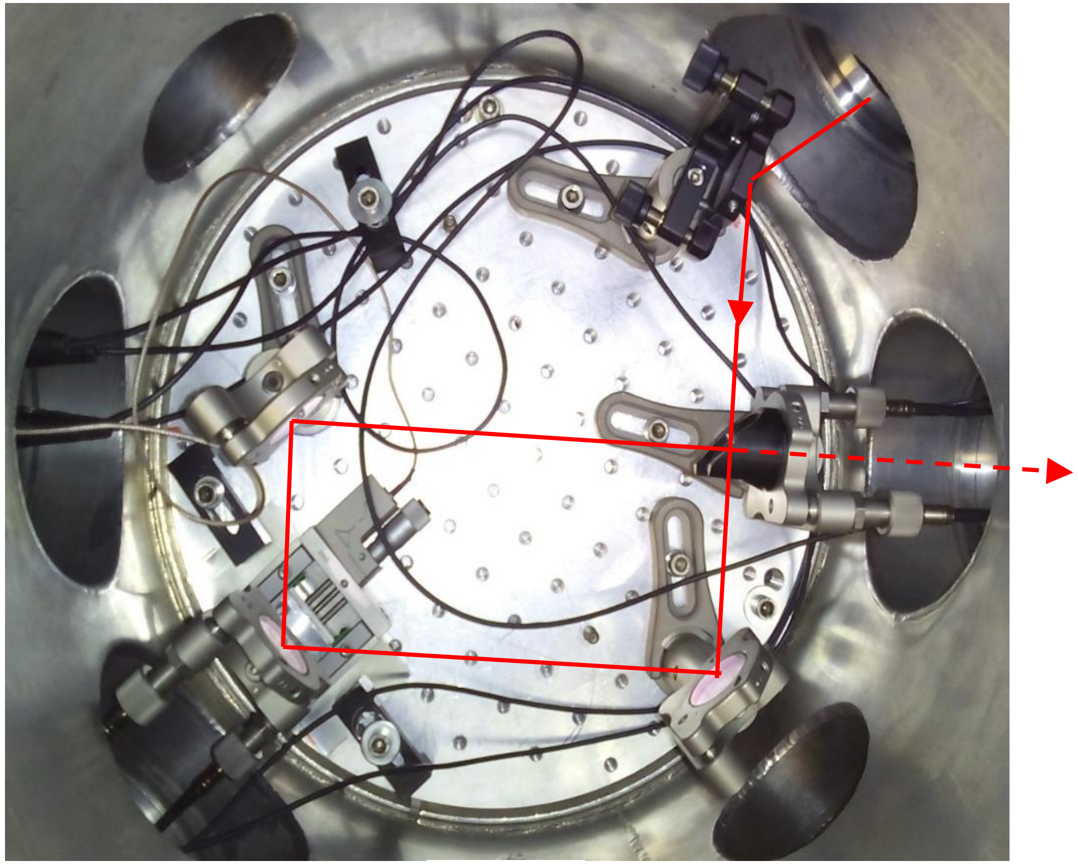
DeLLight-0 prototype



- 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

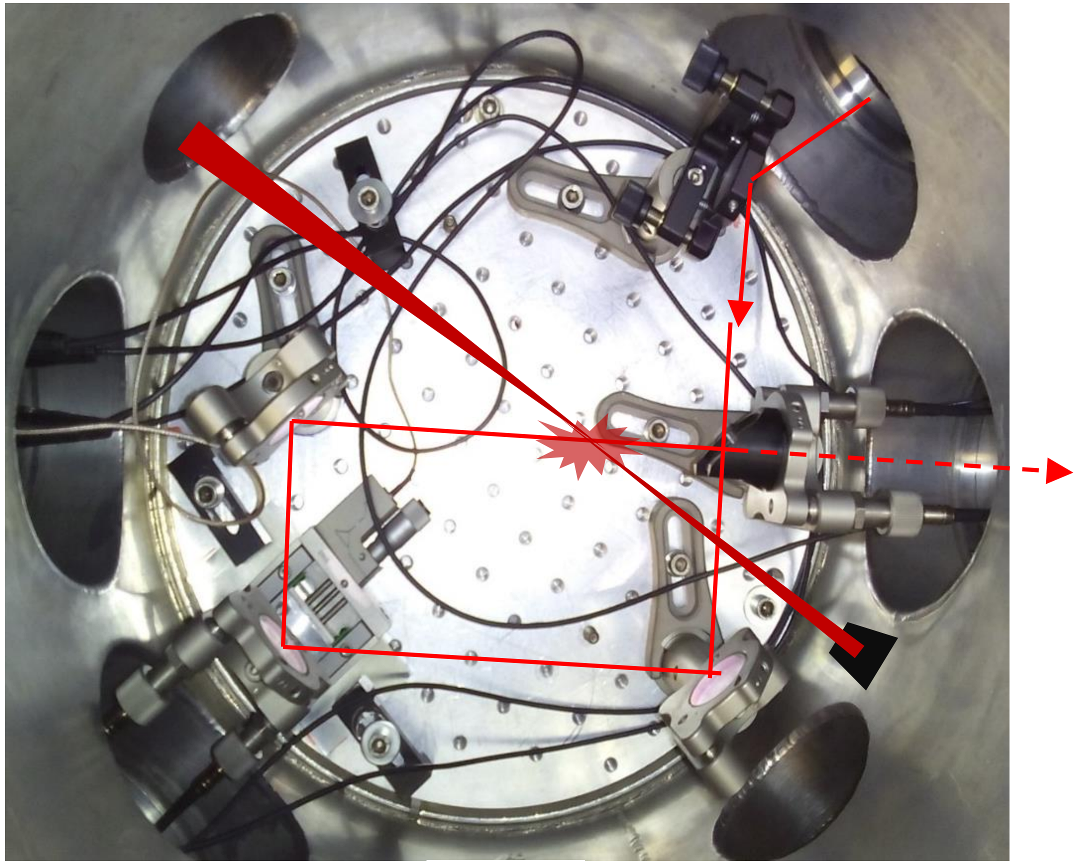
DeLLight-0 demonstrator



⟵ 20 cm ⟶

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

DeLLight-0 demonstrator



20 cm

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- ✓ Flat silver mirror standard (λ/10)
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- ✓ Fused silica window (6mm thick)

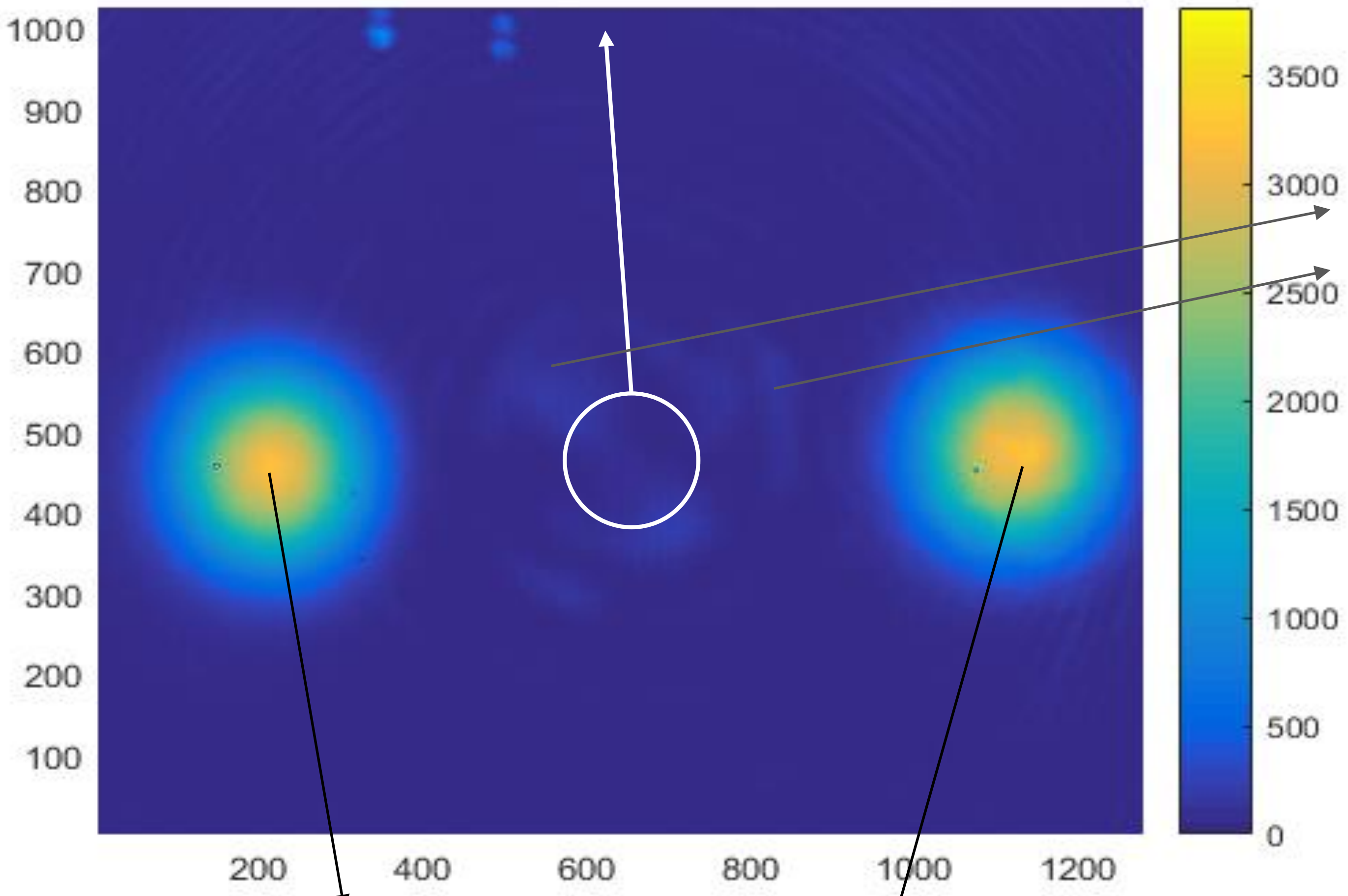
Experimental challenges

- ✓ Extinction: $\mathcal{F} = 4\epsilon^2$ ($\epsilon = 10^{-3}$)
- ✓ Spatial resolution: σ_x
- ✓ Waist at focus as low as possible

  + stability of the pump-probe overlap

Extinction of the interferometer

Signal : Extinction ~ 10^{-5}



Hot spots :

Surface defects on mirors inside the Sagnac

Back reflection (~ 10^{-3})

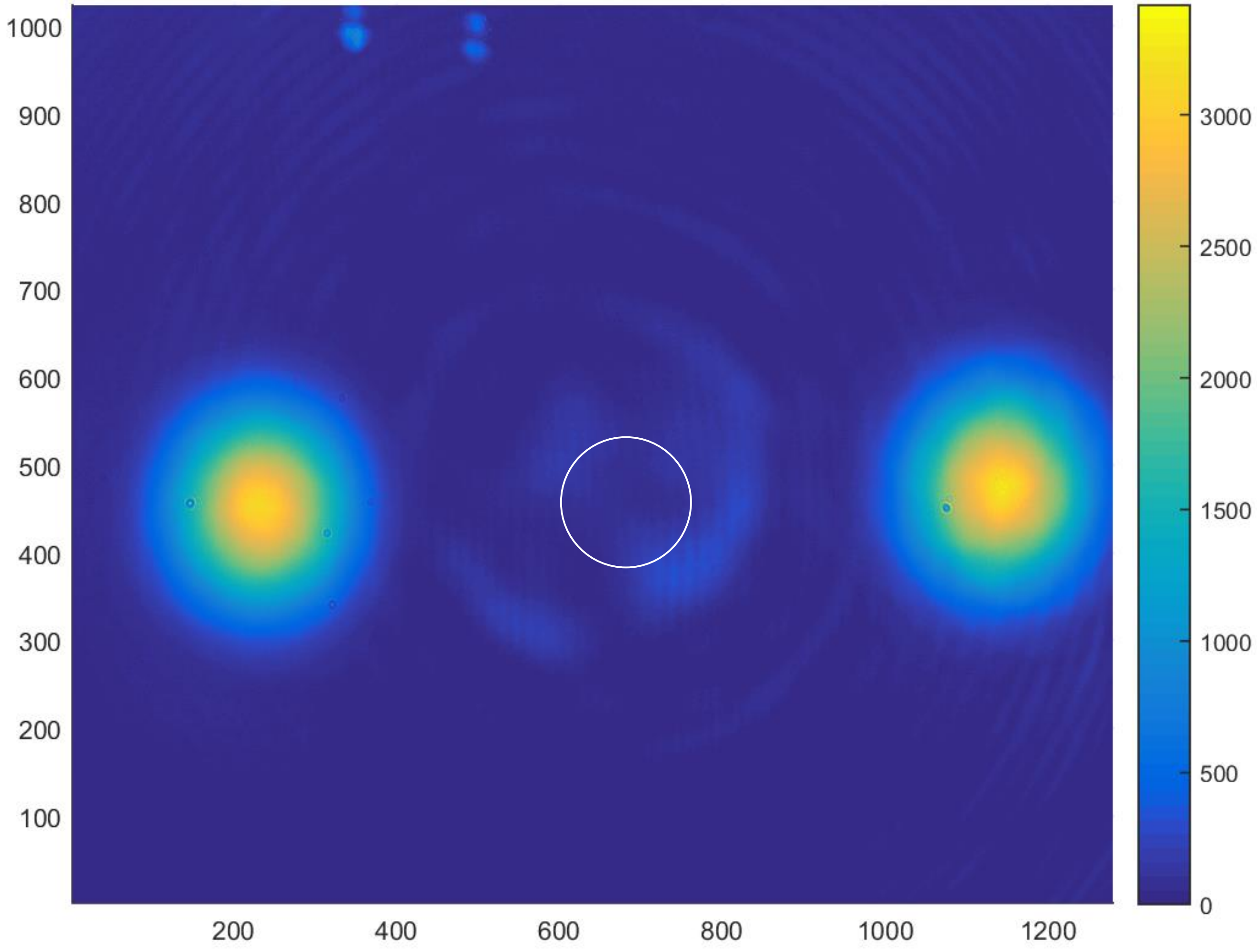
Extinction of the interferometer

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



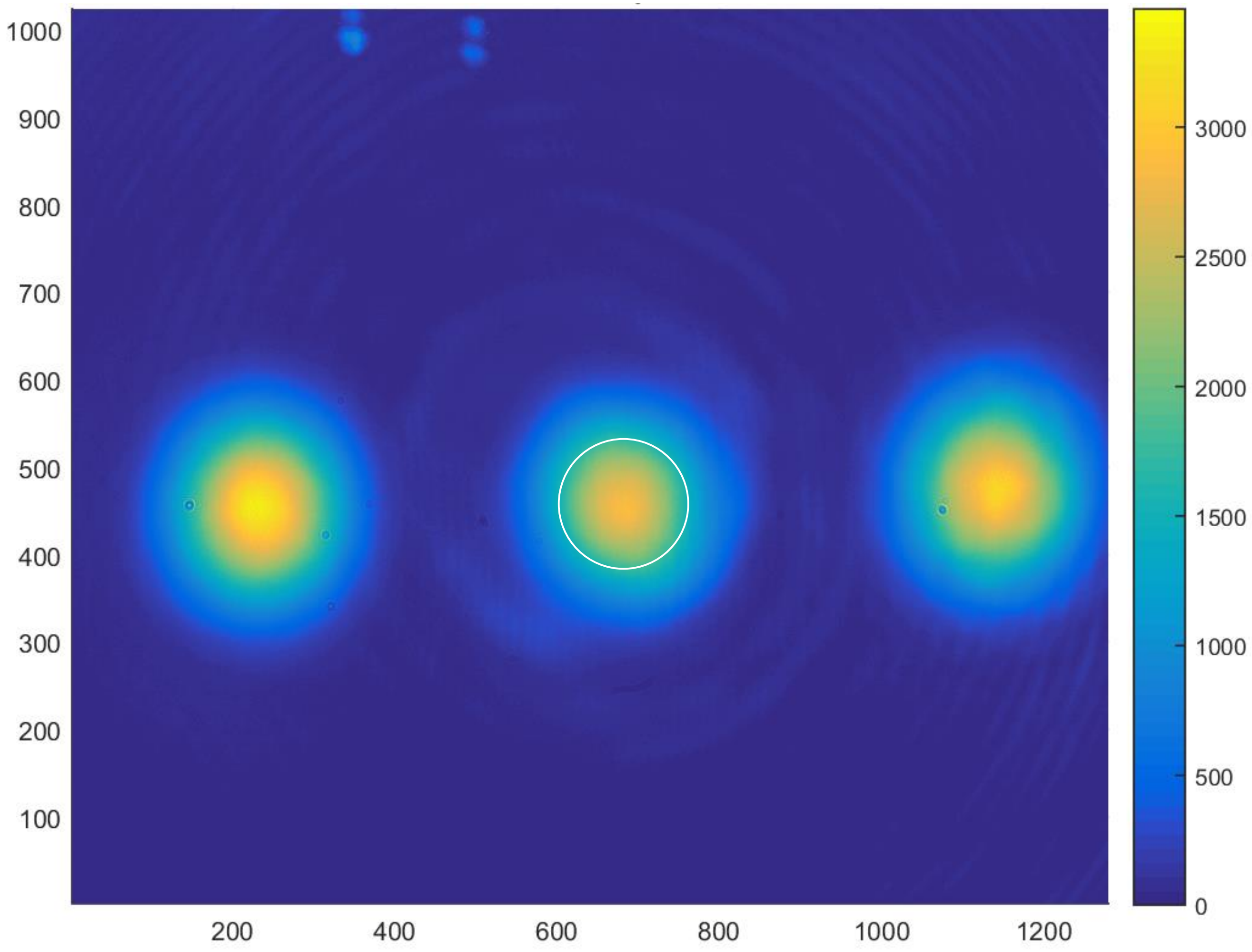
Extinction of the interferometer

Rotation of the polarization $\Rightarrow$ 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

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

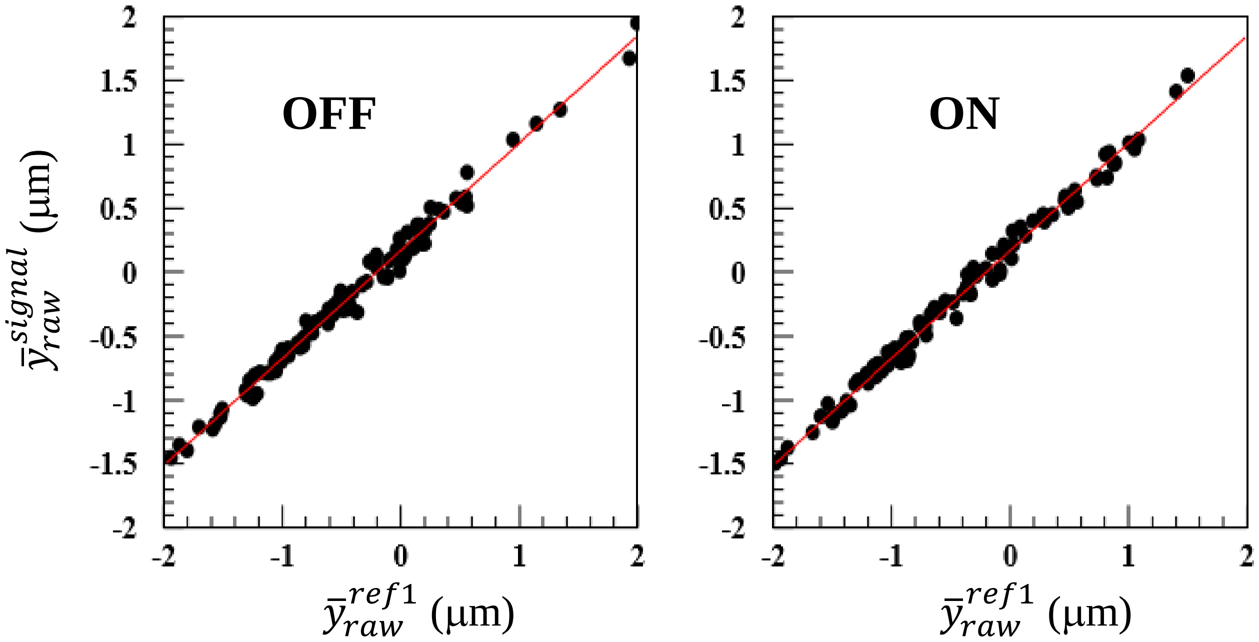
- With better CCD *BASLER ™* (*acA4024-29um*):
  - Pixel size d_{pix}: 1.8×1.8 μm^2
  - Charge saturation $N_{e-}^{max} \cong 10^4$ e$^-$/pixel

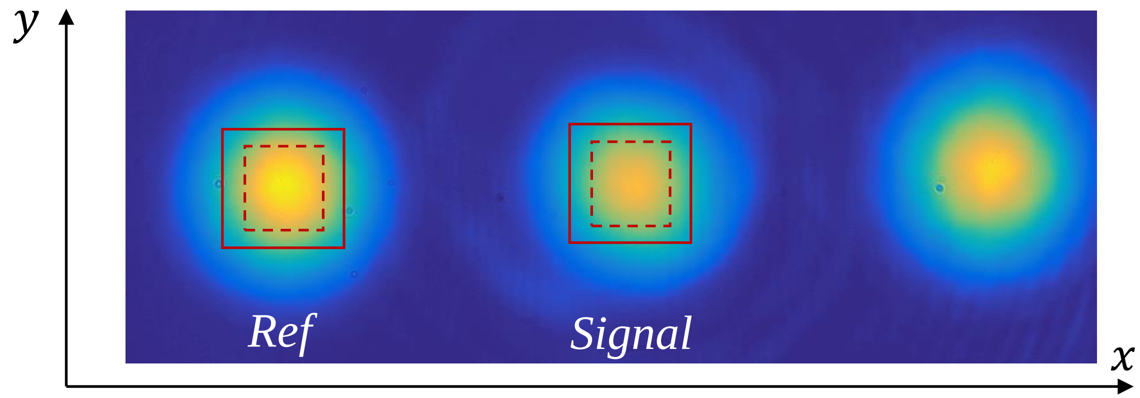
$$\boxed{\Rightarrow \; \boldsymbol{\sigma_x} \cong \mathbf{10\ nm}}$$

Spatial resolution

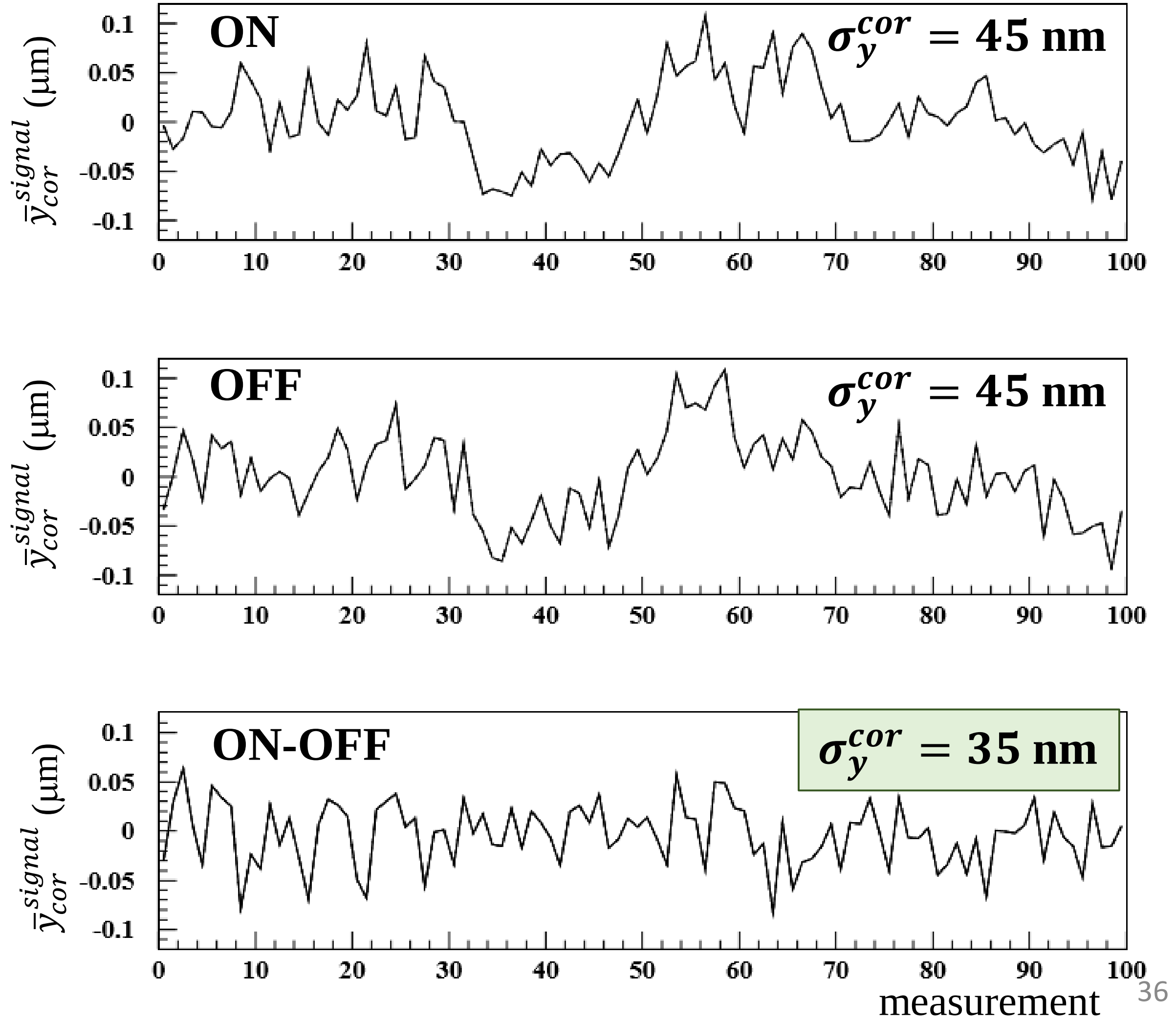
Preliminary analysis based on a barycenter calculation in a simple square analysis window (RoI)

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

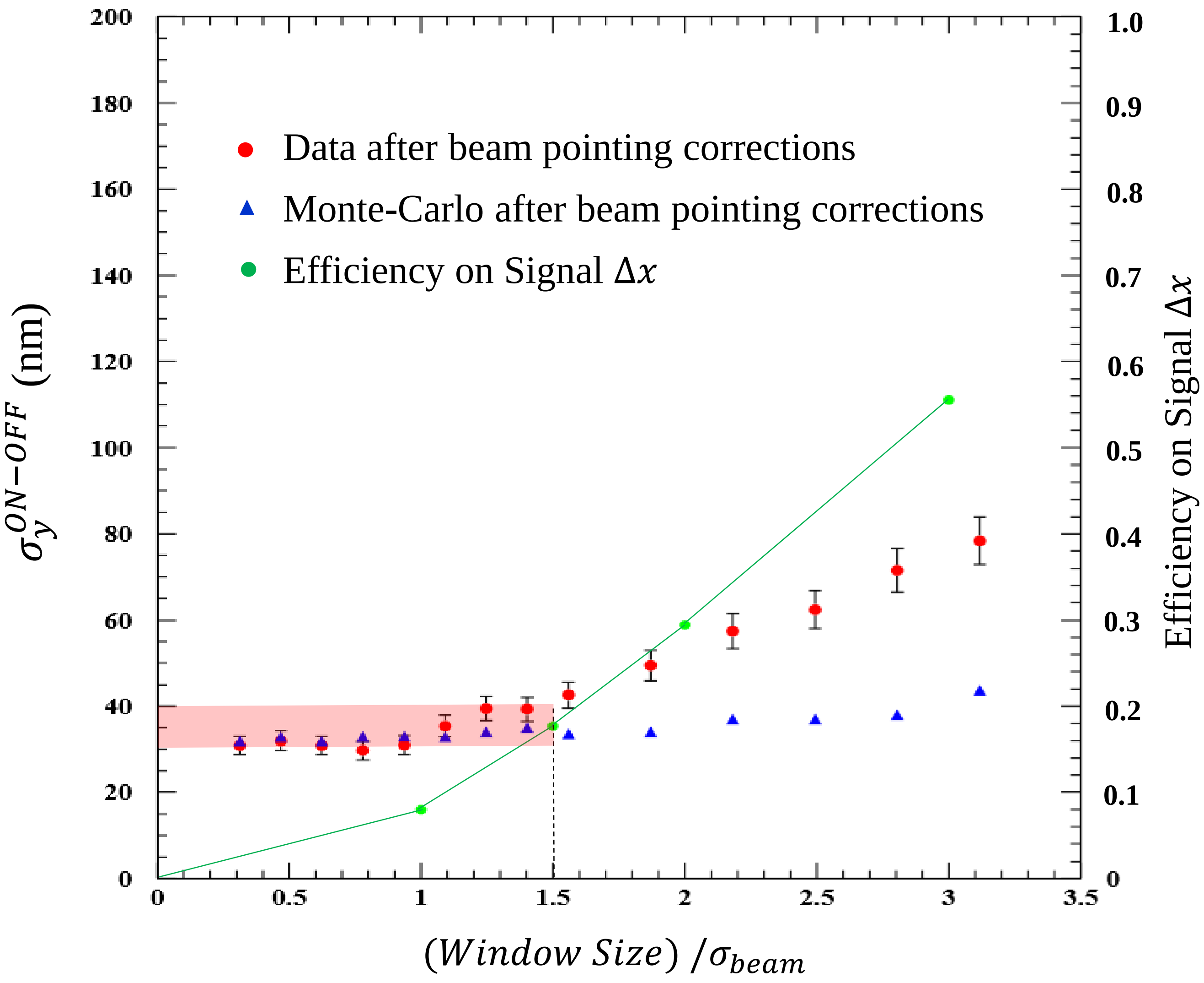




After beam pointing correction
⇒ low frequency drift supressed by ON-OFF subtraction



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:

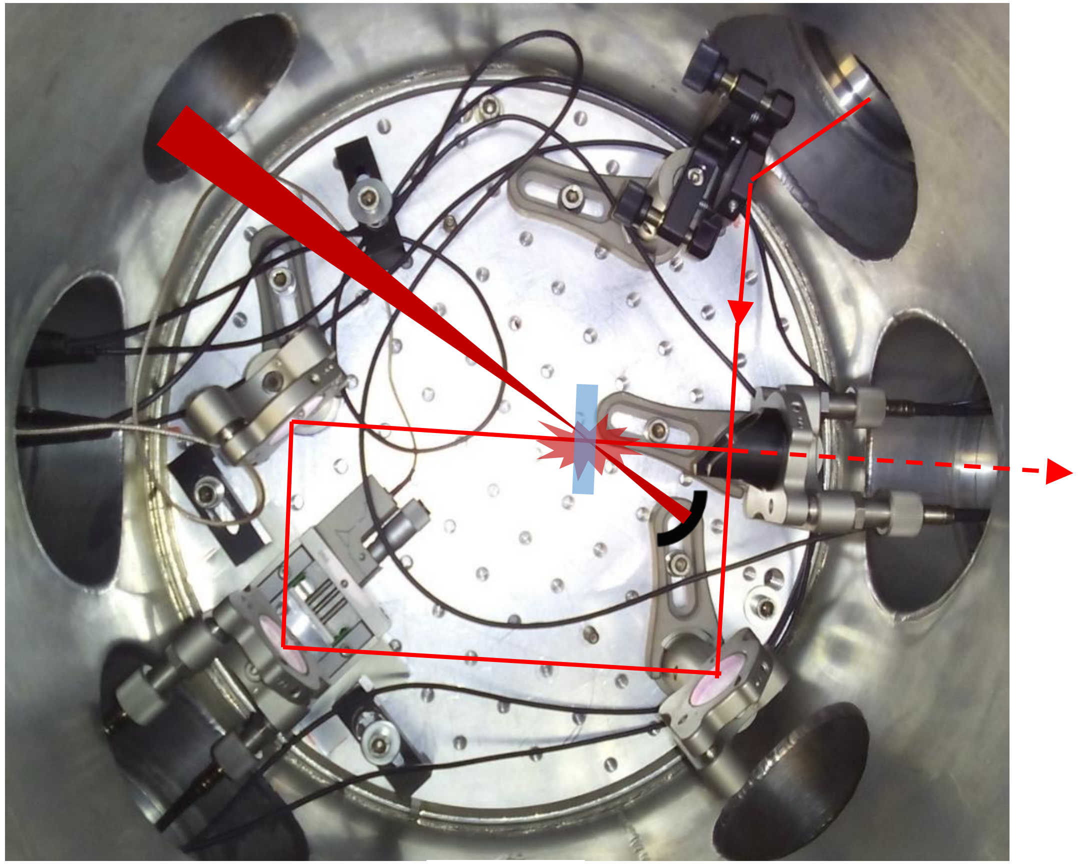
- Background mapping & substraction
- Fit of the profiles
- Surface quality of the optics
- CCD uniformity
- Etc…

Experimental challenges

- ✓ Extinction: $\mathcal{F} = 4\epsilon^2 \cong 10^{-5}$
- ✓ Spatial resolution: 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 (6mm thick)



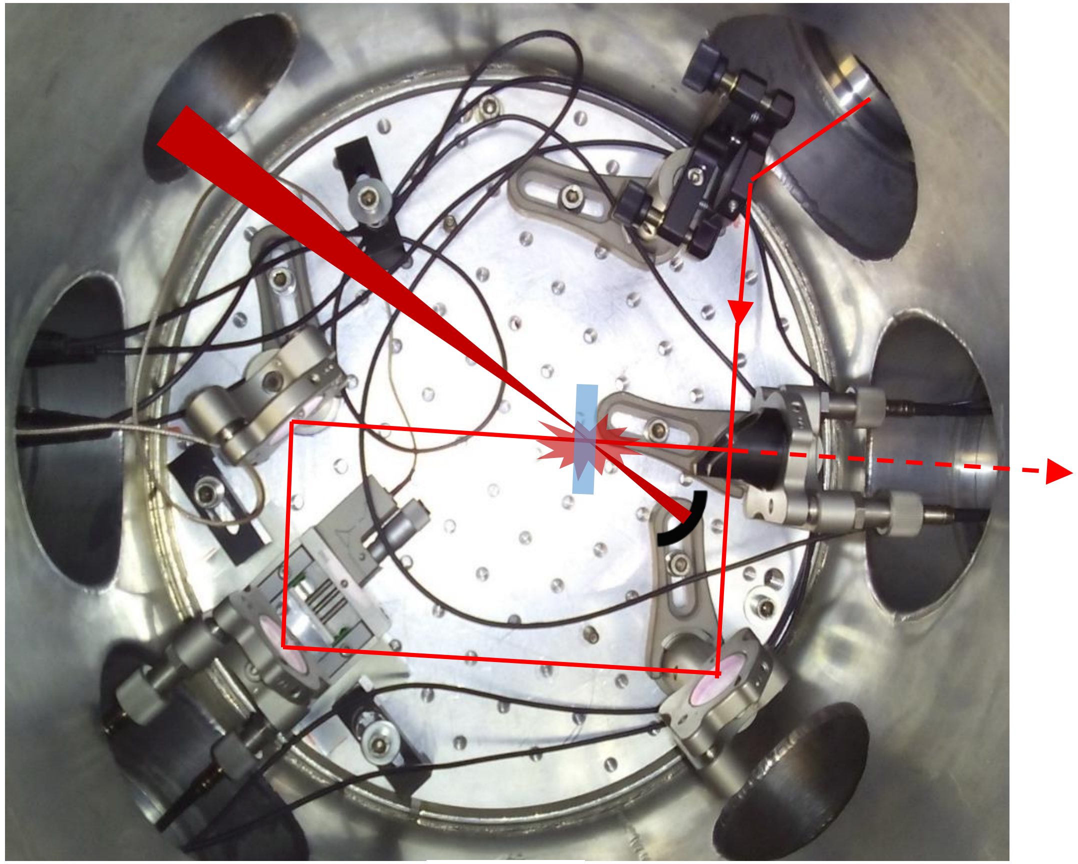
20 cm

$$n(I) = n_0 + n_2 \times I(\mathrm{W/cm^2})$$
$$n_2(\mathrm{Silica}) \approx 3 \times 10^{-16}\ \mathrm{cm^2/W}$$

Data taken in June & July 2018

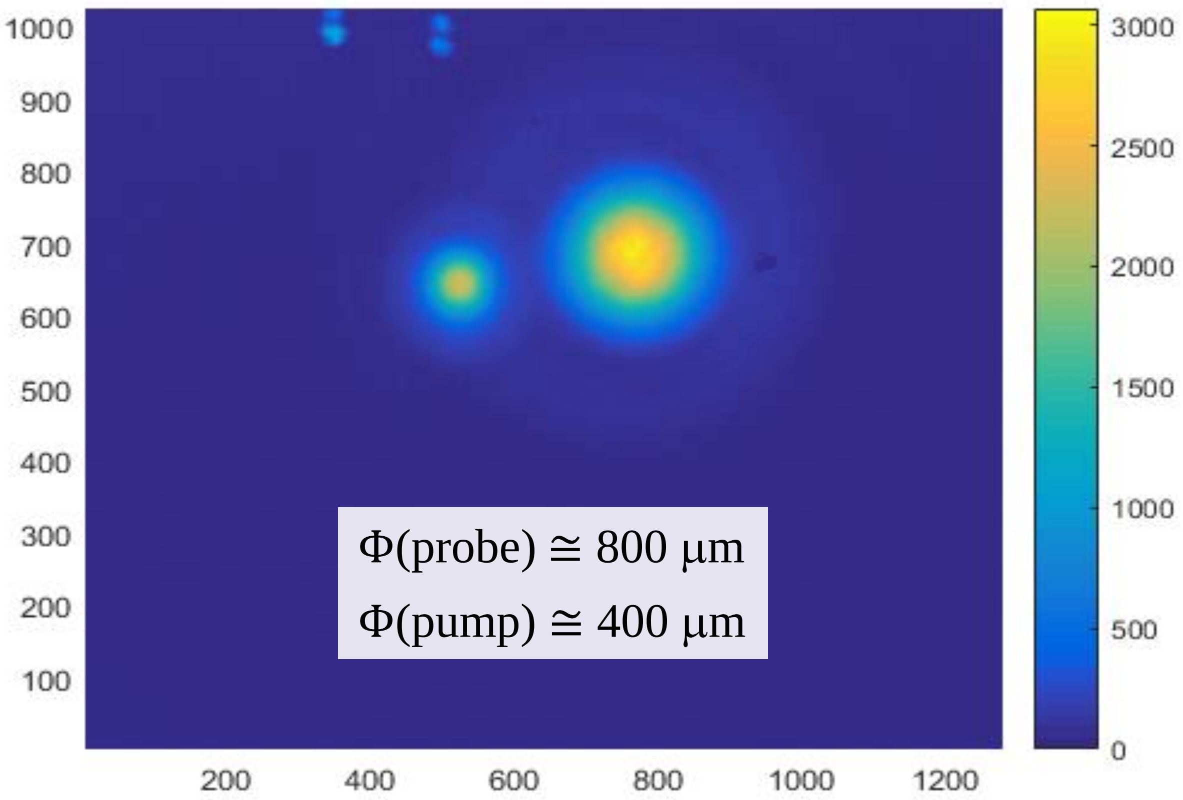
- Φ(probe) $\cong$ 800 μm (fwhm)
- Φ(pump) $\cong$ 400 μm (fwhm)
- Duration of the pulses Δt ~ 50 – 100 fs
- Energy Pump varies from ~12 μJ down to ~300 nJ

Observation of the non linear Kerr effect



20 cm

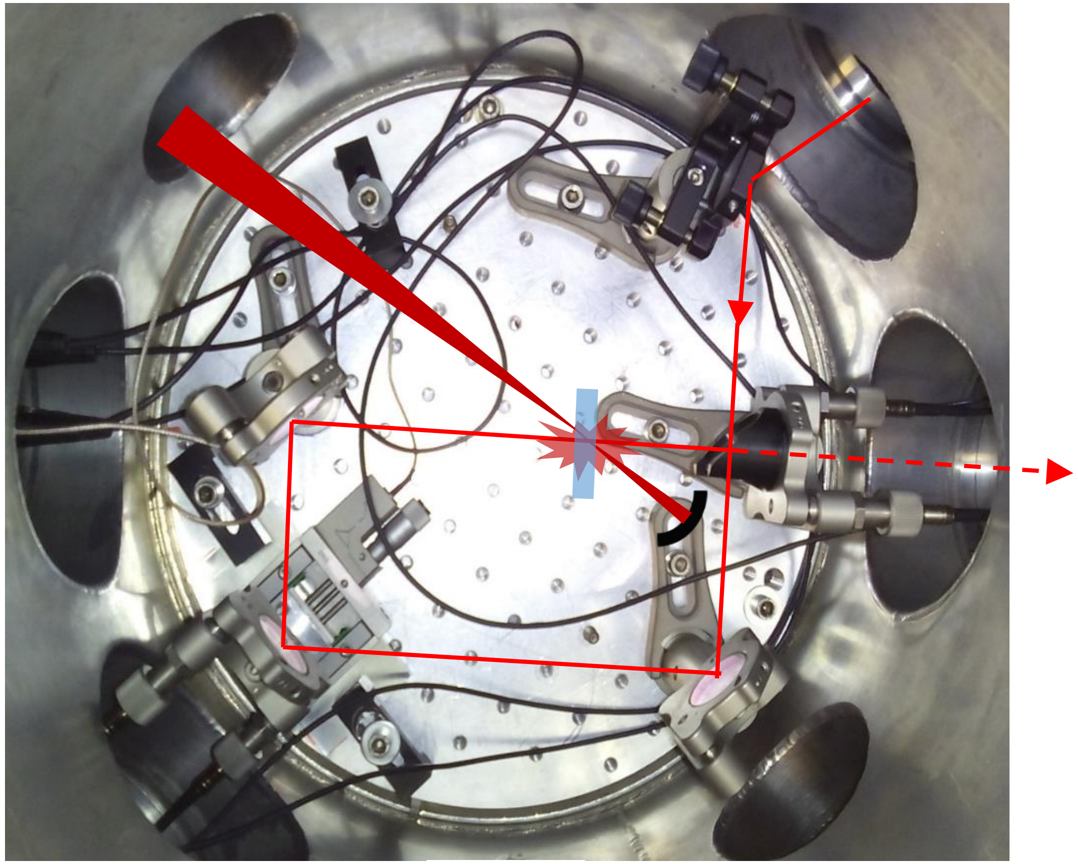
Intensity profiles of the Pump & Probe
in the interaction area



Φ(probe) ≅ 800 μm

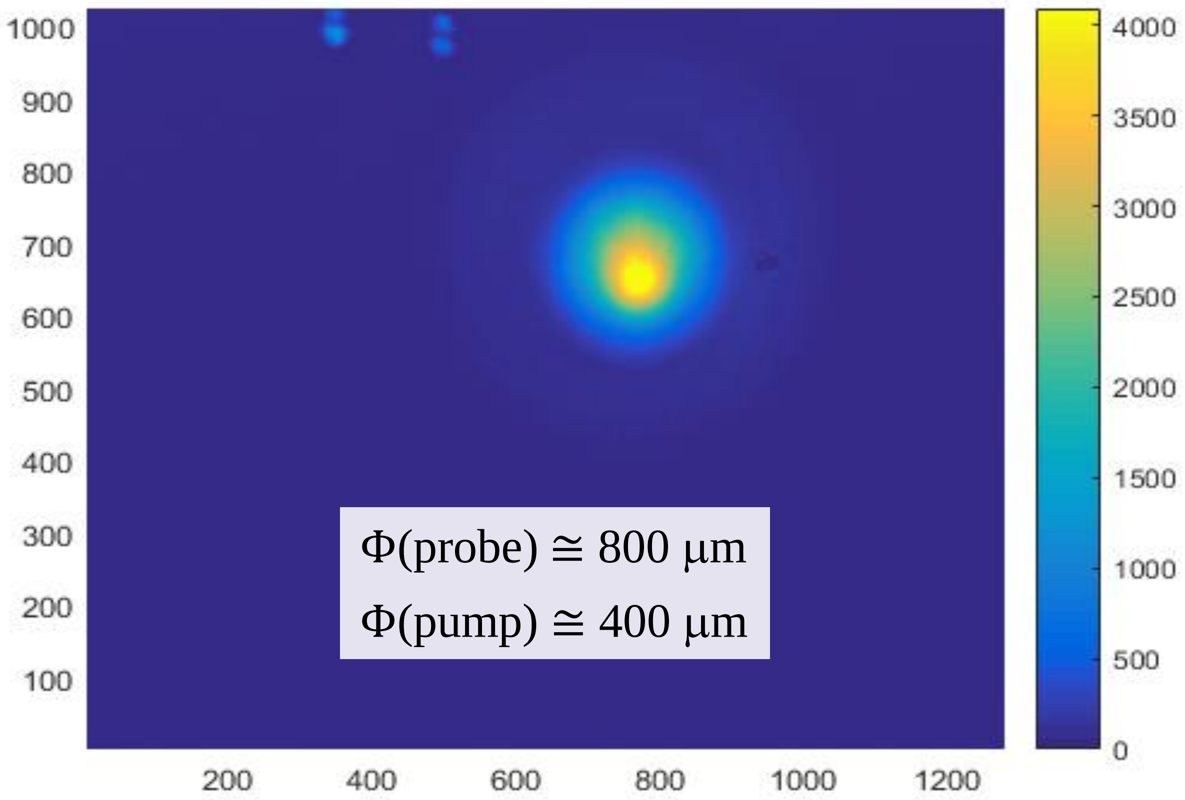
Φ(pump) ≅ 400 μm

Observation of the non linear Kerr effect



← 20 cm →

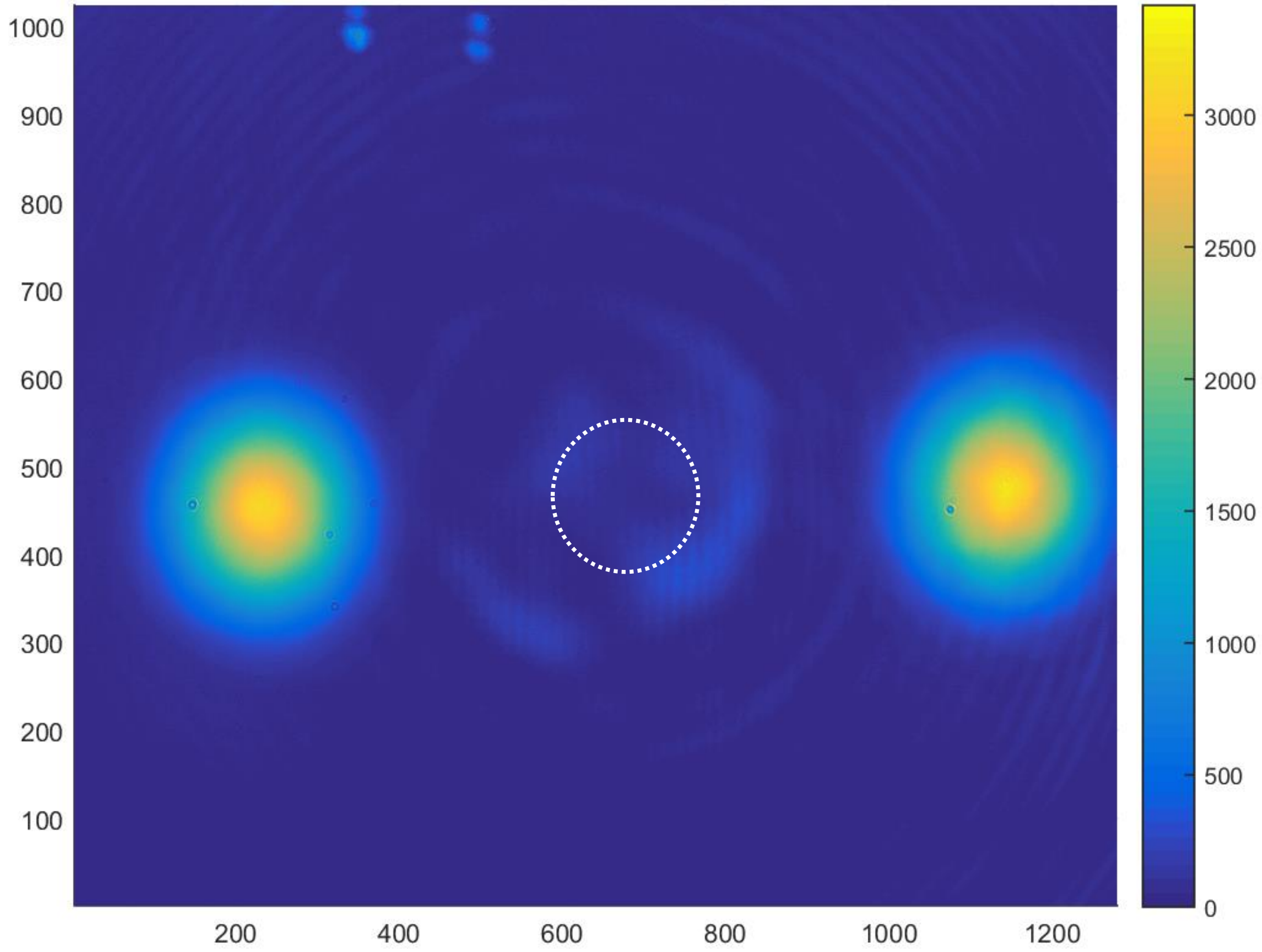
Intensity profiles of the Pump & Probe
in the interaction area



Measurement of the Kerr signal in SiO_2

Maximal extinction

Without pump



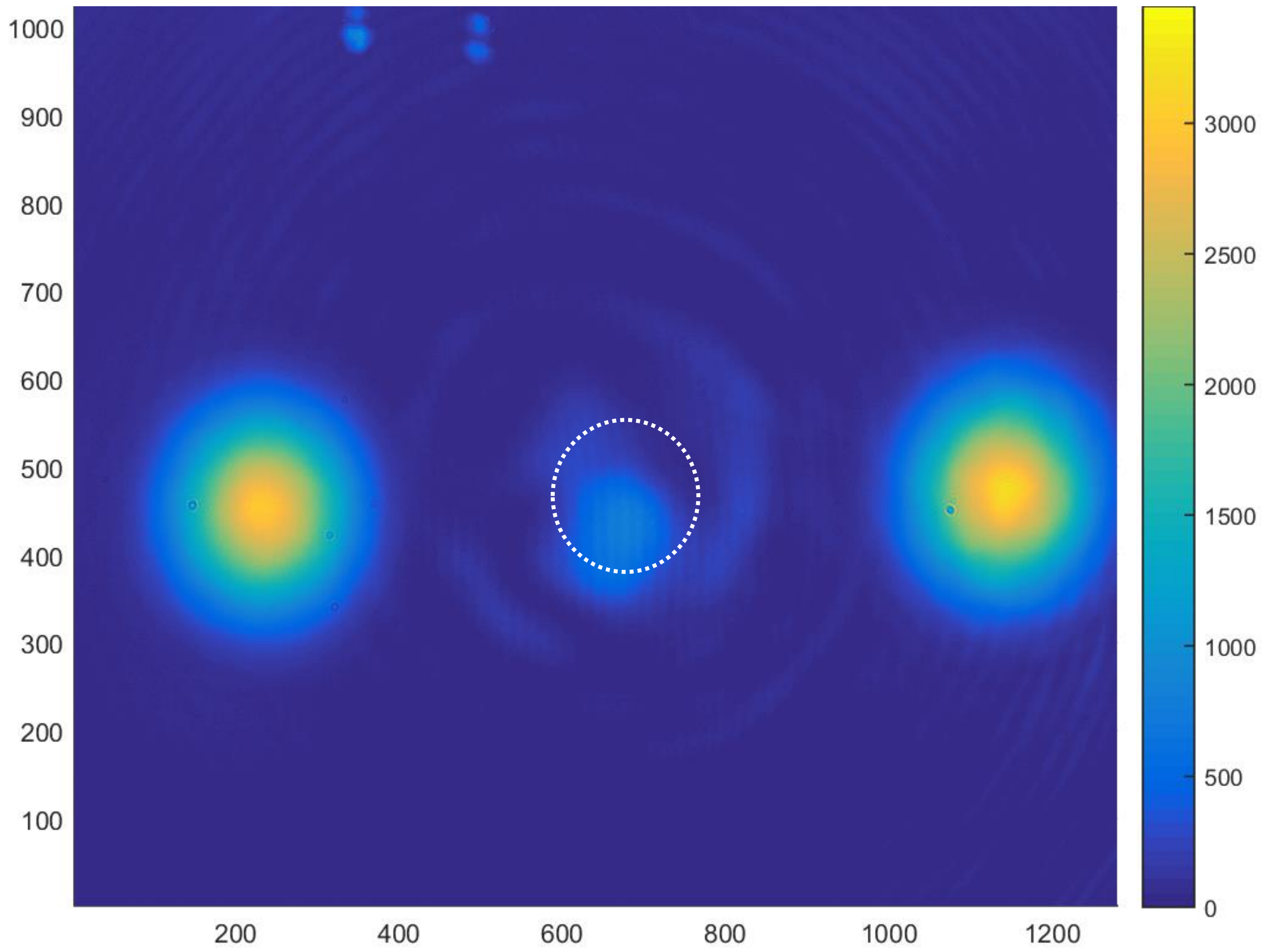
Intensity profiles in the dark output
of the Sagnac interferometer

Measurement of the Kerr signal in SiO_2

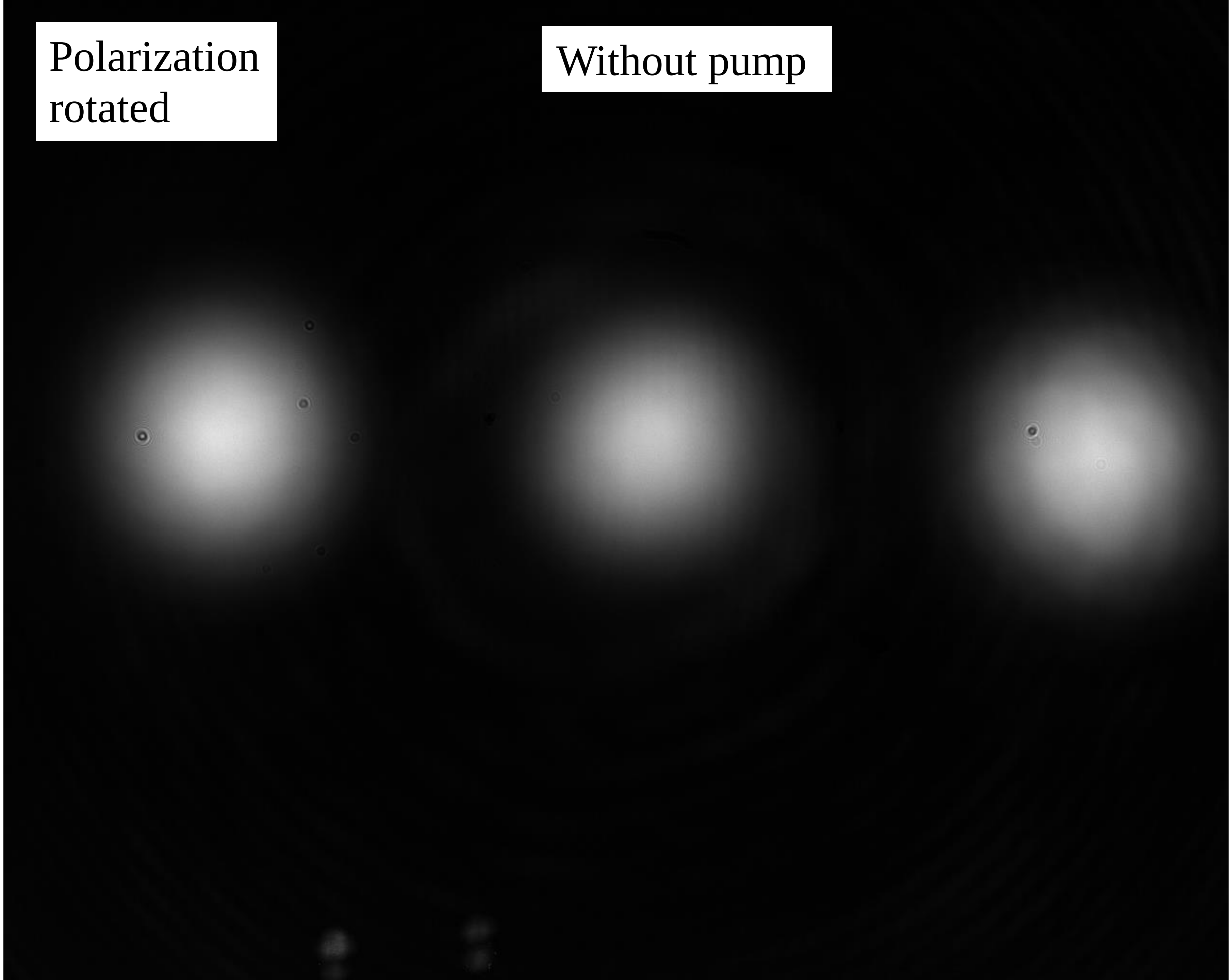
Maximal extinction

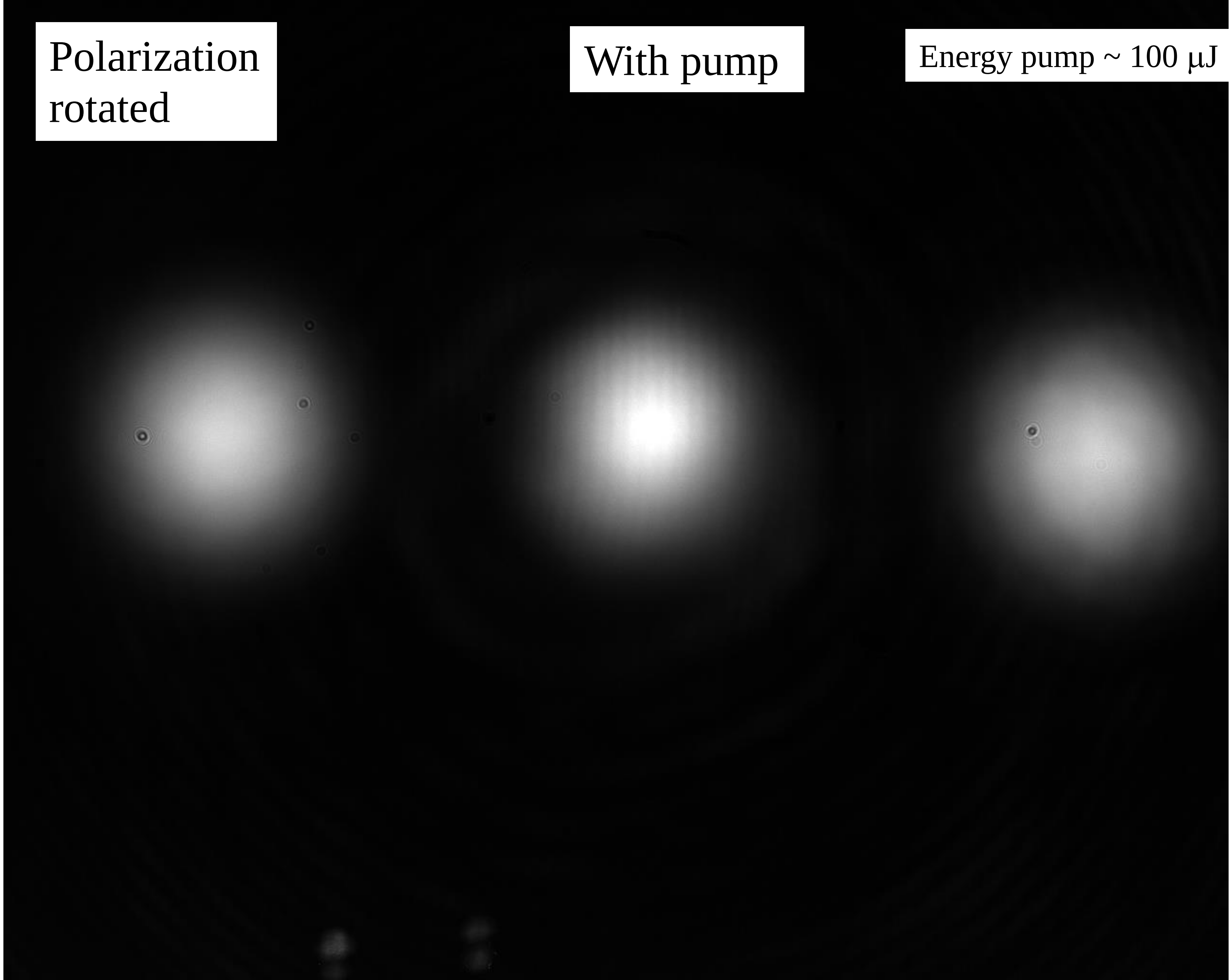
With pump $I \sim 10^{11}$ W/cm^2

Energy pump ~ 20 μJ

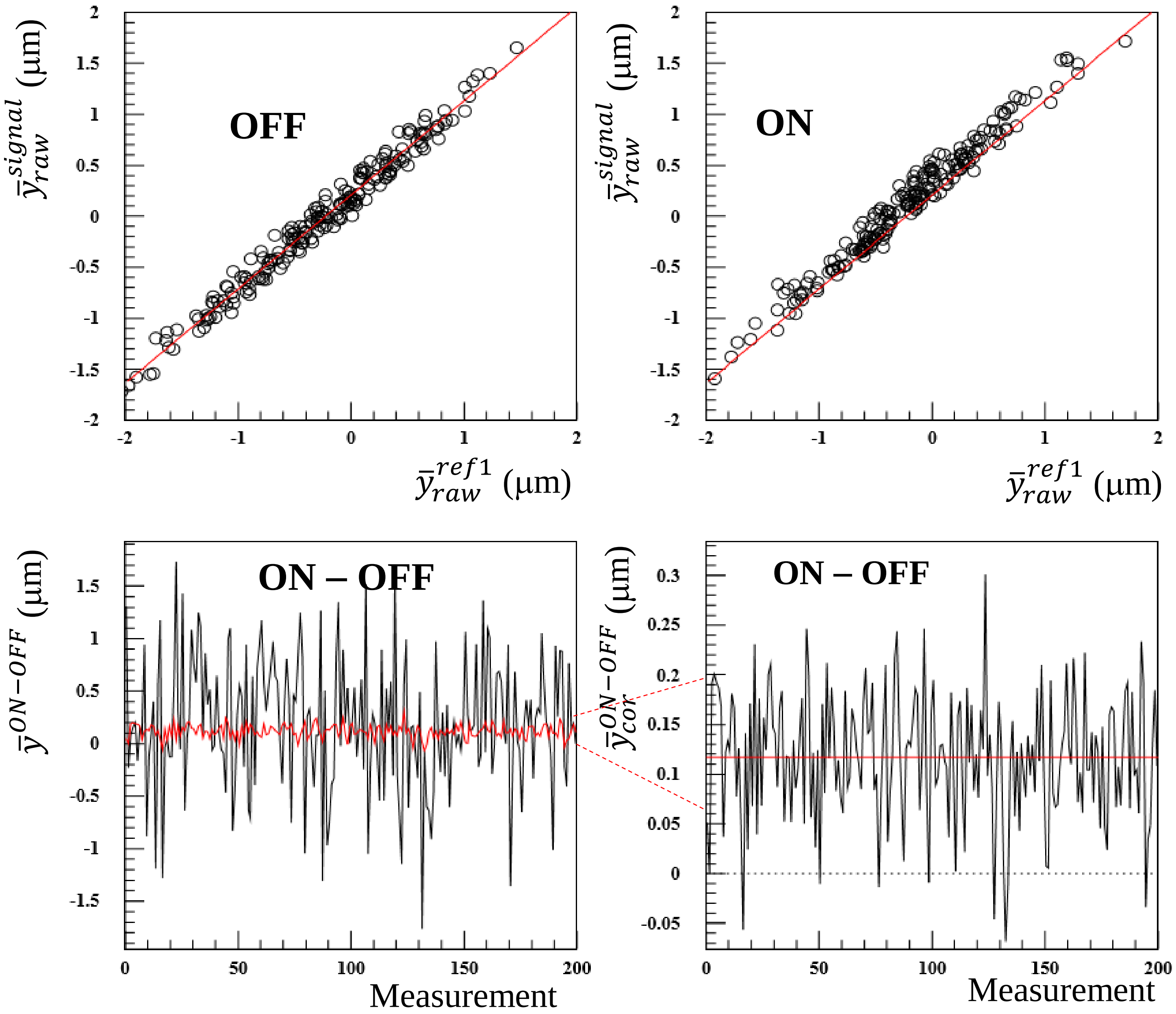


Intensity profiles in the dark output
of the Sagnac interferometer


Polarization rotated
Without pump


Polarization rotated
With pump
Energy pump ~ 100 μJ

Measurement of the Kerr signal in SiO_2



Energy pump ~ 300 nJ

Δt ~ 50 – 100 fs

Φ(pump) ~ 400 µm

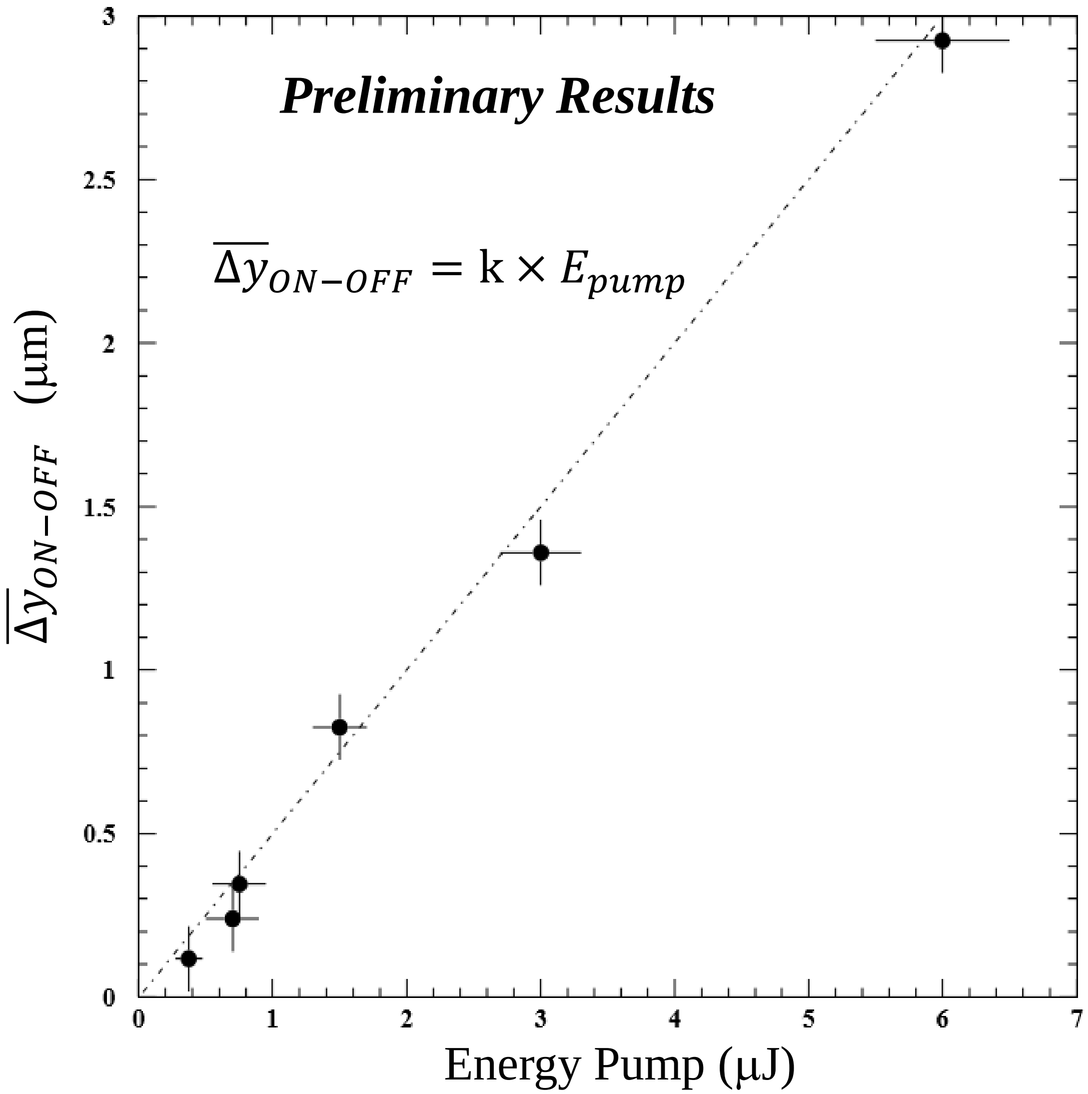
➡ I ~ 10^9 W/cm^2

➡ $\boldsymbol{\Delta n / n \approx 5 \times 10^{-7}}$

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

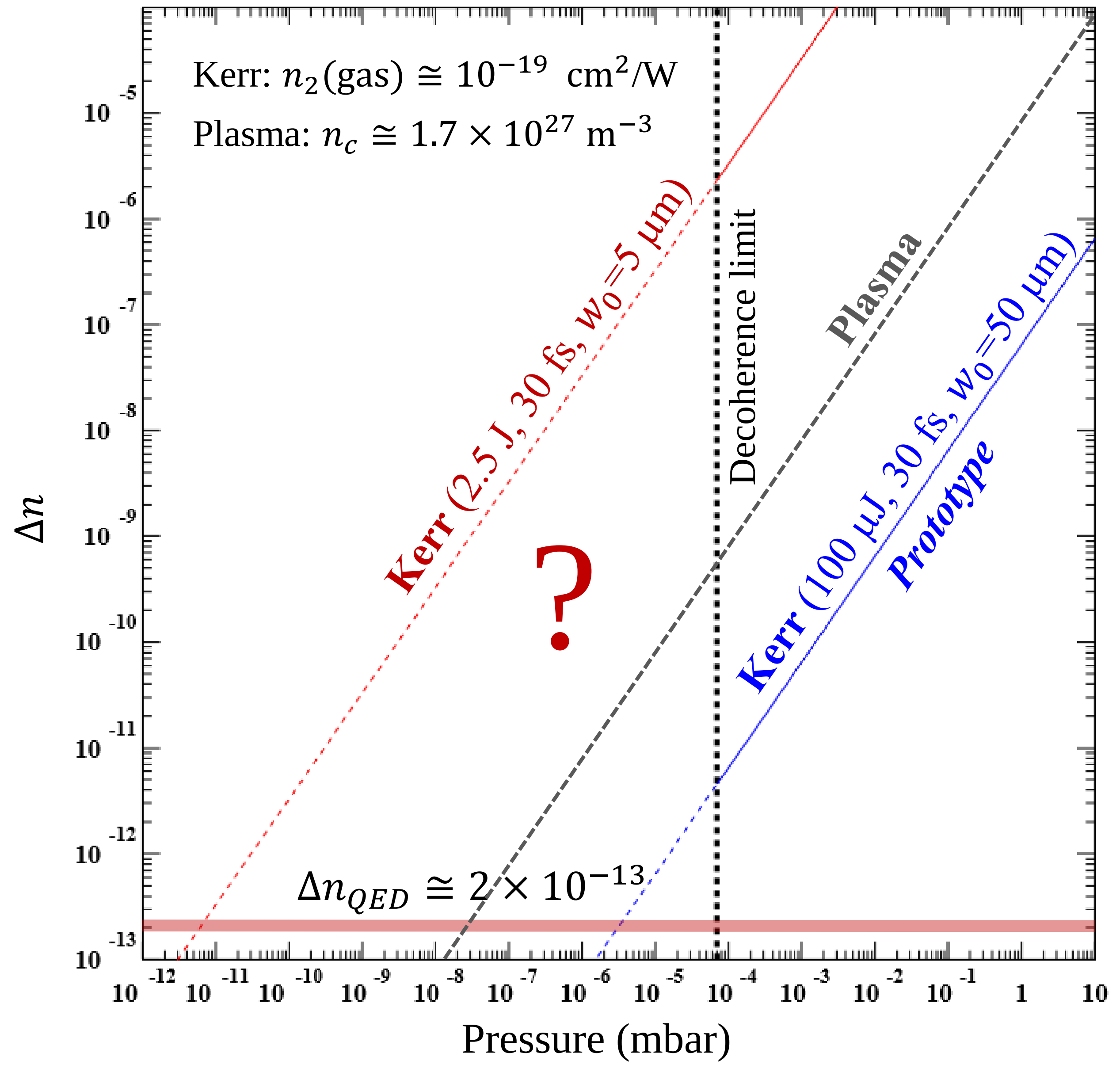
(200 meas. ON-OFF; 40 sec.)

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 Oct. 2018 – Oct. 2021

2/3 Equipement

1/3 2-years post-doc (starting spring 2019)

Partners: LAL, LPGP, LUMAT, APC

Program:

1. DeLLight-0 (2019):
   - 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 (2019-2020): Measure in vacuum with 2 Joules & focus $w_0 = 10 – 20\ \mu m$

3. DeLLight Phase 2 (2020-2021): Measure in vacuum with focus $w_0 = 5\mu m$ ⇒ $\delta n \approx 2 \times 10^{-13}$

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

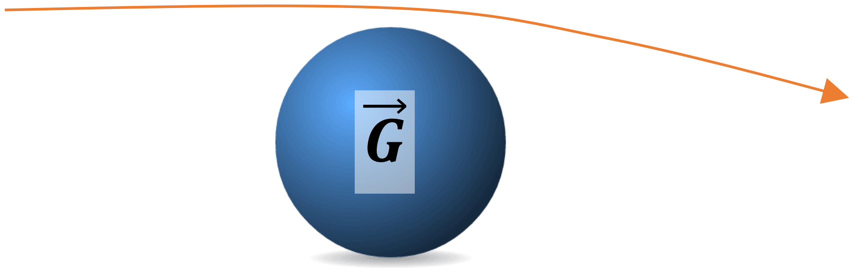
  June 2018: 16 joules, 27 femtosecond pulse duration (0.5 PW) @ 3.3Hz

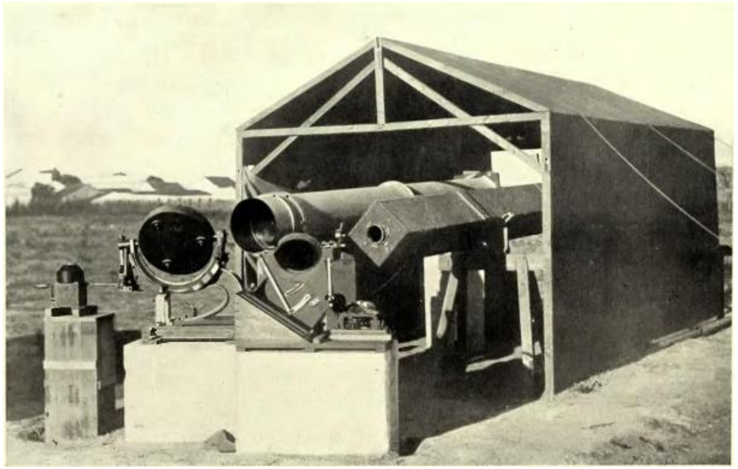
  2019 : 30 J, 30 fs $\Rightarrow$ **1 PW @ 10 Hz** $\Rightarrow \boldsymbol{\Delta x_{HAPLS}} \approx$ **0.1 nm**

  Target: ~200 Joules, 30 fs $\Rightarrow$ ~6 PW @ 10 Hz $\Rightarrow \boldsymbol{\Delta x_{HAPLS} \approx 1}$**nm**

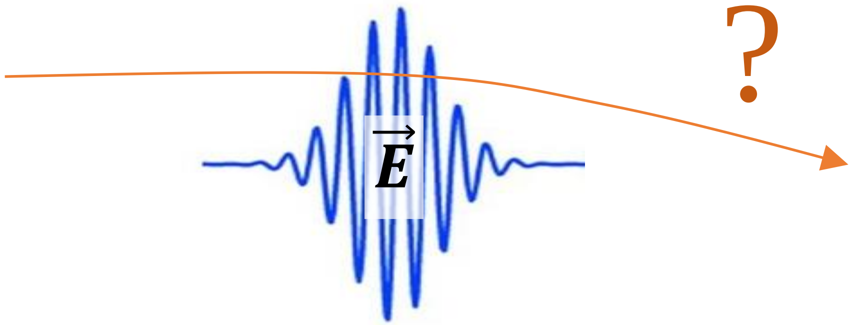
Conclusions

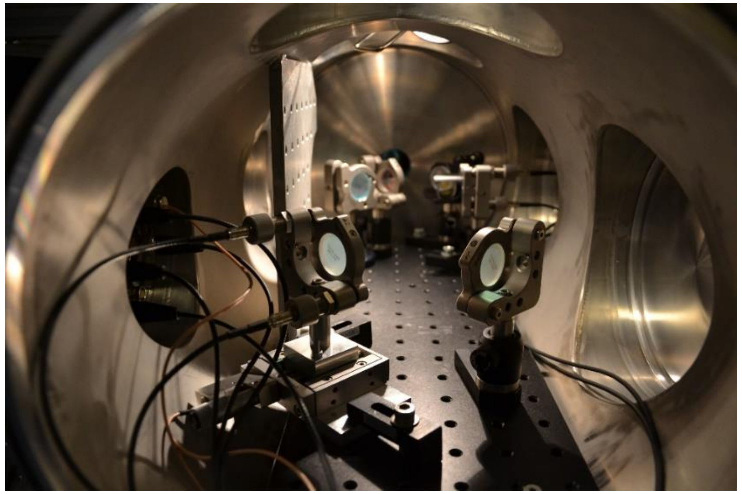
- In May 29, 1919 Eddington measured the deflection of light by a gravitational field





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





Backup

Pressure in the interaction area

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

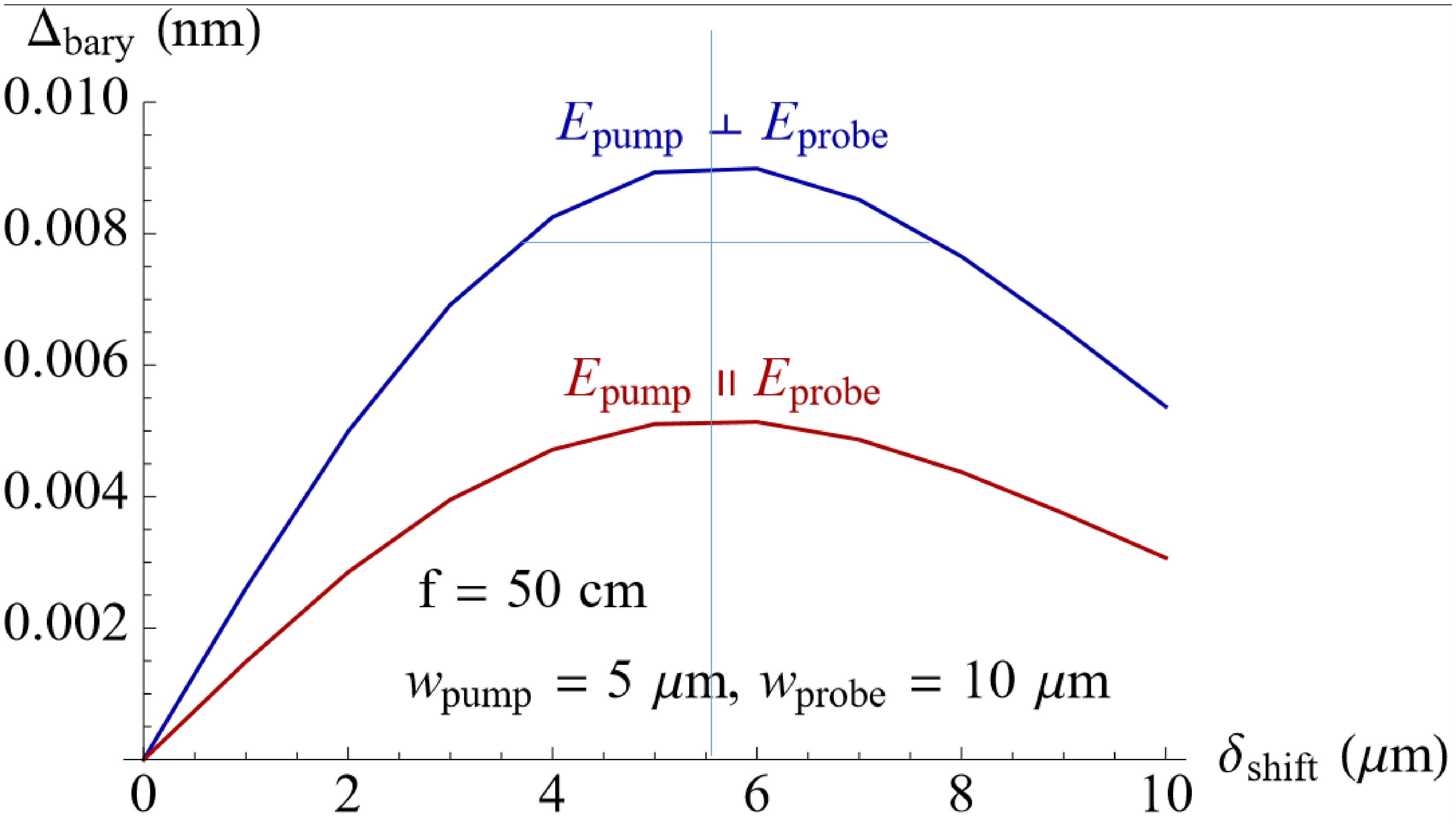
$\Rightarrow$ ~ 10 molecules in the volume $V = w_0^2 \times \Delta t \times c$ $\quad (\Delta t \times c = 10\mu s)$

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

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

Numerical Simulations

Systematics due to pump-probe jitter

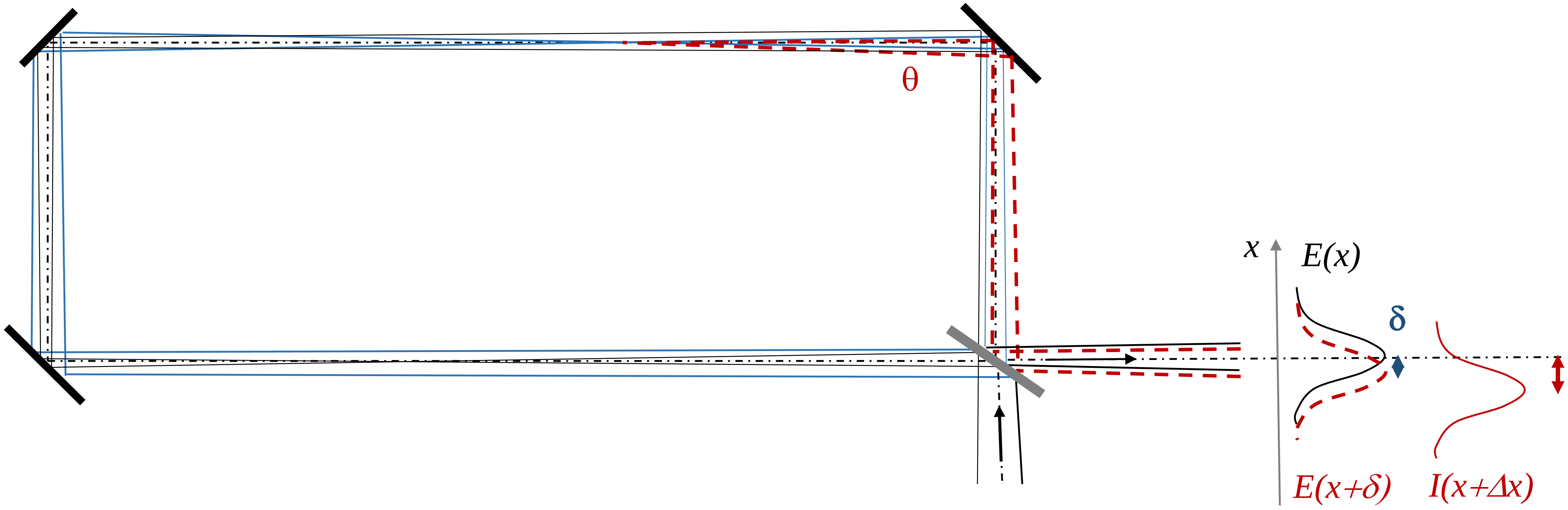


Amplification with a Sagnac Interferometer

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

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

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



Expected sensitivity

Sensitivity depends strongly on the waist of the pump at focus $T_{obs} \propto w_0^6$