DeLLight

(Deflection of Light by Light in vacuum)

with LASERIX @ IJCLab

Slowing down the light in vacuum with intense laser pulses

Adrien Kraych, Seminar LLR, December 2024

Is the vacuum optical index constant ?

- **Classical electrodynamics: Maxwell's equations are « linear » in vacuum**

$$\begin{cases} \mathbf{D} = \varepsilon_0 \mathbf{E} \\ \mathbf{B} = \mu_0 \mathbf{H} \end{cases} \qquad c = \frac{1}{\sqrt{\varepsilon_0 \mu_0}} \quad \Rightarrow \quad \boxed{c,\ \varepsilon_0 \text{ and } \mu_0 \text{ are UNIVERSAL CONSTANTS}}$$

No dependence of the optical index on external fields (E,B) $\Rightarrow \boldsymbol{n = 1}$

- **Maxwell's equations are not linear in dielectric media**

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

- Optical index depends on external fields E,B $\Rightarrow$ ***n*(E,B)**
- Nonlinear interaction between the electromagnetic fields, through the medium

➡ A well known nonlinear optical phenomenon is the **optical Kerr effect**:

$$n = n_0 + n_2 \times I(\mathrm{W/cm^2}) \qquad \begin{cases} n_2(Silica) \cong 10^{-16}\ \mathrm{cm^2/W} \\ n_2(Air) \cong 10^{-19}\ \mathrm{cm^2/W} \end{cases}$$

Is the vacuum a nonlinear optical medium as other material mediums ?

Can the speed of light be reduced by an external e.m. field ?

Three new facts at the beginning of the 20th century that changed the classical scenario:

- Einstein's energy-mass relation
- Heisenberg's uncertainty principle
- Dirac's relativistic equation of the electron admitting anti-matter (positron)

These facts allow a fluctuation of the vacuum and, consequently,

non linear electrodynamic effects in the vacuum.

Nonlinear electrodynamics in vacuum

- **Heisenberg & Euler** (1936) : Nonlinearity in vacuum induced by the coupling of the e.m. field with the e+/e− virtual pairs in the *Dirac sea* vacuum *[Heisenberg and Euler, Z. Phys. 98, 714 (1936)]*

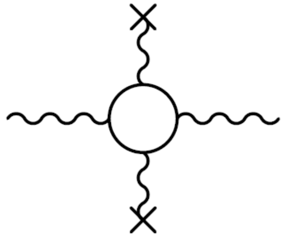
$$\Rightarrow \begin{cases} \mathbf{P} = \xi \varepsilon_0^2 [(E^2 - c^2 B^2)\mathbf{E} + 7c^2(\mathbf{E}.\mathbf{B})\mathbf{B}] \\ \mathbf{M} = -\xi \varepsilon_0^2 c^2 [(E^2 - c^2 B^2)\mathbf{B} - 7(\mathbf{E}.\mathbf{B})\mathbf{E}] \end{cases} \qquad \xi^{-1} = \frac{45 m_e^4 c^5}{2\alpha^2 \hbar^3}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

- **Schwinger** (1951) derived later the H-E result within the QED frame

[J. Schwinger, Phys. Rev. 82, 664 (1951)]

Schwinger critical field for e+/e- pair creation

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



Nonlinear electrodynamics in vacuum

Because of the possible photon-photon interaction in vacuum, the vacuum should behave as a nonlinear optical medium: The speed of light in vacuum

should be reduced at **macroscopic** scale,

in the classical (optical) sense,

when it is stressed by intense e.m. fields

Has this ever been observed ?

Nonlinear electrodynamics in vacuum

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Nonlinear electrodynamics in vacuum

(1) PHOTON – PHOTON SCATTERING has already been measured:

- Delbrück scattering: photon scattering in the Coulomb field of a nucleus.

  R. R. Wilson, Phys. Rev. 90, 720-721 (1953)

- Collisions of High-energy gamma photon with several laser photons at SLAC in 1997.

  D. L. Burke *et al*, Phys. Rev. Lett 79, 1626 (1997)

- Photon Splitting into two photons by interaction with external fields.

  S. Z. Akhmadaliev *et al*, Phys. Rev. Lett. 79, 1626-1629 (2002)

- High energy gamma-gamma pair emission from virtual gamma-gamma scattering in Pb-Pb collisions at LHC (2017-2019)

  ATLAS Collaboration, Nat. Phys. 13, 852 (2017)
  CMS Collaboration, Phys. Lett. B 797, 132826 (2019)

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Has this ever been observed ?

Nonlinear electrodynamics in vacuum

(2) Never observed for a classical optical wave propagating in a macroscopic electromagnetic field.

Some attempts over the last century :

Farr & Bandwell (1932)

R. V. Jones (1960s)

PVLAS experiment (1992 – today)

W. H. Watson (1929)

J. Stark (1940s)

1992

A. Ejlli *et al*, *Physics* Reports 871 (2020) 1–74

K. Scharnhorst, arXiV: 1711.05194 (2017)

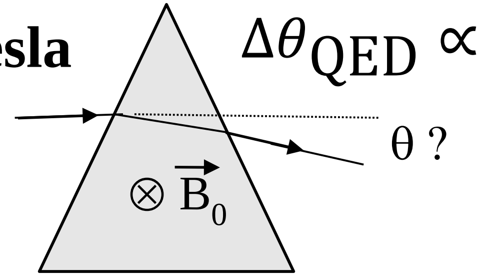
Magnetic prism in vacuum with a static external field **B = 1 Tesla**

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

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

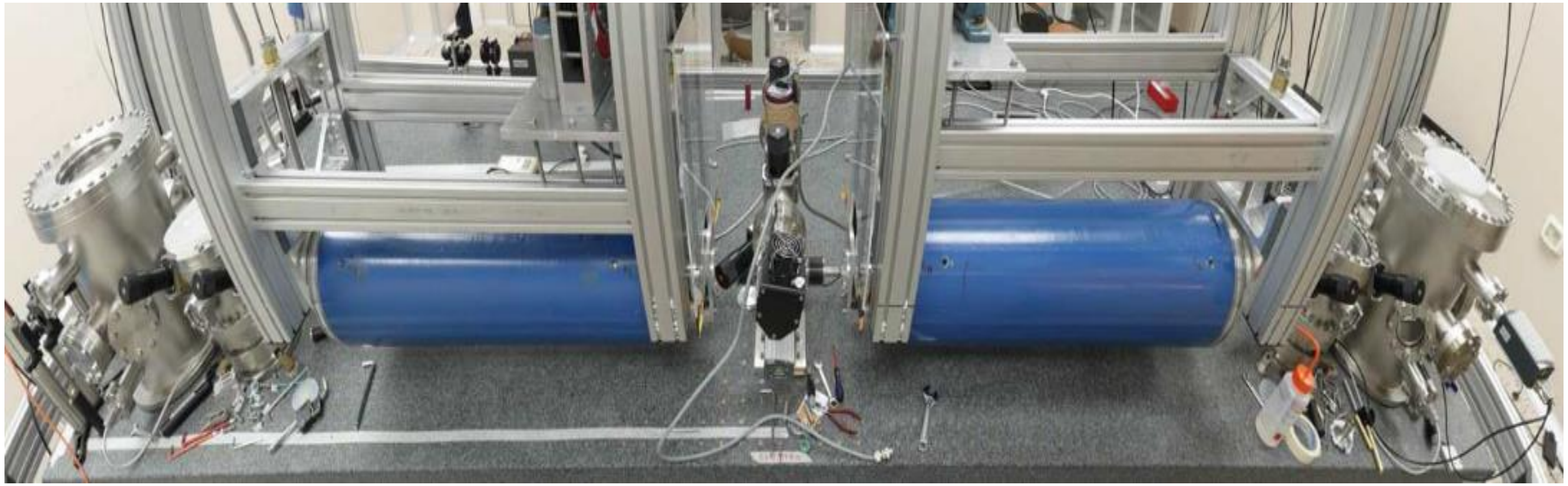
Sensitivity ≅ 0.5 picorad (!)

R. V. Jones, Nature, 186.4726 (1960)



The PVLAS experiment

- Search for vacuum birefringence induced by an external continuous magnetic field
- Best sensitivity achieved by **PVLAS** [*Physics Reports 871 (2020) 1–74*]
  - **Sensitivity must be improved by a factor ~ 50 in order to measure a signal at 5σ in 100 days**
  - Limitations: magnetic field (B ~ 2.5 T) and birefringence of the mirrors



Ultra-intense laser : a new promising window

The advent of ultra-intense laser pulses, delivering ultra-intense electromagnetic fields in laboratory, opens a new promising window to observe the optical non linearity of vacuum !

This is the goal of the DeLLight project

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

2.5 J, 30 fs, w_0=5μm $\Rightarrow$ I ~ 2×10^{20} W/cm^2

$\Rightarrow \boldsymbol{E} \sim \mathbf{3 \times 10^{13} V/m},\ \boldsymbol{B} \sim \mathbf{10^{5}\ T}$

The DeLLight Experiment

- Principle of the DeLLight experiment (2016)

X. Sarazin et al., Eur. Phys. J. D, 70 1 (2016)

- Consolidated by Scott J. Robertson's theoritical work (2019)

S. Robertson, Phys. Rev. A 100, 063831 (2019)

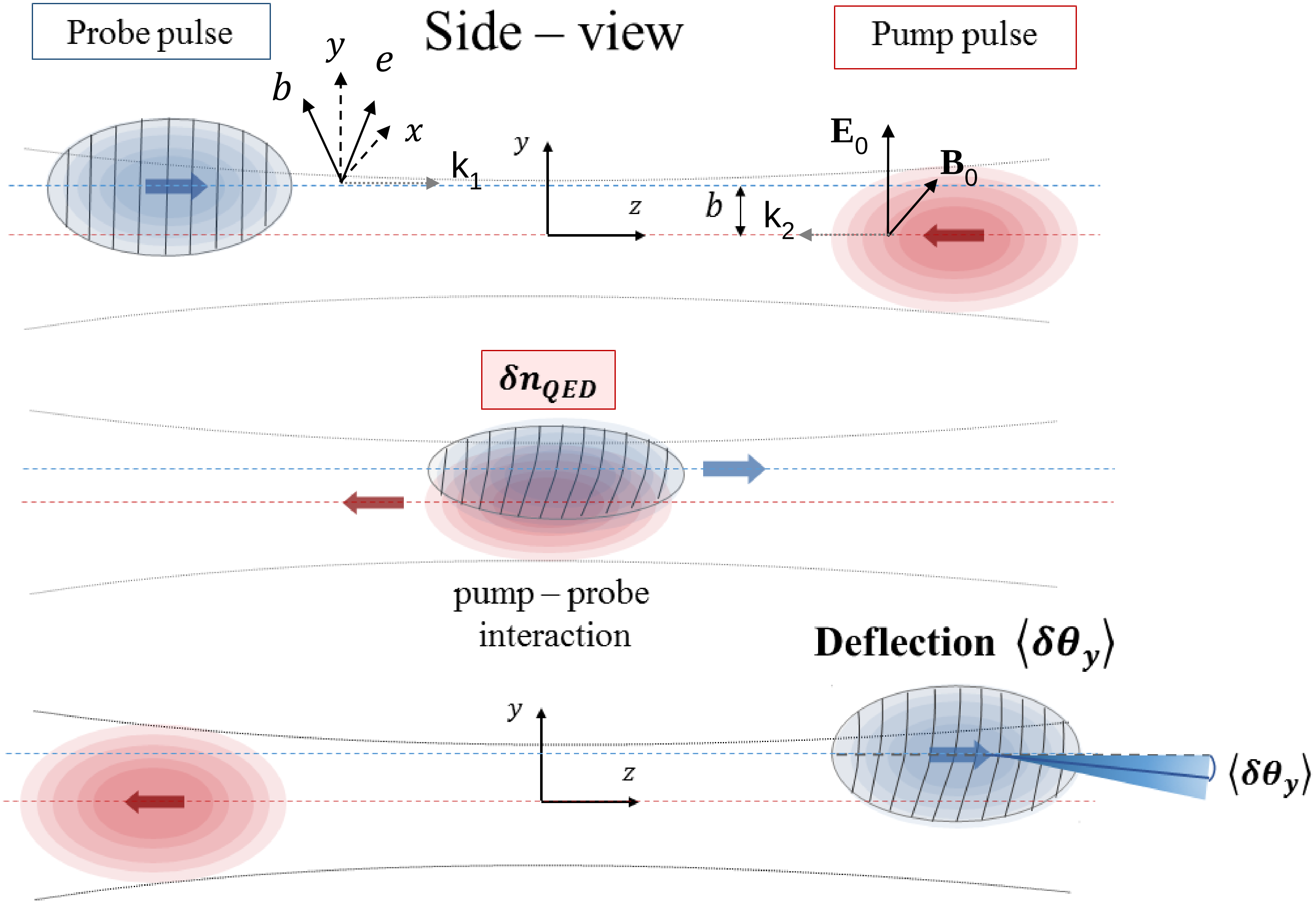
- First experimental results (2021)

S. Robertson, Phys. Rev. A 103, 023524 (2021)

- Validation of the experiment method with a DeLLight pilot experiment (2024)

A. Kraych *et al*, Physical Review A 109.5 (2024)
A. Mailliet *et al*, Physical Review A 109.4 (2024)

Pump-Probe interaction



Optical Kerr index in vacuum
$n_2(QED) = 1.6 \times 10^{-33}$ cm²/W
$n_2(air) \sim 10^{-19}\ cm^2/W$

Pump specifications (*LASERIX*)

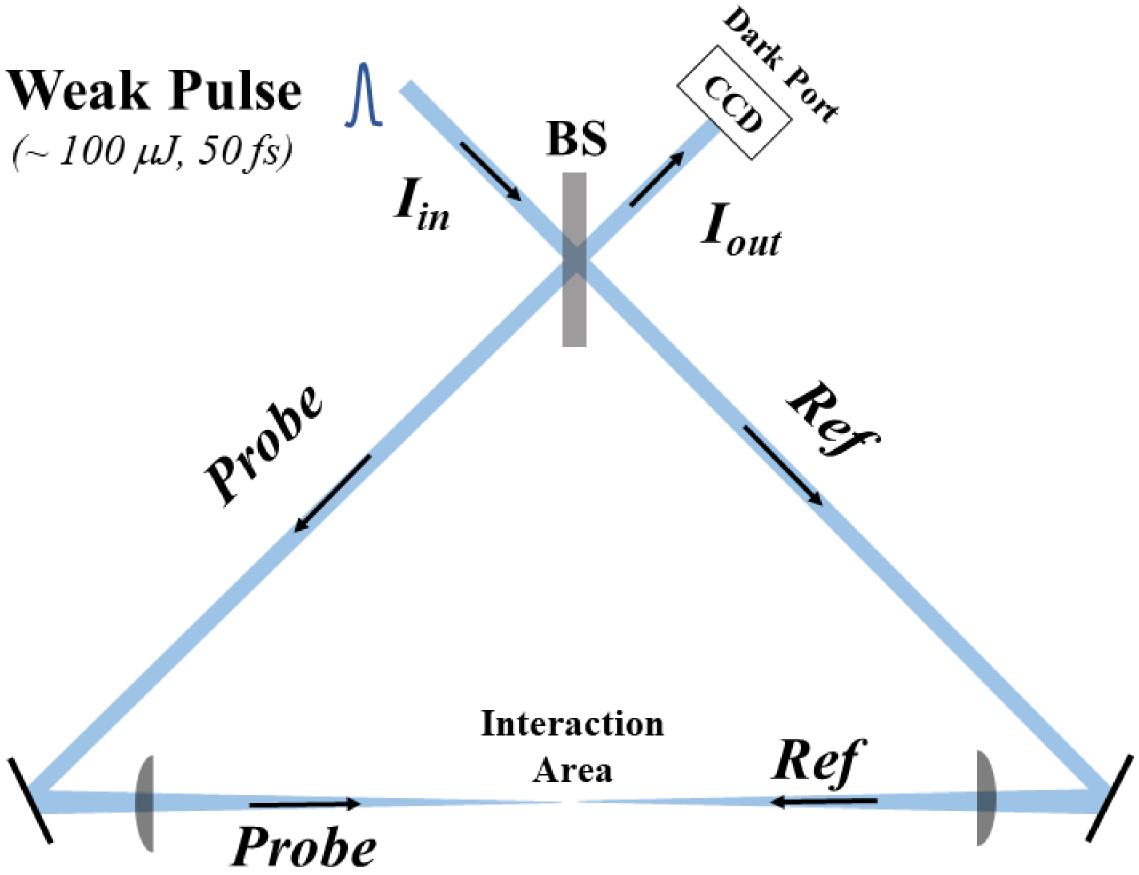
- ✓ **Energy ≈ 2.5 Joules**
- ✓ Duration ≈ 50 fs
- ✓ **Waist @ focus ≈ 5 µm**

$\Rightarrow I_{pump} \sim 2 \times 10^{20}$ W/cm^2
$\Rightarrow B \sim 10^5$ T

→ **$\delta\theta \sim 0.1$ prad**
$\delta n \sim 3 \times 10^{-13}$

Electromagnetic lensing in vacuum in analogy to the gravitation lensing

Refraction measured with a Sagnac Interferometer



- **Extinction factor** $\mathcal{F} = \frac{I_{out}}{I_{in}}$
  - **R/T asymmetry $\boldsymbol{\delta a}$** of the BS **:**

    $$\begin{cases} R = (1 - \delta a)/2 \\ T = (1 + \delta a)/2 \end{cases}$$

  - **Phase noise between Probe and Ref :**
    - – Intrinsic phase of the BS → $\delta\phi_0$
    - – Surface defects of the optics → $\delta\phi(x, y)$

$$\Rightarrow \quad \boxed{\mathcal{F} = \delta a^2 + (\delta\phi(x, y) + \delta\phi_0)^2}$$

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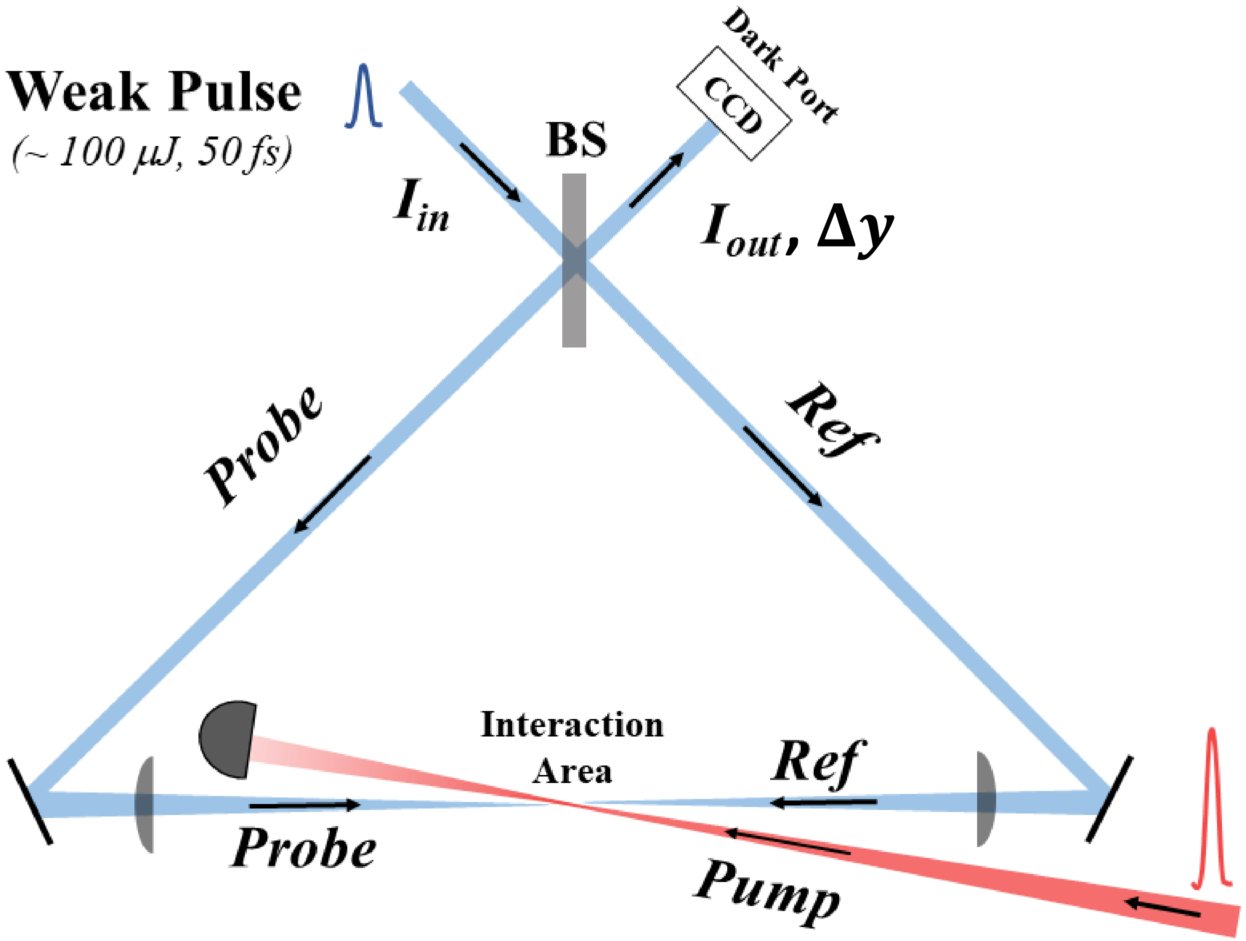
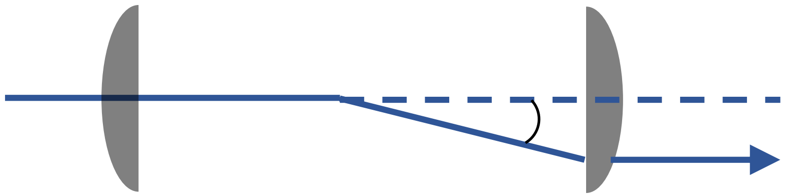




$$\delta y = f \times \delta\theta$$

- Direct vertical shift $\boldsymbol{\delta y}$ inside the Sagnac
- Reference is unaffected by the pump (not in time coincidence)
- Vertical shift $\boldsymbol{\Delta y}$ of the interference intensity profile is **amplified** in the dark output (*Weak Value Amplification*)

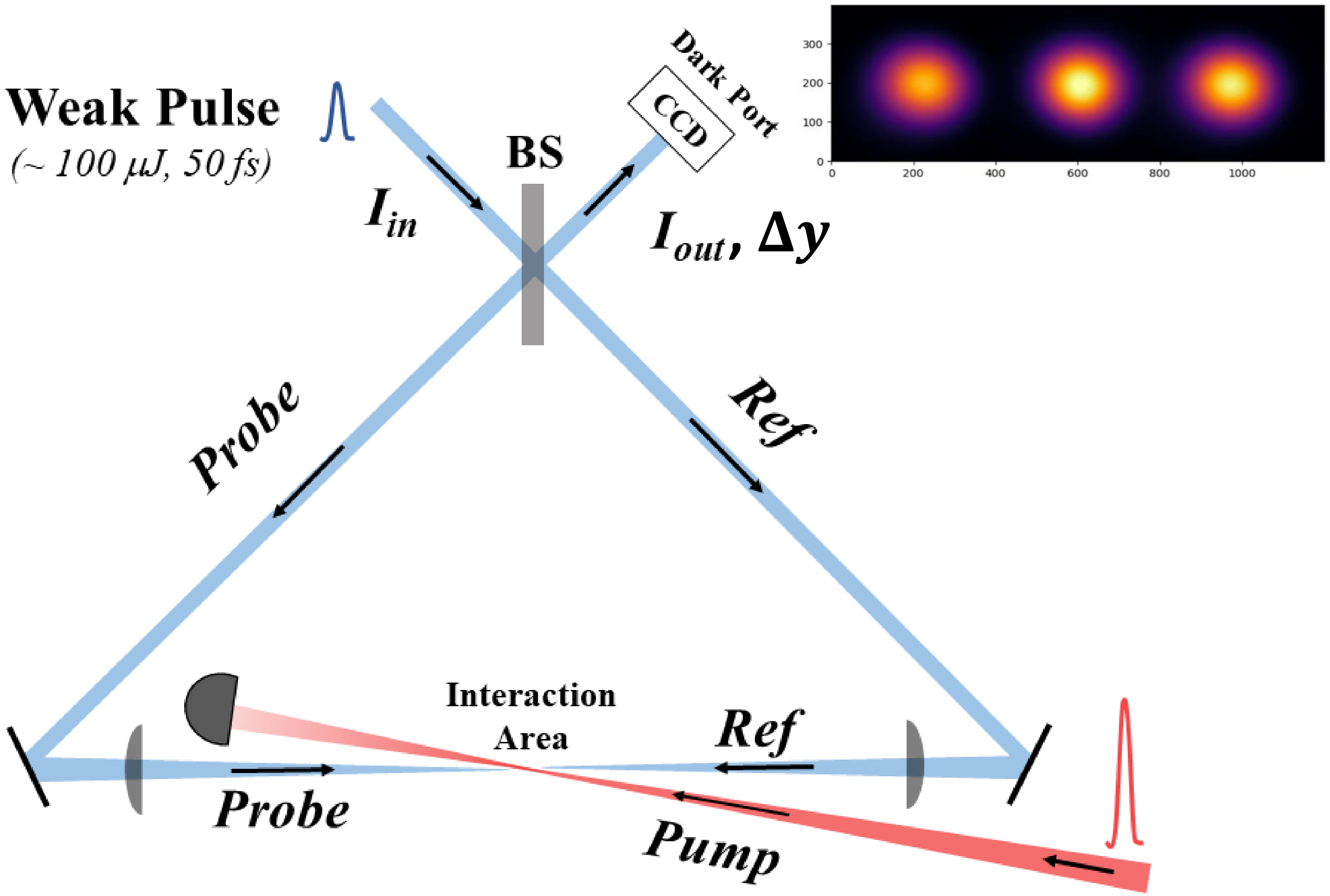
$$\Rightarrow \ \Delta \boldsymbol{y} = \mathcal{A} \times \boldsymbol{\delta y}$$

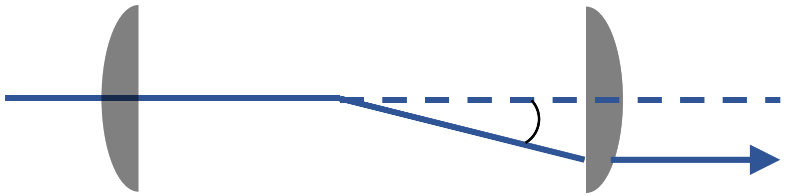
- Amplification factor $\mathcal{A}$:

$$\Rightarrow \ \mathcal{A} = \frac{1}{2\delta a} \approx \pm \frac{1}{2\sqrt{\mathcal{F}}}$$

- ON-OFF measurements @ 5 Hz

Refraction measured with a Sagnac Interferometer





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Expected signal and sensitivity

Expected signal: $$\Delta y = 2.7\ \text{nm}\ \times \frac{E(Joule) \times f(m)}{\left(w_0^2 + W_0^2\ (\mu\text{m})\right)^{3/2} \times \sqrt{\mathcal{F}/10^{-5}}}$$ (with $\theta_{tilt} \sim 15°$)

- ✓ **Energy $E = 2.5$ J @ LASERIX (10 Hz repetition)**
- ✓ **Extinction** $\mathcal{F} = 4 \times 10^{-6}$ ($\mathcal{A} = 250$) (best extinction measured)
- ✓ **Waist at focus** $w_0 = W_0 = 5\ \mu\text{m}$ (typical achievable value)

→ $\Delta y \sim 15$ pm

- ✓ **Spatial resolution** $\sigma_y = 10$ nm (CCD shot noise resolution)

→ ON-OFF measurements @ 5 Hz

Statistical sensitivity (without bias) : 1 sigma sensitivity within ~ 4 days with LASERIX

Expected signal and sensitivity

Expected signal:

$$\Delta y = 2.7\ \text{nm} \times \frac{E(Joule) \times f(m)}{\left(w_0^2 + W_0^2\ (\mu\text{m})\right)^{3/2} \times \sqrt{\mathcal{F}/10^{-5}}} \quad (\text{with } \theta_{tilt} \sim 15°)$$

- ✓ **Energy** E **= 180 J @ APOLLON laser (0.1 Hz repetition)**
- ✓ **Extinction** $\mathcal{F} = 4 \times 10^{-6}$ $(\mathcal{A} = 250)$ (best extinction measured)
- ✓ **Waist at focus** $w_0 = W_0 = 5\ \mu\text{m}$ (typical achievable value)

➡ $\Delta y \sim 1\ \text{nm}$

- ✓ **Spatial resolution** $\sigma_y = 10$ nm (CCD shot noise resolution)

➡ ON-OFF measurements @ 0.1 Hz

Statistical sensitivity (without bias) : 1 sigma sensitivity within ~ 30 minutes with APOLLON

Objectives:

1. **Is it really possible to amplify a deflection signal with a Sagnac Interferometer ?**

2. **Can we reach such « goal values » ? What are the limits and how can they be overcome ?**

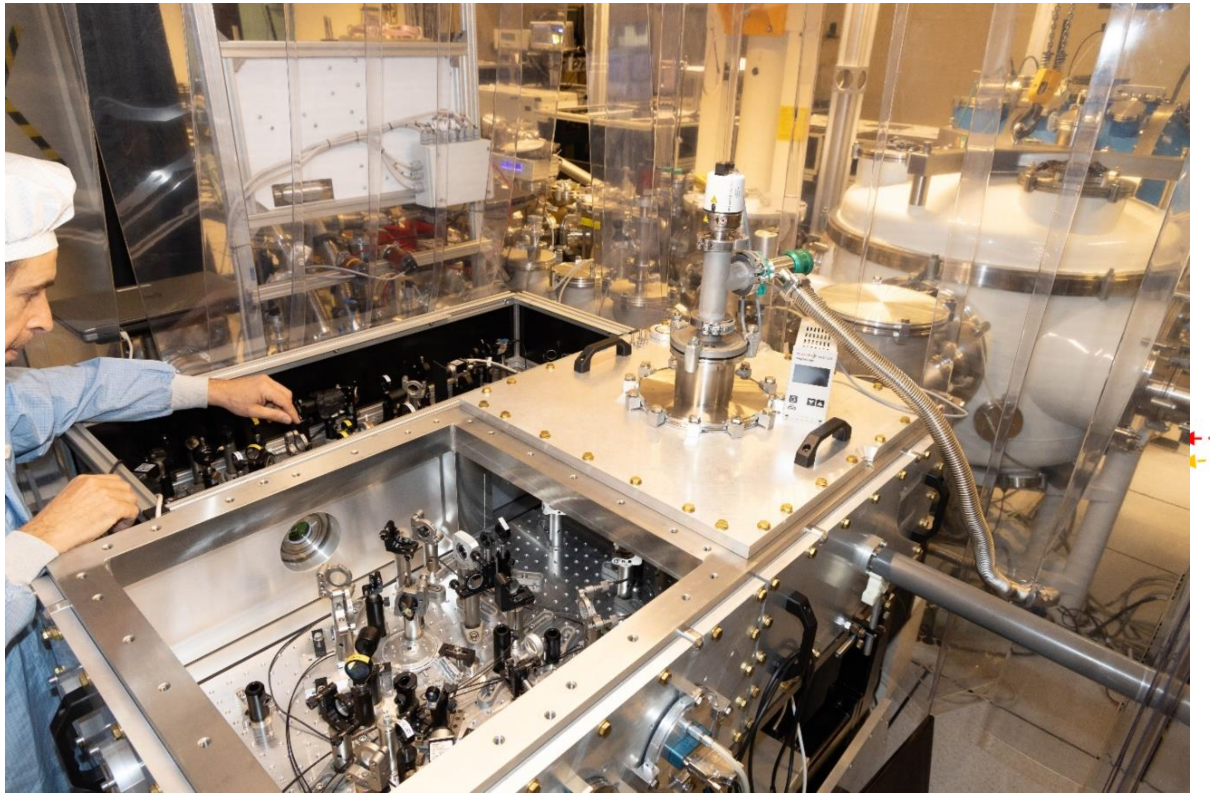
- ✓ **Extinction** $\mathcal{F} = 4 \times 10^{-6}$ $(\mathcal{A} = 250)$
- ✓ **Waist at focus** $w_0 = W_0 = 5$ µm
- ✓ **Spatial resolution** $\sigma_y = 10$ nm (CCD shot noise resolution)

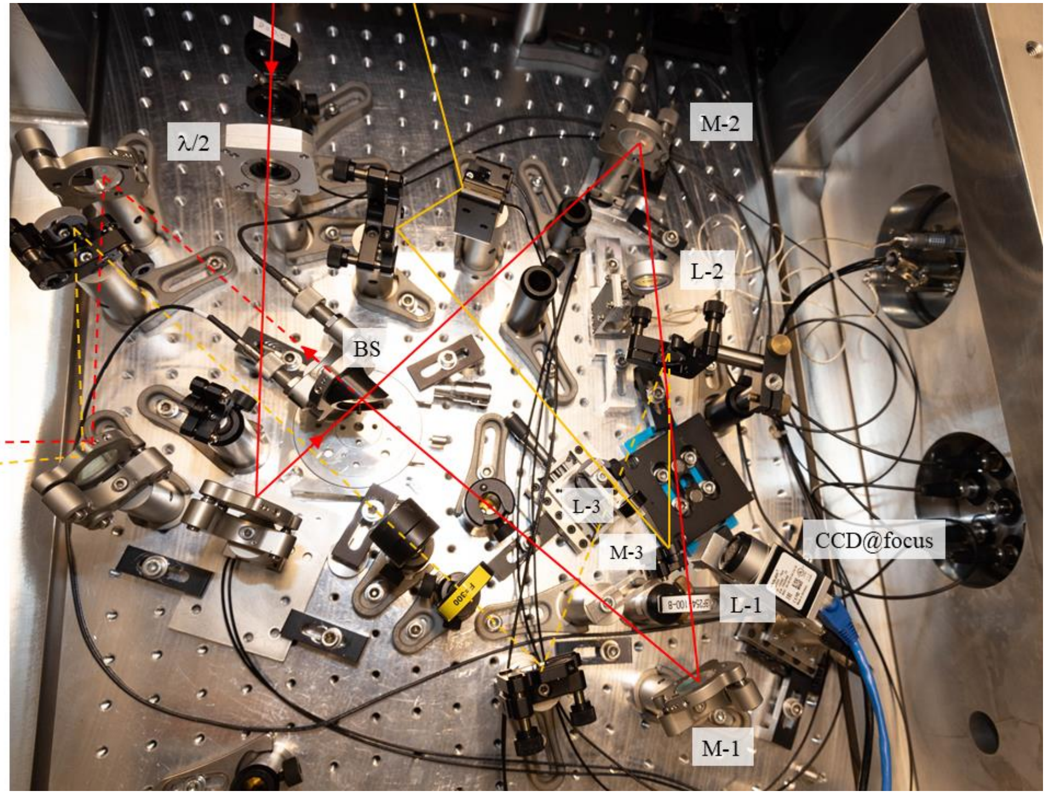
The DeLLight pilot experiment

Pilot experiment in vacuum chamber

Sagnac interferometer with focus of the probe and pump beams

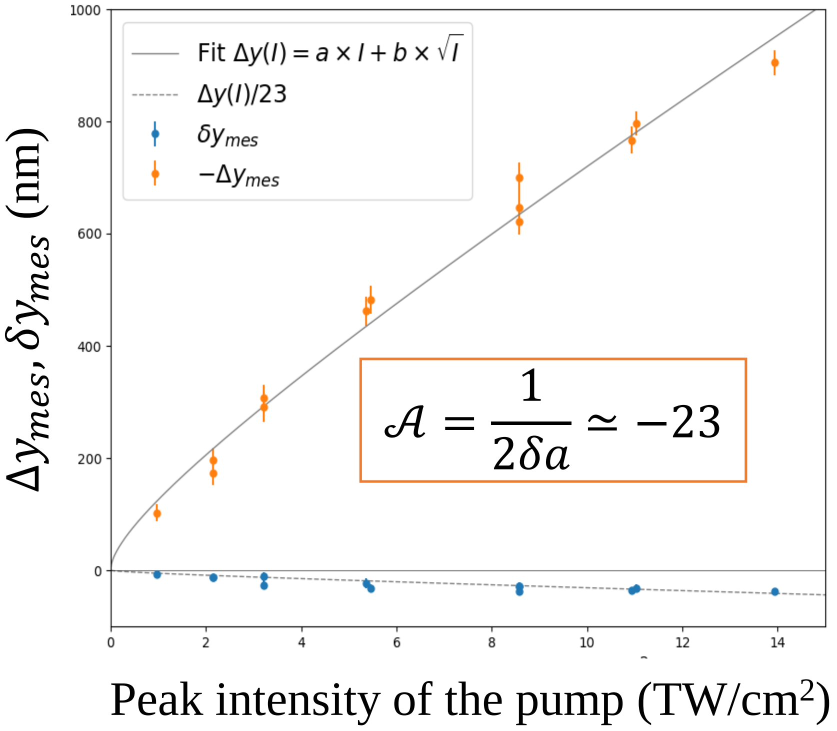
→ DeLLight deflection measured in air with a low pump energy



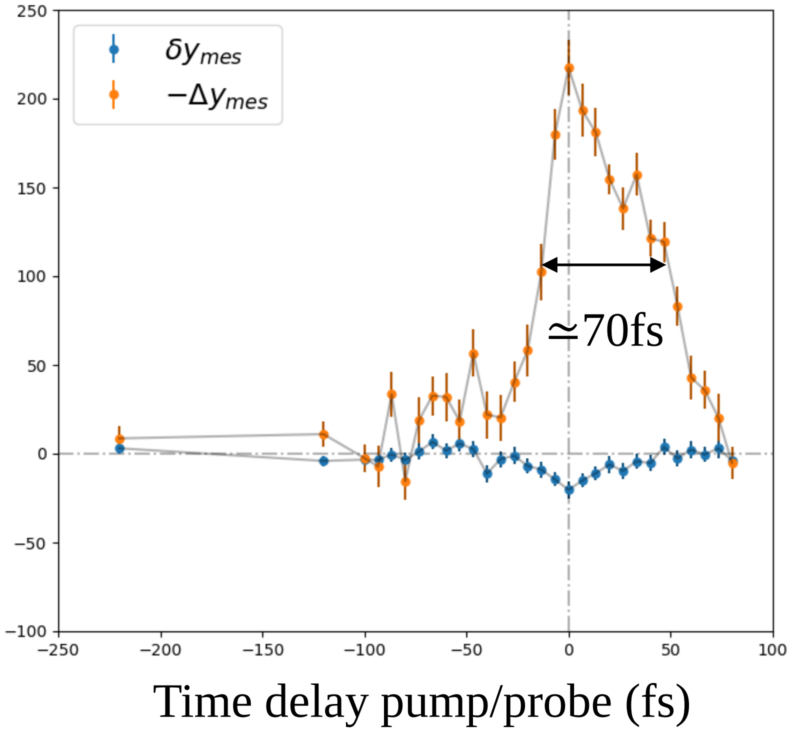


Measurement of the DeLLight signal in air

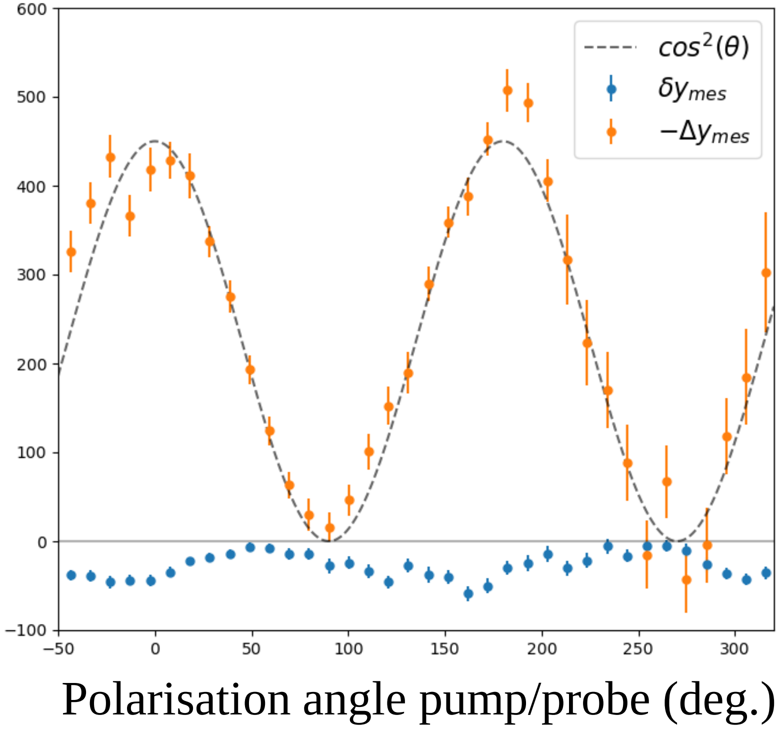
$\Delta y = f(\text{Intensity})$



$\Delta y = f(\text{time delay})$



$\Delta y = f(\text{polarisation})$



Validation of the DeLLight experimental method based on interferometric amplification !

More details in A. Kraych *et al*, Physical Review A 109.5 (2024)

Current sensitivity vs Goal values

DeLLight pilot experiment in Air:

- **E** = ~ 2 μJ & $W_0 = 25$ μm
- $\rightarrow \delta n = 3 \times 10^{-7}$- Optical Kerr Effect

Current sensitivity:

Extinction $\mathcal{F} = 5 \times 10^{-4}$ ($\mathcal{A} = 25$)

Waist at focus $w_0 = 25$ μm

Spatial resolution $\sigma_y \in [200{,}800]$ nm

- 1σ sensitivity in 1s

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Final DeLLight experiment in Vacuum:

- **E = 2.5** μJ & $W_0 = 5$ μm
- $\rightarrow \delta n = 3 \times 10^{-13}$ - QED

GOAL VALUES:

Extinction $\mathcal{F} = 4 \times 10^{-6}$ ($\mathcal{A} = 250$)

Waist at focus $w_0 = 5$ μm

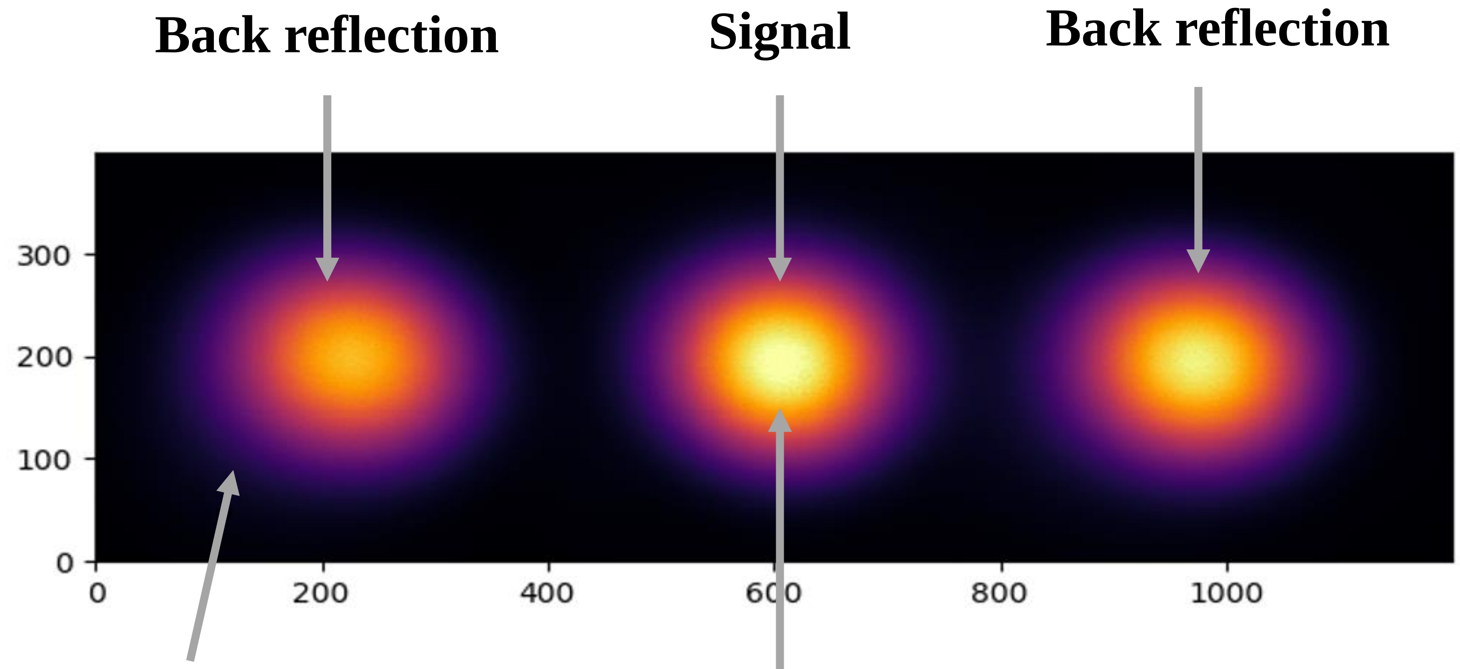
Spatial resolution $\sigma_y = 10$ nm

- 1σ sensitivity in 4 days

Extinction Factor

From $\mathcal{F} = 5 \times 10^{-4}$ **to** $\mathcal{F} = 3 \times 10^{-6}$!

Extinction in the dark output



$\mathcal{F}_{AR} = R_{AR}/2$

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

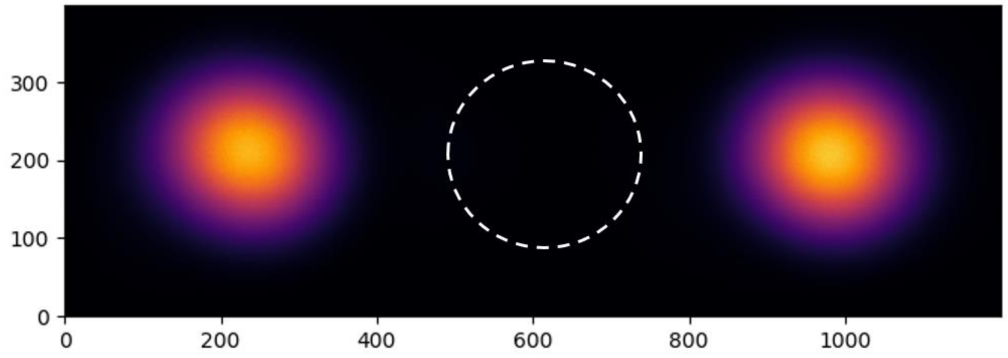
Extinction

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

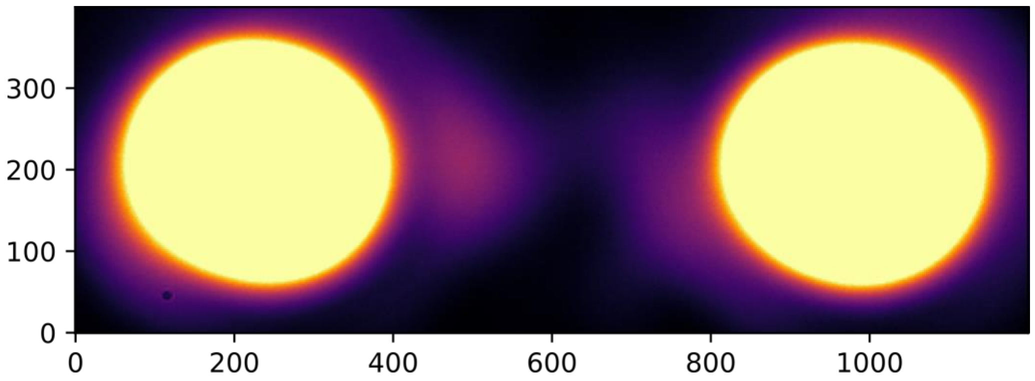
Extinction in the dark output

The best extinction is achieved by optimising the angle of incidence of the beamsplitter to maximise R/T symmetry

$$\mathcal{F} = 5 \times 10^{-6}$$

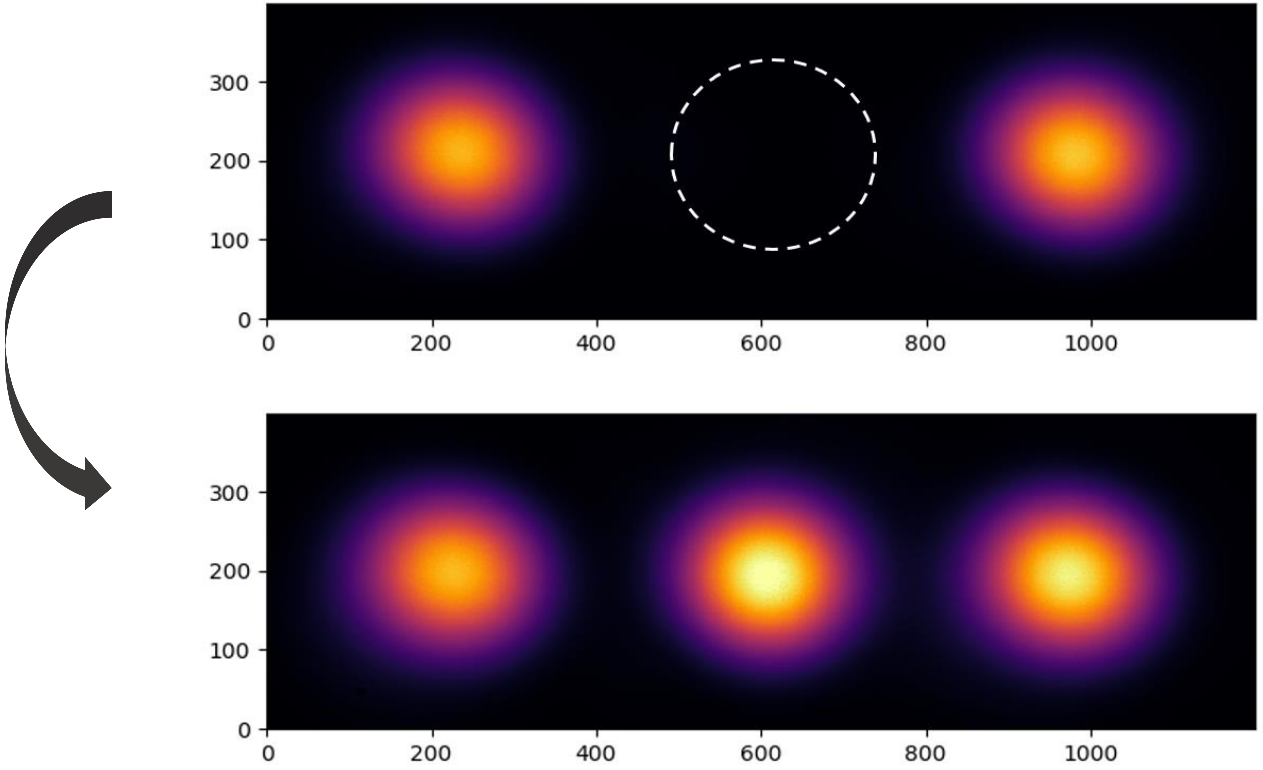


But because of the saturation of the backreflection, the destructive interference is polluated :



Extinction in the dark output

- With the current beamsplitter, the extinction must be reduced in order to measure the interference signal



$\mathcal{F} = 5 \times 10^{-6}$ - Best extinction configuration

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

- Signal saturation caused by the back reflections necessitates the development of a newbeamsplitter with low R_{AR} , in order to work at $\mathcal{F} \approx 3 \times 10^{-6}$

Spatial Resolution

Spatial resolution in the dark output limited by:

- Shot noise (ultimate resolution) of the CCD
- Beampointing fluctuations
- Phase noise fluctuations of the interferometer (induced by the external mechanical vibration)

Measurement of the shotnoise

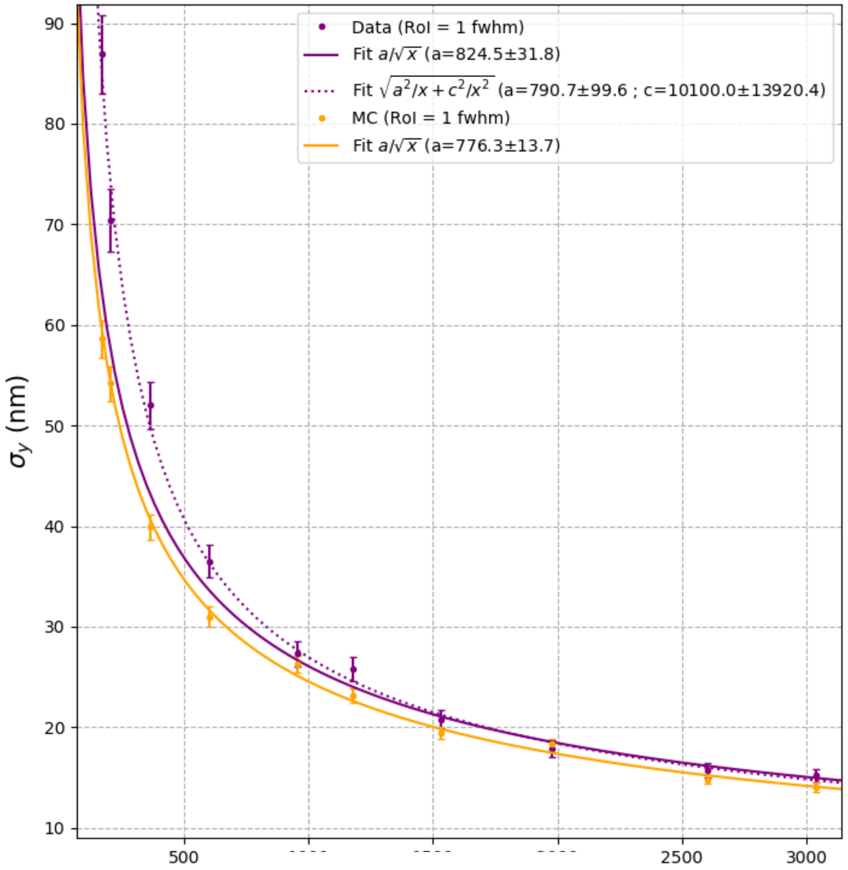
- **Shot noise:** inherent quantum noise (stat. fluctuations) of the number of detected photons

- Dedicated testbench to measure the ultimate shotnoise of available commercial CCD camera

- **Best CCD** (pixel size: $1.85 \times 1.85\ \mu m^2$): $\boldsymbol{\sigma_y \simeq 13\ \text{nm}}$

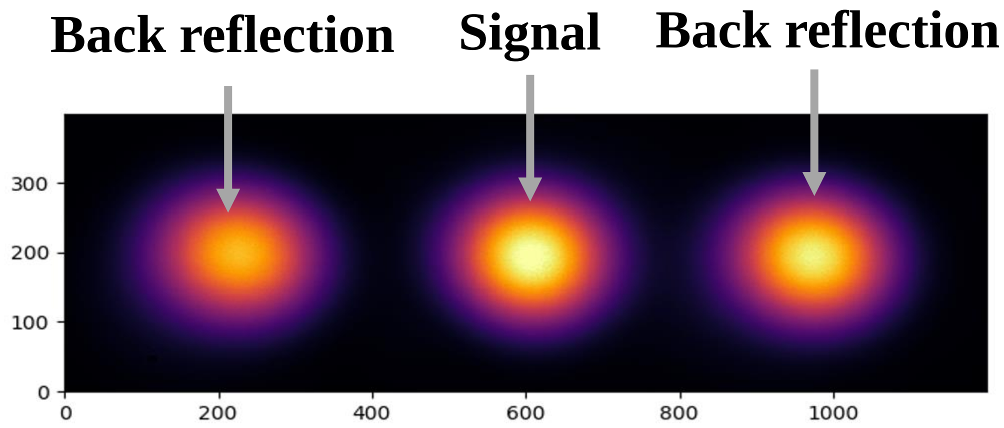
See Max Mailliet, PhD thesis, 2023

Pixel size: $1,85 \times 1,85\ \mu m^2$ (goal CCD)

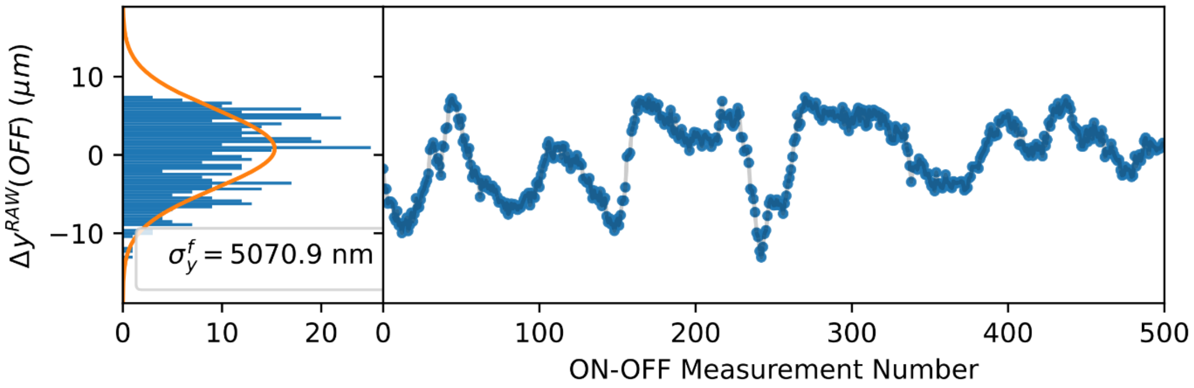


I_{ref} (ADC)

Spatial resolution: The beam pointing fluctuations



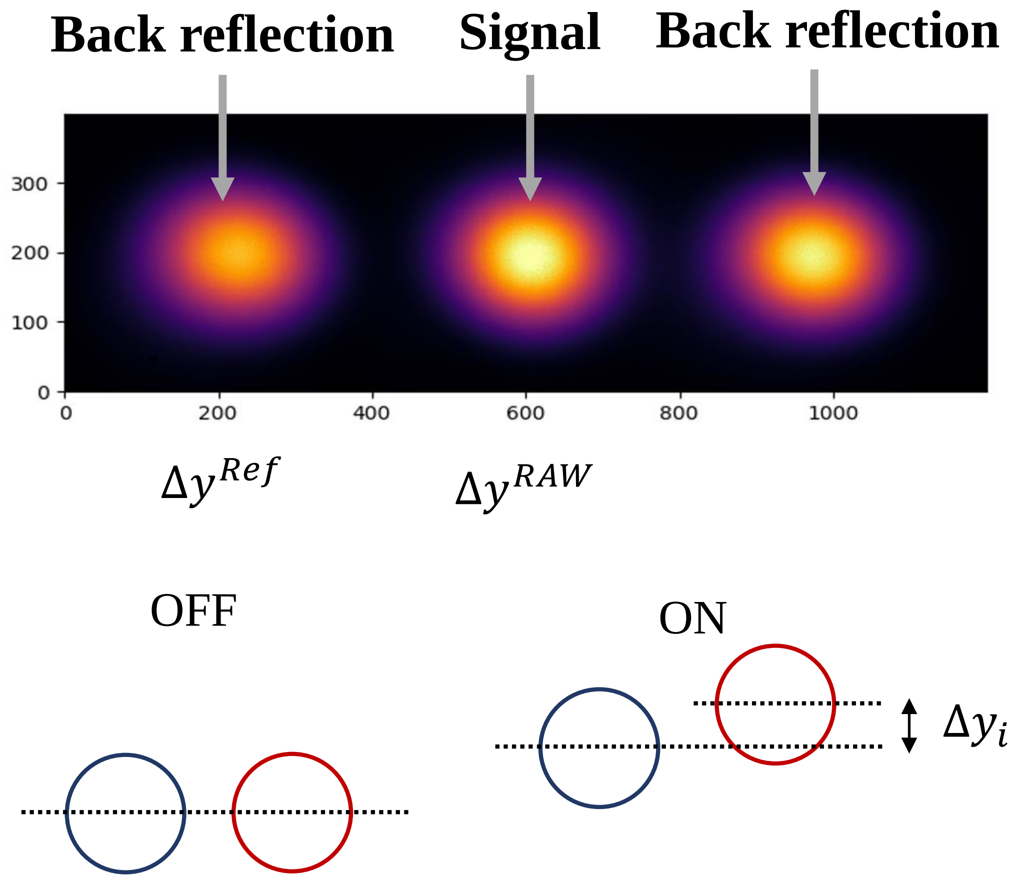
Δy^{RAW}

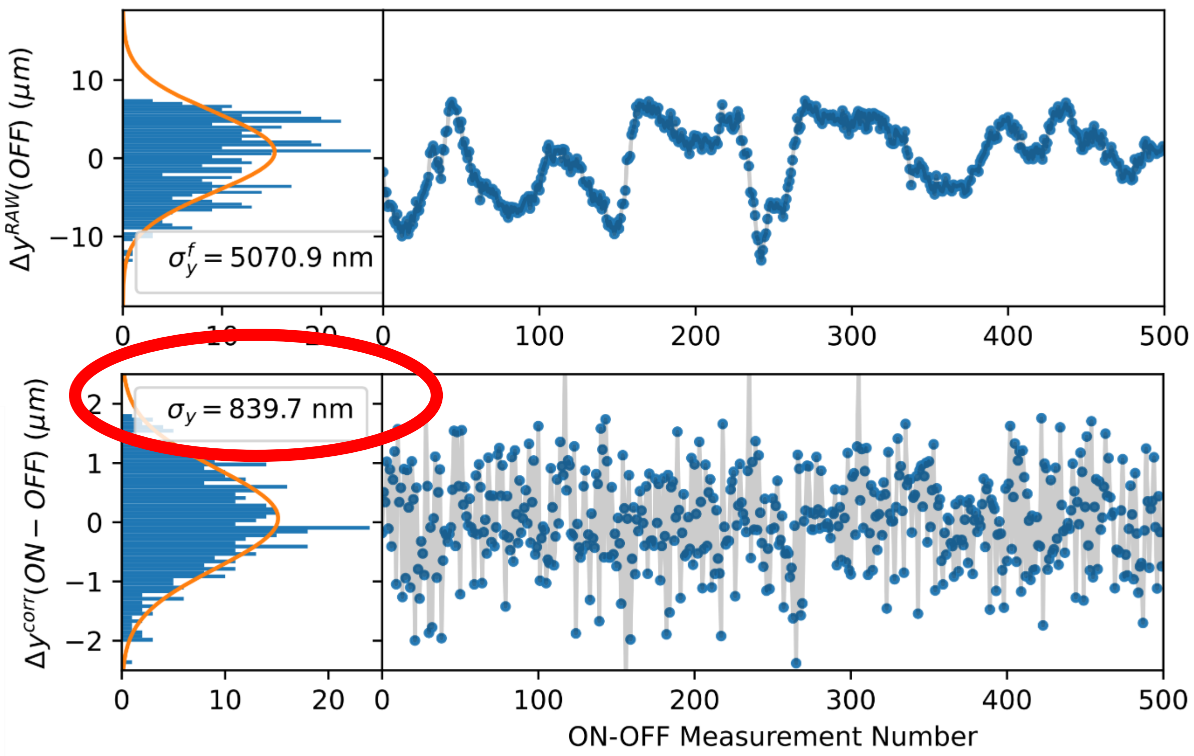


- By making « OFF-OFF » measurements (without laser pump pulse), we measure the spatial resolution of Δy^{RAW}.

- Without any pointing correction : $\sigma_y = 5\ \mu m$ far from ${\sigma_y}^{SN} = 10\ nm$.

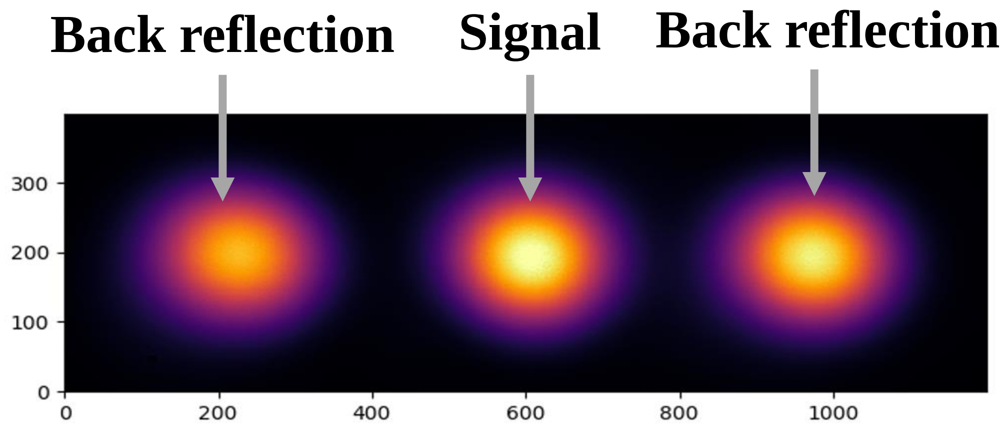
Spatial resolution: The beam pointing fluctuations





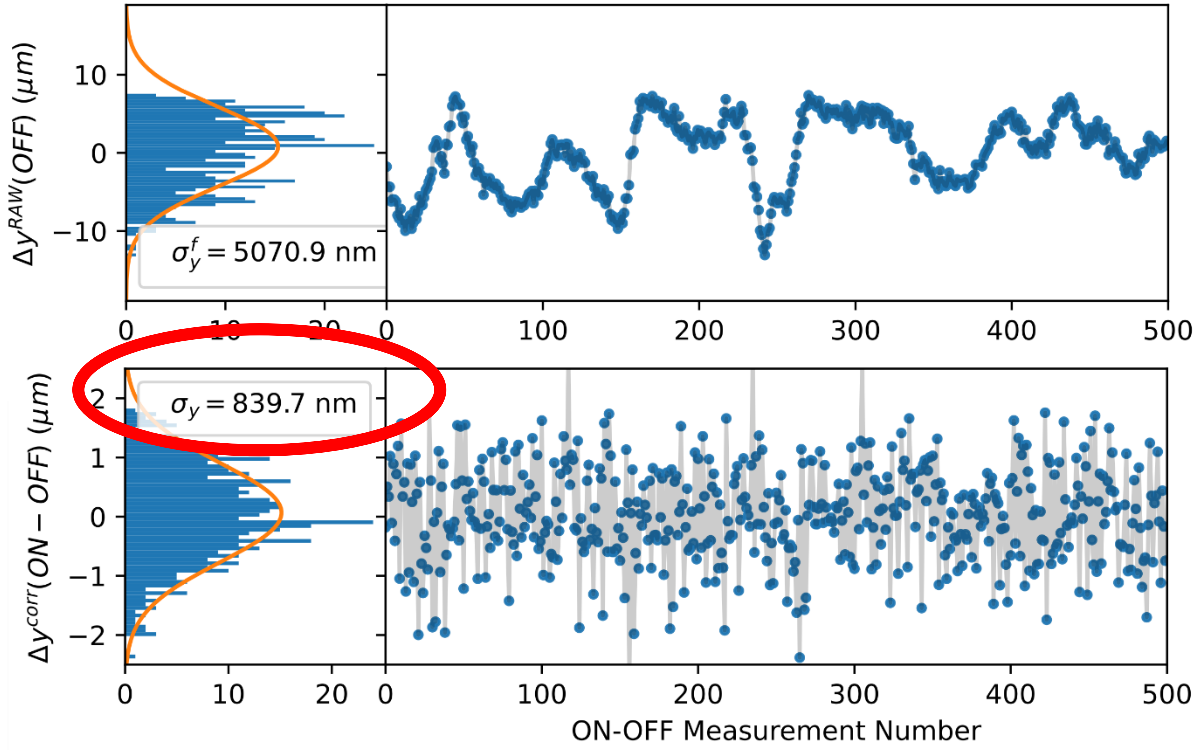
$$\Delta y^{corr} = \Delta y^{RAW} - \Delta y^{Ref}$$

Spatial resolution: The beam pointing fluctuations



Δy^{Ref} Δy^{RAW}

$\Delta y^{corr} = \Delta y^{RAW} - \Delta y^{Ref}$



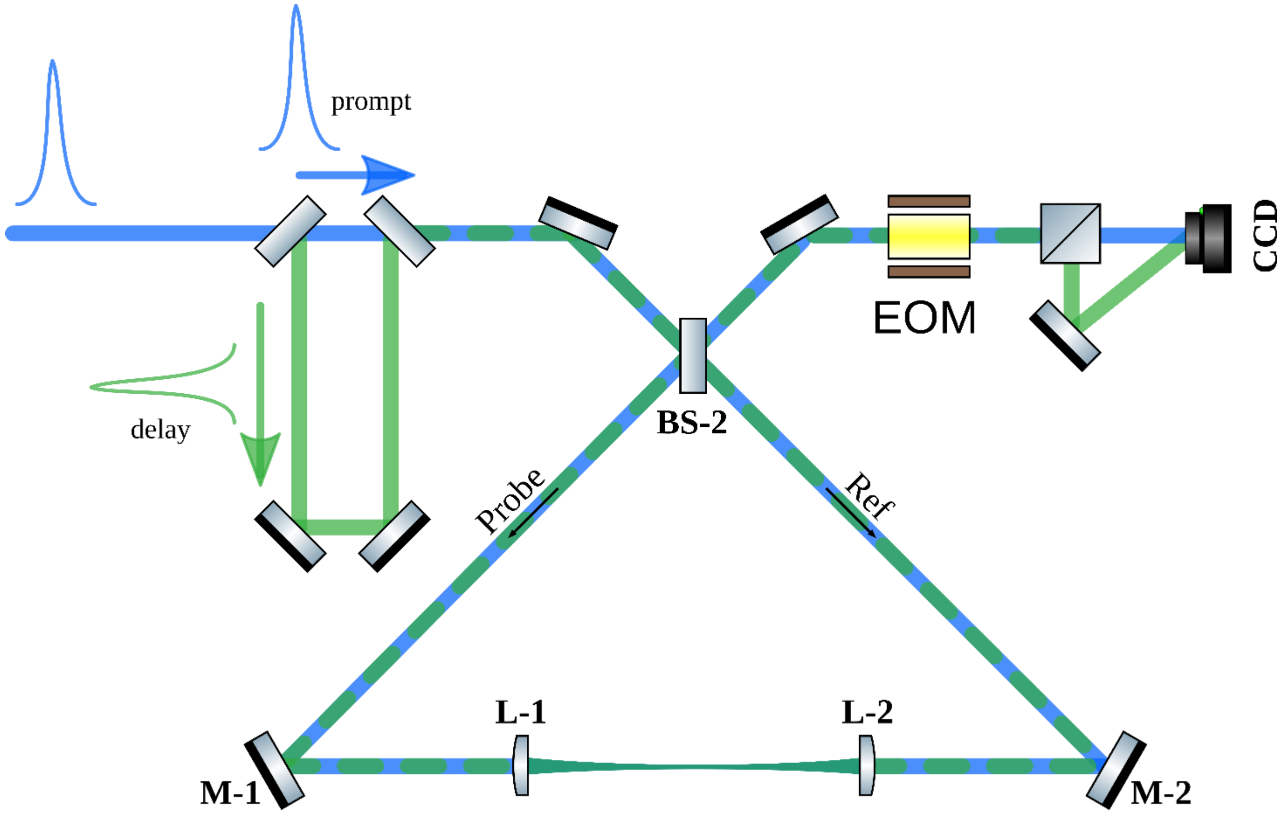
- **Suppression of the beampointing fluctuations by monitoring the back-reflection positions but still far from the shot noise !** : $\sigma_y = 800\ nm$ versus ${\sigma_y}^{SN} = 10\ nm$.

- **Residual noise : phase noise fluctuations induced by the mechanical vibrations of the interferometer**

HFPNS : High Frequency Phase Noise Suppression

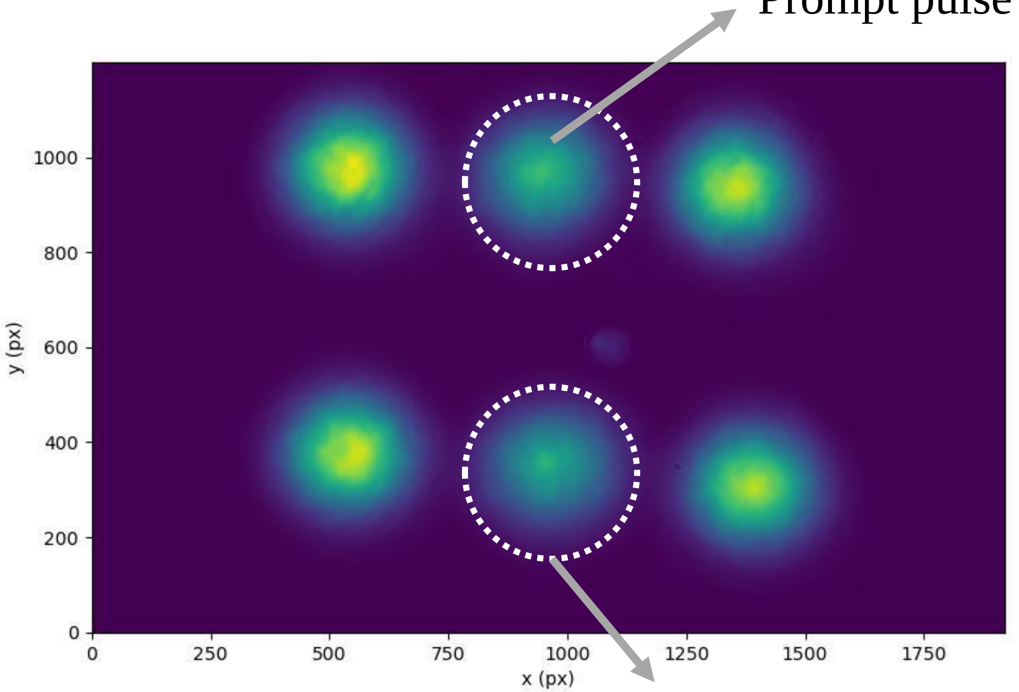
➢ **Synchronous phase noise suppression**:

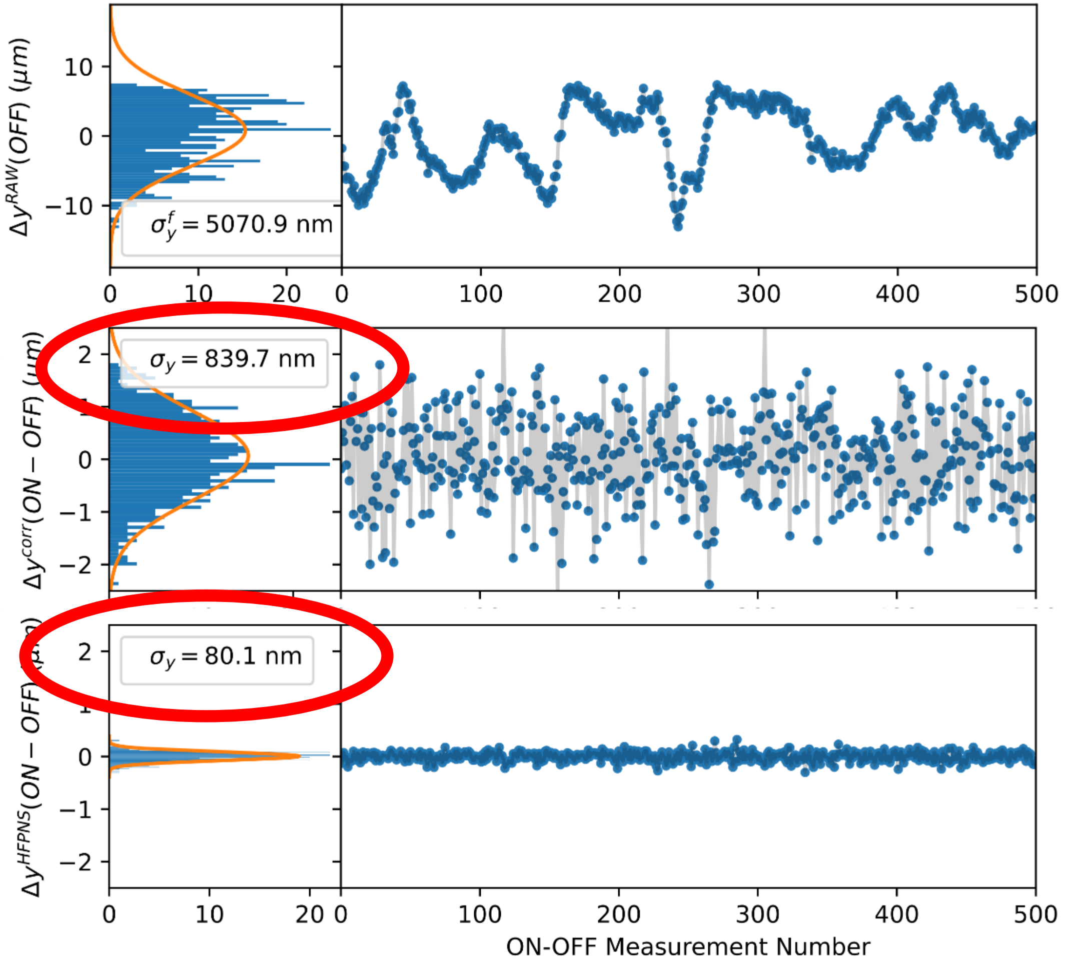
- Two incident probe pulses delayed by ~ 5 ns
- Delayed pulse is not refracted by the pump and is used to measure ~ simultaneously the phase noise
- Similar to the beam pointing suppression



HFPNS method was proposed two years ago, and it is now further developed as part of Ali Aras' PhD research, yielding already impressive results !

HFPNS : High Frequency Phase Noise Suppression





Preliminary results of HFPNS show improvement of the spatial resolution of one order of magnitude : results will be published soon

What next ?

Reach the GOAL VALUES (R&D) :

- **Reduction of the phase noise of the interferometer : Still one order of magnitude missing !**

- **Validation of a new beamsplitter with improved features** $\Rightarrow R_{AR} < 10^{-6}$ **to work at** $\mathcal{F} \approx 5 \times 10^{-6}$

- **Reduction of the beam size of the probe in the interaction area from** $w_0 = 25$ µm to $w_0 = 5$ µm .

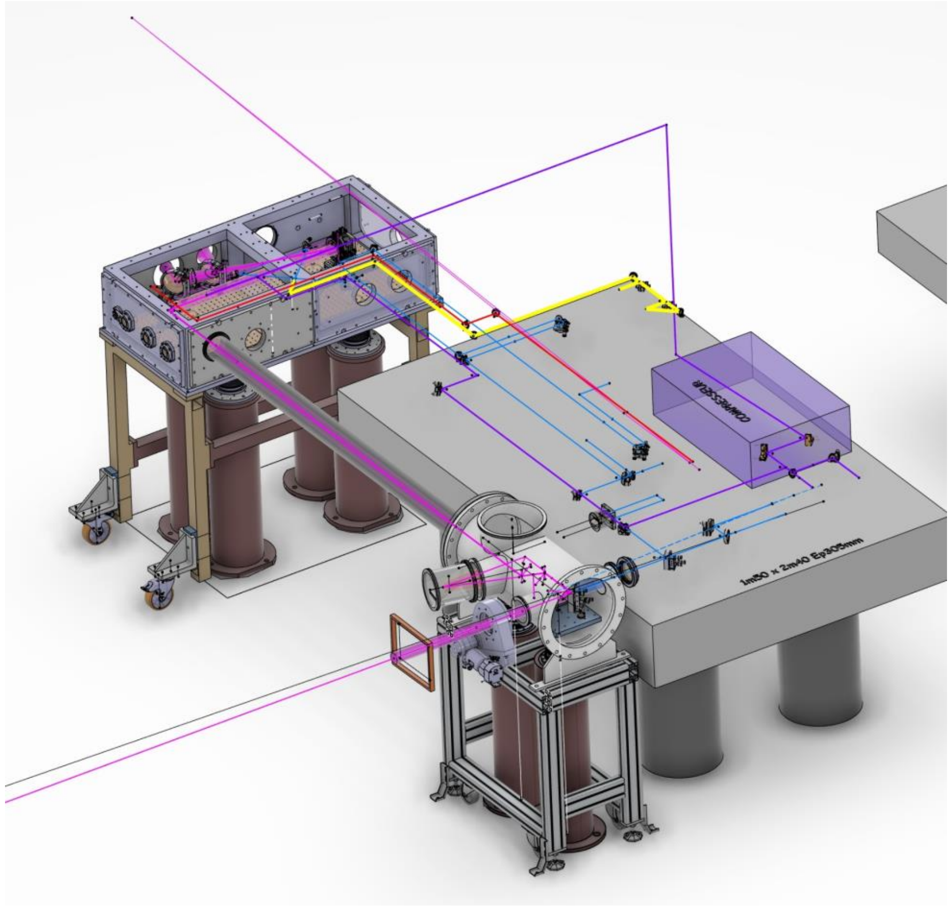
$\Rightarrow$ Increase the transverse size of the incident beam entering in the interferometer & work at 400 nm.

ERC-STARTING GRANT "Ultimate-DeLLight" submitted last October with the aim of achieving the GOAL VALUES sensitivity !

What next ?

Start the experiment in vacuum:

- **Installation of the FINAL DeLLight experiment in the new room funded by IJCLab**



What next ?

Start the experiment in vacuum:

- **Start measurement (in the end of 2025) in vacuum with co-propagating pump and prob pulses to measure the background coming from possible signal of the plasma.**

- **First DeLLight measurement in vacuum with LASERIX** (2 Joules, ~10^{20} W/cm^2**) from 2026 to 2030.**

- **DeLLight measurement in new generation laser facilities**

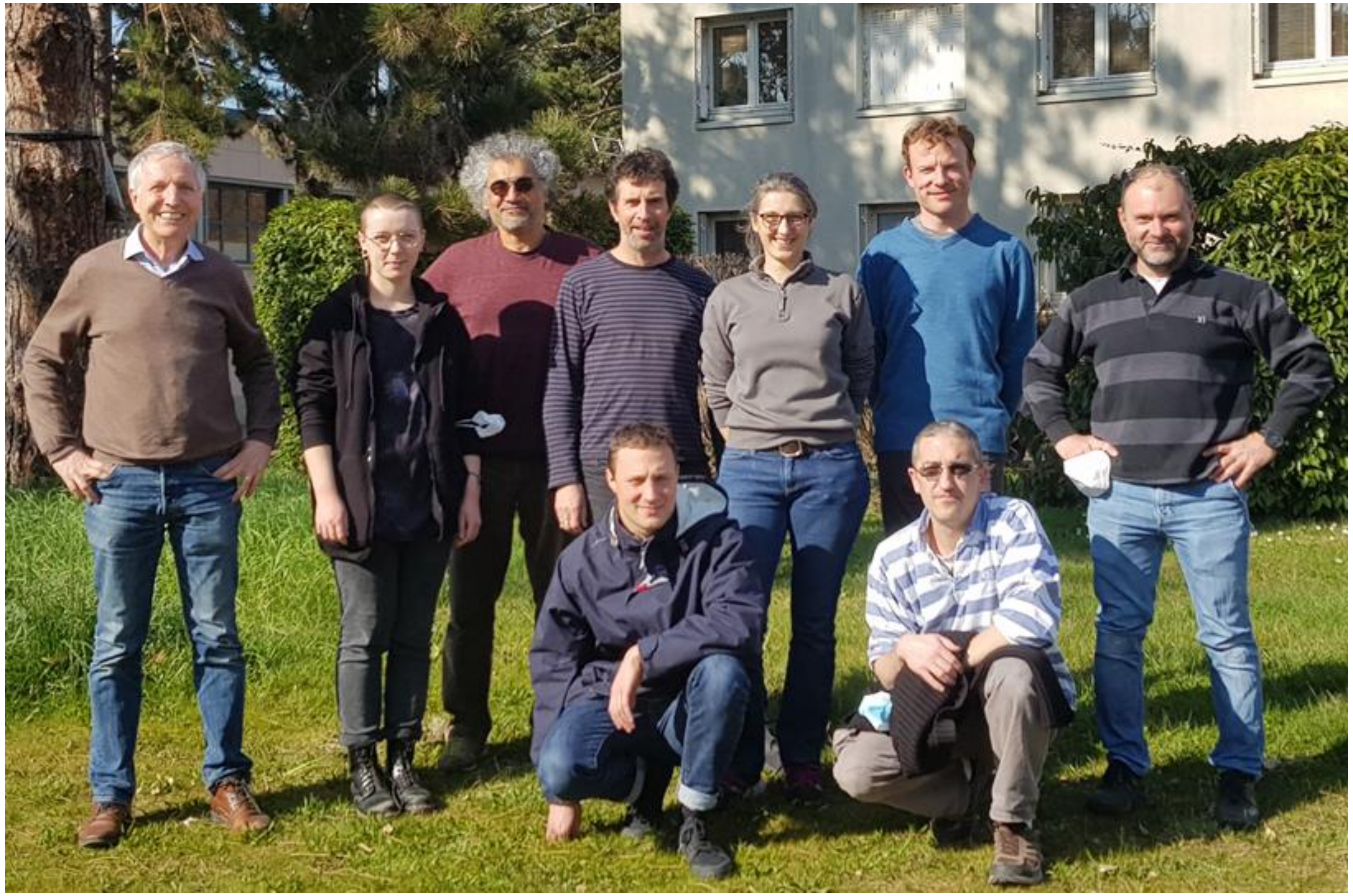
  APOLLON (180 J, 0.1 Hz rep. rate) ⇒ Expected signal: $\Delta y \sim 1$ nm

  ⇒ **Expected sensitivity: 1 sigma within ~ 30 minutes**

Conclusions

- A positive measurement would demonstrate that the speed of light in vacuum can be reduced, in the classical sense of the term on a macroscopic scale, in the presence of intense fields.
- Chalenging project but no showstopper identified so far.
- New collaborators are welcome (needed) !

The DeLLight/LASERIX group @ IJCLab



DeLLight group

- Ali Aras (PhD) since April 2023
- Adrien Kraych (postdoc) since Nov. 2021
- Aurélie Maillet (former PhD) (2019- 2023)
- Scott Robertson (former postdoc) (2018 – 2021)
- François Couchot (CNRS)
- Xavier Sarazin (CNRS)

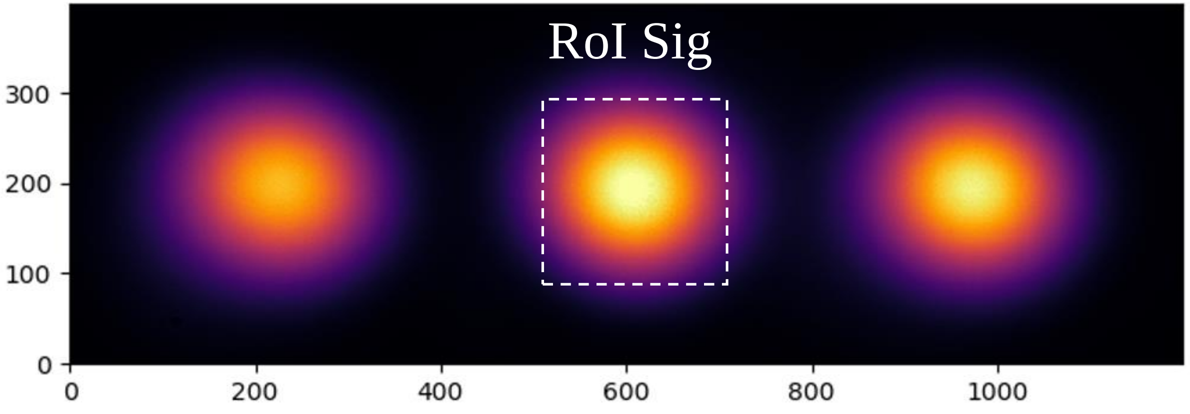
LASERIX

- Elsa Baynard
- Moana Pitmann

BACKUP

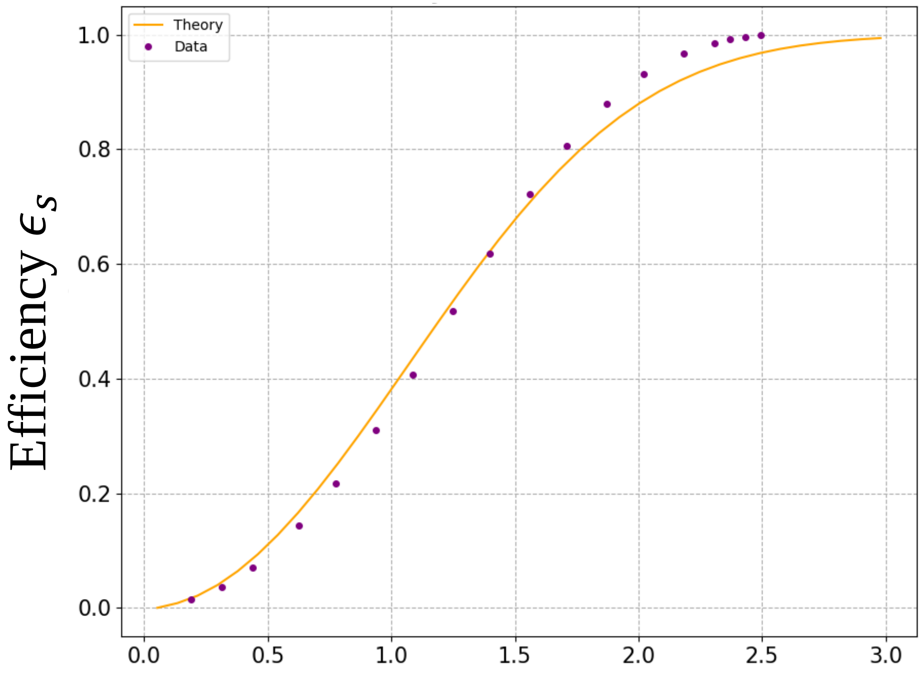
Calculation of the barycenters

Barycenters calculated inside a Region of Interest (RoI)



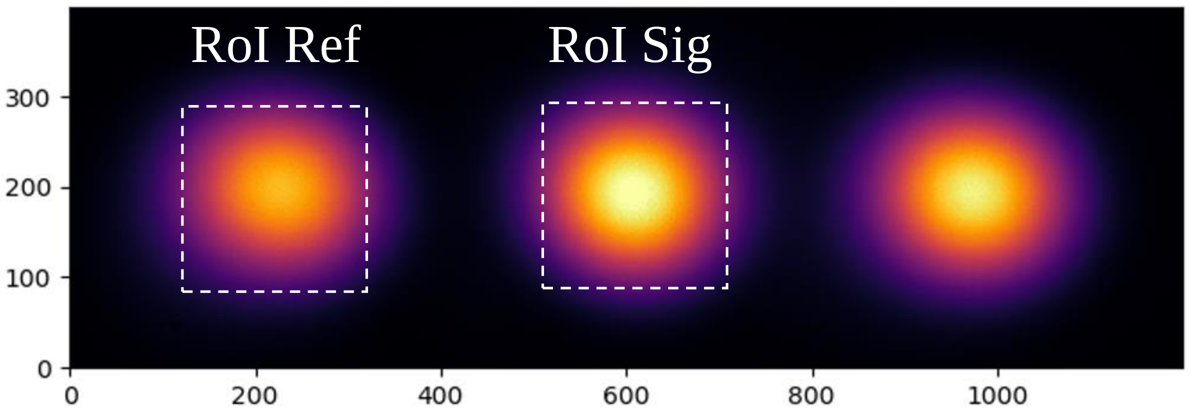
The measured displacement Δy_{mes} depends on the size of the RoI

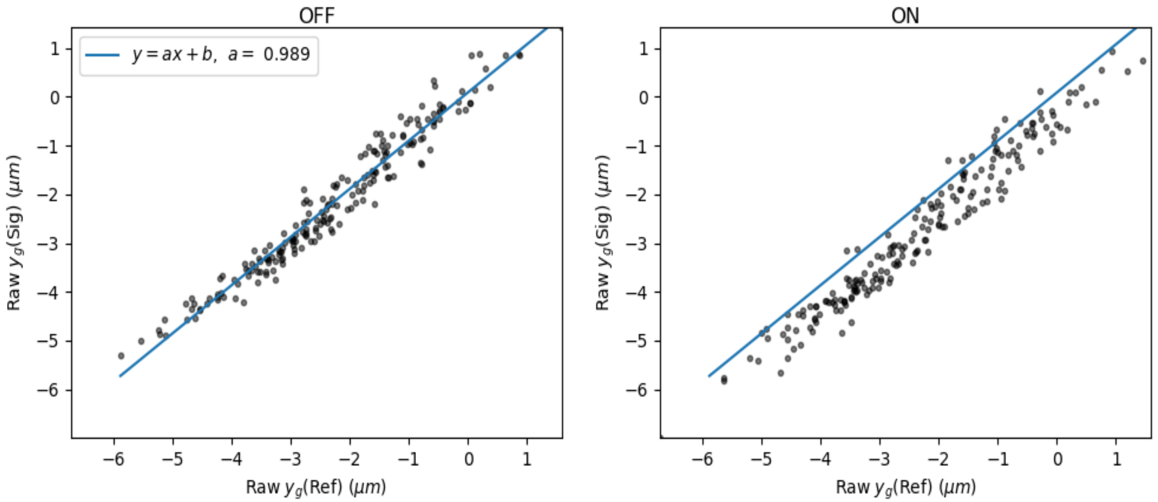
$$\epsilon_s = \frac{\Delta y_{mes}}{\Delta y_{real}} = f(RoI\_size)$$

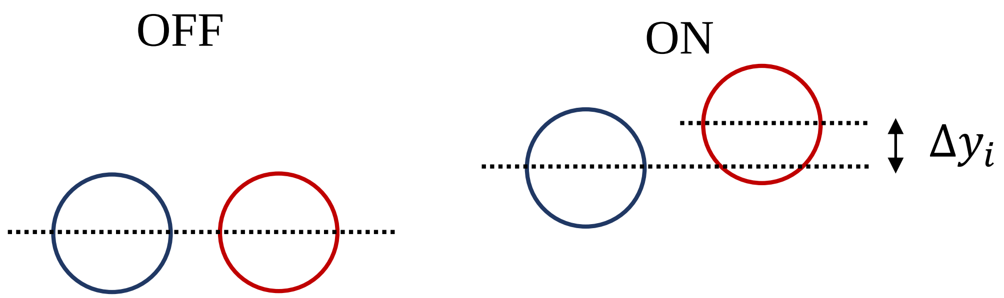


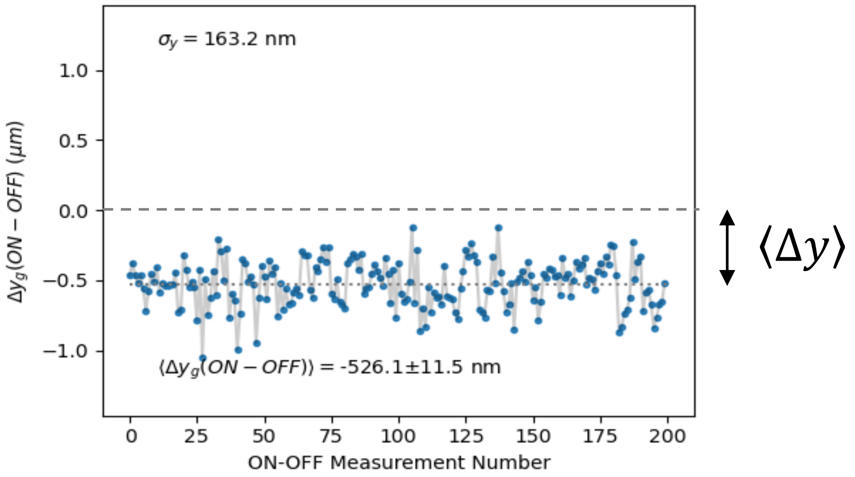
Suppression of the beam pointing fluctuations

Suppression of the beam pointing fluctuations by monitoring the back-reflection positions

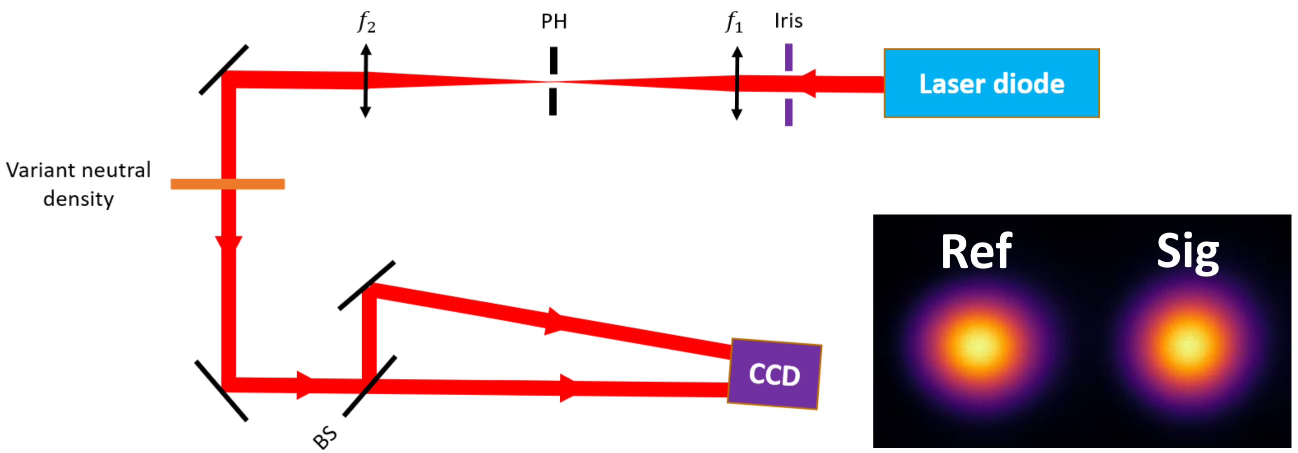






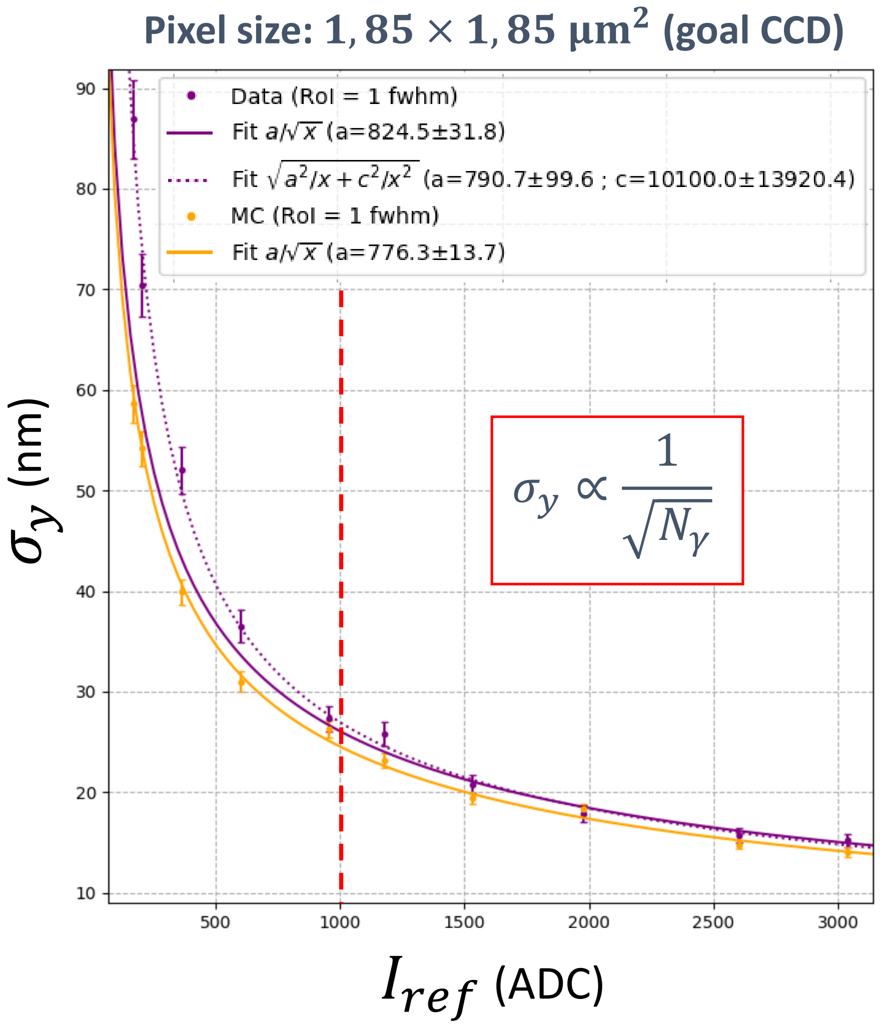


Shot Noise for the CCD Cameras



Shot noise: inherent quantum noise (stat. fluctuations) of the number of detected photons

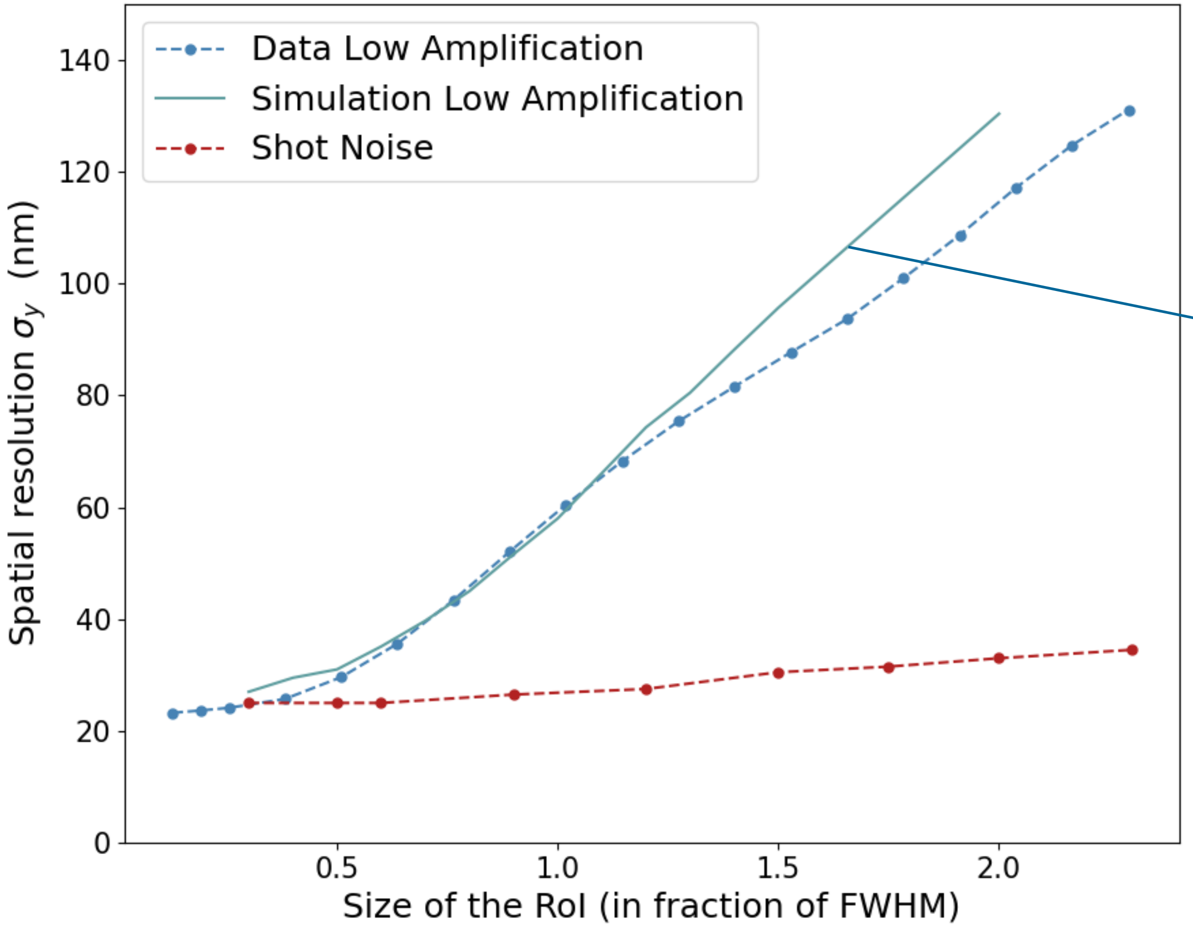
- **Current CCD** (pixel size: 5.86×5.86 µm^2): $\boldsymbol{\sigma_y \simeq 30}$ **nm**
- **Best CCD** (pixel size: 1.85×1.85 µm^2): $\boldsymbol{\sigma_y \simeq 13}$ **nm**



Spatial resolution

The spatial resolution is degraded when increasing the RoI-size

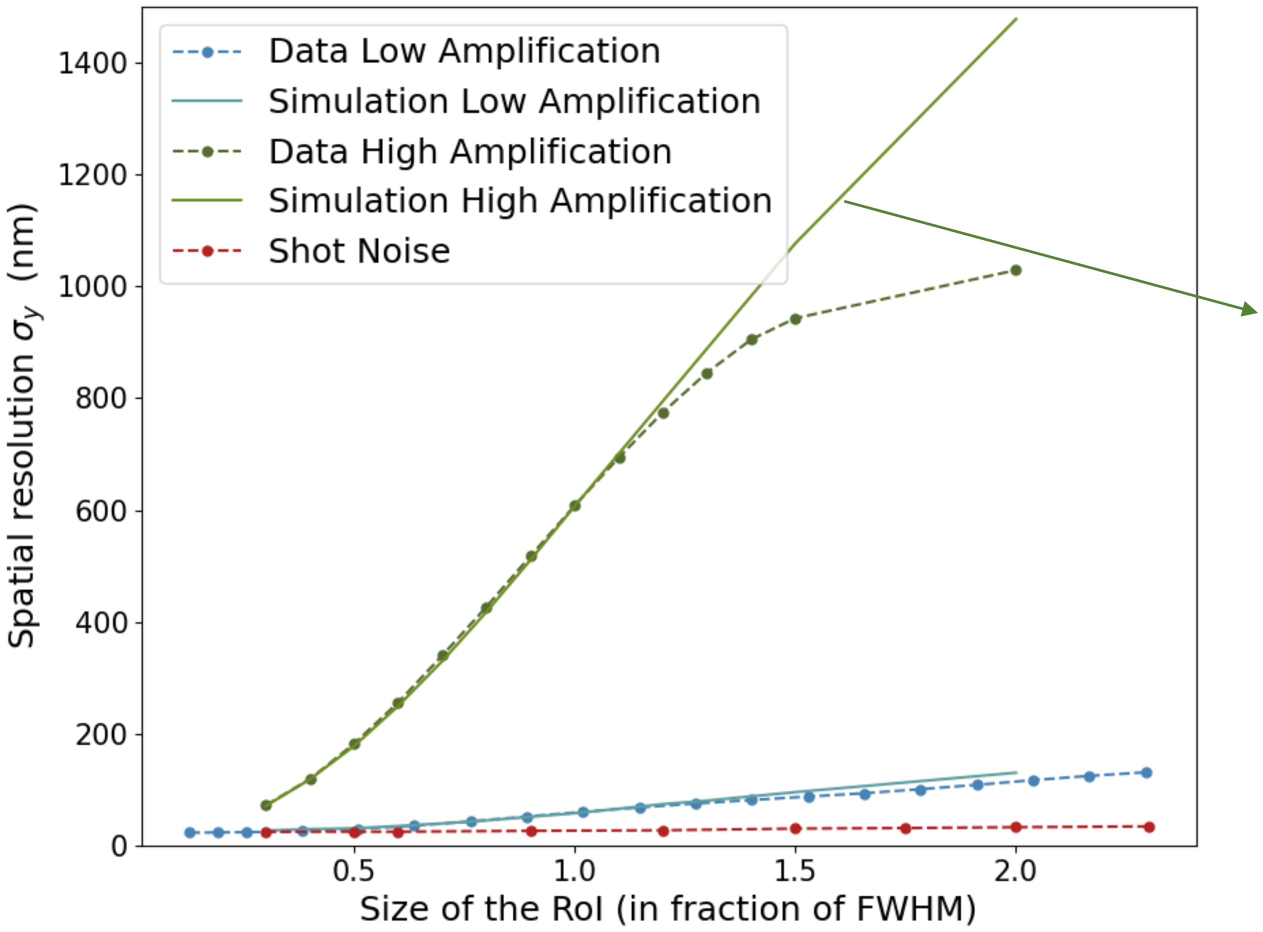
$\Rightarrow$ Limited by mechanical vibration of the interferometer



MC simulation
$\delta\theta \sim 50$ nrad (r.m.s.)

Spatial resolution

The spatial resolution is degraded in the high amplification regime due to the amplification of the mechanical noise…



MC simulataion
$\delta\theta{\sim}70$ nrad (r.m.s.)
Amplification $\mathcal{A} = 25$

Measurement of the DeLLight signal in air

Deflection Signal as a function of the **impact parameter *b***

$$I_{OFF}(y) = \delta a^2 \times I_{in}(y) + \left(\delta\phi(y)\right)^2 \times I_{in}(y)$$

$$I_{ON}(y) = \delta a^2 \times I_{in}\left(y + \mathcal{A} \times \boldsymbol{\delta y(b/b_{opt})}\right) + \left(\delta\phi(y) + \frac{\boldsymbol{\delta\psi(b/b_{opt})}}{2}\right)^2 \times I_{in}(y)$$

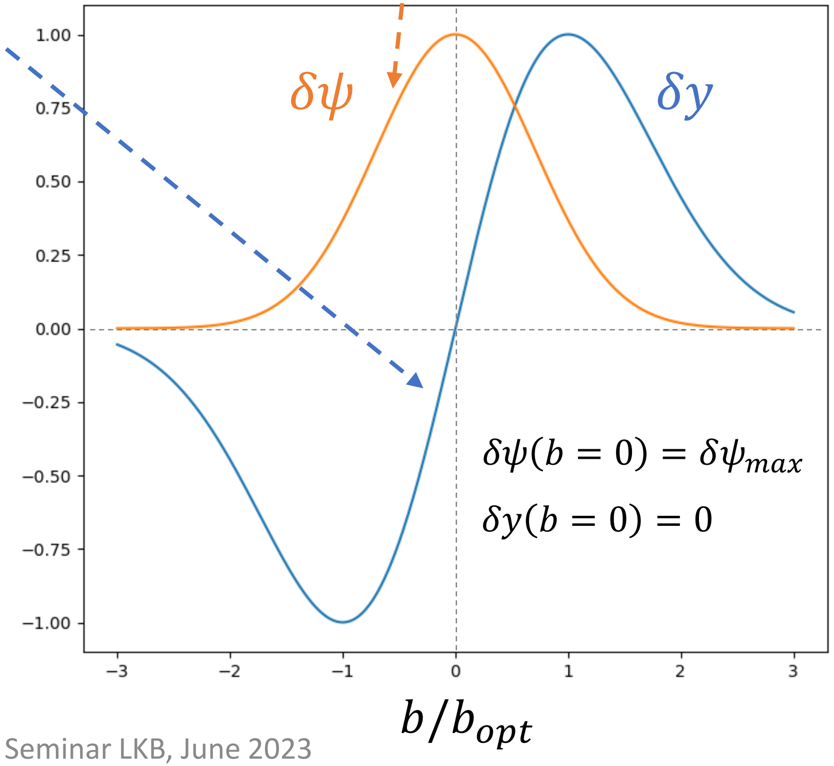
Deflection ***Deceleration***

Deflection Δy:

$$\Delta y = \frac{\delta y}{2\,\delta a} = \mathcal{A} \times \delta y$$

Effective deflection $\widetilde{\Delta y}$:

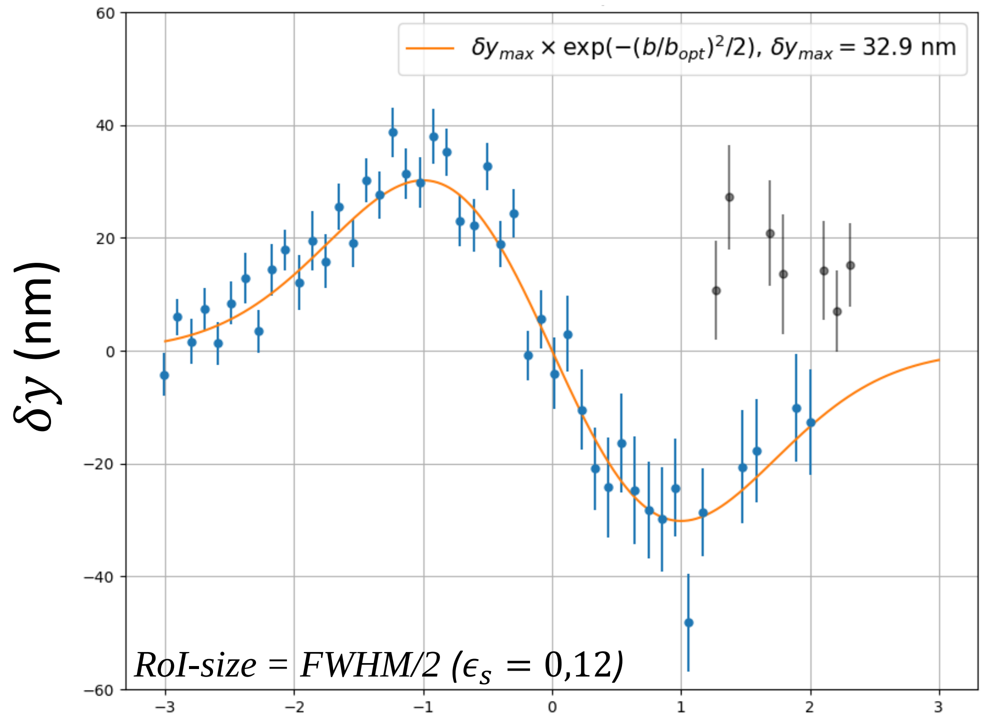
$$\widetilde{\Delta y} = \langle I_{ON}(y)\rangle_y - \langle I_{OFF}(y)\rangle_y$$



Measurement of the DeLLight signal in air

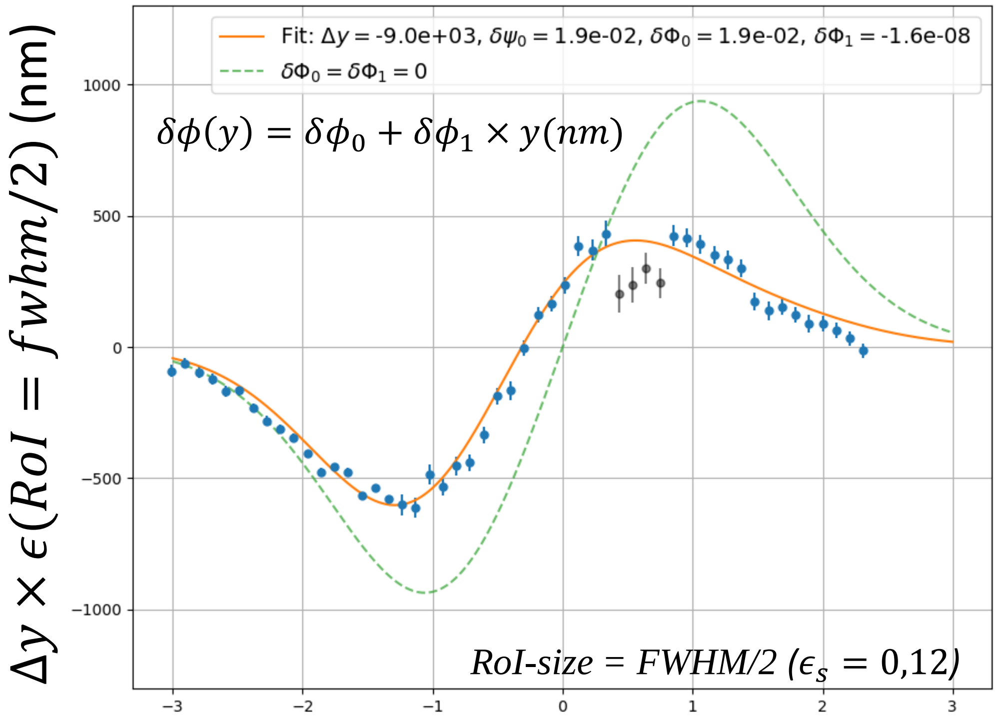
$$I_{ON}(y) = \underbrace{\delta a^2 \times I_{in}\left(y + \mathcal{A} \times \boldsymbol{\delta y(b/b_{opt})}\right)}_{\textit{Deflection}} + \underbrace{\left(\delta\phi(y) + \frac{\boldsymbol{\delta\psi(b/b_{opt})}}{2}\right)^2 \times I_{in}(y)}_{\textit{Deceleration}}$$

Direct deflection $\delta y = f \times \delta\theta$



Impact parameter b/b_{opt}

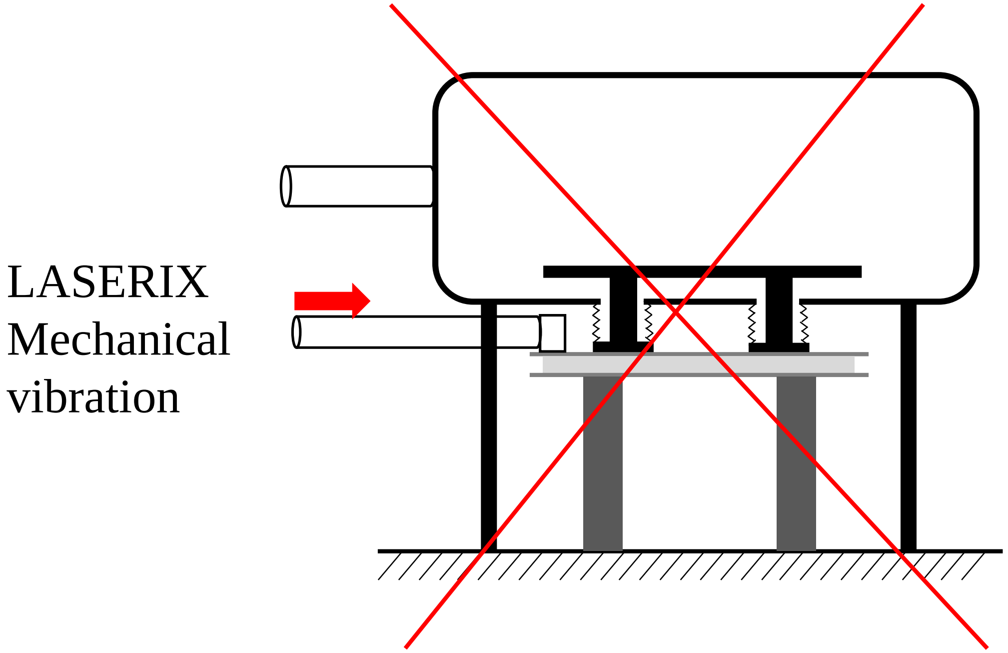
Amplified deflection $\Delta y = \mathcal{A} \times \delta y$

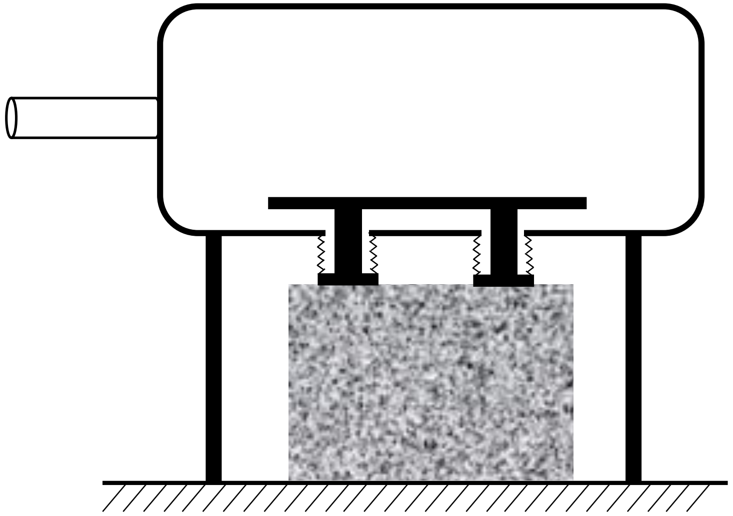


Impact parameter b/b_{opt}

Mechanical noise must be reduced by a factor 100 to reach the shot noise

- ➢ **Improve mechanical isolation**





FOCUS ON THE TERM « MACROSCOPIC » !

PHOTON –PHOTON SCATTERING (Particle Physics Experiment)

- Collisions of High-energy gamma photon with several laser photons at SLAC in 1997.

  D. L. Burke *et al*, Phys. Rev. Lett 79, 1626 (1997)

- High energy gamma-gamma pair emission from virtual gamma-gamma scattering in Pb-Pb collisions at LHC (2017-2019)

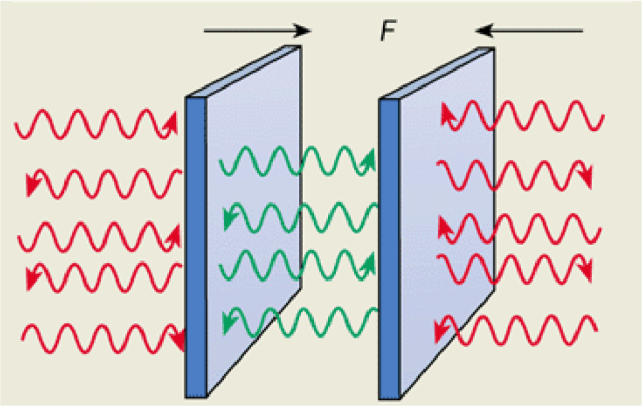
  ATLAS Collaboration, Nat. Phys. 13, 852 (2017)

  CMS Collaboration, Phys. Lett. B 797, 132826 (2019)

- No modification to the electromagnetic constants of the vacuum.

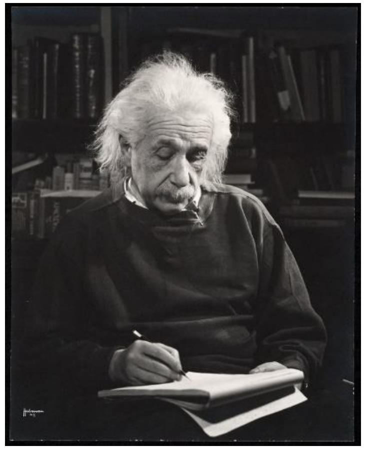
Optical nonlinearity of the vacuum (Optical Experiment)

- A direct manifestation of the optical nonlinearity of the vacuum resulting to a modification of the electromagnetic constants.
- Macroscopic phenomena similar to the Casimir effect:



Nonlinear electrodynamics in vacuum

(2) Never for a classical optical wave : a coherent phenomenon corresponding to a pure undulatory process at large scale and treated classically in the long-wavelenght limite



« I think that der liebe Gott could not have created the world in such fashion that a magnetic field would be unable to influence the velocity of light » A. Einstein

Attempts to make observations over the last century :