DeLLight

(Deflection of Light by Light)

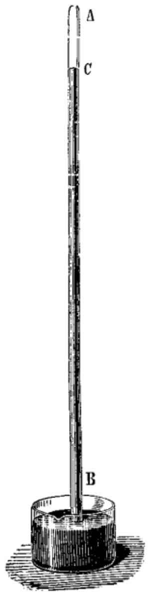
with LASERIX @ IJCLab

Slowing down the light in vacuum with intense laser pulses

Xavier Sarazin, Seminar given at Subatech (Nantes), January 2024

Light and Vacuum

- **Torricelli**: Vacuum is transparent ⇒ Light propagates in vacuum



- **Maxwell**: vacuum is filled with electrical charges and currents

  ⇒ Maxwell's equations are **linear** in vacuum

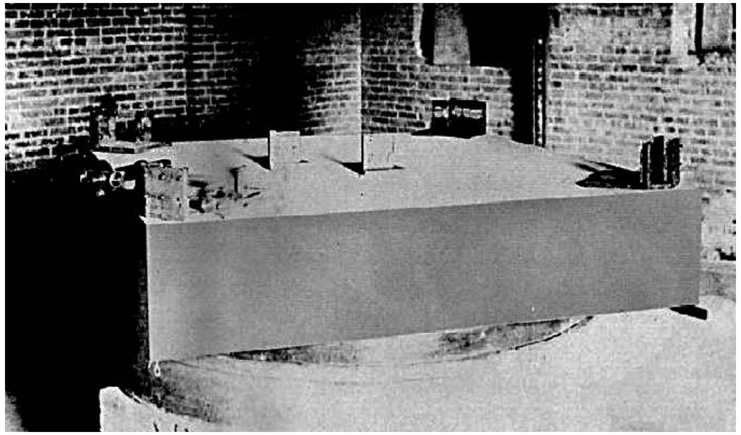
$$\begin{cases} \mathbf{D} = \varepsilon_0 \mathbf{E} \\ \mathbf{B} = \mu_0 \mathbf{H} \end{cases} \qquad c = \frac{1}{\sqrt{\varepsilon_0 \mu_0}}$$

➡ **c, ε_0 and μ_0 are UNIVERSAL CONSTANTS**

- **Morley-Michelson** : No Galilean motion relative to light

  ⇒ The **speed of light is constant in galilean reference systems**

  ⇒ Vacuum is not a standard medium (ether)

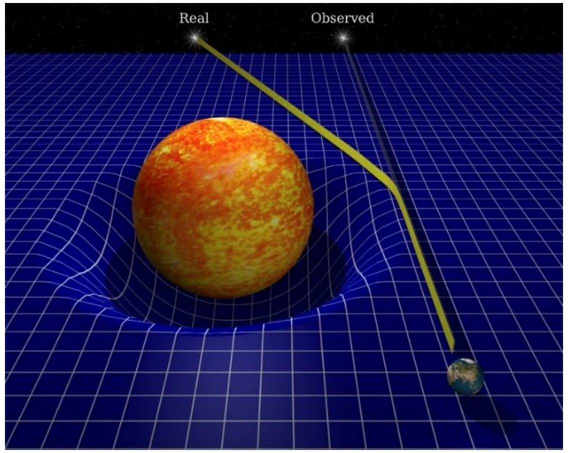


Light and Vacuum

- **Einstein** : The **speed of light is reduced in an accelerated frame** (gravitation field)

https://einsteinpapers.press.princeton.edu/vol2-trans/266 (1907); Ann. der Physik 35, 898 (1911); Ann. der Physik 38, 1059 (1912)

$$c \to c \times \left(1 + \frac{\Phi}{c^2}\right) \quad \Rightarrow \quad \Delta n(\text{vacuum}) \propto \frac{\Phi}{c^2}$$

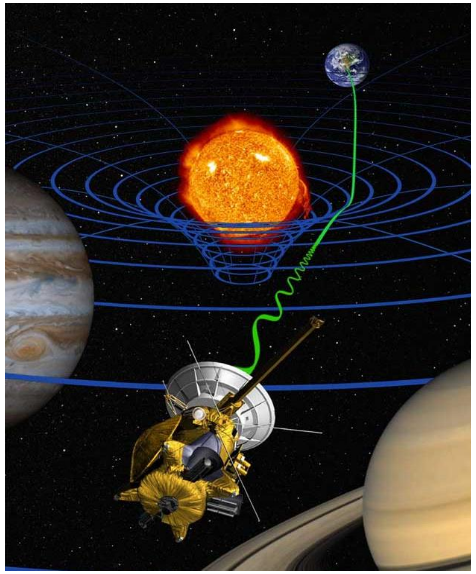


- Einstein introduces of a ***curved spacetime metric to maintain « c=constante »***

  ⇒ General Relativity is a ***geometric theory***

  ⇒ **Vacuum is *empty***: vacuum has no physical role anymore

- **Deflection of light first observed by Eddington in 1919**



- **Shapiro effect:** time delay induced by a « decrease of the speed of light »

__Because__, according to the general theory, __the speed of a light wave depends on the strength of the gravitational potential__ along its path, these time delays should thereby be increased by almost 2×10^{-4} sec when the radar pulses pass near the sun.

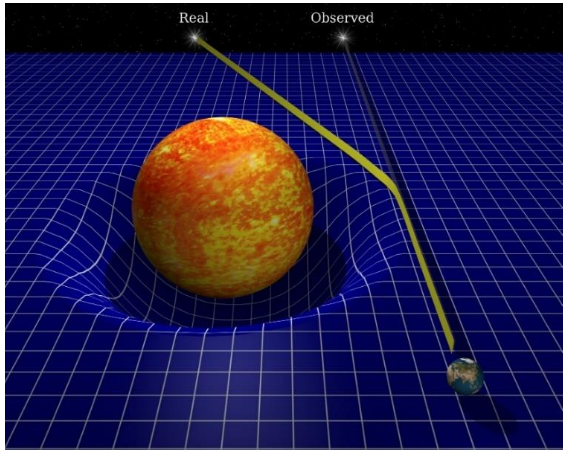
I. Shapiro, PRL 13, 26, 789 (1964)

Light and Vacuum

- **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 the vacuum optical index *n* (and the inertial mass *m*) by the gravitational potential**



$$\begin{cases} n(r) = \left(1 - \dfrac{2\Phi}{c_\infty^2}\right)^{-1} \approx 1 + \dfrac{2GM}{rc_\infty^2} \\ m(r) = m_\infty \times n^{3/2}(r) \quad \text{(to preserve the equivalence principle)} \end{cases}$$

- **Vacuum optical index $n(r)$ formally identical to 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* $\varepsilon_0 = \mu_0 = 1/\sqrt{g_{00}}$*"*

Light and Vacuum

Cosmology in a static Euclidean flat metric with
a vacuum optical index increasing with time

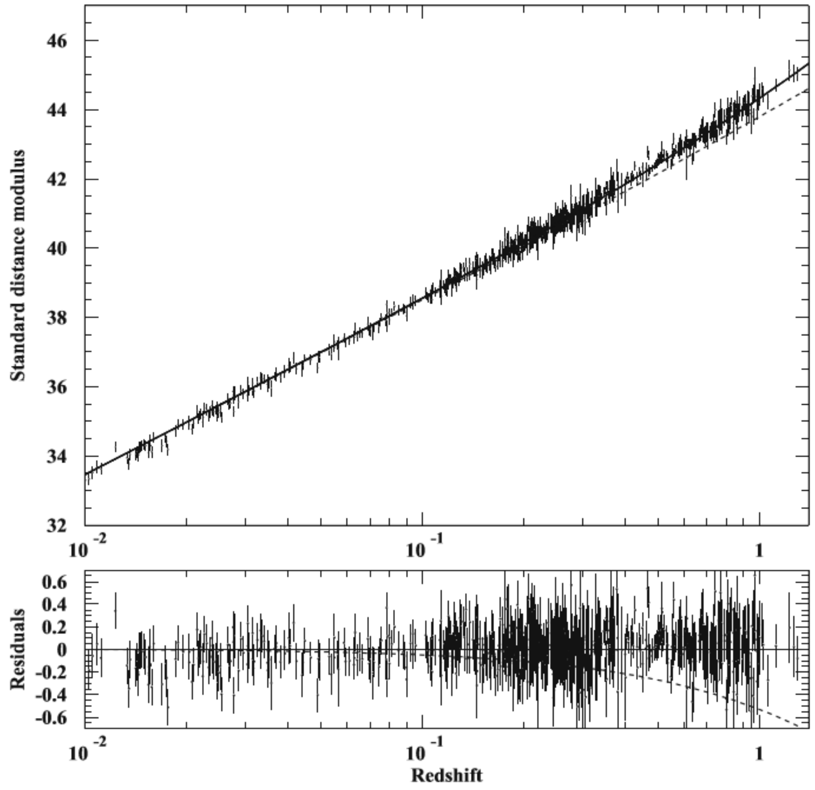
Hubble cosmological redshift due to a time variation of both $n(t)$ and inertial masses

SN-Ia data are well fitted by an exponantial variation of the vacuum optical index:

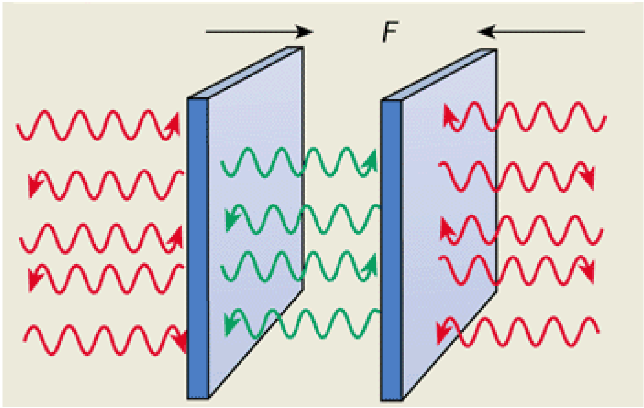
$$n(t) = e^{t/\tau_0}$$

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

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



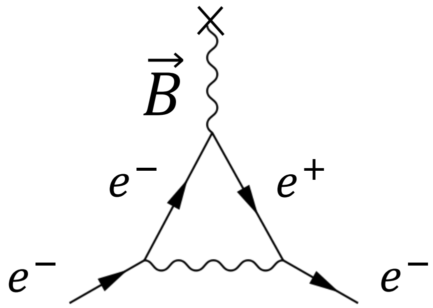
Light and Vacuum

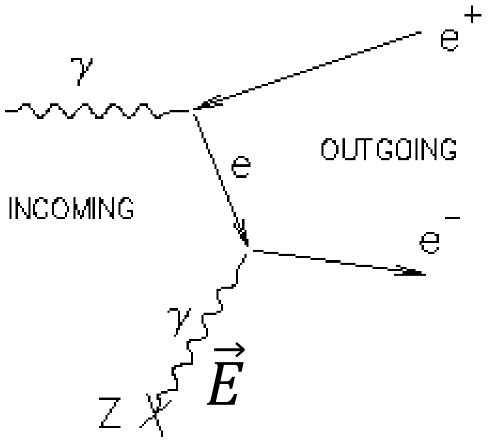


- **Quantum electrodynamics (QED)**:

The vacuum is filled by quantum fluctuations of the zero-point e.m. fields and e^+/e^- virtual pairs

- ✓ Casimir force
- ✓ Modified spontaneous emission in a quantum vacuum cavity
- ✓ Anomalous magnetic moment: $g-2=\frac{\alpha}{2\pi}$ *(Schwinger, 1951)*
- ✓ e^+/e^- pairs emitted from vacuum …





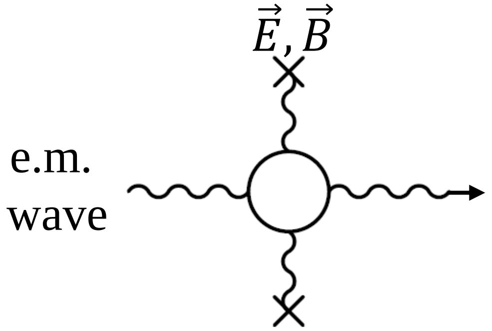
Nonlinear electrodynamics in vacuum

A not so well-known QED prediction:

Optical nonlinearity in vacuum induced by the coupling of the e.m. field with the e^+/e^- virtual pairs

Schwinger (1951)

Predicted initially by Euler and Heisenberg (1936) within the Dirac see model



$c \Rightarrow c(E^2, B^2)$

Maxwell's equation in vacuum are not linear:

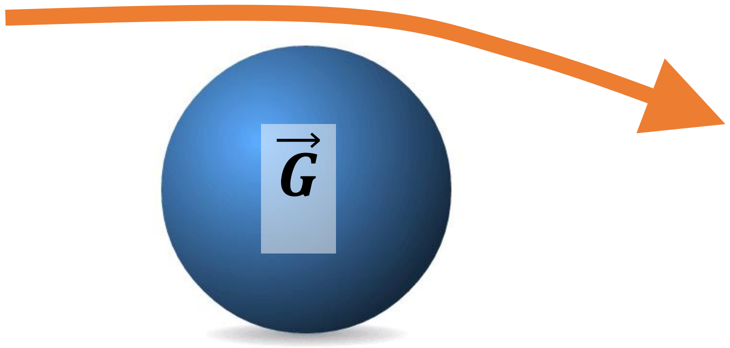
$$\begin{cases} \mathbf{D} = \varepsilon_0 \boldsymbol{E} + \boldsymbol{P} \\ \mathbf{B} = \mu_0 \boldsymbol{H} + \mathbf{M} \end{cases} \quad \text{with} \quad \begin{cases} \mathbf{P} = \xi \varepsilon_0^2 [(E^2 - c^2 B^2)\mathbf{E} + 7c^2(\mathbf{E}.\mathbf{B})\mathbf{B}] \\ \mathbf{M} = -\xi \varepsilon_0^2 c^2 [(E^2 - c^2 B^2)\mathbf{B} - 7(\mathbf{E}.\mathbf{B})\mathbf{E}] \end{cases}$$

$\xi^{-1} \approx 3\ 10^{29}$ J/m^3

Nonlinear electrodynamics in vacuum

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

Vacuum and Gravitation



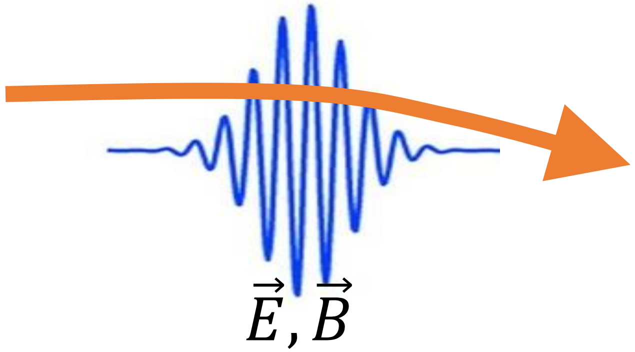
General Relativity

Vacuum is empty and replaced by an effective curvature of the space-time

The role of the quantum vacum is absent

Is it the origin of dark matter and dark energy ?

Vacuum and Electrodynamics



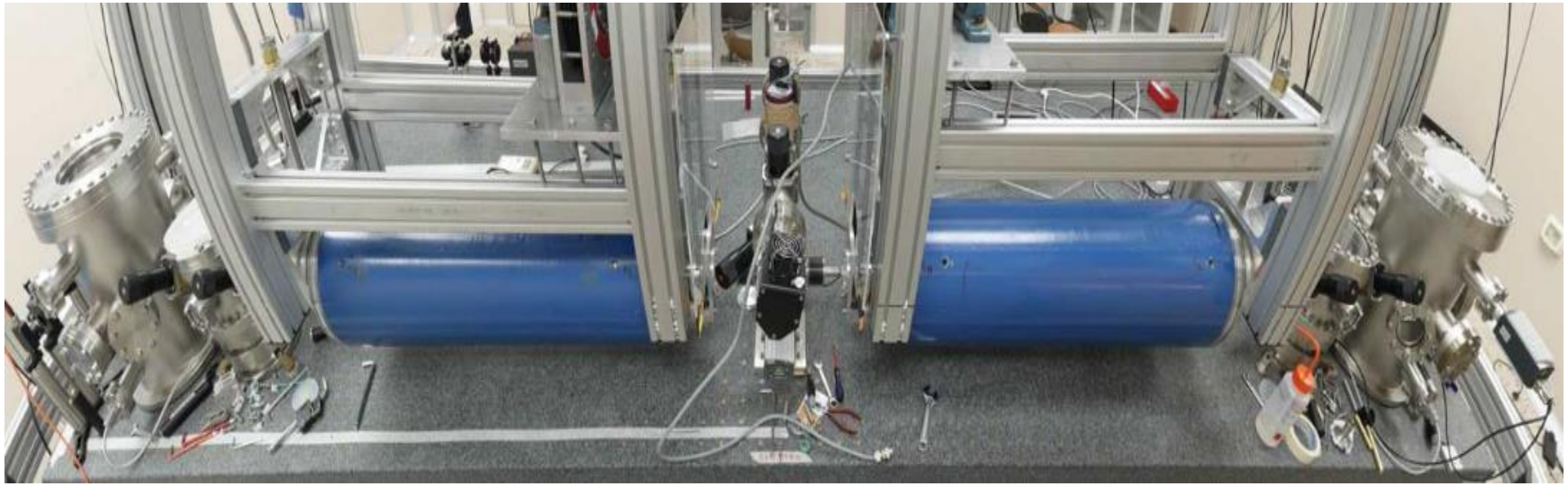
QED

ε_0, μ_0 and c are modified at macroscopic scale by the polarisation of e+/e- pairs in vacuum

Never observed experimentaly

Current experimental tests: Vacuum Magnetic Birefringence

- Search for vacuum birefringence induced by an external continuous magnetic field
- Use a Fabry-Perot cavity with a transversal external B field $\Rightarrow$ search for a polarisation rotation
- Best sensitivity achieved by **PVLAS** [*Physics Reports 871 (2020) 1–74*]
  - **Sensitivity must be improved by a factor 35 in order to measure a signal at 5σ in 100 days**
  - Limitations: magnetic field (B ~ 2.5 T) and birefringence of the mirrors



The DeLLight Experiment

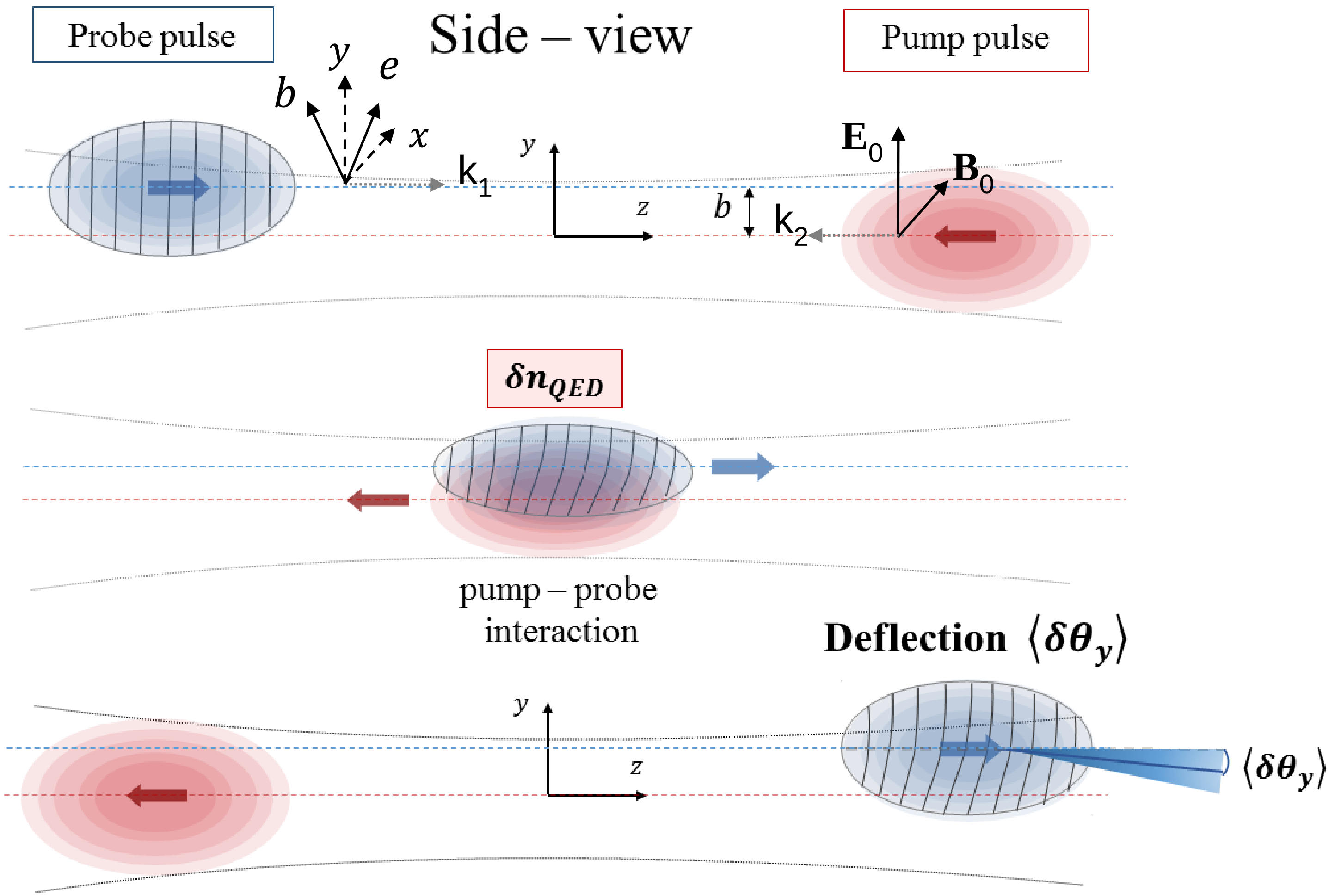
DeLLight with intense laser fields

DeLLight uses highly focused intense laser pulses
produced by LASERIX @ IJCLab
to achieve strong fields

$$\left\{ \begin{array}{l} 2.5\ \text{J} \\ 30\ \text{fs} \\ w_0 = 5\mu\text{m} \end{array} \right. \quad \Rightarrow \quad \left\{ \begin{array}{l} \text{I} \sim 2 \times 10^{20}\ \text{W/cm}^2 \\ \boldsymbol{E \sim 3 \times 10^{13}\,\mathrm{V/m}} \\ \boldsymbol{B \sim 10^{5}\ \mathrm{T}} \end{array} \right.$$

DeLLight with intense laser fields @LASERIX

Use highly focused laser pulses to achieve strong fields



Pump specifications (*LASERIX*)

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

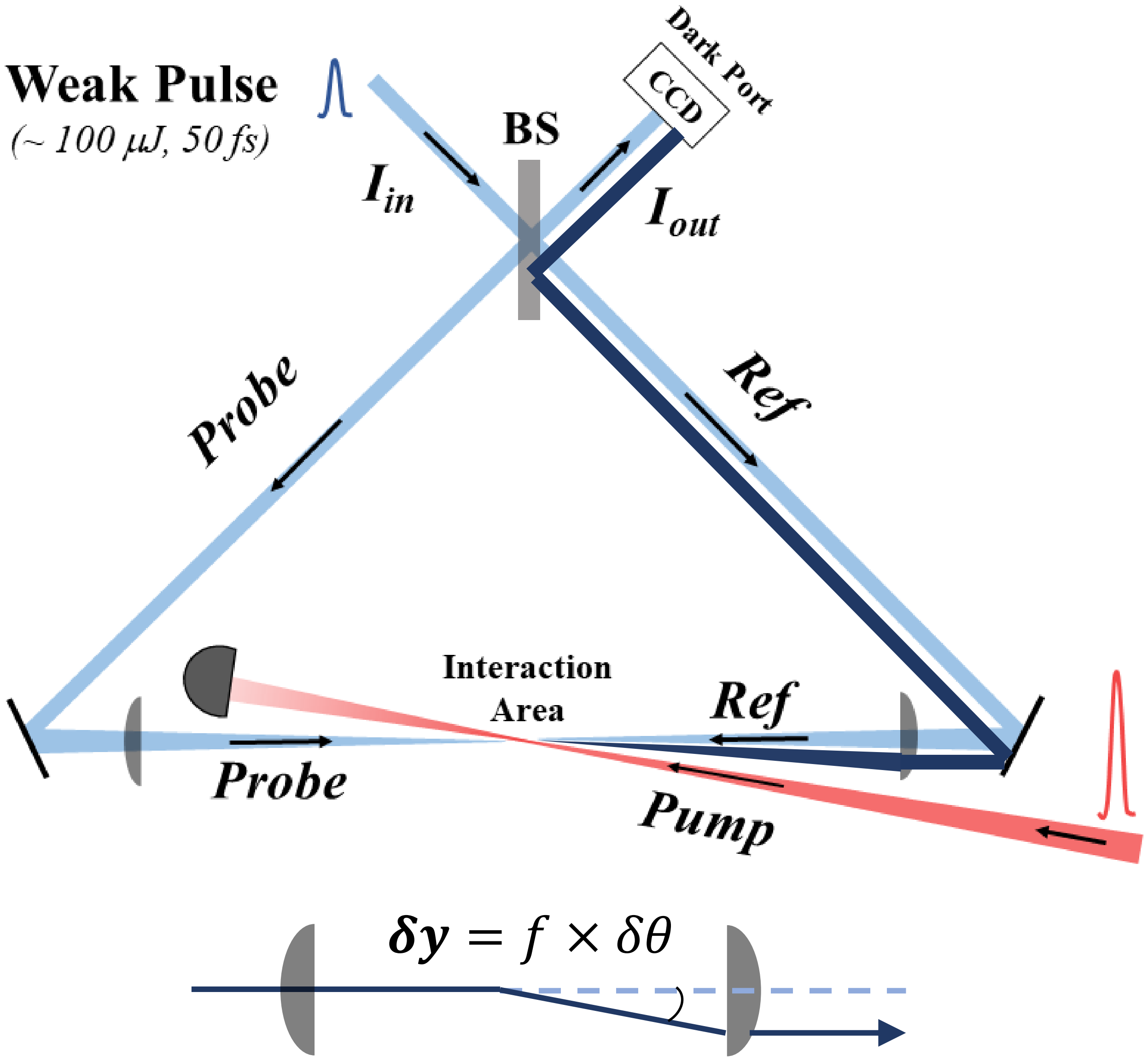
$\Rightarrow I_{pump} \sim 2 \times 10^{20}$ W/cm^2

$\Rightarrow B \sim 10^5$ T

$\delta n \sim 3 \times 10^{-13}$

$\delta\theta \sim 0.1$ prad

Refraction measured with a Sagnac Interferometer



- Extinction factor in the dark output

$$\Rightarrow \quad \mathcal{F} = \frac{I_{out}}{I_{in}}$$

- $\boldsymbol{\delta y}$ = Direct vertical shift of the probe inside the Sagnac
- $\boldsymbol{\Delta y}$ = Vertical shift of the interference intensity profile is **amplified** in the dark output (*Weak Value Amplification*)

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

- Amplification factor $\mathcal{A} = \pm \frac{1}{2\sqrt{\mathcal{F}}}$
- « *Up – Down* » measurements @ 5 Hz

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 $\theta_{tilt} \sim 10°$)

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

➡ $\Delta y \sim 15$ pm

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

➡ ON-OFF measurements @ 5 Hz

1 sigma sensitivity per $\sqrt{T_{obs}(days)}$ with LASERIX

Expected signal and sensitivity

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

- ✓ **Energy $E = 30$ J @ HAPLS laser (10 Hz repetition)**
- ✓ **Extinction** $\mathcal{F} = 4 \times 10^{-6}$ ($\mathcal{A} = 250$)
- ✓ **Waist at focus** $w_0 = W_0 = 5\ \mu\text{m}$
- ✓ **Spatial resolution** $\sigma_y = 10$ nm (CCD shot noise resolution)

➡ $\Delta y \sim 0.2$ nm

➡ ON-OFF measurements @ 5 Hz
1 sigma sensitivity within ~ 10 minutes with HAPLS

Expected signal and sensitivity

Expected signal:

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

- ✓ **Energy $E = $ 30 J @ HAPLS laser (10 Hz repetition)**
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- ✓ **Spatial resolution** $\sigma_y = 10$ nm (CCD shot noise resolution)

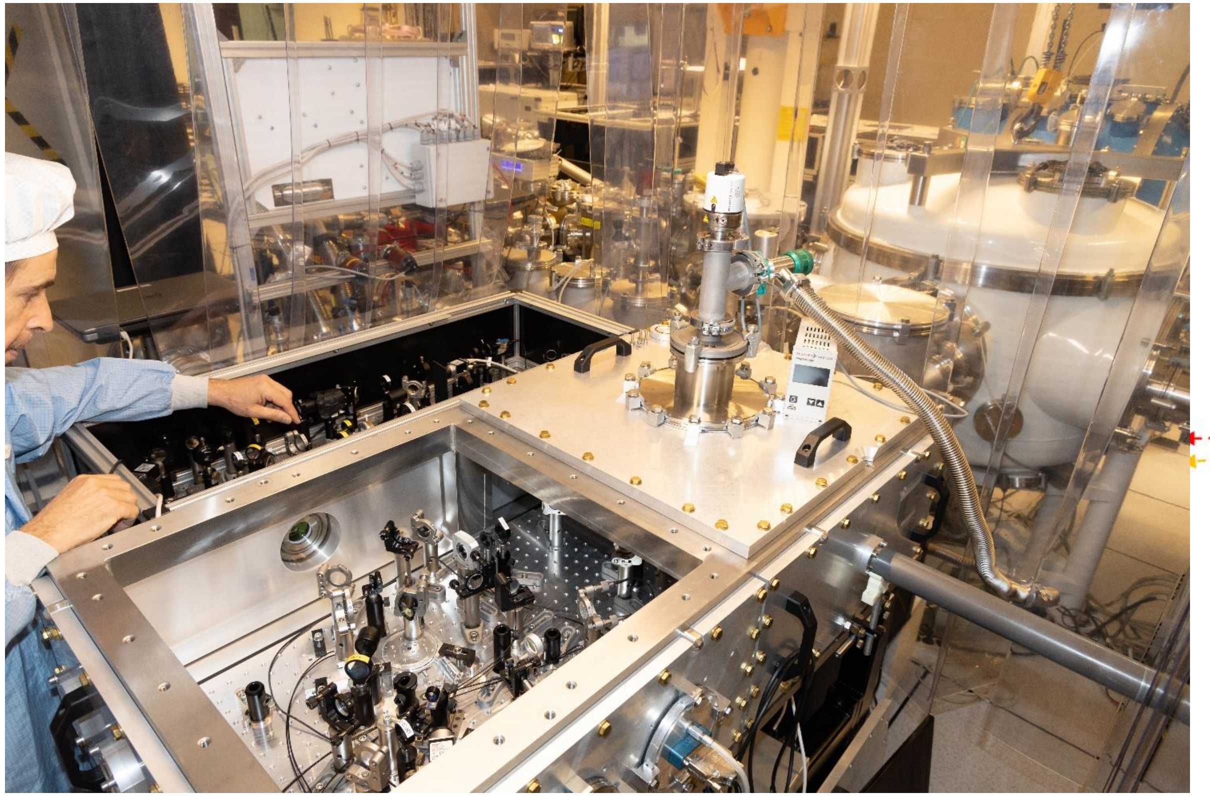
→ DeLLight pilot experiment

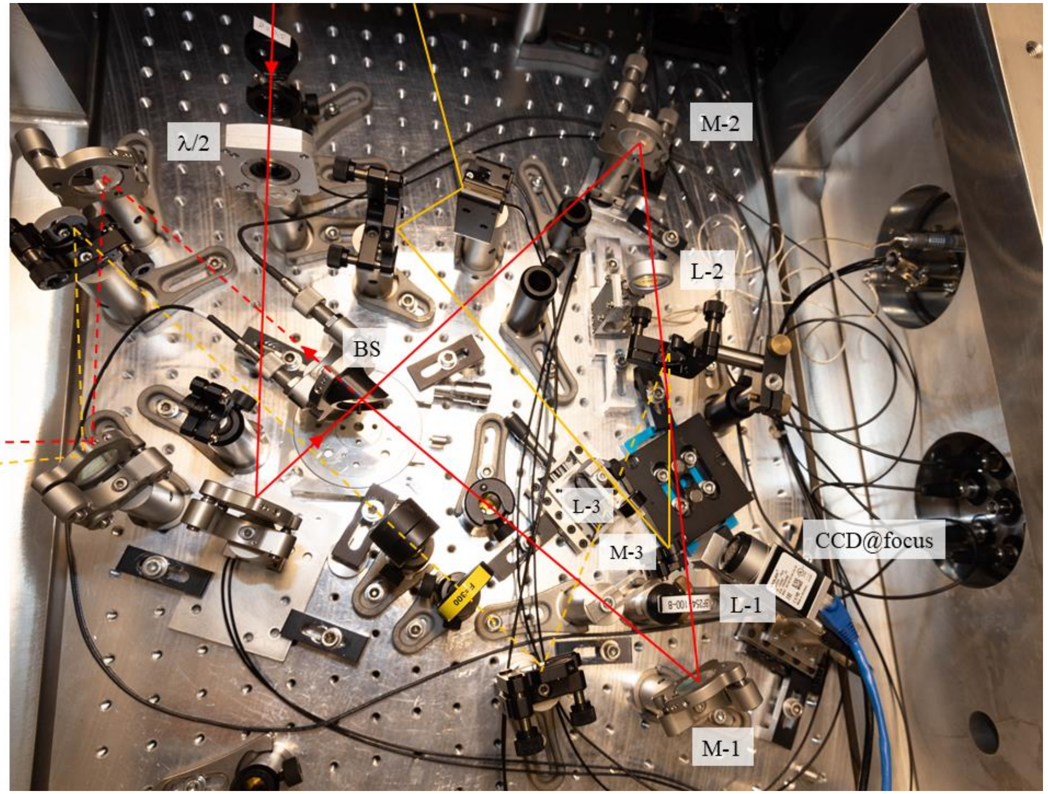
The DeLLight pilot experiment

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



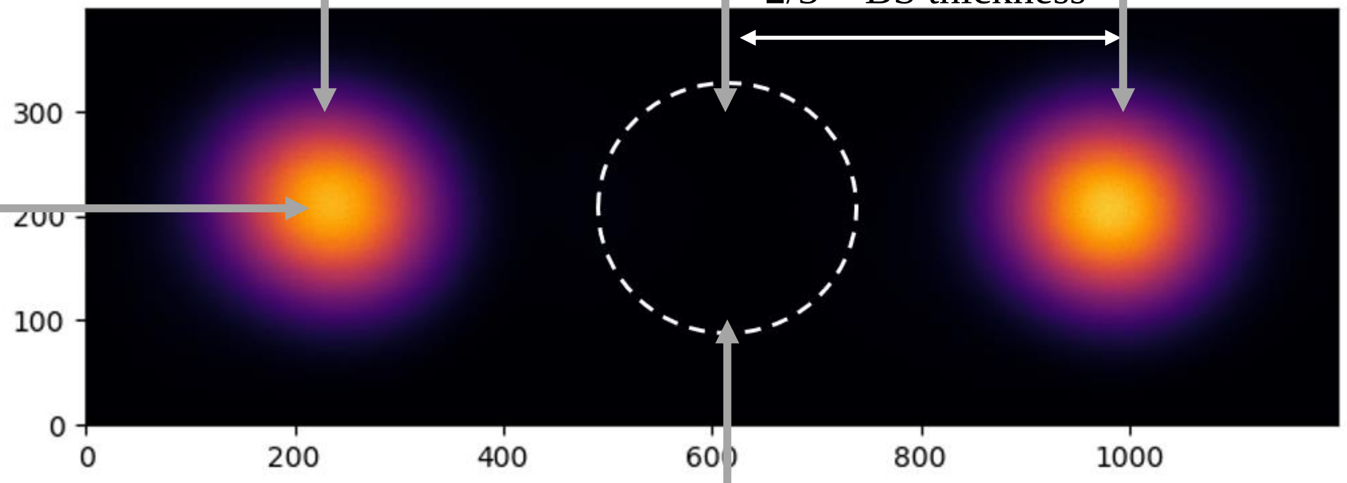


Extinction Factor

Extinction in the dark output

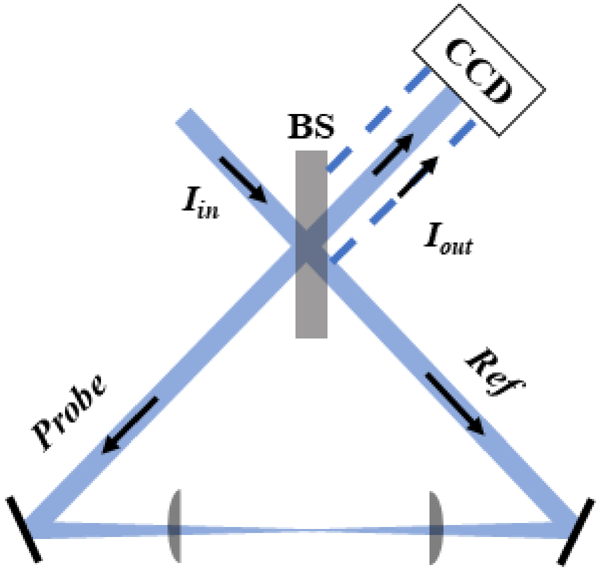
Back reflection **Signal** **Back reflection**

2/3 × BS thickness



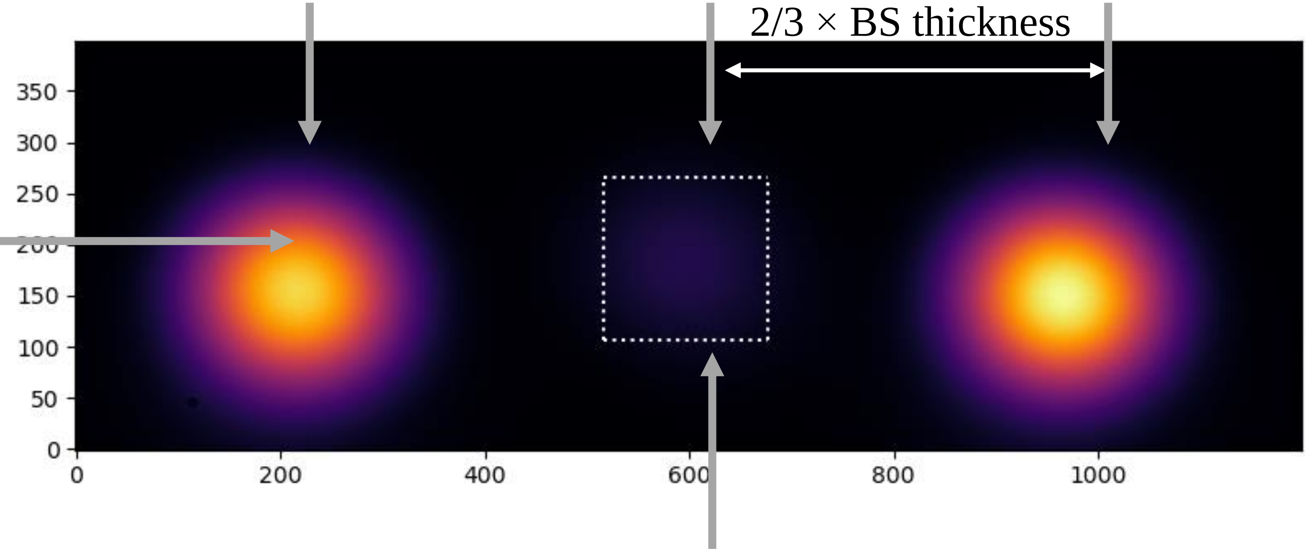
$\mathcal{F}_{AR} = R_{AR}/2$
$= 5 \times 10^{-4}$

$\mathcal{F} \approx 3 \times 10^{-6}$ with $\Delta\lambda \approx 5$ nm



$\frac{R}{T} = (50 \pm 0.1)\%$

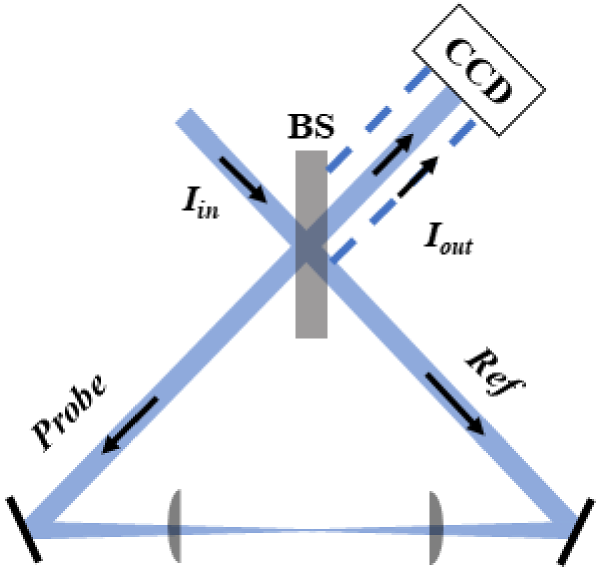
Extinction in the dark output



$$\mathcal{F}_{AR} = R_{AR}/2 = 5 \times 10^{-4}$$

$$\mathcal{F} \approx 5 \times 10^{-5} \text{ with full spectrum}$$

$$\frac{R}{T} = (50 \pm 0.35)\%$$



Development of a new **thicker** beamsplitter with $\boldsymbol{R}_{\mathbf{AR}} < \mathbf{10^{-4}}$ and $\boldsymbol{\mathcal{F}} < \mathbf{10^{-5}}$ **in full spectrum**

Extinction in the dark output

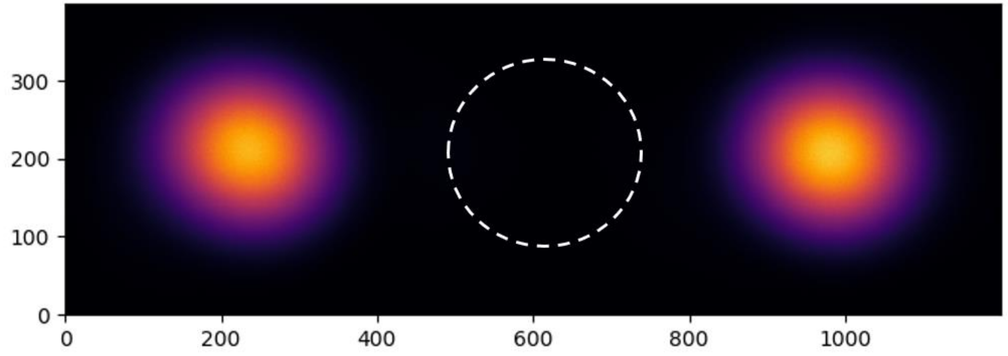
With the current beamsplitter, the extinction must be reduced in order to measure the interference signal

Small **rotation** (~1°) of the **beamsplitter**

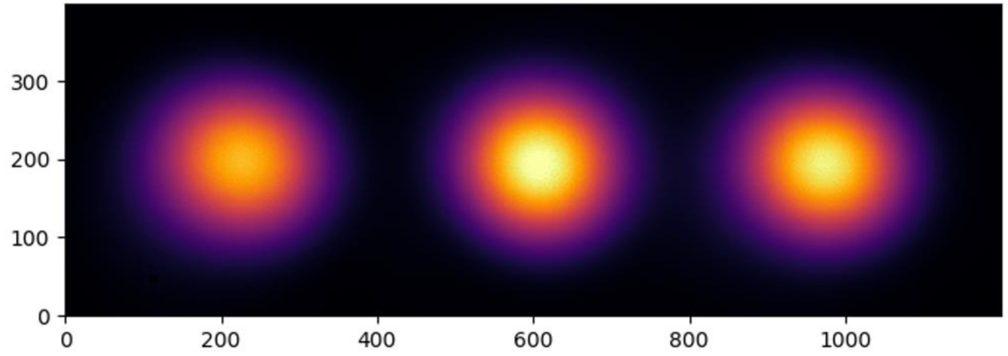
$\Rightarrow\ \boldsymbol{\mathcal{F} = 5 \times 10^{-4}}$

$\Rightarrow$ **Amplification factor** $\boldsymbol{\mathcal{A} = 25}$

$\mathcal{F} = 3 \times 10^{-6}$



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



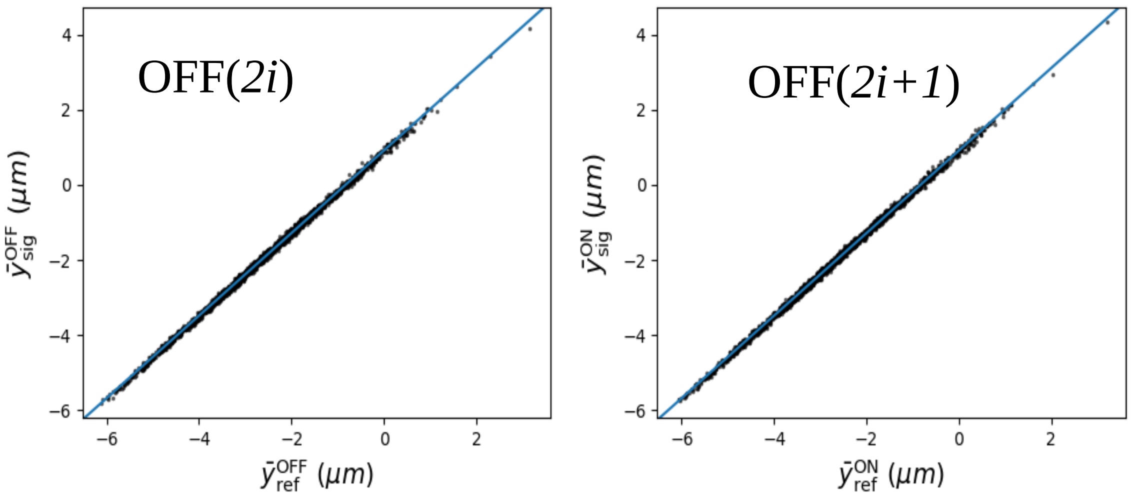
Spatial Resolution

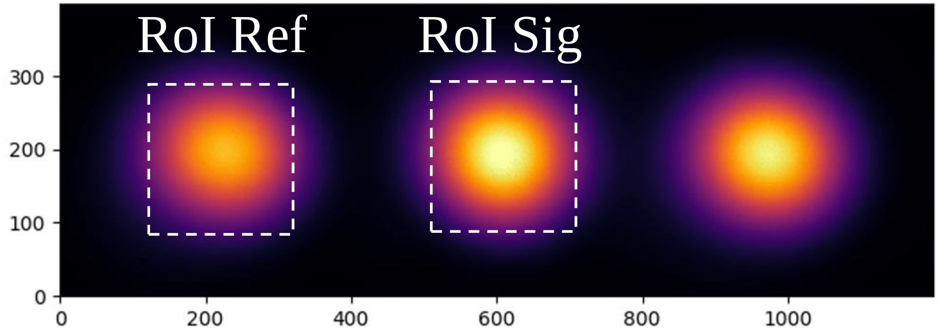
Spatial resolution in the dark output limited by:

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

Spatial Resolution: Beam Pointing Fluctuations

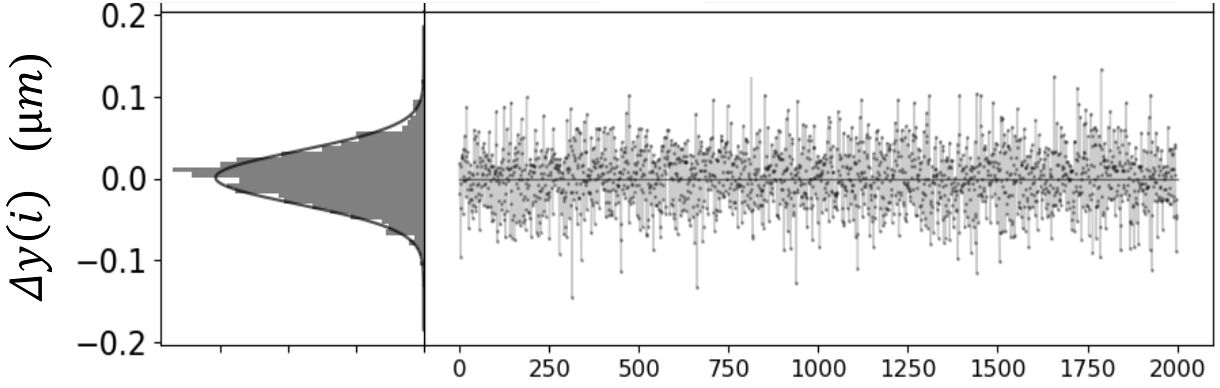
Dedicated "OFF-OFF" measurement at low amplification





4000 laser shots (~7 minutes)

$w_{RoI} = FWHM/2 \quad (\epsilon_s = 0.12)$

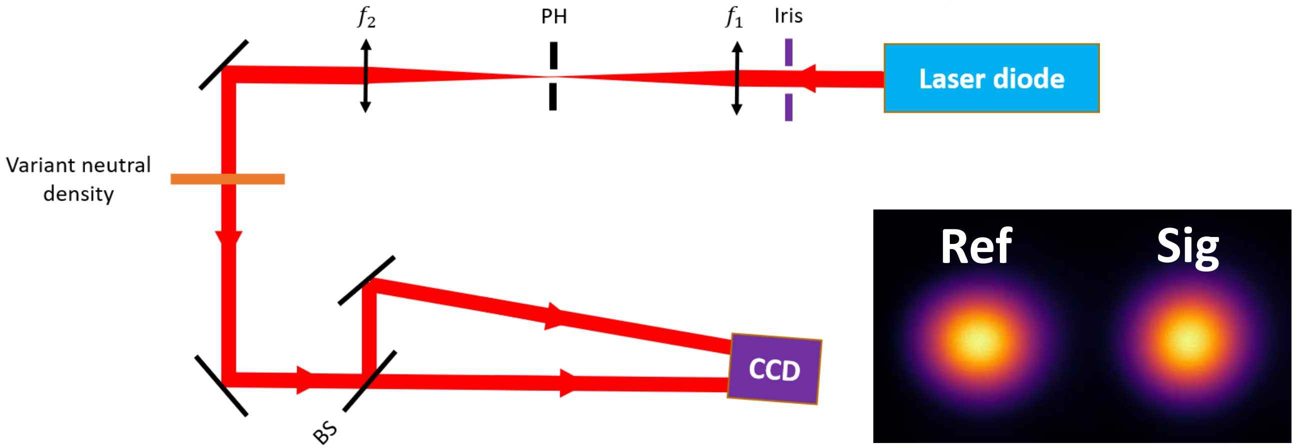


"OFF-OFF" measurement number *i*

Spatial Resolution: σ_y = 32.5 nm
→ limited by the CCD shot noise

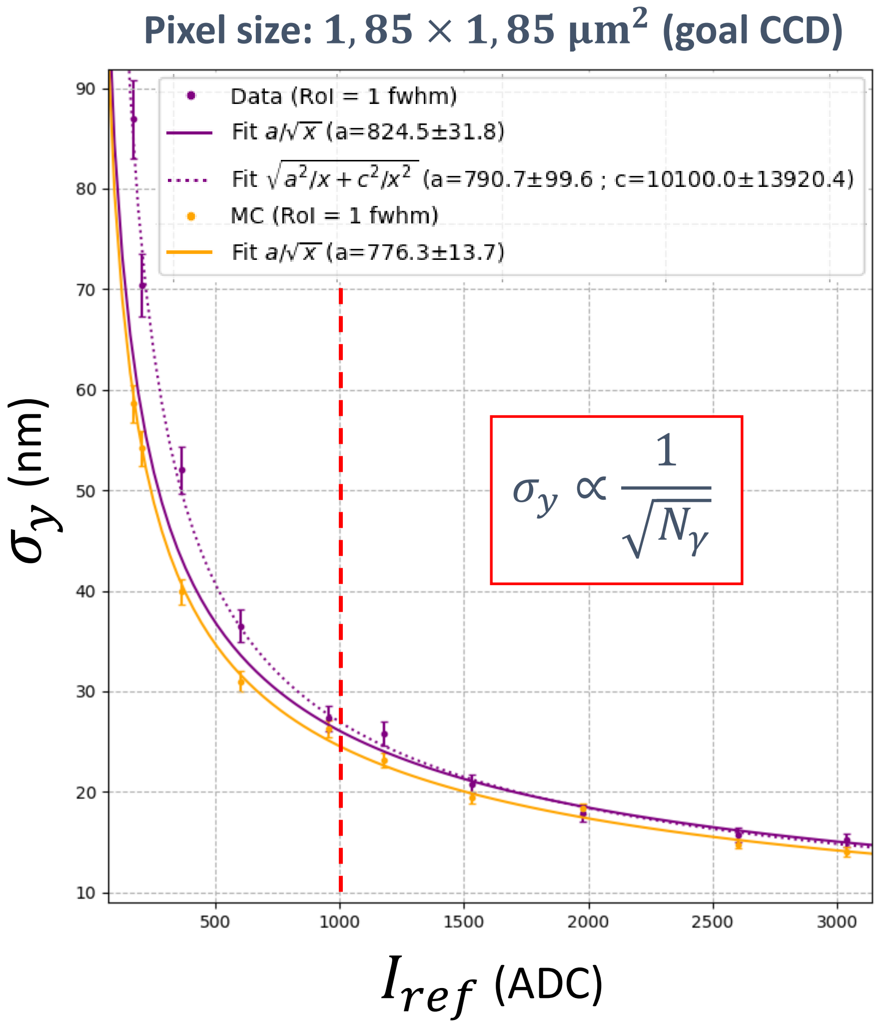
$$\Delta y = \langle \Delta y(i) \rangle \pm \frac{\sigma_y}{\sqrt{N_{mes}}} = 0.9 \pm 0.73 \text{ nm}$$

Spatial Resolution: Shot Noise



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

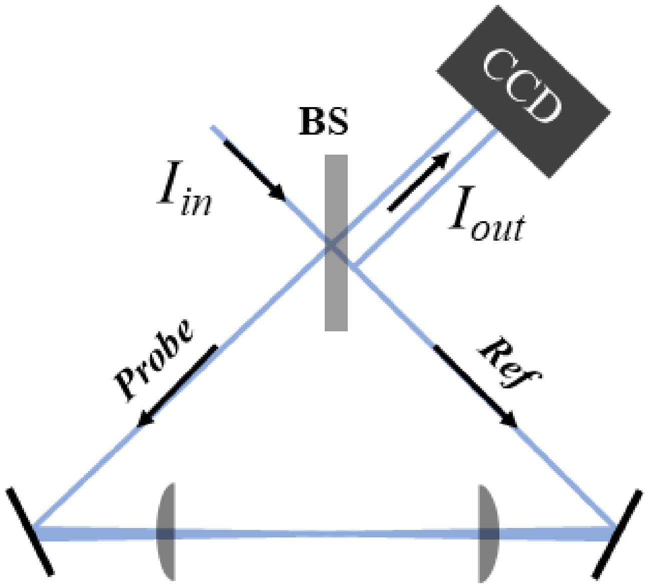
- **Current CCD** (pixel size: $5.86 \times 5.86\ \mu m^2$): $\boldsymbol{\sigma_y \simeq 30}$ **nm**
- **Best CCD** (pixel size: $1.85 \times 1.85\ \mu m^2$): $\boldsymbol{\sigma_y \simeq 13}$ **nm**

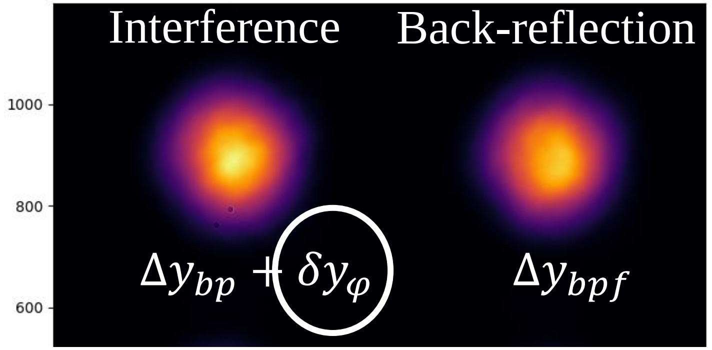


Spatial Resolution: Phase Noise

➢ **Phase noise** induced by mechanical vibrations of the interferometer

- It limits the spatial resolution when working with high amplification interferometer
- Current setup (without any isolation) : $\boldsymbol{\sigma_\theta} \approx$ **50 nrad** ⇒ Noise **~50 times to high**





Spatial Resolution: Phase Noise

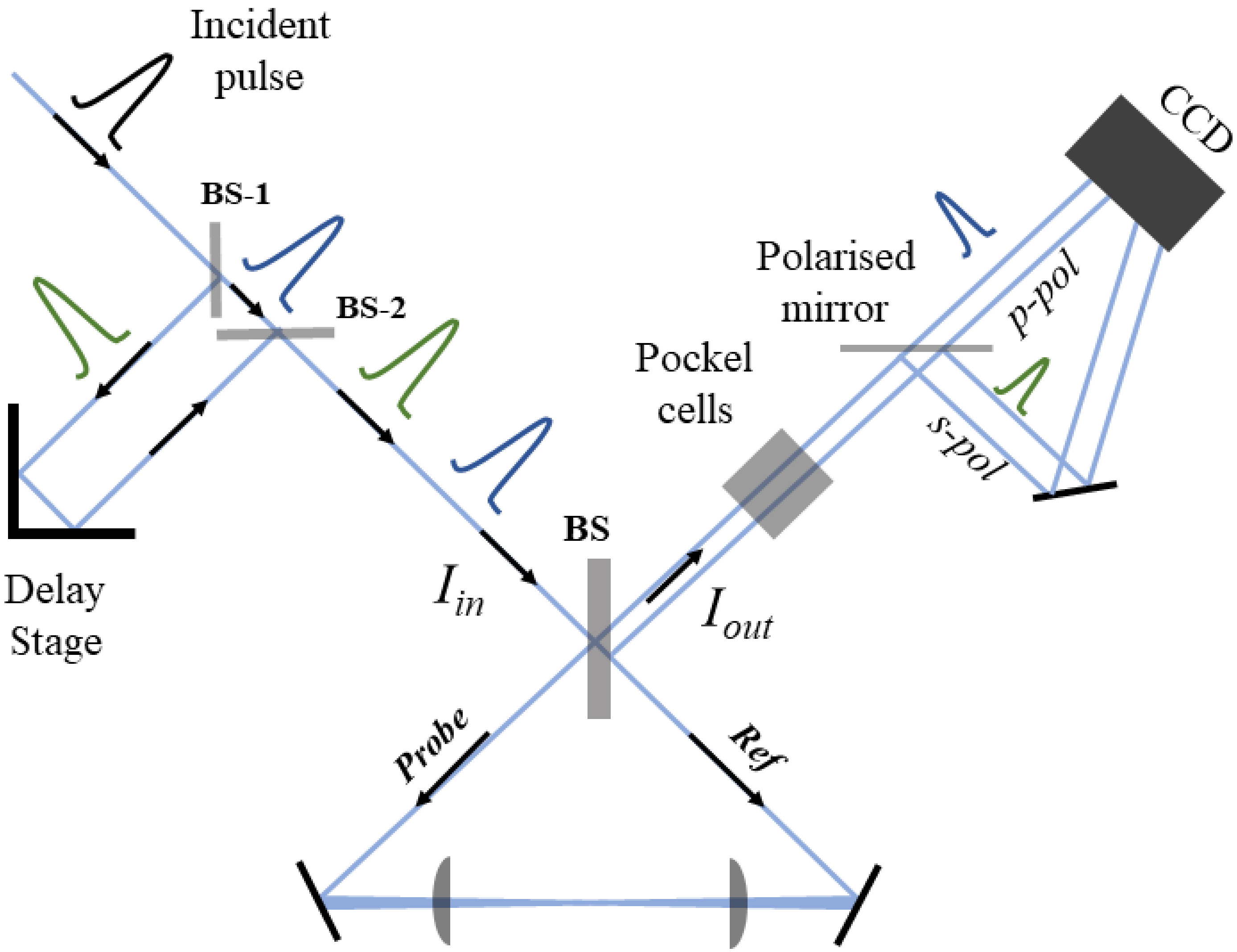
- **Phase noise** induced by mechanical vibrations of the interferometer
  - It limits the spatial resolution when working with high amplification interferometer
  - Current setup (without any isolation) : $\boldsymbol{\sigma_\theta \approx 50}$ **nrad** ⇒ Noise **~50 times to high**

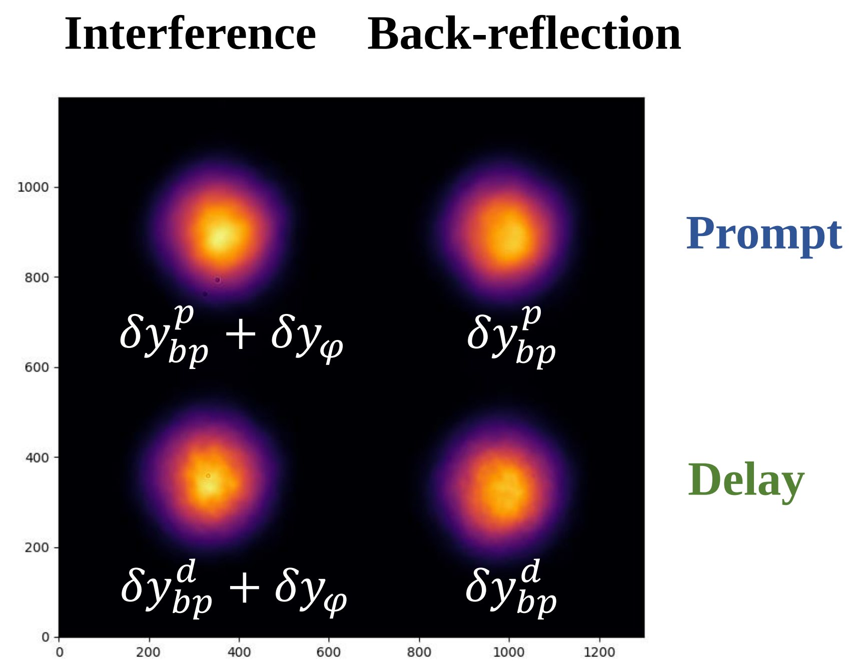
    ⇒ Need to improve the **vibration isolation**

    ⇒ We are developping a « **High frequency Phase Noise Suppression** » method, by using a secondary 5 ns delay pulse (in a similar way to the monitoring and suppression of the beam pointing fluctuations)

⇨ PhD Thesis Ali Aras

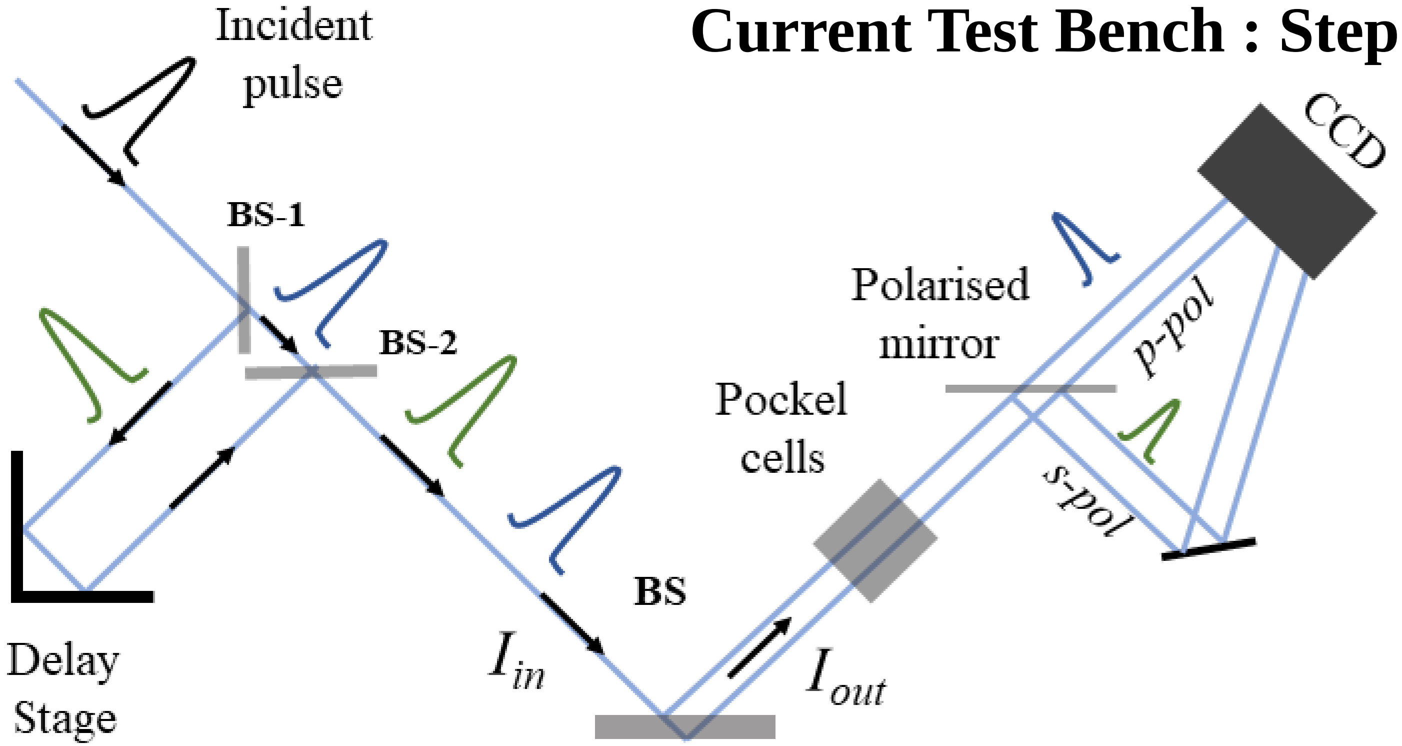
High Frequency Phase Noise Suppression

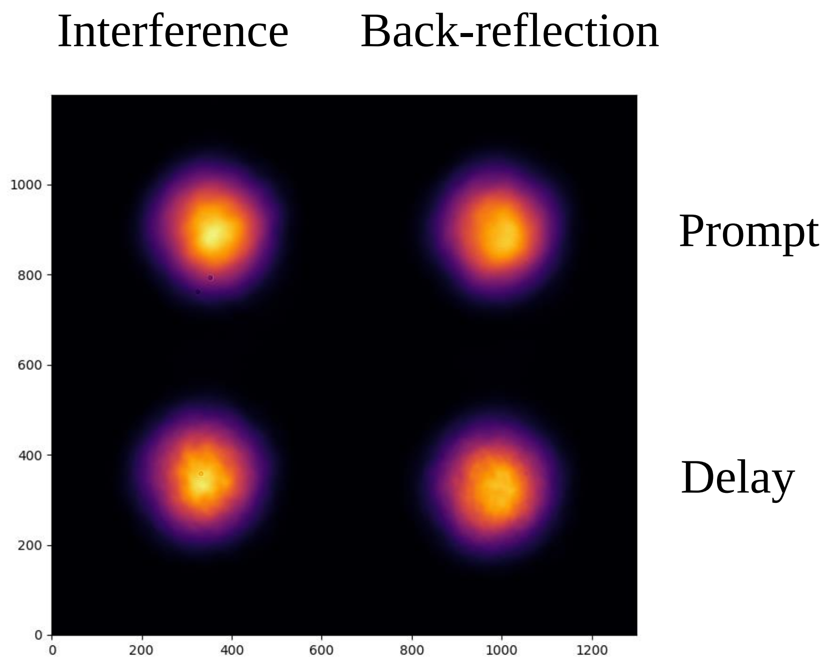


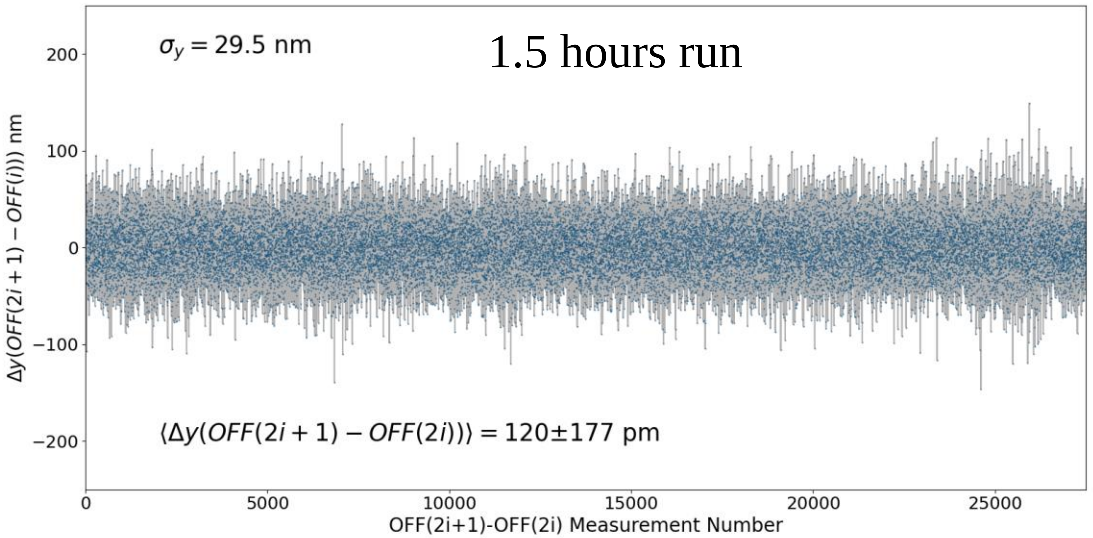


High Frequency Phase Noise Suppression

Current Test Bench : Step 1







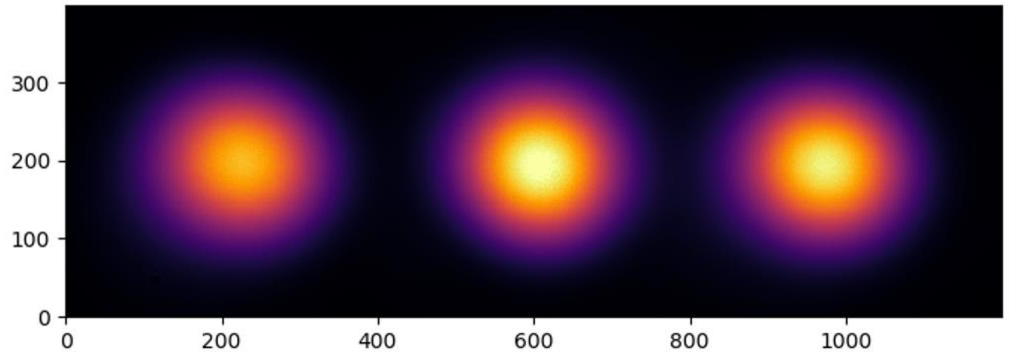
$\sigma_y = 29.5$ nm = shot noise

$\langle \Delta y \rangle = 120 \pm 177$ pm

Measurement of the DeLLight signal induced by optical Kerr effect in air with low energy pump

Measurement of the DeLLight signal in air

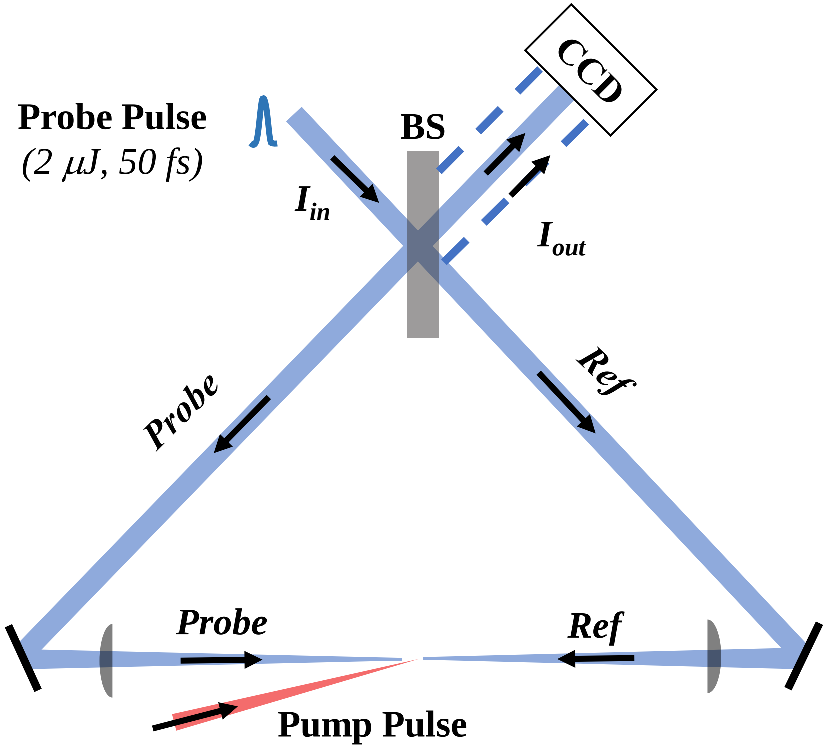
- Measurement of a DeLLight signal induced by optical Kerr effect in air
  - **Low energy pump pulse**: E ~ 1 – 10 μJ
  - Pump and probe are co-propagating
  - **Extinction $\mathcal{F} = 5 \times 10^{-4} \Rightarrow$ Amplification $\mathcal{A}$ ~ 25**
  - **Waist at focus $w_0 \approx 25\ \mu m$**
  - We measure simultaneously δy and $\Delta y = \mathcal{A} \times \delta y$



Reference beam

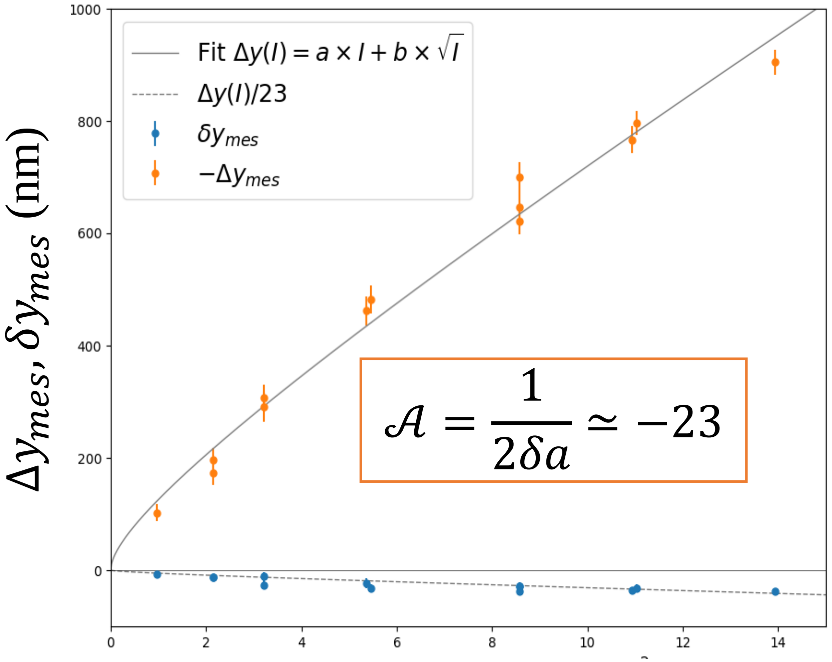
Interference Signal $\Rightarrow \Delta y$

Direct Deflection $\Rightarrow \delta y$



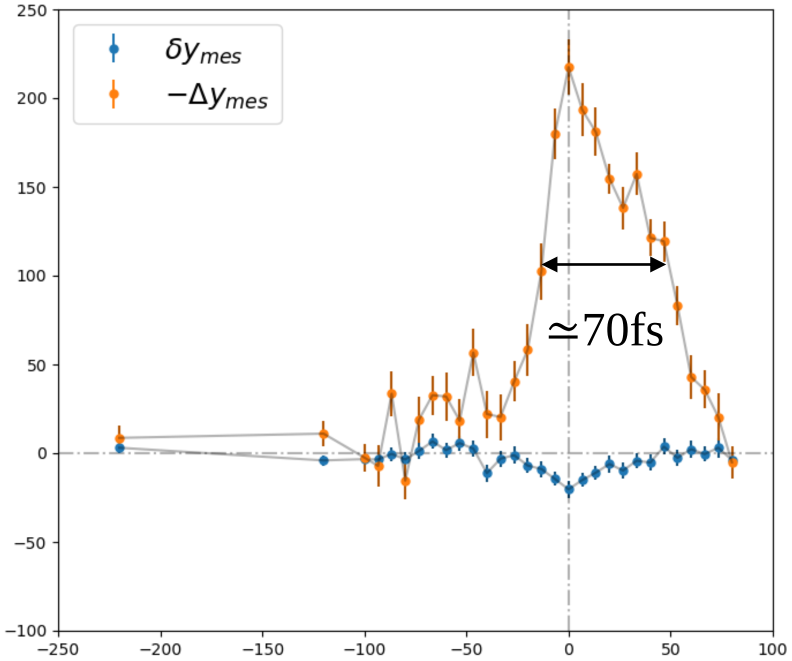
Measurement of the DeLLight signal in air

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



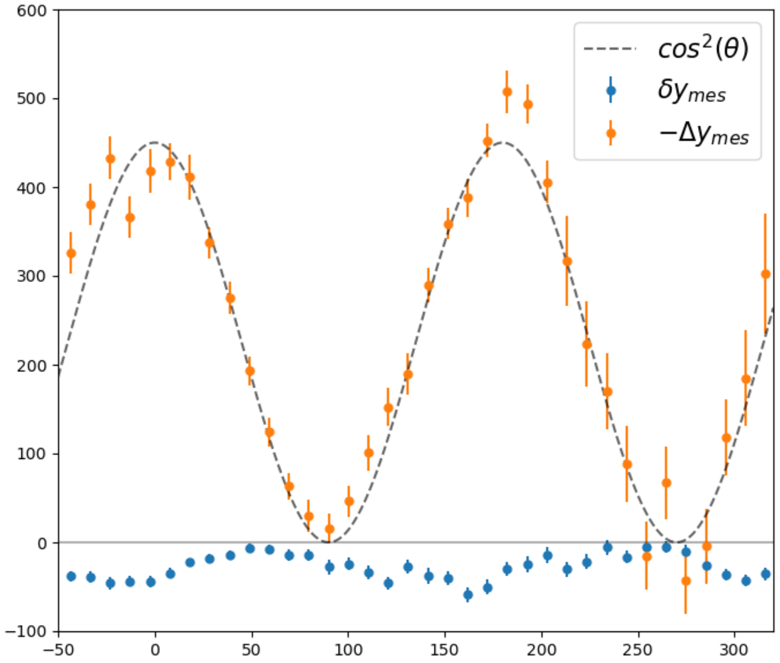
Peak intensity of the pump (TW/cm^2)

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



Time delay pump/probe (fs)

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



Polarisation angle pump/probe (deg.)

1-sigma sensitivity of the current pilot experiment

$$\boldsymbol{\delta n \cong 10^{-7}/\sqrt{T_{obs}(sec)}}$$

arXiv:2401.13506

What next ?

- **Reduction of the phase noise of the interferometer**
  - Isolation of the mechanical vibrations
  - High frequency phase noise suppression
- **Validation of a new beamsplitter with improved features**

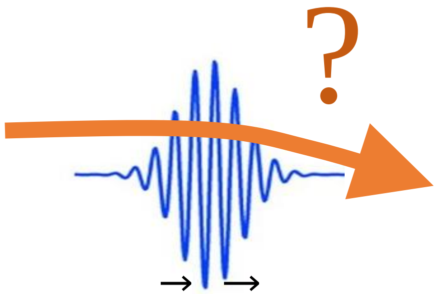
  $\Rightarrow R_{AR} < 10^{-4}, \delta a = 10^{-3}$ for $780 < \lambda < 820$ nm, Thickness = 10 mm
- **Pump-Probe interaction**
  - Reduction of the beam size of the probe in the interaction area
  - Need counter-propagating pump and probe
- **First DeLLight measurement in vacuum with LASERIX** (2 Joules, ~10^{20} W/cm^2) in 2025
- **Future DeLLight measurement in new generation laser facilities**

  HAPLS ELI Beamline (30 J, 10 Hz rep. rate) $\Rightarrow$ Expected signal: $\Delta y \sim 0.2$ nm

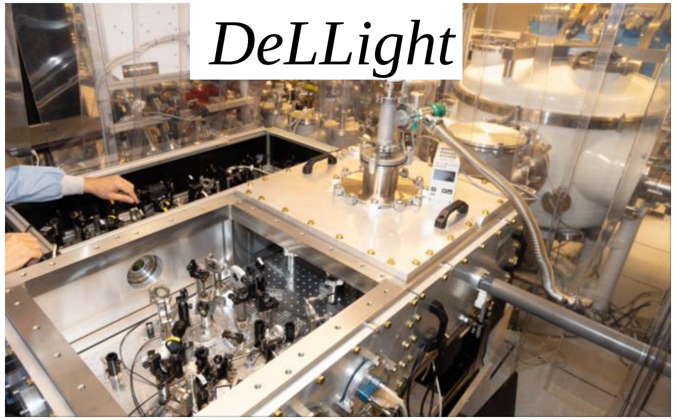
  $\Rightarrow$ **Expected sensitivity: 1 sigma within ~ 30 minutes**

Conclusions

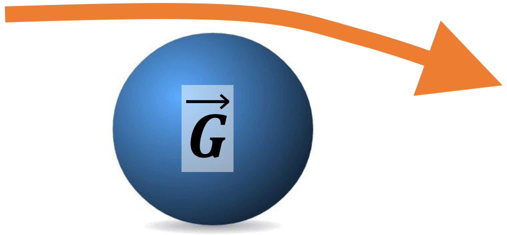
- A positive measurement would demonstrate that the speed of light in vacuum can be reduced, in the classical sense of the term on a macroscopic scale, in the presence of e.m. fields.



$\vec{E}, \vec{B}$

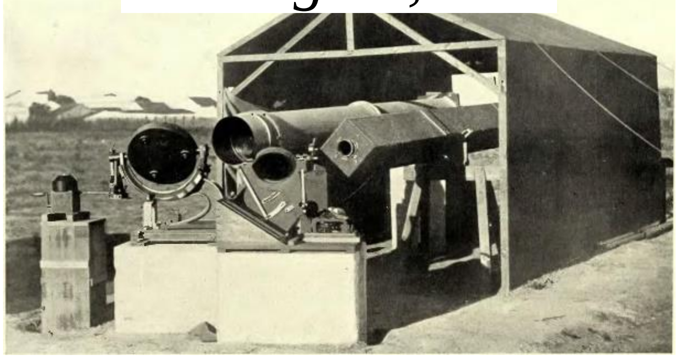


DeLLight



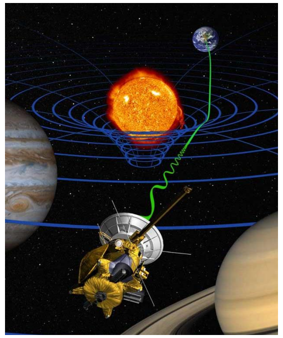
Deflection

Eddington, 1919



Deceleration

Shapiro



The DeLLight/LASERIX group @ IJCLab

DeLLight group

- Ali Aras (PhD) (Oct. 2023 – Oct. 2026)
- Adrien Kraych (postdoc) since Nov. 2021
- Scott Robertson (Theory, former postdoc) (2018 – 2021)
- François Couchot (CNRS)
- Xavier Sarazin (CNRS)

Former PhD

- Max Mailliet (Oct. 2019 – March 2023)

LASERIX

- Elsa Baynard
- Julien Demailly
- Sophie Kazamias
- Moana Pitmann

Collaborators :

- Arach Djanatti-Ataï (CNRS, APC)
- Marcel Urban (Emeritus)