Testing the electromagnetic and gravitational properties of the QED vacuum

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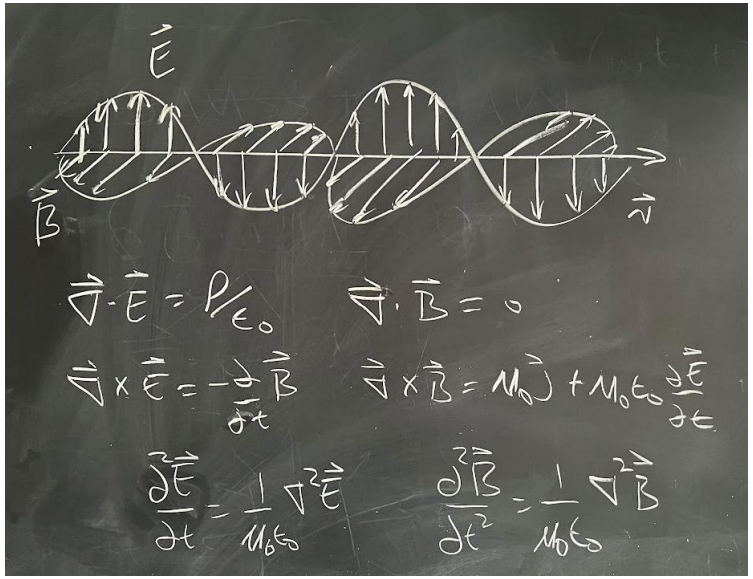
Le Vide dans tous ses états
31 Mars 2026

Classical electromagnetic vacuum

The classical electromagnetic vacuum is described as a linear optical and unalterable medium:

- ✓ The speed of light in vacuum c, and the related vacuum permeability μ_0 and permittivity ε_0 are universal constants
- ✓ c, ε_0 et μ_0 are unaffected by any perturbation or external fields

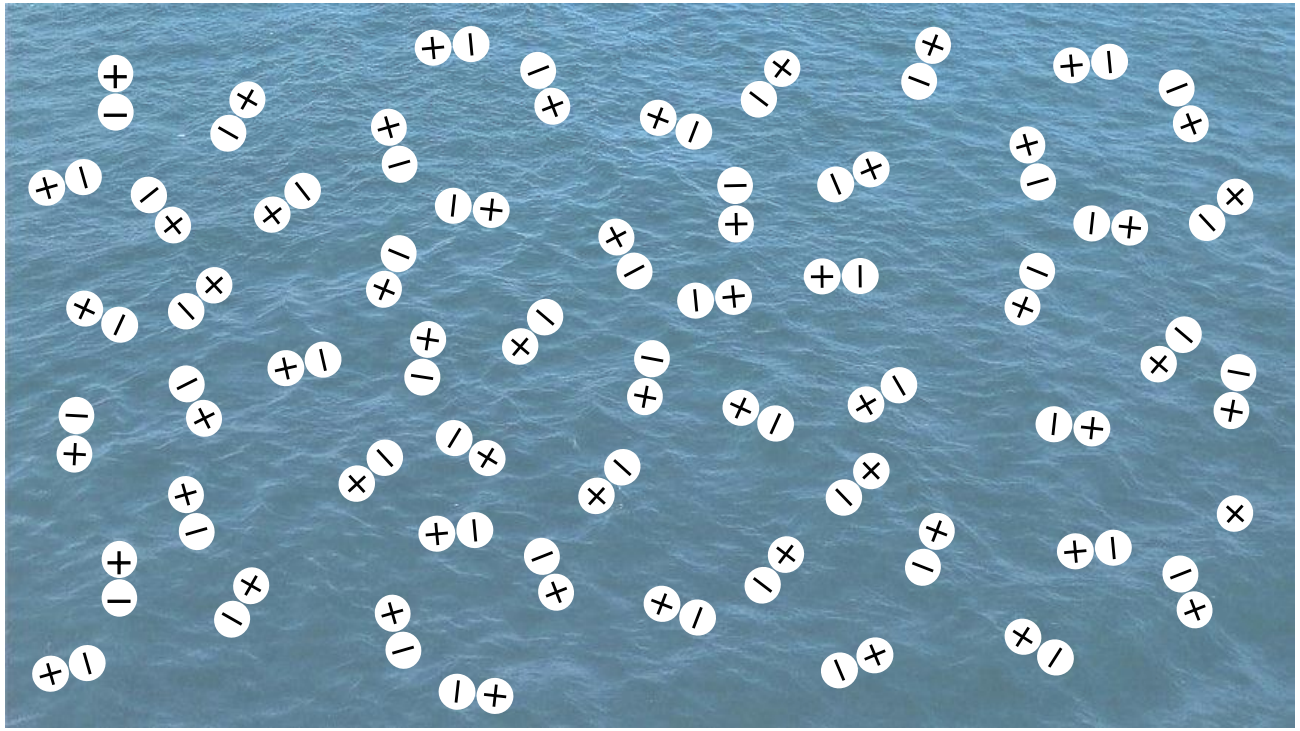
$$c = \frac{1}{\sqrt{\varepsilon_0 \mu_0}}$$



Vacuum in QED

The QED vacuum is a dynamical quantum medium, filled with quantum energy density fluctuations of the zero-point electromagnetic field

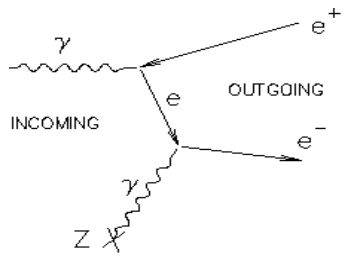
- ✓ A sum of stationary electromagnetic vibration modes with energy per mode $e_v(k) = \hbar\omega_k/2$
- ✓ Continuous appearance and disappearance of virtual pairs e^+/e^-

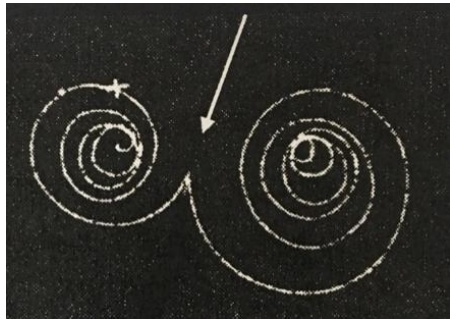


Tests of QED vacuum properties

So far, we have mainly tested and observed the perturbations produced by the QED vacuum on the quantum system under study

- **Lamb shift**: anomalous splitting in Hydrogen atom of the 2-electrons orbital energy in $2s_{1/2}$ and $2p_{1/2}$
- **γ–nuclei Delbrück's scattering and e^+/e^- pair creation**

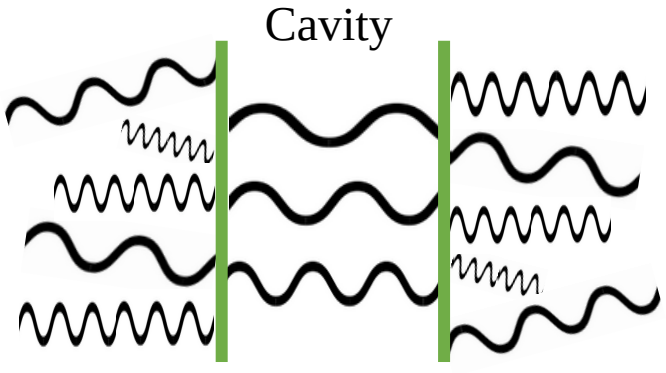




What interests us here is the opposite:

- **Can we disturb the vacuum ?**
- **Can we modify the vacuum properties, at a macroscopic scale ?**
- **Does it change « fundamental constants »** resulting from the vacuum properties ?

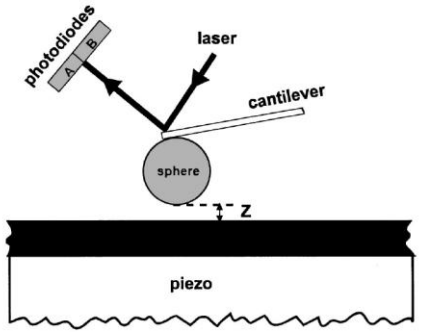
Casimir Effect



The Casimir pressure for two perfectly conducting parallel plates by a distance L is:

$$P_{\mathrm{Cas}} = -\frac{\hbar c \pi^2}{240 L^4}$$

H.B.G. Casimir, Proc. K. Ned. Akad. Wet. 51 793 (1948)
P.W. Milonni, Phys. Rev. A 38, 1621 (1988)



- ✓ First observation in 1997 at Seattle Univ. Of Washington *S. K. Lamoreaux, Phys. Rev. Lett. 78, 5 (1997)*
- ✓ Precise experiment (1%): resonance frequency of a microelectromechanical resonator L=100–500nm F(L=100nm) ~ 10^{-10} N *Mohideen et al., Phys. Rev. D **60** 111101 (1999)*
- ✓ First measurement between Parallel Metallic Surfaces in 2002 G. Bressi et al., Phys. Rev. Lett. 88 (2002)

- ✓ **Test of Newton law at short range** (100nm – 10um): When setting the cutoff of the vacuum energy density to fit the cosmological dark energy density, one finds a length scale of few tens of μm below which gravity should be modified

  → Need accurate surface calculations (See i.e. Lambrecht, Reynaud, et al. *arXiv:1106.3848, arXiv:1108.1761*)

- ✓ **Scharnhorst's effect**: Change in the light velocity in vacuum, propagating perpendicular to the plates

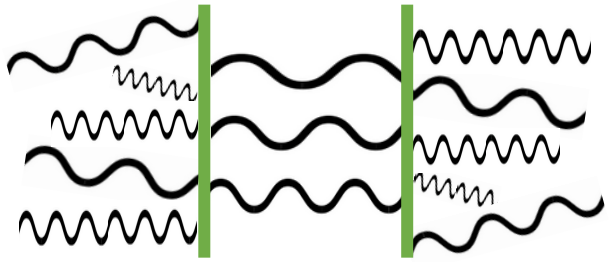
$$\frac{\Delta c}{c} \sim 1.6 \times 10^{-60} L^{-4} \qquad L = 1\mu m \Longrightarrow \frac{\Delta c}{c} \sim 1.6 \times 10^{-36}$$

Phys. Lett. B, Vol. 236, 354 (1990)

Change of spontaneous emission lifetimes

- Spontaneous emission is the most visible manifestation of the interaction between matter and the vacuum
  → Spontaneous emission ≡ Stimulated emission by the zero point field fluctuations modes of the vacuum

- But vacuum states can be radically altered by a resonant cavity



Resonant cavity

➡ It becomes possible to modify the spontaneous emission lifetime of an atom *E.M. Purcell, Phys. Rev. 69, 681 (1946)*

Resonant mode = ΔE(atom) ➡ Enhanced Spontaneous emission ➡ Lifetime is reduced

Supressed mode = ΔE(atom) ➡ Reduce Spontaneous emission ➡ Lifetime is increased

➡ First observation of enhanced atomic spontaneous emission with superconducting niobium cavities developed by S. Haroche's team

Phys. Rev. Lett. Vol. 55, 1903 (1983)

Tests of QED vacuum properties

So far, we have modified the vacuum on a macroscopic scale,
by applying boundary conditions to it via a cavity

Can we now modify the properties of the vacuum on a macroscopic scale
but this time by applying external electromagnetic fields to it ?

QED vacuum is a nonlinear optical medium

- **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 et μ_0 are unaffected by any perturbation or external fields

Interaction between two different e.m. fields is impossible in classical vacuum

- **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

➡ Is it the case for the quantum vacuum ?

QED vacuum is a nonlinear optical medium

- **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

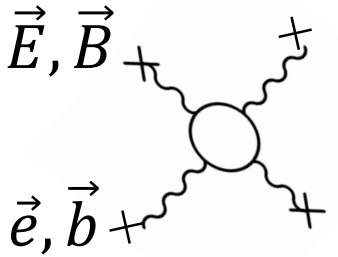
Heisenberg and Euler, Z. Phys. 98, 714 (1936)

➡ Maxwell's equations are not linear anymore

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

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

➡ The speed of light c in vacuum can be reduced, at macroscopic scale in the classical (optical) sense, when vacuum is subject to external e.m. fields

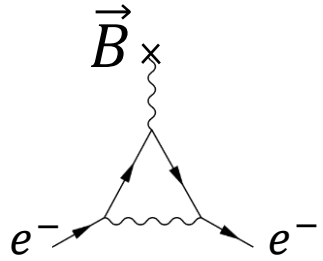


- **Schwinger** (1951) derived later the H-E result within the QED frame

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

In the same article, we find the prediction of the anomalous magnetic moment of the electron

$$g - 2 = \frac{\alpha}{2\pi}$$



QED vacuum is a nonlinear optical medium

The light velocity in vacuum should be modified

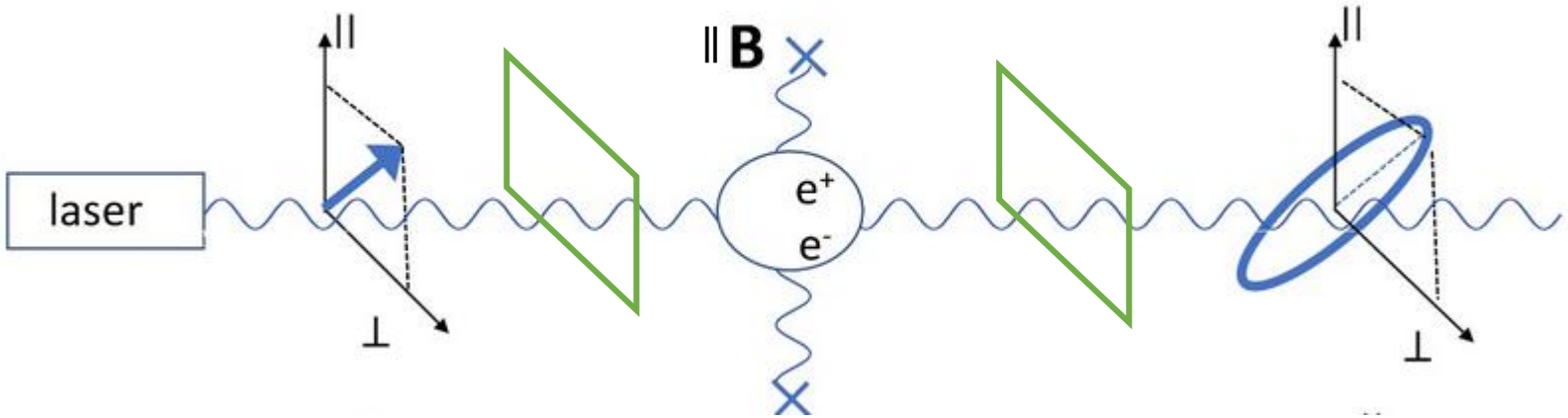
at macroscopic scale

in the classical (optical) sense

when vacuum is subject to external e.m. fields

Search for optical nonlinearity in vacuum

Search for Vacuum Birefringence
produced by an external continuous magnetic field



$$\Delta n = n_{\parallel} - n_{\perp} = k_{\mathrm{CMV}} |\vec{B}|^2$$

$$k_{\mathrm{CMV}} = \frac{1}{\mu_0} \frac{\alpha}{\pi} \frac{1}{30} \left(\frac{e\hbar}{m^2 c^2} \right)^2 \approx 4.0 \cdot 10^{-24} \text{ (in T}^{-2}\text{)}$$

Search for optical nonlinearity in vacuum

- **BMV@ LNCMI** (Toulouse) *A. Cadène et al., Eur. Phys. J. D 68, 16 (2014)*

  Pulse B field ~ 6.5 T, Cavity L ~ 2.27m, F ~ 440 000

  Noise level (3σ) after 200 magnetic pulses: $k_{CMV} \sim 8 \times 10^{-21}\ \mathrm{T}^{-2}$

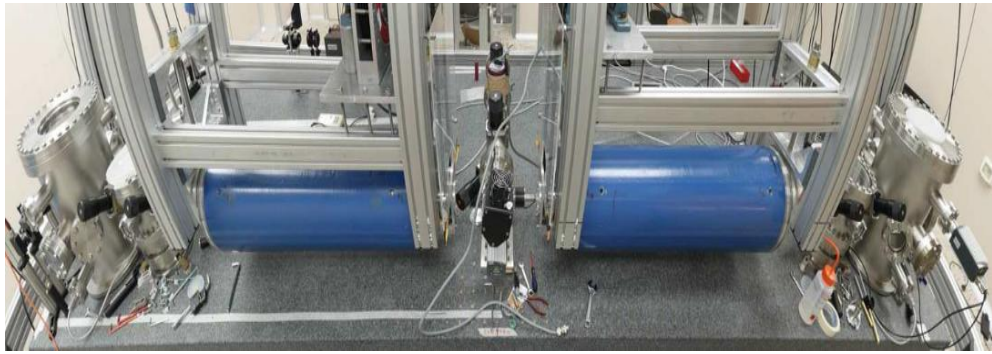
  New setup: Pulse B=11 T, Cavity: F = 530 000, L = 2.5m

- **PVLAS@ Ferrare Univ.** (Italy) *A. Ejlli et al., Physics Reports 871, 1–74 (2020)*

  Continuous B field = 2.5 T rotating @ 5 Hz

  Noise level (1σ) after 100 days of data collection : $k_{CMV} \sim 3 \times 10^{-22}\ \mathrm{T}^{-2}$

  ➡ **Noise (1σ) ~ 7 × QED prediction**



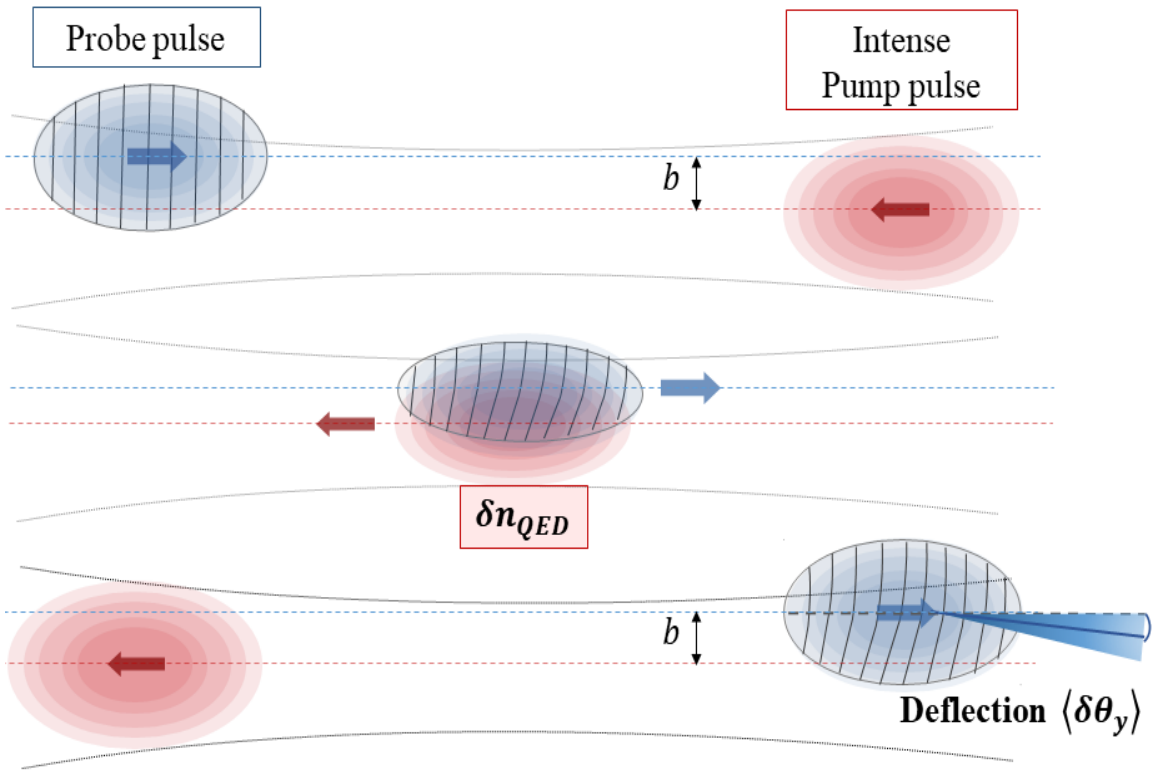
Sensitivity limited by the intensity of the magnetic field and the birefringence of the mirror coatings in the cavity

Search for optical nonlinearity in vacuum

Another approach:

Intense electromagnetic fields delivered by new generation intense femtosecond lasers

DeLLight Experiment: *Deflection of Light by Light*



LASERIX Pump specifications

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

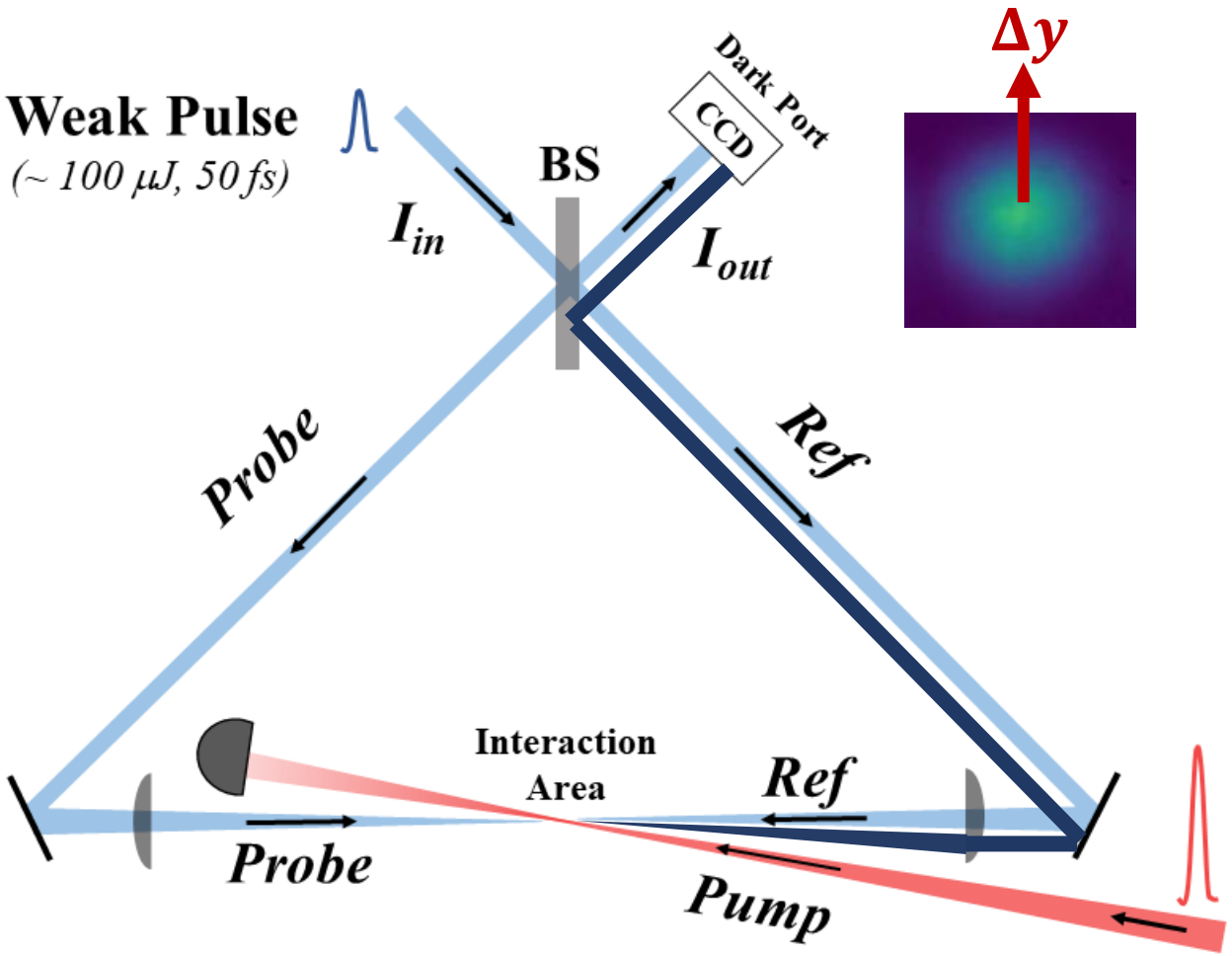
$$\Rightarrow \boldsymbol{B \sim 10^5\,\mathrm{T}} \qquad \boldsymbol{E \sim 3 \times 10^{13} V/m}$$

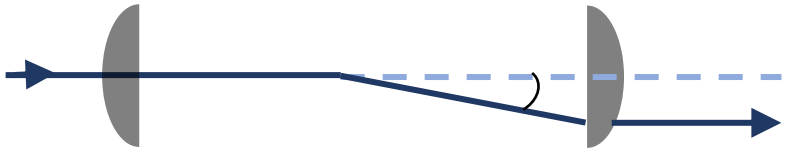
$$\boldsymbol{\delta n \sim 3 \times 10^{-13}}$$
$$\boldsymbol{\delta\theta \sim 0.1\ \mathrm{prad}}$$

« *Electromagnetic Lensing* »

DeLLight Experiment: *Deflection of Light by Light*

Refraction measured with a Sagnac Interferometer





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

- δy = Direct vertical shift of the probe inside the Sagnac
- Δy = Vertical shift of the interference intensity profile is **amplified** in the dark output (*Weak Value Amplification*)

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

- **Amplification factor** $\mathcal{A} = \pm \frac{1}{2\sqrt{\mathcal{F}}}$

$$\mathcal{F} = \frac{I_{out}}{I_{in}} = \text{ Extinction Factor}$$

- « *UP-DOWN*» measurements @ 5 Hz

DeLLight Experiment: *Deflection of Light by Light*

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

- ✓ **Energy** $E = 2.5$ **J @ LASERIX** (**10 Hz** repetition)
- ✓ **Extinction** $\mathcal{F} = 10^{-5}$ ($\mathcal{A} = 100$) (best extinction measured)
- ✓ **Waist at focus** $w_0 = W_0 = 5$ µm (typical achievable value)
- ✓ **Spatial resolution** $\sigma_y = 15$ nm (CCD shot noise resolution)

→ $\Delta y \sim 10$ pm

UP – DOWN measurements @ 5 Hz

→ **1 sigma** sensitivity within ~ **4 days** with **LASERIX**

M. Mailliet et al., Phys. Rev. A 109, 043526 (2024)

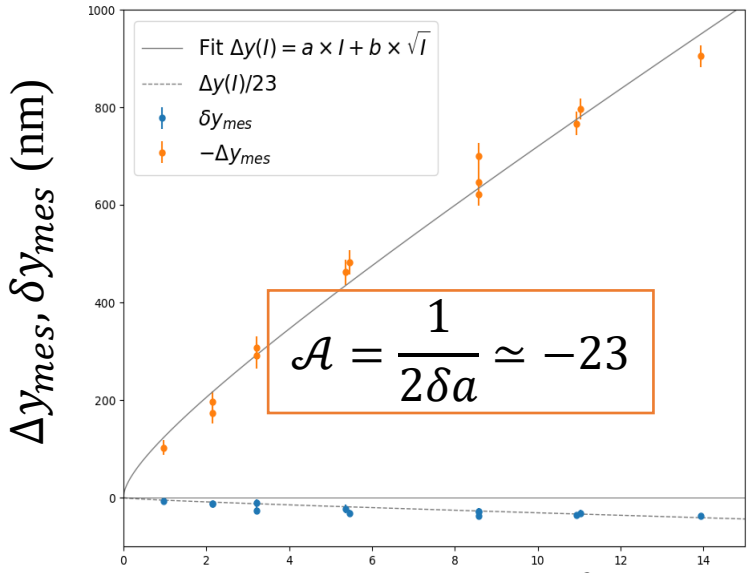
With **KALDERA** laser (under development @ DESY): 3 J @ **1 kHz**

→ **1 sigma** sensitivity within ~ **1 hour** with **KALDERA**

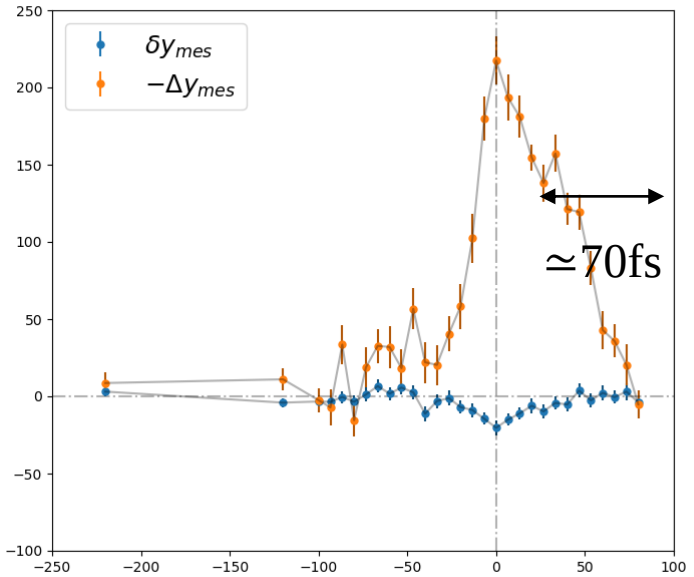
DeLLight Experiment: *Deflection of Light by Light*

Proof of concept: Measurement of the interferometric DeLLight signal in air with a low intensity pump

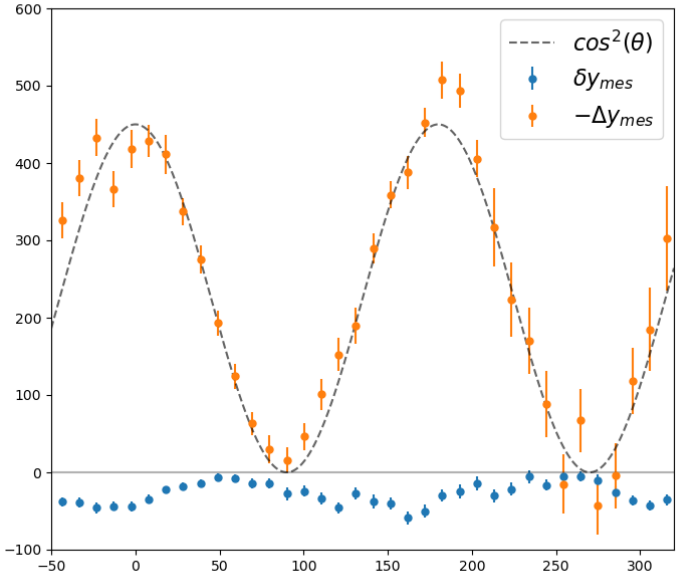
$\Delta y = f(\text{Intensity})$



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



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



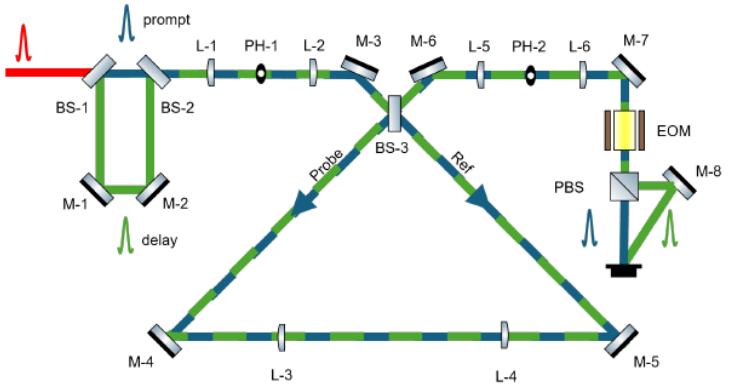
➡ Validation of the DeLLight experimental method based on interferometric amplification

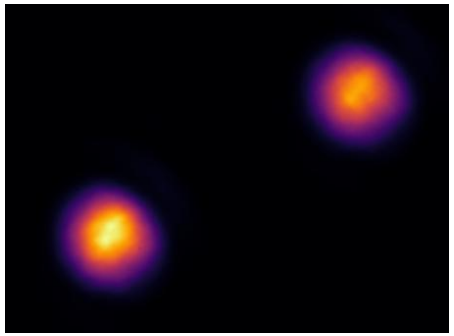
A. Kraych et al, Physical Review A 109.5 (2024)

DeLLight Experiment: *Deflection of Light by Light*

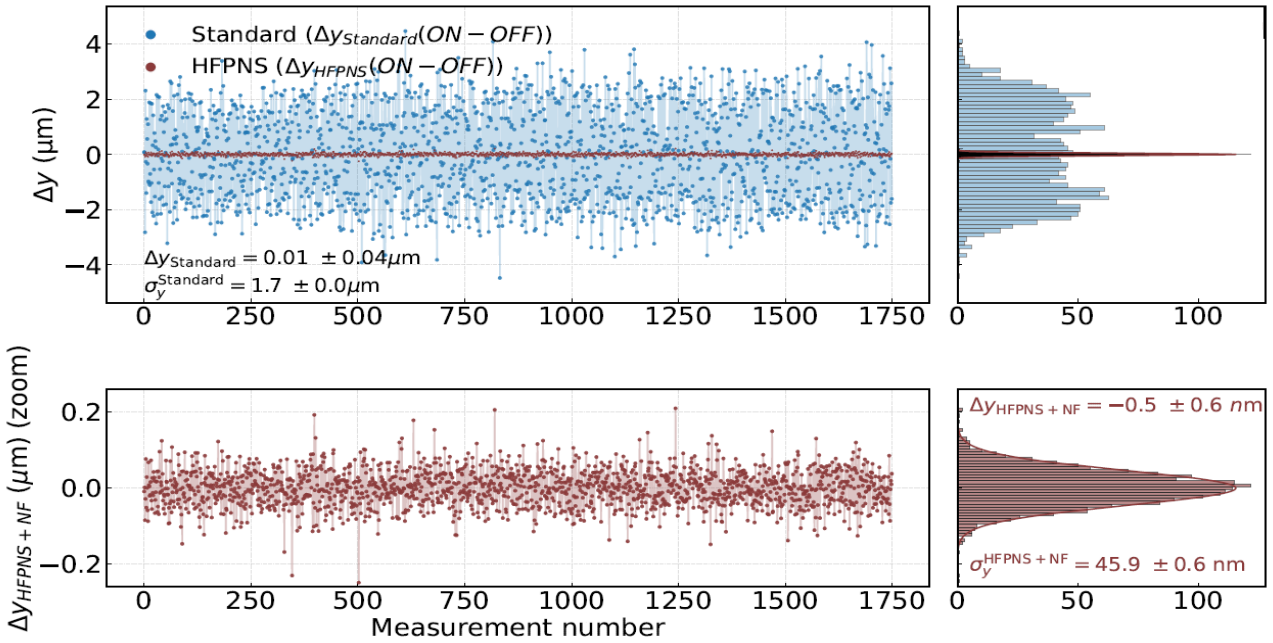
- Beam pointing fluctuations and interferometric phase noise are suppressed by measuring simultaneously (200 MHz) the interferometric signal of a delayed (5ns) pulse, used as reference (unrefracted by the pump)

  → High Frequency Phase Noise Suppression (HFPNS)





« OFF-OFF » Noise Measurement



Without correction: $\sigma_y \approx 2$ µm

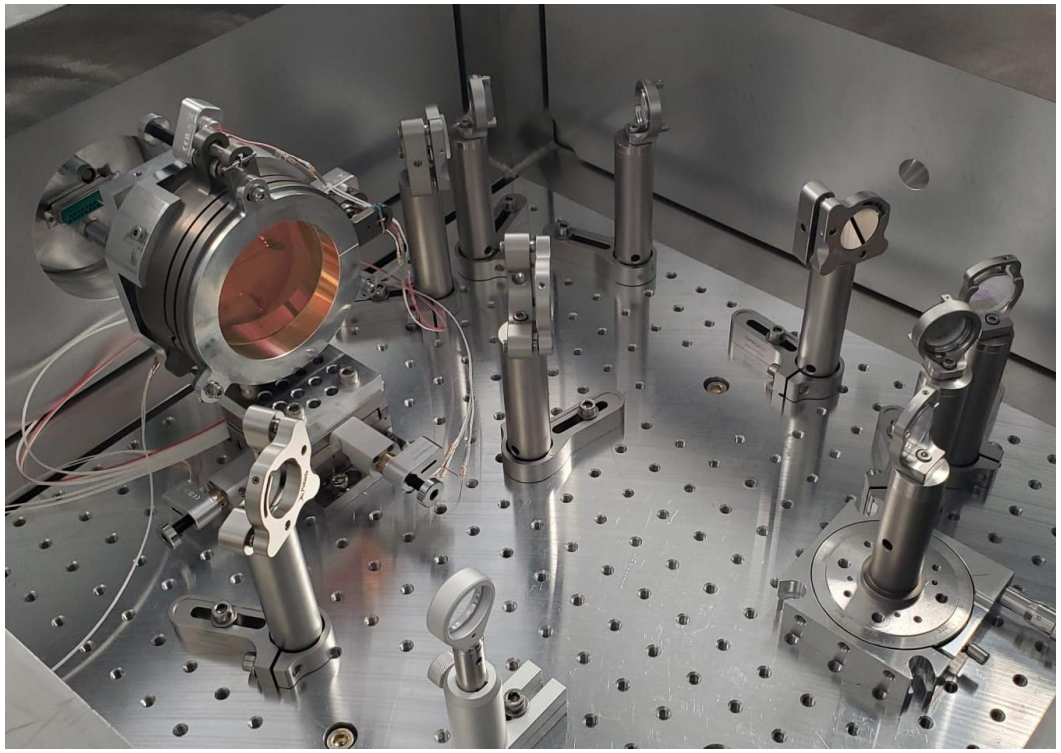
After **HFPNS** correction: $\sigma_y \approx 46$ nm

Expected **Quantum Noise**: $\sigma_y = 38$ nm

arXiv:2602.10896

DeLLight Experiment: *Deflection of Light by Light*

Installation of the final setup in progress



Commissioning of the setup in vacuum with intense laser pulses by the end 2026

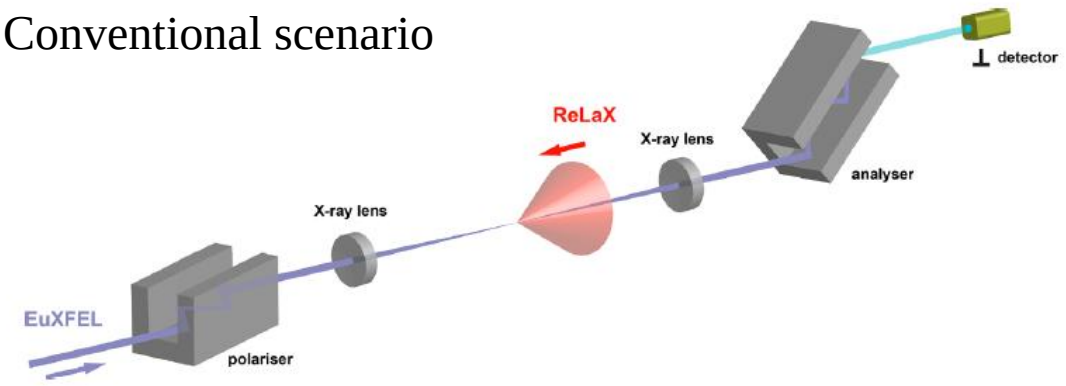
BIREF Project at XFEL (Germany)

N. Ahmadiniaz et al., *High Power Laser Science and Engineering*, (2025), Vol. 13, e7
arXiv:2405.18063

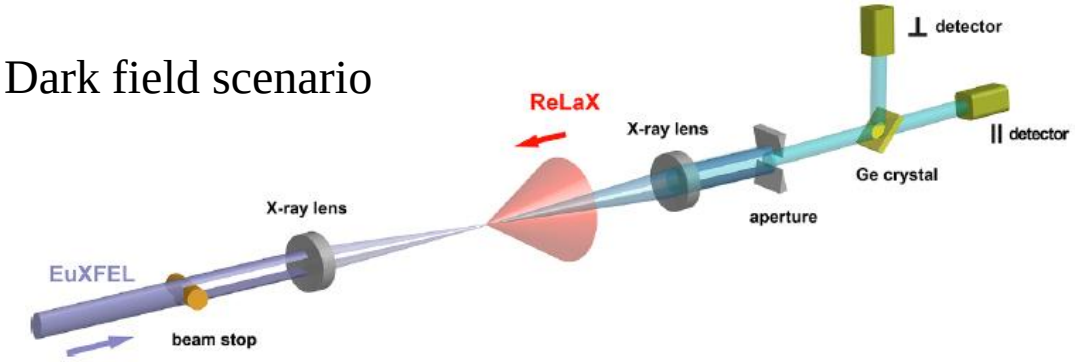
- A new proposal at XFEL using **coherent X-rays pulses as probe and RELAX laser pulses as pump** (3J, 30fs, 5Hz)
- Search for rotation of the X-ray polarisation

I(pump) = 10^{21} W/cm^2 at focus, $\lambda_X = 0.02$nm → Flip probability ~10^{-12}
→ Need very high polarization purity (current record ~10^{-11})

Conventional scenario



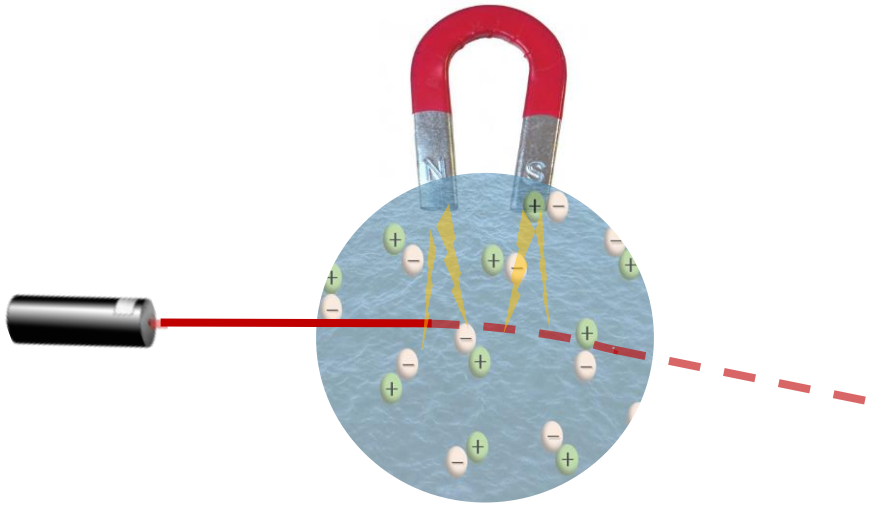
Dark field scenario



Proof of concept:
arXiv:2506.11649
Phys. Rev. A, 063512 (2025)

QED Vacuum and Gravitation ?

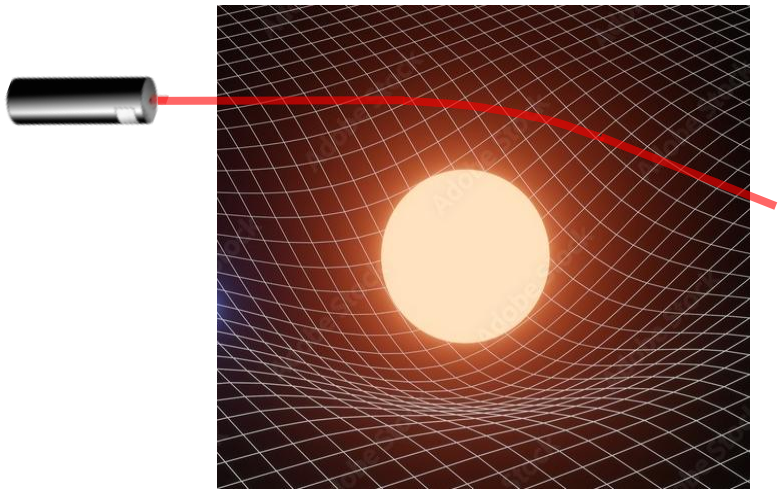
$\vec{E}, \vec{B}$



Quantum Electrodynamics

Vacuum Polarisation

$\vec{G}$



General Relativity

Curvature of the metric

What about quantum fluctuations of the vacuum energy densities in a gravitational field?

Vacuum catastrophe in General Relativity ?

→ The mean value of the vacuum energy does not contribute to gravitation

A test mass set in the middle of the infinite uniform isotropic vacuum will not feel gravitation force

Now, a gravitation mass is added

→ Our test mass will undoubtedly feel the gravitational force caused by this asymmetry

Do vacuum energy density fluctuations gravitate ?

Do virtual e+/e- pairs gravitate ?

Is the vacuum density modified by gravitation ?

Could it be the origin of the dark matter ?

Is the space-time curvature in RG a geometrical equivalence of the change of the vacuum energy density ?

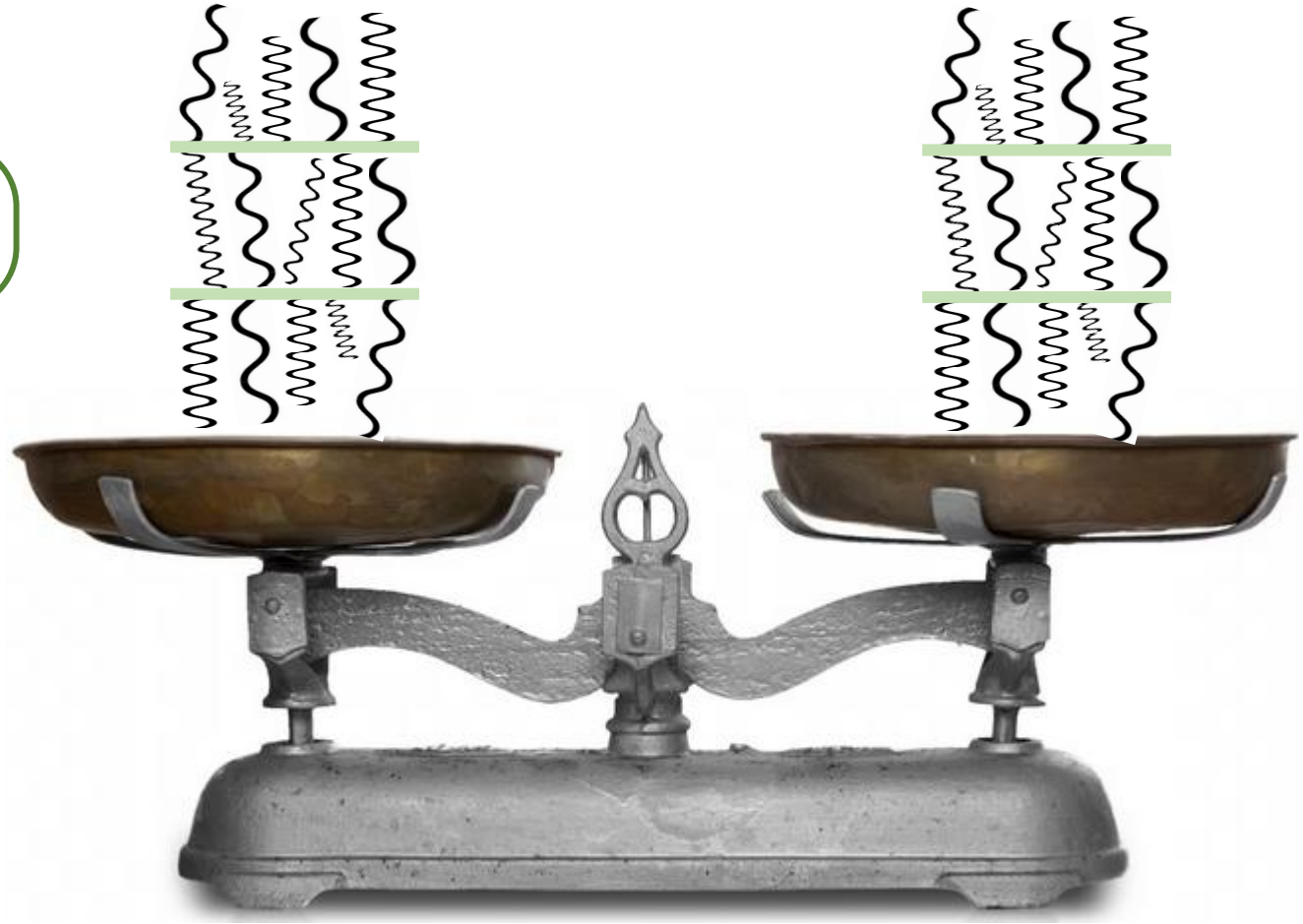
R.H. Dicke, Rev. Mod. Phys. ***29****, 363 (1957)*

Do energy density fluctuations of the QED vacuum gravitate ?

QED Vacuum and Gravitation

Do the quantum vacuum gravitate ?

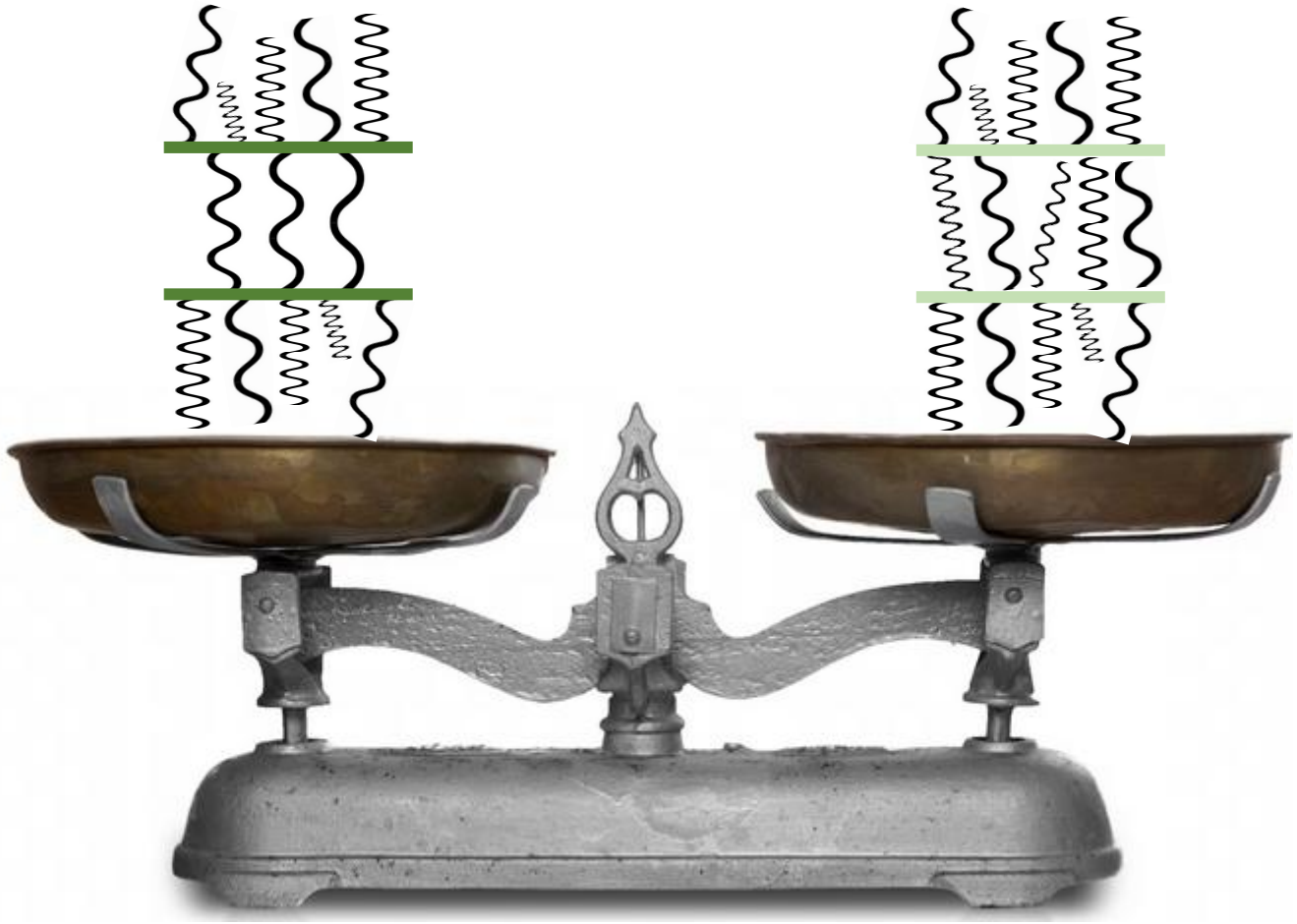
Passive (transparent) Cavity



QED Vacuum and Gravitation

Do the quantum vacuum gravitate ?

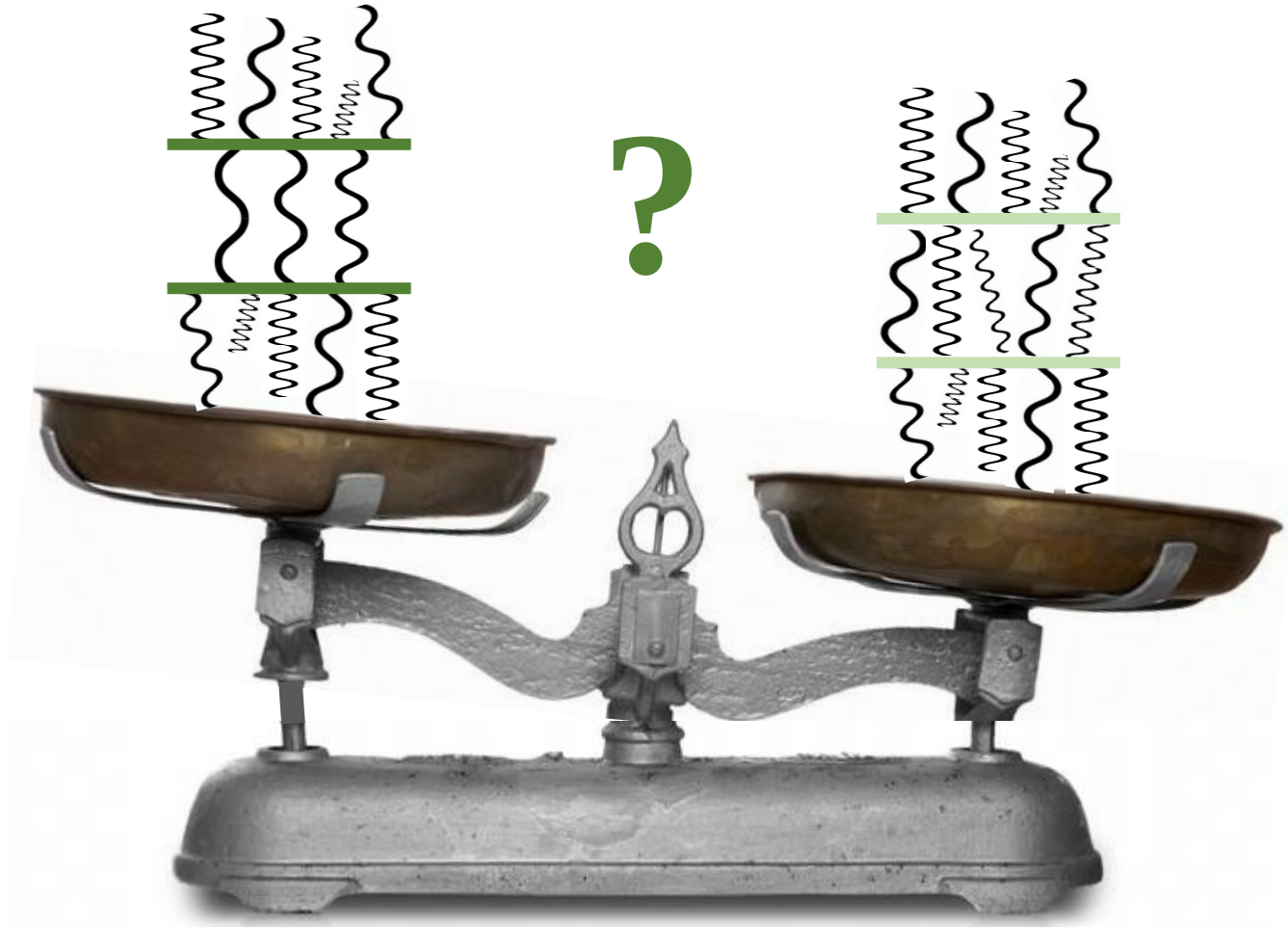
Superconducting Resonant Cavity



QED Vacuum and Gravitation

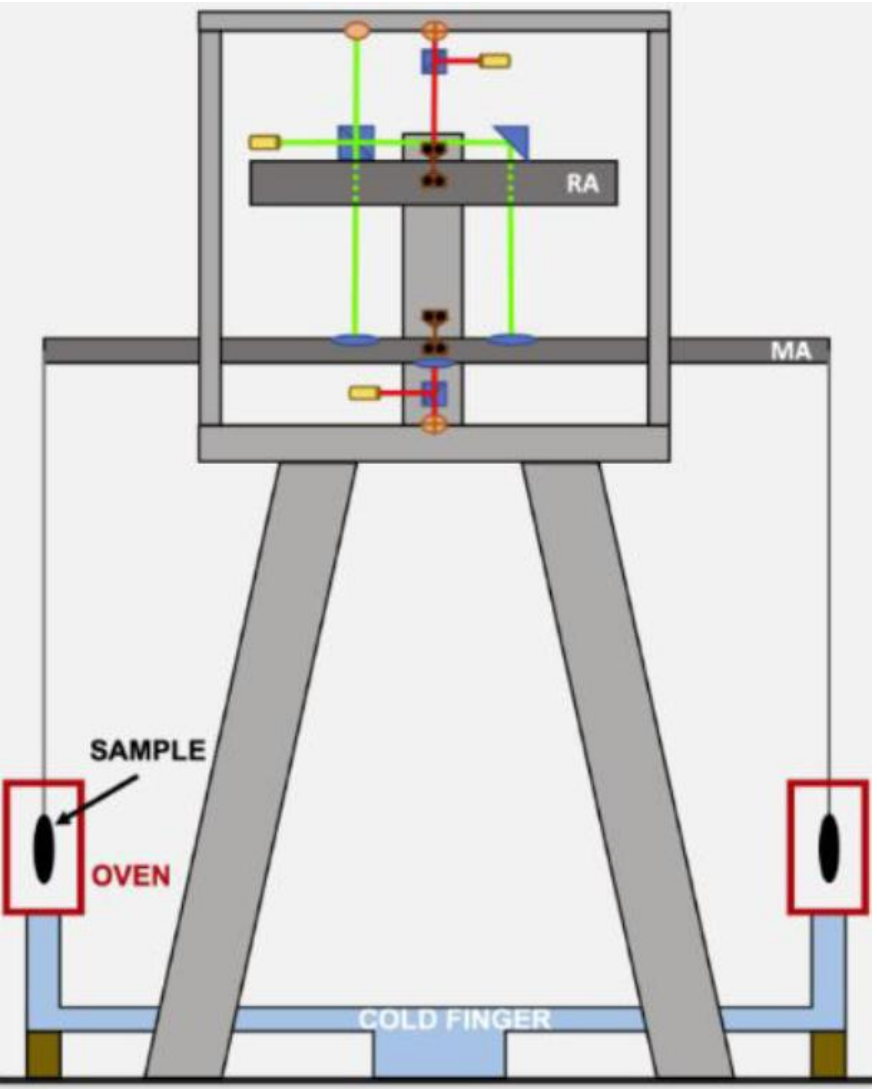
Do the quantum vacuum gravitate ?

Superconducting Resonant Cavity



Archimedes Experiment

(from A. Alloca's talk @ Rencontres de Moriond March 2025)



Balance arm length = 1.4 m

Archimedes experiment @ Sar-Grav surface laboratories (Sardinia, Italy)

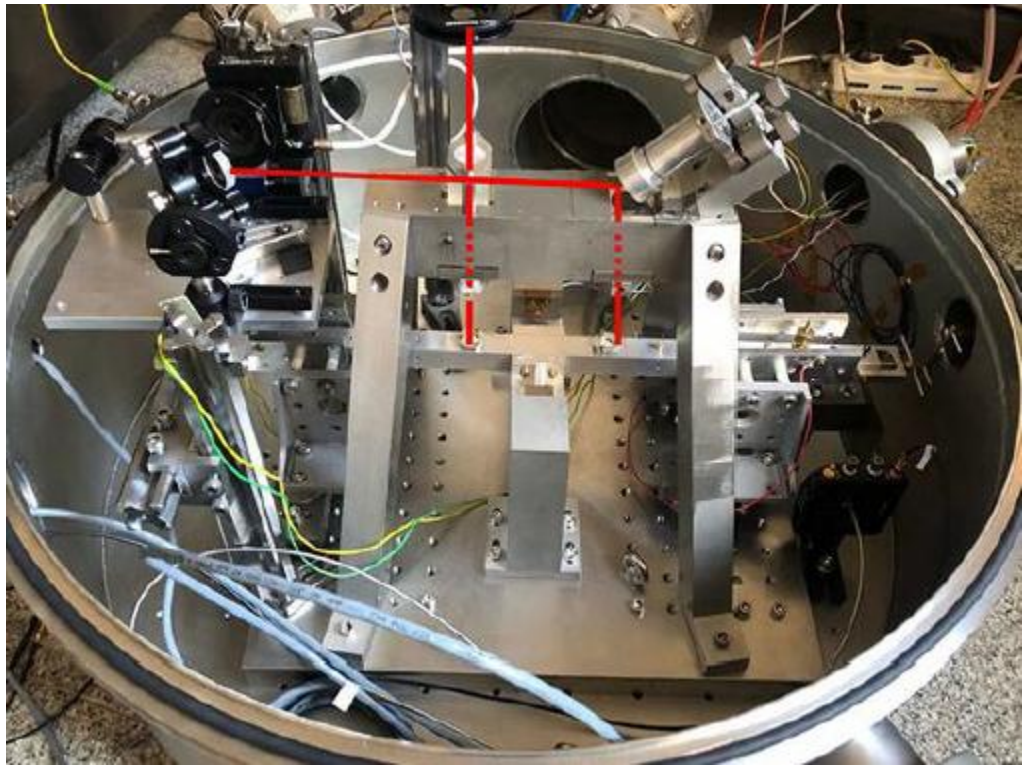
- Ultra sensitive interferometric balance (reference arm and balance arm)
- Modulate the reflectivity of the Casimir plates to modulate the density of vacuum modes inside the Casimir cavity
- Suspend samples composed of Casimir cavities to the balance arm and try to detect a possible weight variation at the modulation frequency
- Superconducting YBCO crystal (Tc=92K) as natural multilayered Casimir cavity
- Disk-shape R=5cm, e=5mm → F= 5×10^{-16} N → Torque $\tau = 3.5\times10^{-16}$ N.m

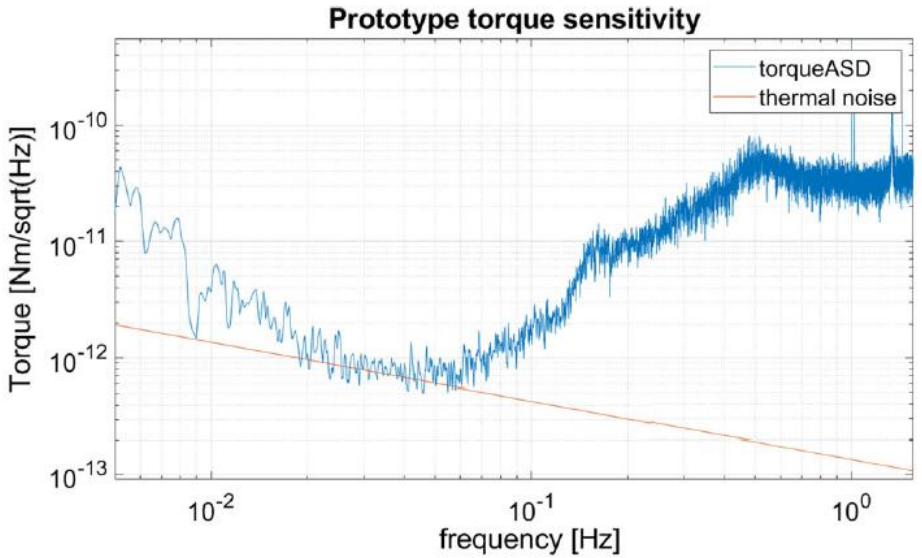
Eur. Phys. J. Plus 137, 826 (2022)
Phys. Rev. B 106, 134502 (2022)

- Thermal modulation of the crystal @ 10mHz for heterodyne detection
- Spectral signal (integration 10^6 s): $\tau_s = 3.5\times10^{-13}$ N.m/$\sqrt{\text{Hz}}$

Archimedes Experiment

The balance prototype





Torque sensitivity achieved at room teamperature with the prototype: ~10^{-12} N.m/$\sqrt{\text{Hz}}$

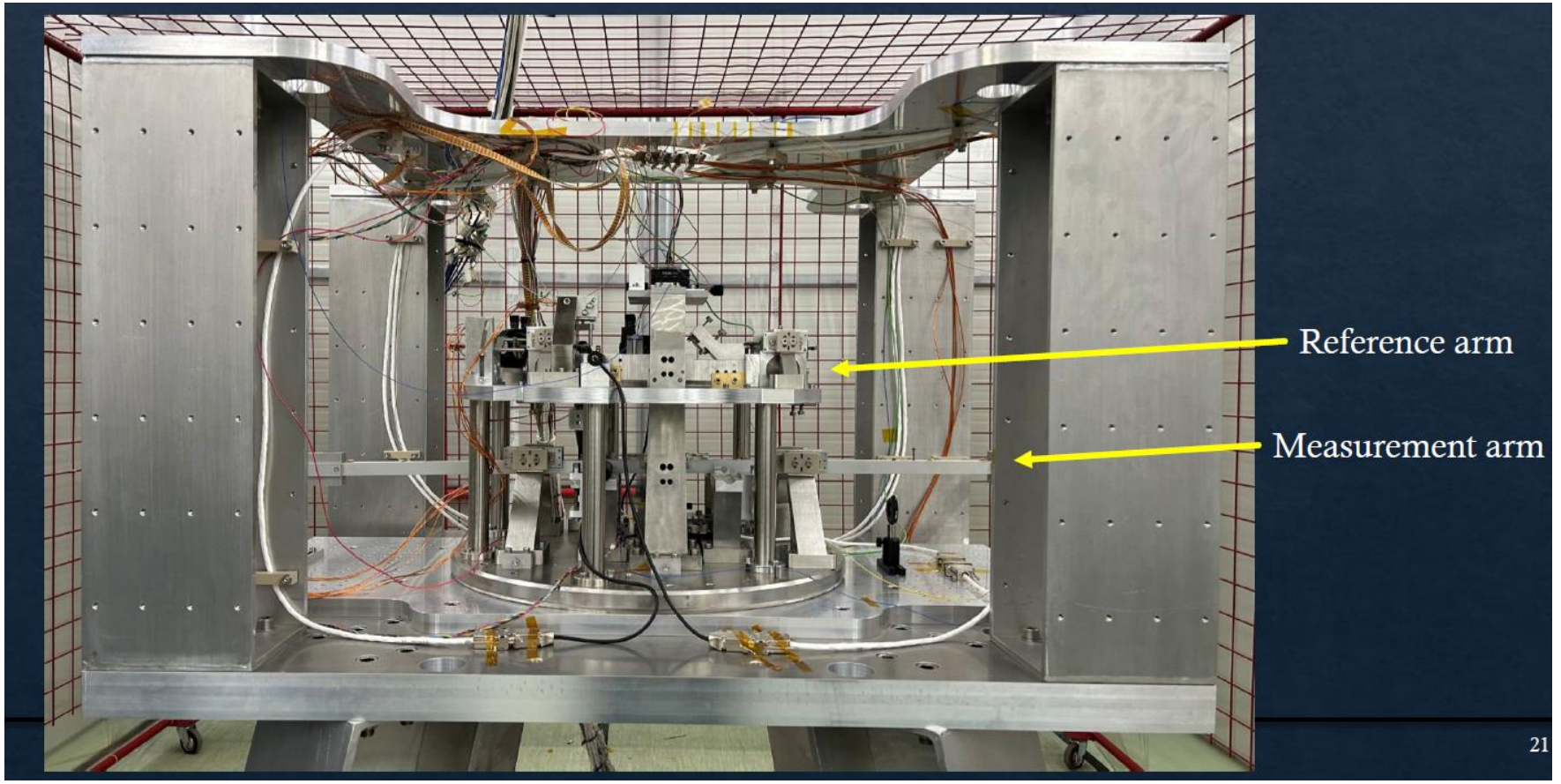
A. Allocca et al., Eur. Phys. J. Plus 139 (2024)

Only a factor ~10 above the required sensitivity

Archimedes Experiment

(from A. Alloca's talk @ Rencontres de Moriond March 2025)

Archimedes final balance



Setup in cryogeny by the end of 2026 for first measurements campaign of sensitivity

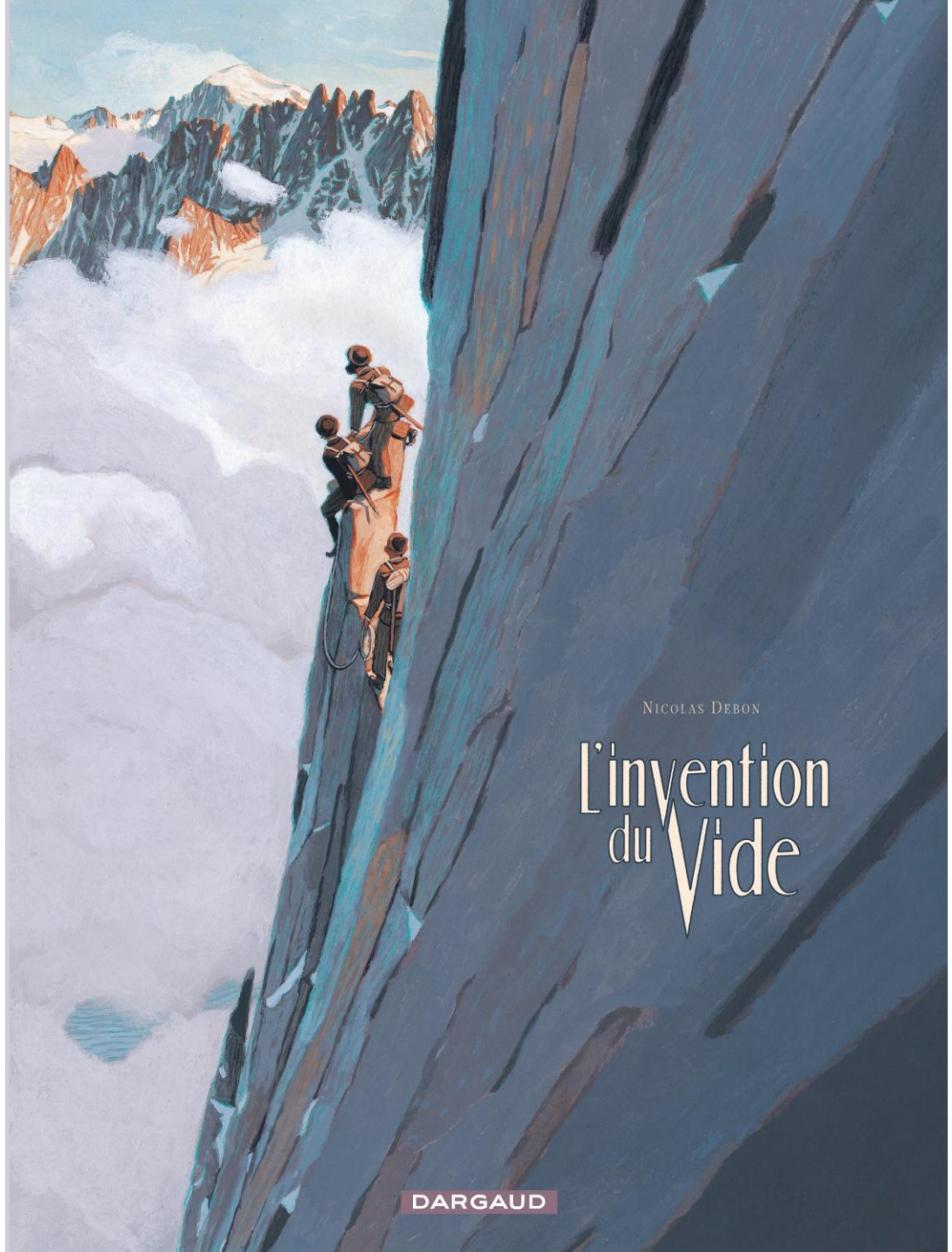
Conclusion

- **Quantum QED Vacuum** is a dynamical medium whose properties can be modified at macroscopic scale, by external limit conditions (e.m. cavity) or by applying external e.m. fields
  - **Already measured**: Emergence of forces (**Casimir pressure**) or change of fundamental constants (**change of the spontaneous emission lifetime**)
  - QED predicts also a **change of the speed of light in vacuum** at macroscopic scale, in the classical sense, **when vacuum is subjected to external e.m. field**

    → Only few experiment to test it

    → Its observation would be a major discovery
- What about **QED vacuum in a gravitationnal field** ?
  - Quantum vacuum is absent in RG and gravitation
  - Do energy density fluctuations of the QED vacuum gravitate ?
  - Is there any link with dark matter or dark energy ?
  - Priority is to test it experimentally

    → The **Archimedes experiment**


Nicolas Debon
L'invention du Vide
DARGAUD