Are the electromagnetic constants really constant ?

Do they depend upon the vacuum conditions ?

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On behalf of the FLOWER collaboration

(F. Couchot, A. Djannati-Atai, M. Urban)

Workshop Quantum Vacuum and Gravitation

04-06 November 2013, Toulouse, France

What is the physical origin of the electromagnetic constants c, ε_0 and μ_0 ?

- **The electrodynamical "constants" c, ε_0 and μ_0 are considered to be fundamental constants**

  $\Rightarrow$ There is no physical mechanism explaining their origin

  $\Rightarrow$ They are assumed to be invariant in space and in time

- **Part I**

  - ✓ We propose a mechanism where ε_0 , μ_0 and c originate from the properties of the quantum vacuum and its interaction with photons

    Urban, Couchot, Sarazin, Djannati Atai, Eur. Phys. Journal D 67, 3 (2013) 58

  - ✓ Two main consequences:

    $\Rightarrow$ stochastic fluctuations of c are expected

    $\Rightarrow$ ε_0 , μ_0 and c can vary if the conditions of the vacuum vary

- **Part II**

  - ✓ Analogy of GR with a static space-time metric and variable c and m
  - ✓ Application to cosmological redshift of supernovea with a static (non expanding) space-time metric

    $\Rightarrow$ Possible interpretation of apparent Λ due to a time variation of the vacuum conditions

An effective description of the quantum vacuum

Vacuum filled with continuously appearing and disappearing **ephemeral** fermion pairs $(f,\bar{f})$

Life time of the pair: $\tau = \frac{\hbar}{2} \times \frac{1}{\text{Energy borrowed from vacuum}}$

An effective description of the quantum vacuum

Vacuum filled with continuously appearing and disappearing ***ephemeral*** fermion pairs $(f,\bar{f})$

- Average energy of a pair $$W_f = K_W\, 2E_{rest} = K_W\, 2m_f c_{rel}^2$$
- Life time of the pair $$\tau_f = \frac{\hbar}{2W_f} = \frac{1}{K_W}\frac{\hbar}{4m_f c_{rel}^2}$$
- Density of the pairs (quantum mechanic) $$N_f \approx \frac{1}{\Delta x^3} \approx \left(\frac{2\pi\hbar}{\Delta p}\right)^3 \approx \left(\frac{\sqrt{K_W^2 - 1}}{\lambda_{C_f}}\right)^3$$
- The global electric charge, color and kinetic moment are null

  But the electric and magnetic dipole moments are not null

- Only the charged fermions are considered (leptons & quarks) since we only study electromagnetic constants. However neutral fermions and bosons are also present.

➡ K_W is the single free parameter in this model

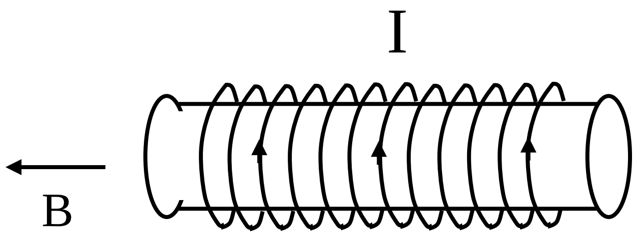
Three distinct definitions for the speed of light in vacuum

- C_{rel} : maximal speed in special relativity $\Rightarrow$ $$E_{rest} = mc_{rel}^2$$
- $C_{E.M.}$: phase velocity of the E.M. wave $\Rightarrow$ $$c_{E.M.} = \frac{1}{\sqrt{\varepsilon_0 \mu_0}}$$
- C_γ : velocity of the photon $\Rightarrow$ $$c_\gamma = \frac{L_{propag}}{T_{propag}}$$

A priori, we have on ***average*** : $$c_{rel} = c_{E.M.} = c_\gamma$$

$$\mu_0$$

Vacuum Permeability μ_0



$B = \mu_0 \times (nI + M)$

M = magnetization of matter

If the matter is removed : $B = \mu_0 nI \neq 0$!!!

The vacuum is "globally" paramagnetic

In our model, μ_0 comes from the magnetization of the $f\bar{f}$ pairs

- We assume that the global kinetic moment of the pair is null

  $\Rightarrow$ spins (fermion, antifermion) = $\uparrow\downarrow$ ou $\downarrow\uparrow$

- But opposite charges $\Rightarrow$ the pair has a global magnetic moment = 2 × Bohr magneton

$$2\mu_f = \frac{2eQ_f\hbar}{2m_f}$$

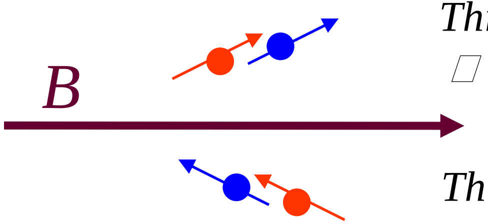
- When an external magnetic field B is applied:

  $\Rightarrow$ pairs whith magnetic moments aligned with B, have a longer life-time τ_f

- The life-time τ_f of the pair depends on its coupling energy with *B:*

$$\tau_f(\theta) = \frac{\hbar/2}{W_f + W_{coupling}}$$

$$W_{coupling} = -2\mu_f B\cos\theta \quad \Longrightarrow \quad \tau_f(\theta) = \frac{\hbar/2}{W_f - 2\mu_f B\cos\theta}$$



This pair has a larger coupling energy
□ it will live longer

This pair has a lower coupling energy
□ it will live shorter

⇒ **The difference of the life-times leads to a global magnetization of the vacuum**

- By Averaging over θ ⇒ $\langle \mathcal{M}_i \rangle = \dfrac{\int_0^\pi 2\mu_i \ \cos\theta \ \tau_i(\theta) \ 2\pi\sin\theta \ d\theta}{\int_0^\pi \tau_i(\theta) \ 2\pi\sin\theta \ d\theta}. \ \simeq \dfrac{4\mu_i^2}{3W_i} B.$

- It lead to a density of magnetization $M_i \ = \ 2N_i \langle \mathcal{M}_i \rangle$

- By summing over all the fermions (3 families)

$$\Longrightarrow \quad \frac{1}{\tilde{\mu}_0} = \sum_i \frac{M_f}{B} = c_{rel}^2 \, e^2 \sum \frac{2N_f Q_f^2 \lambda_{Cf}^2}{3W_f}$$

$$\left.\begin{aligned} W_f &= K_W\, 2m_f c_{rel}^2 \\ N_f &= \left(\frac{\sqrt{K_W^2-1}}{\lambda_{C_f}}\right)^3 \\ \lambda_f &= h/(m_f c_{rel}) \end{aligned}\right\} \Rightarrow \boxed{\tilde{\mu}_0 = \frac{K_W}{\left(\sqrt{K_W^2-1}\right)^3} \times \frac{24\pi^3\hbar}{c_{rel}\, e^2 \sum_f Q_f^2}}$$

We must sum over the 3 charged leptons and the 6 quarks with 3 colors $\Rightarrow$ 3+6×3 = 21 types de fermions.

$$\Rightarrow \sum_f Q_f^2 = e^2 \times \left(3\times 1 + 3\times 3\times\left(\frac{4}{9}+\frac{1}{9}\right)\right) = 8e^2$$

$$\Rightarrow \boxed{\tilde{\mu}_0 = \frac{K_W}{\left(\sqrt{K_W^2-1}\right)^3} \times \frac{3\pi^3\hbar}{c_{rel}\, e^2}}$$

$$\tilde{\mu}_0 = \mu_0 = 4\pi.10^{-7}\,\mathrm{N.A}^{-2} \Rightarrow \boxed{\frac{\left(\sqrt{K_W^2-1}\right)^3}{K_W} = \frac{3\pi^2}{4\alpha}} \Rightarrow \boxed{\mathbf{K_W \approx 32}}$$

The average energy of fermion pairs is ~ 32 times their mass energy ($2mc^2$)

Why $K_W \sim 32$?

If the energy spectrum density of the pairs $f\bar{f}$ is $p(E) = \frac{1}{E^2}$

$$\langle E_f \rangle = \frac{\int_{2mc^2}^{E_{Planck}} E.p(E).dE}{\int_{2mc^2}^{E_{Planck}} p(E).dE} \approx \ln\left(\frac{E_{Planck}}{2m_f c^2}\right) \times 2m_f c^2$$

$$\Rightarrow \begin{cases} K_W \sim 51 \text{ for } e^+e^- \\ K_W \sim 43 \text{ for } t\,\bar{t} \end{cases}$$

$$\varepsilon_0$$

Vacuum Permittivity ε_0

The mechanism is similar to $\mu_0 \Rightarrow \varepsilon_0$ due to the polarization of the pairs $f\bar{f}$ in vacuum

- Electric dipole moment of the pairs $f\bar{f}$ $\quad d_i = Q_i e \delta_i$ $\quad$ (δ_i is the average size of the pair)
- Pairs are polarized during their lifetime τ
- τ depends on the coupling energy of the pair with the electrostatic field E

$$\tau_i(\theta) = \frac{\hbar/2}{\boldsymbol{W_i} - \boldsymbol{d_i E}\cos\theta}$$

- τ is larger when the pair is aligned with E $\Rightarrow$ **POLARISATION**

$$\Rightarrow \quad D = \tilde{\varepsilon}_0 \times E \quad \text{with} \quad \tilde{\varepsilon}_0 = \boldsymbol{e}^2 \sum 2\boldsymbol{N_i Q_i^2} \frac{\delta_i^2}{3\boldsymbol{W_i}}$$

$K_W = 32 \Rightarrow \tilde{\varepsilon}_0 = \varepsilon_0$

- Finally, we can verify that

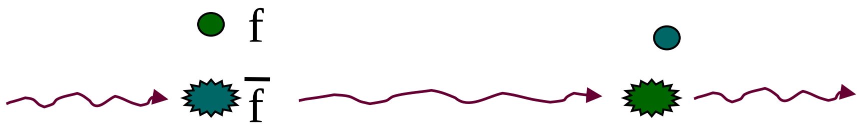
$$c_{E.M.} = \frac{1}{\sqrt{\tilde{\varepsilon}_0 \tilde{\mu}_0}} = c_{rel}$$

Let’s see how a « real » photon would propagate through this vacuum filled by « ephemeral» fermions

Interaction of a photon with the fermion pairs in vacuum

- Real photon is trapped by an ephemeral pair

- As soon as the pair disappears, the photon is relaxed with its initial energy-momentum



- Between two interactions, the vacuum is « empty »

  ⇒ there is no length scale, neither time scale

  ⇒ the photon goes *instantaneously* to the next interaction

- The duration of the capture ≈ the lifetime of the pair ⇒ finite transit time of the photon ⇒ finite velocity

- A photon of a given helicity interact only with a fermion of opposite helicity (in order to flip its spin)

Derivation of the photon velocity c_γ

- σ_f = cross-section for a photon to interact with a $f\bar{f}$ *pair*

- When a photon crosses a length L of vacuum

  The average number of stops on the $f\bar{f}$ pairs is $N_{stop,f} = L \times N_f \times \sigma_f$

  And the average duration of stops on the $f\bar{f}$ pairs is $\bar{T}_f = N_{stop,f} \times \frac{\tau_f}{2}$

- The average total duration for a photon to cross a length L is $\bar{T} = \sum_f N_{stop,f} \times \frac{\tau_f}{2}$

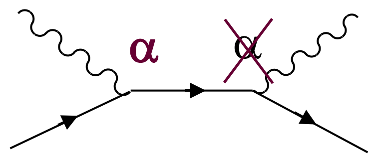
- One obtains the general expression of the photon velocity in vacuum:

$$c_\gamma = \frac{L}{\bar{T}} = \frac{1}{\sum \sigma_f \times N_f \times \tau_f / 2}$$

Derivation of the photon velocity c_γ

$$c_\gamma = \frac{L}{\overline{T}} = \frac{1}{\sum \sigma_f \times N_f \times \tau_f / 2} \Rightarrow \left.\begin{array}{l} \tau_f = \dfrac{1}{K_W}\dfrac{\hbar}{4 m_f c_{rel}^2} \\ N_f = \left(\dfrac{\sqrt{K_W^2 - 1}}{\lambda_{C_f}}\right)^3 \\ K_W \approx 32 \end{array}\right\} \Rightarrow c_\gamma = \frac{64\alpha}{3\pi} \times \frac{1}{\sum \sigma_f^2 / \lambda_{C_f}^2} \times c_{rel}$$

We can show that: $c_\gamma = c_{rel}$ if $\sigma_f = 4 \times \dfrac{\sigma_{\text{Thomson}}}{\alpha}$



We get a complete coherent model:

$$\langle c_\gamma \rangle = c_{E.M.} = c_{rel} \quad \left\{ \begin{array}{l} \langle c_\gamma \rangle = \text{average velocity of the photon} \\ c_{E.M.} = \dfrac{1}{\sqrt{\mu_0 \varepsilon_0}} \\ c_{rel} : \quad E = m c_{relativiste}^2 \end{array} \right.$$

Stochastic fluctuations of the speed of light

The successives interactions of the photon are independant

$\Rightarrow$ The number of captures and their duration fluctuate statistically

$\Rightarrow$ The propagation time of a photon to cross a length L of vacuum must fluctuate as

$$\sigma_t(L) = \sqrt{L} \times \frac{1}{c} \times \sqrt{\frac{\lambda_{Ce}}{96\pi\, K_W}}$$

$$\boxed{K_W \approx 32 \;\Rightarrow\; \sigma_t(L) = 50\,\mathrm{as} \times \sqrt{L(\mathrm{m})}}$$

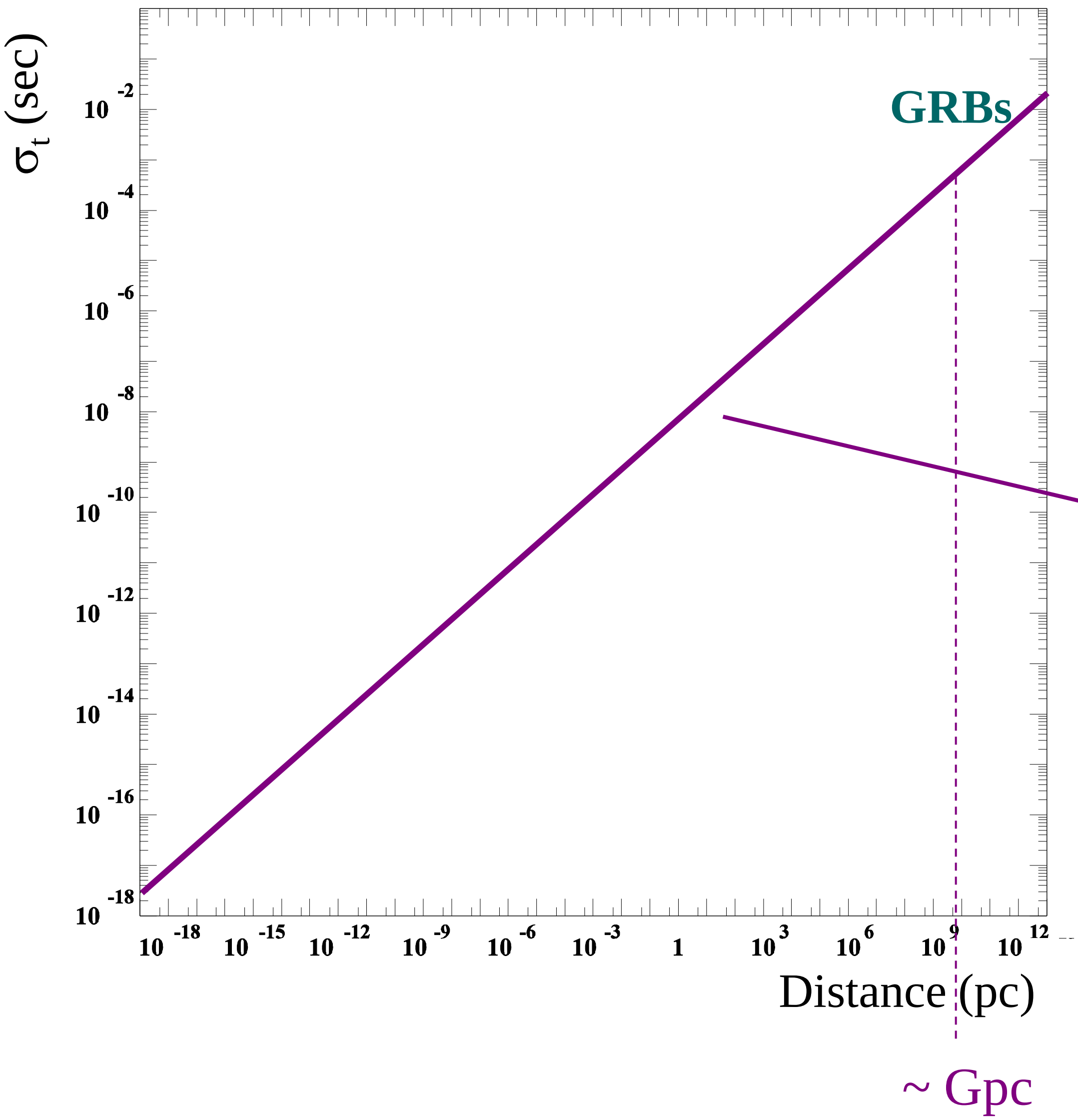
Search for a broadening of the time width of a light pulse
as the square root of the transit length

Remarks:

• No dispersion in frequency is expected (energy of the photon is conserved)

• Phase fluctuations are expected to be much lower (see "*reply to comment*" in EPJ 2013)

Available constraints



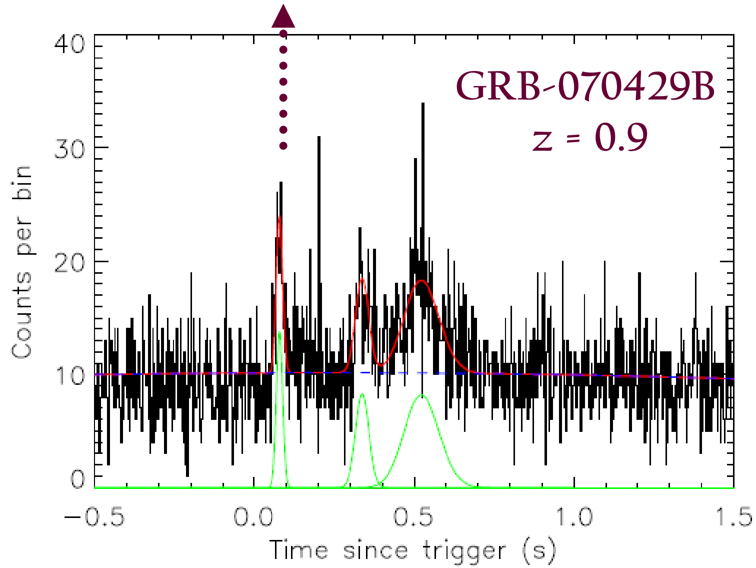
0.05 fs.m$^{1/2}$
~ 9 ns.pc$^{1/2}$

(1 m ≈ 30 zpc)

Gamma Ray Bursts

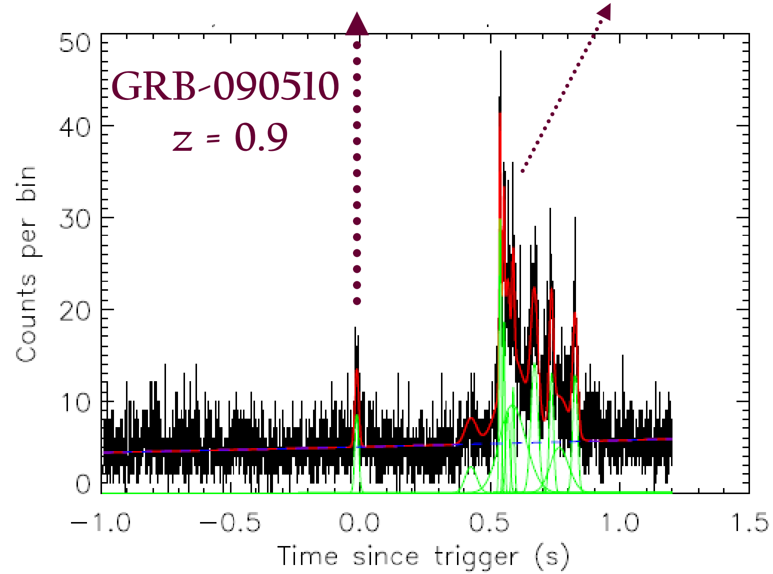
- ~ 20 short GRB's have been observed by SWIFT, Konus-Wind of FERMI with a reliable measured redshift
- An analysis of their light curve is in progress, in coll. with N. Bhat (Univ. Alabama in Huntsville)
- Preliminary results (after analysing 7 GRBs):

σ_t = 10 ms



σ_t = 9 ms

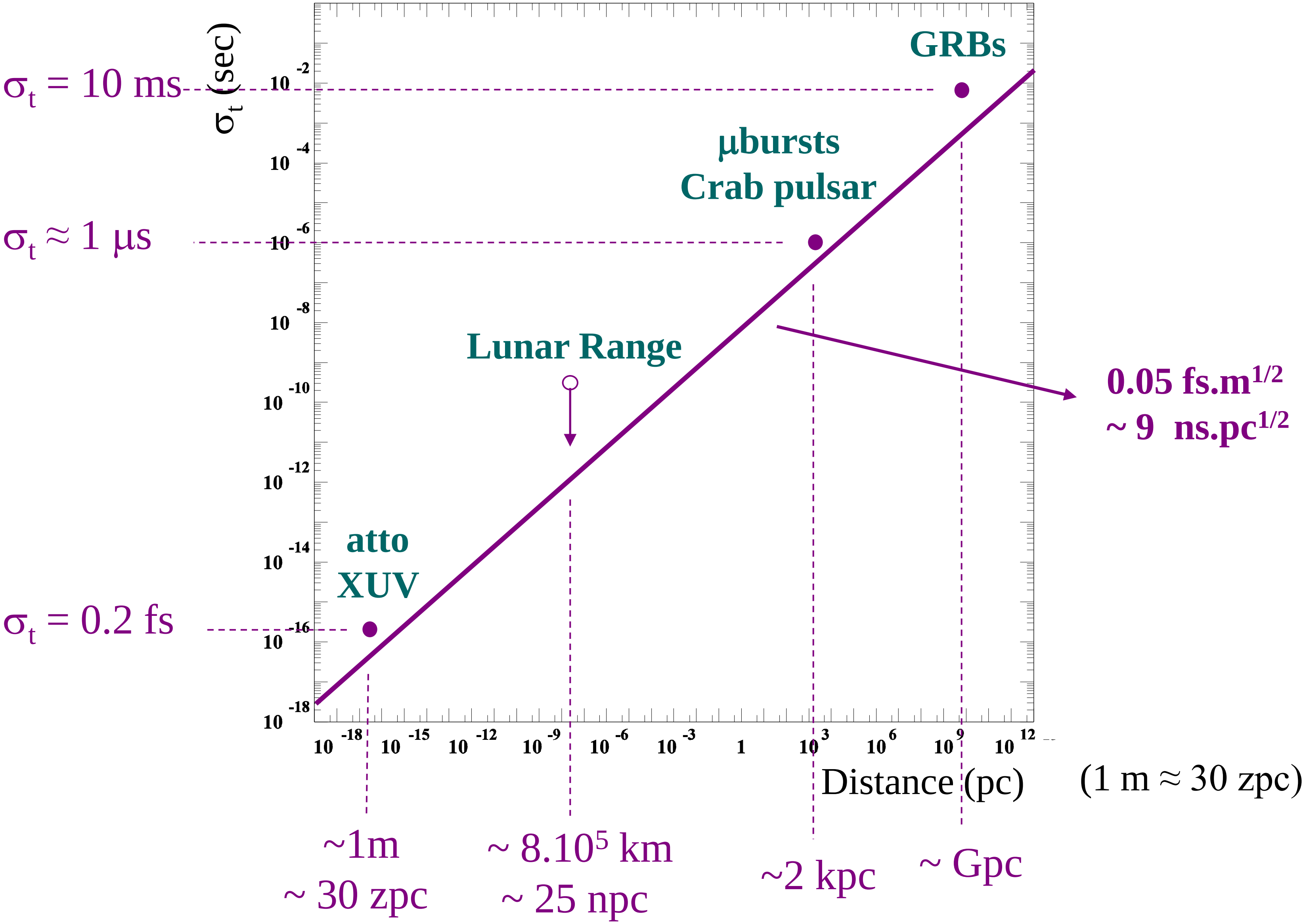
$\sigma_t = 4\ ms\ ?$



$z = 0.9 \;\Rightarrow\; d_L \approx 2.10^{26}$ m

$\boxed{\boldsymbol{\sigma_0 \leq 750\ \text{as.m}^{-1/2}}}$

Available constraints

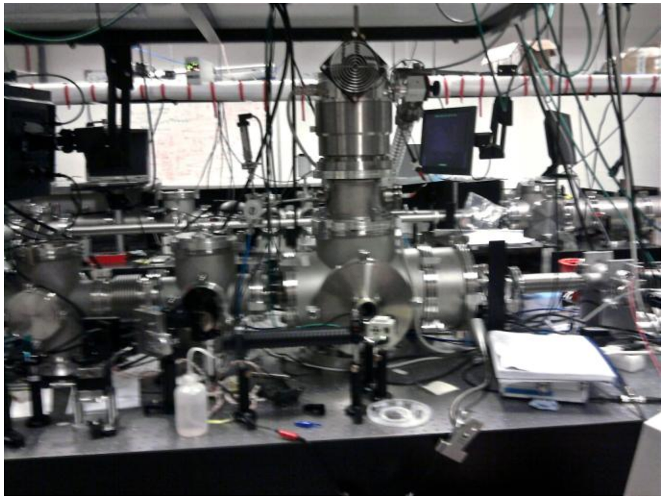


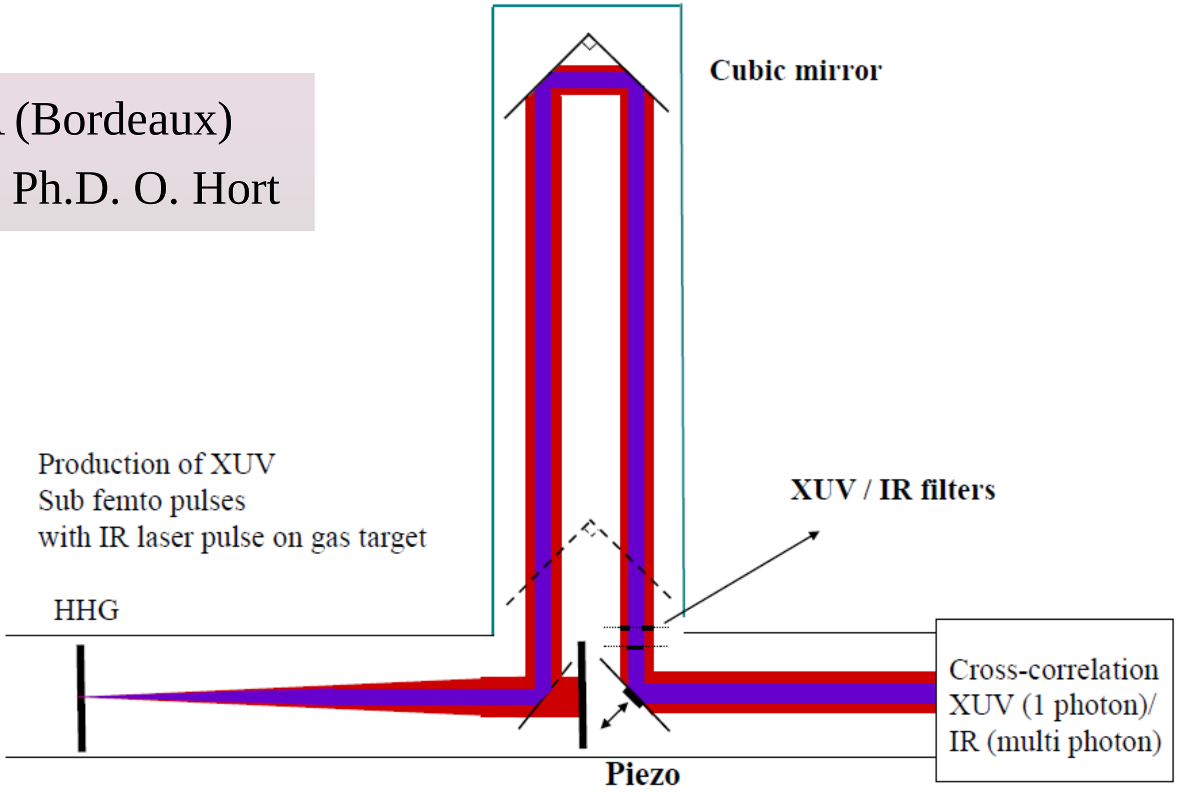
The *atto-FLOWER* experimental project

We propose to measure the duration of attosecond XUV pulses after crossing few tens of meter of vacuum

Assuming XUV pulse $\sigma_t = 0.1$ fs $\xrightarrow[\sigma\, =\, 0.05\ \mathrm{fs.m}^{1/2}]{2\times 25\ \mathrm{m}}$ $\sigma_t \approx 0.4$ fs ?

New collaboration with CELIA (Bordeaux)
E. Constant, E. Mevel, F. Catoire, Ph.D. O. Hort





PART II

Variation of the electromagnetic constants

- **ε_0, μ_0 and *c* are not constant but depend upon the vacuum parameters**

  $\Rightarrow$ they should vary when the vacuum parameters are modfied by an external field

- **They should vary when the vacuum is stressed by an external field**

  $\Rightarrow$ Gravitational field : analogy with the General Relativity

- **They could vary in time if the vacuum also varies in time**

  $\Rightarrow$ Cosmology : analogy with the apparent expansion and its acceleration

- We will assume that *e* and $\hbar$ are fundamental constants

$$\varepsilon_0 = \mathrm{cte} \times \frac{e^2}{\hbar c_{rel}} \Rightarrow \varepsilon_0 \times c = \mathrm{cte}$$

$$\Rightarrow \boxed{\alpha = \frac{e^2}{4\pi\varepsilon_0 \hbar c} = \mathrm{cte}}$$

The vacuum stressed by a gravitationnal field

- **General relativity**: geometrical theory based on the equivalent principle
  - ✓ The constants are constant
  - ✓ But we must modify the “mathematical” space-time coordinates

- **A possible physical analogy**:
  - ✓ We do not modify the “mathematical” space-time coordinates
    - $\Rightarrow$ Static and flat space-time metric (no curvature)
  - ✓ But we accept that *c* and *m* are modified (the vacuum conditions are modified)
    - – Variation of *c*: deflection of light, shapiro effect
    - – Variation of *m* and *c*: gravitational redshift, perihelion shift

Deflection of the light

➢ **The analogy of GR with varying vacuum optical index in a flat space time is an old idea** to explain the deflection of light by a gravitational mass

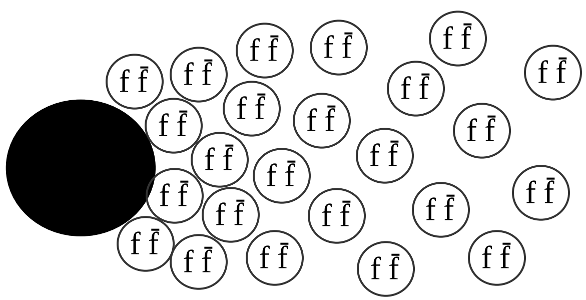
- Eddington *(Space, Time and Gravitation*, p. 109 Cambridge University Press 1920)
- Landau & Lifshitz: *(The Classical Theory of Fields, Pergamon Press 1975)*
- Felice *(Gen. Rel. Grav., Vol. 2, 334 1971)* & Evans, Nandi & Islam *(Gen. Rel. Grav. 28, 413, 1996)*

$$\boxed{c(r) = \frac{c_\infty}{n(r)} \approx c_\infty\left(1 - \frac{2GM}{rc_\infty^2}\right)}$$

c decreases when the photon get closer to the mass M

➢ **In this model, a mechanism exists to modify *c***

M



$$\begin{cases} N_f \text{ is larger close to the mass M} \\ t_f \text{ is larger close to the mass M} \end{cases}$$

$$\Rightarrow \quad c(r) = c_\infty \times \frac{N_\infty \tau_\infty \sigma_\infty}{N(r)\tau(r)\sigma(r)} < c_\infty$$

Gravitational Blueshift

- Generalization for gravitational redshift, and other GR effects with variable optical index have been proposed

  See: Evans, Nandi & Islam *(Gen. Rel. Grav. 28, 413, 1996)*

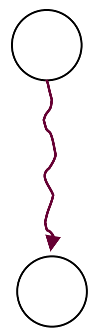
  However:

  - The energy of the photon was not conserved during its propagation
  - The advance of the perihely was not correctly explained…

Gravitational Blueshift

In order to **conserve the energy of the photon during its propagation, we also assume that the inertial mass of a particle varies** when the vacuum is stressed by a gravitational field

$$E(r_1) = \mathrm{cte} \times m_e(r_1) c^2(r_1)$$



$\boldsymbol{E_\gamma = pc = \mathrm{cte}}$

c decreases

p increases

$$E(r_2) = \mathrm{cte} \times m_e(r_2) c^2(r_2)$$

Pound & Rebka : $E(r_2) = E(r_1) \times \left(1 - \dfrac{(r_1 - r_2)}{r_1 r_2} \dfrac{GM}{c_\infty^2}\right)$

$$m(r) c^2(r) = m_\infty c_\infty^2 \left(1 - \frac{GM}{r c_\infty^2}\right) \Rightarrow \boxed{m(r) = m_\infty \left(1 + \frac{3GM}{r c_\infty^2}\right)}$$

Varying inertial mass

$$\boxed{m(r) = m_{\infty}\left(1 + \frac{3GM}{rc_{\infty}^{2}}\right)}$$

✓ This is what we expect if *m* corresponds to an electromagnetic self-energy with vayring ε_0

(see Wilson Phys. Rev. 17, 54, 1921)

✓ Variation of the v.e.v. of the Higgs field ?

✓ Higgs doublet = condensate of $t\bar{t}$ +$\nu_R\nu_L$ from vacuum fluctuation

$\Rightarrow$ mass = self-energy ?

(see Smetana arXiv:1309.4688)

With varying *c* and *m* in a static and flat space-time metric

$$\boxed{\begin{aligned} c(r) &= \frac{c_\infty}{n(r)} = c_\infty\left(1-\frac{2GM}{rc_\infty^2}\right) \\ m(r) &= m_\infty\left(1+\frac{3GM}{rc_\infty^2}\right) \end{aligned}}$$

we can fit well the observables

– Deflection of light

– Shapiro effect

– Gravitational redshift

– Perihelion shift of Mercury

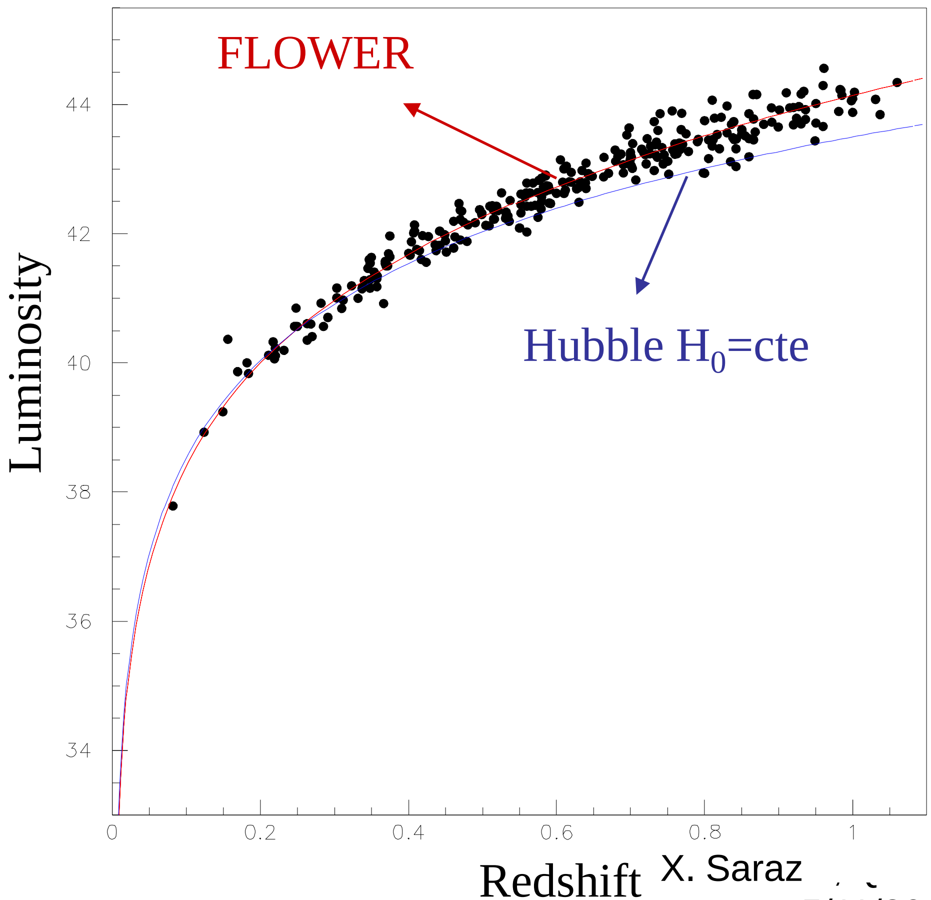
Cosmological Redshift

We follow the same idea:

✓ Static & flat space-time metric (no expansion of the metric)

✓ Vacuum conditions modified in time: *m* and *c* vary in time

Supernovae Survey



$$c(t) = \frac{c_0}{n(t)} = \frac{c_0}{\sqrt{(1+t/\tau)}}$$

$$m(t) = m_0 (1+t/\tau)^{3/2}$$

t = epoch of the supernovae

Today *t* = 0

τ is the only free parameter of the fit

τ ~ 3.5 Gy

$$\boxed{n(t) = \sqrt{(1+t/\tau)}\ \ ?}$$

What $n(t) = \sqrt{(1+t/\tau)}$ could mean ?

"F=ma" optics, Evans, Am. J. Phys. 54, 876 (1986)

Fermat's principle $\equiv$ Principle of least action

$$\delta\left(\int n(r)dr\right) = 0 \qquad \delta\left(\int L(r)dr\right) = 0$$

$$\frac{n^2}{2} \equiv \phi$$

n = optical index $\qquad$ ϕ = potential energy

$$n(t) = \sqrt{(1+t/\tau)} \equiv \phi(t) \propto 1 + \frac{t}{\tau}$$

$$\boxed{\text{The potential energy of the vacuum decreases } \textbf{\textit{linearly}} \text{ in time}}$$

And do not ask me what it means !…

Conclusions

- ε_0, μ_0 and *c* originate from the properties of the vacuum and its interaction with photons
- It is a discrete description of the vacuum
- Stochastic fluctuations of the photon propagation time in vacuum are predicted

$$\sigma_t(L) \approx 50\,\mathrm{as} \times \sqrt{L(\mathrm{m})}$$

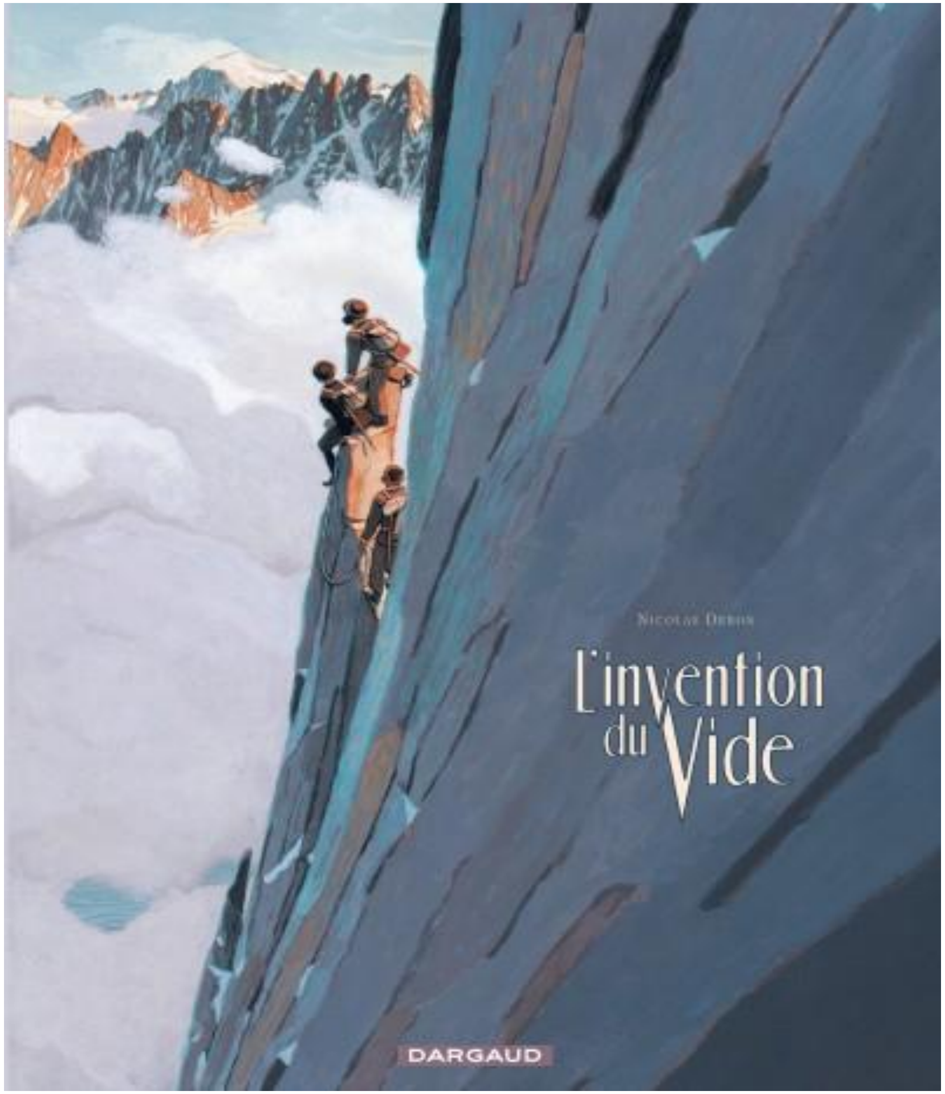
We have started an experimental test in collaboration with CELIA using atto XUV pulses

- ε_0, μ_0 and *c* are not constant but can vary if the parameters of the vacuum vary
- Analogy of GR is possible with a static metric but with varying *c* and *m*
- Cosmology with a static space-time metric (no metric expansion) but time varying vacuum
  - ✓ Cosmological redshift is due to time variation of *c* and *m*
  - ✓ Apparent acceleration of Supernovae redshift is well fitted by a simple time variation of *c* equivalent to a linear vacuum potential variation

FLOWER

Fluctuations of the Light velOcity WhatEver the Reason

François Couchot, Arache Djannati-Atai, Xavier Sarazin, Marcel Urban
LAL Paris-Sud Orsay, APC Paris-Diderot



2^{nd} experimental test

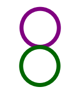
The “vacuum optical index” n

n < 1 inside an ultra high intensity laser pulse

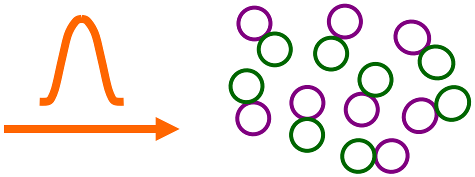
Effet SHADOK

The probe pulse, circularly polarized +1, moves with a velocity c

Virtual fermion antifermion pair

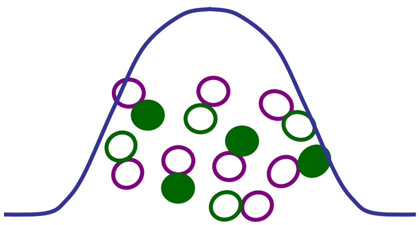


s = +1/2
s = −1/2



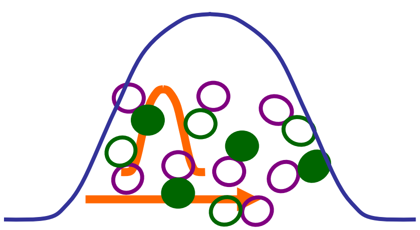
$$c = \frac{1}{\sum \sigma_i \times N_i \times \tau_i / 2} = 3.10^8\, ms^{-1}$$

A pump laser, circularly polarized +1, with ultra high intensity, masks some virtual pairs



Number of occupied pairs $\Delta N = N_\gamma \sum (\sigma_i \times N_i)$

The probe pulse (circularly polarized +1) will move with a higher velocity c^*



$$c^* = \frac{1}{\sum \sigma_i \times (N_i - \Delta N_i) \times \tau_i / 2} \approx \frac{c}{1 - N_\gamma / (64 N_e)}$$

$$\boxed{\frac{\delta c}{c} = 1 - n \approx \frac{N_\gamma}{64 N_e}}$$

N_e is the e^+e^- pair density in vacuum

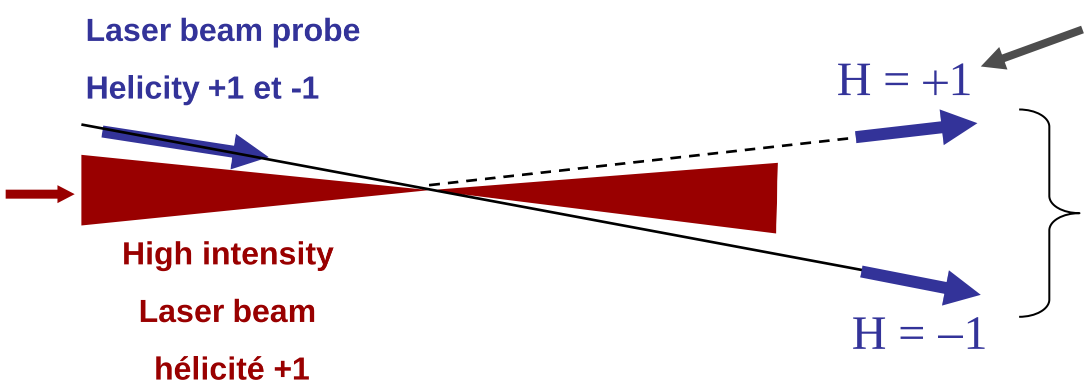
Light Saber

$$\boxed{1-n \approx \frac{N_\gamma}{64\,N_e}}$$ with $$N_e \approx \left(\frac{\sqrt{K_W^2-1}}{\lambda_C}\right)^3 \approx \left(\frac{32}{\lambda_C}\right)^3 \approx \left(\frac{1}{76\,\mathrm{fm}}\right)^3 \approx 2.10^{39}\ \mathrm{cm}^{-3}$$

Laserix @ Orsay (40 J, 30 fs, 0.1 Hz)
Focalized in 10 μm^2

➡ $\tilde{N}_\gamma \approx 10^{21}$ photons/pulse
$V_{pulse} \approx 4\ 10^{-17}\ \mathrm{m}^3$

➡ $$\boxed{1-n \approx 2\,10^{-4}}$$



This guy should literally bounce back from the intense beam (like internal reflections from glass to air)

Angular separation $\Delta\theta$ between the two helicities

➡ $$\boxed{\Delta\theta \approx \sqrt{2(1-n)} \approx 1\,\mathrm{mrad}}$$