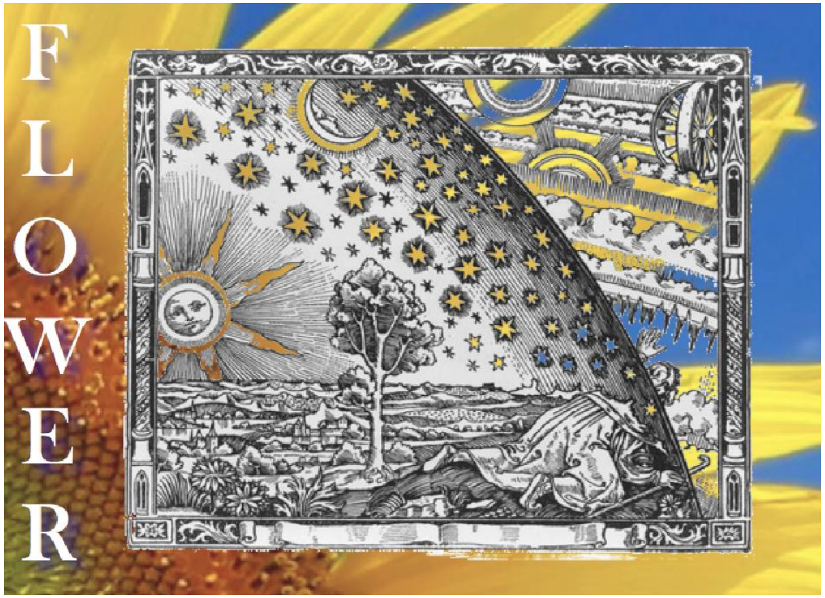
FLOWER

Fluctuations of the **L**ight vel**O**city **W**hat**E**ver the **R**eason

François Couchot, Xavier Sarazin, Marcel Urban
LAL Paris-Sud, Orsay

Arache Djannati-Atai
APC, Paris-Diderot



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

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

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

  $\Rightarrow$ stochastic fluctuations of c are expected

M. Urban et al., Eur. Phys. Journal D 67, 3 (2013) 58

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
- All the charged fermions are considered: leptons & quarks

➡ 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 $\Rightarrow$ $E_{rest} = mc_{rel}^2$

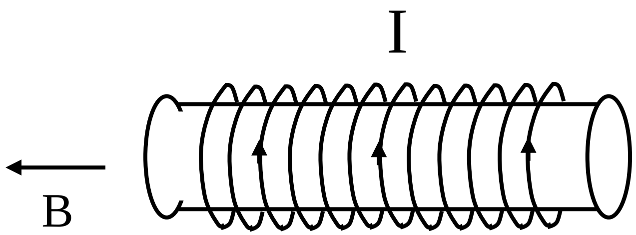
- ***C**$_{E.M.}$* : phase velocity of the E.M. wave $\Rightarrow$ $c_{E.M.} = \dfrac{1}{\sqrt{\varepsilon_0 \mu_0}}$

- ***C**$_{\gamma}$* : velocity of the photon $\Rightarrow$ $c_{\gamma} = \dfrac{L_{propag}}{T_{propag}}$

A priori, we have in ***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) = ↑↓ ou ↓↑

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

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

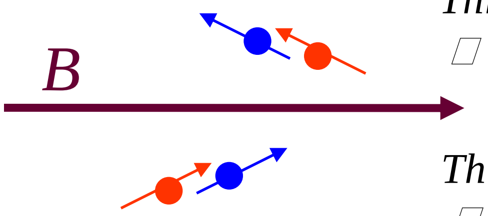
- When an external magnetic field B is applied:

  $\Rightarrow$ The magnetic moment of the pair aligns along B during its life-time τ_f

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

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

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



This pair has a larger energy
□ it will live longer

This pair has a lower energy
□ it will live shorter

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

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

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

- By summing over all the fermions (3 families)

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

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

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 ($2mc^2$)

$$\varepsilon_0$$

Vacuum Permittivity ε_0

- The mechanism is similar to μ_0
  $\Rightarrow$ ε_0 due to the polarization of the pairs $f\bar{f}$ in vacuum

- Electric dipole moment of the pairs $f\bar{f}$ $\quad d_i = Q_i e \delta_i$
  (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**

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

➢ If the « natural » size of a pair is the **Compton wavelength** $\delta_i = \lambda\!\!\!^{-}_i$

$$\Rightarrow \quad \tilde{\varepsilon}_0 = \frac{\left(\sqrt{K_W^2 - 1}\right)^3}{K_W} \times \frac{e^2}{24\pi^3 \hbar c_{rel}} \times \sum_f Q_f^2 = \frac{\left(\sqrt{K_W^2 - 1}\right)^3}{K_W} \times \frac{e^2}{3\pi^3 \hbar c_{rel}}$$

➢ We remind that $\tilde{\mu}_0 = \mu_0 \Rightarrow \frac{\left(\sqrt{K_W^2 - 1}\right)^3}{K_W} = \frac{3\pi^2}{4\alpha}$

$$\Rightarrow \quad \tilde{\varepsilon}_0 = \frac{3\pi^2}{4\alpha} \times \frac{e^2}{3\pi^3\, \hbar c_{rel}} = \frac{e^2}{4\pi\, \alpha\, \hbar c_{rel}} = \varepsilon_0$$

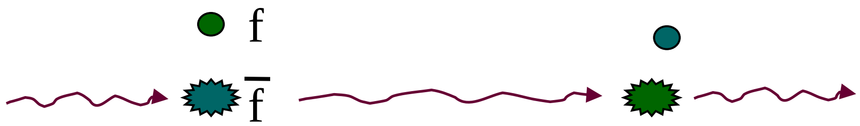
$$\Rightarrow \quad \tilde{\varepsilon}_0 = \varepsilon_0$$

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 $\bar{T} = \sum_f N_{stop,f} \times \frac{\tau_f}{2}$

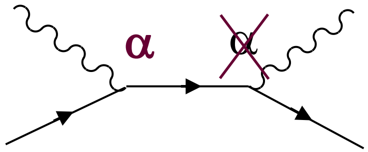
- One obtains the general expression of the photon velocity in vacuum:

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

Derivation of the photon velocity c_γ

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

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



We get a complete coherent model:

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

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

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

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

Remarks:

- no dispersion in frequency is expected (energy of the photon is conserved)
- no phase fluctuation is expected (fluctuations are canceled in $c_{E.M.}$)

Few comments

- This model proposes a mechanism where ε_0 , μ_0 and c are not fundamental constants but originate from the properties of the quantum vacuum

- These "constants" can vary if the parameters of the vacuum vary (density or lifetime of the fermions pairs)

- This simple model must be considered as a « Toy Model » to predict new experimental phenomena

- **I will review two experimental predictions:**

  - ✓ **Stochastic fluctuations of the propagation time of photons in vacuum**

    $\Rightarrow$ tests in progress with GRBs and with XUV atto pulses in CELIA

  - ✓ **Variation of μ_0 when vacuum is stressed by high intensity laser**

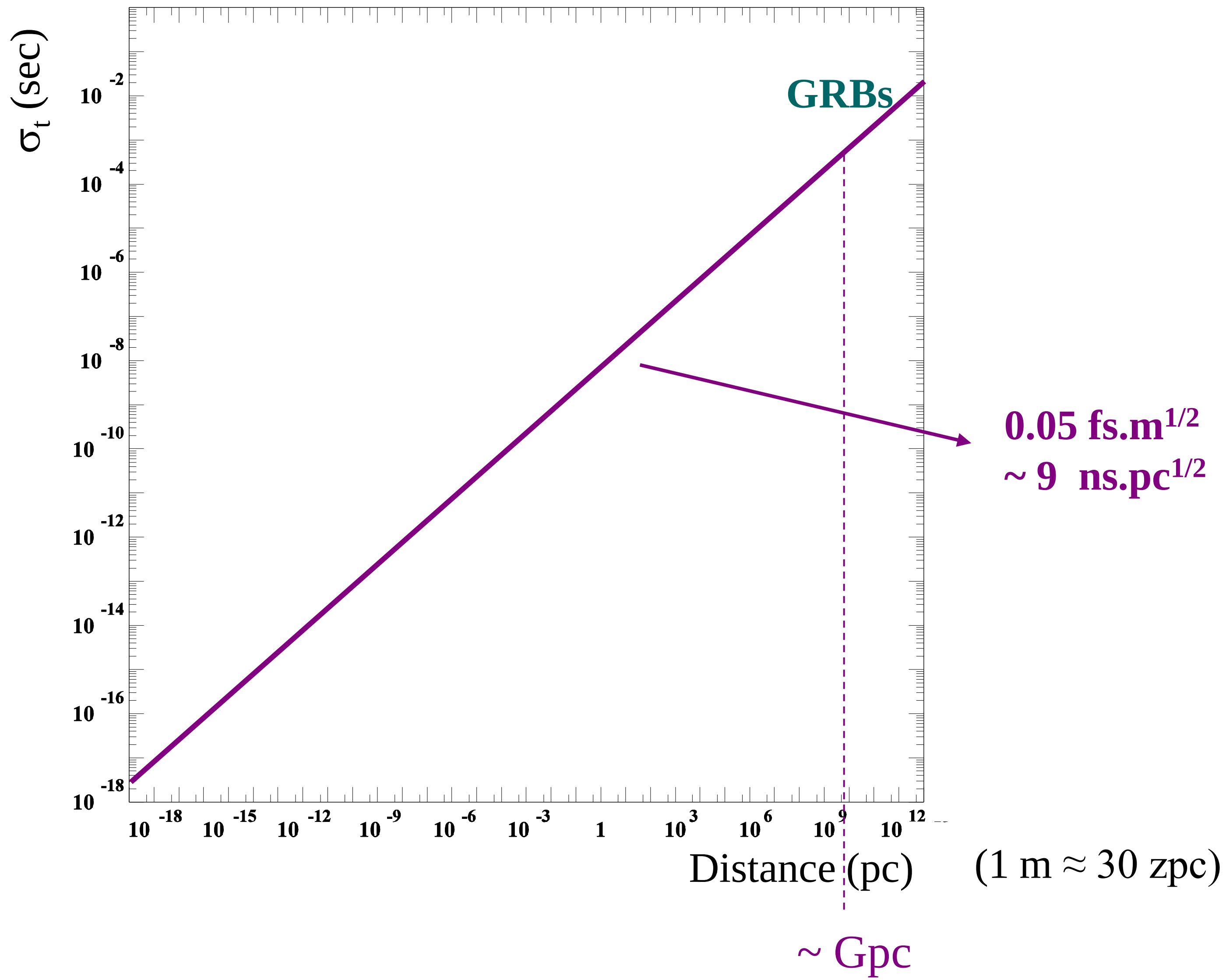
1st experimental test

Stochastic Fluctuations
of the photon propagation time in vacuum

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

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

Available constraints



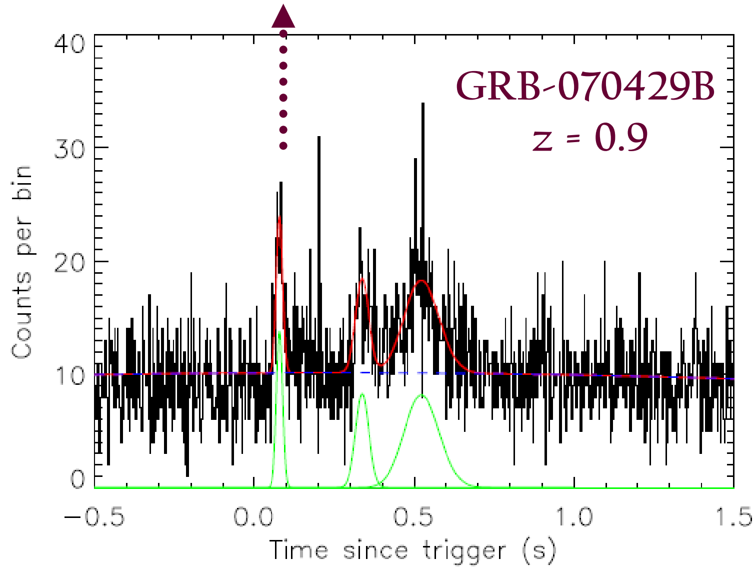
Gamma Ray Bursts

➢ ~ 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)

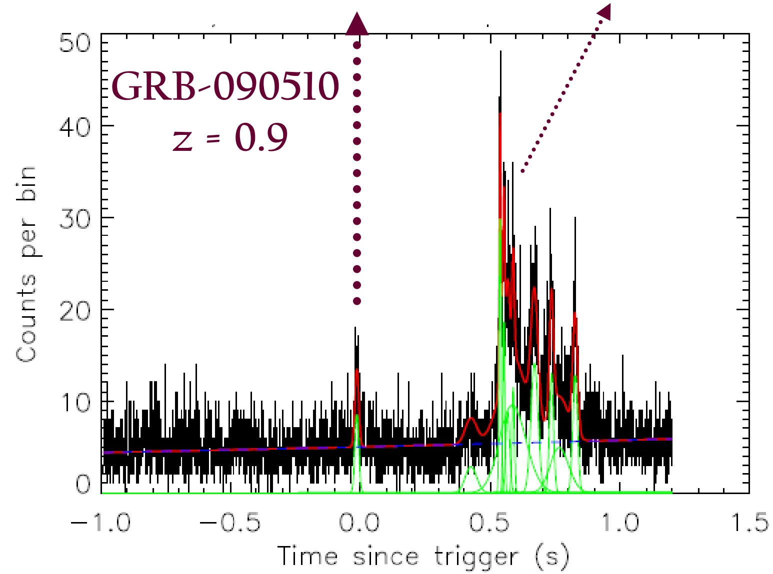
➢ Preliminary results (after analysing 7 GRBs):

σ_t = 10 ms



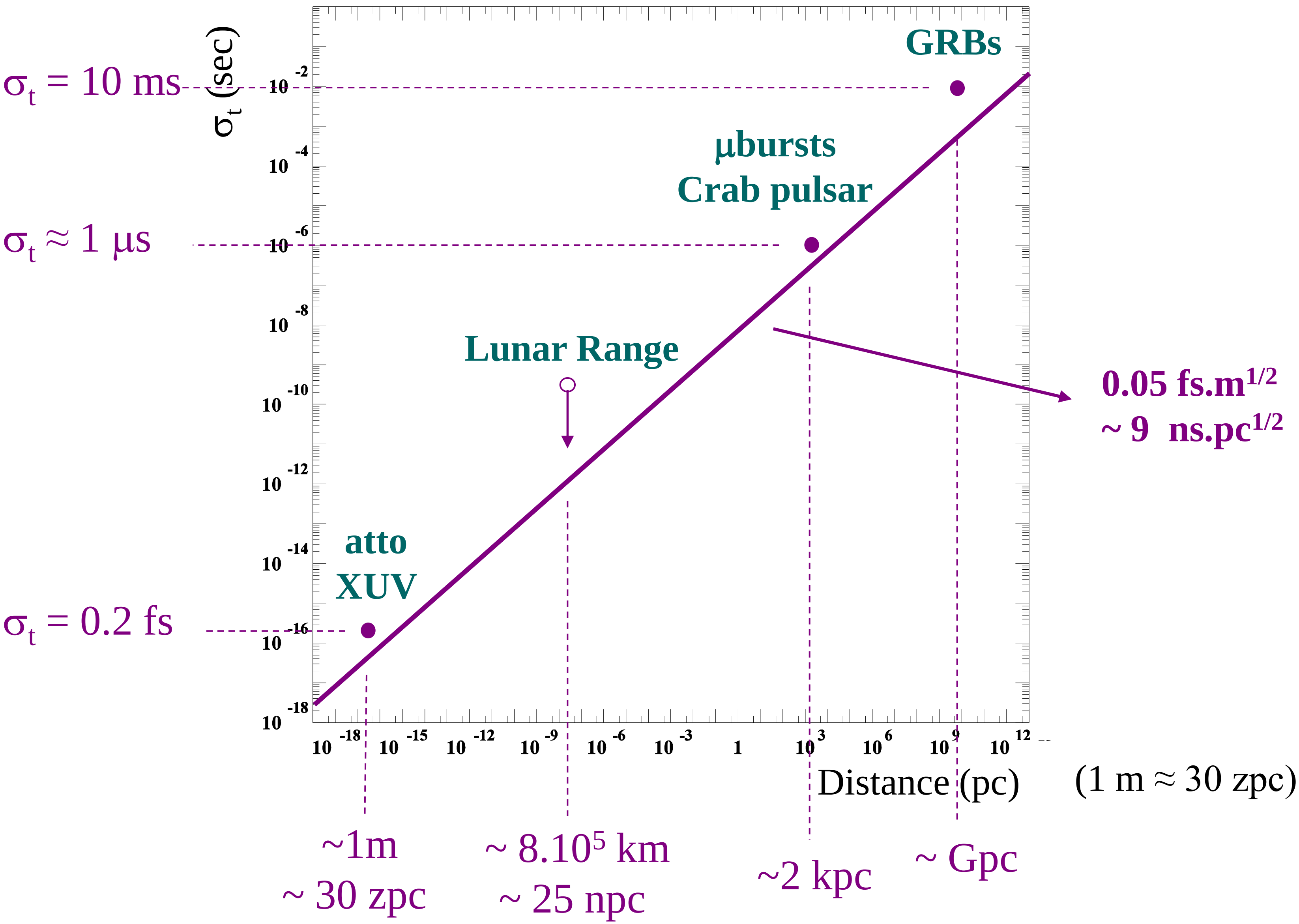
σ_t = 9 ms

σ_t = 4 ms ?



$z = 0.9 \Rightarrow d_L \approx 2.10^{26}$ m ➡ $\boldsymbol{\sigma_0 \leq 750}$ **as.m$^{-1/2}$**

Available constraints

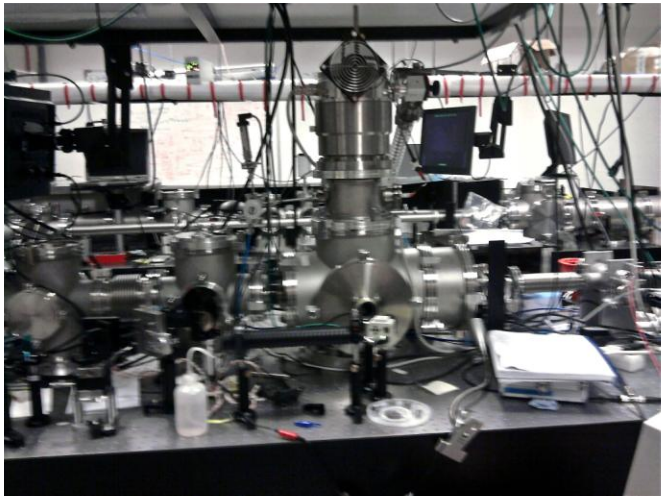


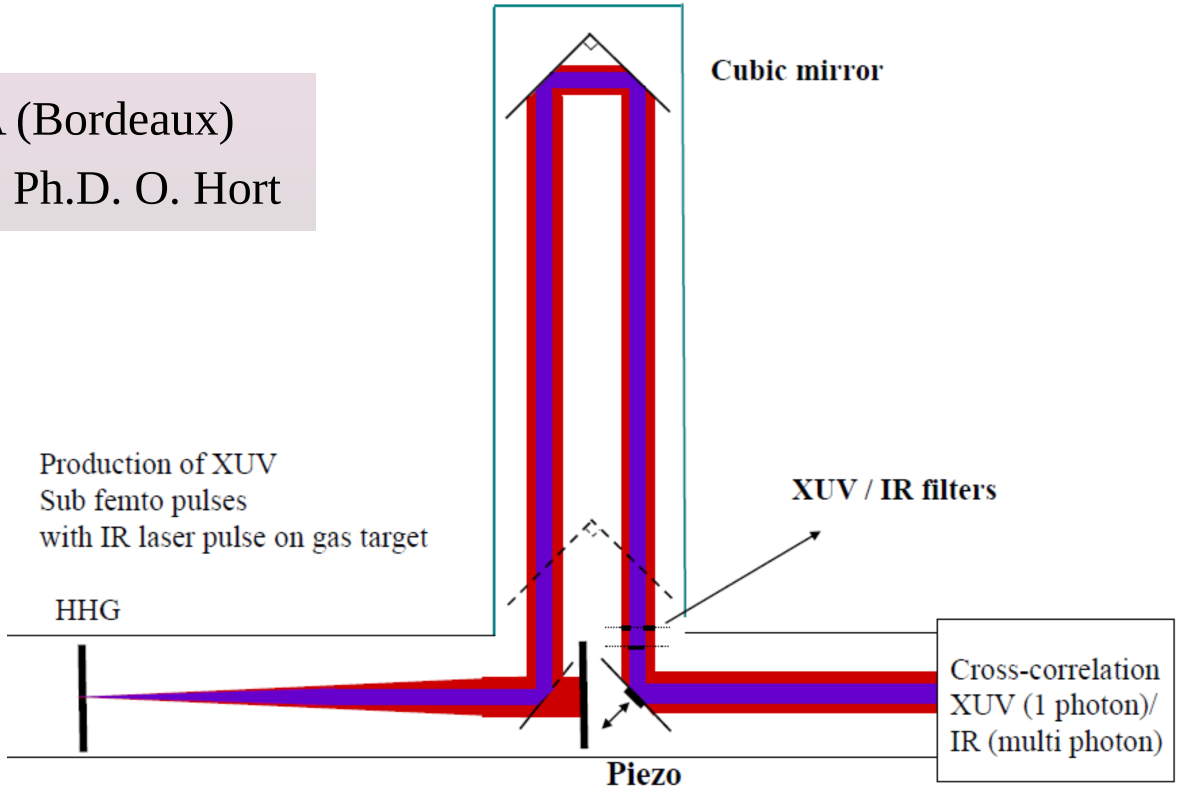
The *atto-FLOWER* experimental project

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

Assuming XUV pulse $\sigma_t = 0.2$ fs $\xrightarrow[\sigma = 0.05\ \text{fs.m}^{1/2}]{2\times 25\ \text{m}}$ $\sigma_t \approx 0.4$ fs ?

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





2^{nd} experimental test

Variation of μ_0 or ε_0

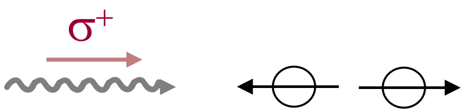
when the vacuum is stressed

by an ultra high intensity laser pulse ?

Transient variation of μ_0 inside an high intensity laser pulse

In our model, a photon is equivalent to
a $f\bar{f}$ fermion pair with a magnetic moment = 0

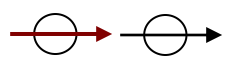
Photon arriving
on a free $f f$ pair



σ=−1/2 σ=+1/2

$\Rightarrow \boldsymbol{\mu_f = 2 \times \mu_B}$

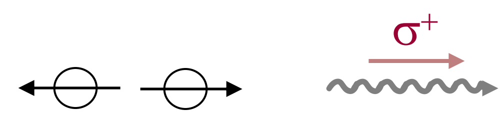
Photon trapped
by the $f f$ pair
The pair is “occupied”



σ=+1/2 σ=+1/2

$\Rightarrow \boldsymbol{\mu_f = 0}$

Photon released
by the $f f$ pair
The pair is free again



σ=−1/2 σ=+1/2

$\Rightarrow \boldsymbol{\mu_f = 2 \times \mu_B}$

A polarized light pulse should modify the vacuum

$\Rightarrow$ The density of magnetization is reduced inside the pulse

$\Rightarrow$ The vacuum permeability μ_0 should increase !

Transient variation of μ_0 inside an high intensity laser pulse

$$\left.\begin{array}{l} \mathbf{N_\gamma \approx 10^{20}\ photons/pulse} \\ \text{Pulse } \Delta t \sim 100\text{ ps } (\sim 3\text{cm}) \\ \text{Waist} \sim 100\ \mu\text{m} \end{array}\right\} \Rightarrow \ \sim 4\ 10^{29}\ \text{photons/m}^3$$

The density of ephemeral e^+/e^- pairs in vacuum is

$$N_e \approx \left(\frac{\sqrt{K_W^2 - 1}}{\lambda_C}\right)^3 \approx \left(\frac{32}{\lambda_C}\right)^3 \approx 2.10^{39}\ \text{electrons/ m}^3$$

$$\Rightarrow \quad \frac{\Delta\mu_0}{\mu_0} \approx \frac{1}{8} \times \frac{N_\gamma}{N_e} \approx \frac{1}{4} 10^{-10}$$

(exact calculation is needed)

This expected effect could be tested

Also 2nd order non linear effects (as in QED) are expected: exact calculations are needed

Conclusions

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

  $\Rightarrow \varepsilon_0$, μ_0 and c can vary if the parameters of the vacuum vary

- **Two experimental predictions :**

  - ✓ Stochastic fluctuations of the photon propagation time in vacuum

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

    An experimental test in under progress in CELIA with XUV attosecond pulses

  - ✓ Transient variation of μ_0 or ε_0 inside an ultra high intensity laser pulse

Why $K_W \sim 32$?

$K_W \sim 32$ if the energy spectrum density of the pairs $f\bar{f}$ is $p(E) = \dfrac{1}{E^2}$

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

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