Could the apparent expansion of the Universe be due to a decreasing vacuum refractive index ?

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Gravitation and Vacuum

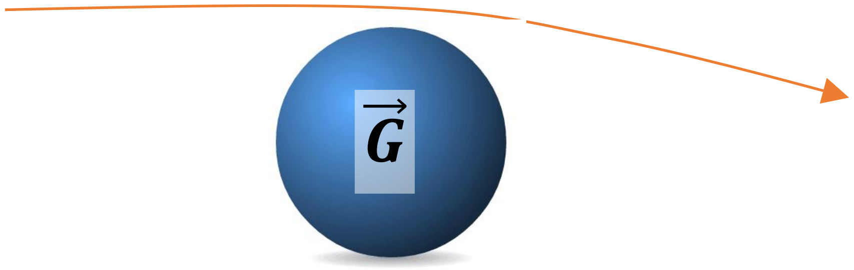
- Theory of General Relativity is a geometric description
  - Gravitation = curvature of the spacetime metric
  - Vacuum has no physical role

- Physical description of static field (*initially proposed by Wilson 1921 and Dicke 1957*)
  - Gravitation = real spatial change of ε_0 and μ_0 around the grav. mass

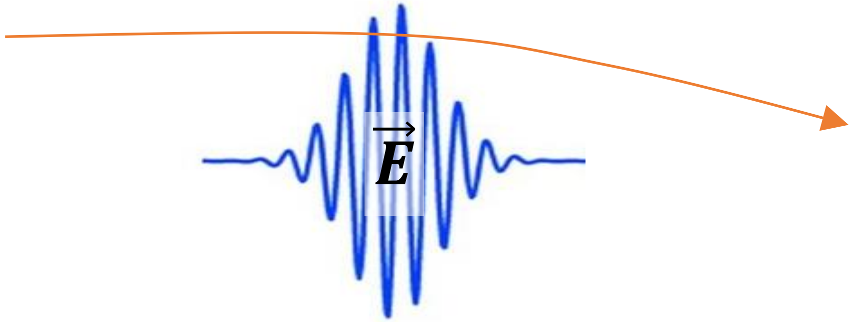
  $\Rightarrow$ Modification of the vacuum refractive index around the grav. mass

  Wilson-Dicke Analogy

Wilson (1921)
Dicke (1957)
Eddington (1920)
Pauli (1958)
Landau & Lifshitz (1975)
Felice (1971)
Evans et al. (1996)



No quantum field theory to understand the change of ε_0 and μ_0



Non linear QED: vacuum refractive index (ε_0, μ_0) modified by strong E,B fields

- *Battesti & Rizzo, Rep. Prog. Phys. (2013)*
- ***DeLLight experiment*** *(X.S et al., Eur. Phys J D, 70, 13 (2016)*

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  Wilson-Dicke Analogy

Exemple : Static spherical gravitational field

$$n(r) = 1 + \frac{2GM}{rc_\infty^2}$$

$\boldsymbol{n(r)}$ formally identical to $\boldsymbol{g_{00}}$ in General Relativity

Landau & Lifshitz (1975) : "A static gravitational field plays the role of a medium with electric and magnetic permeabilities $\varepsilon_0 = \mu_0 = 1/\sqrt{g_{00}}$ *"*

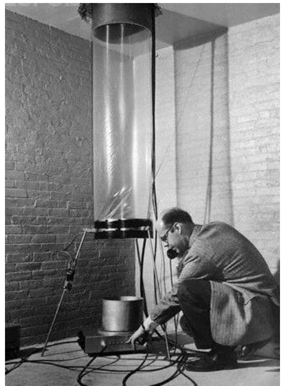
Varying Vacuum Refractive Index

- **Flat metric (x,y,z,t)**
- Defined by the speed of light c_∞ in the absence of gravitational potential $(n(r \to \infty) = 1)$

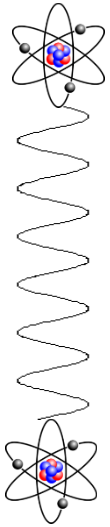
$$\begin{cases} \varepsilon_0(r) = n(r) \times \varepsilon_{0,\infty} \\ \mu_0(r) = n(r) \times \mu_{0,\infty} \\ c(r) = n^{-1}(r) \times c_\infty \\ E_{atom}(r) = n^{-1/2}(r) \times E_{atom,\infty} \\ \mathrm{m}(r) = n^{3/2}(r) \times m_\infty \end{cases}$$

$e, \hbar$ are constant

$\Rightarrow \alpha = \dfrac{e^2}{4\pi\varepsilon_0 \hbar c}$ is constant



- **Example : Gravitational blue-shift observed by Pound & Rebka (in a static spherical gravitational field)**



$$E_{atom}(r+h) = n^{-1/2}(r+h) \times E_{atom,\infty}$$

$\boldsymbol{E_\gamma}$ **= constant**

$E_\gamma = hc/\lambda$

λ varies as c

$$E_{atom}(r) = n^{-1/2}(r) \times E_{atom,\infty} < E_{atom}(r+h)$$

- The photon energy keeps constant during its propagation
- The atomic energy levels are really modified

$$n(r) = 1 + \frac{2GM}{rc_\infty^2} \quad \Rightarrow \quad \Delta E = \frac{GM}{Rc_\infty^2}\frac{h}{R} \times E_{atom,\infty}$$

in agreement with R.G.

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  Wilson-Dicke Analogy

There is no prediction for an experimental test to favor one of the two approaches

We extend the Wilson-Dicke analogy to a time dependence vacuum index

$$n(r) = 1 + \frac{2GM}{rc_\infty^2} \qquad (n_\infty = n(r \to \infty) = 1)$$

$$n(t) = n_\infty(t) + \frac{2G(t)M(t)}{rc_\infty^2(t)}$$

$n(t)$: Possible variation of the vacuum refractive index with cosmological time ?

Time dependent Vacuum Refractive Index

We assume :

- Flat and static metric (x,y,z,t) $\rightarrow$ **There is no expansion of the metric**
- The metric is defined by the speed of light today c_0 $(n(t=0)=1)$

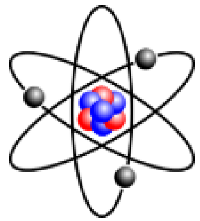
Spacetime metric expansion is replaced by a variation with time of ε_0 and μ_0

$$\begin{cases} \varepsilon_0(t) = n(t) \times \varepsilon_{0,0} \\ \mu_0(t) = n(r) \times \mu_{0,0} \\ c(t) = n^{-1}(t) \times c_0 \\ E_{atom}(t) = n^{-1/2}(t) \times E_{atom,0} \\ \mathrm{m}(t) = n^{3/2}(t) \times m_0 \end{cases}$$

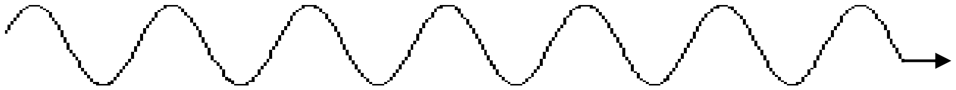
$e, \hbar$ and α are constant

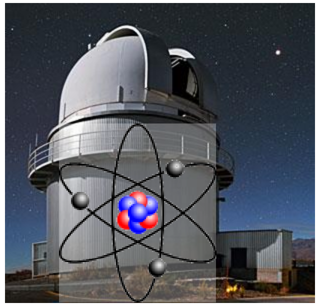
Cosmological redshift

Supernovae t<0 — ***Telescope*** t = 0 — *Cosmological time*



$$E_{\gamma,SN} = E_{atom}(t) = \text{constant}$$





$E_{atom}(t)$

$$E_{atom,0}(\text{reference}) = \sqrt{n(t)} \times E_{atom}(t) > E_{atom}(t)$$

$$E_{\gamma,SN} = E_{atom}(t) = \frac{hc(t)}{\lambda_{emission}(t)}$$

$$E_{\gamma,SN} = \frac{hc_0}{\lambda_{observed}(t=0)}$$

$$\Rightarrow \quad \lambda_{observed} = \frac{hc_0}{E_{atom}(t)}$$

To be compared to $\lambda_{reference} = \dfrac{hc_0}{E_{atom,0}}$

$$\Rightarrow \quad 1 + z = \frac{\lambda_{observed}}{\lambda_{reference}} = \frac{E_{atom,0}}{E_{atom}(t)} = \sqrt{n(t)} > 1 \qquad (t < 0)$$

$$\Rightarrow \quad n(t) = (1+z)^2$$

Redshift $\Rightarrow$ Refractive index decreasing with time
Speed of light increasing with time

Fit Supernovae Type Ia

- Hubble diagram: Distance modulus $\boldsymbol{\mu_{mes}}$ vs redshift $\boldsymbol{z}$

$$\mu_{mes} = m_b - M_b + \alpha X - \beta C = 5 log_{10}\left(\frac{d_L(z)}{10\text{ pc}}\right)$$

X = stretch factor
C = color-band factor
α and β : global nuisance parameters

m_b = magnitude at peak = $-2.5\log(\mathcal{F}) + M_b$ $\quad$ $M_b = -19.25$ (*Richardson, AJ, 2014*)

$\mathcal{F}$ = obs. flux in the SNIa rest frame (at emission) = $\dfrac{\mathcal{L}}{4\pi d_L^2(1+z)^2}$

$\mathcal{L}$ = peak luminosity

d_L = luminosity distance

$$d_L = \int_t^0 c(t')dt' = c_0 \int_t^0 \frac{dt'}{n(t')}$$

$$\Rightarrow n(t) = ?$$

Linear time dependence of the vacuum potential energy

Fermat's principle		**Principle of least action**
$\delta\left(\int n(r)dr\right) = 0$	$\equiv$	$\delta\left(\int \mathcal{L}(r)dr\right) = 0$
$\frac{n^2}{2}$	$\equiv$	ϕ
n = refractive index		ϕ = potential energy

Goldstein H., Classical mechanics 2nd Ed., pp. 484-492

$$\delta\left(\int n(t)dt\right) = 0 \quad \equiv \quad \delta\left(\int \mathcal{L}(t)dt\right) = 0$$

$$n^2(t) = 1 + t/\tau_0 \quad \equiv \quad \phi(t) \propto 1 + t/\tau_0 \qquad t < 0$$

$$\Rightarrow \quad \boldsymbol{n(t) = \sqrt{1 + t/\tau_0}}$$

Fit Supernovae Type Ia

Hubble diagram: Distance modulus μ_{mes} vs redshift z

$$\mu_{mes} = m_b - M_b + \alpha X - \beta C = 5 log_{10}\left(\frac{d_L}{10\text{ pc}}\right)$$

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$\mathcal{L}$ = peak luminosity

d_L = luminosity distance

$$d_L = \int_t^0 c(t')dt' = c_0 \int_t^0 \frac{dt'}{n(t')}$$

$$n(t) = \sqrt{1 + t/\tau_0} \implies d_L = 2c_0\tau_0(n(t) - 1) = 2c_0\tau_0\left((1+z)^2 - 1\right)$$

$$\mu_p = 5 log_{10}\left((1+z)^2 - 1\right) + 5 log_{10}\left(\frac{2c_0\tau_0}{10\text{ pc}}\right)$$

Fit Supernovae Type Ia

Data from the joint analysis SDSS-II and SNLS
(*Betoule et al., A&A, 2014*)

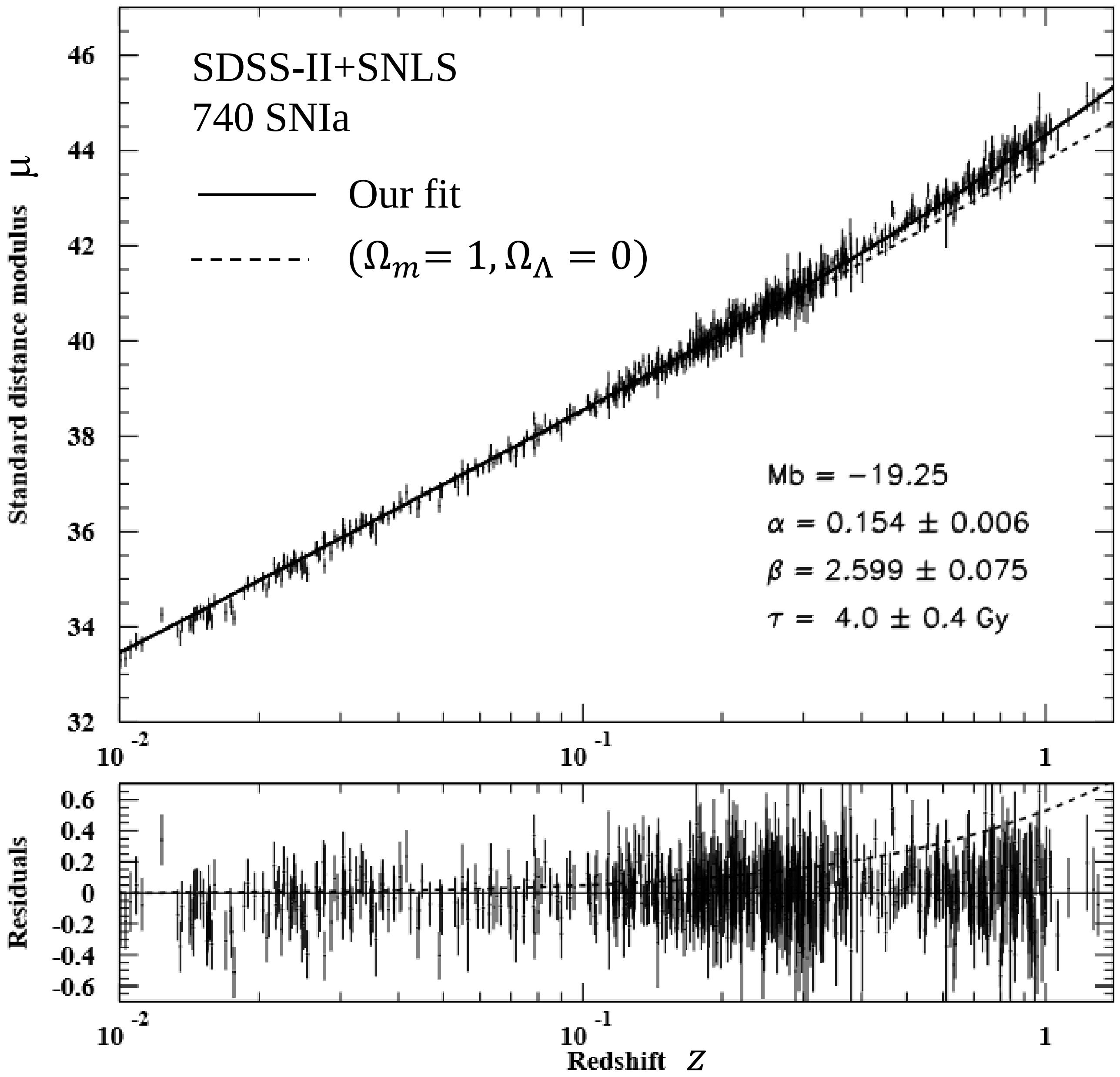
$$\chi^2(\alpha,\beta,\tau_0) = \sum_i \frac{\left(\mu_{mes,i}(\alpha,\beta) - \mu_{p,i}(z,\tau_0)\right)^2}{\sigma^2_{\mu,i}}$$

$$\mu_p = 5log_{10}\left((1+z)^2 - 1\right) + 5log_{10}\left(\frac{2c_0\tau_0}{10\ \text{pc}}\right)$$

$$n(t) = \sqrt{1 + t/\tau_0}$$

$\tau_0 = 4.0 \pm 0.4$ Gy

$$\Longrightarrow \frac{\Delta n}{n} = 4\ 10^{-18}\ \ \text{s}^{-1}$$



Experimental prediction:

Local apparent expansion

Decrease of n with time

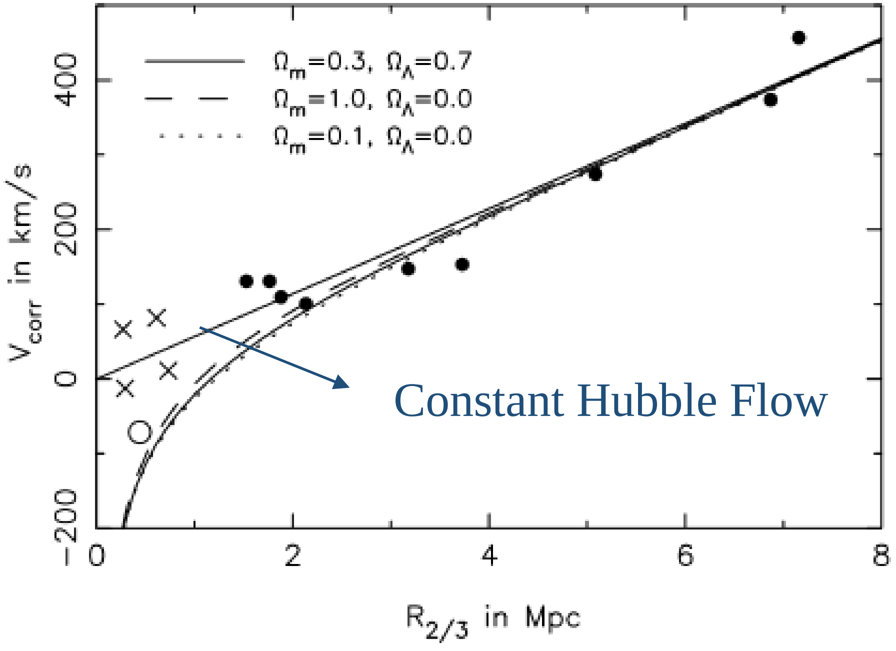
$$\frac{\Delta n}{n} = 4\ 10^{-18}\ \ \mathrm{s}^{-1}$$

Increase of E_{atom} with time

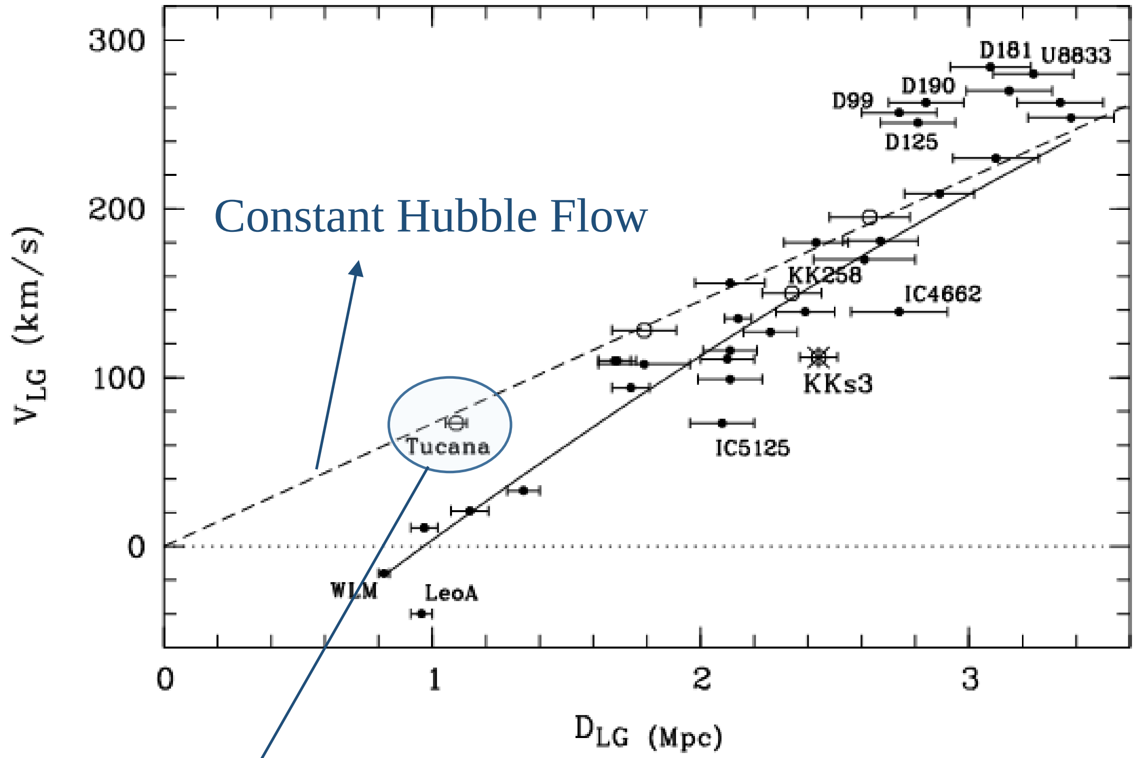
$$\frac{\Delta E_{atom}}{E_{atom}} = 2\ 10^{-18}\ \ \mathrm{s}^{-1} = \ H_0$$

Hubble flow at small scale (inside the galaxy cluster, solar system ?)

Local apparent expansion



Ekholm et al., A&A 368, L17 (2001)



Karachentsev et al. Astron. Nachr. 366, 7, 707 (2015)

The Tucana dwarf galaxy is gravitationaly isolated

Experimental prediction:

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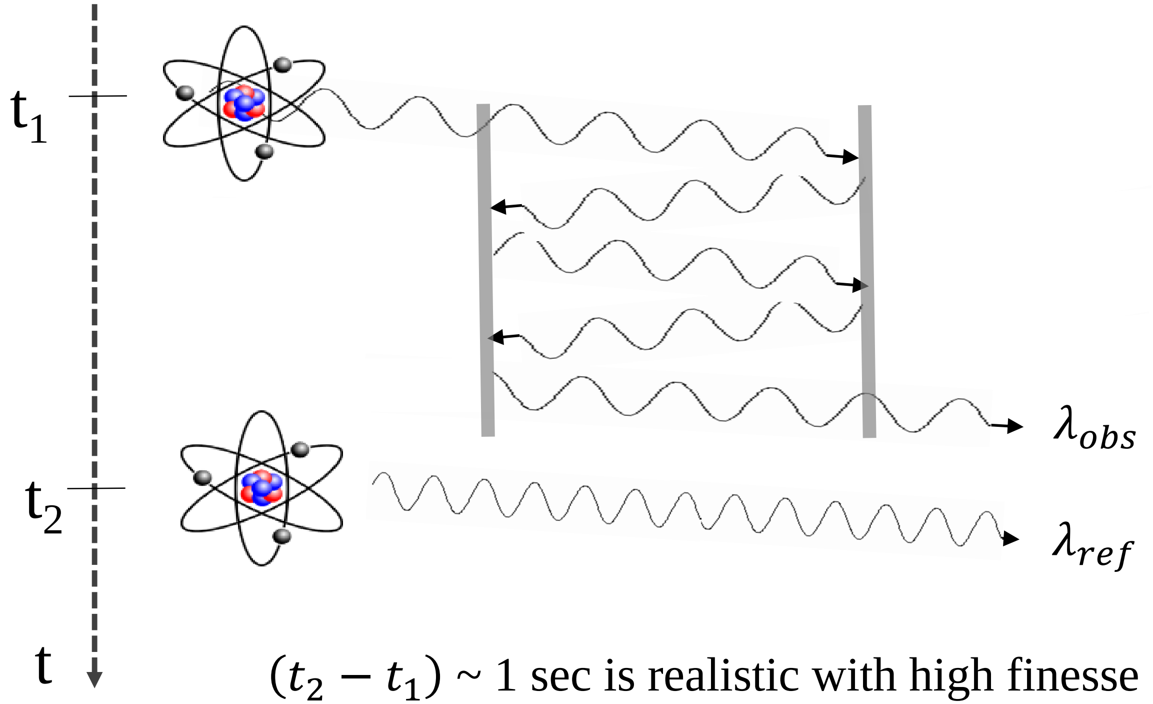
- Hubble flow at small scale (galaxy cluster, solar system ?)
- Cosmological redshift must affect any atoms, in deep space but also in the laboratory

Laboratory experiment to measure the increase of atomic energy level ?

Laboratory test of Local apparent expansion



$$\frac{\lambda_{obs}}{\lambda_{ref}} = \frac{E_{atom}(t_2)}{E_{atom}(t_1)} = 1 + 2.10^{-18} \times (t_2 - t_1)$$

$(t_2 - t_1)$ ~ 1 sec is realistic with high finesse cavity

Damping time in the cavity $= \dfrac{\mathcal{F}\times d}{\pi\times c}$

Virgo-Ligo: $d = 4$ km, $\mathcal{F} \approx 1600$ (today ~400) $\Rightarrow \ \tau = 60$ ms $\ \Rightarrow \dfrac{I_{out}}{I_{in}}$(after 1 sec) $= 10^{-7}$

The stability of the emitting clock must be controlled at 10^{-18} during 1 second

It could be provided in a near future by new generation ^{87}Sr optical lattice clocks

cf Nicholson et al., Nature Commun. 6:6896 (2015)

Conclusion

- Gravitation plays the role of a medium with a real change of ε_0 and μ_0

  $\Rightarrow$ Curvature of the spacetime metric is replaced by a real change of the vacuum refractive index

- We propose additional real change with cosmological time of ε_0 and μ_0

  $\Rightarrow$ Expansion of the spacetime metric is replaced by a real change with time of the vacuum index

- Cosmological redshift $\Rightarrow$ decreasing vacuum index with time

  SNIa data are very well fitted by $n(t) = \sqrt{1 + t/\tau_0}$ with $\tau_0 = 4.0 \pm 0.4$ Gy

  Equivalent to a vacuum potential energy which varies linearly with time

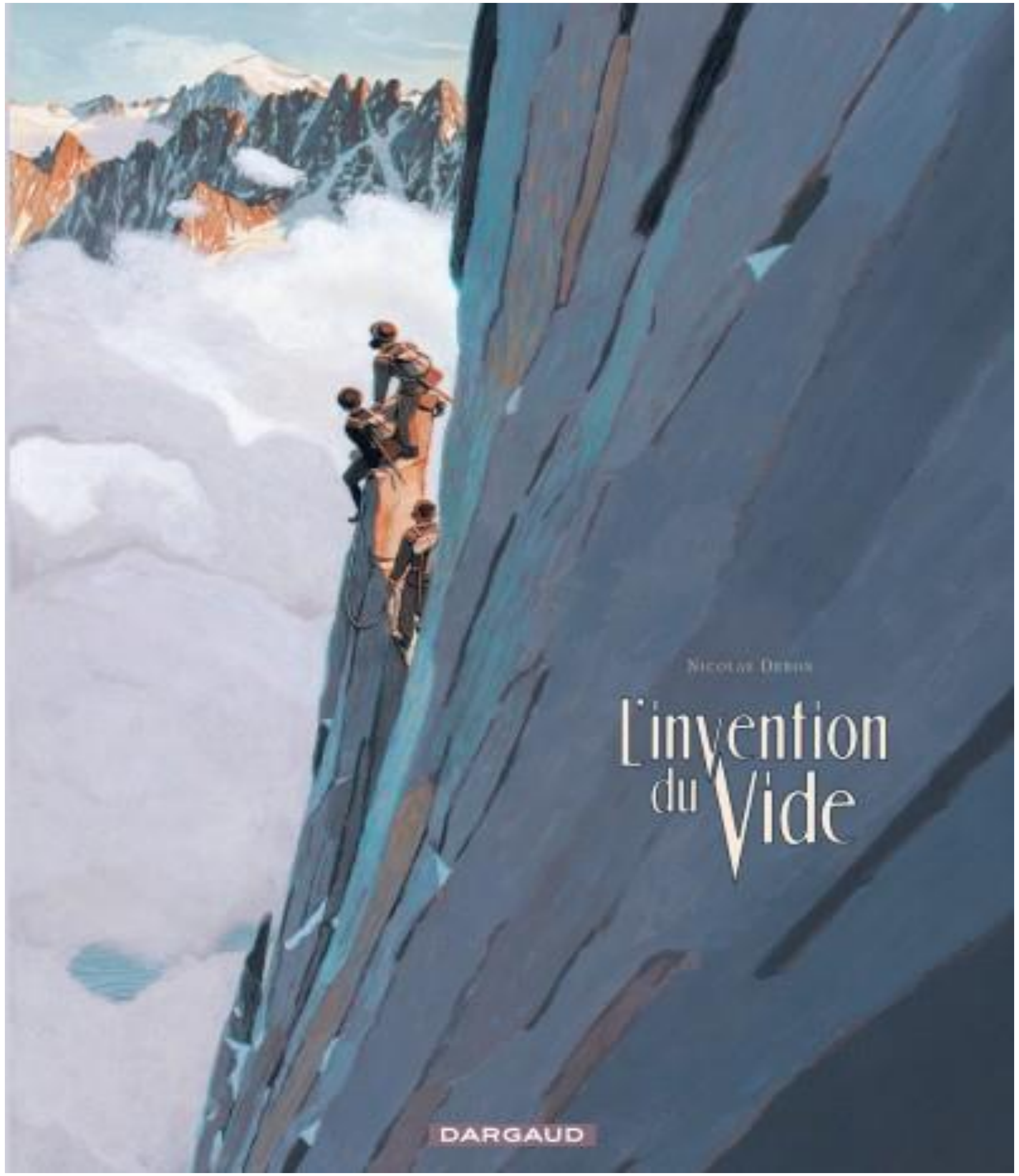
- **Friedman scale factor a(t) and Λ are replaced by $\boldsymbol{n^2(t) = 1 + t/\tau_0}$ (t<0)** or $\boldsymbol{n(z) = (1+z)^2}$

  (*there is no expansion of the metric*)

- **Strong experimental prediction: the atomic energy levels must increase with time**

  $$\frac{\Delta E_{atom}}{E_{atom}} = 2\ 10^{-18}\ \mathrm{s}^{-1} = H_0$$ $\Rightarrow$ **Laboratory test ?**

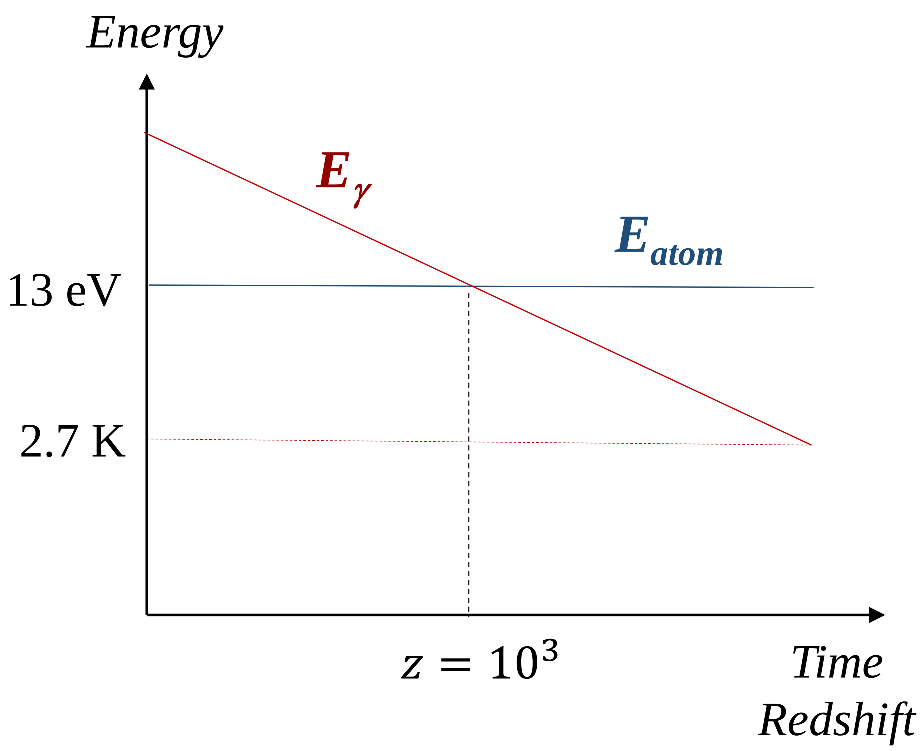
Article in preparation, available in arXiv in a couple of week


L'invention du Vide
DARGAUD

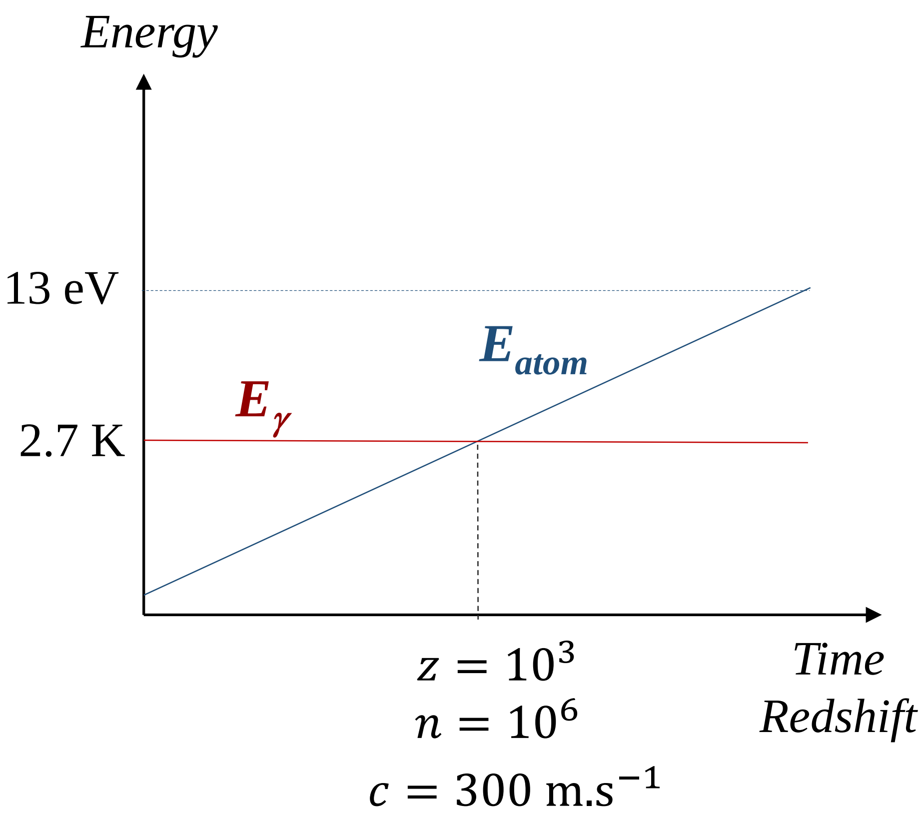
BACKUP

Cosmic Microwave Background

Standard Cosmology

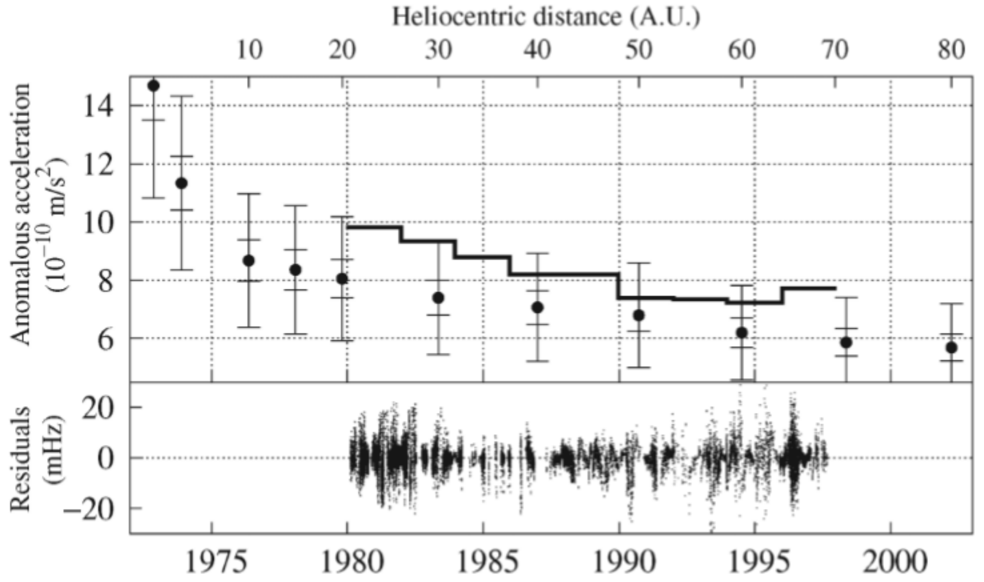


Vacuum index model



$\Rightarrow$ 2.7 K is a characteristic energy

Pioneer 10



$$\frac{\Delta f}{f} = H_0 \times T_{AR} = 2.10^{-18} \times \frac{2 \times 40\ A.U.}{c} = 8.10^{-14}$$

$f = 2.2$ GHz $\Rightarrow \Delta f = 0.2$ mHz $\ll$ residuals

$$\left.\begin{aligned} \frac{\Delta f}{f}(t) &= 2\frac{L(t)}{c}H_0 \\ \frac{\Delta f}{f}(t) &= 2\frac{v(t)}{c} \end{aligned}\right\} \Rightarrow \quad 2\frac{L(t+\delta t)-L(t)}{c}H_0 = 2\frac{v(t+\delta t)-v(t)}{c}$$

$$\Rightarrow \quad \frac{dL}{dt}H_0 = \frac{dv}{dt}$$

$$\Rightarrow \quad a = H_0 \times v = 2.10^{-18} \times \frac{40\ A.U}{c} = 2.6\ 10^{-14}\ \mathrm{m}.s^{-2}$$

Cosmological time dilatation

SNIa light curves result from β-decays $^{56}Ni \rightarrow {}^{56}Co \rightarrow {}^{56}Fe$.

The duration of the process is driven by the $T_{1/2}(\beta)$

if $\left[\begin{array}{l} g_W \text{ (weak V-A coupling factor in leptonic sector)} \\ V_{ud} \text{ (CKM matrix element)} \\ g_A/g_V \text{ (axial to vector coupling constants)} \end{array}\right]$ are constant then $T_{1/2}(\beta)$ varies as $(mc^2)^{-1} \propto \sqrt{n(t)} = z + 1$

⇒ The SNIa light curve widths vary as 1 + z