Cosmology with an increasing refractive index

Xavier Sarazin, LAL, CNRS-IN2P3 / Univ. Paris-Saclay

en collaboration avec François Couchot (LAL), Marcel Urban (LAL) et Arache Djannati-Ataï (APC)

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Gravitation and Vacuum

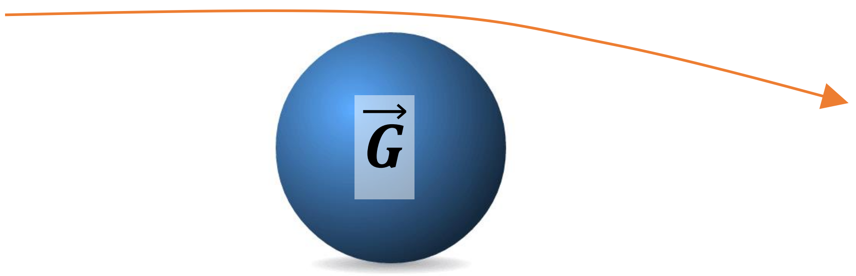
- Einstein is the first one to note that the vacuum refractive index and *c* are affected by the gravitation:
  - Einstein, A. 'Über den Einfluss der Schwerkraft auf die Ausbreitung des Lichtes', Annalen der Physik 35, 898-908 (1911)
  - *"The constancy of the velocity of light can be maintained only insofar as one restricts oneself to spatio-temporal regions of constant gravitational potential"* *(Einstein A., Ann. Physik 38 (1912) 1059)*

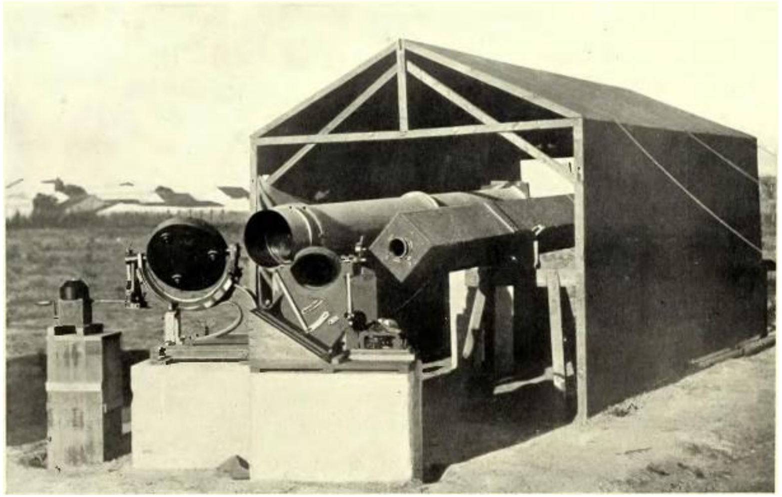
- Einstein generalized the « $\boldsymbol{c = \text{constante}}$ » relativity principle thanks to the introduction of a ***curved spacetime metric***

  $\Rightarrow$ General Relativity is a « *geo-metric* » theory

  $\Rightarrow$ Vacuum has no physical role anymore

Deflection of light first observed by Eddington in 1919





Gravitation 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 ε_0 and μ_0** by the gravitational potential

$\Rightarrow$ Modification of the vacuum optical index and inertial test mass

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

$\Rightarrow$ *See Landau & Lifshitz (1975) : "A static gravitational field is formally identical to a medium with electric and magnetic permeabilities* $\varepsilon_0 = \mu_0 = 1/\sqrt{g_{00}}$*"*

Exemple : Static spherical gravitational field *(Wilson-Dicke Analogy)*

$$\begin{cases} n(r) = 1 + \dfrac{2GM}{rc_\infty^2} \\ m(r) = m_\infty \times n^{3/2}(r) \end{cases}$$

(to preserve the equivalence principle)

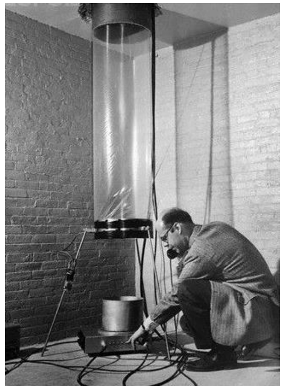
Gravitation and Vacuum

- **Flat metric (x,y,z,t)** $dx^2 + dy^2 + dz^2 = c_\infty^2 \times dt^2$
- Defined by the speed of light c_∞ in the absence of gravitational potential $(n(r \to \infty) = 1)$

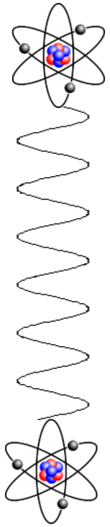
$$\begin{cases} \varepsilon_0(r) = n(r) \times \varepsilon_{0,\infty} \\ \mu_0(r) = n(r) \times \mu_{0,\infty} \\ c(r) = n^{-1}(r) \times c_\infty \\ E_{atom}(r) = n^{-1/2}(r) \times E_{atom,\infty} \\ \mathrm{m}(r) = n^{3/2}(r) \times m_\infty \end{cases}$$

$e, \hbar$ 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

- 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.

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

Cosmology with a vacuum index increasing with time

- **1st Dicke's remark**

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

?

Dicke's idea: $1 = n(t=0) = \int \frac{2G(r)4\pi\rho r^2}{rc^2(r)}dr$

$\Rightarrow n(t)$ increases with time

- **2nd Dicke's remark**

e.m. wave propagating through a medium with an index increasing in time, uniformely in space

$\Rightarrow$ Frequency ν (energy $h\nu$) increases with time as $\nu(t) = \nu_0/n(t)$

Cosmology with a vacuum index increasing with time

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 $c_0 = c(t=0)$

$$n(t=0) = 1 \qquad \text{and} \qquad dt^2 = 1/c_0^2 \times (dx^2 + dy^2 + dz^2)$$

- $\boldsymbol{n(t)}$ **increases with time**
- The relative index variation is time-independent (at least for recent epoch of the Univers)

$$dn(t)/n(t) \ = \text{constant} \ \Rightarrow \ n(t) = \exp(-t/\tau_0)$$

- **A photon propagates in vacuum with $\boldsymbol{\lambda}$ = constant, and $\boldsymbol{\nu(t) = \nu_0/n(t)}$**
- **Spacetime metric expansion is replaced by an increase with time of $\boldsymbol{\varepsilon_0}$ and $\boldsymbol{\mu_0}$**

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

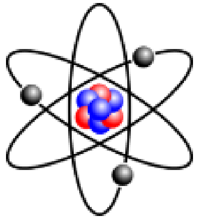
$e, \hbar$ are constant $\Rightarrow$ α constant

Cosmological redshift

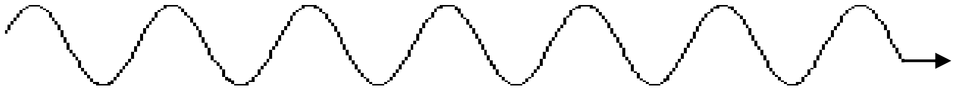
Supernovae t<0

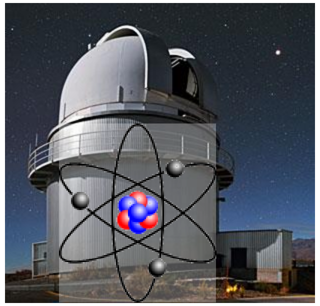
Telescope t = 0

Cosmological time



$\lambda = \text{constant} = \lambda_{emission}(t)$





$E_{atom}(t)$

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

$$\left.\begin{aligned} \lambda_{observed} = \lambda_{emission} &= \frac{hc(t)}{E_{atom}(t)} \\ \lambda_{reference} = \lambda_0 &= \frac{hc_0}{E_{atom,0}} \end{aligned}\right\} \Rightarrow \quad 1 + z = \frac{\lambda_{observed}}{\lambda_{reference}} = \frac{c(t)}{c_0}\frac{E_{atom,0}}{E_{atom}(t)} = \frac{1}{n(t)}\sqrt{n(t)} = \frac{1}{\sqrt{n(t)}} > 1 \qquad (t < 0)$$

$$\Rightarrow \quad \boxed{\begin{aligned} n(t) &= \frac{1}{(1+z)^2} \\ \sqrt{n(t)} &\equiv a(t) \end{aligned}}$$

Refractive index increasing with time $\Rightarrow$ Redshift
(speed of light decreasing with time)

Fit Supernovae Type Ia

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

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

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

m_b = magnitude at peak $= -2.5\log(\mathcal{F}) + M_b$ $\qquad M_b = -19.25$ (*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 $\quad d_L = \displaystyle\int_t^0 c(t')dt' = c_0 \int_t^0 \frac{dt'}{n(t')}$

$$\boxed{n(t) = \exp(t/\tau_0)\ \ (t<0)} \implies d_L = 2c_0\tau_0(n^{-1}(t) - 1) = 2c_0\tau_0\left((1+z)^2 - 1\right)$$

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

Fit Supernovae Type Ia

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

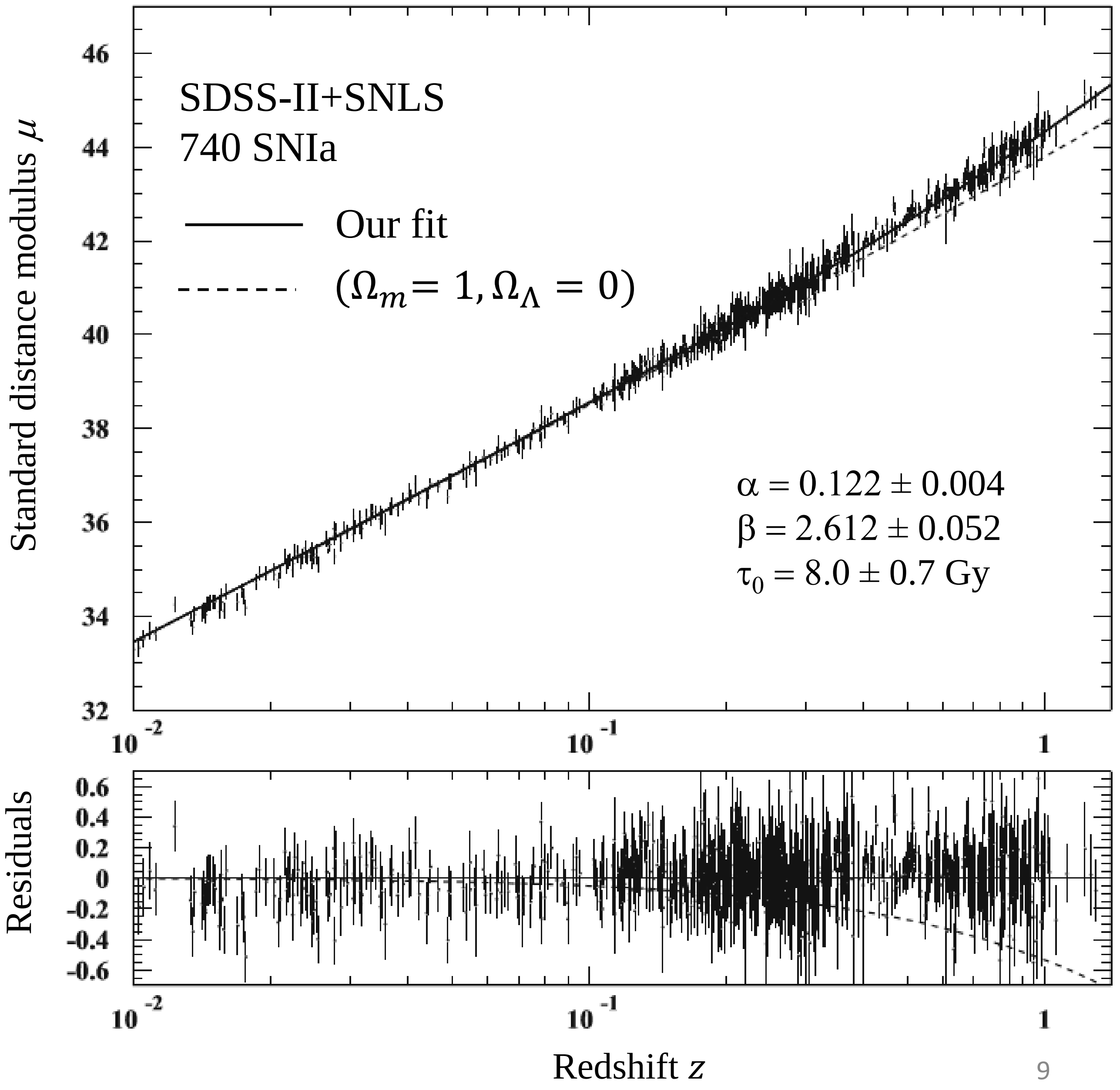
$$\chi^2(\alpha, \beta, \tau_0) = \sum_i \frac{\left(\mu_{mes,i}(\alpha, \beta) - \mu_{p,i}(z, \tau_0)\right)^2}{\sigma_{\mu,i}^2}$$

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

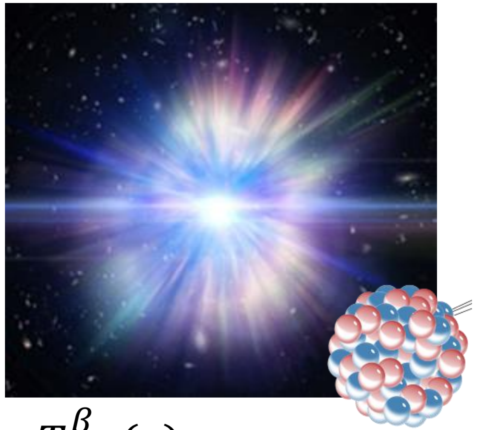
$n(t) = \exp(t/\tau_0)$ (t<0)

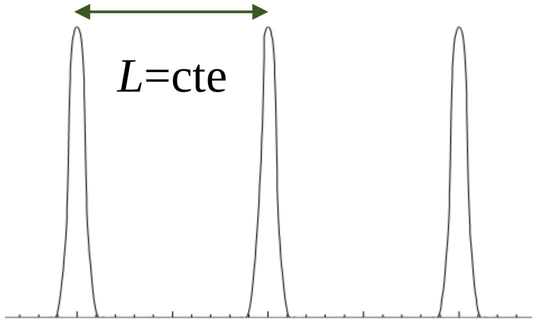
$\tau_0 = 8.0 \pm 0.7$ Gy

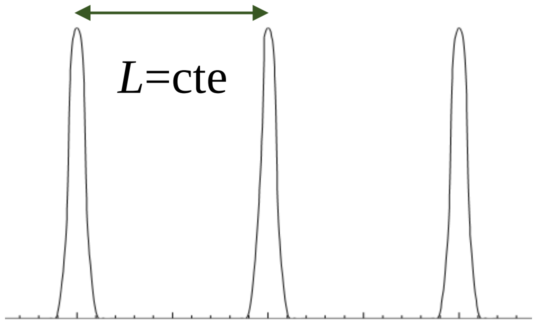
$$\Longrightarrow \frac{\Delta n}{n} = 4\ 10^{-18}\ \text{s}^{-1}$$



Cosmological time dilatation in SN-Ia







$$L = T^{\beta}_{1/2}(z) \times c(z)$$

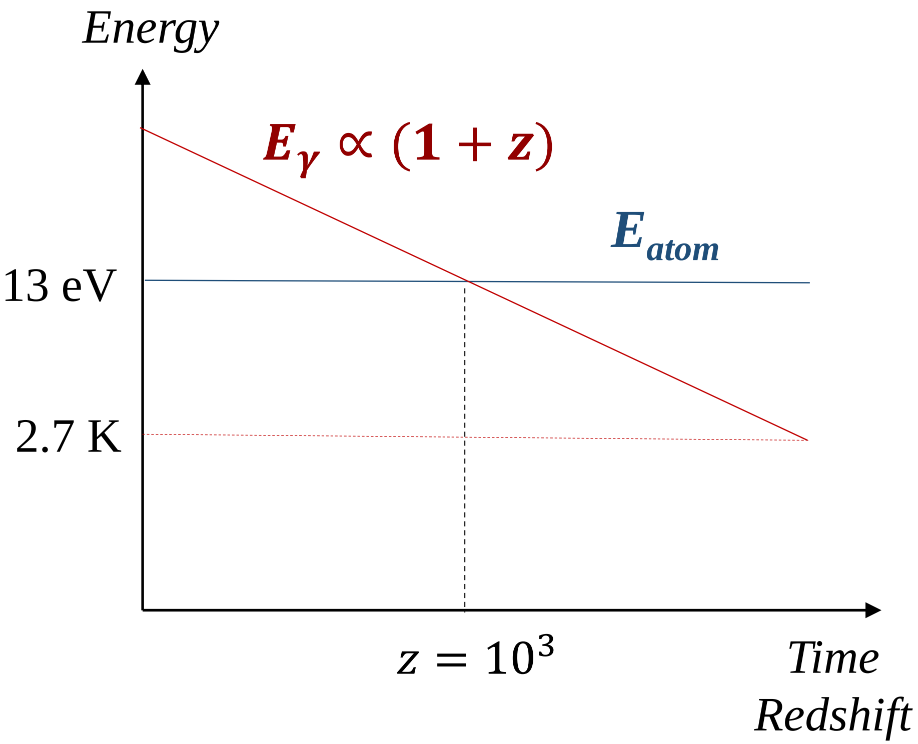
$$\begin{cases} \Delta t = \dfrac{L}{c_0} = T^{\beta}_{1/2}(z) \times \dfrac{c(z)}{c_0} = T^{\beta}_{1/2}(z) \times n^{-1}(z) \\ T^{\beta}_{1/2}(z) = T^{\beta}_{1/2}(z=0) \times n^{1/2}(z) \end{cases}$$

$$\boxed{\Delta t(z) = \Delta t(z=0) \times (1+z)}$$

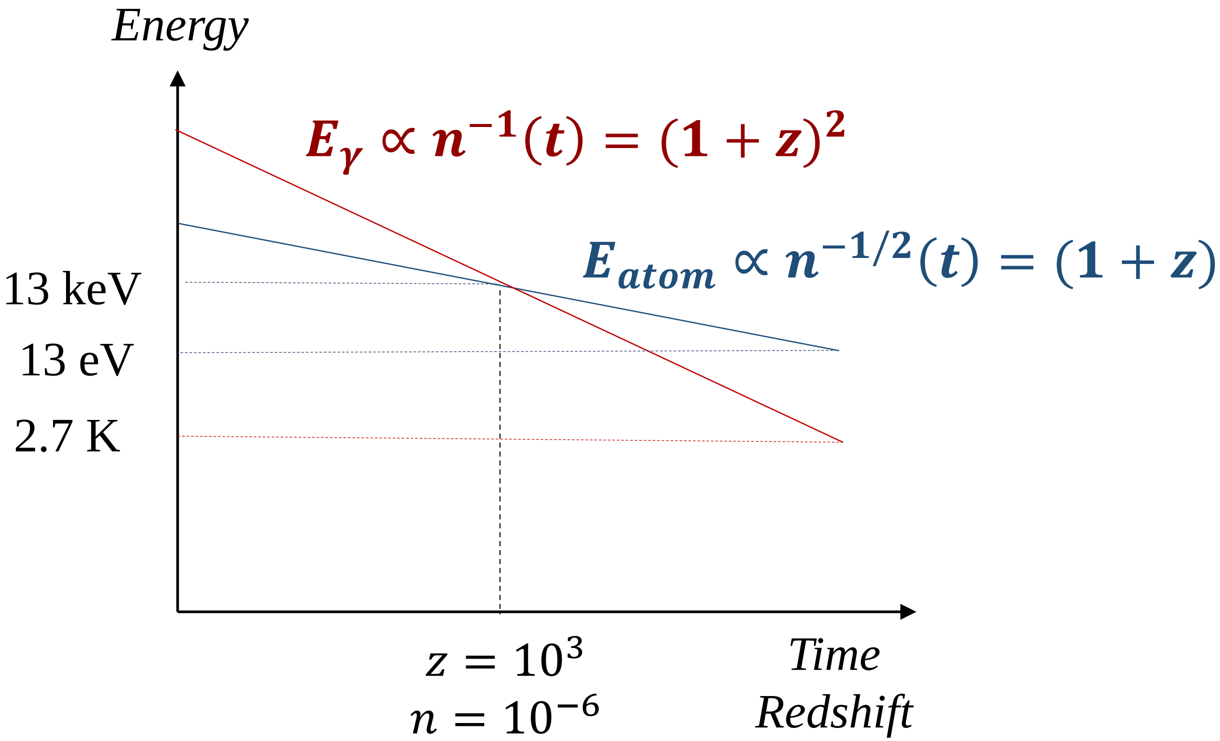
$$T^{\beta}_{1/2} \propto 1/(\text{Rest Energy})$$

Evolution of the CMB

Standard Cosmology



Vacuum index model



$\boxed{E_\gamma / E_{atom} \propto (1+z)}$ in both models

Evolution of the CMB

The energy density $\mathcal{E}_\gamma$ of the CMB radiation is $\mathcal{E}_\gamma(\nu)d\nu = \frac{8\pi h}{c^3}\frac{\nu^3 d\nu}{\exp\left(\frac{h\nu}{k_B T}\right) - 1}$

- **Standard cosmology:**

Energy γ : $E_\gamma \propto (1+z)$

Energy mass of baryons E_b = constante

$\mathcal{E}_\gamma = n_\gamma \times E_\gamma \propto (1+z)^3 \times (1+z) = (1+z)^4$

$$\mathcal{E}_\gamma = \frac{\pi^2 k_B^4}{15\hbar^3 c^3}T^4 \quad \left.\begin{array}{r}\Rightarrow T = 1+z \\ \nu = 1+z\end{array}\right\} \Rightarrow \text{CMB black body shape is preserved}$$

- **Cosmology with increasing index:**

$$\left.\begin{array}{l}E_\gamma \propto n^{-1}(t) = (1+z)^2 \\ E_b = mc^2 \propto n^{-1/2}(t) = (1+z)\end{array}\right\} \Rightarrow \text{Apparent energy } \gamma\text{, relatively to baryon, decreases as } n^{-1/2}(t) = (1+z)$$

In a volume defined with physical rods, $n_\gamma \propto n^{-3/2}(t) = (1+z)^3$

⇒ The energy density $\mathcal{E}_\gamma$, relatively to baryons, decreases as $(1+z)^4$, as in standard cosmology

⇒ If k_B is constant (as $\hbar$), then the temperature (relatively to physical temp.°) $T \propto n^{-1/2}(t) = 1+z$, as in standard cosmology, and the black body spectral shape is preserved

Also n_γ/n_b is constant with time

Variation of the gravitational constant G ?

$$\alpha = \frac{e^2}{4\pi\varepsilon_0 \hbar c}$$ is constant with time

$$\alpha_G = \frac{Gm^2}{\hbar c}$$ is also constant with time ?

$$\boxed{G(t) = G(t=0) \times n^{-4}(t)}$$

Some consequences:

- ✓ Intensity of the gravitational force $G \times m^2$ varies as $n^{-1}(t)$
- ✓ In highest redshift, gravitation was much stronger
- ✓ Acoustic waves started when the gravitation became weaker than the radiation pressure
- ✓ Gravitation of the seed was much more intense

$\Rightarrow$ CMB anisotropy and acoustic waves must be studied within this new framework…

Local apparent expansion ?

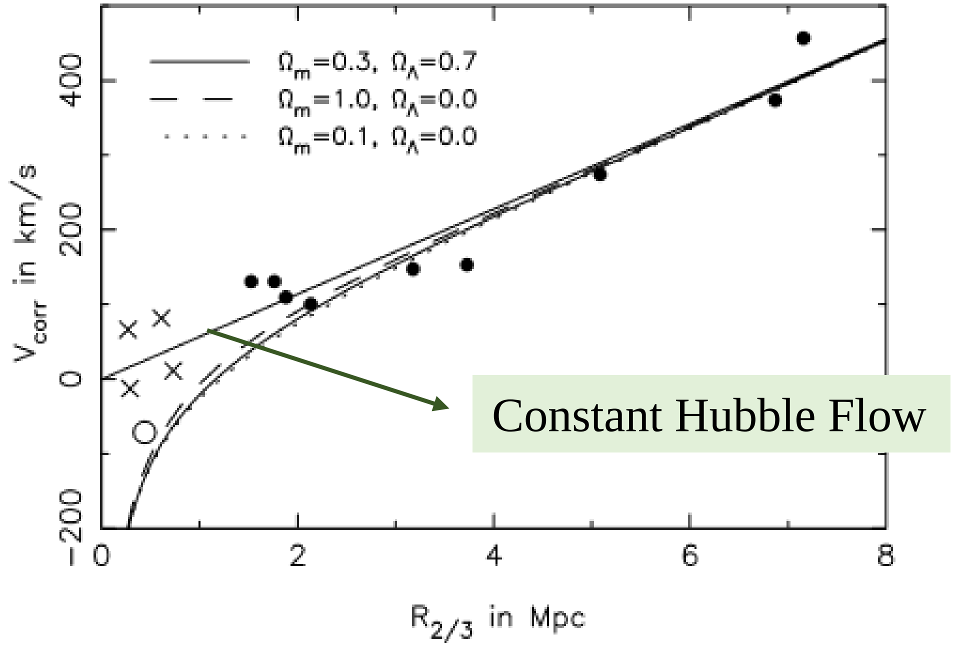
Increase of n with time

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

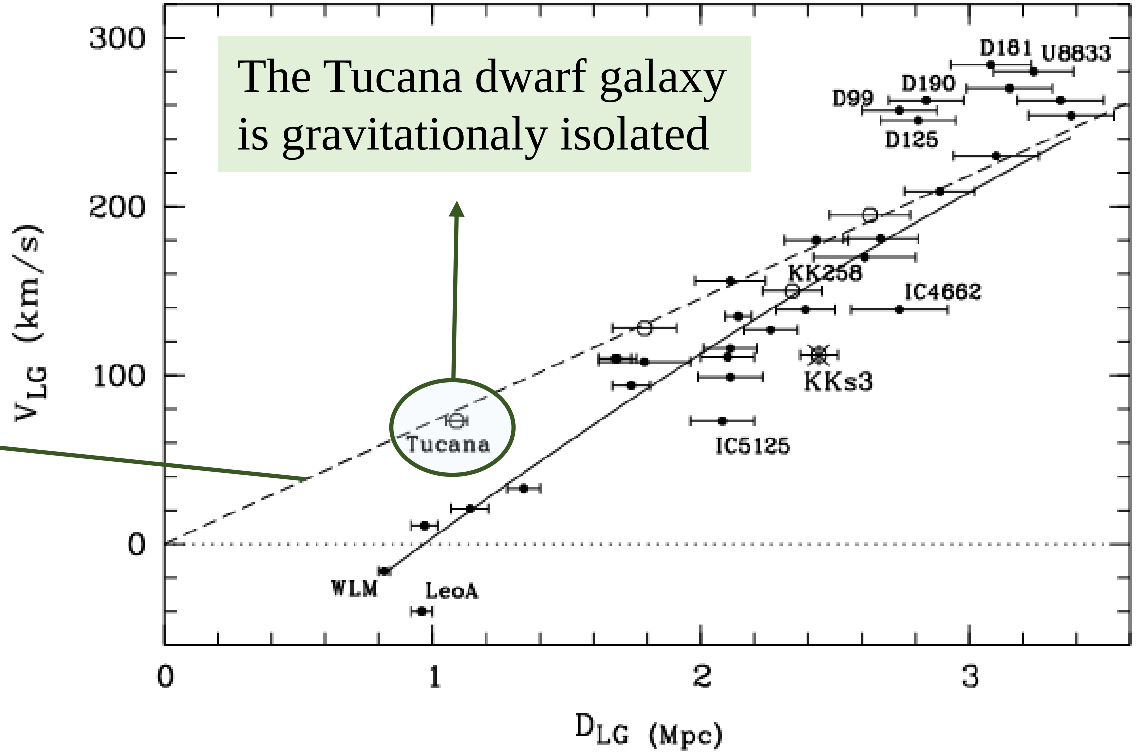
Decrease of E_{atom} with time

$$\Delta E_{atom}/E_{atom} = -\,2\ 10^{-18}\ \ s^{-1} \cong\ H_0$$

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



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



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

Local apparent expansion ?

Increase of n with time

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

Decrease of E_{atom} with time

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

Cosmological redshift must affect any atoms, in deep space but also in the laboratory

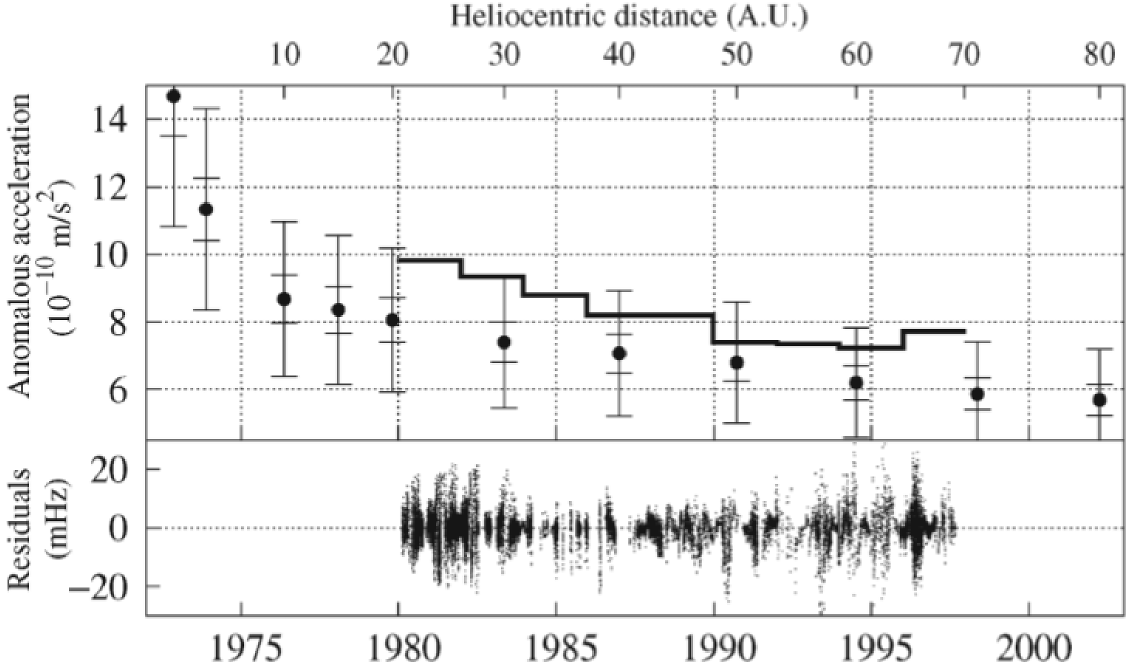
Laboratory experiment to measure the decrease of atomic energy level ?

Pioneer 10

$$\frac{\Delta f}{f} = -2.\,10^{-18} \times T_{AR} = -2.\,10^{-18} \times \frac{2 \times 40\ A.\,U.}{c}$$

$$\Rightarrow \frac{\Delta f}{f} = -8 \times 10^{-14}$$

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



Cosmology with a vacuum index increasing with time

- ✓ Cosmological redshift of the SN-Ia well fitted by a simple exponential increase $n(t) = \exp(-t/\tau_0)$
- ✓ Cosmological dilatation of clocks as (1+z)
- ✓ Evolution of the CMB consistent with the standard cosmology
- ✓ This study is obviously not complete. Other cosmological probes as CMB anisotropies must be studied
- ✓ The observed flateness of the Univers does not require any fine-tuning since the metric is Euclidean
- ✓ If $n(t) = \exp(-t/\tau_0)$ is true at the highest redshift

  $\Rightarrow$ Absence of begining (*t*=0) of the Universe

  $\Rightarrow$ Two given location is space were causally connected in past, which solve the horizon problem

Conclusion

- ✓ Cosmology with static Euclidean metric + vacuum index increasing with time
  - Cosmological redshift of the SN-Ia well fitted by $n(t) = \exp(-t/\tau_0)$
  - Cosmological dilatation of clocks as (1+z)
  - Evolution of the CMB consistent with the standard cosmology
  - Despite the static metric, the universe is not stationary: early universe is also hot with radiative period…
  - This framework is different to « tired light » models and VSL

- ✓ This study is obviously not complete. Other cosmological probes as CMB anisotropies must be studied

  $\Rightarrow$ Possible variation of G with time

- ✓ The observed flateness of the Univers does not require any fine-tuning since the metric is Euclidean

  $\Rightarrow$ Dark energy is not required…

- ✓ If $n(t) = \exp(-t/\tau_0)$ is true at the highest redshift, then absence of begining (t=0) of the Universe

  $\Rightarrow$ two given location is space were causally connected in past, which solve the horizon problem

- ✓ Local apparent expansion is a possible but challenging experimental test

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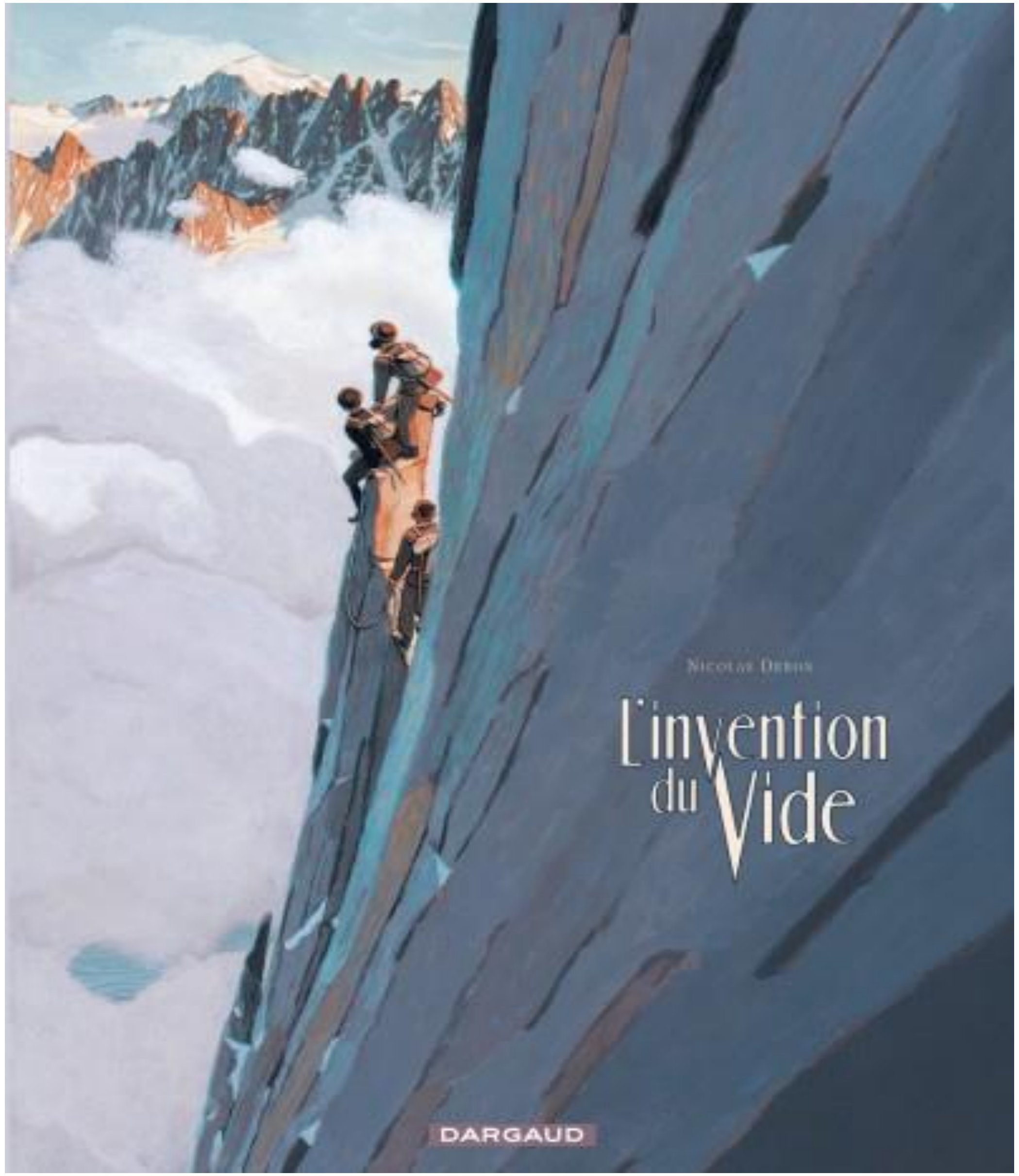
L'invention du Vide
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