Testing the equivalence principle with fundamental constants

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Outline

- Some words on fundamental constants

- Links between constants and gravity [Equivalence principle]

- Links with cosmology

All technical details:
JPU, Liv. Rev. Relat. ***4*** *(2011) 2; [arXiv/1009.5514]*

Constants

Physical theories involve constants

These parameters cannot be determined by the theory that introduces them.

These arbitrary parameters have to be assumed constant:

- *experimental validation*
- *no evolution equation*

By testing their constancy, we thus test the laws of physics in which they appear.

A physical measurement is always a comparison of two quantities, one can be thought as a unit

- *it only gives access to dimensionless numbers*
- *we consider variation of dimensionless combinations of constants*

JPU, Rev. Mod. Phys. **75**, 403 (2003); Liv. Rev. Relat. **4**, 2 (2011)
JPU, [astro-ph/0409424, arXiv:0907.3081]
R. Lehoucq, JPU, *Les constantes fondamentales* (Belin, 2005)
G.F.R. Ellis and JPU, Am. J. Phys. **73** (2005) 240
JPU, B. Leclercq, De *l'importance d'être une constante* (Dunod, 2005)
translated as "*The natural laws of the universe*" (Praxis, 2008).

Reference theoretical framework

The number of physical constants depends on the level of description of the laws of nature.

In our present understanding [*General Relativity* + *SU(3)xSU(2)xU(1)*]:

- G : Newton constant (**1**)
- **6** Yukawa coupling for quarks
- **3** Yukawa coupling for leptons
- mass and VEV of the Higgs boson: **2**
- CKM matrix: **4** parameters
- Non-gravitational coupling constants: **3**
- Λ_{uv}: **1**
- c, ħ : **2**
- cosmological constant

22 constants
19 parameters

Number of constants may change

This number is « time-dependent ».

Neutrino masses

Add **3** Yukawa couplings + **4** MNS parameters = **7** more

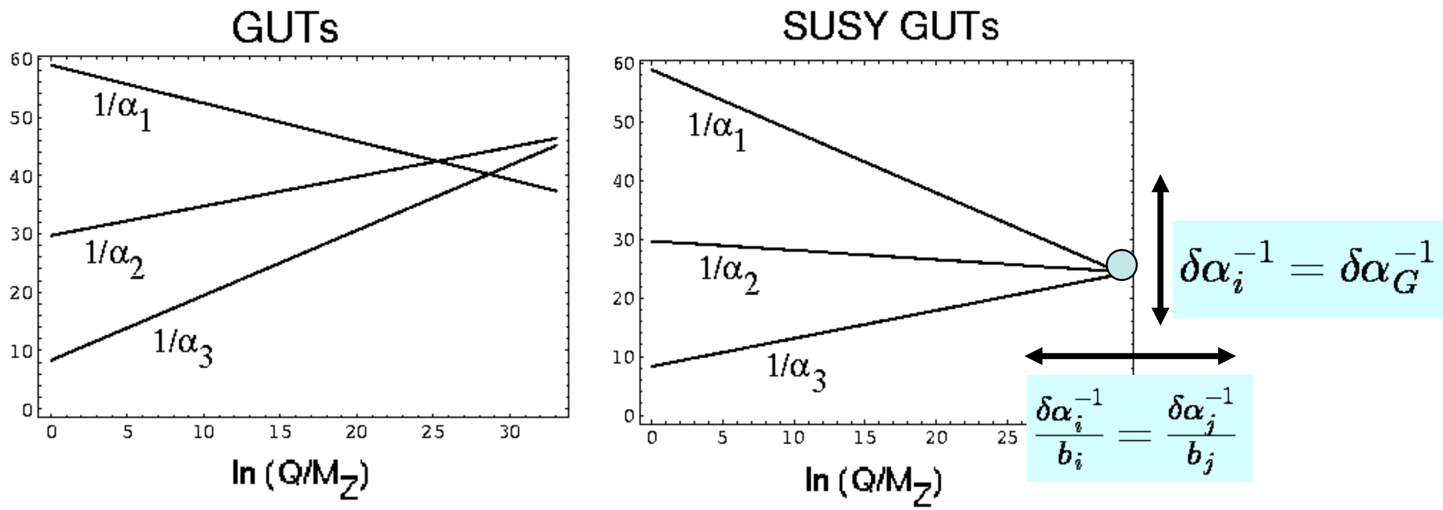
Unification

$$\alpha_i^{-1}(E) = \alpha_{GUT}^{-1} + \frac{b_i}{2\pi}\ln\frac{M_{GUT}}{E}$$

SM : $b_i = (41/10, -19/6, -7)$

MSSM : $b_i = (33/5, 1, -3)$

$$\alpha^{-1} = \frac{5}{3}\alpha_1^{-1} + \alpha_2^{-1}$$



Importance of unification

Unification $$\alpha_i^{-1}(E) = \alpha_{GUT}^{-1} + \frac{b_i}{2\pi}\ln\frac{M_{GUT}}{E}$$

Variation of α is accompanied by variation of other coupling constants

QCD scale $$\Lambda_{\rm QCD} = E\left(\frac{m_c m_b m_t}{E^3}\right)^{2/27}\exp\left[-\frac{2\pi}{9\alpha_s(E)}\right]$$

Variation of Λ_{QCD} from α_S and from Yukawa coupling and Higgs VEV

Theories in which EW scale is derived by dimensional transmutation $$v \sim \exp\left[-\frac{8\pi^2}{h_t^2}\right]$$

Variation of Yukawa and Higgs VEV are coupled

String theory All dimensionless constants are dynamical – their variations are all correlated.

These effects cannot be ignored in realistic models.

New degrees of freedom

On the basis of general relativity

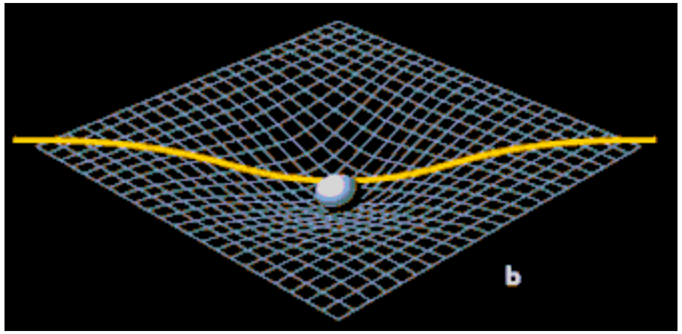
The equivalence principle takes much more importance in general relativity

It is based on **Einstein equivalence principle**

universality of free fall
local Lorentz invariance
local position invariance

The outcome of any local non-gravitational experiment in a freely falling laboratory is independent of the velocity of the laboratory and its location in spacetime.

If this principle holds then gravity is a consequence of the geometry of spacetime



This principle has been a driving idea in theories of gravity from Galileo to Einstein

GR in a nutshell

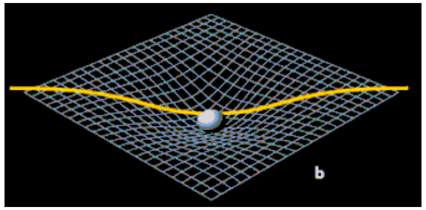
Underlying hypothesis

Equivalence principle

- Universality of free fall
- Local lorentz invariance
- Local position invariance

Physical metric

$$S_{matter}(\psi, g_{\mu\nu})$$



gravitational metric

Dynamics

$$S_{grav} = \frac{c^3}{16\pi G}\int\sqrt{-g_*}\,R_*\,d^4x$$

Relativity

$$g_{\mu\nu} = g^*_{\mu\nu}$$

Equivalence principle and constants

Action of a test mass:

$$S = -\int mc\sqrt{-g_{\mu\nu}v^\mu v^\nu}\,dt$$

with

$$v^\mu = dx^\mu/dt$$
$$u^\mu = dx^\mu/d\tau$$

$$\delta S = 0$$

$$a^\mu \equiv u^\nu \nabla_\nu u^\mu = 0$$

(geodesic)

$$g_{00} = -1 + 2\Phi_N/c^2$$

(Newtonian limit)

$$\dot{\mathbf{v}} = \mathbf{a} = -\nabla\Phi_N = \mathbf{g}_N$$

The equivalence principle in Newtonian physics

The deviation from the universality of free fall is characterized by

$$\eta \equiv 2\frac{|a_1 - a_2|}{|a_1 + a_2|}$$

Second law: $F = m_I a$

Definition of weight $F = m_G g$

$$\left.\begin{array}{l} F = m_I a \\ F = m_G g \end{array}\right\} \quad a = (m_G/m_I)g,$$

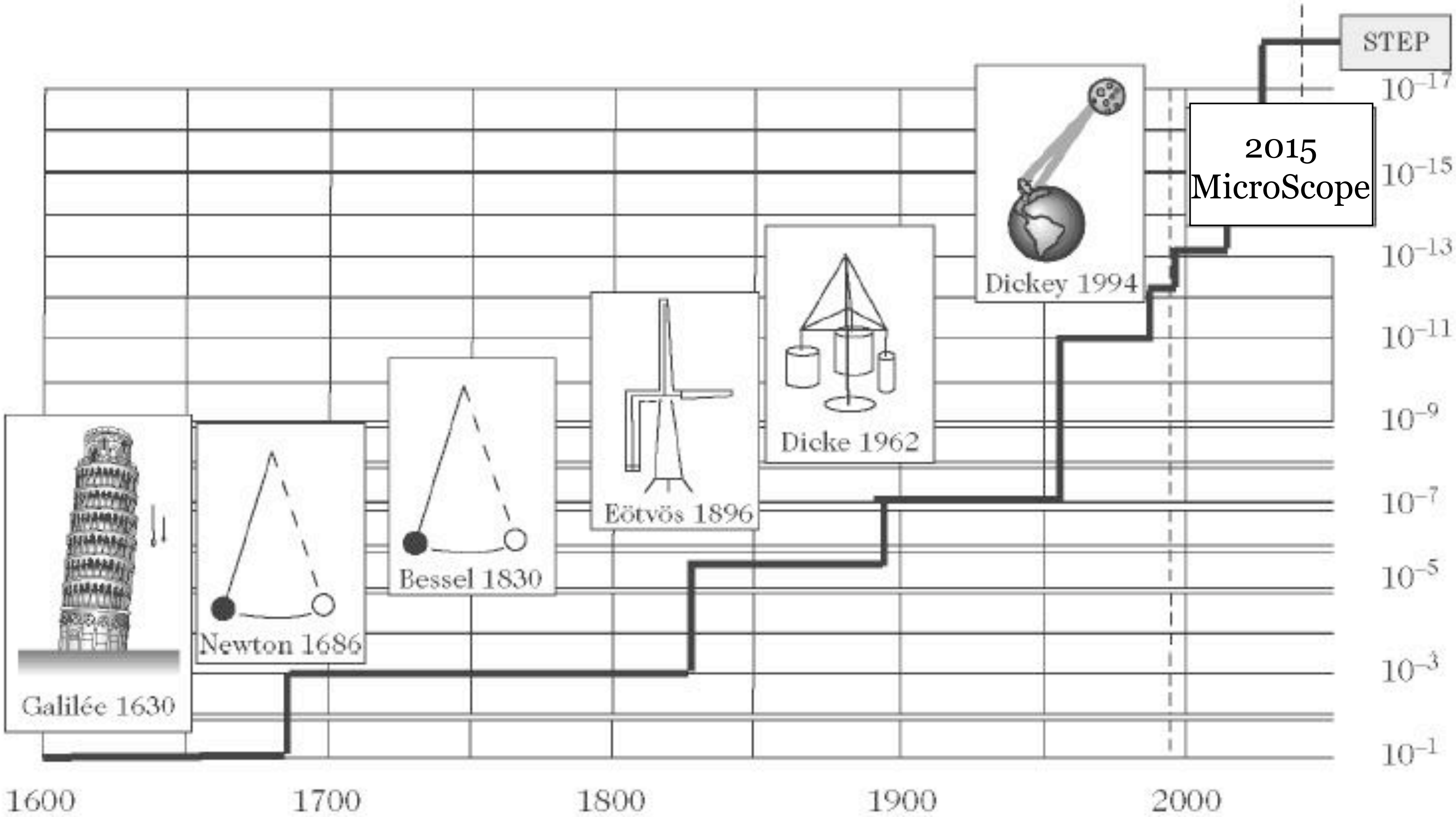
So that $$\eta = 2\frac{|m_G^1/m_I^1 - m_G^2/m_I^2|}{m_G^1/m_I^1 + m_G^2/m_I^2}$$

Consider a pendumum of length L in a gravitational field g,

$$\ddot{\theta} + \omega^2\theta = 0 \quad \text{où} \quad \omega \equiv \omega_0\sqrt{\frac{m_G}{m_I}} \quad \text{et} \quad \omega_0 \equiv \sqrt{\frac{g}{L}}.$$

Then $$\eta \approx 2\frac{|\omega_B - \omega_A|}{\omega_0}$$

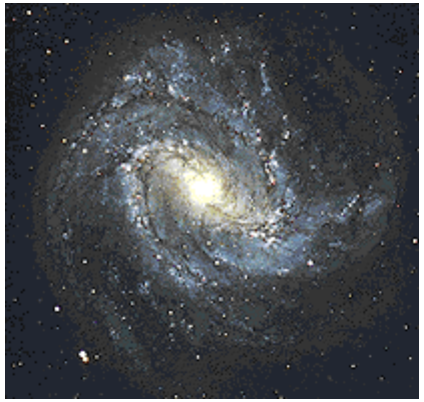
Tests on the universality of free fall



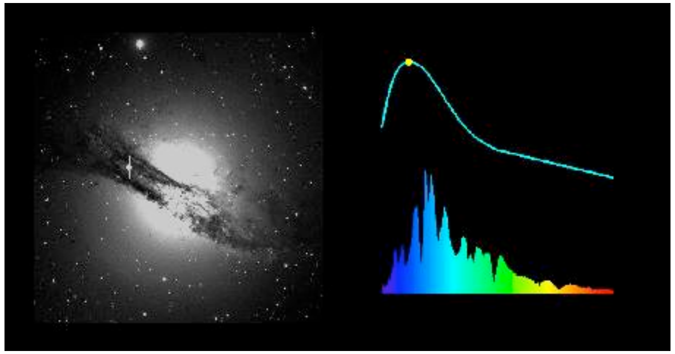
Testing general relativity on astrophysical scales

There is a growing need to test general relativity on astrophysical scales

dynamics of galaxies
and ***dark matter***



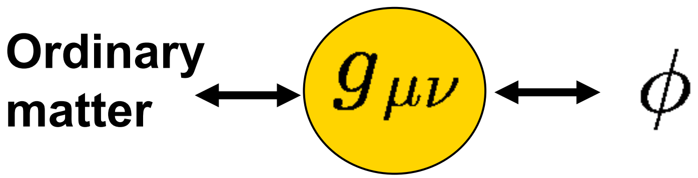
acceleration of the universe
and ***dark energy***



but also theoretical motivations…

Can we extend the test of the equivalence principle on astrophysical scales?

Universality classes of extensions



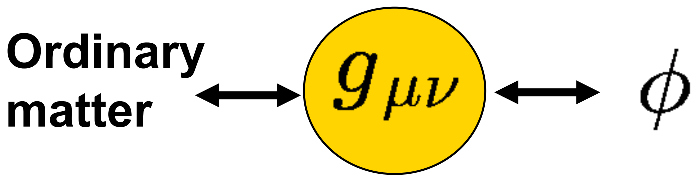
Ex : quintessence, ...

$$S_{\rm de}[{\rm de}; g_{\mu\nu}]$$

JDEM workshop, 2004

[JPU, Aghanim, Mellier, PRD 05]
[JPU, GRG 2007]

Universality classes of extensions



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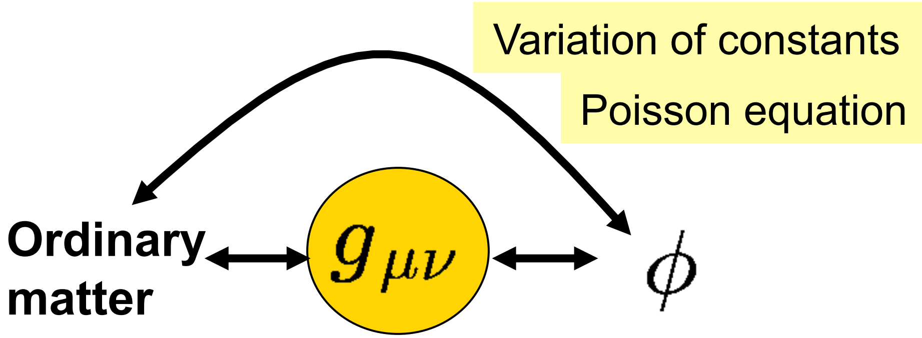


Ex : scalar-tensor, TeVeS ....

$$S_\varphi[\varphi; g_{\mu\nu}]$$

$$S_m[{\rm mat}; g_{\mu\nu}] \to S_m[{\rm mat}_i; A_i^2(\varphi) g_{\mu\nu}].$$

[JPU, Aghanim, Mellier, PRD 05]
[JPU, GRG 2007]

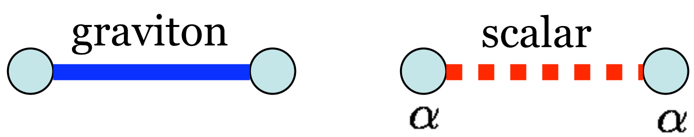
Famous example: Scalar-tensor theories

$$S = \frac{c^3}{16\pi G}\int\sqrt{-g}\{R - 2(\partial_\mu\phi)^2 - V(\phi)\} + S_m\{\mathrm{matter}, \tilde{g}_{\mu\nu} = A^2(\phi)g_{\mu\nu}\}$$

spin 2

spin 0

$$G_{\mathrm{cav}} = G(1+\alpha^2)$$

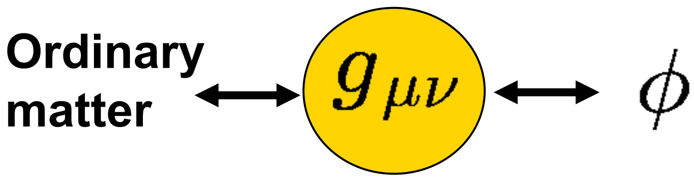


$$\alpha = \mathrm{d}\ln A/\mathrm{d}\phi$$

Motion of massive bodies determines $G_{cav}M$ **not** GM.

G_{cav} is a priori space-time dependent

Universality classes of extensions



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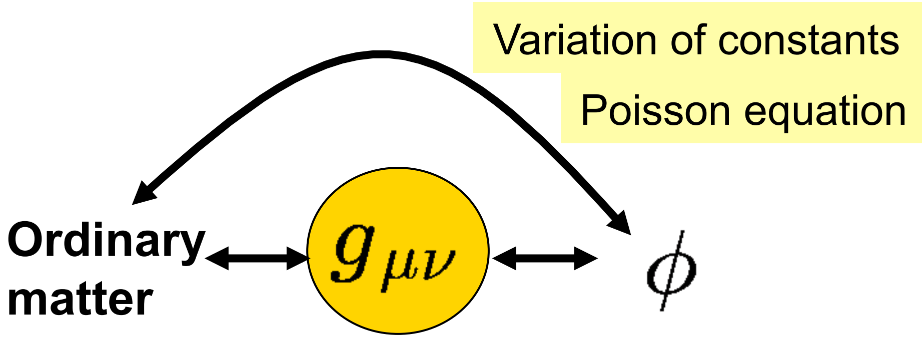
$S_{\rm de}[{\rm de}; g_{\mu\nu}]$

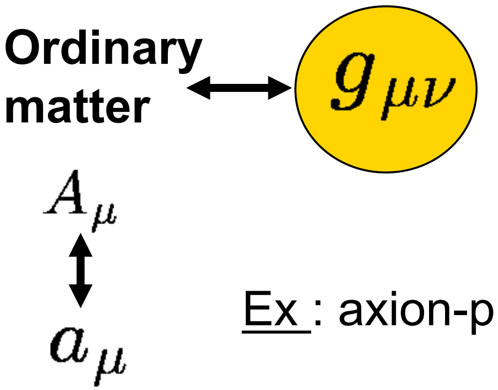


Ex : scalar-tensor, TeVeS ....

$S_\varphi[\varphi; g_{\mu\nu}]$

$S_m[{\rm mat}; g_{\mu\nu}] \to S_m[{\rm mat}_i; A_i^2(\varphi) g_{\mu\nu}].$

$S_{\rm em}[A_\mu; g_{\mu\nu}] \to S_{\rm em}[A_\mu, a_\mu; g_{\mu\nu}].$



Ex : axion-photon mixing

Distance duality

Always need **NEW** fields

[JPU, Aghanim, Mellier, PRD 05]
[JPU, GRG 2007]

Equivalence principle
and
fundamental constants

[Dicke 1964,...]

Equivalence principle and constants

Action of a test mass:

$$S = -\int m_A[\alpha_i] c \sqrt{-g_{\mu\nu} v^\mu v^\nu}\, dt \quad \text{with} \quad \begin{aligned} v^\mu &= dx^\mu/dt \\ u^\mu &= dx^\mu/d\tau \end{aligned}$$

Dependence on some constants

$$\delta S = 0$$

$$f_{A,i}$$

$$a^\mu_A = -\sum_i \left(\frac{\partial \ln m_A}{\partial \alpha_i} \frac{\partial \alpha_i}{\partial x^\beta} \right) (g^{\beta\mu} + u^\beta u^\mu)$$

(NOT a geodesic)

$$g_{00} = -1 + 2\Phi_N/c^2$$

(Newtonian limit)

$$\mathbf{a} = \mathbf{g}_N + \delta \mathbf{a}_A$$

$$\delta \mathbf{a}_A = -c^2 \sum_i f_{A,i} \left(\nabla \alpha_i + \dot{\alpha}_i \frac{\mathbf{v}}{c^2} \right)$$

Anomalous force
Composition dependent

[Dicke 1964,...]

Equivalence principle and constants

Forget all this, and think Newtonian.

Mass of test body = mass of its constituants + binding energy

$$\frac{d\vec{p}}{dt} = \vec{0} = m\vec{a} + \underbrace{\frac{dm}{d\alpha}\dot{\alpha}\vec{v}}_{m\vec{a}_{\text{anomalous}}}$$

[Dicke 1964,...]

Varying constants

The new fields can make the constants become dynamical.

The constant has to be replaced by a dynamical field or by a function of a dynamical field

This has 2 consequences:

1- the equations derived with this parameter constant will be modified

one cannot just make it vary in the equations

2- the theory will provide an equation of evolution for this new parameter

The field responsible for the time variation of the « constant » is also responsible for a long-range (composition-dependent) interaction

i.e. at the origin of the deviation from General Relativity.

In most extensions of GR (e.g. string theory), one has varying constants.

Example of varying fine structure constant

It is a priori « **easy** » to design a theory with varying fundamental constants

Consider

$$S = \int \{ \frac{1}{16\pi G} R - 2(\partial_\mu \phi)^2 - V(\phi) - \frac{1}{4} B(\phi) F_{\mu\nu}^2 \} \sqrt{-g}\, d^4x$$

But that may have dramatic implications.

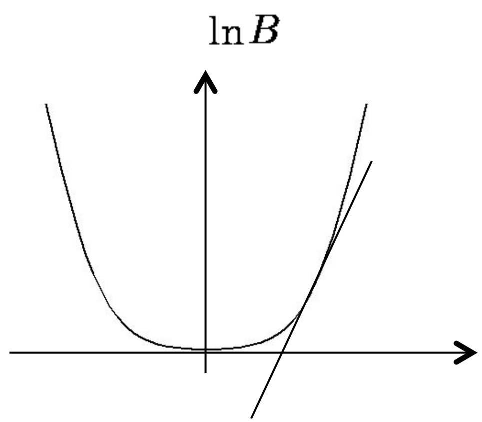
$$m_A(\phi) \supset 98.25 \alpha \frac{Z(Z-1)}{A^{1/3}} \mathrm{MeV} \longrightarrow f_i = \partial_\phi \ln m_i \sim 10^{-2} \frac{Z(Z-1)}{A^{4/3}} \alpha'(\phi)$$

Violation of UFF is quantified by

$$\eta_{12} = 2 \frac{|\vec{a}_1 - \vec{a}_2|}{|\vec{a}_1 + \vec{a}_2|} = \frac{f_{\rm ext} |f_1 - f_2|}{1 + f_{\rm ext}(f_1 + f_2)/2}$$

It is of the order of

$$\eta_{12} \sim 10^{-9} \underbrace{\mathrm{X}_{1,2,\mathrm{ext}}(A, Z)}_{\mathcal{O}(0.1-10)} \times (\partial_\phi \ln B)_0^2$$



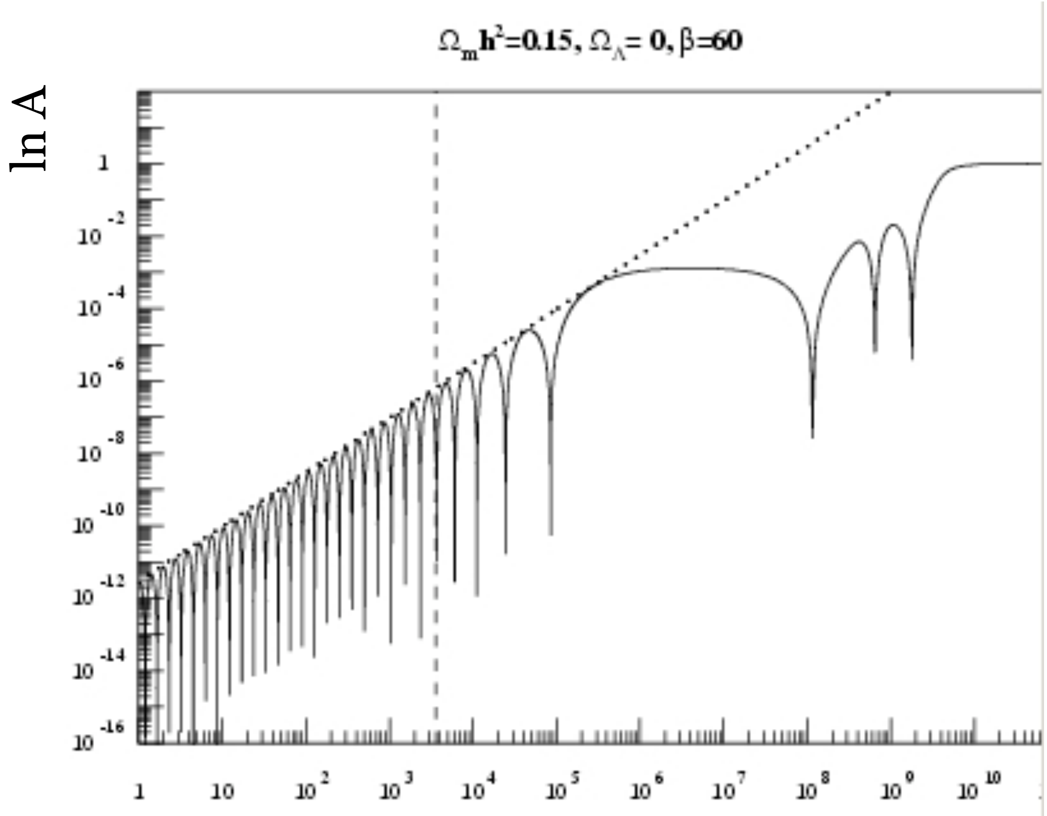
Requires to be close to the minimum

Screening & decoupling mechanisms

To avoid large effects, one has various options:

- *Least coupling principle*: all coupling functions have the same minimum and the theory can be attracted toward GR

[Damour, Nordtvedt & Damour, Polyakov]



$$V = \mathrm{cst}, \qquad A = \exp\left(\frac{1}{2}\beta\phi^2\right)$$

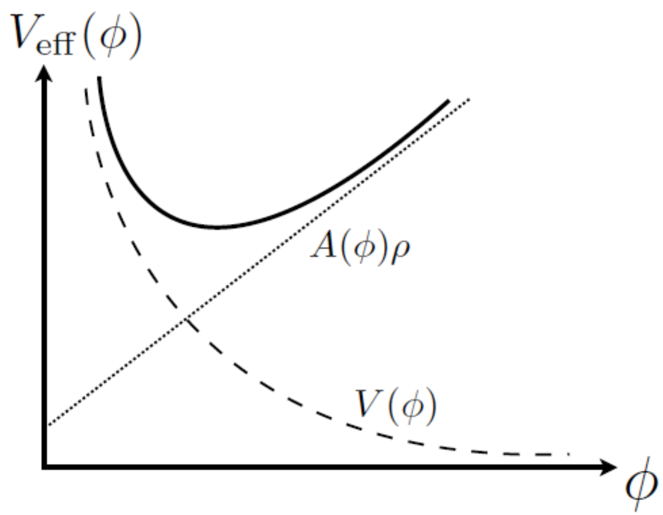
Screening & decoupling mechanisms

To avoid large effects, one has various options:

- *Least coupling principle*: all coupling functions have the same minimum and the theory can be attracted toward GR

[Damour, Nordtvedt & Damour, Polyakov]

- *Chameleon mechanism*: Potential and coupling functions have different minima.



$$m^2_{\rm min} = V_{,\phi\phi}(\phi_{\rm min}) + A_{,\phi\phi}(\phi_{\rm min})\rho$$

The field can become massive enough to evade existing constraints.

[Khoury, Weltmann, 2004]
[Ellis et al., 1989]

Screening & decoupling mechanisms

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- *Least coupling principle*: all coupling functions have the same minimum and the theory can be attracted toward GR

[Damour, Nordtvedt & Damour, Polyakov]

- *Chameleon mechanism*: Potential and coupling functions have different minima.

[Khoury, Weltmann, 2004]

- *Symmetron mechanism*: similar to chameleon but VEV depends on the local density.

[Pietroni 2005; Hinterbichler,Khoury, 2010]

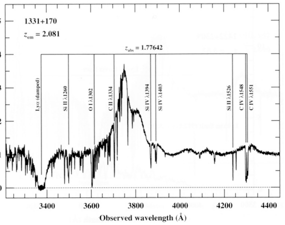
$$\left.\begin{aligned} V(\phi) &= -\frac{1}{2}\mu^2\phi^2 + \frac{1}{4}\lambda\phi^4 \\ A(\phi) &= 1 + \frac{1}{2M^2}\phi^2 + \mathcal{O}(\phi^4/M^4) \end{aligned}\right] \quad V_{\rm eff}(\phi) = \frac{1}{2}\left(\frac{\rho}{M^2} - \mu^2\right)\phi^2 + \frac{1}{4}\lambda\phi^4$$

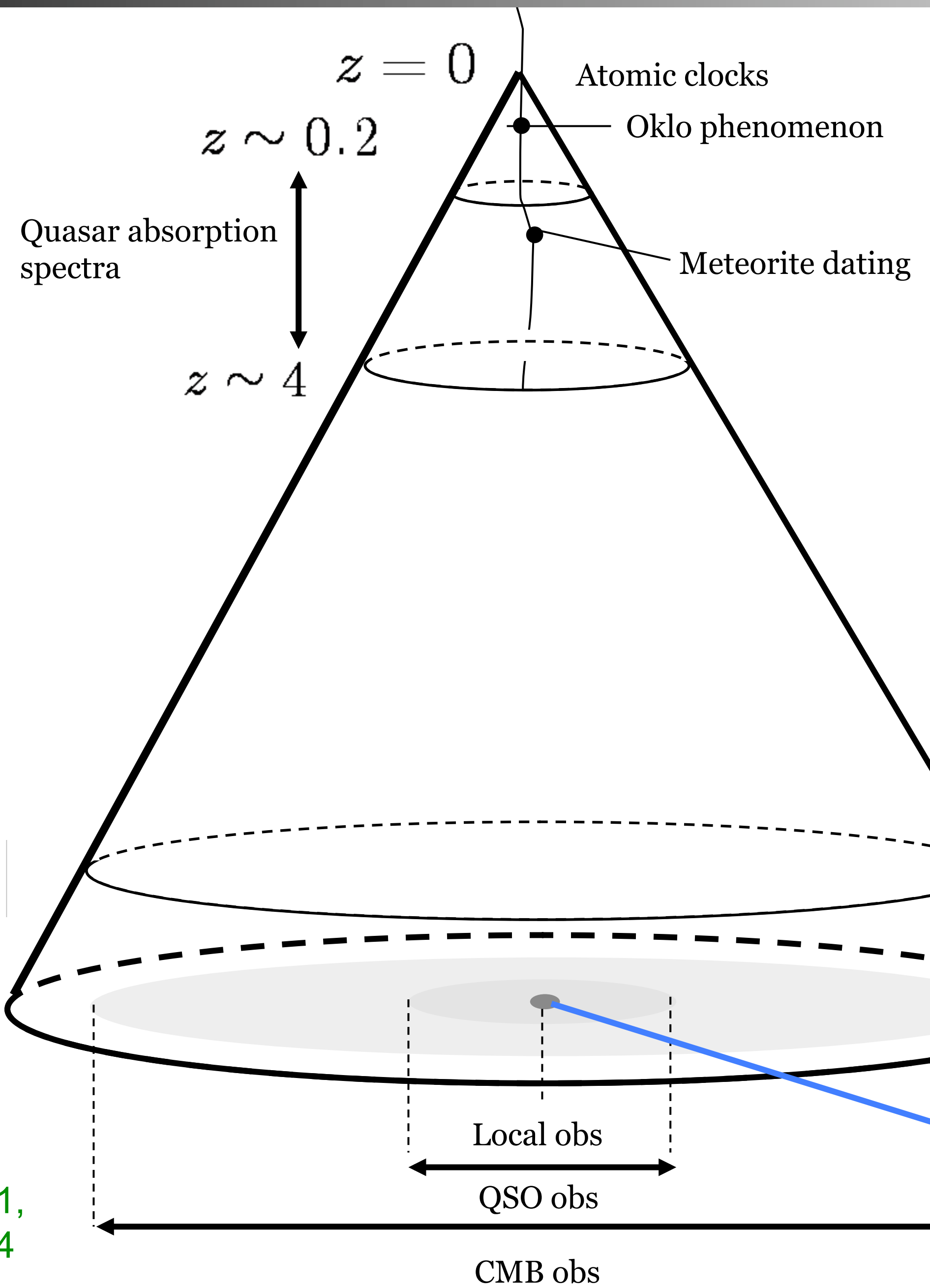
Symmetry is restored at high density.

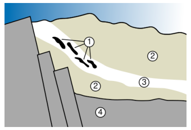
Environmental dependence

Atomic clocks
and
astrophysical systems

Physical systems

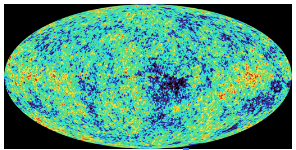


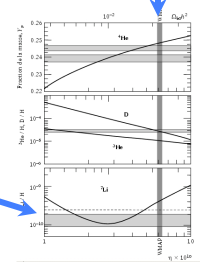




$z = 0.14$

$z = 0.43$





JPU, RMP (2003);
arXiv:0907.3081,
arXiv:1009.5514

Atomic clocks

Based the comparison of atomic clocks using different transitions and atoms

e.g. hfs Cs vs fs Mg : $g_p\mu$;

hfs Cs vs hfs H: $(g_p/g_I)\alpha$

Examples $$\frac{\nu_{Cs}}{\nu_{Rb}} \propto \frac{g_{Cs}}{g_{Rb}}\alpha^{0.49}$$ $$\frac{\nu_{Cs}}{\nu_H} \propto g_{Cs}\mu\alpha^{2.83}$$

High precision / redshift 0 (local)

Clock 1	Clock 2	Constraint (yr^{-1}) $\frac{d}{dt}\ln\left(\frac{\nu_{clock_1}}{\nu_{clock_2}}\right)$	Constants dependence	Reference
^{87}Rb	^{133}Cs	$(0.2 \pm 7.0) \times 10^{-16}$	$\frac{g_{Cs}}{g_{Rb}}\alpha_{EM}^{0.49}$	Marion (2003)
^{87}Rb	^{133}Cs	$(-0.5 \pm 5.3) \times 10^{-16}$		Bize (2003)
^{1}H	^{133}Cs	$(-32 \pm 63) \times 10^{-16}$	$g_{Cs}\mu\alpha_{EM}^{2.83}$	Fischer (2004)
^{199}Hg$^+$	^{133}Cs	$(0.2 \pm 7) \times 10^{-15}$	$g_{Cs}\mu\alpha_{EM}^{6.05}$	Bize (2005)
^{199}Hg$^+$	^{133}Cs	$(3.7 \pm 3.9) \times 10^{-16}$		Fortier (2007)
^{171}Yb$^+$	^{133}Cs	$(-1.2 \pm 4.4) \times 10^{-15}$	$g_{Cs}\mu\alpha_{EM}^{1.93}$	Peik (2004)
^{171}Yb$^+$	^{133}Cs	$(-0.78 \pm 1.40) \times 10^{-15}$		Peik (2006)
^{87}Sr	^{133}Cs	$(-1.0 \pm 1.8) \times 10^{-15}$	$g_{Cs}\mu\alpha_{EM}^{2.77}$	Blatt (2008)
^{87}Dy	^{87}Dy			Cingöz (2008)
^{27}Al$^+$	^{199}Hg$^+$	$(-5.3 \pm 7.9) \times 10^{-17}$	$\alpha_{EM}^{-3.208}$	Blatt (2008)

Atomic clocks

The gyromagnetic factors can be expressed in terms of g_p and g_n (shell model).

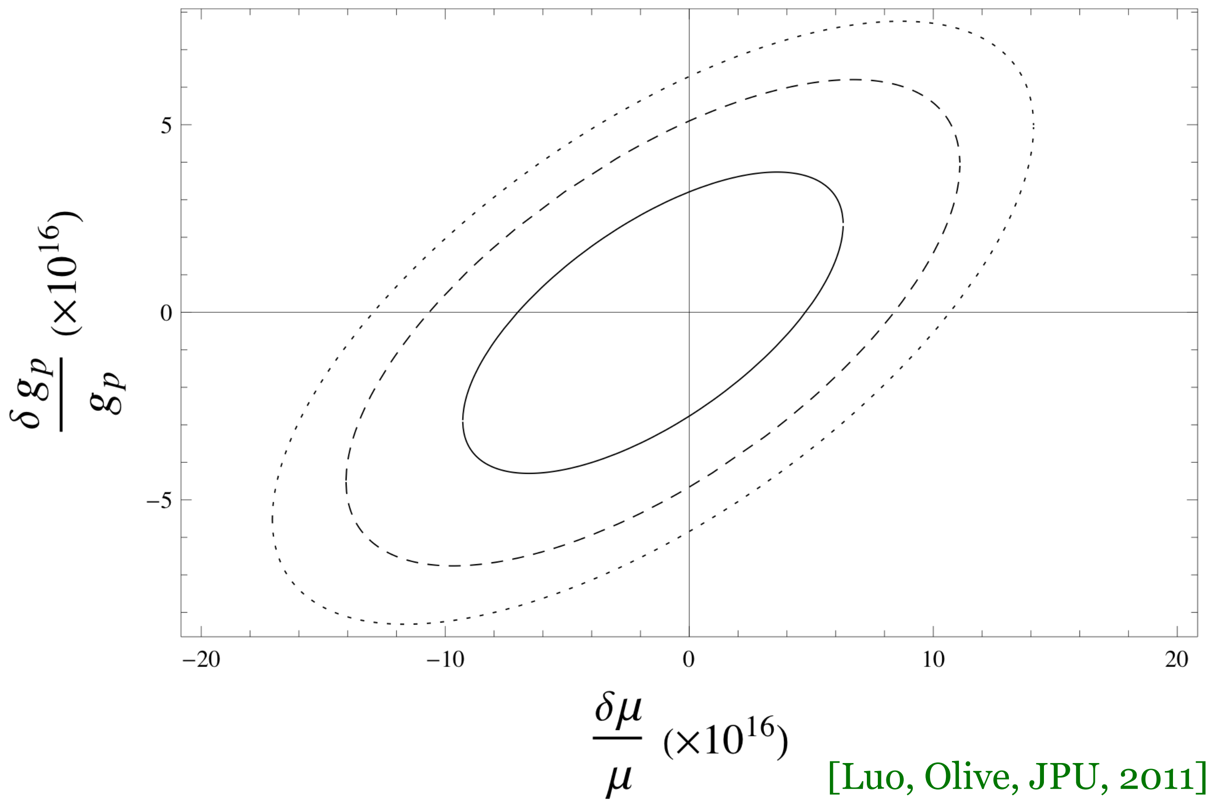
$$\frac{\delta g_{\rm Cs}}{g_{\rm Cs}} \sim -1.266\frac{\delta g_p}{g_p} \qquad \frac{\delta g_{\rm Rb}}{g_{\rm Rb}} \sim 0.736\frac{\delta g_p}{g_p}$$

All atomic clock constraints take the form $\frac{\dot\nu_{AB}}{\nu_{AB}} = \lambda_{g_{\rm p}}\frac{\dot g_{\rm p}}{g_{\rm p}} + \lambda_\mu\frac{\dot\mu}{\mu} + \lambda_\alpha\frac{\dot\alpha}{\alpha}$

Using Al-Hg to constrain α, the combination of other clocks allows to constraint $\{\mu, g_p\}$.

Note: one actually needs to include the effects of the polarization of the non-valence nucleons and spin-spin interaction.

[Flambaum, 0302015,...



[Luo, Olive, JPU, 2011]

Atomic clocks

One then needs to express m_p and g_p in terms of the quark masses and Λ_{QCD} as

$$\frac{\delta g_{\rm p}}{g_{\rm p}} = \kappa_{\rm u}\frac{\delta m_{\rm u}}{m_{\rm u}} + \kappa_{\rm d}\frac{\delta m_{\rm d}}{m_{\rm d}} + \kappa_{\rm s}\frac{\delta m_{\rm s}}{m_{\rm s}} + \kappa_{\rm QCD}\frac{\delta \Lambda_{\rm QCD}}{\Lambda_{\rm QCD}},$$

$$\frac{\delta m_{\rm p}}{m_{\rm p}} = f_{T_{\rm u}}\frac{\delta m_{\rm u}}{m_{\rm u}} + f_{T_{\rm d}}\frac{\delta m_{\rm d}}{m_{\rm d}} + f_{T_{\rm s}}\frac{\delta m_{\rm s}}{m_{\rm s}} + f_{T_{\rm g}}\frac{\delta \Lambda_{\rm QCD}}{\Lambda_{\rm QCD}},$$

$$m_i = h_i v$$

Assuming unification.

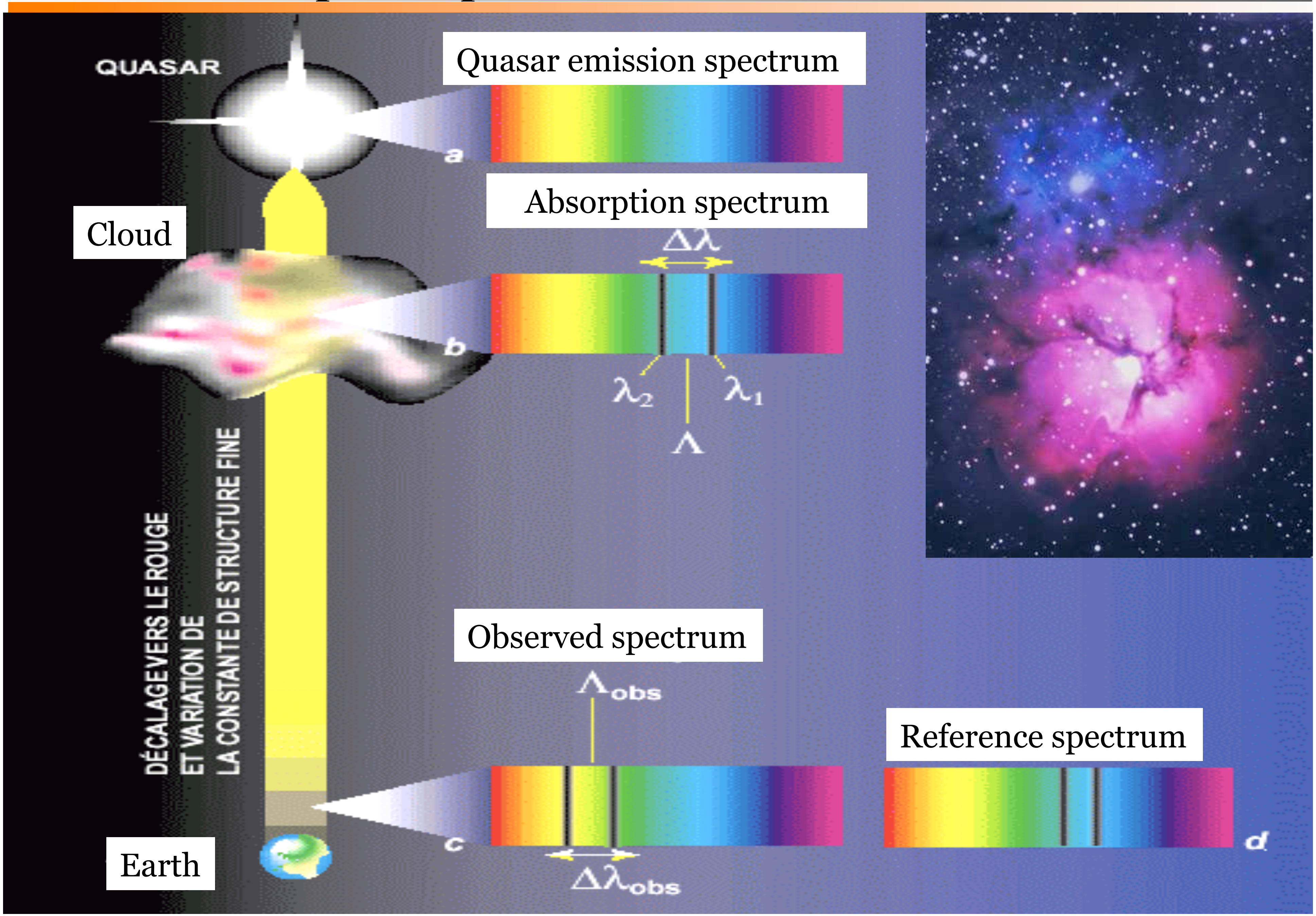
$$\frac{\dot\nu_{AB}}{\nu_{AB}} = \lambda_{g_{\rm p}}\frac{\dot g_{\rm p}}{g_{\rm p}} + \lambda_\mu\frac{\dot\mu}{\mu} + \lambda_\alpha\frac{\dot\alpha}{\alpha} \longrightarrow \frac{\dot\nu_{AB}}{\nu_{AB}} = C_{AB}\frac{\dot\alpha}{\alpha}$$

C_{AB} coefficients range from 70 to 0.6 typically.

Model-dependence remains quite large.

[Luo, Olive, JPU, 2011]

Quasar absorption spectra



Generalities

The method was introduced by Savedoff in 1956, using Alkali doublet

Most studies are based on optical techniques due to the profusion of strong UV transitions that are redshifted into the optical band

e.g. SiIV @ z>1.3, FeIIλ1608 @ z>1

Radio observations are also very important

e.g. hyperfine splitting (HI21cm), molecular rotation, lambda doubling, ...

- offer high spectral resolution (<1km/s)
- higher sensitivity to variation of constants
- isotopic lines observed separately (while blending in optical observations)

Shift to be detected are small

e.g. a change of α of 10^{-5} corresponds to

- a shift of 20 mÅ (i.e. of 0.5 km/s) at z~2
- ⅓ of a pixel at R=40000 (Keck/HIRES, VLT/UVES)

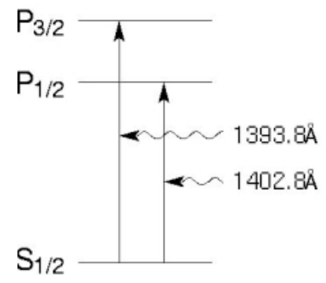
Many sources of uncertainty

- absorption lines have complex profiles (inhomogeneous cloud)
- fitted by Voigt profile (usually not unique: require lines not to be saturated)
- each component depends on z, column density, width

QSO absorption spectra

3 main methods:

Si IV alkali doublet



Alkali doublet (AD) Savedoff 1956

Fine structure doublet, $\Delta\lambda/\lambda \propto \alpha^2$

Single atom

Rather weak limit

VLT/UVES: Si IV in 15 systems, *1.6<z<3*

$$\frac{\Delta\alpha}{\alpha} = (0.15 \pm 0.43) \times 10^{-5}$$

Chand et al. 2004

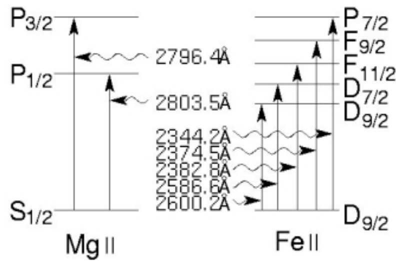
HIRES/Keck: Si IV in 21 systems, *2<z<3*

$$\frac{\Delta\alpha}{\alpha} = (-0.5 \pm 1.3) \times 10^{-5}$$

Murphy et al. 2001

Many multiplet (MM) Webb et al. 1999

Compares transitions from multiplet and/or atoms
s-p vs d-p transitions in heavy elements
Better sensitivity



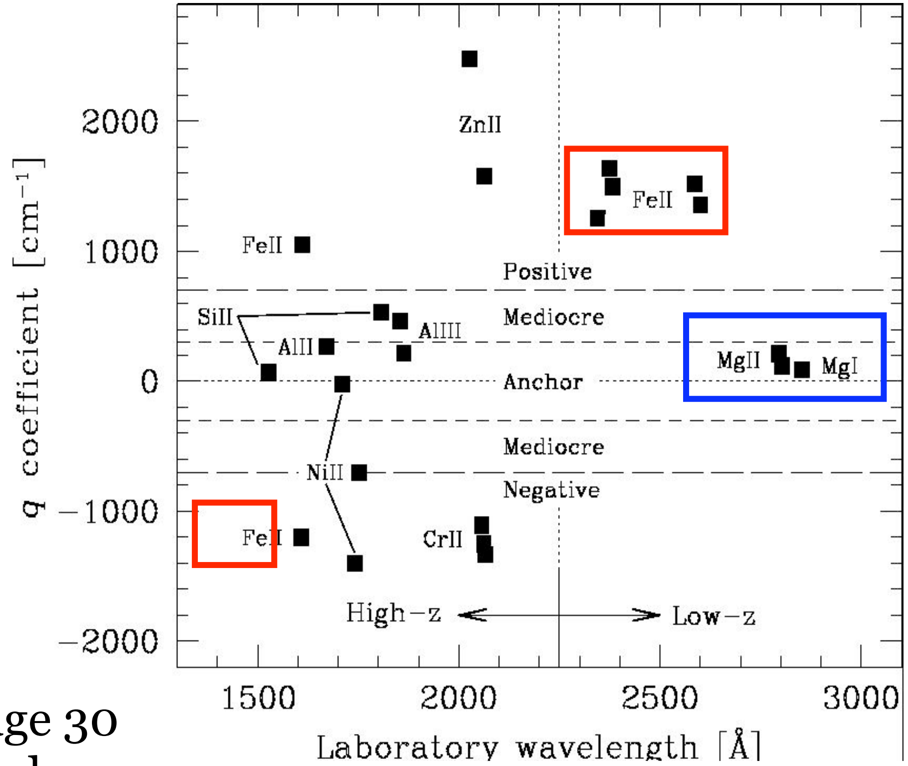
Single Ion Differential α Measurement (SIDAM) Levshakov et al. 1999

Analog to MM but with a single atom / FeII

QSO: many multiplets

The many-multiplet method is based on the corrrelation of the shifts of different lines of different atoms.

Dzuba et al. 1999-2005



Relativistic N-body with varying α:

$$\omega = \omega_0 + 2\,q\,\frac{\Delta\alpha}{\alpha}$$

First implemented on 30 systems with MgII and FeII

Webb et al. 1999

R=45000,
S/N per pixels between 4 & 240, with average 30
Wavelength calibrated with Thorium-Argon lamp

HIRES-Keck, 143 systems, *0.2<z<4.2*

$$\frac{\Delta\alpha}{\alpha} = (-\,0.57 \pm 0.11) \times 10^{-5}$$

Murphy et al. 2004

5σ detection !

QSO: VLT/UVES analysis

Selection of the absorption spectra:

- lines with similar ionization potentials

  most likely to originate from similar regions in the cloud
- avoid lines contaminated by atmospheric lines
- at least one anchor line is not saturated

  redshift measurement is robust
- reject strongly saturated systems

Only 23 systems

lower statistics / better controlled systematics

R>44000, S/N per pixel between 50 & 80

VLT/UVES

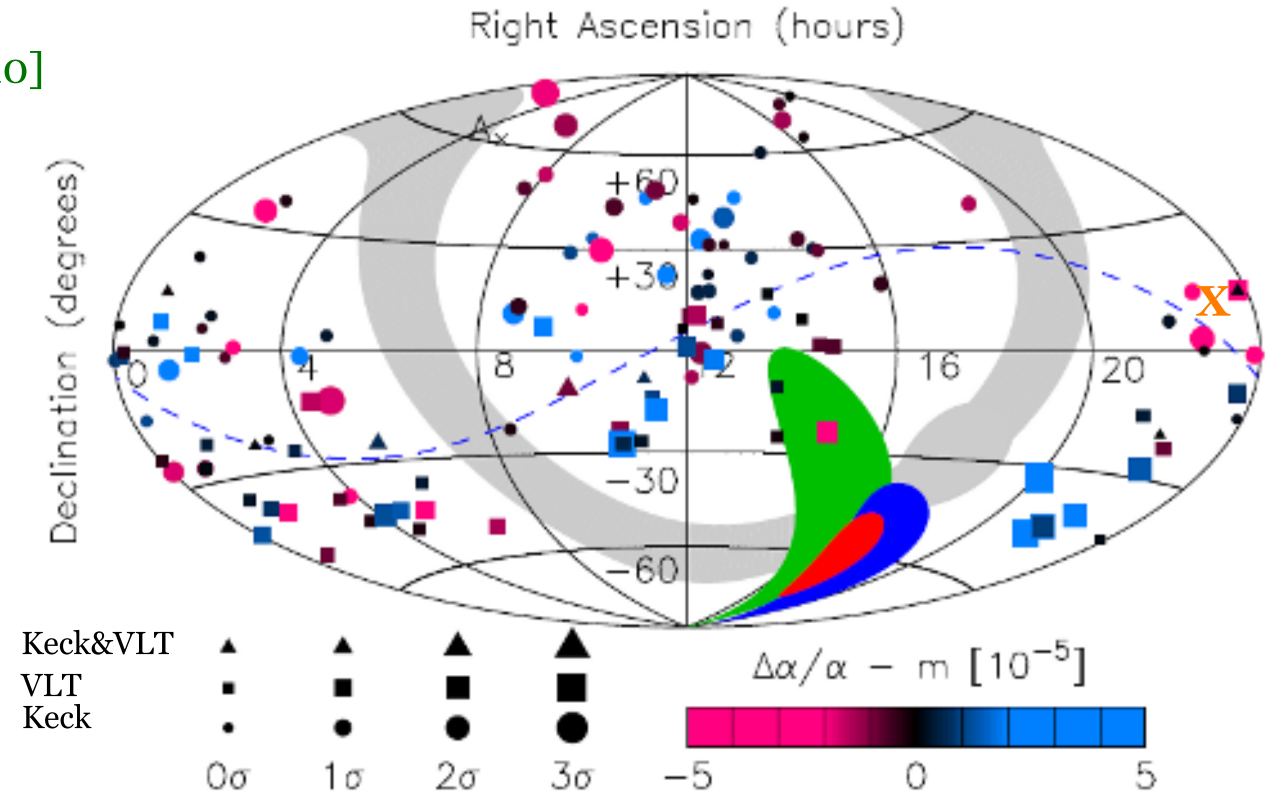
$$\Delta\alpha_{\rm EM}/\alpha_{\rm EM} = (0.01 \pm 0.15) \times 10^{-5}$$

Srianand et al. 2007

DOES NOT CONFIRM HIRES/Keck DETECTION

To vary or not to vary

[Webb et al., 2010]



$(\Delta\alpha_{EM}/\alpha_{EM})_{VLT;\, z<1.8} = (-0.06 \pm 0.16) \times 10^{-5}$

$(\Delta\alpha_{EM}/\alpha_{EM})_{VLT\, z>1.8} = (+0.61 \pm 0.20) \times 10^{-5}$

$(\Delta\alpha_{EM}/\alpha_{EM})_{Keck;\, z<1.8} = (-0.54 \pm 0.12) \times 10^{-5}$

$(\Delta\alpha_{EM}/\alpha_{EM})_{Keck;\, z>1.8} = (-0.74 \pm 0.17) \times 10^{-5}$

<u>Claim:</u> Dipole in the fine structure constant [« Australian dipole »]

Indeed, this is a logical possibility to reconcile VLT constraints and Keck claims of a variation.

Can it make sense?

- Dipole is not aligned with the CMB dipole

- With such a dipole, CMB fluctuations must be modulated

[Moss et al., 2010]

$$D_{\ell m}^{(0)} \equiv \langle a_{\ell m}^{\mathrm{obs}} a_{\ell+1 m}^{\mathrm{obs}*} \rangle = \varepsilon_0 \sqrt{\frac{3}{4\pi}} \frac{\sqrt{(\ell+1)^2 - m^2}}{\sqrt{(2\ell+1)(2\ell+3)}} (C_\ell + C_{\ell+1})$$

$$D_{\ell m}^{(1)} \equiv \langle a_{\ell m}^{\mathrm{obs}} a_{\ell+1 m+1}^{\mathrm{obs}*} \rangle = \sqrt{\frac{3}{4\pi}} \sqrt{\frac{(\ell+2+m)(\ell+1+m)}{(2\ell+1)(2\ell+3)}} [C_\ell + C_{\ell+1}] \frac{\varepsilon^*}{\sqrt{2}}$$

[Prunet, JPU, Bernardeau, Brunier, 2005]

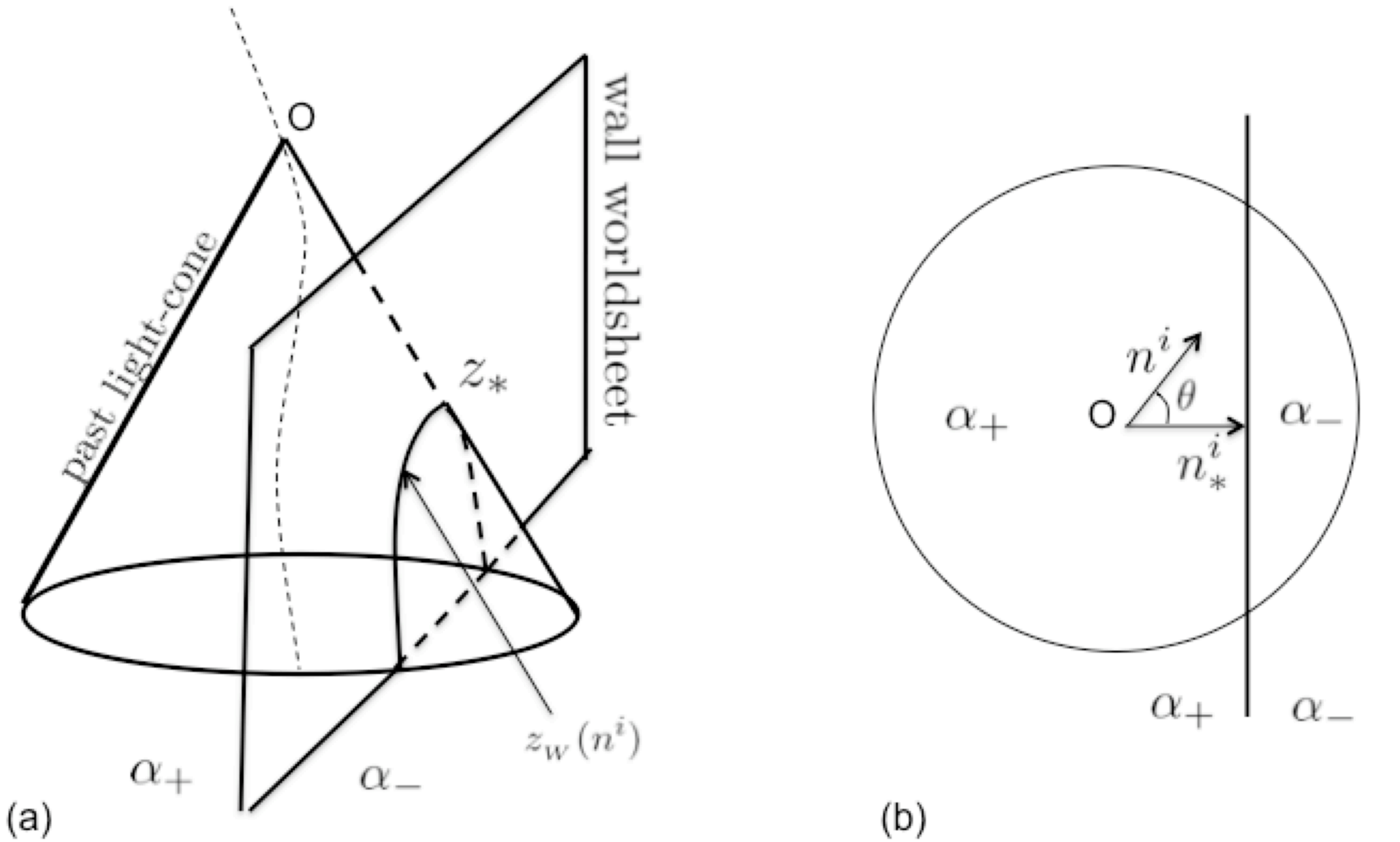
- Theoretically: in all existing models, time variation is larger than spatial variation

Is it possible to design a model compatible with such a claim?

Wall of fundamental constant

[Olive, Peloso, JPU, 2010]

Idea: Spatial discontinuity in the fundamental constant due to a domain wall crossing our Hubble volume.



Wall of fundamental constants

$$S = \int \Big[\frac{1}{2} M_p^2 R - \frac{1}{2}(\partial_\mu \phi)^2 + V(\phi) + \frac{1}{4} B_F(\phi) F_{\mu\nu}^2 - \sum_j i \bar{\psi}_j \not{D} \psi_j - B_j(\phi) m_j \bar{\psi}_j \psi_j \Big] \sqrt{-g}\, d^4x,$$

$$B_i(\phi) = \exp\left(\xi_i \frac{\phi}{M_*}\right) \simeq 1 + \xi_i \frac{\phi}{M_*}$$

$$V(\phi) = \frac{1}{4} \lambda (\phi^2 - \eta^2)^2$$

-Parameters $(\lambda, M_*, \eta, \xi_F, \xi_i)$

- We assume only ξ_F is non vanishing BUT the scalar field couples radiatively to nucleons $\xi_N = m_N^{-1} \langle N | (\xi_F/4) F_{\mu\nu}^2 | N \rangle$

$$\xi_p = -0.0007 \xi_F \qquad \xi_n = 0.00015 \xi_F$$

$$V_{\text{eff}} = V(\phi) + \xi_N \frac{\phi}{M_*} \rho_{\text{baryon}}$$

Constraints

$(\lambda, M_*, \eta, \xi_F, \xi_i)$

-Constraints from atomic clocks / Oklo / Meteorite dating are trivially satisfied

- To reproduce the «observations»

$$\frac{\Delta\alpha}{\alpha} \simeq 2\xi_F \frac{\eta}{M_*} \sim \text{few} \times 10^{-6}$$

- The contribution of the walls to the background energy is

$$\Omega_{\text{wall}} \equiv \frac{U_{\text{wall}} H_0}{\rho_0} \simeq \left(\frac{\eta}{100\ \text{MeV}}\right)^3,$$

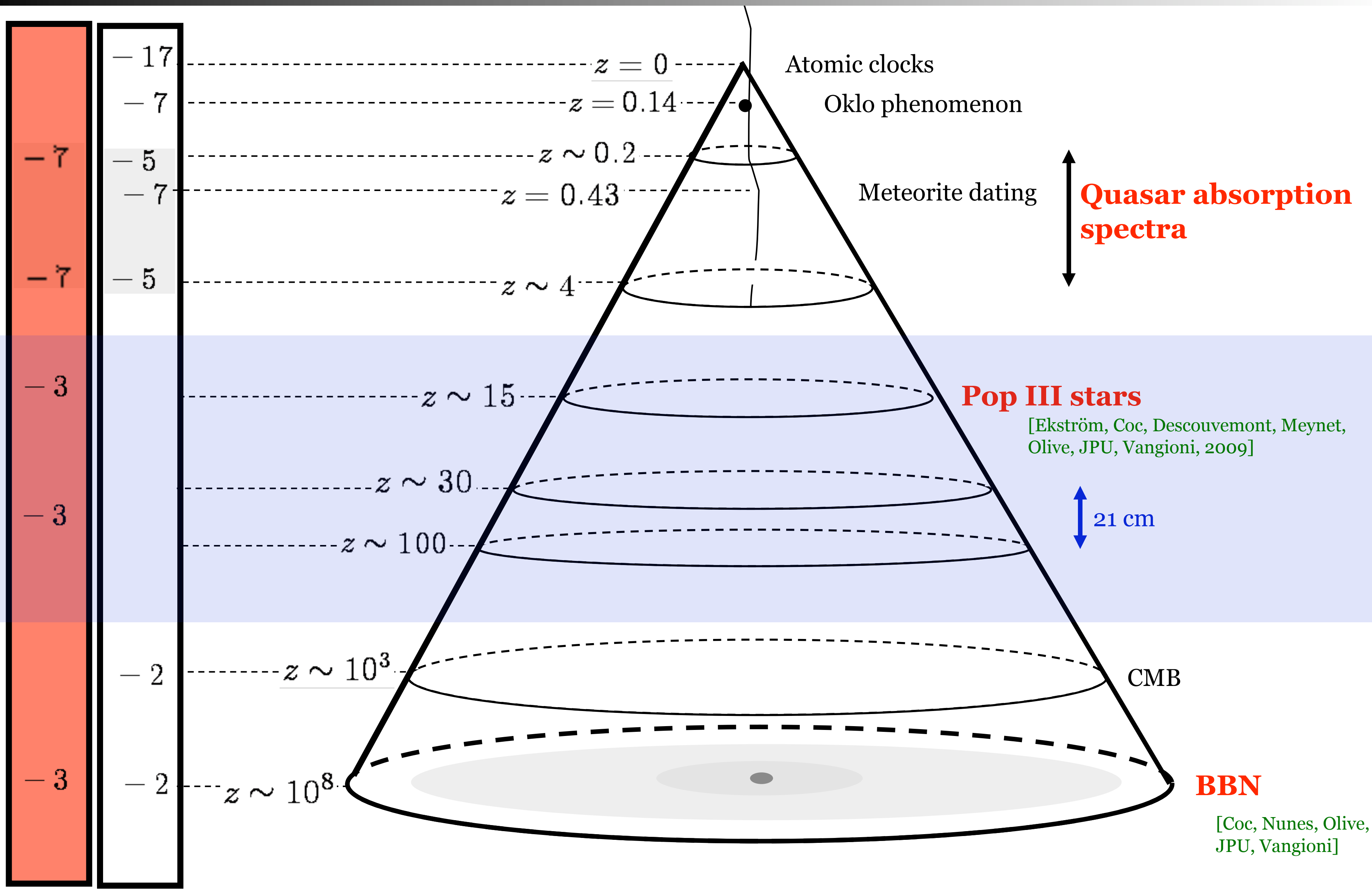
Assume $\eta = \mathcal{O}\,(\text{MeV})$

- CMB constraints $\left(\frac{\delta T}{T}\right)_{\text{CMB}} \sim 10^{-6}\left(\frac{\eta}{1\ \text{MeV}}\right)^3.$

-Valid field theory up to an energy scale $M_*/\xi_F \sim 10^6\ \text{MeV}$

- Astrophysical constraints
- Tunelling to the true vacuum
- Walls form at a redshift of order $8\text{x}10^9$

Physical systems: new and future



JPU, Liv. Rev. Relat., arXiv:1009.5514

Conclusions

The constancy of fundamental constants is a **test of the equivalence principle**.

The variation of the constants, violation of the universality of free fall and other deviations from GR are of the same order.

« Dynamical constants » are **generic** in most extenstions of GR (extra-dimensions, string inspired model.

Need for a stabilisation mechanism (least coupling principle/chameleon)
Why are the constants so constant?
Variations are expected to be larger in the past (cosmology)
All constants are expected to vary (unification)

Observational developments allow to set **strong constraints** on their variation

New systems [Stellar physics] / new observations

They offer tests of GR i**ndependently** of LSS and may offer signature in regimes where LSS cannot

e.g. can set constraints of time variation of a scalar field even if it does not dominate the matter content of the universe.

Question concerning their actual values and a possible fine-tuning.