Fundamental constants, gravitation and cosmology

Jean-Philippe UZAN

Overview

- Some generalities on fundamental constants and their variations
- Link to general relativity
- Constraints on their variations

Constants

Fundamental constants play an important role in physics

- set the order of magnitude of phenomena;
- allow to forge new concepts;
- linked to the structure of physical theories;
- characterize their domain of validity;

- *gravity:* linked to the equivalence principle;
- *cosmology*: at the heart of reflections on fine-tuning/naturalness/design/ multiverse;

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Any parameter not determined by the theories we are using.

It has to be assume constant (no equation/ nothing more fundamental)

Reproductibility of experiments.

One can only measure them.

[JPU, arXiv:1009.5514; hep-ph/0205340]

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)*]:

Thus number can *increase* or *decrease* with our knowledge of physics

Constant	Symbol	Value
Speed of light	c	299 792 458 m s^{-1}
Planck constant (reduced)	$\hbar$	1.054 571 628(53) × 10^{-34} J s
Newton constant	G	6.674 28(67) × 10^{-11} m^2 kg^{-1} s^{-2}
Weak coupling constant (at m_Z)	$g_2(m_Z)$	0.6520 ± 0.0001
Strong coupling constant (at m_Z)	$g_3(m_Z)$	1.221 ± 0.022
Weinberg angle	$\sin^2\theta_W(91.2\text{ GeV})_{\overline{\text{MS}}}$	0.23120 ± 0.00015
Electron Yukawa coupling	h_e	2.94 × 10^{-6}
Muon Yukawa coupling	h_μ	0.000607
Tauon Yukawa coupling	h_τ	0.0102156
Up Yukawa coupling	h_u	0.000016 ± 0.000007
Down Yukawa coupling	h_d	0.00003 ± 0.00002
Charm Yukawa coupling	h_c	0.0072 ± 0.0006
Strange Yukawa coupling	h_s	0.0006 ± 0.0002
Top Yukawa coupling	h_t	1.002 ± 0.029
Bottom Yukawa coupling	h_b	0.026 ± 0.003
Quark CKM matrix angle	$\sin\theta_{12}$	0.2243 ± 0.0016
	$\sin\theta_{23}$	0.0413 ± 0.0015
	$\sin\theta_{13}$	0.0037 ± 0.0005
Quark CKM matrix phase	δ_{CKM}	1.05 ± 0.24
Higgs potential quadratic coefficient	$\hat{\mu}^2$	? -(250.6 ±1.2) GeV^2
Higgs potential quartic coefficient	λ	? 1.015 ±0.05
QCD vacuum phase	θ_{QCD}	< 10^{-9}

m_H=(125.3±0.6)GeV

v=(246.7±0.2)GeV

Variation of constants

- Most constants have units.
- Any measurement is a comparison between two physical systems.
- Only the variations of dimensionless ratio makes sense.

c is the speed of light, isn't it?

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Constants and relativity

« C'est alors, considérant ces faits, qu'il me vint à l'esprit que si l'on supprimait totalement la résistance du milieu, tous les corps descendraient avec la même vitesse. »

Galilée, *in Discours concernant deux sciences nouvelles*, 1638
Traduction de Maurice Clavelin, PUF, 1995.

« Il y a une puissance de la gravité, qui concerne tous les corps, proportionnelle aux différentes quantités de matière qu'ils contiennent. »

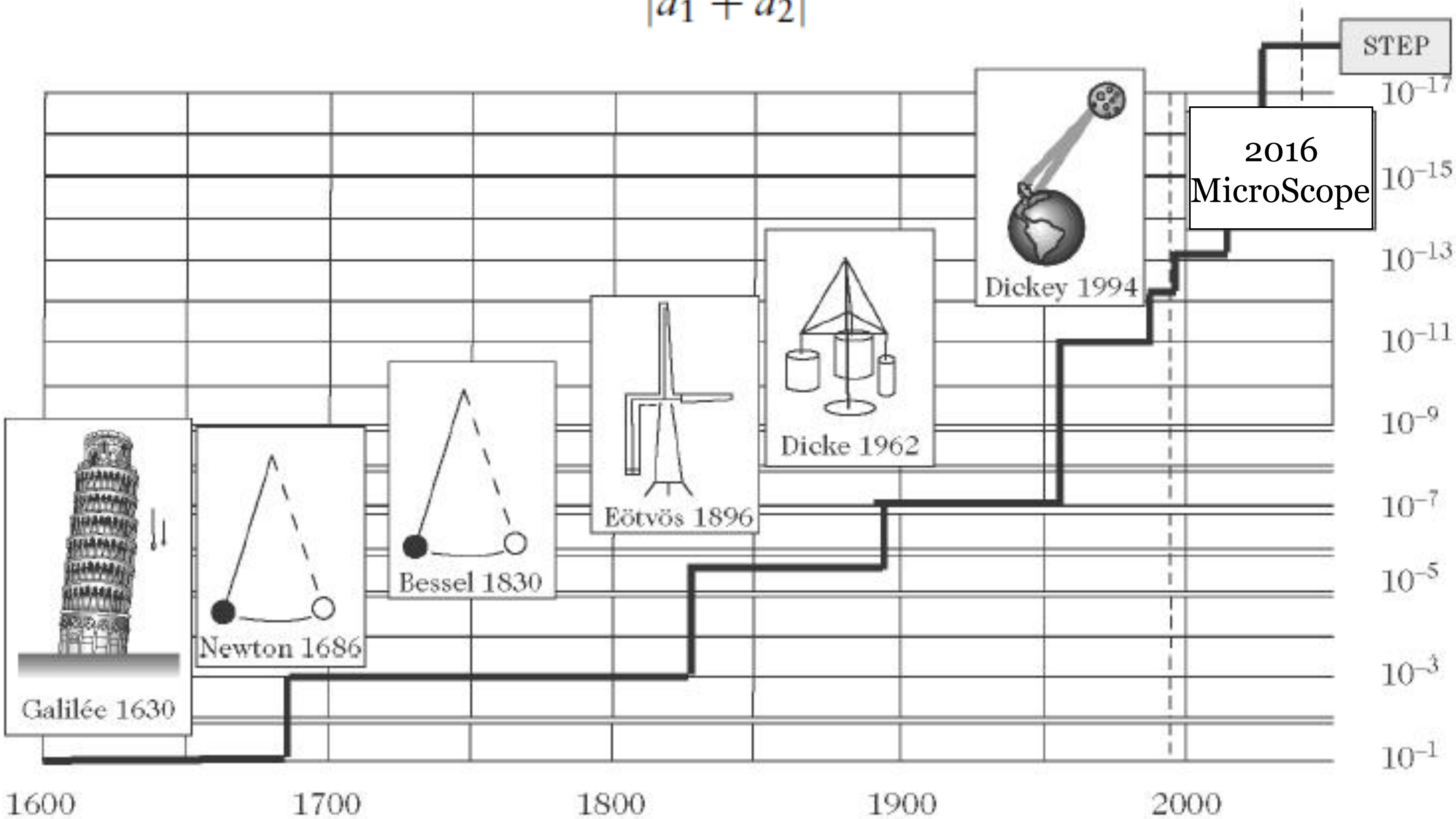
« Cette force est toujours proportionnelle à la quantité de matière des corps, *&* elle ne diffère de ce qu'on appelle l'inertie de la matière que par la manière de la concevoir. »

« La force de la pesanteur entre les différentes particules de tout corps est inversement proportionnelle au carré des distances des positions des particules. »

Isaac Newton, *in Principia*, Londres, 1687
Traduction d'Émilie du Châtelet, Paris, 1759.

Tests on the universality of free fall

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



GR in a nutshell

Underlying hypothesis

Equivalence principle

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

Physical metric

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

Not a basic principle of physics but mostly an empirical fact.

GR in a nutshell

Underlying hypothesis

Equivalence principle

- Universality of free fall
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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

In general relativity, any test particle follows a geodesic, which does not depend on the mass or on the chemical composition

Imagine some constants are space-time dependent

1- Local position invariance is violated.

2- Universality of free fall has also to be violated

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

In Newtonian terms, a free motion implies $\frac{d\vec{p}}{dt} = m\frac{d\vec{v}}{dt} = \vec{0}$

But, now

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

Varying constants: constructing theories

$$S[\phi, \bar{\psi}, A_\mu, h_{\mu\nu}, \ldots; c_1, \ldots, c_2]$$

If a constant is varying, this implies that it has to be replaced by 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.

[Ellis & JPU, gr-qc/0305099]

Example: ST theory

Most general theories of gravity that include a scalar field beside the metric

Mathematically **consistent**

Motivated by **superstring**

dilaton in the graviton supermultiplet,

modulii after dimensional reduction

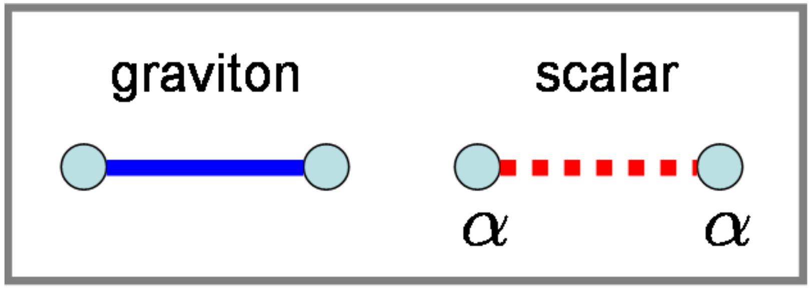
Consistent field theory to satisfy WEP

Useful extension of GR (simple but general enough)

spin 2

spin 0

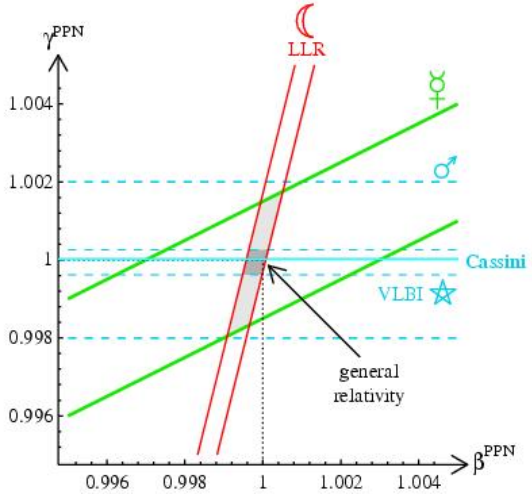
$$S = \frac{c^3}{16\pi G}\int\sqrt{-g}\{R - 2(\partial_\mu\phi)^2 - V(\phi)\}$$
$$+ S_m\{\text{matter}, \tilde{g}_{\mu\nu} = A^2(\phi)g_{\mu\nu}\}$$

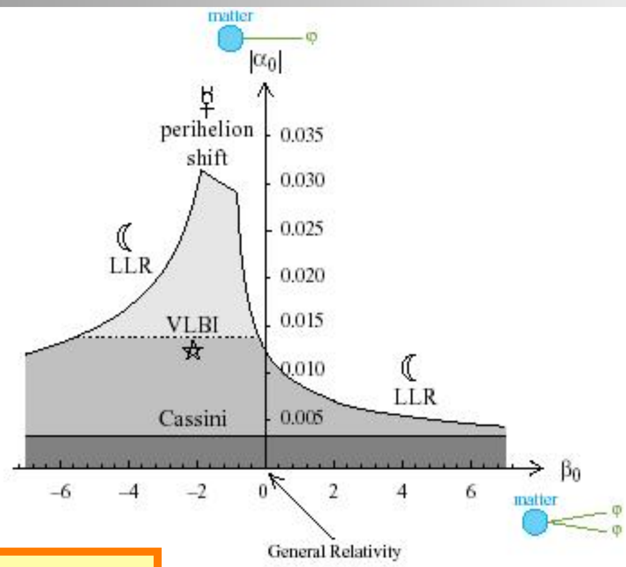


$$\alpha = \mathrm{d}\ln A/\mathrm{d}\phi$$
$$\beta = \mathrm{d}\alpha/\mathrm{d}\phi$$

ST theory: déviation from GR and variation

Courtesy of Esposito-Farèse

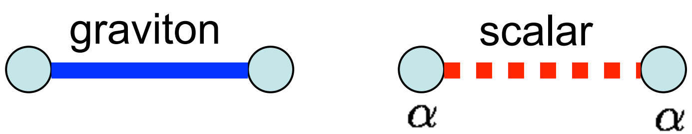




$$\alpha_0^2 < 10^{-5}, \qquad -4.5 < \beta_0$$

Time variation of G

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



$$\left.\frac{\dot G}{G}\right|_0 \equiv \sigma_0 H_0$$

$$\frac{\dot G}{G} < 10^{-12}\,\mathrm{yr}^{-1}$$

$$\sigma_0 < 10^{-2}$$

Constraints valid for a (almost) massless field.

Example of varying fine structure constant

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

Consider

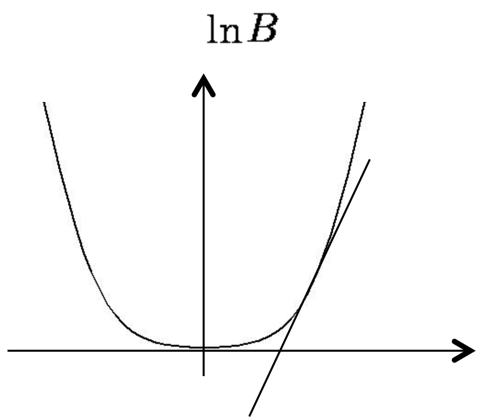
$$S = \int \left\{ \frac{1}{16\pi G} R - 2(\partial_\mu \phi)^2 - V(\phi) - \frac{1}{4} B(\phi) F^2_{\mu\nu} \right\} \sqrt{-g}\, d^4x$$

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

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

Generically: variation of fund. Cst. gives a too large violation of UFF

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.

[Khoury, Weltmann, 2004]

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

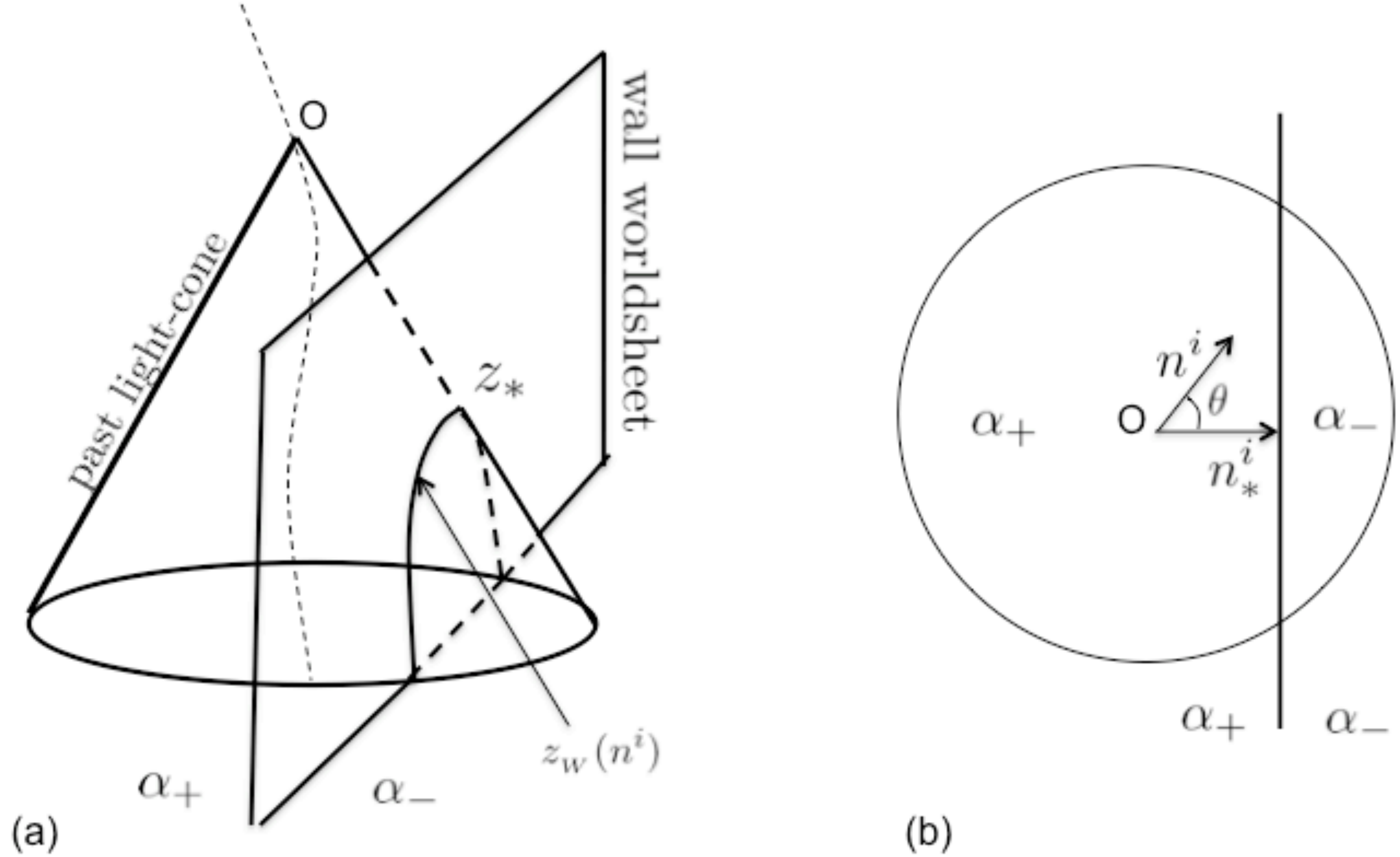
[Pietroni 2005; Hinterbichler,Khoury, 2010]

Environmental dependence

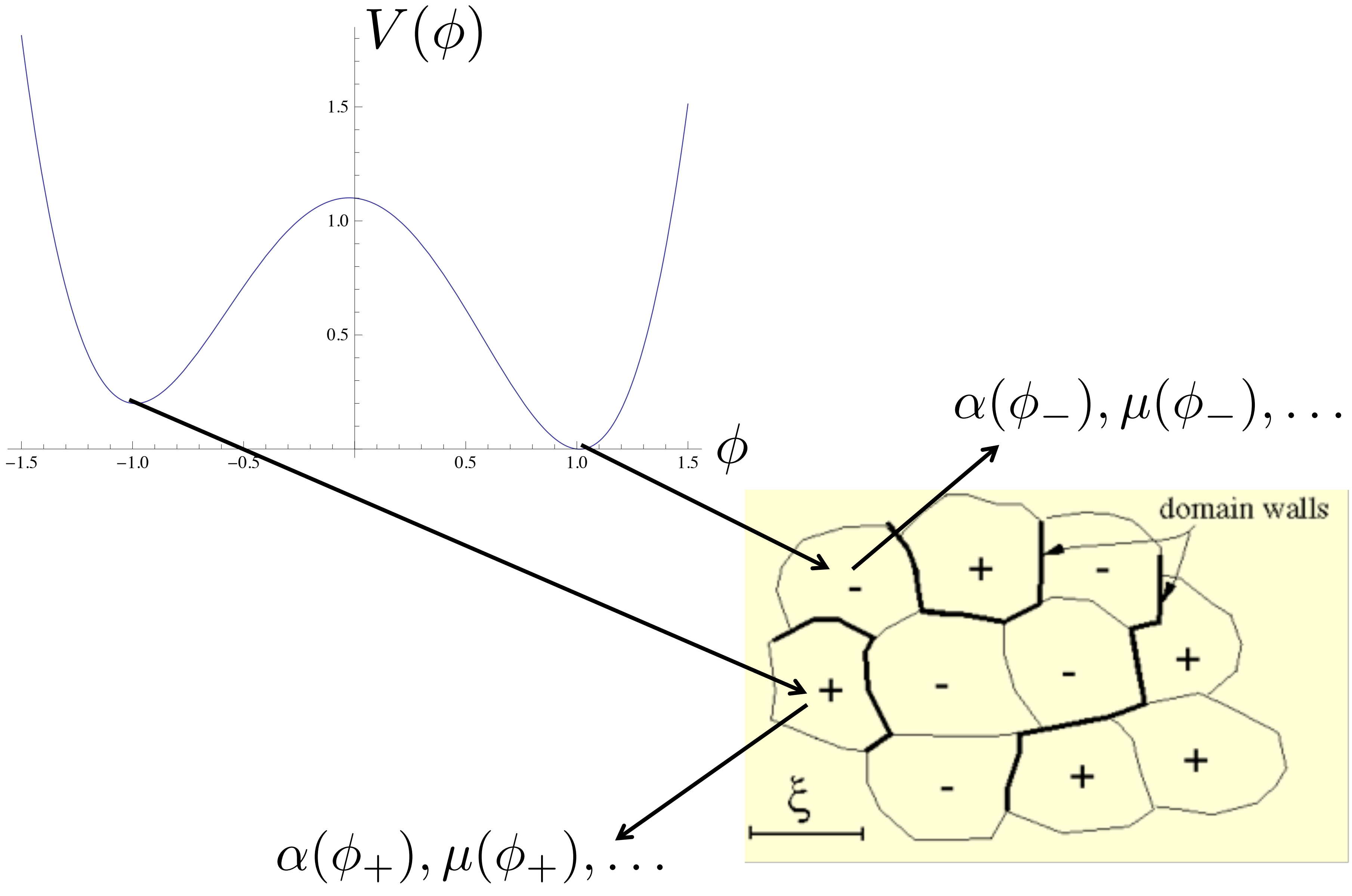
Wall of fundamental constant

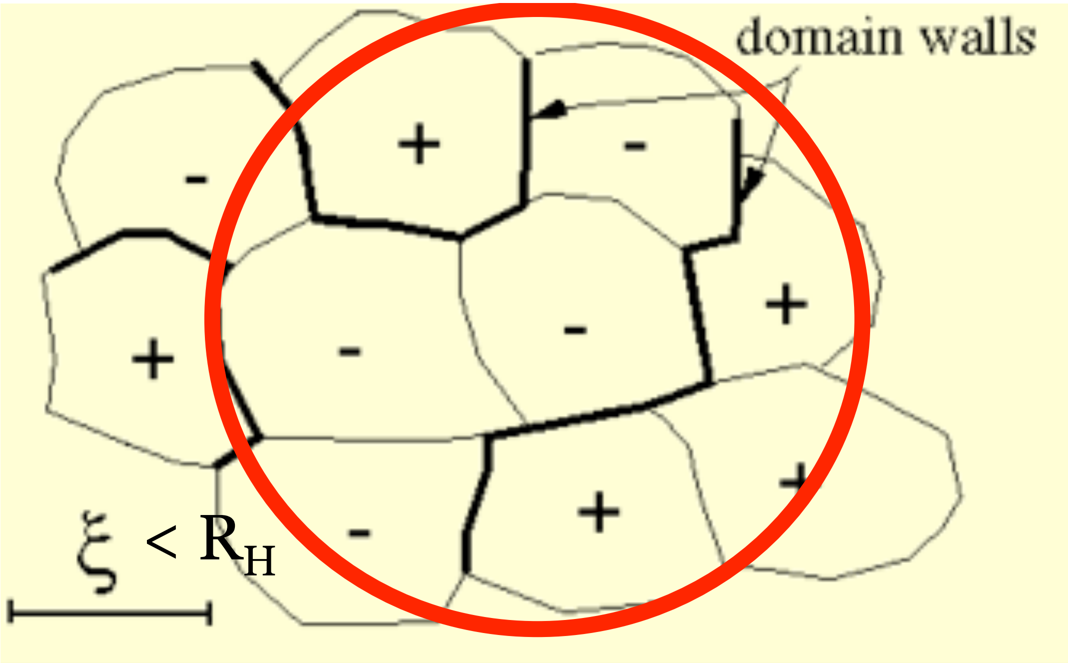
[Olive, Peloso, JPU, 2010]

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

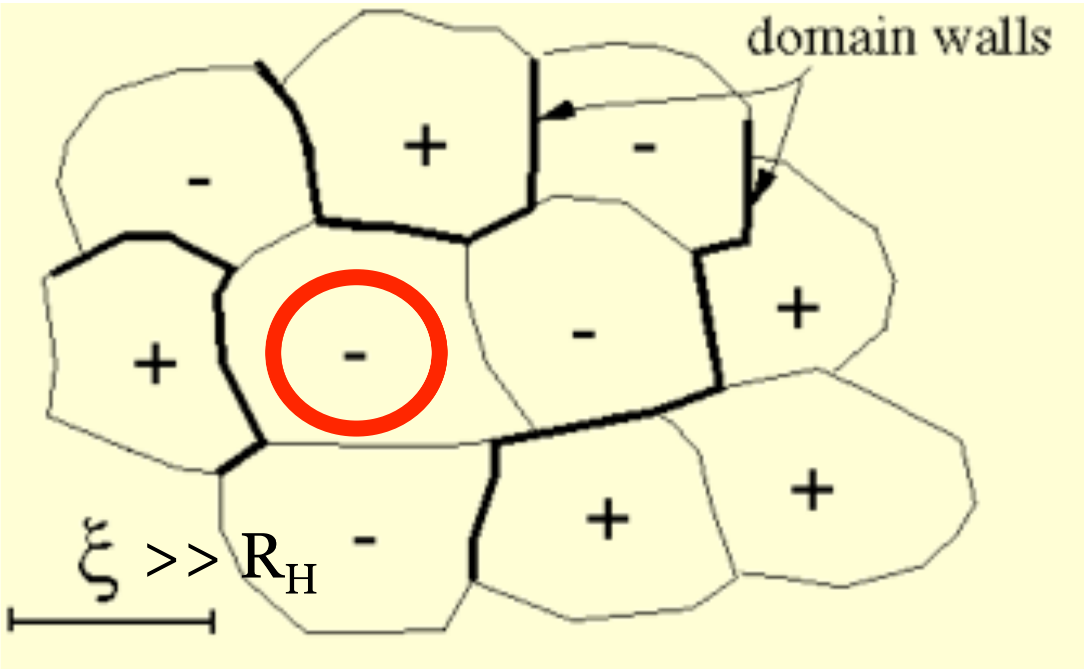


Spatial distribution of the constants





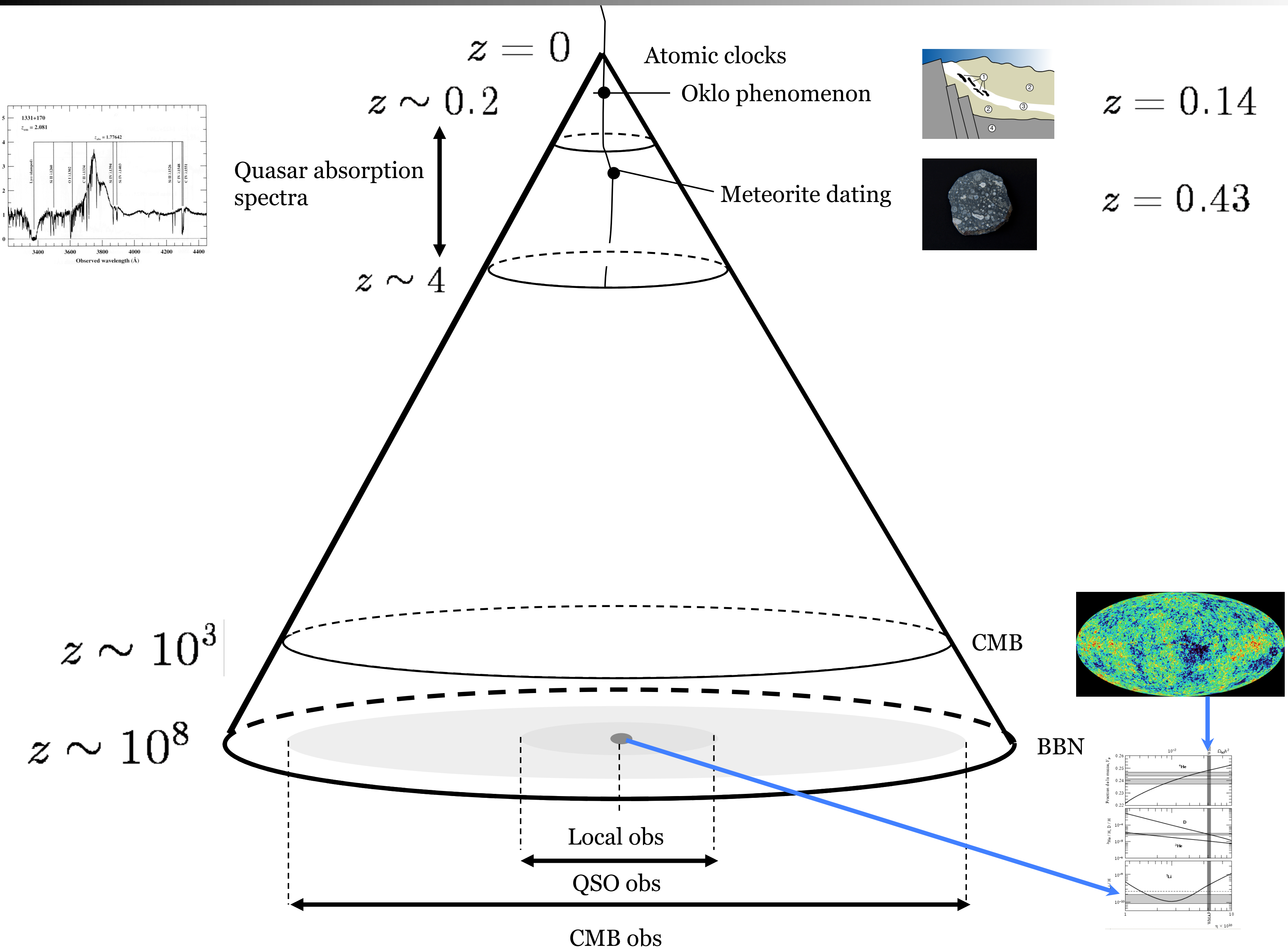
Constants vary on sub-Hubble scales.
- may be detected
- microphysics in principle acessible



Constants vary on super-Hubble scales.
- landscape ?
- exact model of a theory which dynamically gives a distribution of fondamental constants
- no variation on the size of the observable universe

[JPU, 2011]

Physical systems



Observables and primary constraints

A given physical system gives us an observable quantity

$$O(G_k, X)$$

→ External parameters: *temperature,...:*

→ Primary physical parameters

Step 1:

From a physical model of our system we can deduce the sensitivities to the primary physical parameters

$$\kappa_{G_k} = \frac{\partial \ln O}{\partial \ln G_k}$$

Step 2:

The primary physical parameters are usually not fundamental constants.

$$\Delta \ln G_k = \sum_i d_{ki} \Delta \ln c_i$$

Physical systems

System	Observable	Primary constraint	Other hypothesis
Atomic clocks	Clock rates	α, μ, g_i	-
Quasar spectra	Atomic spectra	α, μ, g_p	Cloud physical properties
Oklo	Isotopic ratio	E_r	Geophysical model
Meteorite dating	Isotopic ratio	λ	Solar system formation
CMB	Temperature anisotropies	α, μ	Cosmological model
BBN	Light element abundances	Q, τ_n, m_e, m_N, α, B_d	Cosmological model

Two approaches

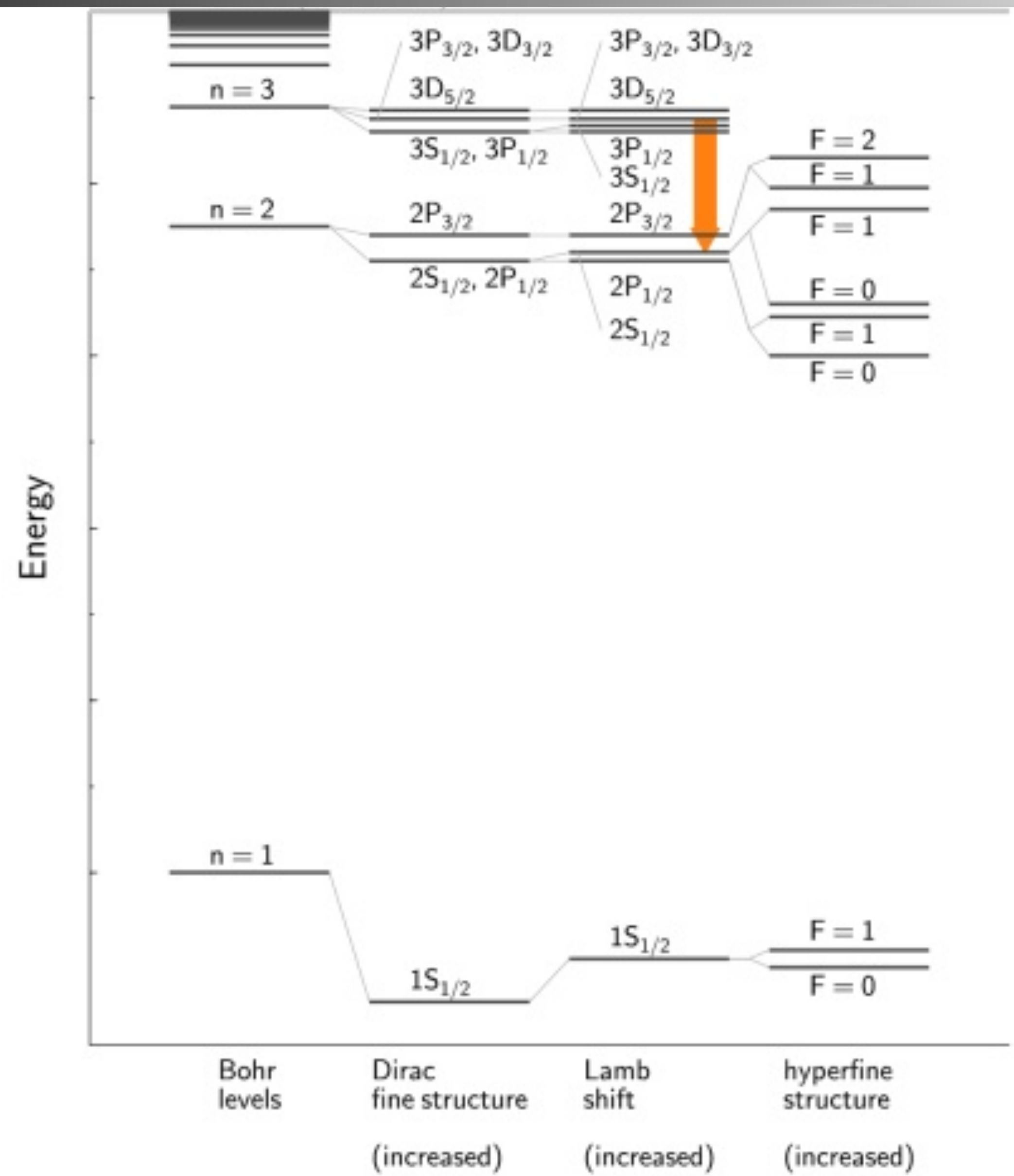
- Model-dependent
  - Correlation between dynamics of different constants
  - Full dynamics
  - Allow to compare different set of observations
  - Leads to sharper constraints

- Model-independent
  - Measure its value in a system

Atomic clocks
&
quasar absorption spectra

[Luo, Olive, JPU, 2011]

Hydrogen atom



$\nu \propto cR_\infty$ $\nu \propto cR_\infty \alpha_{\mathrm{EM}}^2$ $\propto cR_\infty \alpha_{\mathrm{EM}}^2 g_{\mathrm{p}} \bar{\mu}$

Atomic clocks

General atom

$$\nu_{\rm hfs} \simeq R_\infty c \times A_{\rm hfs} \times g_i \times \alpha_{\rm EM}^2 \times \bar{\mu} \times F_{\rm hfs}(\alpha)$$

$$\nu_{\rm elec} \simeq R_\infty c \times A_{\rm elec} \times F_{\rm elec}(Z, \alpha)$$

$$\kappa_\alpha \equiv \frac{\partial \ln F}{\partial \ln \alpha_{\rm EM}}$$

Atom	Transition	sensitivity κ_α
^{1}H	$1s - 2s$	0.00
^{87}Rb	hf	0.34
^{133}Cs	$^2S_{1/2}(F=2) - (F=3)$	0.83
^{171}Yb$^+$	$^2S_{1/2} - {}^2D_{3/2}$	0.9
^{199}Hg$^+$	$^2S_{1/2} - {}^2D_{5/2}$	–3.2
^{87}Sr	$^1S_0 - {}^3P_0$	0.06
^{27}Al$^+$	$^1S_0 - {}^3P_0$	0.008

Atomic clocks

Clock 1	Clock 2	Constraint (yr^{-1})	Constants dependence	Reference
	$\frac{\mathrm{d}}{\mathrm{d}t}\ln\left(\frac{\nu_{\mathrm{clock}_1}}{\nu_{\mathrm{clock}_2}}\right)$			
$^{87}\mathrm{Rb}$	$^{133}\mathrm{Cs}$	$(0.2 \pm 7.0) \times 10^{-16}$	$\frac{g_{\mathrm{Cs}}}{g_{\mathrm{Rb}}}\alpha_{\mathrm{EM}}^{0.49}$	Marion (2003)
$^{87}\mathrm{Rb}$	$^{133}\mathrm{Cs}$	$(-0.5 \pm 5.3) \times 10^{-16}$		Bize (2003)
$^{1}\mathrm{H}$	$^{133}\mathrm{Cs}$	$(-32 \pm 63) \times 10^{-16}$	$g_{\mathrm{Cs}}\mu\alpha_{\mathrm{EM}}^{2.83}$	Fischer (2004)
$^{199}\mathrm{Hg}^{+}$	$^{133}\mathrm{Cs}$	$(0.2 \pm 7) \times 10^{-15}$	$g_{\mathrm{Cs}}\mu\alpha_{\mathrm{EM}}^{6.05}$	Bize (2005)
$^{199}\mathrm{Hg}^{+}$	$^{133}\mathrm{Cs}$	$(3.7 \pm 3.9) \times 10^{-16}$		Fortier (2007)
$^{171}\mathrm{Yb}^{+}$	$^{133}\mathrm{Cs}$	$(-1.2 \pm 4.4) \times 10^{-15}$	$g_{\mathrm{Cs}}\mu\alpha_{\mathrm{EM}}^{1.93}$	Peik (2004)
$^{171}\mathrm{Yb}^{+}$	$^{133}\mathrm{Cs}$	$(-0.78 \pm 1.40) \times 10^{-15}$		Peik (2006)
$^{87}\mathrm{Sr}$	$^{133}\mathrm{Cs}$	$(-1.0 \pm 1.8) \times 10^{-15}$	$g_{\mathrm{Cs}}\mu\alpha_{\mathrm{EM}}^{2.77}$	Blatt (2008)
$^{87}\mathrm{Dy}$	$^{87}\mathrm{Dy}$			Cingöz (2008)
$^{27}\mathrm{Al}^{+}$	$^{199}\mathrm{Hg}^{+}$	$(-5.3 \pm 7.9) \times 10^{-17}$	$\alpha_{\mathrm{EM}}^{-3.208}$	Blatt (2008)

Atomic clocks: from observations to constraints

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

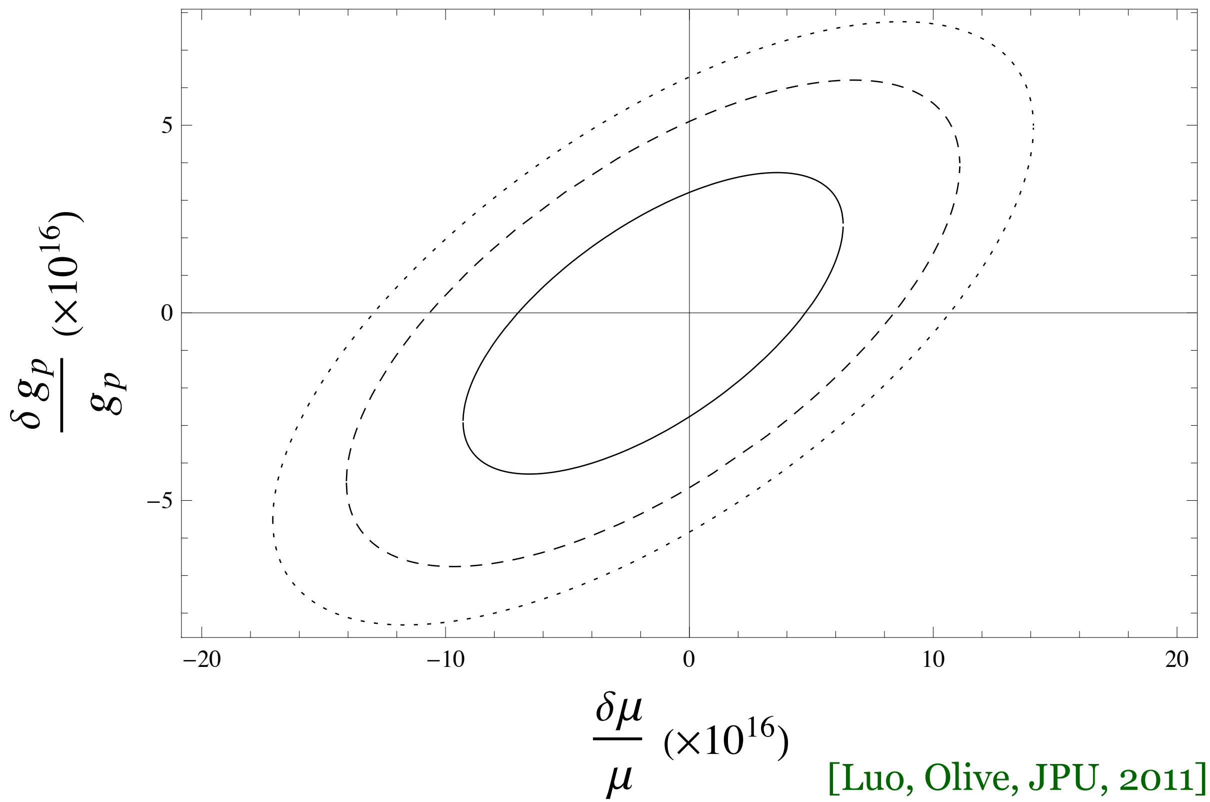
$$\frac{\delta g_{\rm Cs}}{g_{\rm Cs}} \sim -1.266\frac{\delta g_p}{g_p} \qquad \frac{\delta g_{\rm Rb}}{g_{\rm Rb}} \sim 0.736\frac{\delta g_p}{g_p}$$

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 $\{\mu, g_p\}$.

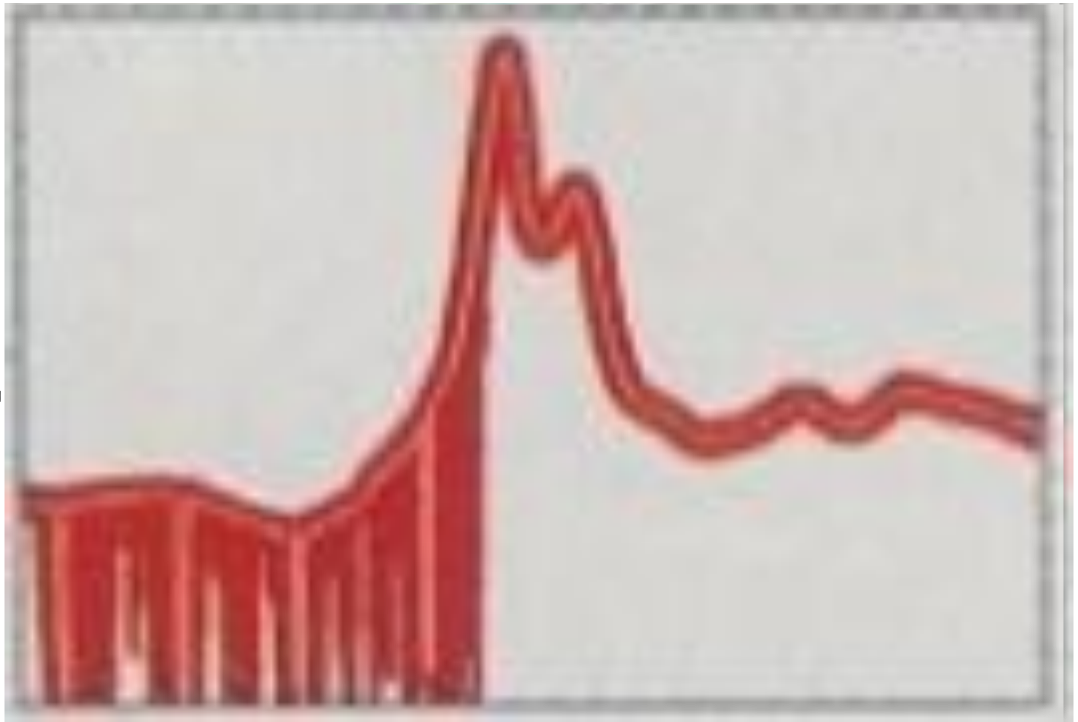
Note: one actually needs to include the effects of the polarization of the non-valence nucleons and spin-spin interaction.

[Flambaum, 0302015,...



[Luo, Olive, JPU, 2011]

Absorption spectra



Cosmic expansion redshift all spectra (achromatic)

We look for achromatic effects

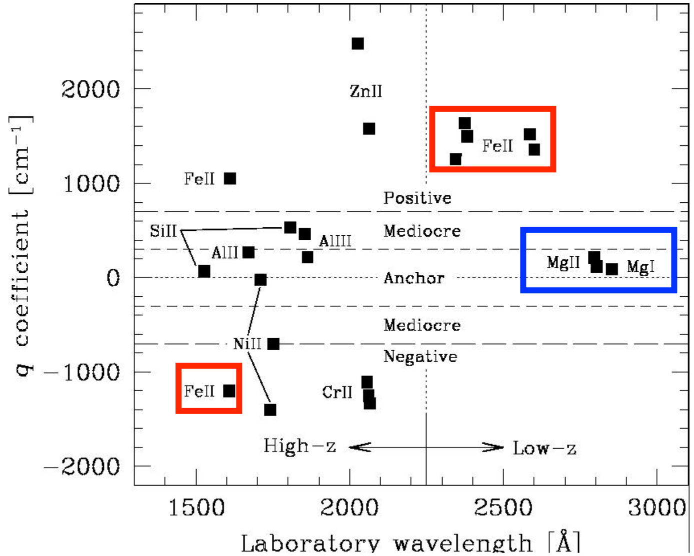
QSO: many multiplets

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

Relativistic N-body with varying α:

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

Dzuba et al. 1999-2005



First implemented on 30 systems with MgII and FeII

Webb et al. 1999

HIRES-Keck, 153 systems, *0.2<z<4.2*

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

Murphy et al. 2004

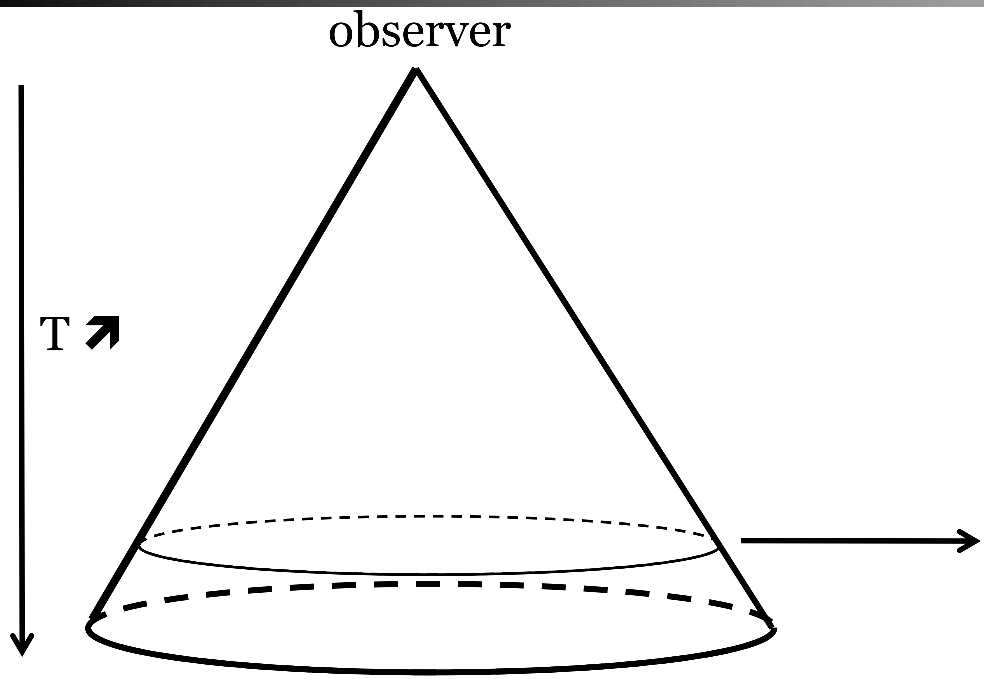
5σ detection !

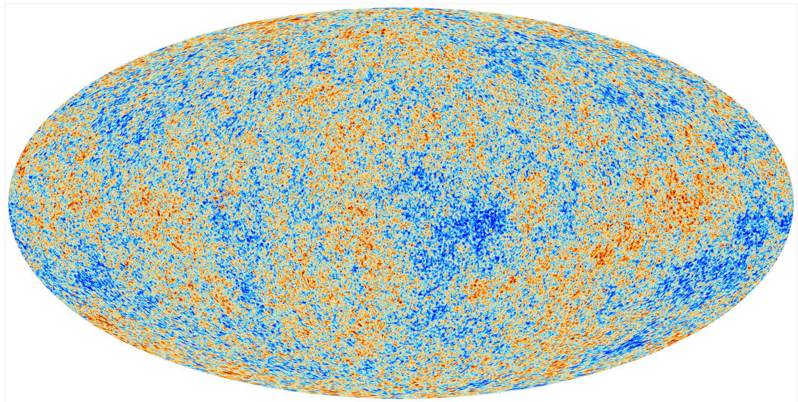
Many studies & systems since then. NOT CONFIRMED.

Cosmic microwave background

[with S. Galli, O. Fabre, S. Prunet, E. Menegoni, et al. (2013)]

Recombination





$$p + e \longleftrightarrow \mathrm{H} + \gamma$$

Reaction rate $\Gamma_{\mathrm{T}} = n_{\mathrm{e}}\sigma_{\mathrm{T}}$

1- Recombination $n_e(t)$,…
2- Decoupling $\Gamma \ll H$
3- Last scattering

Out-of-equilibrium process – requires to solve a Boltzmann equation

Dependence on the constants

Recombination of hydrogen and helium
Gravitational dynamics (expansion rate)

predictions depend on G, α, m_e

$$\sigma_{\rm T} = \frac{8\pi}{3}\frac{\hbar^2}{m_{\rm e}^2 c^2}\alpha_{\rm EM}^2$$

We thus consider the parameters: $\{\omega_{\rm b}, \omega_{\rm c}, H_0, \tau, n_s, A_s, \alpha \text{ or } m_e\}$

$$\frac{Gm_e^2}{\hbar c}$$

All the dependences of the constants can be included in a CMB code (recombination part: RECFAST):

- E=hν Binding energies
- σ_T Thomson cross-section
- σ_n photoionisation cross-sections
- α recombination parameters
- β photoionisation parameters
- K cosmological redshifting of the photons
- A Einstein coefficient
- Λ_{2s} 2s decay rate by 2γ

$$\nu_i = \nu_{i0}\left(\frac{\alpha}{\alpha_0}\right)^2\left(\frac{m_{\rm e}}{m_{\rm e0}}\right)$$

$$\sigma_{\rm T} = \sigma_{\rm T0}\left(\frac{\alpha}{\alpha_0}\right)^2\left(\frac{m_{\rm e}}{m_{\rm e0}}\right)^{-2}$$

$$\sigma_n = \sigma_{n0}\left(\frac{\alpha}{\alpha_0}\right)^{-1}\left(\frac{m_{\rm e}}{m_{\rm e0}}\right)^{-2}$$

$$\alpha_i = \alpha_{i0}\left(\frac{\alpha}{\alpha_0}\right)^3\left(\frac{m_{\rm e}}{m_{\rm e0}}\right)^{-3/2}$$

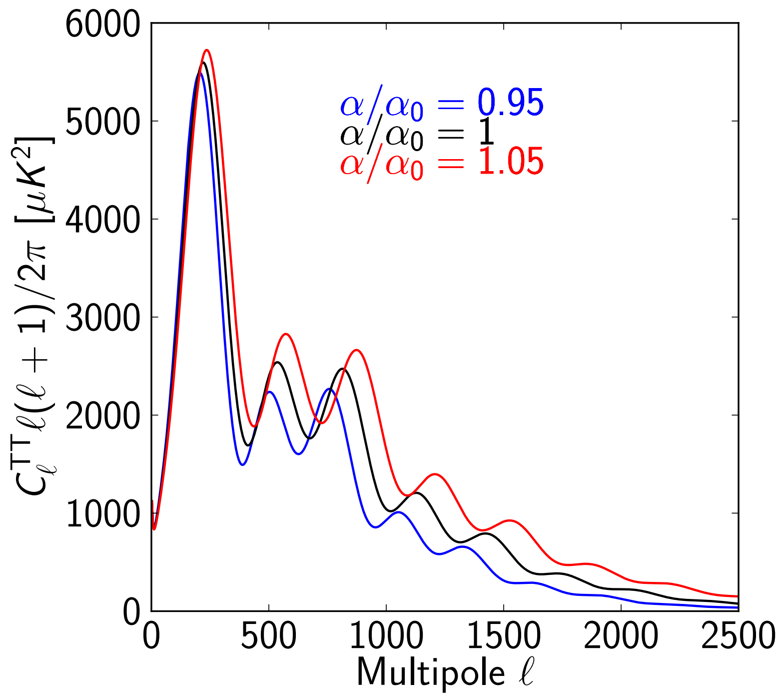
$$\beta_i = \beta_{i0}\left(\frac{\alpha}{\alpha_0}\right)^3$$

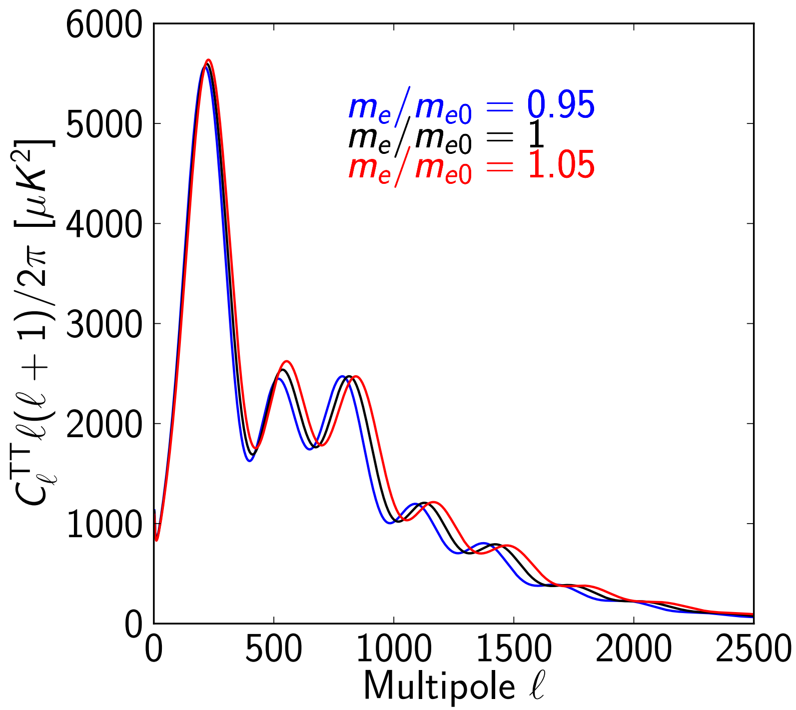
$$K_i = K_{i0}\left(\frac{\alpha}{\alpha_0}\right)^{-6}\left(\frac{m_{\rm e}}{m_{\rm e0}}\right)^{-3}$$

$$A_i = A_{i0}\left(\frac{\alpha}{\alpha_0}\right)^5\left(\frac{m_{\rm e}}{m_{\rm e0}}\right)$$

$$\Lambda_i = \Lambda_{i0}\left(\frac{\alpha}{\alpha_0}\right)^8\left(\frac{m_{\rm e}}{m_{\rm e0}}\right),$$

Effect on the temperature power spectrum

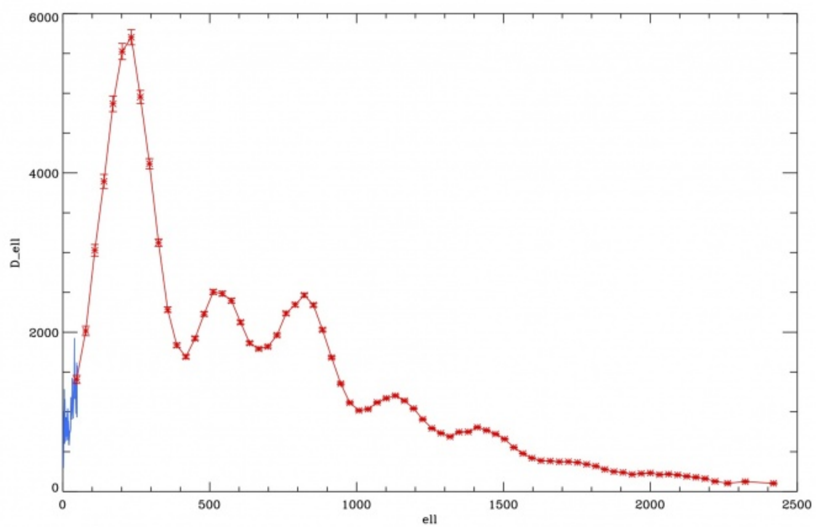




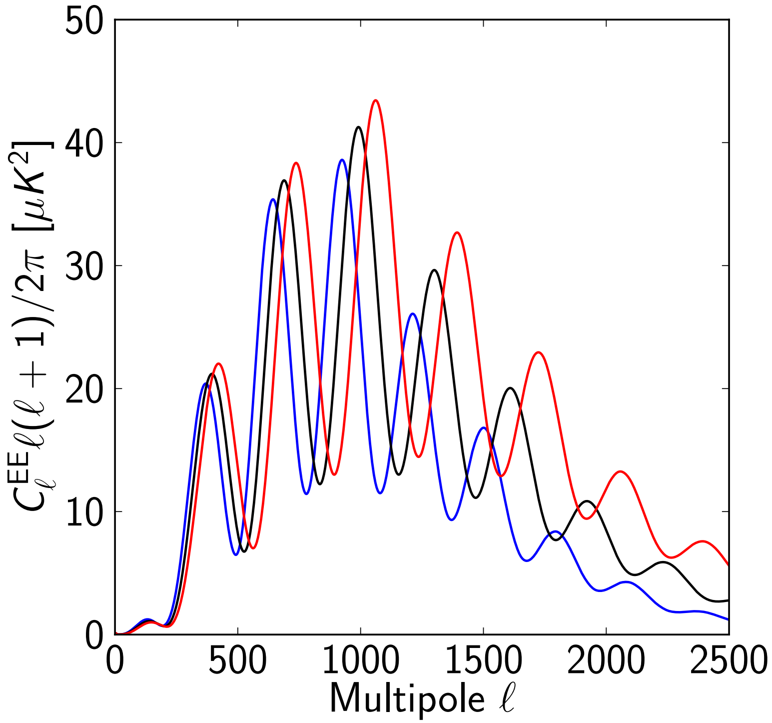
Increase of α induces
- an earlier decoupling
- smaller sound horizon
- shift of the peaks to higher multipoles

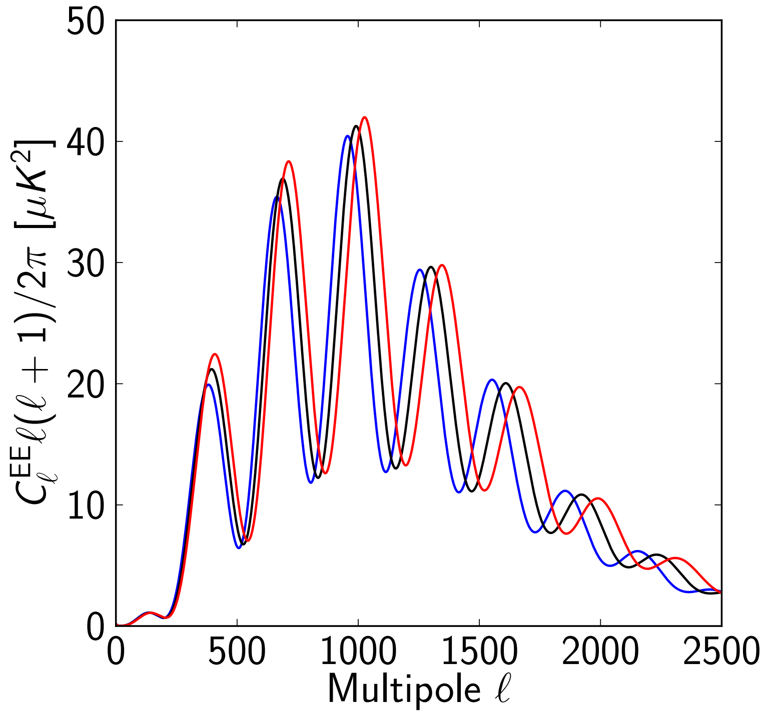
- an increase of amplitude of large scale (early ISW)
- an increase of amplitude at small scales (Silk damping)

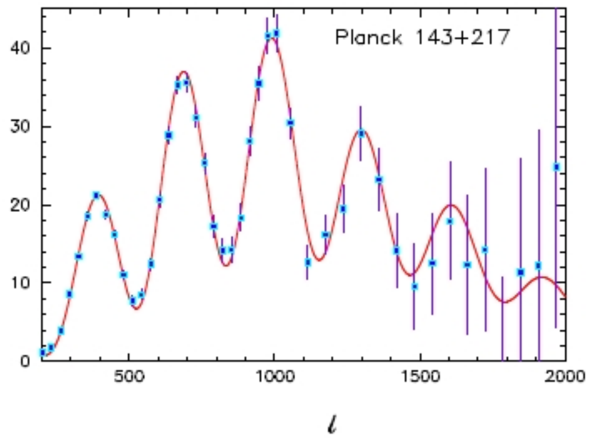
$$\lambda_D^2 = \frac{1}{6}\int_0^{\eta_{dec}} \frac{d\eta}{\sigma_T n_e a}\left[\frac{R^2 + \frac{16}{15}(1+R)}{(1+R)^2}\right] \propto \frac{1}{\sigma_T} \propto \frac{1}{\alpha^2 m_e^{-2}}$$



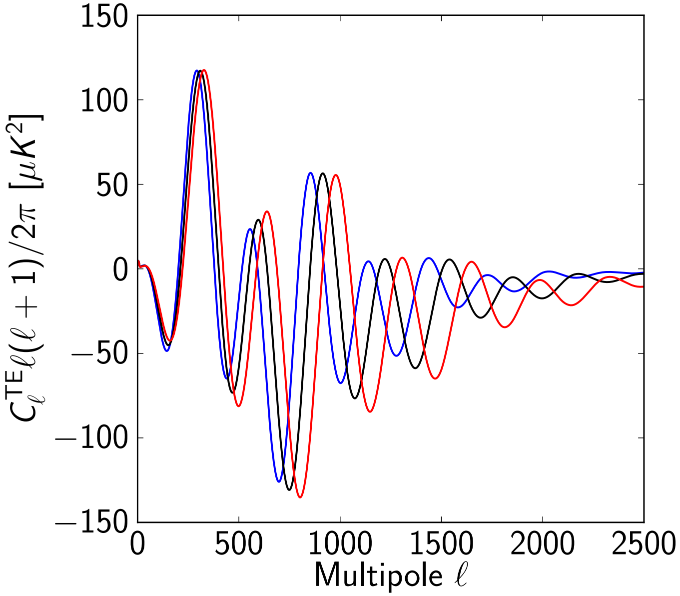
Effect on the polarization power spctrum

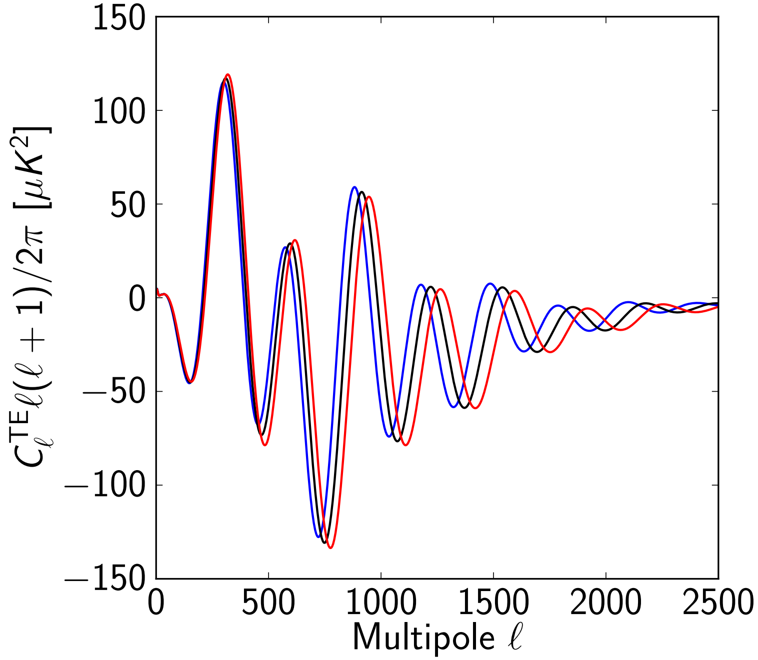


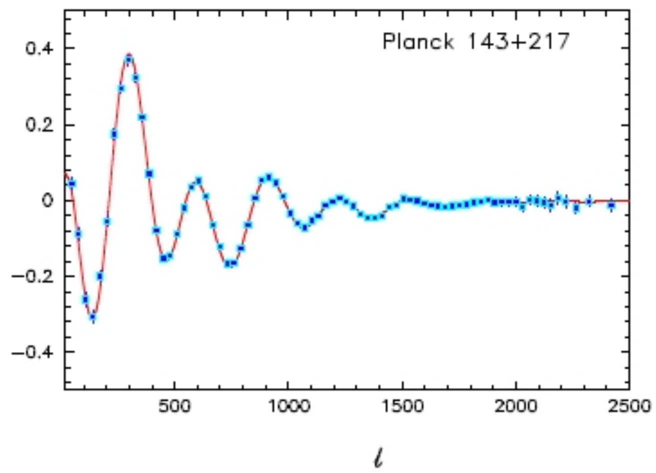




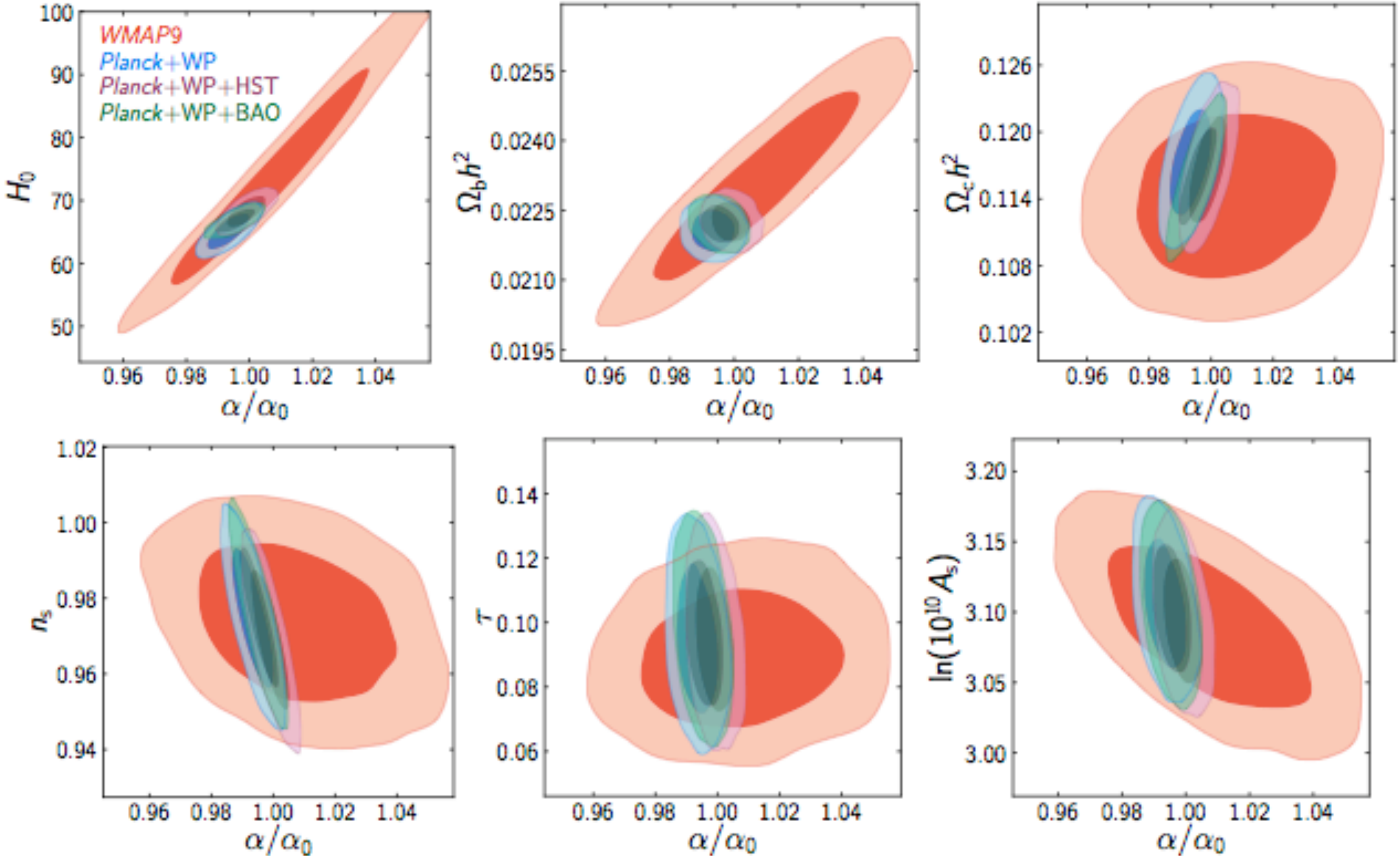
Effect on the cross-correlation





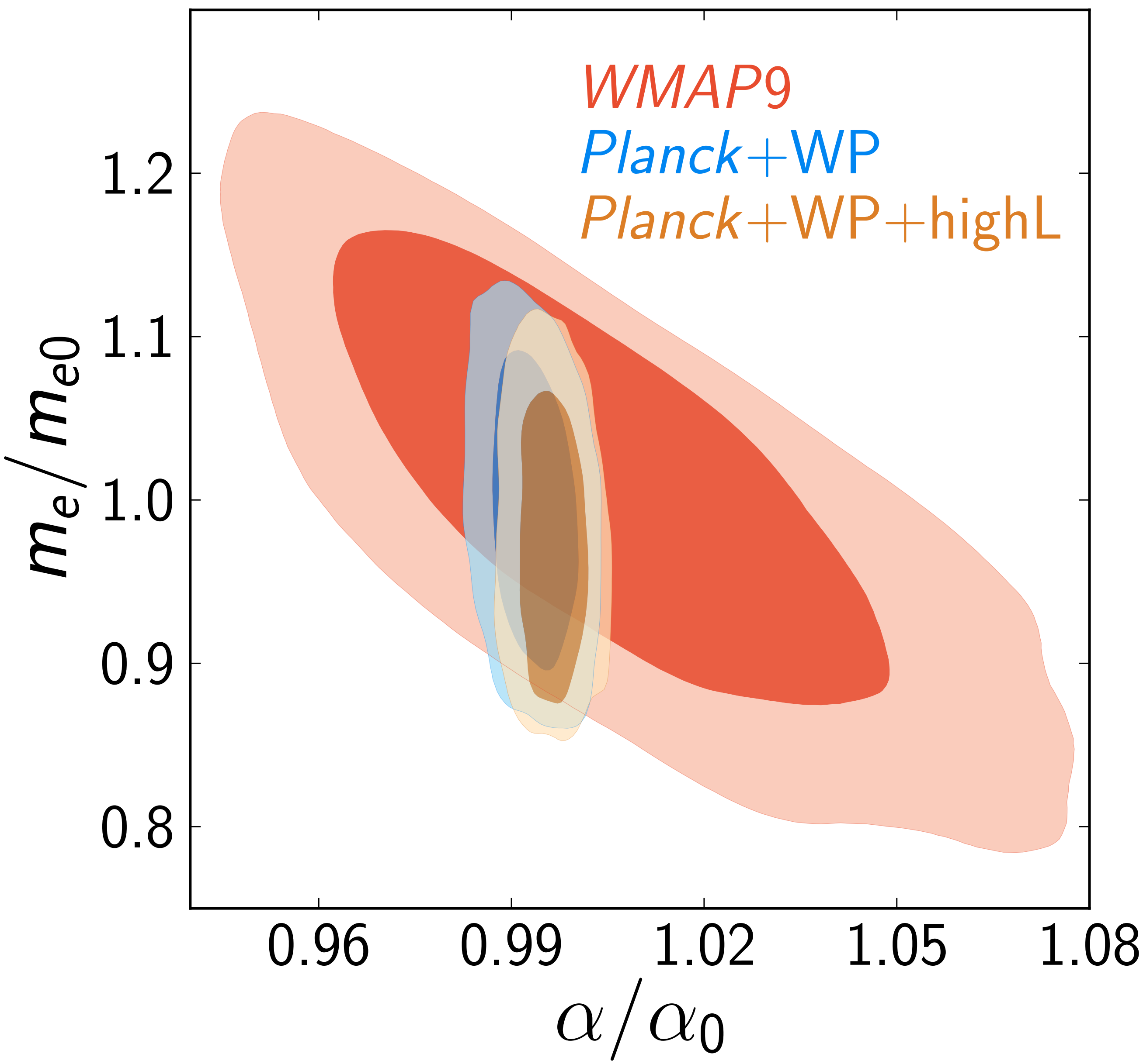


Varying α alone



$$\{\omega_{\rm b}, \omega_{\rm c}, H_0, \tau, n_s, A_s, \alpha \text{ or } m_e\}$$

(α, m_e)-degeneracy

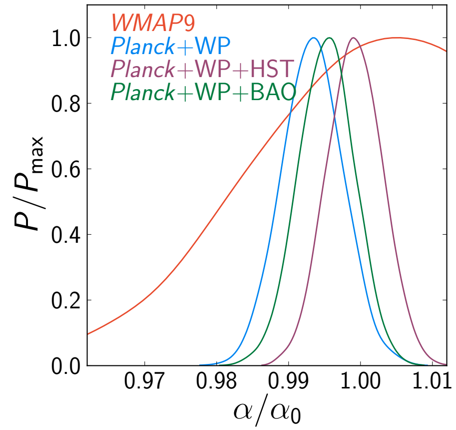


In conclusion

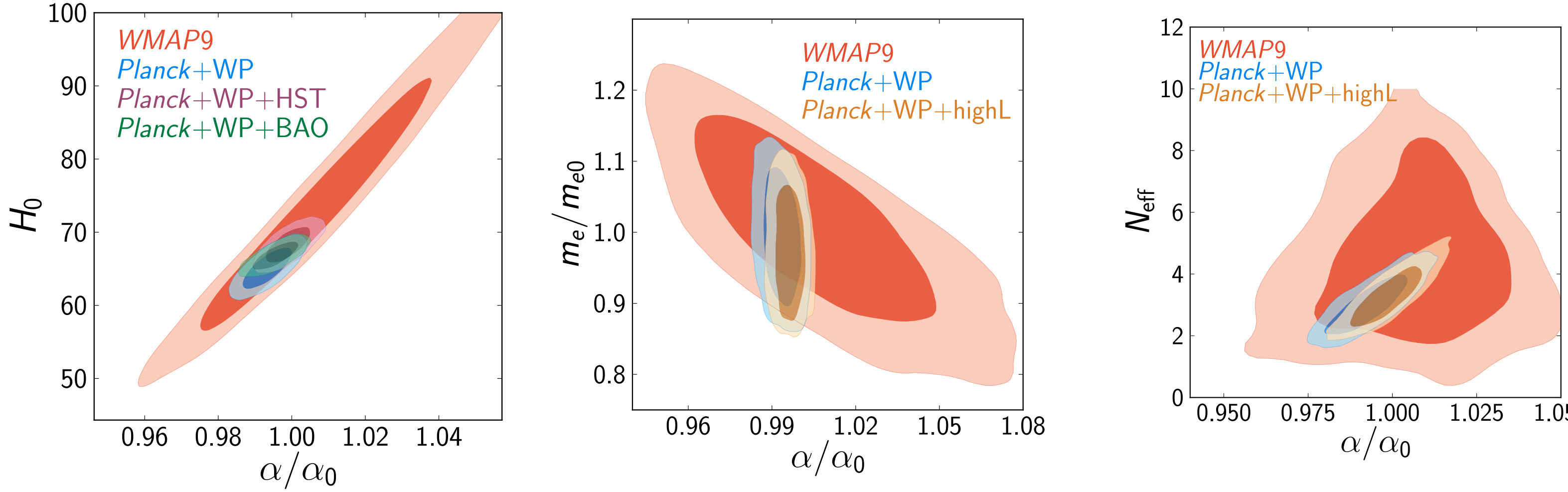
Independent variations of α and m_e are constrained to be

$\Delta\alpha/\alpha=(3.6\pm3.7)\times10^{-3}$ $\Delta m_e/m_e=(4\pm11)\times10^{-3}$

This is a <u>factor 5</u> better compared to WMAP analysis



Planck breaks the degeneracy with H_0 and with m_e and other cosmological parameters (e.g. N_ν or helium abundance)

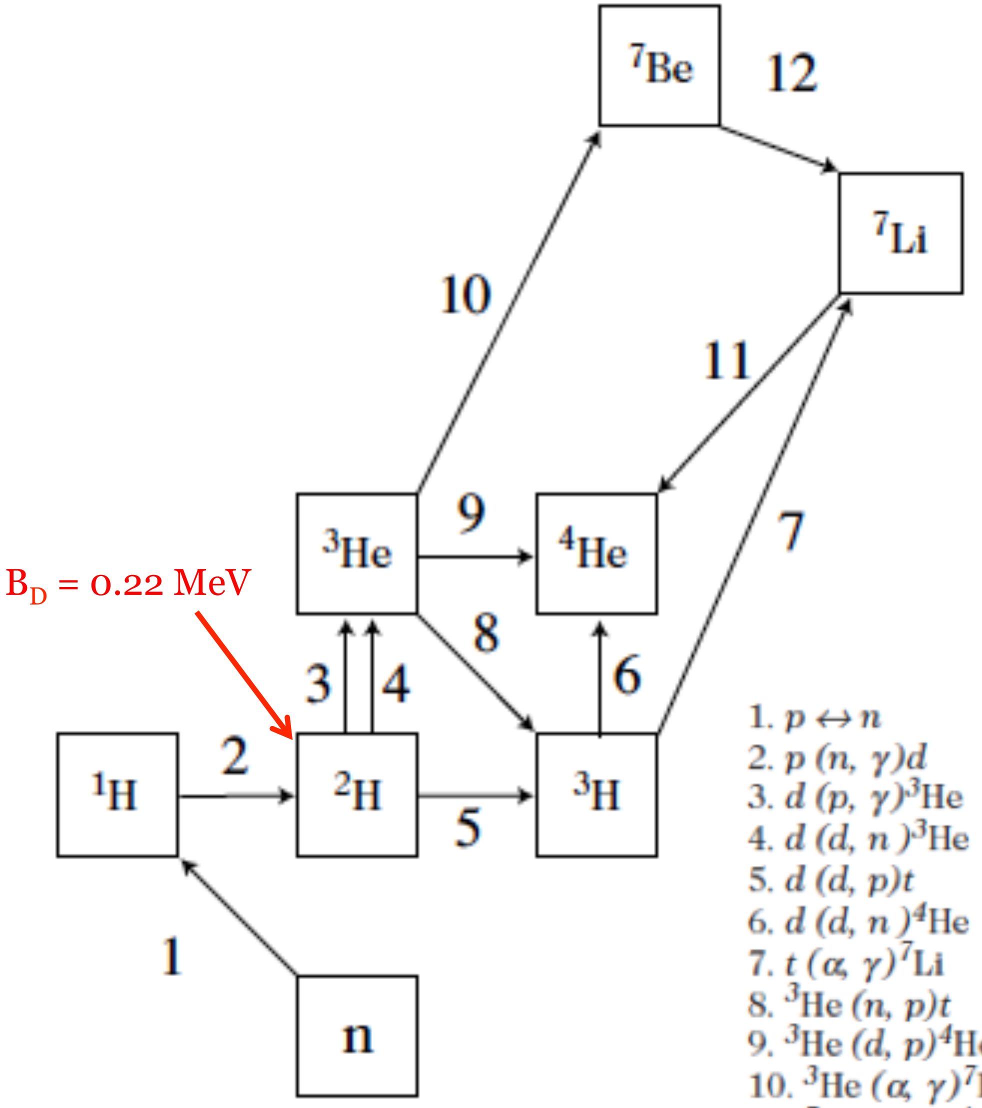


Big bang nucleosynthesis
&
Population III stars

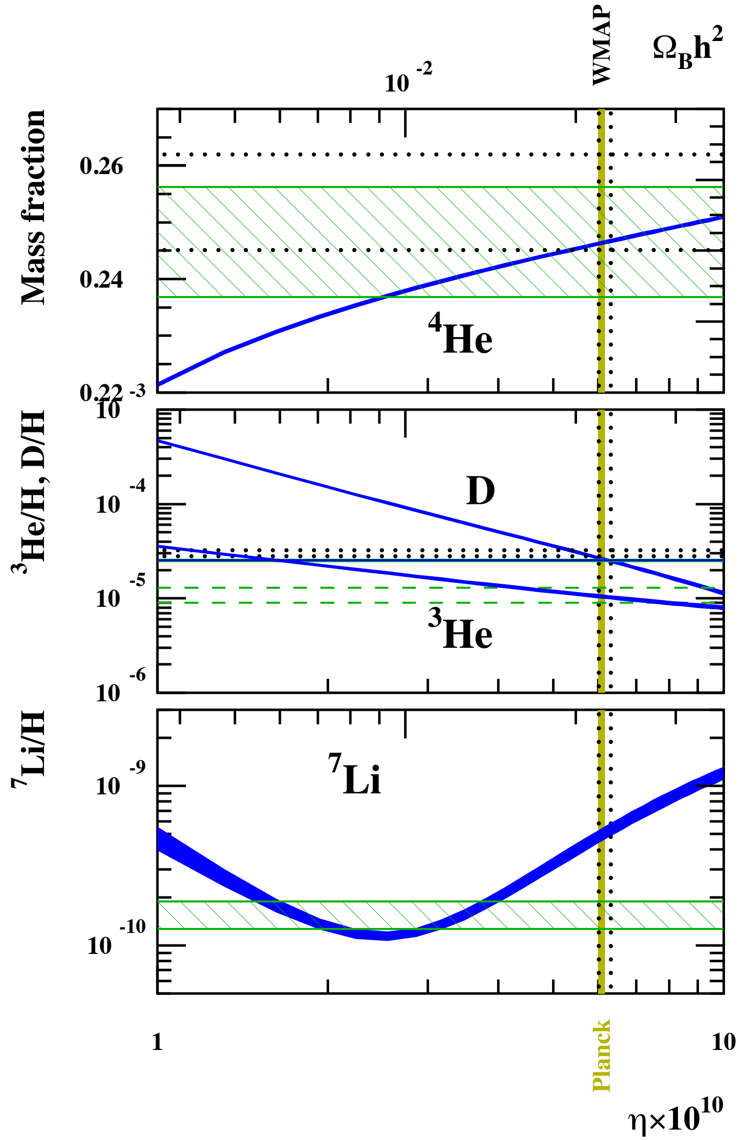
Nuclear physics at work in the universe

[Coc,Nunes,Olive,JPU,Vangioni 2006
Coc, Descouvemont, Olive, JPU, Vangioni, 2012
Ekström, Coc, Descouvemont, Meynet, Olive, JPU, Vangioni,2009]

BBN: basics



1. $p \leftrightarrow n$
2. $p\,(n,\,\gamma)d$
3. $d\,(p,\,\gamma)^3$He
4. $d\,(d,\,n\,)^3$He
5. $d\,(d,\,p)t$
6. $d\,(d,\,n\,)^4$He
7. $t\,(\alpha,\,\gamma)^7$Li
8. ^{3}He $(n,\,p)t$
9. ^{3}He $(d,\,p)^4$He
10. ^{3}He $(\alpha,\,\gamma)^7$Be
11. ^{7}Li $(p,\,\alpha\,)^4$He
12. ^{7}Be $(n,\,p\,)^7$Li



Stellar carbon production

Triple α coincidence (Hoyle)

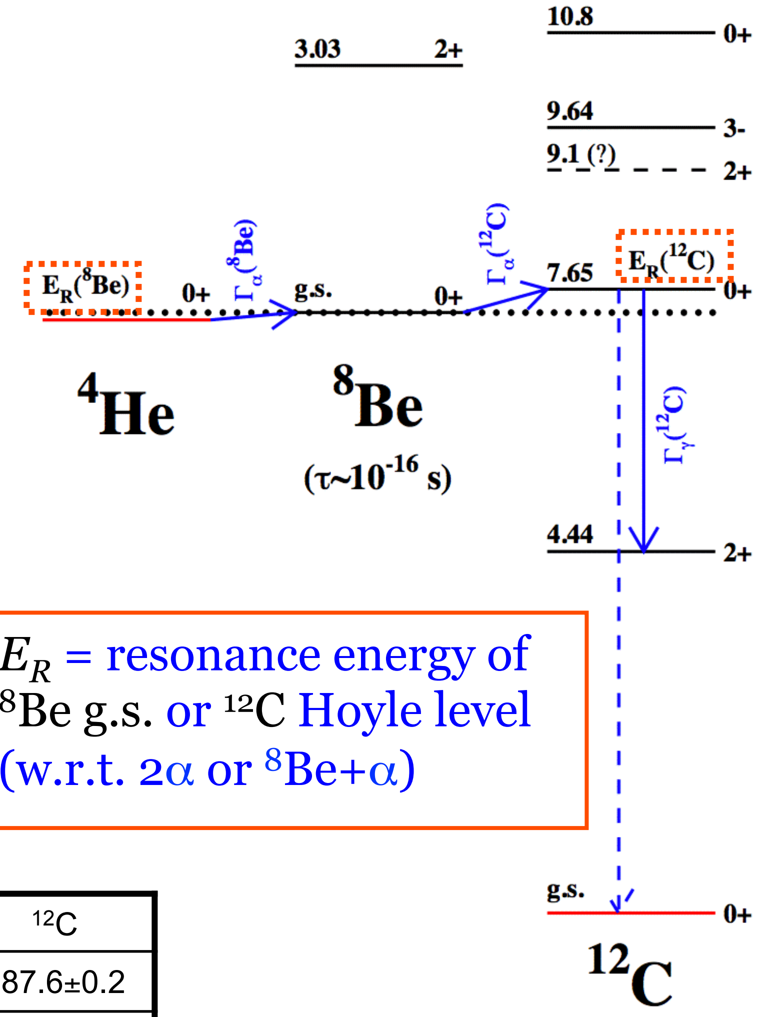
1. Equillibrium between ^{4}He and the short lived (~10^{-16} s) ^{8}Be : αα↔^{8}Be
2. Resonant capture to the (l=0, J^π=0^+) Hoyle state: ^{8}Be+α→^{12}C*(→^{12}C+γ)

Simple formula used in previous studies

1. Saha equation (thermal equilibrium)
2. Sharp resonance analytic expression:

$$N_A^2\langle\sigma v\rangle^{\alpha\alpha\alpha} = 3^{3/2}6N_A^2\left(\frac{2\pi}{M_\alpha k_B T}\right)^3\hbar^5\gamma\exp\left(\frac{-Q_{\alpha\alpha\alpha}}{k_B T}\right)$$

with $Q_{\alpha\alpha\alpha}$= E_R(^{8}Be) + E_R(^{12}C) and $\gamma\approx\Gamma_\gamma$



E_R = resonance energy of ^{8}Be g.s. or ^{12}C Hoyle level (w.r.t. 2α or ^{8}Be+α)

Nucleus	^{8}Be	^{12}C
E_R (keV)	91.84±0.04	287.6±0.2
Γ_α (eV)	5.57±0.25	8.3±1.0
Γ_γ (meV)	-	3.7±0.5

[Ekström, Coc, Descouvemont, Meynet, Olive, JPU, Vangioni,2009]

BBN: dependence on constants

Light element abundances mainly based on the balance between
1- expansion rate of the universe
2- weak interaction rate which controls n/p at the onset of BBN

Example: helium production

$$Y = \frac{2(n/p)_N}{1+(n/p)_N}$$

$$(n/p)_f \sim \mathrm{e}^{-Q/k_B T_f}$$

(B_D, η)

$$(n/p)_N \sim (n/p)_f \, \mathrm{e}^{-t_N/\tau_\mathrm{n}}$$

freeze-out temperature is roughly given by $$G_F^2 (k_B T_f)^5 = \sqrt{GN}\,(k_B T_f)^2$$

Coulomb barrier: $$\sigma = \frac{S(E)}{E}\,\mathrm{e}^{-2\pi\alpha Z_1 Z_2 \sqrt{\mu/2E}}$$

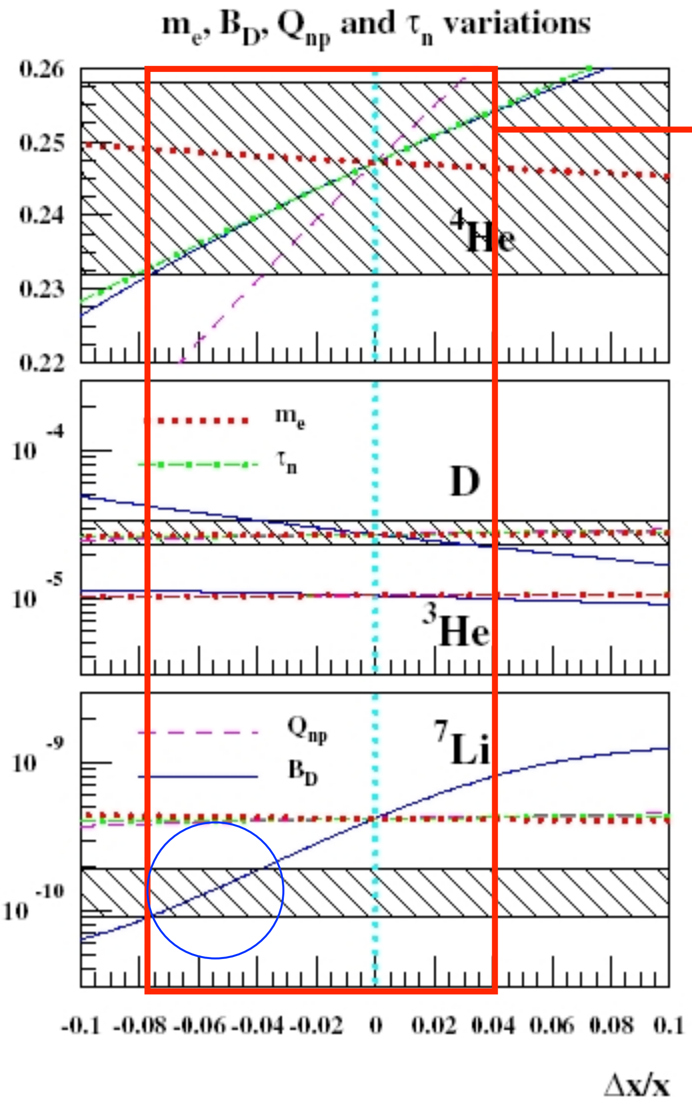
Predictions depend on

$$G_k = (G, \alpha, \tau_n, m_e, Q, B_D, \sigma_i)$$
$$X = (\eta, h, N_\nu, \ldots)$$

Coc,Nunes,Olive,JPU,Vangioni 2006

Sensitivity to the nuclear parameters

Independent variations of the BBN parameters



$$-7.5\times10^{-2} < \frac{\Delta B_D}{B_D} < 6.5\times10^{-2}$$

$$-8.2\times10^{-2} < \frac{\Delta\tau_n}{\tau_n} < 6\times10^{-2}$$

$$-4\times10^{-2} < \frac{\Delta Q}{Q} < 2.7\times10^{-2}$$

Abundances are very sensitive to $B_{D.}$
Equilibrium abundance of D and the reaction rate p(n,γ)D depend exponentially on B_D.

These parameters are not independent.

Difficulty: QCD and its role in low energy nuclear reactions.

Coc,Nunes,Olive,JPU,Vangioni 2006

Constraints

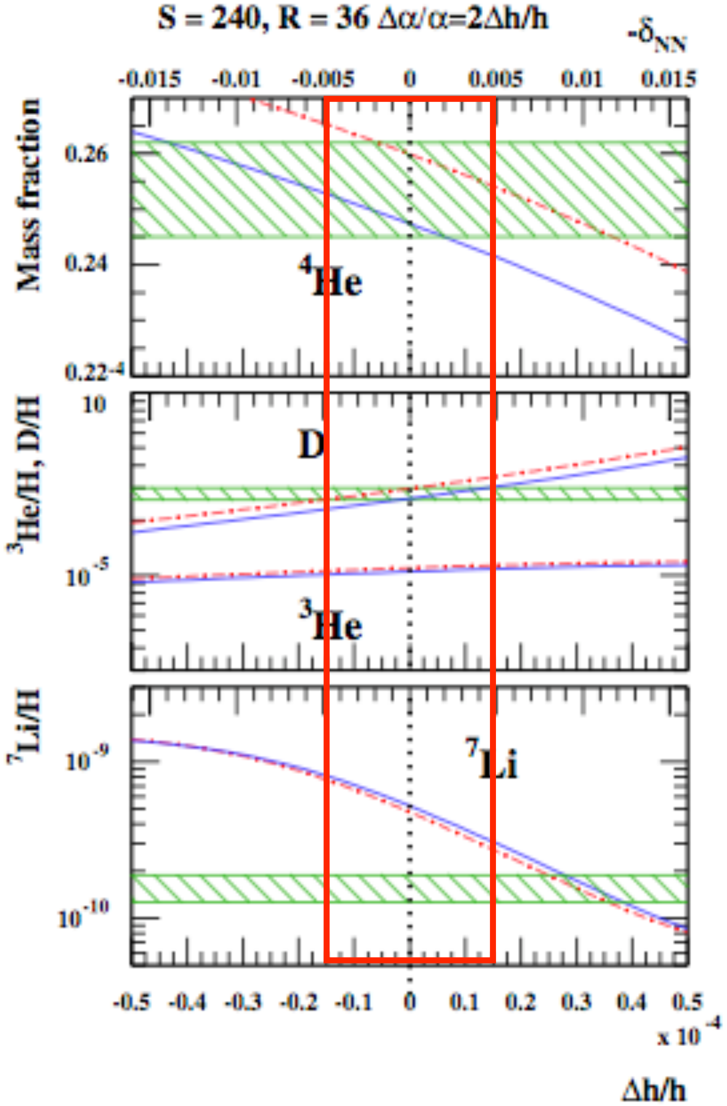
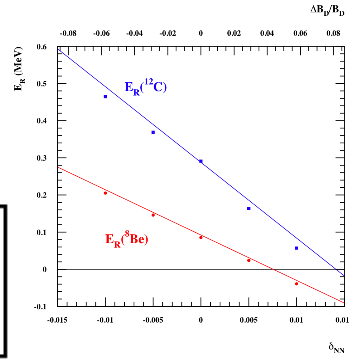


FIG. 12 (color online). Update Fig. 4 of Ref. [22] assuming $S = 240$ and $R = 36$ (solid blue line), using new rates for $^3\text{He}(\alpha,\gamma)^7\text{Li}$ [73] and $^1\text{H}(n,\gamma)\text{D}$ [74] and the Ω_b value from WMAP7 [4]. The top axis is $-\delta_{NN}$ from Eq. (5.8) (mind the sign) and the dashed red line assumes $N_\nu = 4$.

Coc, Descouvemont,Olive, JPU,Vangioni 2012

Stellar evolution – 3α



Fundamental constants

$\alpha_i \supset \{\alpha, h_a, v, \ldots\}$

Step I

Nuclear parameters

$Q_i \supset \{B_D, E_R(^8\mathrm{Be}), E_R(^{12}\mathrm{C}) \ldots\}$

Effective N-N interaction
Minnesota model
Parameters: $(\delta_\alpha, \delta_{NN})$

Step II
Integration over energy

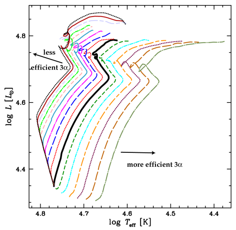
Reaction rates

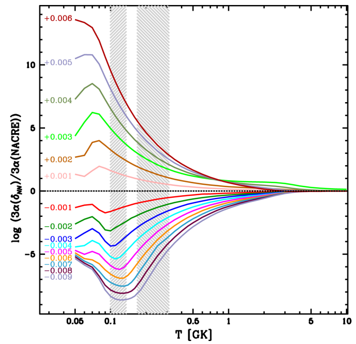
$\sigma_i(T, Q_j), \quad \lambda_i(T, Q_j)$

Step III

- Nuclear abundances,
(^{12}C, ^{16}O, ^{20}Ne, ^{24}Mg, ...)
- Lifetime of stars, HR diagram

Mass of the star
Initial metallicity
Rotation?
Mass loss?



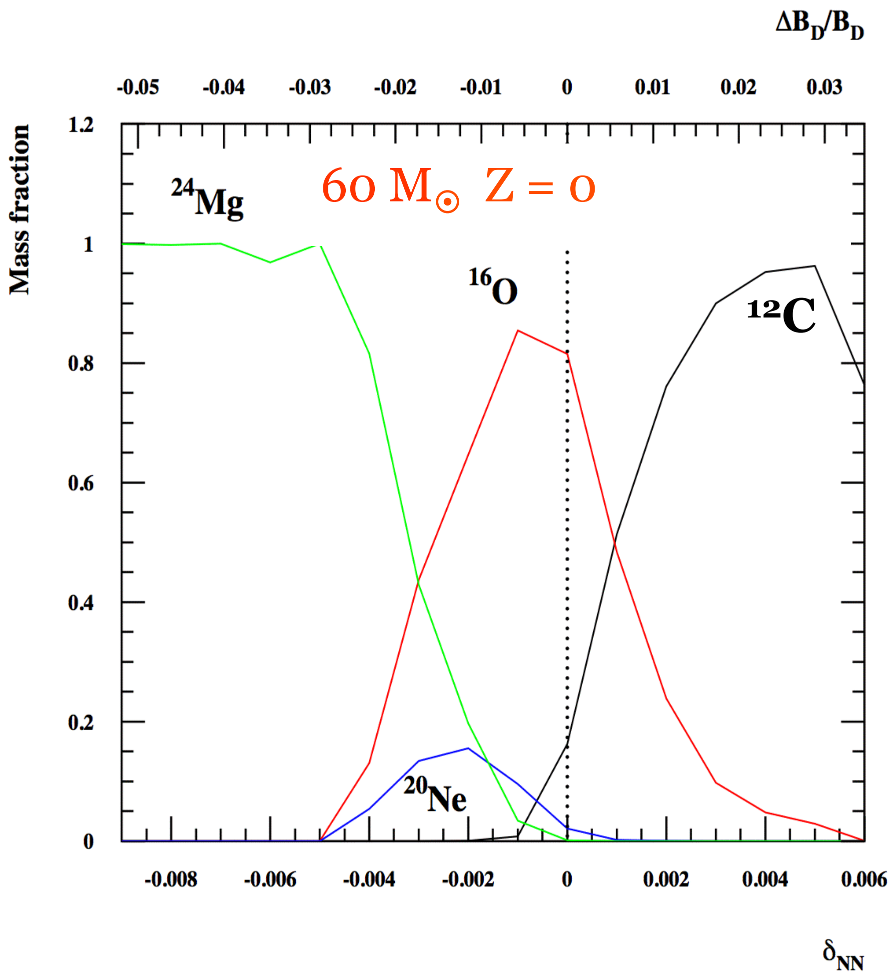


Constraints on the variation of constants

Composition at the end of core He burning

Stellar evolution of massive Pop. III stars

*We choose **typical** masses of 15 and 60 $M_\odot$ stars/ Z=0 ⇒Very specific stellar evolution*



- **The standard region:** Both ^{12}C and ^{16}O are produced.
- **The ^{16}O region:** The 3α is slower than $^{12}C(\alpha,\gamma)^{16}O$ resulting in a higher T_C and a conversion of most ^{12}C into ^{16}O
- **The ^{24}Mg region:** With an even weaker 3α, a higher T_C is achieved and $^{12}C(\alpha,\gamma)^{16}O(\alpha,\gamma)^{20}Ne(\alpha,\gamma)^{24}Mg$ transforms ^{12}C into ^{24}Mg
- **The ^{12}C region:** The 3α is faster than $^{12}C(\alpha,\gamma)^{16}O$ and ^{12}C is not transformed into ^{16}O

Constraint

$^{12}C/^{16}O \sim 1 \Rightarrow -0.0005 < \delta_{NN} < 0.0015$

or $-0.003 < \Delta B_D/B_D < 0.009$

Oklo-constraints

Shlyakhter, Nature **264** (1976) 340
Damour, Dyson, NPB **480** (1996) 37
Fujii et al., NPB **573** (2000) 377
Lamoreaux, torgerson, nucl-th/0309048
Flambaum, shuryak, PRD**67** (2002) 083507

Natural nuclear reactor in Gabon,
operating 1.8 Gyr ago (**z~0.14**)

Abundance of Samarium isotopes

$$^{149}\mathrm{Sm} + n \rightarrow ^{150}\mathrm{Sm} + \gamma \qquad E_r = 0.0973\,\mathrm{eV}$$

From isotopic abundances of Sm, U and Gd, one can
measure the cross section averaged on the thermal neutron flux

$$\hat{\sigma}_{149}(T, E_r) = 91 \pm 6\,\mathrm{kb}$$

From a model of Sm nuclei, one can infer $s = \Delta E_r / \Delta \ln \alpha$

s~1Mev so that

$$\Delta\alpha/\alpha \sim 1\mathrm{Mev}/0.1\mathrm{eV} \sim 10^{-7}$$

$\Delta\alpha/\alpha = (0.5 \pm 1.05) \times 10^{-7}$ Damour, Dyson, NPB **480** (1996) 37

Fujii et al., NPB **573** (2000) 377 2 branches.

Meteorite dating

Bounds on the variation of couplings can be obtained by
Constraints on the lifetime of long-lives nuclei (α and β decayers)

For β decayers,

$$\lambda \sim \Lambda(\Delta E)^p \propto G_F^2 \alpha^s$$

Rhenium:

$$^{187}_{75}\mathrm{Re} \longrightarrow {}^{187}_{76}\mathrm{Os} + \bar{\nu}_e + e^-$$

Peebles, Dicke, PR **128** (1962) 2006

$$\Delta E \sim 2.5\,\mathrm{keV}, \qquad s \sim -18000$$

Use of laboratory data +meteorites data

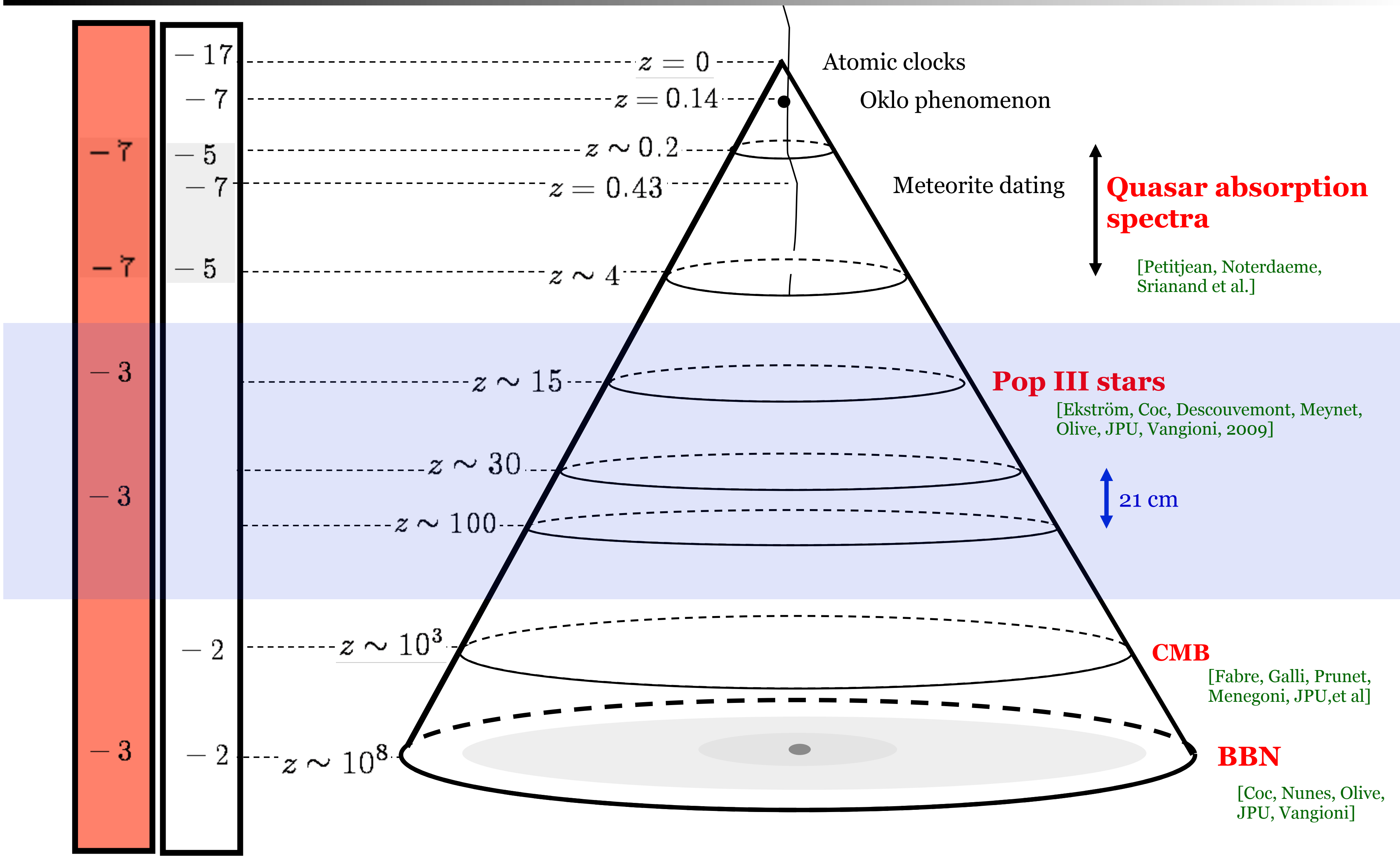
$$-24 \times 10^{-7} < \Delta\alpha/\alpha < 8 \times 10^{-7}$$

Olive et al., PRD **69** (2004) 027701

Caveats: meteorites datation / averaged value

Conclusions and perspective

Physical systems: new and future



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

To remember

- Constants are defined in a theoretical framework to be specified
- Constants can be dynamical if they are fields
- Many ways & motivations to implement this
- Only the variation of dimensionless ratio is measurable
- This is an important test of the euqivalence principle
- Many constraints from the lab to the cosmos. Each system requires a refined and long analysis
- No hint of variation on any scale. Huge improvement during the last decade.