Constantes fondamentales, gravitation et cosmologie

Développements récents

Jean-Philippe UZAN

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

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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

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

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. »

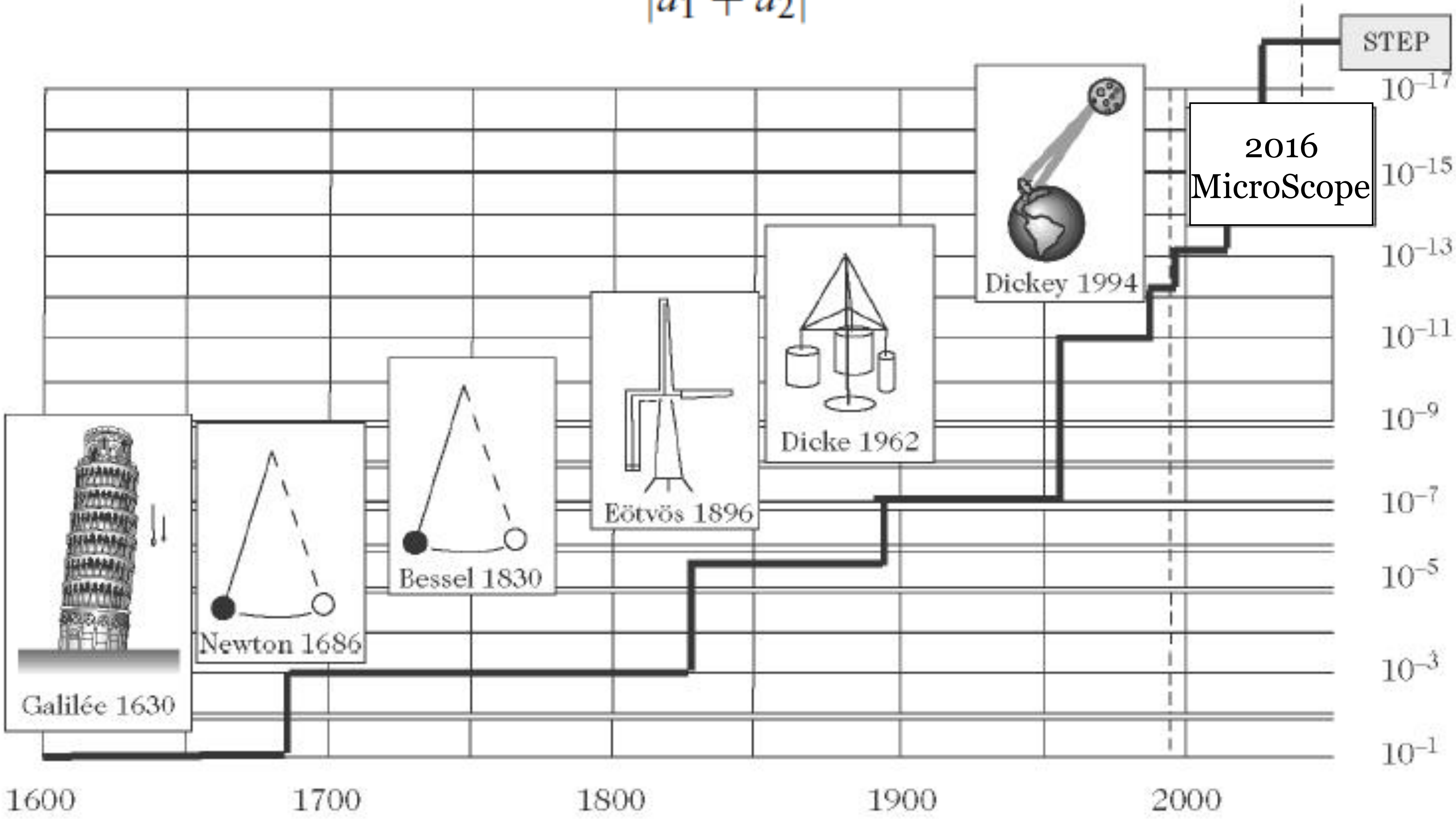
« Cette force est toujours proportionnelle à la quantité de matière des corps, *&* elle ne diffère de ce qu'on appelle l'inertie de la matière que par la manière de la concevoir. »

« 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

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



On the basis of general relativity

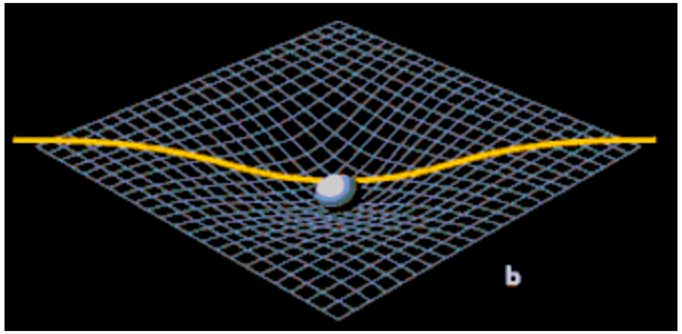
The equivalence principle takes much more importance in general relativity

It is based on **Einstein equivalence principle**

universality of free fall
local Lorentz invariance
local position invariance

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

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

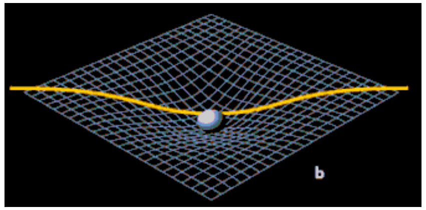
Underlying hypothesis

Equivalence principle

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

Physical metric

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



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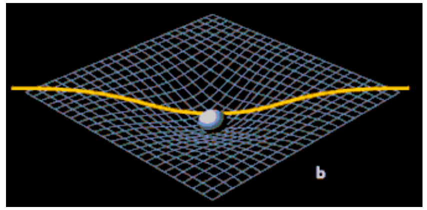

gravitational metric

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.

Equivalence principle and constants

In general relativity, any test particle follow 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

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

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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

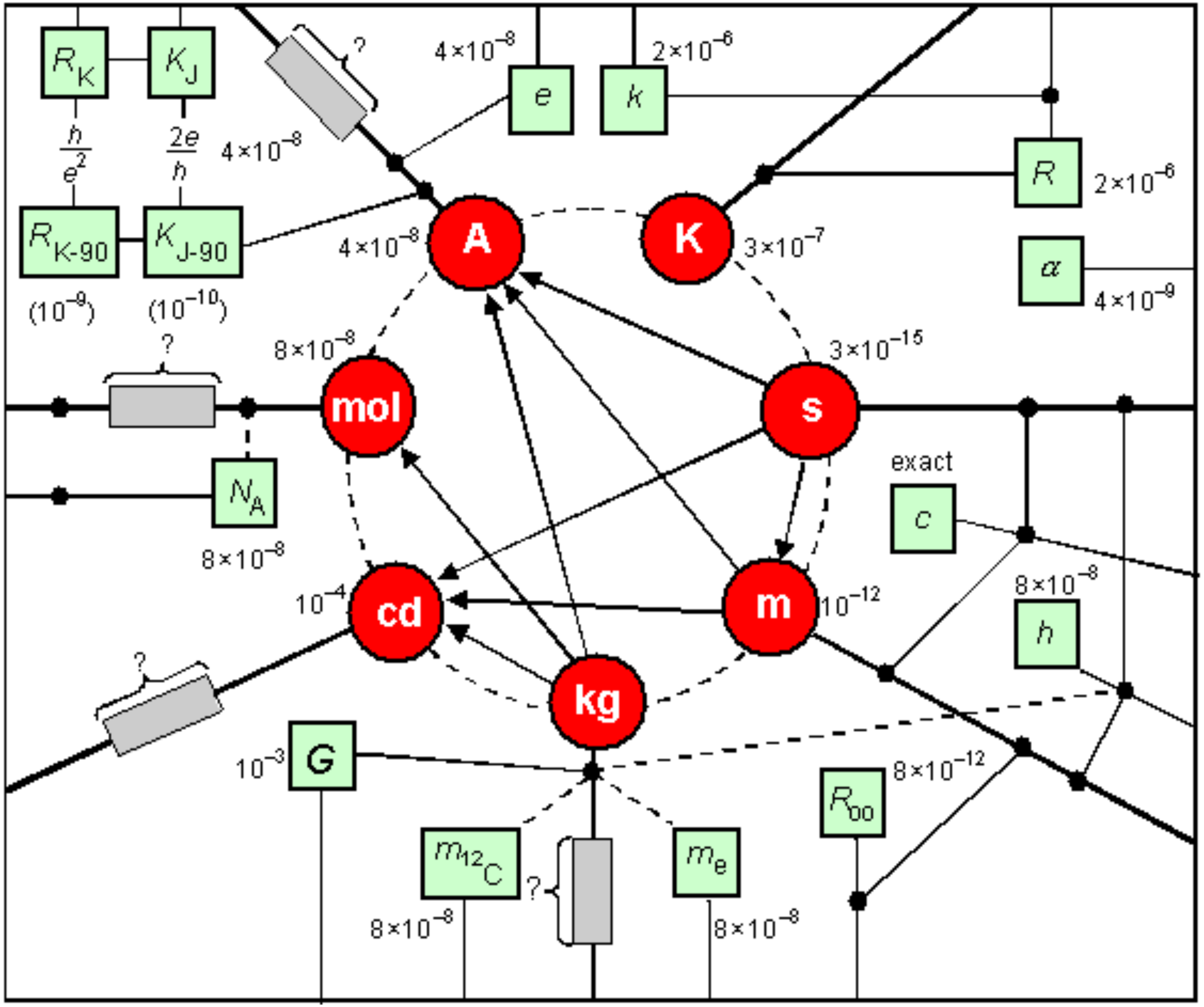
2- the theory will provide an equation of evolution for this new parameter

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]

Constants and systems of units



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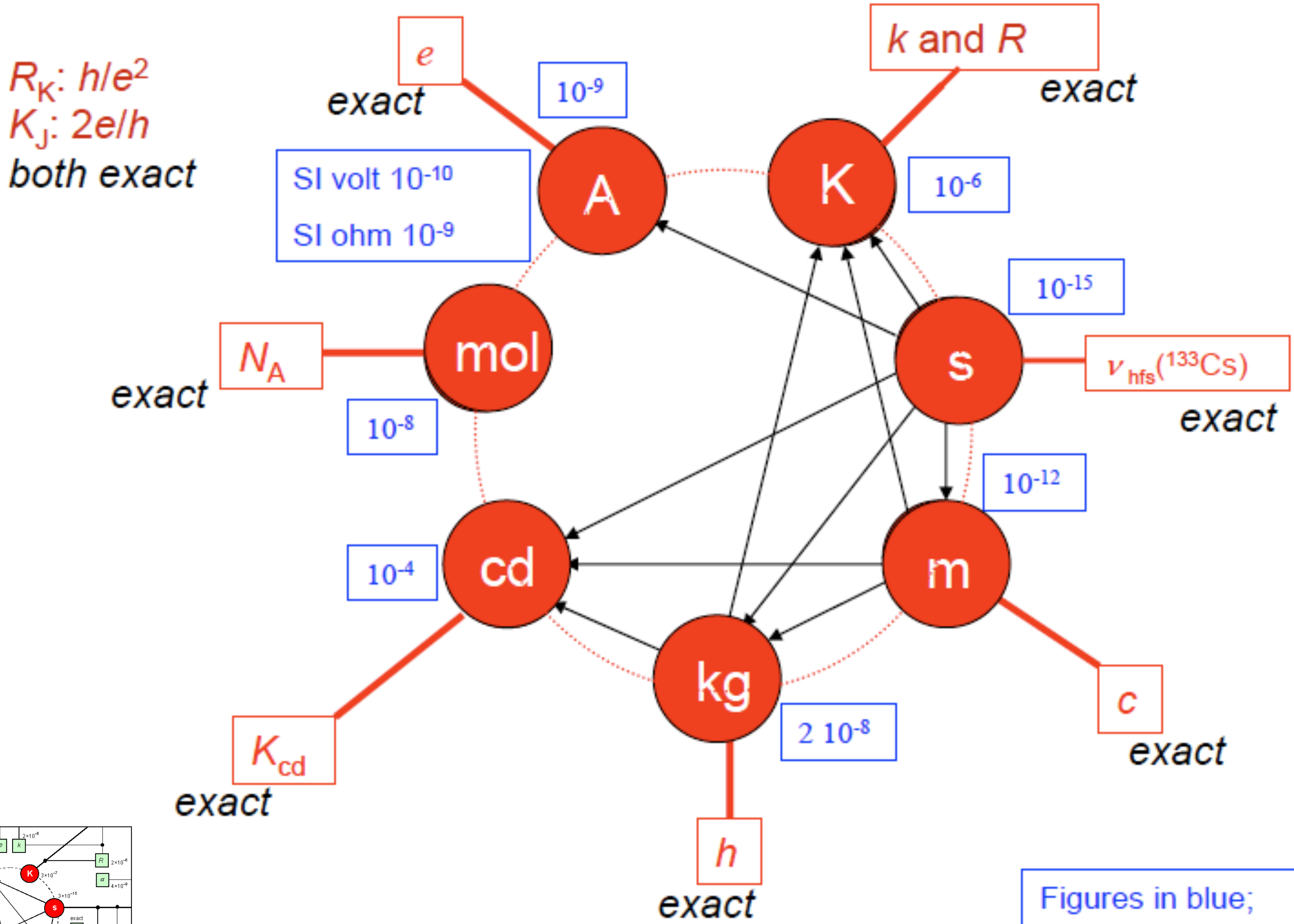
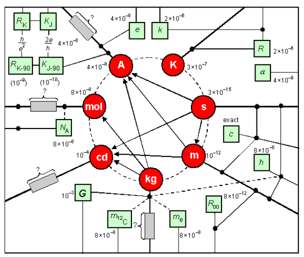




http://www.bipm.org/en/si/new_si/

Figures in blue;
approximate relative
uncertainty of realization

Overview

- Modelisation of gyromagnetic factors
  [with K. Olive & Fang Luo (2011)]

- Planck & CMB constraints
  [with S. Galli, O. Fabre, S. Prunet, E. Menegoni, & Planck collaboration (2013)]

- Big bang nucleosynthesis
  [with A. Coc, E Vangioni, L. Olive (2007-2013)]

- Population III stars
  [with A. Coc, E. Vangioni, K. Olive, P. Descouvemont, G. Meynet,S. Ekström (2010)]

ANR VACOUL (PI: Patrick Petitjean) / ANR Thales (PI: Luc Blanchet)

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

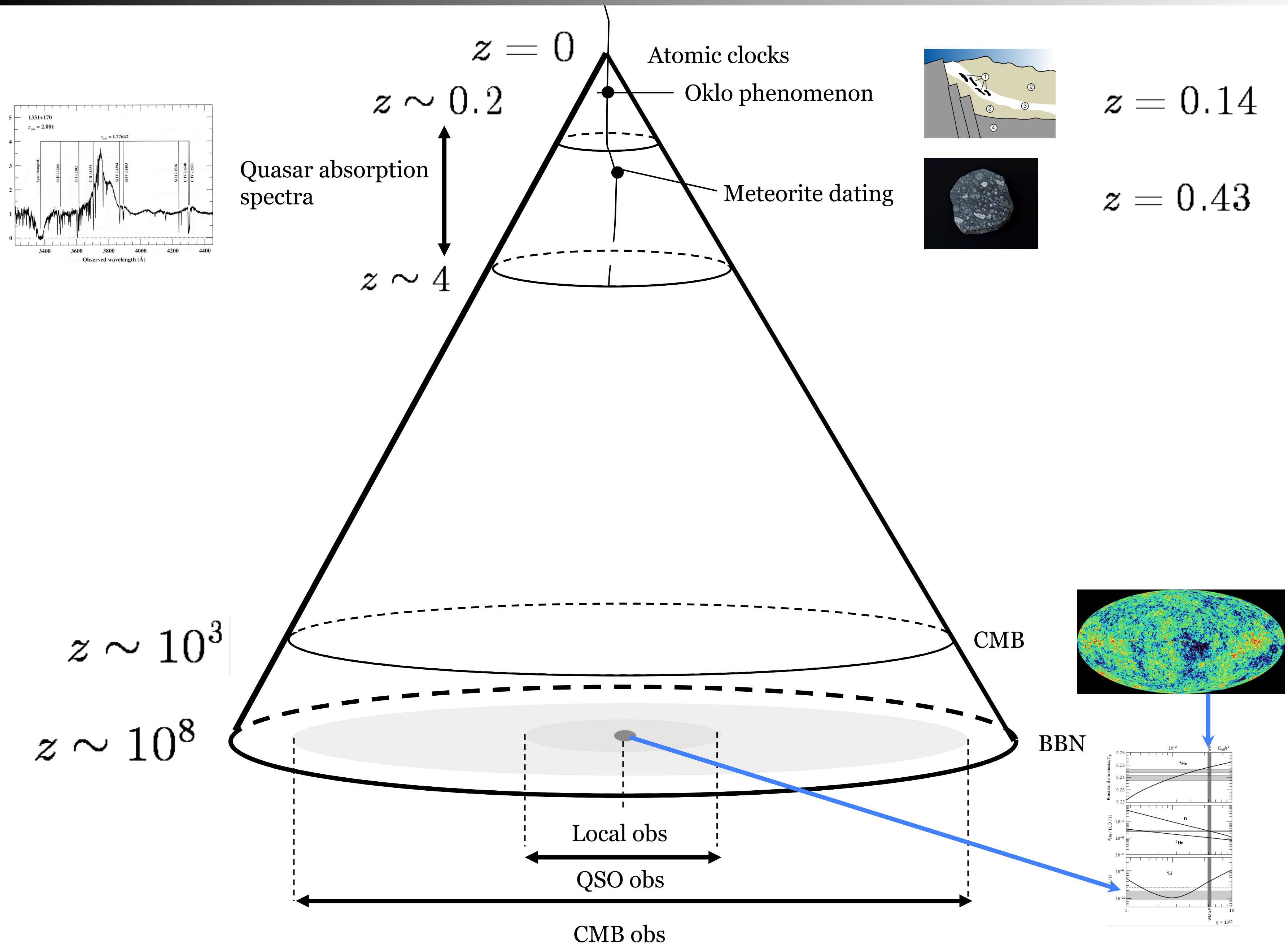
$$\kappa_{G_k} = \frac{\partial \ln O}{\partial \ln G_k}$$

Step 2:

The primary physical parameters are usually not fundamental constants.

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

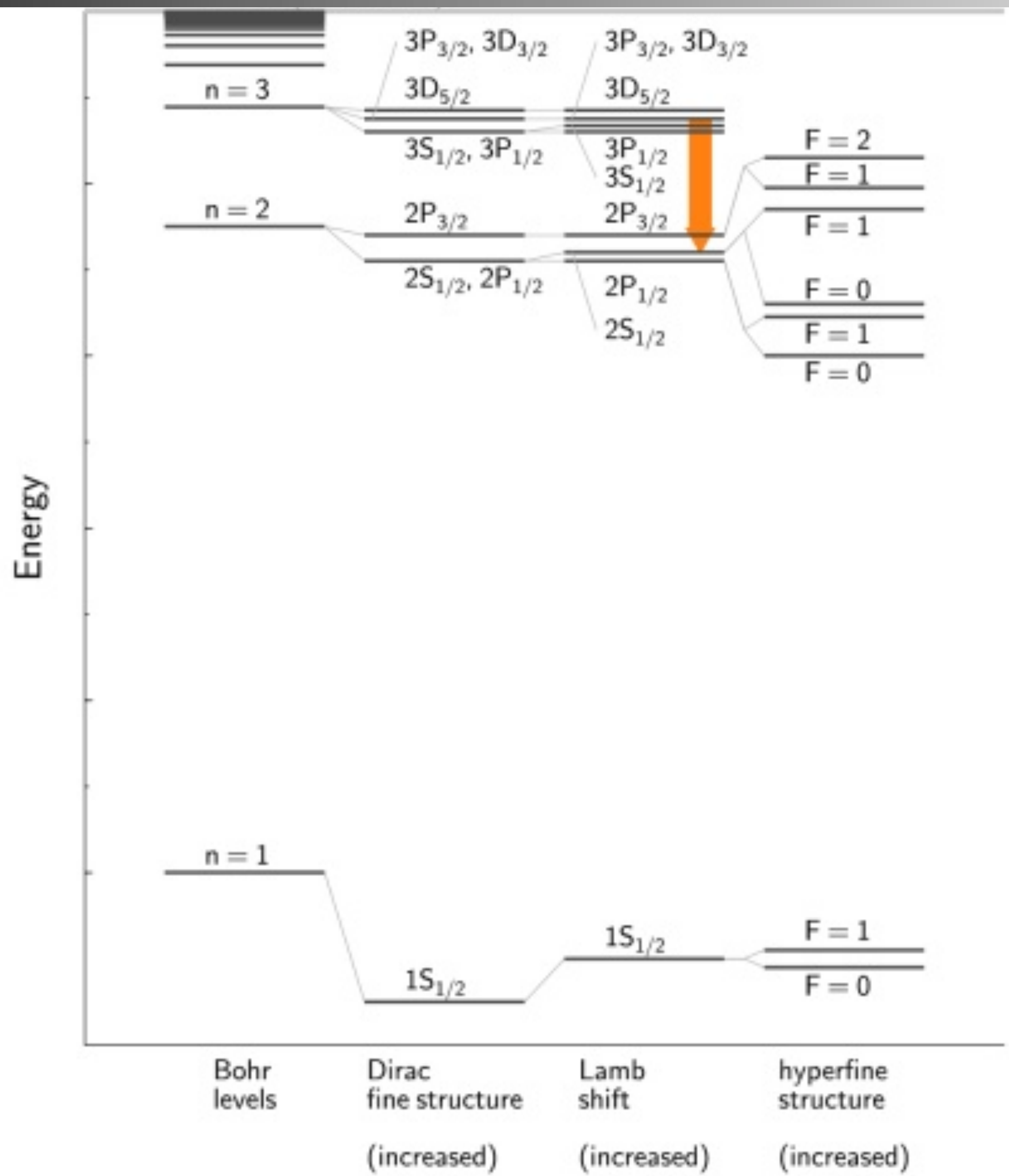
Physical systems



Atomic clocks
&
modelisation of gyromagnetic factors

[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 $\frac{d}{dt}\ln\left(\frac{\nu_{clock_1}}{\nu_{clock_2}}\right)$	Constraint (yr^{-1})	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: from observations to constraints

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

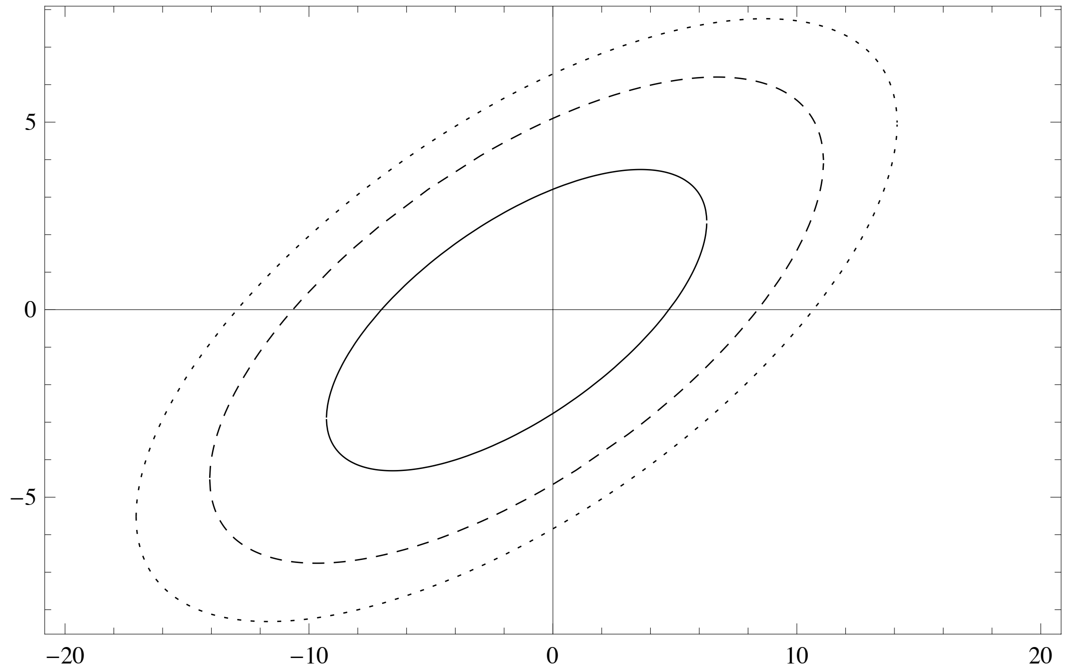
$$\frac{\delta g_{\rm Cs}}{g_{\rm Cs}} \sim -1.266\frac{\delta g_p}{g_p} \qquad \frac{\delta g_{\rm Rb}}{g_{\rm Rb}} \sim 0.736\frac{\delta g_p}{g_p}$$

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,...



$\frac{\delta g_p}{g_p}$ $(\times 10^{16})$

$\frac{\delta\mu}{\mu}$ $(\times 10^{16})$

[Luo, Olive, JPU, 2011]

Atomic clocks: from observations to constraints

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

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

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

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.

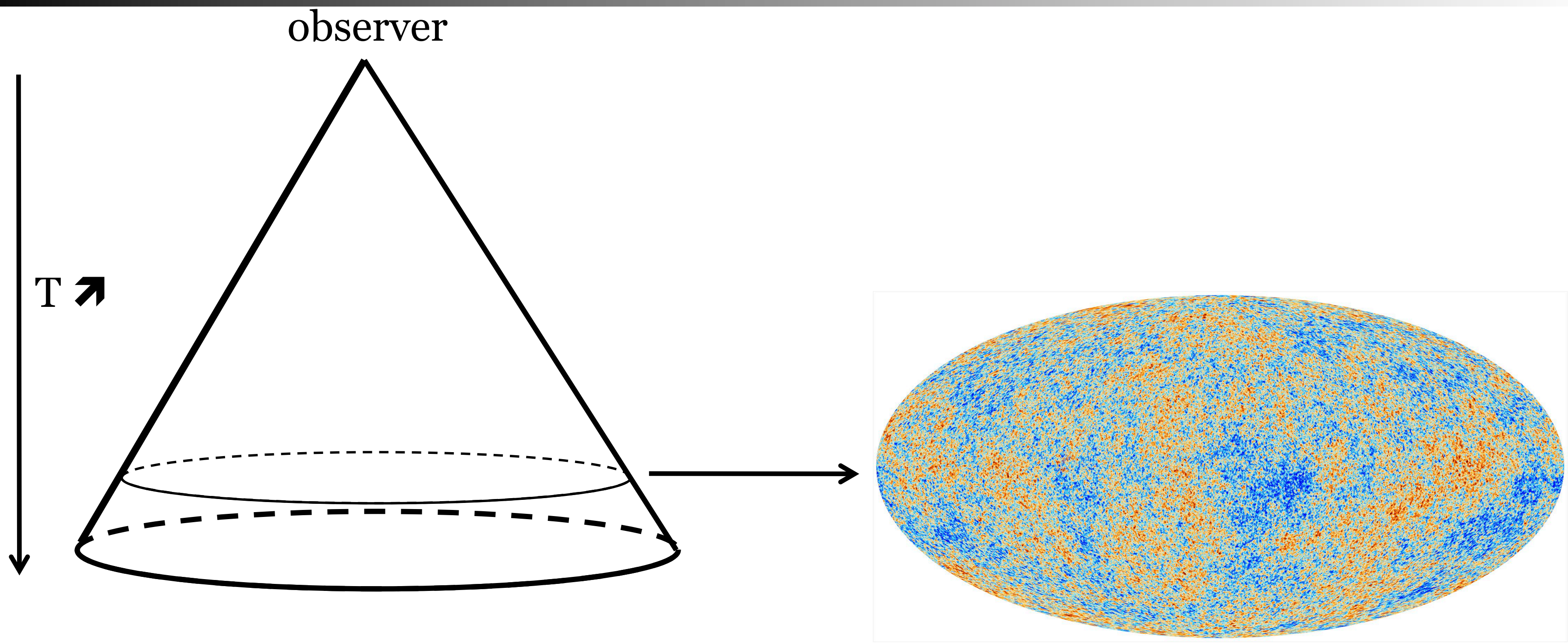
Model-dependence remains quite large.

[Luo, Olive, JPU, 2011]

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

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

- $E=h\nu$ 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

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

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

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

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

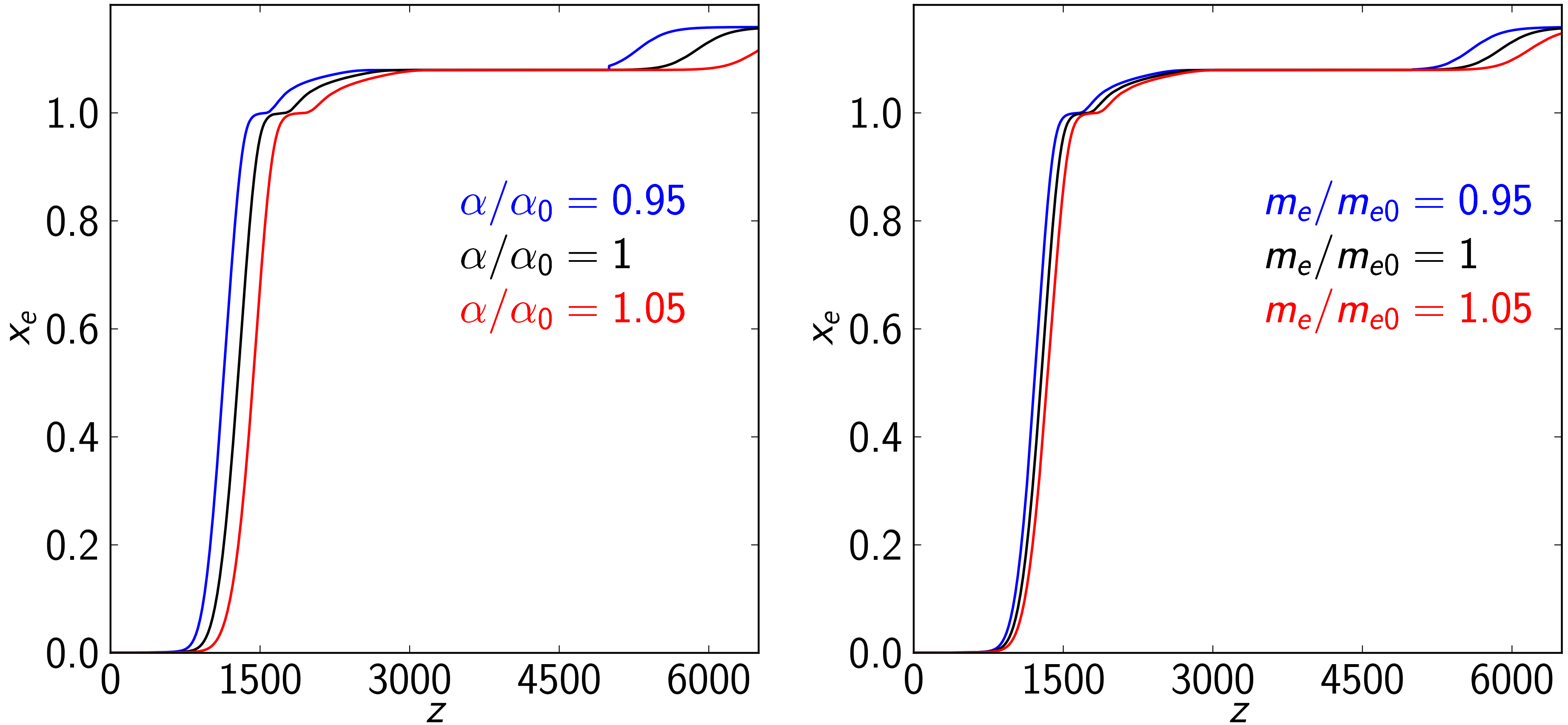
$$\beta_i = \beta_{i0}\left(\frac{\alpha}{\alpha_0}\right)^3$$

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

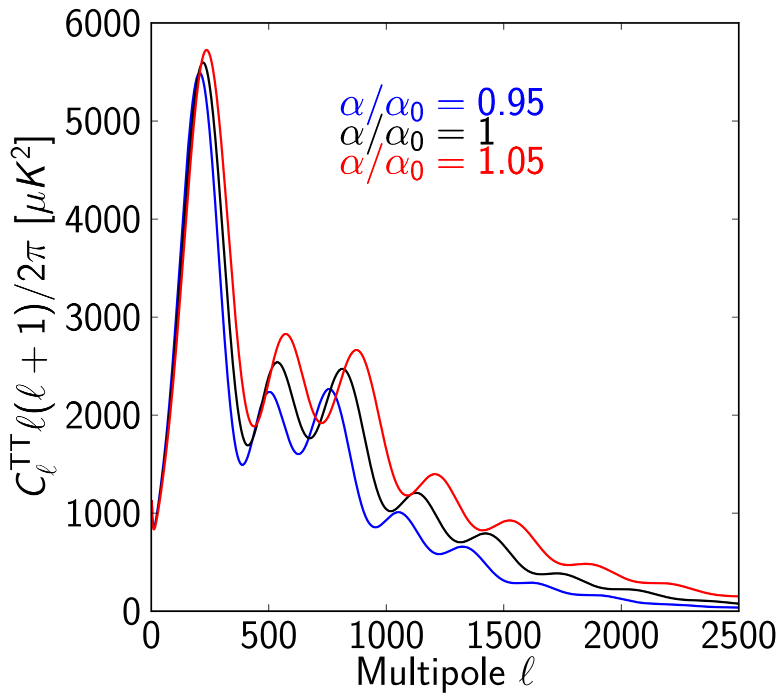
$$A_i = A_{i0}\left(\frac{\alpha}{\alpha_0}\right)^5\left(\frac{m_{\rm e}}{m_{\rm e0}}\right)$$

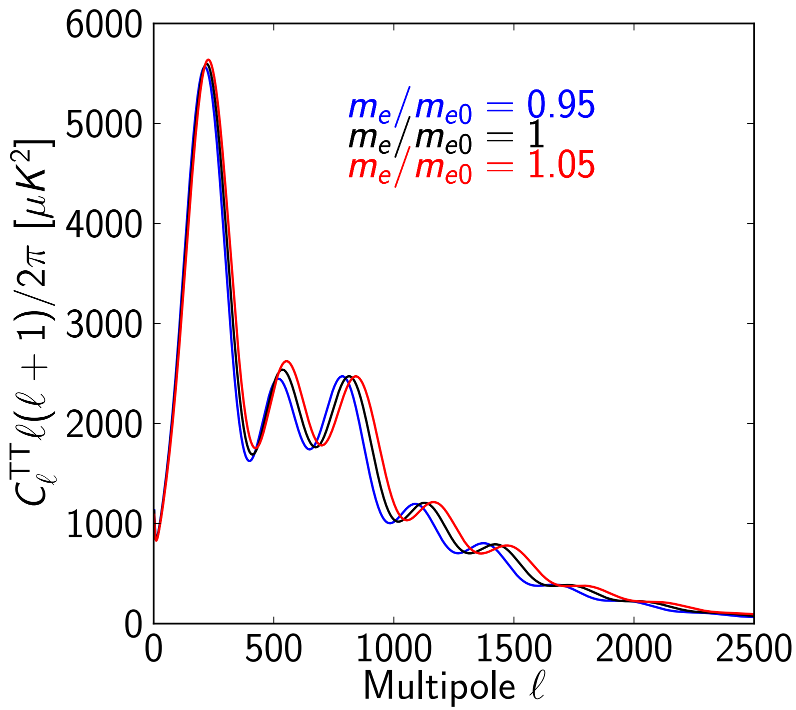
$$\Lambda_i = \Lambda_{i0}\left(\frac{\alpha}{\alpha_0}\right)^8\left(\frac{m_{\rm e}}{m_{\rm e0}}\right),$$

Dependence on the constants



Effect on the temperature power spectrum



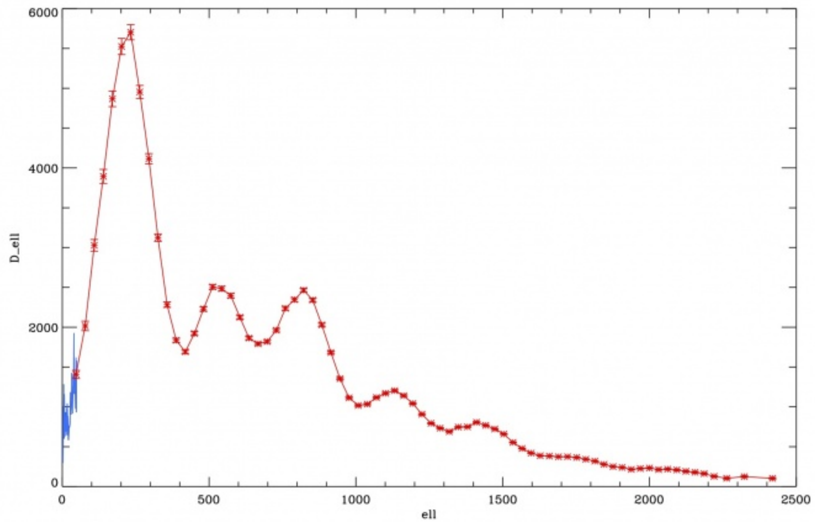


Increase of α induces

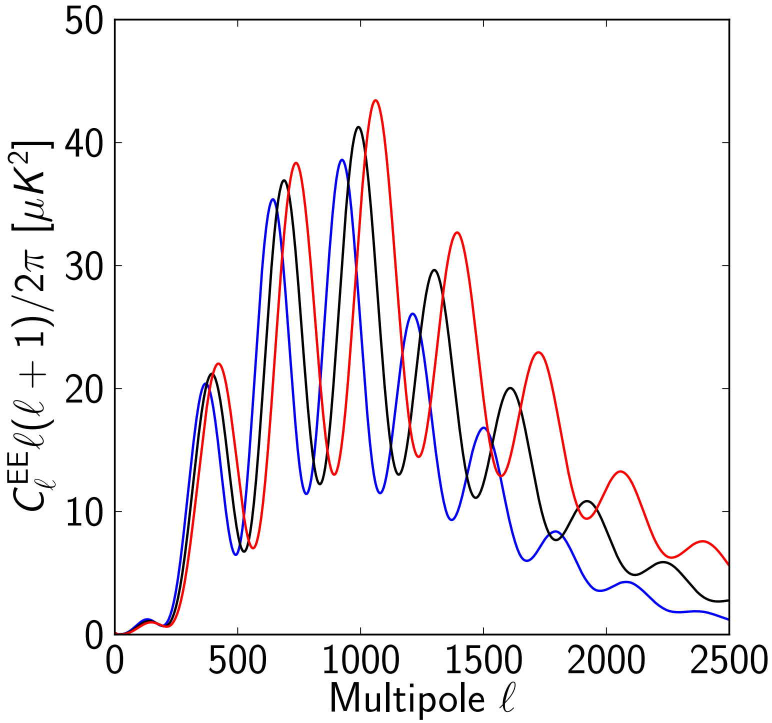
- an earlier decoupling
- smaller sound horizon
- shift of the peaks to higher multipoles

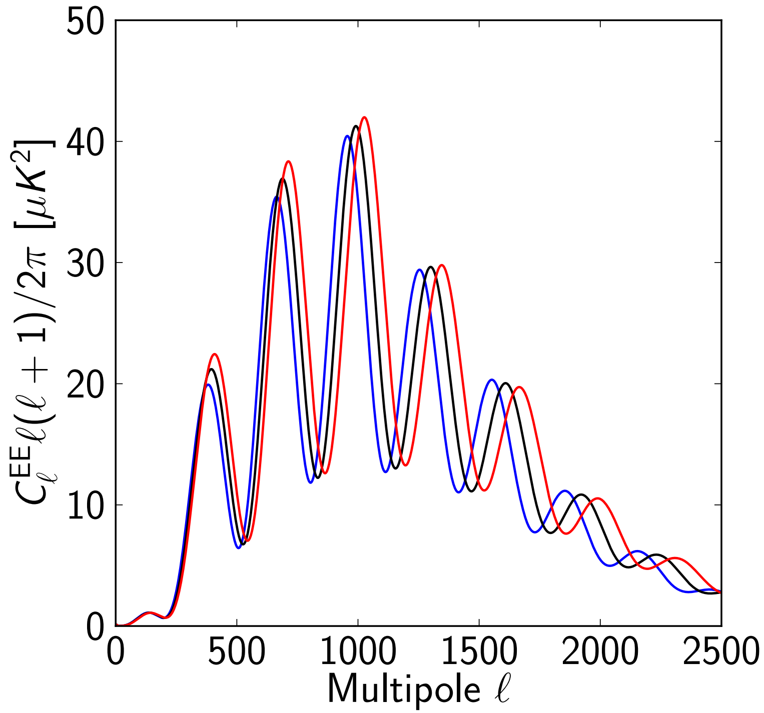
- an increase of amplitude of large scale (early ISW)
- an increase of amplitude at small scales (Silk damping)

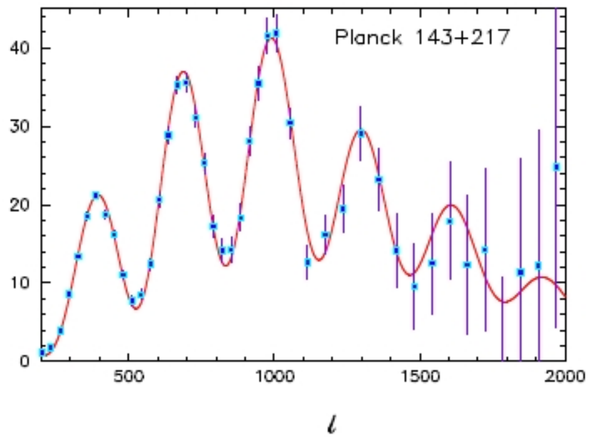
$$\lambda_D^2 = \frac{1}{6}\int_0^{\eta_{dec}} \frac{d\eta}{\sigma_T n_e a}\left[\frac{R^2 + \frac{16}{15}(1+R)}{(1+R)^2}\right] \propto \frac{1}{\sigma_T} \propto \frac{1}{\alpha^2 m_e^{-2}}$$



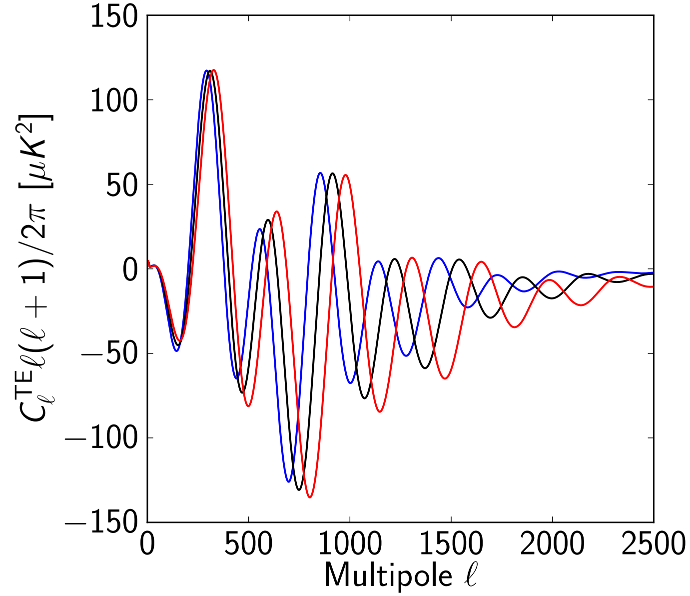
Effect on the polarization power spctrum

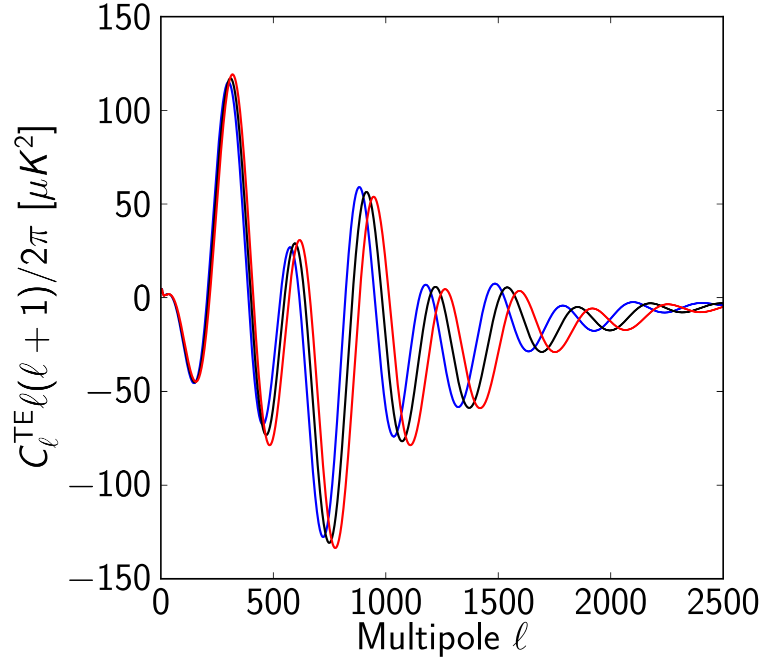


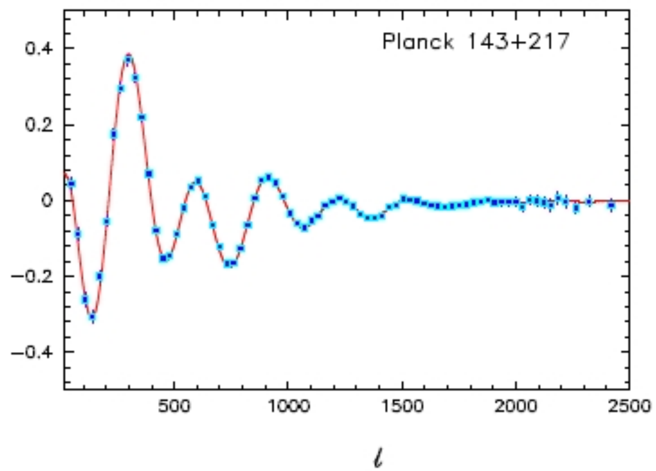




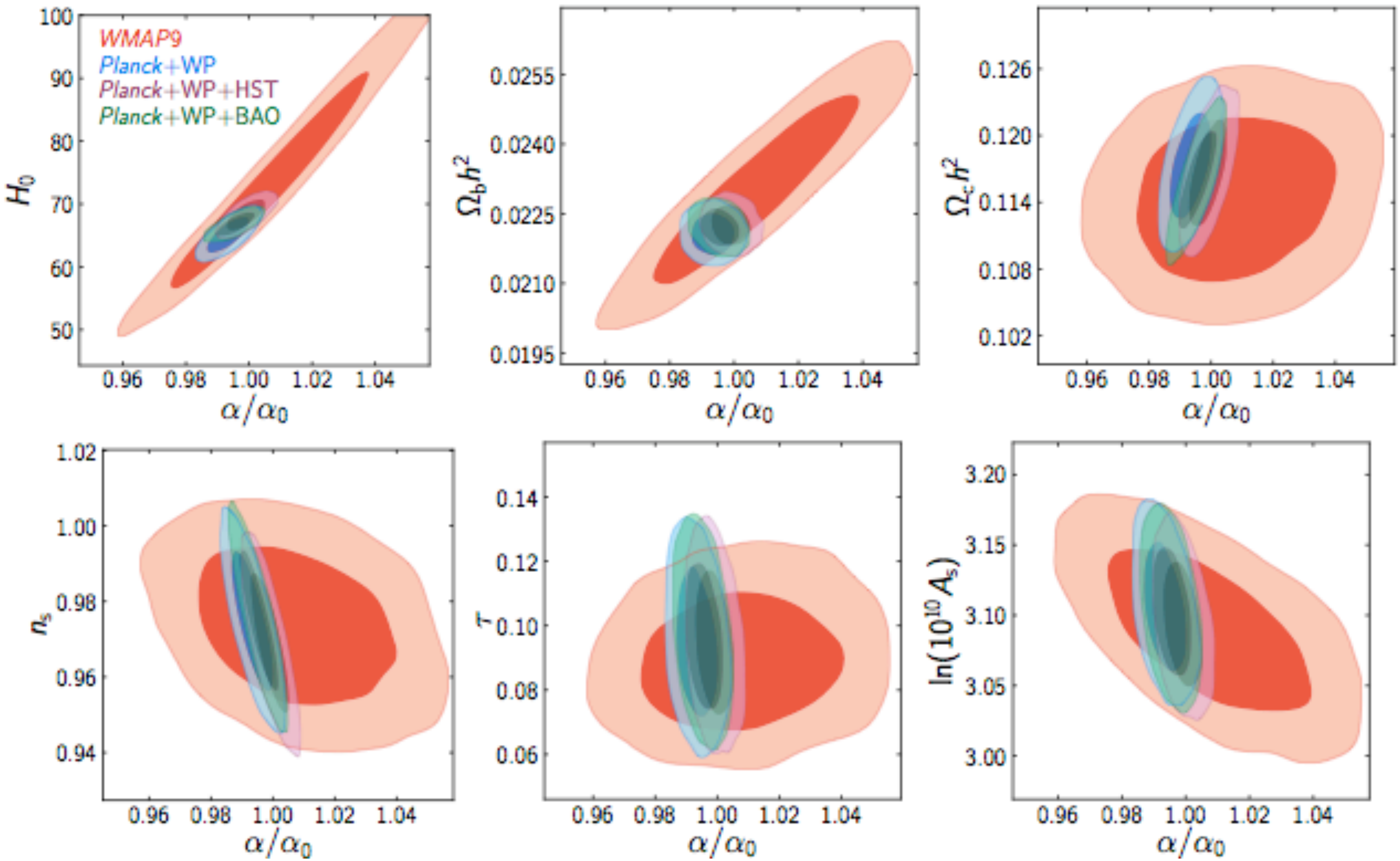
Effect on the cross-correlation





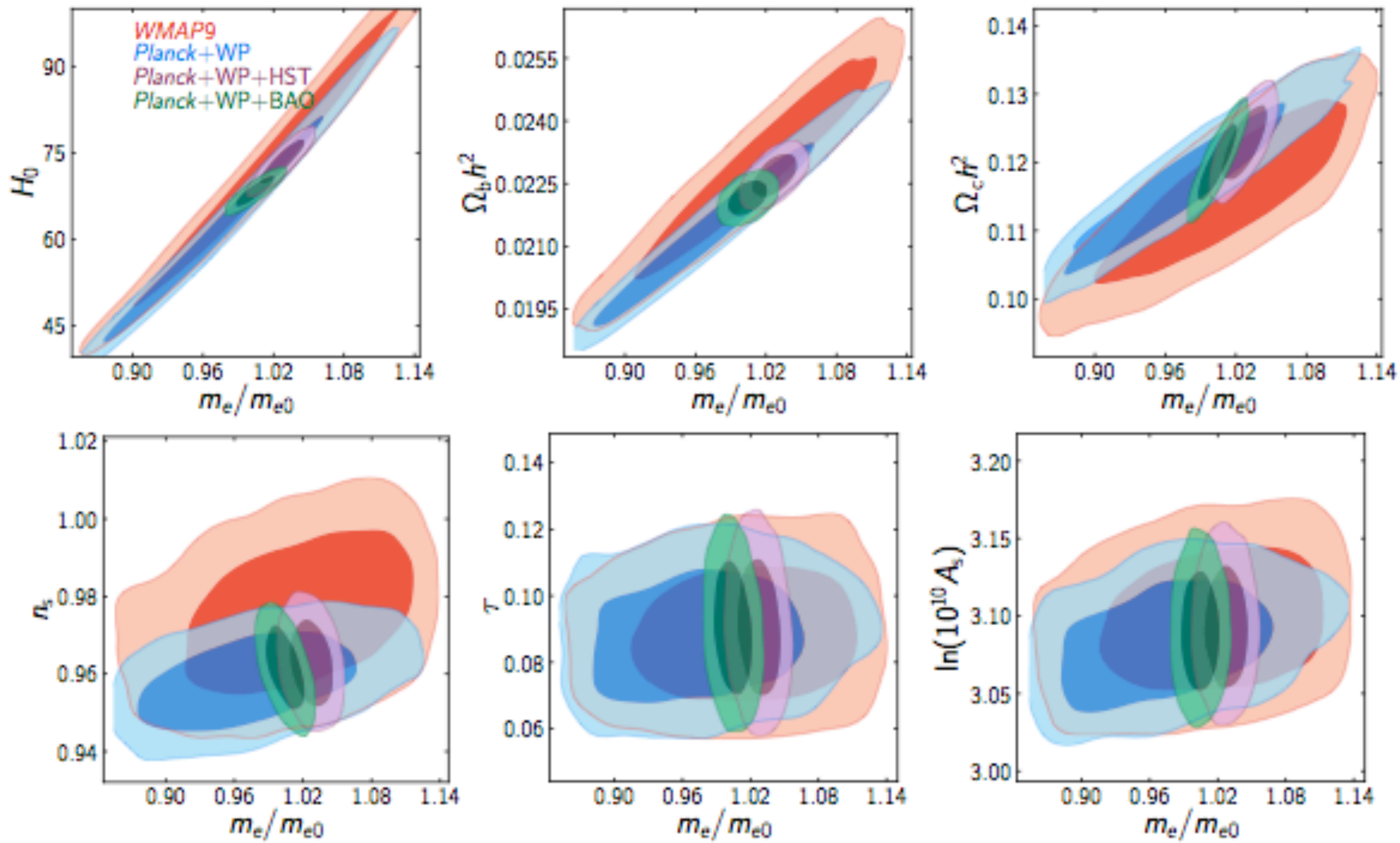


Varying α alone



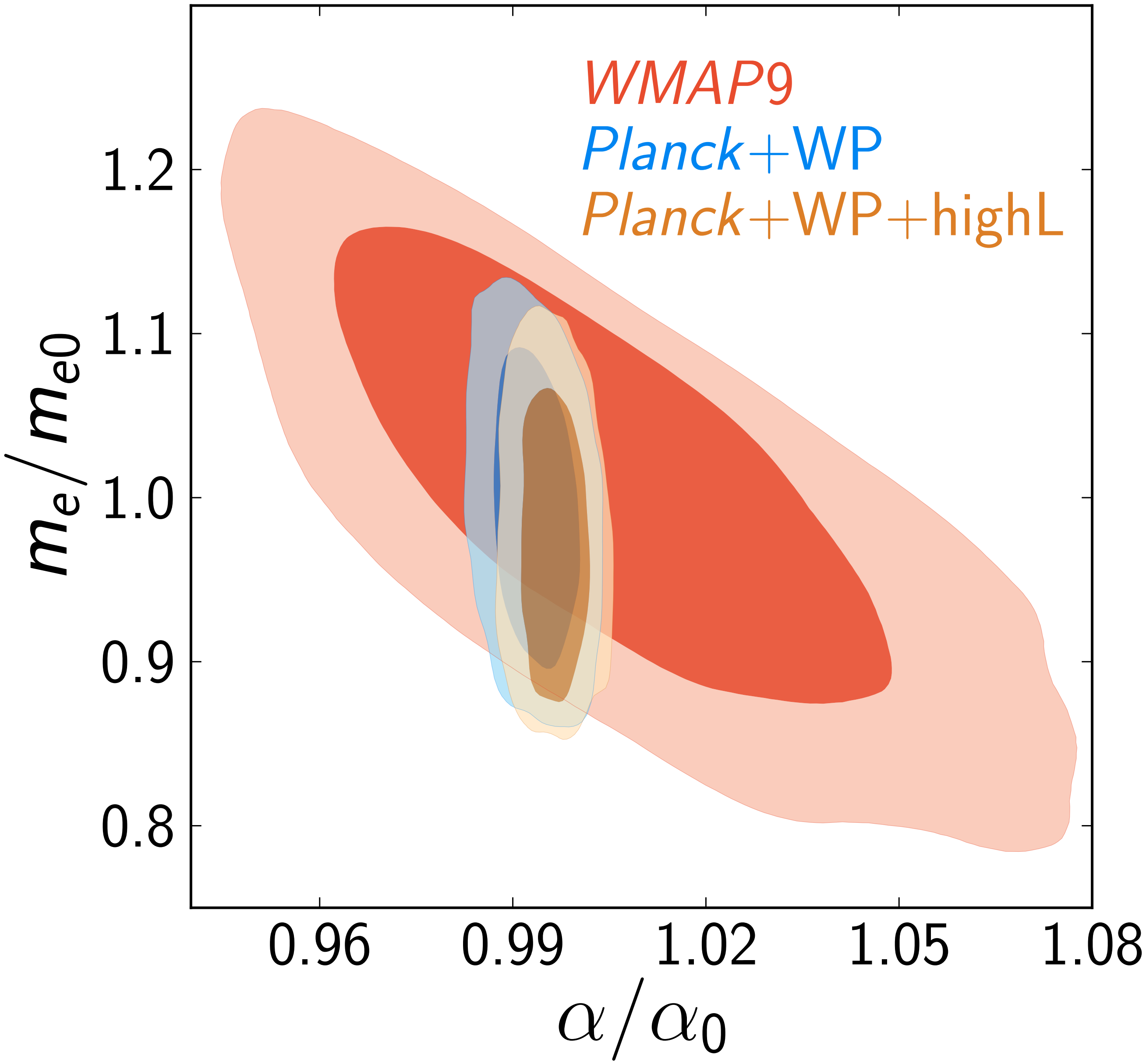
$$\{\omega_b, \omega_c, H_0, \tau, n_s, A_s, \alpha \text{ or } m_e\}$$

Varying m_e alone

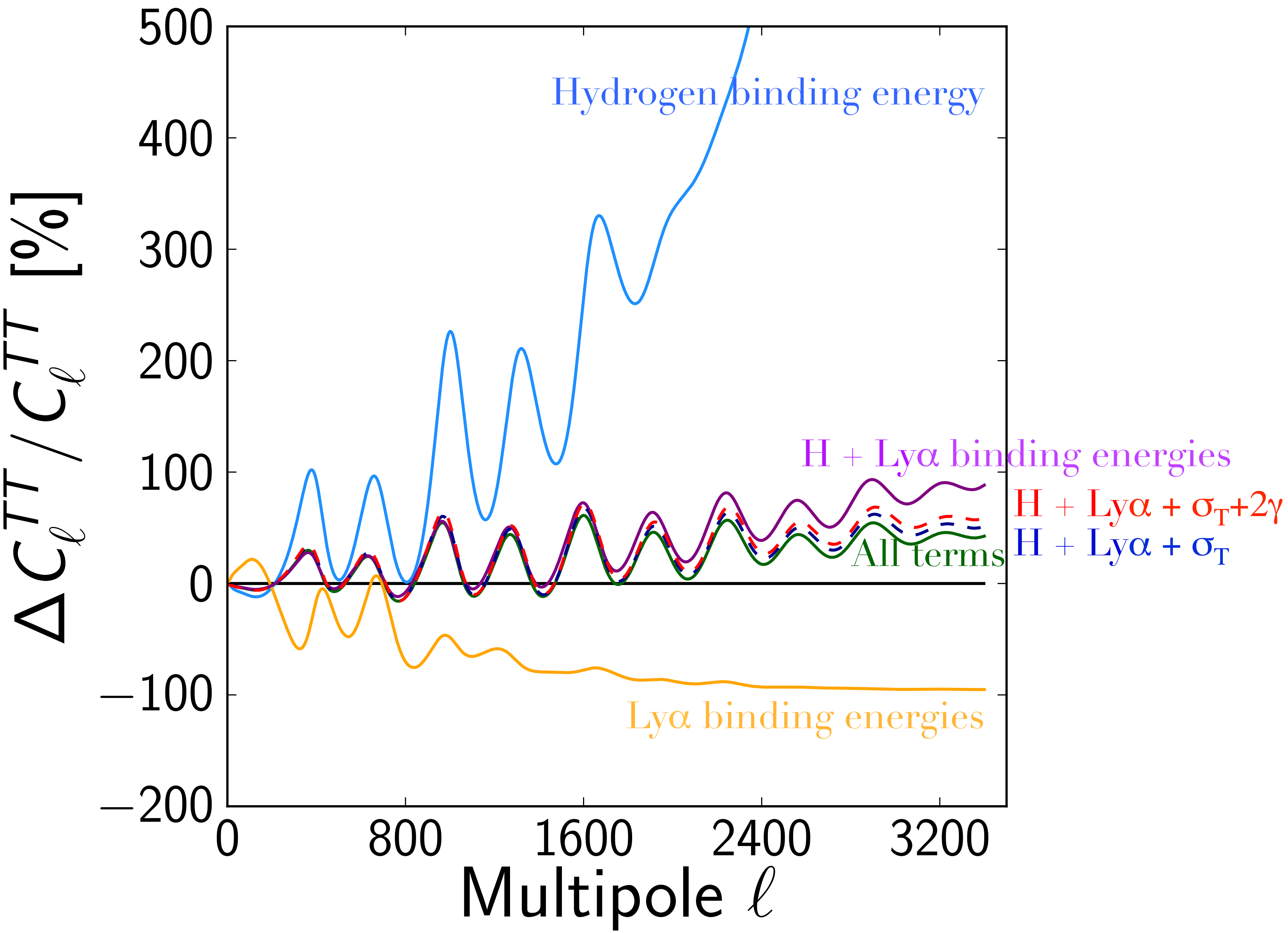


$\{\omega_{\rm b}, \omega_{\rm c}, H_0, \tau, n_s, A_s, \alpha \text{ or } m_e\}$

(α, m_e)-degeneracy



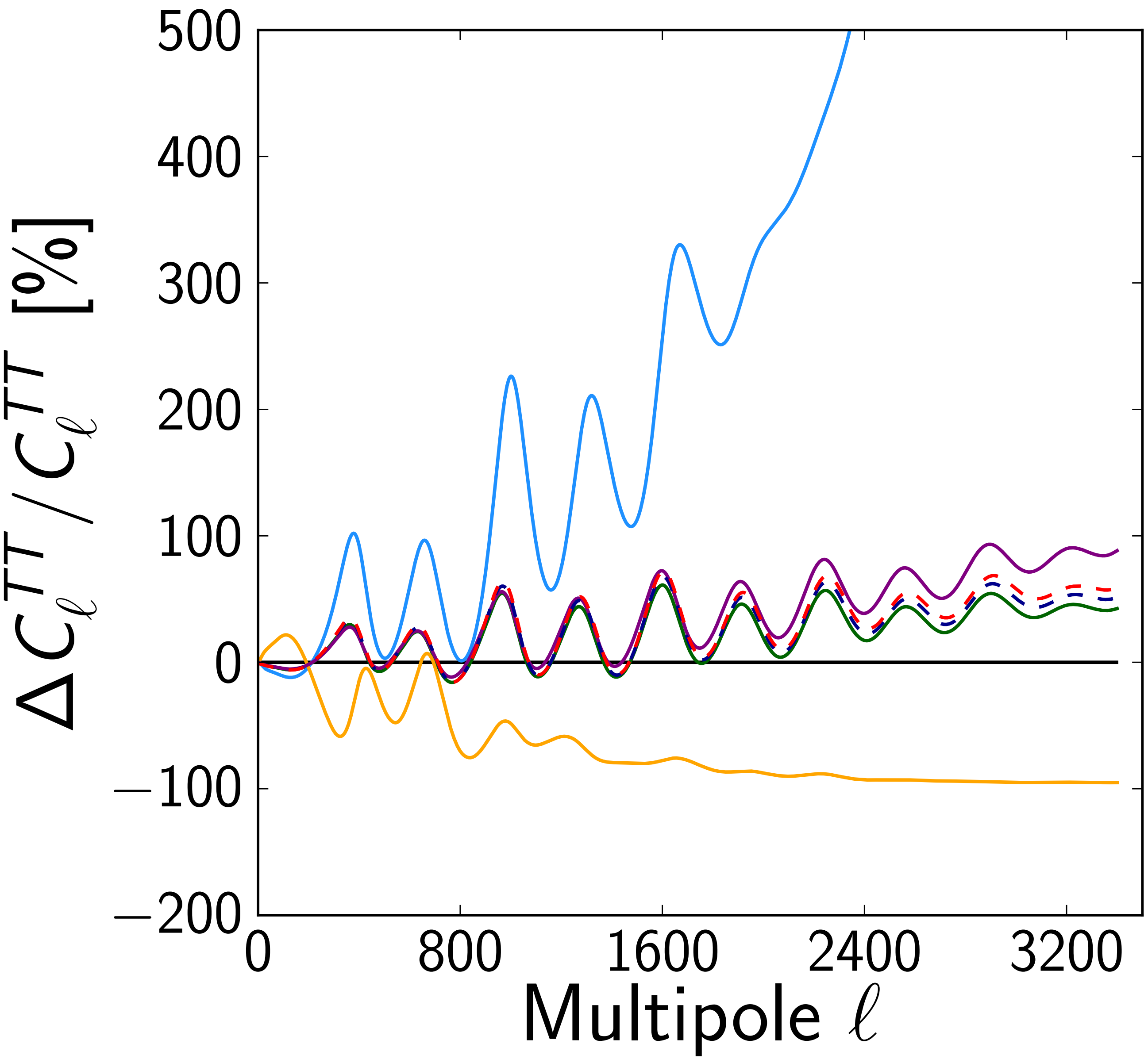
Why *Planck* does better



Why Planck does better

$\delta\alpha$ = 5%
δm_e=10.025%

$\alpha^2 m_e$ identical



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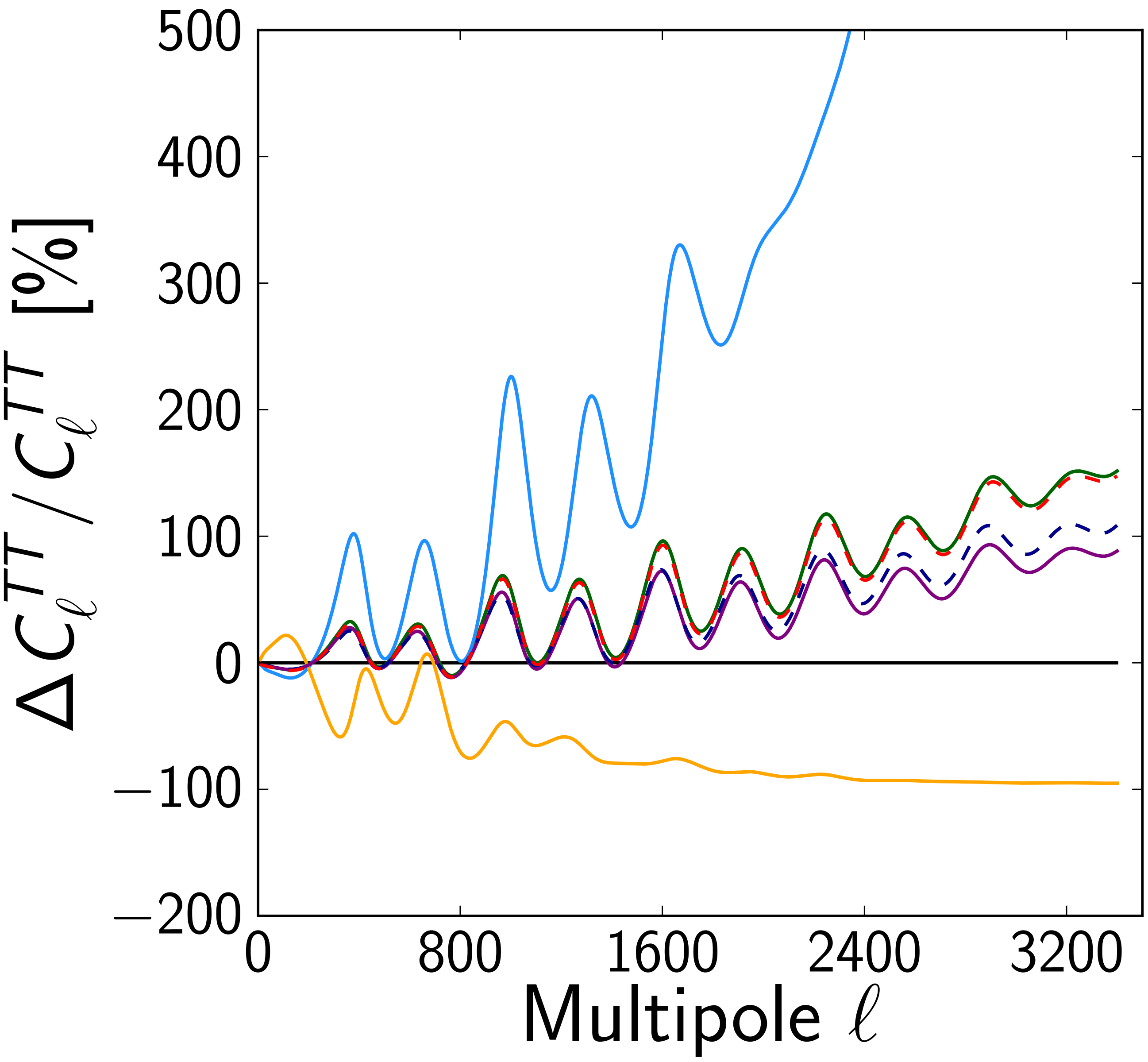
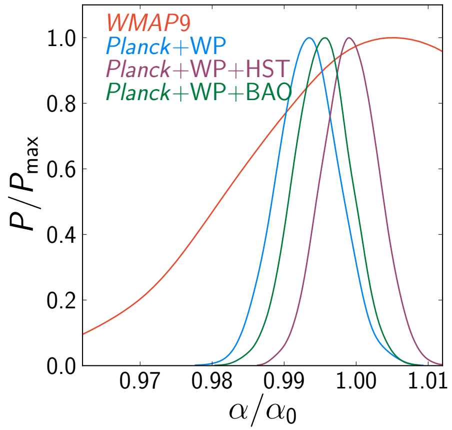


In conclusion

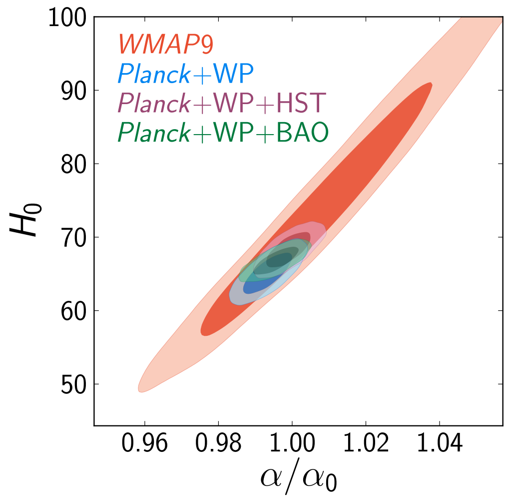
Independent variations of α and m_e are constrained to be

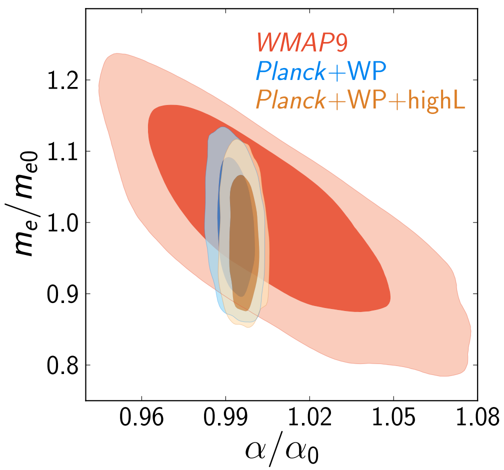
$\Delta\alpha/\alpha=(3.6\pm3.7)\times10^{-3}$ $\Delta m_e/m_e=(4\pm11)\times10^{-3}$

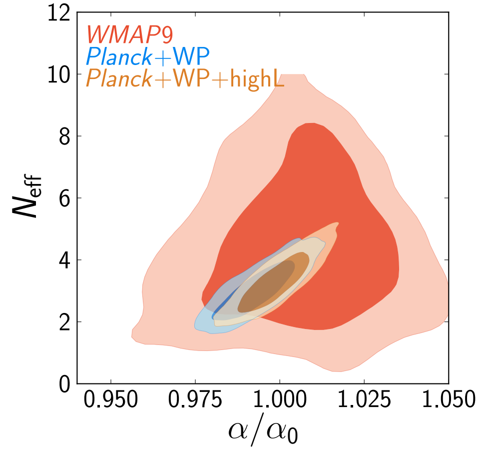


This is a <u>factor 5</u> better compared to WMAP analysis

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





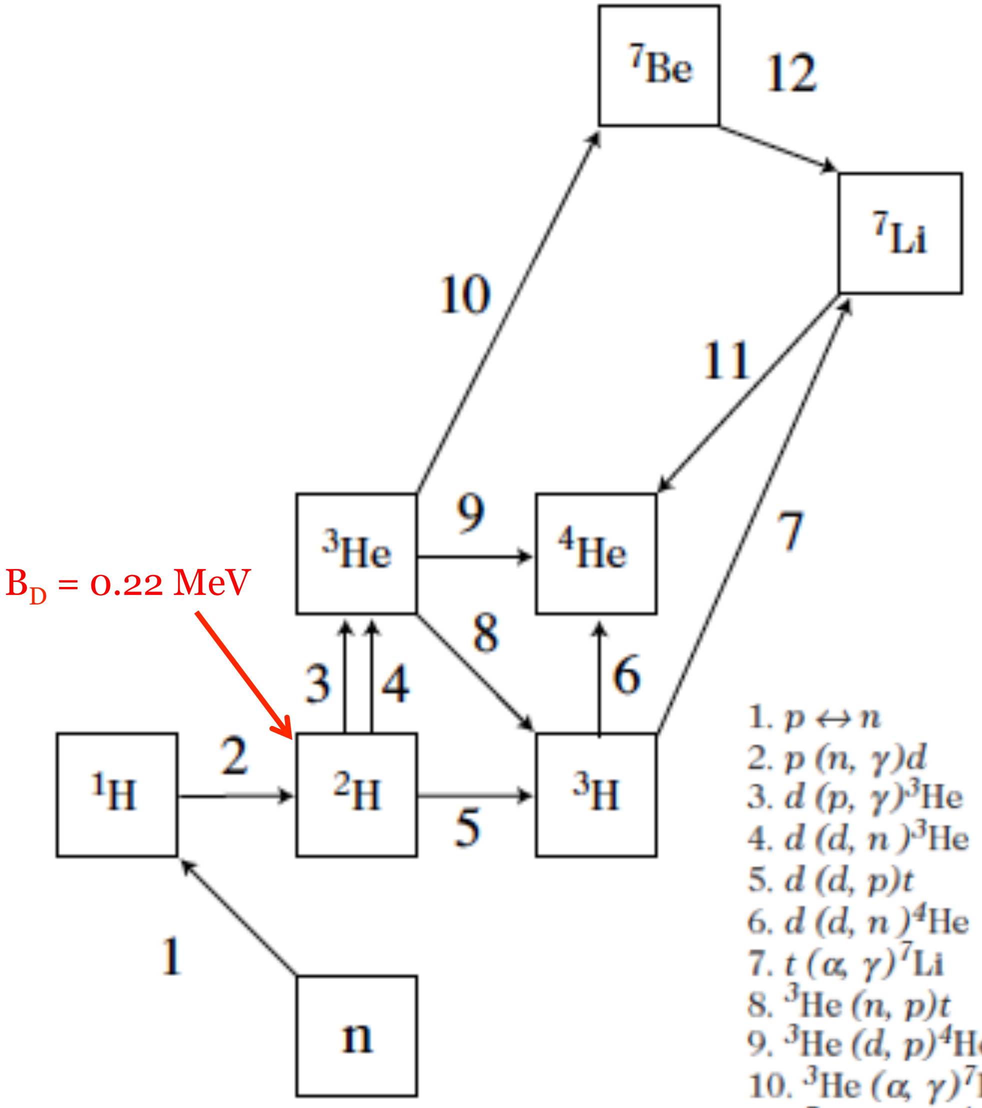


Big bang nucleosynthesis
&
Population III stars

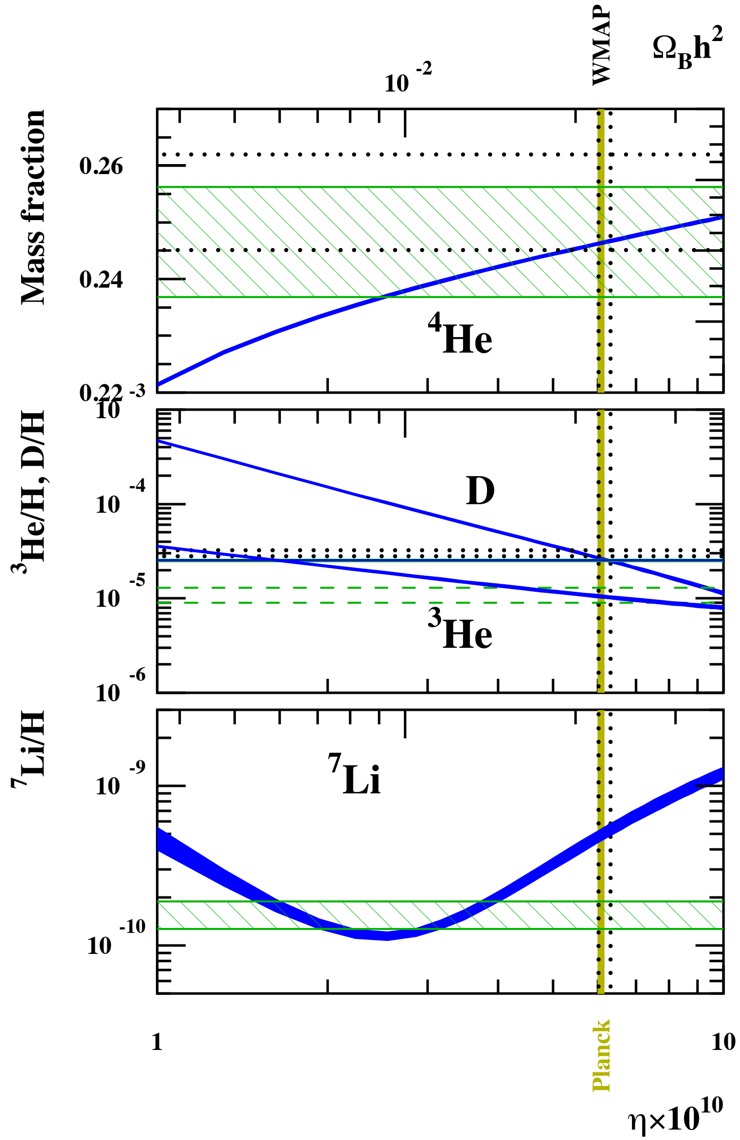
Nuclear physics at work in the universe

[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)

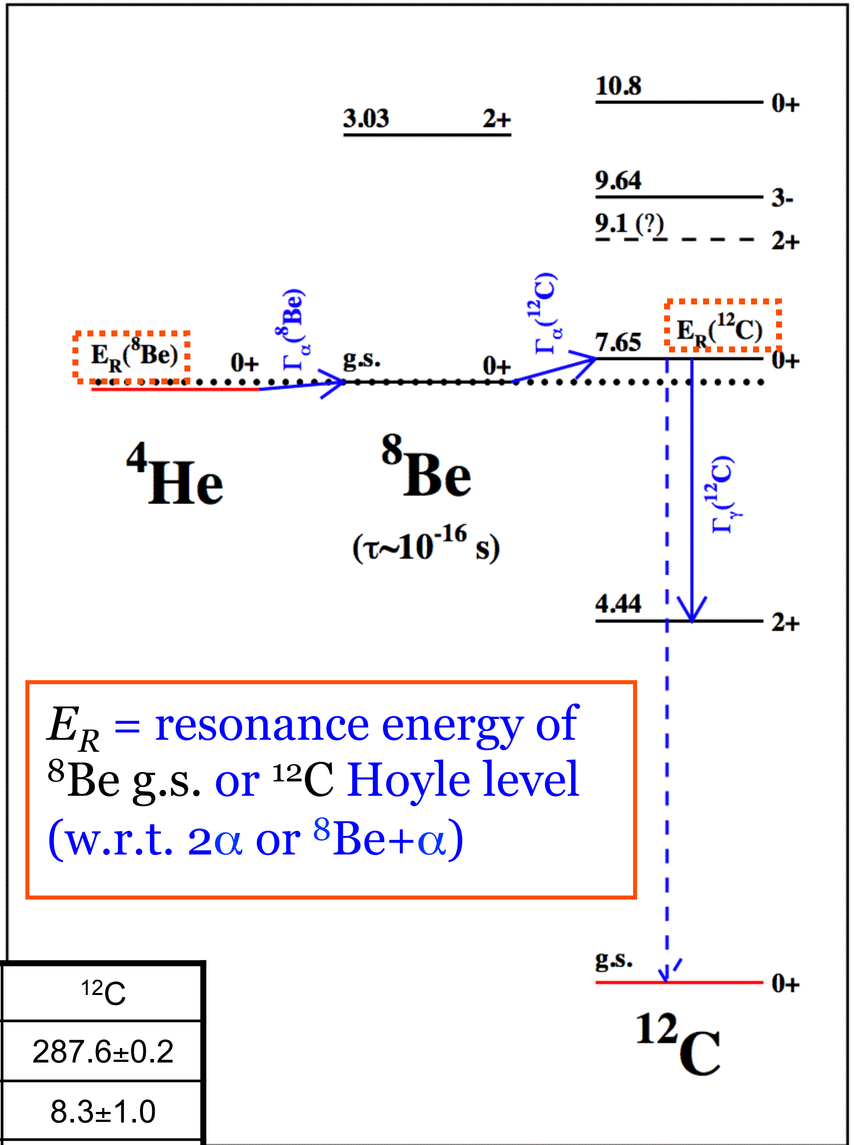
1. Equillibrium between ^{4}He and the short lived (~10^{-16} s) ^{8}Be : $\alpha\alpha \leftrightarrow {}^8$Be
2. Resonant capture to the (l=0, J^π=0$^+$) Hoyle state: ^{8}Be+α→^{12}C*(→^{12}C+γ)

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 $Q_{\alpha\alpha\alpha} = E_R(^8\text{Be}) + E_R(^{12}\text{C})$ 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]

Nuclear physics

Both phenomena involve nuclear physics.

The microphysics involves binding energies / resonnance energies / cross-sections

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

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

$$(B_D, \eta)$$

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

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

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

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

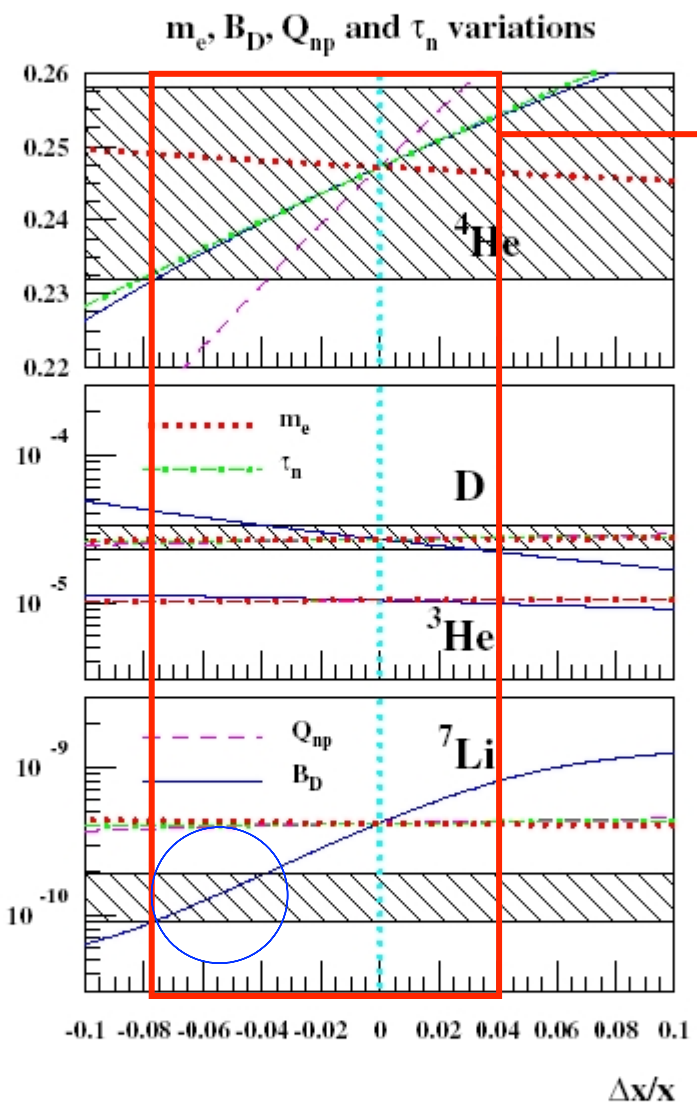
Predictions depend on

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

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

BBN: fundamental parameters (1)

Neutron-proton mass difference:

$$Q = m_n - m_p = a\alpha\Lambda + (h_d - h_u)v$$

$$\frac{\Delta Q}{Q} = -0.6\left(\frac{\Delta\alpha}{\alpha} + \frac{\Delta\Lambda}{\Lambda}\right) + 1.6\left(\frac{\Delta(h_d - h_u)}{h_d - h_u} + \frac{\Delta v}{v}\right)$$

Neutron lifetime:

$$\tau_n^{-1} = G_F^2 m_e^5 f(Q/m_e) \qquad m_e = h_e v$$

$$G_F = 1/\sqrt{2}\,v^2$$

$$\frac{\Delta\tau_n}{\tau_n} = -4.8\frac{\Delta v}{v} + 1.5\frac{\Delta h_e}{h_e} - 10.4\frac{\Delta(h_d - h_u)}{h_d - h_u} + 3.8\left(\frac{\Delta\alpha}{\alpha} + \frac{\Delta\Lambda}{\Lambda}\right)$$

BBN: fundamental parameters (2)

D binding energy:

Use a potential model
$$V_{nuc} = \frac{1}{4\pi r}(-\, g_s^2 e^{-rm_\sigma} + g_v^2 e^{-rm_\omega})$$

$$\frac{\Delta B_D}{B_D} = -\,48\frac{\Delta m_\sigma}{m_\sigma} + 50\frac{\Delta m_\omega}{m_\omega} + 6\frac{\Delta m_N}{m_N}$$

Flambaum,Shuryak 2003

This allows to determine BD as a function of mass of the quarks (u,d,s), Λ_{QCD}, α.

This allows to determine all the primary parameters in terms of (h_i, v, Λ,α)

BBN: assuming GUT

GUT:

The low-energy expression for the QCD scale

$$\Lambda = \mu \left(\frac{m_c m_b m_t}{\mu^3}\right)^{2/27} \exp\left(-\frac{2\pi}{9\alpha_3(\mu)}\right)$$

We deduce

$$\frac{\Delta\Lambda}{\Lambda} = R\frac{\Delta\alpha}{\alpha} + \frac{2}{27}\left(3\frac{\Delta v}{v} + \sum_{i=c,b,t}\frac{\Delta h_i}{h_i}\right)$$

The value of *R* depends on the particular GUT theory and particle content which control the value of M_{GUT} and of $\alpha(M_{GUT})$. Typically R=36.

Assume (for simplicity) h_i=h

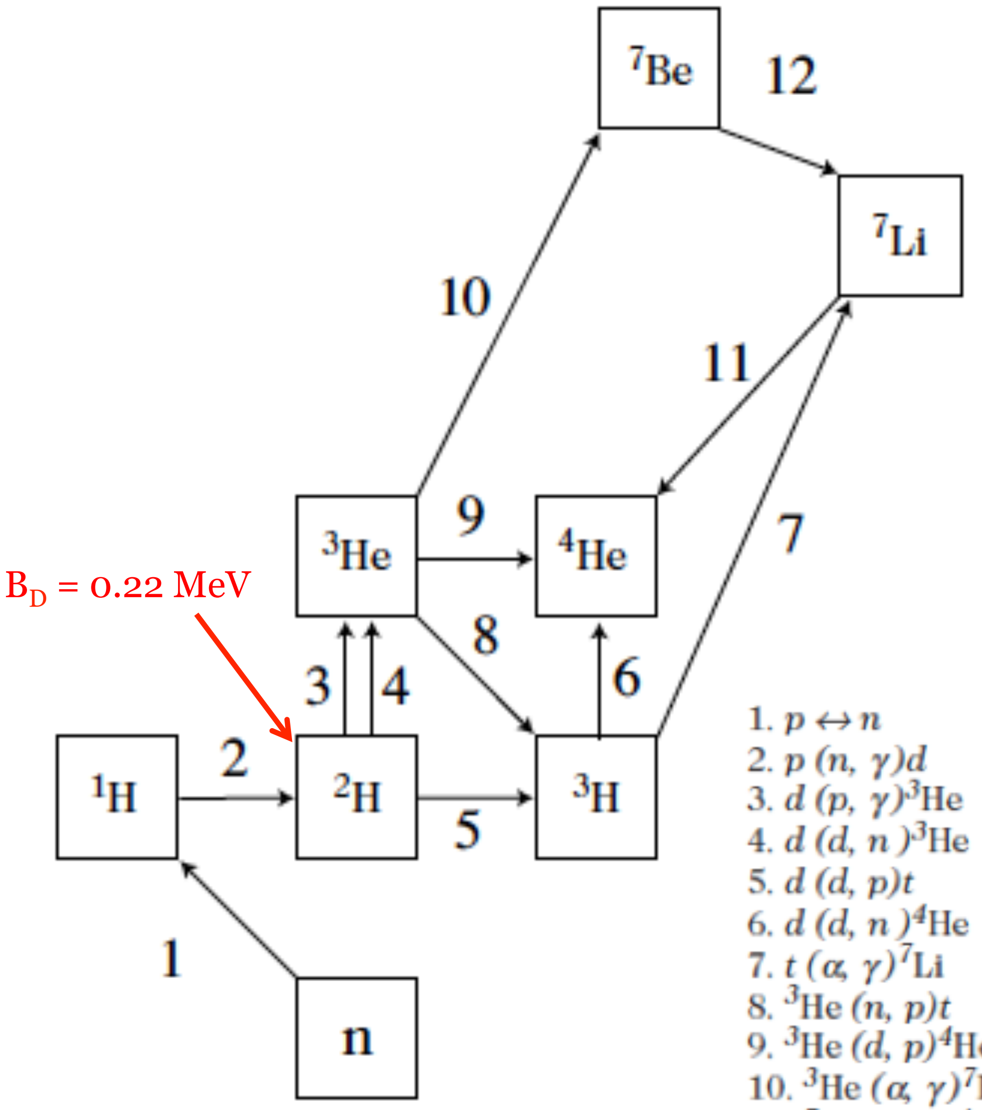
$$\frac{\Delta B_D}{B_D} = -13\left(\frac{\Delta v}{v} + \frac{\Delta h}{h}\right) + 18R\frac{\Delta\alpha}{\alpha}$$

$$\frac{\Delta Q}{Q} = 1.5\left(\frac{\Delta v}{v} + \frac{\Delta h}{h}\right) - 0.6(1+R)\frac{\Delta\alpha}{\alpha}$$

$$\frac{\Delta\tau_n}{\tau_n} = -4\frac{\Delta v}{v} - 8\frac{\Delta h}{h} + 3.8(1+R)\frac{\Delta\alpha}{\alpha}$$

$$(\alpha, v, h)$$

A=5 & A=8



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12. ^{7}Be $(n,\,p\,)^7$Li

To go further:
- influence on helium-5, lithium-5, beryllium-8, carbon-12
- cross-sections such as

$$^3\mathrm{H}(\mathrm{d},\,\mathrm{n})^4\mathrm{He},\ \ ^3\mathrm{He}(\mathrm{d},\,\mathrm{p})^4\mathrm{He}\ \text{ and }\ ^4\mathrm{He}(\alpha\alpha,\,\gamma)^{12}\mathrm{C}$$

To that goal, we introduced a modelisation that will also allow to study the stellar physics.

Cluster model & δ_{NN}

Cluster approach:

- solve the Schrödinger equation by considering Be8/C12 as clusters of α particle

$$\Psi^{JM\pi}_{^8\mathrm{Be}} = \mathcal{A}\phi_\alpha\phi_\alpha g_2^{JM\pi}(\rho)$$
$$\Psi^{JM\pi}_{^{12}\mathrm{C}} = \mathcal{A}\phi_\alpha\phi_\alpha\phi_\alpha g_3^{JM\pi}(\rho, \boldsymbol{R}),$$

- The Hamiltonian is then given by

$$H = \sum_{i=1}^{A} T(r_i) + \sum_{i<j=1}^{A} \left(V_{Coul.}(r_{ij}) + V_{Nucl.}(r_{ij})\right)$$

- We assume that

$$V_{ij} = (1 + \delta_\alpha)V_{ij}^C + (1 + \delta_{\mathrm{NN}})V_{ij}^N.$$ to obtain B_D, $E_R(^8\mathrm{Be})$, $E_R(^{12}\mathrm{C})$

- δ_{NN} is an effective parameter

Cluster model ⟷ Theoretical analysis

$$\Delta B_D/B_D = 5.716 \times \delta_{\mathrm{NN}}.$$

$$\frac{\Delta B_D}{B_D} = 18\frac{\Delta\Lambda_{\mathrm{QCD}}}{\Lambda_{\mathrm{QCD}}} - 17\left(\frac{\Delta v}{v} + \frac{\Delta h_s}{h_s}\right),$$

Microscopic calculation

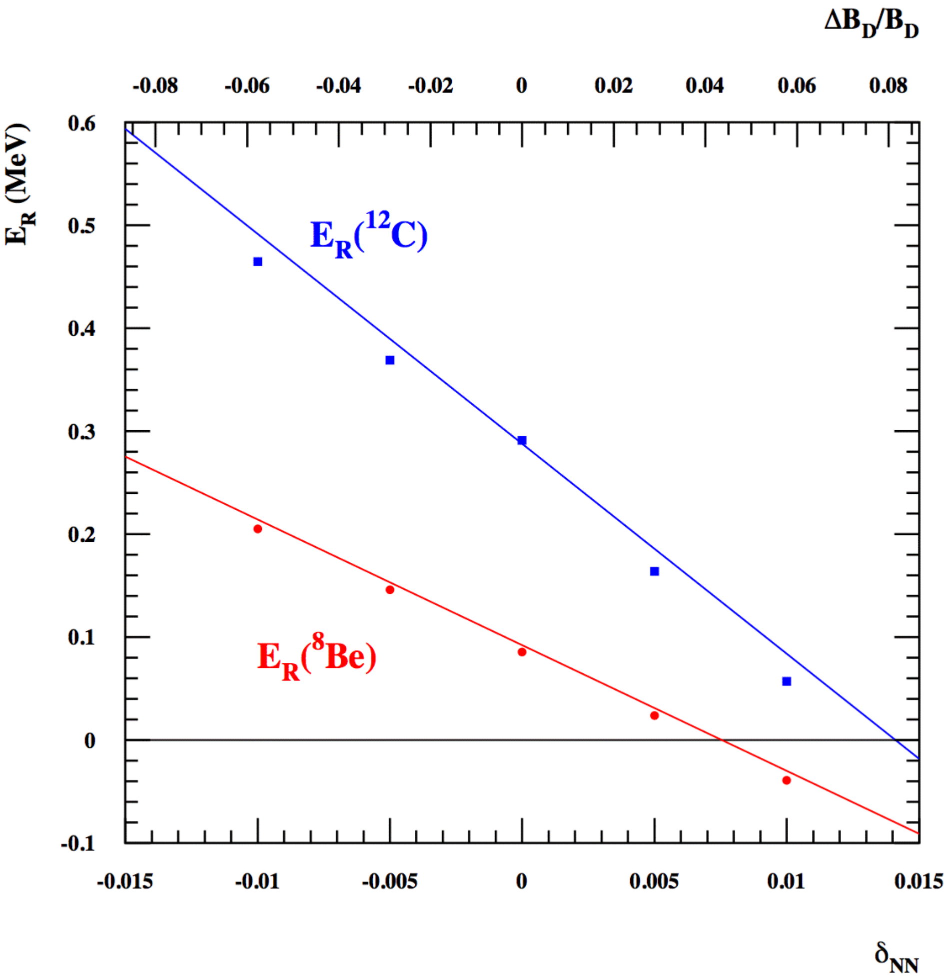
$$\Delta B_D / B_D = 5.716 \times \delta_{NN}.$$

$$E_R(^8\mathrm{Be}) = (0.09184 - 12.208 \times \delta_{NN})\ \mathrm{MeV}$$

$$E_R(^{12}\mathrm{C}) = (0.2876 - 20.412 \times \delta_{NN})\ \mathrm{MeV}$$

Note:

- $\delta_{NN} > 7.52\mathrm{x}10^{-3}$, Be8 becomes stable
- $\delta_{NN} > 0.15$, dineutron is stable
- $\delta_{NN} > 0.35$, diproton is stable
- effect of α is subdominant



❑ Link to fundamental couplings through B_D or δ_{NN}

Primordial CNO production

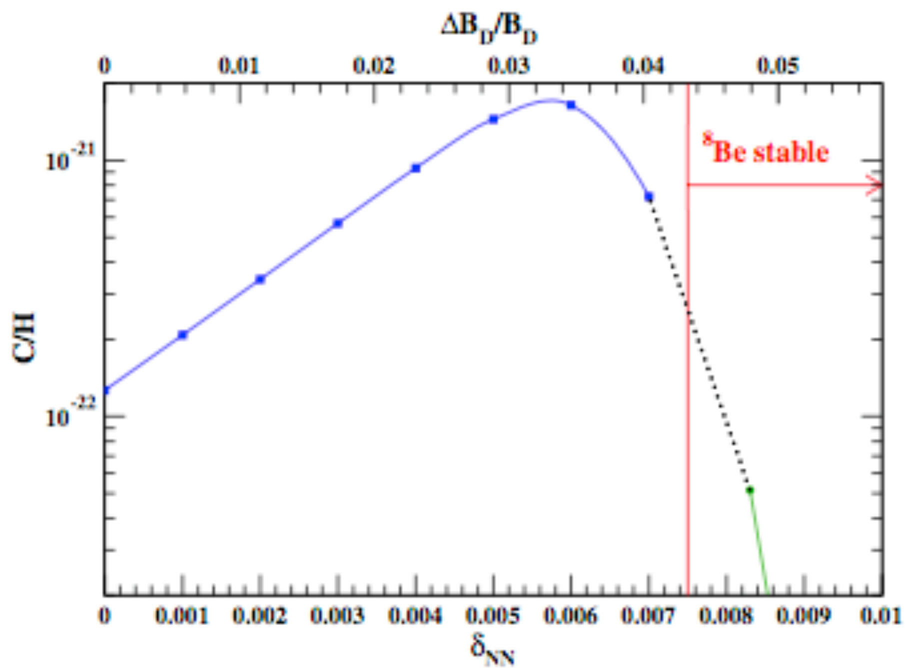
Primordial CNO may affect dynamics of Pop III if CNO/H>10^{-12}-10^{-10}

In standard BBN CNO/H=(0.2-3)10^{-15} [Iocco et al (2007); Coc et al. (1012)].
It proceeds as

$^{7}Li(\alpha,\gamma)^{11}B$ $\quad$ $^{7}Li(n,\gamma)^{8}Li(\alpha,n)^{11}B$ $\quad$ $^{11}B(p,\gamma)^{12}C$ $\quad$ $^{11}B(d,n)^{12}C$, $\quad$ $^{11}B(d,p)^{12}B$ $\quad$ $^{11}B(n,\gamma)^{12}B$

which bridge the gap between A=7 and A=12.

Just consider the 3α-reactions: *6 orders of magnitude below SBBN.*



Effect on He-5 and Li-5 were also studied.

Stable A=5 & A=8 do not affect the standard BBN abundances

Constraints

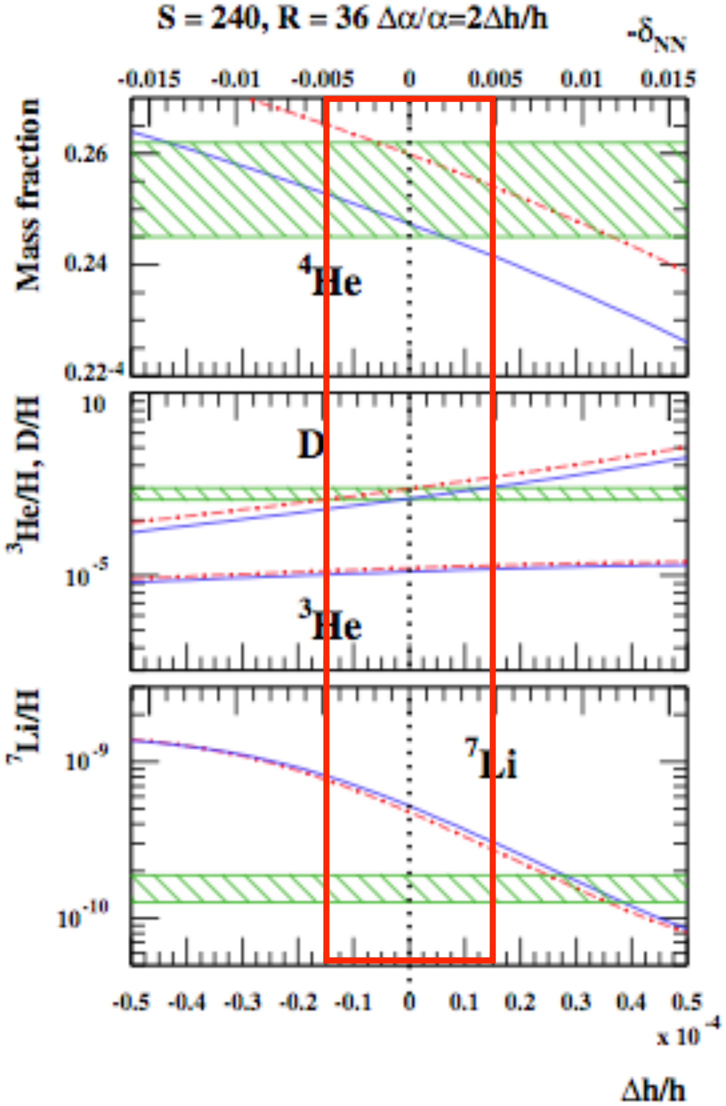


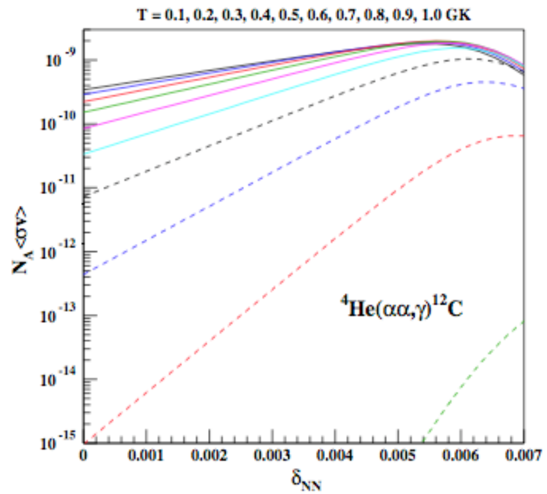
FIG. 12 (color online). Update Fig. 4 of Ref. [22] assuming $S = 240$ and $R = 36$ (solid blue line), using new rates for ^{3}He$(\alpha, \gamma)^7$Li [73] and ^{1}H(n, γ)D [74] and the Ω_b value from WMAP7 [4]. The top axis is $-\delta_{NN}$ from Eq. (5.8) (mind the sign) and the dashed red line assumes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

BBN / Pop III

In the temperature range 0.1 GK -1 GK, the baryon density during BBN changes from 0.1 to 10^{-5} g/cm^3.

-Variation of the reaction rates is limited at higher T

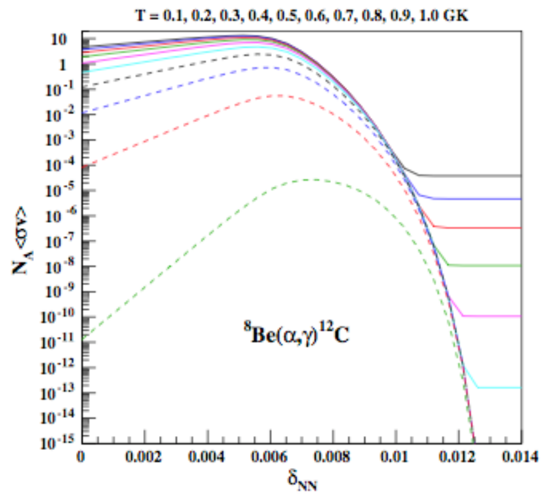
-3-body reactions are less efficient



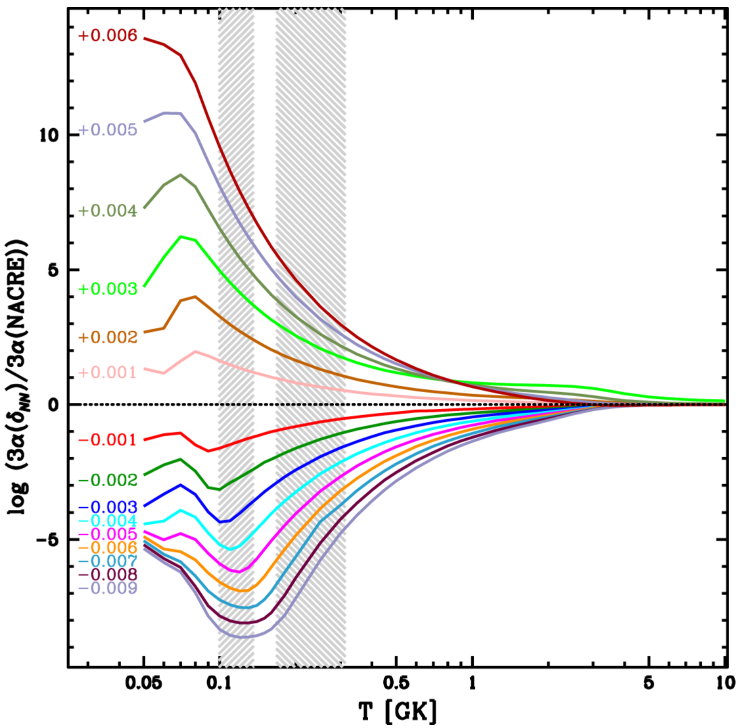
In population III stars, the situation is however different:

- density varies between 30 to 3000 g/cm^3,

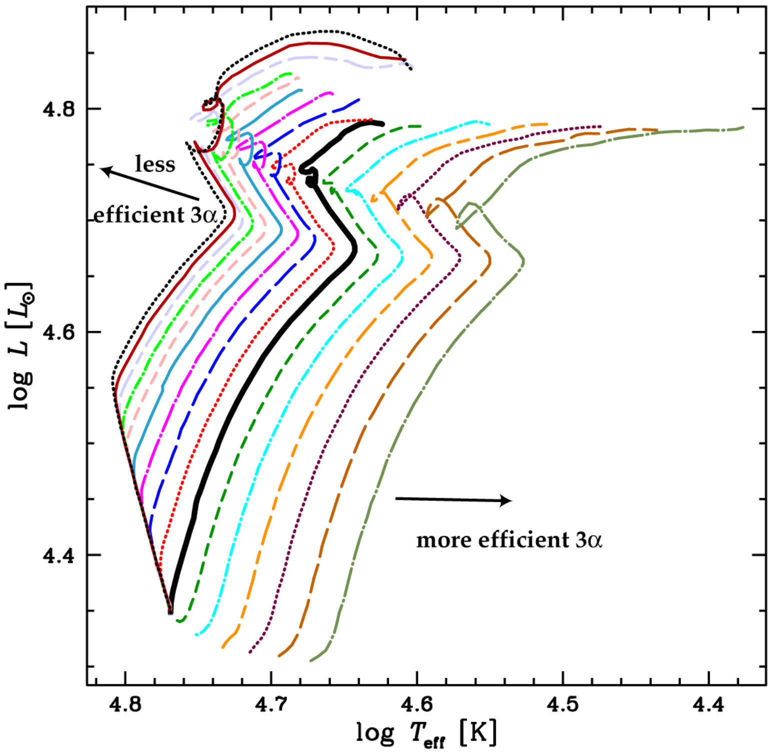
- 3α occurs during the helium burning phase, without significant sources of Li-7, D, p, n so that the 2-body « route » is not effective.



Effects on the stellar evolution



3α-reaction rate

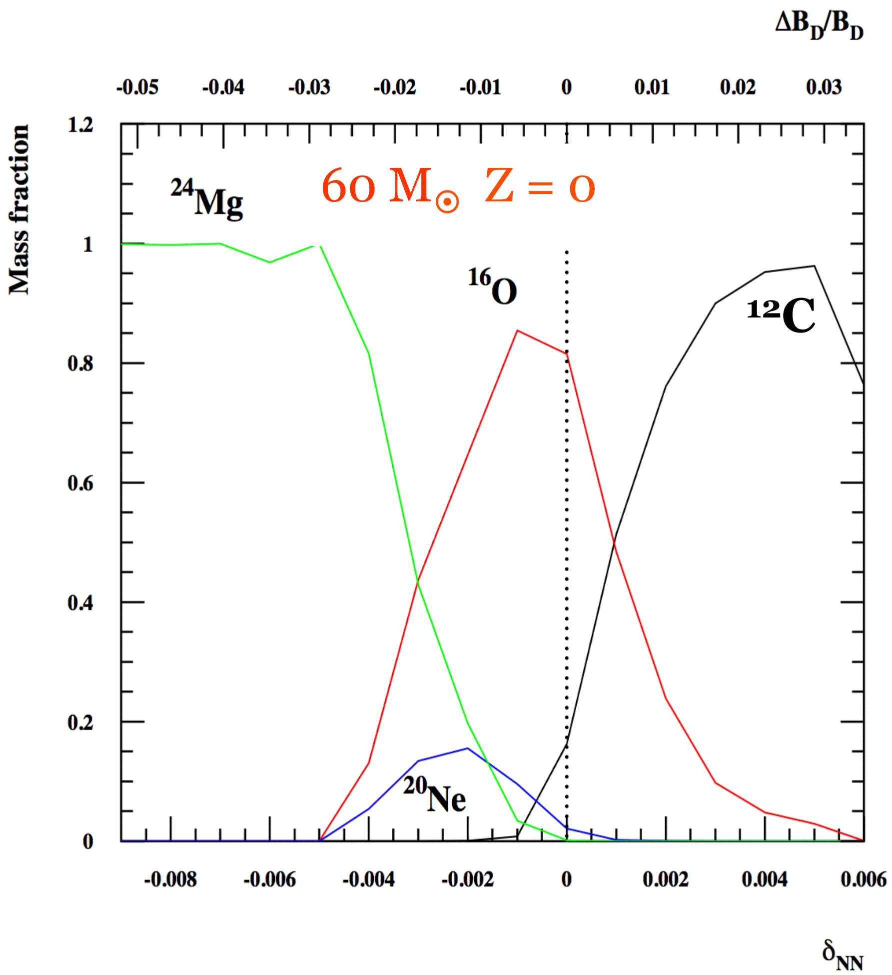


60 $M_\odot$ stars/ Z=0

Composition at the end ofcore 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(α,γ)^{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(α,γ)^{16}O(α,γ)^{20}Ne(α,γ)^{24}Mg transforms ^{12}C into ^{24}Mg
- **The ^{12}C region:** The 3α is faster than ^{12}C(α,γ)^{16}O and ^{12}C is not transformed into ^{16}O

Constraint

^{12}C/^{16}O ~1 ⇒ -0.0005 < δ_{NN} < 0.0015

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

Conclusions

The effect of the variation of fundamental constants on the nuclear physics processes needed to infer BBN predictions & describe the evolution of Pop . III stars have been modelled.

Constraints on the variation of the nuclear interaction

It can be related to fundamental constants (via Deuterium)

Stable A=5 & A=8 does not affect primordial CNO predictions

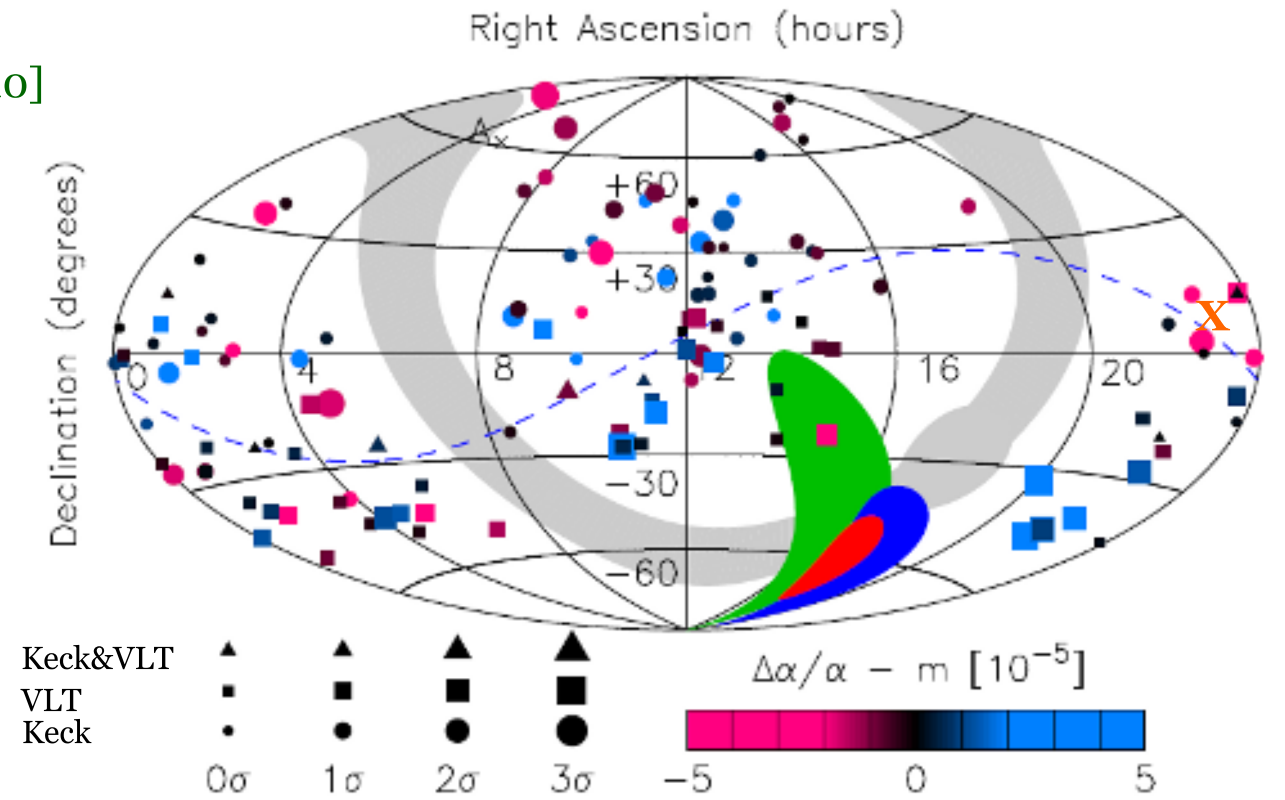
Evolution of Pop. III stars can be significantly affected

The tuning required to get C/O or order 1 is 1/1000 (Hoyle fine tuning)

Spatial variation

Spatial variation?

[Webb et al., 2010]



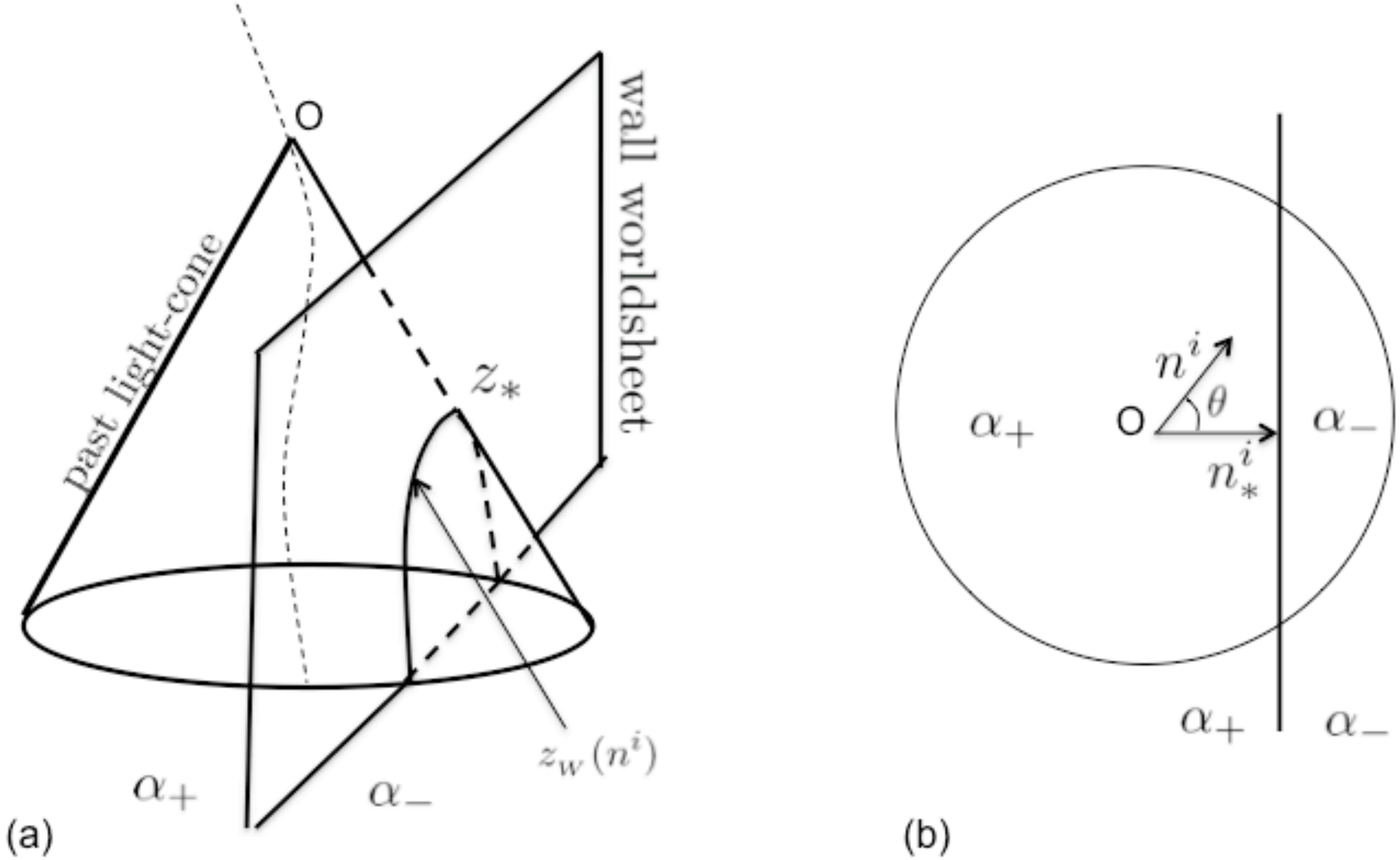
Claim: Dipole in the fine structure constant [« Australian dipole »]

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

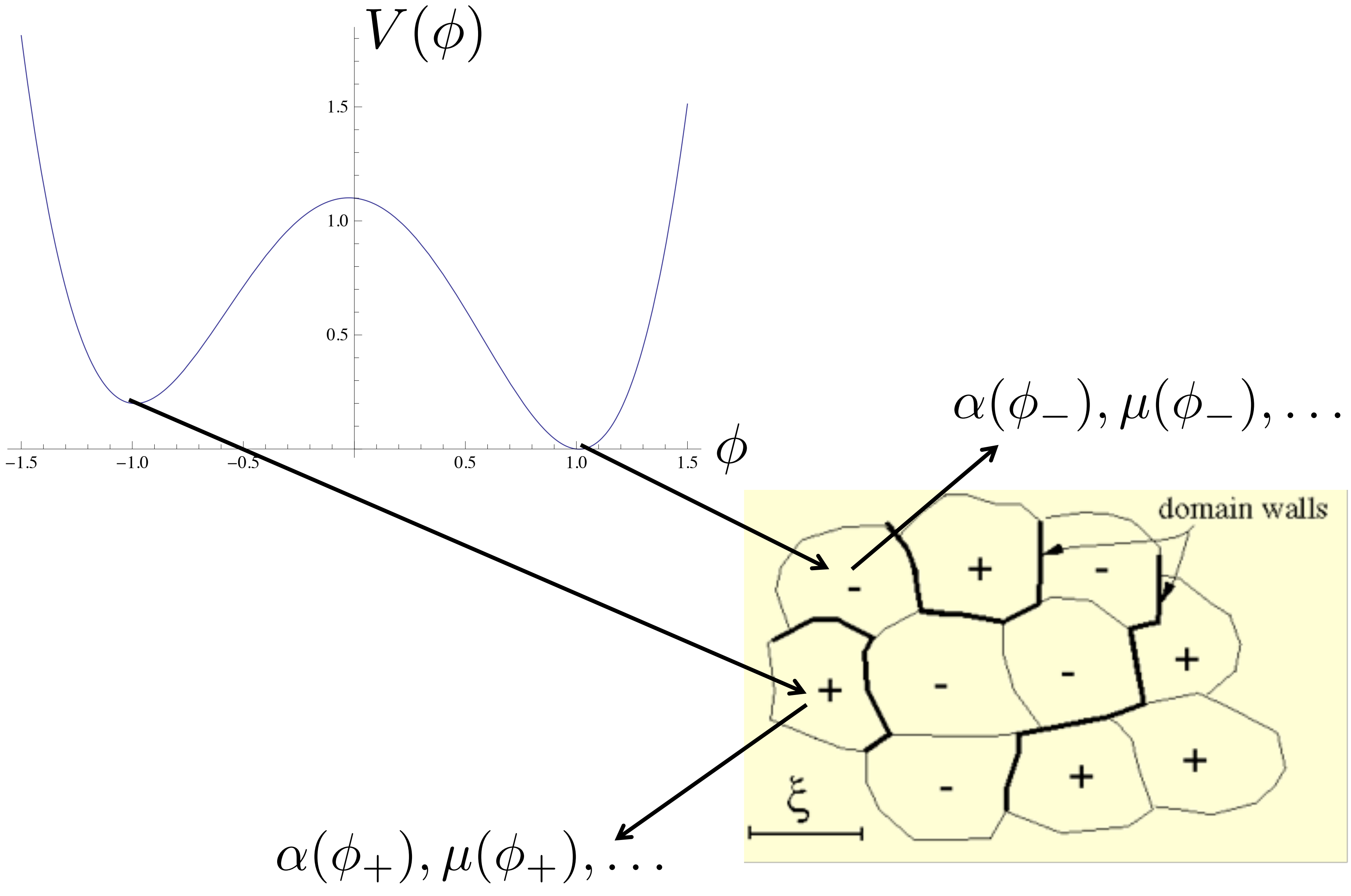
A possible theoretical model

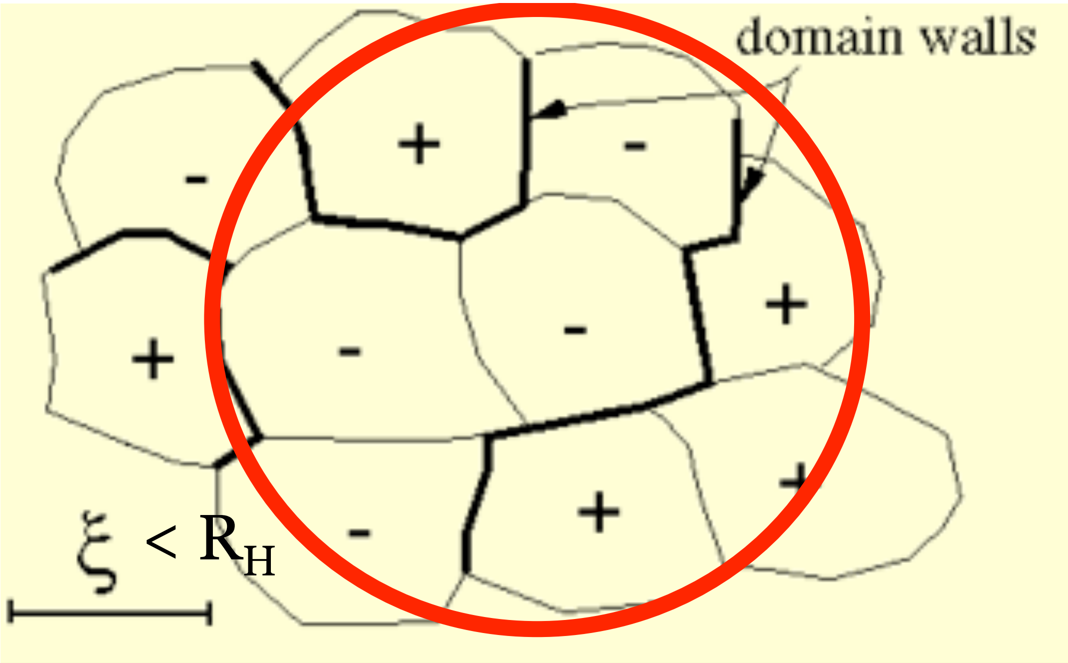
[Olive, Peloso, JPU, 2010]

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

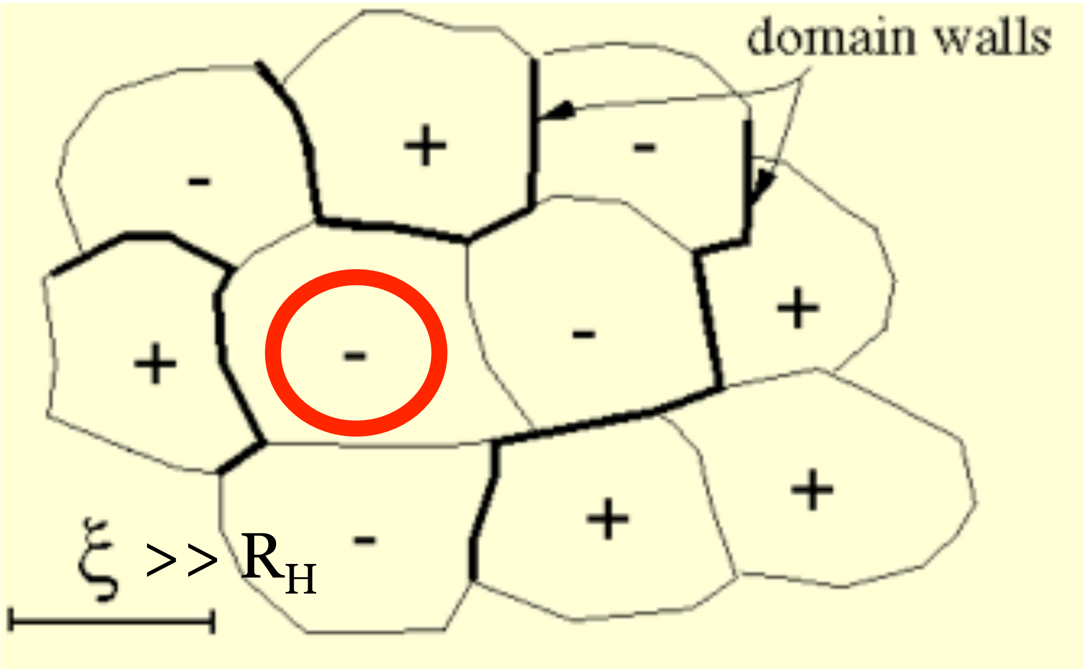


Spatial distribution of the constants





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]

Spatial variation on CMB

If one assumes that some constants have a dipolar variation

$$c_a(\boldsymbol{n}, z) = c_{0a}(z) + \sum_{i=-1}^{1} \delta c_a^{(i)}(z) Y_{1i}(\boldsymbol{n}).$$

then the CMB temperature can be expanded as

$$\begin{aligned}
\Theta(\boldsymbol{n}) &= \bar{\Theta}[\boldsymbol{n}, c_a(\boldsymbol{n})] \\
&= \bar{\Theta}\left[\boldsymbol{n}, c_{0a} + \sum_{i=-1}^{1} \delta c_a^{(i)}(z) Y_{1i}(\boldsymbol{n})\right] \\
&\simeq \bar{\Theta}[\boldsymbol{n}] + \sum_a \sum_{i=-1}^{+1} \frac{\partial \bar{\Theta}[\boldsymbol{n}]}{\partial c_a} \delta c_a^{(i)}(z) Y_{1i}(\boldsymbol{n})
\end{aligned}$$

The coefficients of the multipolar expansion are thus

$$a_{\ell m} = \bar{a}_{\ell m} + \sqrt{\frac{3}{4\pi}} \sum_a \sum_i \delta c_a^{(i)} (-1)^m \sum_{LM} \frac{\partial \bar{a}_{LM}}{\partial c_a} \times \sqrt{(2\ell+1)(2L+1)} \begin{pmatrix} \ell & L & 1 \\ -m & M & i \end{pmatrix} \begin{pmatrix} \ell & L & 1 \\ 0 & 0 & 0 \end{pmatrix}$$

Spatial variation on CMB

[Prunet, JPU, Brunier, Bernardeau, 2005]

This implies multipole correlations

$$D^{(i)}_{\ell m} \equiv \langle a_{\ell m}\, a^*_{\ell+1 m+i} \rangle = f_i(\ell, m) \sum_a \delta c^{(i)}_a \Gamma^{(a)}_\ell$$

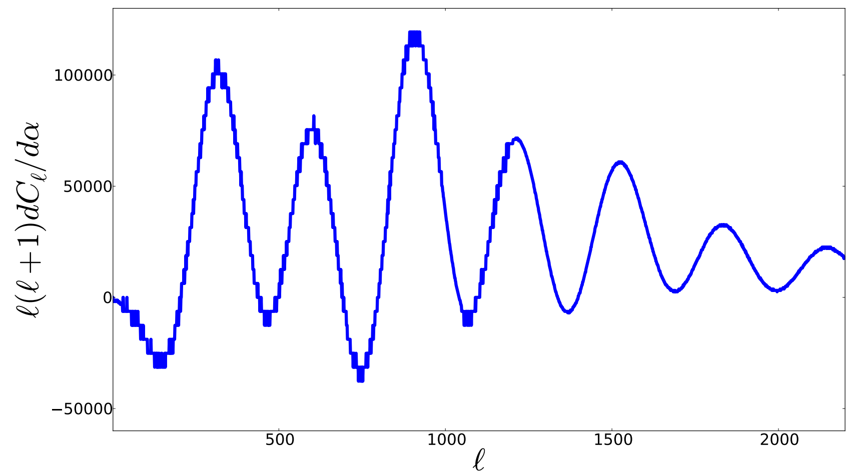
Known functions of l and m

Amplitude of the modulation

$$\Gamma^{(a)}_\ell \equiv \frac{1}{2}\left(\frac{\partial \bar{C}_\ell}{\partial c_a} + \frac{\partial \bar{C}_{\ell+1}}{\partial c_a}\right)$$

$$f_0(\ell, m) = \sqrt{\frac{3}{4\pi}} \frac{\sqrt{(\ell+1)^2 - m^2}}{\sqrt{(2\ell+1)(2\ell+3)}}$$

$$f_1(\ell, m) = \sqrt{\frac{3}{8\pi}} \sqrt{\frac{(\ell+2+m)(\ell+1+m)}{(2\ell+1)(2\ell+3)}}$$

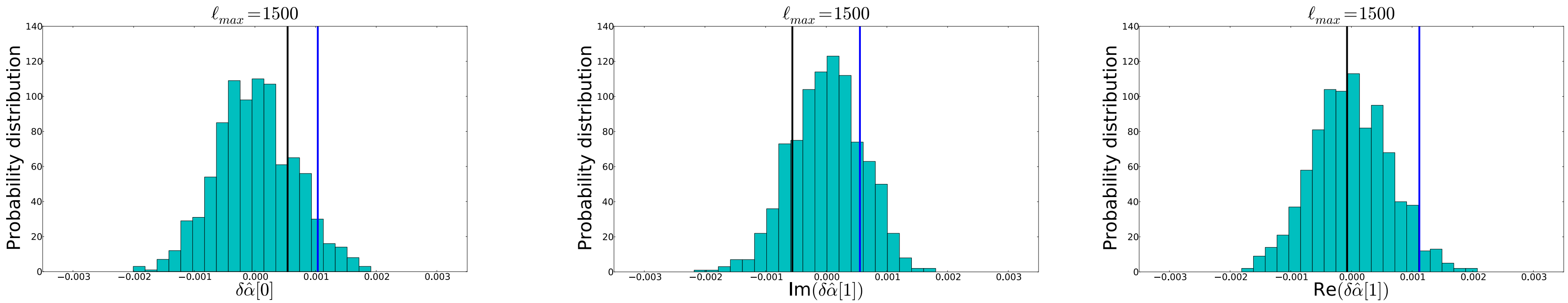


Analysis of *Planck* data

This allows to design an estimator of the D_{lm} [prunet et al (2005); Hansen-Lewis (2009)]

Masking effect also induces l-correlations

Simulations of 10^3 maps with no modulation + Planck masking
Simulation of a CMB with α modulation



Simulated map with $\delta\alpha = 10^{-3}$ / Planck data

The amplitude of a modulation of α is constrained to $\delta\alpha < 6 \times 10^{-4}$ (1σ) at z= 1000
First constraint from the CMB
To be compared with $\delta\alpha/\alpha = (0.97 \pm 0.22) \times 10^{-4}$ (4σ) at z=2 [webb et al. (2011)]

Conclusions and perspective

Conclusions

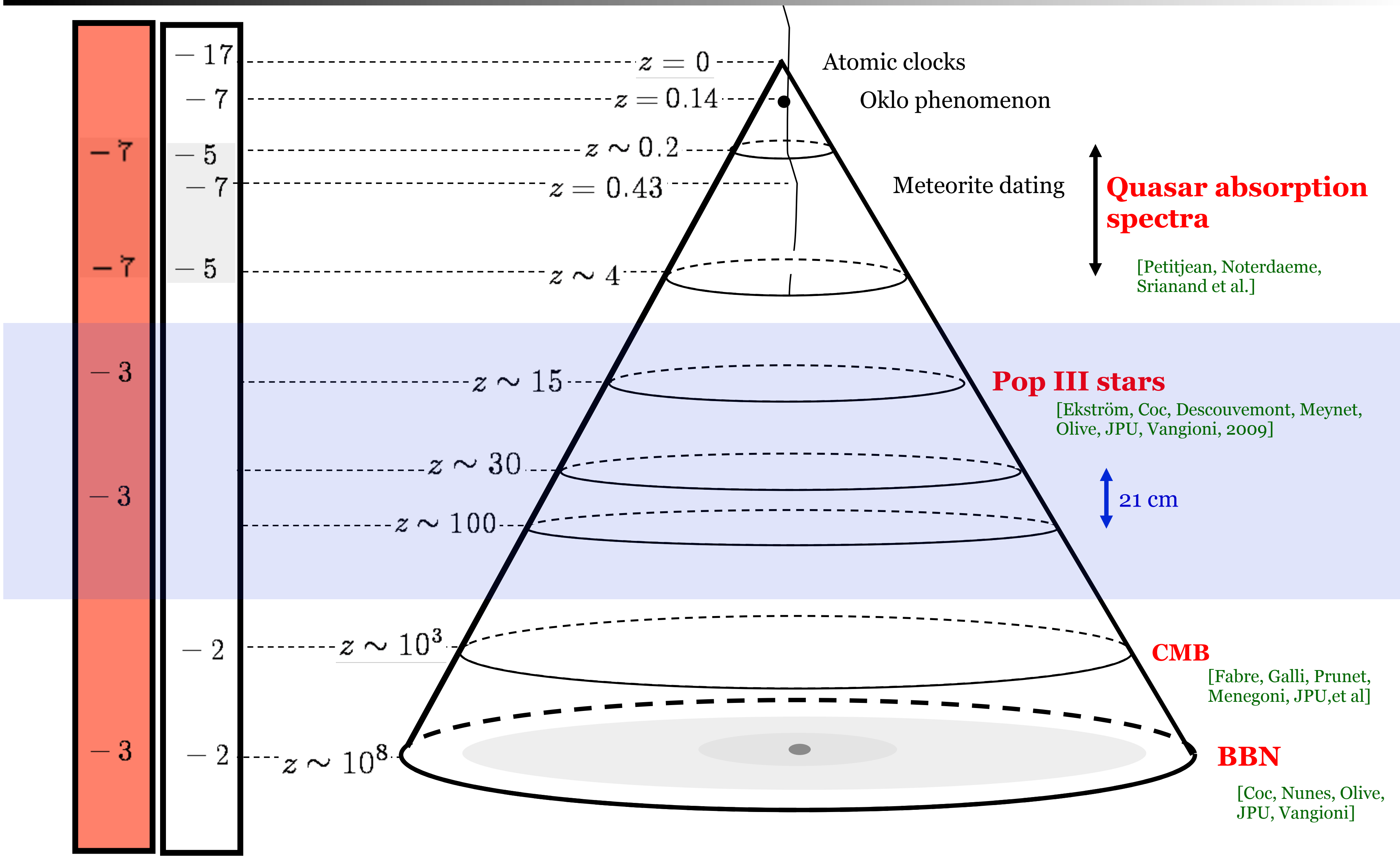
In the past years, we have obtained a series of results concerning the variation of fundamental constants:

- Theoretical modelling of g_p; useful for clock & quasars
- Study of coupled variations in GUT
- First model of pure spatial variations

-CMB
  - improved constraint by a factor 5 compared to WMAP
  - lift the degeneracy between α, m_e and H_o
  - First constraint on spatial variation

- Nuclear physics:
  -BBN: improved constraints; detailed study of A=5 & A=8
  -Pop III stars: fine tuning at 10^{-3} (anthropic)

Physical systems: new and future



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