Test of the equivalence principle and Fundamental constants

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]

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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}

$m_H=(125.3\pm0.6)$GeV

$v=(246.7\pm0.2)$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. »

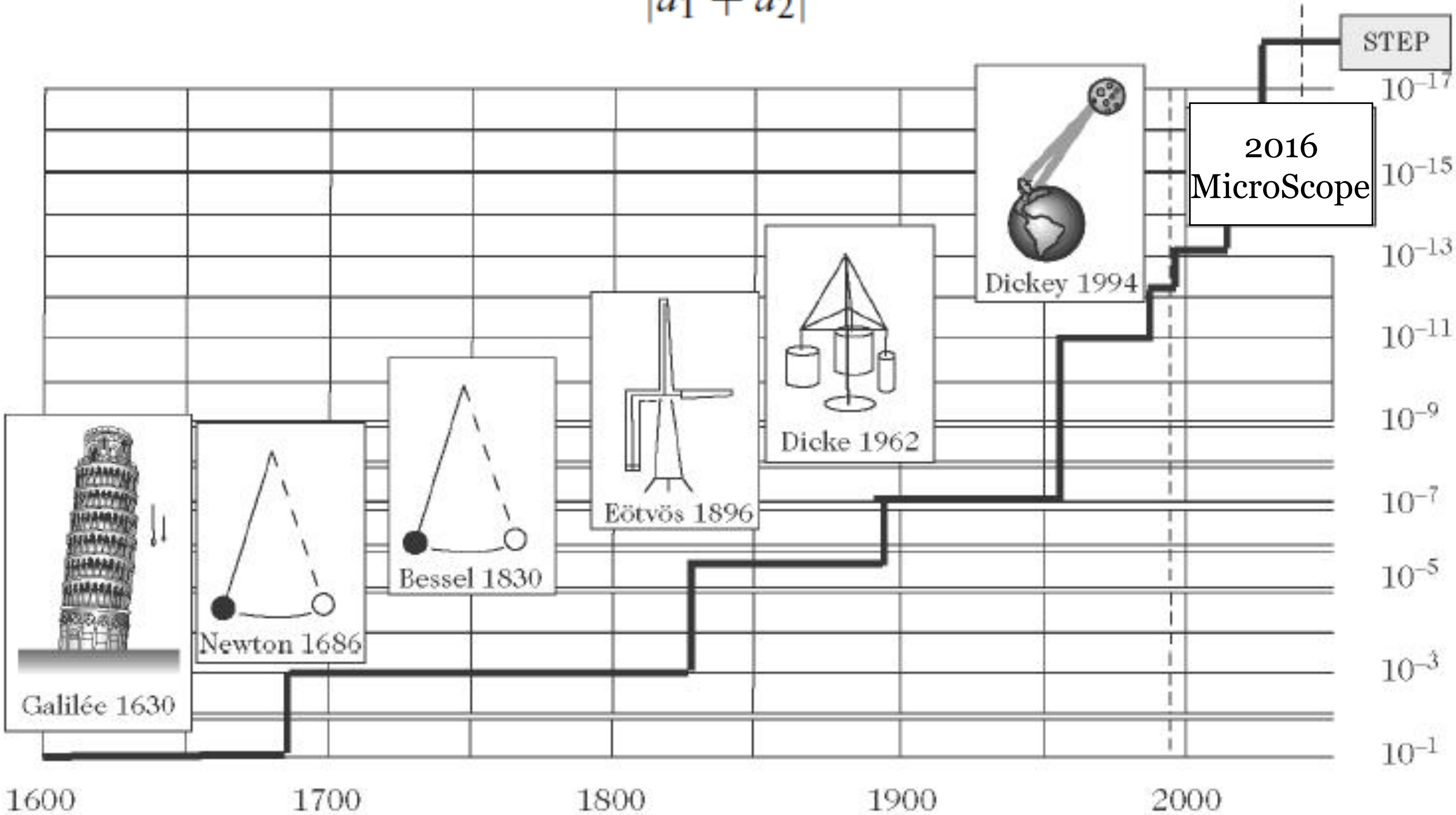
« Cette force est toujours proportionnelle à la quantité de matière des corps, *&* elle ne diffère de ce qu'on appelle l'inertie de la matière que par la manière de la concevoir. »

« 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

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



GR in a nutshell

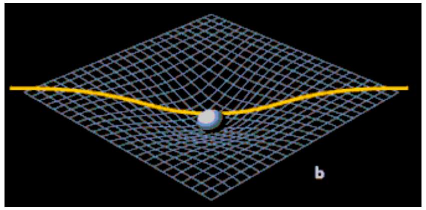
Underlying hypothesis

Equivalence principle

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

Physical metric

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



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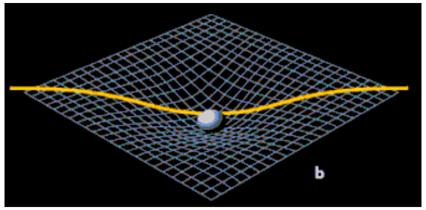


gravitational metric

Dynamics

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

Relativity

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

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

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

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]

Overview

- 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)]

- Variations on BBN

  [with A. Coc, E Vangioni, M. Pospelov (2013-2015)]

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

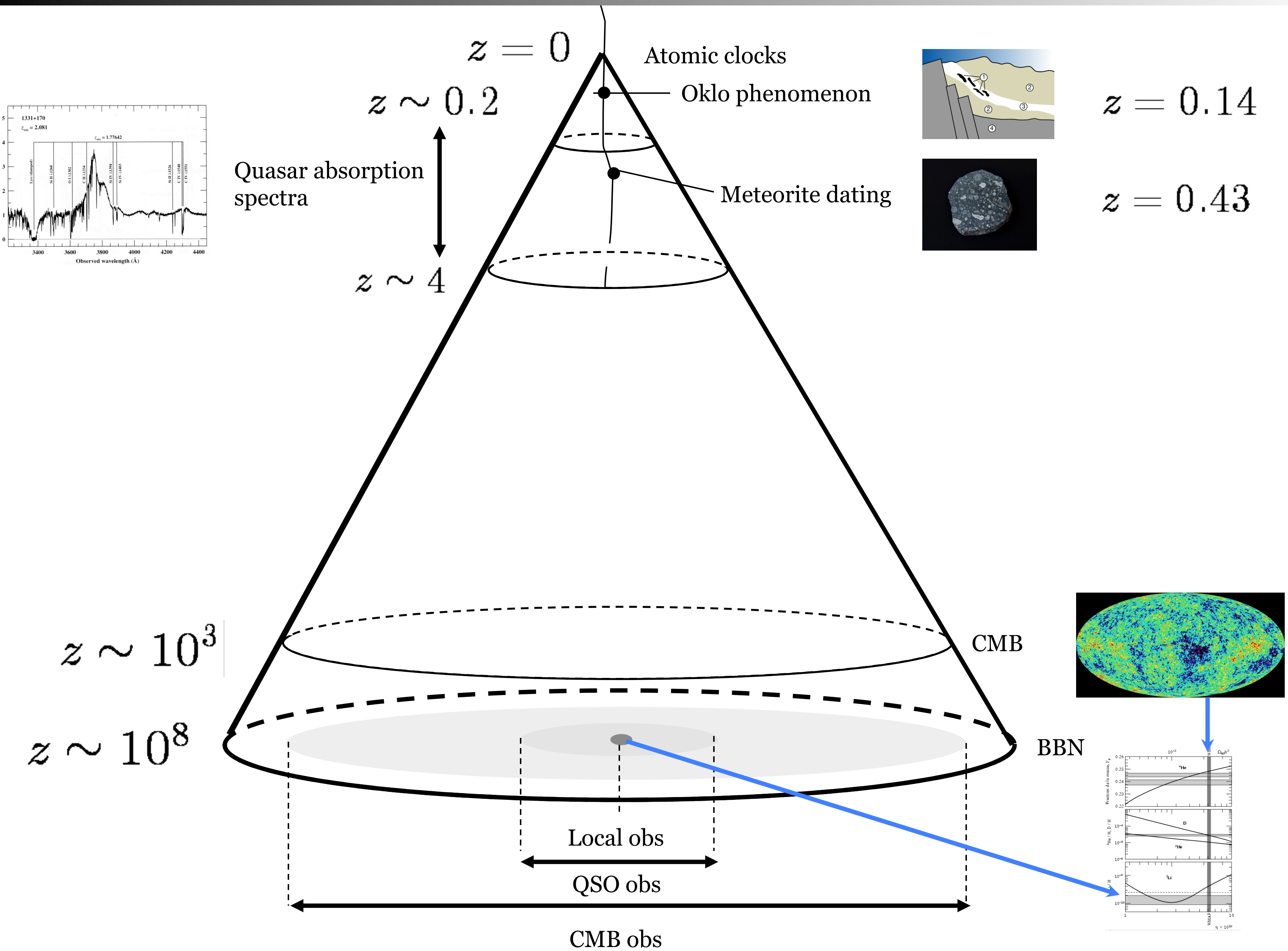
$$\boxed{\kappa_{G_k} = \frac{\partial \ln O}{\partial \ln G_k}}$$

Step 2:

The primary physical parameters are usually not fundamental constants.

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

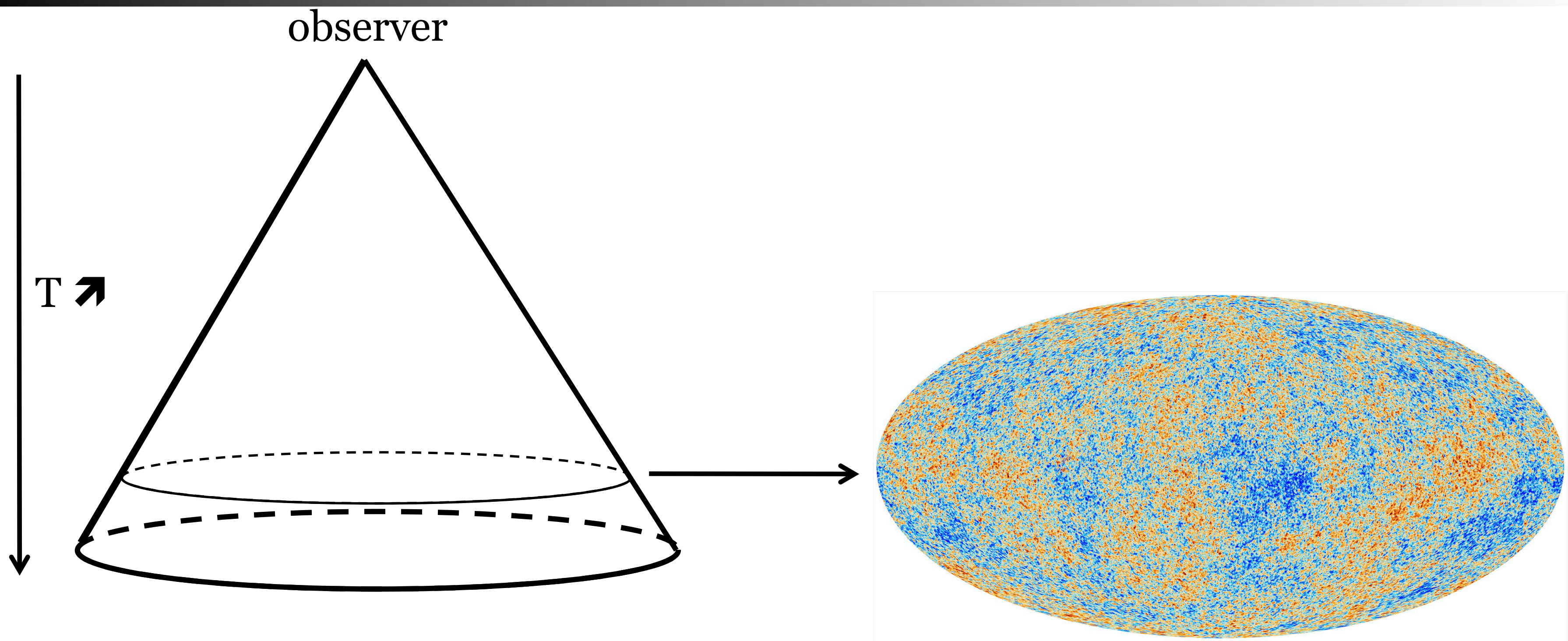
Physical systems



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

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

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

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

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

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

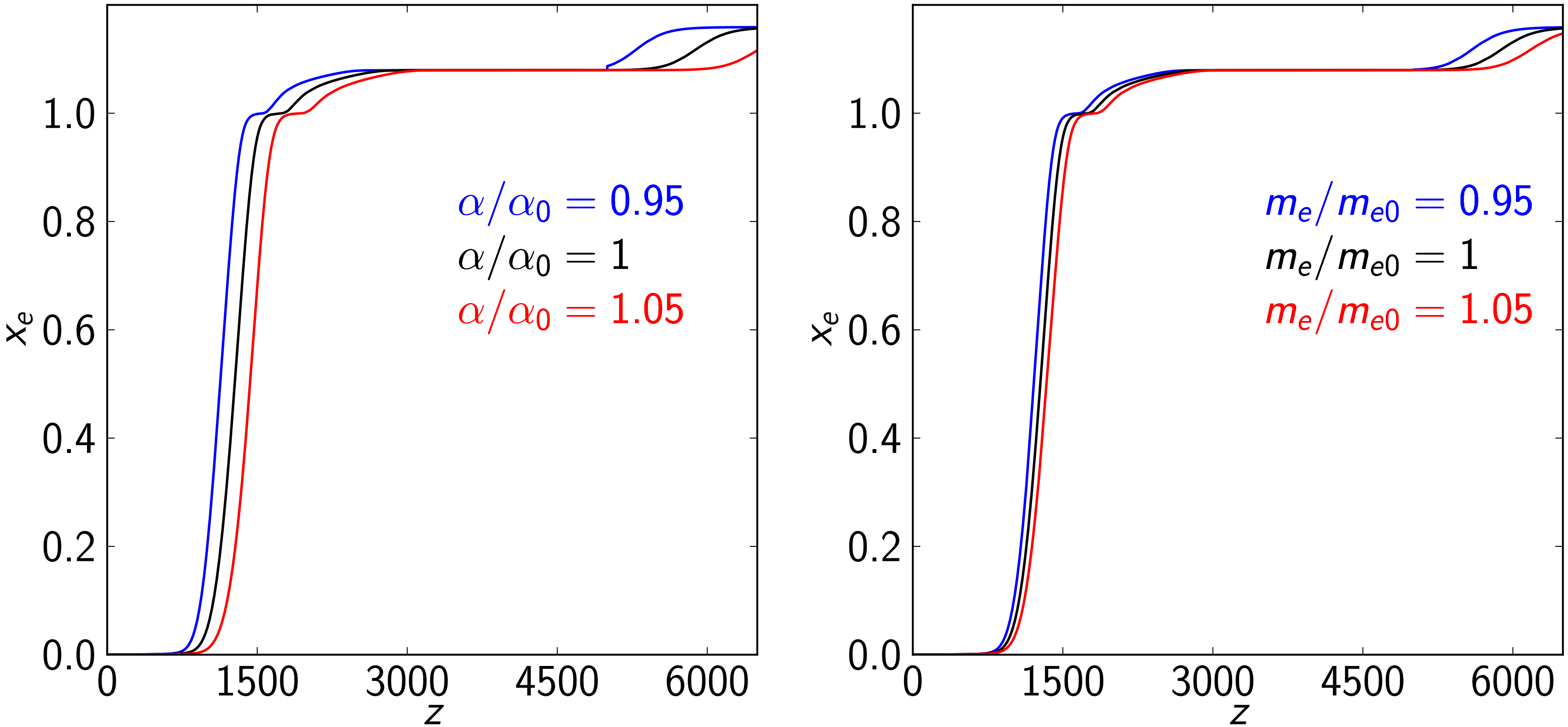
$$\beta_i = \beta_{i0}\left(\frac{\alpha}{\alpha_0}\right)^3$$

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

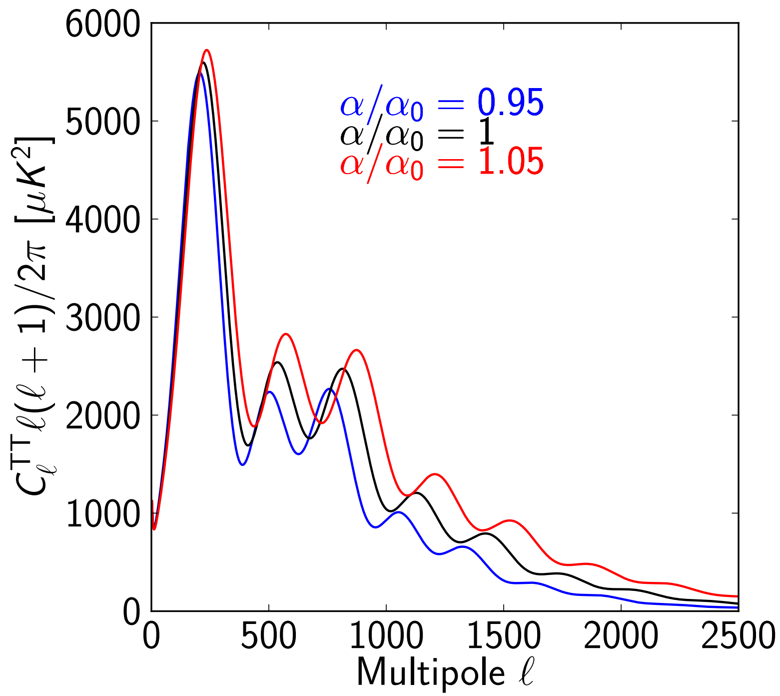
$$A_i = A_{i0}\left(\frac{\alpha}{\alpha_0}\right)^5\left(\frac{m_{\rm e}}{m_{\rm e0}}\right)$$

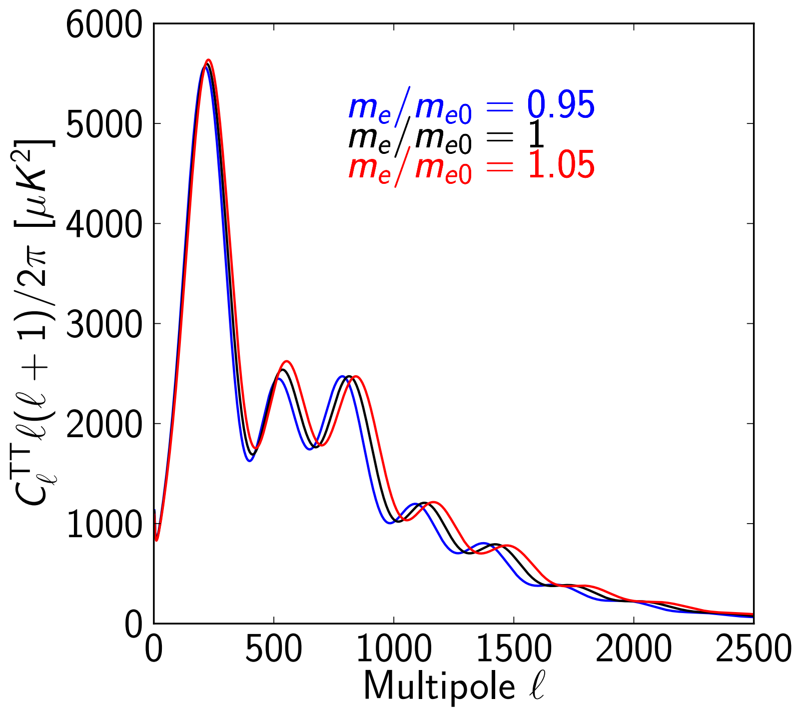
$$\Lambda_i = \Lambda_{i0}\left(\frac{\alpha}{\alpha_0}\right)^8\left(\frac{m_{\rm e}}{m_{\rm e0}}\right)$$

Dependence on the constants



Effect on the temperature power spectrum

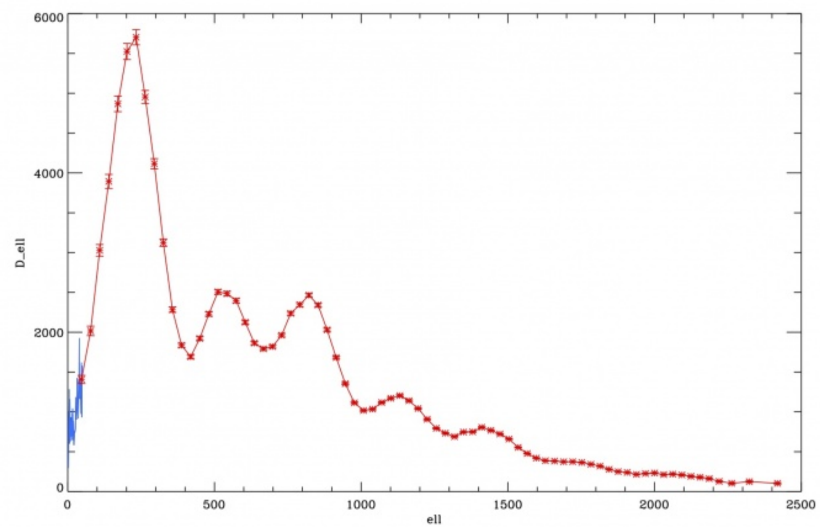




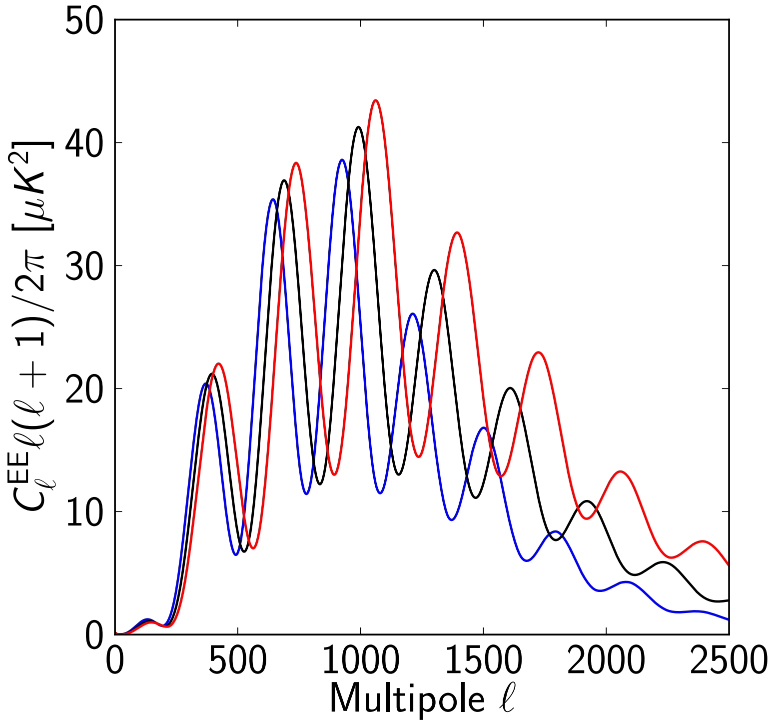
Increase of α induces
- an earlier decoupling
- smaller sound horizon
- shift of the peaks to higher multipoles

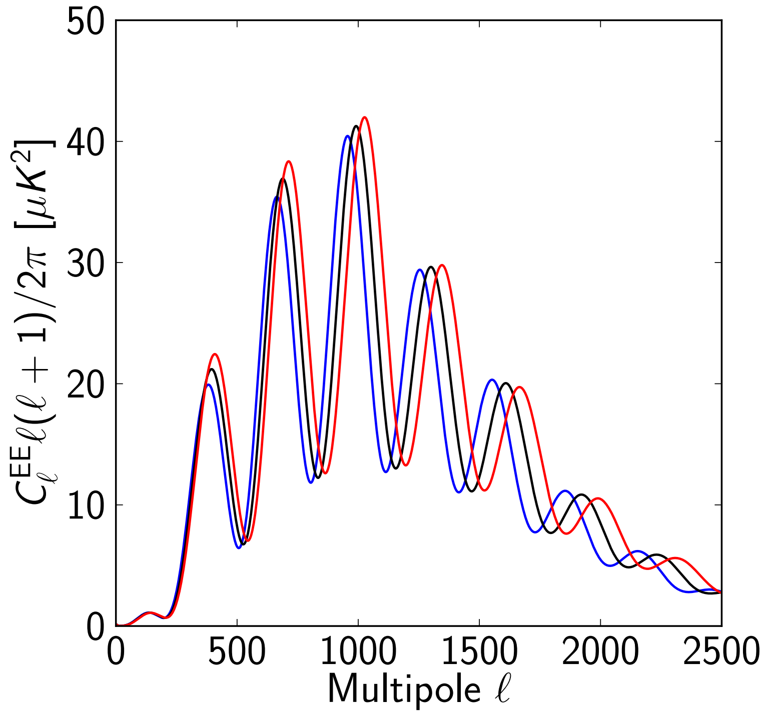
- an increase of amplitude of large scale (early ISW)
- an increase of amplitude at small scales (Silk damping)

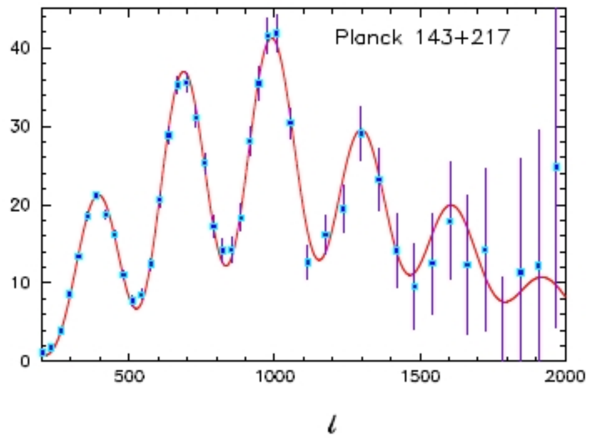
$$\lambda_D^2 = \frac{1}{6}\int_0^{\eta_{dec}} \frac{d\eta}{\sigma_T n_e a}\left[\frac{R^2 + \frac{16}{15}(1+R)}{(1+R)^2}\right] \propto \frac{1}{\sigma_T} \propto \frac{1}{\alpha^2 m_e^{-2}}$$



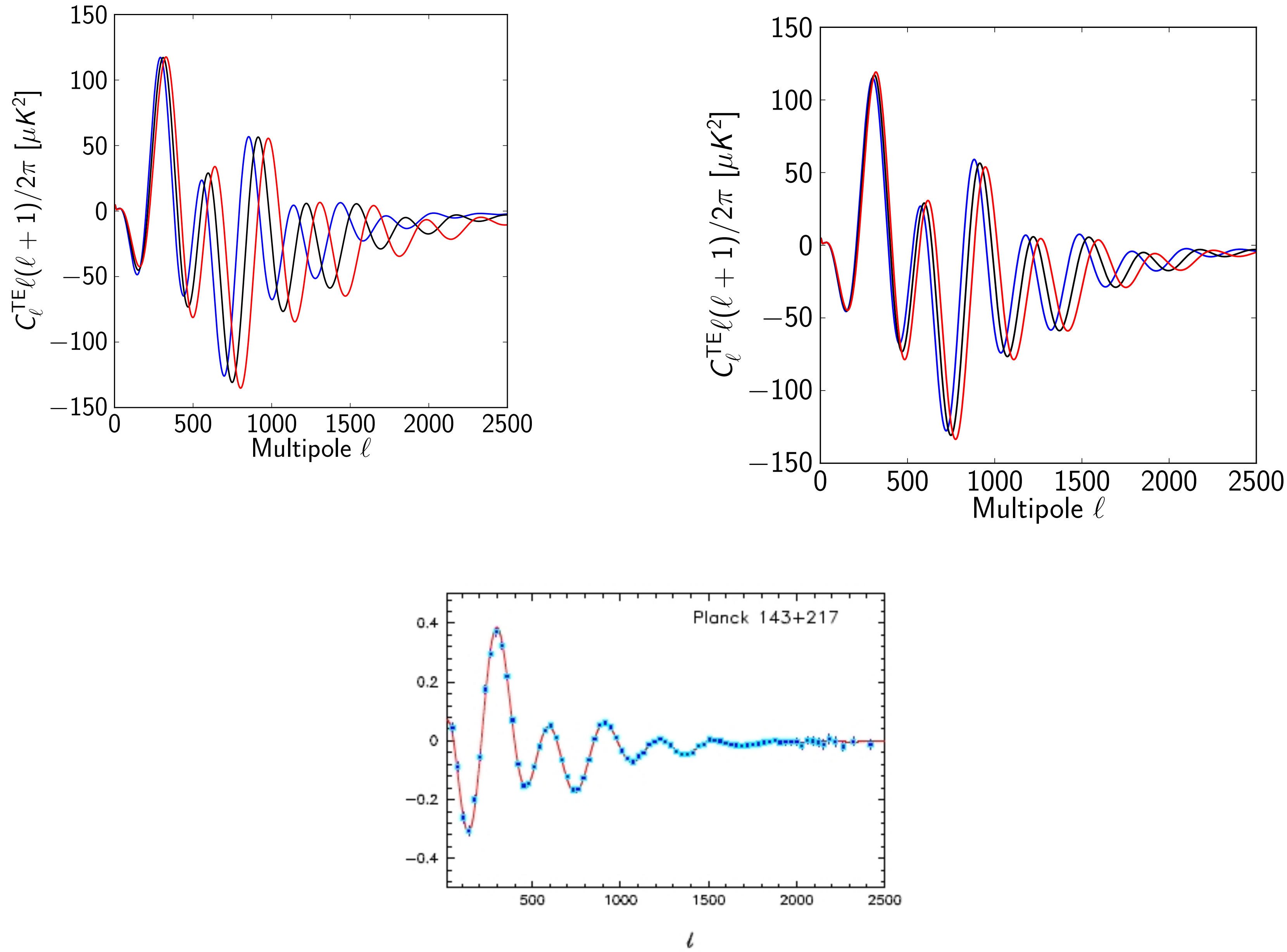
Effect on the polarization power spctrum



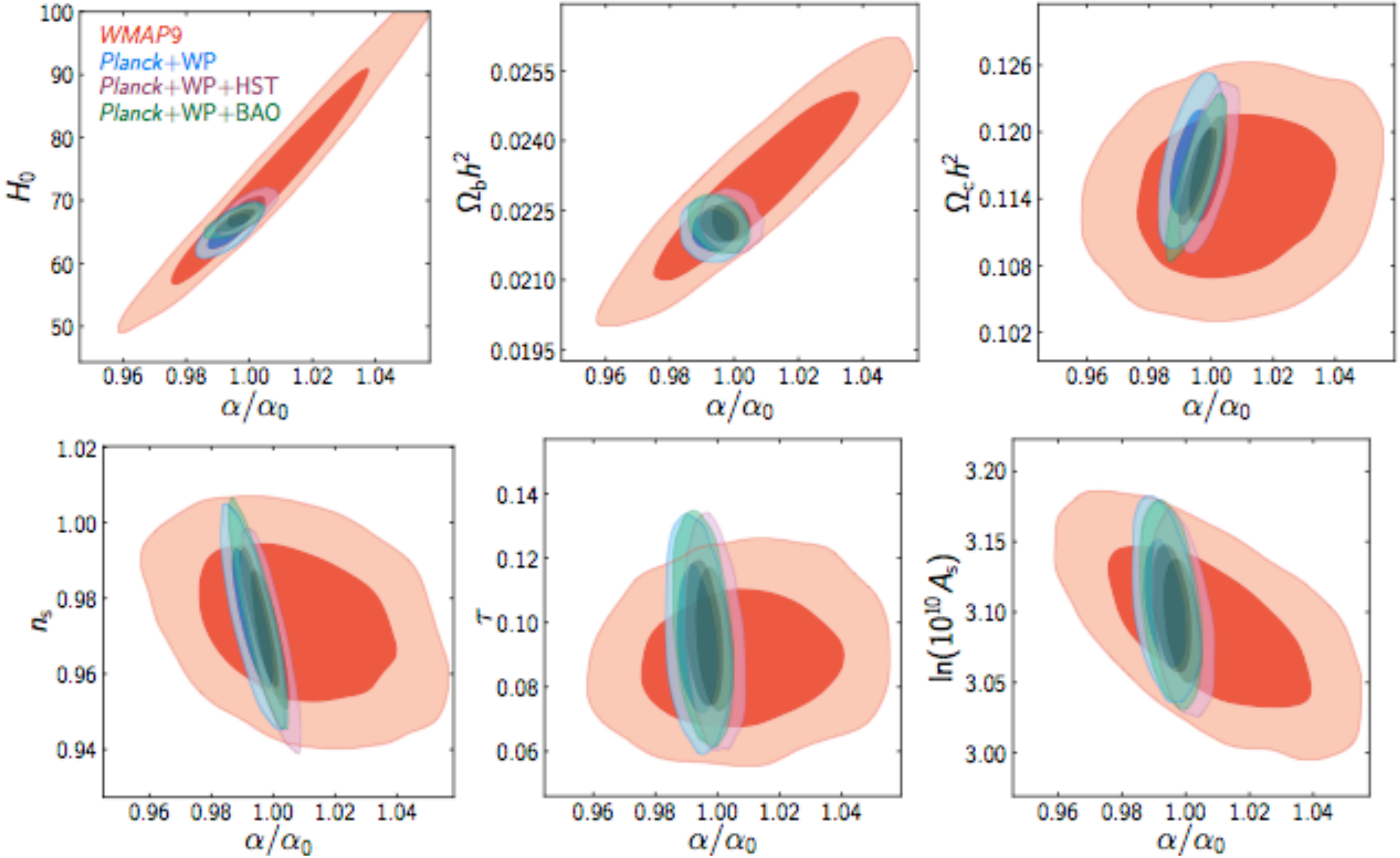




Effect on the cross-correlation

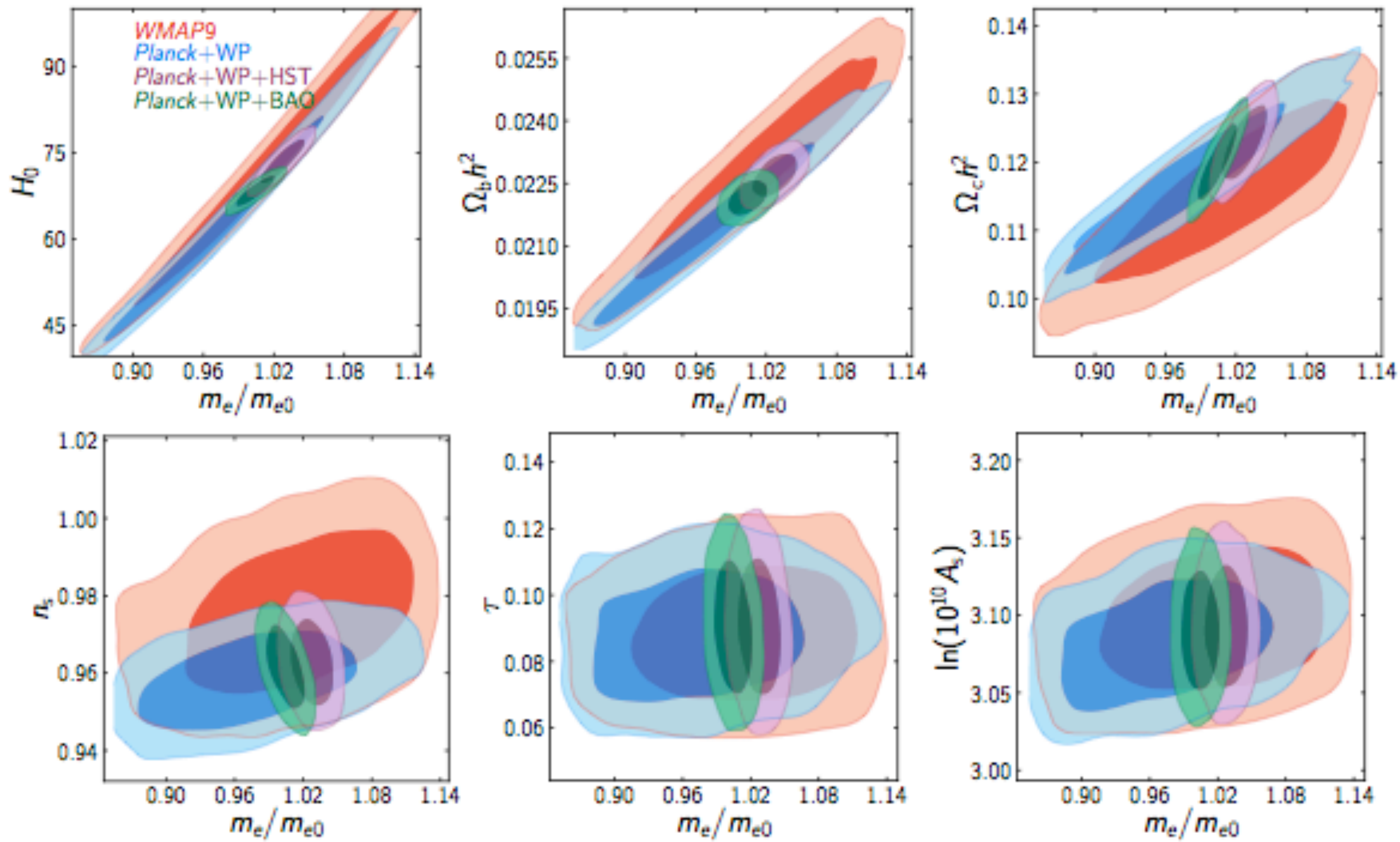


Varying α alone



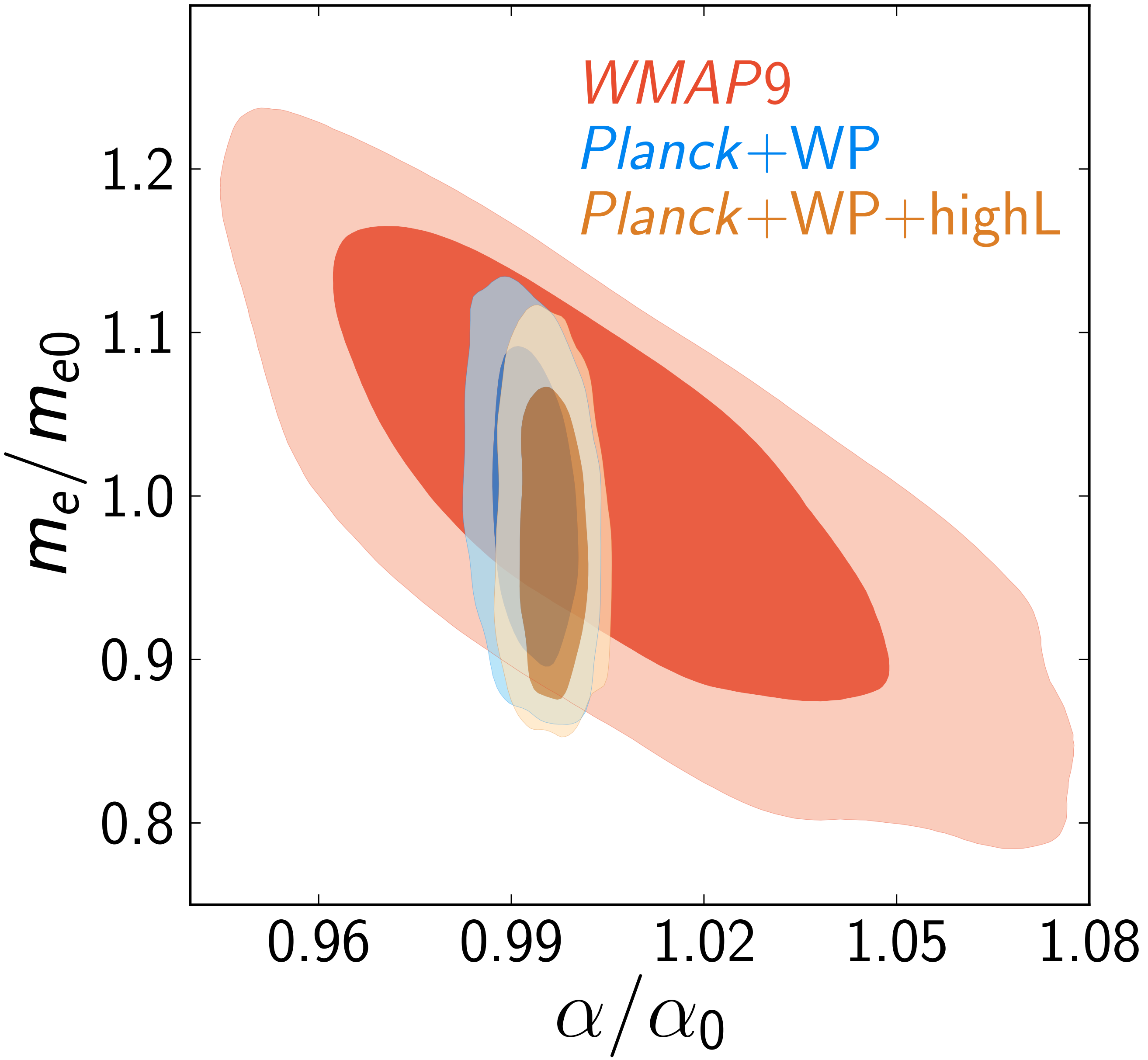
$\{\omega_b, \omega_c, H_0, \tau, n_s, A_s, \alpha \text{ or } m_e\}$

Varying m_e alone

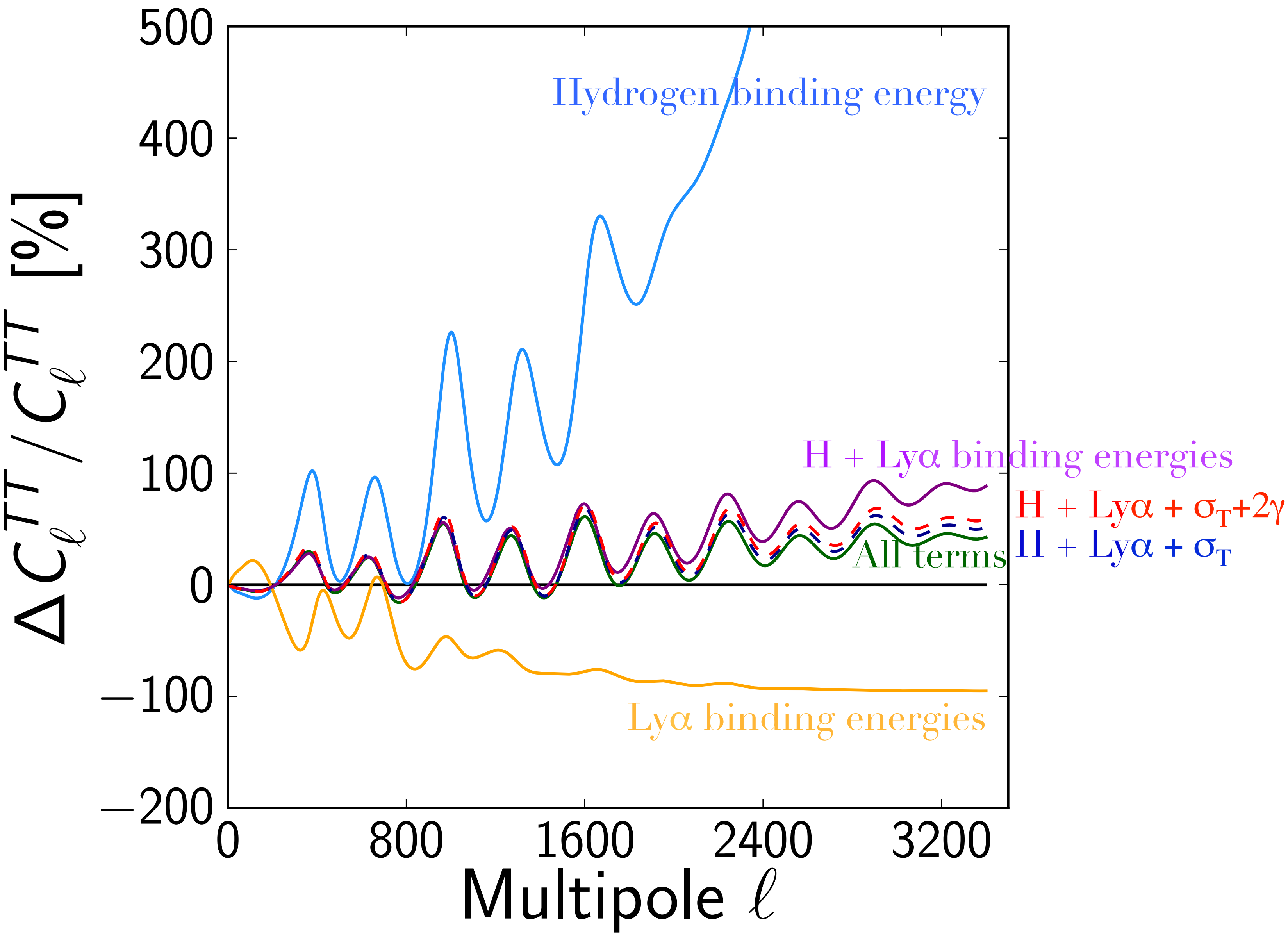


$\{\omega_b, \omega_c, H_0, \tau, n_s, A_s, \alpha \text{ or } m_e\}$

(α, m_e)-degeneracy



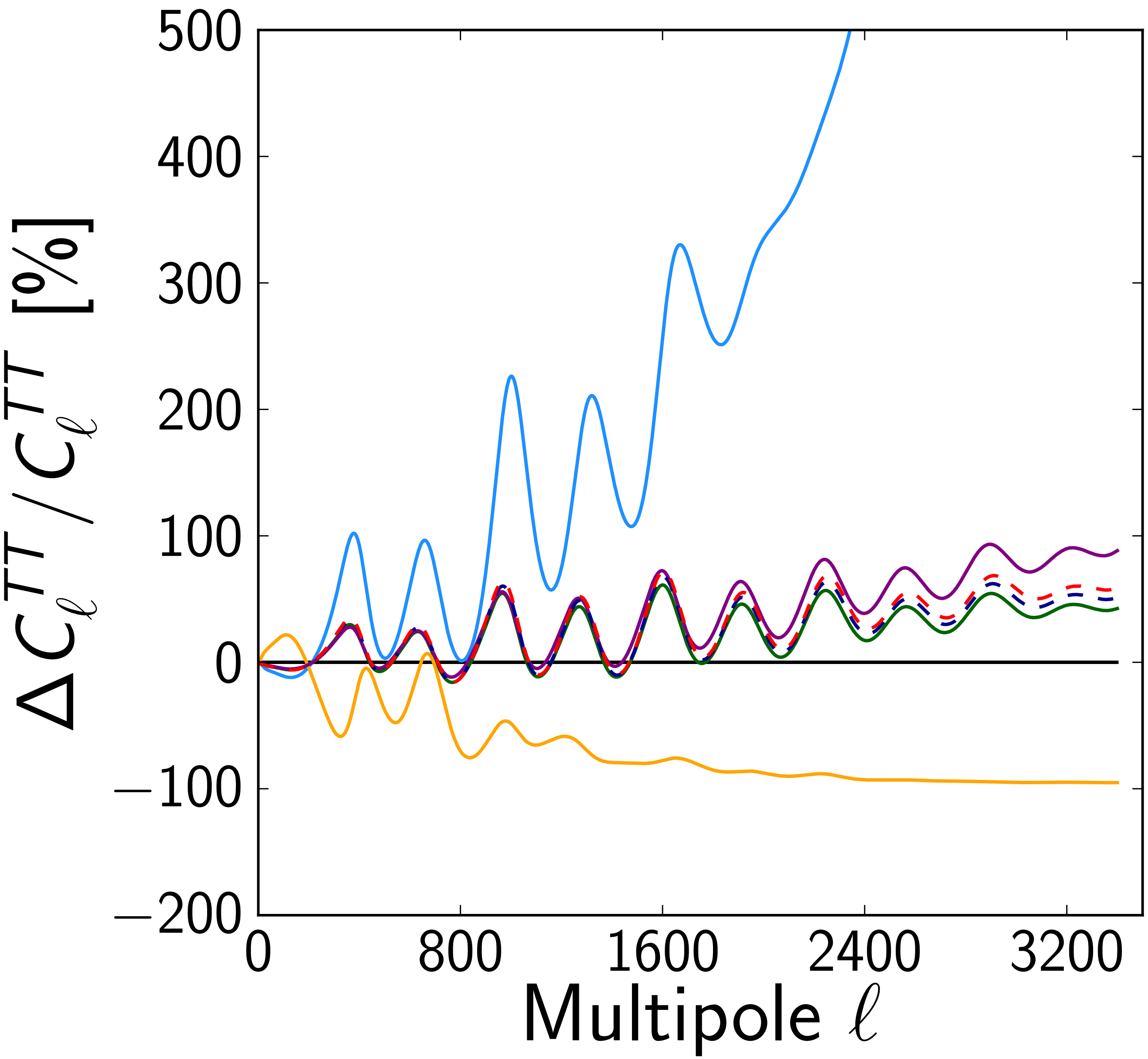
Why *Planck* does better



Why Planck does better

$\delta\alpha$ = 5%
δm_e=10.025%

$\alpha^2 m_e$ identical



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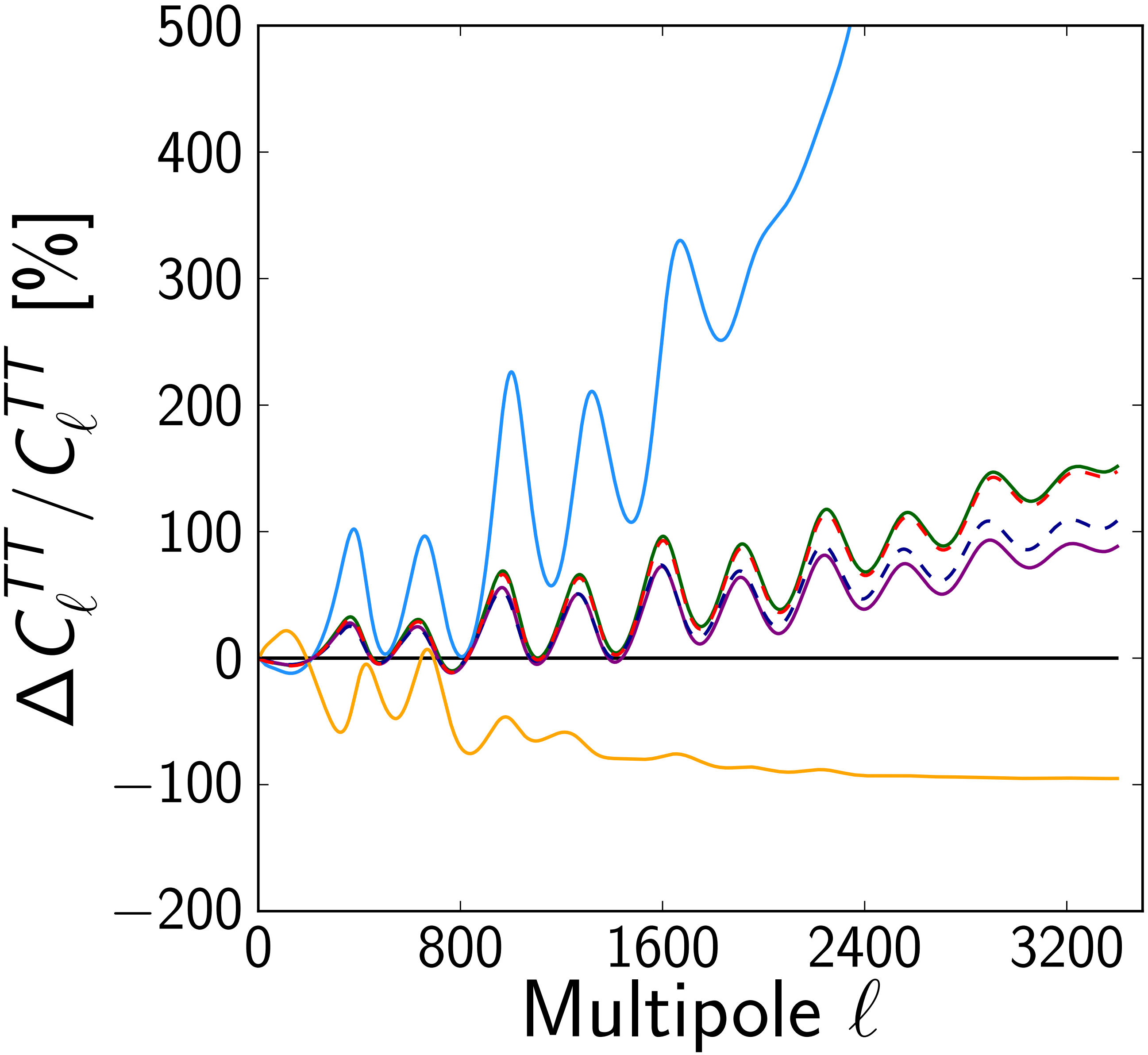
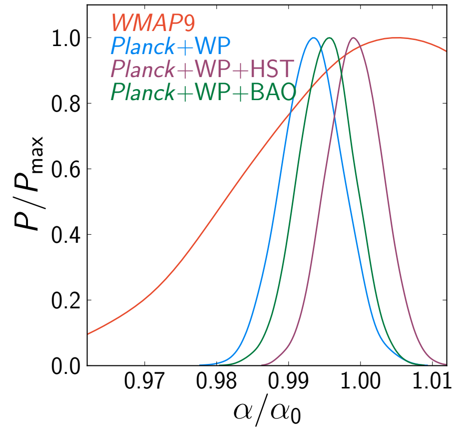


In conclusion

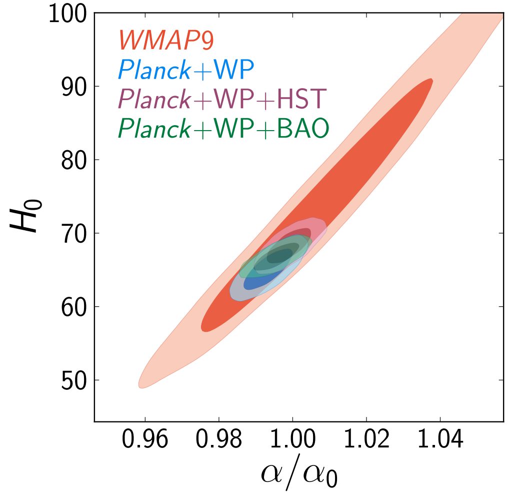
Independent variations of α and m_e are constrained to be

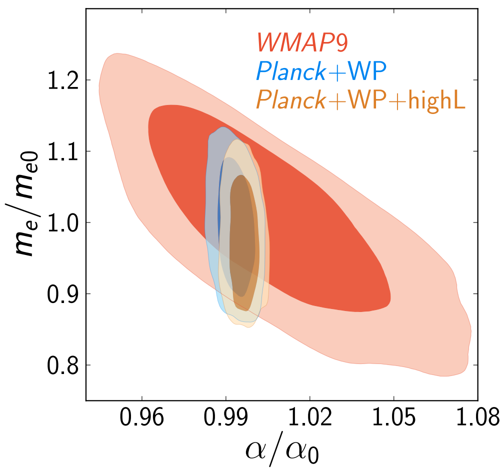
$\Delta\alpha/\alpha=(3.6\pm3.7)\times10^{-3}$ $\Delta m_e/m_e=(4\pm11)\times10^{-3}$

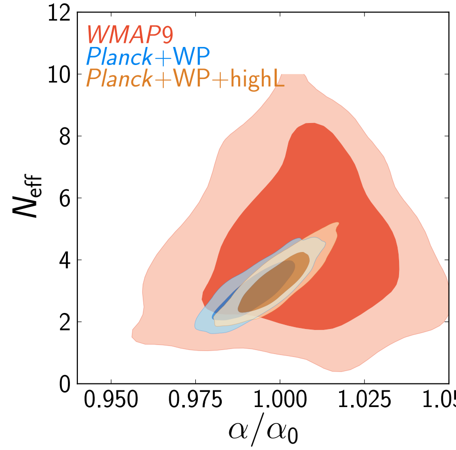
This is a <u>factor 5</u> better compared to WMAP analysis



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





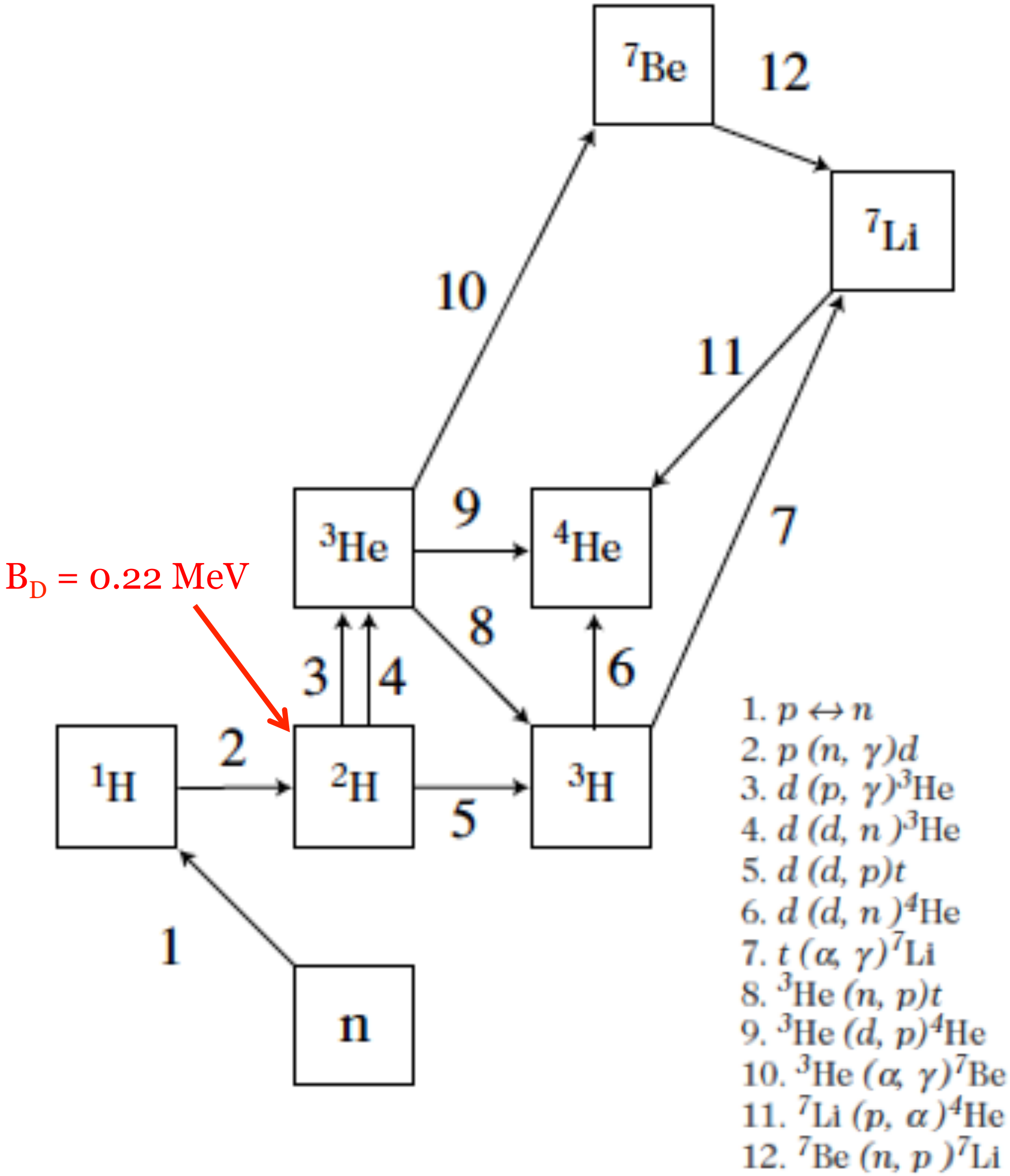


Big bang nucleosynthesis
&
Population III stars

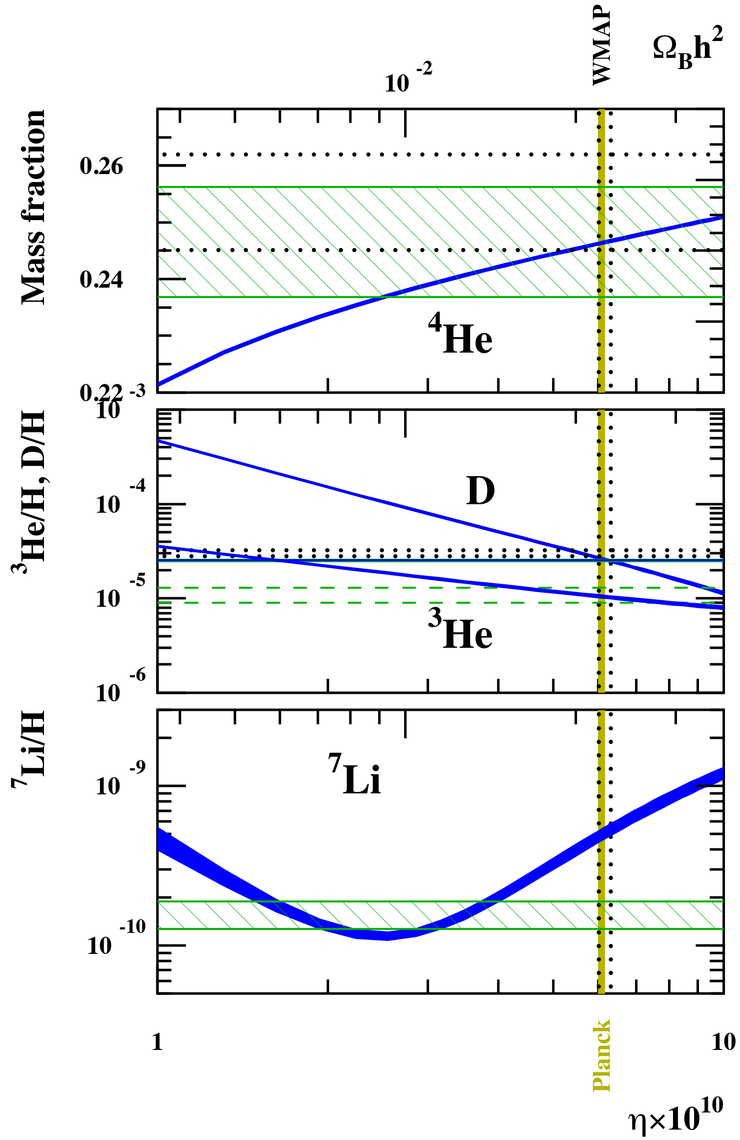
Nuclear physics at work in the universe

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

BBN: basics



B_D = 0.22 MeV
n
^{1}H
^{2}H
^{3}H
^{3}He
^{4}He
^{7}Be
^{7}Li
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



WMAP
$\Omega_B h^2$
10^{-2}
Mass fraction
^{4}He
^{3}He/H, D/H
D
^{3}He
^{7}Li/H
^{7}Li
Planck
$\eta\times10^{10}$

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

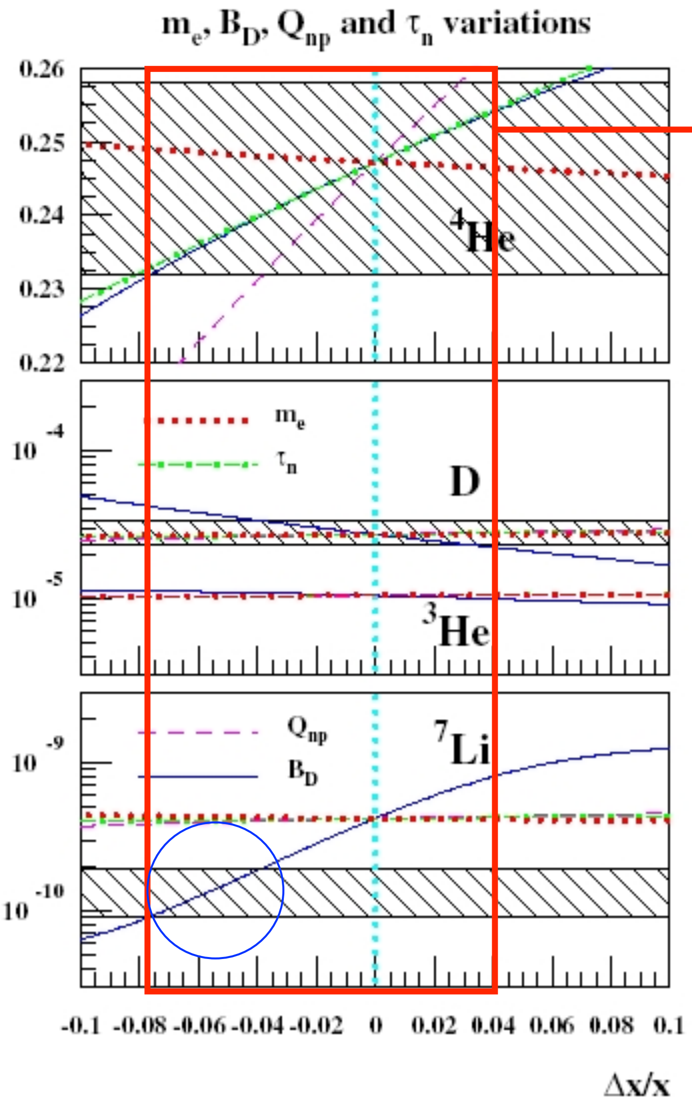
Predictions depend on

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

Coc,Nunes,Olive,JPU,Vangioni 2006

Sensitivity to the nuclear parameters

Independent variations of the BBN parameters



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

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

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

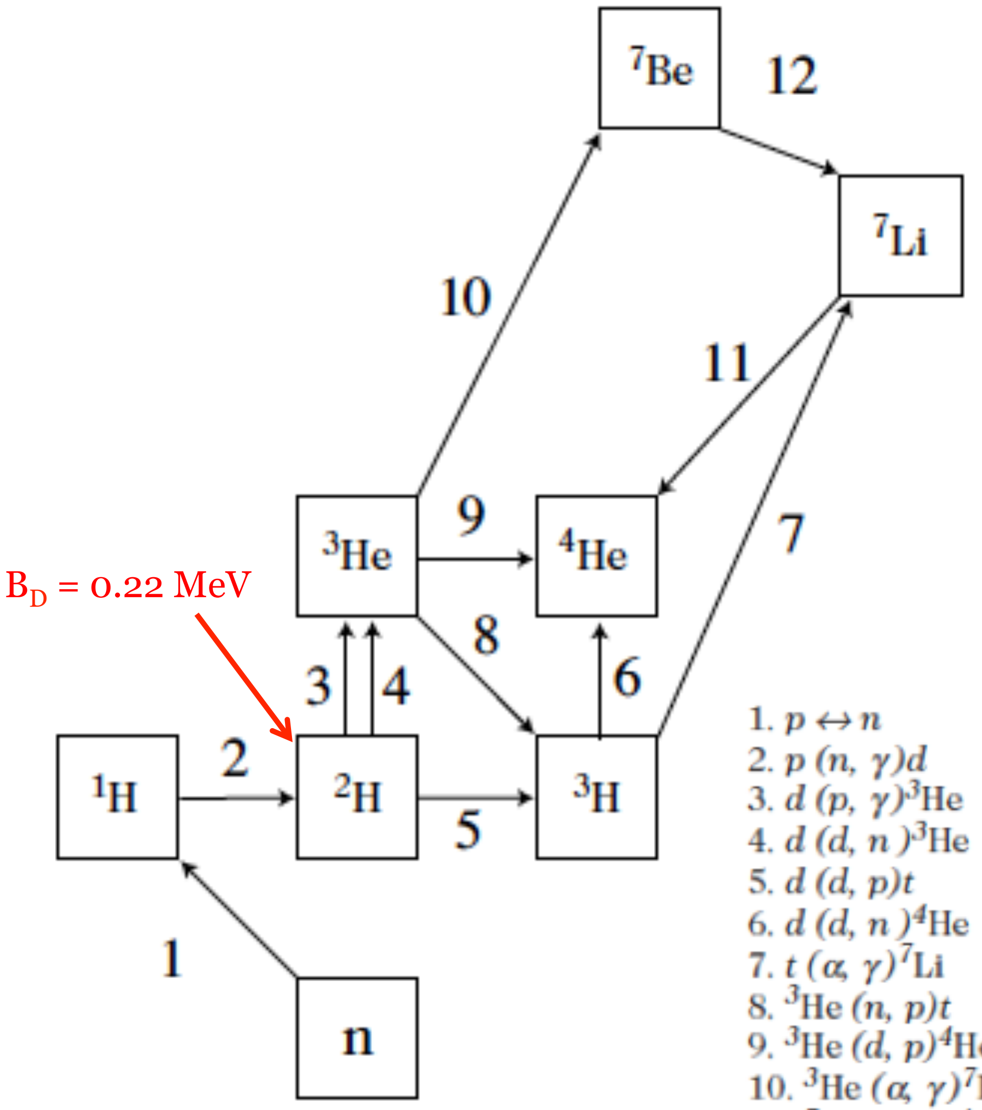
Abundances are very sensitive to B_D.
Equilibrium abundance of D and the reaction rate p(n,γ)D depend exponentially on B_D.

These parameters are not independent.

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

Coc,Nunes,Olive,JPU,Vangioni 2006

A=5 & A=8



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11. ^{7}Li $(p,\,\alpha\,)^4$He
12. ^{7}Be $(n,\,p\,)^7$Li

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

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

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

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

- We assume that

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

- δ_{NN} is an effective parameter

Cluster model ⟷ Theoretical analysis

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

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

Constraints

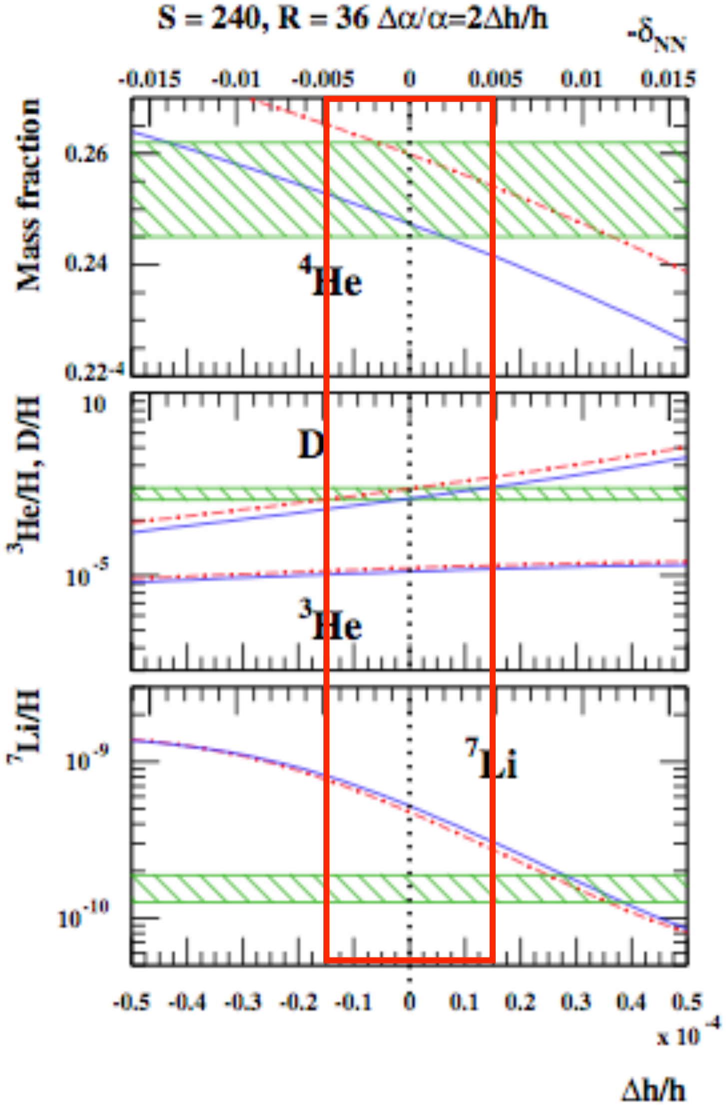


FIG. 12 (color online). Update Fig. 4 of Ref. [22] assuming $S = 240$ and $R = 36$ (solid blue line), using new rates for ^{3}He$(\alpha, \gamma)^7$Li [73] and ^{1}H(n, γ)D [74] and the Ω_b value from WMAP7 [4]. The top axis is $-\delta_{\rm NN}$ from Eq. (5.8) (mind the sign) and the dashed red line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

Primordial CNO production

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

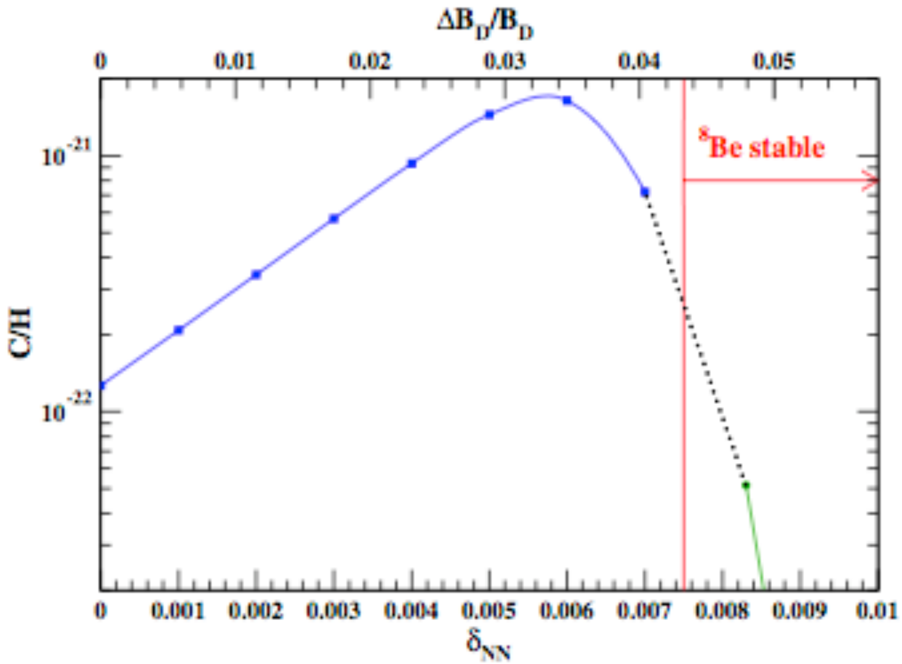
In standard BBN CNO/H=(0.2-3)10^{-15} [Iocco et al (2007); Coc et al. (1012)].
It proceeds as

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

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

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

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



Variation on BBN

(that may be of interest for bi-people)

Li problem

This model not only explain the large scale structure etc. but also the way all the elements of Mendeleev table were synthetized.

Analysis of the Planck CMB data

$$\eta = 6.047 \pm 0.074 \longrightarrow {}^{7}\mathrm{Li/H_{BBN}} = (4.89^{+0.41}_{-0.39}) \times 10^{-10},$$

Measurements of Li-7 abundance give

$$(1.23^{+0.34}_{-0.16}) \times 10^{-10}$$

[Ryan, Beers, Olive,Fields, Norris, (2000).]

$$(1.58 \pm 0.31) \times 10^{-10}$$

[Sbordone (2010)
Aoki et al. (2010)
Melendez et al (2010)]

Solution may be:

- Astrophysical (extrapolation to zero metallicity)
- Cosmological [see e.g. Regis & Clarkson (2010)]
- Physical

Li problem: model of neutron injection

Neutron injection lead to the suppression of the freeze-out abundance of Be-7.

This mechanism works by

- enhancing the conversion of beryllium to lithium, ^{7}Be(n,p)^{7}Li, immediately after ^{7}Be is created,
- followed by more efficient proton burning of ^{7}Li, ^{7}Li(p, α) α.

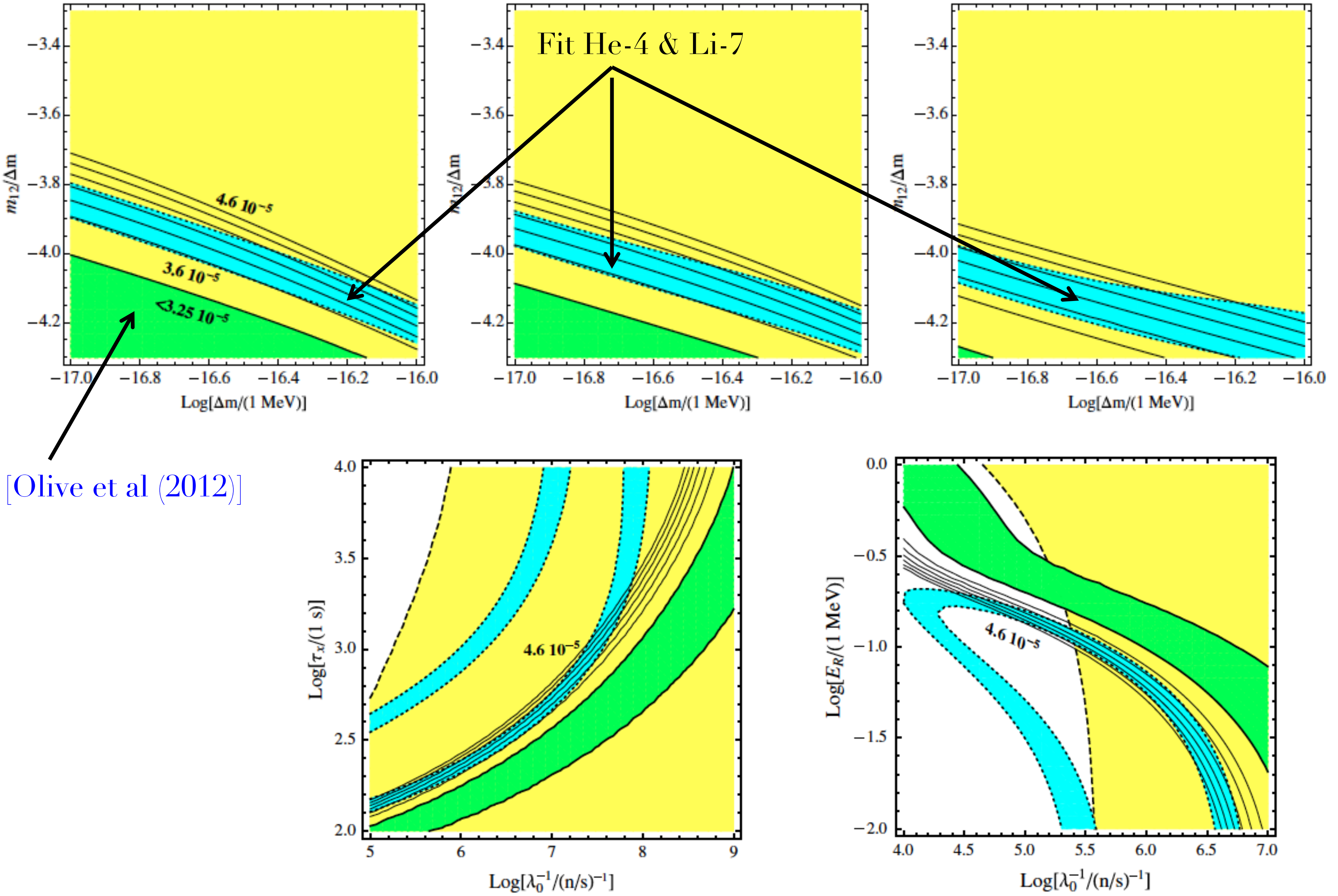
[Reno & Seckel (1988), Jedamzik (2004),…]

We consider 4 classes of models

[Coc, Pospelov, JPU, Vangioni (2014)]

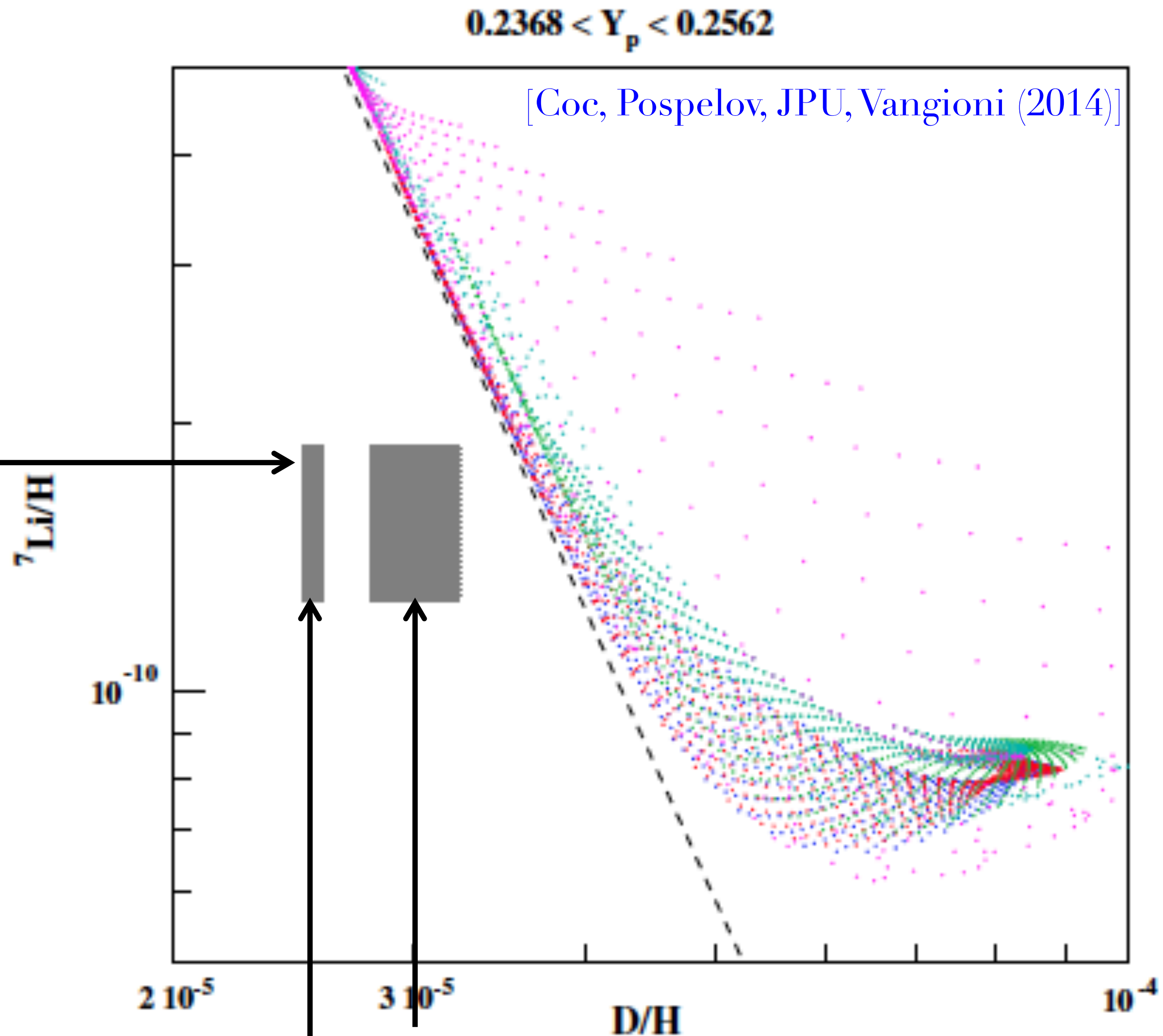
Model	Physical parameters	Cosmological parameters
$n - n'$ oscillation	$\Delta m, m_{12}$	x, η'
Particle decay	τ_X	Y_X
Particle annihilation	λ_0	Y_X
Resonant annihilation	E_r	Y_X

Li problem



[Olive et al (2012)]

Li problem – neutron injection models



[L. Sbordone (2010)
Aoki et al. (2010)
Melendez et al (2010)]

[Olive et al (2012)]

[Cooke et al (2014)]

None of these models can be in agreement with both lithium-7 and deuterium.

Conclusions and perspective

Conclusions

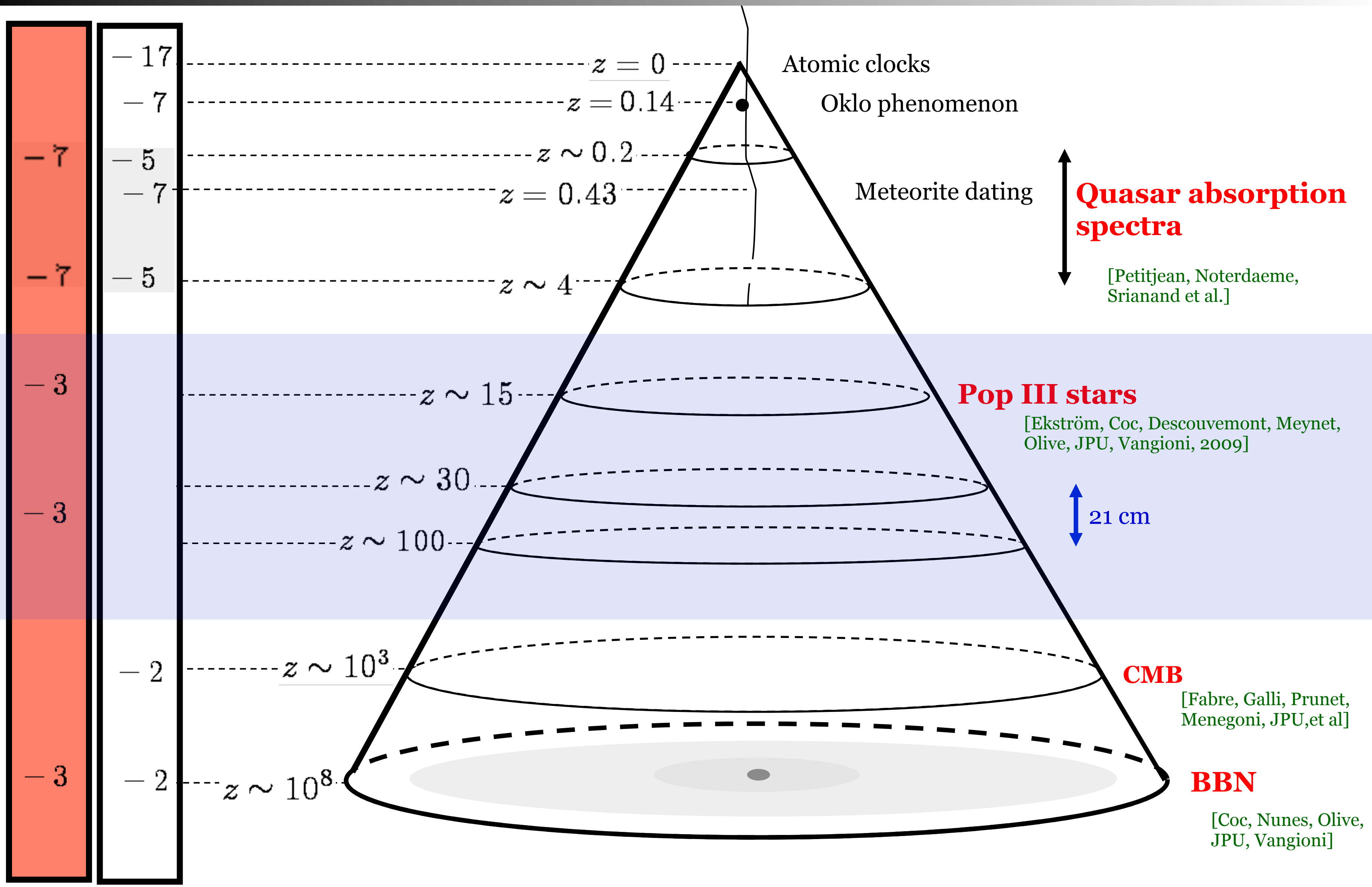
In the past years, we have obtained a series of results concerning the variation of fundamental constants:

- 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_0
  - 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