Fundamental constants, gravity and dark energy

Jean-Philippe UZAN

Dark energy

Standard Cosmological model relies on

Theory: Grav=RG + SM + **DM** + **Λ**

Solutions: Copernican principle

Data drive us to include in an **effective way** two extra-components:

- Dark matter appears as a *low acceleration* problem
- Dark energy appears as *low curvature* or *low acceleration* problem

Solutions to the dark energy problem range in:

- Astrophysical [NOT favored anymore]
- Cosmological
- Physical

It involves the **introduction of new degrees of freedom**:

- geometrical or physical

Universality classes of extensions *(slide from 2004)*

Ordinary matter $\longleftrightarrow g_{\mu\nu} \longleftrightarrow \phi$

Ex : quintessence, ...

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

Variation of constants

Poisson equation

Ordinary matter $\longleftrightarrow g_{\mu\nu} \longleftrightarrow \phi$

Ex : scalar-tensor, f(R),TeVeS .... $S_\varphi[\varphi; g_{\mu\nu}]$

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

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

Ordinary matter $\longleftrightarrow g_{\mu\nu}$

$A_\mu \updownarrow a_\mu$

Ex : axion-photon mixing

Distance duality

Variation of constants

Poisson equation

Ordinary matter $\longleftrightarrow \tilde{g}^{(i)}_{\mu\nu}$

Ex : brane induced gravity
multigravity,...

Always need NEW fields

[JPU, JDEM meeting, 03/2004,
JPU, Aghanim, Mellier, 2005]
[JPU, GRG 2007]

A series of tests

This has triggered an activity to test the hypothesis of the standard cosmological model.

- Tests of the Copernican principle:
  Homogeneity [JPU, Clarkson, Ellis, PRL (2008)]
  Isotropy [see e.g. Pereira, Pitrou, JPU, A&A Lett. (2016)]

- Tests of General Relativity
  * Not new on small scales
  * Use of LSS with large surveys [JPU, Bernardeau , PRD (2001)]

  * Test of the EEP outside the Solar system
  and in particular with constants.

Gravitation

Definition: Long range interaction that is not screened
Description: General relativity

- Einstein equivalence principle (weak and strong)
- dof = massless spin 2

Einstein theory (1915) relies heavily on the **universality of free fall**, and its generalisation under the form of **Einstein Equivalence principle**:

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

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

Not a basic principle of physics but an empirical fact.
Allows to define a local freely falling laboratory.
It implies that we need to define only 1 kilogram!

Equivalence principle and constants

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

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

Equivalence principle and constants

Action of a test mass:

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

Dependence
on some
constants

$$\delta S = 0$$

$$f_{A,i}$$

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

(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

Field theory

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

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.

JPU, Rev. Mod. Phys (2003)
JPU & G. Ellis, Am. J. Phys (2005)
JPU, Liv. Rev. Relat. (2011)

Example of varying fine structure constant

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

Consider

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

But that may have dramatic implications.

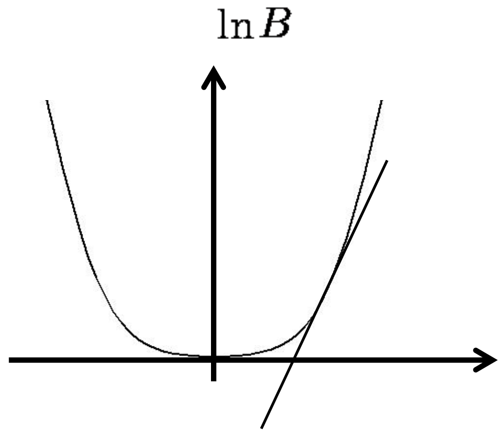
$$m_A(\phi) \supset 98.25\alpha\frac{Z(Z-1)}{A^{1/3}}\mathrm{MeV} \longrightarrow f_i = \partial_\phi \ln m_i \sim 10^{-2}\frac{Z(Z-1)}{A^{4/3}}\alpha'(\phi)$$

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

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



Requires to be close to the minimum

Famous example: Scalar-tensor theories

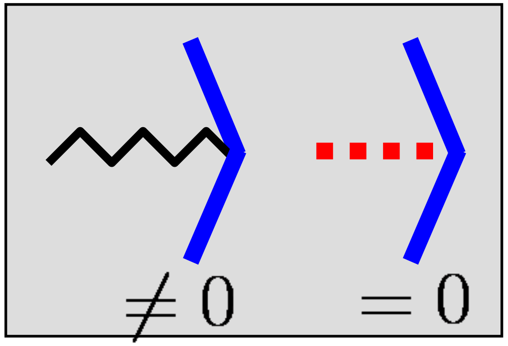
spin 2

spin 0

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

Maxwell electromagnetism is conformally invariant in d=4

$$S_{em} = \frac{1}{4}\int\sqrt{-\tilde{g}}\,\tilde{g}^{ab}\tilde{g}^{cd}F_{ac}F_{bd}\mathrm{d}^d x$$
$$= \frac{1}{4}\int\sqrt{-g}\,g^{ab}g^{cd}F_{ac}F_{bd}A^{d-4}(\phi)\mathrm{d}^d x$$



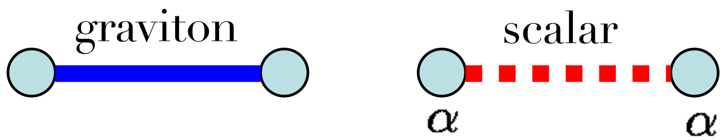
Light deflection is given as in GR

$$\delta\theta = \frac{4GM}{bc^2}$$

What is the difference?

The difference with GR comes from the fact that massive matter feels the scalar field

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



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

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

Thus, in terms of observable quantities, light deflection is given by

$$\delta\theta = \frac{4G_{\rm N}M}{(1+\alpha^2)bc^2} \leq \frac{4GM}{bc^2}$$

which means

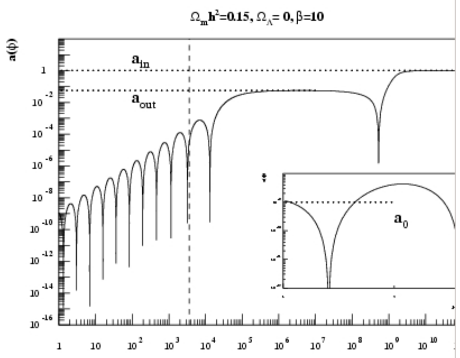
$$M_{\rm lens} \leq M_{\rm rot}$$

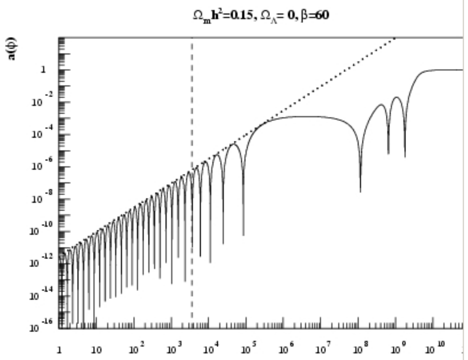
[Stratified theory, AQUAL,…, TeVeS,…]

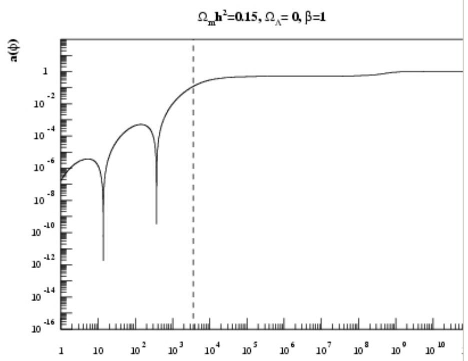
Local AND Global scales: exemple of BBN

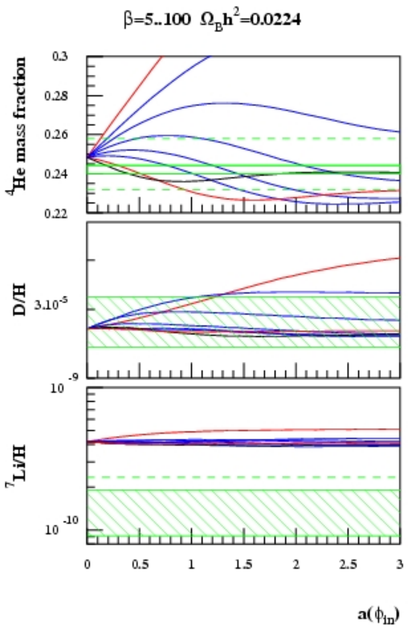
$$V = \text{cst}, \quad A = \exp\left(\frac{1}{2}\beta\phi^2\right) \qquad a = \frac{1}{2}\beta\phi^2, \quad \alpha = \beta\phi$$

Full dynamics ⟶ Abundances ⟶ constraints





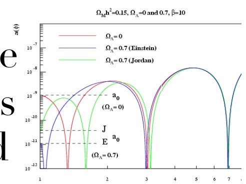


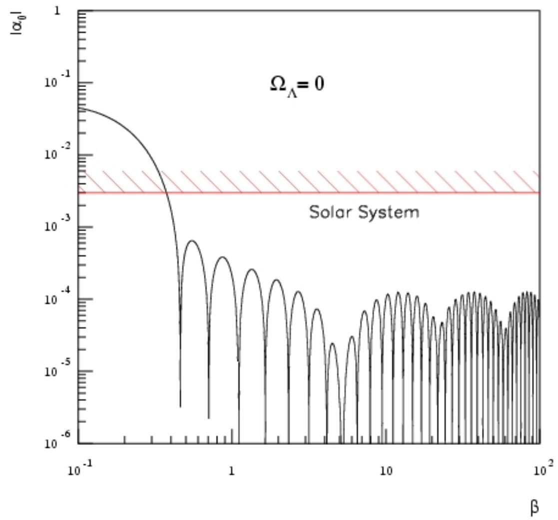


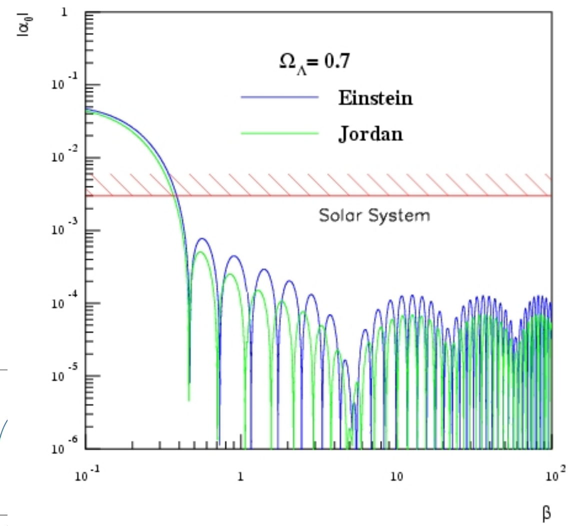
a_{in}/a_{out} relation not injective

Max value of a_o but not all a_o smaller
are acceptable

Late time
dynamics
modified



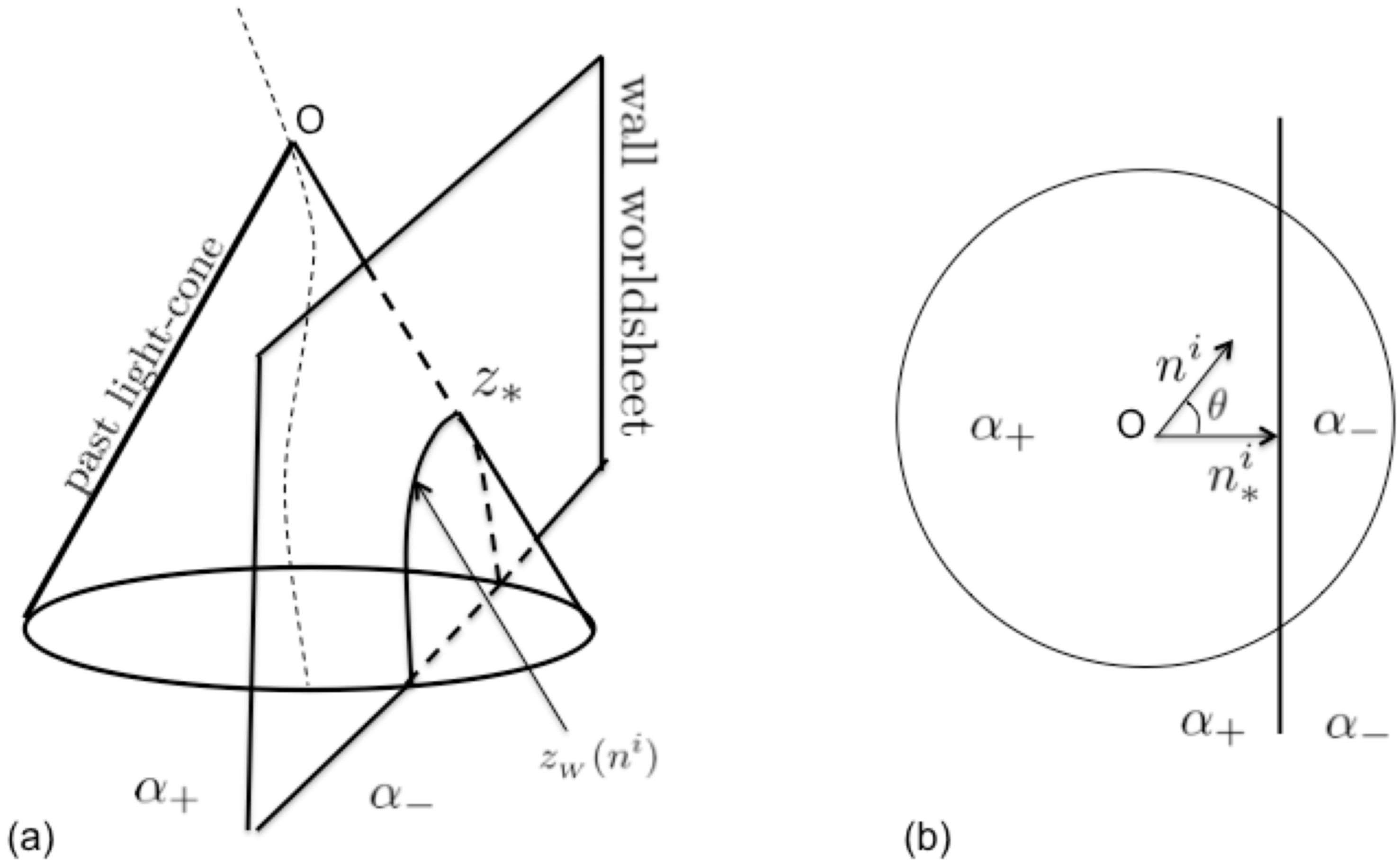




Wall of fundamental constant

[Olive, Peloso, JPU, 2010]

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



What is a constant?

<u>Constant</u>: PHYS., Numerical value of ***some*** quantity that allows to characterize a body. Quantity whose value is fixed (***e.g.*** mass and charge of the electron, speed of light) and that plays a ***central*** role in physical theories.

This definition asks more questions than it gives answers!

- *How many constants?*
- *Are they all on the same footing?*
- *What role do they play in laws of physics?*
- *Can they vary? (according to the dictionary, NO!)*

<u>Proposed definition</u>:

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

Fundamental constants are <u>the free parameters of a theory</u>

- *the theory cannot determine them*
- *we need to measure them (need of a theoretical AND experimental definition)*
- *they shall be measurable*
- *their number and status will change over time*

Are we sure constants do remain constant?

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

Then:

- **3 base units** defined by 3 constants (e.g., c, G, h)
  numerical values fix units

- all other constants are then **dimensionless**
  numerical values are independent of all units
  value is important / fine tuning / ....

JPU, Rev. Mod. Phys (2003)
JPU & G. Ellis, Am. J. Phys (2005)
JPU, Liv. Rev. Relat. (2011)

Reference theoretical framework

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

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	$\sin^2\theta_W(91.2\ \mathrm{GeV})_{\overline{MS}}$	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) GeV²
Higgs potential quartic coefficient	λ	? 1.015 ±0.05
QCD vacuum phase	θ_{QCD}	< 10^{-9}

v=(246.7±0.2)GeV
m_H=(125.3±0.6)GeV

26th CGPM
16/11/2018

22 constants
19 parameters
(+ cosmological constant)

This number can *increase* or *decrease* with our knowledge of physics:
Unification / conversion factor / new constants (e.g. neutrinos) / …

Observables and primary constraints

A given physical system gives us an observable quantity

$$O(G_k, X)$$

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

G_k → 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.

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

Theory:

Shall give the relation to the low energy constants that we measure in the lab in terms of new fields and arbitrary function

JPU, Liv. Rev. Relat. (2011)

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

Atomic spectra

General atom

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

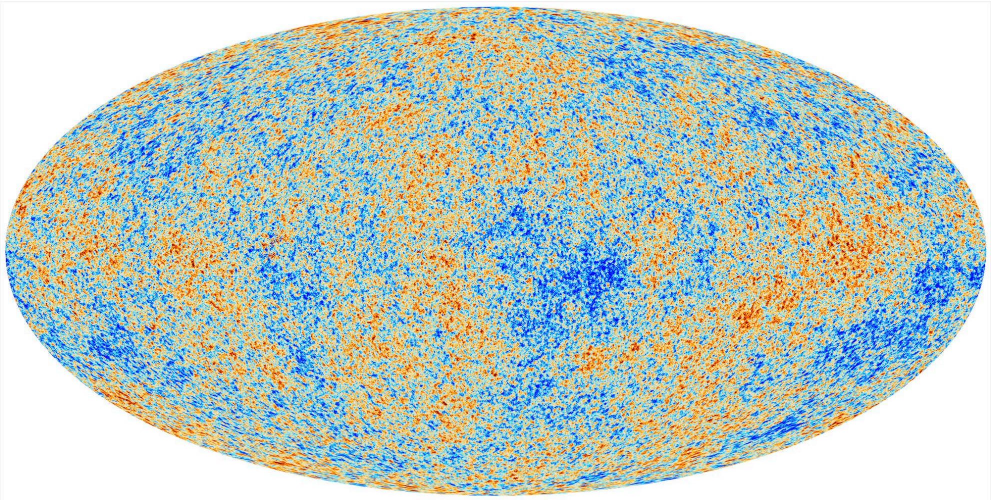
$$\nu_{\rm elec} \simeq R_\infty c \times A_{\rm elec} \times F_{\rm elec}(Z,\alpha)$$

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

To be updated (sorry)

No variation larger than 10^{-5} on a time scale of 10 Gyr

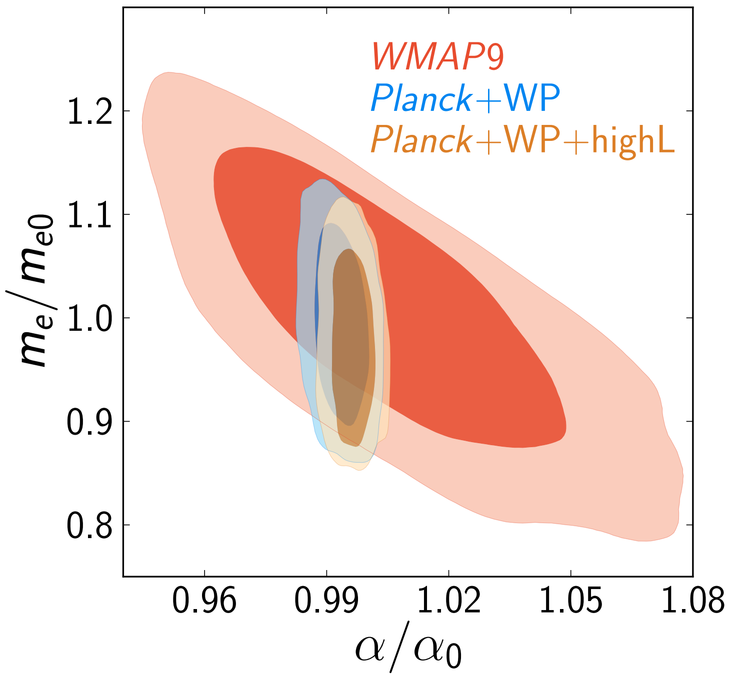
Cosmic microwave background (CMB)



Recombination of hydrogen and helium
Gravitational dynamics (expansion rate)

predictions depend on $Gm_p^2, \alpha, m_e/m_p$

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



Independent variations of α and m_e are constrained to be

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

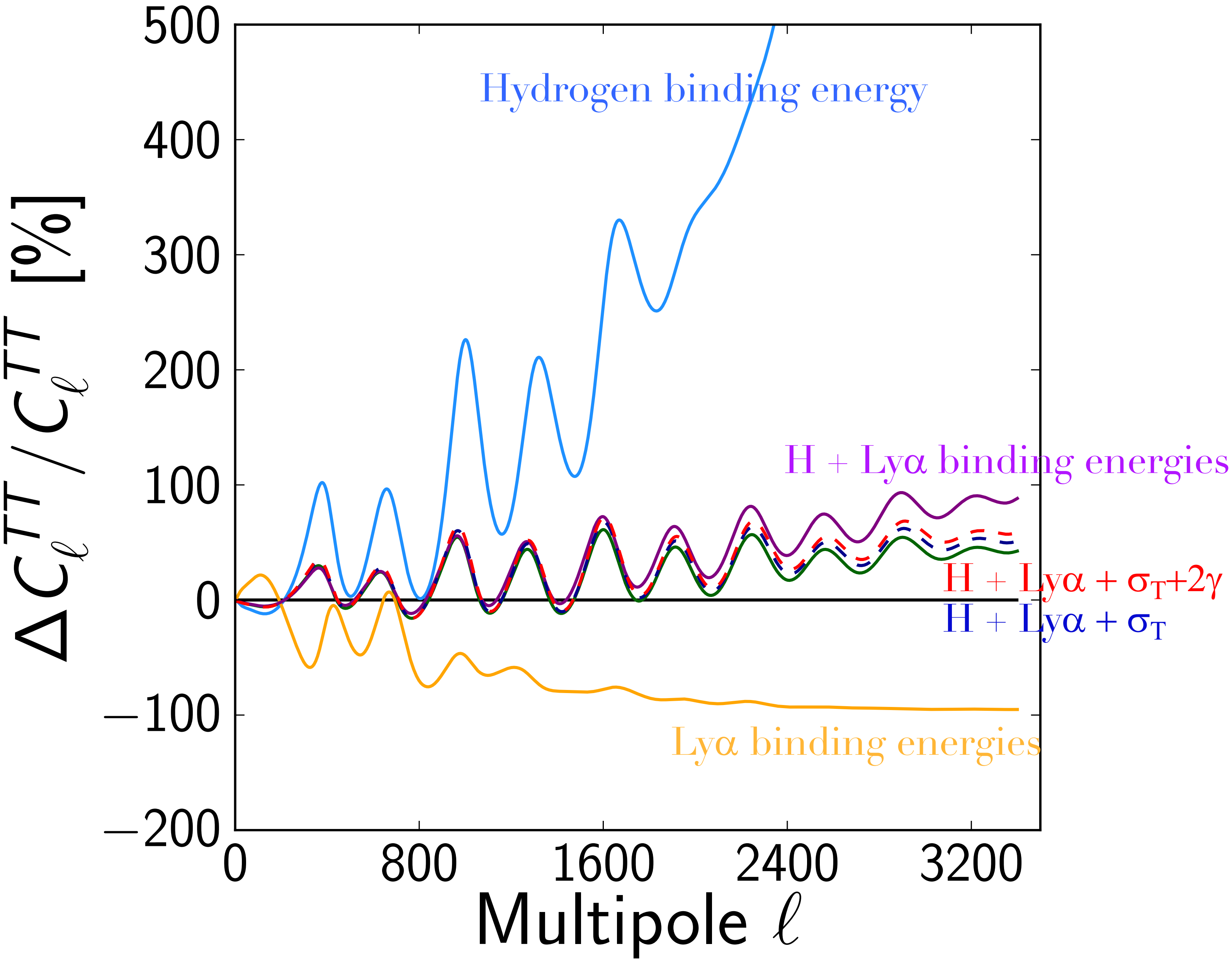
This is a <u>factor 5</u> better compared to WMAP analysis

Planck team. (2013) – Galli, Prunet, JPU

Why *Planck* does better

$\delta\alpha$ = 5%
δm_e=10.025%

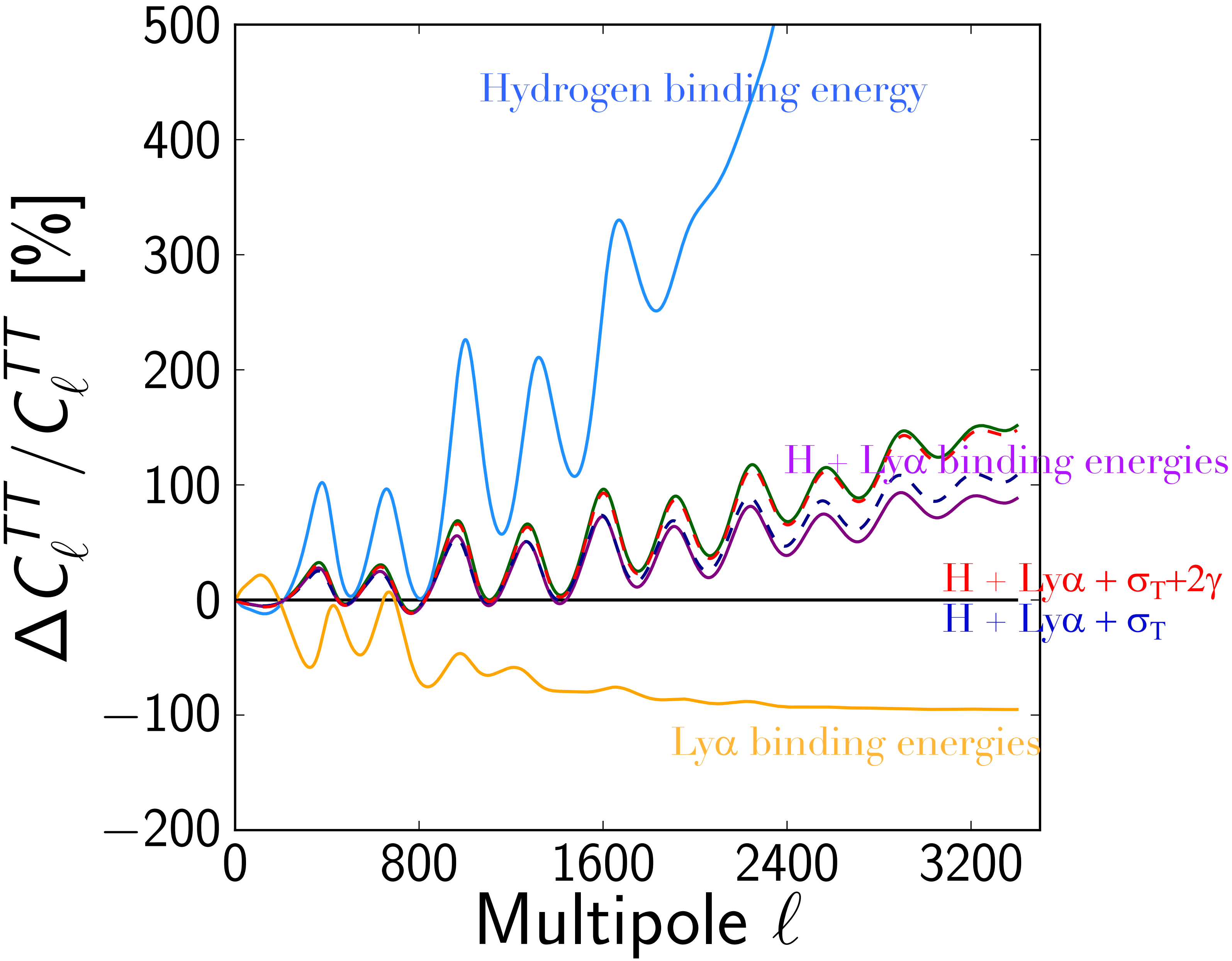
$\alpha^2 m_e$ identical



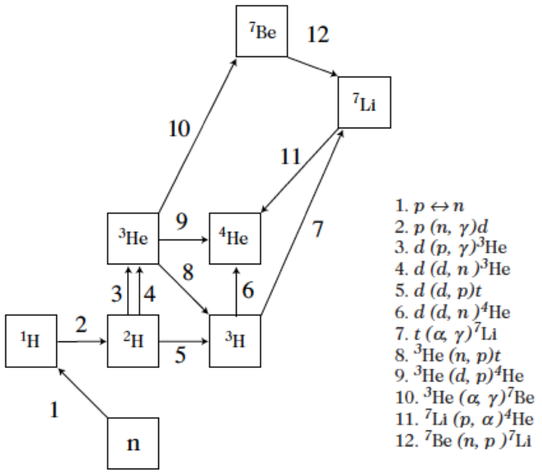
Why *Planck* does better

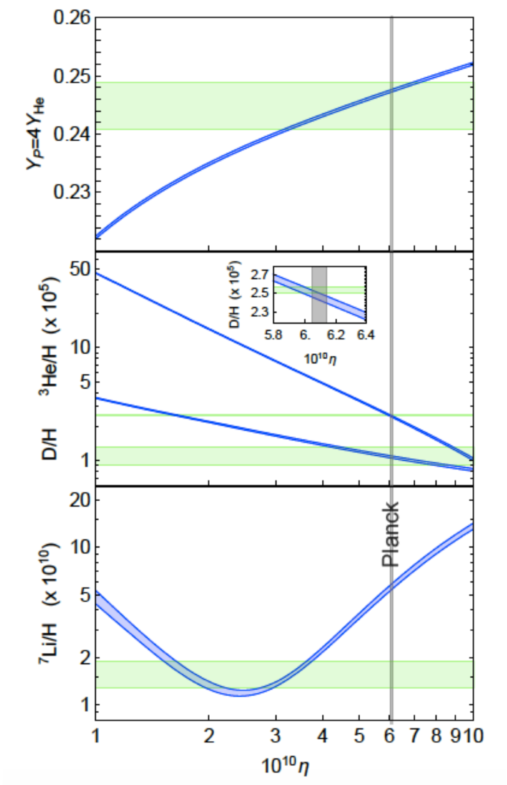
$\delta\alpha$ = 5%
δm_e=10.025%

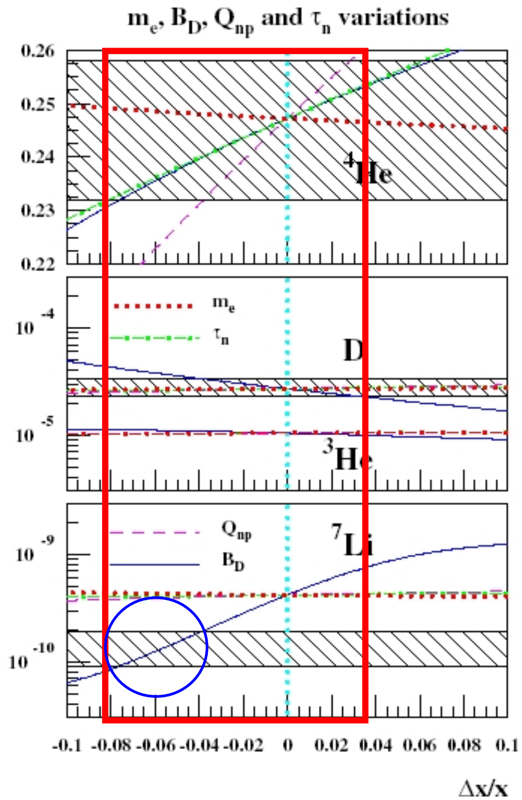
$\alpha^2 m_e$ identical



Big bang nucleosynthesis







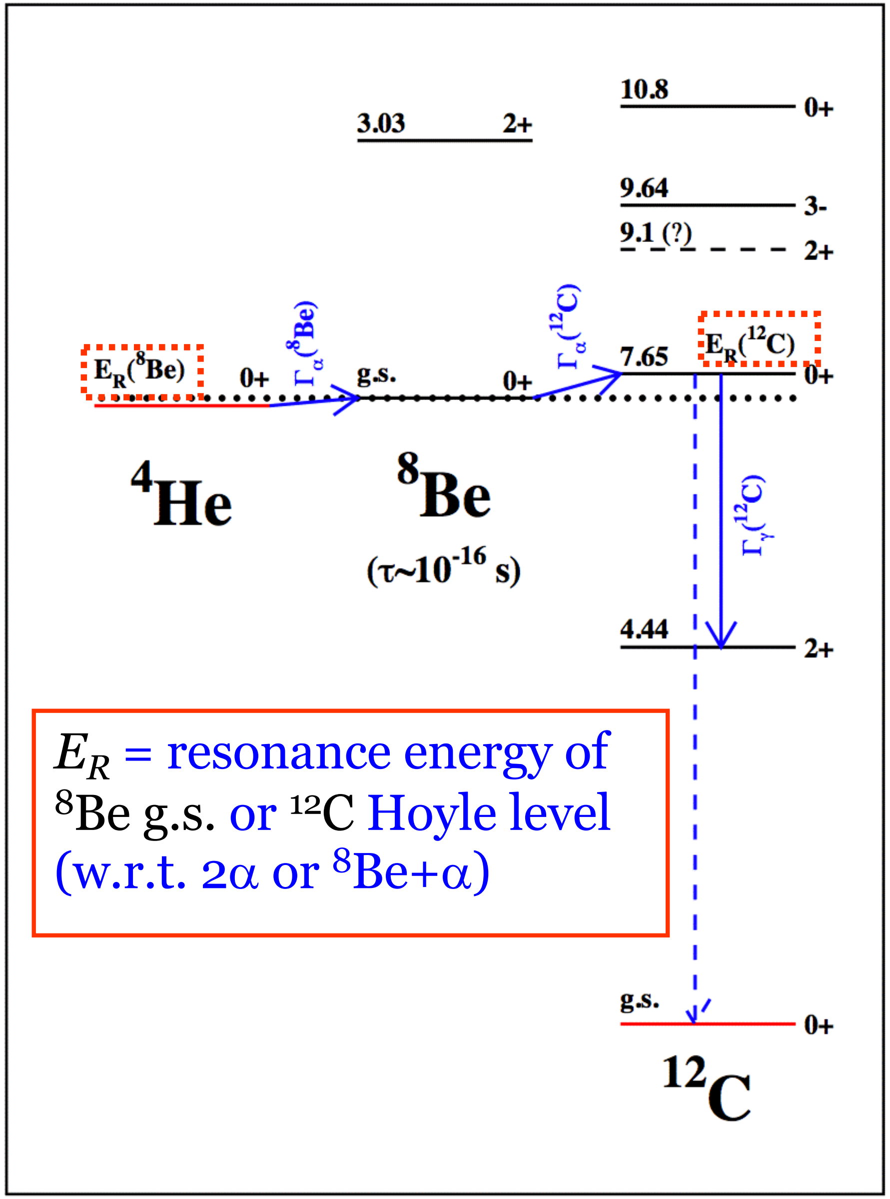
$$-7.5\times10^{-2} < \frac{\Delta B_D}{B_D} < 6.5\times10^{-2}$$

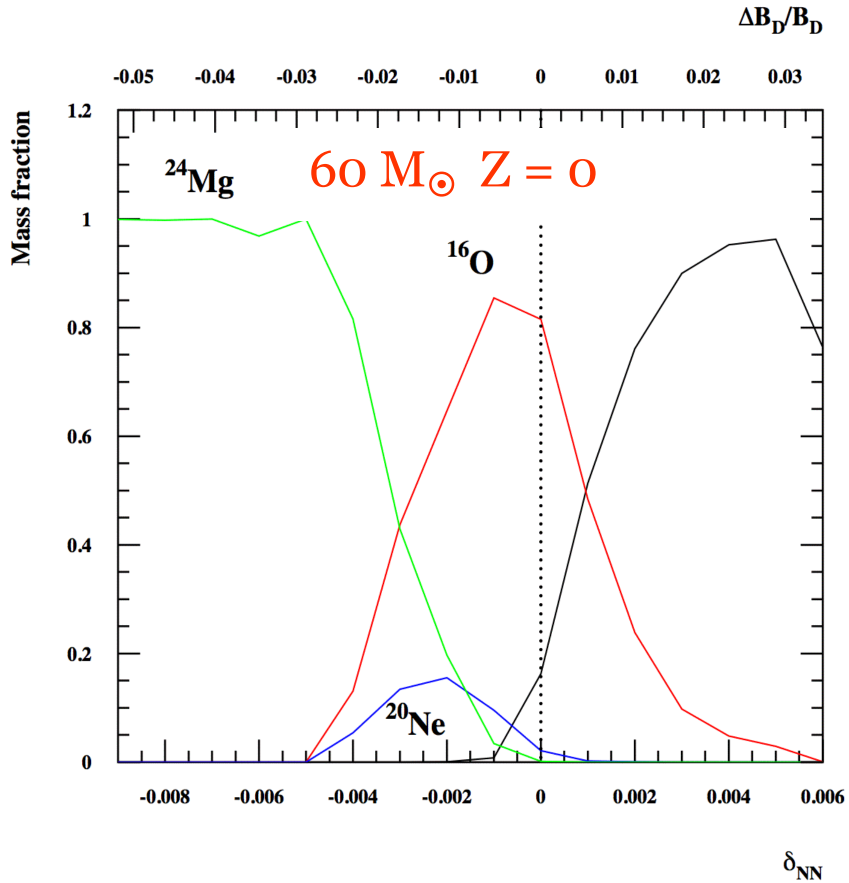
$$-8.2\times10^{-2} < \frac{\Delta\tau_n}{\tau_n} < 6\times10^{-2}$$

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

[Coc,Nunes,Olive,JPU,Vangioni 2006
Coc, Descouvemont, Olive, JPU, Vangioni, 2012]

Stellar carbon/oxygen synthesis





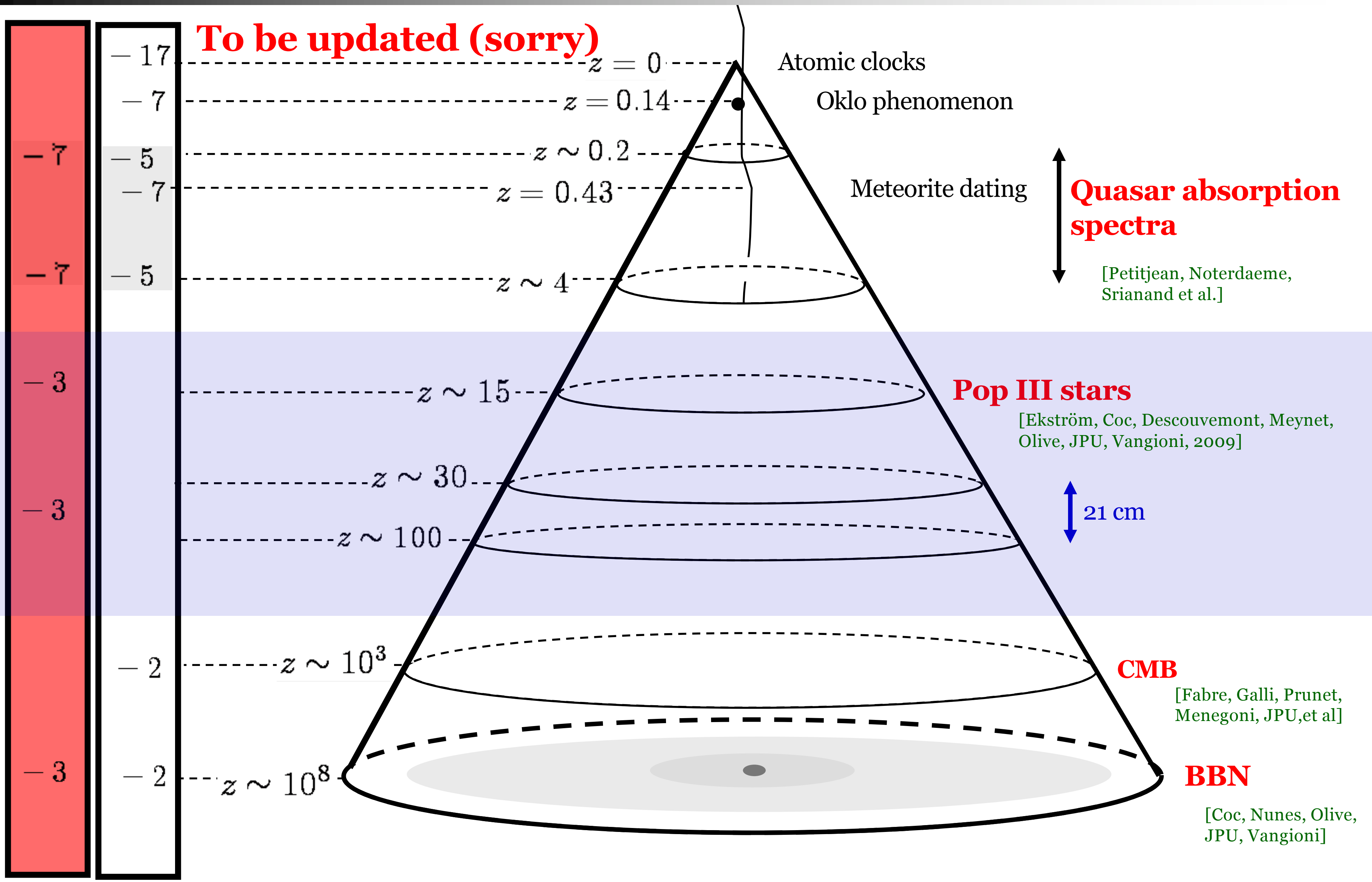
Constraint ($^{12}C/^{16}O \sim 1$)

$$-0.0005 < \delta_{NN} < 0.0015$$

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

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

Physical systems: new and future



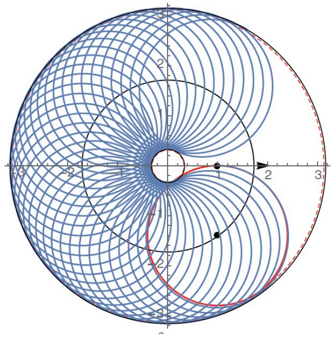
JPU, Liv. Rev. Relat. (2011), arXiv:1009.5514

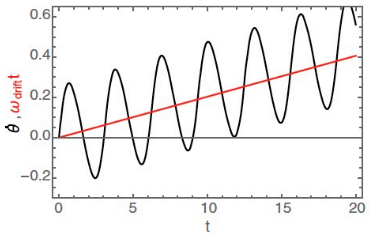
New laboratory test

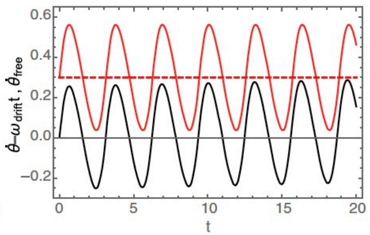
Take a charged particle in ST-theory with B-field

$$mc^2\gamma^\mu = \frac{q}{A(\phi)}F^\mu{}_\nu u^\nu - mc^2\frac{\partial \ln A}{\partial \phi}\perp^{\mu\nu}\nabla_\nu\phi$$

The **5th force** induces a **drift**

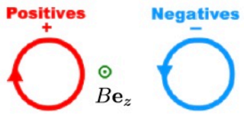


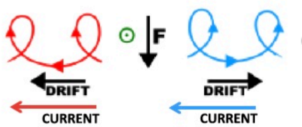


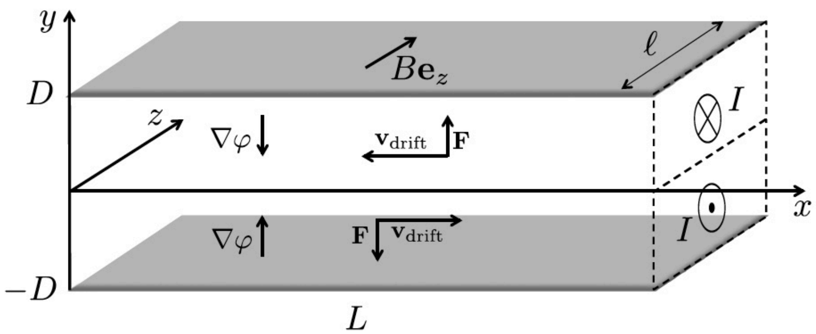


$$\boldsymbol{v}_{\rm drift} = \frac{\boldsymbol{F}\wedge\boldsymbol{B}}{qB^2},$$

For **chameleon** in screened regime, one can design the profile of the scalar field.







$$\frac{I}{1\ \mathrm{nA}} = 5\left(\frac{\eta_q}{\eta_0}\right)\left(\frac{B}{1\ \mathrm{T}}\right)^{-1}\left(\frac{m}{m_p}\right)\left(\frac{S_\perp}{1\ \mathrm{m}^2}\right)\left(\frac{F_0}{10^{-7}\ \mathrm{m/s}^2}\right)$$

$\varphi_0 > 0 \quad q > 0$

[JPU, Pernot-Borras, Joel Bergé, PRD (2020)]

Conclusions

- General Relativity is well-tested in the Solar system. Not a single experimental sign that it needs to be modified.

- Dark energy, **if not Λ,** requires that we introduce new d.o.f

- One needs to identify the dof of the model: can be either *geometrical* or *physical.*

- **We have tests** of RG(LSS) + EEP + Copernican principle (*isostropy+homogeneity*) + of other couplings. Tests of GR are **not LSS only**.

- **Physical d.o.f**.: new matter field and/or modification of general relativity, i.e. characterize nature+couplings to SM fields + range

  *We do **not** vary constants in equations.*

- **Constancy of dimensionless constants** related to the EEP.

  We have **strong constraints** from $z=0$ to $z=10^8$.

- **Local and global** are required.

  local physics is very constraining (fifth force/constants)
  attraction toward RG

- The **cosmological model** is required to compare and interpret the constraints.