Equivalence principle, fundamental constants, spatial isotropy

Jean-Philippe UZAN

Overview of the lectures

Equivalence principle and the fundamental constants

- lecture 1: equivalence principle
  constants and gravity

- lecture 2: Observational constraints on the variation of constants

Test of local isotropy

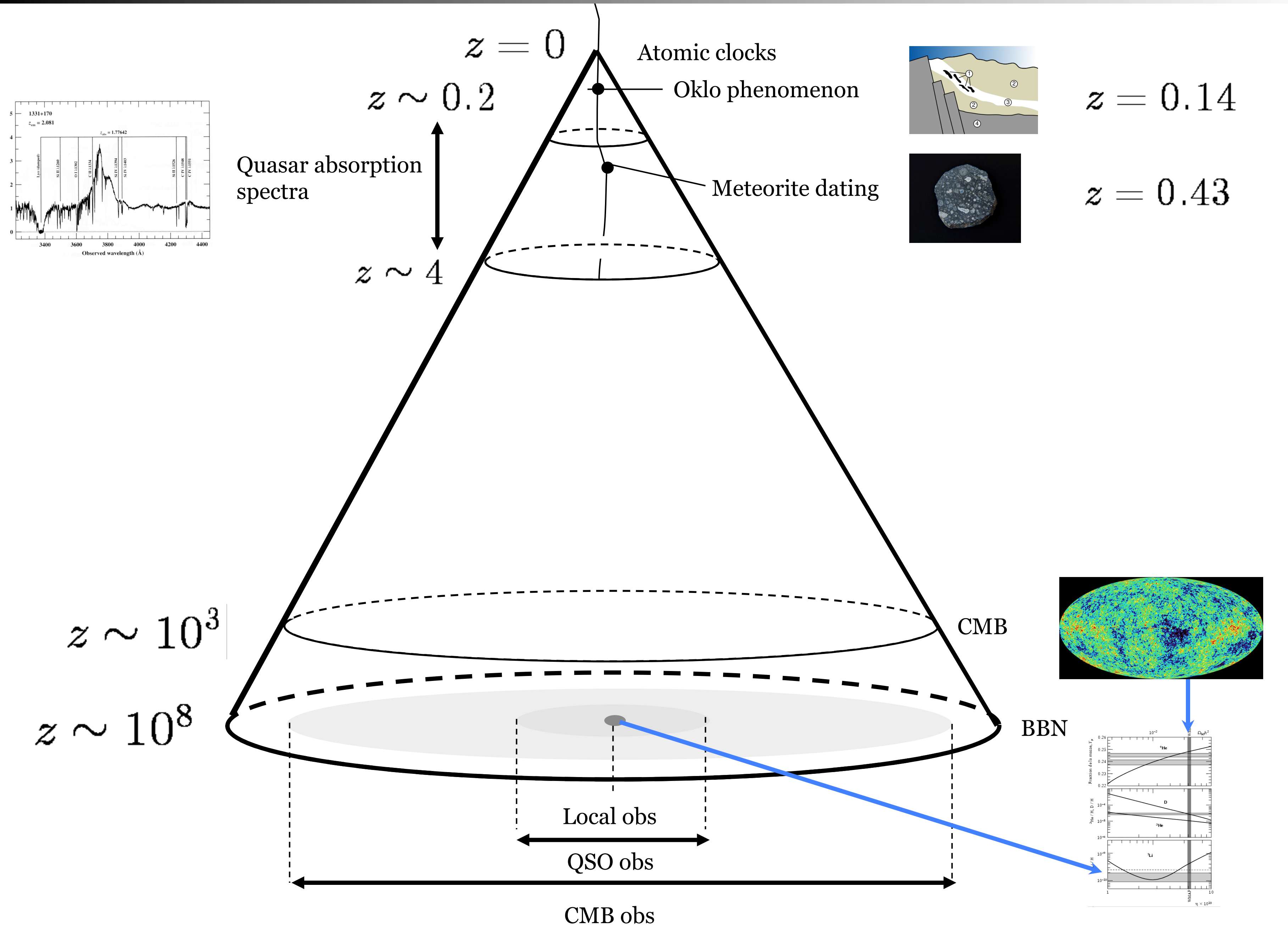
- lecture 3: Weak lensing as a test of local spatial isotropy

complementary to Chris' lectures on Copernican principle

Observational constraints on the variation of fundamental constants

Jean-Philippe UZAN

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

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

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

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

Atomic clocks

Atomic clocks

Based the comparison of atomic clocks using different transitions and atoms

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

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

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

High precision / redshift 0 (local)

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

Atomic clocks

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

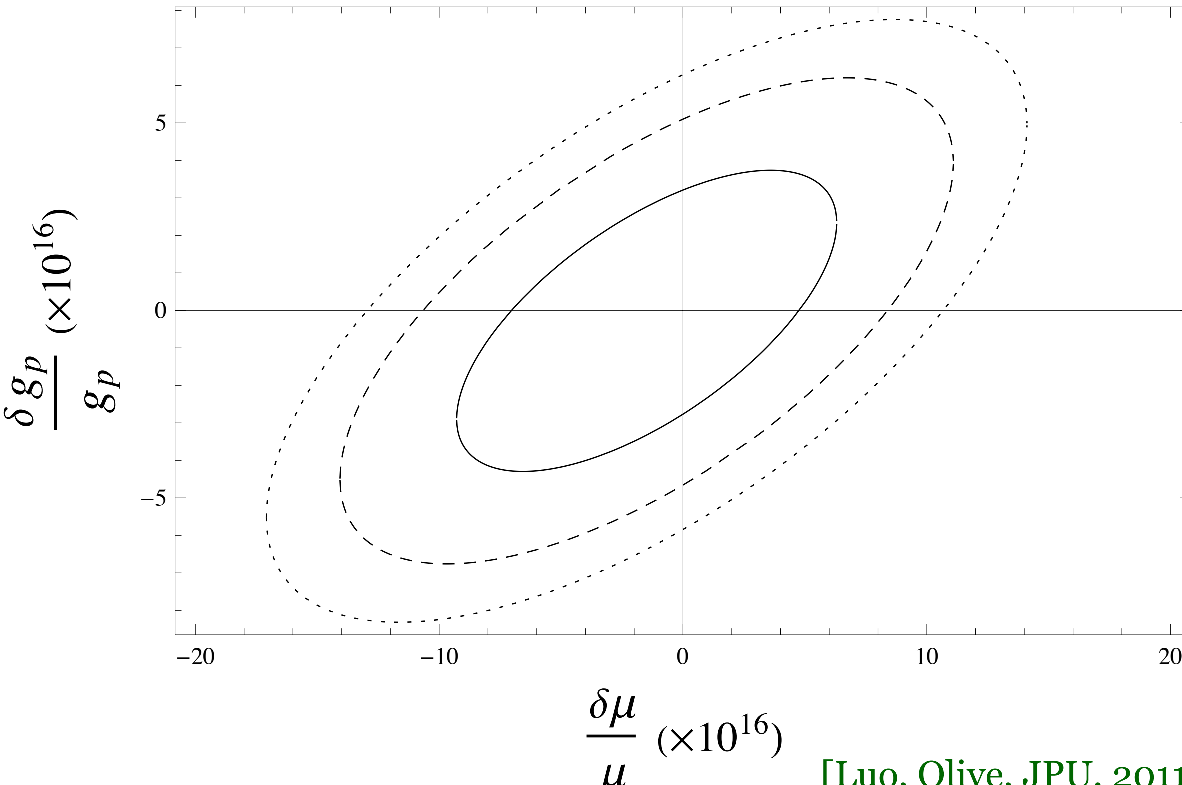
$$\frac{\delta g_{\rm Cs}}{g_{\rm Cs}} \sim -1.266\frac{\delta g_p}{g_p} \qquad \frac{\delta g_{\rm Rb}}{g_{\rm Rb}} \sim 0.736\frac{\delta g_p}{g_p}$$

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

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

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

[Flambaum, 0302015,...



[Luo, Olive, JPU, 2011]

Importance of unification

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

Variation of α is accompanied by variation of other coupling constants

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

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

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

Variation of Yukawa and Higgs VEV are coupled

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

These effects cannot be ignored in realistic models.

Atomic clocks

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

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

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

$$m_i = h_i v$$

Assuming unification.

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

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

Model-dependence remains quite large.

[Luo, Olive, JPU, 2011]

Nuclear methods

(Oklo / meteorite dating)

Oklo- a natural nuclear reactor

It operated 2 billion years ago, during 200 000 years !!

Oklo: why?

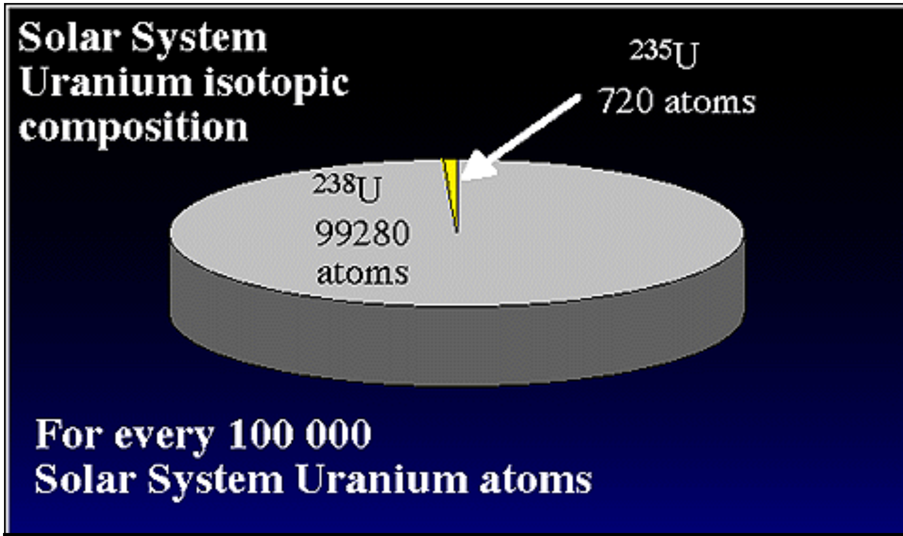
<u>4 conditions :</u>

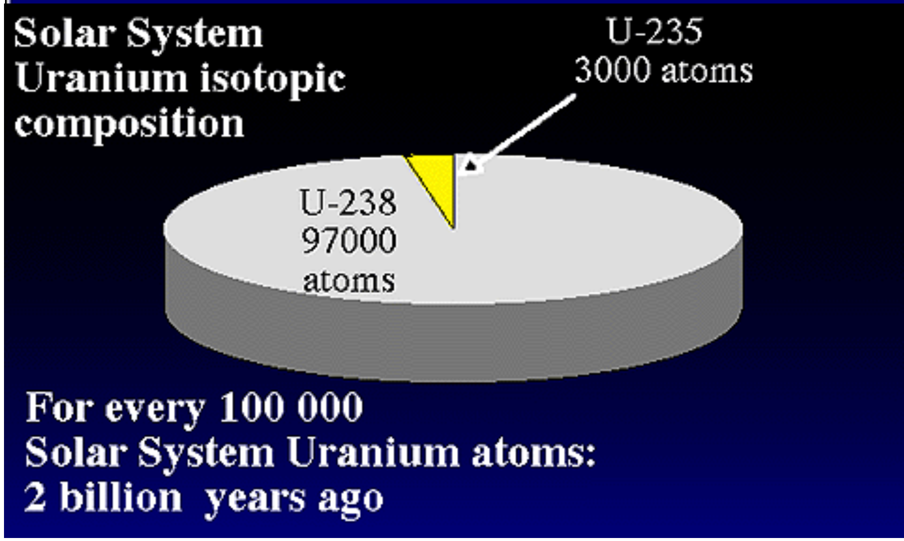
1- Naturally high in U^{235},

2- moderator : water,

3- low abundance of neutron absorber,

4- size of the room.





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

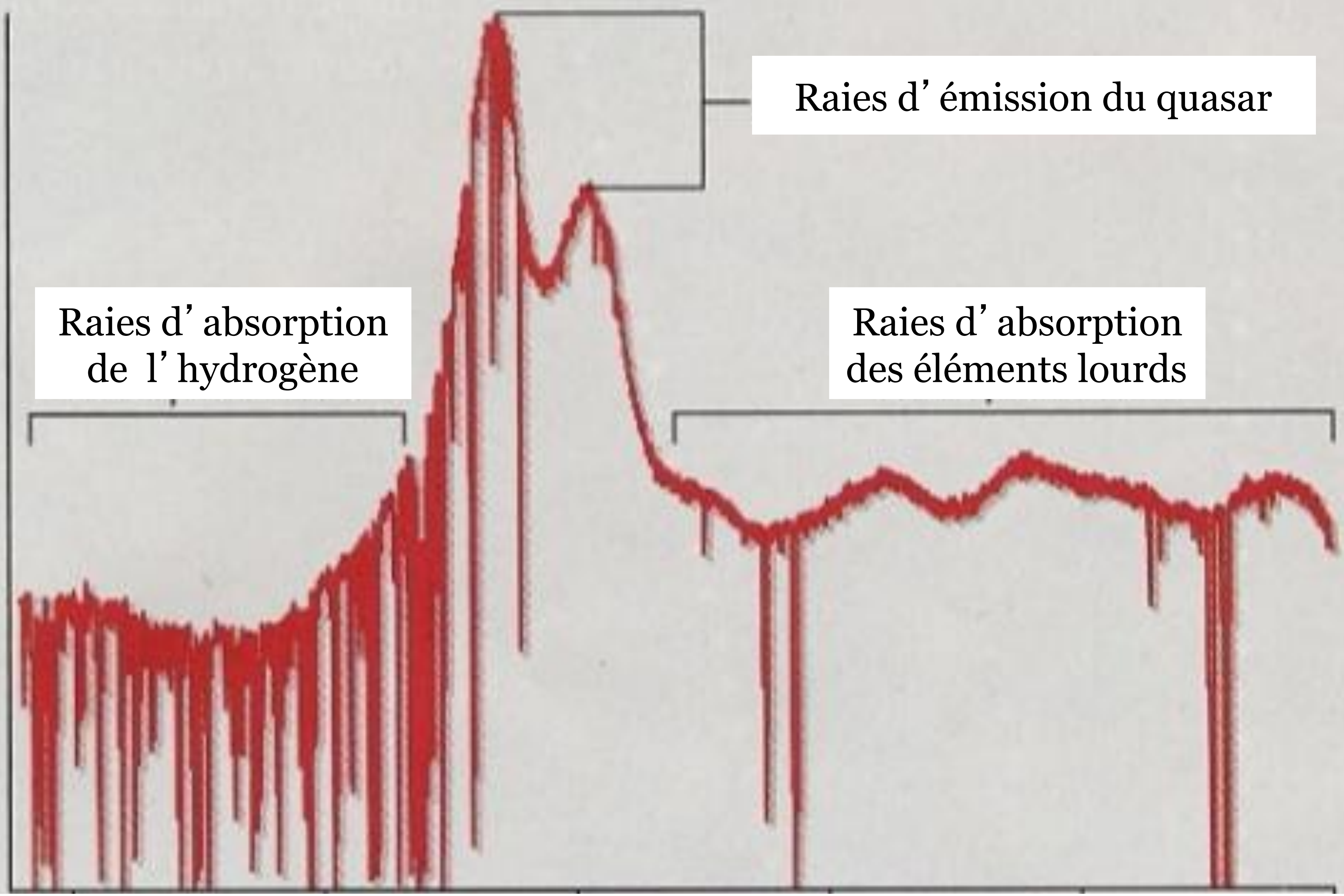
$$-24 \times 10^{-7} < \Delta\alpha/\alpha < 8 \times 10^{-7}$$

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

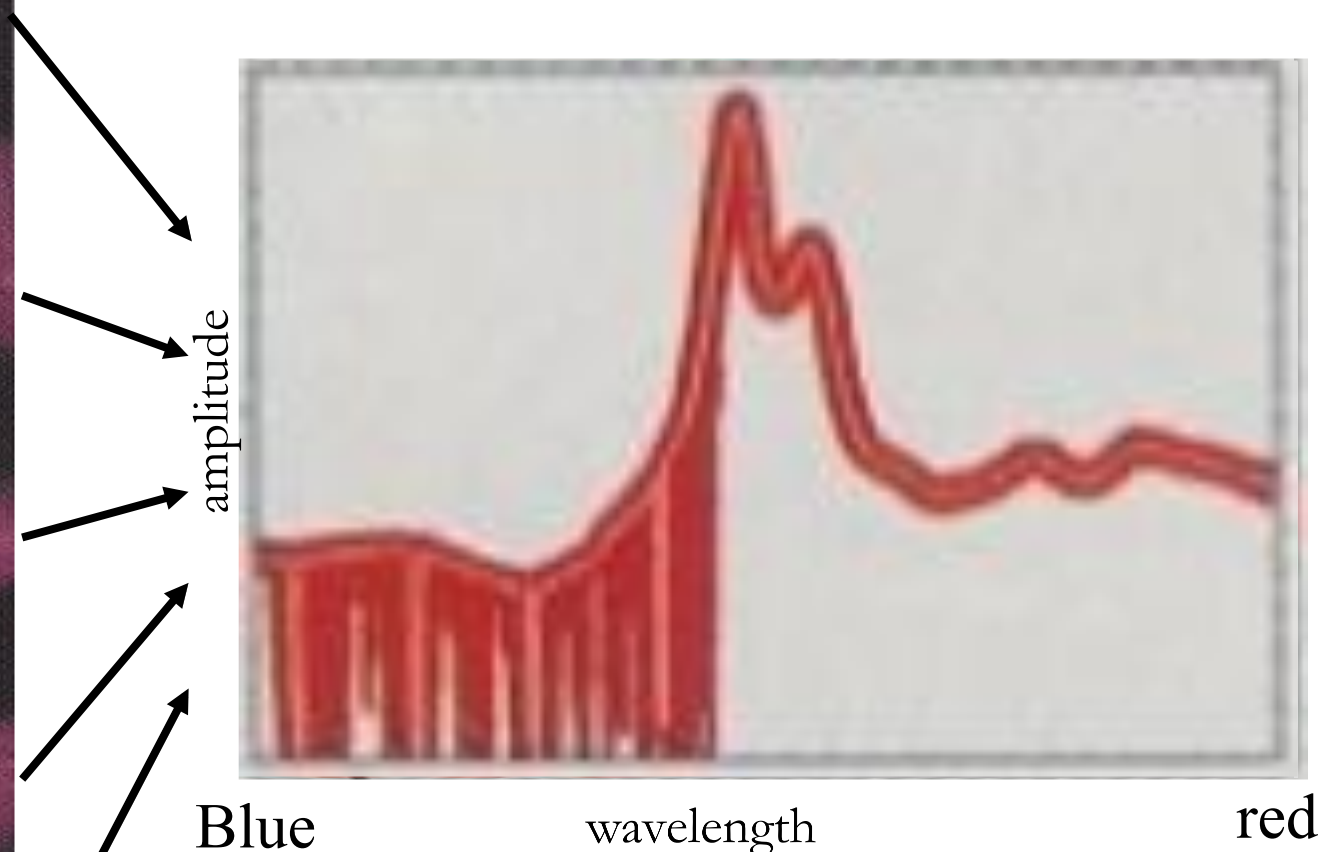
Caveats: meteorites datation / averaged value

Quasar absorption spectra

Spectres d’absorption de quasars



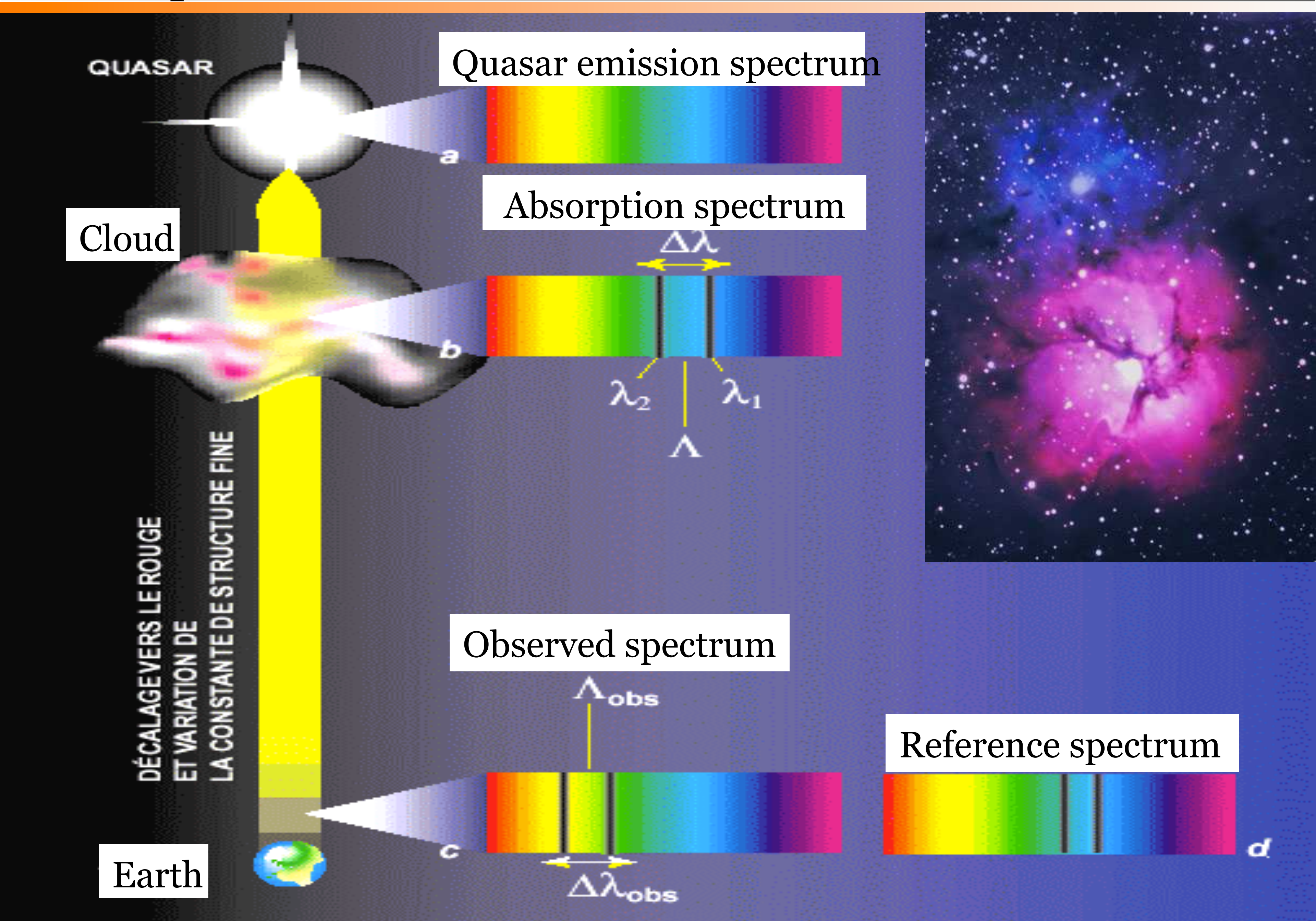
Absorption spectra



Cosmic expansion redshift all spectra (achromatic)

We look for achromatic effects

Paleo-spectra



Generalities

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

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

e.g. SiIV @ z>1.3, FeIIl1608 @ z>1

Radio observations are also very important

e.g. hyperfine splitting (HI21cm), molecular rotation, lambda doubling, ...
- offer high spectral resolution (<1km/s)
- higher sensitivity to variation of constants
- isotopic lines observed separately (while blending in optical observations)

Shift to be detected are small

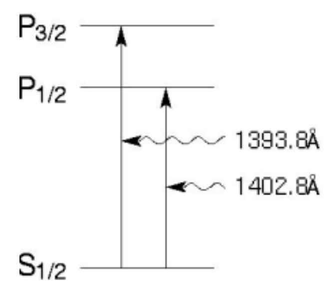
e.g. a change of a of 10^{-5} corresponds to
- a shift of 20 mÅ (i.e. of 0.5 km/s) at z~2
- ⅓ of a pixel at R=40000 (Keck/HIRES, VLT/UVES)

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

QSO absorption spectra

3 main methods:

Si IV alkali doublet



Alkali doublet (AD) Savedoff 1956

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

Single atom

Rather weak limit

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

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

Chand et al. 2004

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

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

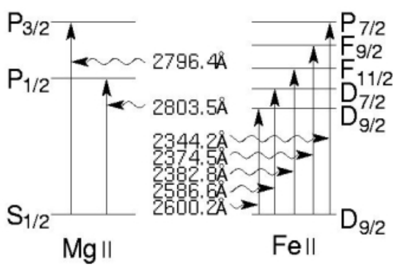
Murphy et al. 2001

Many multiplet (MM) Webb et al. 1999

Compares transitions from multiplet and/or atom

s-p vs d-p transitions in heavy elements

Better sensitivity



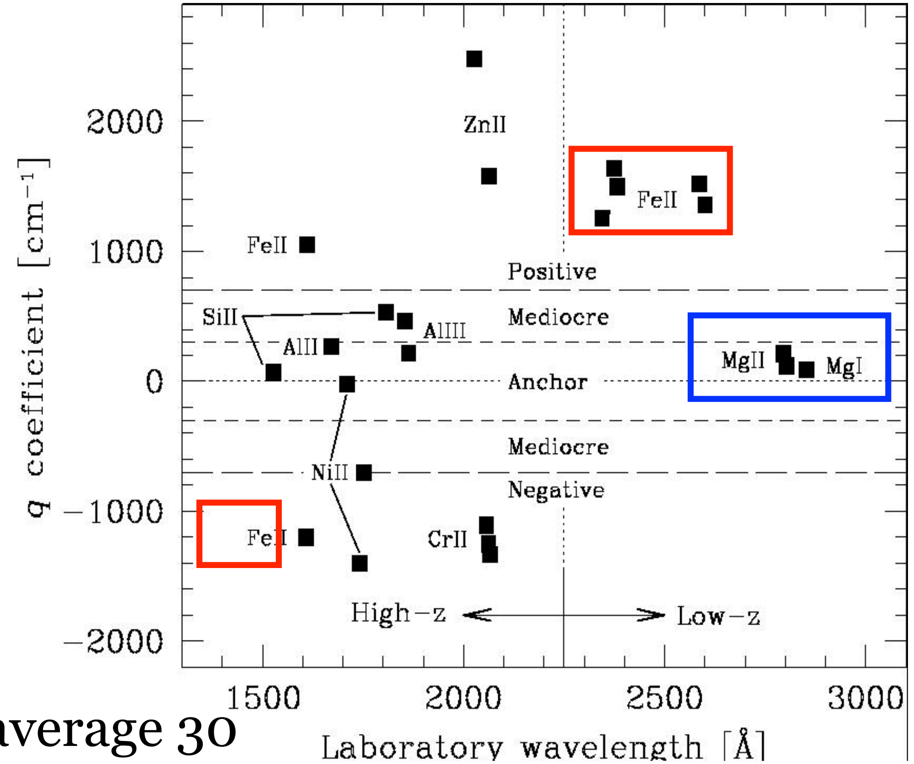
Single Ion Differential α Measurement (SIDAM) Levshakov et al. 1999

Analog to MM but with a single atom / FeII

QSO: many multiplets

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

Dzuba et al. 1999-2005



Relativistic N-body with varying α:

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

First implemented on 30 systems with MgII and FeII

Webb et al. 1999

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

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

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

Murphy et al. 2004

5σ detection !

QSO: uncertainties

- Error in the determination of laboratory spectra
- Different atoms may not be located in the same part of the cloud (relative Doppler)
- Lines may be blended by transitions in another system
- Variation of velocity of the Earth during integration can induce a differential Doppler shift
- Atmospheric dispersion
- Magnetic fields in the clouds
- Temperature variation during the integration
- Instrumental effects (e.g. variation of the intrinsic profile of the instrument)

Isotopic abundance of MgII (used as an anchor)

- affects the value of the effective rest-wavelengths
- assumed to be close to terrestrial $^{24}Mg{:}^{25}Mg{:}^{26}Mg=79{:}10{:}11$
- $r=(26+25)/24$ cannot be measured directly
- from molecular absorption of MgH: r decreases with metallicity
- But r found to be high in giant stars in NGC6752
- Ashenfelter et al proposed a enhancement of r from stars in (2-8)M_{sun} in their asymptotic giant branch phase
- If $r=0.62$ instead of $r=0.27$, then no variation of α
- But overproduction of P, Si, Al

QSO: VLT/UVES analysis

Selection of the absorption spectra:

- lines with similar ionization potentials

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

  redshift measurement is robust
- reject strongly saturated systems

Only 23 systems

lower statistics / better controlled systematics

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

VLT/UVES

$$\frac{\Delta\alpha}{\alpha} = (-0.01 \pm 0.15) \times 10^{-5}$$

Srianand et al. 2007

DOES NOT CONFIRM HIRES/Keck DETECTION

Going further

Other transitions:

- HI21cm vs UV of heavy element transitions: $\alpha^2 g_p/\mu$

- HI vs molecular transitions (CO, HCO+, HCN): $g_p\alpha^2$

- OH18cm: ground state $^2\Pi_{3/2}J=3/2$ of OH is split in 2 levels further split in 2 hyperfine states,

  It constrains $g_p(\alpha^2\mu)^{1.57}$

- FIR fine-structure lines (CO) $\alpha^2\mu$

- Conjugate OH lines (emission+absorption lines with same shape): $g_p(\alpha\mu)^{1.85}$

- Molecular lines (H_2, NH_3, HD): μ

Table 10: Summary of the latest constraints on the variation of fundamental constants obtained from the analysis of quasar absorption spectra. We recall that $y \equiv g_{\rm p}\alpha_{\rm EM}^2$, $F \equiv g_{\rm p}(\alpha_{\rm EM}^2\mu)^{1.57}$, $x \equiv \alpha_{\rm EM}^2 g_{\rm p}/\mu$, $F' \equiv \alpha_{\rm EM}^2\mu$ and $\mu \equiv m_{\rm p}/m_{\rm e}$, $G = g_{\rm p}(\alpha\mu)^{1.85}$.

Constant	Method	System	Constraint ($\times 10^{-5}$)	Redshift	Ref.
$\alpha_{\rm EM}$	AD	21	(-0.5 ± 1.3)	2.33 – 3.08	[366]
	AD	15	(-0.15 ± 0.43)	1.59 – 2.92	[87]
	AD	9	(-3.09 ± 8.46)	1.19 – 1.84	[339]
	MM	143	(-0.57 ± 0.11)	0.2 – 4.2	[356]
	MM	21	(0.01 ± 0.15)	0.4 – 2.3	[86]
	SIDAM	1	(-0.012 ± 0.179)	1.15	[351]
	SIDAM	1	(0.566 ± 0.267)	1.84	[351]
y	HI - mol	1	(-0.16 ± 0.54)	0.6847	[364]
	HI - mol	1	(-0.2 ± 0.44)	0.247	[364]
	CO, CHO^+		(-4 ± 6)	0.247	[519]
F	OH - HI	1	$(-0.44 \pm 0.36 \pm 1.0_{\rm syst})$	0.765	[266]
	OH - HI	1	(0.51 ± 1.26)	0.2467	[134]
x	HI - UV	9	(-0.63 ± 0.99)	0.23 – 2.35	[479]
	HI - UV	2	$-(0.17 \pm 0.17)$	3.174	[457]
F'	CII - CO	1	(1 ± 10)	4.69	[316]
	CII - CO	1	(14 ± 15)	6.42	[316]
G	OH	1	< 1.1	0.247, 0.765	[91]
	OH	1	< 1.16	0.0018	[91]
	OH	1	(-1.18 ± 0.46)	0.247	[268]
μ	H_2	1	(2.78 ± 0.88)	2.59	[417]
	H_2	1	(2.06 ± 0.79)	3.02	[417]
	H_2	1	(1.01 ± 0.62)	2.59	[281]
	H_2	1	(0.82 ± 0.74)	2.8	[281]
	H_2	1	(0.26 ± 0.30)	3.02	[281]
	H_2	1	(0.7 ± 0.8)	3.02, 2.59	[475]
	NH_3	1	< 0.18	0.685	[355]
	NH_3	1	< 0.38	0.685	[343]
	HC_3N	1	< 0.14	0.89	[243]
	HD	1	< 9	2.418	[398]
	HD	1	$(0.56 \pm 0.55_{\rm stat} \pm 0.27_{\rm syst})$	2.059	[332]

Cosmic microwave background

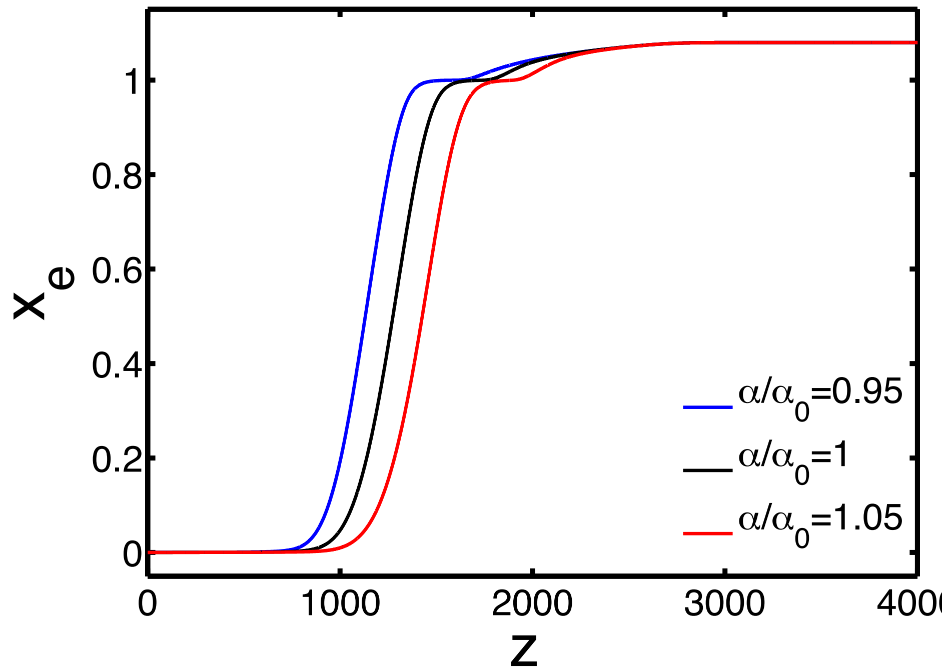
CMB

It changes the recombination history

1- modifies the optical depth

2- induces a change in the hydrogen and helium abundances (x_e)

$$\dot{\tau} = x_e n_e c \sigma_T$$



Effect on the position of the Doppler peak on polarization (reionisation)

Degeneracies:

- cosmological parameters
- electron mass
- origin of primordial fluctuations

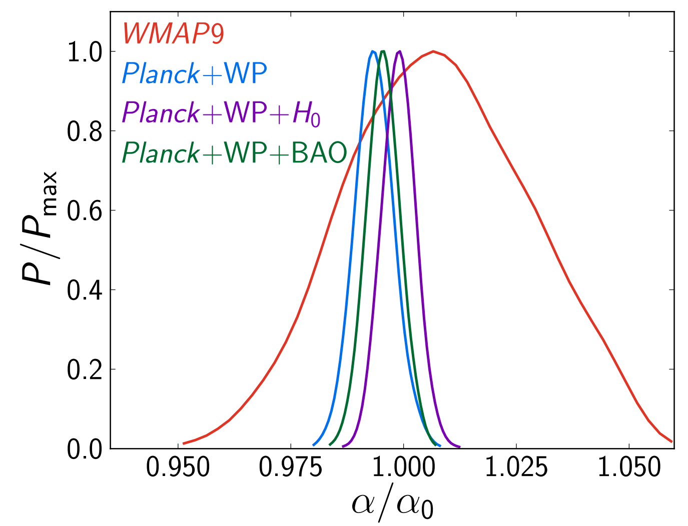
$$\sigma_T \propto \alpha^2 / m_e$$

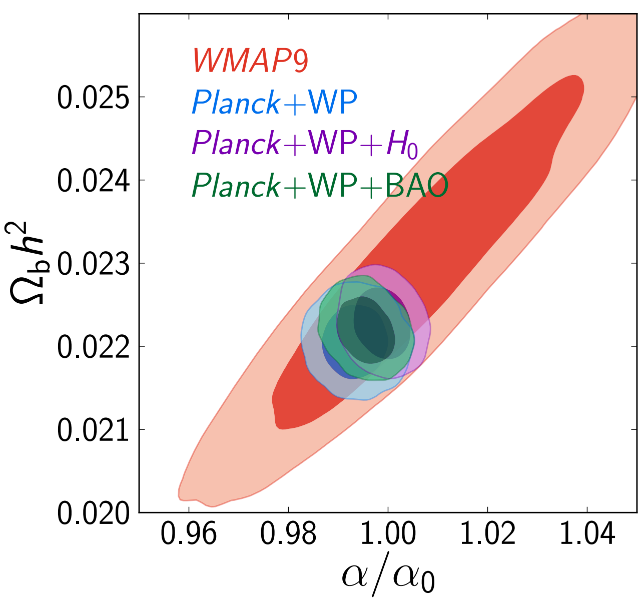
Planck analysis

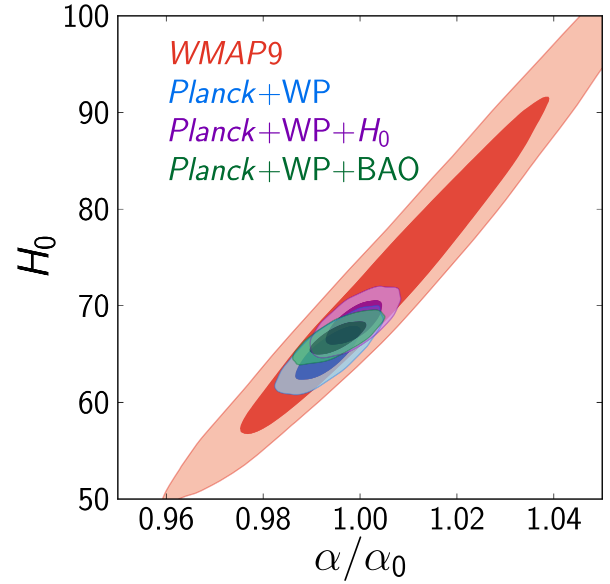
Parameters of the fit

$$(\alpha, \Omega_b, \Omega_c, H_0, n_s, A_s, \tau)$$

Marginalized distribution on α







Planck analysis

	Planck+WP	Planck+WP+Lensing	WMAP9
$\Omega_b h^2$	0.02206 ± 0.00028	0.02220 ± 0.00027	0.02309 ± 0.0013
$\Omega_c h^2$	0.1174 ± 0.0030	0.1161 ± 0.0027	0.1148 ± 0.0048
τ	0.0949 ± 0.0143	0.0949 ± 0.0145	0.089 ± 0.014
H_0	65.2 ± 1.8	66.0 ± 1.7	73.9 ± 10.9
n_s	0.9651 ± 0.0128	0.9768 ± 0.0116	0.9732 ± 0.0137
$log(10^{10} A_s)$	3.106 ± 0.029	3.102 ± 0.028	3.09 ± 0.039
α/α_0	0.9936 ± 0.0043	0.9940 ± 0.0043	1.008 ± 0.020

	Planck+WP+HST	Planck+WP+HighL	Planck+WP+BAO
$\Omega_b h^2$	0.02228 ± 0.00027	0.02210 ± 0.0027	0.02220 ± 0.0025
$\Omega_c h^2$	0.1166 ± 0.0030	0.1185 ± 0.0031	0.1161 ± 0.0028
τ	0.096 ± 0.014	0.094 ± 0.015	0.097 ± 0.014
H_0	68.3 ± 1.5	66.2 ± 1.6	66.7 ± 1.1
n_s	0.9695 ± 0.0115	0.9666 ± 0.0114	0.9748 ± 0.0118
$log(10^{10} A_s)$	3.097 ± 0.028	3.10 ± 0.029	3.10 ± 0.029
α/α_0	0.9989 ± 0.0037	0.9965 ± 0.037	0.9955 ± 0.038

Big bang nucleosynthesis

BBN: generality

BBN predicts the primordial abundances of D, He-3, He-4, Li-7

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

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

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

$$(B_D, \eta)$$

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

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

Scalar-tensor theories

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

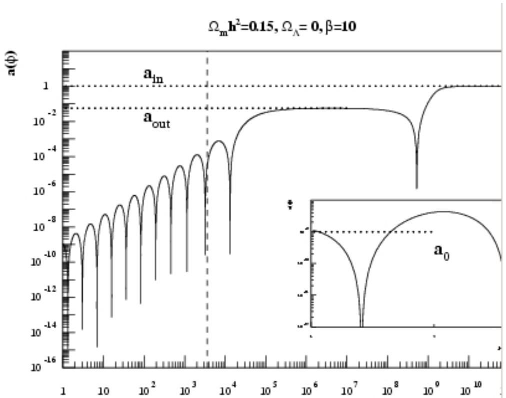
spin 0

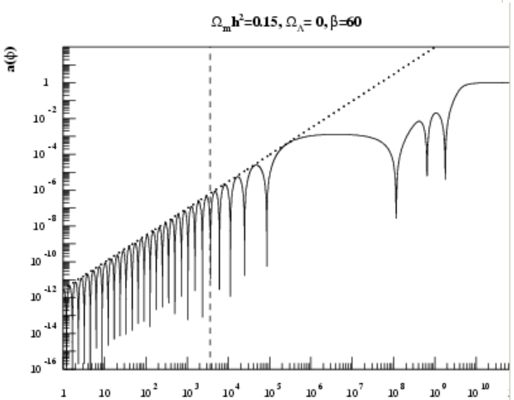
$$S = \frac{c^3}{16\pi G}\int\sqrt{-g}\{R - 2(\partial_\mu\phi)^2 - V(\phi)\} + S_m\{\mathrm{matter}, \tilde{g}_{\mu\nu} = A^2(\phi) g_{\mu\nu}\}$$

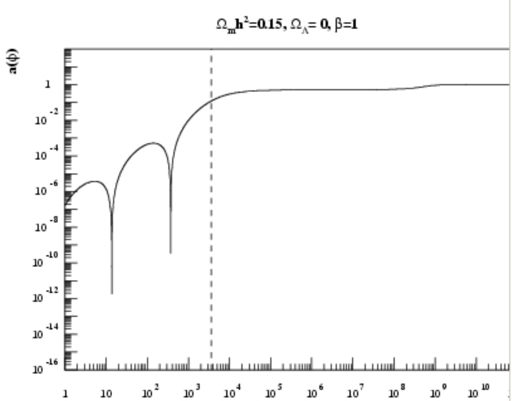
$$\alpha = \mathrm{d}\ln A/\mathrm{d}\phi \qquad \beta = \mathrm{d}\alpha/\mathrm{d}\phi$$

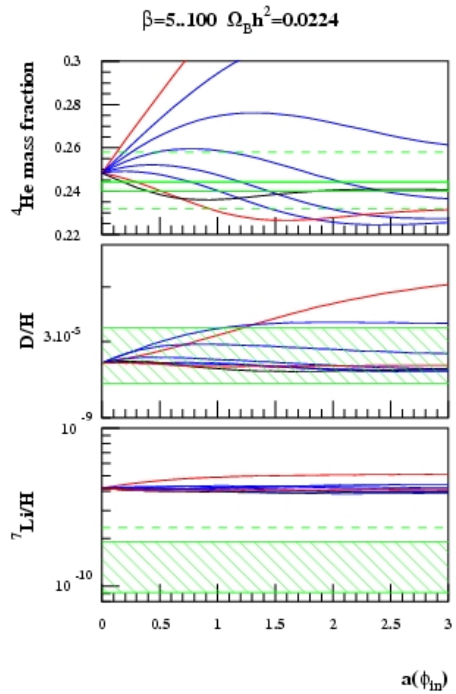
BBN constraints

Full dynamics ⟶ Abundances ⟶ constraints



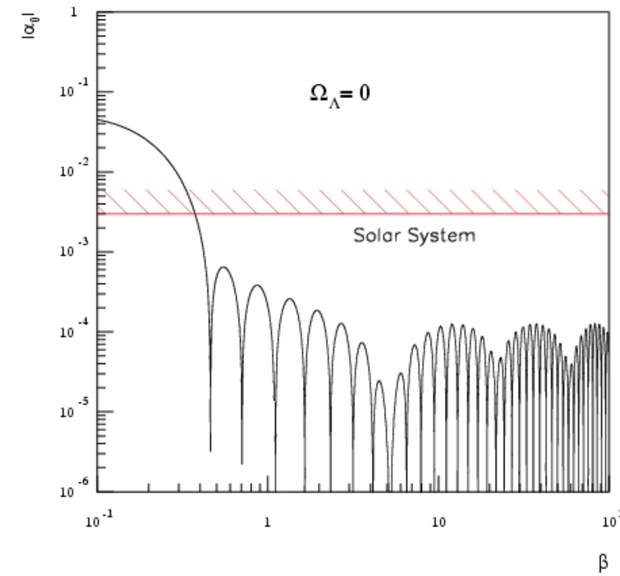


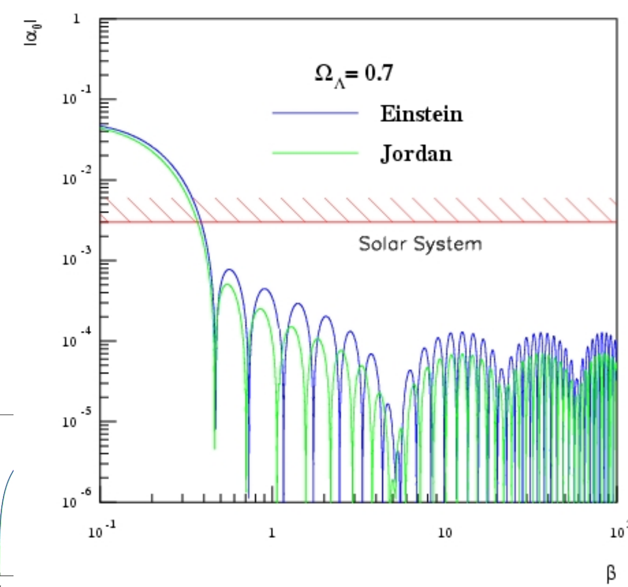




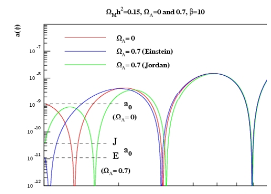
a_{in}/a_{out} relation not injective

Max value of α_0 but not all α_0 smaller are acceptable





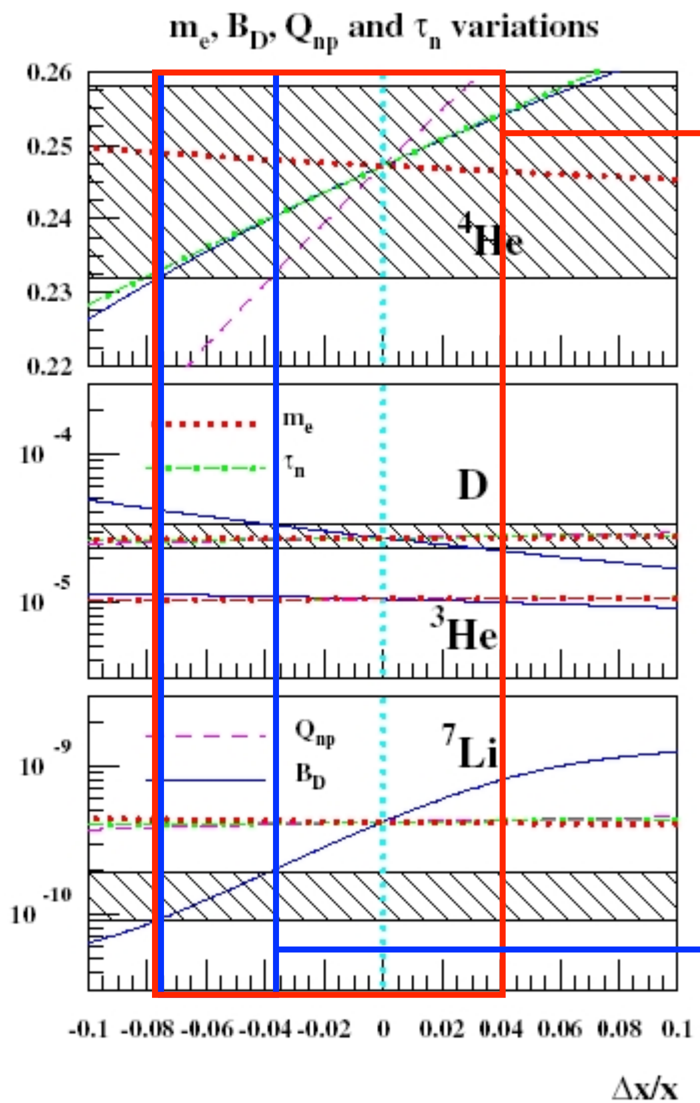
Late time dynamics modified



Coc et al. 2006
Pichon, Damour

BBN: effective BBN 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.

$$-7.5\times10^{-2} < \frac{\Delta B_D}{B_D} < -4\times10^{-2}$$

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

Most important parameter beside Λ is the strange quark mass.
One needs to trace the dependence in m_s.

$$\frac{\Delta m_\sigma}{m_\sigma} \sim 0.54\frac{\Delta m_s}{m_s}$$

$$\frac{\Delta m_\omega}{m_\omega} \sim 0.15\frac{\Delta m_s}{m_s}$$

$$\frac{\Delta m_N}{m_N} \sim 0.12\frac{\Delta m_s}{m_s}$$

$$\frac{\Delta B_D}{B_D} = 18\frac{\Delta\Lambda}{\Lambda} - 17\left(\frac{\Delta v}{v} + \frac{\Delta h_s}{h_s}\right)$$

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

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

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

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

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

Stellar physics

Stellar carbon production

Triple α coincidence (Hoyle)

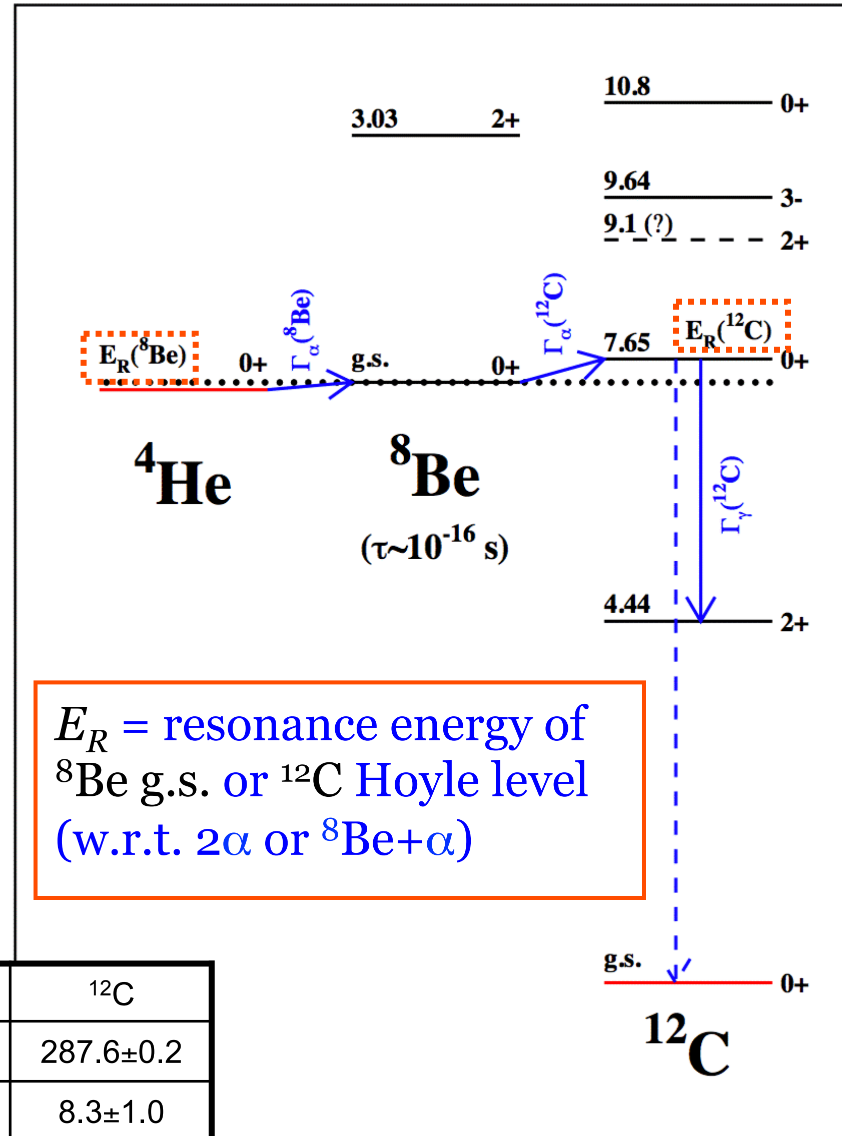
1. Equillibrium between ^{4}He and the short lived (~10^{-16} s) ^{8}Be : $\alpha\alpha \leftrightarrow {}^8$Be
2. Resonant capture to the (l=0, J^π=0$^+$) Hoyle state: $^8\mathrm{Be}+\alpha \rightarrow {}^{12}\mathrm{C}^*(\rightarrow {}^{12}\mathrm{C}+\gamma)$

Simple formula used in previous studies

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

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

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

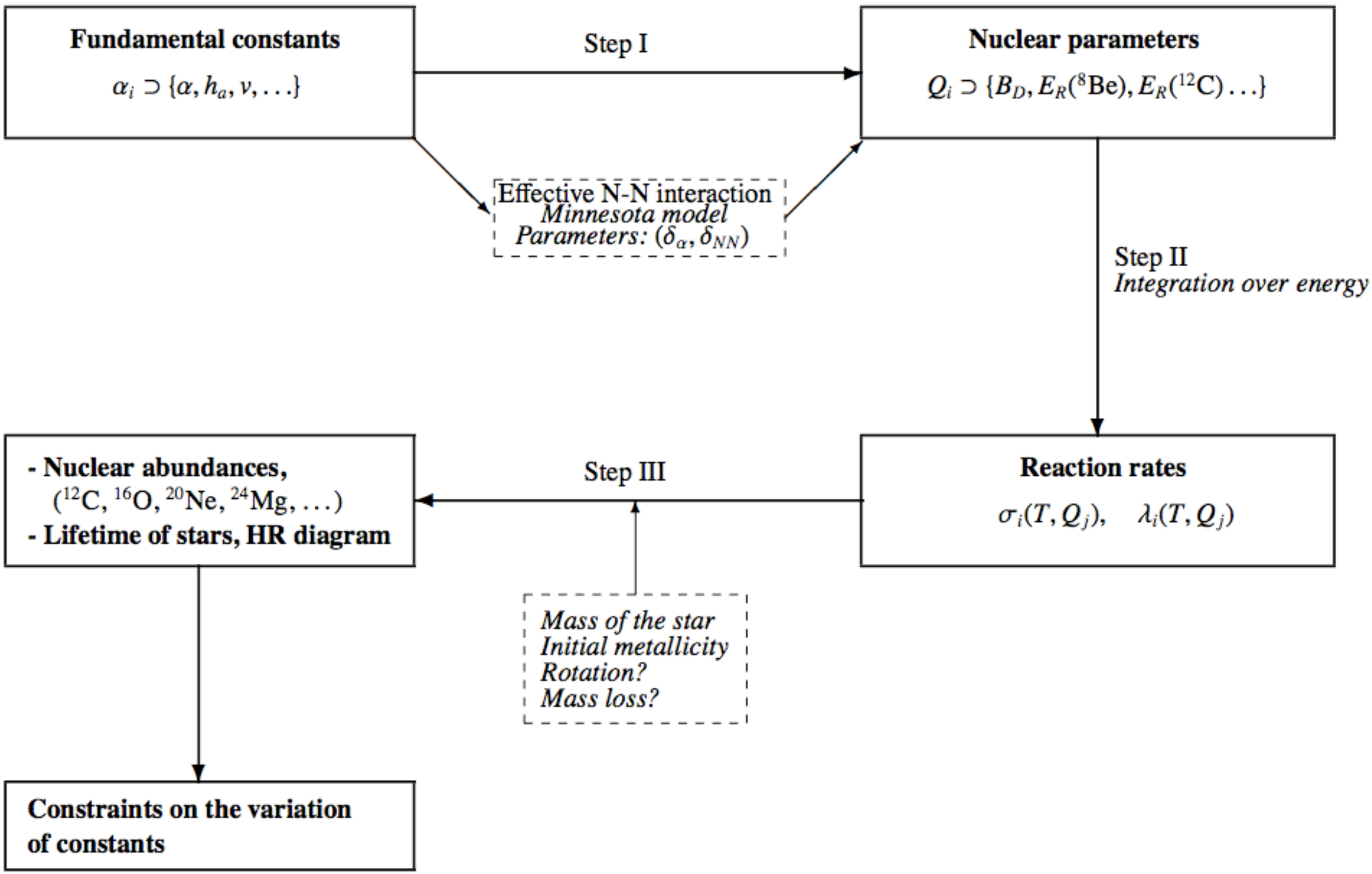


E_R = resonance energy of ^{8}Be g.s. or ^{12}C Hoyle level (w.r.t. 2α or ^{8}Be+α)

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]

Modelisation



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

Microscopic calculation

- Hamiltonian:

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

Where $V_{Nucl.}(r_{ij})$ is an effective Nucleon-Nucleon interaction

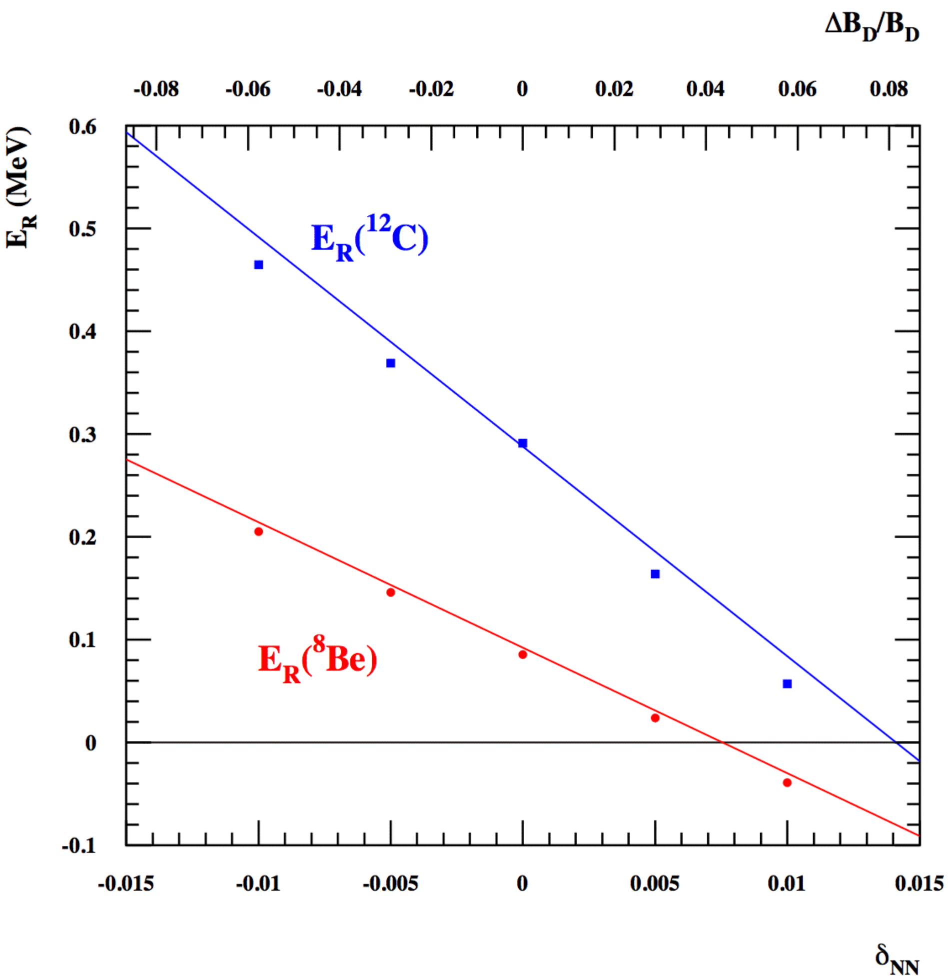
- Minnesota N-N force *[Thompson et al. 1977]* optimized to reproduce low energy N-N scattering data.

- α-cluster approximation for $^{8}Be^{g.s.}$ (2α) and the Hoyle state (3α) *[Kamimura 1981]*

- Scaling of the N-N interaction

$$V_{Nucl.}(r_{ij}) \rightarrow (1+\delta_{NN}) \times V_{Nucl.}(r_{ij})$$

to obtain B_D, $E_R(^{8}Be)$, $E_R(^{12}C)$ as a function of δ_{NN} :

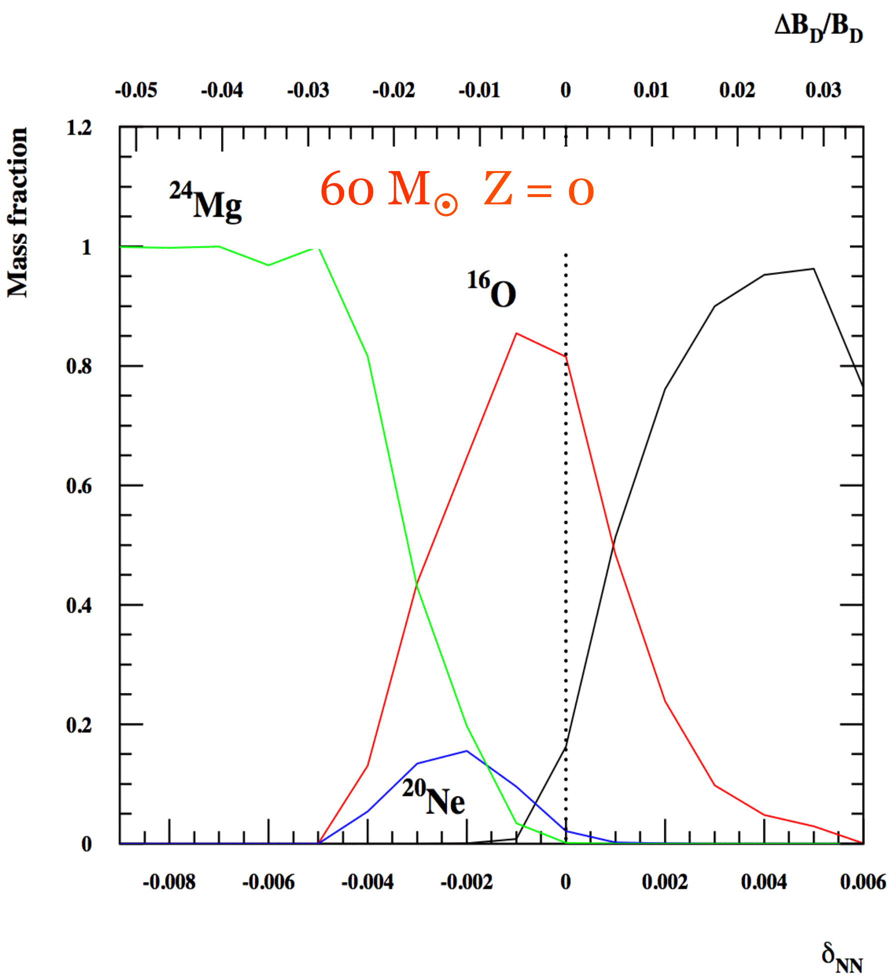


- Link to fundamental couplings through B_D or δ_{NN}

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

Constraints

From stellar evolution of zero metallicity 15 and 60 $M_\odot$ at redshift z = 10 - 15

- Excluding a core dominated by ^{24}Mg $\Rightarrow \delta_{NN} > -0.005$

  or $\Delta B_D/B_D > -0.029$

- Excluding a core dominated by ^{12}C $\Rightarrow \delta_{NN} < 0.003$

  or $\Delta B_D/B_D < 0.017$

- Requiring ^{12}C/^{16}O close to unity $\Rightarrow -0.0005 < \delta_{NN} < 0.0015$

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

$$\Delta B_D/B_D \approx 5.77 \times \delta_{NN}$$

Conservative constraint on Nucleosynthesis

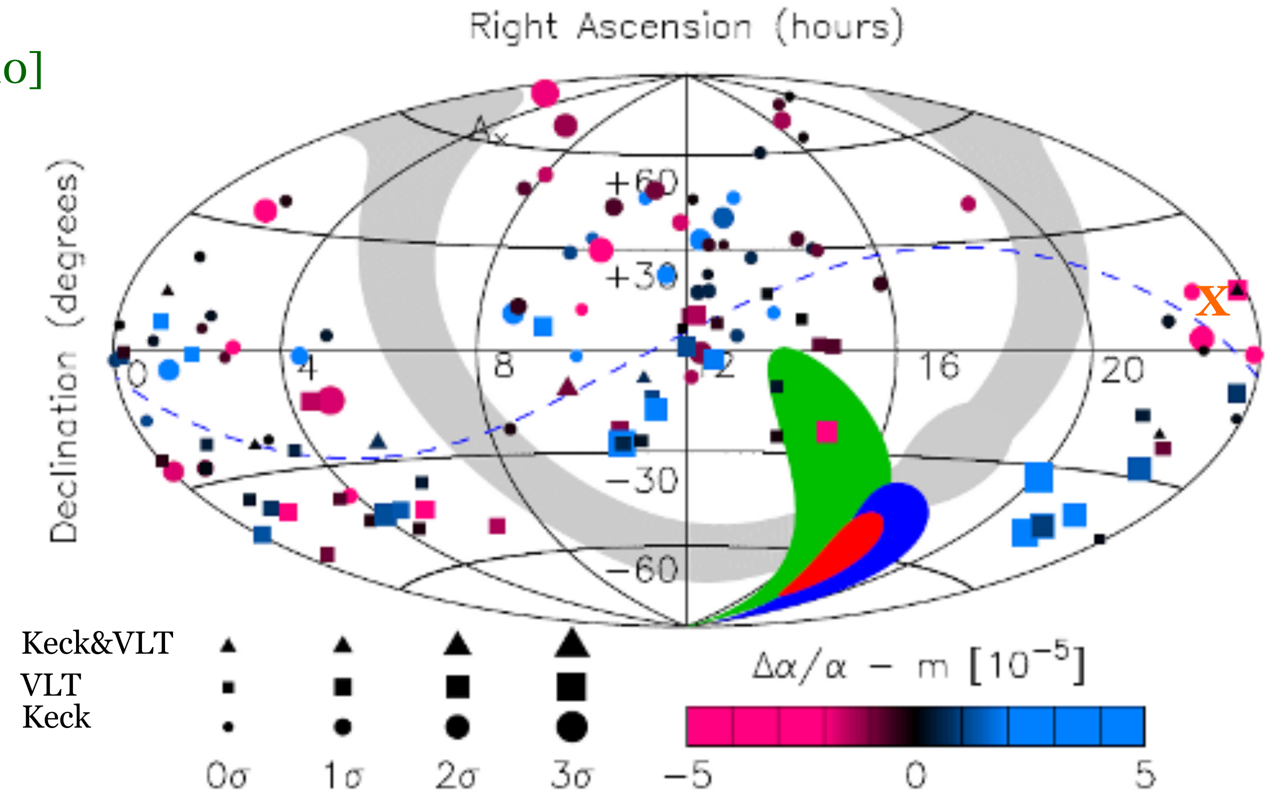
^{12}C/^{16}O ~1 $\Rightarrow -0.0005 < \delta_{NN} < 0.0015$

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

Spatial variations

To vary or not to vary

[Webb et al., 2010]



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

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

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

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

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

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

Planck analysis

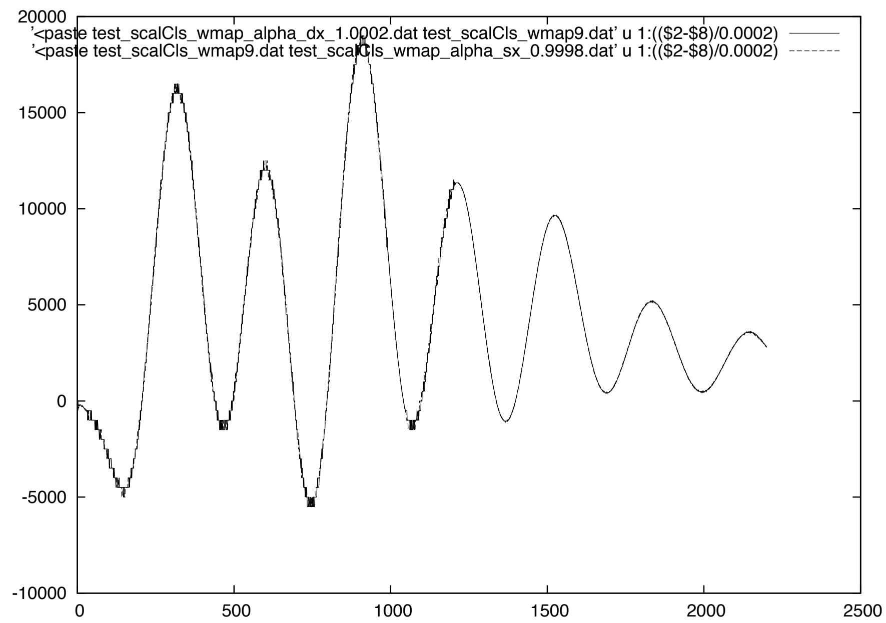
$$\Theta(\mathbf{n}) = \bar{\Theta}[\mathbf{n}, c_a(\mathbf{n})]$$
$$= \bar{\Theta}\left[\mathbf{n}, c_{0a} + \sum_{i=-1}^{1} \delta c_a^{(i)}(z) Y_{1i}(\mathbf{n})\right]$$
$$\simeq \bar{\Theta}[\mathbf{n}] + \sum_a \sum_{i=-1}^{+1} \frac{\partial \bar{\Theta}[\mathbf{n}]}{\partial c_a} \delta c_a^{(i)}(z)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

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

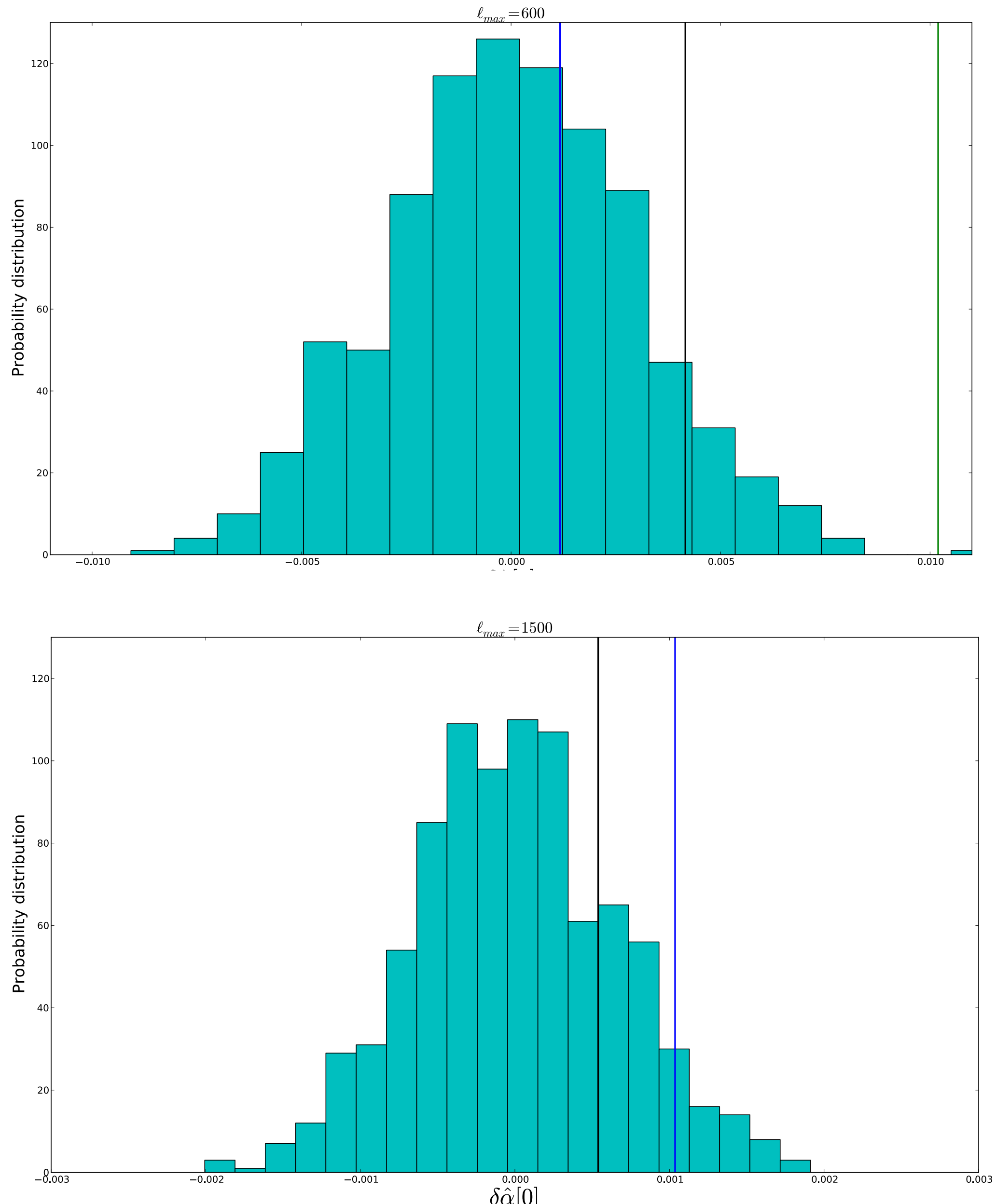
Mode coupling: $D_{\ell m}^{(i)} \equiv \langle a_{\ell m}\, a^*_{\ell+1 m+i} \rangle$

$$D_{\ell m}^{(i)} = f_i(\ell, m) \sum_a \delta c_a^{(i)} \Gamma_\ell^{(a)}$$

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



Planck analysis

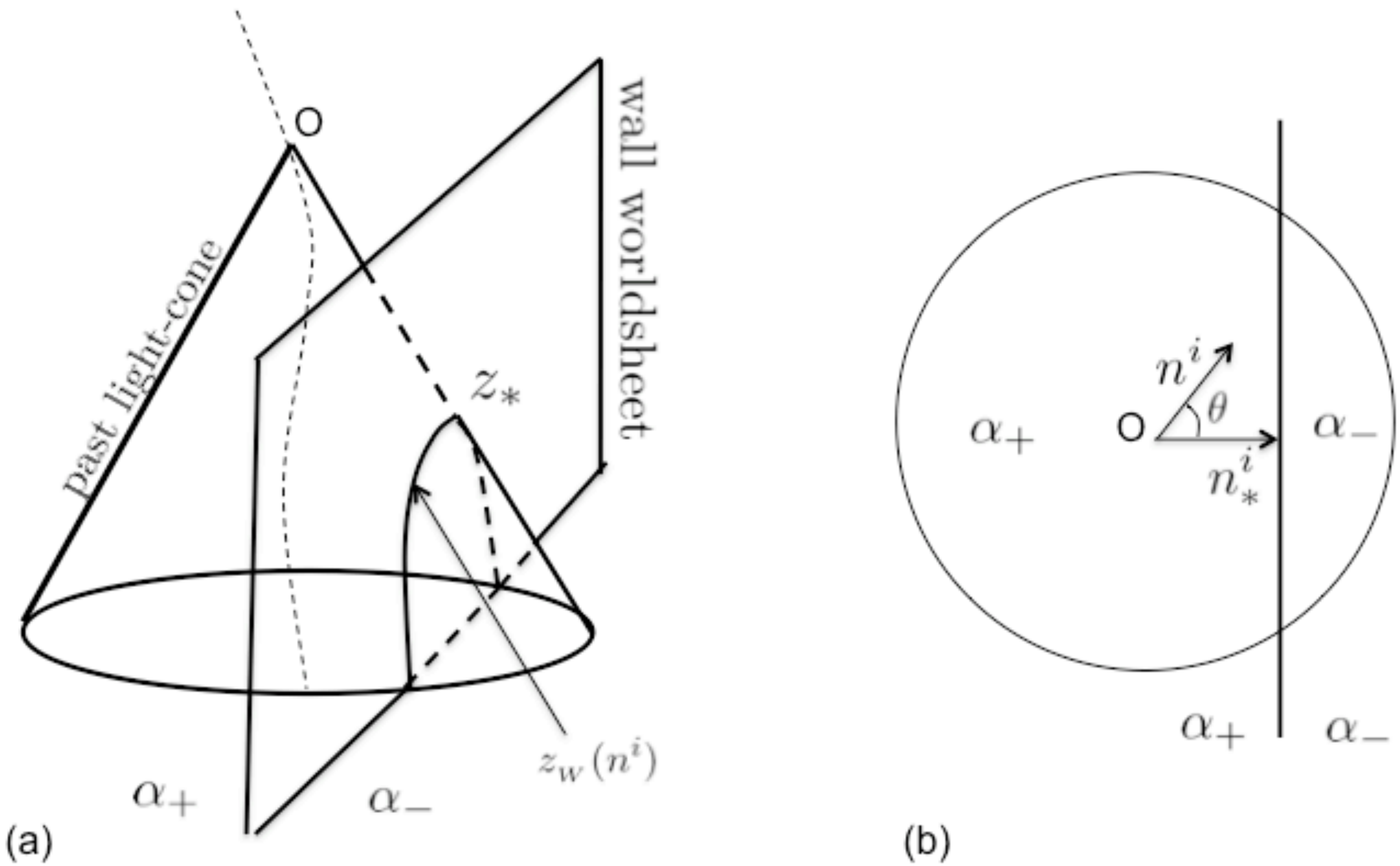


[Fabre *et al* (Planck collaboration)]

Wall of fundamental constant

[Olive, Peloso, JPU, 2010]

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



Wall of fundamental constants

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

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

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

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

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

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

Constraints

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

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

- To reproduce the «observations»

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

- The contribution of the walls to the background energy is

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

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

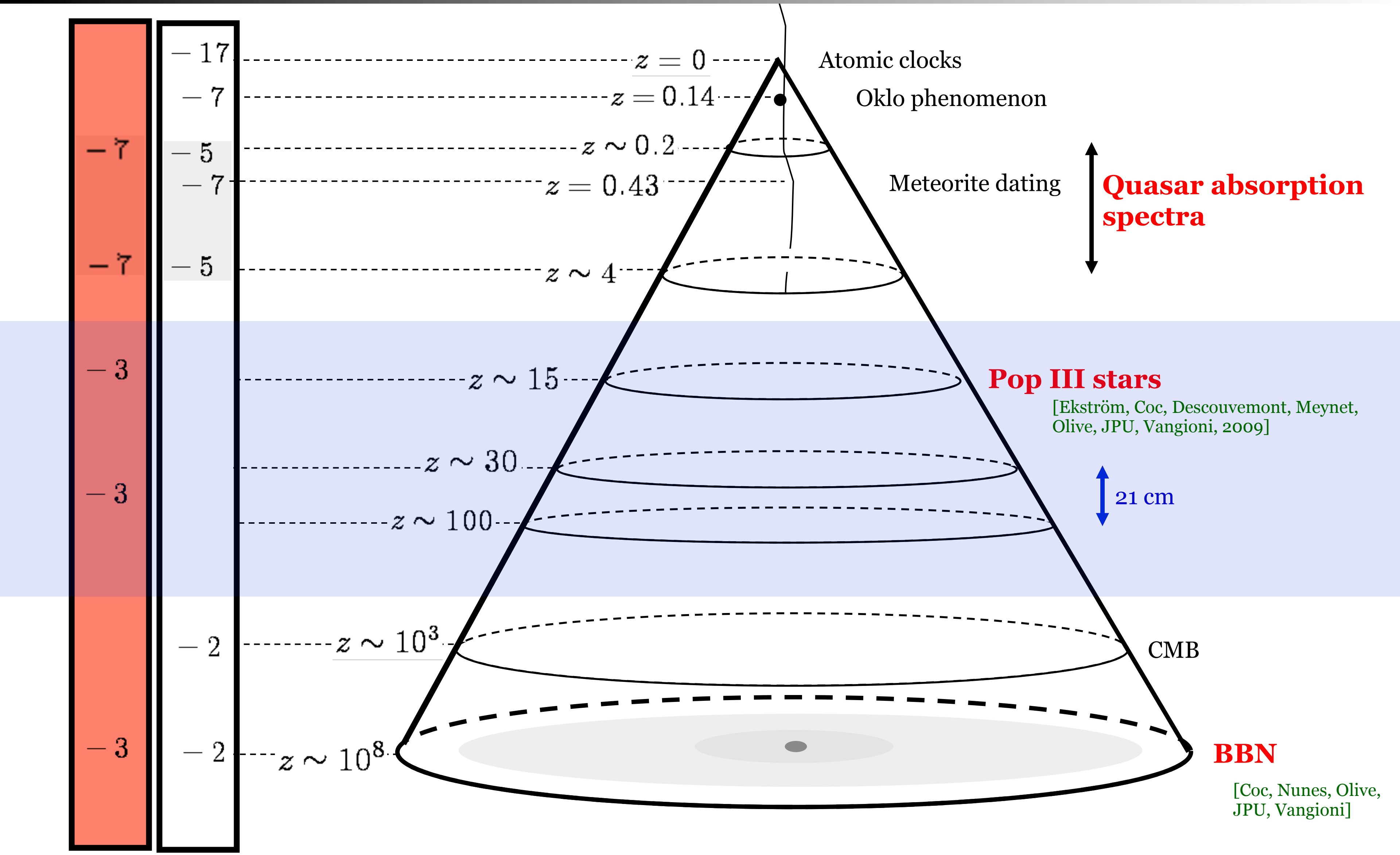
- CMB constraints $$\left(\frac{\delta T}{T}\right)_{\rm CMB} \sim 10^{-6}\left(\frac{\eta}{1\ \text{MeV}}\right)^3.$$

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

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

Future

Physical systems: new and future



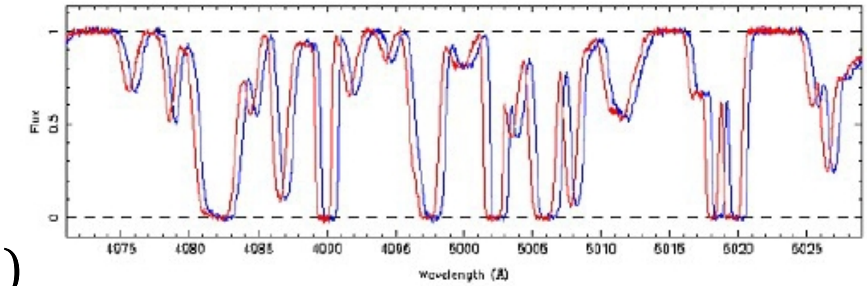
JPU, Liv. Rev. Relat. **100** (2010) 1, arXiv:1009.5514

CODEX: COsmic Dynamics EXperiment

Time drift of the redshifts

$$\Delta\lambda = \frac{\Delta t}{1+z}\left[H_0(1+z) - H(z)\right]\lambda_0$$

Given the cosmological parameters
shift of 10^{-6}/an

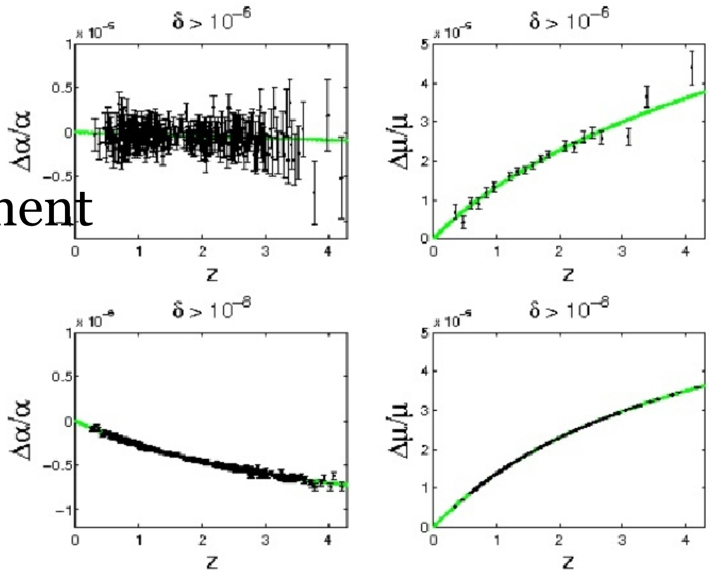


CODEX:

spectral domain: 400-680 nm
R=150000
10-20 times HARPS on 10 years!
long term calibration (atomic clocks...)

Constants

The accuracy of a variability measurement is determined by the precision of measurement of the line positions.



Precision on α et μ: 10^{-8}
2 order of magnitude better
than VLT/UVES

Conclusions

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

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

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

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

In the case of quintessence: time variations linked to the equation of state and allow to Constrain the dynamics of the scalar field even when not dominant.

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

New systems [Stellar physics] / new observations