Variation des constantes

Progrès des méthodes astrophysiques et en laboratoire

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Introduction

Constants:

parameters not determined by the theory at hand.
have to be assumed constant (theory+experiment)
list depend on the actual description of the law of nature.

RG + standard model of particle physics

21 parameters

Dimensionless parameters (search for a better explanation/variation)

Testing constants:

Einstein equivalence principle – link with the universality of free fall
window on GR at astrophysical scales

Dynamical constants:

new fields to be introduces (nature-couplings)

Cosmology:

if small variation today, one needs in general slow-rolling fields

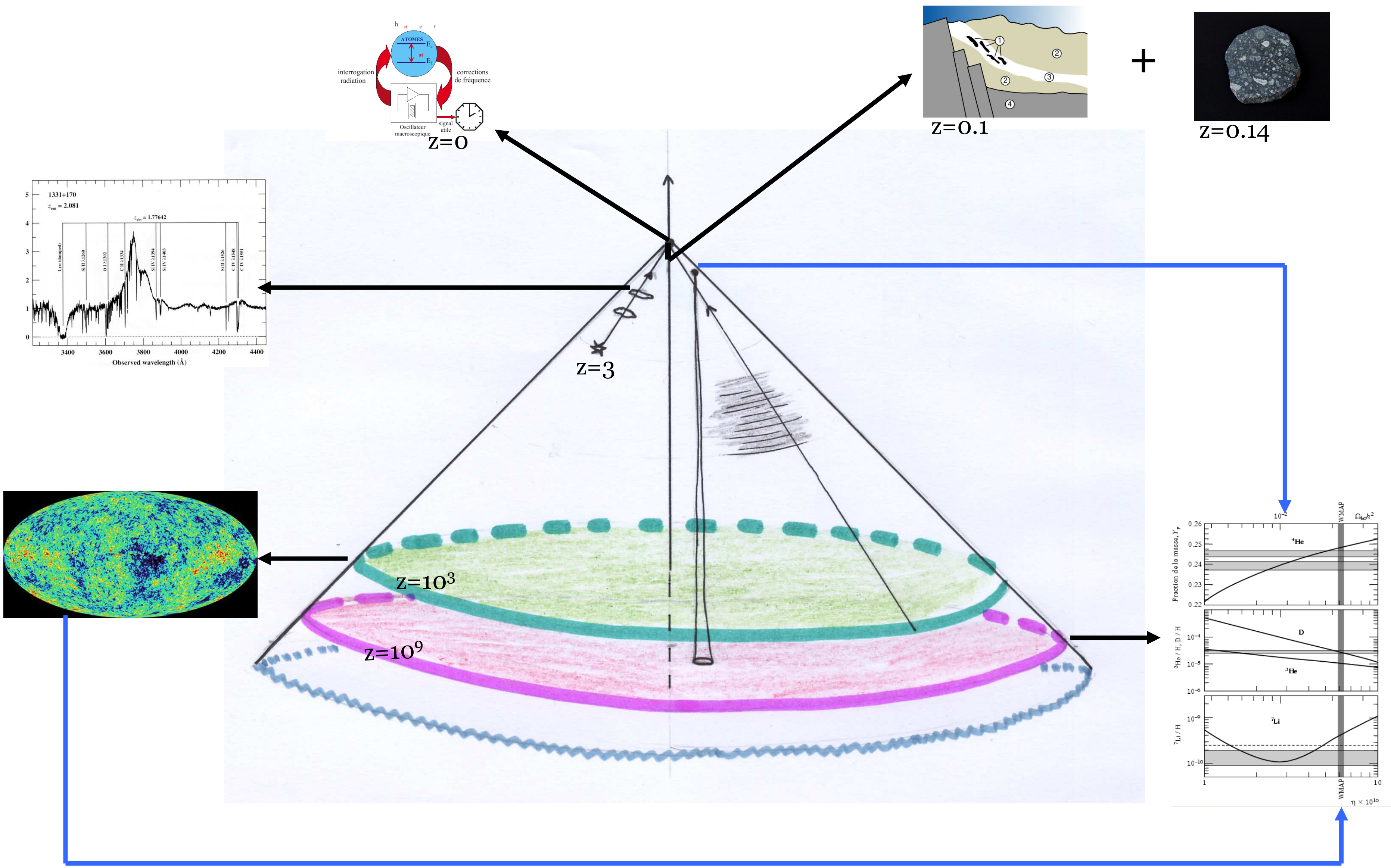
$$\ddot{\varphi} + 3H\dot{\varphi} + m^2\varphi = \ldots$$

Most works: homogeneous fields.
But may be some environment dependences.

Choices

- Overview of the observables
- Quasar absorption spectra
- Primordial nucleosynthesis
- Future observations
- Some theoretical issues

What do we observe?



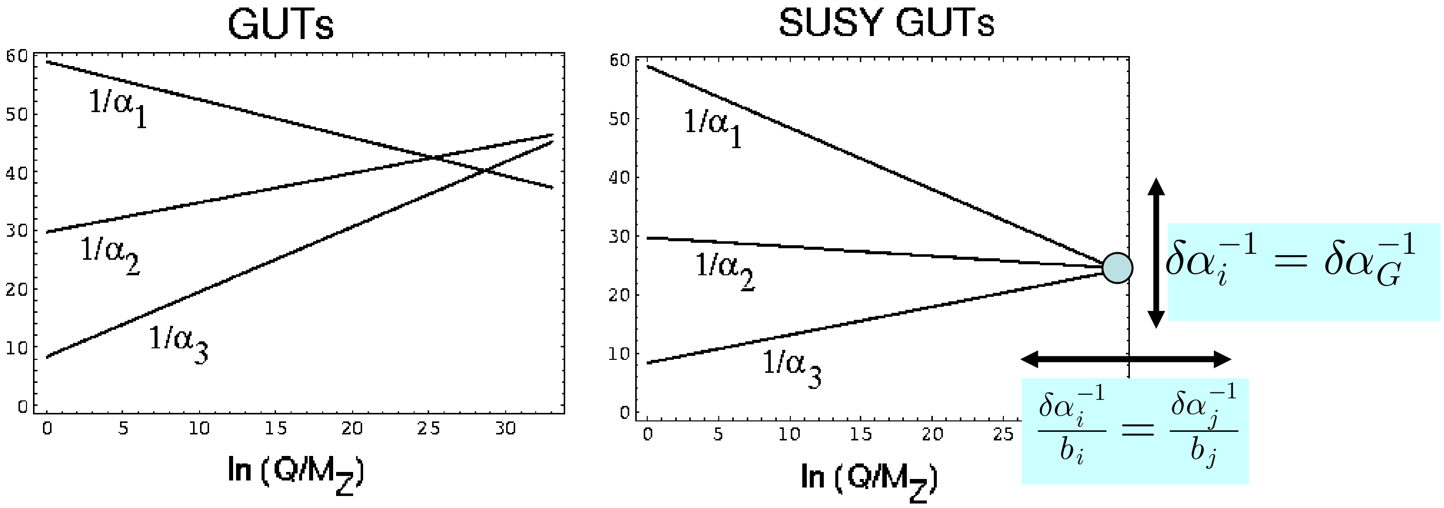
Which constants?

Generally, observables depend on <u>many</u> constants.
These constants are a priori not independent.

Example: assume grand unification

$$\alpha_i^{-1}(M_Z) = \alpha_G^{-1} + \frac{b_i}{2\pi} \ln \frac{M_{GUT}}{M_Z}$$

$$\text{SM}: \quad b_i = (41/10, -19/6, -7)$$
$$\text{MSSM}: \quad b_i = (33/5, 1, -3)$$



$$\alpha^{-1} = \frac{5}{3}\alpha_1^{-1} + \alpha_2^{-1}$$

Which constants?

Zeroth order QCD: Λ is so dominant that all parameters are porportional to Λ
Dimensionless parameters do not change!

One needs to take into account the dependence on quark masses.

Quite generally, one can reduce all parameters to

$$(\alpha, m_q, m_e)$$

Flambaum,Tedesco 2006

Most of the time, these relations are highly model dependent

I shall illustrate that on BBN

QSO

3 main methods:

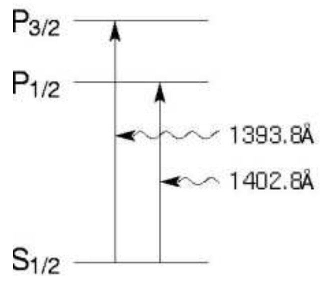
<u>*Alkali doublet (AD)*</u> Savedoff 1956

Fine structure doublet, $\frac{\Delta\nu}{\nu} \propto \alpha^2$

Single atom

Rather weak limit

Si IV alkali doublet



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

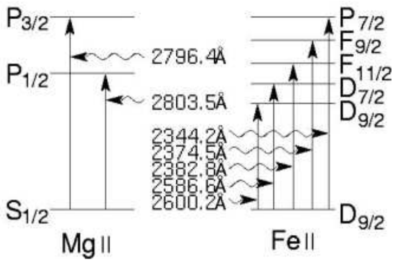
HIRES/Keck: Si IV in 21 systems, *2<z<3*

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

Murphy et al. 2001

<u>*Many multiplet (MM)*</u> Webb et al. 1999

Compares transitions from multiplet and/or atoms
s-p vs d-p transitions in heavy elements
Better sensitivity



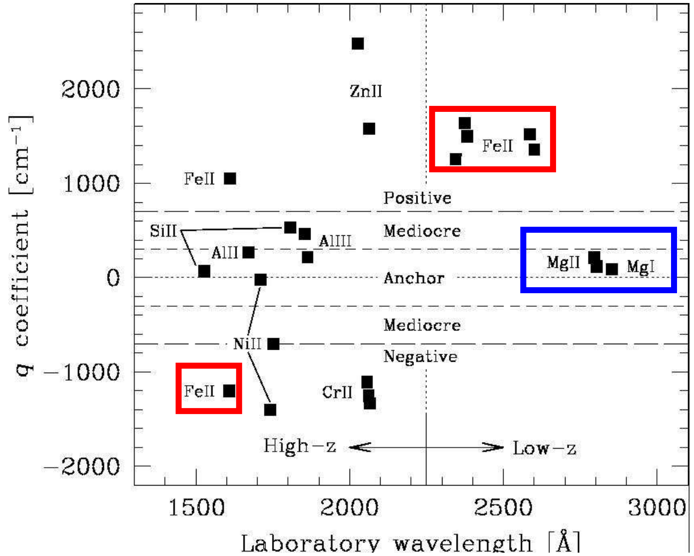
<u>*Single Ion Differential α Measurement (SIDAM)*</u> Levshakov et al. 1999

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

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

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

Murphy et al. 2004

5σ detection !

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

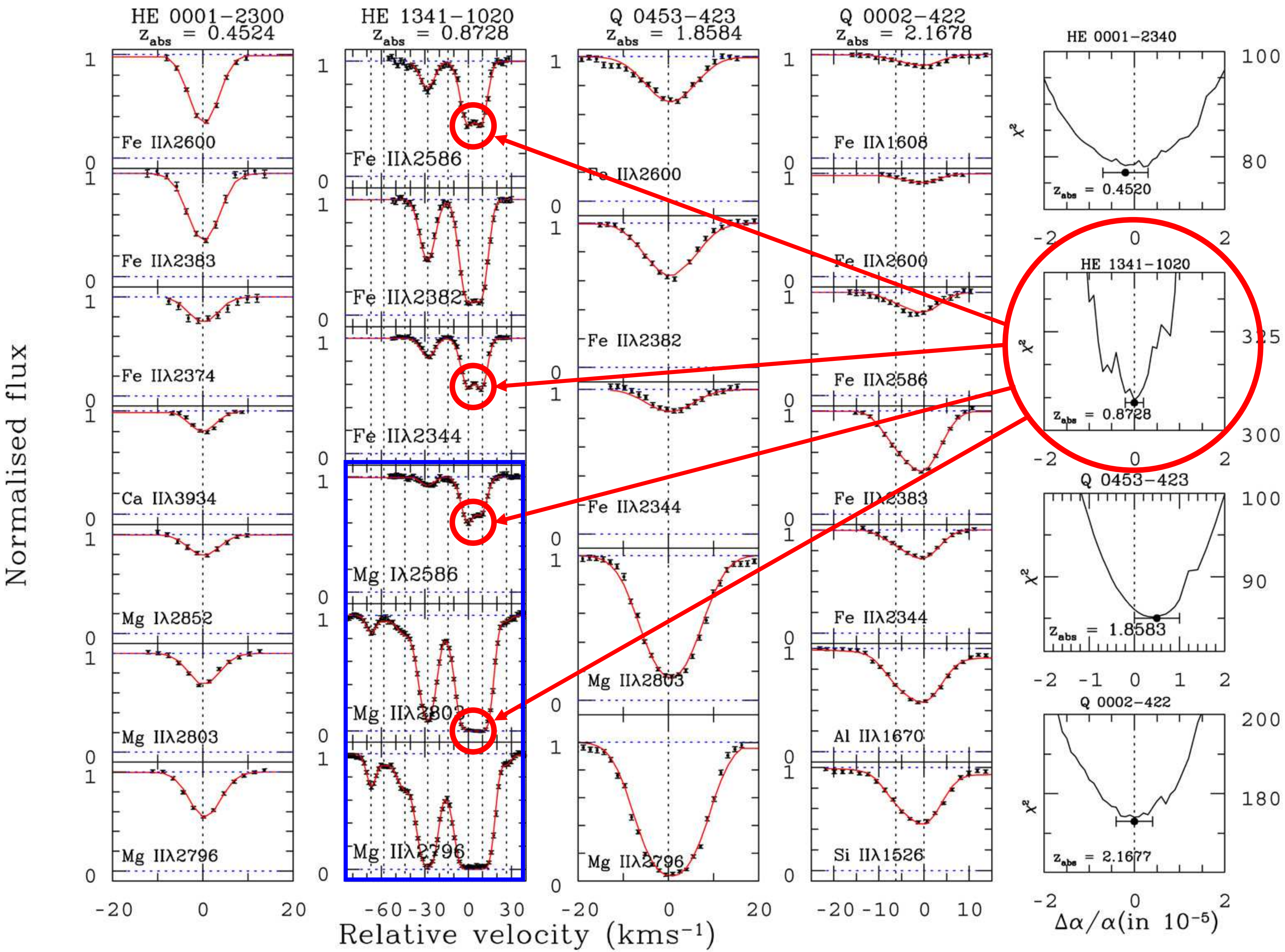
lower statistics / better controlles systematics

VLT/UVES

$$\frac{\Delta\alpha}{\alpha} = (-\,0.06 \pm 0.06) \times 10^{-5}$$

Chand et al. 2004

DOES NOT CONFIRM HIRES/Keck DETECTION



HE 0001-2300 z_{abs} = 0.4524
HE 1341-1020 z_{abs} = 0.8728
Q 0453-423 z_{abs} = 1.8584
Q 0002-422 z_{abs} = 2.1678
Fe IIλ2600
Fe IIλ2383
Fe IIλ2374
Ca IIλ3934
Mg Iλ2852
Mg IIλ2803
Mg IIλ2796
Fe IIλ2586
Fe IIλ2382
Fe IIλ2344
Mg Iλ2586
Mg IIλ2803
Mg IIλ2796
Fe IIλ2600
Fe IIλ2382
Fe IIλ2344
Mg IIλ2803
Mg IIλ2796
Fe IIλ1608
Fe IIλ2600
Fe IIλ2586
Fe IIλ2383
Fe IIλ2344
Al IIλ1670
Si IIλ1526
Normalised flux
Relative velocity (kms⁻¹)
HE 0001-2340 z_{abs} = 0.4520
HE 1341-1020 z_{abs} = 0.8728
Q 0453-423 z_{abs} = 1.8583
Q 0002-422 z_{abs} = 2.1677
χ^2
$\Delta\alpha/\alpha$(in 10^{-5})

Controversy

VLT/UVES:

selection a priori of the systems

data publicly available on the WEB

HIRES/Keck:

signal comes from only some systems

data not public

Reanalysis of the VLT/UVES data by Murphy et al.

χ^2 no smooth for some systems

argue

$$\frac{\Delta\alpha}{\alpha} = (-\,0.64 \pm 0.36) \times 10^{-5}$$

Murphy et al. 2006

χ^2 not smooth for some systems

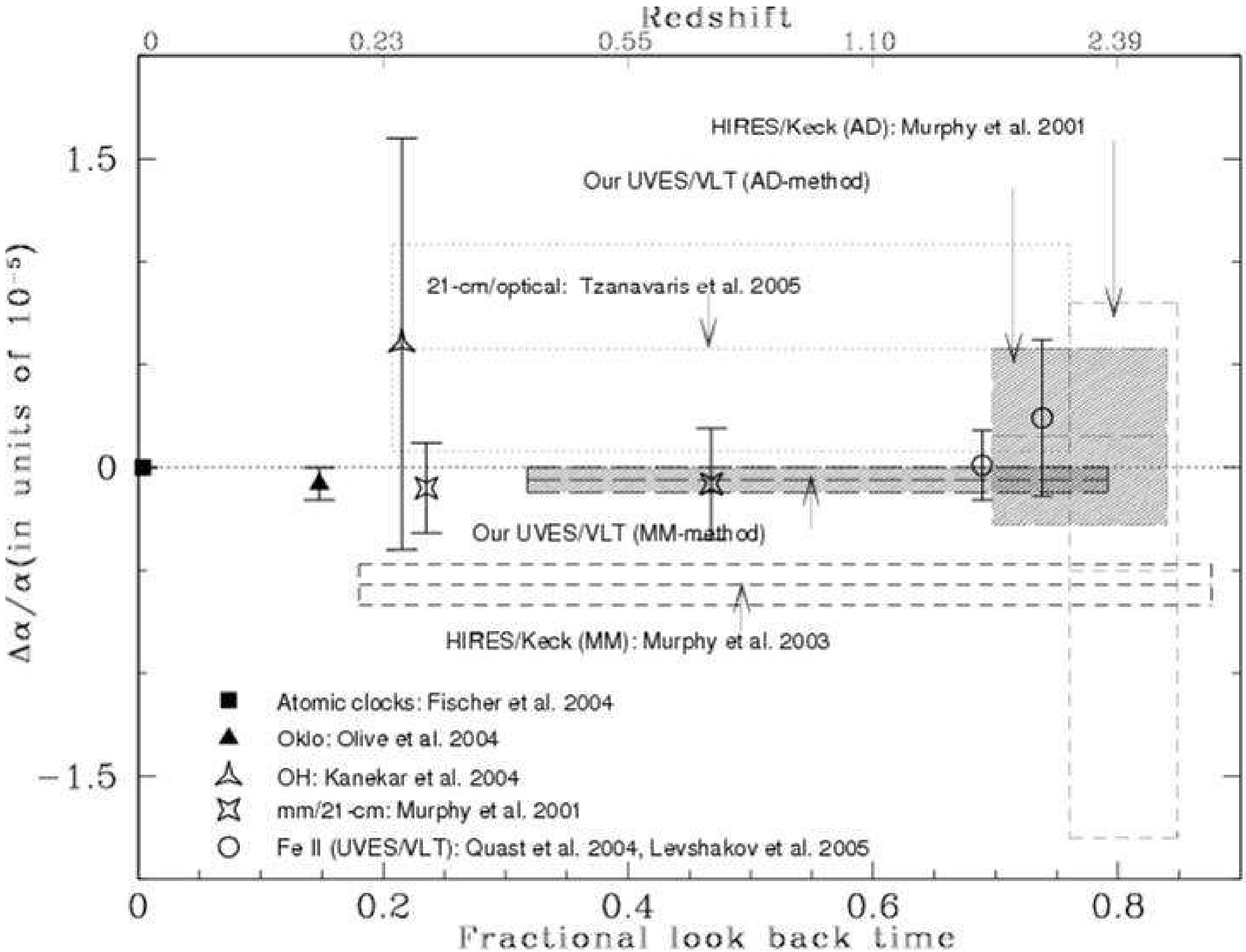
2 problematic systems that dominate the analysis

If removed

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

Srianand et al. 2007

QSO: status


Redshift
0
0.23
0.55
1.10
2.39
HIRES/Keck (AD): Murphy et al. 2001
Our UVES/VLT (AD-method)
21-cm/optical: Tzanavaris et al. 2005
Our UVES/VLT (MM-method)
HIRES/Keck (MM): Murphy et al. 2003
1.5
0
−1.5
Δα/α(in units of 10⁻⁵)
Atomic clocks: Fischer et al. 2004
Oklo: Olive et al. 2004
OH: Kanekar et al. 2004
mm/21-cm: Murphy et al. 2001
Fe II (UVES/VLT): Quast et al. 2004, Levshakov et al. 2005
0
0.2
0.4
0.6
0.8
Fractional look back time

QSO: isotopes...

Assumption in the MM analysis

- Ionization and chemical homogeneity of the different species used
- Isotopic composition of Mg

No direct measurement of r=(Mg^{25}+Mg^{26})/Mg^{24} is feasible

$$\mathrm{Mg}^{24} : \mathrm{Mg}^{25} : \mathrm{Mg}^{26} = 79 : 10 : 11$$

r is expected to decrase with metallicity

BUT, assuming $\mathrm{Mg}^{24} : \mathrm{Mg}^{25} : \mathrm{Mg}^{26} = 100 : 0 : 0$

Chand et al. 2004

$$\frac{\Delta\alpha}{\alpha} = (-\,0.06 \pm 0.06) \times 10^{-5}$$

Murphy et al. 2004

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

become

$$\frac{\Delta\alpha}{\alpha} = (-\,0.36 \pm 0.06) \times 10^{-5}$$

$$\frac{\Delta\alpha}{\alpha} = (-\,0.87 \pm 0.11) \times 10^{-5}$$

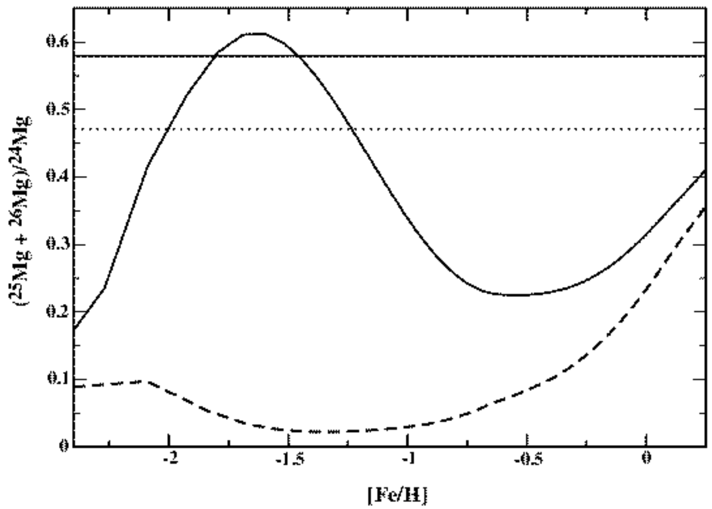
QSO: ways out

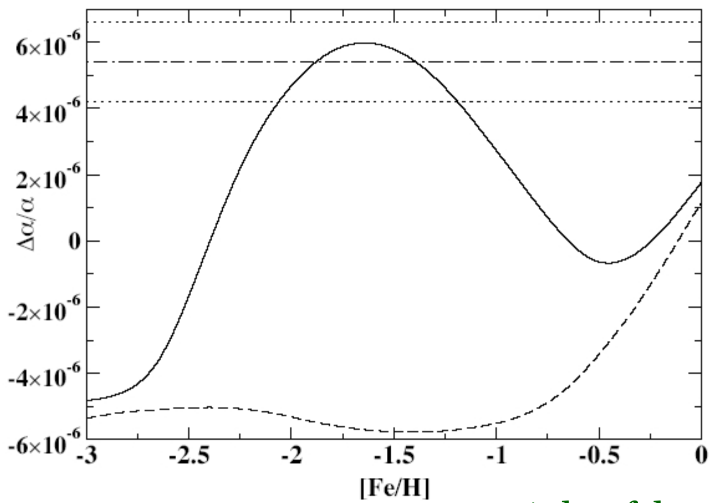
High *r* for some giant stars in globualr cluster NGC 6752

Yong et al. 2003

<u>Hypothesis:</u> polluted by asymptotic giant branch stars(AGB)

What *r* to reconcile observations with no variation?





Ashenfelter et al. 2003

r~ 0.6 instead of 0.27 for Solar system abudances to explain HIRES/Keck

But, overproduce N, Si, Al and P: can be tested!

A word on μ

Diatomic molecule

vibrorotational transitions: $\nu = E_I(c_1 + c_2/\sqrt{\mu} + c_2/\mu)$

so that $\lambda_i = \lambda_i^0(1+z_{\rm abs})\left(1+K_i\frac{\Delta\mu}{\mu}\right) \longrightarrow z_i = z_{\rm abs} + bK_i$

laboratory expansion calculated

H_2 lines of Lyman and Werner Band from 2 systems at z=2.597 and z=3.0249 (resp. 42 and 40 lines) + 2 sets of laboratory spectra:

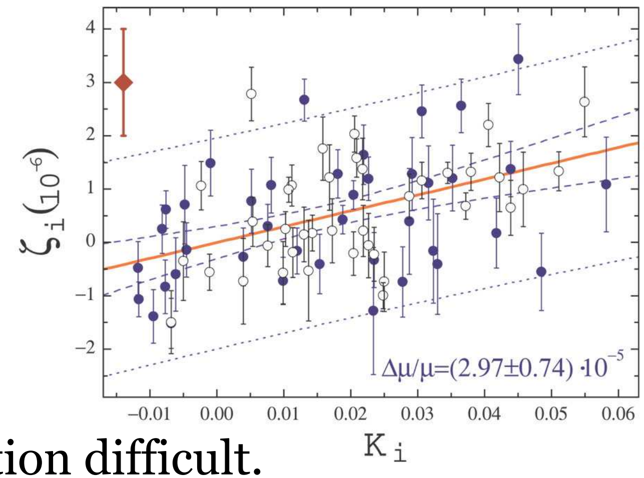
$$\frac{\Delta\mu}{\mu} = (3.05 \pm 0.75)\times 10^{-5} \quad \text{or} \quad \frac{\Delta\mu}{\mu} = (1.65 \pm 0.74)\times 10^{-5}$$

Ivanchik et al. 2005

Improvement of laboratory spectra

$$\frac{\Delta\mu}{\mu} = (2.4 \pm 0.6)\times 10^{-5}$$

Reinhold et al. 2006



But, only 7 lines in both spectra: intercalibration difficult.

Primordial nucleosynthesis

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

$$Y = \frac{2(n/p)_N}{1+(n/p)_N} \qquad (n/p)_f \sim \mathrm{e}^{-Q/k_B T_f}$$

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

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

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

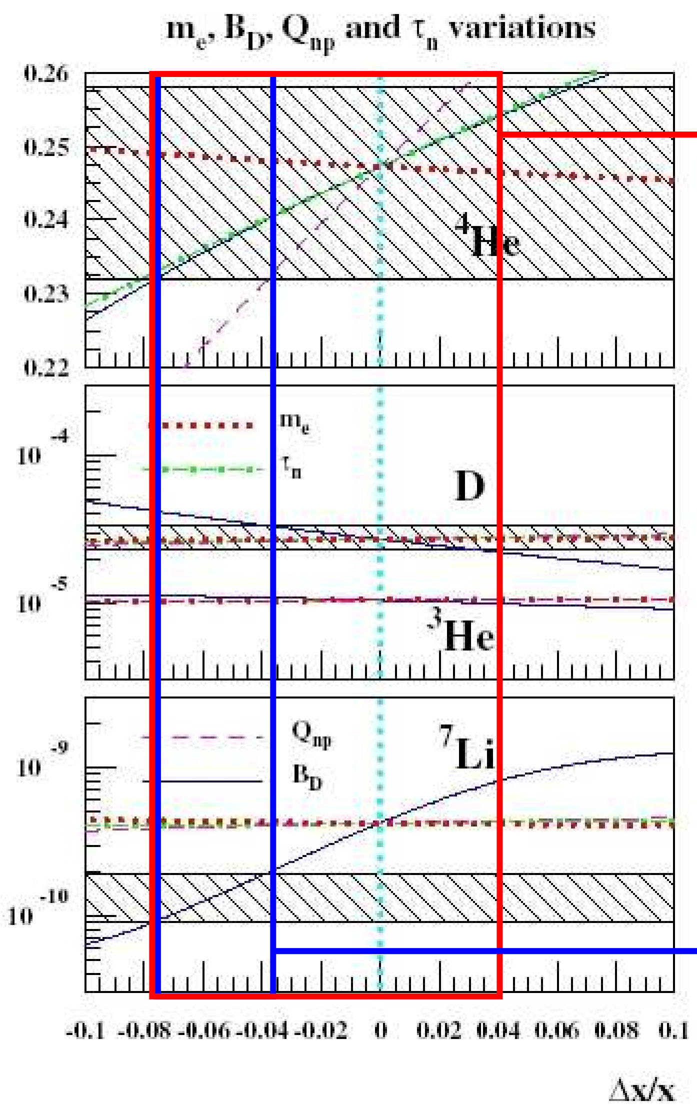
Predictions depend on

$$(G, \alpha, \tau_n, m_e, Q, B_D, \sigma_i)$$

Coc,Nunes,Olive,JPU,Vangioni 2006

BBN: sensibilities

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: intricate structure of QCD and Of its role in low energy nuclear reactions.

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

BBN: modelisation-nuclear sector (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:

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

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

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

BBN: modelisation-nuclear sector (II)

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.

$$\frac{\Delta m_\sigma}{m_\sigma} \sim 0.54\frac{\Delta m_s}{m_s}$$
$$\frac{\Delta m_\omega}{m_\omega} \sim 0.15\frac{\Delta m_s}{m_s}$$
$$\frac{\Delta m_N}{m_N} \sim 0.12\frac{\Delta m_s}{m_s}$$

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

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) $h_i=h$

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

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

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

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

BBN: relating v and h

We can go one step further if we assume that the weak scale is determined
By dimensional transmutation

Then $$v = M_p \exp\left(-\frac{8\pi^2}{h_t^2}\right)$$

It follows that $$\frac{\Delta v}{v} = \frac{16\pi^2}{h^2}\frac{\Delta h}{h} \sim 160\frac{\Delta h}{h}$$

(160 → S)

$$\frac{\Delta B_D}{B_D} = -13(1+S)\frac{\Delta h}{h} + 18R\frac{\Delta\alpha}{\alpha}$$

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

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

(α, h)

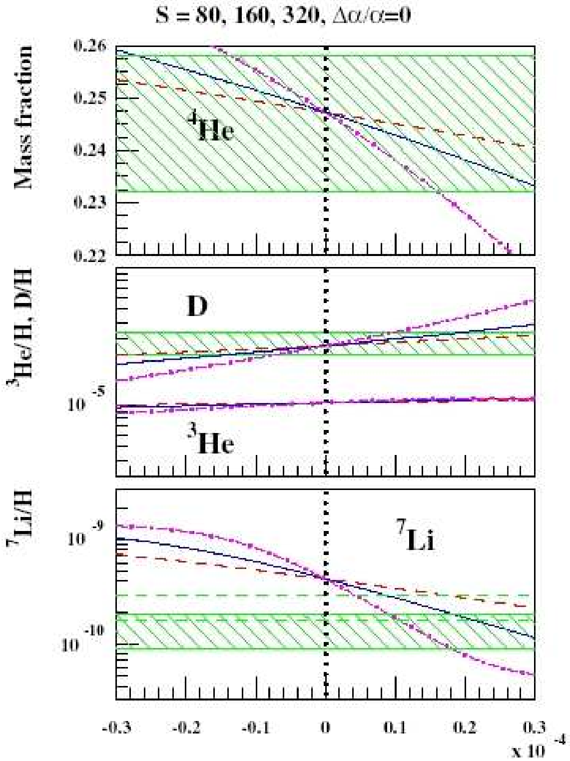
We can also deduce that

$$\frac{\Delta\mu}{\mu} = 0.8R\frac{\Delta\alpha}{\alpha} - 0.6(S+1)\frac{\Delta h}{h}$$

BBN: constraints

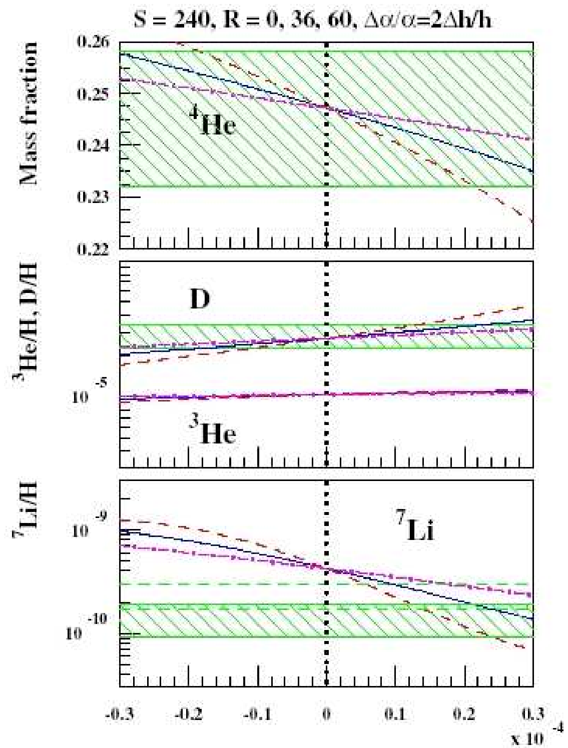
If one just takes Coulombian barriers into account $\left|\frac{\Delta\alpha}{\alpha}\right| < 0.02$

$$\frac{\Delta\alpha}{\alpha} = 0$$



$$-1.5\times10^{-5} < \frac{\Delta h}{h} < 1.9\times10^{-5}$$

$$\frac{\Delta\alpha}{\alpha} = 2\frac{\Delta h}{h}$$



$$-1.6\times10^{-5} < \frac{\Delta h}{h} < 2.1\times10^{-5}$$

Extended later by Dent et al. Confirms that B_D is the most important parameter.

Correlations

Some numerology!

Assume that $\frac{\Delta\mu}{\mu} \sim 3 \times 10^{-5}$ at z~3.

We infer that

$$\frac{\Delta\alpha}{\alpha} \sim -1.5 \times 10^{-6} \left(\frac{202}{3(S+1)-8R} \right)$$

Compare with $\left.\frac{\Delta\alpha}{\alpha}\right|_{\mathrm{Keck}} \sim -0.6 \times 10^{-5}$

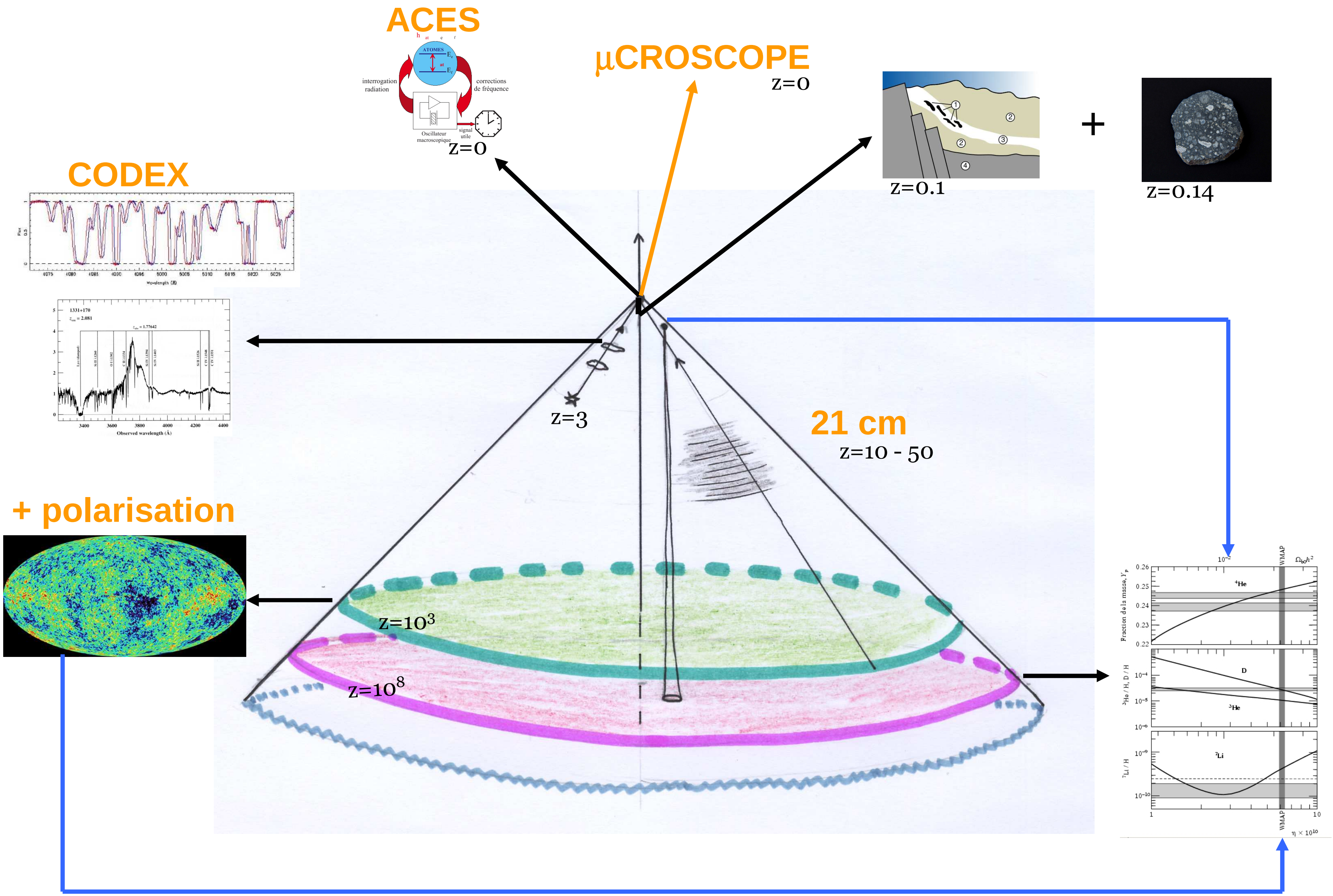
Order of magnitude is not crazy!

$$\frac{\Delta\mu}{\mu} = T \frac{\Delta\alpha}{\alpha}$$

→ $T \sim 50$

→ Window on the messy nuclear physics.

Future...


ACES
ATOMES
interrogation radiation
corrections de fréquence
Oscillateur macroscopique
signal utile
z=0
μCROSCOPE
z=0
z=0.1
+
z=0.14
CODEX
wavelength (Å)
Observed wavelength (Å)
z=3
21 cm
z=10 - 50
+ polarisation
z=10³
z=10⁸
⁴He
D
³He
⁷Li
WMAP
η × 10¹⁰

CODEX: COsmic Dynamics EXperiment

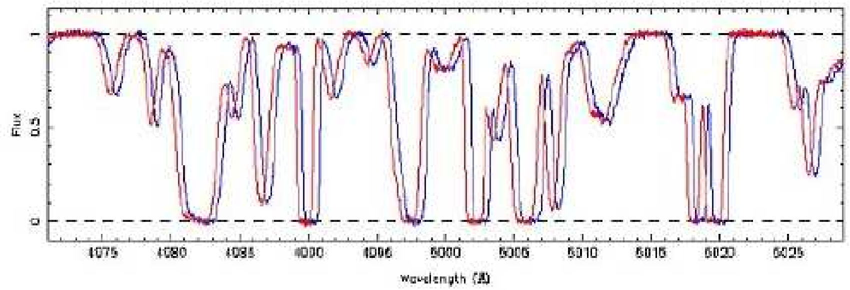
Time drift of the redshifts

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

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

CODEX:

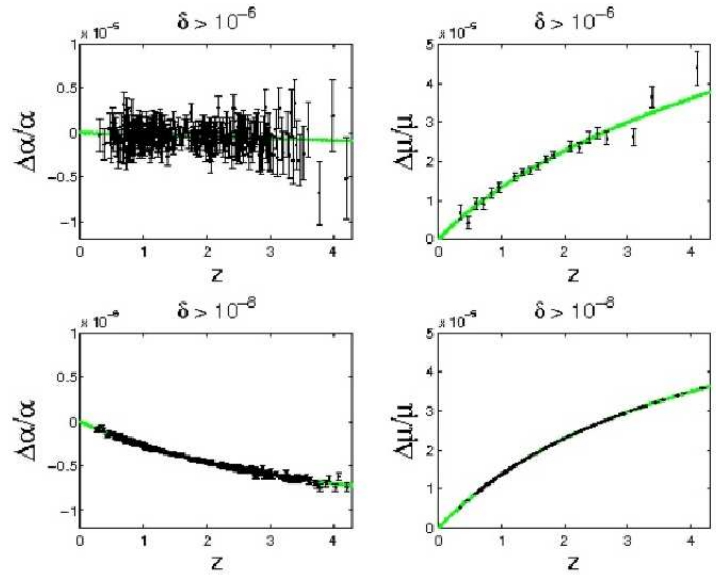
spectral domain: 400-680 nm
R=150000
10-20 times HARPS on 10 years!
long term calibration (atomic clocks...)



Constants

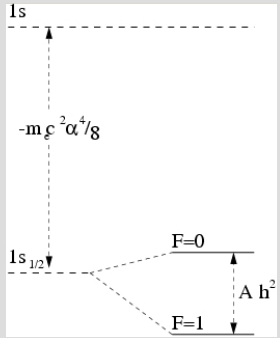
The accuracy of a variability measurement
is determined by the precision of measurement
of the line positions.

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



Absorption of CMB photon by neutral atomic hydrogen

Map of 21 cm emission $I_\nu \rightarrow T_b = \frac{I_\nu c^2}{2k_B \nu^2}$



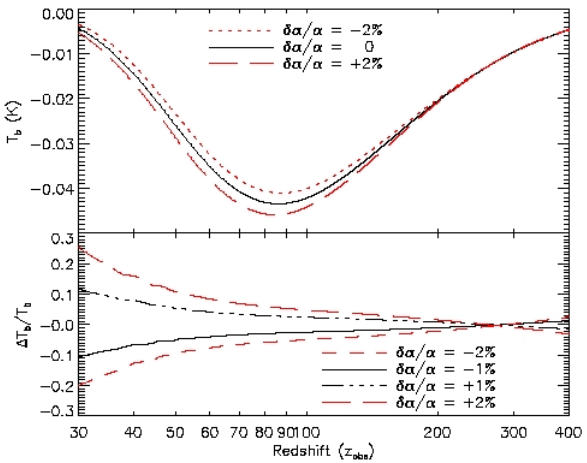
$\lambda_{21} \sim 21\,\mathrm{cm}$
$\nu_{21} \sim 1420\,\mathrm{MHz}$

Theoretical analysis

$$T_b \propto \frac{A}{\nu_{21}^2(1+z)}$$

$$\nu_{21} \propto \alpha^2 Ry \propto \alpha^4$$
$$A \propto \alpha^{13}$$

$$T_b \propto \alpha^5$$



Expected: $\Delta\alpha/\alpha \sim 0.85\%$

Noise Galactic foregrounds (22 Mhz)
Pollution: @ z=15, 87.8MHz !!

Degeneracies: cosmological parameters
1% on Ω_b, h induces 2% or 3% on T_b

Advantages:
Dark age / spatial dependence

Conclusions

- Progresses in the constraints on variation of fundamental constants
  - New observables/better data

- Difficulty in relating the constants
  - Level of description
  - Intricate structure of QCD/ freedoms in GUT construction
  - Allow to get better constraints

- BBN: example
  - *Step 1*: effective BBN parameters
  - *Step 2*: nuclear physics -> nuclear parameters
  - *Step 3*: GUT assumption $\Lambda[v,\alpha,h]$
  - *Step 4*: weak sector $v[h]$
  - *Step 5*: possible link $\alpha[h]$

- New directions [not mentioned here]
  - G
  - Spatial dependence
  - Model building
  - Stellar physics