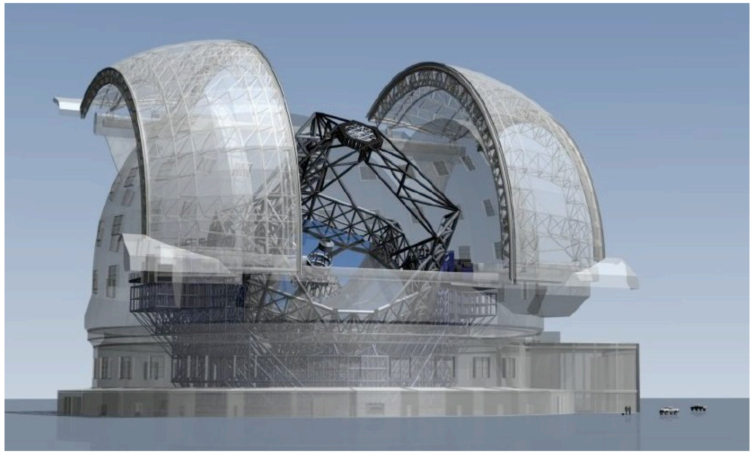
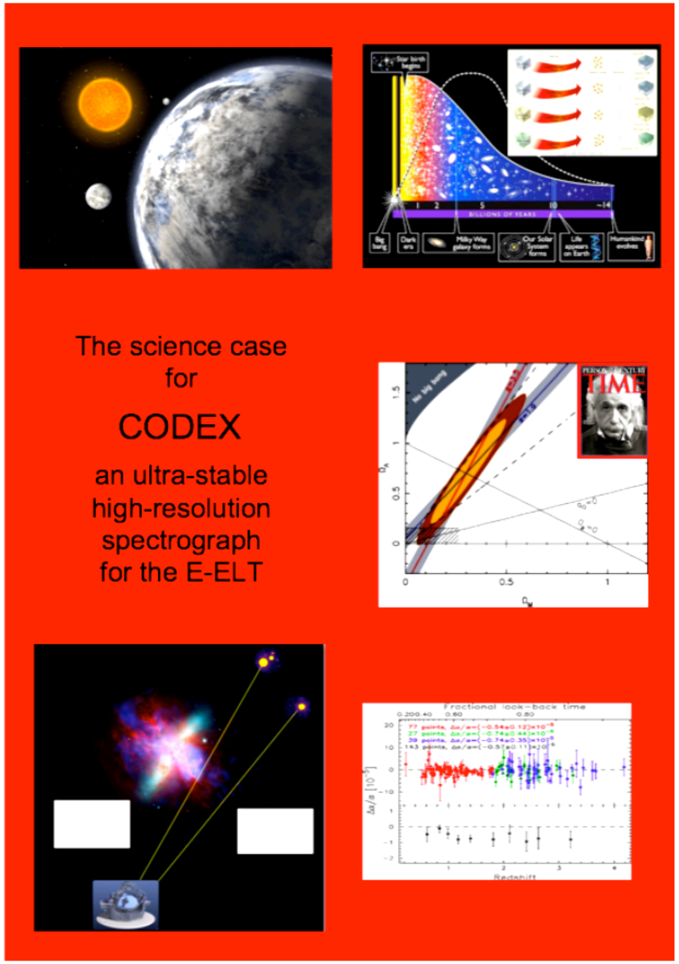
search for varying constants @ELT

Paolo Molaro
INAF-OAT



Other Earths (S. Udry)

Nucleochronology



Expansion (J. Liske)

IGM High z metals

Fundamental constants

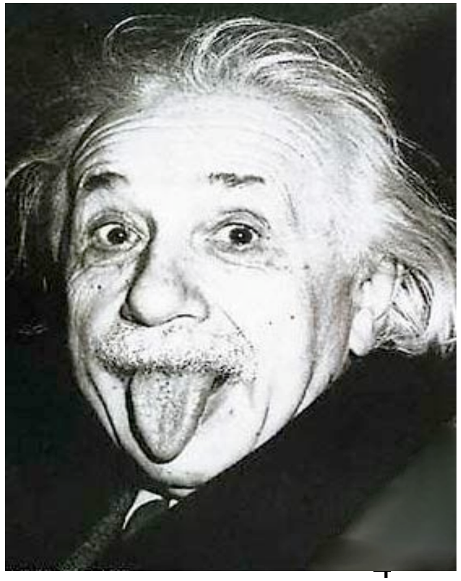
Outline

- What are the fundamental constants and why they should vary
- Observational status and controversies (Lab astronomical and geological bounds)
- What we can expect with CODEX

Albert Einstein 1945 letter to Rosenthal-Schneider

With the question of universal constants you have broached one of the most interesting questions that may be asked at all. There are two type of constants: apparent and real ones. The apparent are simply the outcome of the introduction of arbitrary units, but are eliminable. The real [true] ones are genuine numbers which God had to choose arbitrarily, as it were, when He deigned to create this world"

What I'm really interested in is wether God could have made the world in a different way



- Fundamental constant is any parameter that cannot be calculated
- And which are, to the best of our knowledge, independent of any other measured quantities

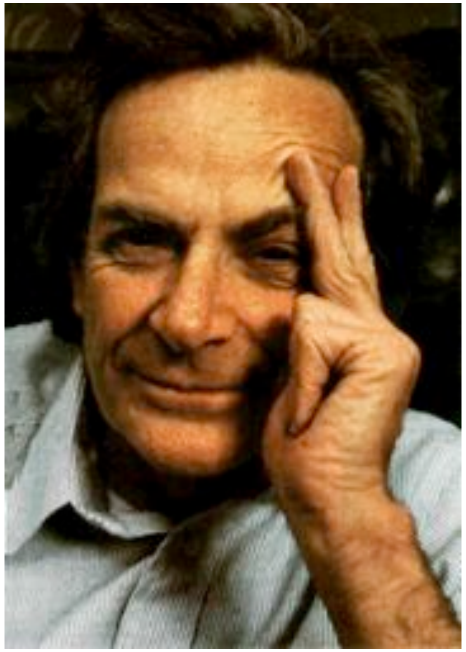
- Einstein Equivalence principle:

  invariant in space and time

- Standard Model: 28 constants
  - the constant of Gravity G
  - the fine structure α
  - the coupling constants of weak interactions
  - the coupling constant of the strong interaction (or scale of QCD)
  - the mass of the W-boson
  - the mass of the Higgs boson
  - the masses of the 3 charged leptons
  - the masses of the 3 neutrinos
  - the masses of the 6 quarks
  - the 4 parameters, describing the flavour mixing of the quarks
  - the 6 parameters describing the flavour of mixing of the leptons

[about alpha] it is one of the greatest mysteries of physics: a magic number that comes to us with no understanding by man...”

R. Feynman



“Constants encode our greatest knowledge and our greatest ignorance about the cosmos”

John Barrow

dimensionless constants

Only changes in dimensionless constants are physically meaningful

- Gravitational constant G is dimensional constant

. If a '*dimensionful*' constant varies but all dimensionless quantities stay fixed this just represents a changes in ones units and not the underlying laws of physics.

- Dimensionless constants and related to the fundamental forces:

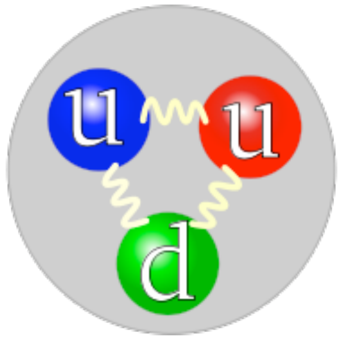
1. The fine-structure α ➡ Electromagnetic force

$$\alpha_{\mathrm{EM}} = \frac{e^2}{\hbar c} \approx \frac{1}{137.035999679}$$

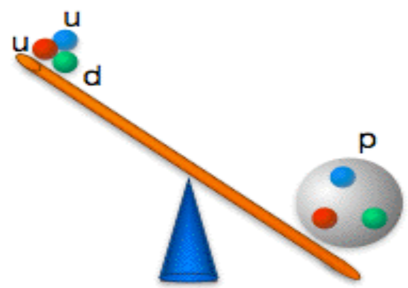
- The electromagnetic fine structure constant, α_{EM}, is constructed out of three other constants, the unit of electric charge, e, Planck's constant, $\hbar$, and the speed of light, c:

2. electron-to-proton mass ratio

$$\mu \equiv \frac{m_e}{m_p}$$



- $m_e = 0.5$ Mev
  - $\propto$ the vacuum expectation value of the Higgs field. ➡ The weak scale



- $m_p \;\; = 938 = (862_{QCD} + 74_q + 2_{QED})$ Mev

$\propto \Lambda_{QCD}$ ➡ strong forces

α and μ can be probed by astronomy

- Different transitions depend on different combinations of the dimensionless constants.

Transition		Scaling
Atomic	Gross Structure	Ry
	Fine Structure	α^2 Ry
	Hyperfine Structure	$\alpha^2 (g_p\mu)$ Ry
Molecular	Electronic Structure	Ry
	Vibrational Structure	$\mu^{1/2}$ Ry
	Rotational Structure	μ Ry
Relativistic Corrections		α^2

- Where Ry is the Rydberg constant: $\mathrm{Ry} = \frac{\alpha^2 m_e c^2}{2}$

Large Number Hypothesis

$$\frac{Gm_p m_e}{e^2} \sim 3.7 \times 10^{-40} \qquad \frac{H_0 e^2}{m_e c^3} = 4\pi\alpha\mu\delta \sim 2.4 \times 10^{-40}$$

- Dirac (1937) relative magnitude of electrostatic and gravitational forces between proton and electron is the inverse of the age of the Universe in atomic time

$$\Rightarrow \alpha_G \propto 1/t$$

- Dicke (1961) conflict with astronomical evidences

It is usually assumed that the laws of nature have always been the same as they are now. There is no justification for this. (...) in particular quantities which are considered to be constants of nature may be varying with cosmological time.

Paul Dirac

Tiny variations!

- if their values were different by even as little as few percent the consequences for life, as we understand it, would be disastrous.
  - If α_{EM} were increased by 4% the carbon-12 resonance at 7.6MeV (the 'Hoyle resonance') would not exist and the amount of carbon produced in stellar cores would be drastically reduced.
  - If μ where much larger than its current value, no ordered molecular structures would exist.

- Antropic Principle. Fine tuning: we appeared in area of the Universe where values of fundamental constants are suitable for our existence.

Why constants should vary?

- Theoretical foundations:
  - through coupling with a scalar field.
- If a scalar field is coupled with the electromagnetic field than can lead to a variation of constants.

$$\alpha \Rightarrow \alpha(\phi)$$

$$\frac{\Delta\alpha}{\alpha} \equiv \frac{\alpha(\phi) - \alpha_0}{\alpha_0} = \frac{\lambda}{\alpha_0}\frac{\Delta\phi}{M_{\rm Pl}}$$

We do not know if Scalar fields exist, but they are easy to obtain!

Higgs Field (and possibly the first scalar field to be detected LHC)

Inflation

Dark energy (quintessence)

Moduli Fields (string inspired models).

f(R) theories (modifications of gravity)

Chameleon Fields

Scalar tensor theories

Gravitation. The Jordan (1937)-Brans-Dicke (1961) theory:

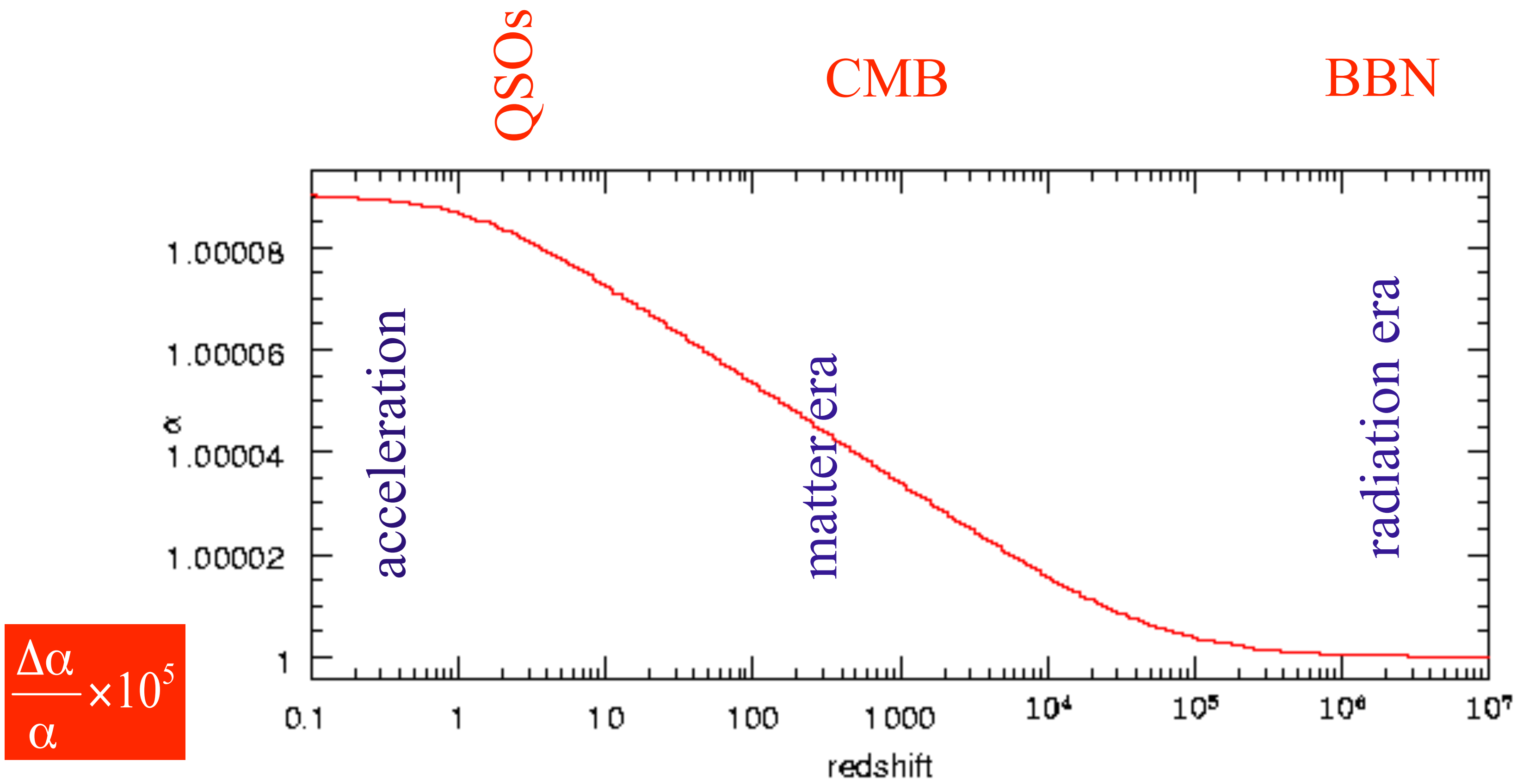
- first example of self-consistent varying constant theory: Metric tensor + scalar field (varying G).
- The gravitational constant is replaced by a scalar field that can vary both in space and time

BSBM model: the simplest and most studied varying-α_{EM} model was proposed in 1982 by Bekenstein (B) and extended to a cosmological setting by Sandvik (S), Barrow (B) and Magueijo (M) 2002. The BSBM model:

- in the matter era, α varies slowly as a logarithm of time:

$$\alpha_{\rm EM} \propto e^{2\varphi} \sim 1 - \frac{\zeta_{\rm m}}{\pi G \omega}(H_0 t_0)^2 \ln a(t)$$

- Key feature: the onset of accelerated expansion quickly turns off the cosmological variation of the constants



Quintessence

- Dark Energy is possibly a scalar field (Quintessence)
  - Required cosmological constant value is so small that a dynamical scalar field is likely (Wetterich 1988, Ratra Peebles 1988)

- if the variation in a constant is driven by a scalar field rolling down a potential, and that same potential is responsible for the current acceleration of the Universe,

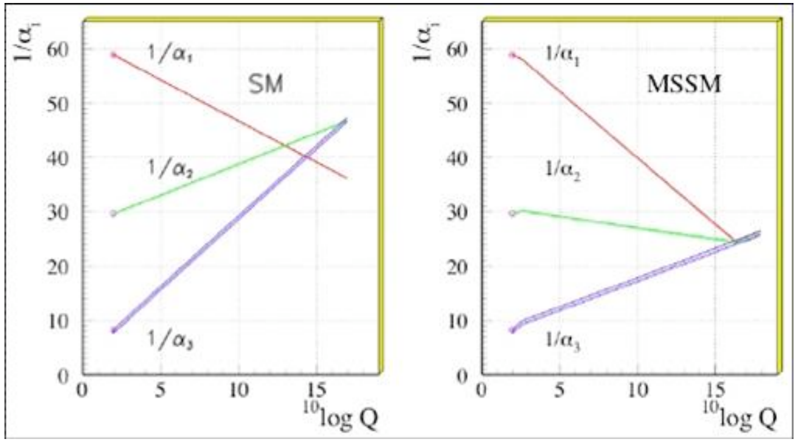
- ==> Varying constants can be used to infer the evolution of the scalar field and of $w = p/\rho$. *Like the reconstruction of the potential from the motion of a particle (*Avelino Martins Nunes Olive 2006 astroph/0605690)

- it opens a new door: to the possibility that future measurements of constant variation can be used to *gain a greater understanding of dark energy*

GUTs

experimental evidence shows that fundamental couplings run with energy

this suggests that at some high energy that the different forces might be unified: at about 10^{15} GeV,



- At low energies in GUTs where a dynamical scalar field is responsible for varying α, the other gauge and Yukawa couplings are also expected to vary
  - ➡ there's a relation between the variation of α and μ

$$\frac{\dot{\mu}}{\mu} \sim \frac{\dot{\Lambda}_{QCD}}{\Lambda_{QCD}} - \frac{\dot{v}}{v} \sim R\frac{\dot{\alpha}}{\alpha};$$

- R is model dependent (|R|<50, larger possible.
  - The strong-coupling constant is running faster than α and ➡ Δμ should be larger
  - simultaneous measurements of Δα & Δμ are a key discriminant tool of GUTs models!

M-brane, extra dimensions, Strings

A general feature of higher dimensional theories is that the true constants are defined in the full higher dimensional theory (see rev Uzan 2003, Garcia-Berro et al AARev 2007)

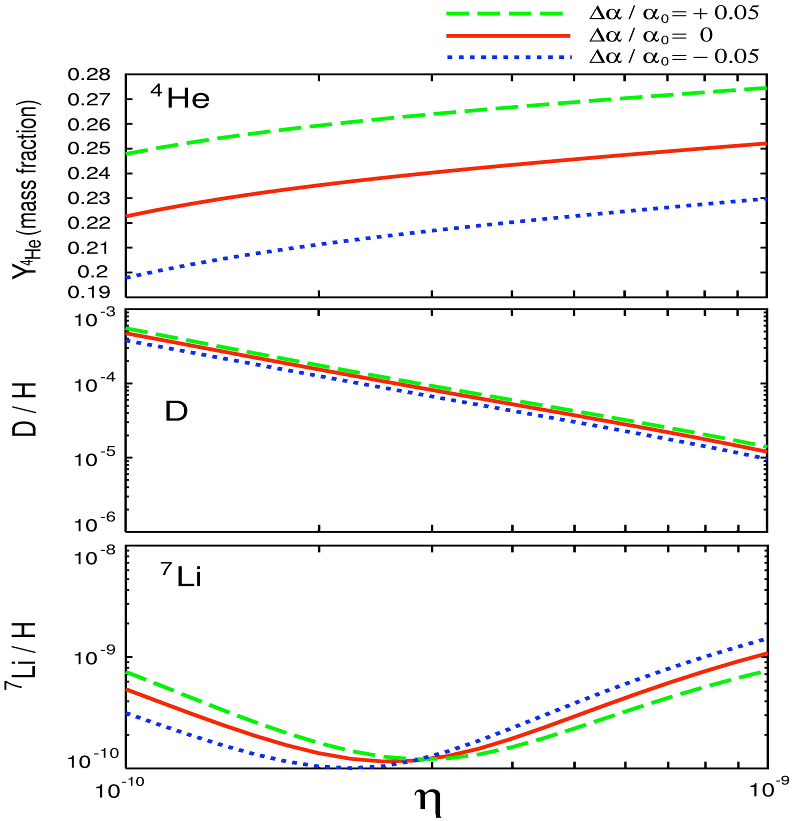
$$ds^2 = -dt^2 + a^2(t) \sum_{i,j=1}^{3} \hat{\gamma}_{ij} dx^i dx^j + R^2(t) \sum_{m,n=4}^{d+3} \hat{\gamma}_{mn} dy^m dy^n.$$

- Multidimensional theories predict variable constants.
- Strings & Superstrings models. Predict the existence of scalar field: the dilaton that couples with matter (Taylor Veneziano 1988)
- Theories have poor predictive power $\Rightarrow$ observations

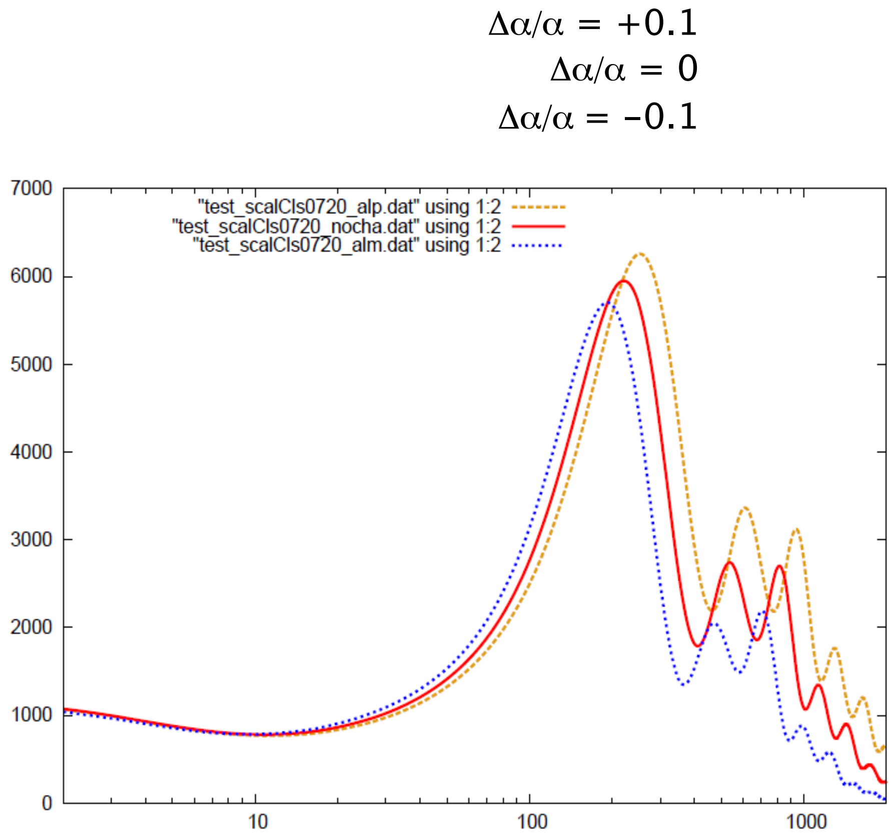
Observational Constraints on α

At the highest z

$\Delta\alpha = (\alpha_z - \alpha_0)/\ \alpha_0$



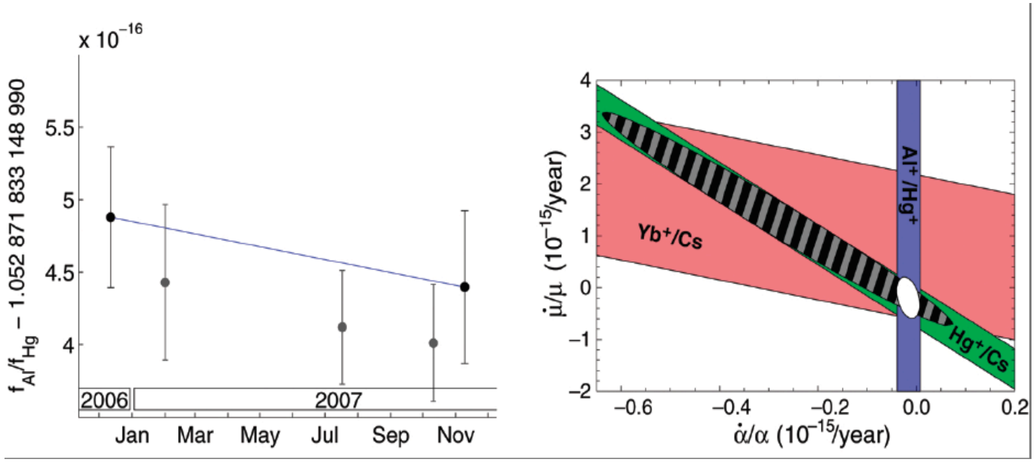
Coc et al 2007, Dent et al 2007



Ichikawa et al 2006
Planck will improve

In the lab

Comparing rates of different clocks over long period of time can be used to study time variation of α**!**



- Rosenband et al 2008 at the 17th decimal place!
  Hg+ and *Al*

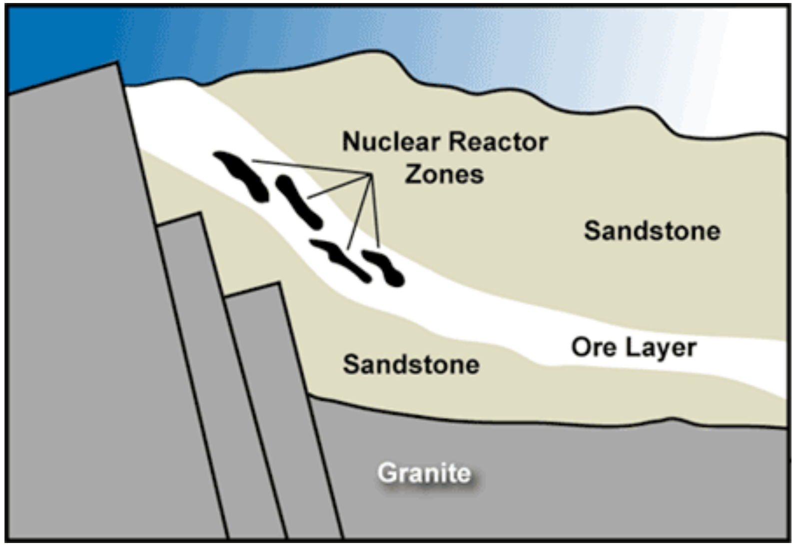
$$d\alpha/dt/\alpha = (-1.6 \pm 2.3)\ 10^{-17}\ \mathrm{yr}^{-1}$$

$$\frac{\delta\mu}{\mu} = (1.6 \pm 1.7) \times 10^{-15}/\mathrm{yr}$$

- at 10 Gyr (z=1.85) ➔ $\Delta\alpha/\alpha = (-1.6 \pm 2.3) \times 10^{-7}$ for linear variation!

Oklo Natural Reactor (z~0.1–0.15)

- Oklo is a natural nuclear fission reactor that operated about 2Gyrs ago in the Oklo uranium mine in Gabon.



  - First discovered in 1972 by French physicist Francis Perrin.
  - 15 reactors in 3 different ore deposits have been identified.
  - Water filtering through crevices moderated the nuclear reactions

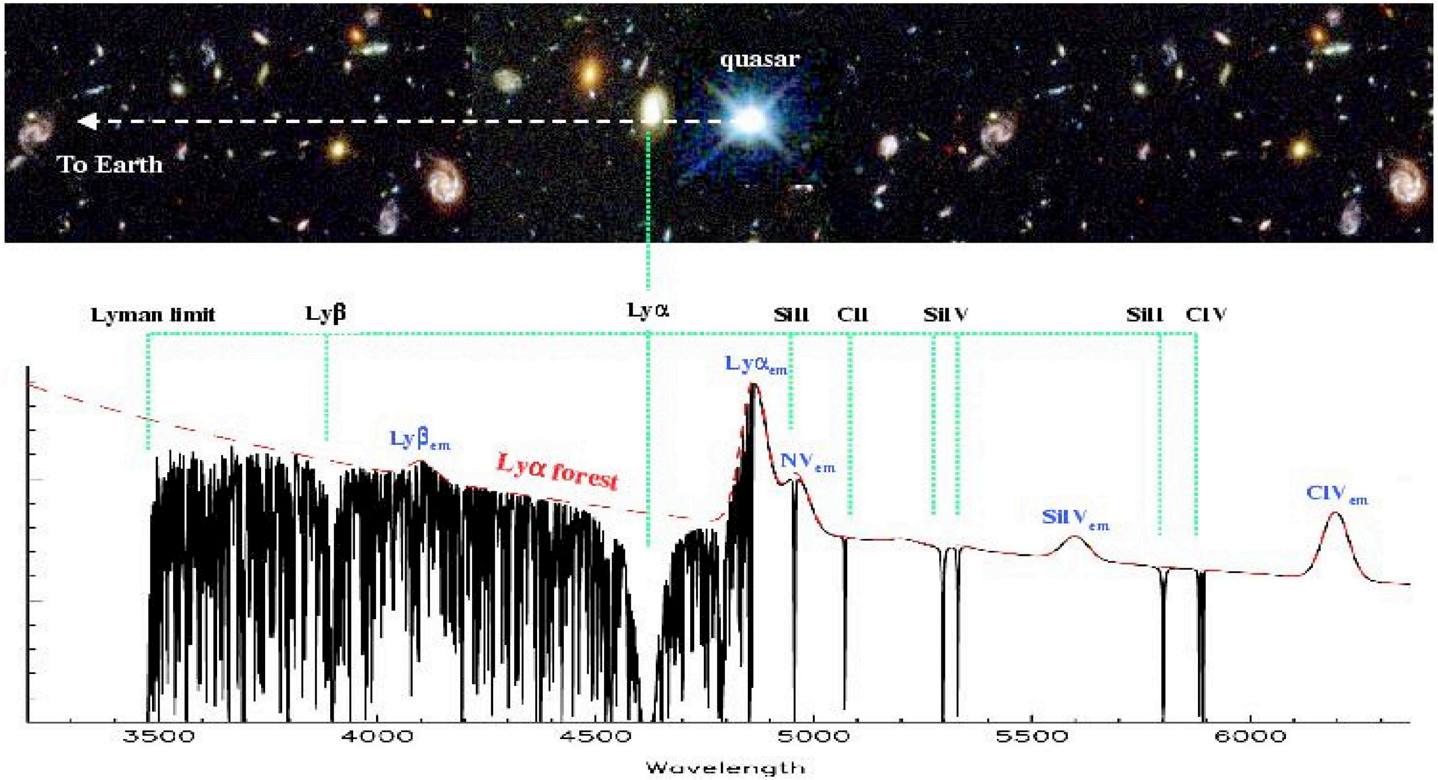
- $^{149}Sm/^{147}Sm$ =0.02 instead of 0.9
- Isotopic abundances related to the cross sections for neutron capture on ^{149}Sm the resonance energy for the nuclear reaction depends on α (Shlyakhter; Damour, Dyson, Fujii)
  - $\Delta\alpha/\alpha < 10^{-7}$ (Fujii 2003)
  - $\Delta\alpha/\alpha \geq 4.5\times10^{-8}$ (Lamoreaux & Torgerson 2004)
  - but no bounds if other constants are varying (Flambaum 2008)

METEORITES 4.5 Gyrs

- β-decay $n \Rightarrow p + e + \text{anti-}\nu_e$
- Rhenium constraint (Peebles Dicke 1962). From the observation of the $^{187}Re/^{187}Os$ ratio in iron-rich meteorites (Olive et al 2002)

  $< 3x10^{-7}$
- but $1.7x10^{-4}$ Fujii Iwamdo (2005)

QSO constraints



George Gamow 1967 to Alpher

TELEGRAM

WU024 DL PD BOULDER COLO AUG 31 127P MDT
DR RALPH ALPHER R & D CENTER
GE CO SCHDY NY

TRIPLET PAPER FLIES TO WASHINGTON. LAST NIGHT I MADE EXCITING
DISCOVERY. IF GRAVITATIONAL [redacted]CONSTANT REMAINS CONSTANT BUT
THE ELEMENTARY CHARGE SQUARED INCREASE
LUMINOSITY OF THE SUN DEFINED BY CHANG
VERY SLOWLY WITH TIME AND PRECAMBRIAN
THE ASSUMPTION OF INCREASING ELEMENTAR
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VALUE ONE, ALL ATOMIC ELECTRONS WILL F
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TELEGRAM

THE ASTROPHYSICAL JOURNAL, Vol. 149, July 1967

AN ANALYSIS OF THE ABSORPTION SPECTRUM OF 3C 191

JOHN N. BAHCALL, WALLACE L. W. SARGENT, AND MAARTEN SCHMIDT
California Institute of Technology and Mount Wilson and Palomar Observatories,
Carnegie Institution of Washington, and California Institute of Technology
Received May 12, 1967

We report on an analysis of a 193 Å/mm spectrum of 3C 191, a quasi-stellar source whose rich absorption spectrum has been described by Burbidge, Lynds, and Burbidge (1966) and by Stockton and Lynds (1966) (hereinafter these papers will be referred to as "BLB" and "SL," respectively). This relatively high dispersion for such a faint object ($m_v = 18.4$) was sought in order to investigate the relative intensity of different fine-structure lines in absorption (Bahcall 1967). The principal results of our analysis are: (1) most of the absorption lines are resolved and have widths of the order of 3 Å in the rest frame of the source; (2) either the electron density is of the order of 10^3 cm^{-3} or the distance between the continuum source and the absorbing region is of the order of $10^{2\pm1}$ pc; (3) the value of the fine structure constant at $z = 2$ equals the laboratory value to within measuring errors (about 5 per cent); (4) the carbon-to-silicon abundance ratio by number is 2.5 to 1 with an uncertainty that is probably less than a factor of 3; (5) there is no evidence for a dependence of absorption redshift, z_{abs}, on ionization potential; and (6) there is no significant evidence for absorption lines from metastable states of

A Search for Time Variation of the Fine Structure Constant

John K. Webb[1], Victor V. Flambaum[1], Christopher W. Churchill[2], Michael J. Drinkwater[1], John D. Barrow[3]
[1] *School of Physics, University of New South Wales, Sydney, NSW 2052, Australia*
[2] *Department of Astronomy & Astrophysics, Pennsylvania State University, University Park, PA, 16802, USA*
[3] *Astronomy Centre, University of Sussex, Brighton, BN1 9QJ, UK*
(Accepted 1998 December 11 for publication in *Physical Review Letters*)

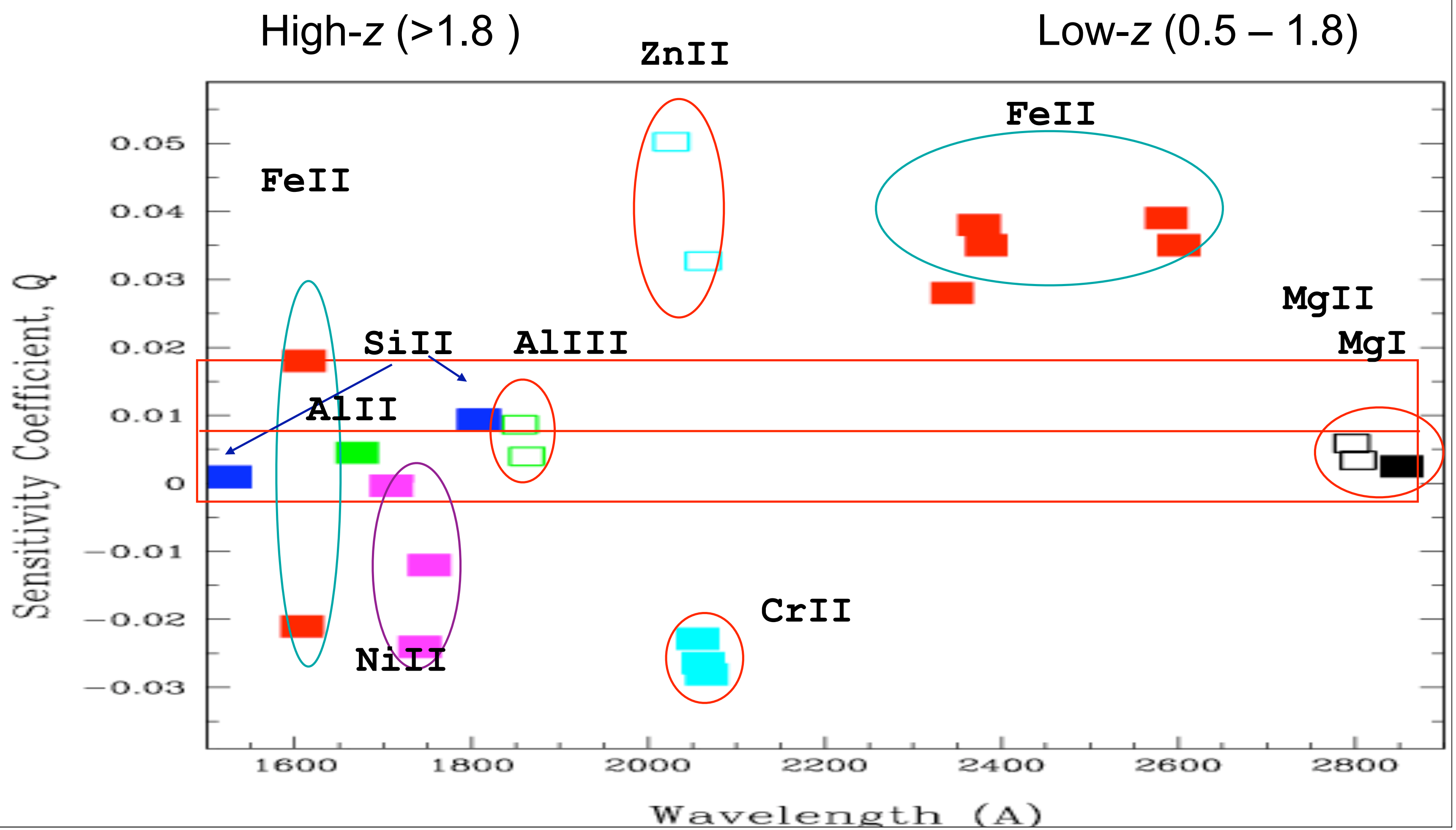
A method offering an order of magnitude sensitivity gain is described for using quasar spectra to investigate possible time or space variation in the fine structure constant α. Applying the technique to a sample of 30 absorption systems, spanning redshifts $0.5 < z < 1.6$, obtained with the Keck I telescope, we derive limits on variations in α over a wide range of epochs. For the whole sample $\Delta\alpha/\alpha = -1.1 \pm 0.4 \times 10^{-5}$. This deviation is dominated by measurements at $z > 1$, where $\Delta\alpha/\alpha = -1.9 \pm 0.5 \times 10^{-5}$. For $z < 1$, $\Delta\alpha/\alpha = -0.2 \pm 0.4 \times 10^{-5}$, consistent with other known constraints. Whilst these results are consistent with a time-varying α, further work is required to explore possible systematic errors in the data, although careful searches have so far not revealed any.

10m telescopes

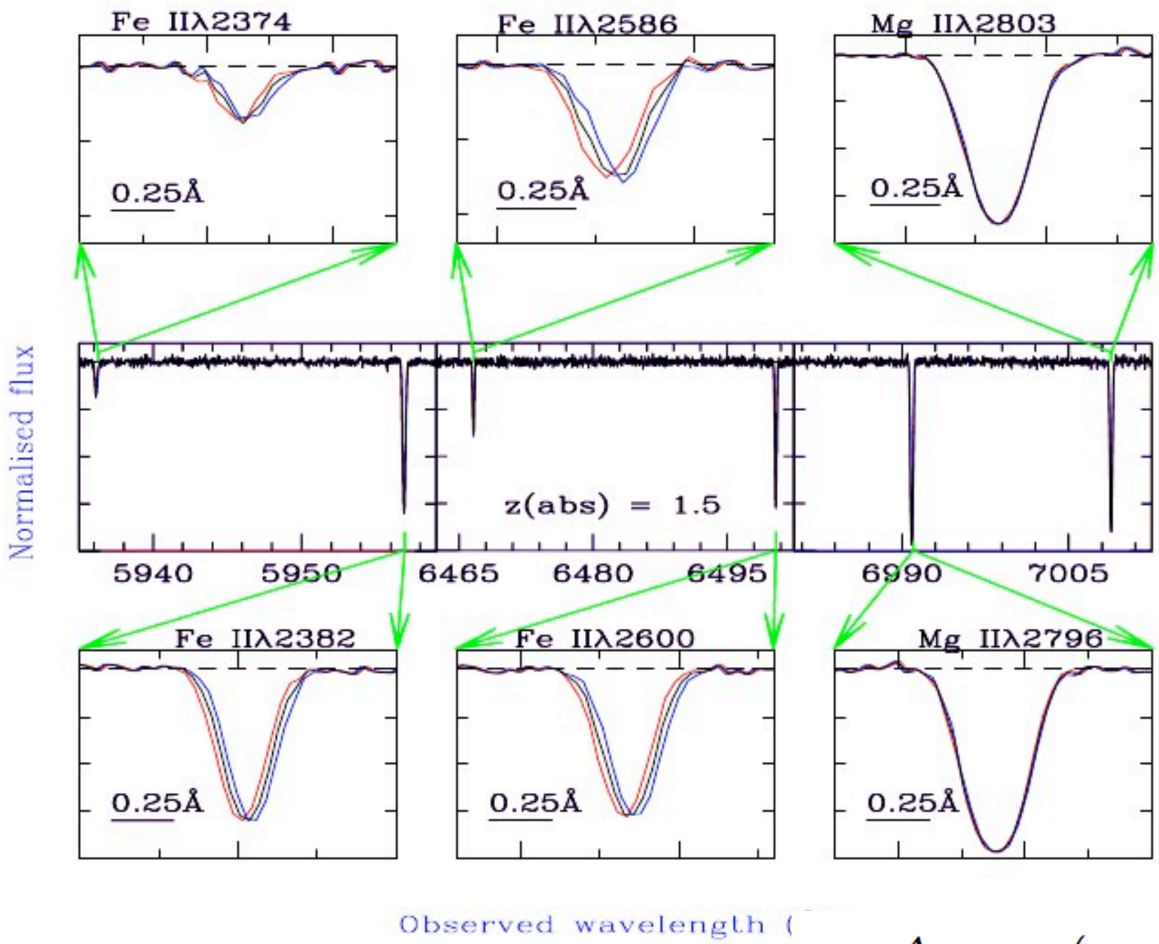
– All atomic transitions depend on α.

$$\omega = \omega_0 + q_1 Z^2 \left[\left(\frac{\alpha}{\alpha_0} \right)^2 - 1 \right] + q_2 Z^4 \left[\left(\frac{\alpha}{\alpha_0} \right)^4 - 1 \right]$$

The sensitivity coefficient q is found by varying α in computer codes with relativistic Hartree-Fock technique Dzuba et al



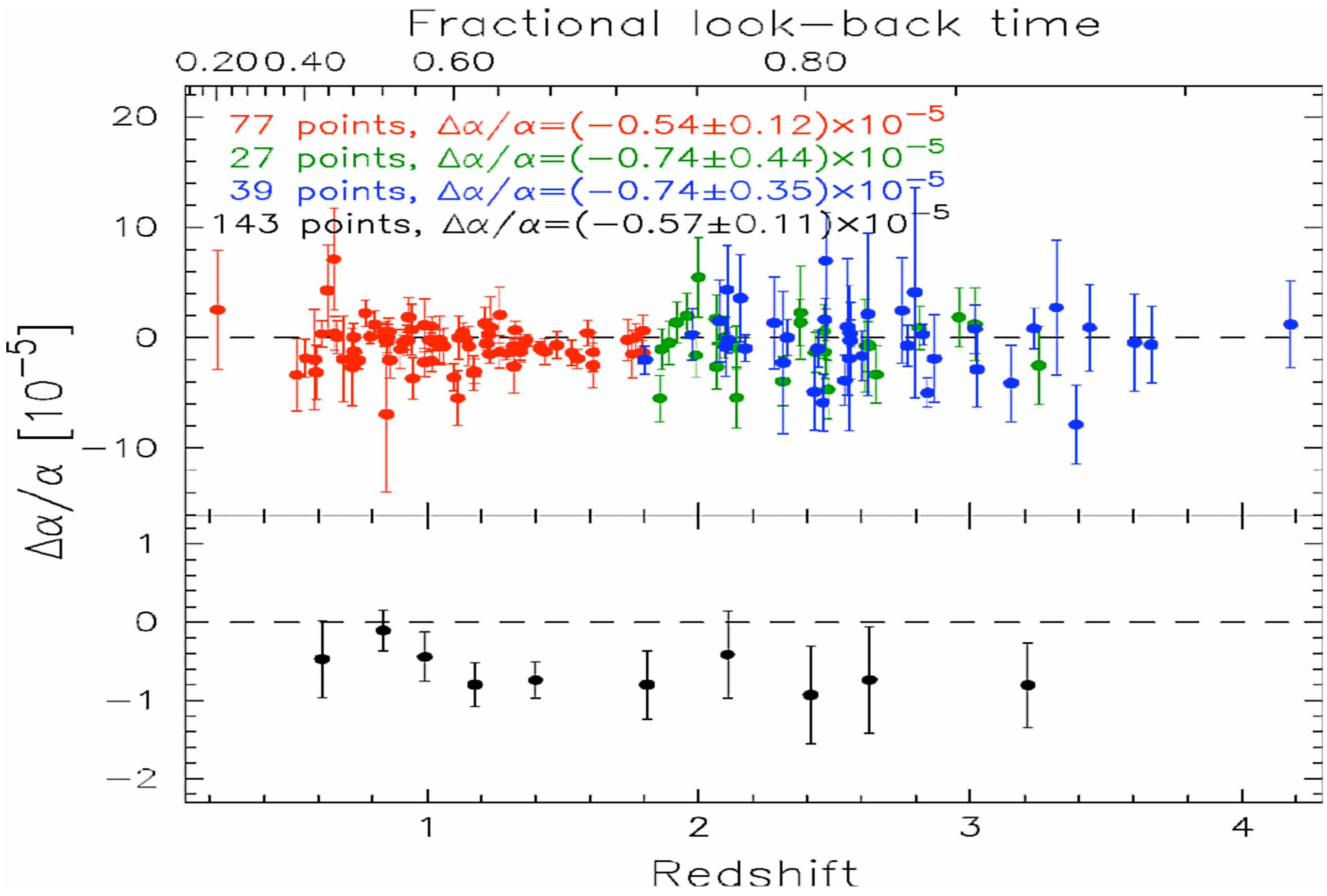
Many Multiplet Method: Simulations



$$\frac{\Delta\alpha}{\alpha} = \frac{(v_2 - v_1)}{2\,c\,(Q_1 - Q_2)} = \frac{\Delta v}{2\,c\,\Delta Q}$$

Shifts shown for 10^{-4} ; or 1.8 km/s

~ $\delta\alpha/\alpha = 10^{-5}$ 180 m/s



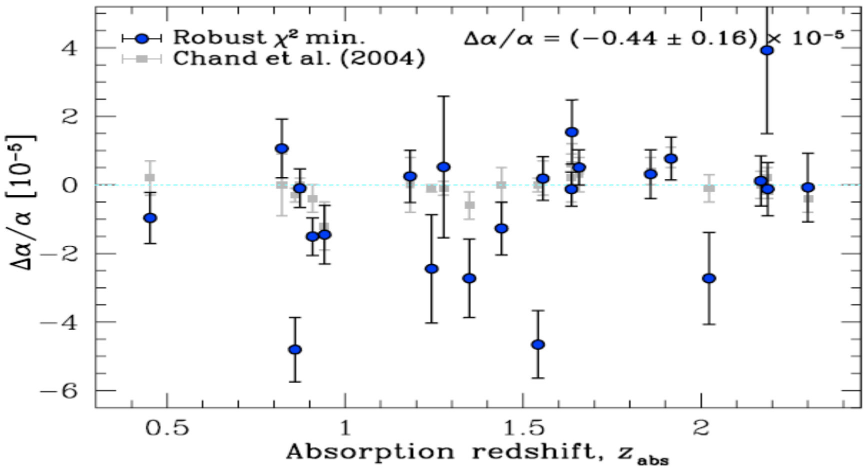
- Murphy Webb Flambaum (2004)

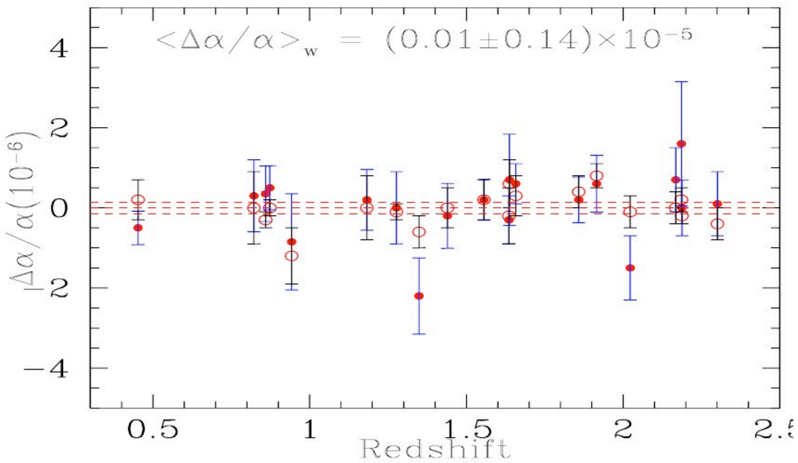
The controversy

Revision of VLT/UVES constraints on a varying fine-structure constant

Michael T. Murphy,[1,*] John K. Webb,[2] and Victor V. Flambaum[2]
[1]Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA, UK
[2]School of Physics, University of New South Wales, Sydney, NSW 2052, Australia
(Dated: April 27, 2007)

Srianand et al 2008





errors much larger than claimed originally (≈ 10 ppm!)

- real scatter, or still larger errors?
- no clear evidence for variability $\Delta\alpha/\alpha$ = (-4.4 ± 1.6) ppm

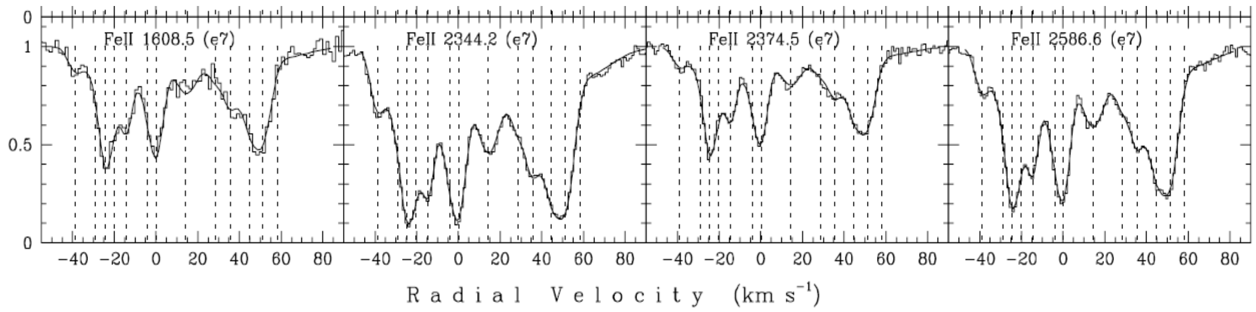
- MgII isotopic problem (Undersolar ^{25,26}Mg/^{24}Mg: negative variation
  - even for Chand et al with only ^{24}Mg $\Delta\alpha/\alpha$ = (-3.6 ± 0.6) ppm

Single Ion (FeII) Method

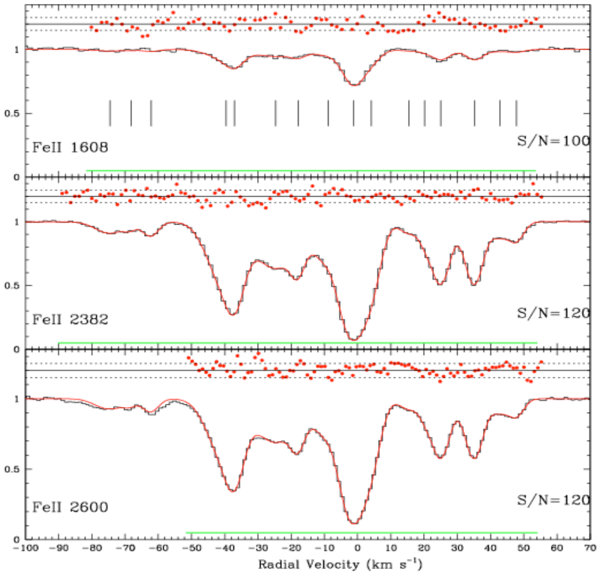
Only FeII lines: q-effective, no doppler or isotopic shifts

QSO HE 0515-4414

- Molaro et al 08
- V = 14.9 ,
- DLA at z_{abs}=1.1



$\Delta\alpha/\alpha$ = -0.12 ± 1.8 ppm



- Q 1101-264 Levshakov et al 07
  - V=16, DLA z_{abs}=1.8
- $\Delta v_{FeII-1608}$= -180 ± 85 m s^{-1}
  - $\Delta\alpha/\alpha$=(5.4±2.5) ppm

m_e / m_p

- H_2 (Thompson 1975)
  - electron-vibro-rotational transitions have different dependence from the reduced mass

Astrophysical Letters
1975, Vol. 16, pp. 3–4

The Determination of the Electron to Proton Inertial Mass Ratio via Molecular Transitions

RODGER I. THOMPSON *Steward Observatory, and Department of Astronomy, University of Arizona*

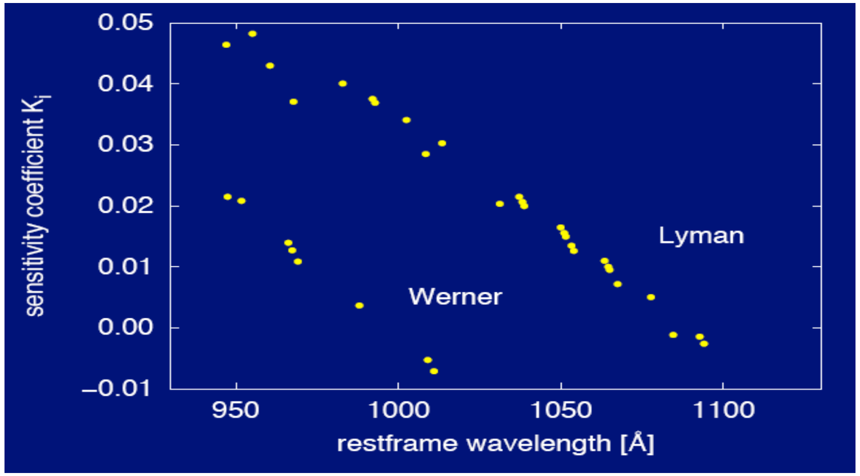
(*Received August 26, 1974; in final form October 16, 1974*)

It is demonstrated that the wavelengths of molecular transitions are sensitive to the ratio of electron to proton inertial mass. Observation of molecular transitions can therefore provide checks on the invariance of this ratio in distant objects. If confirmed, the recent observation of H_2 absorption lines in QSO spectra would allow a determination of m_e/m_p for these objects.

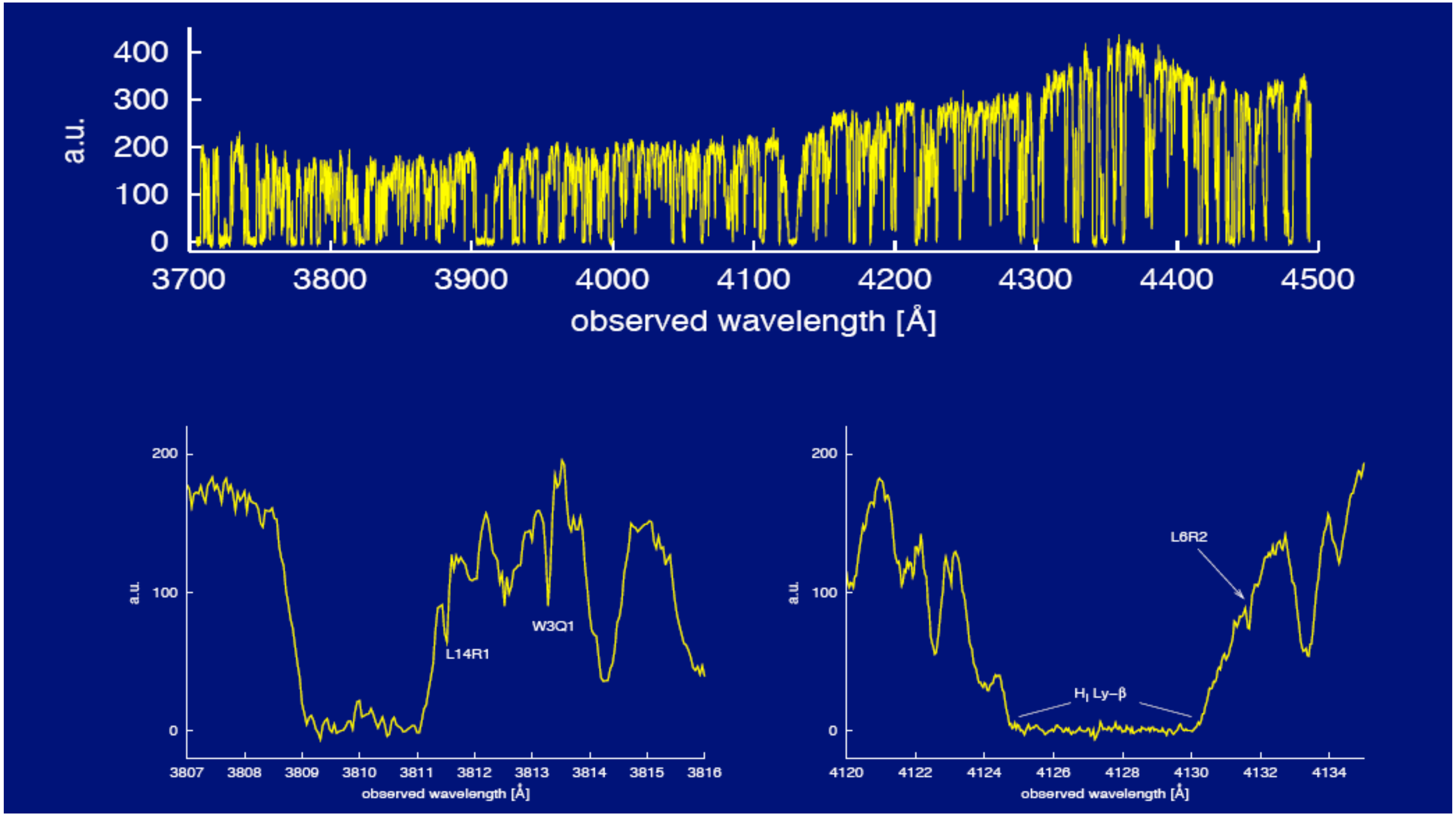
$$\nu \simeq E_I \left(c_{\rm elec} + c_{\rm vib}/\sqrt{\mu} + c_{\rm rot}/\mu\right)$$

$$K_i = -\frac{\mu_n}{\lambda_i}\frac{d\lambda_i}{d\mu_n} = \frac{1}{E_e - E_g}\left(-\frac{\mu_n dE_e}{d\mu_n} + \frac{\mu_n dE_g}{d\mu_n}\right)$$

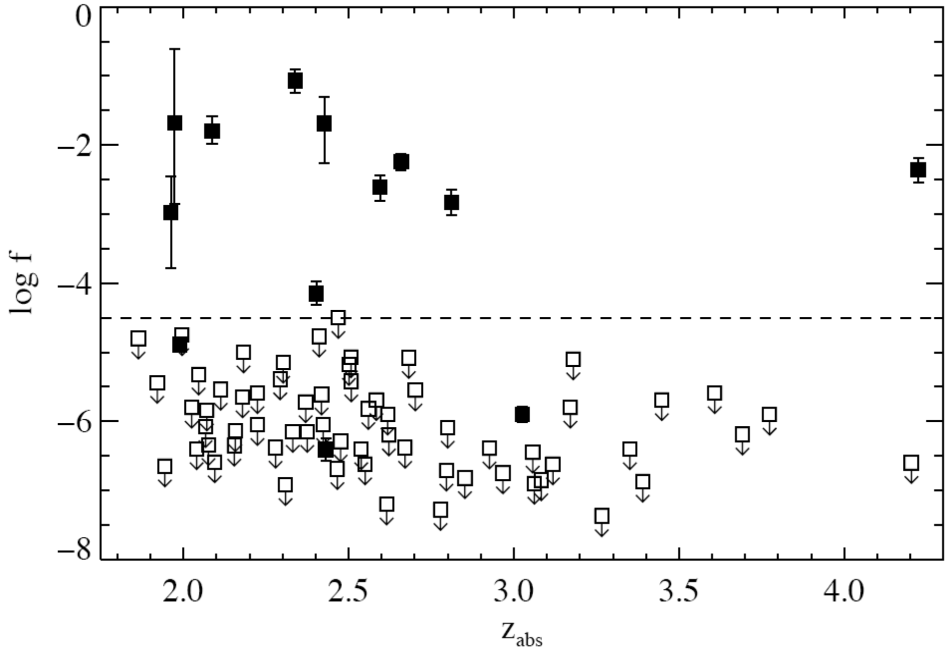
$$\lambda_{obs} = \lambda_{rest}(1+z_{abs})(1+K_i\,\Delta\mu/\mu)$$



Q 0347-383

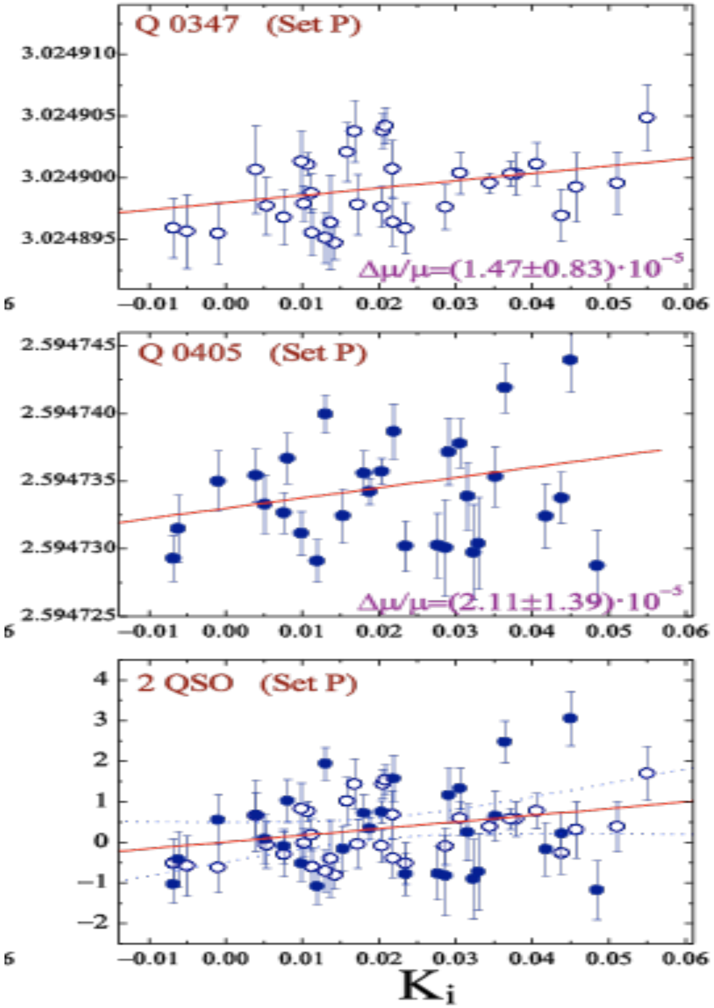


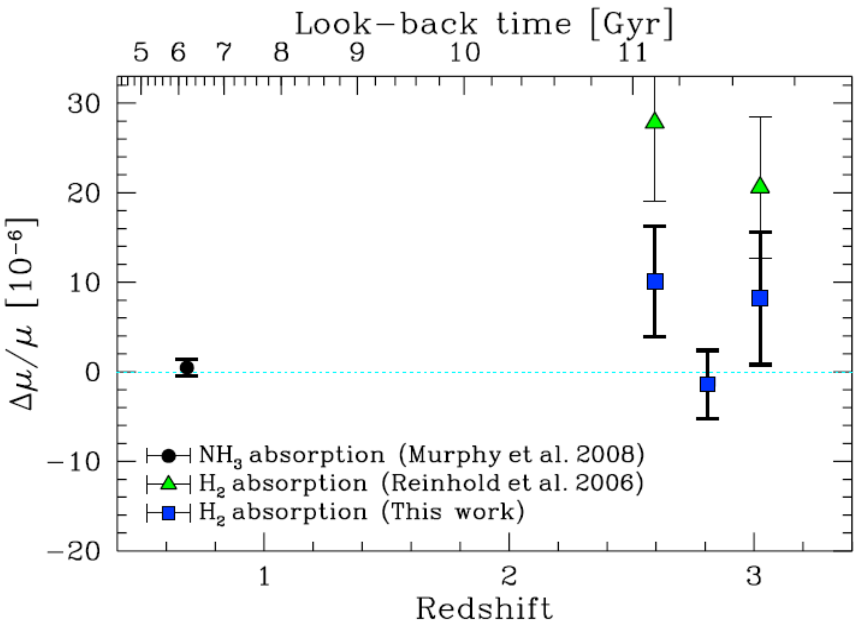
- H_2 in DLA
  - few systems, lines in the UV ~ 950-1050 A ➡ $z_{abs}>2.5$



Noterdaeme et al 2008

- Only 3 (another one soon)
  - PKS 0528 z=2.8 Varshalovich Levshakov (1993)
  - Q 0347-383 Levshakov et al 2002 (first observation with the VLT-UVES),
  - Q 0347-383 and Q 0405-443 Ivanchick et al 2005, Reinhold et al 2006





$\Delta\mu/\mu$ = (24 ± 6) ppm Reinhold et al 2006

- King et al (2008)
  - also PKS 0528-25 z=2.8

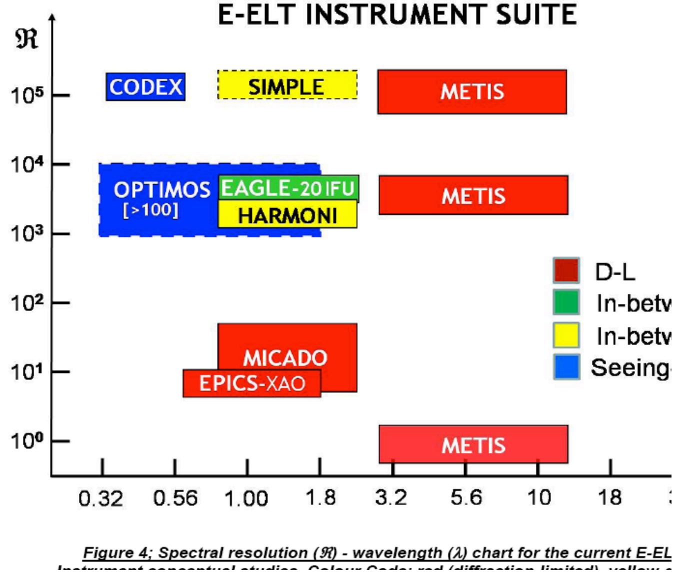
No variation!!

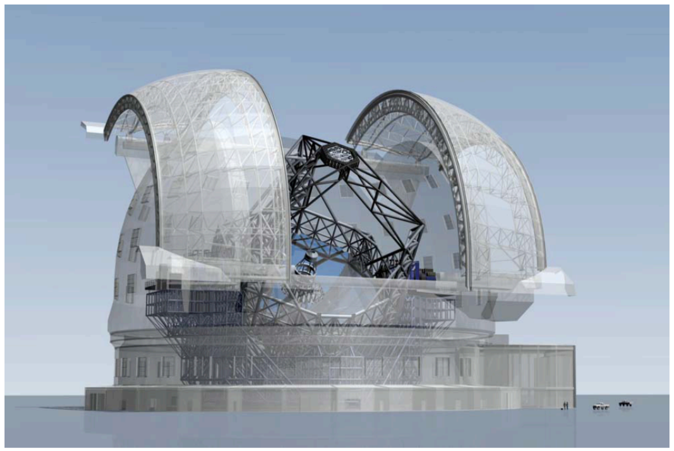
$\Delta\mu/\mu$= <6 ppm

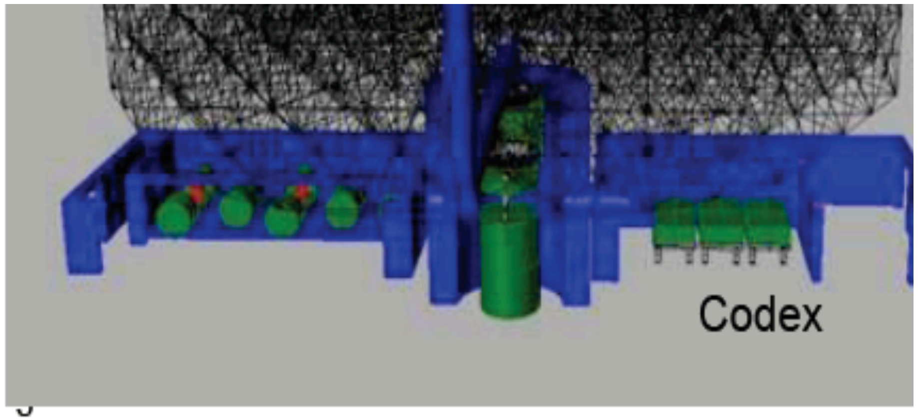
CODEX:

- Resolution
- Photons
- Stability

- an ideal instrument for constants







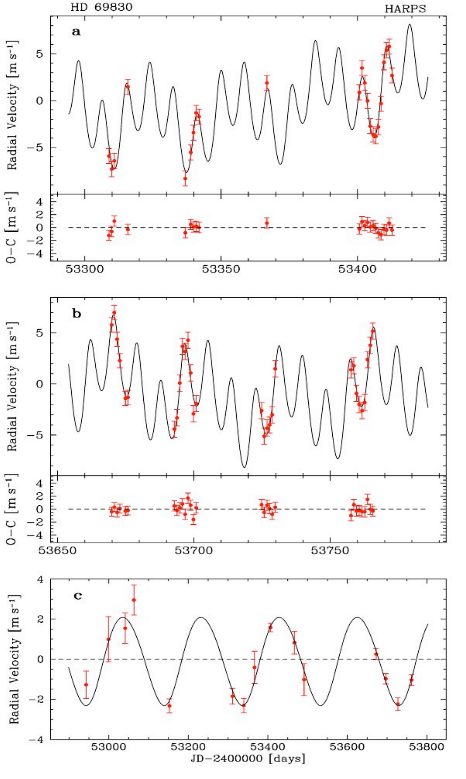
The HARPS heritage

- Vacuum Tank
- No moving parts
- Mechanical stable
- Controlled environment
- Simultaneous Calibration
- Fibre Fed
- Fibre Scrambling

At UVES
ΔT = 0.3 K ==> RV shifts 50 m/s

ΔP = 1 mbar. ==> 50 m/s

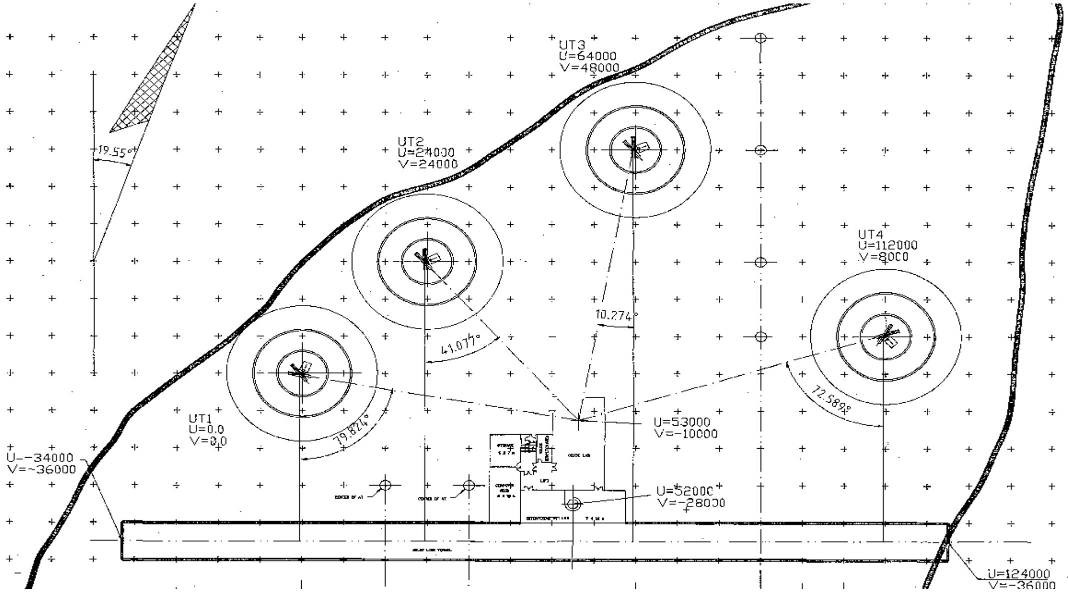
Lovis et al. 2006, 60 cm/s



- ESPRESSO (Super-HARPS at 1UT or 4UT)
  - R=160000, at 1UT, and R=40000 at 4 UTs
  - stability, vacuum and thermal control, fiber-slit

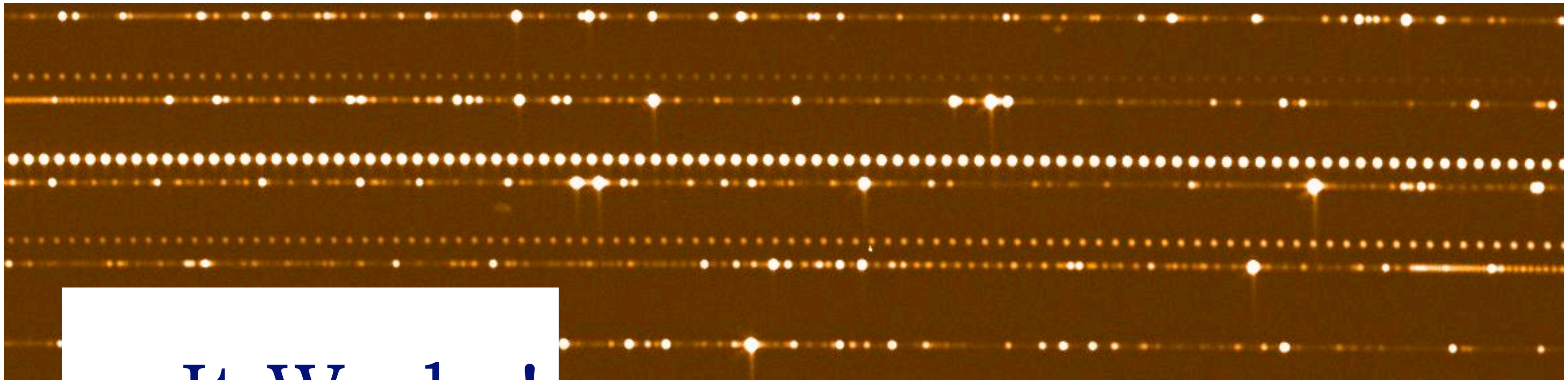
Distances to Combined Lab
UT 1 – 69 m
UT 2 – 48
UT 3 – 63
UT 4 – 63

The 4 VLT Telescopes
and the
Incoherent Combined Laboratory

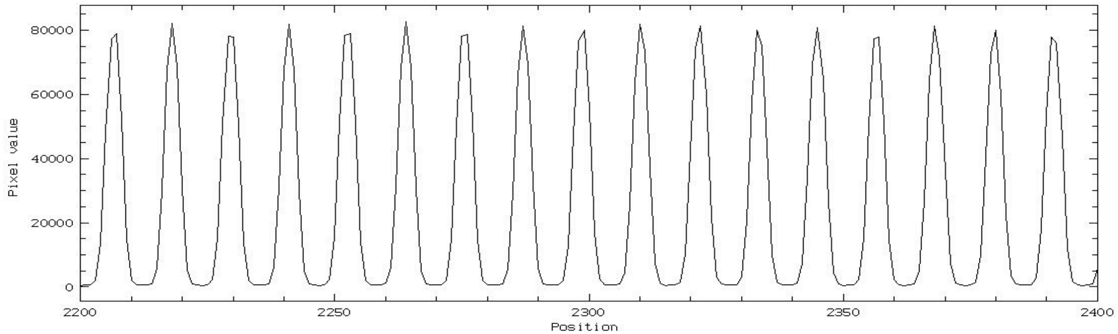


Laser Comb

Comb spectra @ HARPS January 2009



It Works!



Wilken, Lovis, Manescau, Steinmetz Holzwarth, Pasquini, Lo Curto, Hansch, Udem 2009 submitted

- •CCD patter at 512 pixel
- • Deviations up to 60 m/s compared to ThAr

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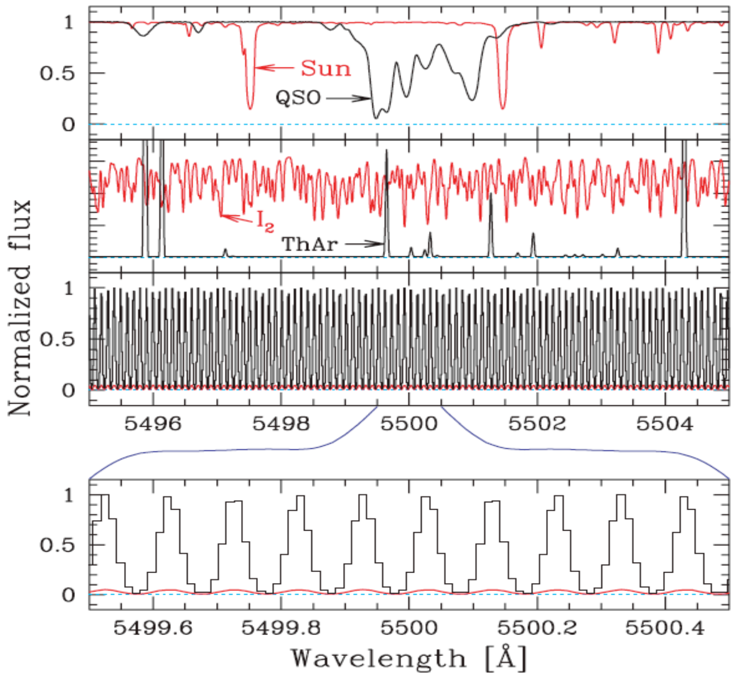
- $\Delta\alpha/\alpha$ or $\Delta\mu/\mu$ are differences of measured wavelengths of few lines (2 MgII versus 5 FeII)



Calibration is a fundamental issue

- For constants a local calibration is important
- 60 m/s local offsets as detected with the laser comb test ==> $\sigma_{\Delta\alpha/\alpha}$ = 4 ppm (FeII/MgII)
- Important contribution to the error budget today (often overlooked)

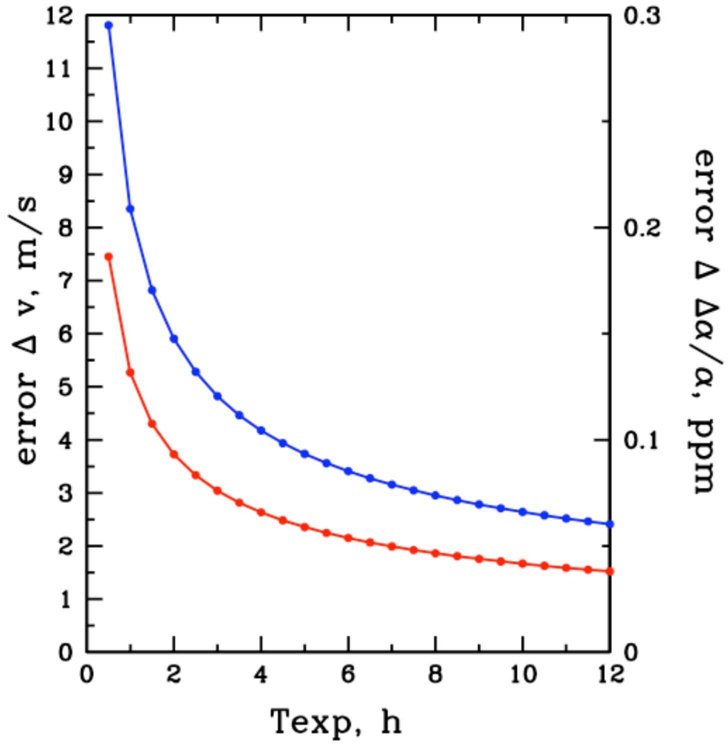
CODEX @E-ELT

- A pair of gaussian lines (too naive?),
- b=2 km/s, pixel size 0.01 A,
- QSO V 16,17 mag

$$\sigma_0 = \frac{1}{(2\pi \ln 2)^{1/4}} \frac{1}{S/N} \sqrt{\Delta_{\rm pixel} {\rm FWHM}}.$$

$$\frac{\Delta\alpha}{\alpha} = \frac{(v_2 - v_1)}{2\,c\,(\mathcal{Q}_1 - \mathcal{Q}_2)} = \frac{\Delta v}{2\,c\,\Delta\mathcal{Q}}$$

Line	$\lambda^a_{\rm vac}$, Å	f^b	$\mathcal{Q}^c_{\rm old}$	$\mathcal{Q}^d_{\rm new}$	$\Delta\mathcal{Q}/\mathcal{Q}$ (%)
Fe II	2600.1722	0.23878	0.035	0.0367	4^d
Fe II	2586.6494	0.06918	0.039	0.0398	3^d
Fe II	2382.7641	0.320	0.035	0.0369	4^d
Fe II	2374.4601	0.0313	0.038	0.0394	4^d
Fe II	2344.2128	0.114	0.028	0.0361	26^d
Fe II	1611.20034	0.00138	0.018	0.0251	32^d
Fe II	1608.45069	0.0580	−0.021	−0.0166	29^d
Mg II	2803.5315	0.3054	0.0034		8^a
Mg II	2796.3543	0.6123	0.0059		5^a



- $\sigma_v \sim 3$ m s^{-1} easy → $\sigma_{\Delta\alpha/\alpha} \sim$ 0.1 ppm
- ==> 0.05 ppm should be within reach

Varying constants & Dark energy

- Varying constant measurements could potentially be used to reconstruct the dark energy potential Avelino Martins Nunes Olive 2006 astroph/0605690

$$\alpha = \frac{\bar{\alpha}}{B_F(\phi)} \Rightarrow \frac{\delta\alpha}{\alpha} \approx -\beta\delta\phi$$

- The energy density and pressure of the scalar field is:

$$\rho_\phi = \frac{\omega\dot{\phi}^2}{2} + V(\phi); \quad p_\phi = \frac{\omega\dot{\phi}^2}{2} - V(\phi)$$

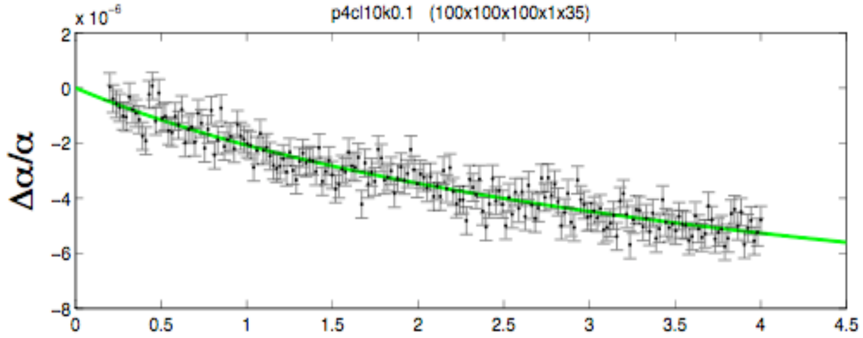
- The dark energy equation of state parameter is given by:

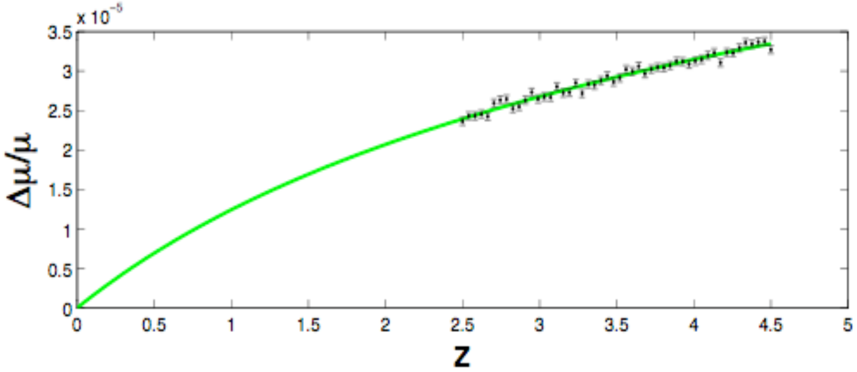
$$\omega_\phi = \frac{p_\phi}{\rho_\phi} = -1 + \frac{\rho_\phi + p_\phi}{\rho_\phi} = -1 - \frac{\rho'_\phi}{3\rho_\phi} = -1 - \frac{1}{3}\frac{\sigma'}{\sigma}$$

- Assuming flatness, we can reconstruct $w_\phi(z)$ if we can measure the variation of alpha

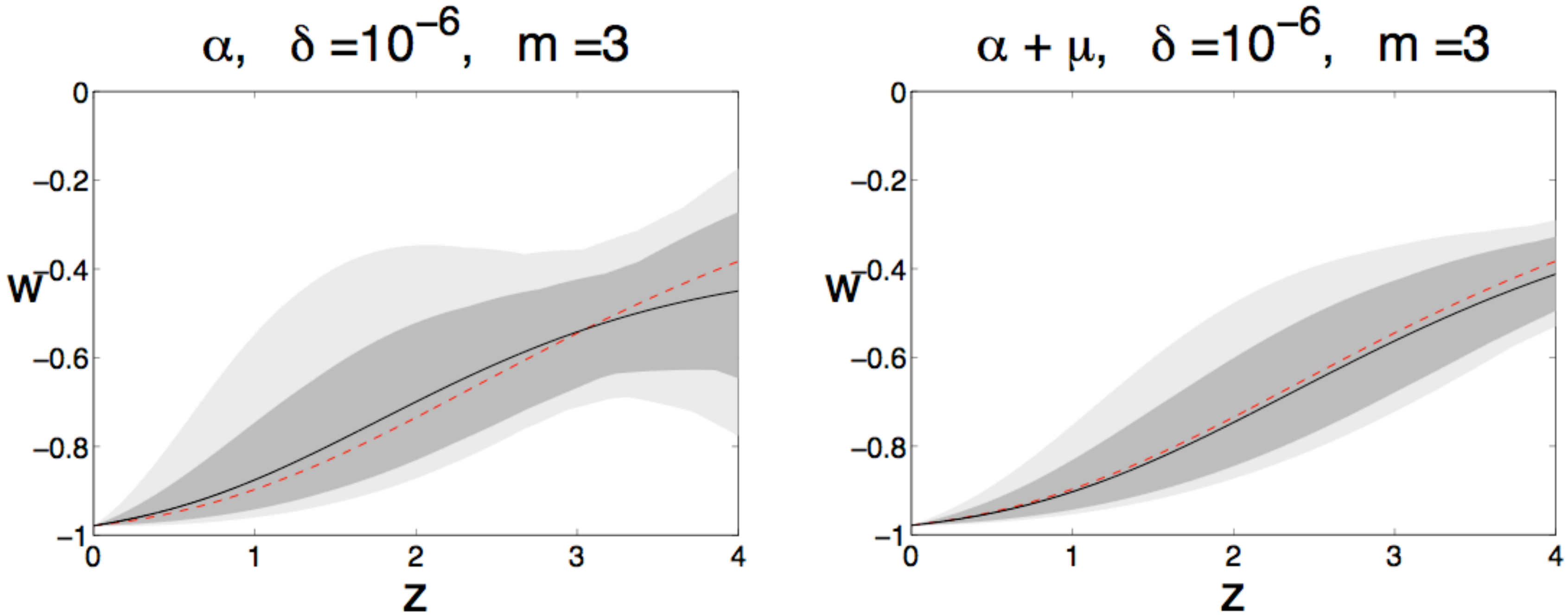
Simulation

- Monte Carlo data based on redshift dependence of the scalar potential.
  - Sample size: 200 for α and 50 for μ
  - Errors: 0.5 ppm for α and μ.
  - Assumed variation:
    - $\Delta\alpha/\alpha$ = -5 ppm at z=3 (as Murphy et al)
    - assuming R = -6 to derive μ
- Scalar potential which account for the observed accelerated expansion:
  - $V(\phi) = V_0(\exp(10k\phi) + \exp(0.1k\phi))$





reconstruction



- Red line assumed w(z), black line recovered w(z). (Shaded regions show 1 and 2 CL reconstruction)

- Only few points are sufficient to show that w(z) change with redshift

Conclusions

- Variability of physical constants is important for physics
- Only astronomy can probe it in space-time (a low hanging fruit)
- Important implications:
  - *new force* (related to scalar fields)
  - Possible reconstruction of *W(z)* Dark Energy
  - pointer for GUTs theories
- Status: hints of variation for μ and α, but results controversial.
- CODEX will improve present accuracy by about two orders of magnitude
  - This will clarify if present claims are real or probe variability at much lower level (two orders of mag)
  - a null result has as much impact on our physical view as a positive detection (i.e with the BSBM theory there is already tension between the atomic clocks and QSO varying alpha)

at z=6.46

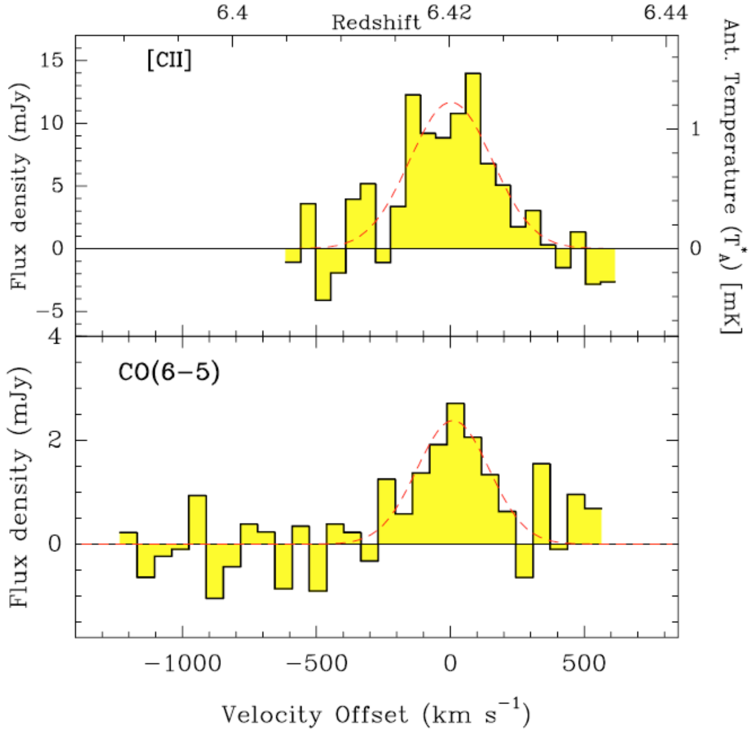
A new approach for testing variations of fundamental constants over cosmic epochs using FIR fine-structure lines

S. A. Levshakov[1*], D. Reimers[1], M. G. Kozlov[2,1], S. G. Porsev[2,1], and P. Molaro[3]

- at z=6.46 towards QSO J1148+5251 Maiolino et al 2004
- Far IR emission lines CII -CO

  ➡ $F=\alpha^2/\mu = (0.1\pm1)\times10^{-4}$

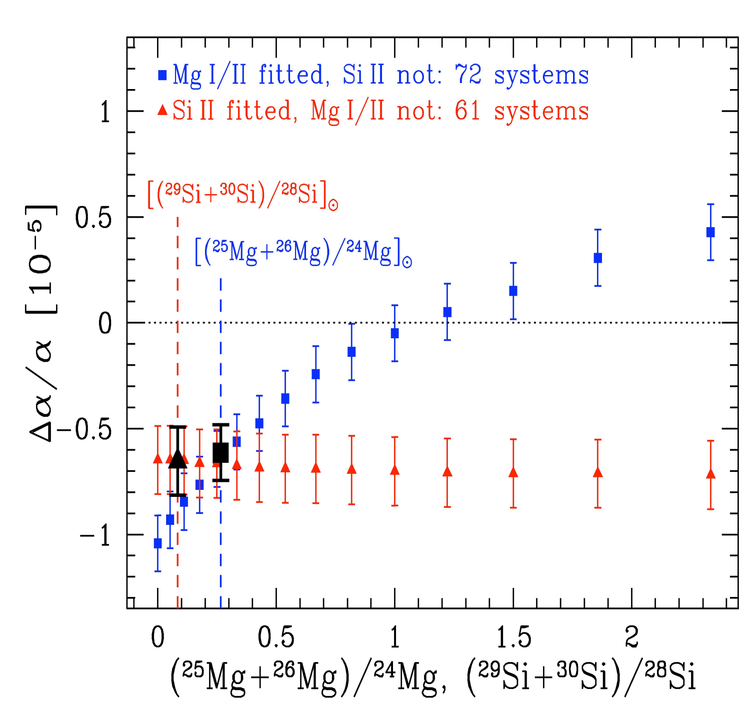
- Emission lines important for z>6
  - targets for ALMA



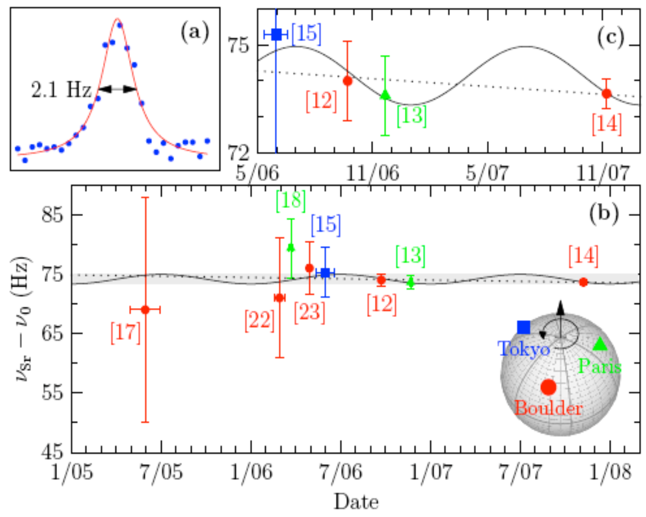
Crucial issues in the MM

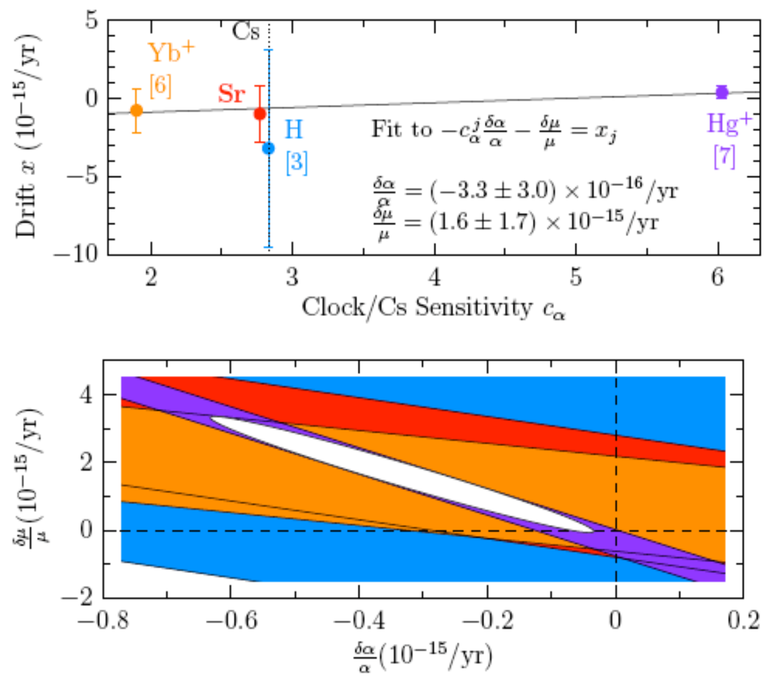
- **Isotopes** produce small shifts on line positions. Assumed solar ratios, but
- Supersolar ^{25,26}Mg/^{24}Mg: positive variation
- Undersolar ^{25,26}Mg/^{24}Mg: negative variation
  - Chand et al is consistent with a variation only ^{24}Mg $\Delta\alpha/\alpha$=(-3.6 ± 0.6) ppm

- ^{25,26}Mg are contributed by Intermediate Mass Stars (4-8 M_{sun}) but we do not know the isotopic composition in the systems or their behaviour.



- **Doppler motions:**
- Different ions form in different regions which may have different velocities





^{87}Sr-Cs in 3 lab Tokio-Paris-Boulder for 3 years (Blatt et al 2008)

An “independent” check:

$$\frac{\dot{\alpha}}{\alpha}(now) \approx 2.98 \times 10^{-16} h(year)^{-1}$$

For:

$$\Omega_\Lambda = 0.71; \Omega_m = 0.29;$$
$$H_0 = 100hKm/s/Mpc$$

Cold atom clocks!!!!