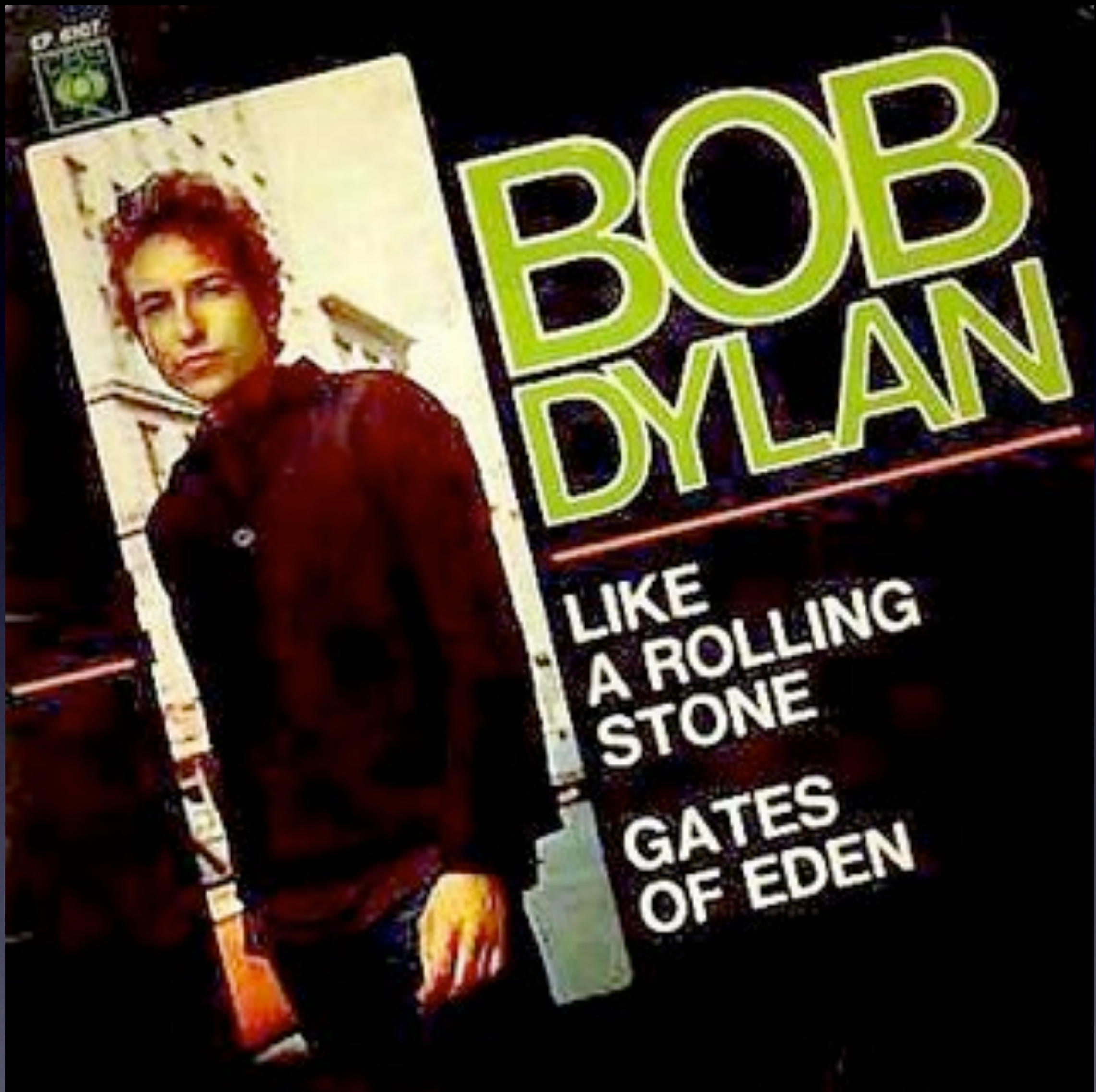


Paolo Molaro
Inaf-OAT

LIKE A ROLLING CONSTANT

1965

EUROPEAN SOUTHERN OBSERVATORY

Organisation Européenne pour des Recherches Astronomiques dans l'Hémisphère Austral
Europäische Organisation für astronomische Forschung in der südlichen Hemisphäre

OBSERVING PROGRAMMES OFFICE • Karl-Schwarzschild-Straße 2 • D-85748 Garching bei München • e-mail: opo@eso.org • Tel.: +49-89-32 00 64 73

APPLICATION FOR OBSERVING TIME　　LARGE PROGRAMME　　PERIOD: **85A**

Important Notice:

By submitting this proposal, the PI takes full responsibility for the content of the proposal, in particular with regard to the names of CoIs and the agreement to act according to the ESO policy and regulations, should observing time be granted

1. Title　　Category: **A–7**

THE UVES LARGE PROGRAM FOR TESTING FUNDAMENTAL PHYSICS

2. Abstract / Total Time Requested

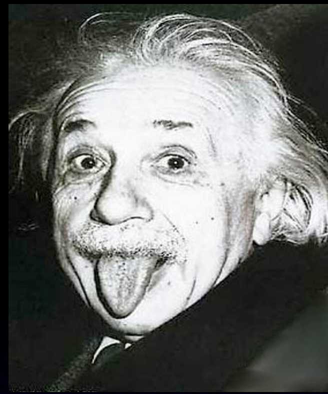
Total Amount of Time:　　Total Number of Semesters:

Astronomical observations represent a unique way to probe possible cosmological variations of dimensionless constants (α, $\mu = m_e/m_p$). A variability of these constants violates Einstein's Equivalence Principle and could

M. Murphy, P. Petitjean, S. Ievshakov, Srianand, S. Lopez, S. D'Odorico, D. Reimers, P. Bonifacio, M. Centurion, et al

- what is a “constant”?
- why should vary?
- measurable constants
- do they vary?
- observational perspective
- ammonia MW survey

What is a constant?



Albert Einstein 1945 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 whether God could have made the world in a different way

Standard Model

Fundamental constant = any parameter that cannot be calculated(free parameter)

In the Standard Model the interactions depend on 28 fundamental constants.
These are:
the constant of gravitiy G,
the finestructure constant α,
the coupling constant g_w of the weak interactions,
the coupling constant g_s of the strong interactions,
the mass of the W-boson,
the mass of the "Higgs"–boson,
the masses of the three charged leptons, m_e, m_μ, m_τ,
the neutrino masses $m(\nu_1), m(\nu_2), m(\nu_3)$,
the masses of the six quarks $m_u, m_d, m_c, m_s, m_t, m_b$,
the four parameters, describing the flavor mixing of the quarks,
and the six parameters, describing the flavor mixing of the leptons, measured by the neutrino oscillations.

H. Fritzsch 2009

Large Number Hypothesis

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.

- 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

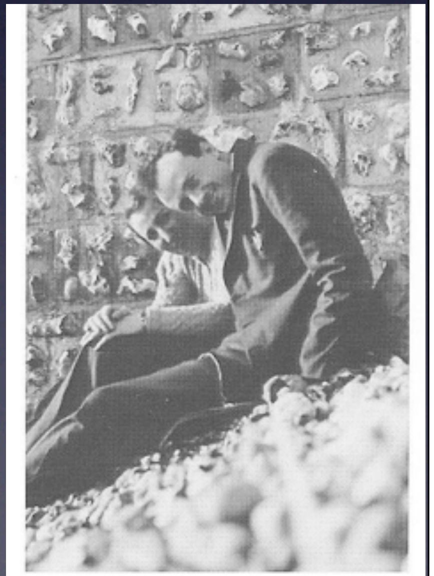
$$\frac{G m_p m_e}{e^2} \sim 3.7 \times 10^{-40}$$

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

$\Rightarrow \alpha_G \propto 1/t$ (but other changes are possible)

∂G/∂t ˜ 10-10 yr-1

- Teller 1948: conflict with astronomical evidence



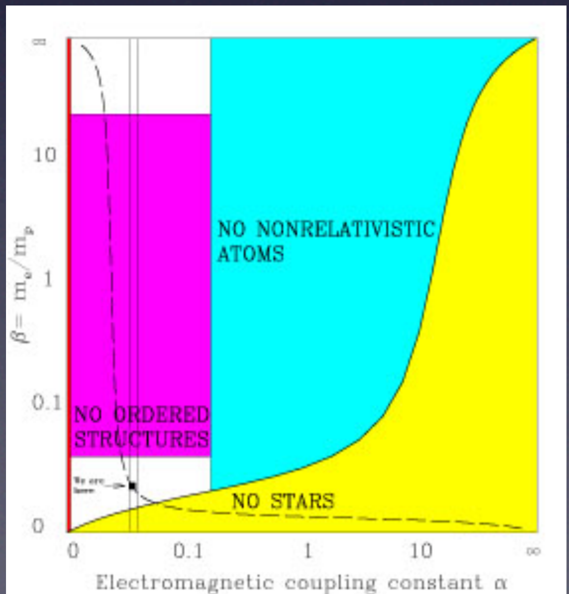
Dirac and Manci on their honeymoon, Brighton, January 1937

Fine Tuning

- Anthropic principle: we appeared in area of the Universe where values of fundamental constants are suitable for our existence.

- Slightly different coupling constants –- no life

  - Example: low-energy resonance in production of C from He in stars ($\alpha + \alpha + \alpha = {}^{12}C$).

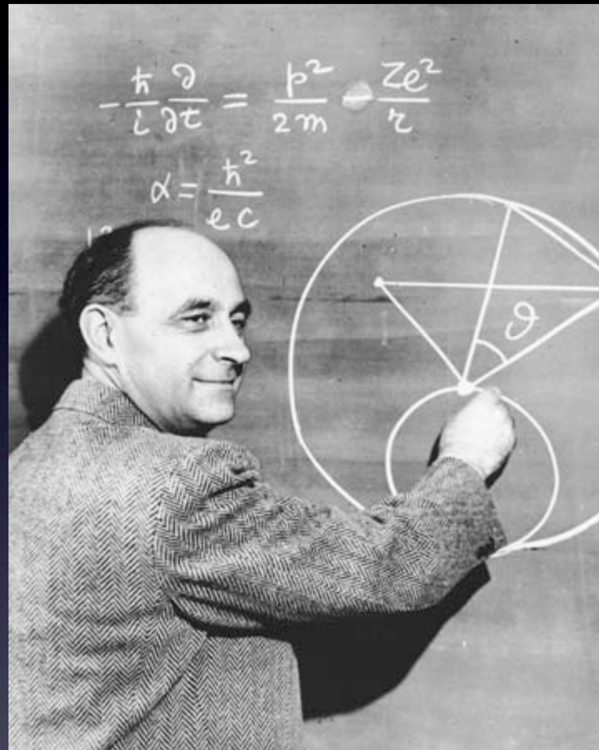


$$\frac{1}{170} < \alpha < \frac{1}{80}$$

Which can be measured?

The fine-structure constant α

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



➡ Electromagnetic force

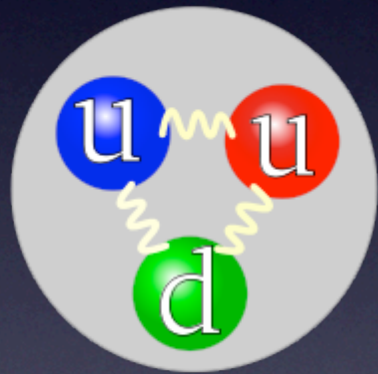
- α_{EM}, is constructed with 3 other constants, the unit of electric charge, e, Planck's constant, $\hbar$, and the speed of light, c:

The electron-to-proton mass ratio

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

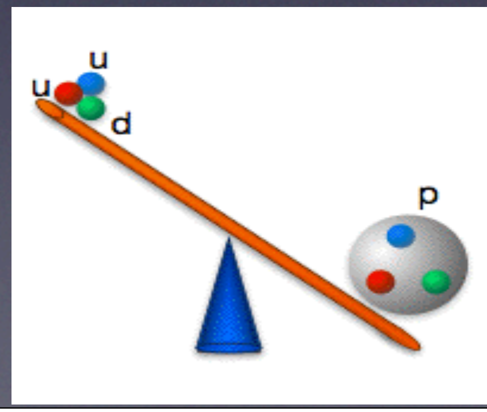
- $m_e = 0.5$ Mev
  - $m_e \propto$ the vacuum expectation value of the Higgs field ➡ The weak scale
    (223 Mev)

Proton



- $m_p = 938$ Mev
  - $m_p = (862_{QCD} + 74_q + 2_{QED})$ Mev
  - $m_p \propto \Lambda_{QCD}$ ➡ strong forces

μ ratio of weak to strong forces



Why constants should vary?

- We do not have a theory of constant variation
- if there is a coupling of a scalar field with one or more terms of the Lagrangian matter-radiation then the physical constants may vary

➡searching for varyation of fundamental constants is a way to search for massless fields which couple with matter

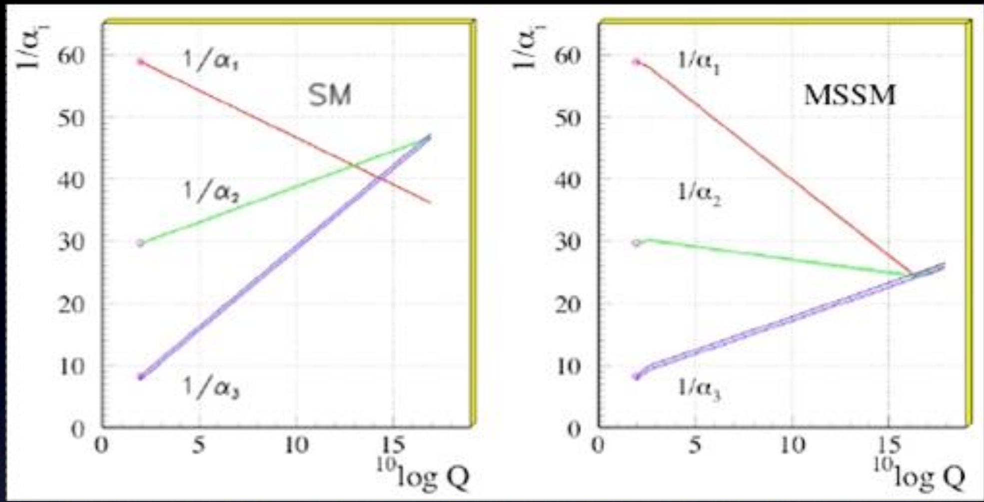
Scalar fields:

- Higgs Field (possibly the first scalar field to be detected LHC)
- Inflation
- Strings: Moduli Fields
- f(R) theories
  - modifications of gravity
- Dark energy (quintessence)

GUTs

- ✦ Experiments show that fundamental couplings run with energy (α=1/128 at Mz)

- ✦ GUTs imposes gauge coupling unification 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

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

Dine et al 2003

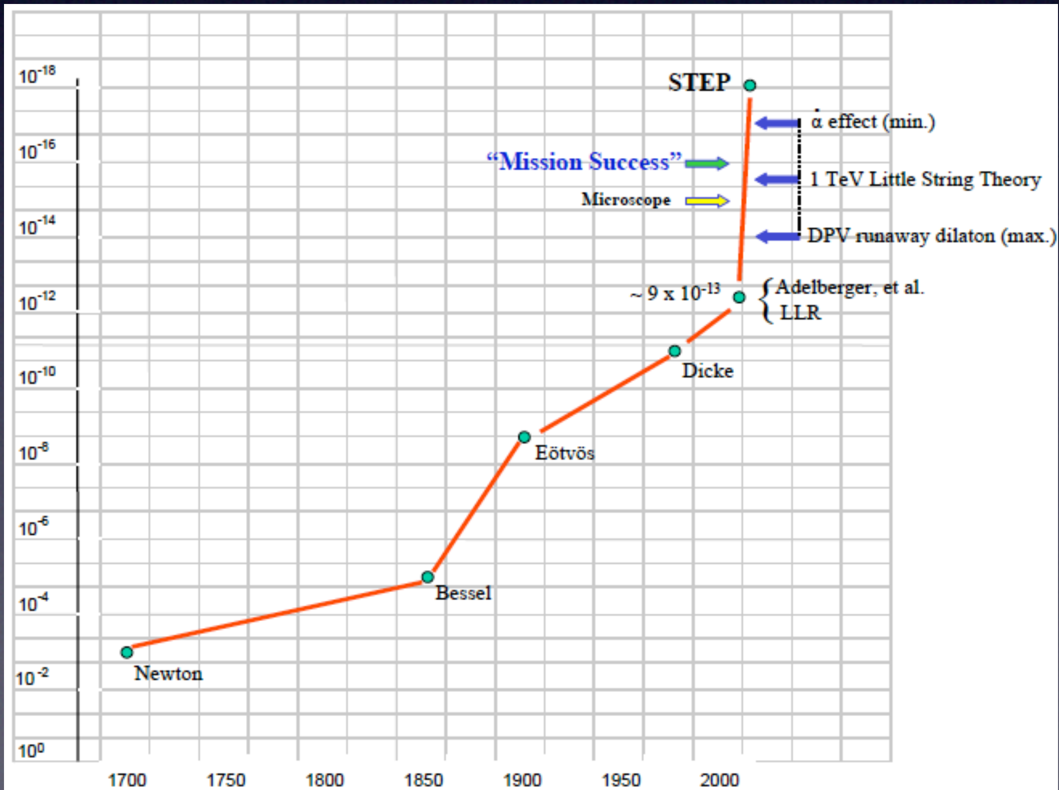
There's a relation between the variation of α and μ R is model dependent

|R|<50, larger possible. The strong-coupling constant is running faster than α and ➡ $\Delta\mu$ should be larger

- simultaneous measurements of $\Delta\alpha$ & $\Delta\mu$ are a key discriminant tool of GUTs models!

Test of constants are tests of the Equivalence Principle:

- universality of free fall
- local position invariance
- local Lorentz invariance



Eotvos

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

Constraint	Body 1	Body 2
$(-1.9 \pm 2.5) \times 10^{-12}$	Be	Cu
$(0.1 \pm 2.7 \pm 1.7) \times 10^{-13}$	Earth-like rock	Moon-like ro
$(-1.0 \pm 1.4) \times 10^{-13}$	Earth	Moon
$(0.3 \pm 1.8) \times 10^{-13}$	Te	Bi
$(-0.2 \pm 2.8) \times 10^{-12}$	Be	Al
$(-1.9 \pm 2.5) \times 10^{-12}$	Be	Cu
$(5.1 \pm 6.7) \times 10^{-12}$	Si/Al	Cu

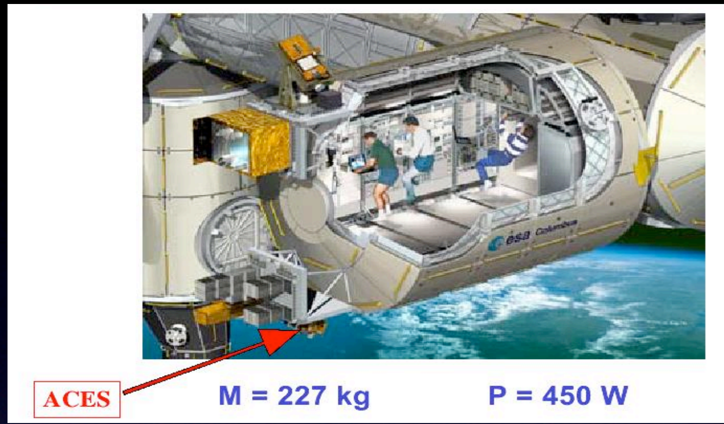
Several space-based missions:

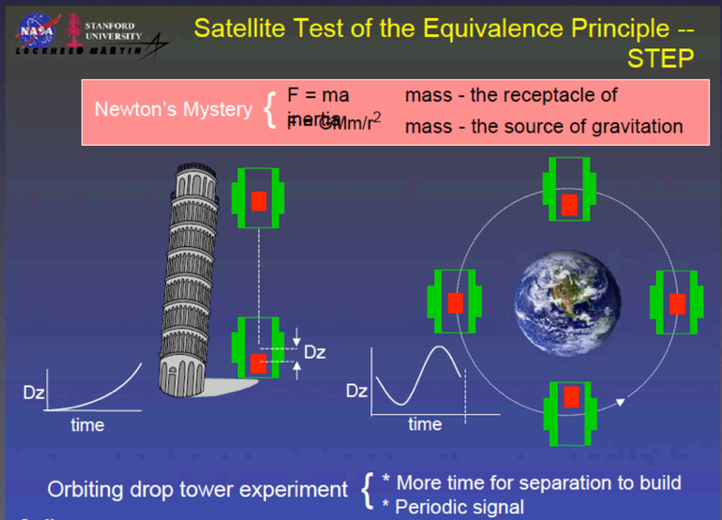
ACES/PHARAO (Atomic Clock Ensemble in Space/Projet d'Horologe Atomique par Rafroidissement d'Atomes en Orbite)

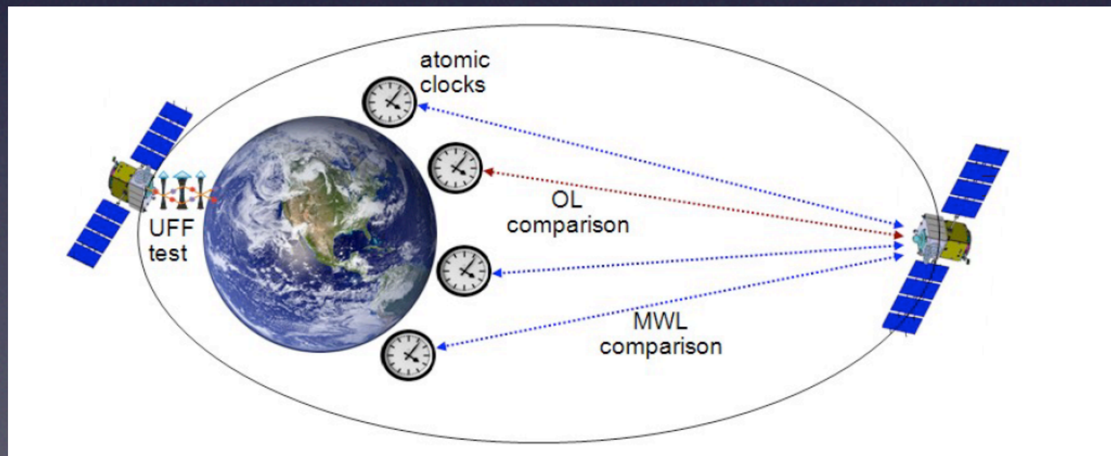
μSCOPE lounch 2011

STEP not approved

STE-QUEST (Space-Time explorer and quantum EP space test) M mission proposal Cosmic Vision 2015-2025







will improve existing bounds by orders of magnitude.

Quintessence

Dark Energy is possibly a scalar field: Quintessence.

Slowly evolving scalar field (Wetterich 1988, Ratra & Peebles 1988).

$$L_\phi = \frac{1}{2}\partial^\mu\phi\partial_\mu\phi - V(\phi)$$

$$\rho_\phi = \frac{1}{2}\dot{\phi}^2 + V(\phi) \quad \text{e} \quad p_\phi = \frac{1}{2}\dot{\phi}^2 - V(\phi)$$

$$H^2 = \frac{8\pi G}{3}(\rho_R + \rho_M + \rho_\phi) \quad \text{(2ª eq. di Friedmann)}$$

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}(2\rho_R + \rho_M + 2\dot{\phi}^2 - 2V(\phi)) \quad \text{(1ª eq. di Friedmann)}$$

$$w \equiv \frac{p_\phi}{\rho_\phi} = \frac{\frac{\dot{\phi}^2}{2} - V(\phi)}{\frac{\dot{\phi}^2}{2} + V(\phi)}$$

w = 1 kinaton

w = -1 slow-roll

- SLOW-ROLL produce acceleration

$$w < -1/3 \qquad q = \frac{1}{2}\sum_i \Omega_i (1 + 3w_i)$$

- very small mass (otherwise energy of the field > total energy)

$$\frac{\Delta\phi}{M_{Pl}} \approx 1 \qquad m_{\phi_0} \approx \sqrt{V''(\phi_0)} \approx H_0 \approx 10^{-33} eV$$

- long ranging forces (from indetermination principle)

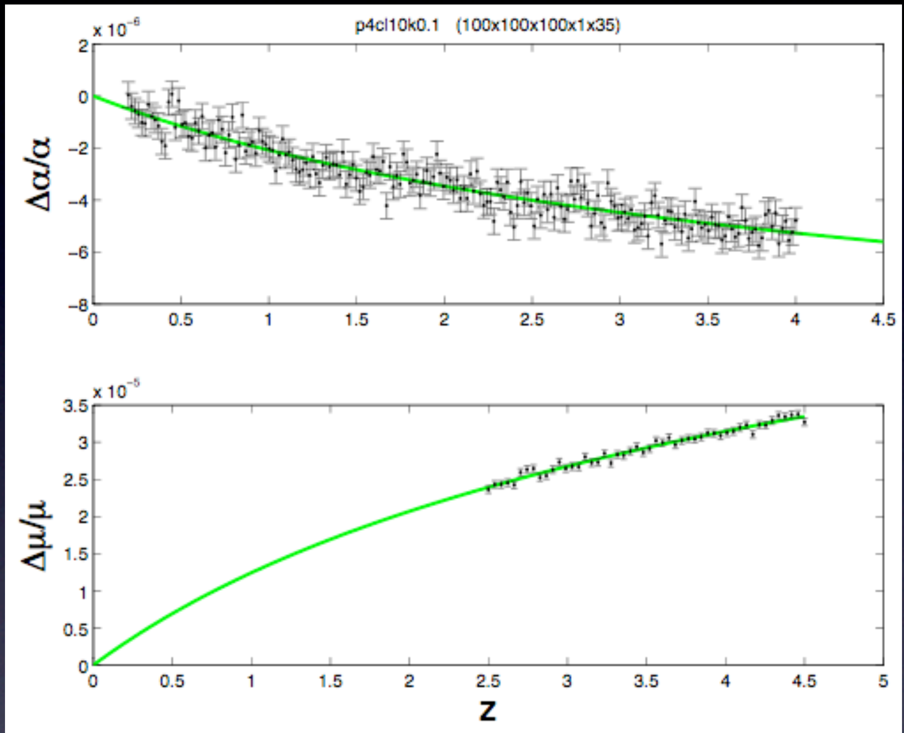
$$r \propto m^{-1}$$

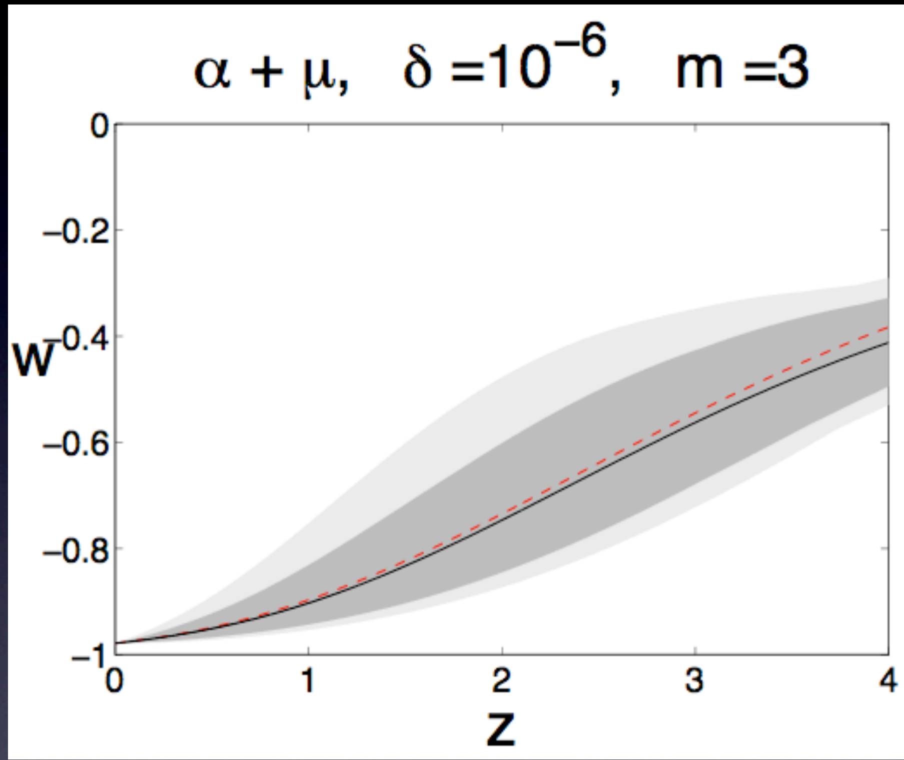
➡ fifth force
➡ violation of universality of free fall (independent from mass and composition)?

$$m_p = m + \alpha B_P$$
$$m_n = m + \alpha B_n$$

- not observed in EP experiments:
  - ➡ minimum coupling (or locally minimum coupling)
  - ➡ Chamaleons fields (dependence of coupling on environmental matter density Khoury & Weltman'04, Bax et al.'04 Feldman et al.'06 Olive & Pospelov'08

Dark Energy reconstruction



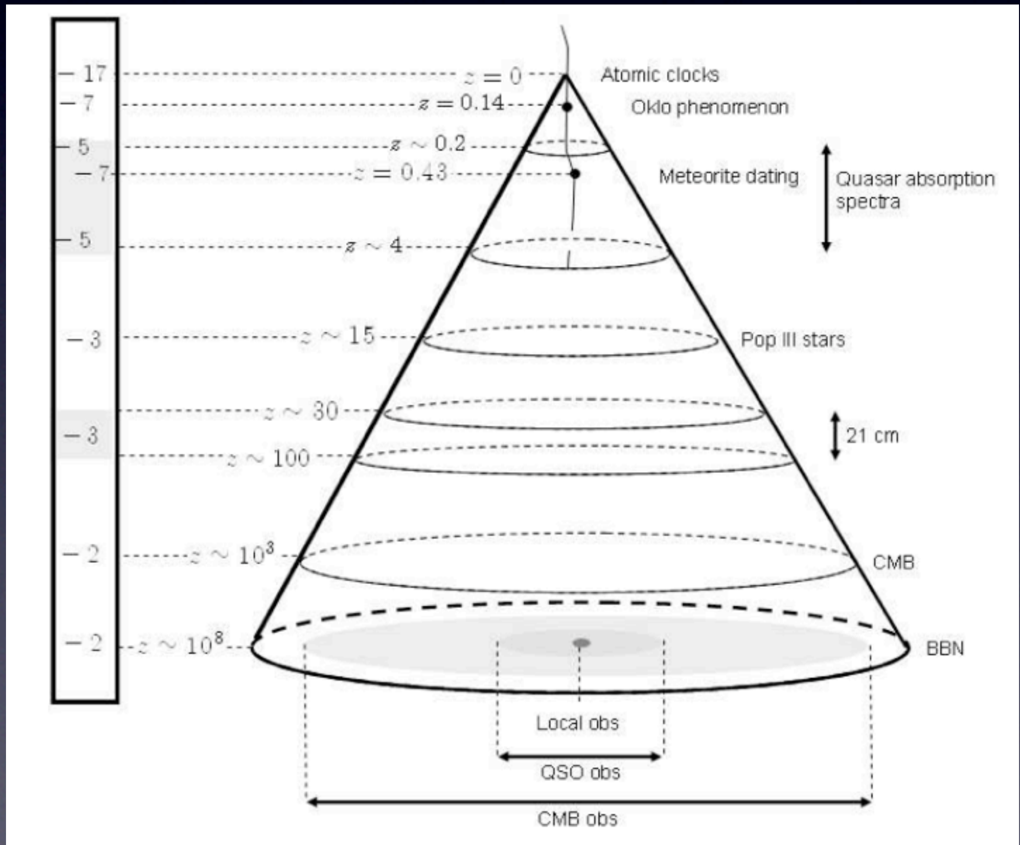


adapted from Avelino et al 2006

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

Observations

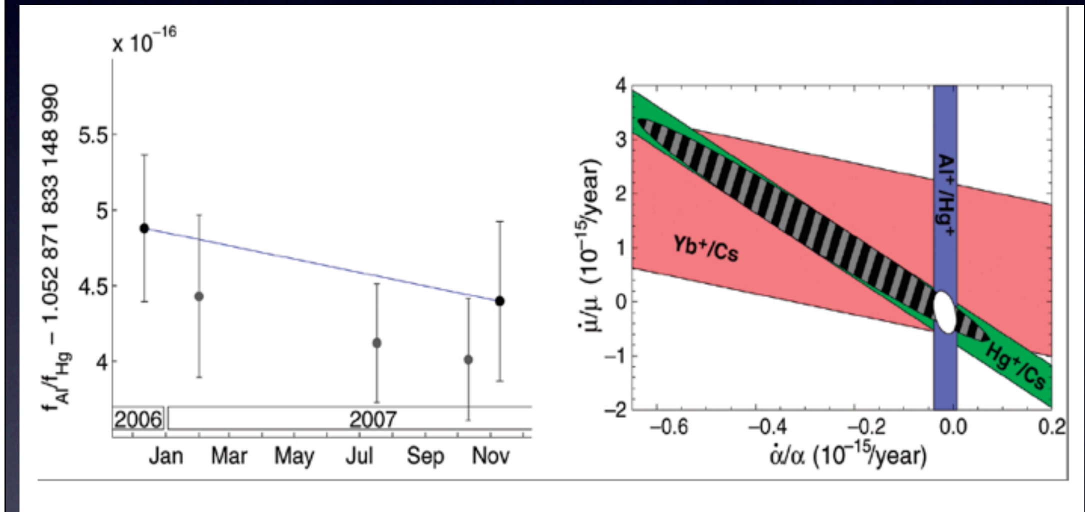
$$\Delta\alpha = (\alpha_z - \alpha_0)/\ \alpha_0$$



In the lab: Atomic Clocks

α

Rosenband et al 2008



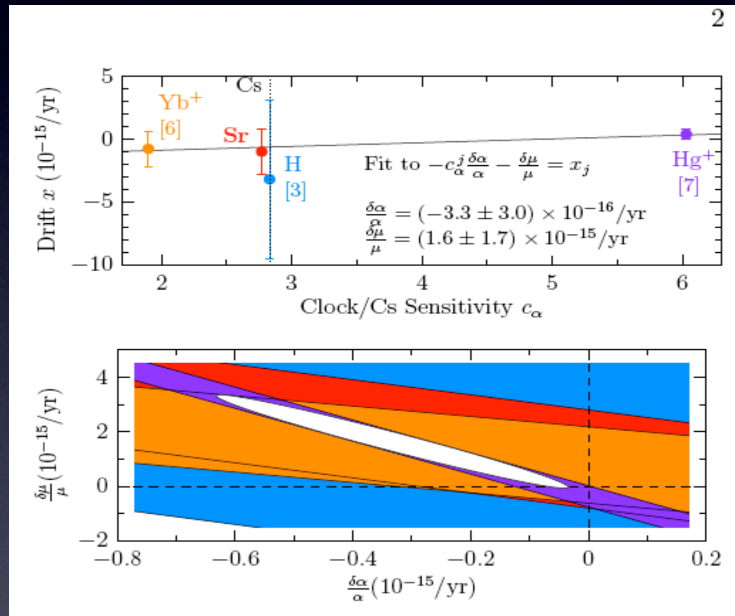
Hg+ and Al

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

17th decimal place!

μ

Blatt et al 2008



$d\mu/dt/\mu = (1.6 \pm 1.7)\ 10^{-15}\ \mathrm{yr}^{-1}$

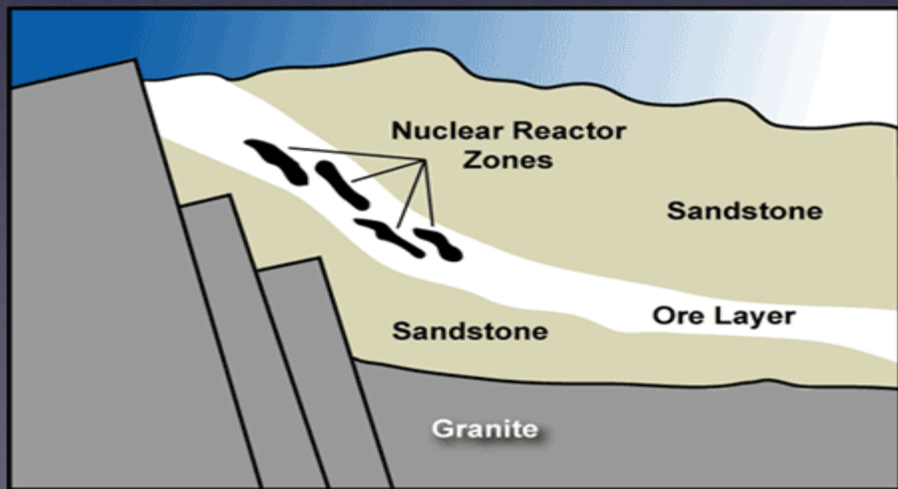
^{87}Sr-Cs in labs: Tokio-Paris-Boulder for 3 years

OKLO

- Natural fission reactor t=1.8 Gyr; ^{235}U ~ 3.7%, today 0.7%
- discovered 1972 in Gabon
  $^{149}Sm/^{147}Sm$ = 0.02 (instead of 0.9)
- Isotopic abundances related to the cross sections for neutron capture on ^{149}Sm + n = ^{150}Sm + gamma
- The resonance energy (E=0.0973 eV) depends on α (Shlyakhter (1976); Damour, Dyson, Fujii)

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

- but if other constants vary this constrain do not apply.



Meteorite dating

- Decay rate depends on α (Wilkinson 1958)

  β-decay $n \Rightarrow p + e + \text{anti-}\nu_e$

  sensitive to the neutron-proton mass difference: an electromagnetic contribution

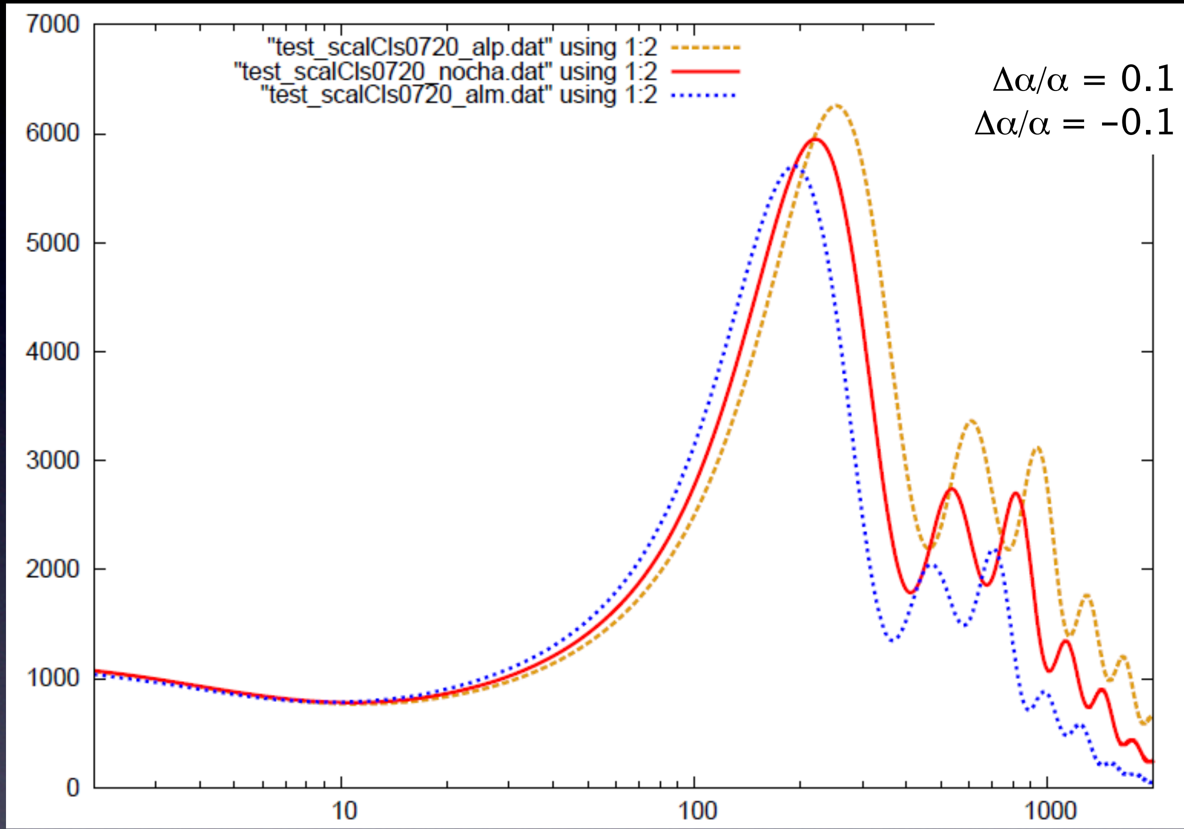
- Rhenium constraint : change in the radioactive half-life (Peebles & Dicke 1959).
- From the observation of the $^{187}Re/^{187}Os$ ratio in iron-rich meteorites 4.5 Gyrs ago

  $\Delta\alpha/\alpha < 3 \times 10^{-7}$ Olive et al 2002

Early Universe: CMB

- A non standard α changes the epoch of recombination
- ➡ change in the height and position of the peaks
- Several effects: Thomson cross section

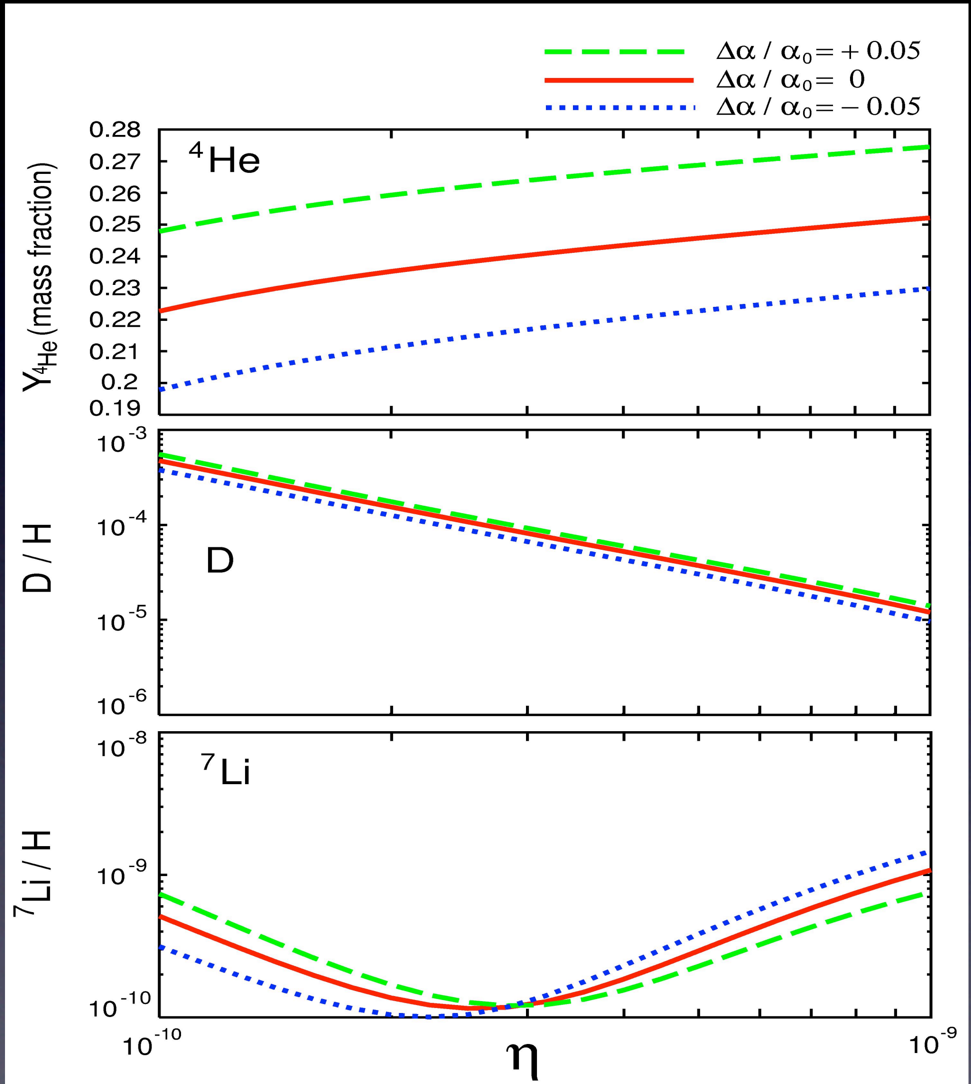
$$\sigma_T = 2\alpha^2 h^2/(3\pi m_e c^2)$$



$$\frac{dT_M}{dz} = \frac{8\sigma_T a_R T_R^4}{3H(z)(1+z)m_e} \frac{x_e}{1+f_{He}+x_e}(T_M - T_R) + \frac{2T_M}{1+z}$$

- Ichikawa et al 2006 <0.04
- Menegoni et al 2009 <0.01
- PLANCK will improve this limit 0.4% (?)

BBN

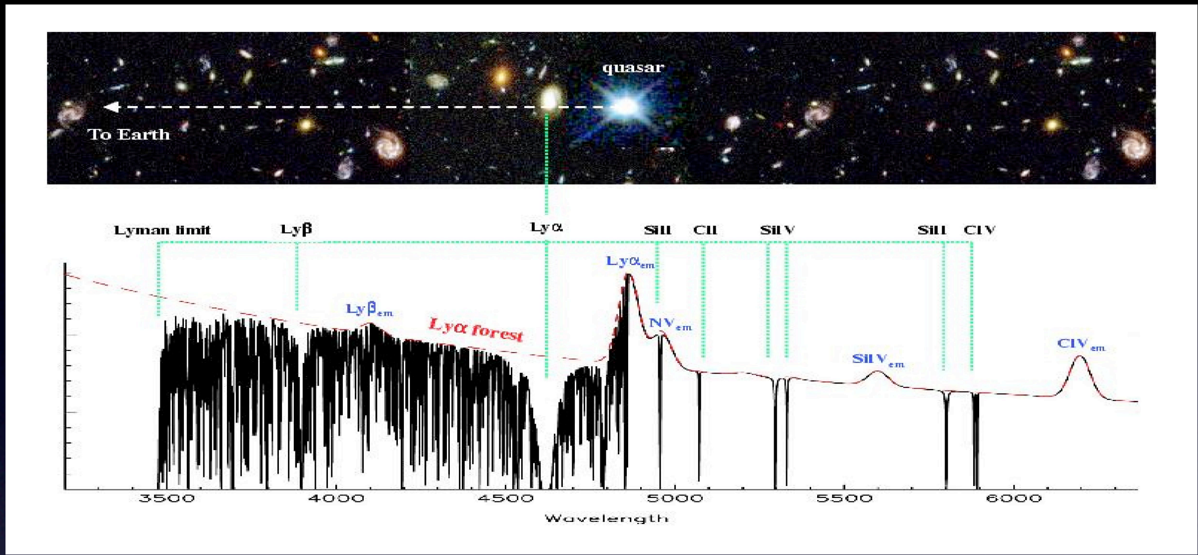


- changes in α induce changes (Kolb et al 1986):
  - in the nucleon mass ➔neutron to proton ratio
  - In the Coulomb barrier of nuclear reactions
- Coc et al 2007 "solve" the Li-D (WMAP) discrepancy,
- to keep everything rather consistent:

$$\Delta\alpha/\alpha < 10^{-2}$$

Ichikawa & Kawasaky 2002 Rocha et al 2004, Sigurdson et al 2004

QSOs



BARCODE with atomic structure at time t(z)

Savedoff (1956)
Bahcall, Sargent, Schmidt 1967

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 C III and S II.

Different transitions depend on different combinations of the dimensionless constants.

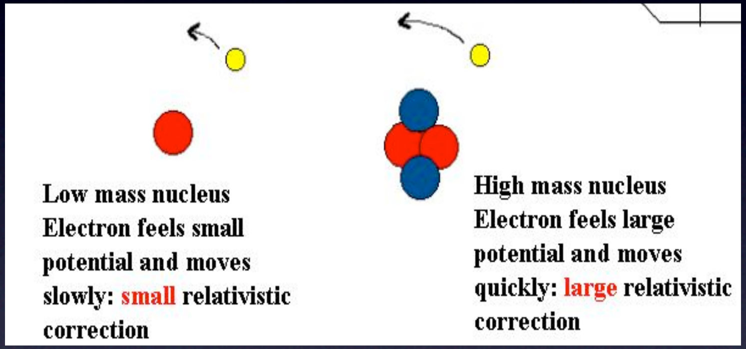
Transition		Scaling
Atomic	Gross Structure	Ry
	Fine Structure	α^2 Ry
	Hyperfine Structure	$\alpha^2 (g_p \mu)$ Ry
Molecular	Electronic Structure	Ry
	Vibrational Structure	$\mu^{1/2}$ Ry
	Rotational Structure	μ Ry
Relativistic Corrections		α^2

$$\mathrm{Ry} = \frac{\alpha^2 m_e c^2}{2}$$

Rydberg constant

Atomic calculations are required to compute ω (α)

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



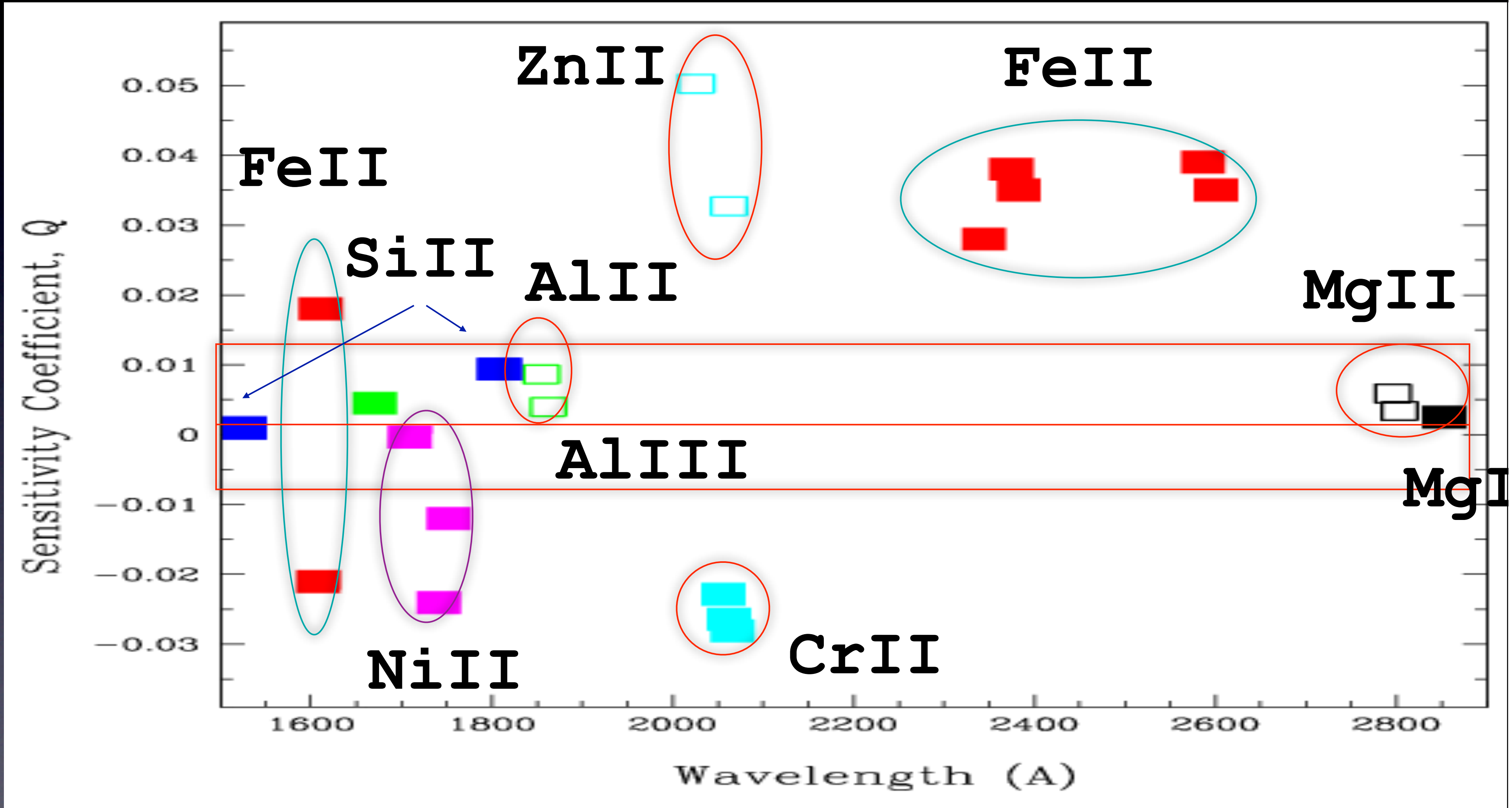
Sensitivity coefficients q are found by varying α in computer codes (Dzuba et al 1999

N_{ve}	Relativistic Hartree-Fock +	Accuracy
1	All-orders sum of dominating diagrams	0.1-1%
2-6	Configuration Interaction + Many-Body Perturbation Theory	1-10%
2-15	Configuration Interaction	10-20%

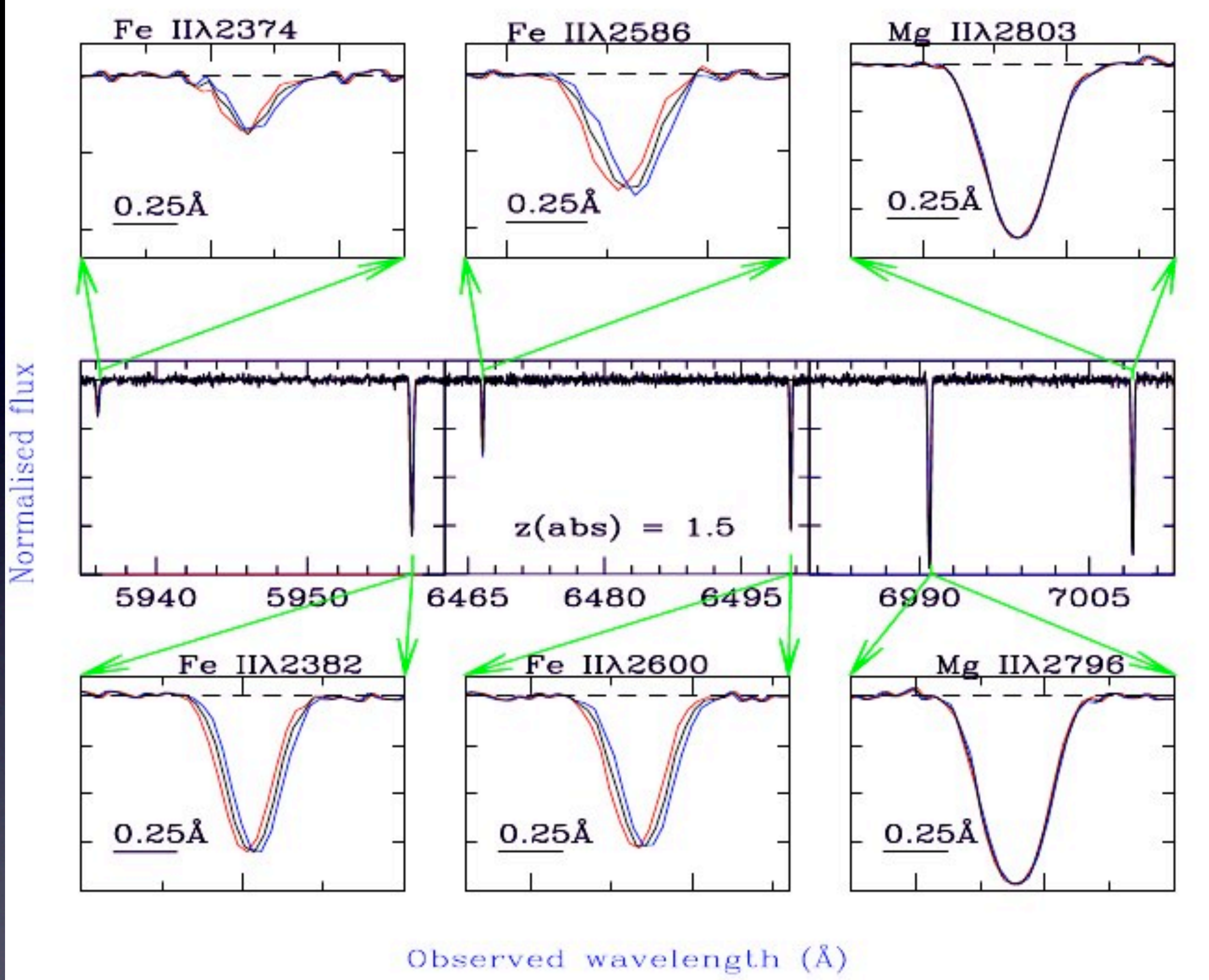
The Many-Multiplet method

High-z (>1.8)

Low-z (0.5 – 1.8)



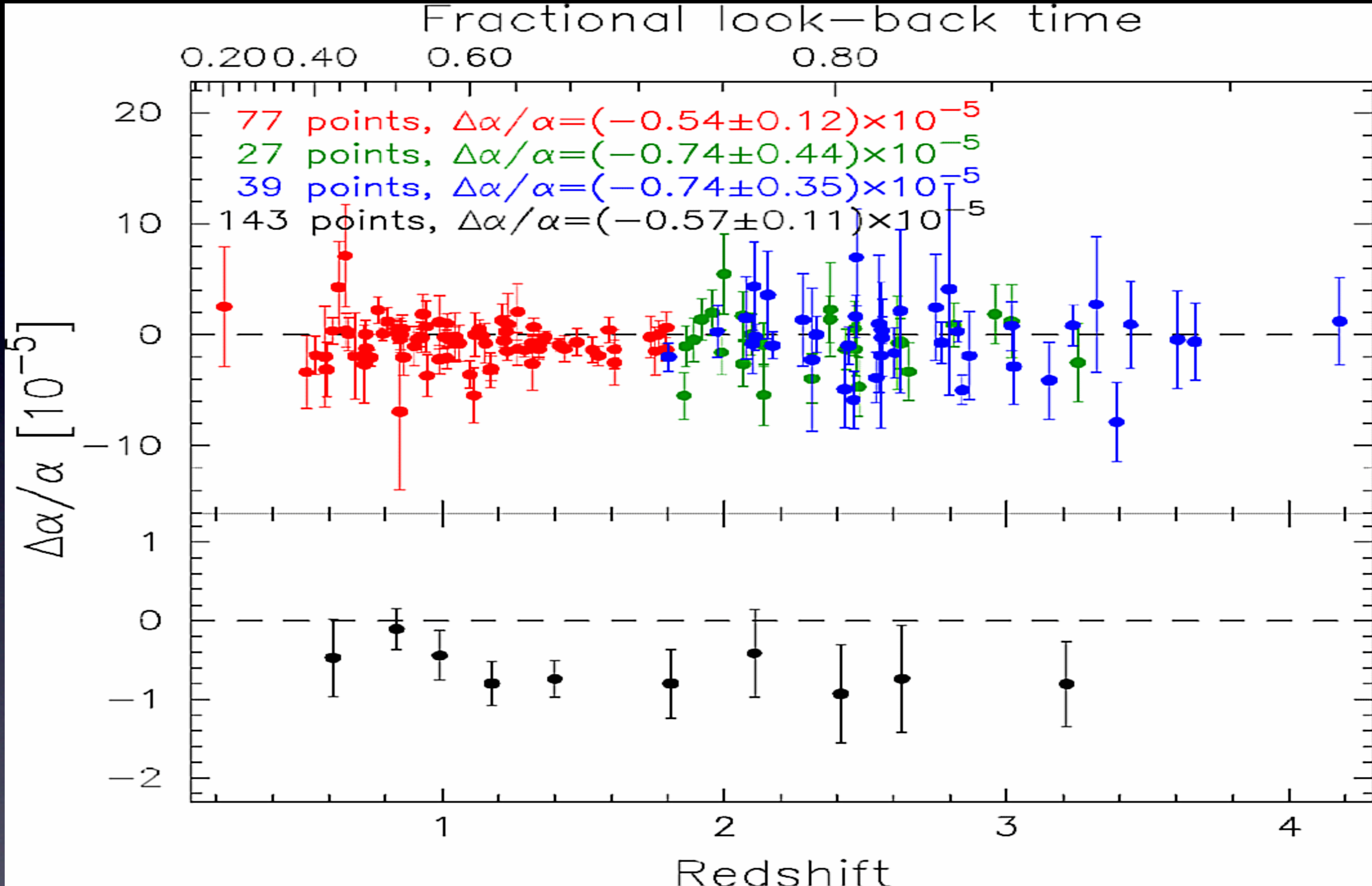
Many Multiplet Method: Simulations



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

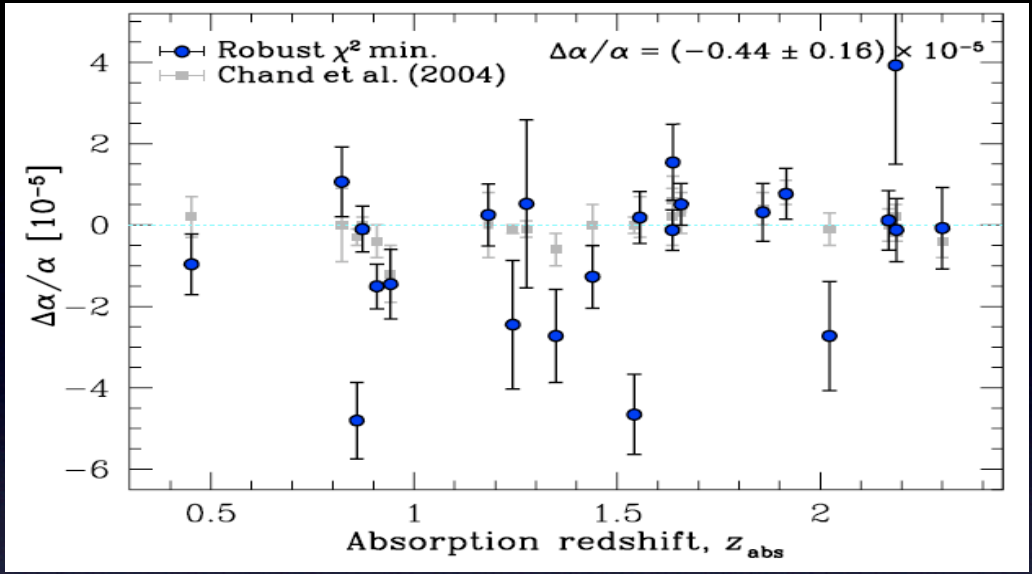
Shifts shown for 10^{-4}; or 1.8 km/s

Murphy Webb Flambaum (2004)



$$\Delta\alpha/\alpha = (-5.7 \pm 1.1) \text{ ppm}$$

the VLT

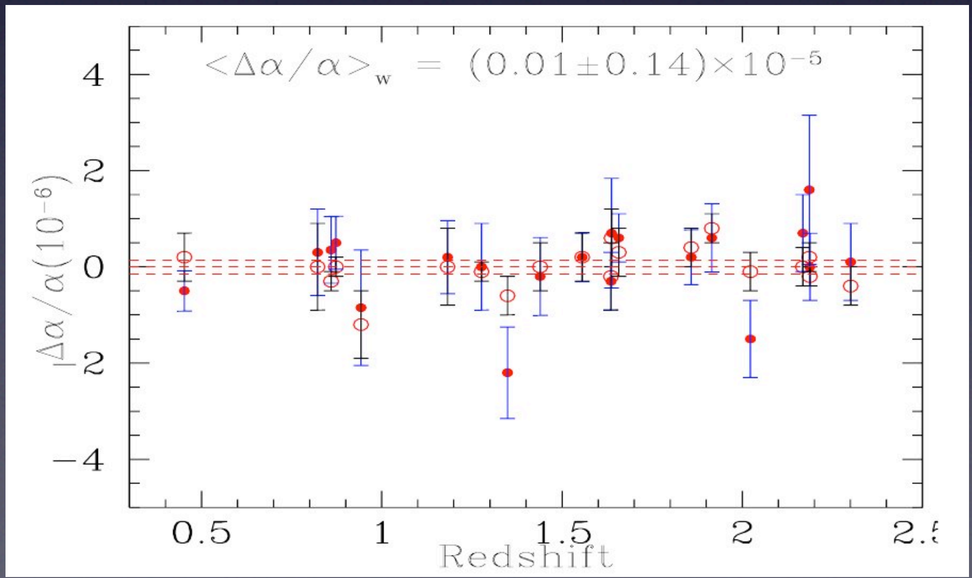


Chand et al 2004

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

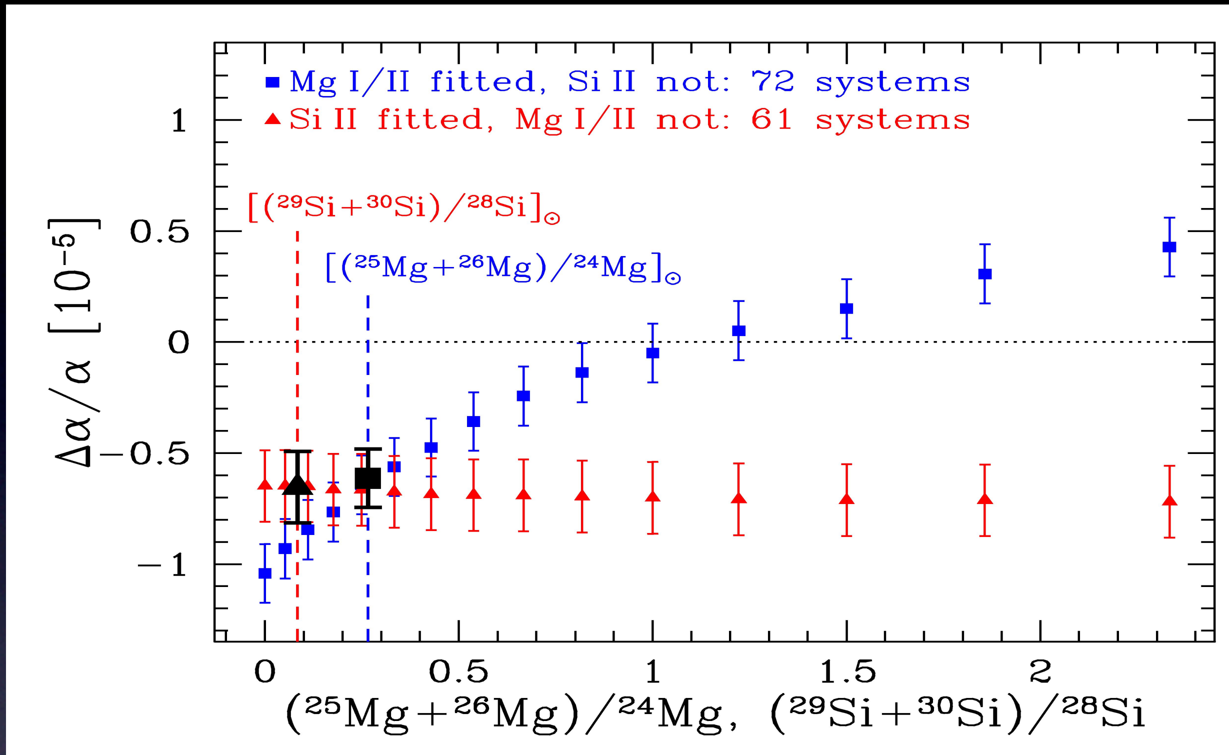
Michael T. Murphy,[1,*] John K. Webb,[2] and Victor V. Flambaum[2]

[1]*Institute of Astronomy, University of Cambridge, Madingley Road, Cambridge CB3 0HA*
[2]*School of Physics, University of New South Wales, Sydney, NSW 2052, Australia*
(Dated: April 27, 2007)



Srianand et al 2009

Mg isotopes



Supersolar $^{25,26}Mg/^{24}Mg$ no need for a variation
Undersolar: variation even more significant
Chand et al is consistent with a variation

$^{25,26}Mg$ are contributed by Intermediate Mass Stars (4-8 M_{sun})
very Little information on isotopic behaviour.

- Murphy et al and Chand et al assume solar ratios

Only FeII

- Only Fe lines! independent from non-solar isotopic composition of Mg

Molaro et al 2007

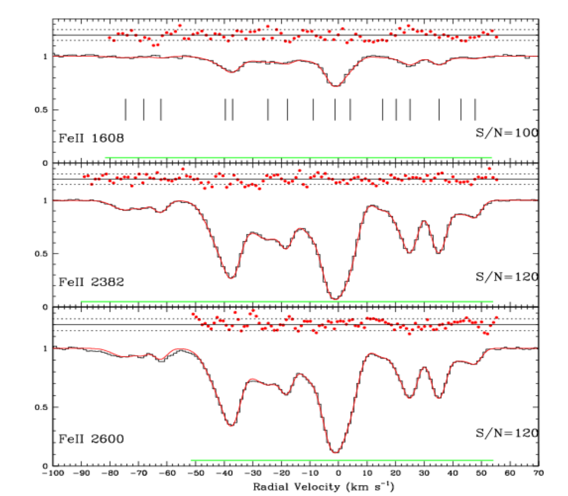
HE 0515-4414 V=14.9, DLA at z_{abs}=1.1

$\Delta\alpha/\alpha$ =(-0.07 ±1.8) ppm

- QSO 1101-264 V=16, DLA z_{abs}=1.84 R=80000

$\Delta\alpha/\alpha$=(5.4±2.5) ppm

Error Like larger surveys!

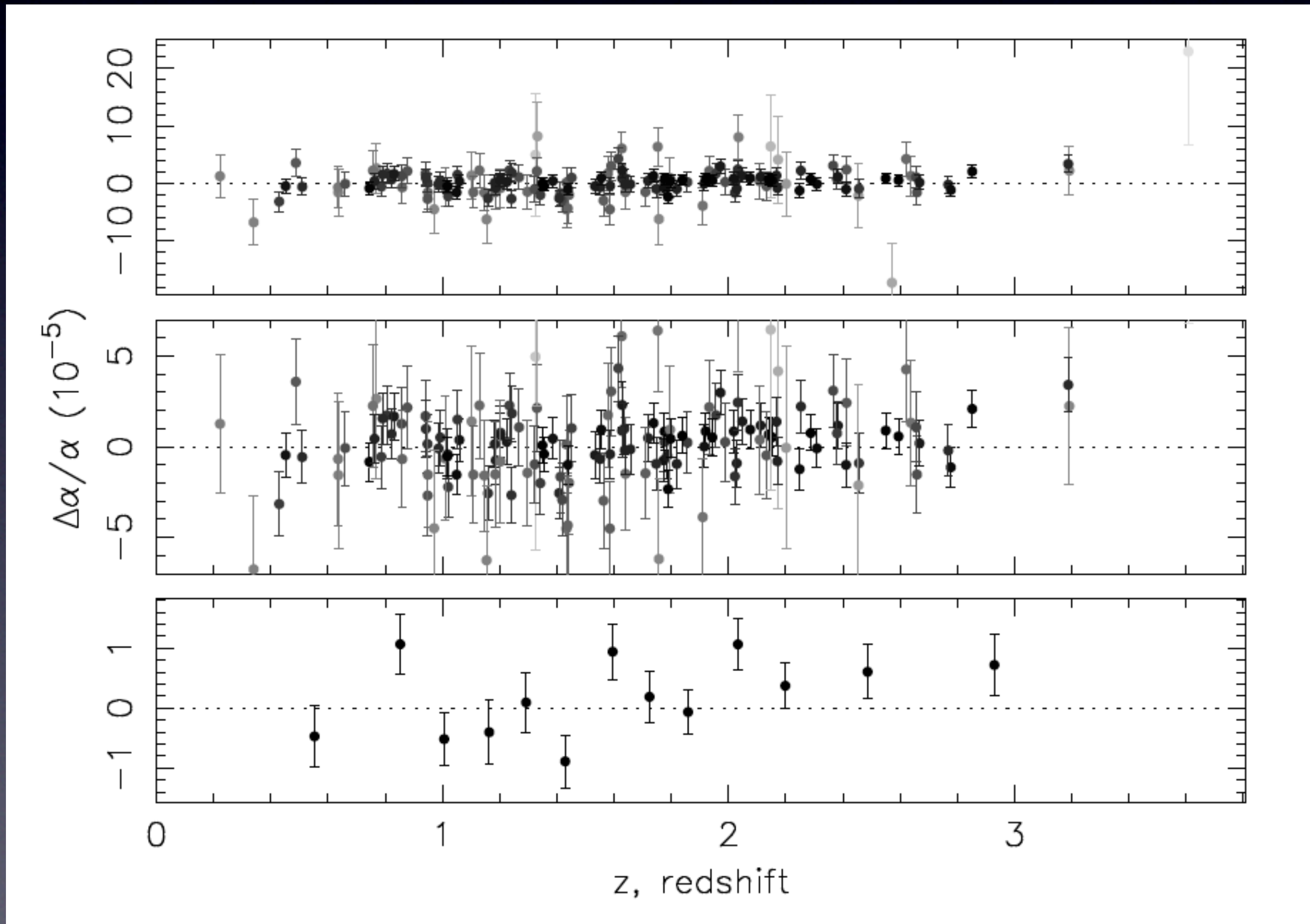


- Levshakov et al 2007

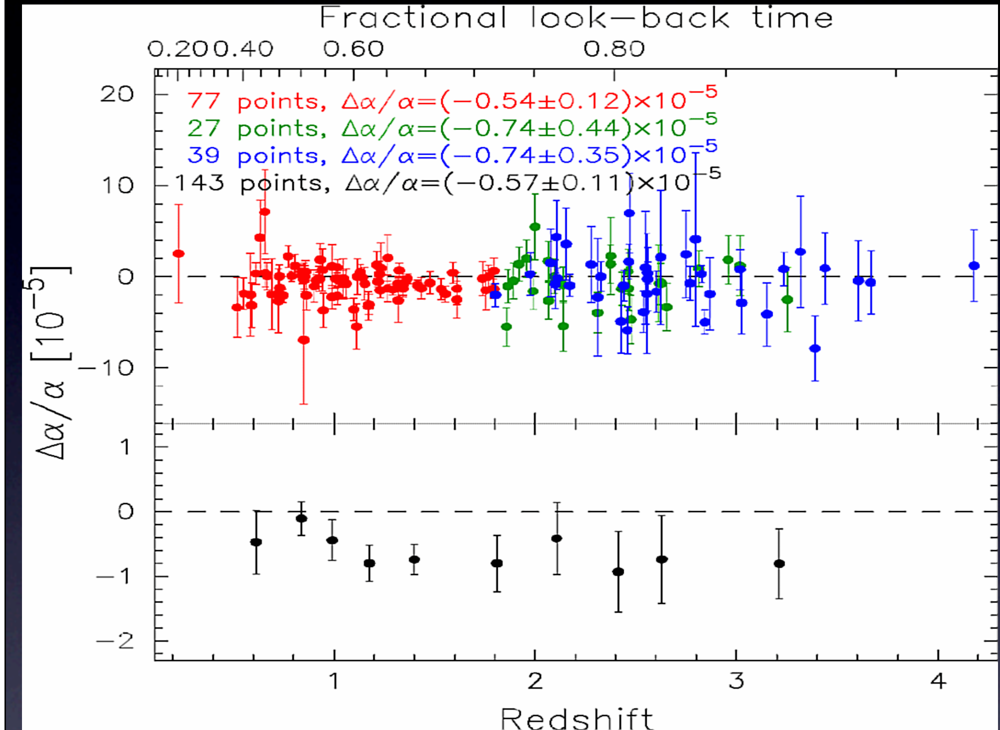
VLT survey

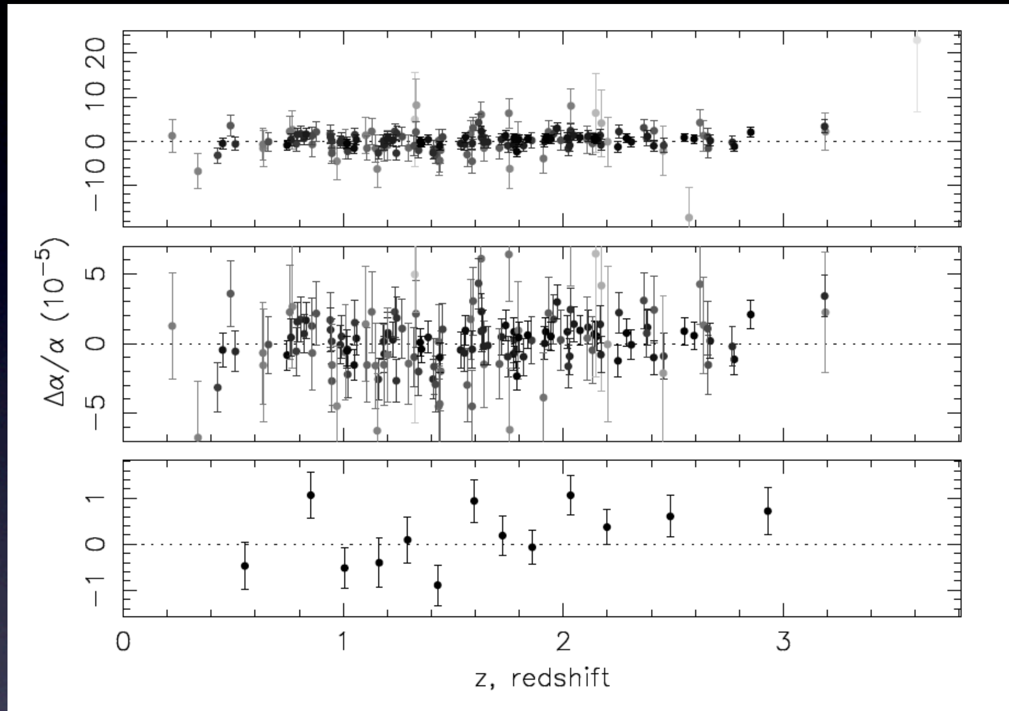
Webb King Murphy et al 2010 arXiv:1008.3907

King Webb Murphy Flambaum Carswell Bainbridge Koch 2011 submitted



153 absorbers $\Delta\alpha/\alpha$ = (2.08 ± 1.24) ppm





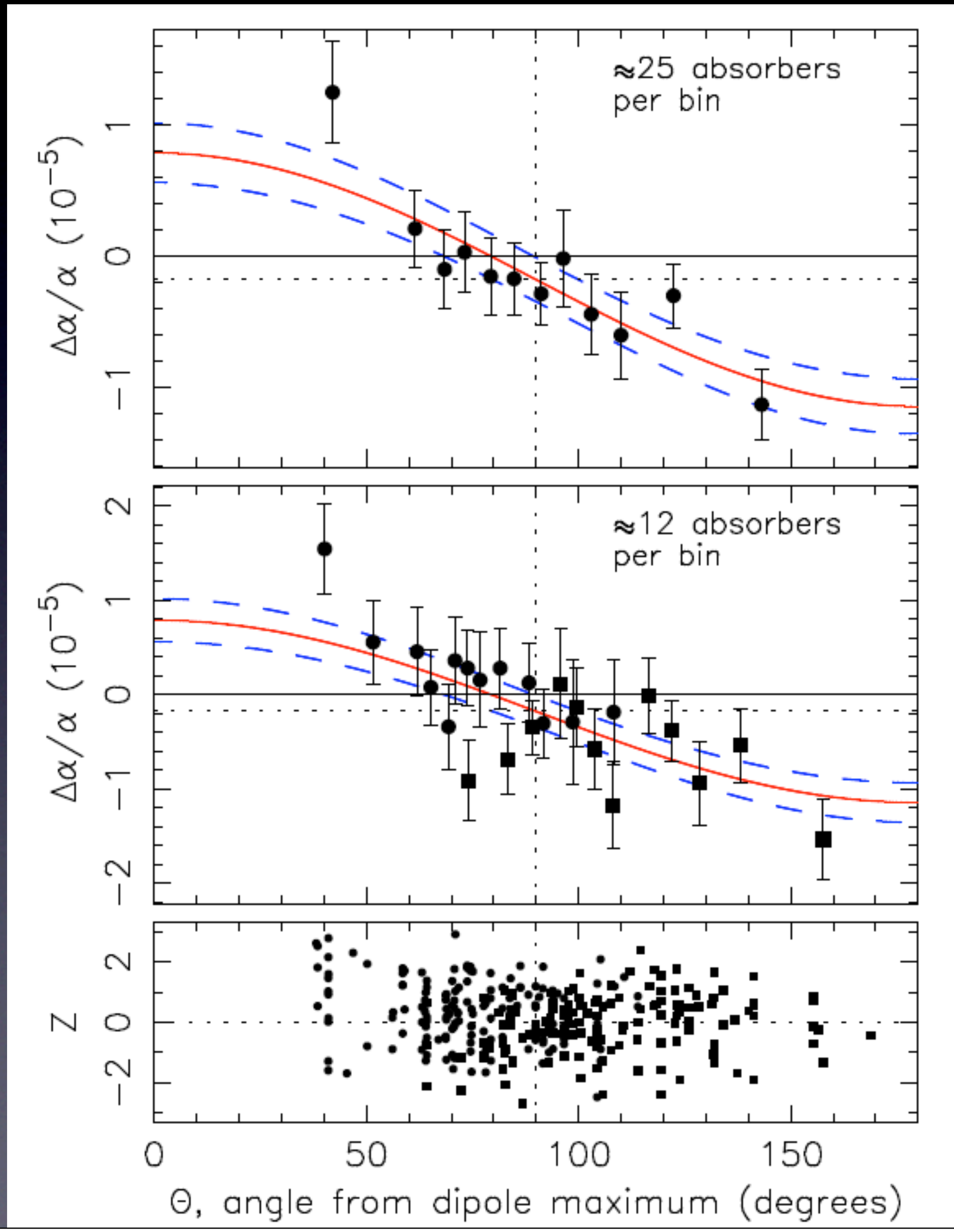
$\Delta\alpha/\alpha$ = (-5.7 ± 1.1) ppm

$\Delta\alpha/\alpha$ = (2.08 ± 1.24) ppm

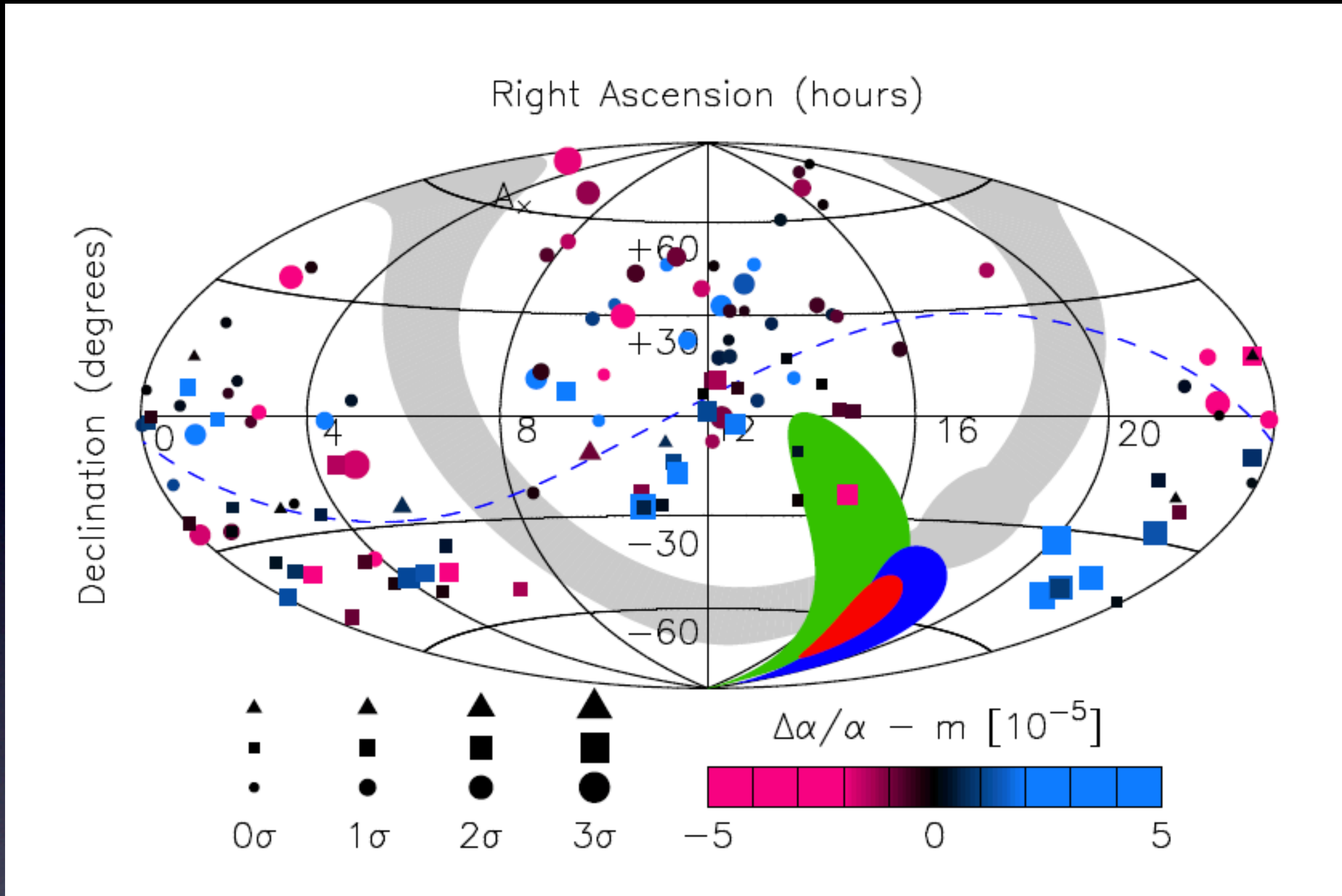
An angular (spatial) dipole?

direction:
RA=17.4 ± 1.0 h
DEC=-61 ± 10

• VLT



■ Keck



- directions of dipole of VLT and Keck samples separately agree
- directions of dipole for z < **1.6** and z > **1.6** cuts of the combined VLT+Keck data agree
- in the equatorial region of the dipole consistency between Keck and VLT

Comparison with accurate measurements

- HE 0515-4414 $\Delta\alpha/\alpha$ predicted by dipole (1.9 ±1.5) ppm

  measured (-0.07 ±1.8) ppm
- QSO 1101-264 $\Delta\alpha/\alpha$ predicted by dipole (3.8 ±2.0) ppm

  measured (5.4 ±2.5) ppm

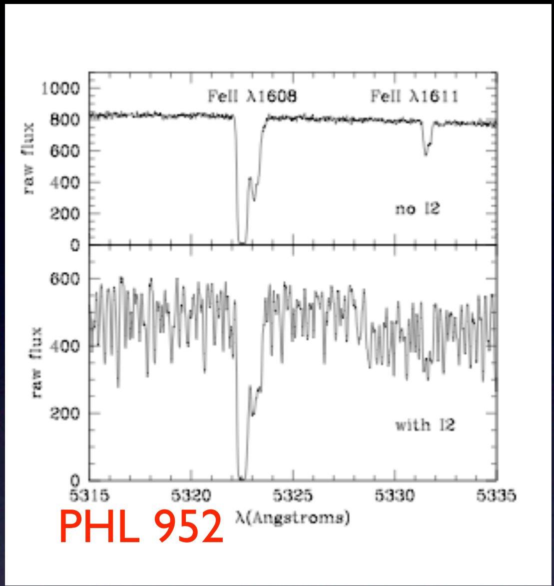
What to say?

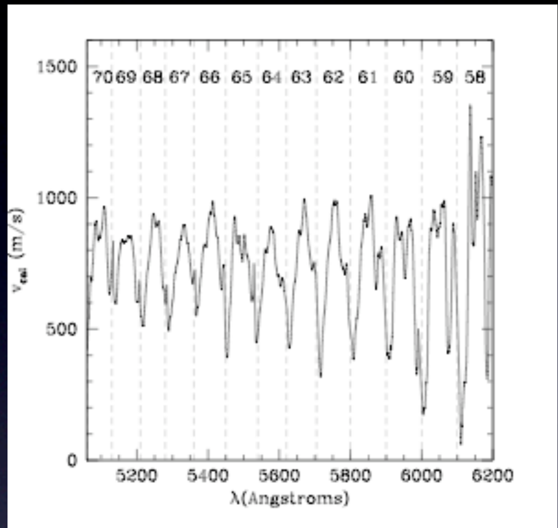
- no existing theories predict a dipole in alpha
- implications for the fine-tuning: constants can take different values!
- a 4 sigma results need to be studied. Peak level : 10 ppm (unfortunately towards the Galactic Center)

Are calibration errors an issue?

Iodine- Th-Ar comparison

Keck-HIRES

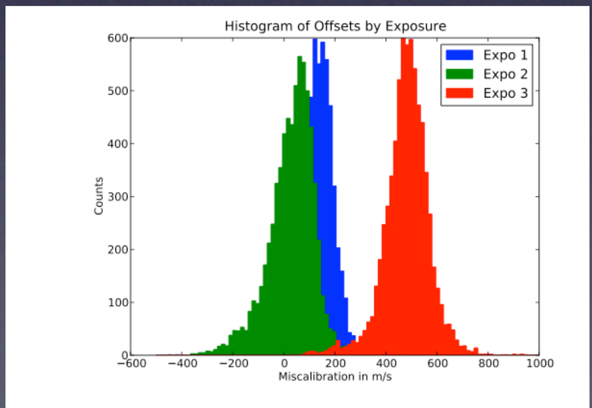


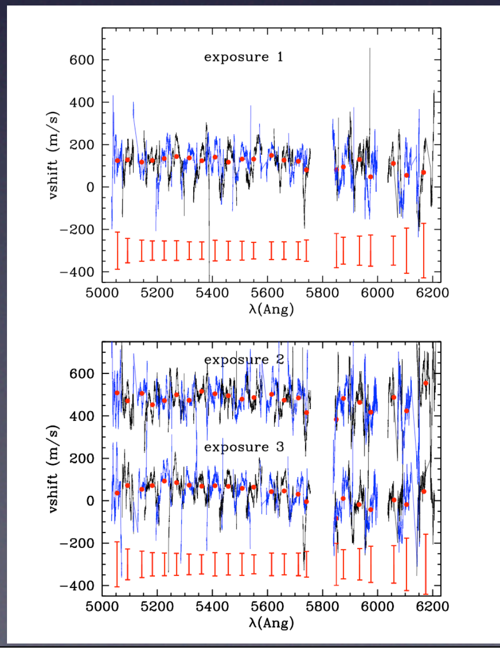


Griest et al 2009
order modulation:

saw-tooth

UVES-VLT





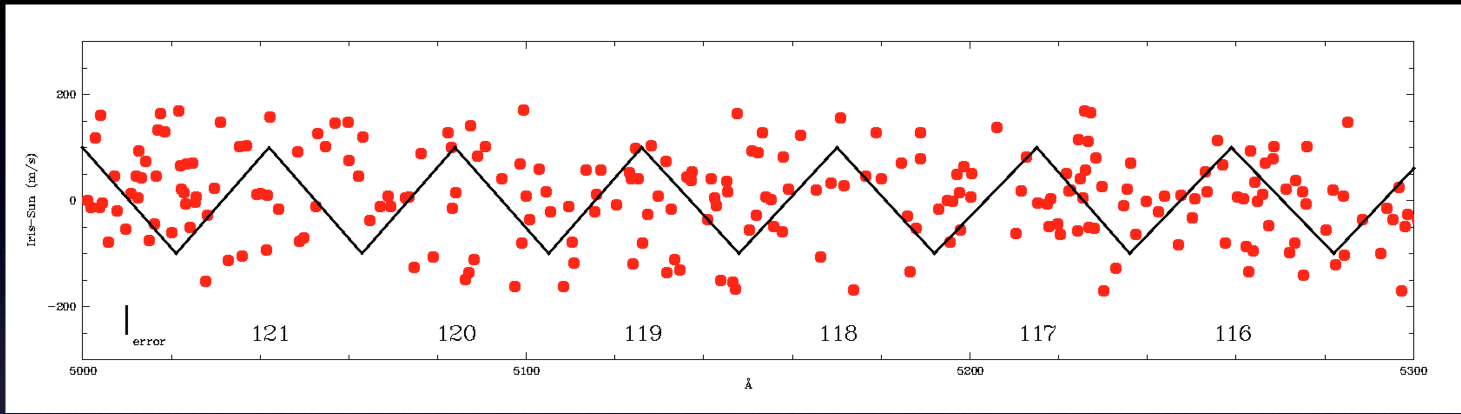
RV offsets up to 1 km/s

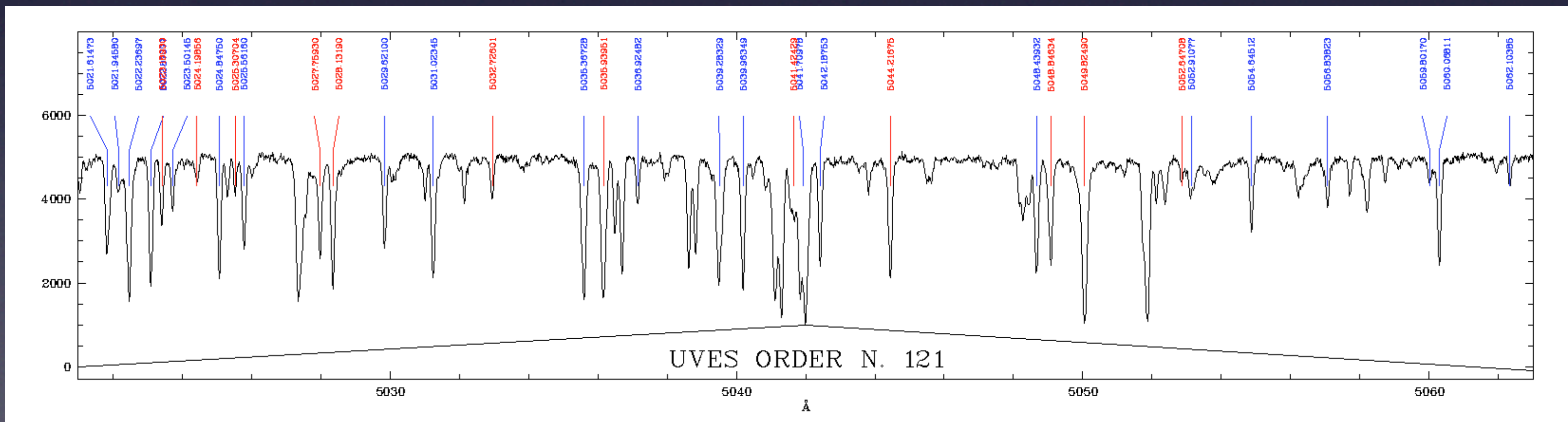
intraorder: +/- 100 m/s

Whitmore et al 2010

Asteroids

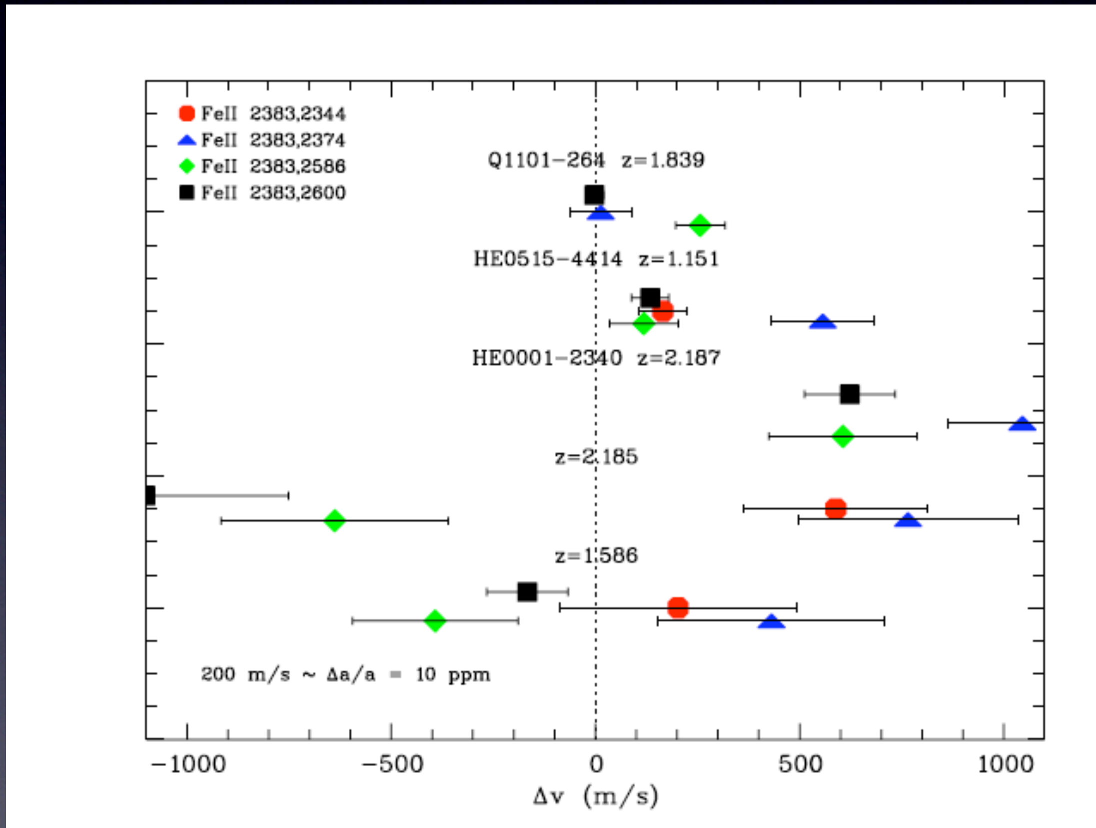
UVES observations of Iris to look for shifts of line positions compared to “absolute” solar HARPS line positions:





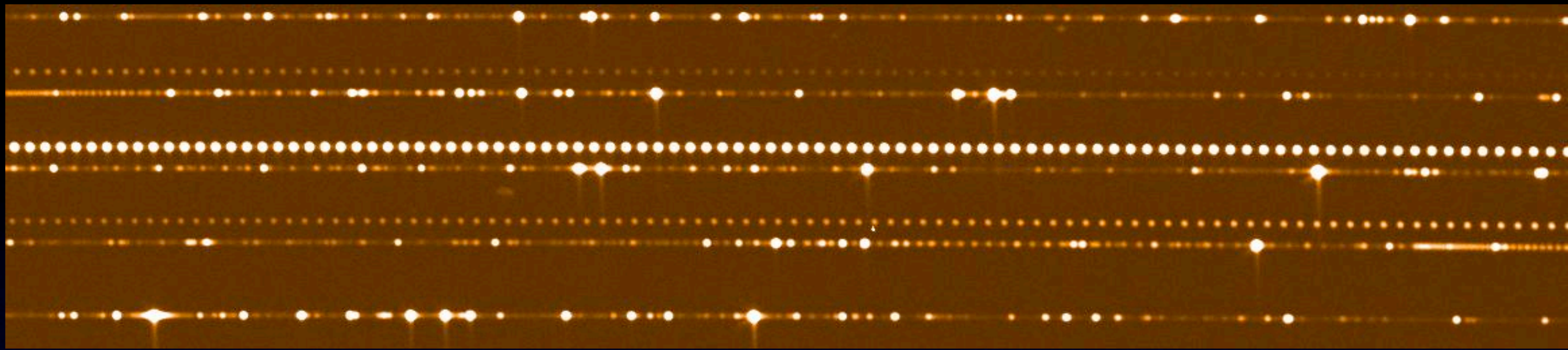
➡ no evidence for a saw-tooth but distorsions at the level of 80 m/s with a length of 10-15 A

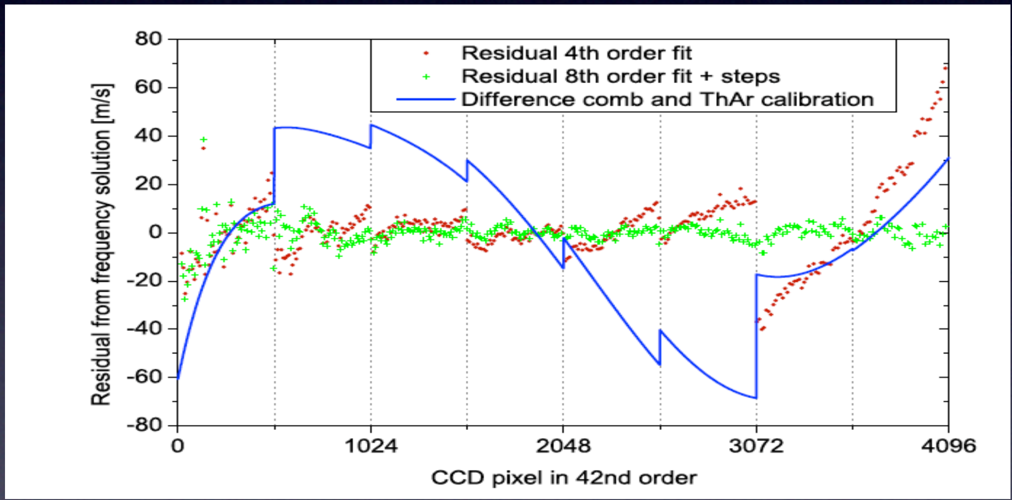
lines which should not vary show unexplained shifts



(Centurion Molaro Levshakov 2009 arXiv0910.4842)

Comb spectra @ HARPS





Wilken et al 2009

- Comb-ThAr up to ~100 m/s (but ~ 0 in the mean)

➡ $d\alpha/\alpha \sim 5 \times 10^{-6}$

- UVES? and HIRES? however difficult to explain the dipole

We need an ESPRESSO!

Echelle **SP**ectrograph for **R**ocky **E**xoplanets and **S**table **S**pectroscopic **O**bservations

ESO STC 2007
II generation VLT instruments

High Resolution-Ultra Stable S.

PI: Francesco Pepe

Consortium:

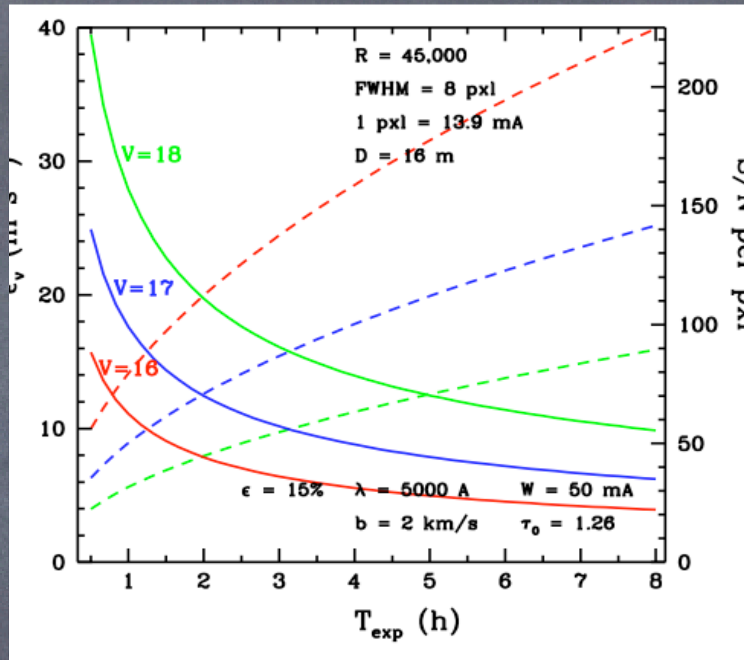
- Observatoire de Geneve
- INAF- Trieste and Milano
- Instituto de Astrofisica de Canarias
- University of Porto
- ESO

Telescope	VLT (8m)	4-VLT mode (D=16m)
Scope	Rocky Planets	constants
Sky Aperture	1 arcsec	1 arcsec
R ($\lambda/\Delta\lambda$)	~150000	~ 40000
λ Coverage	350-730 nm	350-730 nm
λ Precision	5 m/sec	5 m/sec
RV Stability	< 10 cm/sec	RV < 1m/sec

with:

- Fibres feeding
- Thermal-vacuum control and stability
- Laser Comb calibration

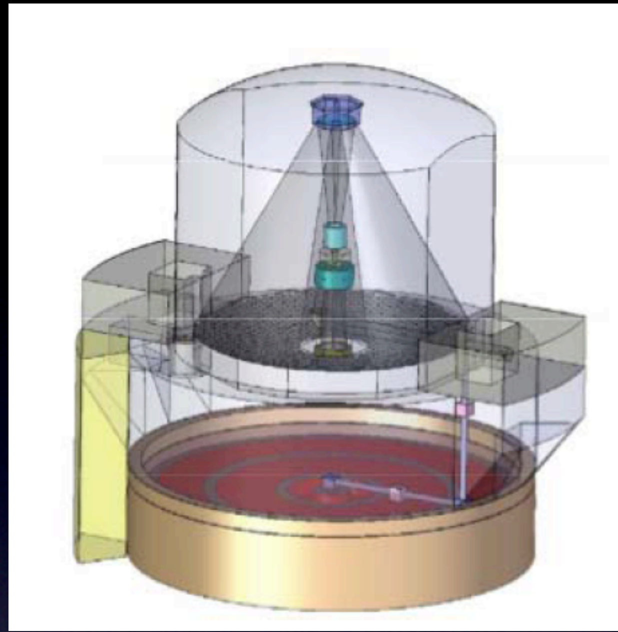
ESPRESSO promise

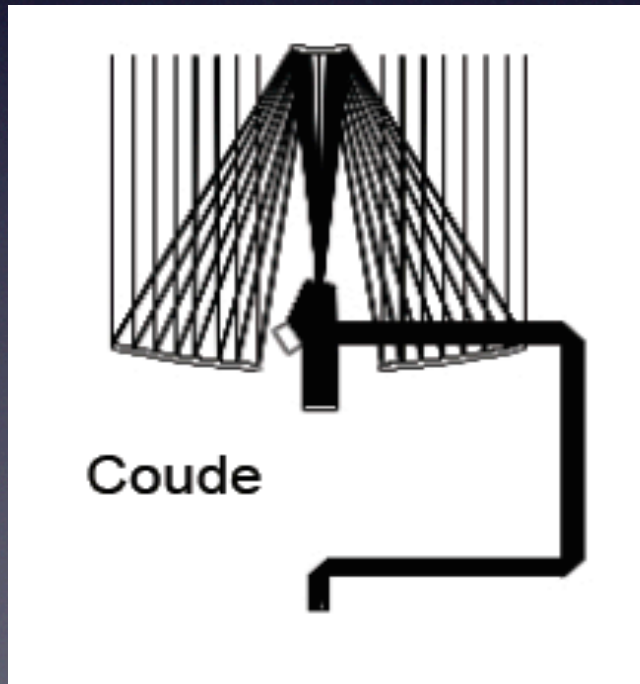


- 1 UT σ_v ~ 20 m s^{-1}
- 4 UT σ_v ~ 5 m s^{-1} → $\sigma_{\Delta\alpha/\alpha}$ ~ 3x 10^{-7} with FeII-MgII
- Observations photon noise limited

CODEX

COsmic Dynamical EXperiment





m_e/m_p

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

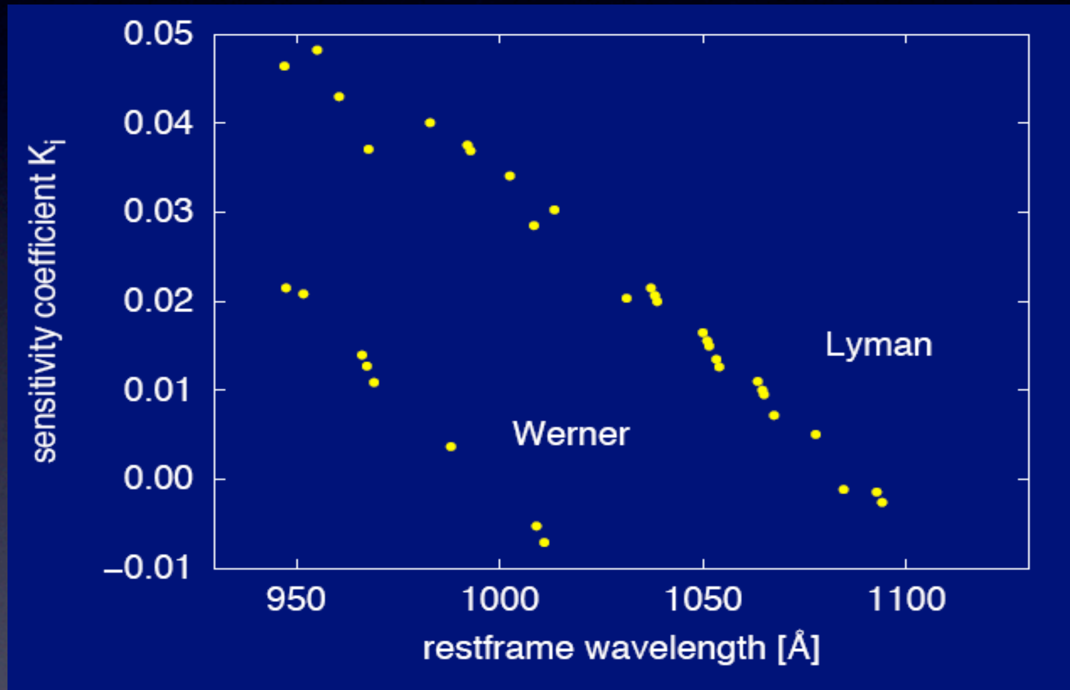
The Determination of the Electron to Proton Inertial Mass Ratio via Molecular Transitions

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.

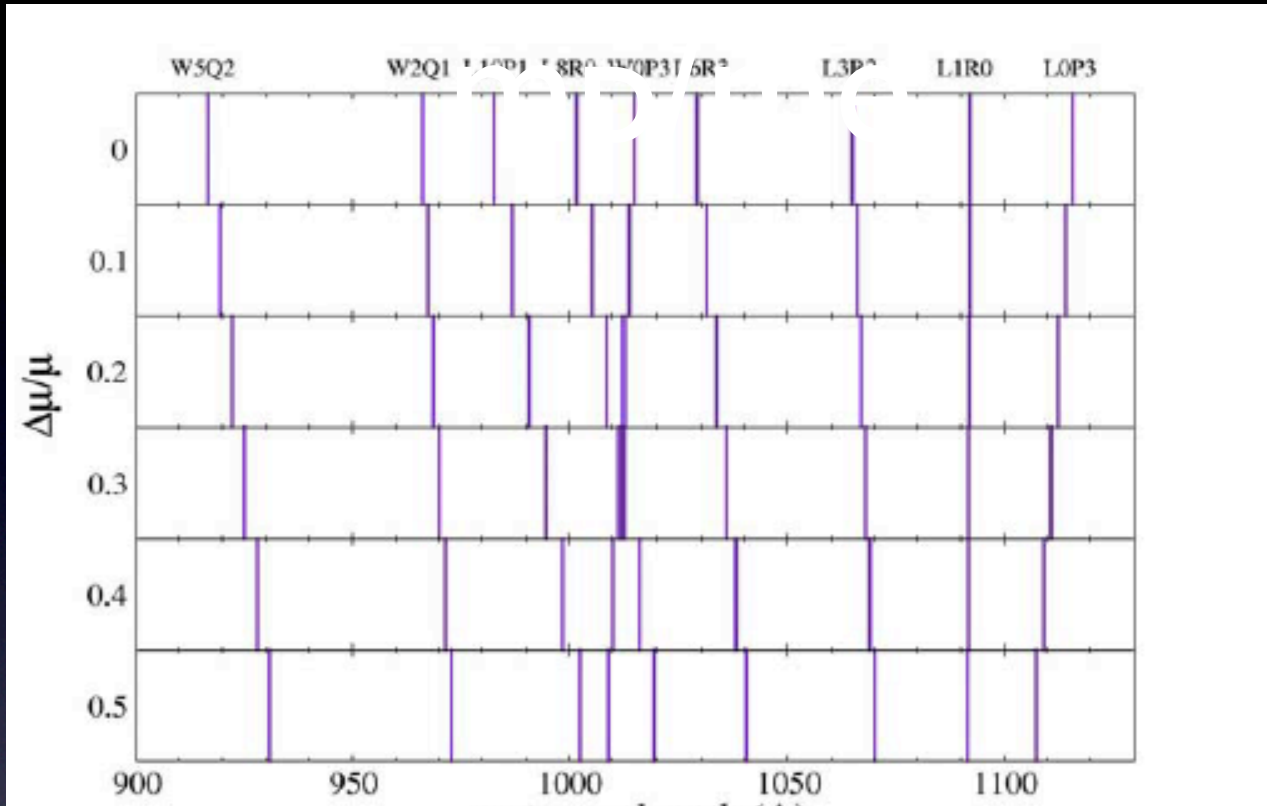
- Molecular Hydrogen (Thompson 1975)
  - electron-vibro-rotational transitions have different dependence from the reduced mass
- PKS 0528 z=2.8 Varshalovich Levshakov (1993)

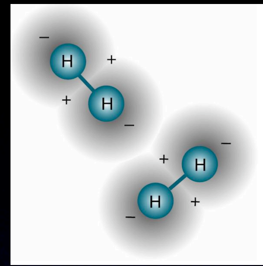


$$\nu \simeq E_I \left(c_{\rm elec} + c_{\rm vib}/\sqrt{\mu} + c_{\rm rot}/\mu \right)$$

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

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

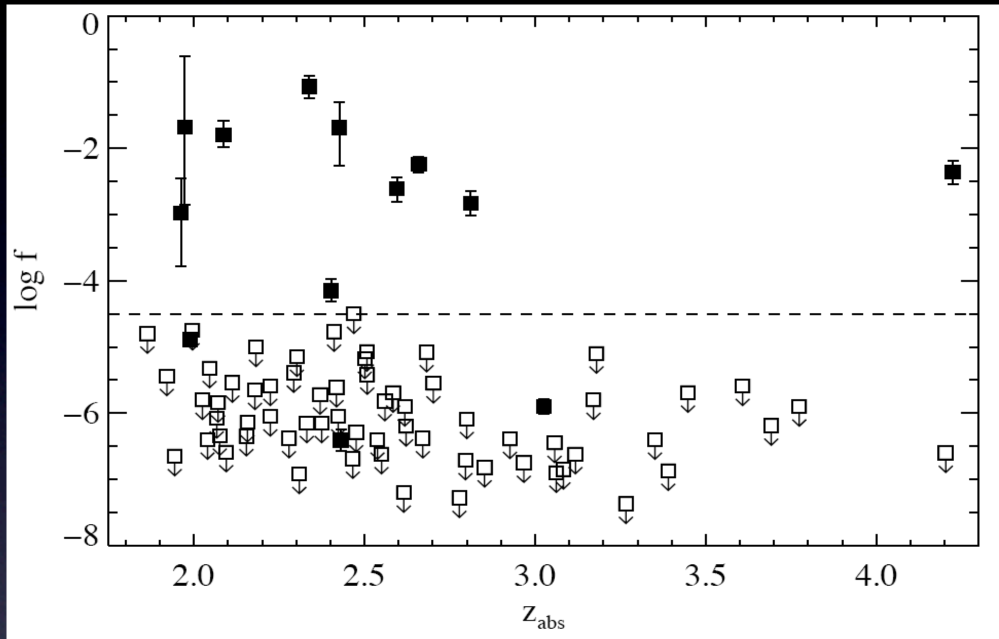




- Werner and Lyman transitions (Ubachs et al 2007)
    - wavelength accuracy 4-10 x10^{-8}
    - K coefficients 0.00-0.05 (accuracy 1-2%)

$\Delta\mu/\mu = \Delta v / c\Delta K$ 15 m/s → 1 ppm

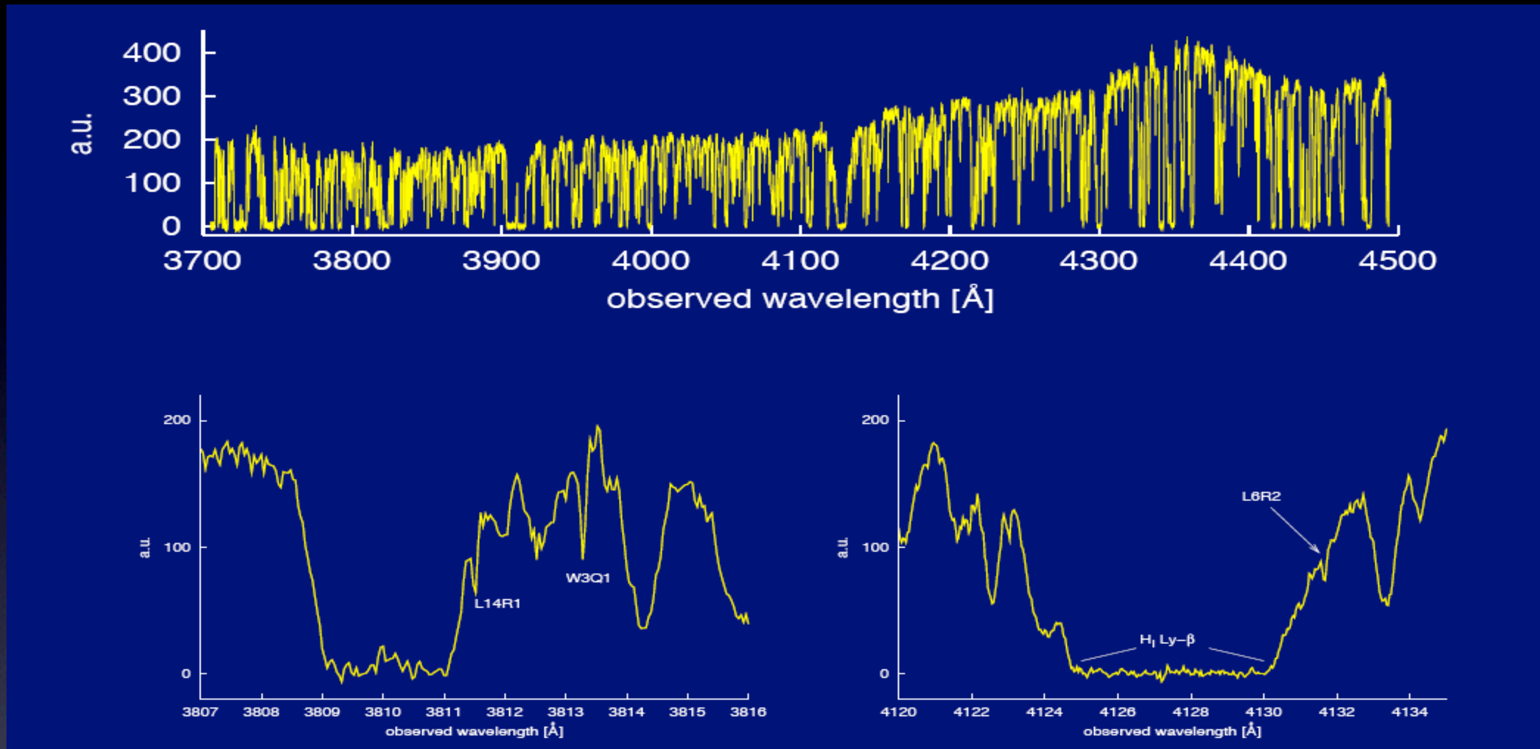
H_2 at high z



Noterdaeme et al 2008

- Only 4 QSOs
  - PKS 0528 z=2.8 Varshalovich Levshakov (1993) Cowie Songaila 1995, Potekhin 1998
  - 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
  - Q 2123-0050 Malec et al 2010 but at z=2

Q 0347-383

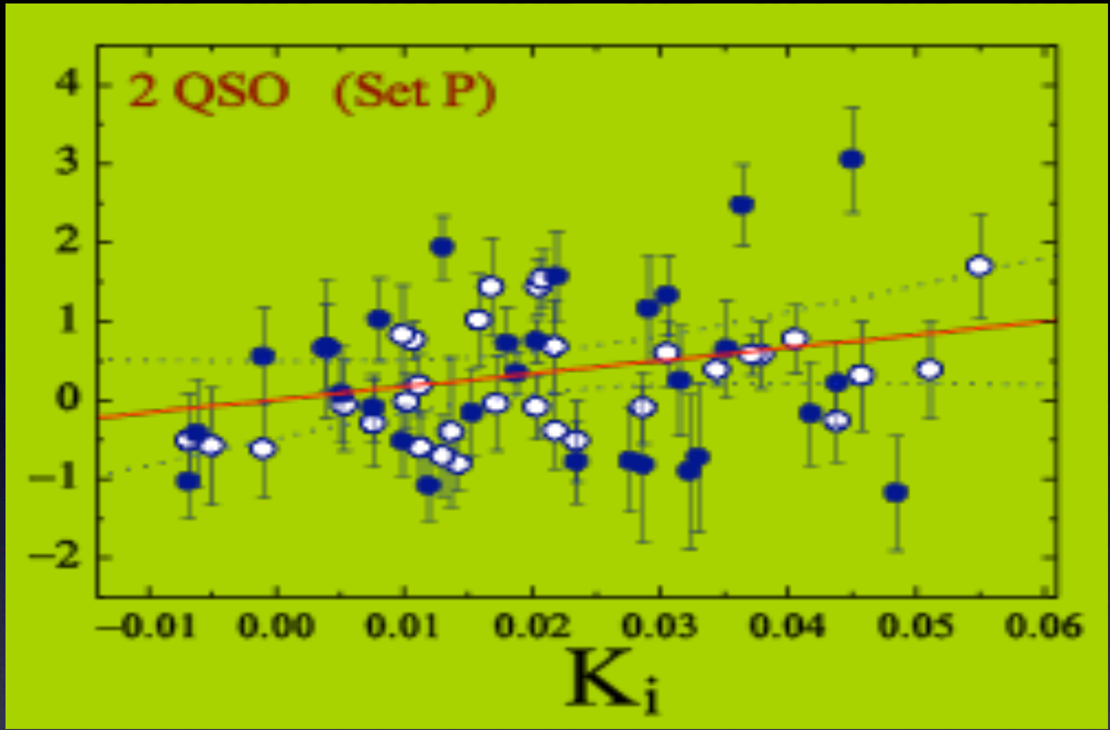


- H_2 in DLA
  - few systems, lines in the UV ~ 950-1050 A ➡ $z_{abs}>2.5$.

- Levshakov, Dessauges-Zavadsky, D'Odorico, Molaro (2002) first UVES analysis of μ (88 lines detected, 15 used)

$\Delta\mu/\mu=(2.1 \pm 3.6)\times 10^{-5}$

QSO 0347-383 & QSO 0405-443



Ivanchik et al 2005
Reinhold et al 2006
Ubach et al 2007

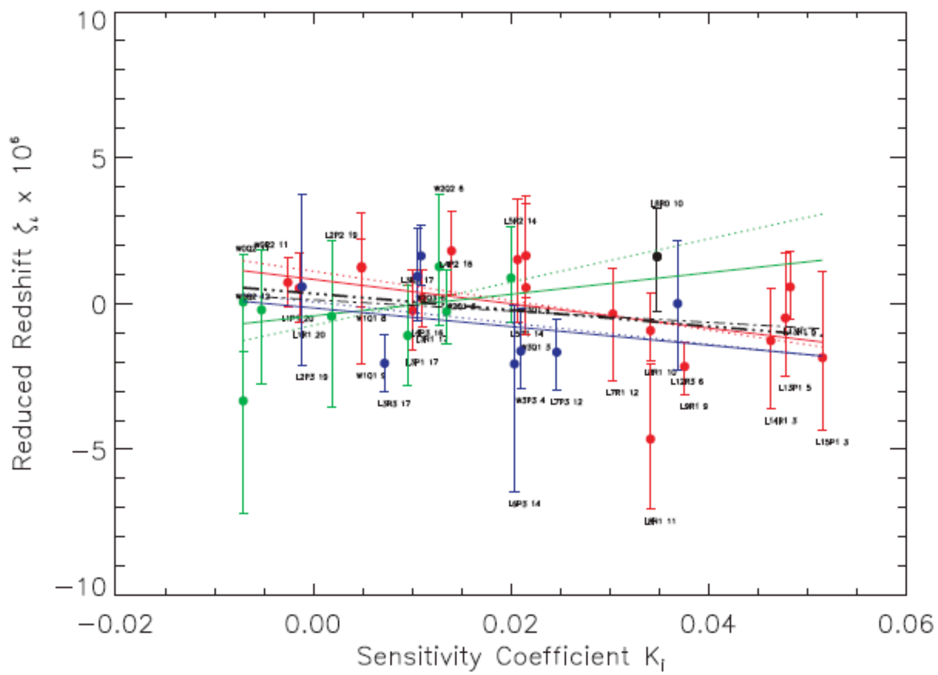
Q 0347-383: $\Delta\mu/\mu$ = (+20.6 ± 7.9) ppm (**parts per milion)**

Q 0405-443: $\Delta\mu/\mu$ = (+27.8 ± 8.8) ppm

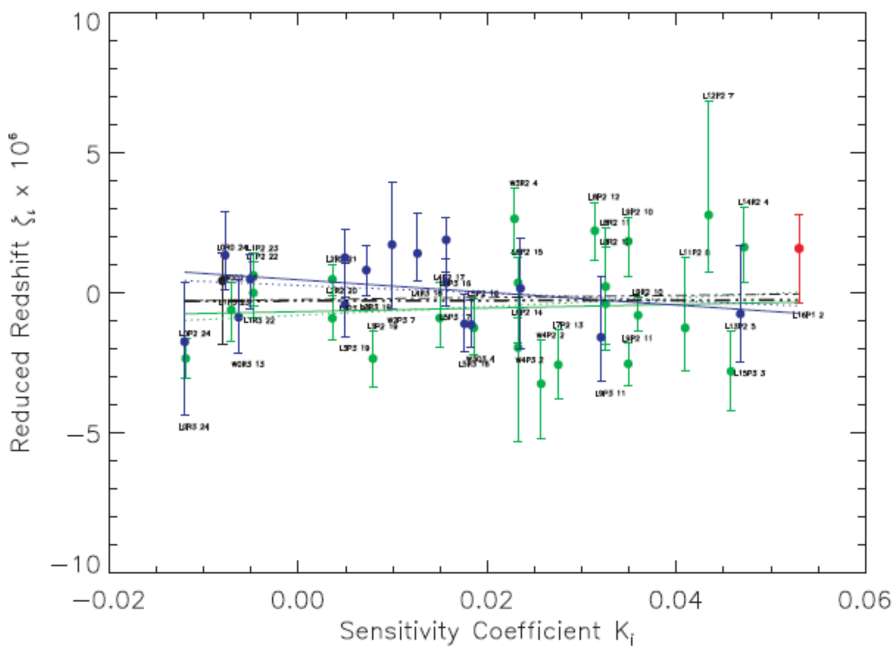
$\Delta\mu/\mu$ = (+24 ± 6) ppm

Thompson et al 2009

QSO 0347-383



QSO 0405-443



$\Delta\mu/\mu$ = (-28 ± 16) ppm

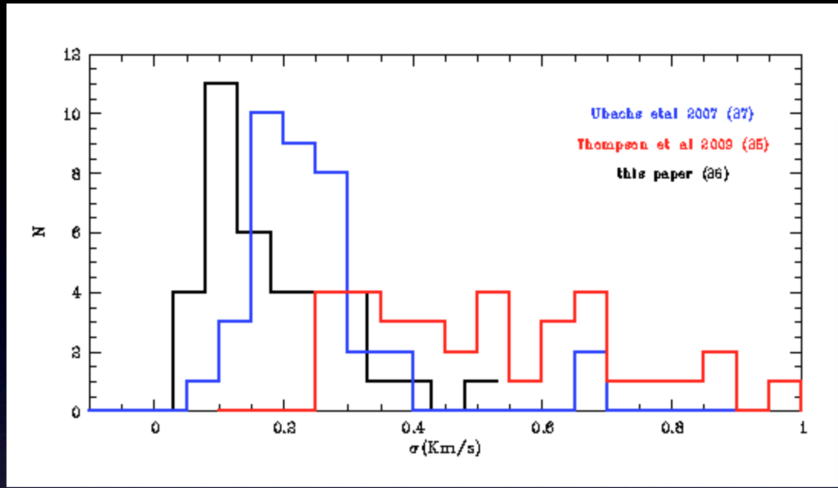
$\Delta\mu/\mu$ = (0.55 ± 10) ppm

$\Delta\mu/\mu$ = (-7 ± 8) ppm

QSO 0347-383 again

(Wendt & Molaro 2010)

We analyzed 8 new spectra not previously considered .

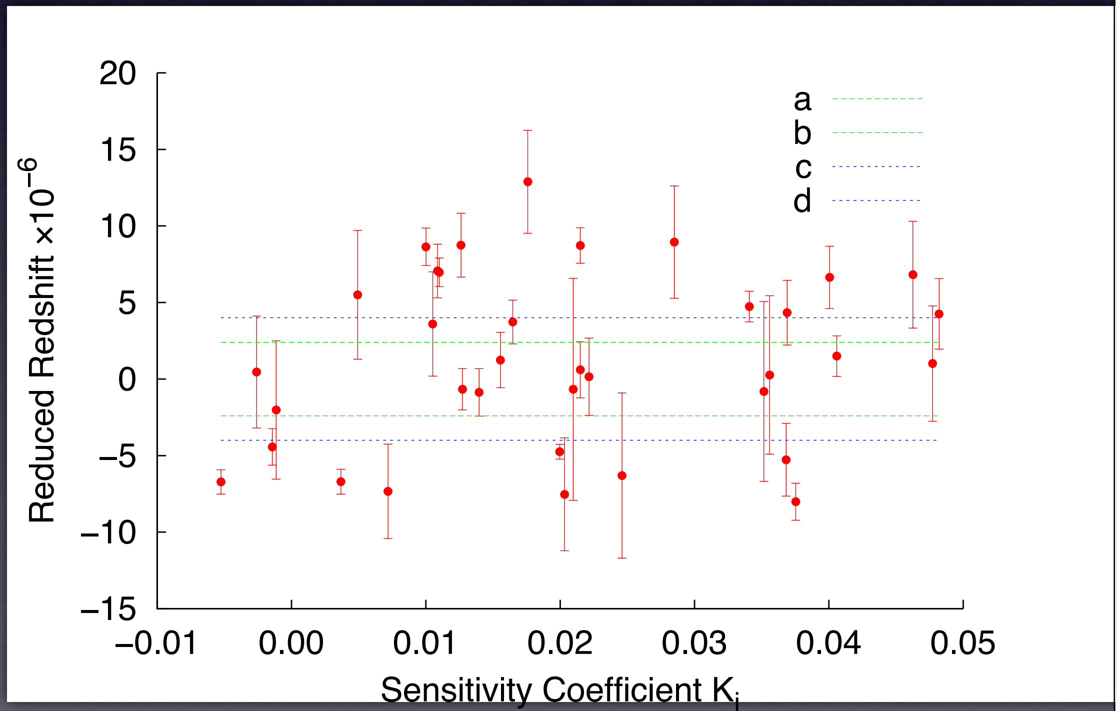


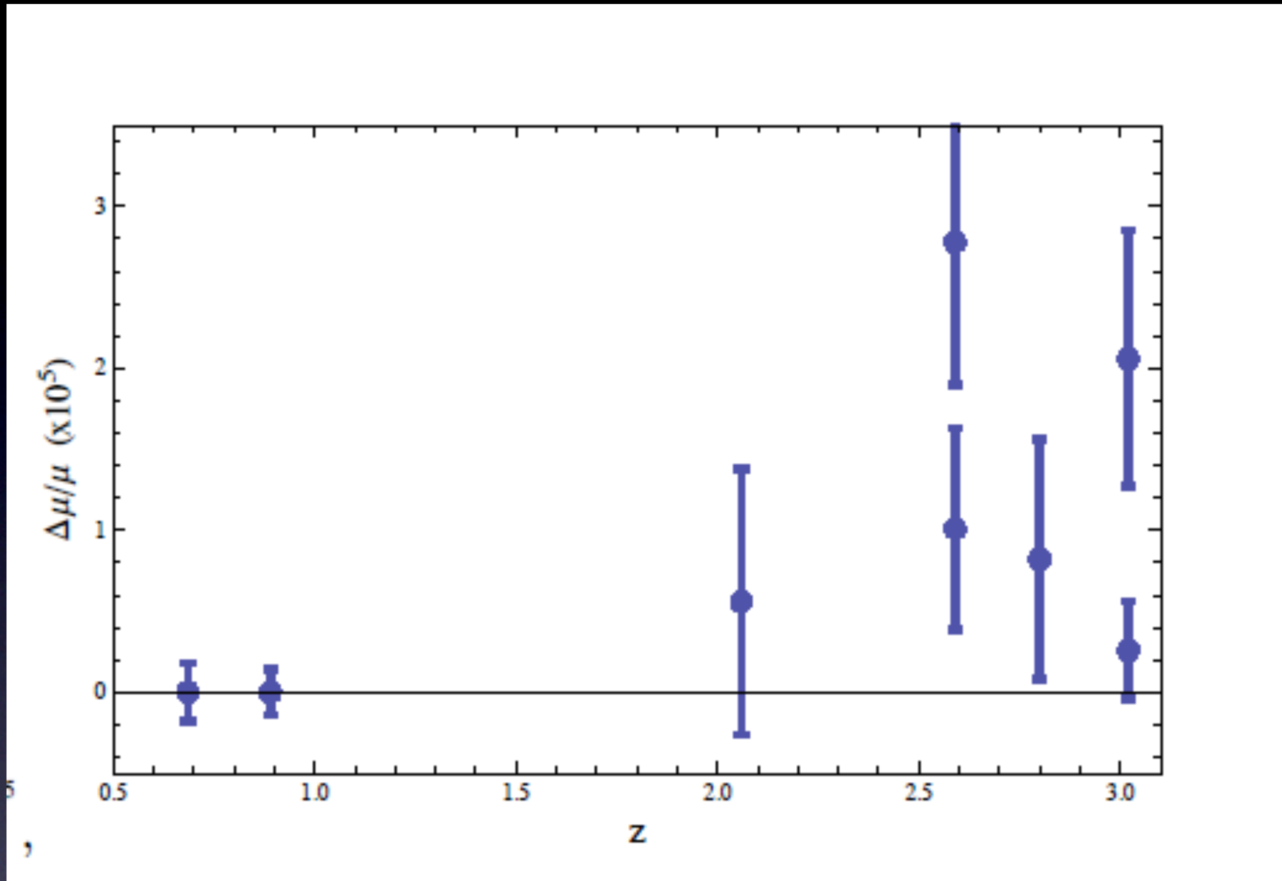
Velocity offsets among 15 spectra Δv=180 m/s (up to 800 m/s)
analysis has been performed on individual spectra

$\Delta\mu/\mu$ = (15 ± 9 stat ± 6 sys) ppm

dominated by systematic errors

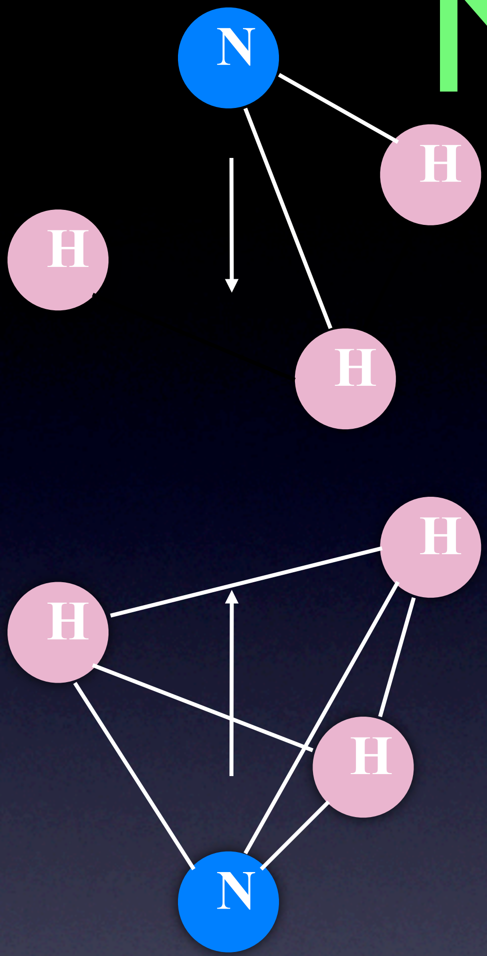
(120 m/s)

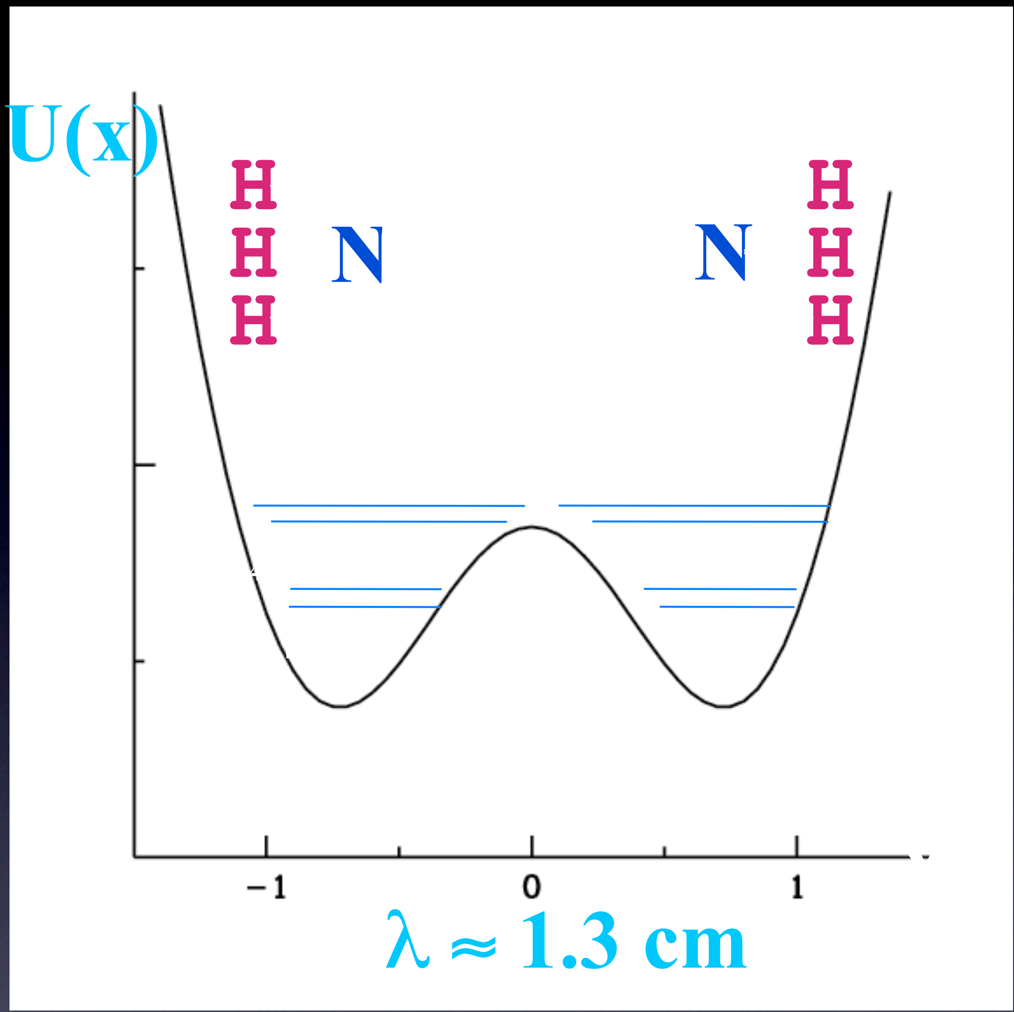




- King et al (2008) PKS 0528-25 z=2.8
- Malec et al 2010 QSO 2123-0050 V=16. z=2.059
- Murphy et al 2008 B0218+357 z=0.68
- Henkel et al 2009 PKS 1830-201 z=89

NH3

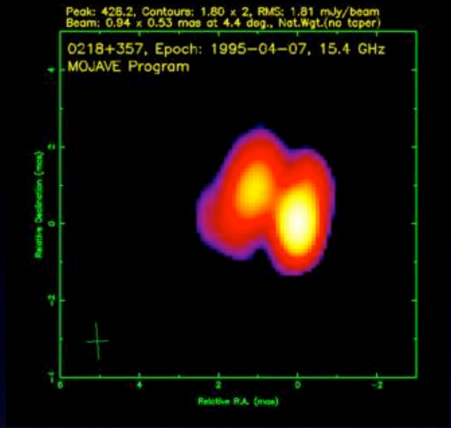


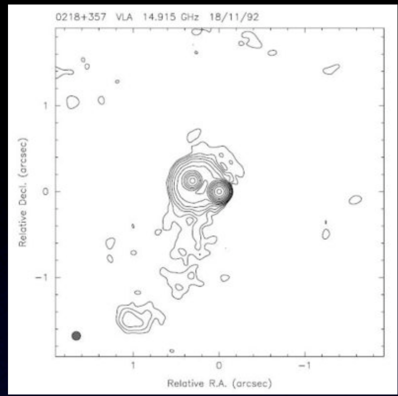


- Due to the tunnelling the two levels are split into inversion doublets

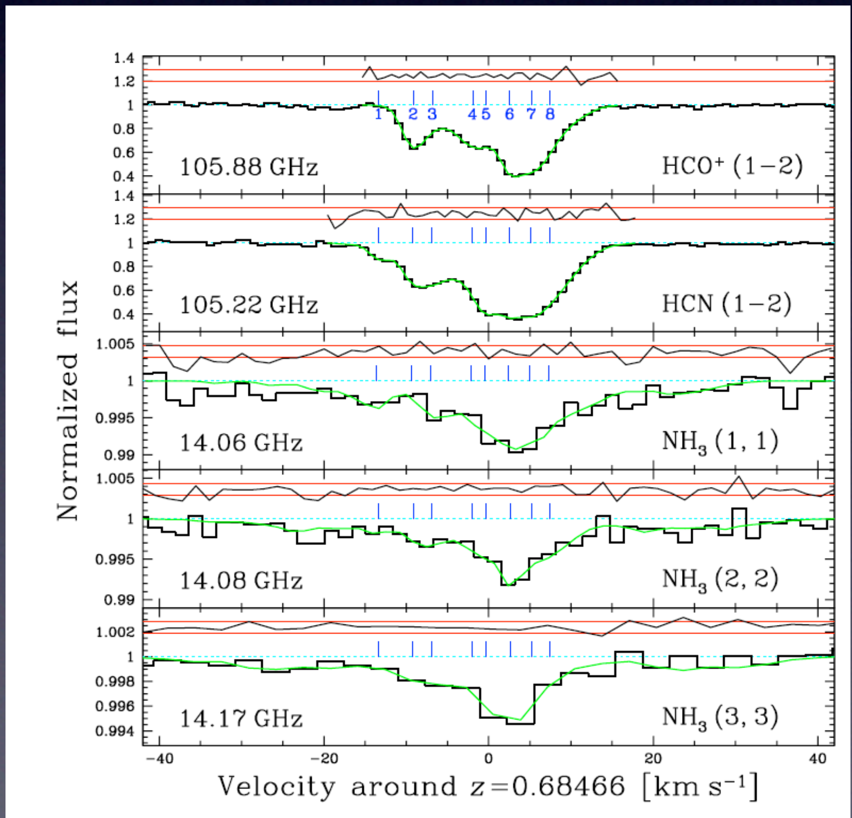
- Flambaum & Kozlov (2007) $\Delta\omega/\omega = -4.46\ \Delta\mu/\mu$

B 0218+357





Murphy et al 2008

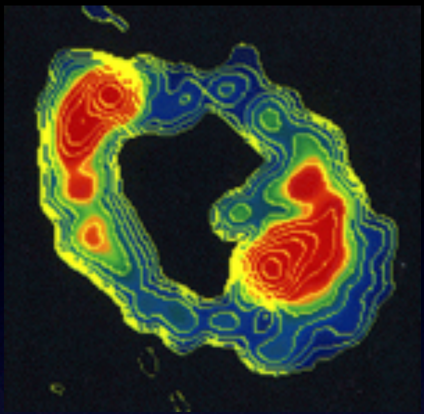


gravitational lens, z=0.68

NH_3 versus CO, HCN, HCO^+

$\Delta\mu/\mu$=(0.74±0.47stat±0.76sys) ppm

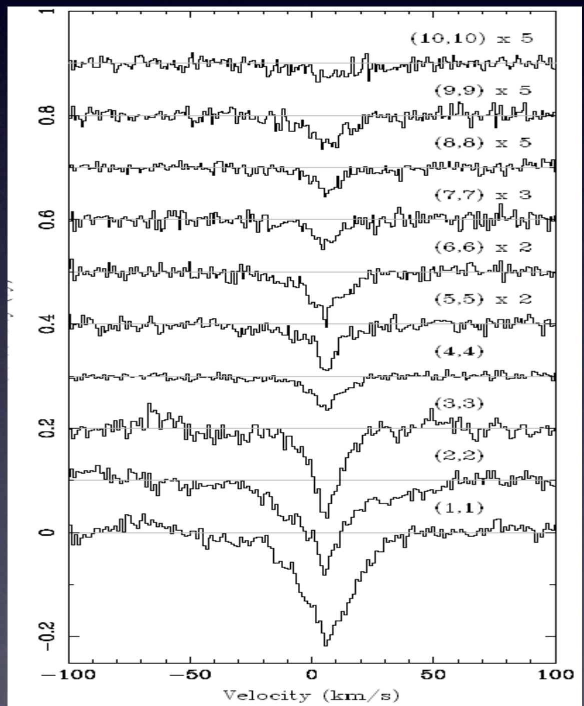
PKS 1830-211

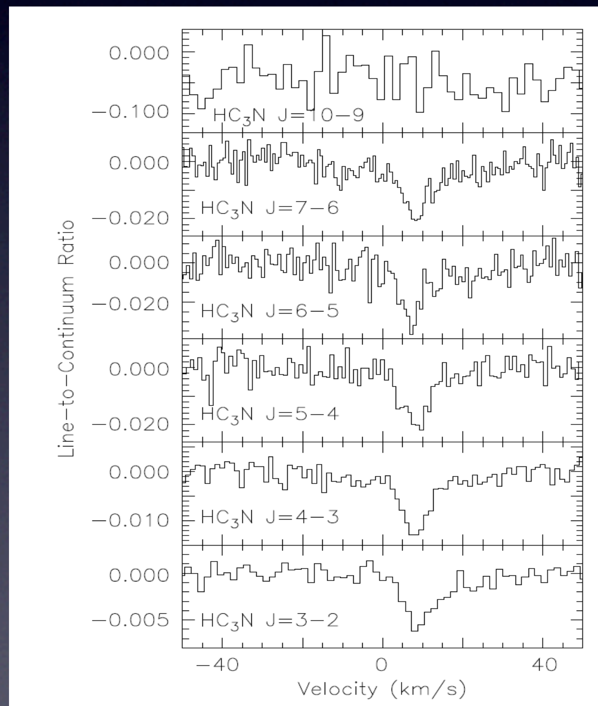


- radio source (z=2.5), lensing face-on spiral galaxy at

z_{abs} =0.89 ==> 3 main components + Einstein ring

- Henkel et al 2009 Effelsberg 100-m: 10 NH_3 inv. lines 5 rot. transition of HC_3N





$\Delta V_{(HC3N-NH3)}$=0.08 ± 0.49 km s^{-1} $\Delta\mu/\mu$ = (0.08 ±0.47) ppm

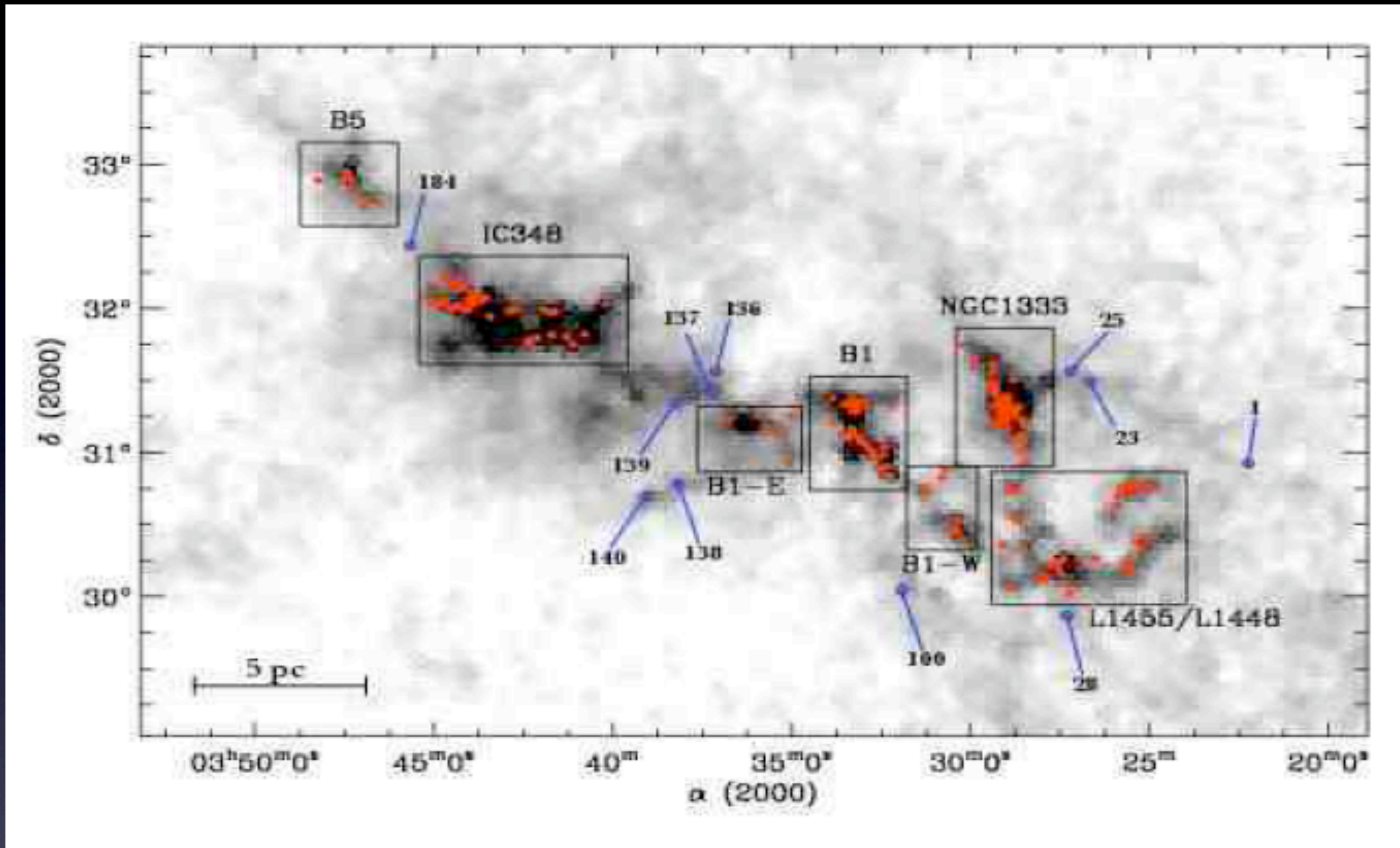
In the Milky Way

Molecular DENSE CORES

- starless
- $T \approx 11$ K
- $\sigma_v \approx 100$ m s^{-1} (simple)
- Masses ≈ 1 Msun,
- Sizes: ≈ 0.1 pc
- Densities n_H ≈ 1 - 10^5 cm^{-3}

- NH_3 sources common in MW Molecular Clouds
- Significant fraction of gas is non forming stars

Perseus Molecular Cloud



Rosolowsky et al 2008

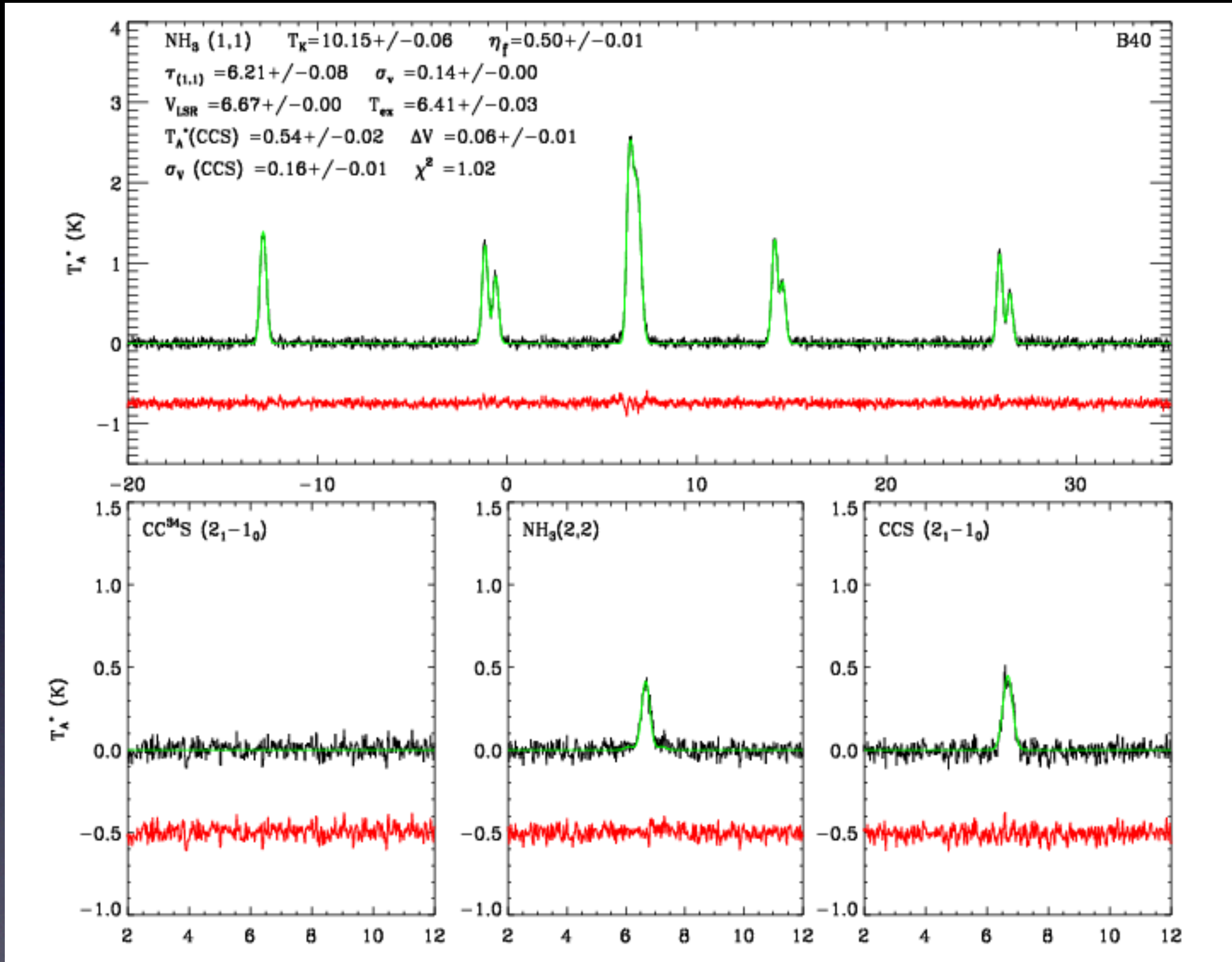
D ≈ *260 pc*

6×2° or *27×9 pc*

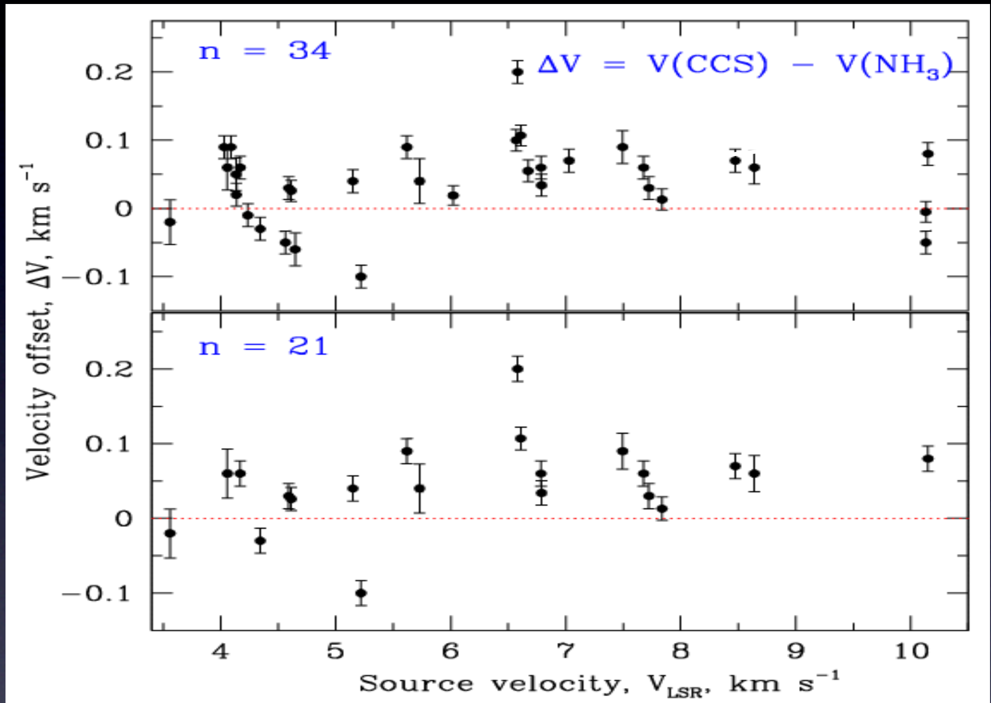
$M \sim 10^4\ M_{solar}$

$n_H \sim 100\ cm^{-3}$

- NH_3 & CCS on 96 cores with 100m Green Bank Telescope
  - Size scores = 0.09 pc
  - **GBT beam at 23 GHz 31 " (0.04 pc at 260pc), Spectral resolution = 24 m/s (!)**
  - **Single-pointing, simultaneous observations of NH_3 and CCS lines**



- NH_3 23.69 GHz (18 hpf transitions); E_u =23 K -
- C_2S 22.34 GHz; E_u<23 K ==> similar distribution



$\Delta V_{n=98} = 44 \pm 13$ m/s

$\Delta V_{n=34} = 39 \pm 10$ m/s
thermal profiles

$\Delta V_{n=21} = 36 \pm 7$ m/s

only symmetric

$\Delta Vr = 36 (\pm 15) \Rightarrow \Delta\mu/\mu = 35 (\pm 14)$ ppb

(Levshakov, Molaro, Kozlov 2008 aeXiv:0808.0583 NOT PUBLISHED!)

Milky Way NH3 Survey

32m MEDICINA (Bologna) Italy

Nov 24-28, 2008

100m EFFELSBERG (Bonn) Germany

Feb 20-22, 2009

45m NOBEYAMA (NRAO) Japan

Apr 8-10, 2009

with

Alexander Lapinov

Christian Henkel

Takeshi Sakai

Sergei Levshakov

Observations

32-m Medicina

2 digital spectrometers ARCOS (ARcetri COrrelation Spectrometer) and MSpec0 (high resolution digital spectrometer)

Spectral res. = 62 m/s (NH_3), 80 m/s (HC_3N) ARCOS

Spectral res. = 25 m/s (NH_3), 32 m/s (HC_3N) MSpec0

beam size at 23 GHz: 1.6' , at 18 GHz: 2.1'

position switching mode

100-m Effelsberg

K-band HEMT (High Electron Mobility Transistor) receiver, backend FFTS (Fast Fourier Transform Spectrometer)

Spectral res. = 30 m/s (NH_3), 40 m/s (HC_3N)

beam size at 23 GHz, FWHM = 40 arcsec

frequency switching mode

45-m Nobeyama

HEMT receiver (NH_3), and SIS (Superconductor-Insulator-Superconductor) receiver (N_2H^+)

Spectral res. = 49 m/s (NH_3), 25 m/s (N_2H^+)

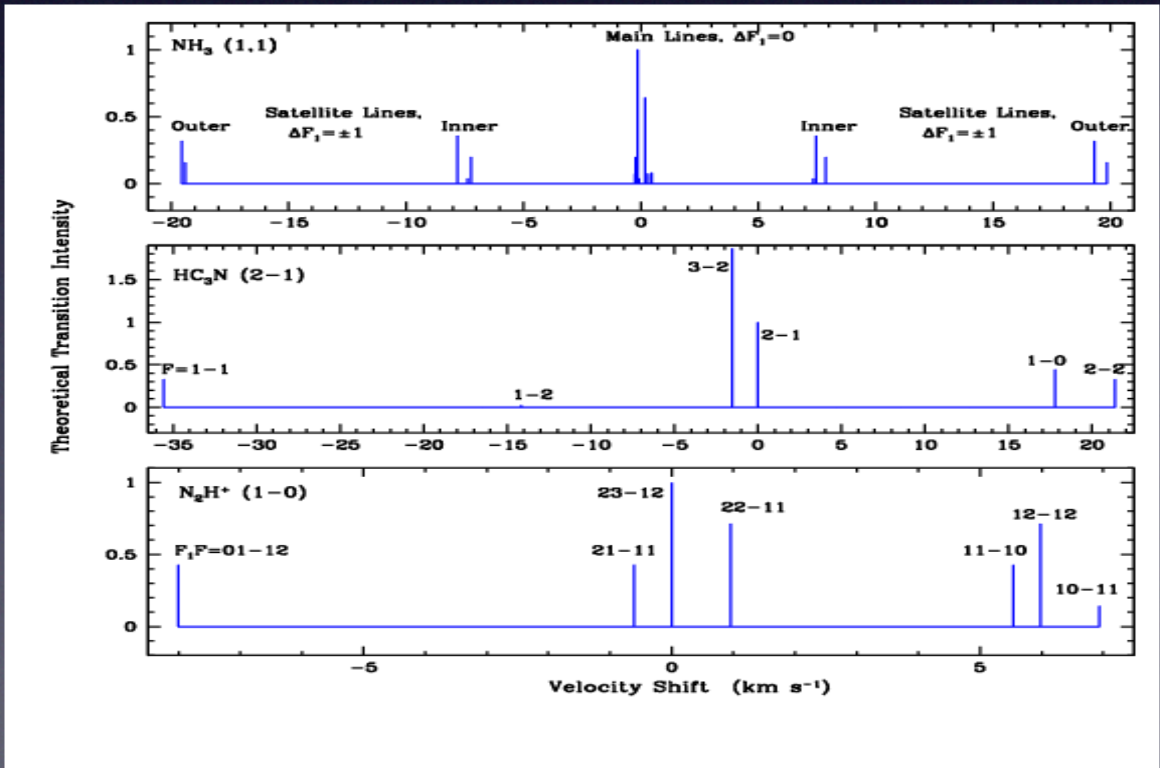
beam size at 23 GHz, FWHM = 73 arcsec , at 93 Ghz 17arcsec

position switching mode

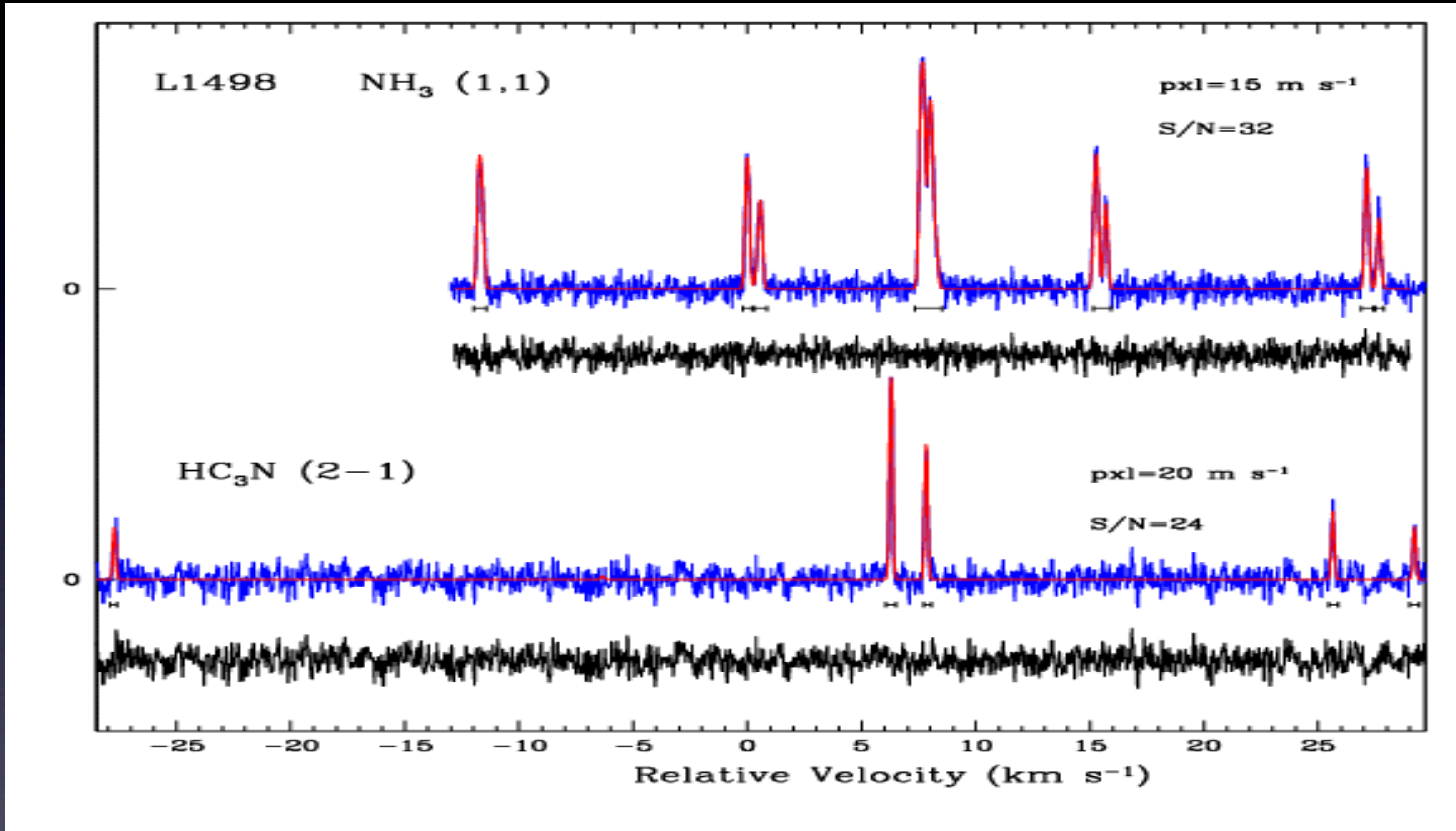
NH_3 , HC_3N & N_2H^+

Transition	ν_{rest}, GHz	λ_{rest}, cm	ε_v, m s^{-1}
CCS $J_N = 2_1 - 1_0$	22.344033(1)[a]	1.34	13.4
NH_3 $(J, K) = (1, 1)$	23.6944955(1)[a]	1.27	1.3
HC_3N $J = 5 - 4$	45.4903102(3)[b]	0.66	2.8
N_2H^+ $J = 1 - 0$	93.173777(4)[b]	0.32	13.5

Hyper-fine splittings



Effelsberg 100-m

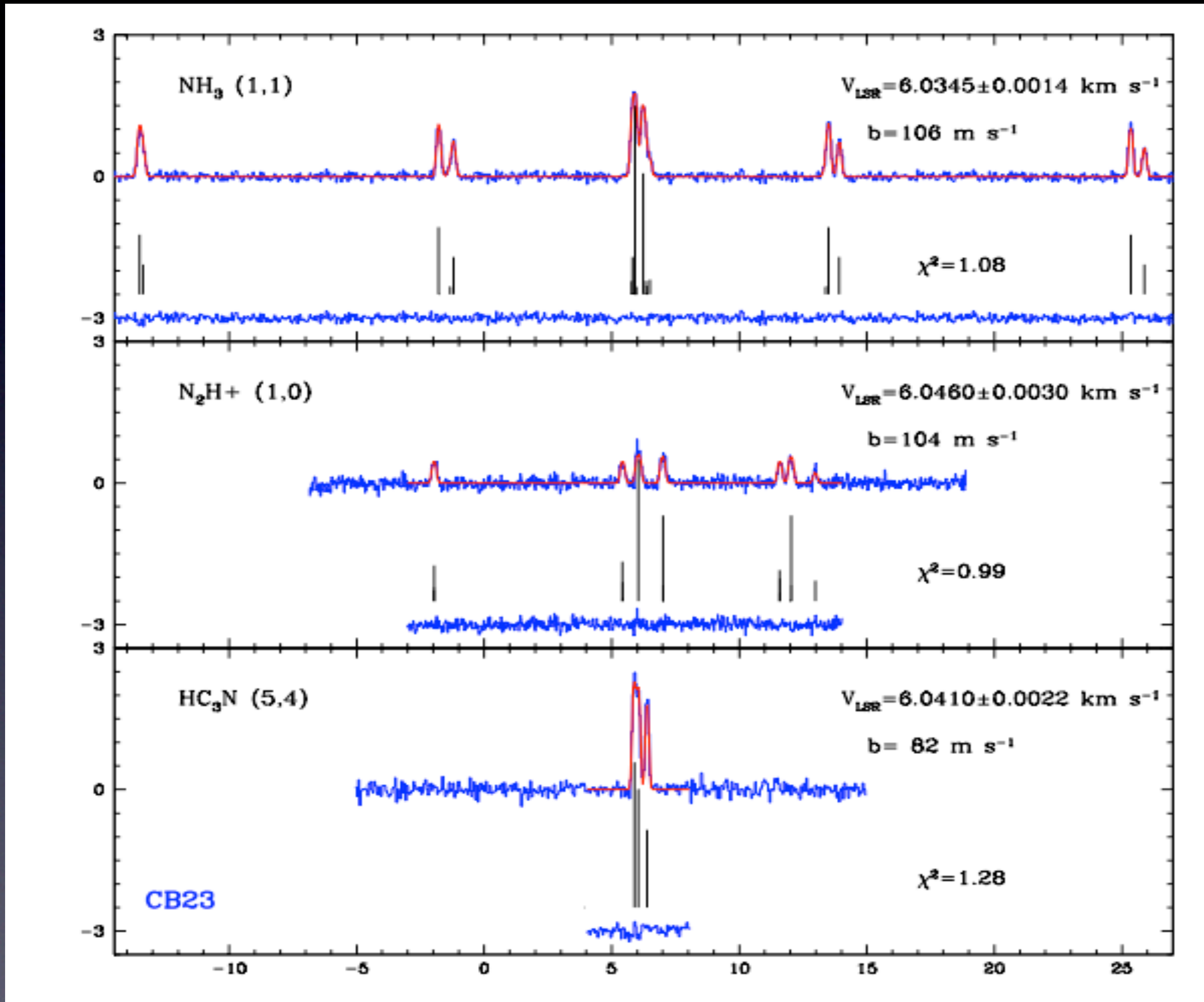


errors of 1 m/s!!

best L1512 errors: 0.8 m/s (NH3) & 0.9 m/s (HC3N)

Nobeyama 45m

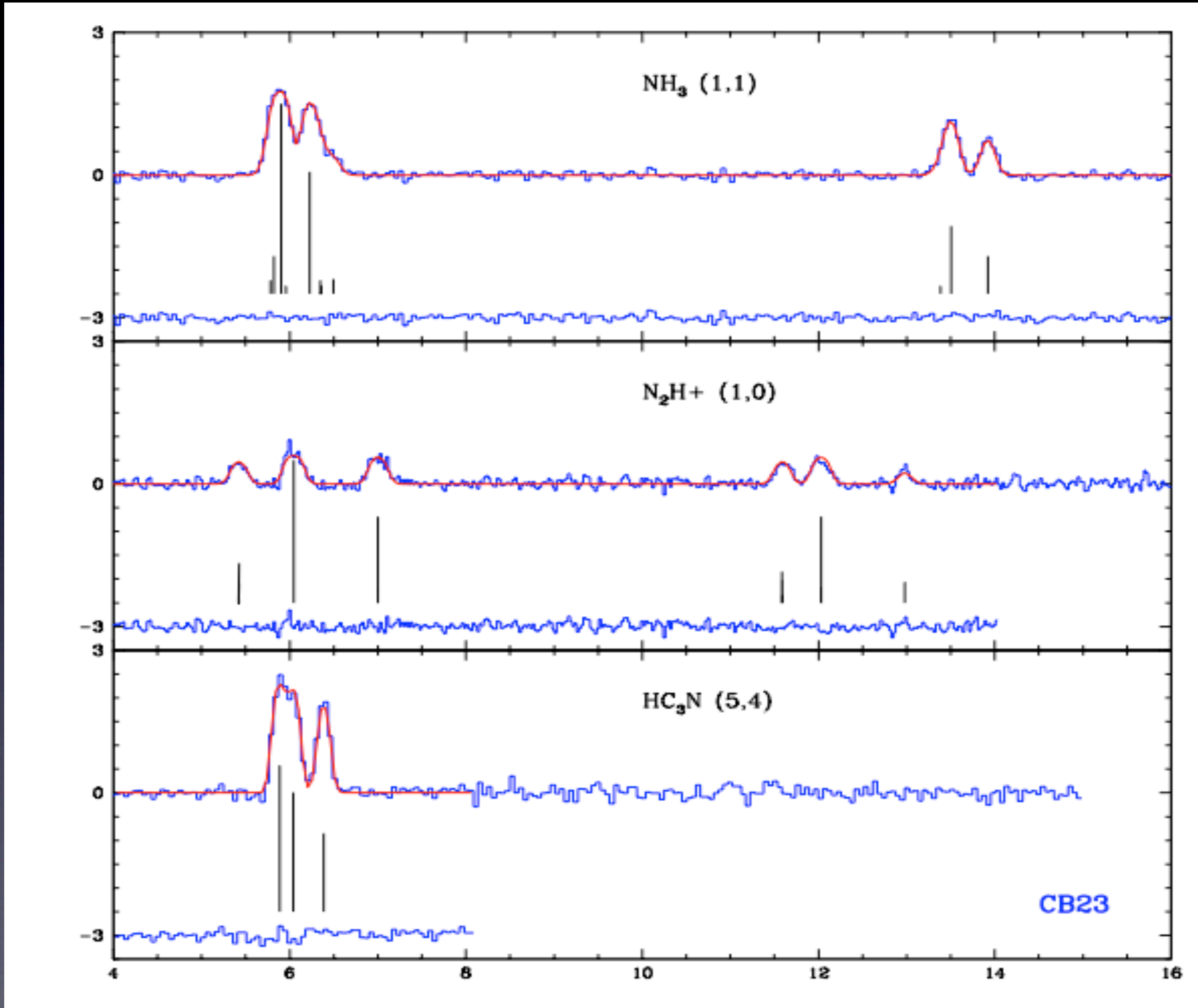
April 2009



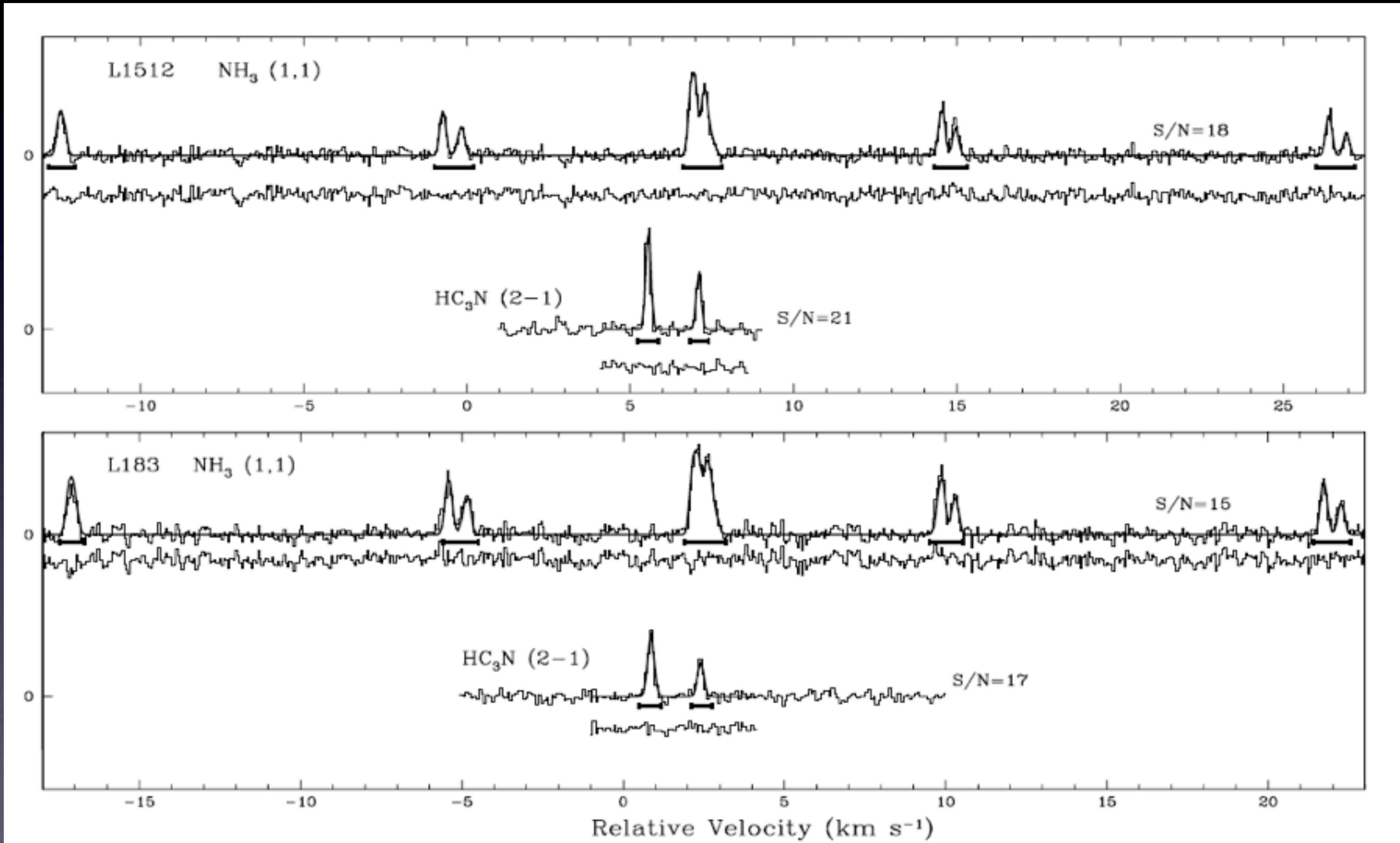
CB 23

NH_3, NH_2+ ,HC_3

Nobeyama 45m



32m Medicina ARCOS Nov 2008 NH_3 and HC_3N



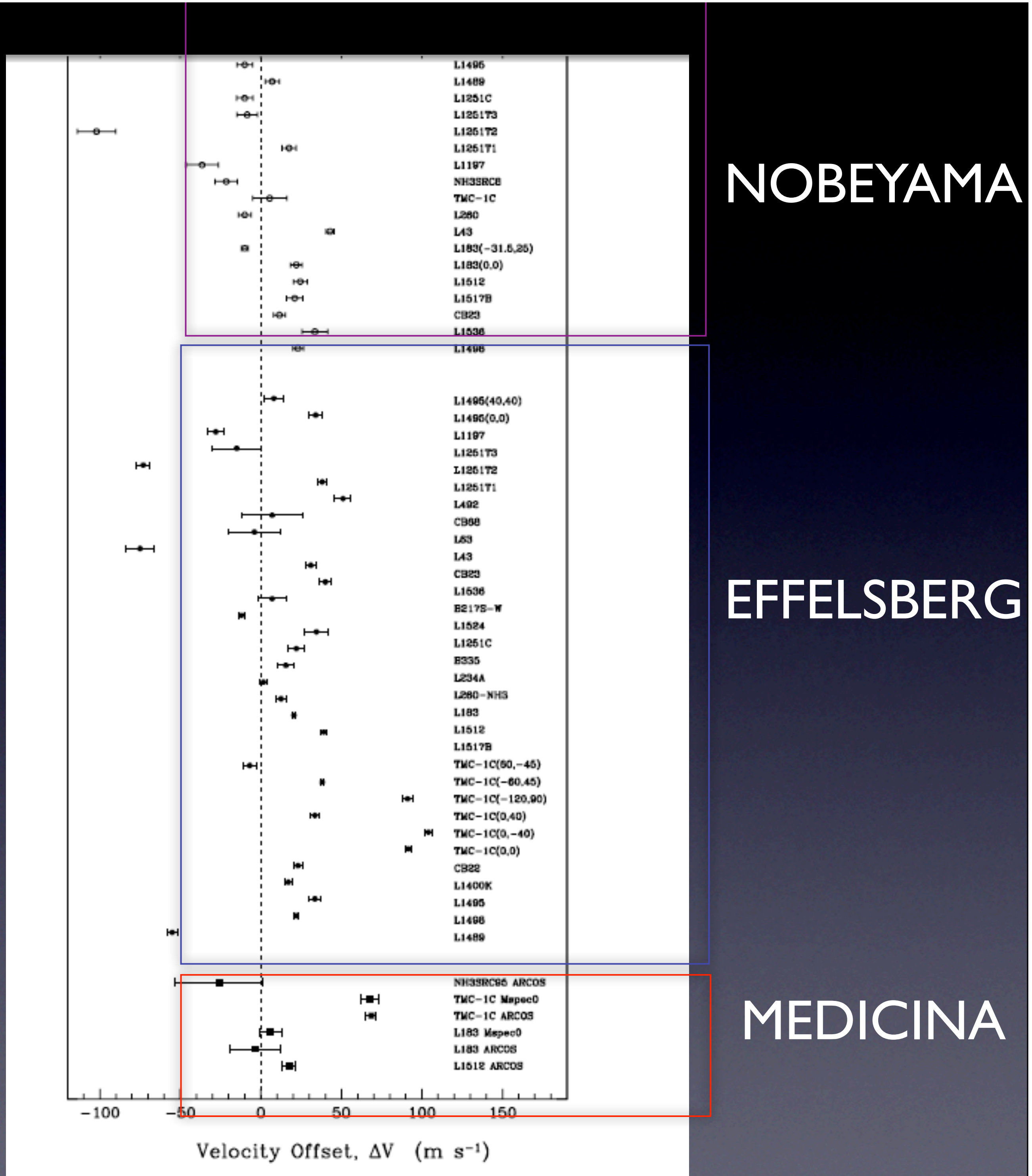
Results:

41 cold and compact cores in Taurus

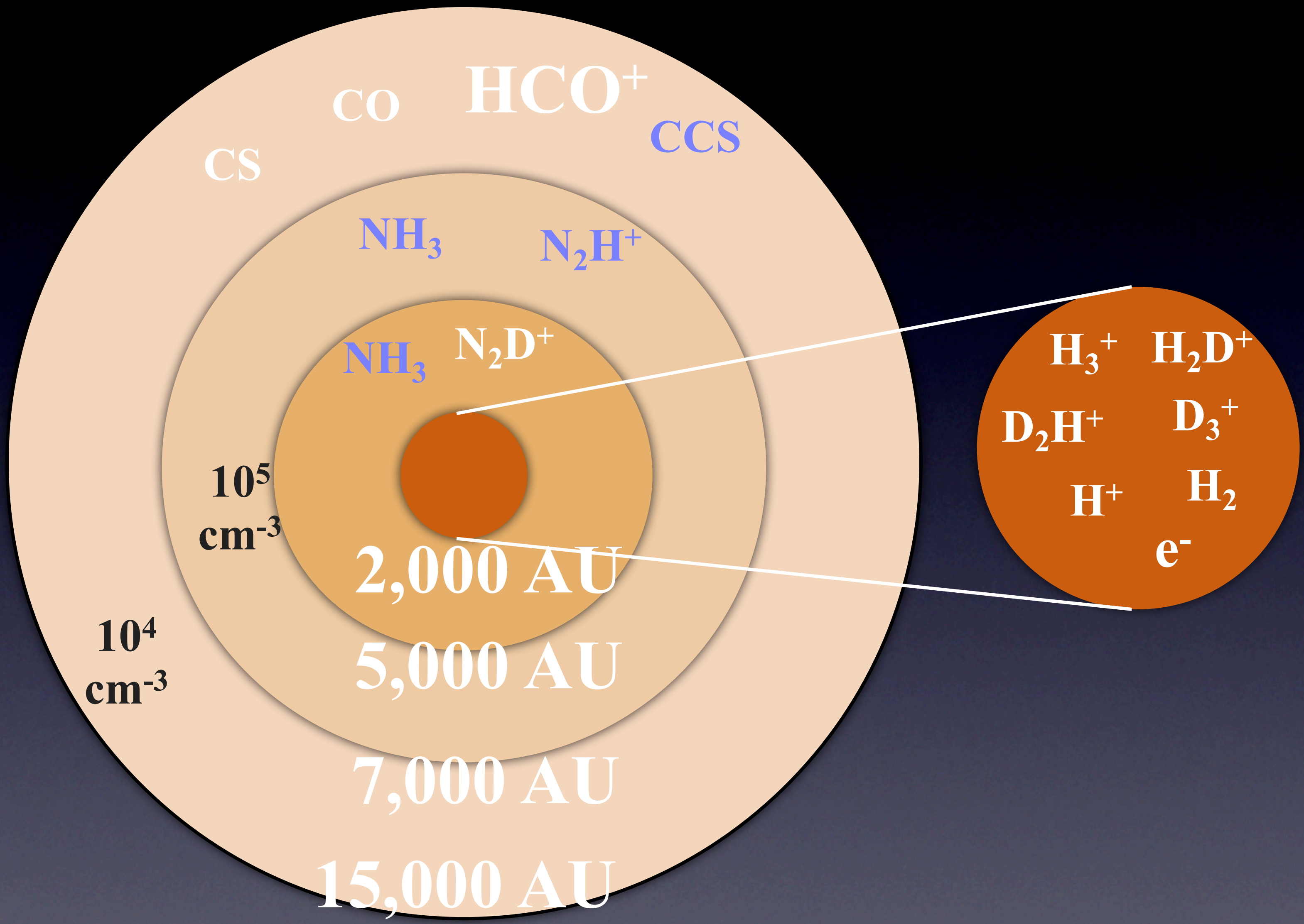
55 molecular pairs

Notes:

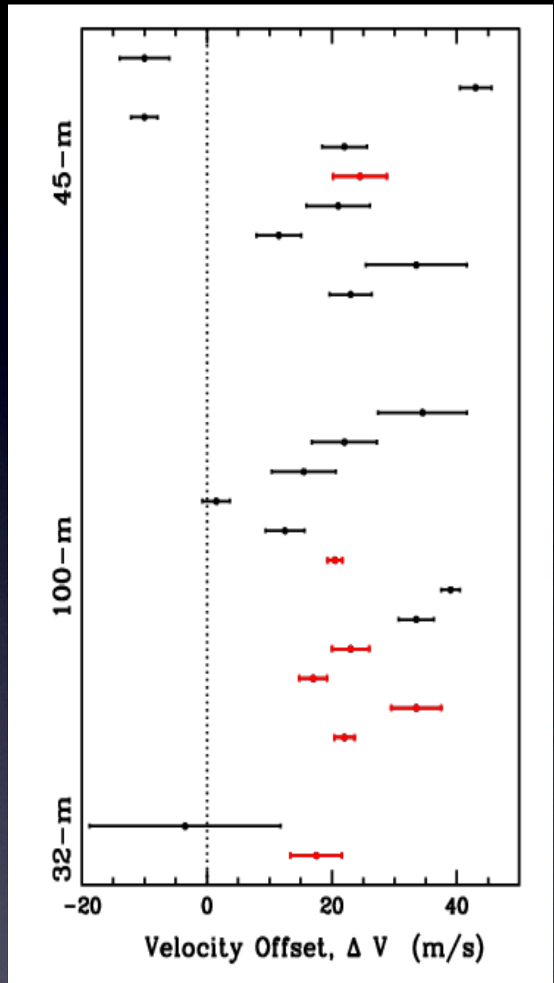
- TMC-1C partially mapped large dispersion
- L1512 by Medicina and Effelsberg consistent



Molecular differentiation within a low-mass core



co-spatially distributed n=23



$$\beta = \frac{b(NH_3)}{b(HC_3N)}$$

Criteria:
- Symmetric,
- narrow b< 100 m/s
- thermally broadened,
- optically thin

$\beta = 1.7$ pure thermal

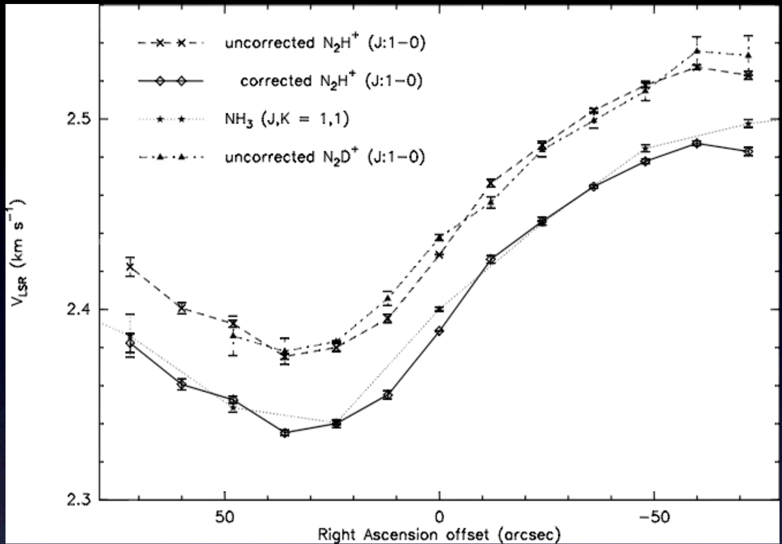
Black:
$1 \leq \beta < 1.2$

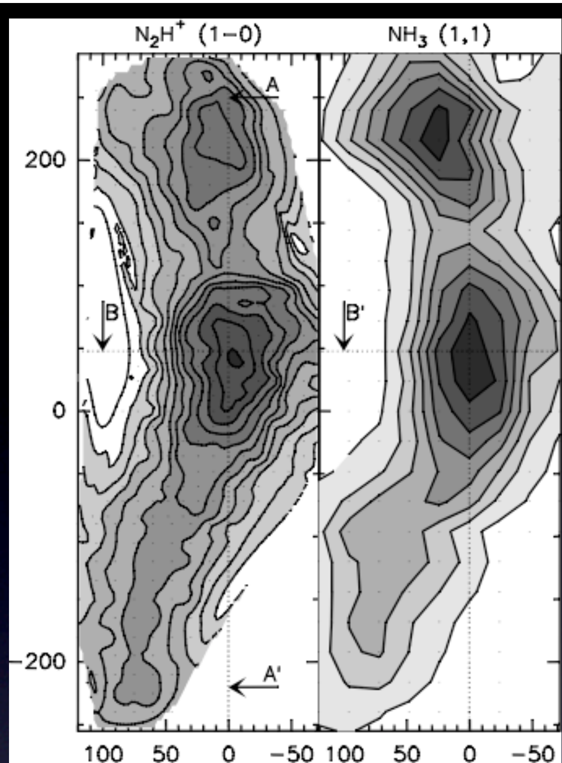
$1.2 \leq \beta < 1.7$

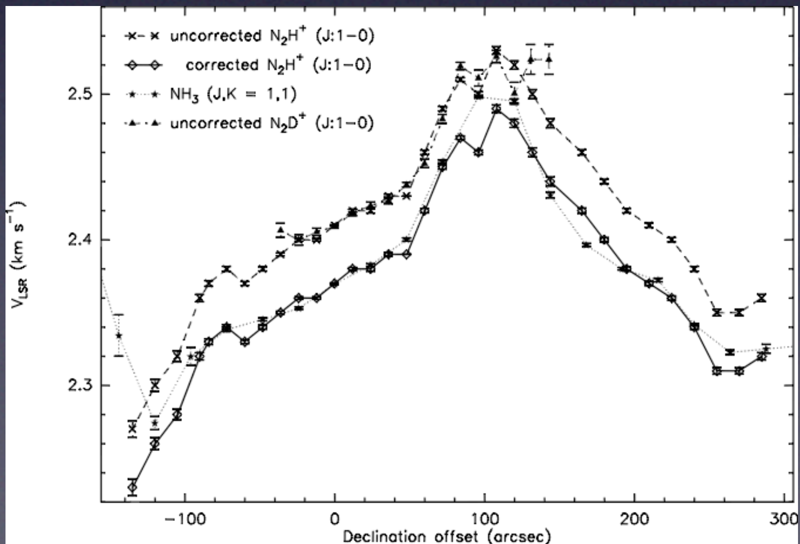
$$\Delta\mu/\mu = (2.6 \pm 0.4_{stat} \pm 0.3_{sys}) \times 10^{-8}$$

Levshakov, Molaro et al 2009 A&A

Mapping L183

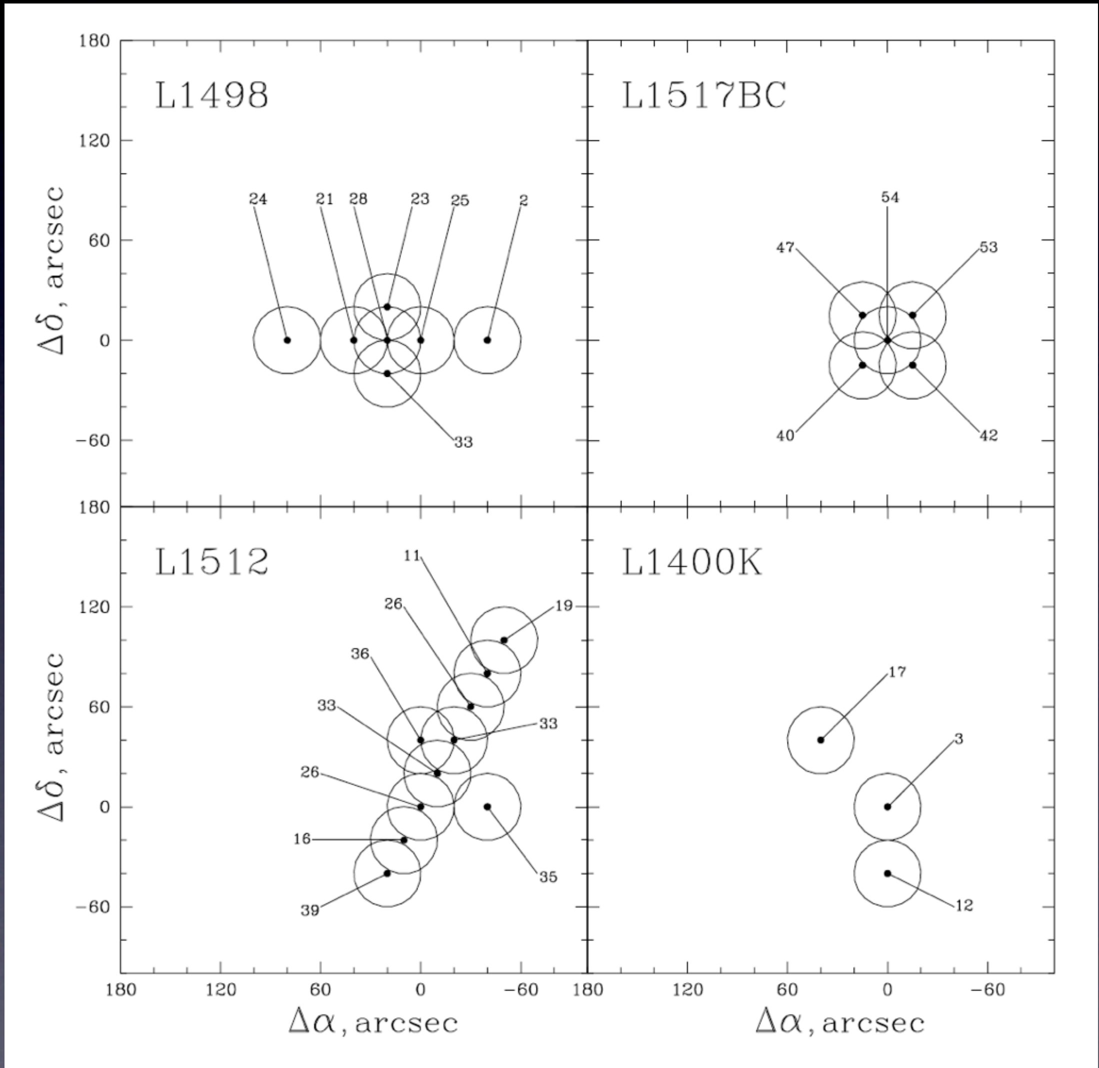






- Pagani et al 2008: NH_3 (at GBT) & N_2H+ (at IRAM)
  - Reference position: Dv= 40.8 ± 0.56 m s^{-1}
  - 65 common positions: 40.8 ± 12.9 m s^{-1}
- Pagani et al correct the frequency for N_2H+
- Molaro et al 2009 propose intrinsic shift

EFFELSBERG 2010



- January 2010:
  - mapping of 4 clouds thermal broadened low turbulence, subsonic velocity

  - NH3 and cyanoacetylene (HC3N)
  - 15.4 & 20.1 m/s channels, angular 40", 50" (pointing 10")

For the 2 clouds L1498, L1512

$$\Delta V = 27 \pm 1_{stat} \pm 3_{sys} \quad m/s$$

$$\Delta\mu/\mu = (27 \pm 1_{stat} \pm 3_{sys}) \times 10^{-9}$$

Levshakov et al 2010

True?

ΔV (m/s)	stat	sys	molecules	Radiotel.	Author	Clouds
26	±3.8	±3	HC3N NH2+	Effelsberg Medicina Nobeyama	Levshakov, Molaro et al 2009 A&A	41
36	±3	±13.5	CCS	Green Belt	Levshakov, Molaro, Kozlov 2008 aeXiv: 0808.0583	21
40	±1	±14	NH2+	GB&IRAM	Molaro et al 2009 data Pagani	1(65)
27	±1	±3	HC3N	Effelsberg	Levshakov et al 2010	4 (40)

$$\Delta\mu/\mu = (27 \pm 1_{stat} \pm 3_{sys}) \times 10^{-9}$$

True?

- reproduced at different facilities by different groups
- no known systematic at the level of 20 m/s
- verification – other molecules, new targets

- $\rho_{ISM}(z=0) \approx \rho_{ISM}(z>0)$

IN DLAs expected $\Delta\mu/\mu \sim 10^{-8}$ with CODEX !

Coupling to gravity?

- distance < 1000 ly
- variations conflict with laboratory bounds, but also spatial!

$$\Delta\mu/\mu = K_{\mu} \Delta\Phi$$

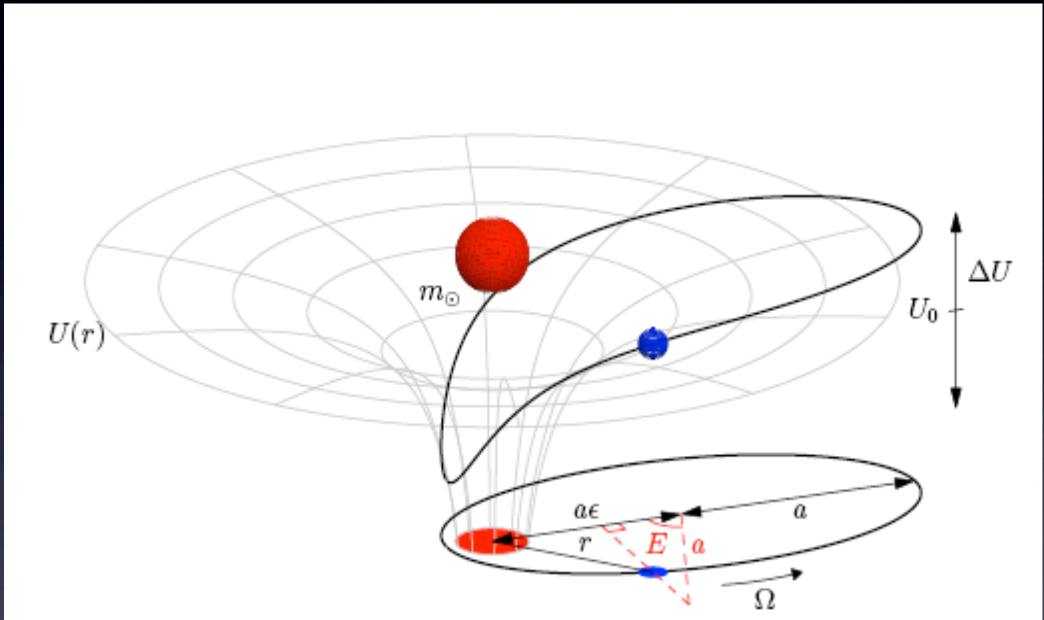
- The Galactic gravitational potential is $\Delta\Phi = 10^{-7}$
- if $\Delta\mu/\mu = 0.03$ ($\pm$ 0.01) ppm

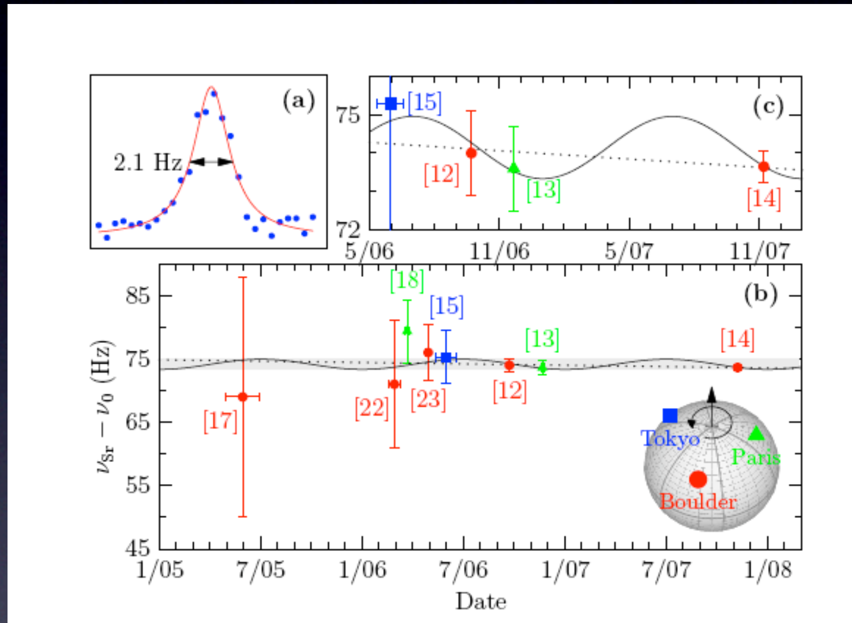
$$\Rightarrow K_{\mu} \approx 1$$

- But atomic clock experiments in the solar system...

Coupling of the scalar field with local gravitational potential

The Earth moves on an elliptic orbit in a varying gravitational potential





$\Delta\alpha/\alpha = K\ \alpha\Delta\Phi$

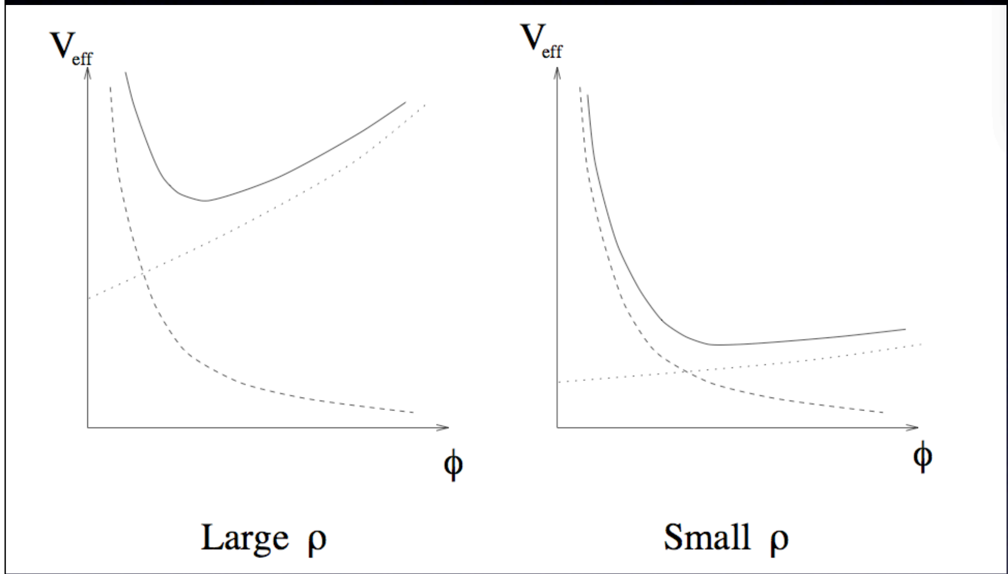
$\Delta\mu/\mu = K_\mu\ \Delta\Phi$

$\Delta\Phi = 3.3\times 10^{-10}$

=> $K\ \alpha = (2.5 \pm 3.1) \times 10^{-6}$ (Blatt et al 2008)

Chameleons in the sky

dependence of masses and coupling constants on environmental matter density **Khoury & Weltman'04, Bax et al.'04 Feldman et al.'06 Olive & Pospelov'08**



ρ - ambient matter density

In the dark clouds:

- ρ_{cloud} 3x10^5 Gev cm^{-3}
- $\rho_{\oplus}$= 3x10^{24} Gev cm^{-3}

$\rho_{lab} / \rho_{ISM} \sim$ **10^{12} - 10^{14}**

$$m_{atm}^{-1} \lesssim 1\ \mathrm{mm} - 1\ \mathrm{cm}$$

$$m_G^{-1} \lesssim 10 - 10^4\ \mathrm{AU}$$

$$m_0^{-1} \lesssim 0.1 - 10^3\ \mathrm{pc}\,,$$

Conclusions

- Variability of physical constants is important for physics (only astronomy can probe it in space-time)
- Implications:
  - *new force* (related to scalar fields)
    - Possible reconstruction of *W(z)* Dark Energy
    - pointer for GUTs theories
- Hints of spatial variation: "Australian Dipole" but TBC
- ESPRESSO @4VLT and CODEX at the E-ELT will improve present accuracy by about 2 order of mag.
- New intriguing variability of mu in the MW from the NH3 method (also TBC)