Search for a drifting proton-electron mass ratio from H_2 and methanol

LaserLaB Amsterdam

Wim Ubachs
Vrije Universiteit Amsterdam

'Hydride Toolbox'
Paris, 13 December 2016

Varying Constants of Nature ?

Coupling constants are free parameters in Standard Model
But cannot be varied at will

$$S = \int \left(L_{mat} + \frac{j_\mu}{c} A^\mu - \frac{\varepsilon_0}{4} F_{\mu\nu} F^{\mu\nu} e^{-2\phi} - \frac{\hbar c}{2l^2} \partial_\mu \partial^\mu \phi \right) d\Omega$$

Bekenstein – Barrow/Sandvik/Mageijo – Flambaum - Martins :
consistent models extending the Standard Model

$$\Delta\alpha, \Delta\mu \rightarrow \phi$$

1) Coupling to matter/energy
Variation on cosmological time scales
"Connection to Dark Energy scenarios"

2) Coupling to environment
-> "chameleon scenario"
Dependence on local density
Dependence on gravity

Empirical search for a change in μ

Compare H_2 in different epochs

Lab

today

QSO

12 Gyr ago

$$\frac{\lambda_i^z}{\lambda_i^0} \equiv 1 + z_i$$

90-112 nm

~275-350 nm

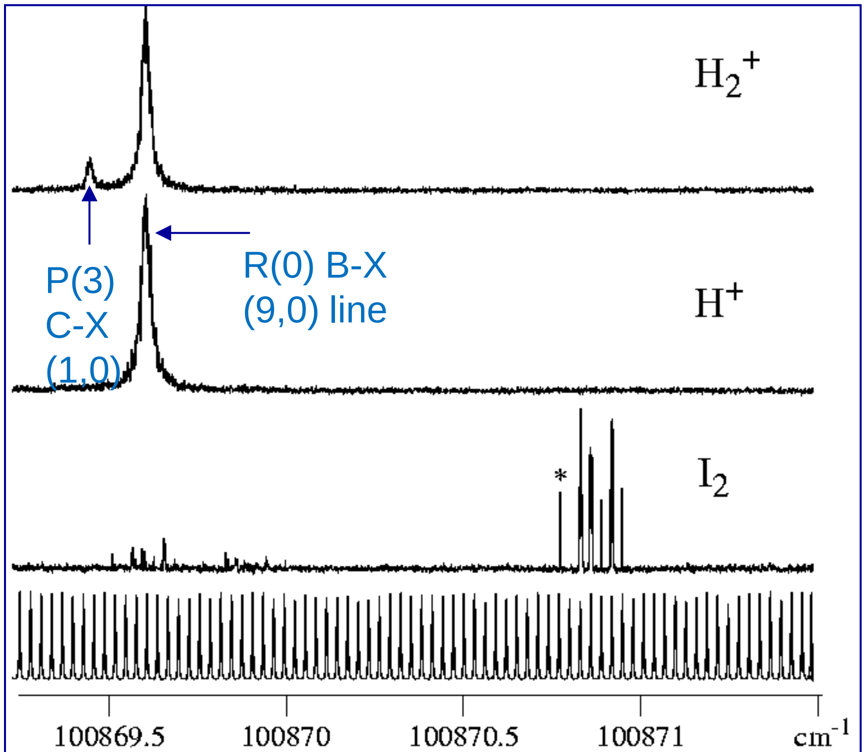
Cosmological redshift

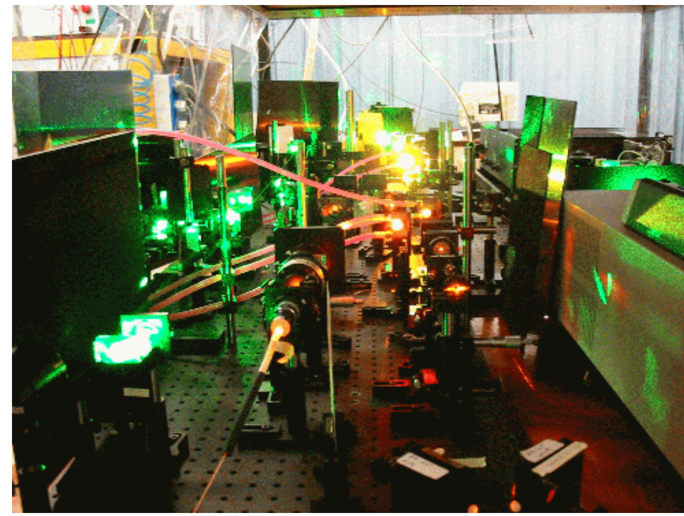
$$T = T_0 \left[1 - \frac{1}{(1 + z_{abs})^{3/2}} \right]$$

Practical: atmospheric transmission only for $z > 2$

H_2 laboratory wavelengths
The Amsterdam “XUV-laser”

XUV-laser excitation (90-115 nm)





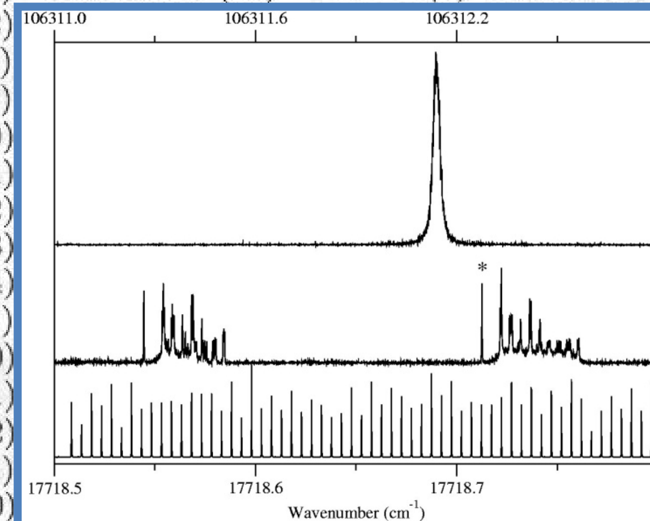
Ubachs, Phys. Rev. Lett. (2004)
Reinhold et al, Phys. Rev. Lett. (2006)

For HD

Ivanov et al., Phys. Rev. Lett. (2008)

TABLE I: Comprehensive list of measured transition wavelengths of the Lyman (L) and Werner (W) lines using the ultr
narrowband XUV laser source in Amsterdam. Values in nm.

Line	λ_0	Line	λ_0	Line	λ_0	Line	λ_0
L0 P(1)	111.006 251 (6)	L8 P(3)	100.838 615 (6)	L13 R(3)	95.894 665 (6)	W1 P(3)	99.138 046 (8)
L0 R(0)	110.812 733 (7)	L8 R(0)	100.182 387 (5)	L13 R(4)	96.215 297 (6)	W1 Q(1)	98.679 800 (5)
L0 R(1)	110.863 326 (7)	L8 R(1)	100.245 210 (5)	L14 P(1)	94.751 403 (10)	W1 Q(2)	98.797 445 (6)
L1 P(1)	109.405 198 (6)	L8 R(2)	100.398 545 (5)	L14 R(0)	94.616 931 (10)	W1 Q(3)	98.972 929 (8)
L1 P(2)	109.643 894 (6)	L8 R(3)	100.641 416 (6)	L14 R(1)	94.698 040 (10)	W1 R(0)	98.563 371 (5)
L1 P(3)	109.978 718 (7)	L9 P(1)	99.280 968 (5)	L14 R(2)			…5)
L1 R(0)	109.219 523 (6)	L9 R(0)	99.137 891 (5)	L15 P(1)			…6)
L1 R(1)	109.273 243 (6)	L9 R(1)	99.201 637 (5)	L15 P(3)			…9)
L1 R(2)	109.424 460 (6)	L9 R(2)	99.355 061 (9)	L15 R(0)			…6)
L1 R(3)	109.672 534 (6)	L9 R(3)	99.597 278 (20)	L15 R(1)			…7)
L2 P(1)	107.892 547 (5)	L10 P(1)	98.283 533 (5)	L15 R(2)			…7)
L2 R(0)	107.713 874 (5)	L10 P(2)	98.486 398 (5)	L15 R(3)			…5)
L2 R(1)	107.769 894 (5)	L10 P(3)	98.776 882 (6)	L15 R(4)			…5)
L2 R(2)	107.922 542 (6)	L10 R(0)	98.143 871 (5)	L16 P(1)			…7)
L2 R(3)	108.171 124 (7)	L10 R(1)	98.207 427 (5)	L16 R(0)			…7)
L2 R(4)	108.514 554 (6)	L10 R(2)	98.359 107 (5)	L16 R(1)			…8)
L3 P(1)	106.460 539 (5)	L10 R(3)	98.596 279 (6)	L16 R(2)			…5)
L3 P(2)	106.690 068 (5)	L11 P(1)	97.334 458 (5)	L17 P(1)			…5)
L3 R(0)	106.288 214 (5)	L11 P(2)	97.534 576 (5)	L17 R(0)			…6)
L3 R(1)	106.346 014 (5)	L11 P(3)	97.821 804 (6)	L17 R(1)	92.464 326 (9)	W2 R(3)	96.678 035 (7)
L3 R(2)	106.499 481 (5)	L11 R(0)	97.198 623 (5)	L18 P(1)	91.841 331 (9)	W3 P(2)	94.961 045 (5)
L3 R(3)	106.747 855 (5)	L11 R(1)	97.263 275 (5)	L18 R(0)			…36 (5)
L4 P(1)	105.103 253 (4)	L11 R(2)	97.415 791 (5)	L18 R(1)			…38 (5)
L4 R(0)	104.936 744 (4)	L11 R(3)	97.655 283 (6)	L18 R(2)			…33 (5)
L4 R(1)	104.995 976 (4)	L11 R(4)	97.980 512 (7)	L19 P(1)			…73 (5)
L4 R(2)	105.149 857 (5)	L11 R(5)	98.389 896 (7)	L19 P(2)			…57 (4)
L4 R(3)	105.397 610 (4)	L12 P(1)	96.431 064 (5)	L19 P(3)			…75 (4)
L5 P(1)	103.815 713 (4)	L12 P(2)	96.627 550 (5)	L19 R(0)			…39 (4)
L5 R(0)	103.654 581 (4)	L12 P(3)	96.908 984 (6)	L19 R(1)	[illegible]		…57 (5)
L5 R(1)	103.714 992 (4)	L12 R(0)	96.297 800 (5)	L19 R(2)	91.295 107 (17)	W3 R(4)	95.031 536 (5)
L5 R(2)	103.869 027 (4)	L12 R(1)	96.360 800 (5)	L19 R(3)	91.521 225 (17)	W4 P(2)	93.260 468 (10)
L5 R(3)	104.115 892 (4)	L12 R(2)	96.504 574 (5)	W0 P(2)	101.216 942 (6)	W4 P(3)	93.479 006 (10)
L6 P(1)	102.593 517 (8)	L12 R(3)	96.767 695 (6)	W0 P(3)	101.450 423 (6)	W4 Q(1)	93.057 708 (10)
L6 R(0)	102.437 395 (8)	L12 R(4)	97.083 820 (8)	W0 Q(1)	100.977 088 (5)	W4 Q(2)	93.178 086 (10)
L6 R(1)	102.498 790 (8)	L12 R(5)	97.488 649 (9)	W0 Q(2)	101.093 845 (6)	W4 Q(3)	93.357 794 (10)

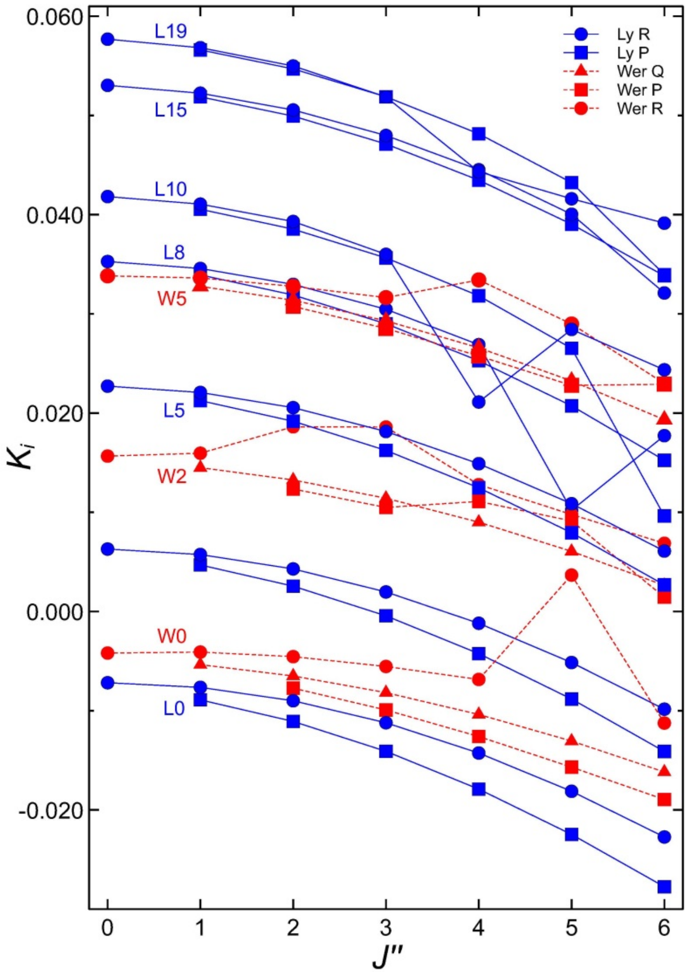


>160 lines measured
at ~ $\Delta\lambda/\lambda$ = 5 x 10^{-8}

Some lines at < 1 x 10^{-8}

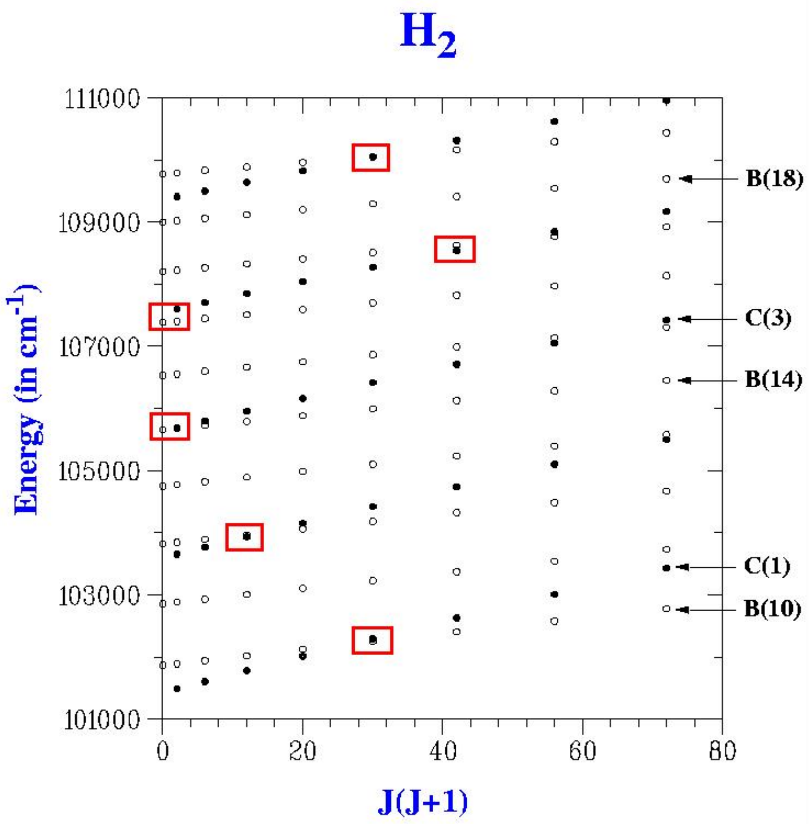
"Sensitivity"

$$K_i = \frac{d \ln \lambda_i}{d \ln \mu}$$



Perturbations

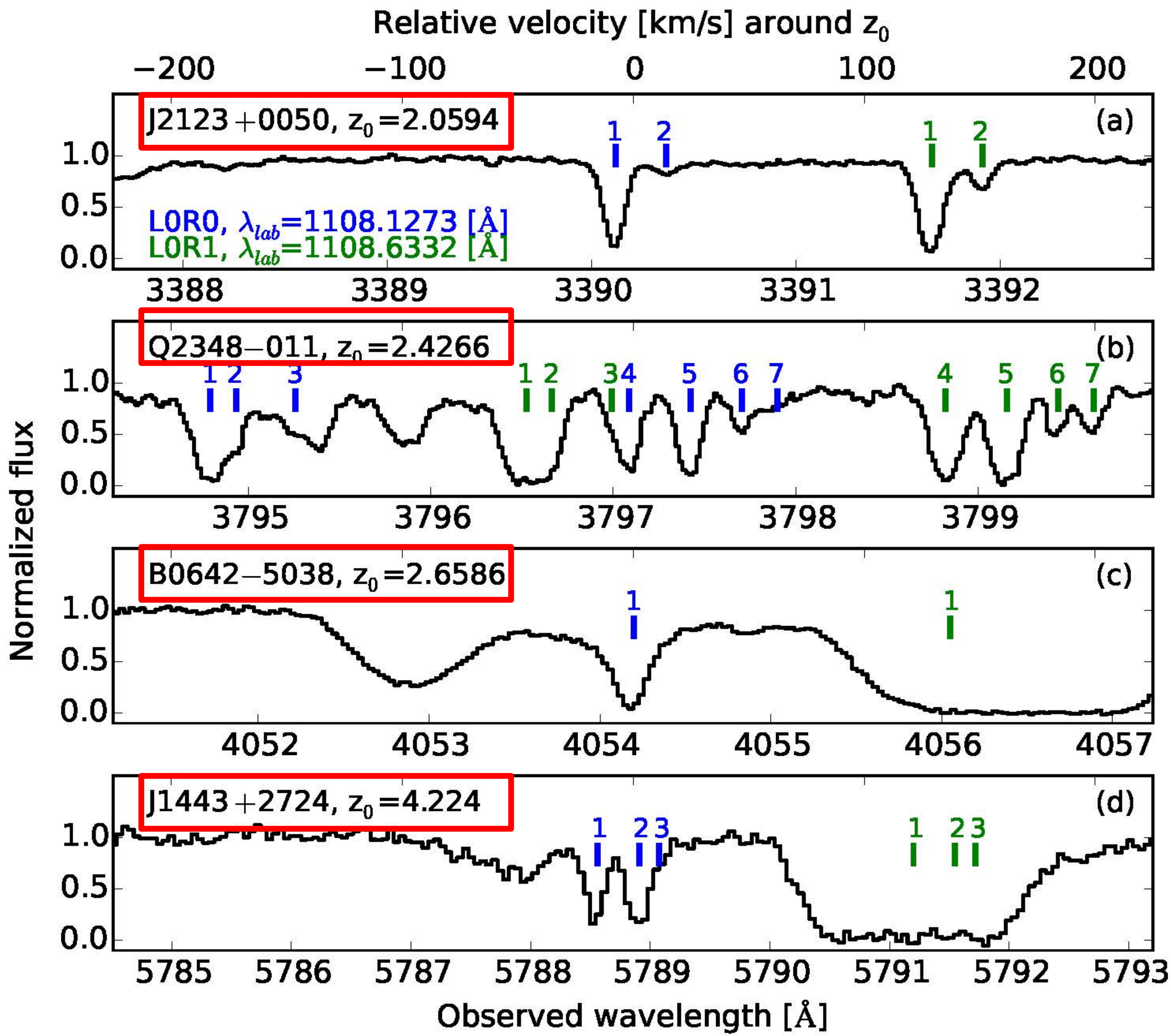
$$\left\langle B^1\Sigma_u^+, v_B, J, p \right| -\frac{\hbar^2}{2\mu R^2} J^+ L^- \left| C^1\Pi_u, v_C, J', p' \right\rangle$$



VLT – UVES
Paranal, Chili

Keck – HIRES
Hawaii

Various systems observed



Analysis method: “comprehensive fitting”

Produce molecular fingerprint

λ_i – set of accurate wavelengths

f_i – set of line oscillator strengths (from ab initio theory - Meudon)

Γ_i – set of damping coefficients (from ab initio theory - Meudon)

Astrophysical conditions

b – Doppler width parameter

z – red shift

N_J – column densities

Fit equation onto spectrum
“Treat” HI and metal lines
Multiple velocity components (?)

$$\frac{\lambda_i^z}{\lambda_i^0} \equiv 1 + z_i = (1 + z_{abs})\left(1 + K_i \frac{\Delta\mu}{\mu}\right)$$

K_i – set of sensitivity coefficients

The best system: J2123-005 at z_{abs}=2.05

Unique spectrum from Keck; Resolution 110000 ; seeing 0.3”

Spectrum from VLT; R=54000; seeing 0.8”; better SNR

37 panels, 3071 – 3421 Å

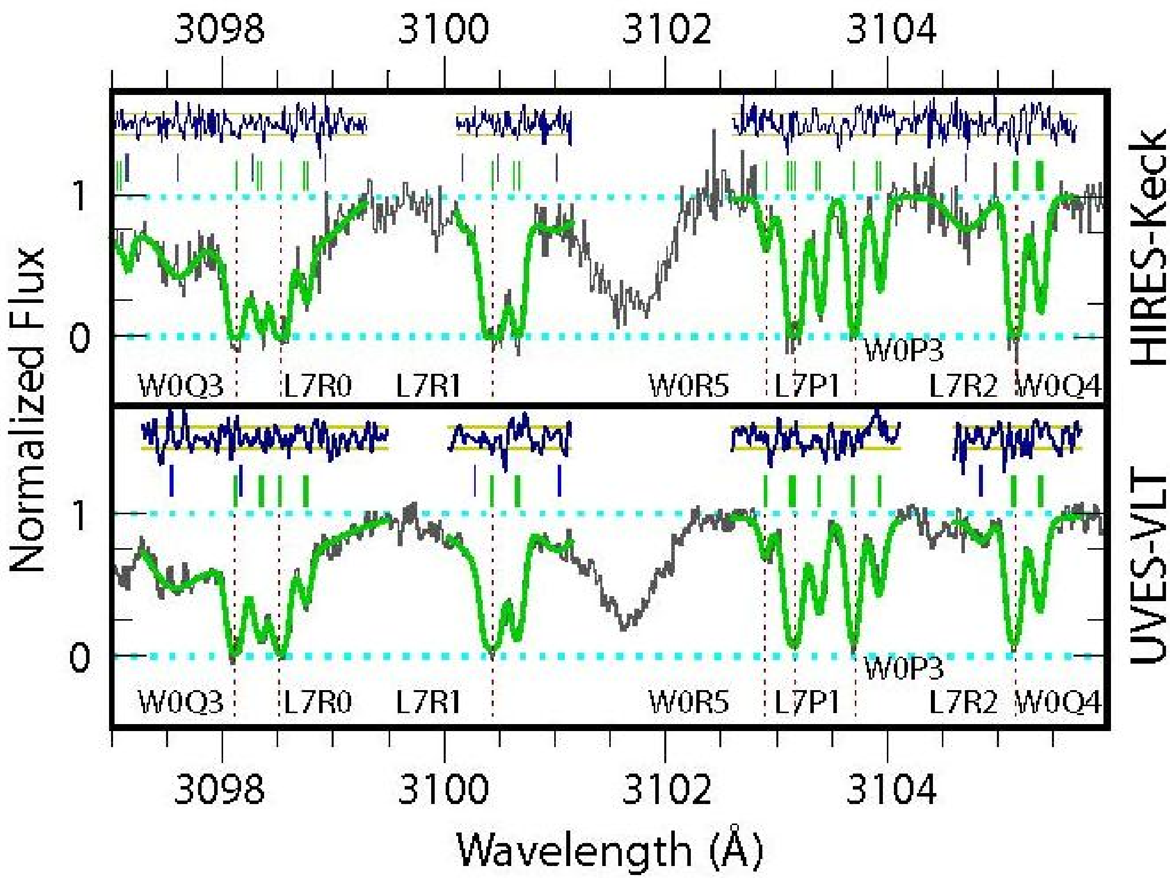
~100 H_2 + 7 HD lines

Keck:

$\Delta\mu/\mu = (5.6 \pm 5.5_{stat} \pm 2.9_{syst}) \times 10^{-6}$

VLT:

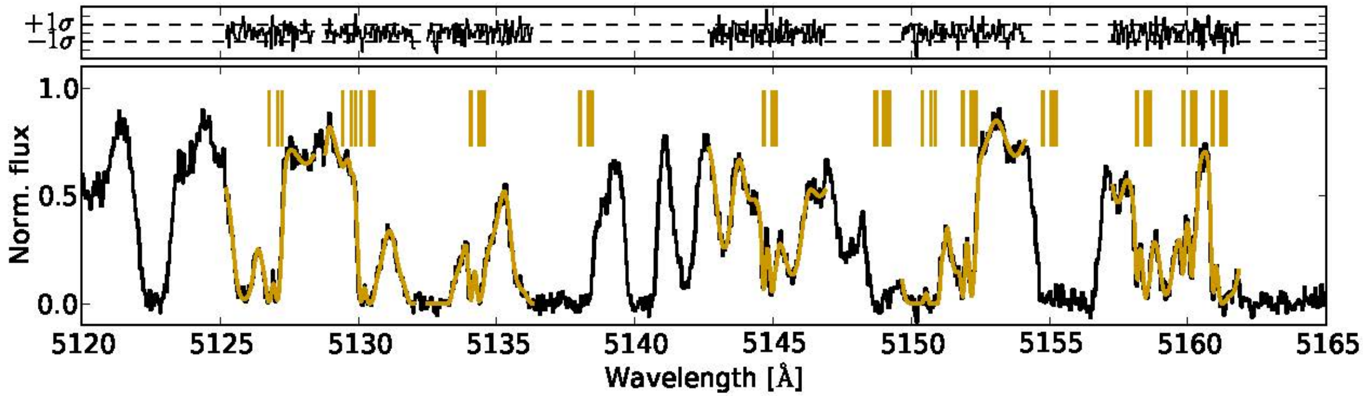
$\Delta\mu/\mu = (8.5 \pm 3.6_{stat} \pm 2.2_{syst}) \times 10^{-6}$



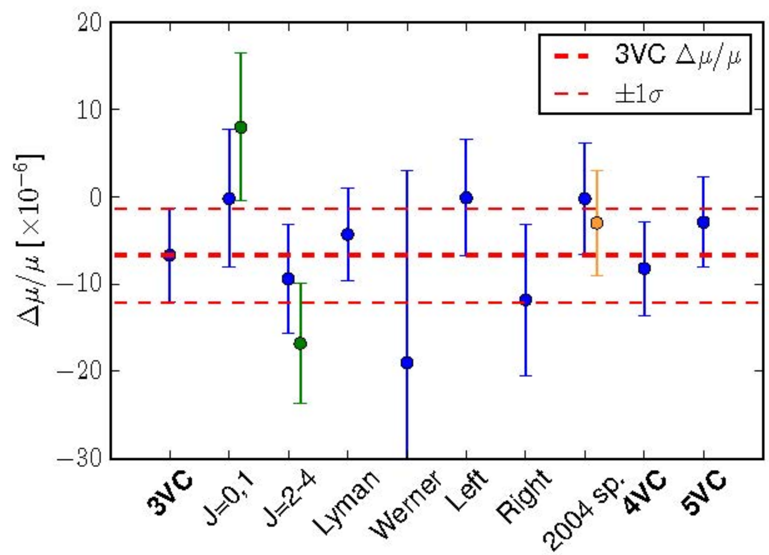
Phys. Rev. Lett. 106, 180802 (2011)

Q1441+272 ; the most distant

z_{abs} = 4.22 ; 1.5 Gyrs after the Big Bang



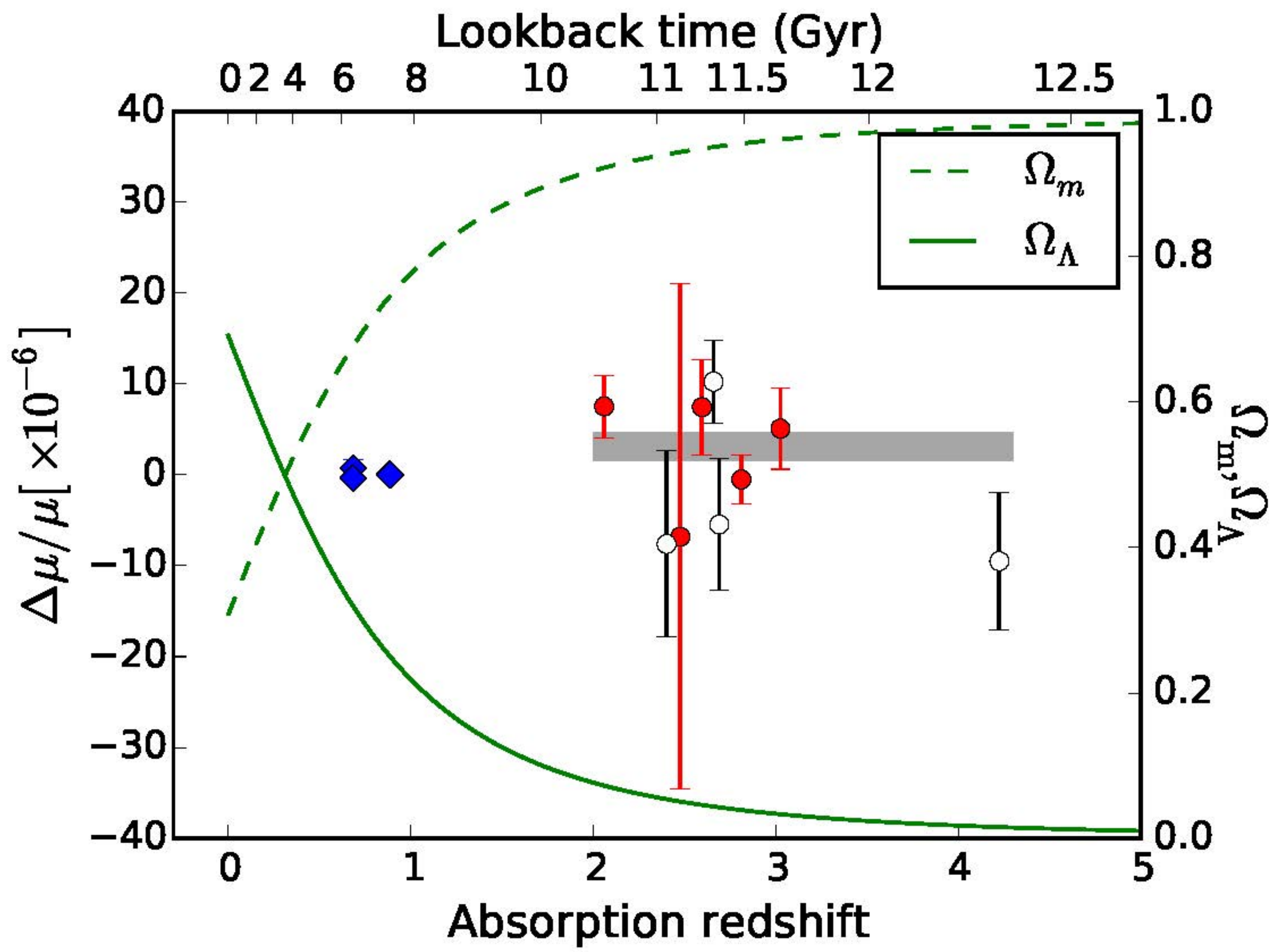
Systematic analysis



Bagdonaite et al. Phys. Rev. Lett. 114, 071301 (2015)

Status

$\Delta\mu/\mu = (3.1 \pm 1.6) \times 10^{-6}$



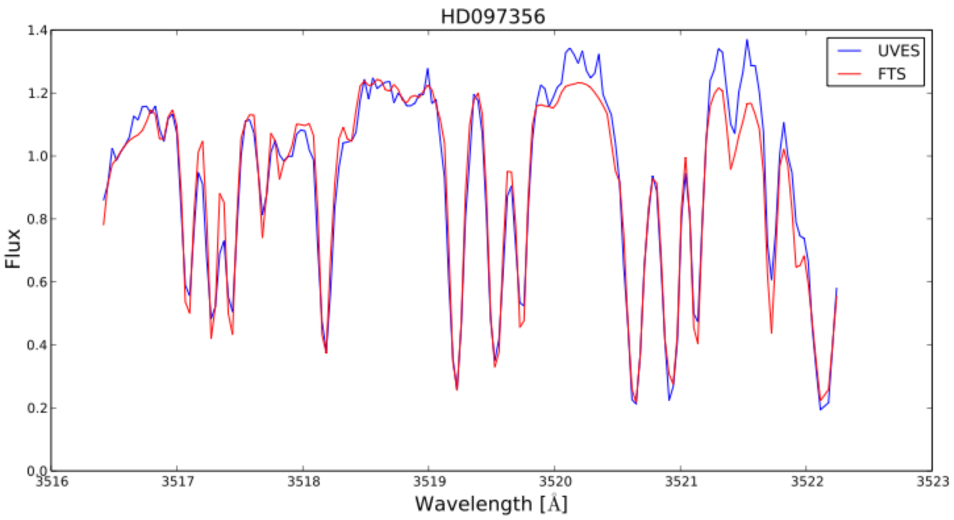
W. Ubachs, J. Bagdonaite, E.J. Salumbides, M.T. Murphy, L. Kaper
[Search for a drifting proton-electron mass ratio from H_2]
Rev. Mod. Phys. 88, 021003 (2016)

Long- rang λ distortions: “Super-calibration corrections”

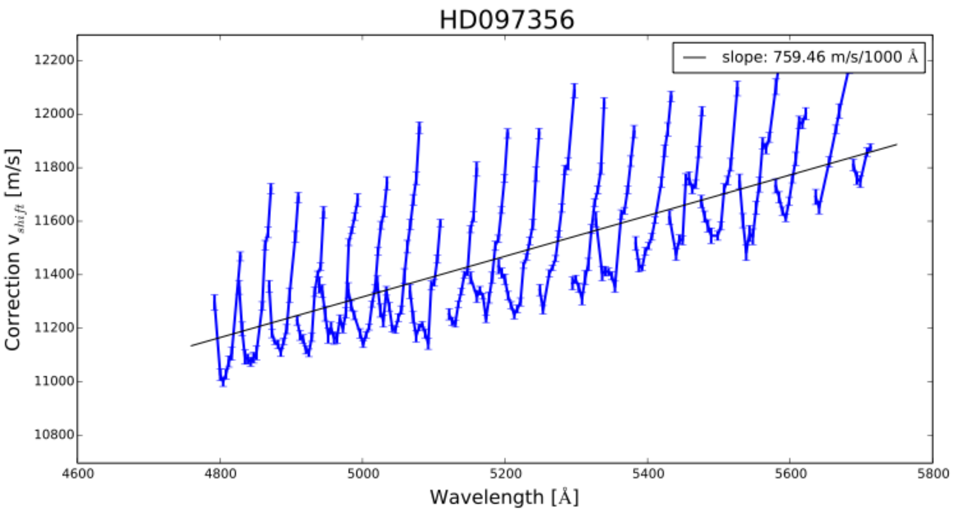
Solar-twin spectra
Asteroid spectra

compared with

Solar spectrum (FTS)



Correction of
wavelength scale
Th-Ar calibration



Papers: Rahmani et al (2013); Whitmore and Murphy (2014); Bagdonaite et al (2015)

H_2 high redshift absorption systems

10 H_2 proper absorption systems towards quasars analyzed:

Quasar	z_{abs}	z_{em}	RA(J2000)	Decl.(J2000)	$N(H_2)$	$N(HD)$	$N(CO)$	$N(HI)$	R_{mag}
HE0027−1836	2.42	2.55	00:30:23.62	−18:19:56.0	17.3			21.7	17.37
Q0347−383	3.02	3.21	03:49:43.64	−38:10:30.6	14.5			20.6	17.48
Q0405−443	2.59	3.00	04:07:18.08	−44:10:13.9	18.2			20.9	17.34
Q0528−250	2.81	2.81	05:30:07.95	−25:03:29.7	18.2	13.3		21.1	17.37
B0642−5038	2.66	3.09	06:43:26.99	−50:41:12.7	18.4			21.0	18.06
Q1232+082	2.34	2.57	12:34:37.58	+07:58:43.6	19.7	15.5		20.9	18.40
J1237+064	2.69	2.78	12:37:14.60	+06:47:59.5	19.2	14.5	14.2	20.0	18.21
J1443+2724	4.22	4.42	14:43:31.18	+27:24:36.4	18.3			21.0	18.81
J2123−0050	2.06	2.26	21:23:29.46	−00:50:52.9	17.6	13.8		19.2	15.83
Q2348−011	2.42	3.02	23:50:57.87	−00:52:09.9	18.4			20.5	18.31

M. Dapra et al, Astroph. J. 826, 192 (2016): CO in J1237
M. Dapra et al. MNRAS 454, 489 (2015): H_2 in J1237
M. Dapra et al. MNRAS in press

+ 23 additional H_2 absorption systems towards quasars known
+ some 20 tentative detections [Balashev et al (2014)]

Take home

μ does not vary

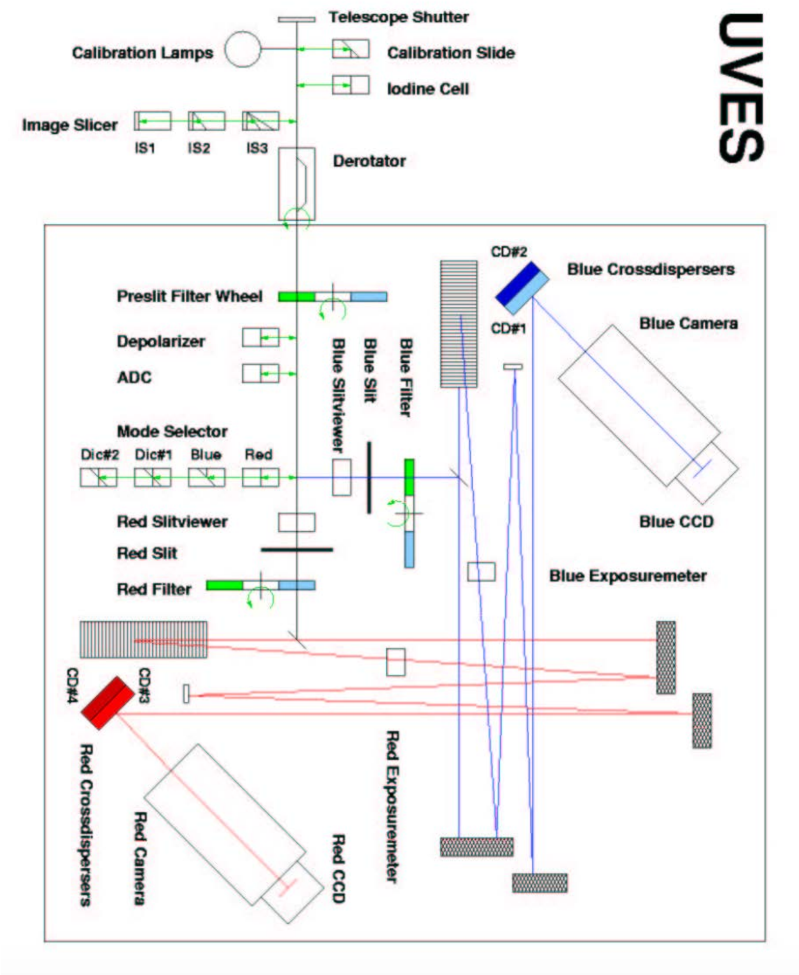
$|\Delta\mu/\mu| < 5 \times 10^{-6}$ at 3σ level

For redshifts $z = 2$-4

Limitations due to spectrometer design

W. Ubachs, J. Bagdonaite, E.J. Salumbides, M.T. Murphy, L. Kaper
Search for a drifting proton-electron mass ratio from H_2
Rev. Mod. Phys. 88, 021003 (2016)

Remark on developments varying constants w.r.t. VLT



Wavelength distortions ThAr relate to beam pointing.

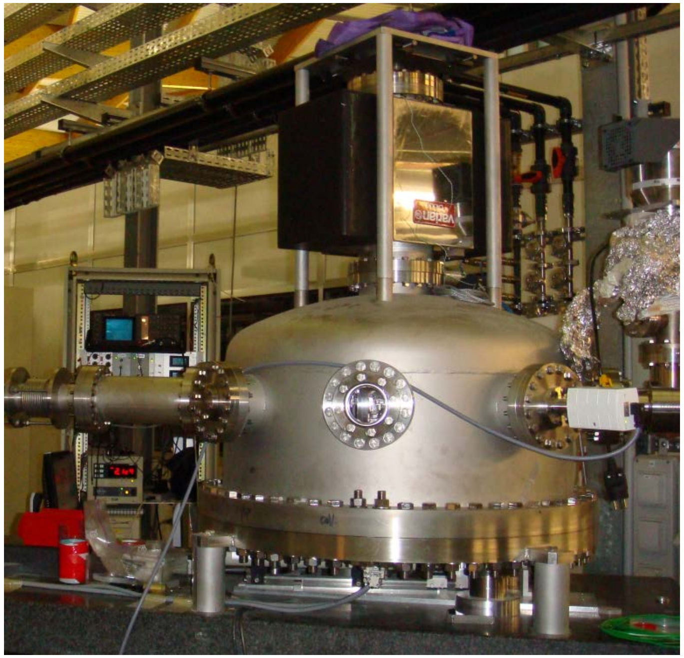
Solutions for 'ESPRESSO'

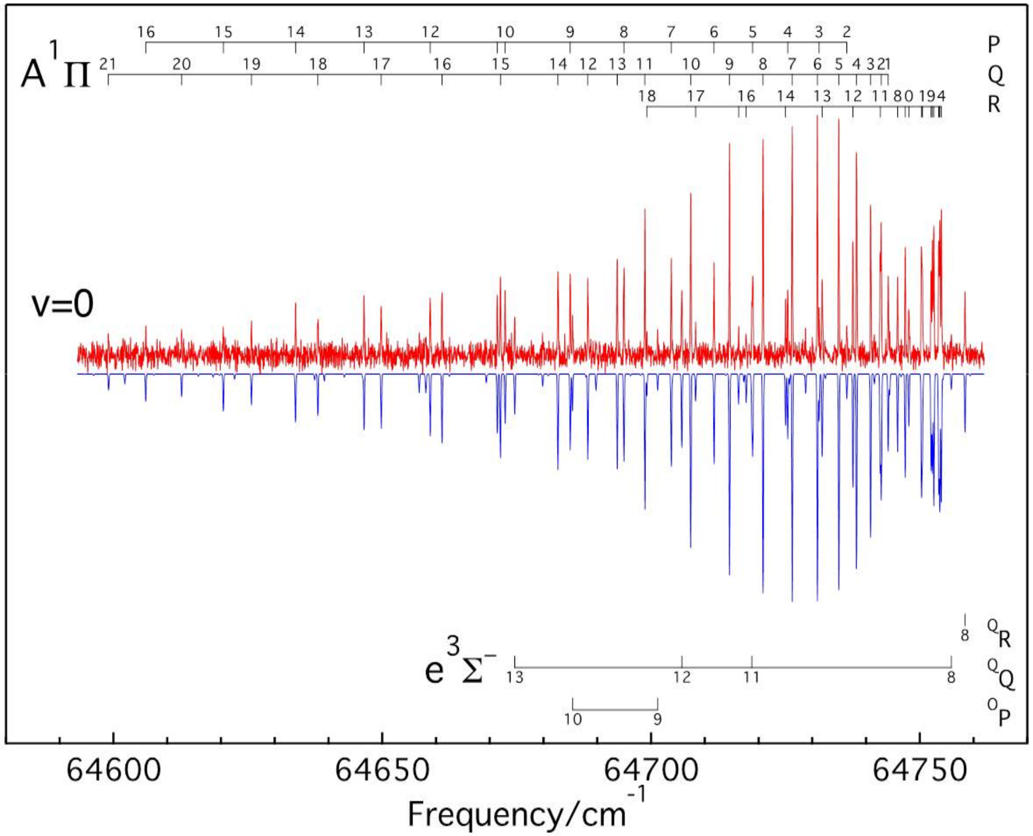
- Frequency comb calibration
- Fiber feeding
- Fibers designed for $\lambda > 3700$ Å

Problematic for H_2 studies, only $z > 3$

New Avenue: CO electronic absorption A-X (v',0) and electronic bands

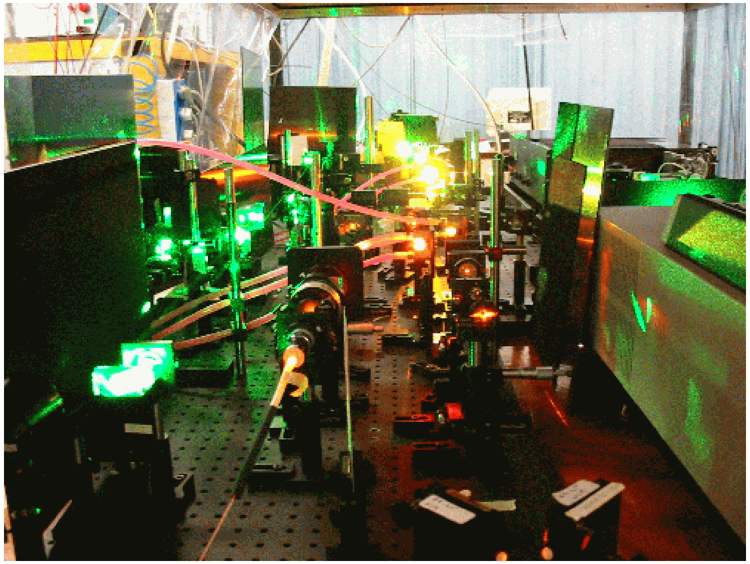
Soleil Fourier-Transform VUV Spectrometer



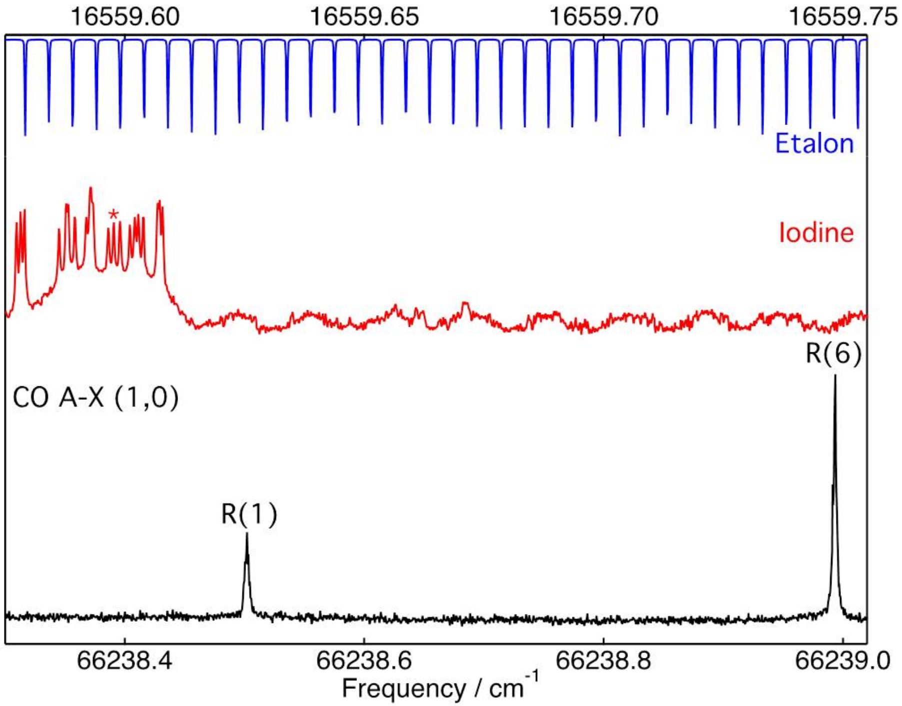


New Avenue: CO electronic absorption A-X (v',0) and electronic bands

Laser Lab
Pulsed dye
amplifier laser



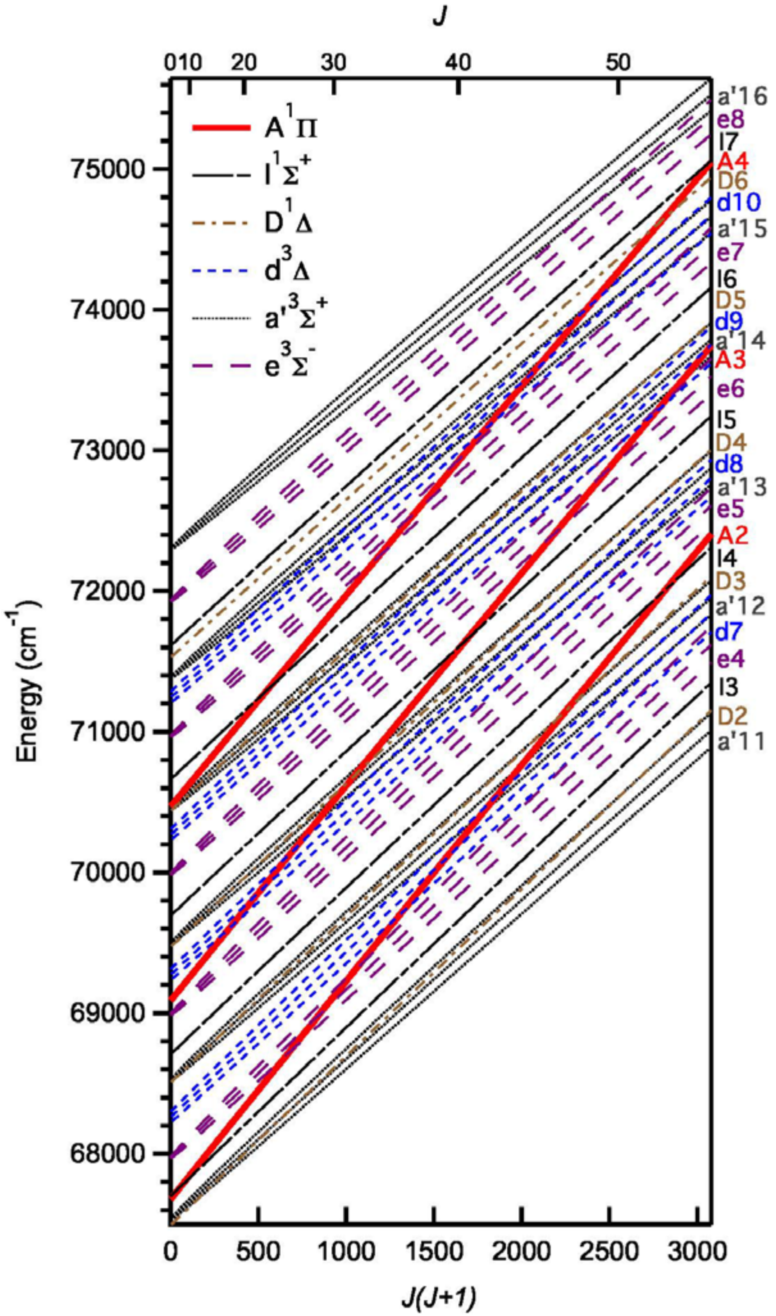
2 + 1' REMPI spectroscopy

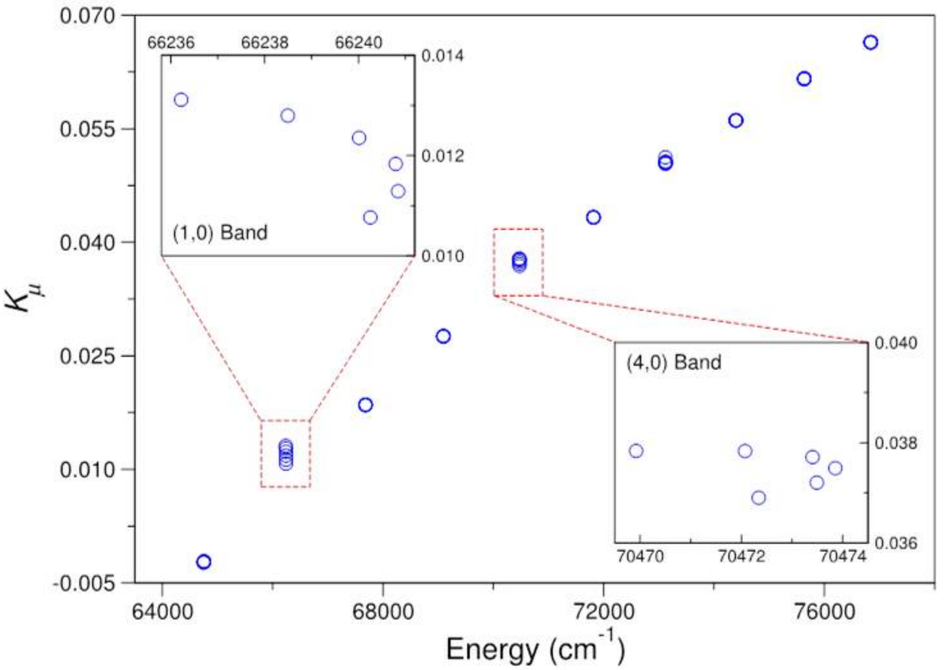


Full database of CO precision spectroscopy + relevant parameters

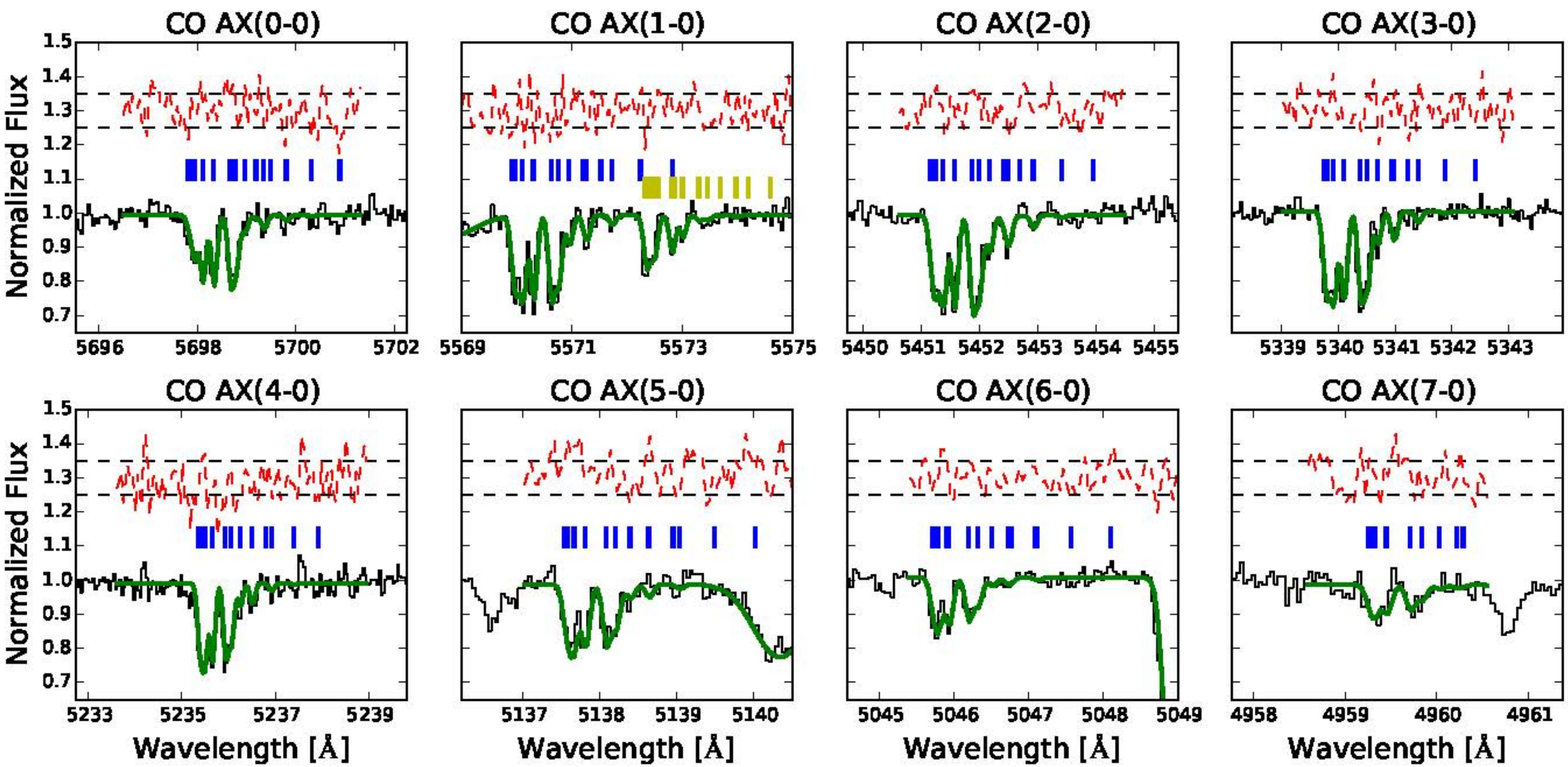
Perturbations:

- Wavelengths
- Intensities
- K-coefficients





CO in J1237+065 at z=2.69



J1237 Result: $\Delta\mu/\mu = (-5.6 \pm 5.6_{stat} \pm 3.1_{syst}) \cdot 10^{-6}$

Based on CO + H_2

Tackling a Chameleon scenario

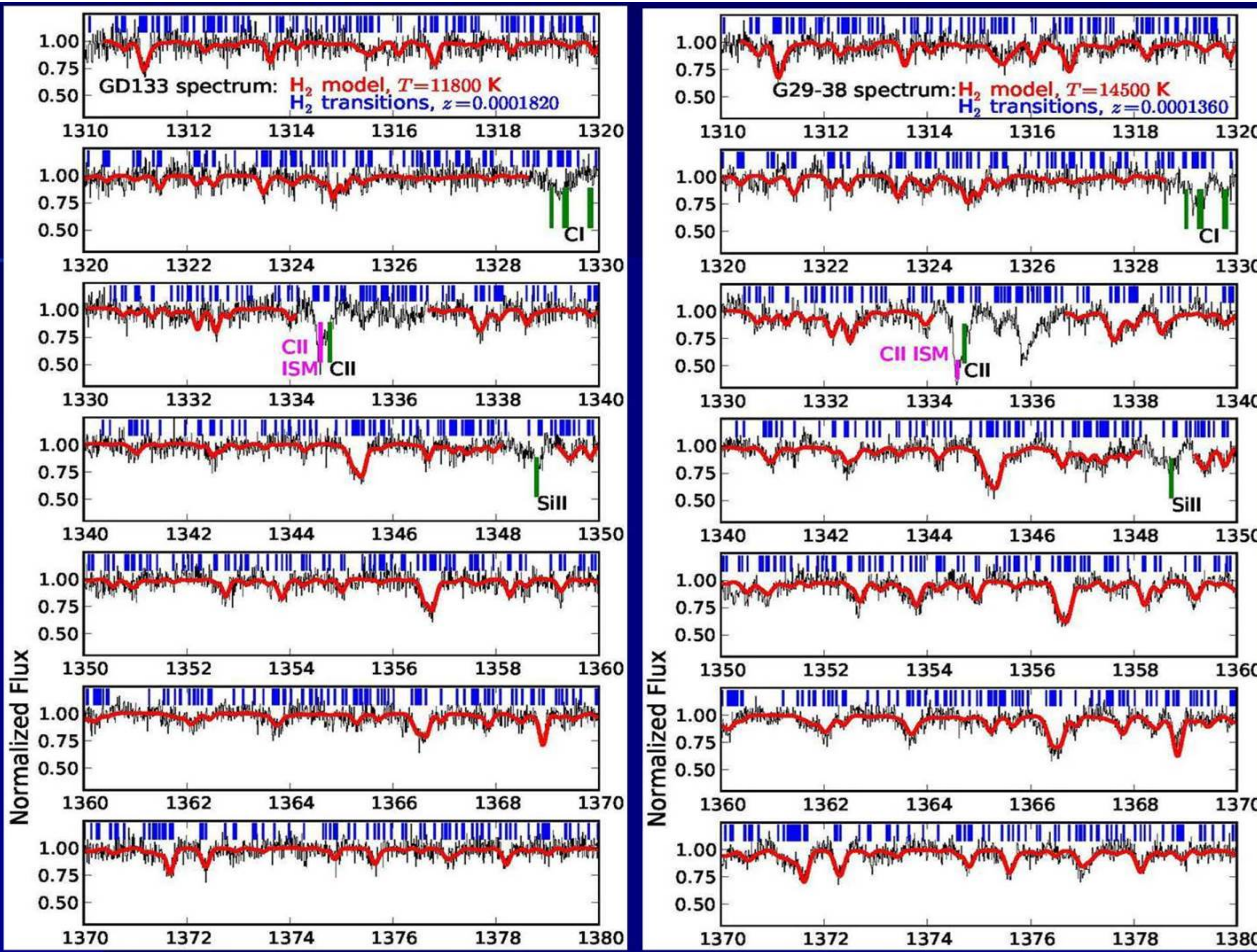
Dependence of μ
on gravitational field ?

Spectrum of GD-133 and GD29-38
Photosphere of White Dwarf stars

H_2 in VUV

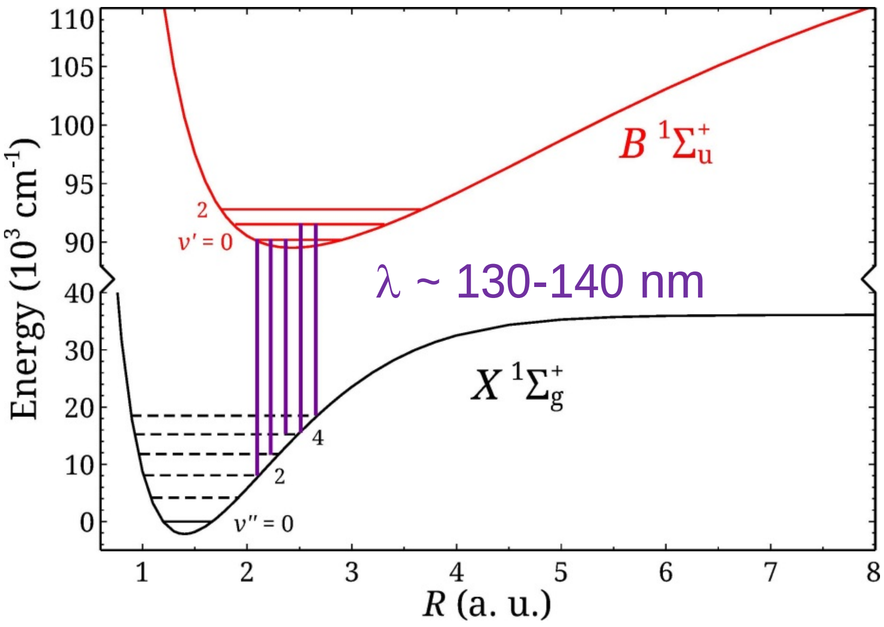
In search for the chameleon
scenario (local conditions - gravity)

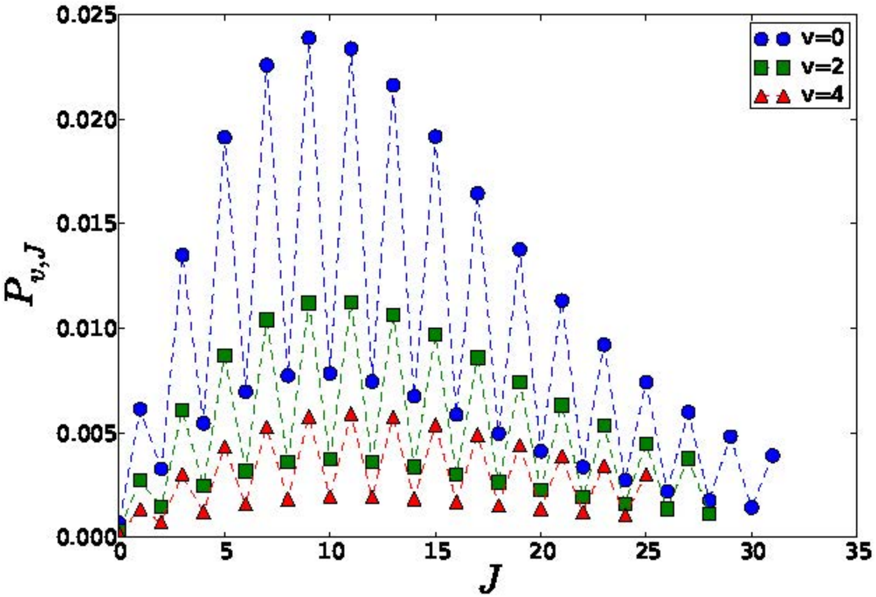
$$\phi_{WD} = \frac{GM}{Rc^2} \sim 10^4 \times \phi_{Earth}$$



GD133 spectrum: H2 model, T=11800 K
H2 transitions, z=0.0001820
G29-38 spectrum: H2 model, T=14500 K
H2 transitions, z=0.0001360
CI
CII ISM
CII
SiII
Normalized Flux

Contributions of many lines in the B-X Lyman system





High temperatures
High v populated
Franck-Condon factors

Dependence of $\Delta\mu/\mu$ on gravitational field

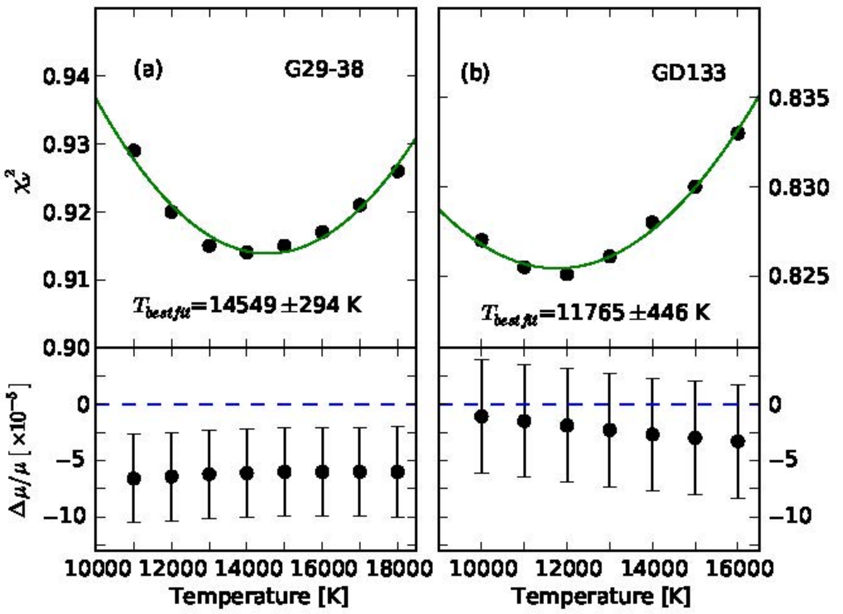
Invoke partition function:

$$P_{vJ}(T) = \frac{g_I(J)(2J+1)\exp\left(\frac{-E_{vJ}}{kT}\right)}{\sum_{v=0}^{v_{\max}} \sum_{J=0}^{J_{\max}(v)} g_I(J)(2J+1)\exp\left(\frac{-E_{vJ}}{kT}\right)}$$

Invoke intensities (1500 lines):

$$I_i = N_{col} f_{v'v''J'J''} P_{v''J''}(T)$$

Fit T and $\Delta\mu/\mu$



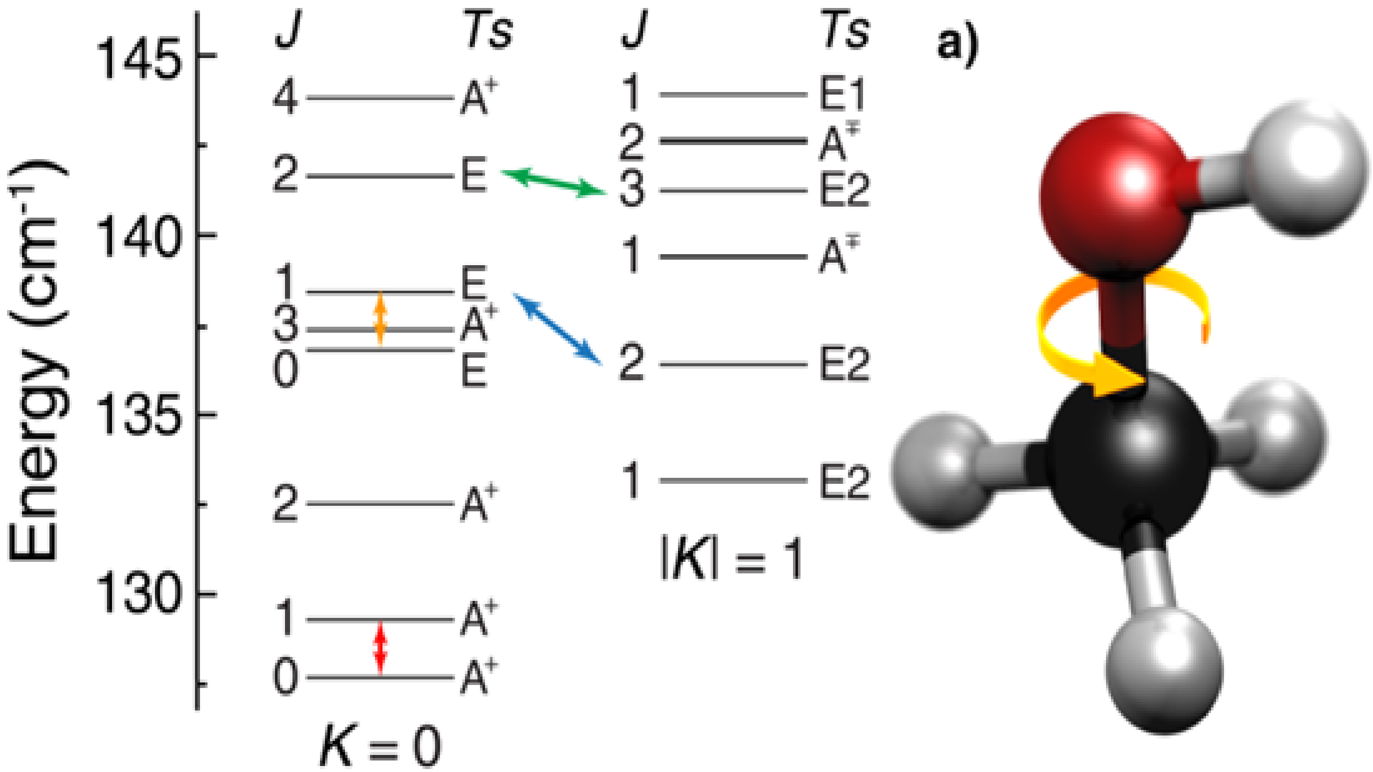
GD133: $\Delta\mu/\mu$ = (-2.7 +/- 4.7) x 10^{-5}

GD29-38: $\Delta\mu/\mu$ = (-5.9 +/-3.8) x 10^{-5}

Bagdonaite et al., Phys. Rev. Lett. 113, 123002 (2014)

What should you look at ??

Methanol: the extreme shifter



48372.4558 MHz; K=-1

48376.892 MHz; K=-1

12178.597 MHz; K=-33

60531.1489 MHz; K=-7

P. Jansen, L.-H. Xu, I. Kleiner, W. Ubachs, H.L. Bethlem, Phys. Rev. Lett. 106, 100801 (2011)

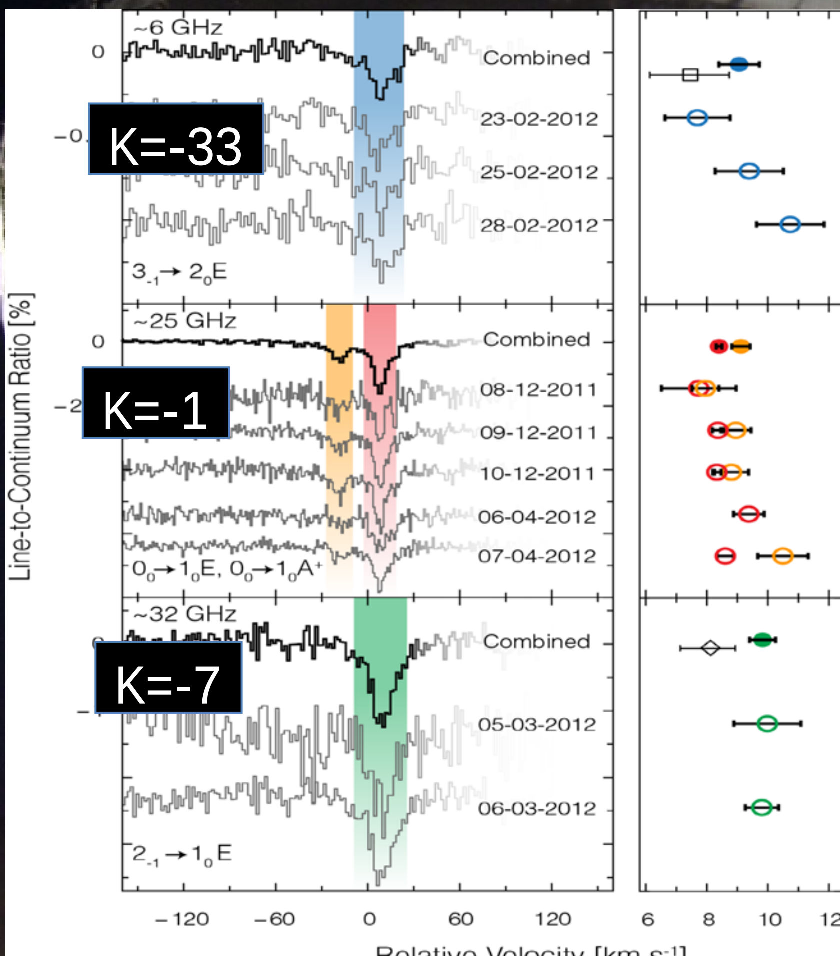
A Stringent Limit on a Drifting Proton-to-Electron Mass Ratio from Alcohol in the Early Universe

Bagdonaite, Jansen, Henkel, Bethlem, Menten, Ubachs,
Science 339 (2013) 46

Effelsberg Radio Telescope

PKS-1830-211
"molecular factory"

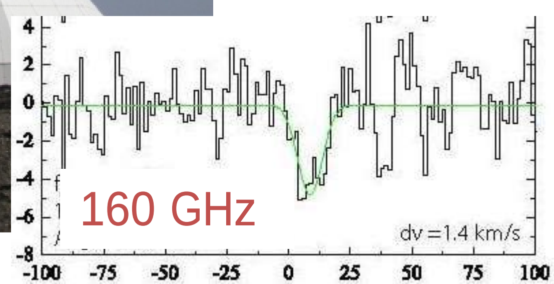
at z=0.88582
(7.5 Gyrs look-back)

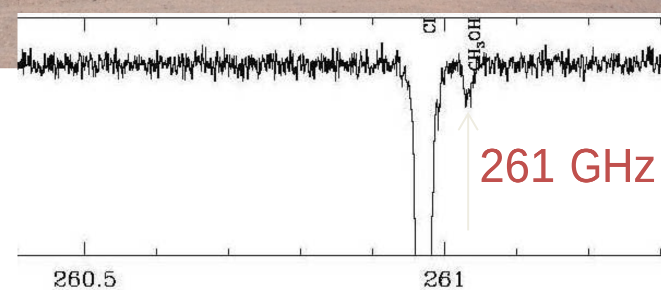


$$\left|\frac{\Delta\mu}{\mu}\right| < 10^{-7}$$

PRL 111, 231101 (2013) PHYSICAL REVIEW LETTERS week ending 6 DECEMBER 2013

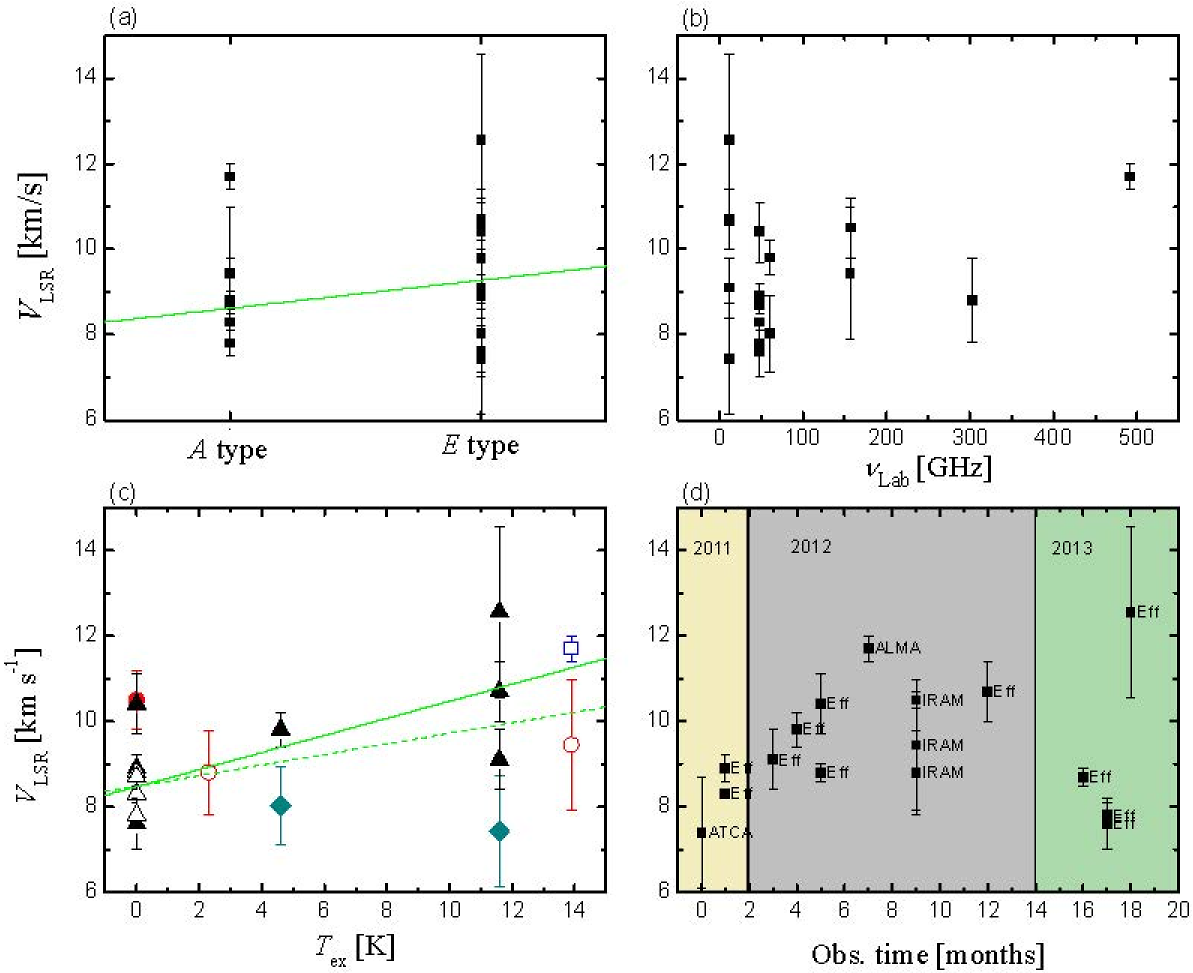
Robust Constraint on a Drifting Proton-to-Electron Mass Ratio at $z = 0.89$ from Methanol Observation at Three Radio Telescopes





PKS1830-211; systematic effects

Observations Effelsberg, IRAM30, ALMA

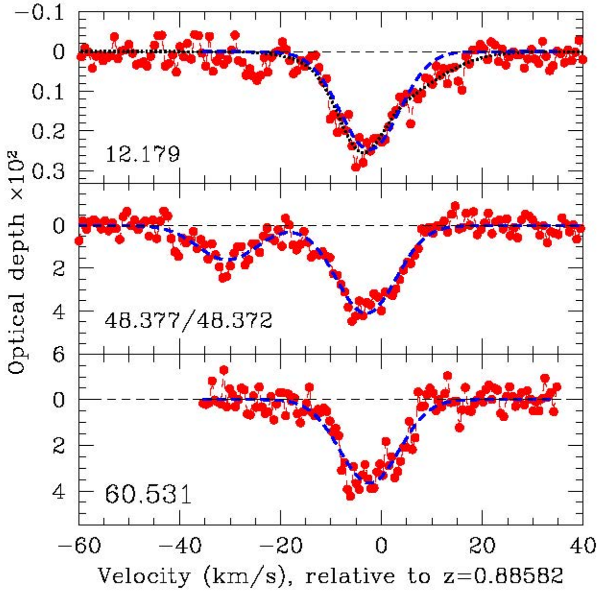


J. Bagdonaite, M. Dapra, P. Jansen, H.L. Bethlem, W. Ubachs, S. Muller, C. Henkel, K.M. Menten, Phys. Rev. Lett. 111, 231101 (2013)

Extended- Very Large Array New Mexico

- Statistical $\left|\frac{\Delta\mu}{\mu}\right| < 6\times10^{-8}$

- Systematic effect lineshape



N. Kanekar, W. Ubachs, K.M. Menten et al., MNRAS 448, L104, 2015

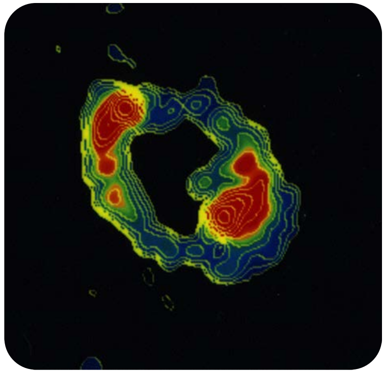
PKS1830-211;
special system (but the only one)

S. Muller et al. A&A 2008, A&A 2011

time varying intensity
frequency dependent spots

Radio-loud quasar
"Blazar"

lensing
methanol in SW



Intervening galaxy
with cold methanol

Work in progress:

- Simultaneous observations at 25/32 GHz at EVLA
- Spatially resolve SE spot
- Frequency close by
- $\Delta K \sim 6.4$

→ most constraining

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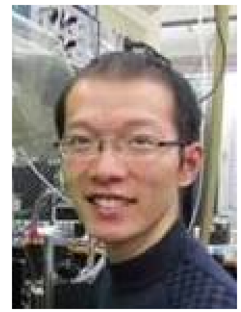

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