On the variation of the proton-electron mass ratio

Laser Centre
vrije Universiteit amsterdam

Wim Ubachs

JENAM
Workshop varying constants
Lisboa, 7 Sept. 2010

H_2 as an empirical probe for μ-variation

Lab

today

QSO

12 Gyr ago

90-112 nm

~275-350 nm

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

Cosmological redshift

Compare H_2 spectra in different epochs:

- high abundance H_2
- multi-line spectrum
- large cross sections

vs.

- transparancy for z>2
- low sensitivity coeffs.
- not that many sources

H_2 laboratory data; the ingredients

1. Determination of transition wavelengths
   a. VUV-laser excitation – 1+1 photoionization detection
   b. FT-VUV direct absorption
   c. Two-step scheme – Doppler free lasers + FT-spectra
2. Oscillator strengths / now from Meudon data (Roueff)
3. Γ damping factors / now from Meudon data (Roueff)
4. Sensitivity coefficients, reliable set for H_2 and HD

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

Lifetime measurements planned at Amsterdam

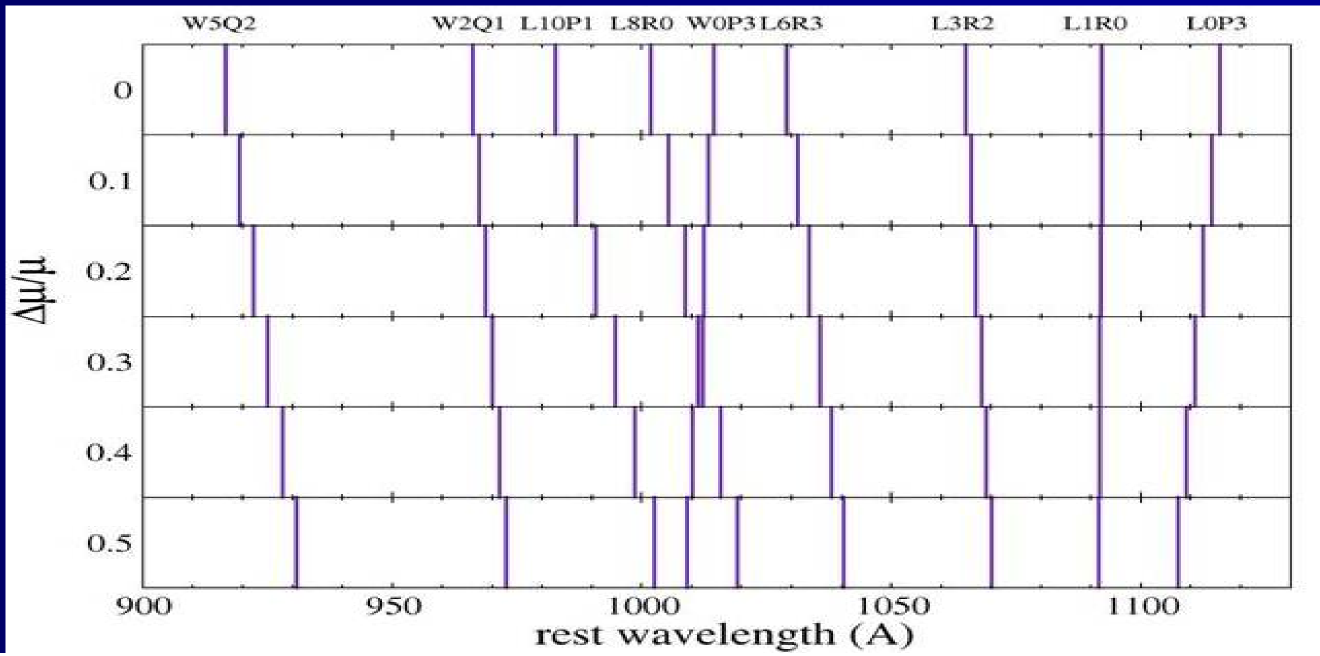
$\Delta\mu/\mu$ and spectrum H_2

QSO: (2-10) x 10^{-7}

Accurately calculated

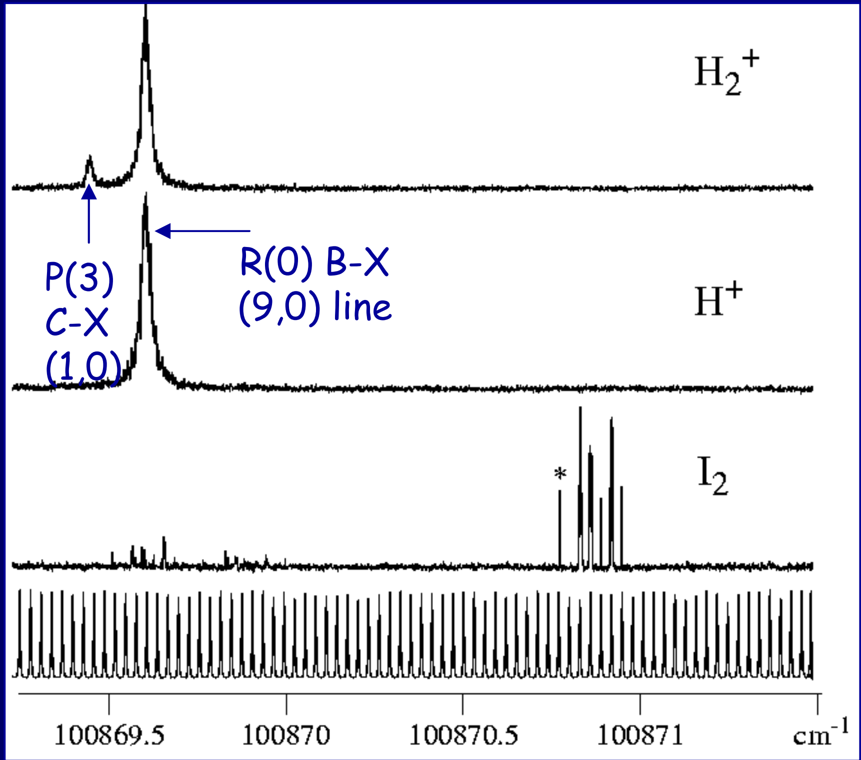
$$\frac{\lambda_i}{\lambda_i^0} \equiv 1 + z_i = (1 + z_{abs})\left(1 + \frac{\Delta\mu}{\mu} K_i\right)$$

From accurate laboratory measurements



H_2 laboratory wavelengths

1. VUV-laser excitation



$\Delta\lambda/\lambda = 5 \times 10^{-8}$

Philip et al. Can. J. Chem 82 (2004) 713
Ubachs et al., J. Mol. Spectr. 241 (2007) 155

For HD

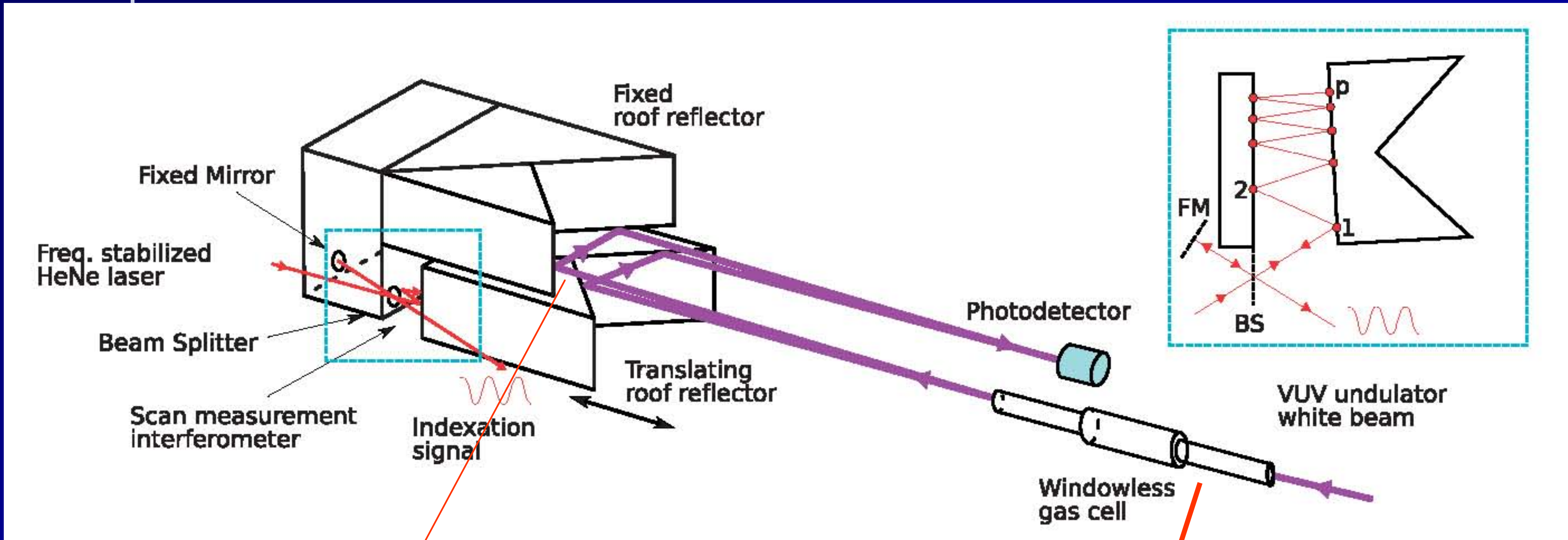
Ivanov et al., Phys. Rev. Lett.

Novel spectroscopic tools for studying H_2/HD spectrum

The DESIRS beam line XUV-FT-spectrometer at the SOLEIL synchrotron
a versatile novel tool for precision spectroscopy

FT-interference in the windowless regime

With SOLEIL team :
Laurent Nahon, Nelson d'Oliveira,
Denis Joyeux, Mourad Roudjane, Michel Vervloet



Wave-front division interferometry

Static gas (Doppler)
Jet in preparation !

FT-interference in the windowless regime

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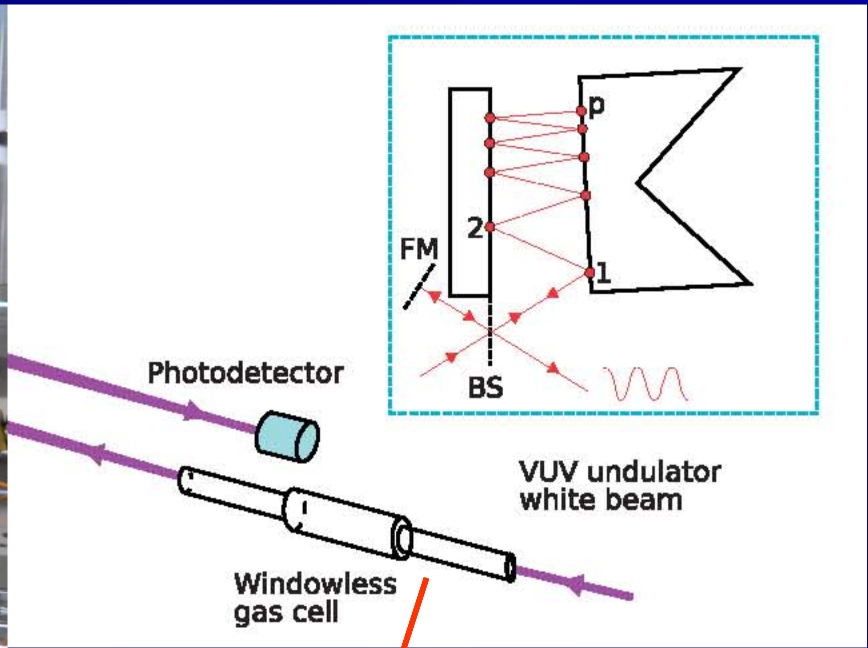


Wave-front division interferometry

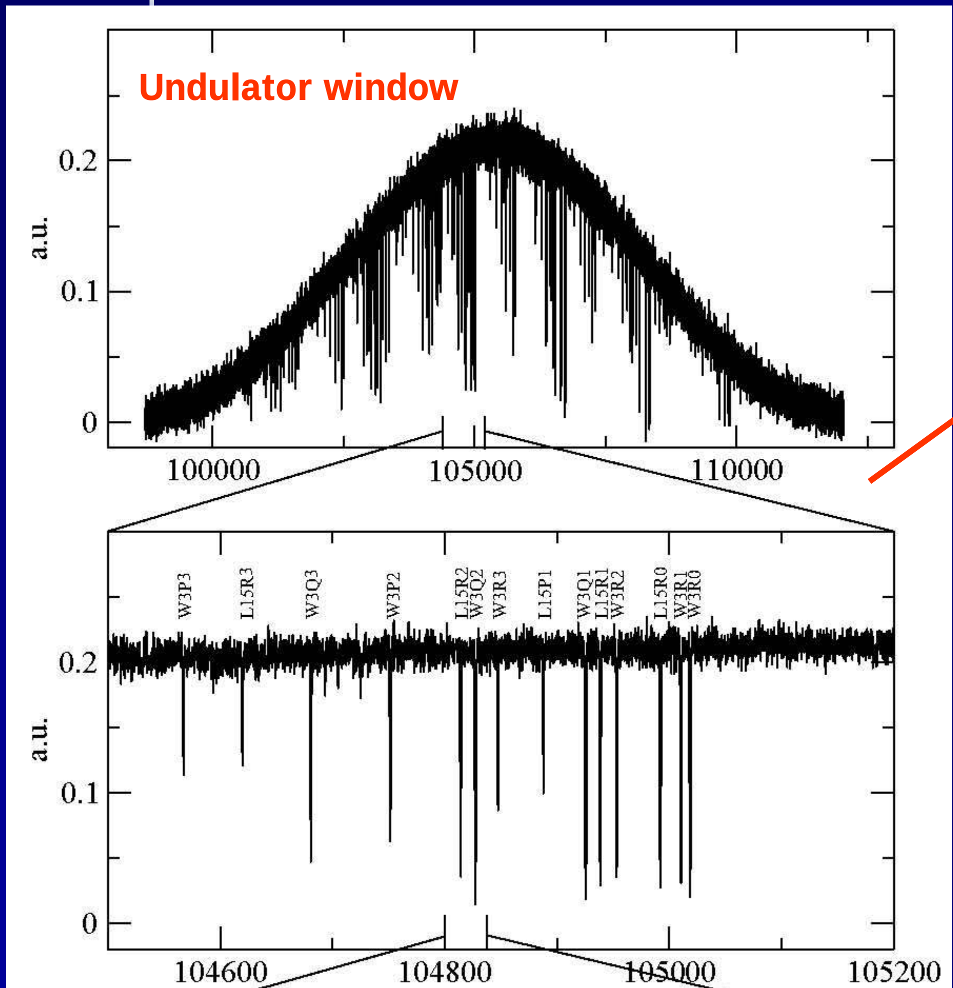
Static gas (Doppler)
Jet in preparation !

RESEARCH ARTICLE

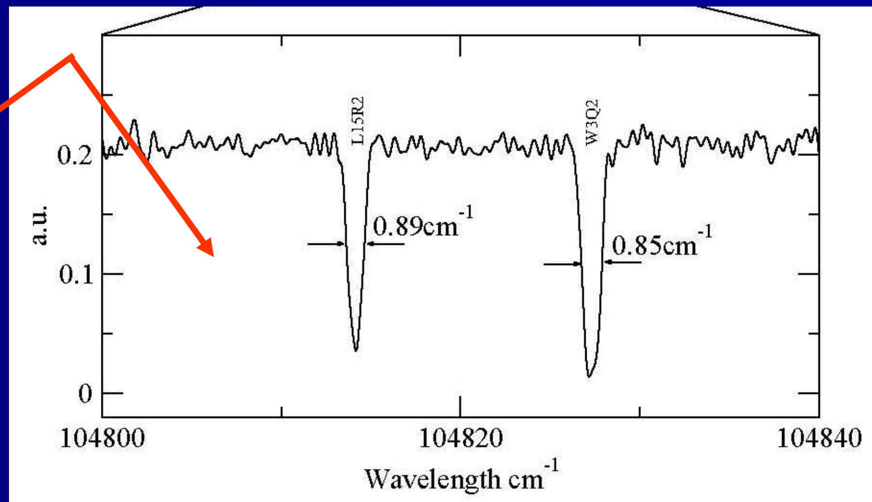
Fourier-transform spectroscopy of HD in the vacuum ultraviolet at λ = 87–112 nm

T.I. Ivanov[a], G.D. Dickenson[a], M. Roudjane[b]†, N. de Oliveira[b], D. Joyeux[bc], L. Nahon[b], W.-Ü.L. Tchang-Brillet[de] and W. Ubachs[a*]

Ivanov et al.
Mol. Phys. 108 (2010) 771



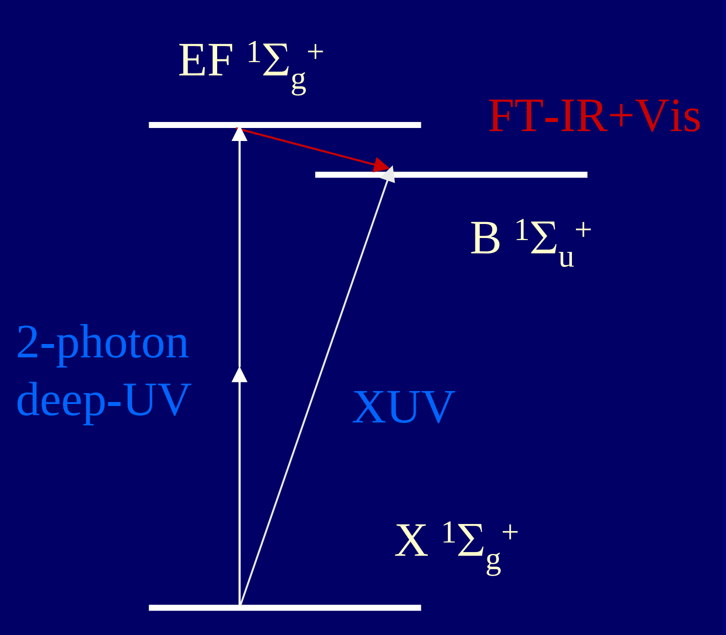
Spectroscopy
Uncertainty ~ 0.04 cm^{-1}



Sept. 2010: **jet absorption**

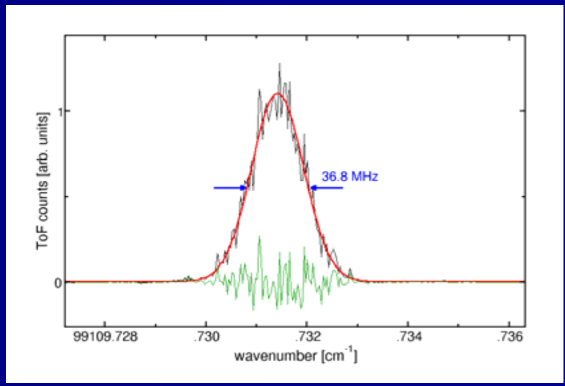
H_2 laboratory wavelengths

Two-step excitation

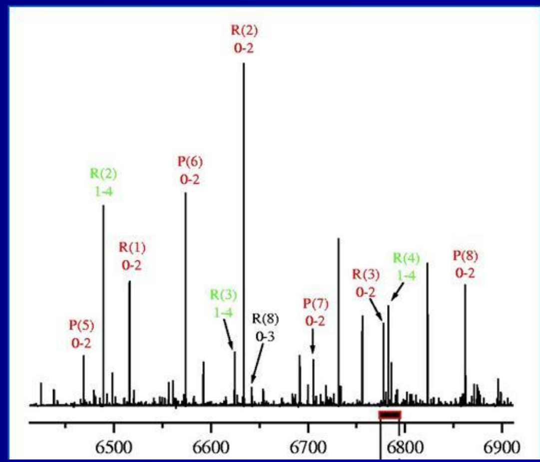


$\rightarrow \Delta\lambda/\lambda \sim (5 - 50) \times 10^{-9}$

Two-photon laser Doppler-free

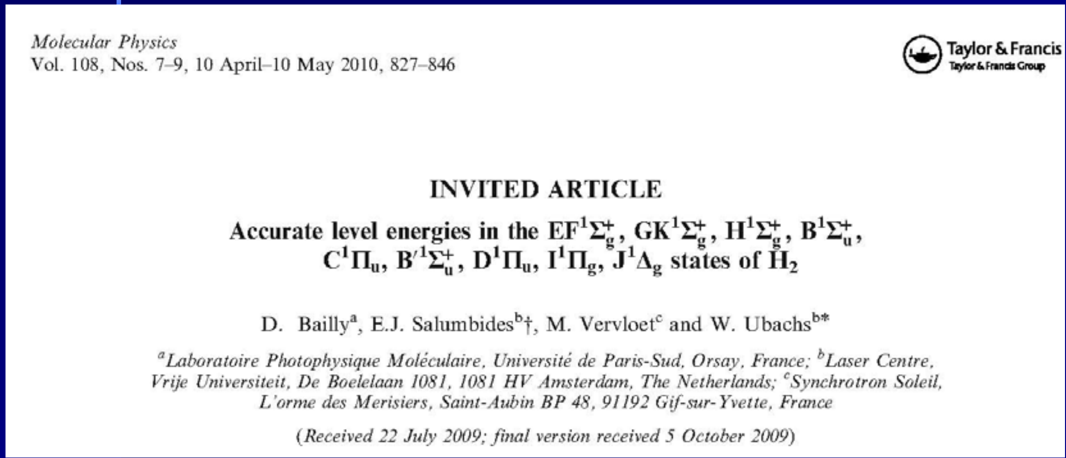


FTIR and FT-VIS



Salumbides et al. Phys. Rev. Lett. 101 (2008) 223001
Bailly et al., Mol. Phys. 108 (2010) 827

The best data set



Molecular Physics
Vol. 108, Nos. 7–9, 10 April–10 May 2010, 827–846

Taylor & Francis
Taylor & Francis Group

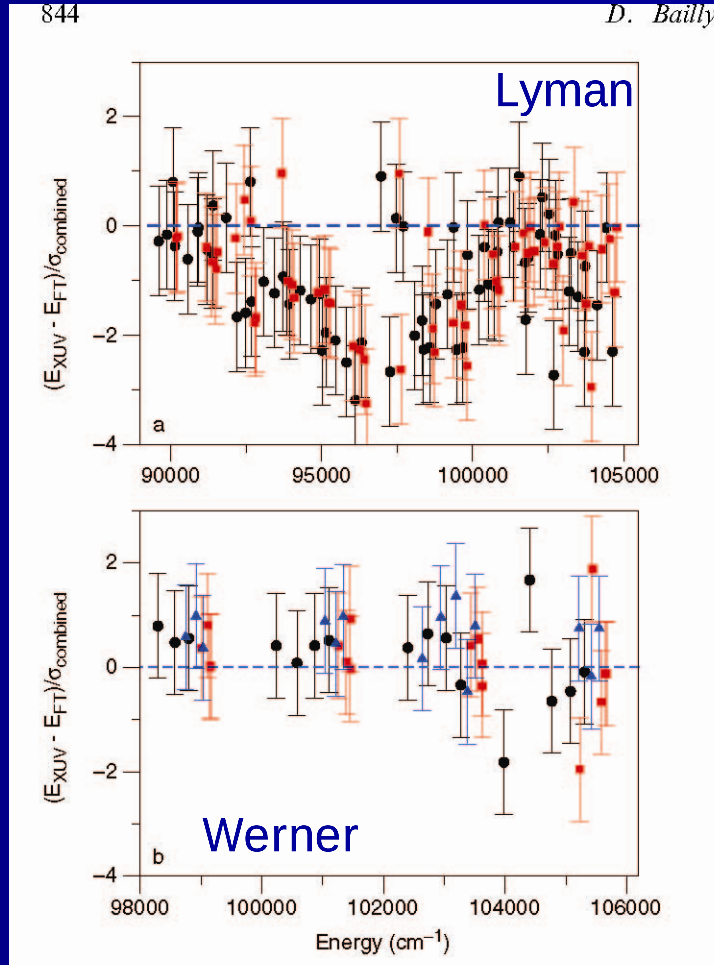
INVITED ARTICLE

Accurate level energies in the $EF^1\Sigma_g^+$, $GK^1\Sigma_g^+$, $H^1\Sigma_g^+$, $B^1\Sigma_u^+$, $C^1\Pi_u$, $B'^1\Sigma_u^+$, $D^1\Pi_u$, $I^1\Pi_g$, $J^1\Delta_g$ states of H_2

D. Bailly[a], E.J. Salumbides[b]†, M. Vervloet[c] and W. Ubachs[b]*

[a]*Laboratoire Photophysique Moléculaire, Université de Paris-Sud, Orsay, France;* [b]*Laser Centre, Vrije Universiteit, De Boelelaan 1081, 1081 HV Amsterdam, The Netherlands;* [c]*Synchrotron Soleil, L'orme des Merisiers, Saint-Aubin BP 48, 91192 Gif-sur-Yvette, France*

(*Received 22 July 2009; final version received 5 October 2009*)



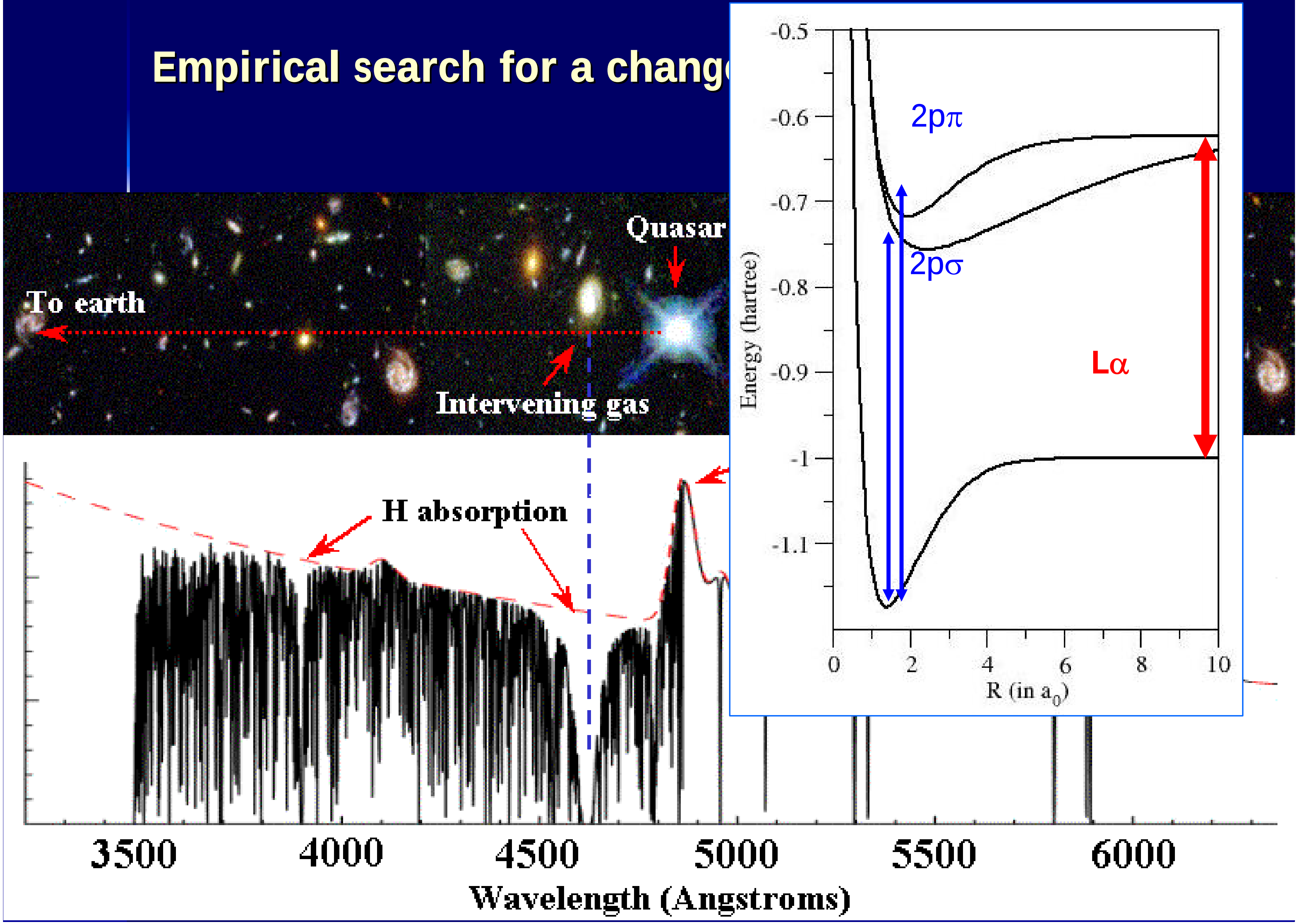
Accuracy better than 1 x 10^{-8}

Comparison between
XUV and new analysis

HD possibly in future


Progress on the astrophysical side

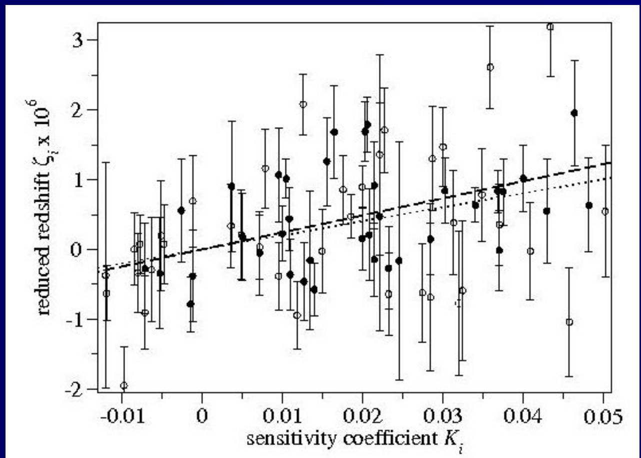
Empirical search for a chang



Δμ/μ determination

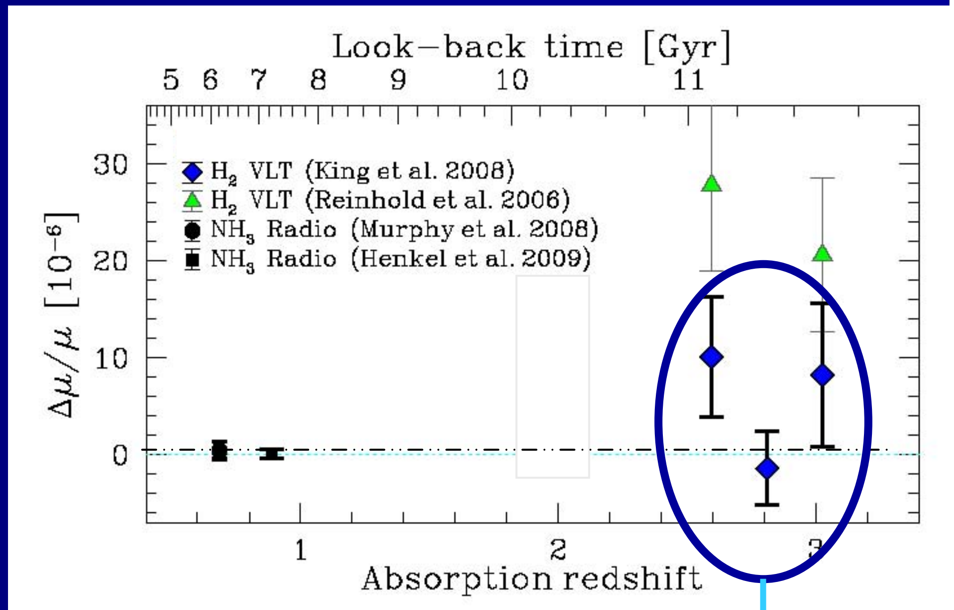
1. Line-by-line fitting

Data on Q0347 and Q0405



Indication: μ has decreased by 0.002% in past 12 billion years (Reinhold et al. PRL 2006)

1. Comprehensive fitting (& recalibration)



King, Webb, Murphy: “Stringent Null Result”

Methods of analyzing the spectra

Line-by-line fitting method

Problems of:

Fitting a proper profile
Overlapping L-α lines
Hidden velocity structure
Saturation of lines
Selection of lines

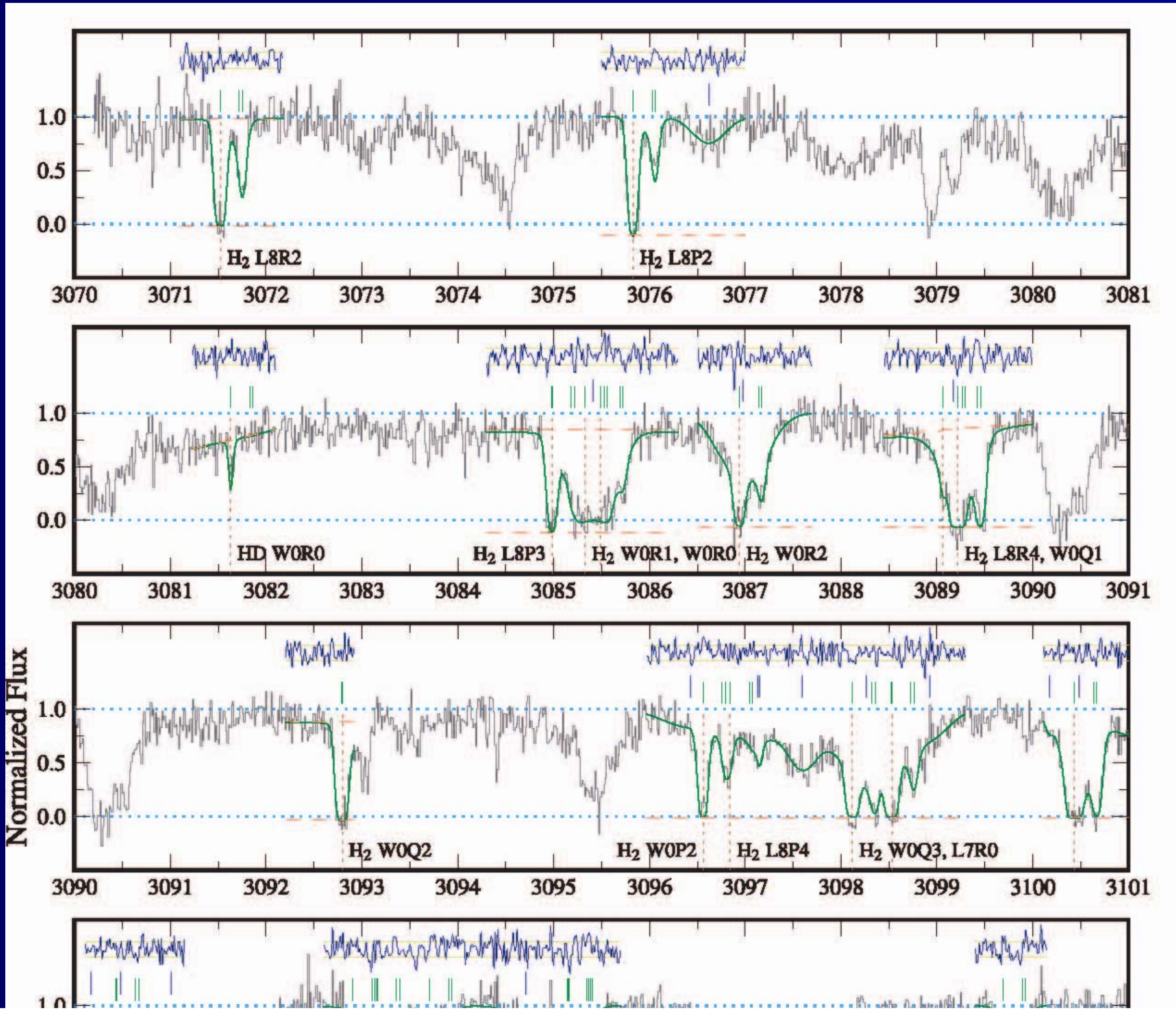
Comprehensive fitting method

Produce a spectrum:

Include a fingerprint of the molecular spectrum
Convolve properly with Γ, b, F_{instr};
Assign all Lyman-α lines and metral lines
Test various velocity component structures
Impose a single $\Delta\mu/\mu$ value for the entire fit

J2123 from HIRES-Keck at Hawaii (Ackn: Jason Prochaska)

Unique spectrum, first from Keck, Resolution 110000 ; z_{abs}=2.0593



37 panels

3071 – 3421 Å

86 Hydrogen lines

7 HD lines

J2123 from HIRES-Keck at Hawaii (Ackn: Jason Prochaska)

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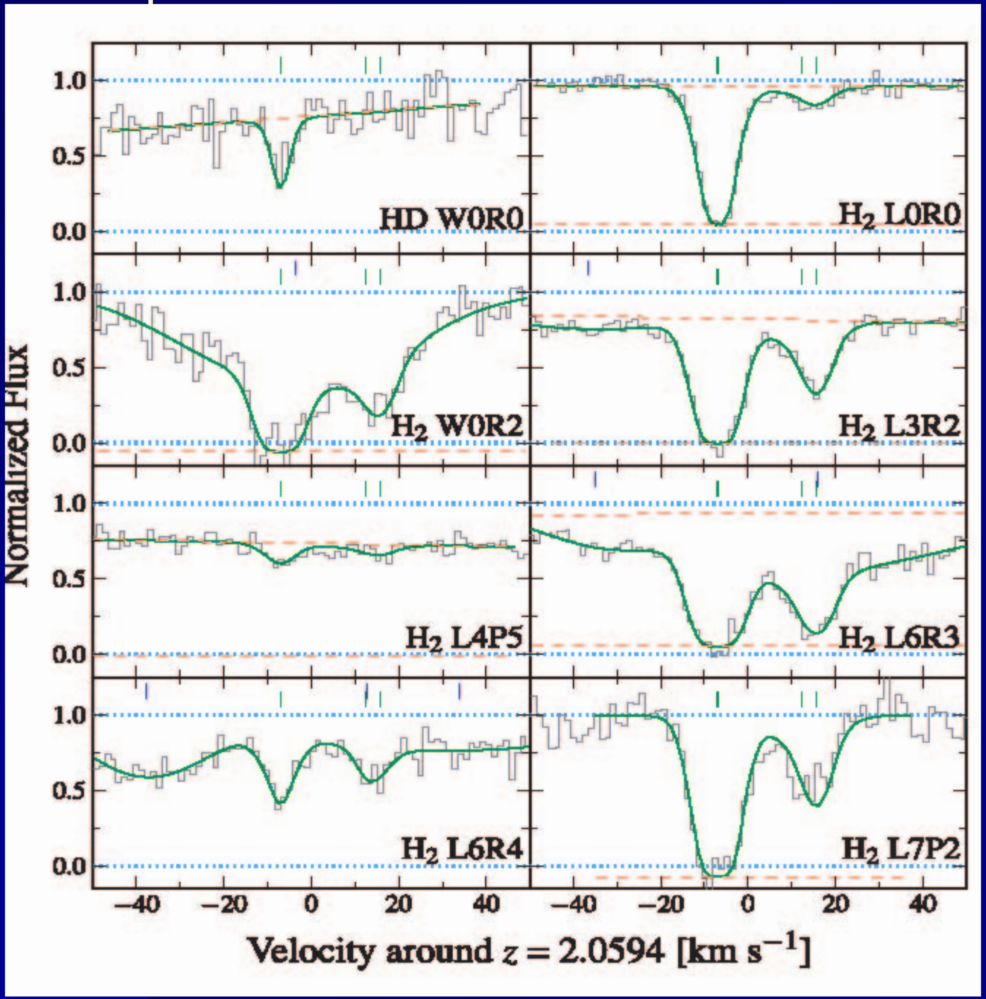


Typical
2-velocity feature
structure of J2123

HD in only one feature

HD colder

HD in J2123 discussed in:
(deuterium at high z)

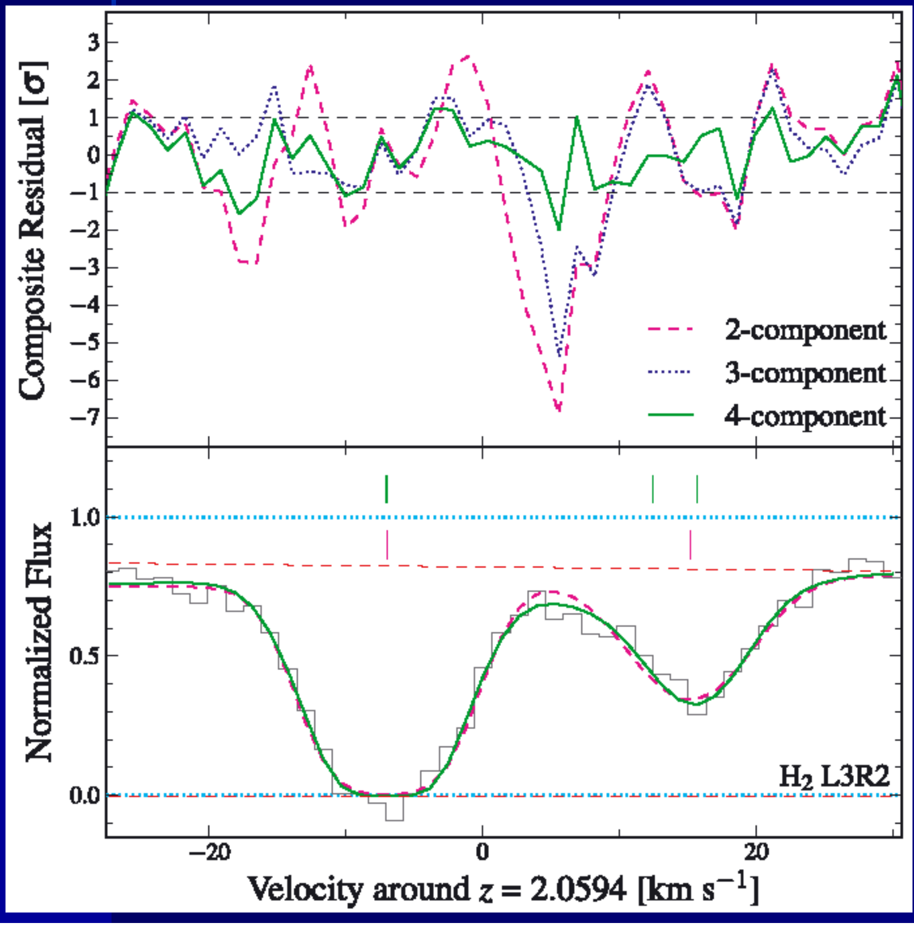
Tumlinson, Murphy, Ubachs et al.
Astroph. J. Lett. 718 (2010) L156

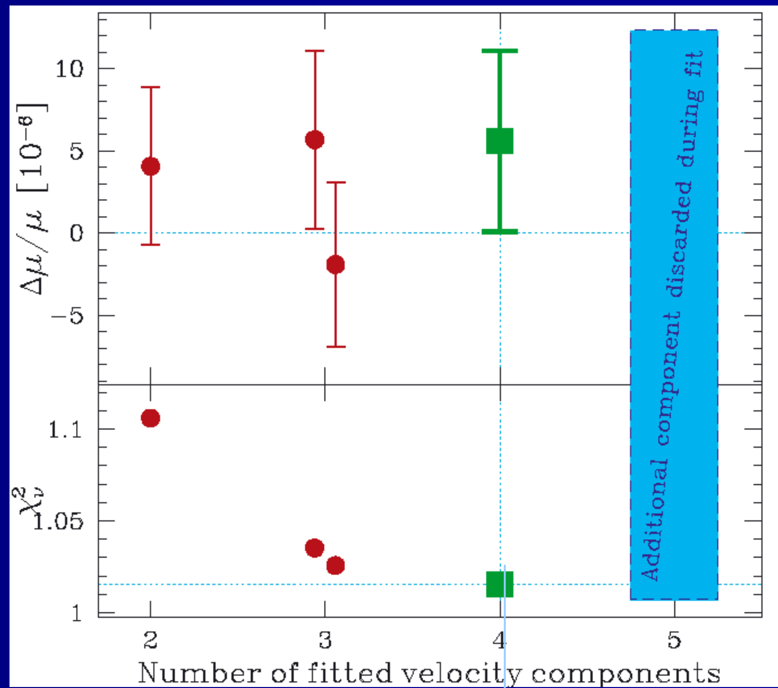
Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
Mon. Not. R. Astron. Soc. 403, 1541–1555 (2010) doi:10.1111/j.1365-2966.2009.16227.x

Keck telescope constraint on cosmological variation of the proton-to-electron mass ratio

A. L. Malec,[1★] R. Buning,[2] M. T. Murphy,[1] N. Milutinovic,[3] S. L. Ellison,[3] J. X. Prochaska,[4] L. Kaper,[2,5] J. Tumlinson,[6] R. F. Carswell[7] and W. Ubachs[2]

Velocity components in comprehensive fitting





Fiducial fit result

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

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Fiducial fit result

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

Systematics investigated

Leave out weak J=4 and J=5 $\Delta\mu/\mu = (4.8 \pm 5.6) \times 10^{-6}$

Without Werner lines / without HD lines $\Delta\mu/\mu = (5.2 \pm 5.6) \times 10^{-6}$ $\Delta\mu/\mu = (4.1 \pm 5.8) \times 10^{-6}$

Problem with intensities L0, L1 lines (overlap with L-β/O IV emission $\Delta\mu/\mu = (7.0 \pm 6.7) \times 10^{-6}$

All intensities fitted $\Delta\mu/\mu = (5.4 \pm 5.5) \times 10^{-6}$

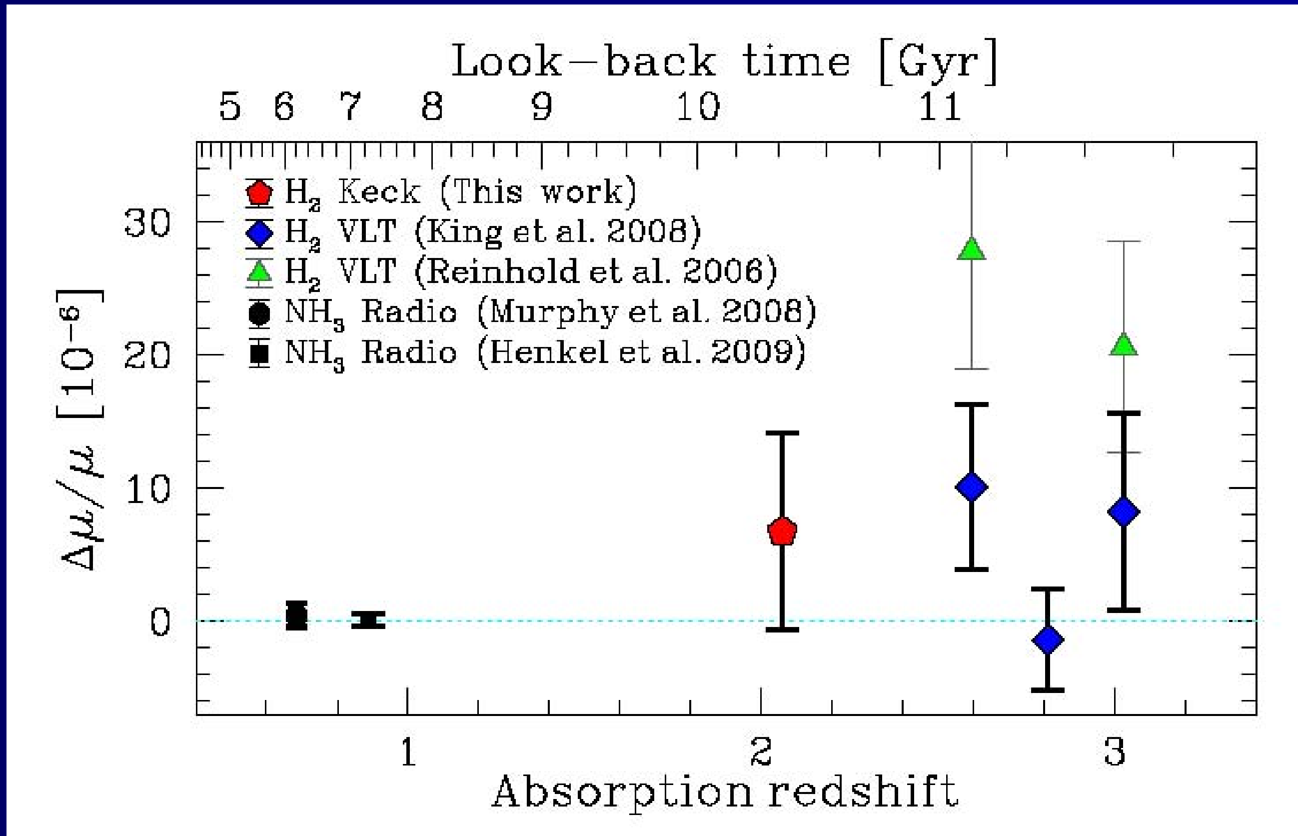
Fitting b(J) Doppler parameters $\Delta\mu/\mu = (7.9 \pm 5.6) \times 10^{-6}$

“Intra-echelle order distortions” (Greist-2010) investigated (Murphy)

estimated < 1.9×10^{-6}

Systematics of Th-Ar calibration and various wavelength checks

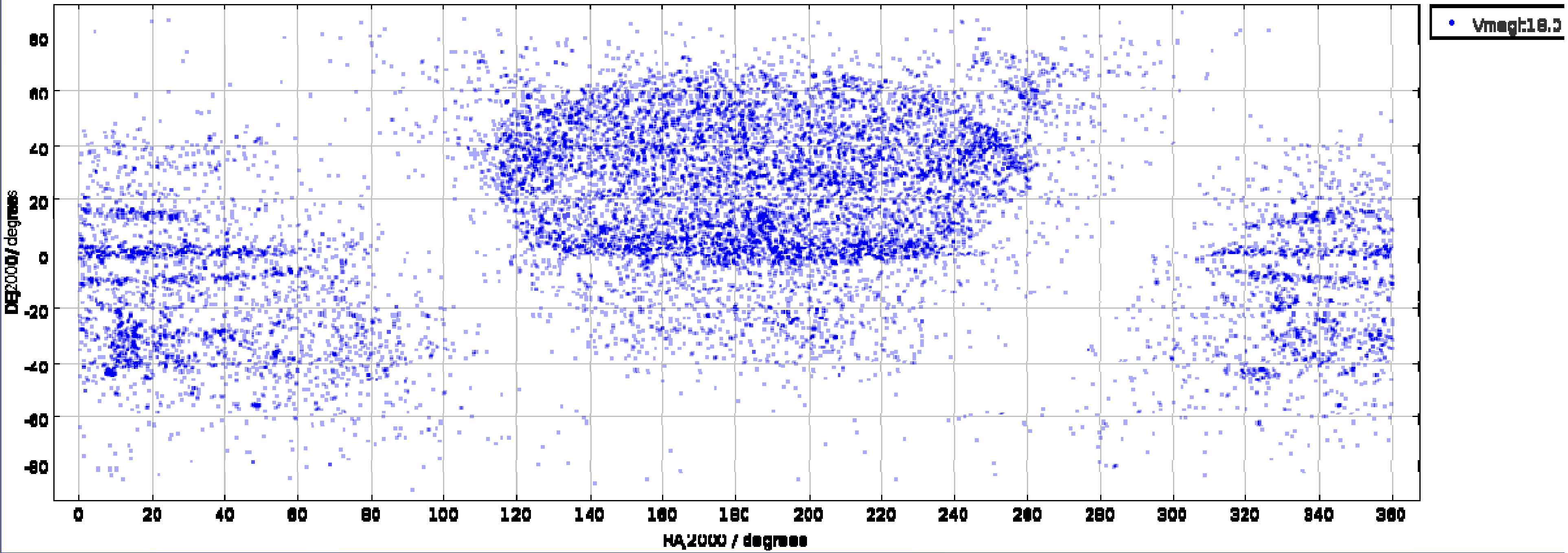
Status of cosmological μ-variation



What do we need ?

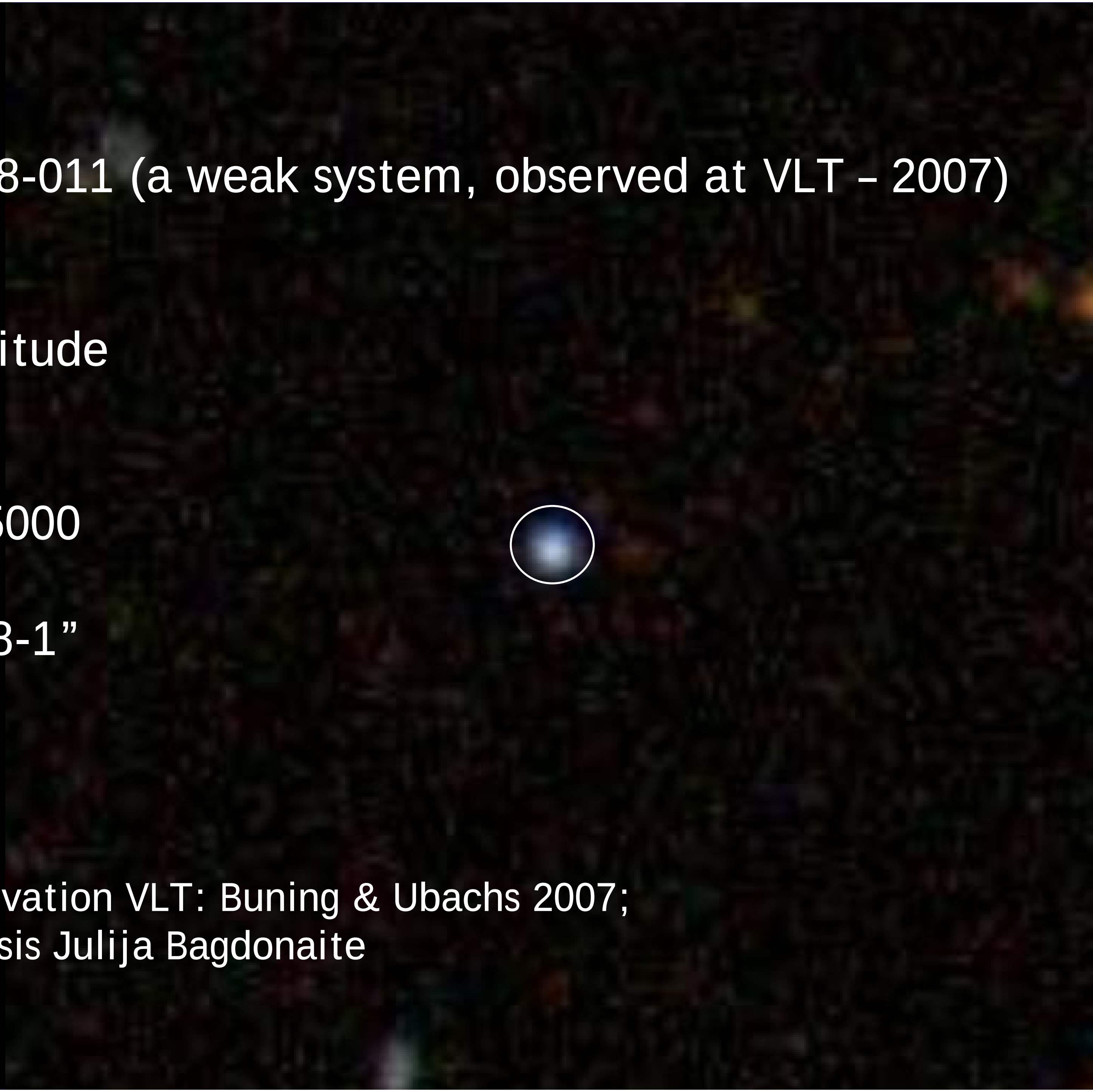
High-quality quasar spectra with> 80 H_2 lines, SNR >50

Known DLA’s (V_{mag} < 18)



Declination

Right Ascension



Q2348-011 (a weak system, observed at VLT – 2007)

Magnitude
18.4

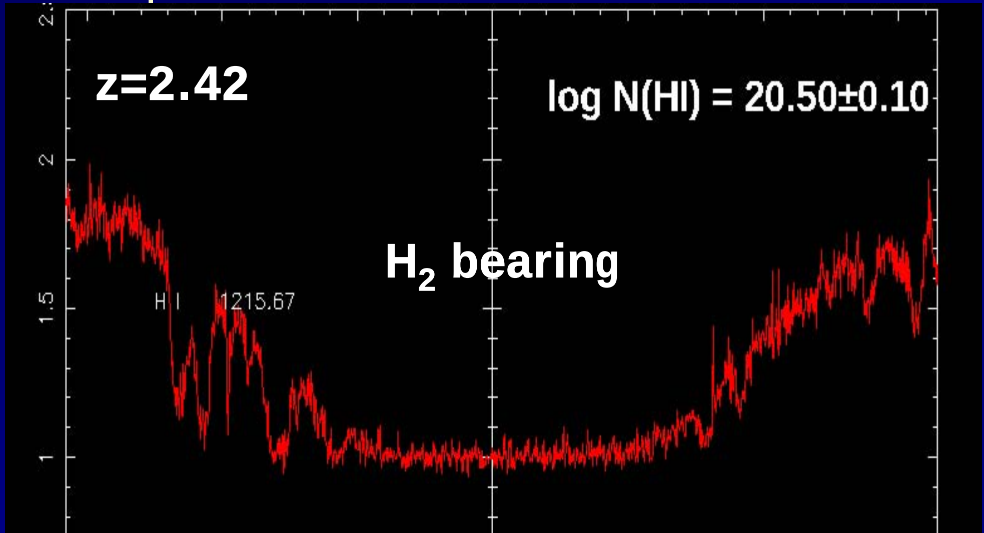
R= 55000

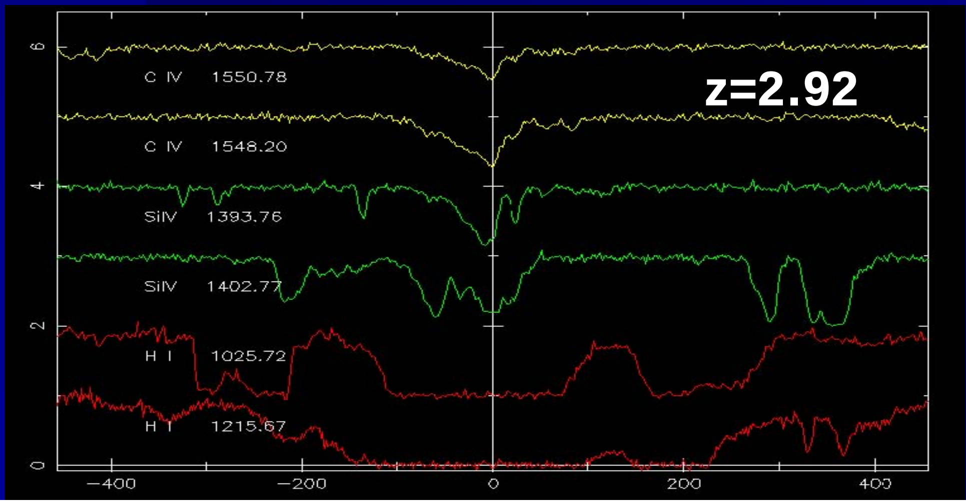
at 0.8-1”

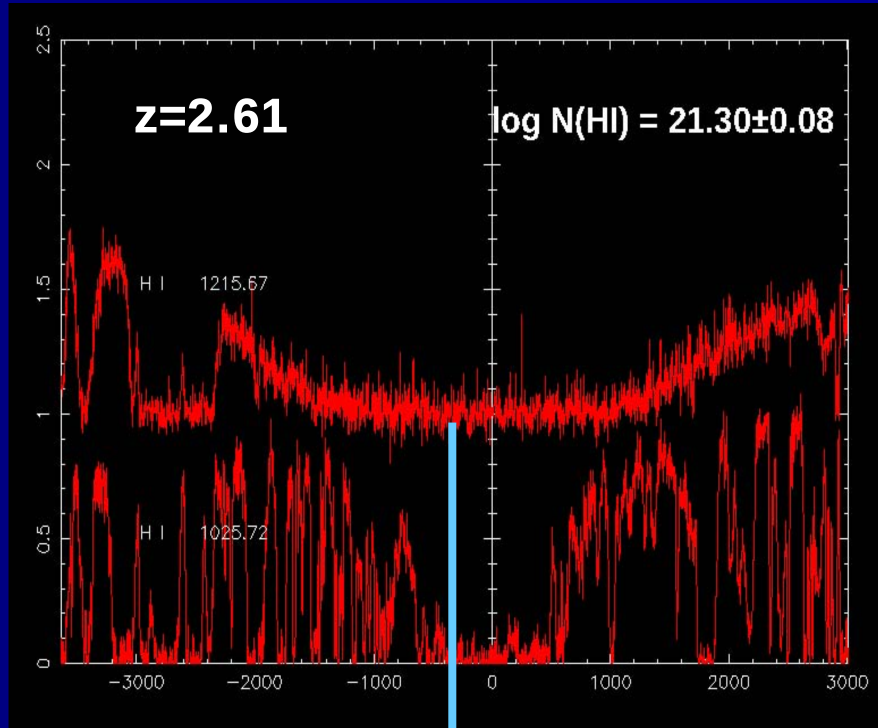
Observation VLT: Buning & Ubachs 2007;
Analysis Julija Bagdonaite

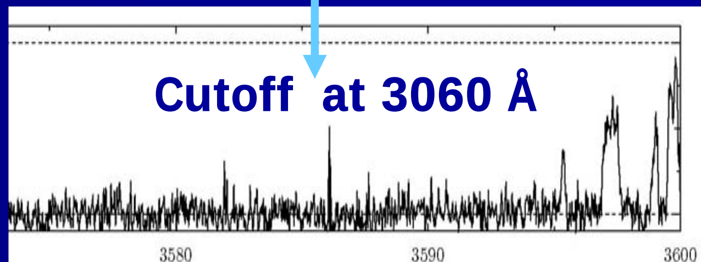
Complex but weak Q2348-011 system many absorbers along line-of-sight

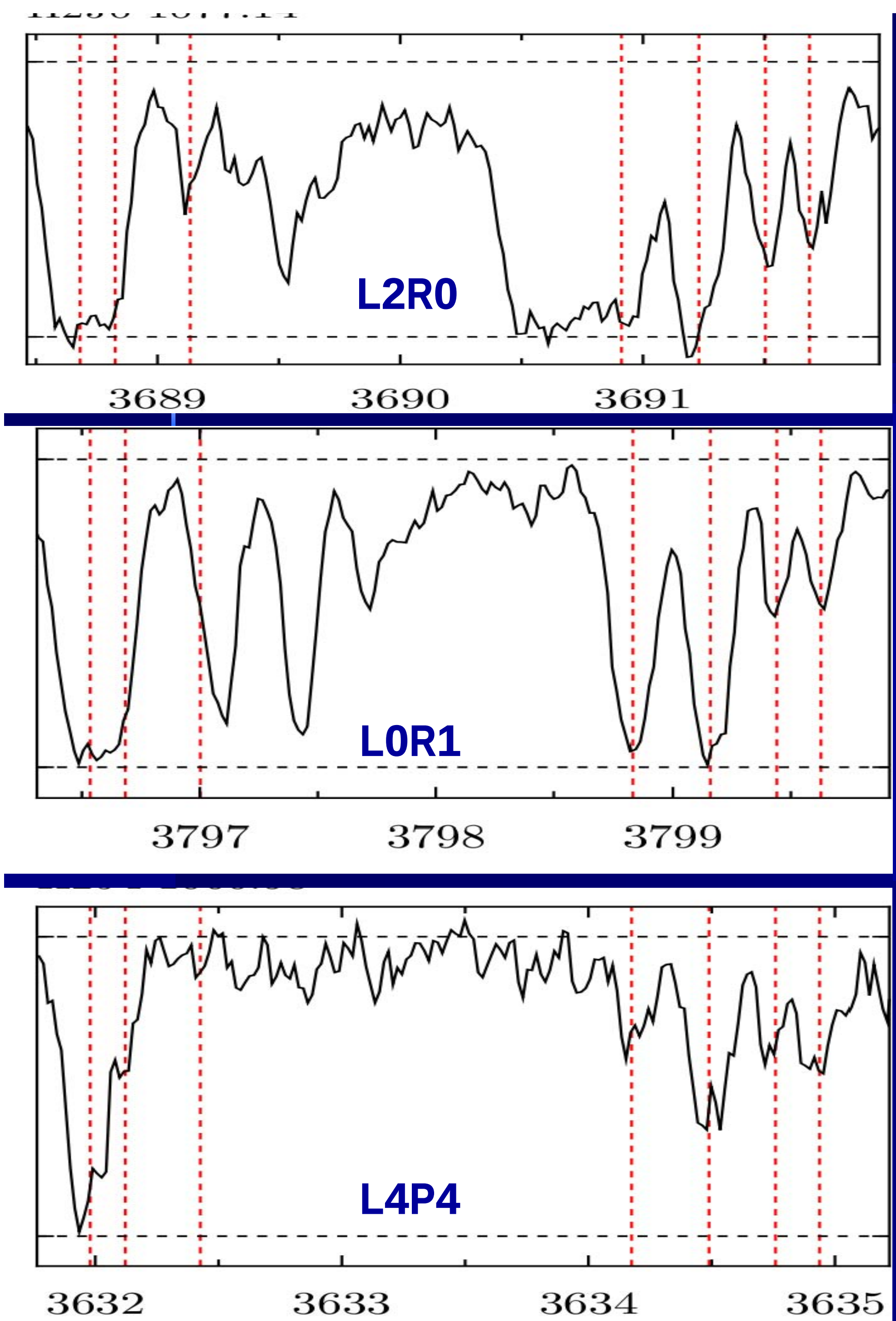
Damped Lα at z=2.42 and z=2.61; further z=2.92, z=2.82, z=2.97
MgII systems at z=0.773 and z=0.863; strong C IV at z=1.444











Q2348-011 -

7 velocity component structure

17 useful lines used due to unfortunate structure absorber(s)

Result:

$\Delta\mu/\mu = (160 \pm 195) \times 10^{-6}$
(preliminary)

Is that all there is ?

Q0347-383
Q0405-443
Q0528-250

analyzed
of Q0528 new VLT campaign (2009),
analysis being done by Julian King

J2123-050

Keck analysis : MNRAS 2010
VLT-analysis : Freek van Weerdenburg

Q2348-011

Analysis done; not a competitive result

Analysis of prospective systems

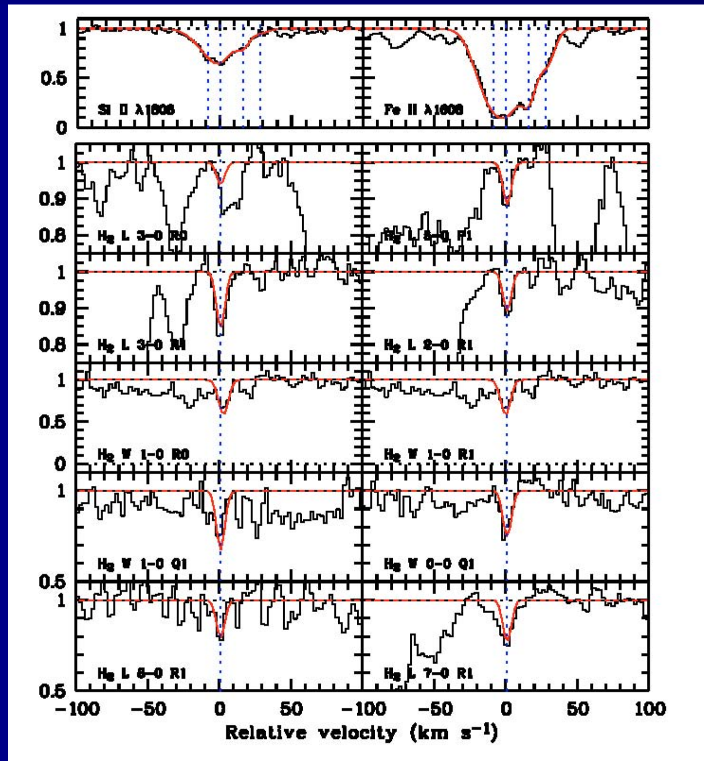
Ubachs and Murphy, Sydney 2010

(Too) weak H_2 absorbers

Q2343+125 z_{abs}=2.431

- M. Dessauges, A & A., 416, (2004) 79.
- P. Petitjean, A & A. 456 (2006) L9.

Column density $N(H_2)$=13.7



Q1337+315 at z_{abs}=3.174

R. Srianand, N. Gupta, P. Petitjean, et al., MNRAS 405 (2010) 1888.

Q0841+129 at z_{abs}=2.37

- C. Ledoux, P. Petitjean, MNRAS 346 (2003) 209.

H_2 only tentative

(Too) strong H_2 absorbers

with HD, even CO

Q1232+082 z_{abs}=2.338

-D.A. Varshalovich, A.V. Ivanchik, P. Petitjean, et al., Astron. Lett. 27 (2001) 683.
-A.V. Ivanchik, P. Petitjean, et al., MNRAS 404 (2010) 1583.

Column density $N(H_2)$=19.3

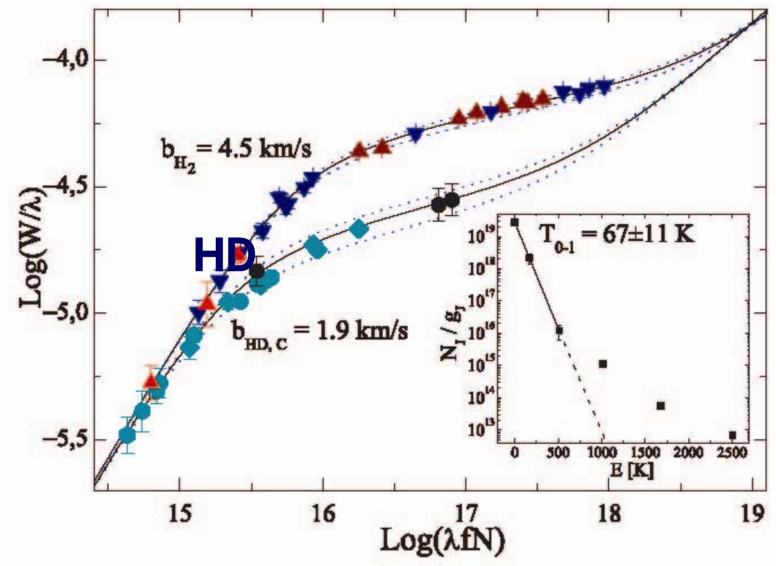


Figure 4. Curves of growth for H_2 (indicated in red, dark blue, brown and blue triangles, respectively, for $J = 5, 4, 3$ and 2 levels), HD (black circles) and C I (cyan circles) absorption lines at $z_{abs} = 2.337\,71$ towards QSO 1232 + 082. Inset: H_2 excitation diagram from which we measure $T_{0-1} = T_{kin} = 67 \pm 11$ K.

Q1439+113 z_{abs}=2.42

P. Noterdaeme, P. Petitjean, et al., Astron. & Astroph. 491 (2008) 397.

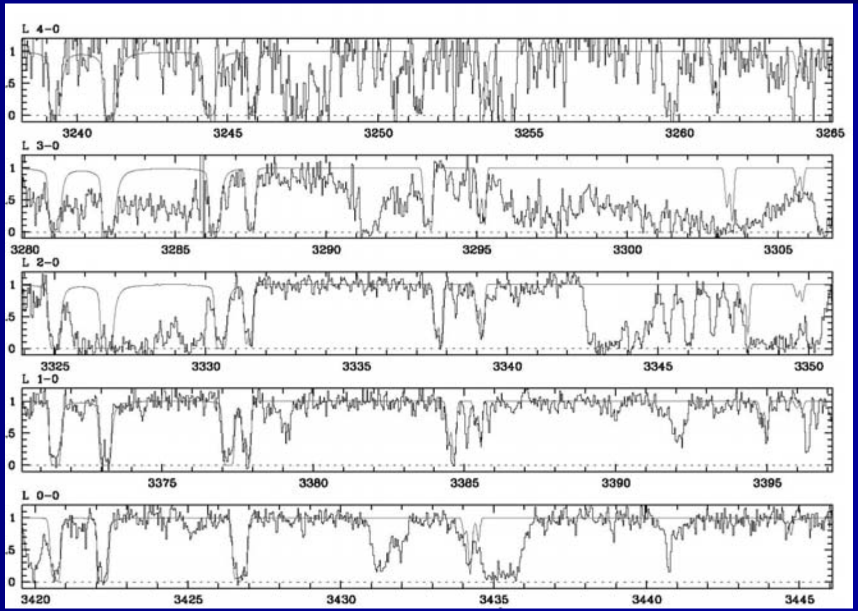
Column density $N(H_2)$=19.4

(Too) faint H_2 absorbers

Q1444+014 z_{abs}=2.08

- C. Ledoux, P. Petitjean, MNRAS 346 (2003) 209.

V=18.48
N(H_2)=18.3



Q1441+272 z_{abs}=4.224

Highest z system with H_2; object is faint (V=19.3) but lines are redshifted to the 4800-5800 A region

- 60 lines
- Strong L-α forest

(Too) low redshift H_2 absorbers

Q0551-366 at z_{abs}=1.96

- C. Ledoux, R. Srianand, P. Petitjean, Astron. Astroph. 392 (2002) 781.

Q2318-111 at z_{abs}=1.99

- P. Noterdaeme, Astron. Astroph. 474 (2007) 393.

Q0013-004 at z_{abs}=1.97

- P. Petitjean, R. Srianand, C. Ledoux, MNRAS 332 (2002) 383.

Q1331+171 at z_{abs}=1.77

Acknowledgement

Freek
Van
Weerdenburg

J2123-VLT

Julija
Bagdonaite

Q2348-VLT
FJ0812 Keck

Ruth
Buning

Q2348/J2123

Adrian Malec

J2123-Keck

Julian King

Q0528-VLT

Michael
Murphy

Lex
Kaper

+ LaserLaB group

Laser Centre
vrije Universiteit amsterdam

FOM

Laserlab
Europe

ESO