Title: In search for mu-variation: laboratory spectroscopy and astronomical observations of molecular hydrogen

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Abstract:

Thanks

The
“lab spectroscopy team”

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The “quasar team”

Ruth Buning
(VU)

Lex Kaper
(UvA Anton Pannekoek)

Michael Murphy
(Cambridge University/
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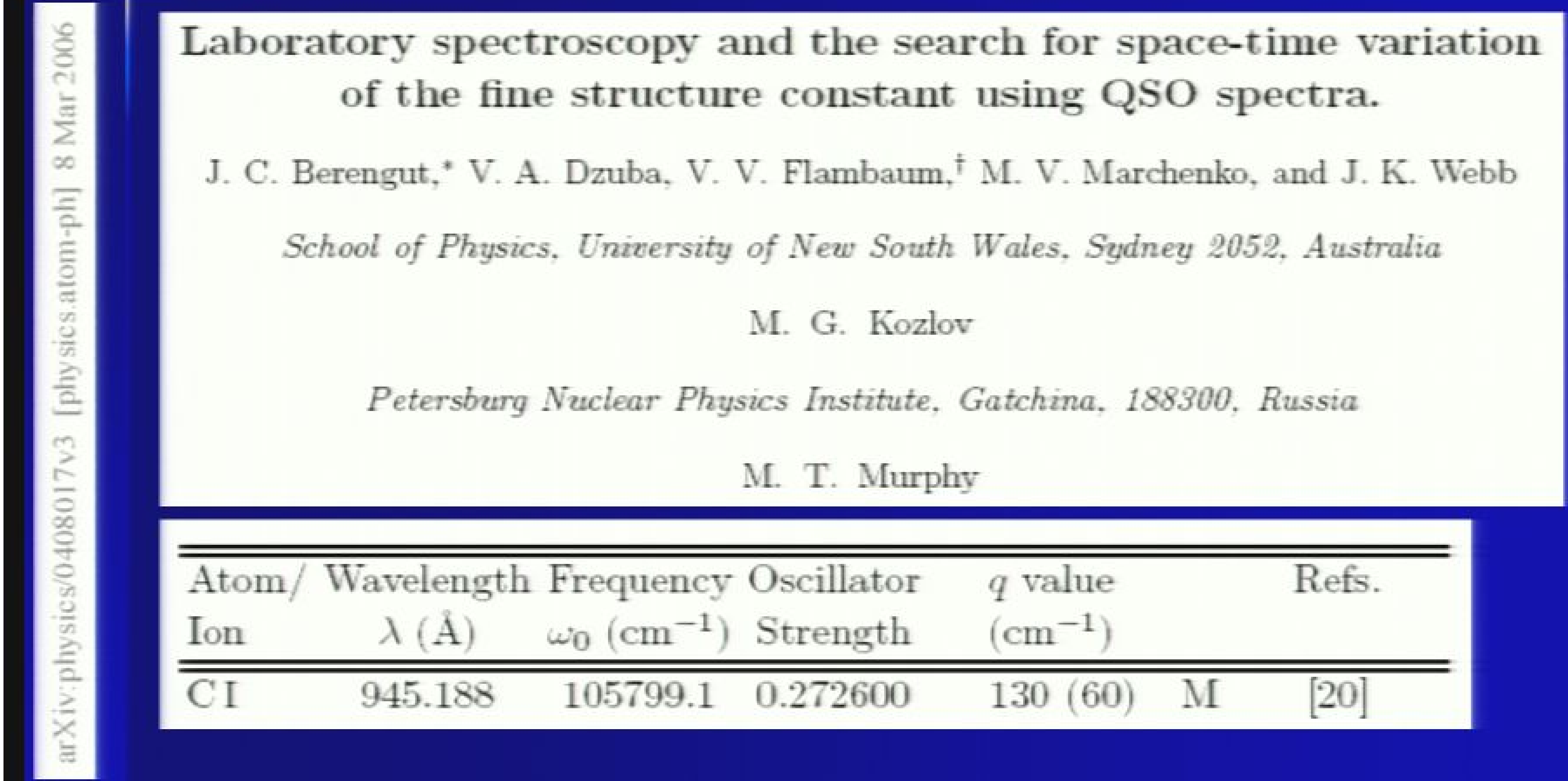
Melbourne)

The importance of spectroscopy



Laboratory spectroscopy and the search for space-time variation of the fine structure constant using QSO spectra.

J. C. Berengut,* V. A. Dzuba, V. V. Flambaum,† M. V. Marchenko, and J. K. Webb

School of Physics, University of New South Wales, Sydney 2052, Australia

M. G. Kozlov

Petersburg Nuclear Physics Institute, Gatchina, 188300, Russia

M. T. Murphy

Atom/ Ion	Wavelength λ (Å)	Frequency ω_0 (cm^{-1})	Oscillator Strength	q value (cm^{-1})		Refs.
C I	945.188	105799.1	0.272600	130 (60)	M	[20]

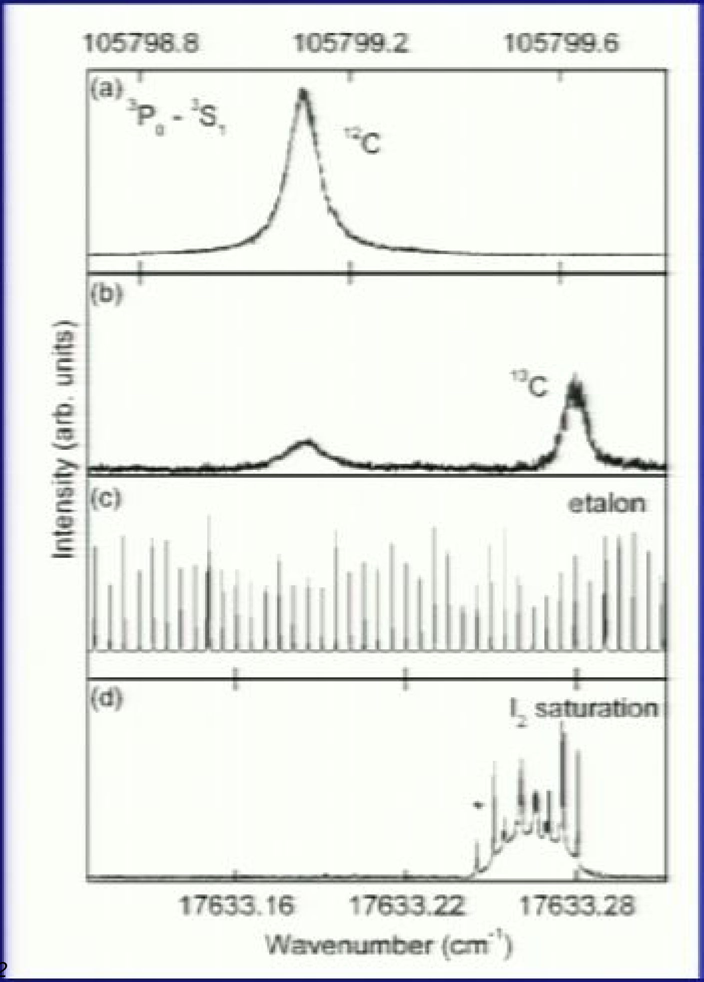
suggestion: an updated list

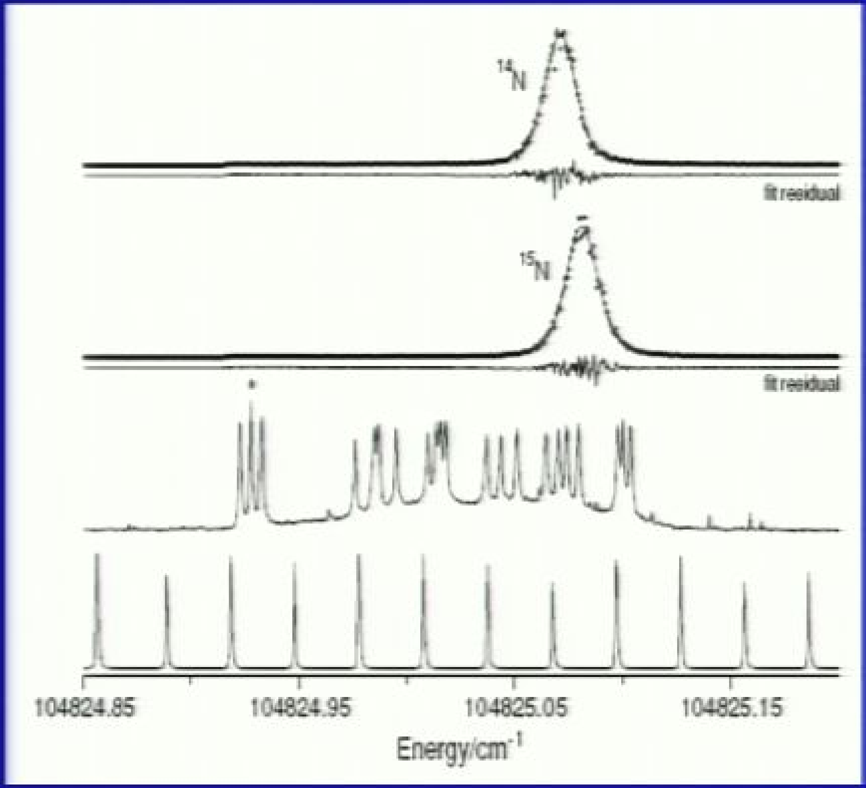
Laboratory studies

on atom/ionic resonance lines for α-variation detection

XUV-laser

$$\frac{\Delta\lambda}{\lambda} = 5\times10^{-8}$$





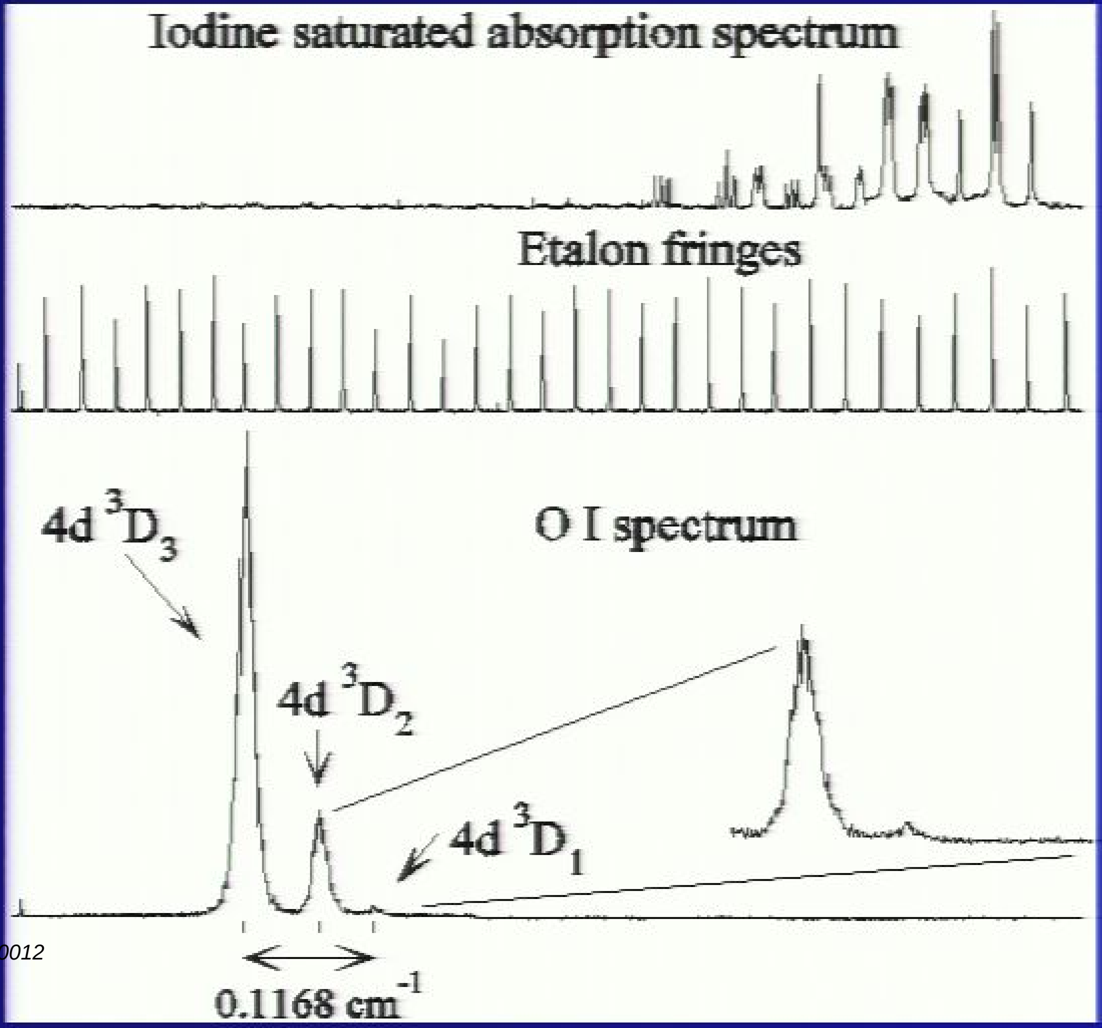
Resonance lines of N I
In range 95.1 - 96.5 nm

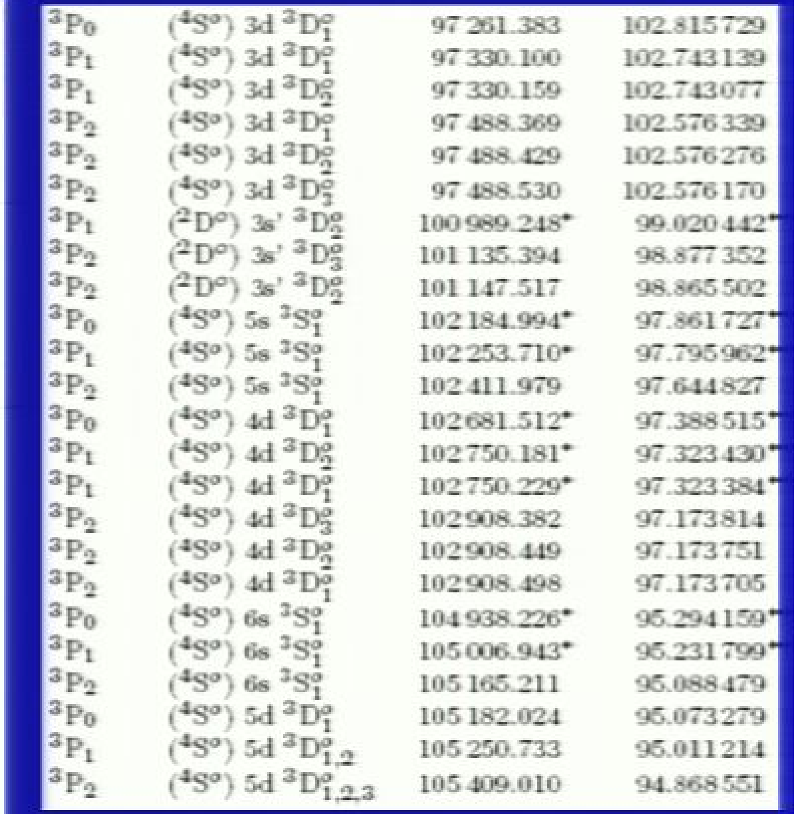
Resonance line of C I at 94.5 nm

Oxygen I

XUV-laser

$$\frac{\Delta\lambda}{\lambda} = 5\times10^{-8}$$





$^3P_0$	$(^4S^o)$ 3d $^3D^o_1$	97 261.383	102.815 729
$^3P_1$	$(^4S^o)$ 3d $^3D^o_1$	97 330.100	102.743 139
$^3P_1$	$(^4S^o)$ 3d $^3D^o_2$	97 330.159	102.743 077
$^3P_2$	$(^4S^o)$ 3d $^3D^o_1$	97 488.369	102.576 339
$^3P_2$	$(^4S^o)$ 3d $^3D^o_2$	97 488.429	102.576 276
$^3P_2$	$(^4S^o)$ 3d $^3D^o_3$	97 488.530	102.576 170
$^3P_1$	$(^2D^o)$ 3s' $^3D^o_2$	100 989.248*	99.020 442*
$^3P_2$	$(^2D^o)$ 3s' $^3D^o_3$	101 135.394	98.877 352
$^3P_2$	$(^2D^o)$ 3s' $^3D^o_2$	101 147.517	98.865 502
$^3P_0$	$(^4S^o)$ 5s $^3S^o_1$	102 184.994*	97.861 727*
$^3P_1$	$(^4S^o)$ 5s $^3S^o_1$	102 253.710*	97.795 962*
$^3P_2$	$(^4S^o)$ 5s $^3S^o_1$	102 411.979	97.644 827
$^3P_0$	$(^4S^o)$ 4d $^3D^o_1$	102 681.512*	97.388 515*
$^3P_1$	$(^4S^o)$ 4d $^3D^o_2$	102 750.181*	97.323 430*
$^3P_1$	$(^4S^o)$ 4d $^3D^o_1$	102 750.229*	97.323 384*
$^3P_2$	$(^4S^o)$ 4d $^3D^o_3$	102 908.382	97.173 814
$^3P_2$	$(^4S^o)$ 4d $^3D^o_2$	102 908.449	97.173 751
$^3P_2$	$(^4S^o)$ 4d $^3D^o_1$	102 908.498	97.173 705
$^3P_0$	$(^4S^o)$ 6s $^3S^o_1$	104 938.226*	95.294 159*
$^3P_1$	$(^4S^o)$ 6s $^3S^o_1$	105 006.943*	95.231 799*
$^3P_2$	$(^4S^o)$ 6s $^3S^o_1$	105 165.211	95.088 479
$^3P_0$	$(^4S^o)$ 5d $^3D^o_1$	105 182.024	95.073 279
$^3P_1$	$(^4S^o)$ 5d $^3D^o_{1,2}$	105 250.733	95.011 214
$^3P_2$	$(^4S^o)$ 5d $^3D^o_{1,2,3}$	105 409.010	94.868 551

Laboratory metrology

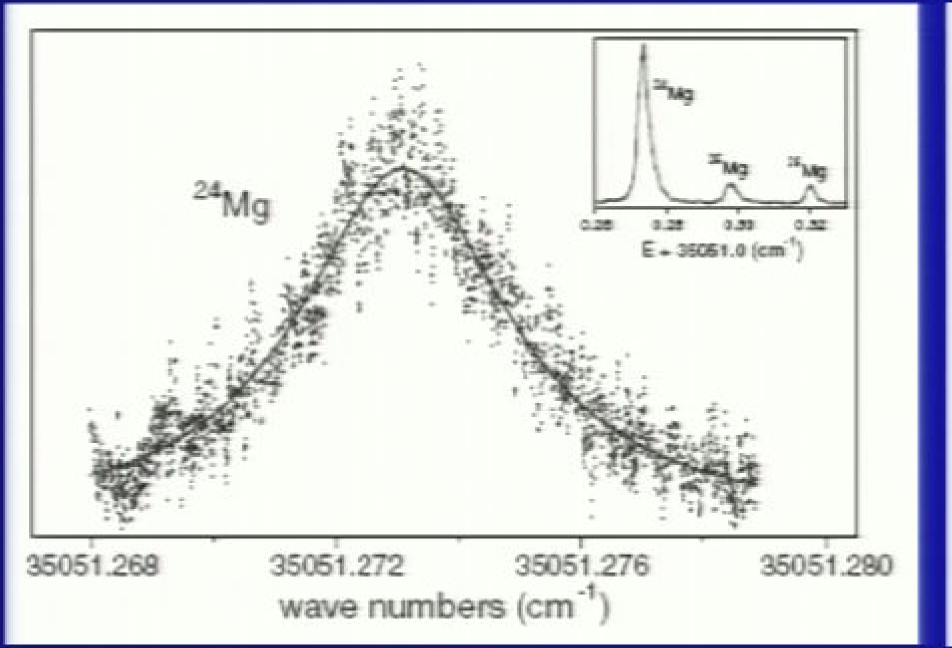
on Mg I

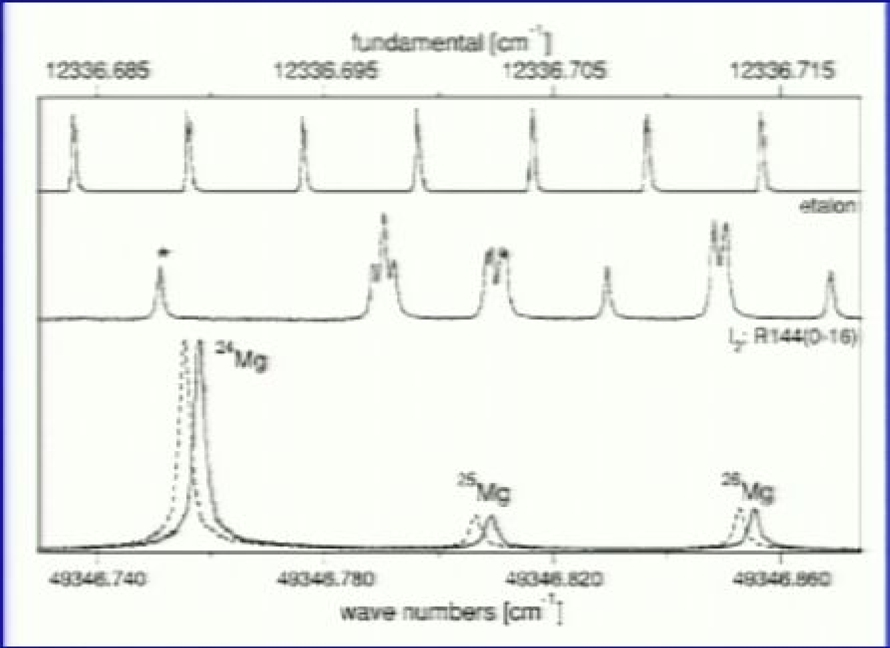
Deep-UV

$$\frac{\Delta\lambda}{\lambda} = 7\times10^{-10}$$

Mg 3s → 3p @ 285 nm

Mg 3s → 4p @ 202 nm



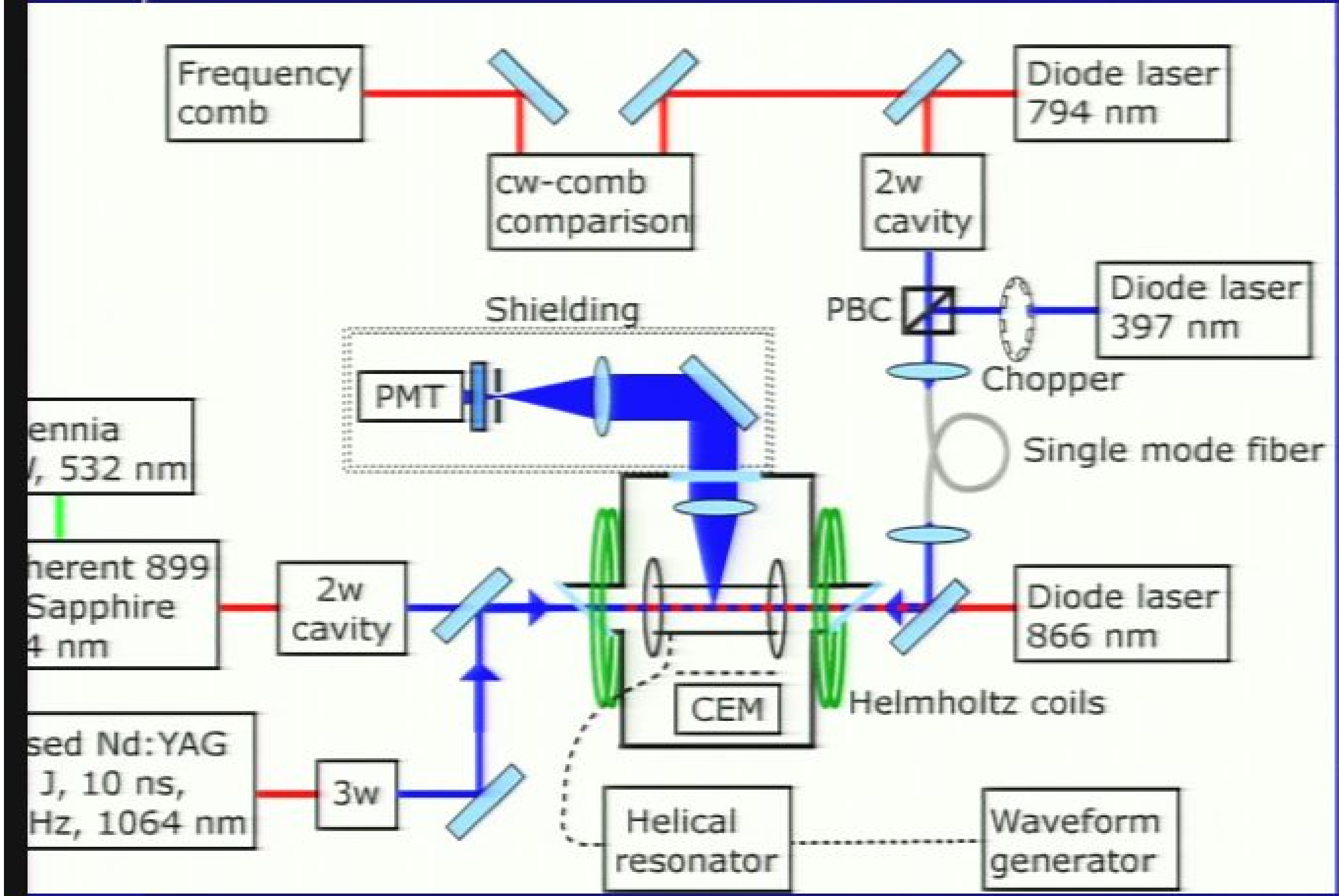


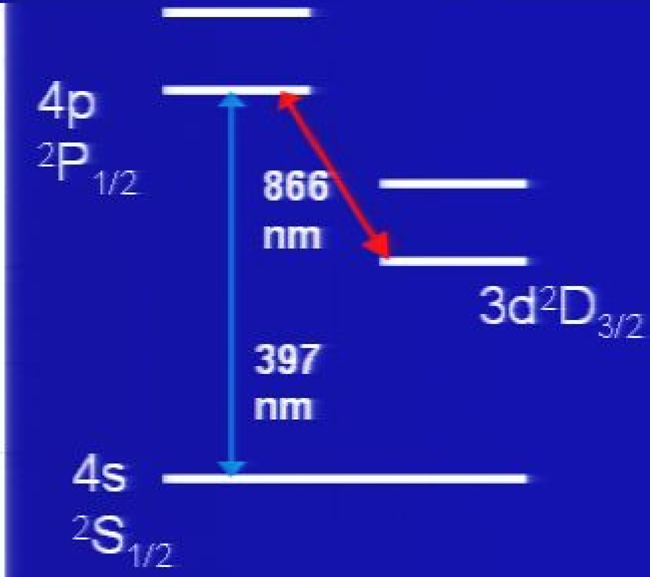
^{24}Mg	35 051.27311(17)
^{25}Mg	35 051.29784(25)

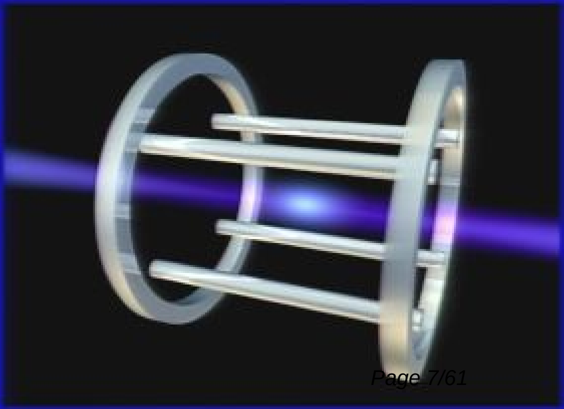
^{24}Mg	49346.756809(35)
^{25}Mg	49346.807724(40)

Ion trap spectroscopy

Ca^+ $f(P_{1/2})$=755222766.2 (1.7) MHz $\frac{\Delta\lambda}{\lambda}=2\times10^{-9}$







Further on atoms/ions

- Precise measurements are test of ab initio calculations → “q”

- Measurement of Ca (423 nm line) performed

- Preparation of Fe atomic beam

- Sympathetic cooling of other ions (Fe^+, Mn^+, Mg^+) via Ca^+

Laboratory metrology

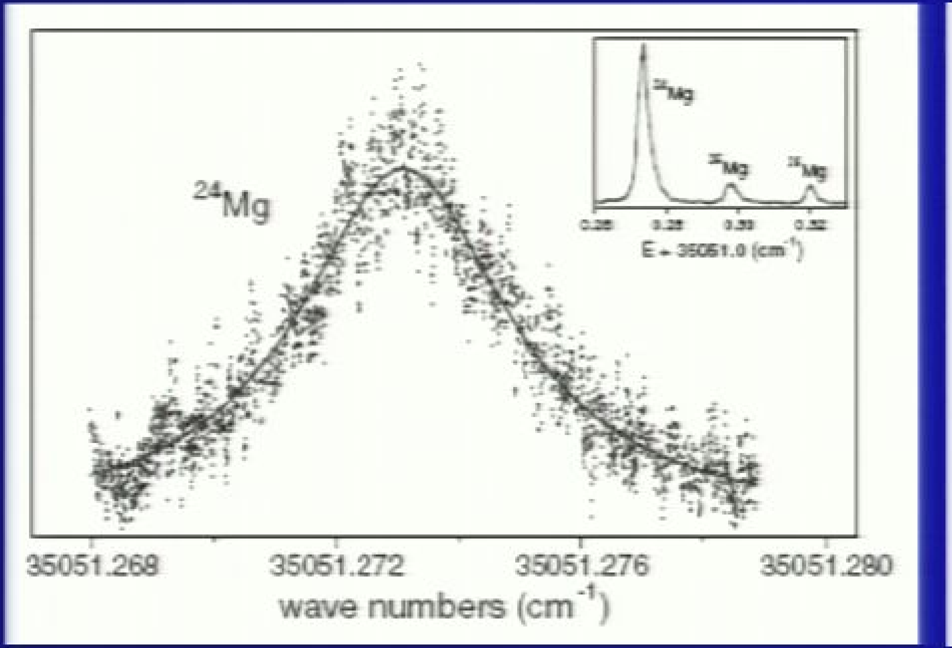
on Mg I

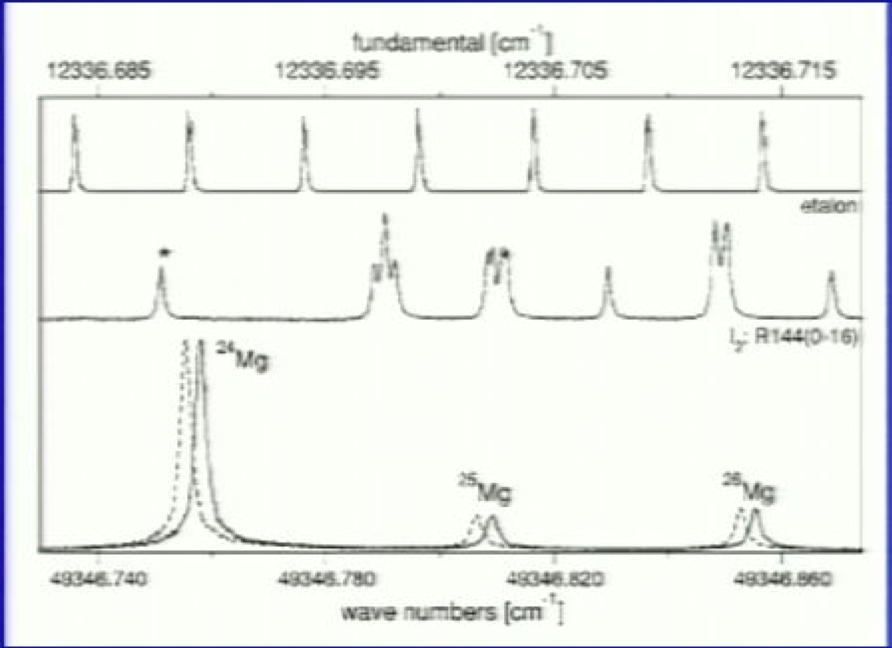
Deep-UV

$$\frac{\Delta\lambda}{\lambda} = 7\times10^{-10}$$

Mg 3s → 3p @ 285 nm

Mg 3s → 4p @ 202 nm





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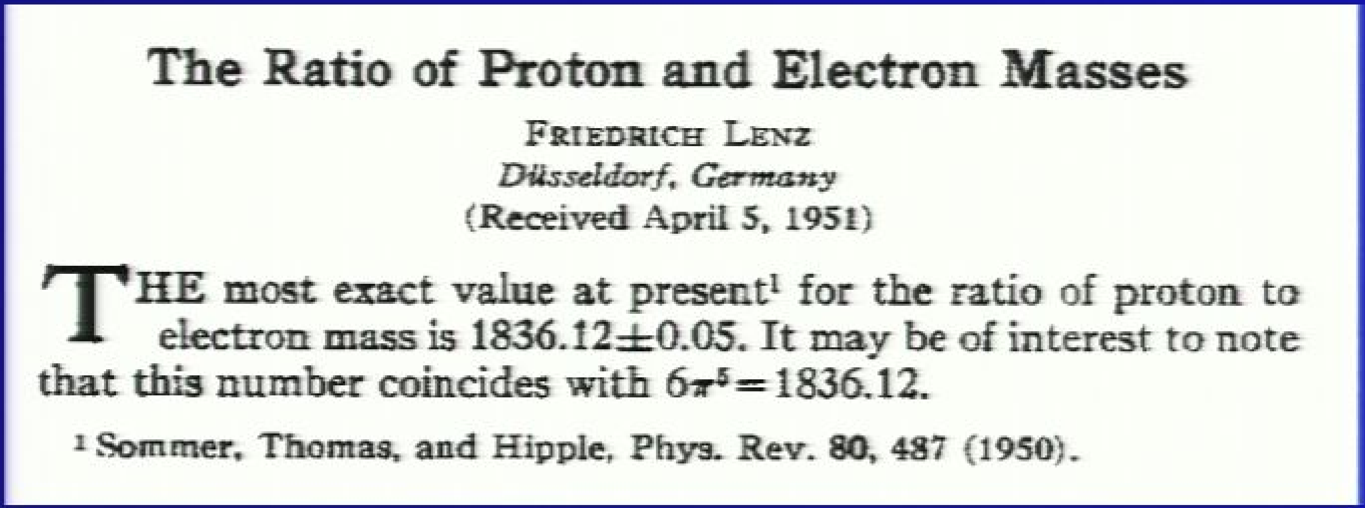
The proton-electron mass ratio

$$\mu = \frac{m_p}{m_e} = 1836.152672\,61(85)$$

The proton-electron mass ratio

$$\mu = \frac{m_p}{m_e} = 1836.15267261(85)$$

No theory ?



The Ratio of Proton and Electron Masses

Friedrich Lenz
Düsseldorf, Germany
(Received April 5, 1951)

THE most exact value at present[1] for the ratio of proton to electron mass is 1836.12±0.05. It may be of interest to note that this number coincides with $6\pi^5 = 1836.12$.

[1] Sommer, Thomas, and Hipple, Phys. Rev. **80**, 487 (1950).

Physical Review 82 (1951) 554

The proton-electron mass ratio

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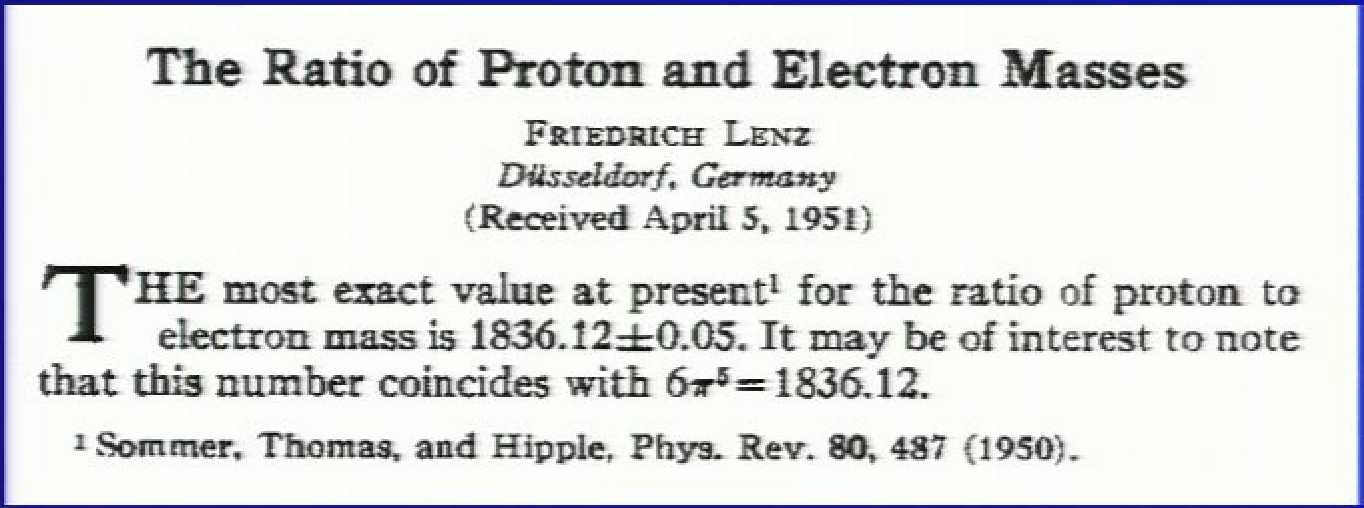

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$$\mu \sim \Lambda_{QCD}$$

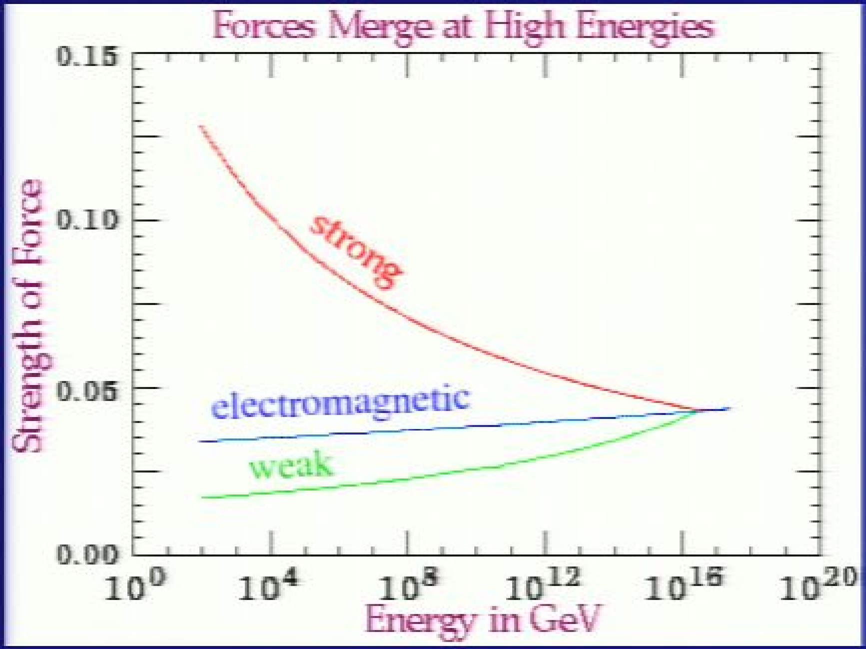
Spectroscopy: tests inertial (kinetic) mass

Variation of constants

μ is a good test ground

Coupling constants interdependent in GUT

$$\frac{\dot{\mu}}{\mu} = R\frac{\dot{\alpha}}{\alpha}$$



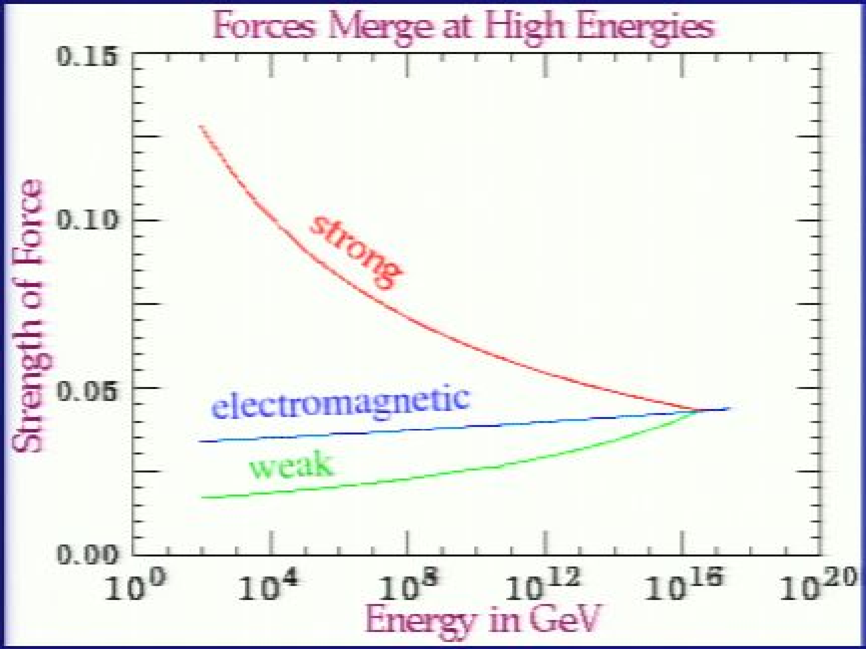
Several theories with $|R|$ large

Variation of constants

μ is a good test ground

Coupling constants interdependent in GUT

$$\frac{\dot{\mu}}{\mu} = R\frac{\dot{\alpha}}{\alpha}$$



Several theories with $|R|$ large

1. μ more sensitive
2. constraint on α_{EM}
3. Test GU theory via R

Empirical search for a change in μ

- Spectroscopy
- Compare H_2 spectra in different epochs:

Lab

today

QSO

12 Gyr ago

90-112 nm

~275-350 nm

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

Cosmological reshift

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

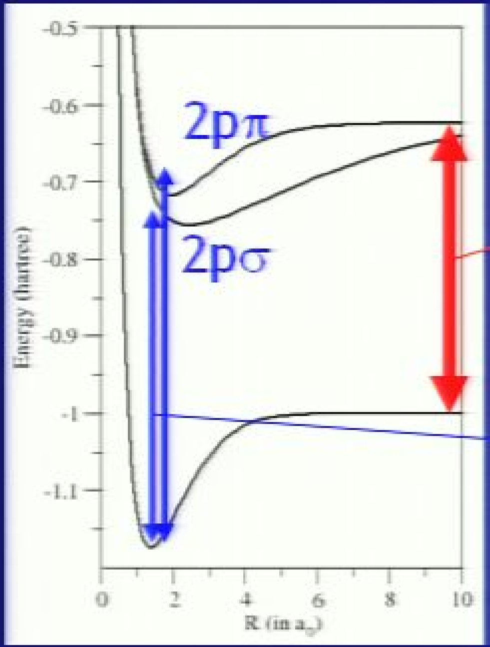
T_0=13.7 Gyrs

Laboratory measurements: spectra of H_2

Composition of the universe:

80 % hydrogen H/H_2
20 % helium
<0.1% other elements

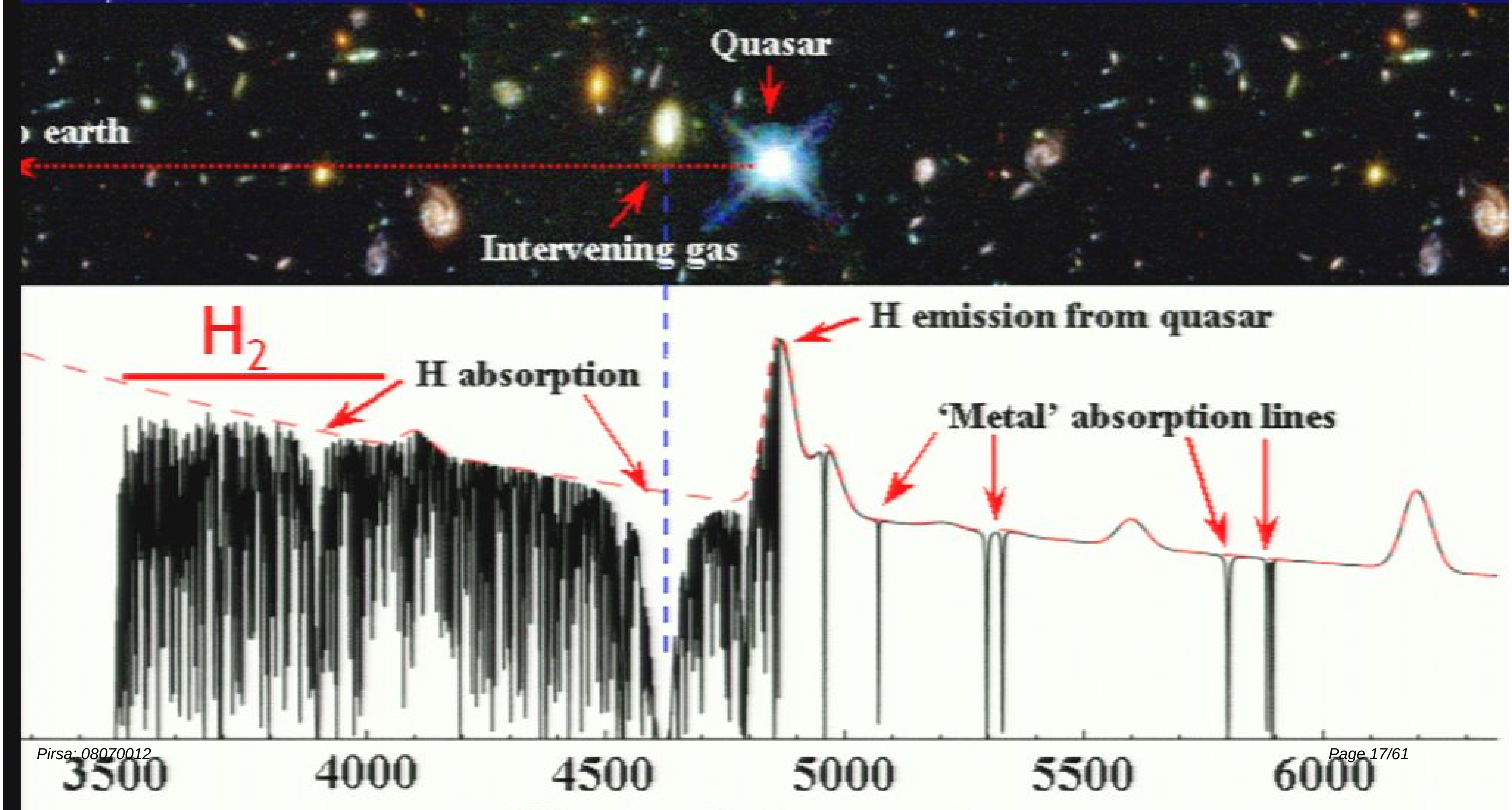
H_2



H (Lyman-α) ~ 121 nm

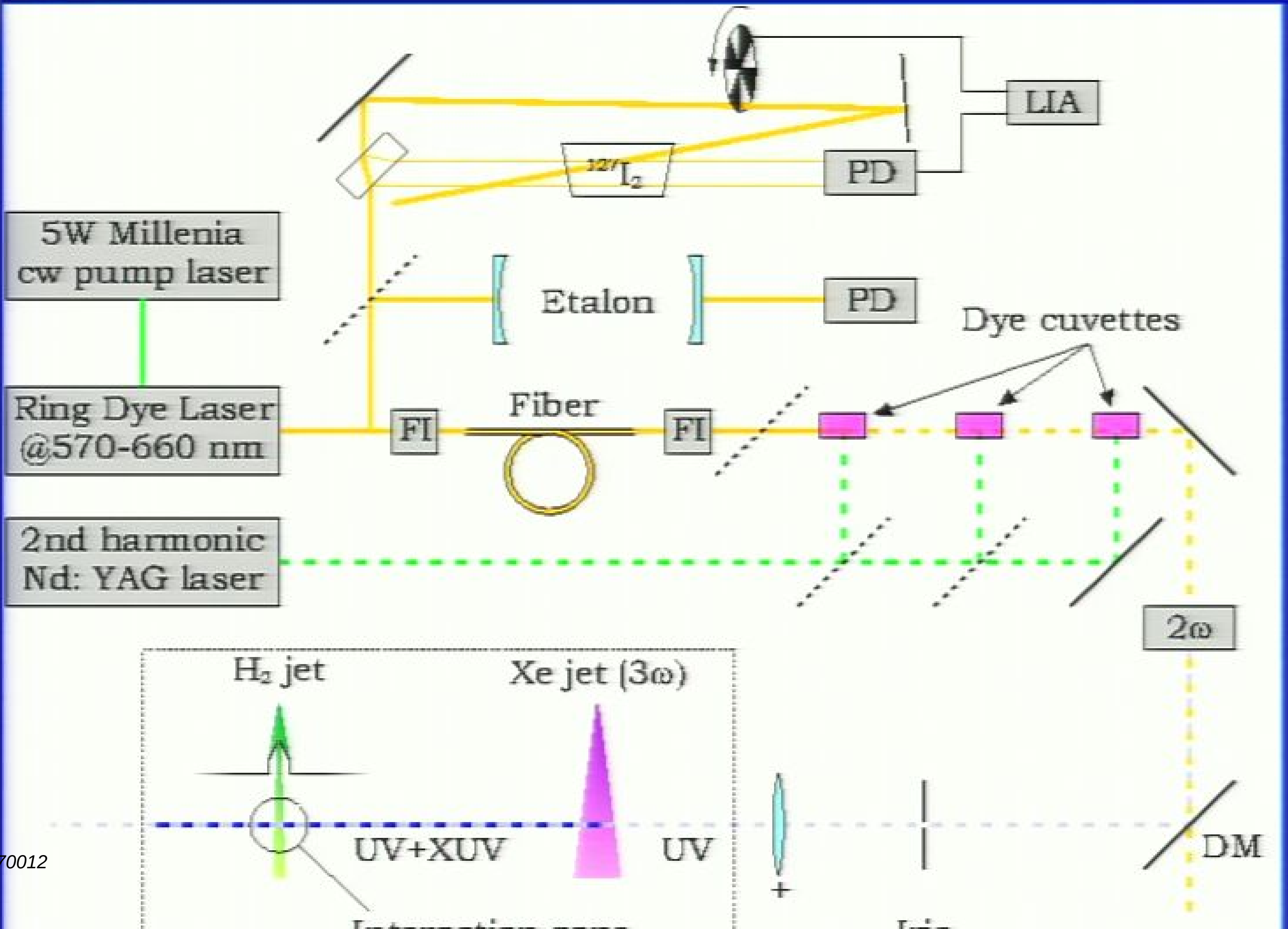
H_2, Lyman en Werner BANDS
~90 - 110 nm
Extreme Ultraviolet Wavelengths

Empirical search for a change in μ: quasars



XUV-laser spectroscopy

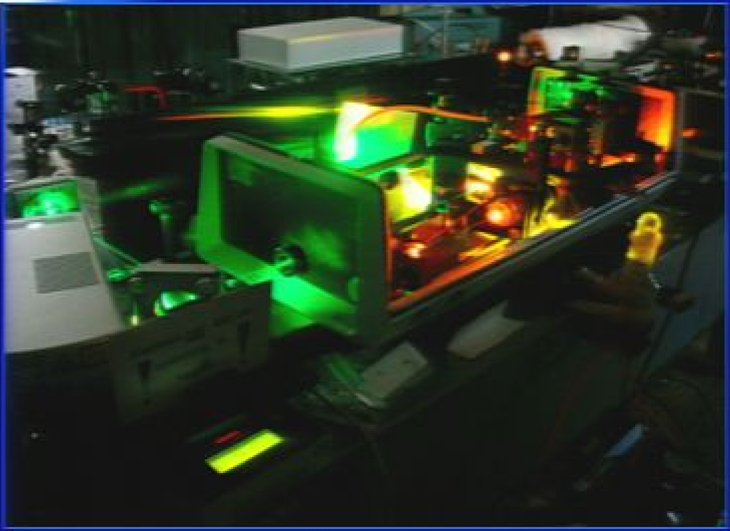
With a narrowband tunable laser-based source



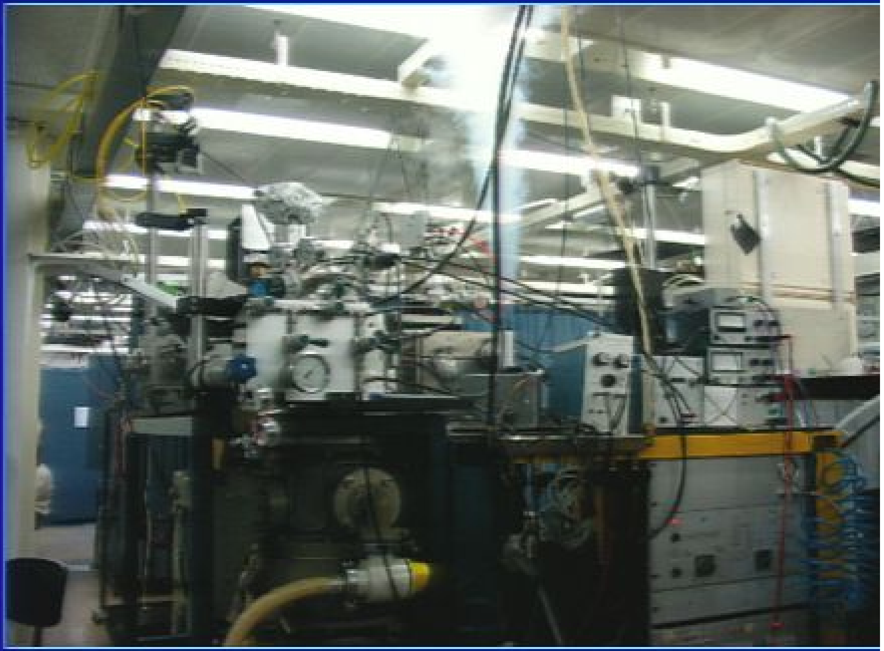
$\lambda_{XUV} = \lambda_{fund}/6$

$\Delta\nu = 250$ MHz

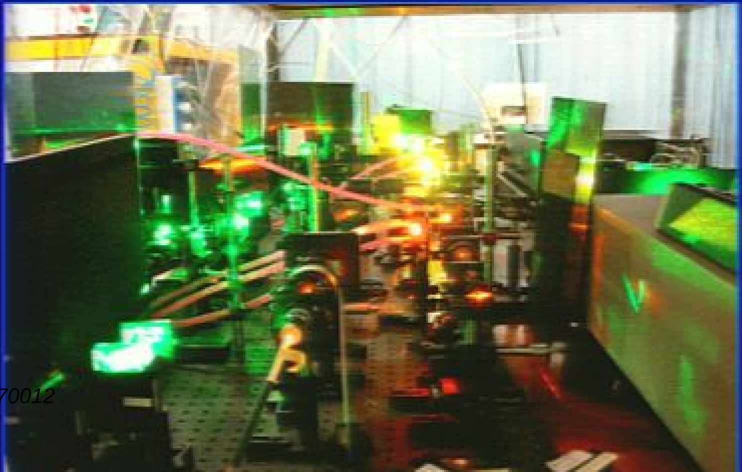
A narrowband and tunable laser at XUV-wavelengths



Ring
Laser



Vacuum setup
Differentially
Pumped chambers

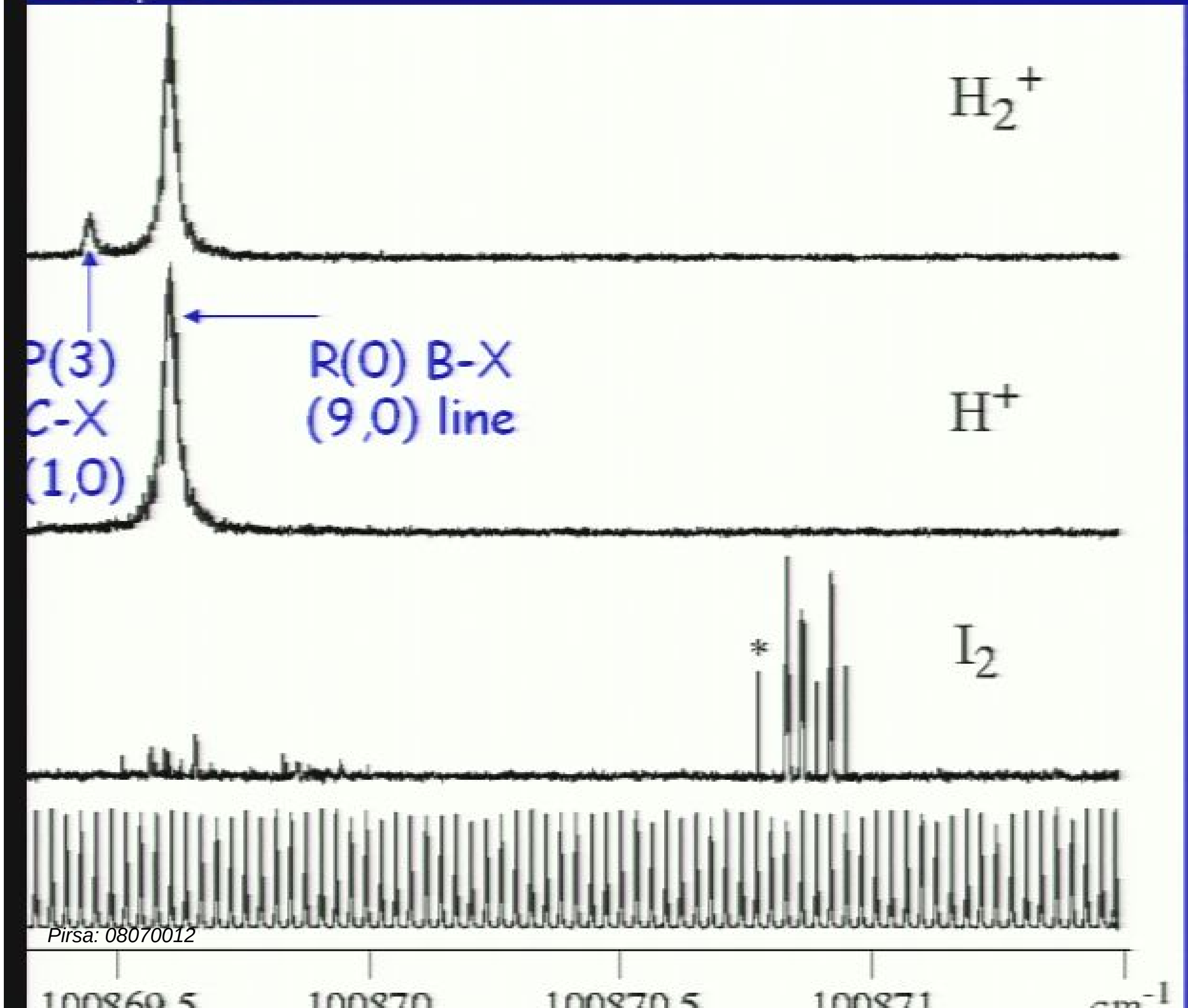


Pulse
Amplifier

XUV-spectroscopy of H_2

Laser Centre
vrije Universiteit amsterdam

The $B^1\Sigma_u^+ - X^1\Sigma_g^+$ Lyman and $C^1\Pi_u - X^1\Sigma_g^+$ Werner bands



Evaluation of uncertainties:
Error budget

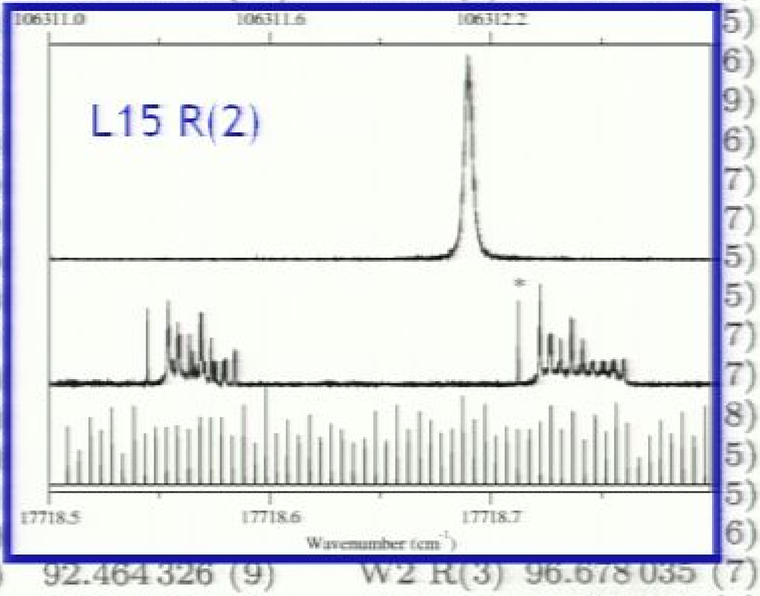
Residual Doppler	40 MHz
AC Stark	30 MHz
Freq chirp (PDA)	100 MHz
I_2 calibration	10 MHz
Statistical	30 MHz

Total (best lines): 0.004 cm^{-1}
0.000004 nm

$\Delta\lambda/\lambda = 4\text{-}6 \times 10^{-8}$

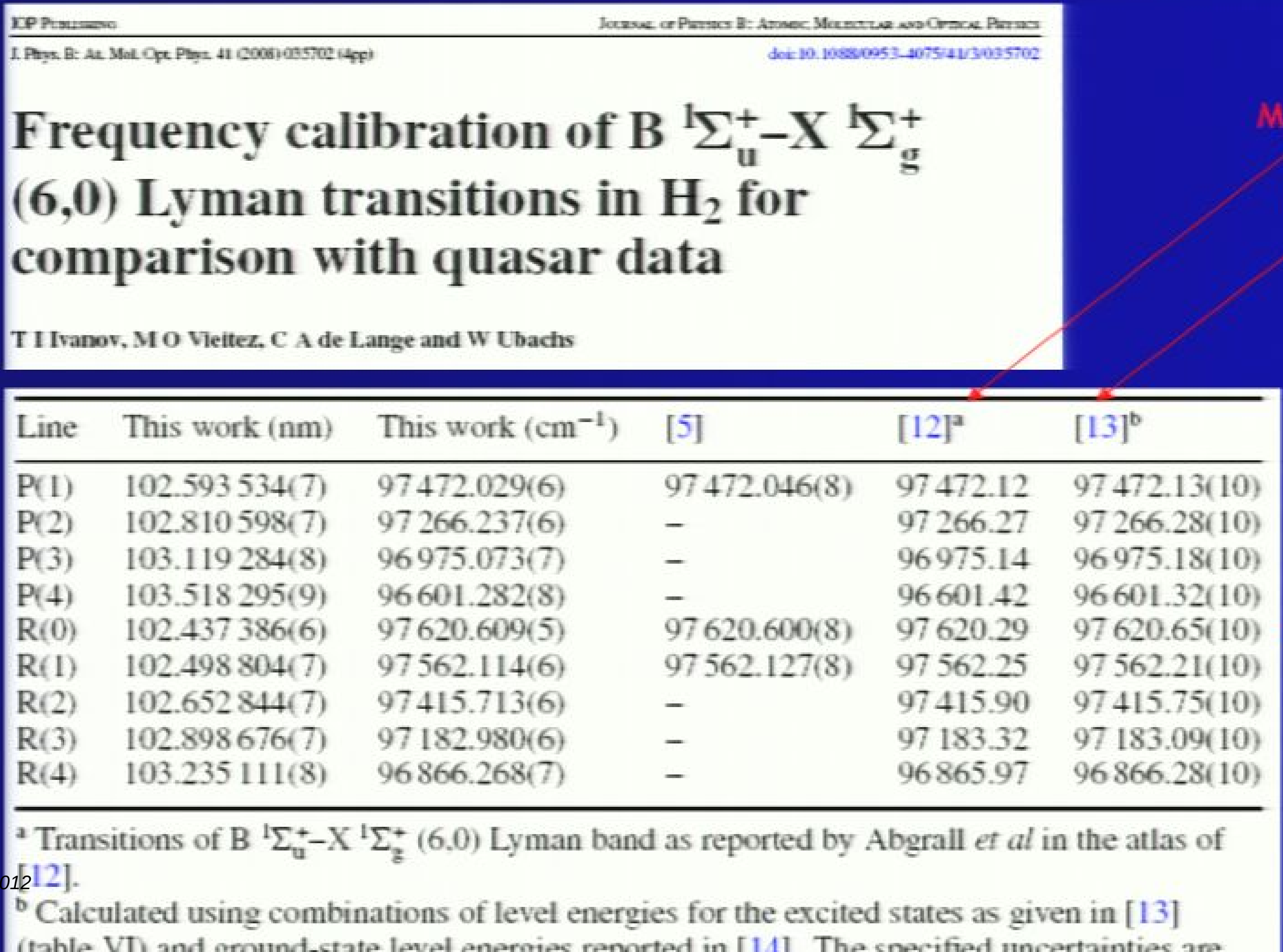
LE I: Comprehensive list of measured transition wavelengths of the Lyman (L) and Werner (W) lines using the ult owband XUV laser source in Amsterdam. Values in nm.

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)	[illegible]	[illegible]	5)
L1 R(0)	109.219 523 (6)	L9 R(0)	99.137 891 (5)	L15 P(1)	[illegible]	[illegible]	6)
L1 R(1)	109.273 243 (6)	L9 R(1)	99.201 637 (5)	L15 P(3)	[illegible]	[illegible]	9)
L1 R(2)	109.424 460 (6)	L9 R(2)	99.355 061 (9)	L15 R(0)	[illegible]	[illegible]	6)
L1 R(3)	109.672 534 (6)	L9 R(3)	99.597 278 (20)	L15 R(1)	[illegible]	[illegible]	7)
L2 P(1)	107.892 547 (5)	L10 P(1)	98.283 533 (5)	L15 R(2)	[illegible]	[illegible]	7)
L2 R(0)	107.713 874 (5)	L10 P(2)	98.486 398 (5)	L15 R(3)	[illegible]	[illegible]	5)
L2 R(1)	107.769 894 (5)	L10 P(3)	98.776 882 (6)	L15 R(4)	[illegible]	[illegible]	5)
L2 R(2)	107.922 542 (6)	L10 R(0)	98.143 871 (5)	L16 P(1)	[illegible]	[illegible]	7)
L2 R(3)	108.171 124 (7)	L10 R(1)	98.207 427 (5)	L16 R(0)	[illegible]	[illegible]	7)
L2 R(4)	108.514 554 (6)	L10 R(2)	98.359 107 (5)	L16 R(1)	[illegible]	[illegible]	8)
L3 P(1)	106.460 539 (5)	L10 R(3)	98.596 279 (6)	L16 R(2)	[illegible]	[illegible]	5)
L3 P(2)	106.690 068 (5)	L11 P(1)	97.334 458 (5)	L17 P(1)	[illegible]	[illegible]	5)
L3 R(0)	106.288 214 (5)	L11 P(2)	97.534 576 (5)	L17 R(0)	[illegible]	[illegible]	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)	[illegible]	[illegible]	95.167 186 (5)
L4 P(1)	105.103 253 (4)	L11 R(2)	97.415 791 (5)	L18 R(1)	[illegible]	[illegible]	742 188 (5)
L4 R(0)	104.936 744 (4)	L11 R(3)	97.655 283 (6)	L18 R(2)	[illegible]	[illegible]	861 583 (5)
L4 R(1)	104.995 976 (4)	L11 R(4)	97.980 512 (7)	L19 P(1)	[illegible]	[illegible]	039 773 (5)
L4 R(2)	105.149 857 (5)	L11 R(5)	98.389 896 (7)	L19 P(2)	[illegible]	[illegible]	94.642 557 (4)
L4 R(3)	105.397 610 (4)	L12 P(1)	96.431 064 (5)	L19 P(3)	91.638 293 (34)	W3 R(1)	94.638 475 (4)
L5 P(1)	103.815 713 (4)	L12 P(2)	96.627 550 (5)	L19 R(0)	91.082 073 (17)	W3 R(2)	94.711 169 (4)
L5 R(0)	103.654 581 (4)	L12 P(3)	96.908 984 (6)	L19 R(1)	91.147 950 (17)	W3 R(3)	94.841 967 (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)
[illegible]	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)	102.437 295 (8)	L12 R(4)	97.083 820 (8)	W0 Q(1)	100.977 088 (5)	W4 Q(2)	93.178 086 (10)



162 lines measured at ~ 5 x 10^{-8}

Struggle with the PDA: λ =617nm



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Frequency calibration of B $^1\Sigma_u^+$–X $^1\Sigma_g^+$ (6,0) Lyman transitions in H_2 for comparison with quasar data

T I Ivanov, M O Vieitez, C A de Lange and W Ubachs

Meudon measurements

Meudon analysis

Line	This work (nm)	This work (cm^{-1})	[5]	[12][a]	[13][b]
P(1)	102.593 534(7)	97 472.029(6)	97 472.046(8)	97 472.12	97 472.13(10)
P(2)	102.810 598(7)	97 266.237(6)	–	97 266.27	97 266.28(10)
P(3)	103.119 284(8)	96 975.073(7)	–	96 975.14	96 975.18(10)
P(4)	103.518 295(9)	96 601.282(8)	–	96 601.42	96 601.32(10)
R(0)	102.437 386(6)	97 620.609(5)	97 620.600(8)	97 620.29	97 620.65(10)
R(1)	102.498 804(7)	97 562.114(6)	97 562.127(8)	97 562.25	97 562.21(10)
R(2)	102.652 844(7)	97 415.713(6)	–	97 415.90	97 415.75(10)
R(3)	102.898 676(7)	97 182.980(6)	–	97 183.32	97 183.09(10)
R(4)	103.235 111(8)	96 866.268(7)	–	96 865.97	96 866.28(10)

[a] Transitions of B $^1\Sigma_u^+$–X $^1\Sigma_g^+$ (6,0) Lyman band as reported by Abgrall *et al* in the atlas of [12].

[b] Calculated using combinations of level energies for the excited states as given in [13] (table VI) and ground-state level energies reported in [14]. The specified uncertainties are

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

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

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

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

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

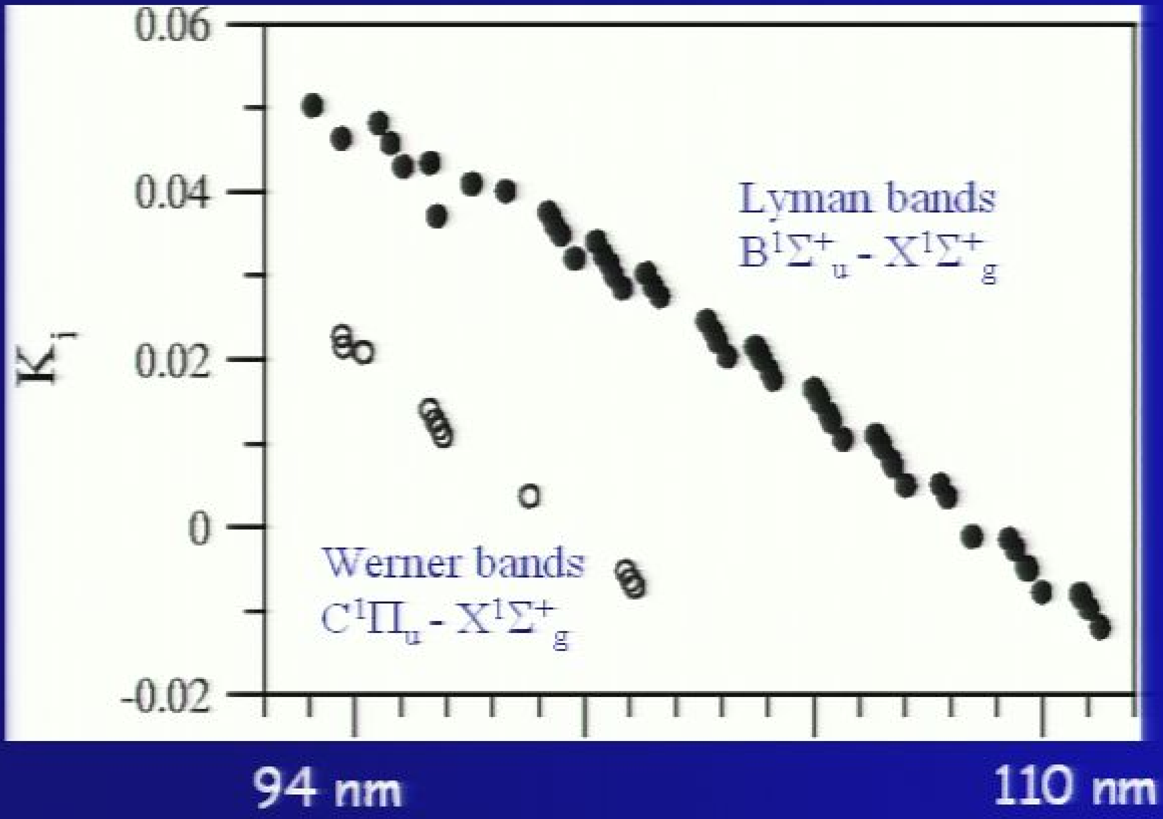
QSO: (2-10) x 10^{-7}

Accurately calculated

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

Lab: 5 x 10^{-8}

K_i different for H_2 lines



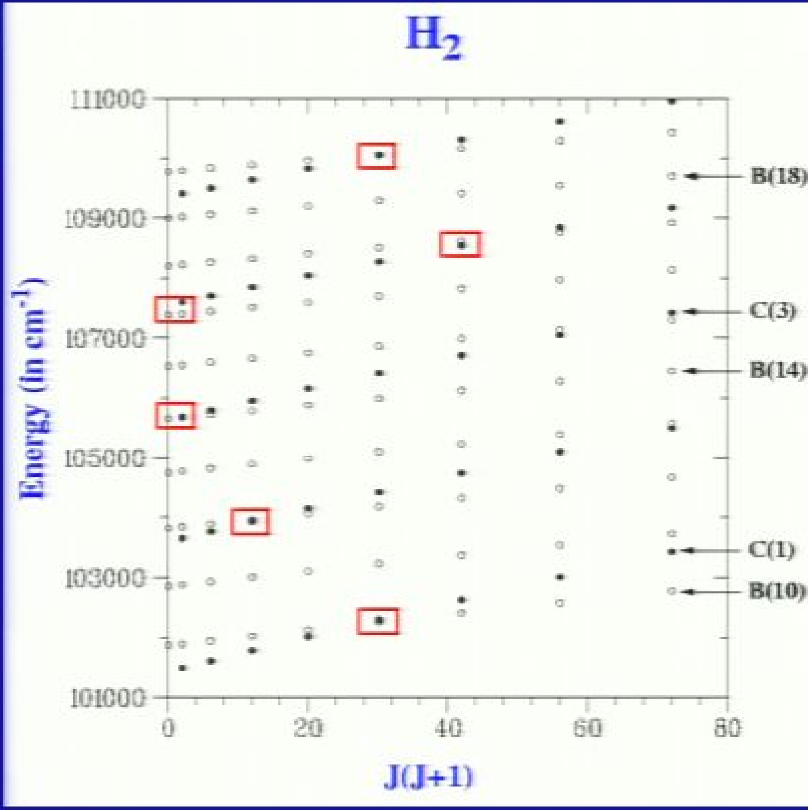
for 76 data in
Q 0405
and Q 0347

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

Semi-empirical model for calculating K_i

1. Dunham representation of accurate level energies

$$E(v,J) = \sum_{k,l} Y_{kl} \left(v + \tfrac{1}{2}\right)^k \left[J(J+1) - \Lambda^2\right]^l$$



2. Treatment of adiabatic and (local) non-adiabatic effects

$$\begin{pmatrix} E^B_{v_B,J} & H_{v_B,v_C}\sqrt{J(J+1)} \\ H_{v_B,v_C}\sqrt{J(J+1)} & E^C_{v_C,J} \end{pmatrix} \Psi = E\Psi$$

$$\frac{dE}{d\mu_n} = \left|c_1^2\right| \frac{dE^B_{v_B,J}}{d\mu_n} + \left|c_2^2\right| \frac{dE^C_{v_C,J}}{d\mu_n} \pm 2\left|c_1 c_2\right| \frac{dH}{d\mu_n}\sqrt{J(J+1)}$$

Meshkov et al. : ab initio calculation (< 1%)

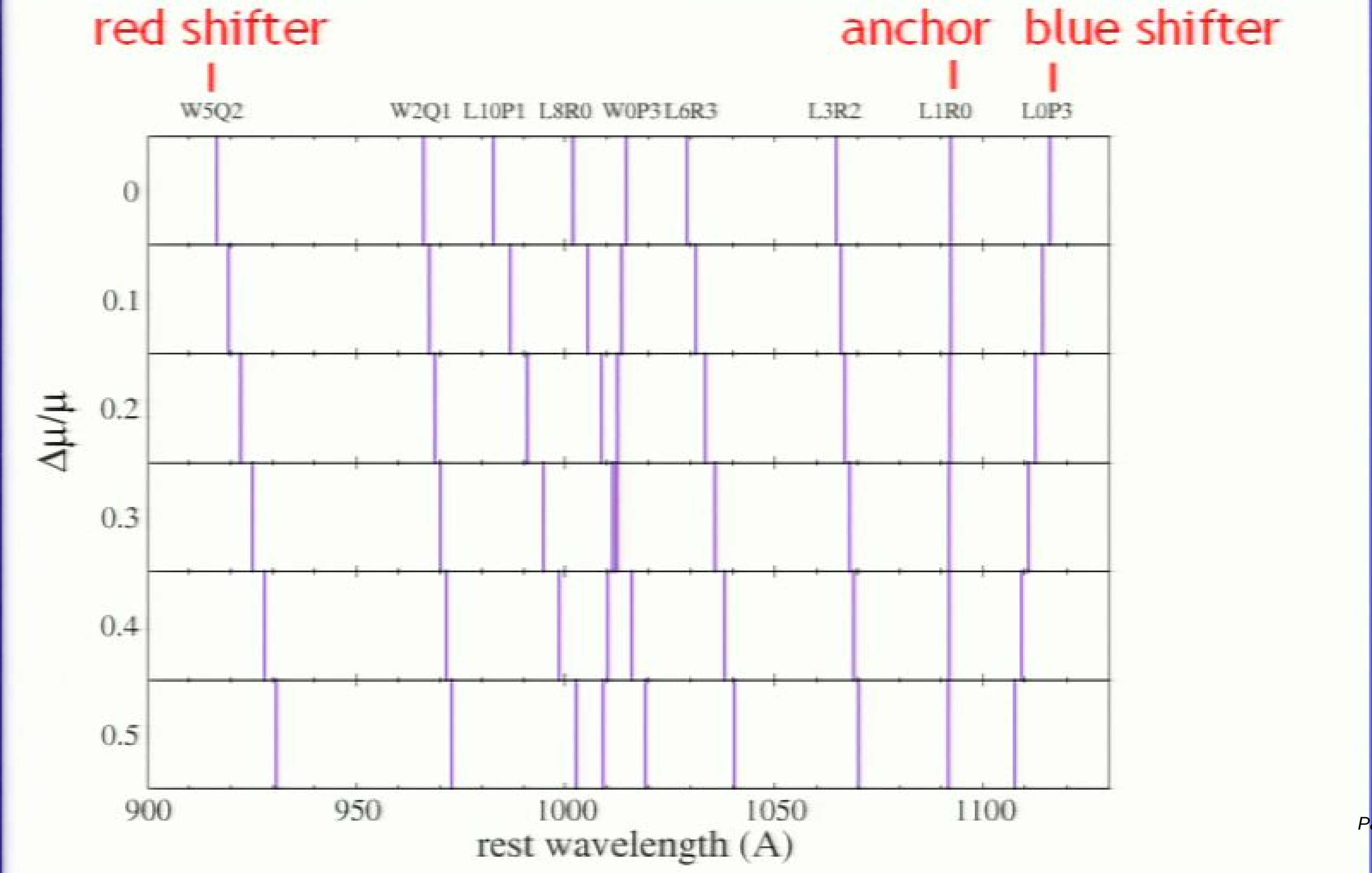
K_i different for H_2 lines

red shifter

anchor

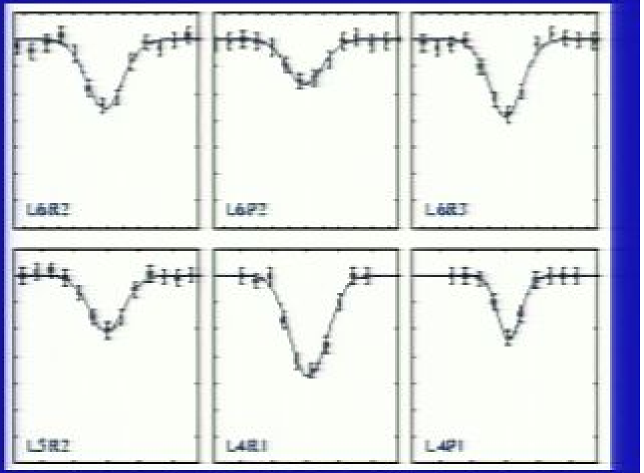
blue shifter

K_i different for H_2 lines



Quasars or QSO's

- >2300 HI absorption systems
- ~600 DLA's
- 15 H_2 absorption systems
- 6 useful
- few high-quality spectra
  - Q0347: 39 lines at $z_{abs}=3.02$
  - Q0405: 37 lines at $z_{abs}=2.59$



Ivanchik, Petitjean et al, A&A 440, 45 (2005)
Uncertainty: 2×10^{-7} - 1×10^{-6}

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

T_0=13.7 Gyrs

T=11.7-12.0 Gyrs

$\Delta\mu/\mu$ determination

Existing data on Q0405 and Q0347: fit to wavelength positions

Ivanchik, Petitjean et al, A&A 440, 45 (2005)

“reduced redshift”

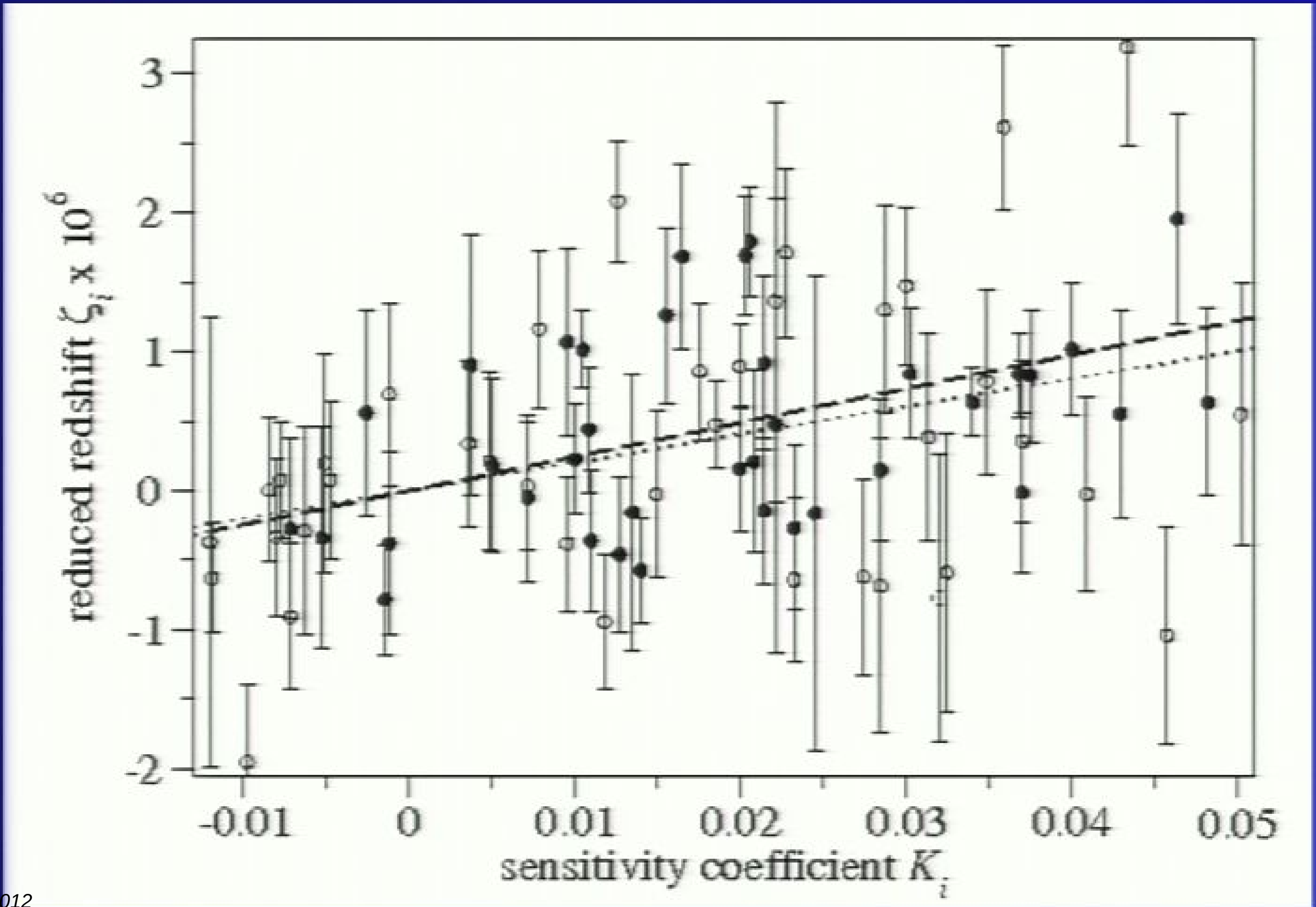
$$\zeta_i = \frac{z_i - \bar{z}_Q}{1 + \bar{z}_Q} = \frac{\Delta\mu}{\mu} K_i$$

Combined fit:

$$\frac{\Delta\mu}{\mu} = (2.5 \pm 0.6) \times 10^{-5}$$

Indication of a Cosmological Variation of the Proton-Electron Mass Ratio Based on Laboratory Measurement and Reanalysis of H_2 Spectra

E. Reinhold,[1] R. Buning,[1] U. Hollenstein,[1,2] A. Ivanchik,[3] P. Petitjean,[4,5] and W. Ubachs[1,*]



Indication of a Cosmological Variation of the Proton-Electron Mass Ratio Based on Laboratory Measurement and Reanalysis of H_2 Spectra

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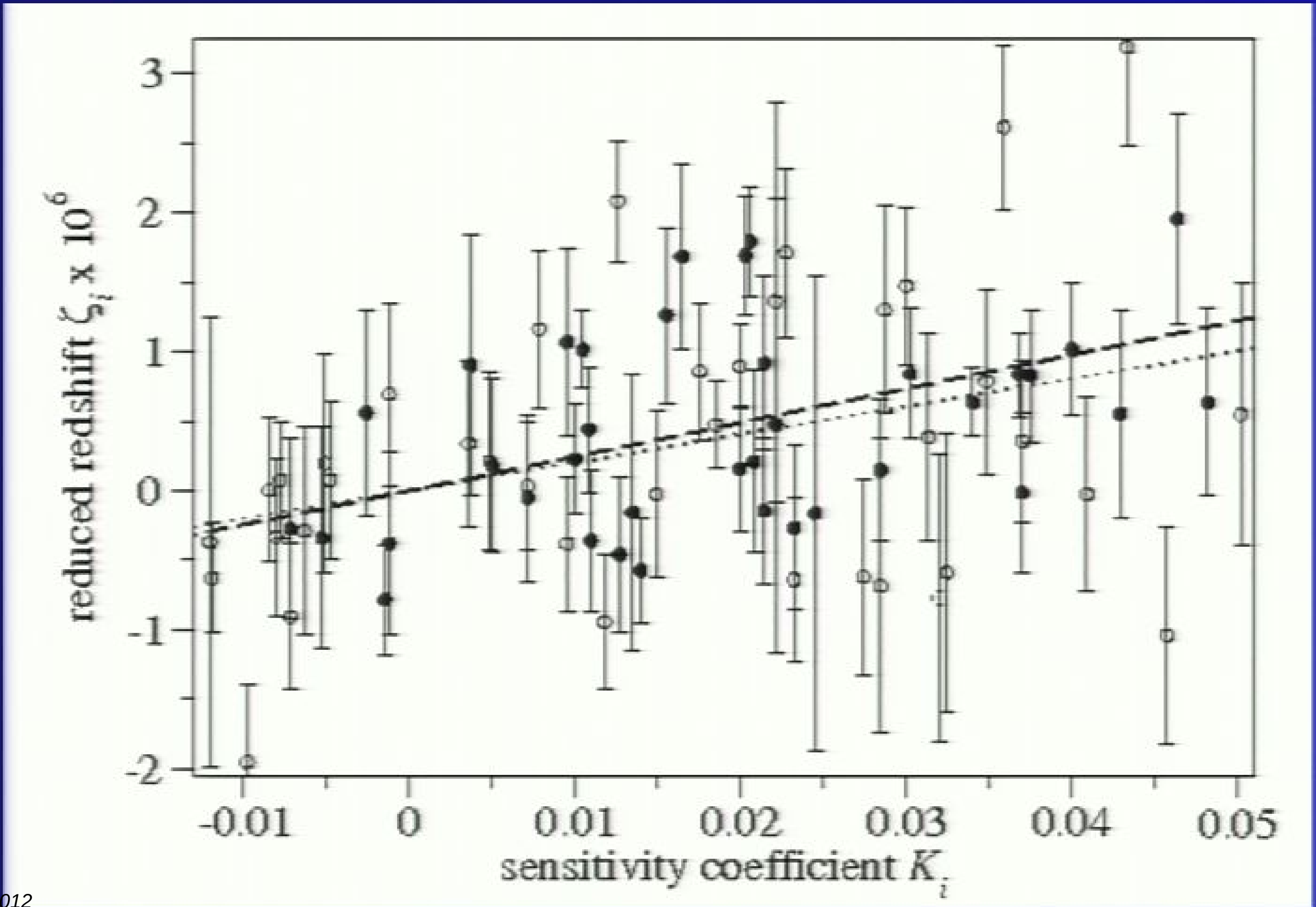
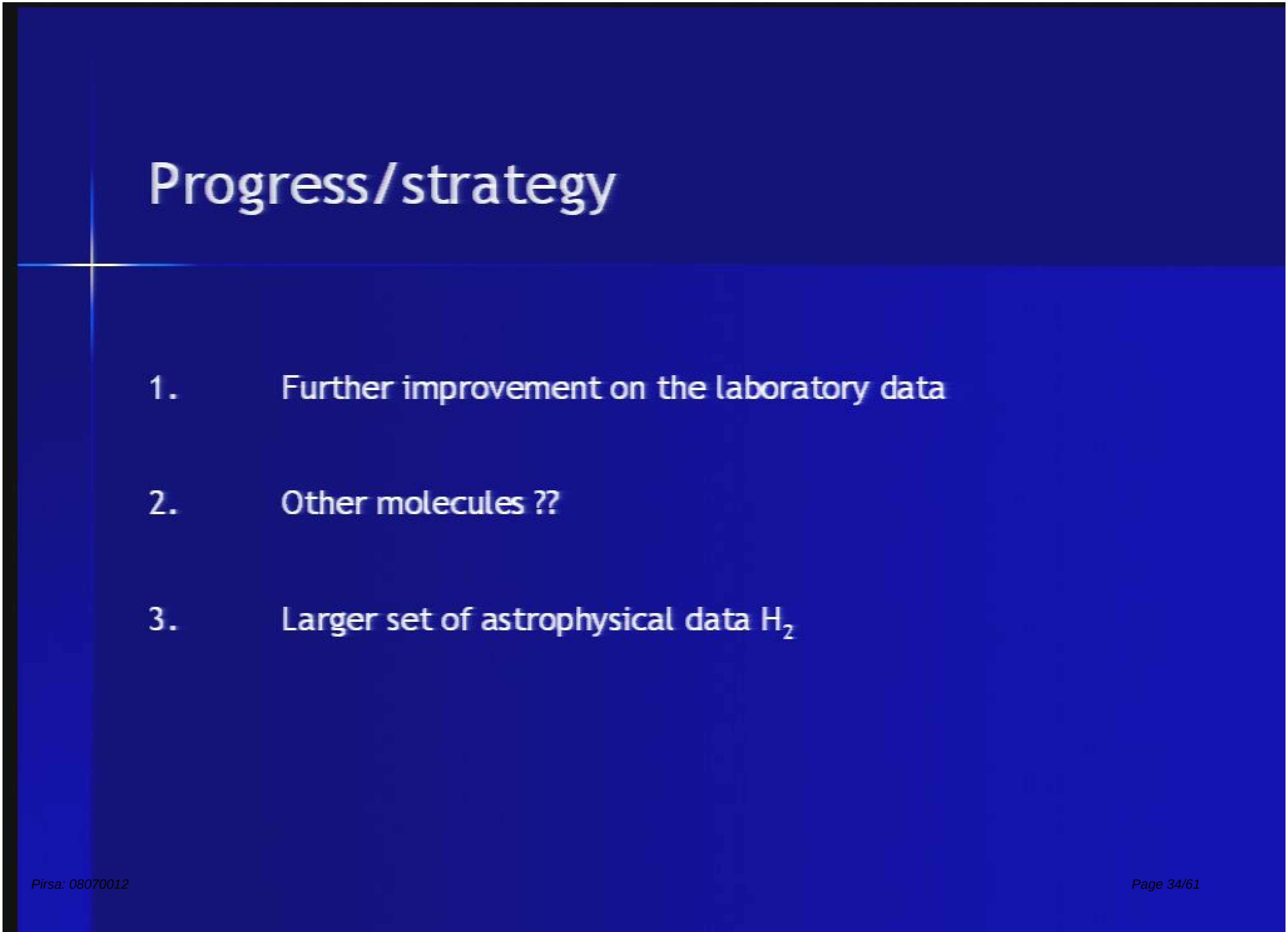




Progress/strategy

1. Further improvement on the laboratory data
2. Other molecules ??
3. Larger set of astrophysical data H_2

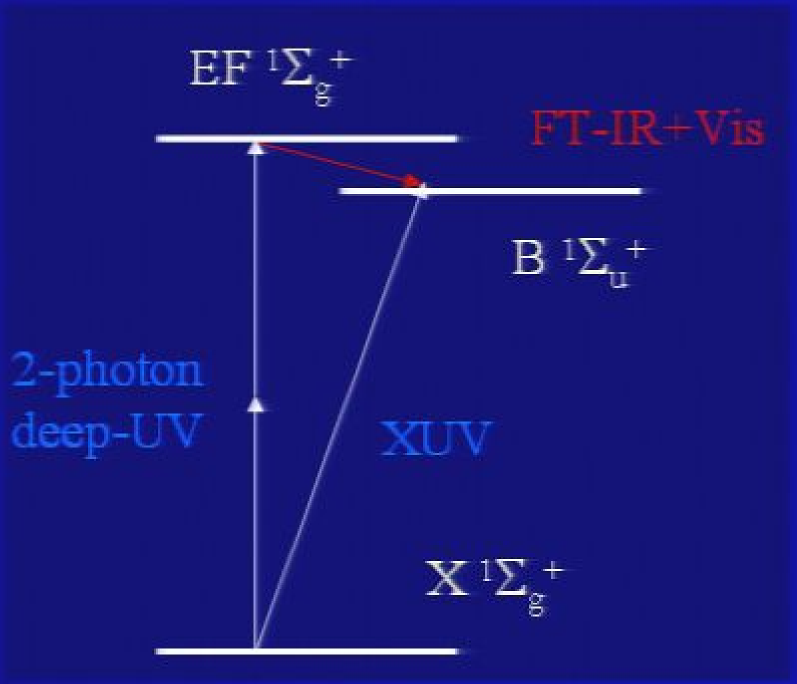
Improvement of H_2 laboratory data

XUV experiments

Total (best lines): $0.005\ \mathrm{cm}^{-1}$
$0.000005\ \mathrm{nm}$
$\Delta\lambda/\lambda = 5 \times 10^{-8}$

↓

Novel combination scheme
Two different experiments
- 2 photon UV excitation
- FTIR



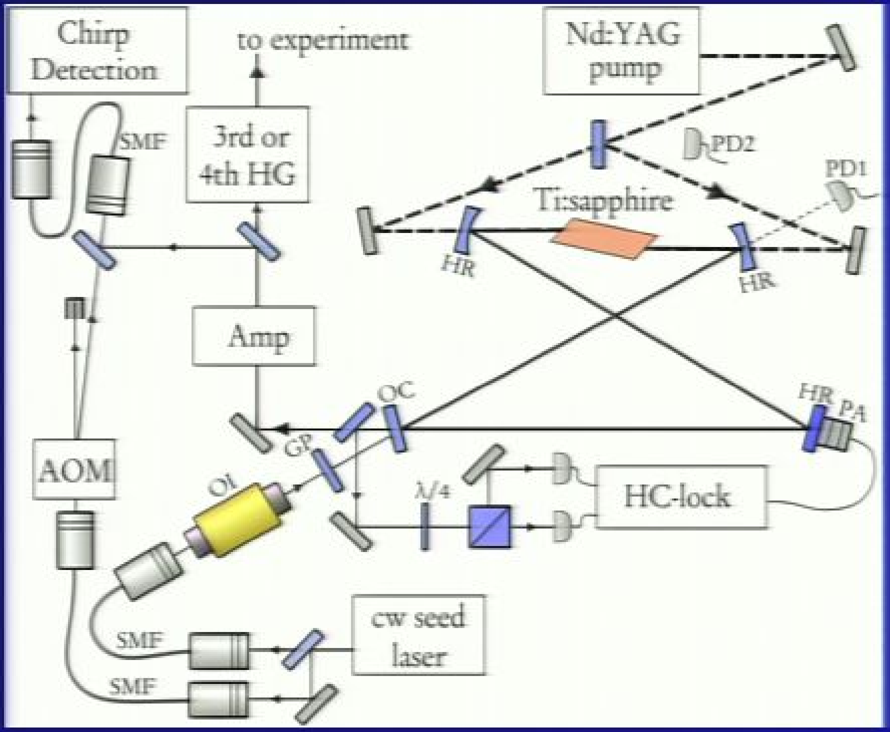
Improvement accuracy on Lyman bands

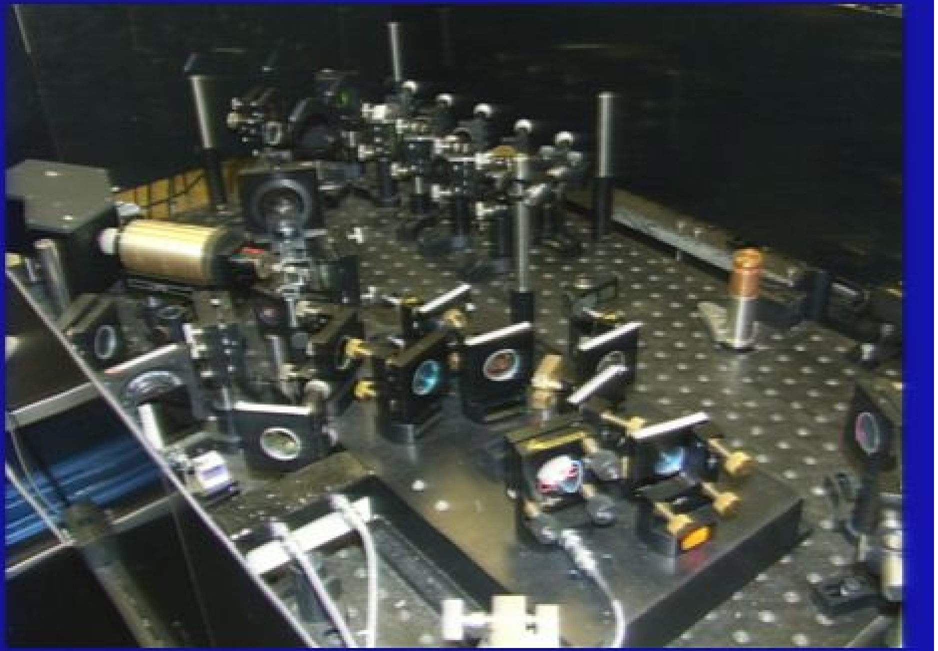
$\rightarrow \Delta\lambda/\lambda \sim 1\text{-}5 \times 10^{-9}$

Laser Centre
vrije Universiteit amsterdam

Narrowband Ti:Sa laser

With conversion to deep-UV



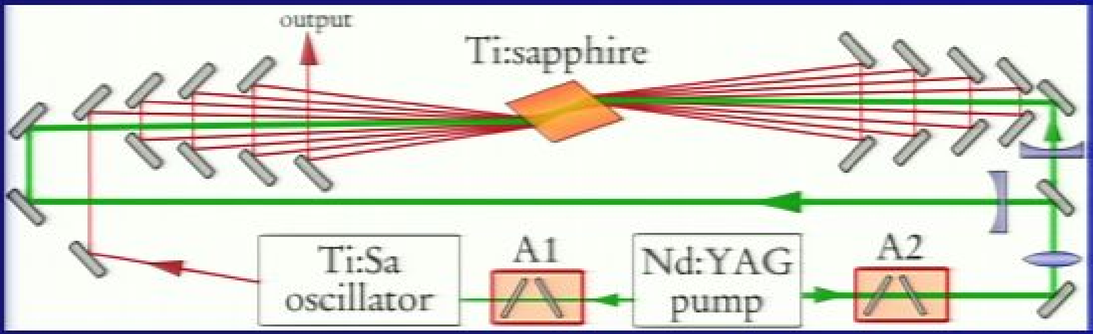


On-line chirp detection

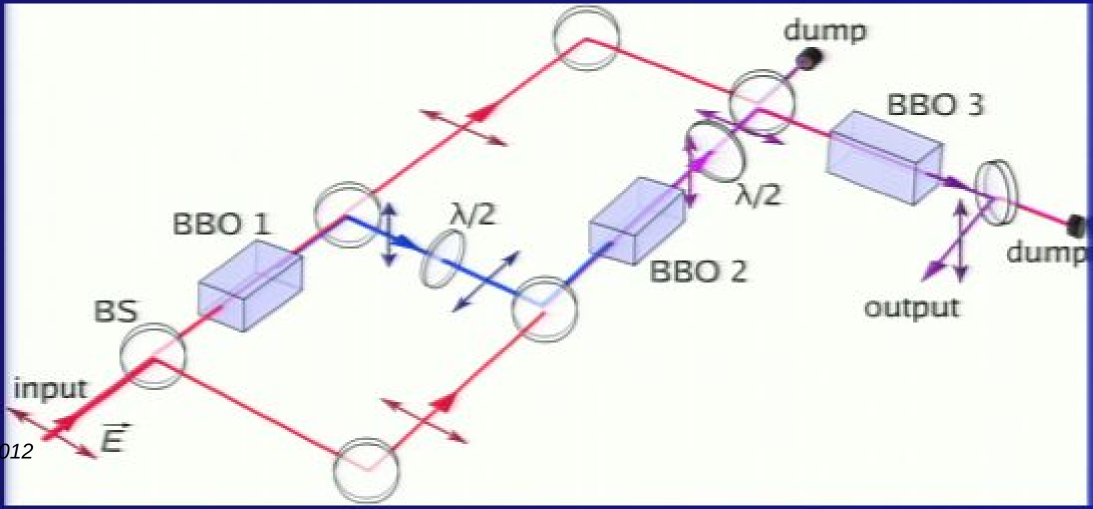
FT-limited pulses at 20-40 ns duration

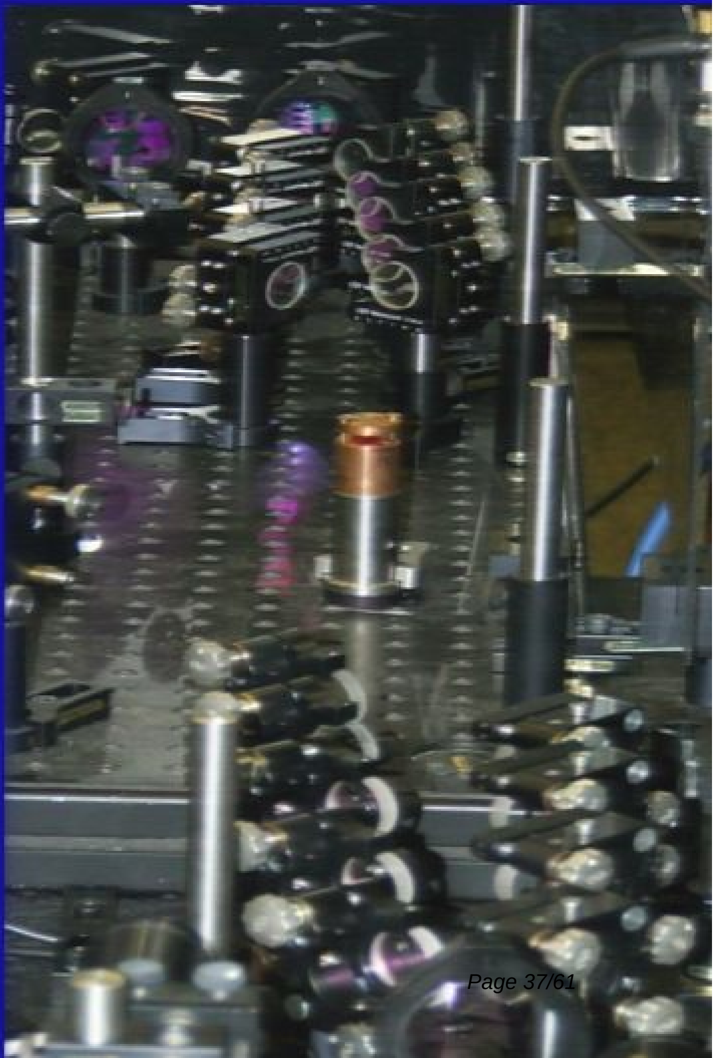
Laser Centre
vrije Universiteit amsterdam

Amplifier and conversion to deep-UV

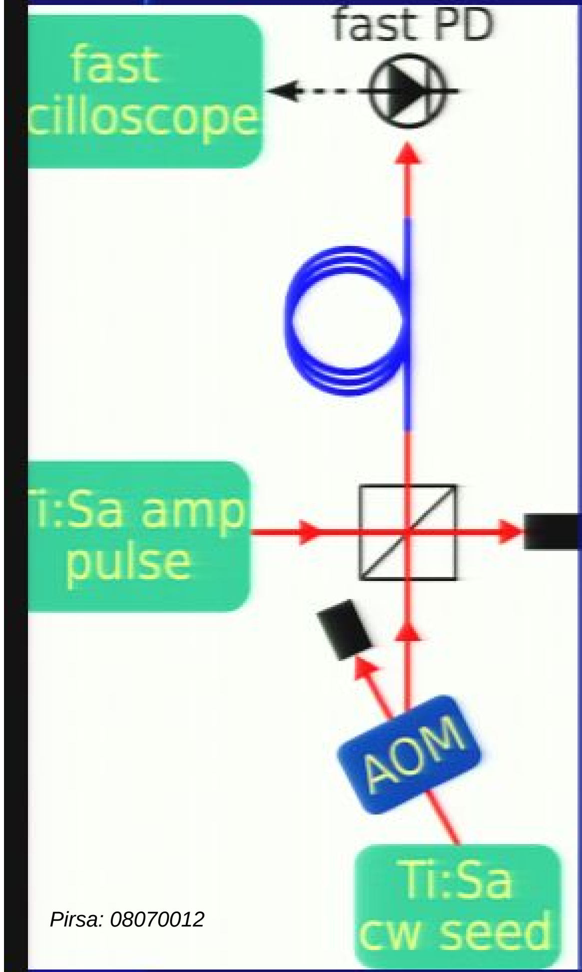


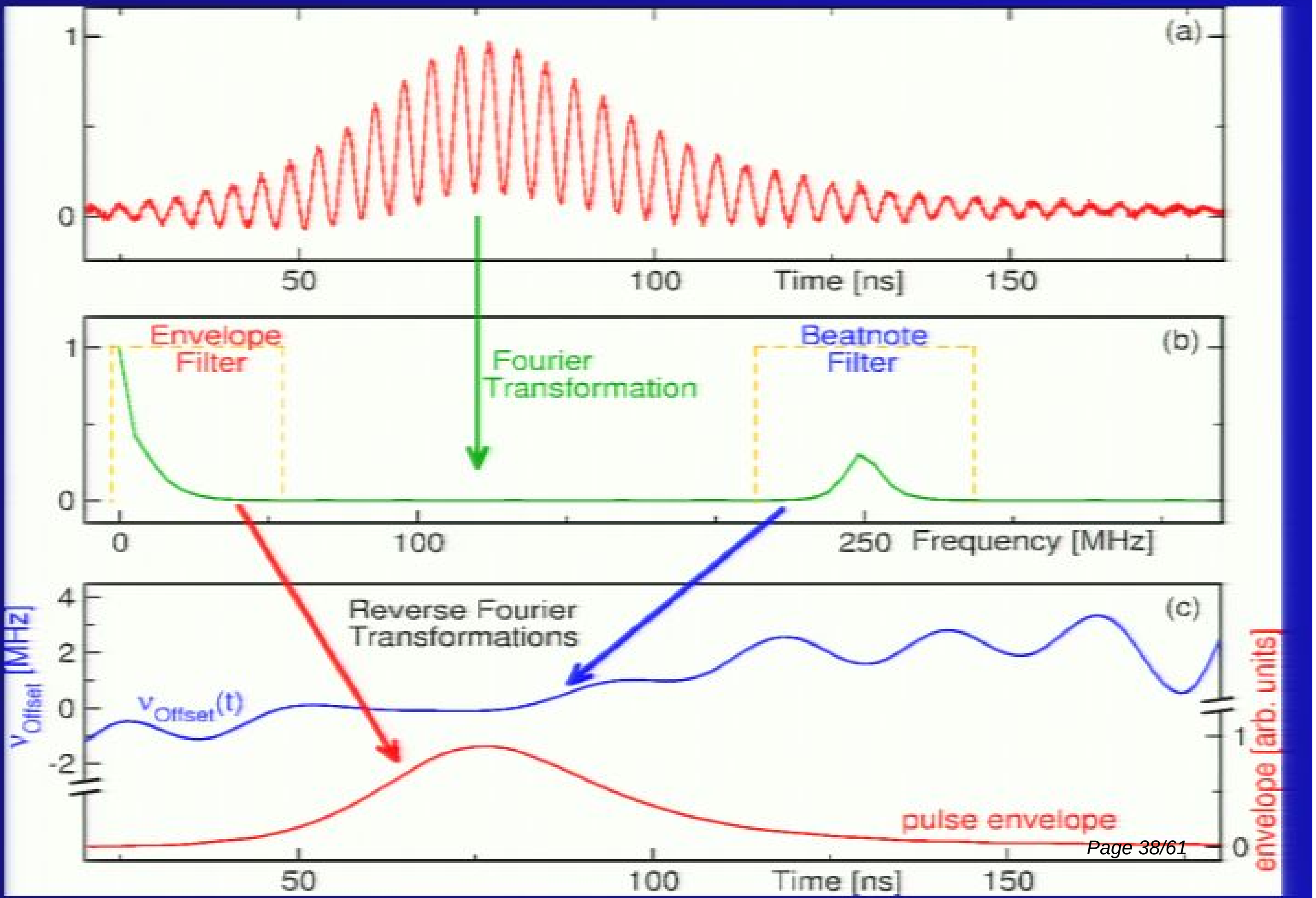
Bowtie amplifier





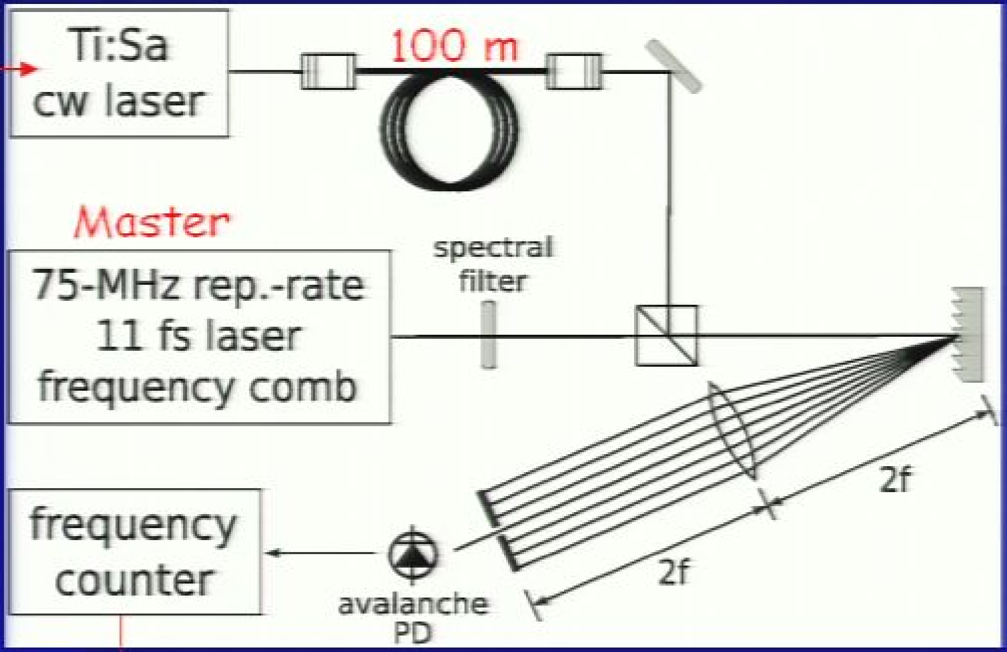
Measurement of frequency chirp: online





1. Absolute calibration via Frequency-comb laser

Measure f_{cw} via beat-note comb



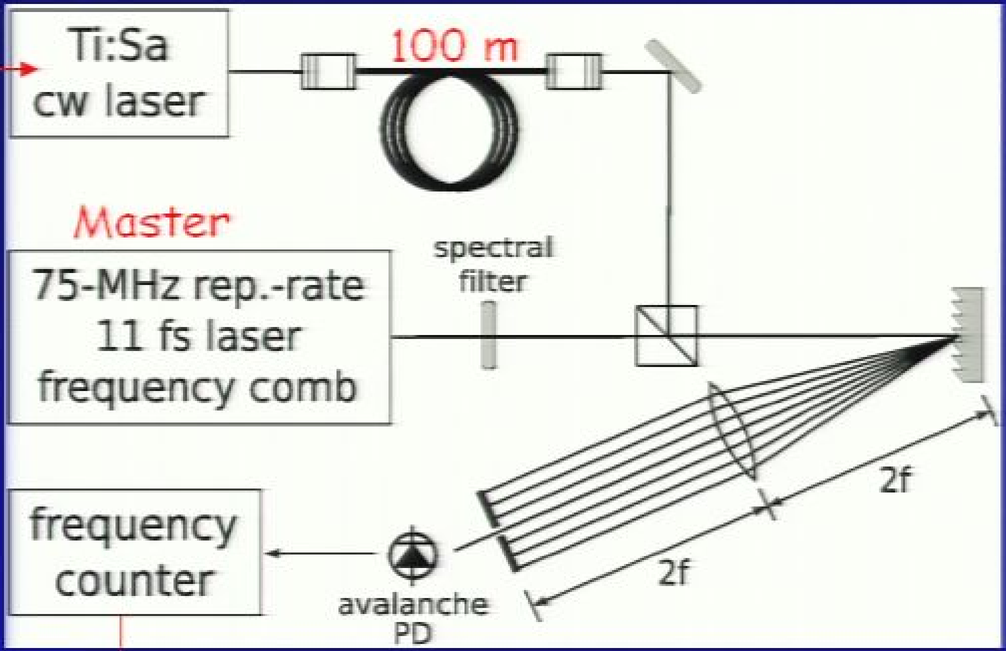
Fix at 22 MHz

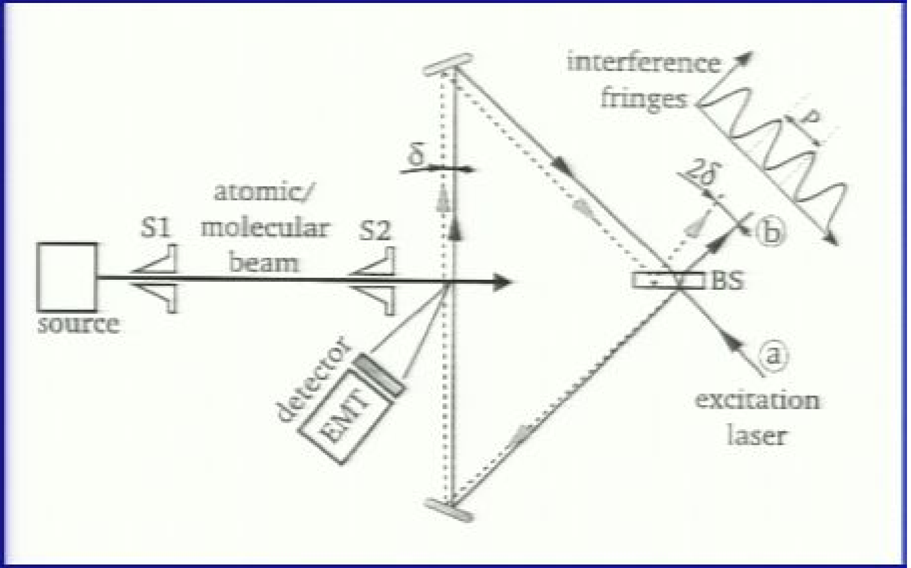
Laser Centre
vrije Universiteit amsterdam

1. Absolute calibration via Frequency-comb laser

2. Two-photon Doppler-free spectroscopy in a Sagnac configuration

Measure f_{cw} via beat-note comb





Sagnac scheme:
Hannemann et al.,
Opt. Lett, June 2007

Fix at 22 MHz

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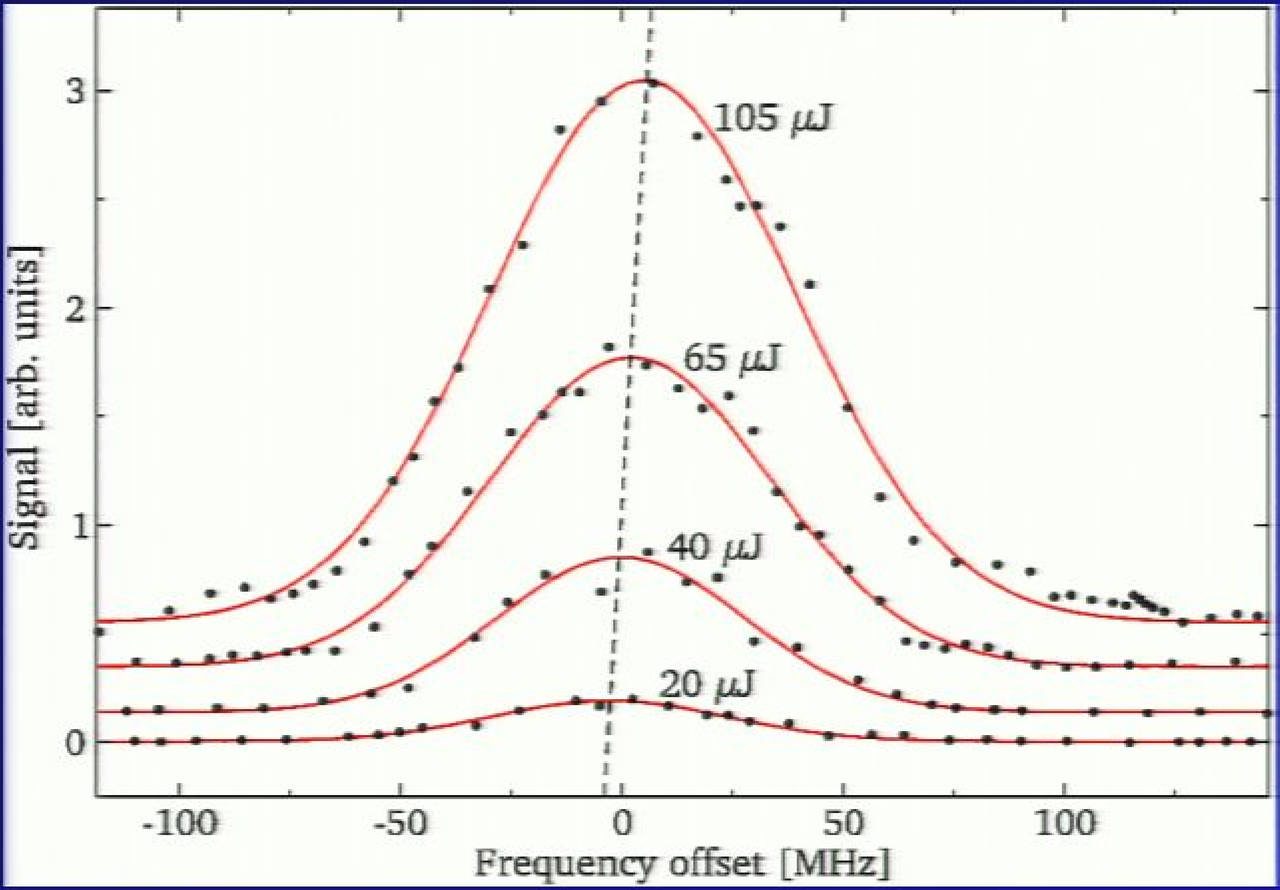
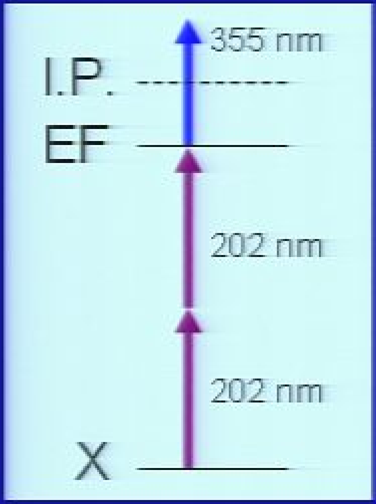
vrije Universiteit amsterdam

Avoiding AC-Stark effect by ionization laser





Two-photon laser at 2-4 μJ/pulse

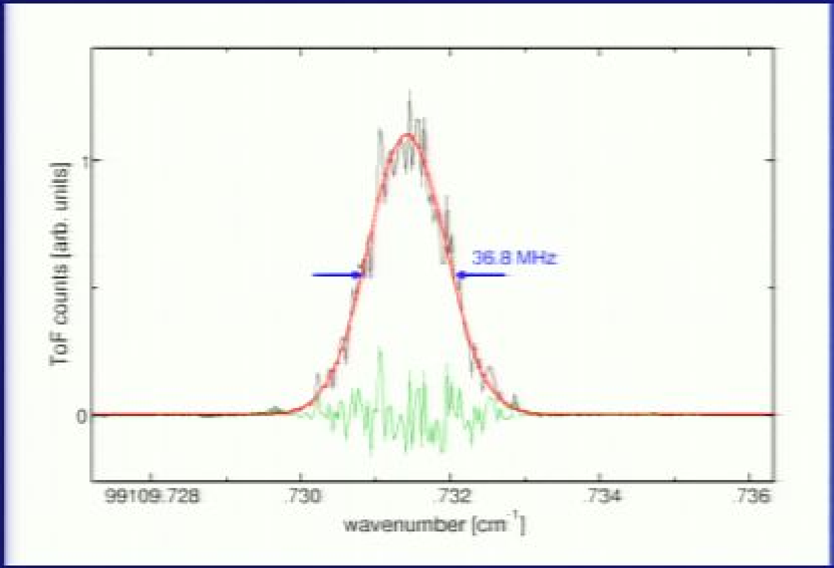
Ionization by delayed pulse at 355 nm

PHYSICAL REVIEW A 74, 062514 (2006)

Frequency metrology on the $EF\ {}^1\Sigma_g^+ \leftarrow X\ {}^1\Sigma_g^+(0,0)$ transition in H_2, HD, and D_2

S. Hannemann, E. J. Salumbides, S. Witte, R. T. Zinkstok, E. -J. van Duijn, K. S. E. Eikema, and W. Ubachs
Laser Centre, Department of Physics and Astronomy, Vrije Universiteit, De Boelelaan 1081, 1081 HV Amsterdam, The Netherlands

(Received 11 October 2006; published 28 December 2006)

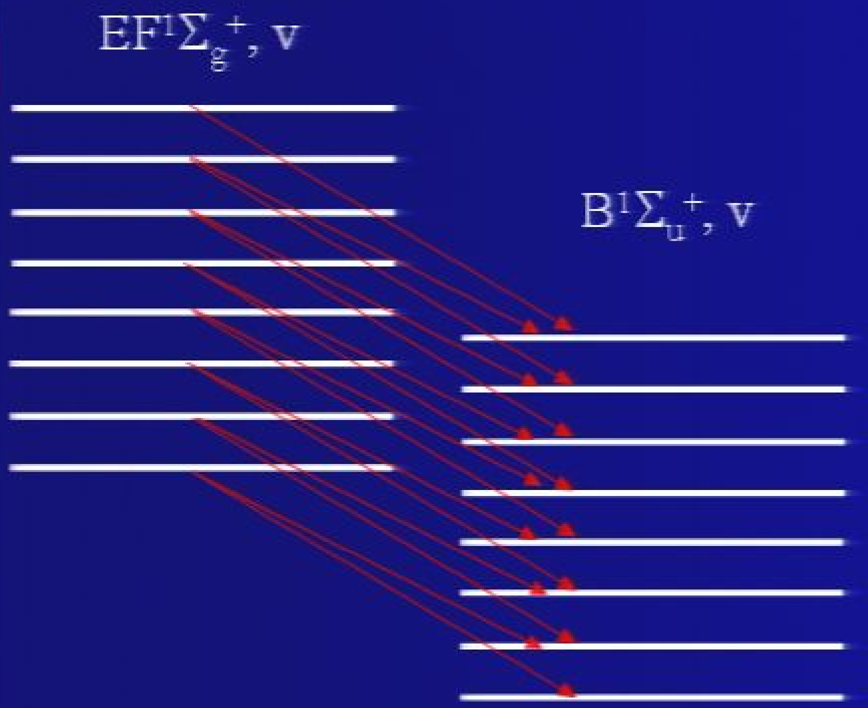


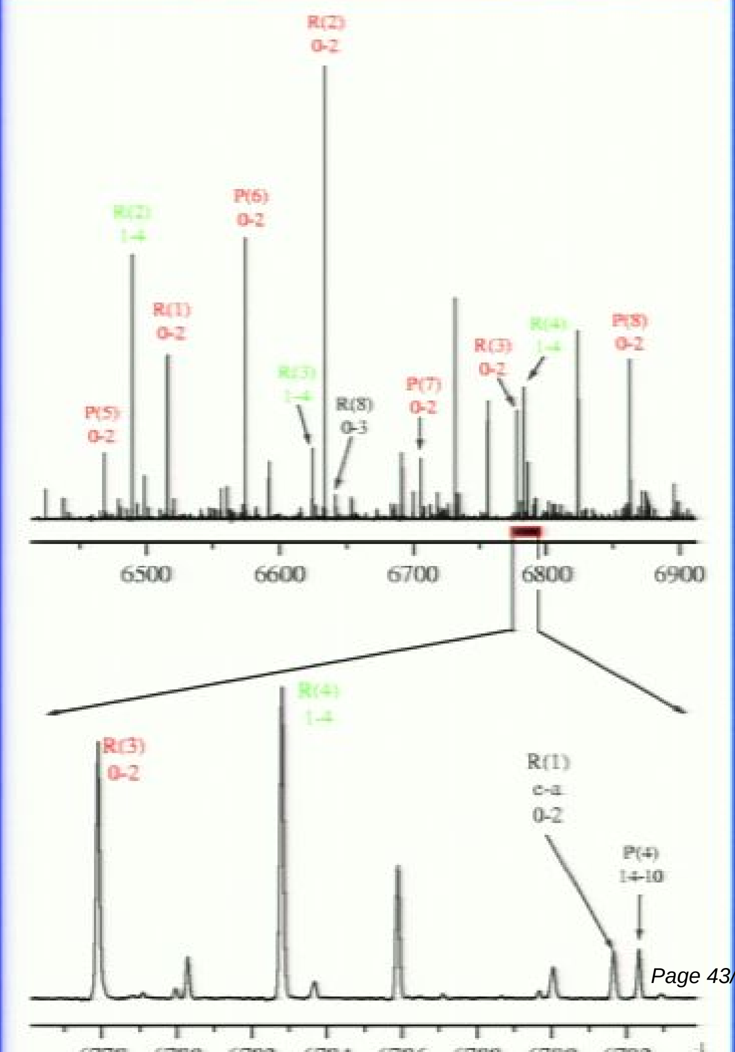
Species	Line	This work (cm^{-1})	Ref. [19] (cm^{-1})	Δ (cm^{-1})
H_2	Q(0)	99 164.786 91(11)	99 164.7871(8)	−0.0002
	Q(1)	99 109.731 39(18)	99 109.7316(8)	−0.0002
	Q(2)	99 000.183 01(11)		
HD	Q(0)	99 301.346 62(20)	99 301.3461(8)	+0.0005
	Q(1)	99 259.917 93(20)	99 259.9184(8)	−0.0005
D_2	Q(0)	99 461.449 08(11)	99 461.4490(8)	+0.0001
	Q(1)	99 433.716 38(11)	99 433.7166(8)	−0.0002
	Q(2)	99 378.393 52(11)	99 378.3937(8)	−0.0002

$\Delta\lambda/\lambda \sim 1 \times 10^{-9}$

FT-IR data on $EF^1\Sigma_g^+$ - $B^1\Sigma_u^+$ under analysis

with Michel Vervloet & Denise Bailly (Orsay)



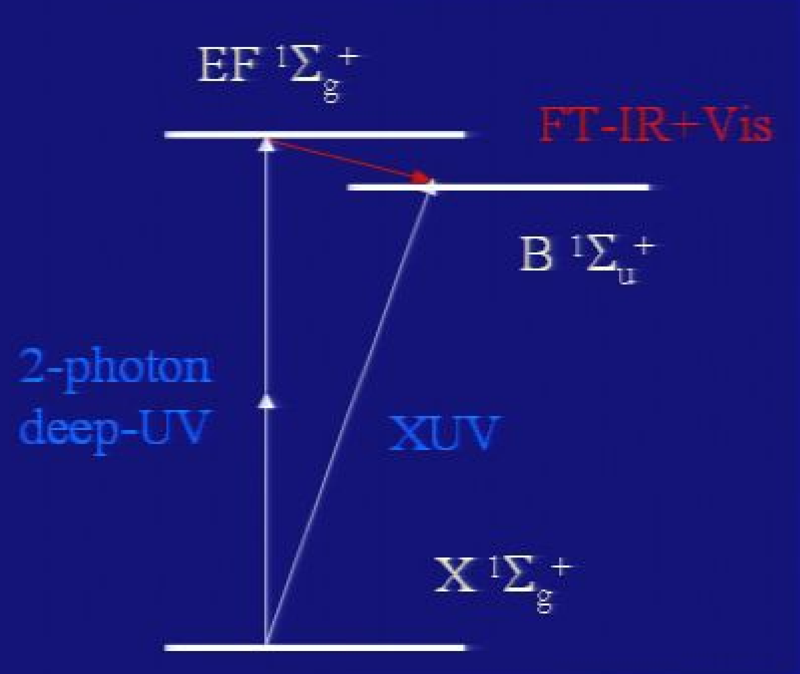


Statistical averaging
Level energies

Accuracy

Improved laboratory data

The quest now fully relies on astrophysical data

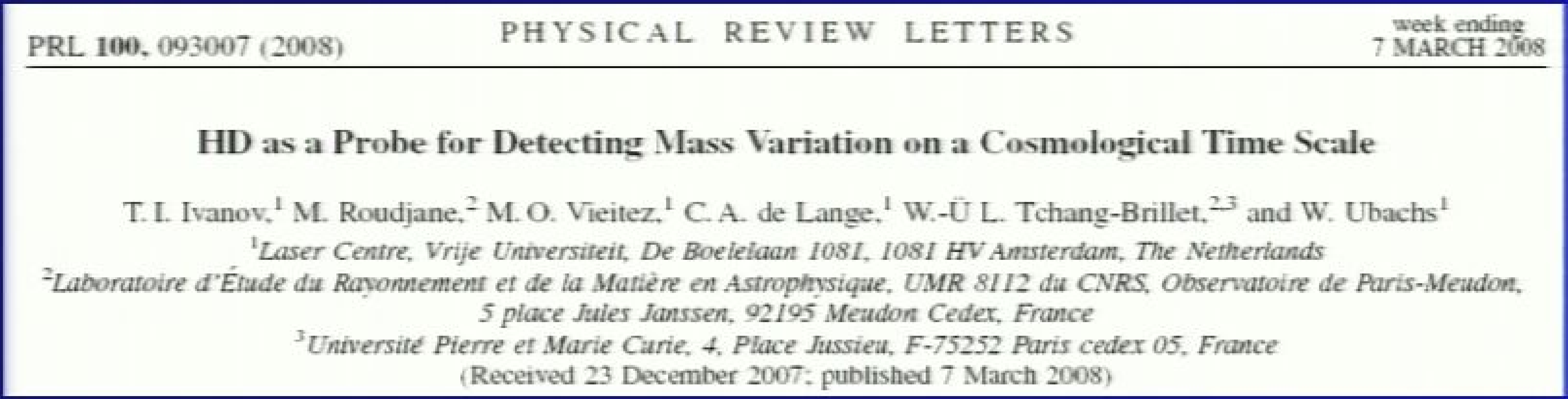


Improvement accuracy on Lyman bands

→ $\Delta\lambda/\lambda \sim 1\text{-}5 \times 10^{-9}$

Werner bands slightly less accurate

HD The "laboratory works"



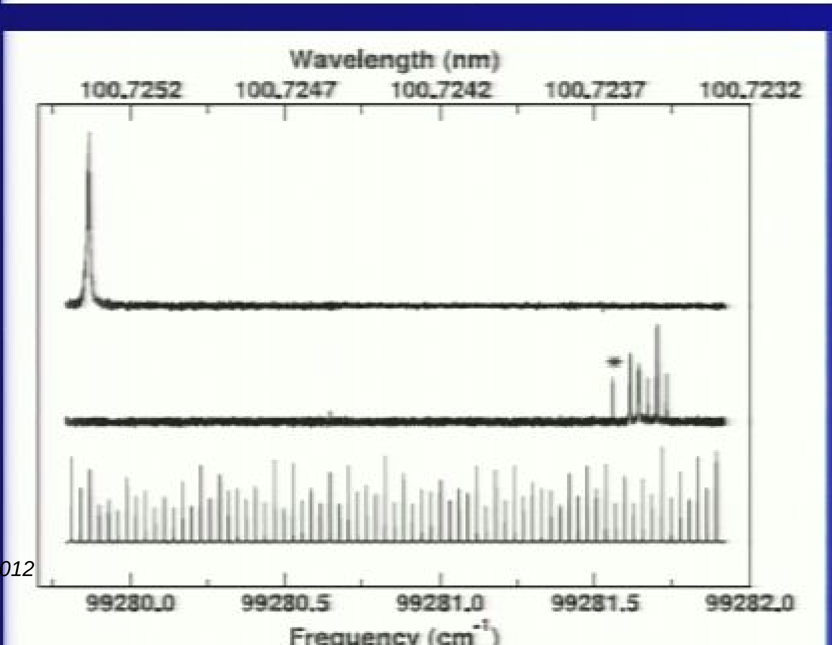
PRL **100**, 093007 (2008) PHYSICAL REVIEW LETTERS week ending 7 MARCH 2008

HD as a Probe for Detecting Mass Variation on a Cosmological Time Scale

T. I. Ivanov,[1] M. Roudjane,[2] M. O. Vieitez,[1] C. A. de Lange,[1] W.-Ü L. Tchang-Brillet,[2,3] and W. Ubachs[1]

[1]*Laser Centre, Vrije Universiteit, De Boelelaan 1081, 1081 HV Amsterdam, The Netherlands*
[2]*Laboratoire d'Étude du Rayonnement et de la Matière en Astrophysique, UMR 8112 du CNRS, Observatoire de Paris-Meudon, 5 place Jules Janssen, 92195 Meudon Cedex, France*
[3]*Université Pierre et Marie Curie, 4, Place Jussieu, F-75252 Paris cedex 05, France*

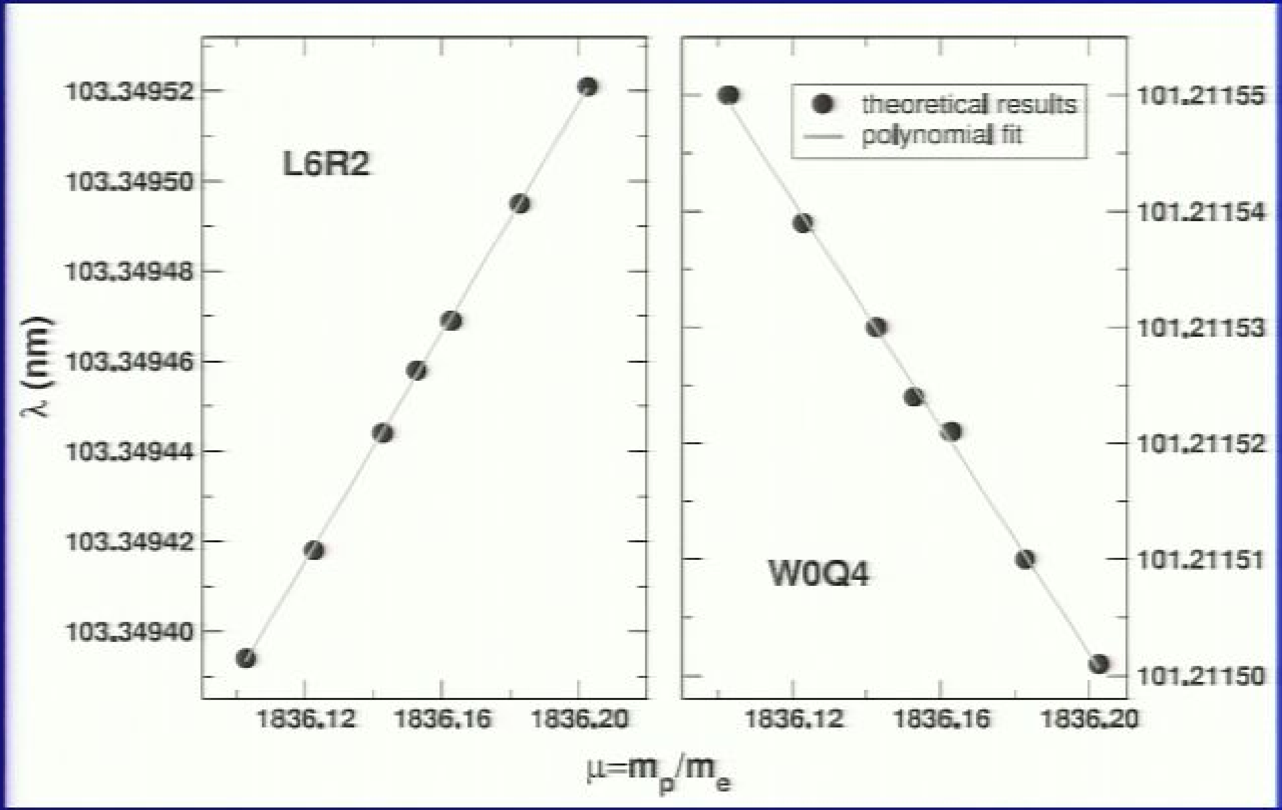
(Received 23 December 2007; published 7 March 2008)



Spectral lines

Limited to range 100-110 nm (5 x 10^{-8})

HD Quantum ab initio calculations of K_i coefficients



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

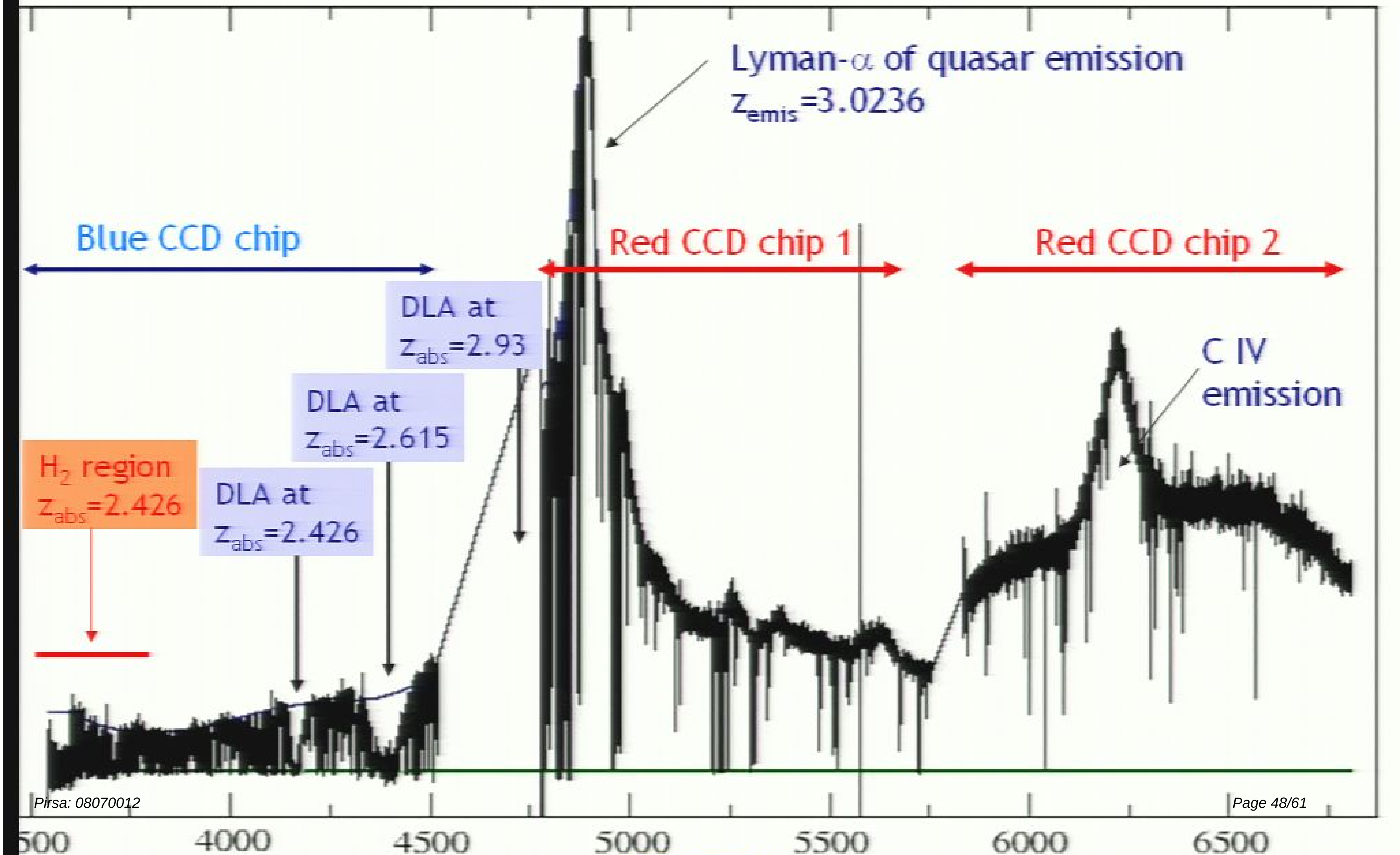
Do molecules probe Mp/me ?

Future:
“composition-
dependent

Progress on the astrophysical side

QSO 1: Q2348 (VLT)

B= 18.5 mag
19.5 h of spectral observation with ThAr calibr.



QSO 1: Q2348 (VLT)

B= 18.5 mag
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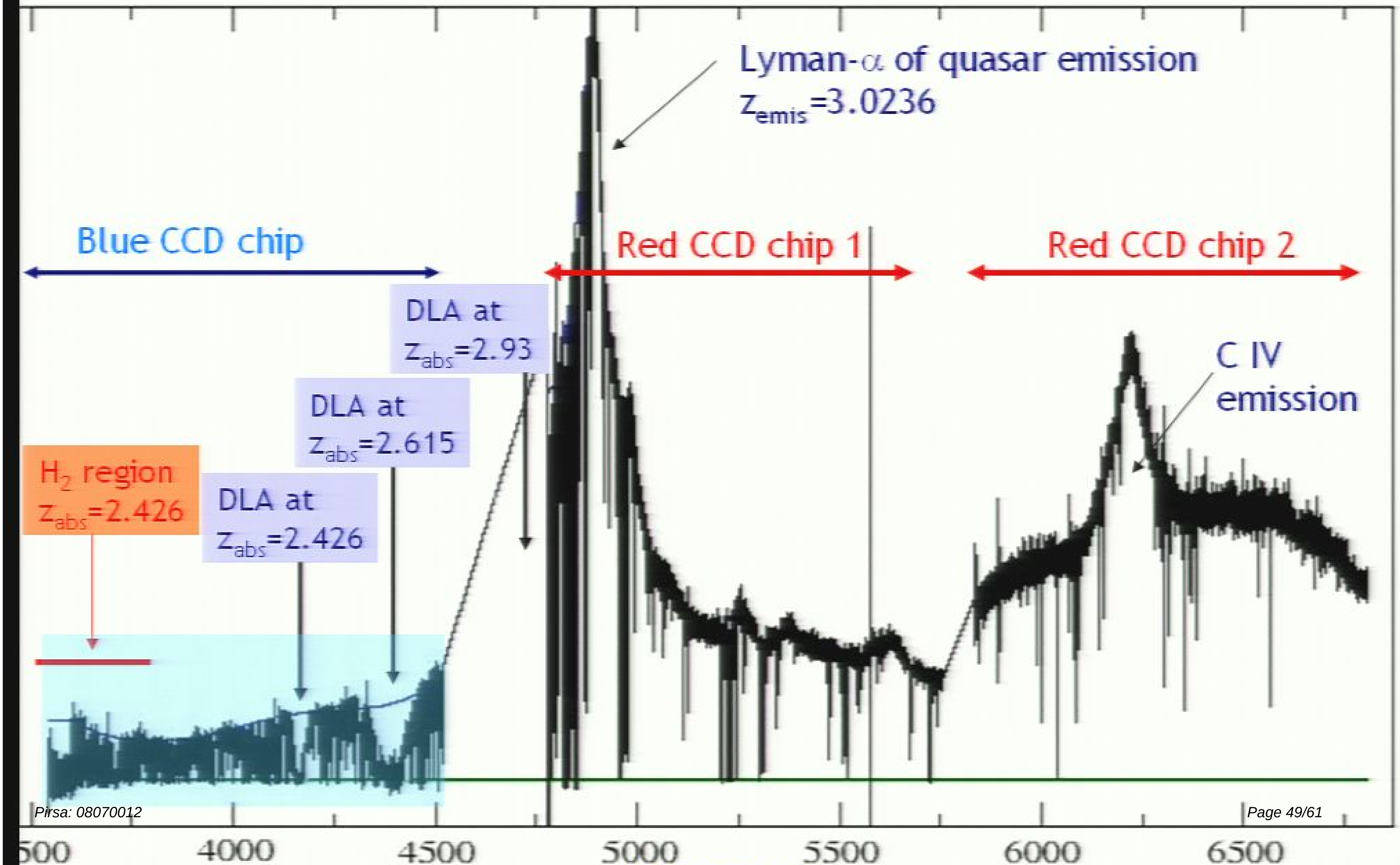


Lyman-α of quasar emission
z_{emis}=3.0236

Blue CCD chip

Red CCD chip 1

Red CCD chip 2

DLA at
z_{abs}=2.93

DLA at
z_{abs}=2.615

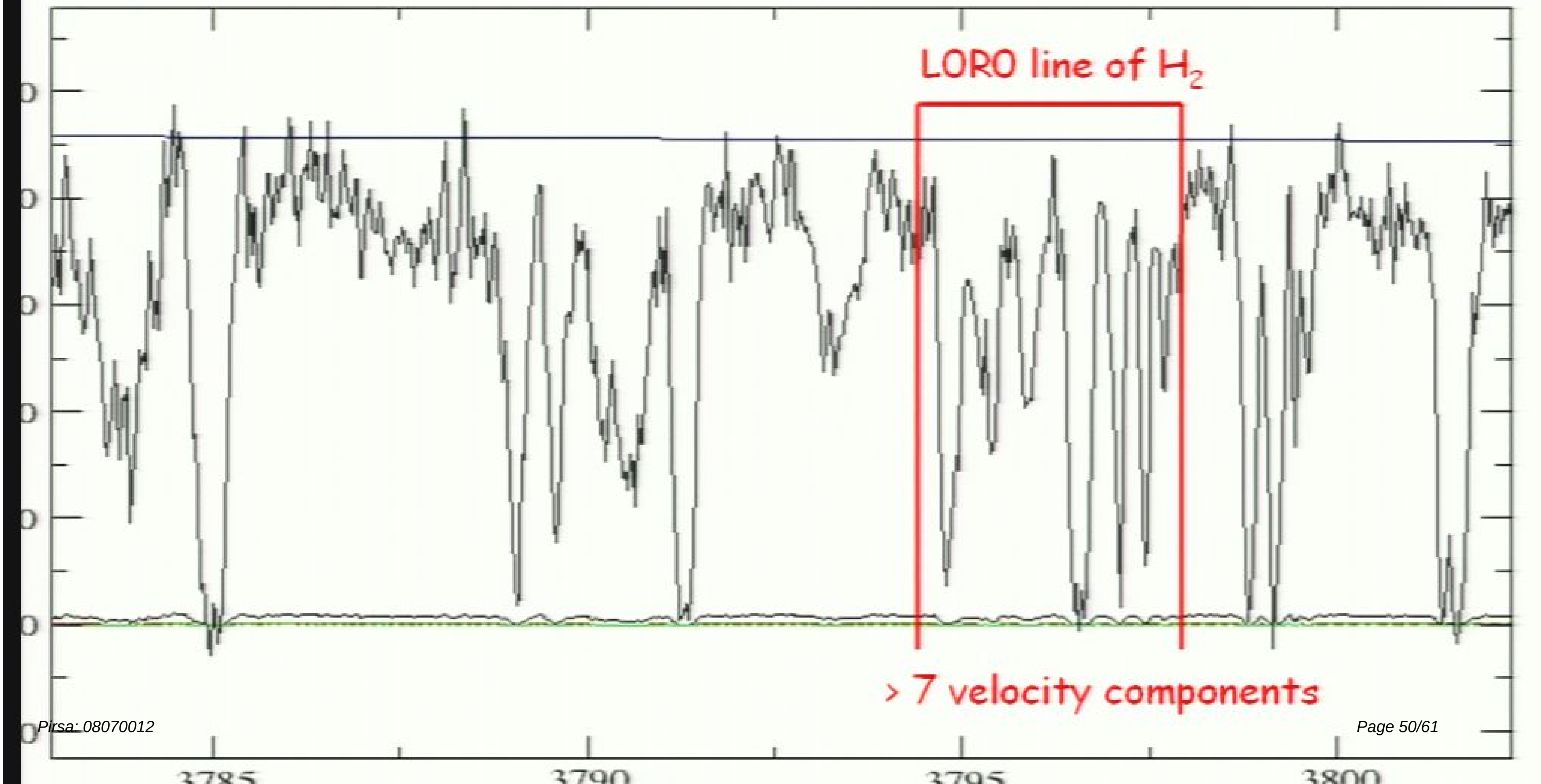
DLA at
z_{abs}=2.426

H_2 region
z_{abs}=2.426

C IV
emission

H_2 in Q2348-011; velocity components

Buning, Murphy, Kaper, Ubachs

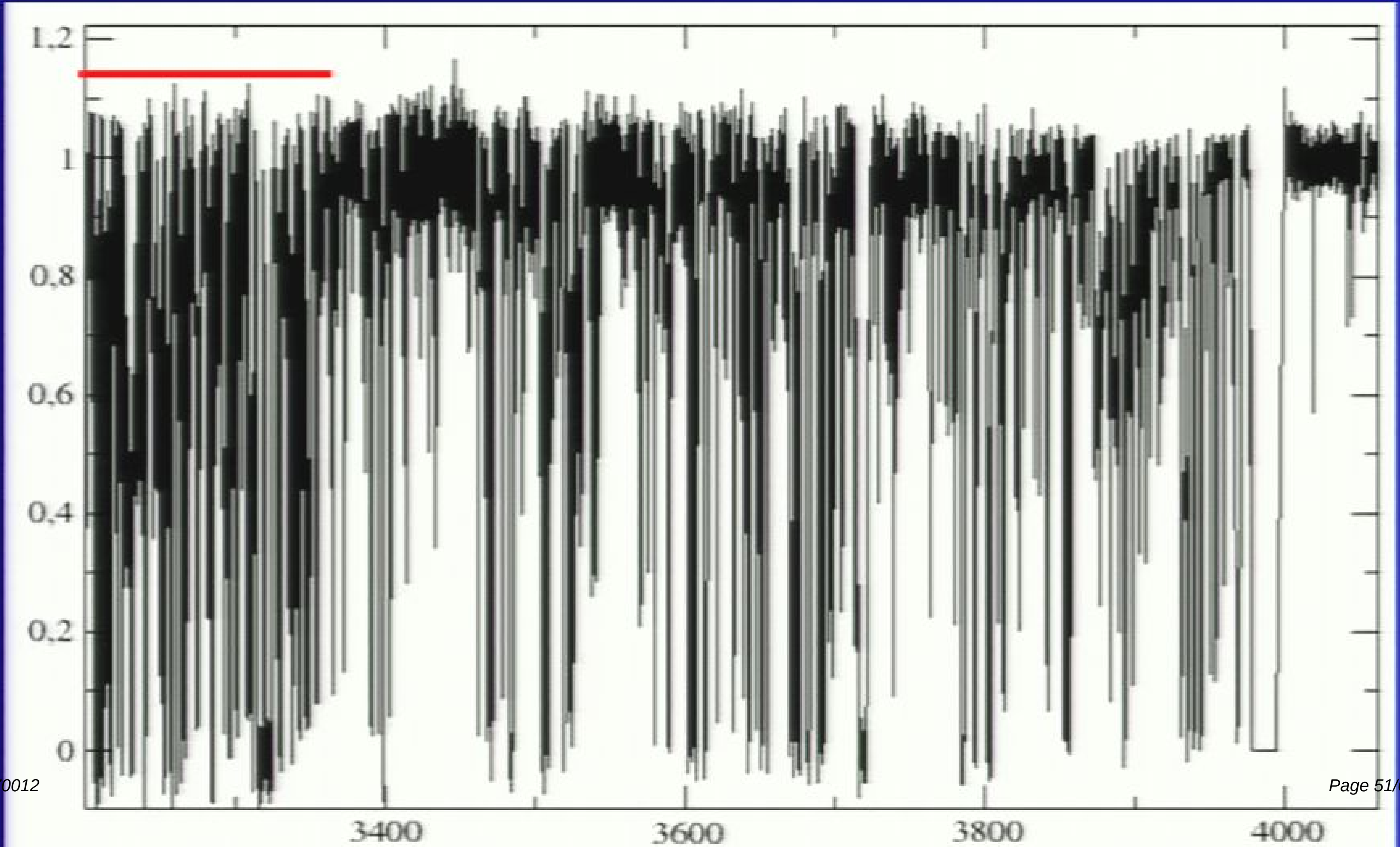


J2123 from HIRES-Keck at Hawaii (normalized)

(J. Prochaska)

Resolution 110000 : z_{abs}=2.0593

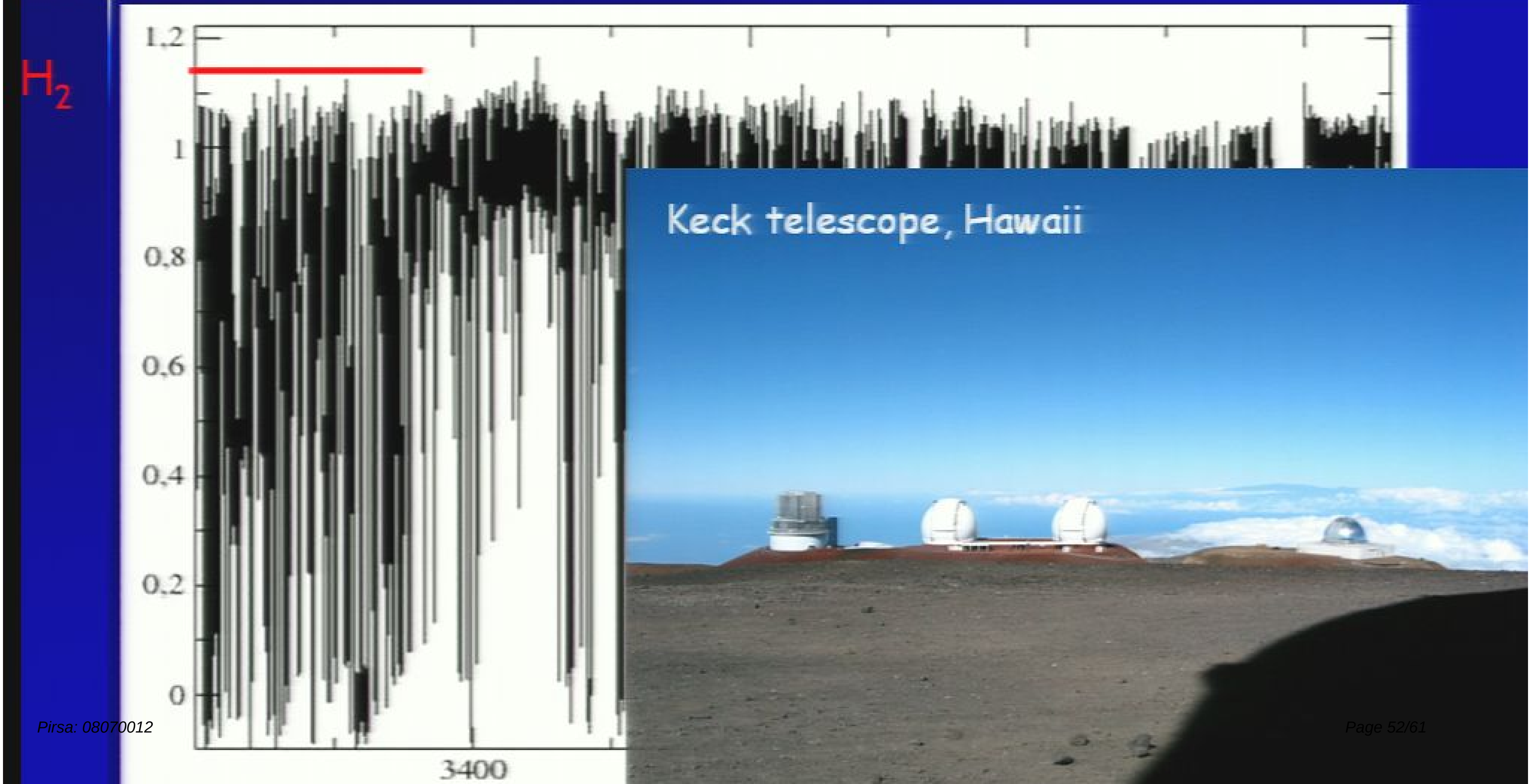
H_2

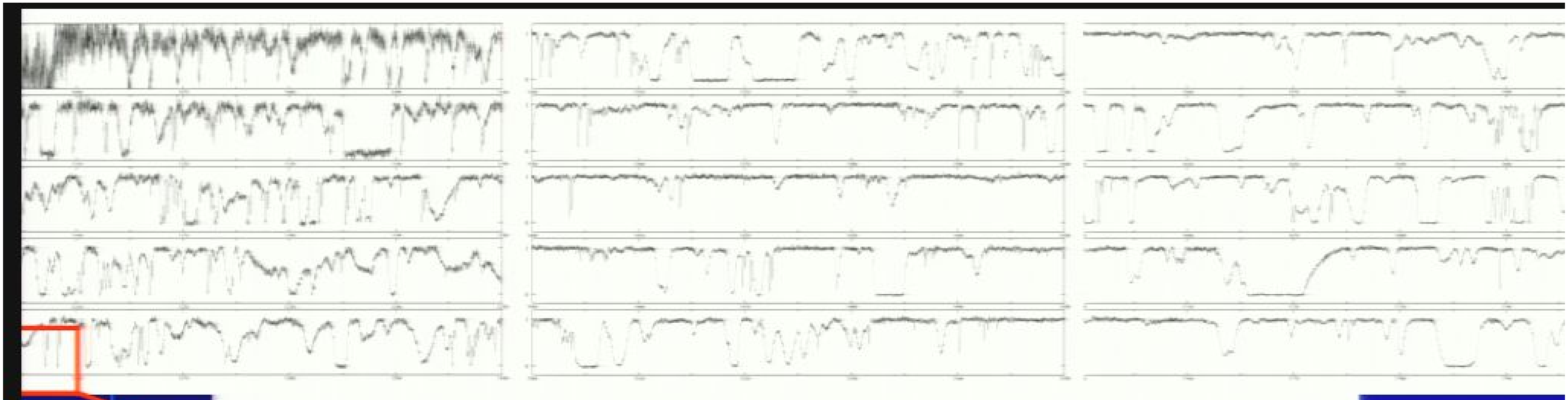


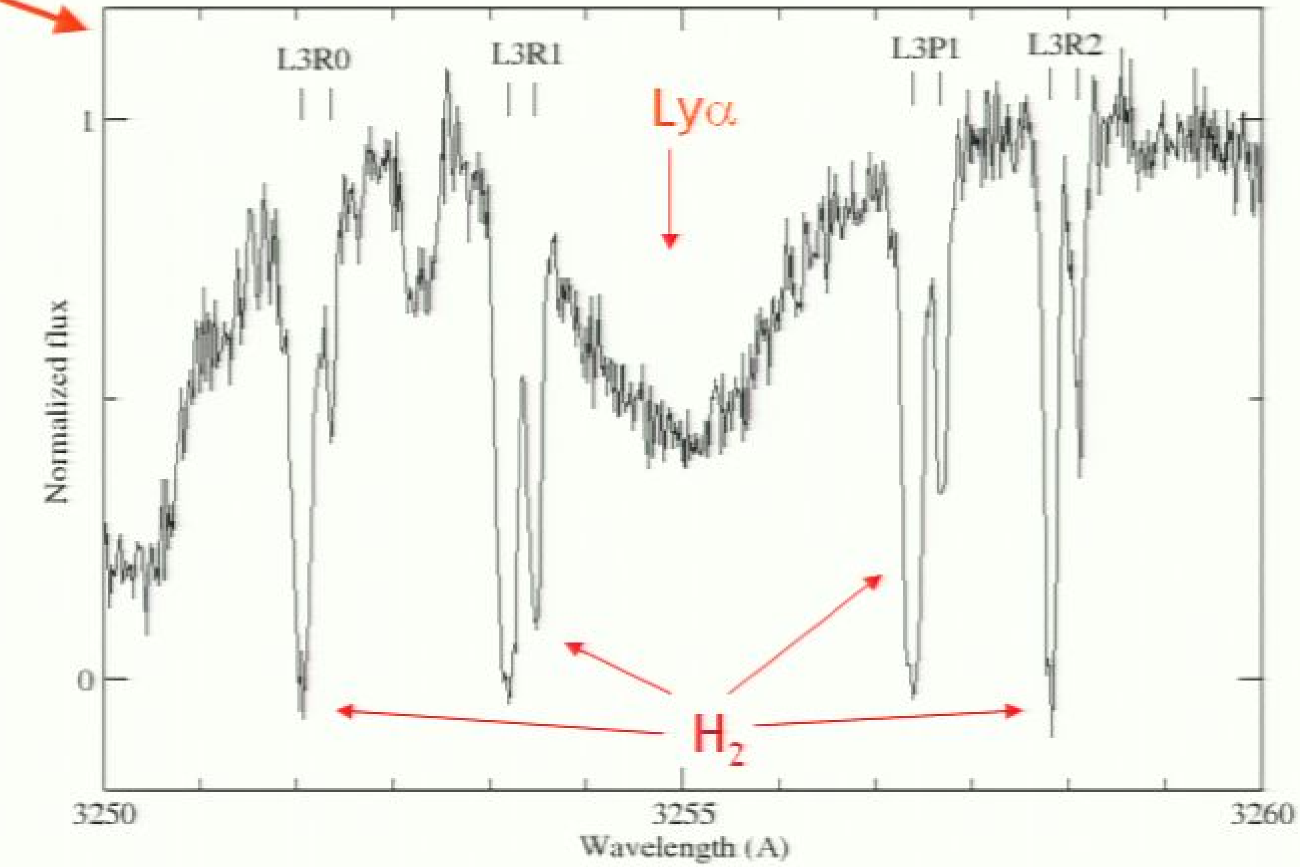
J2123 from HIRES-Keck at Hawaii (normalized)

(J. Prochaska)

Resolution 110000 : z_{abs}=2.0593



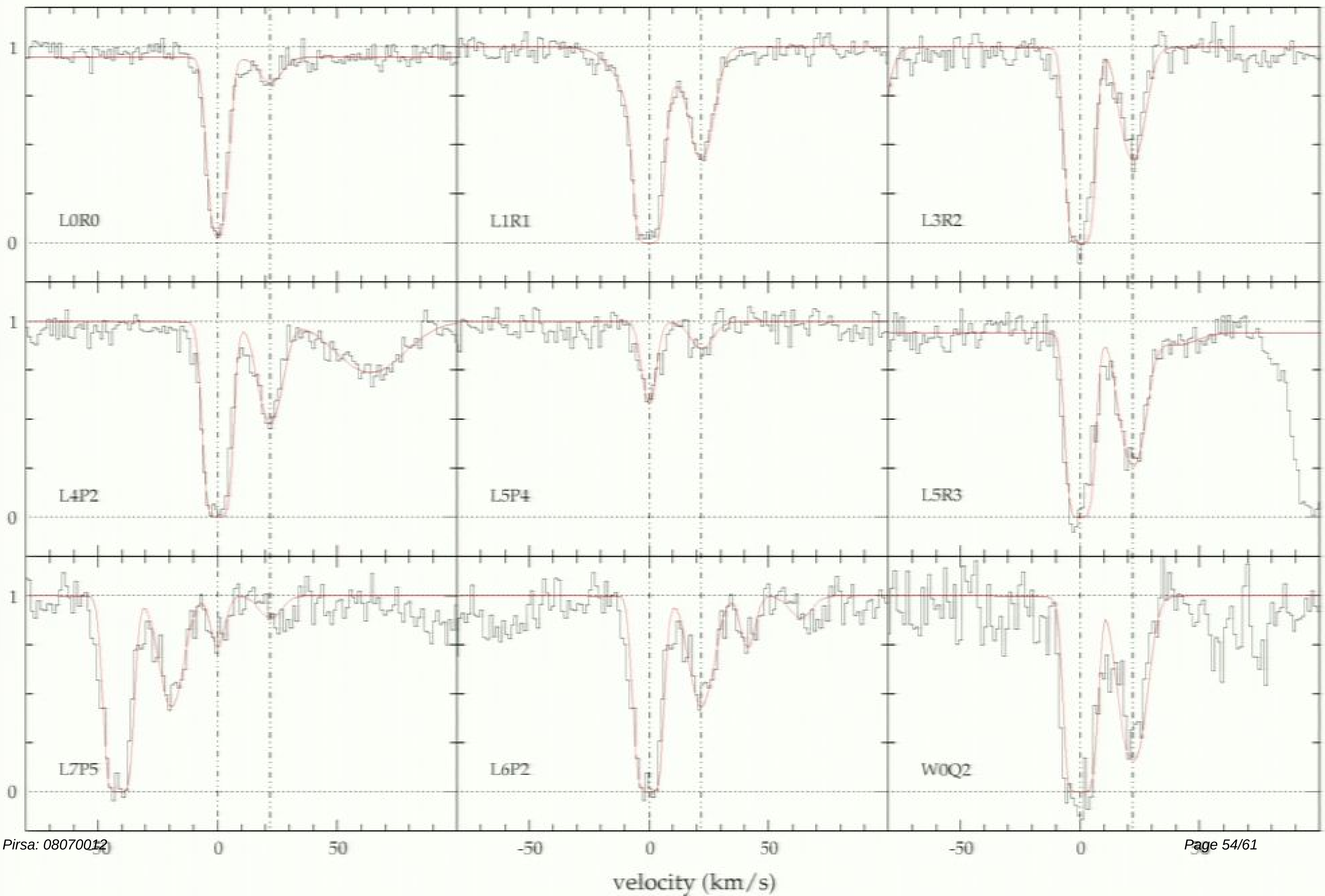




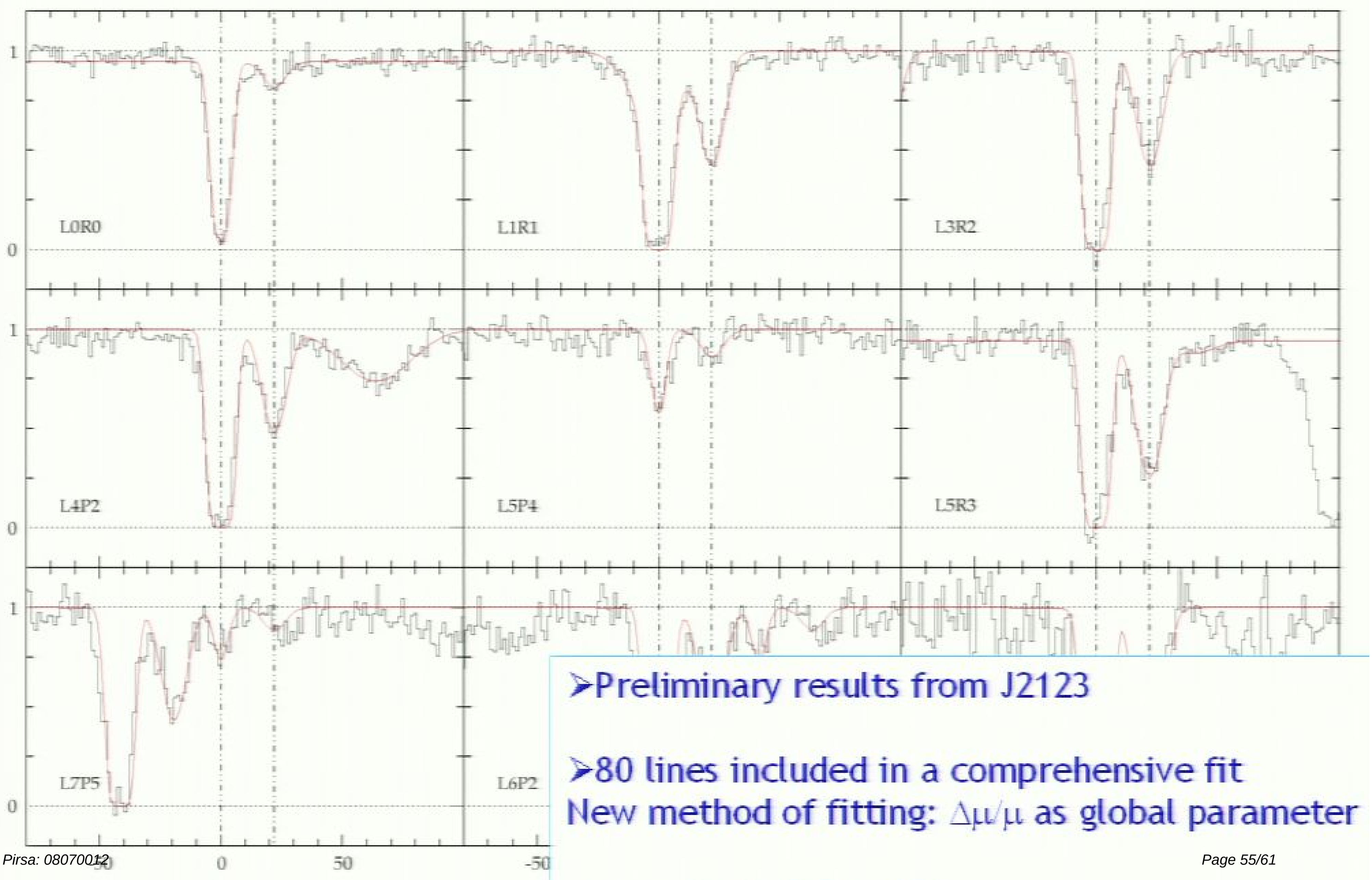
SO:
123
rochaska
al.

=110000

J2123, $z_{abs} = 2.0593426$, H2 lines



J2123, $z_{abs} = 2.0593426$, H2 lines



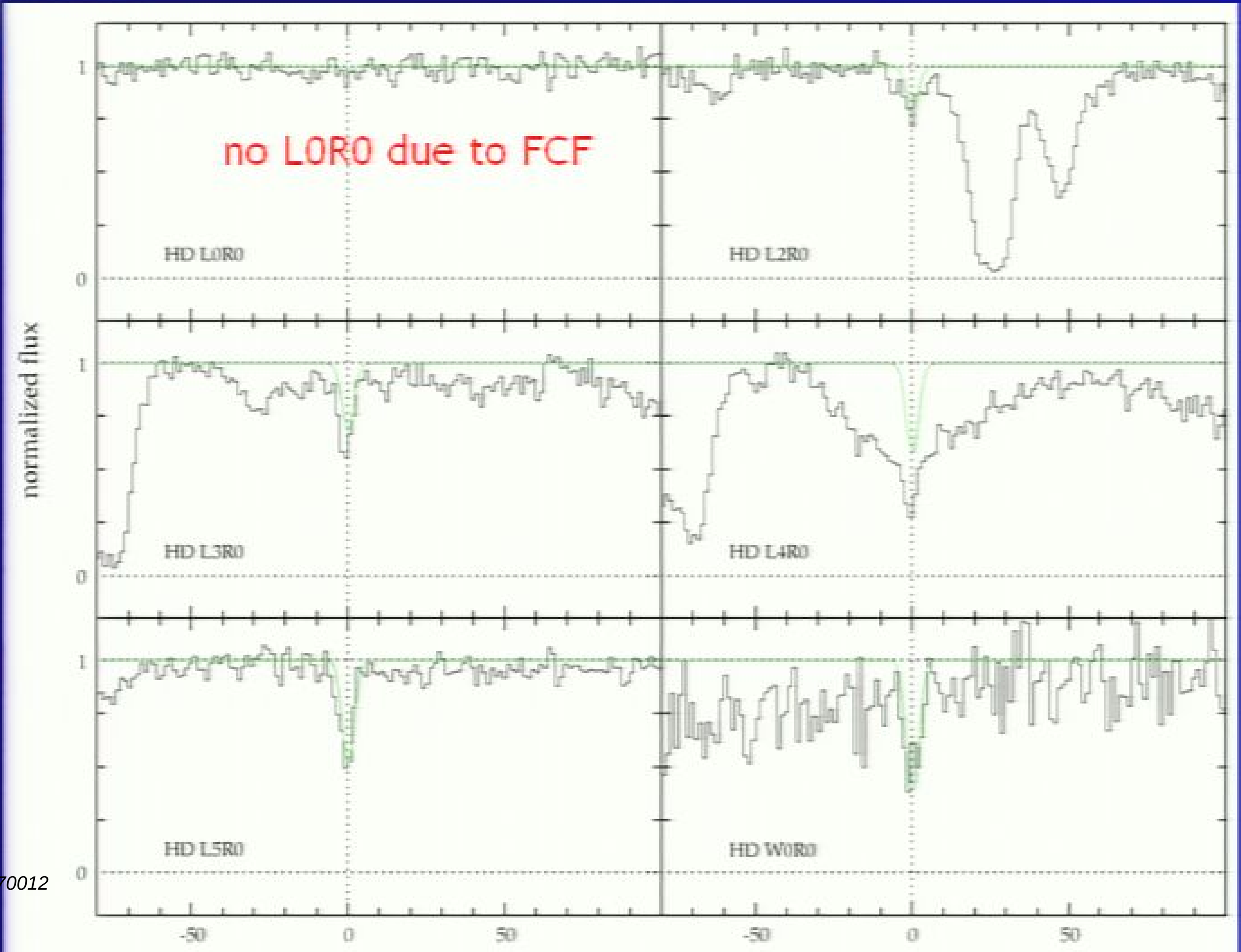
- ➢Preliminary results from J2123

- ➢80 lines included in a comprehensive fit

New method of fitting: $\Delta\mu/\mu$ as global parameter

$\Delta\mu/\mu \approx$ (x.x ± 0.5) x 10^{-5}

HD observed in J2123



HD observed
(7 lines)

-only in J=0
ground state

log N(HD) = 13.75 (3)

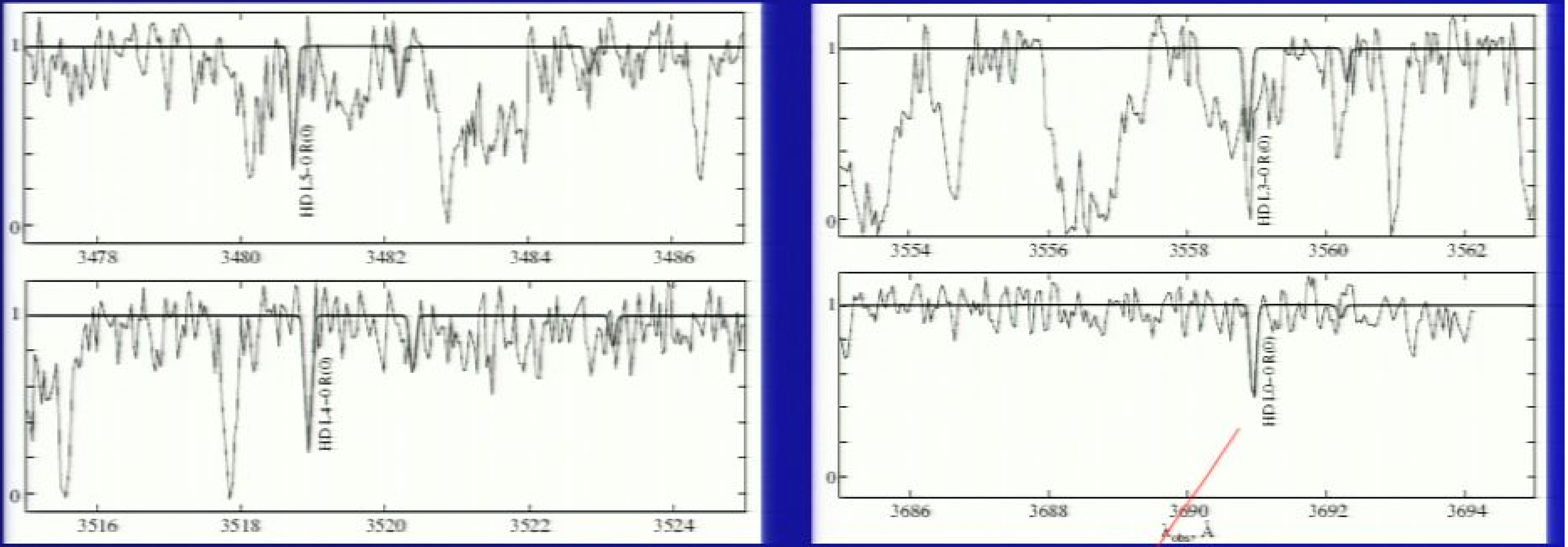
$N(HD/H_2) = 3 \times 10^{-3}$

HD Molecular Lines in an Absorption System at Redshift $z = 2.3377$

D. A. Varshalovich[1, *], A. V. Ivanchik[1], P. Petitjean[2], R. Srianand[3], and C. Ledoux[4]

Q1232

Astronomy Letters 11, 683 (2001)

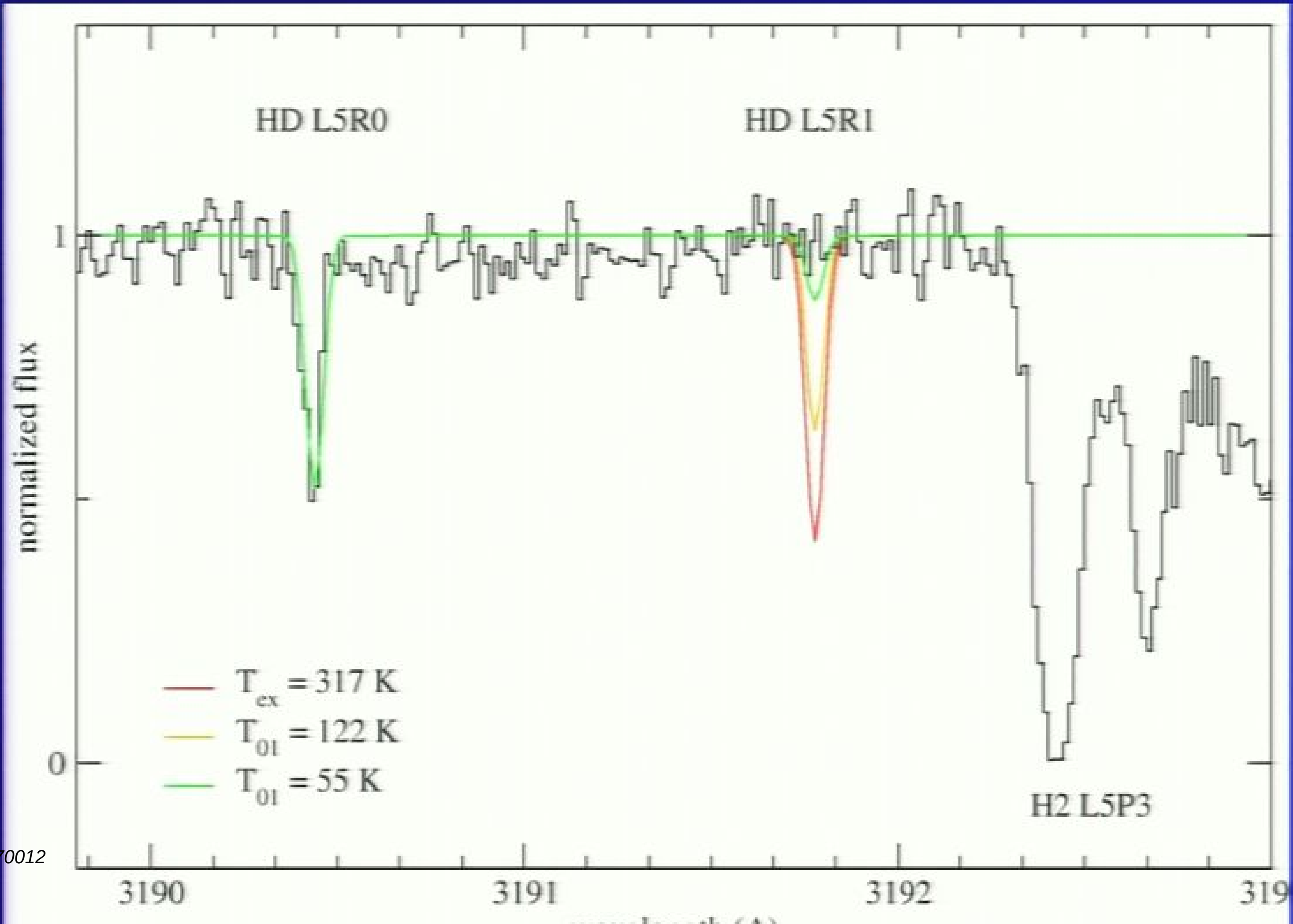


L0 R0

Should be much weaker,

HD density

A possible clue for early chemistry ?



T_{01} (H_2) = 120 K

T (HD) < 50 K

Conclusion:

- QSO H_2 spectra for $\Delta\mu/\mu$ determination

  - Q0347: 37 lines
  - Q0405: 39 lines

$$\left.\begin{array}{l}\\ \\ \end{array}\right\} \frac{\Delta\mu}{\mu} = (2.5 \pm 0.6)\times 10^{-5}$$

Based on line fits

Re-analyses:
-Wendt & Reimers
-King & Webb
-Thompson

Keck

  - J2123: ~ 80 lines (including HD) $\frac{\Delta\mu}{\mu} = (x \pm \Delta x)\times 10^{-5}$

  - Q2348: ~25 lines - observed at VLT- analysis in progress

  - HE0027 ~70 lines (Petitjean team)

VLT

  - J2123: the best spectrum available
    16 hours observation time granted summer 2008 (VLT)

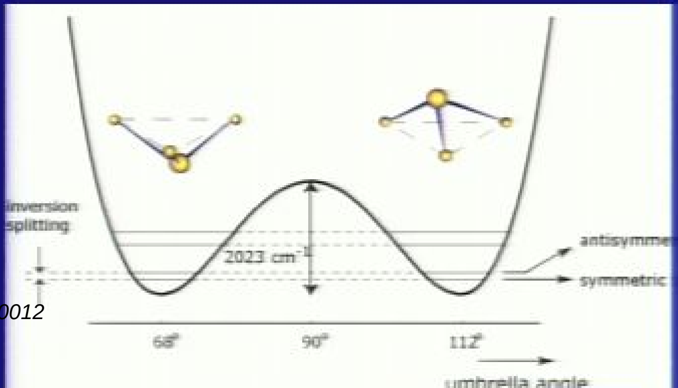
  - Q0528 : to be re-observed at VLT winter 2008, early 2009

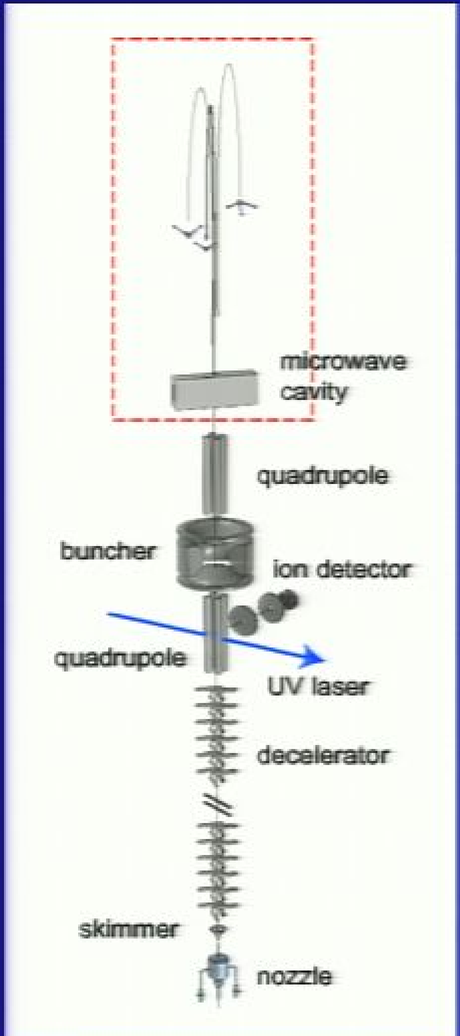
Δμ in the present epoch ?

The Amsterdam molecular fountain

Rick Bethlem

NH_3, the sensitive molecule





Variation of constants: only in the early epoch ?

Phase transition in universe ?