Title: Testing the m_p/m_e cosmological variation from H_2 lines in High-Redshift QSO spectra

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Abstract:

Testing $\mu = m_p/m_e$ *cosmological variation from* H_2 *lines in high-redshifted QSO spectra*

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W.Ubachs, E.Reinhold

2008, Waterloo

Dirac

Nature, 1937

"Large Number Hypothesis"

$$G \sim t^{-1}$$

Contemporary theoretical models of unification of all the physical interactions ***predict variations of fundamental physical constants*** *in the course of the cosmological evolution.*

In particular, Superstring/M-theory predict time-variations of coupling constants and masses of elementary particles:

$$g_i = g_i[f(\phi)] \quad \text{and} \quad m_i = m_i[f(\phi)]$$

However, different theories predict different variations and different relations between constants (e.g. $\alpha = e^2/\hbar c$ and $\mu = m_p/m_e$; Calmet & Fritzsch, 2002, Phys.Lett.B540; Langacker et al., 2002, Phys.Lett.B528; Flambaum & Shuryak, 2002, Phys.Rev.D65):

$$\alpha(\mu) \iff \mu(\alpha)$$

Searching of μ-variation becomes more significant after possible finding of α-variation (Webb et. al.).
Experimental detection or even determination of rigid upper limit on μ-variation would be an important tool for selection of theoretical models of the fundamental physical interactions.

The last observational results

Epoch	Reference	Constant	$\Delta x/x$	$\dot{x}/x$, yr^{-1}
"Now and Here"	2007 Fortier et al.	α	$(3.6 \pm 6.0) \times 10^{-15}$	$(-0.6 \pm 1.0) \times 10^{-15}$
	2006 Peik et al.	α	$(1.6 \pm 2.3) \times 10^{-15}$	$(-0.3 \pm 0.4) \times 10^{-15}$
	2003 Bize et al.	α	$< 2.4 \times 10^{-15}$	$< 1.2 \times 10^{-15}$
	1995 Prestage et al.	α	$< 3.7 \times 10^{-14}$	$< 3.7 \times 10^{-14}$
"Oklo"	2006 Petrov et al.	α	$(0.1 \pm 0.7) \times 10^{-7}$	$(-0.5 \pm 3.5) \times 10^{-17}$
	2004 Lamoreaux et al.	α	$\mathbf{(4.5 \pm 0.2) \times 10^{-8}}$	$(-2.3 \pm 0.1) \times 10^{-17}$
	2003 Fujii et al.	α	$\mathbf{(8.8 \pm 0.7) \times 10^{-8}}$	$(-4.4 \pm 0.4) \times 10^{-17}$
"QSO"	2007 Levshokov et al.	α	$\mathbf{(5.4 \pm 2.5) \times 10^{-6}}$	$(-5.4 \pm 2.5) \times 10^{-16}$
	2004 Chand et al.	α	$(-0.6 \pm 0.6) \times 10^{-6}$	$(0.6 \pm 0.6) \times 10^{-16}$
	2003 Murphy et al.	α	$\mathbf{(-0.5 \pm 0.1) \times 10^{-5}}$	$(6.4 \pm 1.4) \times 10^{-16}$
	1999 Webb et al.	α	$\mathbf{(-1.1 \pm 0.4) \times 10^{-5}}$	$(2.2 \pm 5.1) \times 10^{-16}$
	2006 Reinhold et al.	μ	$\mathbf{(2.0 \pm 0.6) \times 10^{-5}}$	$(2.0 \pm 0.6) \times 10^{-15}$
	2005 Ivanchik et al.	μ	$\mathbf{(1.7 \pm 0.7) \times 10^{-5}}$	$(1.7 \pm 0.7) \times 10^{-15}$
	2005 Kanekar et al.	μ	$< 1.4 \times 10^{-5}$	$< 2.1 \times 10^{-15}$
	1995 Cowie & Songaila	μ	$(0.8 \pm 6.3) \times 10^{-4}$	$(0.8 \pm 6.3) \times 10^{-14}$
	2007 Tzanavaris et al.	$\alpha^2 g_p \mu^{-1}$	$(0.6 \pm 2.0) \times 10^{-5}$	$(0.6 \pm 2.0) \times 10^{-15}$
	1995 Cowie & Songaila	$\alpha^2 g_p \mu^{-1}$	$(0.7 \pm 1.1) \times 10^{-5}$	$(0.7 \pm 1.1) \times 10^{-15}$

What advantage have astrophysical methods in comparison with precise laboratory ones ?

Using quasar spectra Astrophysicists can study physical conditions which were existing Gyr ago.

aboratory measurements

We measure $\Delta\mu$ with high accuracy (!) during
days
months
a few years

e. Δt = day – some years

$$\frac{\Delta\mu}{\Delta t} - ?$$

Astrophysical measurements

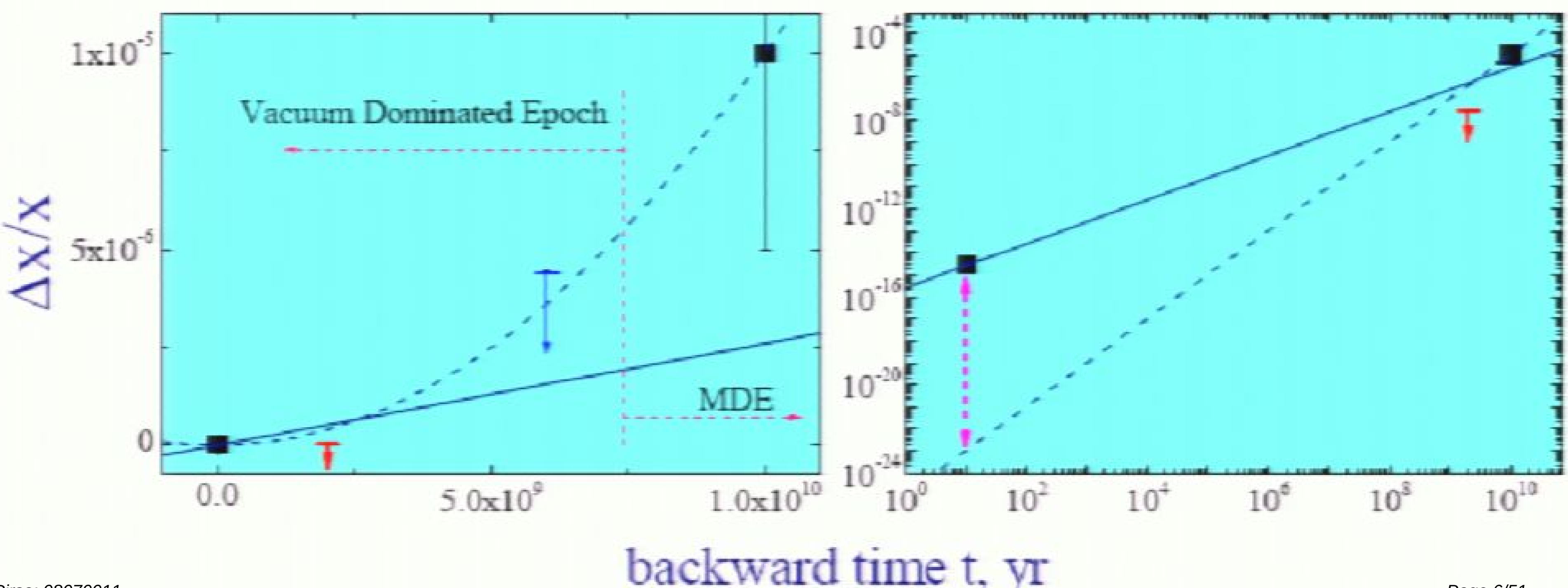
You measure $\Delta\mu$ not so precise

but

the Universe gives us

Δt = 10 – 14 Gyr

$$\Delta\mu/\mu = f(t) = a_0(=0) + a_1 t + a_2 t^2 + \ldots$$

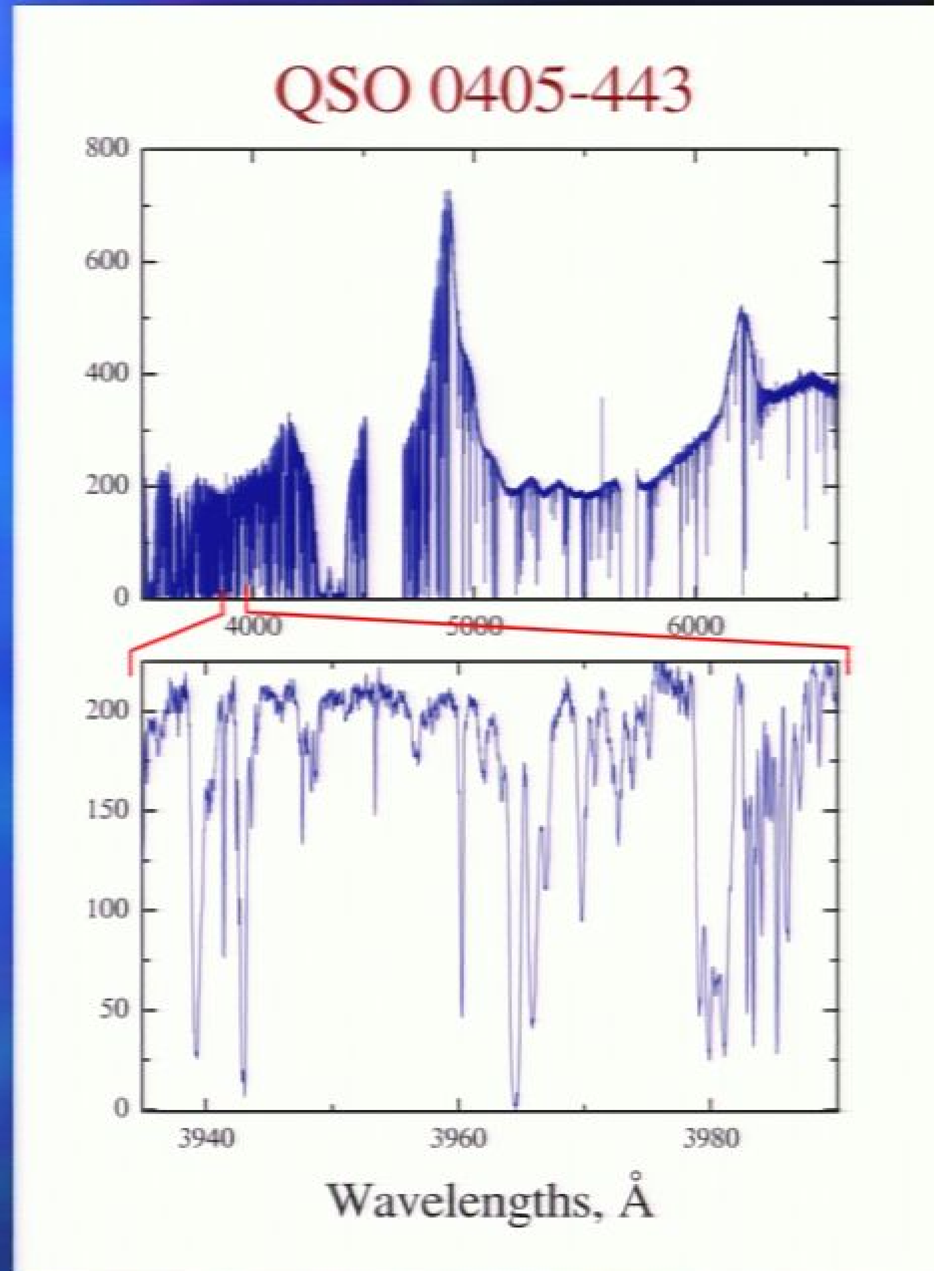


Why quasar spectra ?

Quasars are the most luminous nd distant visible objects in the niverse.

herefore, the light traveling rom QSO to observer bring us n information about earlier pochs of the Universe (10-14 yr ago).

tudying of absorption systems QSO spectra we obtained formation about physical onditions at the epochs of the pectrum formation.



The real possibility of experimentally testing the cosmological variation of μ appeared only after the discovery of H_2 molecule clouds at high redshift (1985).

Today more than 100 000 quasars are identified and only in 17 of them H_2 absorption systems were observed because for detecting such systems we need a high-resolution spectrograph and very large optical telescopes (10m Keck or 8m VLT)

And (2+2) of 17 have H_2 absorption systems which are suitable for our analyses (number of lines is about 40 for each systems, well-determined line profile, ...)

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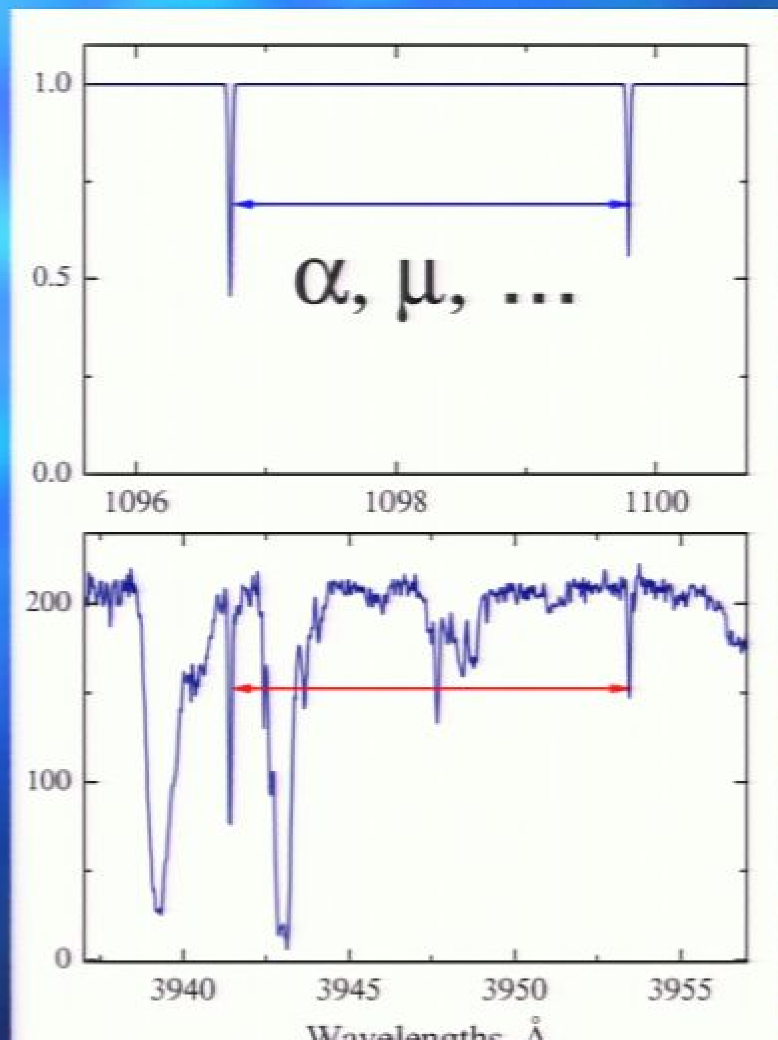
determined line pro

Q 0515 -441	1.15	HST
Q 1331+170	1.78	HST
Q 0551 -336	1.96	VLT
Q 0013 -004	1.97	MMT, VLT
Q 1444+014	2.09	VLT
Q 1232+082	2.34	VLT
Q 0027 -183	2.40	VLT
Q 2343+125	2.43	VLT
Q 2348 -011	2.44	VLT
Q 0405 -443	2.59	VLT
Q 0528 -250	**2.81**	**AAT, Keck, VLT**
Q 0347 -383	3.02	VLT
Q 1443+272	4.22	VLT

Astrophysical methods of determination of possible fundamental constant changes are based on comparison of wavelengths measured in quasar spectra with ones measured in laboratory

"Here"
and
"Now"

"There"
and
"12 Gyr ago"



$$\lambda_{obs} = \lambda_{lab}(1 + z)$$

So, for solving the problem of possible cosmological variation of $\mu = m_p/m_e$ we need to have

1. Observed wavelengths of H_2 lines formed at the earlier epochs
2. Laboratory wavelengths of this lines
3. A function $\lambda(\alpha, \mu, \ldots)$ that shows us how wavelengths depend on fundamental constants

1. New astronomical observations of H_2 lines
   / A. Ivanchik, P. Petitjean, D. Varshalovich, B. Aracil, R. Srianand, H. Chand, C. Ledoux, and P. Boissé
   Astronomy & Astrophysics 404, 2005 /

2. New laboratory measurements of H_2 lines
   / E. Reinhold, R. Buning, U. Hollenstein, A. Ivanchik, P. Petitjean, and W. Ubachs
   PRL 96, 2006 /

3. New calculations of Sensitivity Coefficients
   / V. Meshkov, A. Stolyarov, A. Ivanchik, and D. Varshalovich
   JETP Letters 83, 2006 /

1.

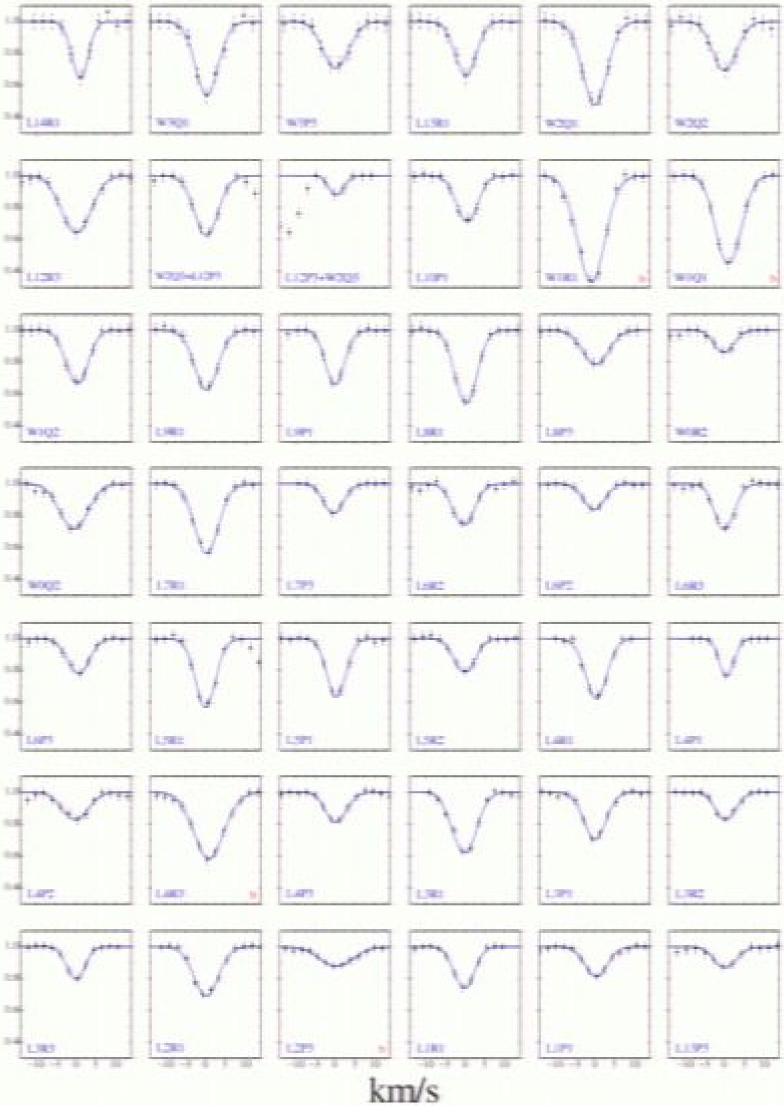
We have high-quality optical spectrum (S/N ~ 40, R ~ 53 000)
for two quasars
(Q 0347-383 z_{em}=3.22 and Q 0405-443 z_{em}=3.02)
obtained by 8m-VLT/UVES of the ESO

In each of the QSO spectra there is an H_2 absorption system
at z_{abs} = 3.0249 and 2.5947

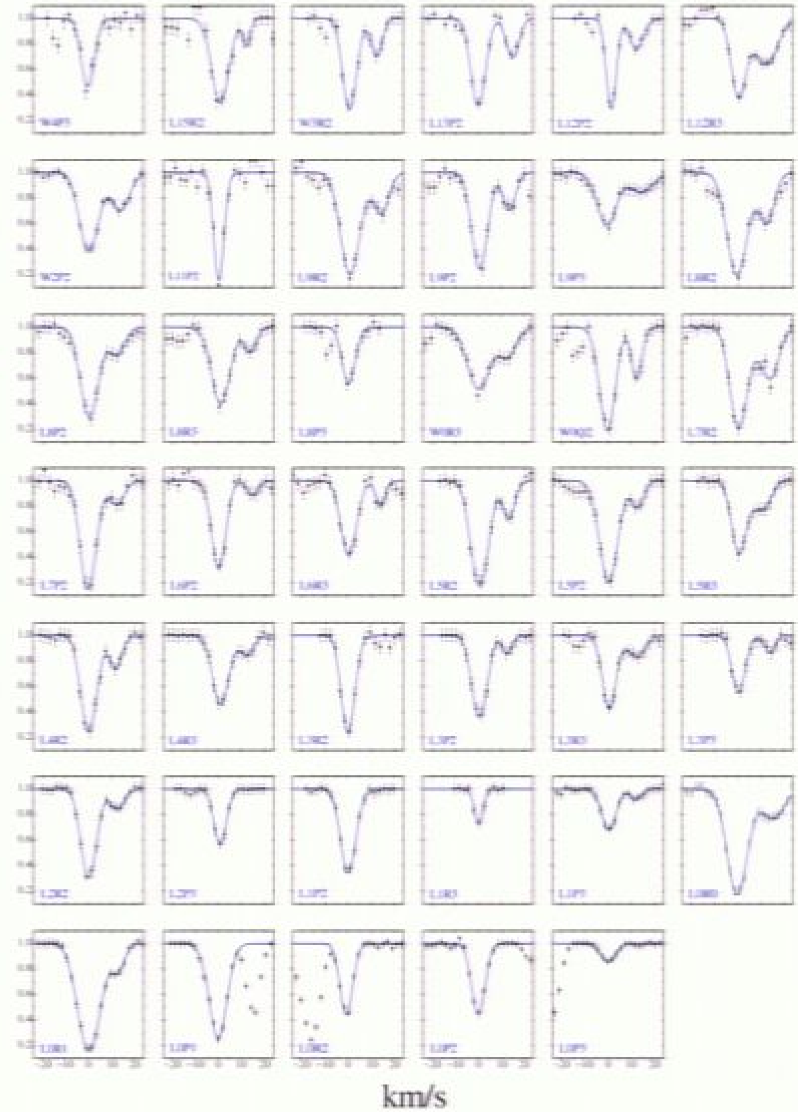
and

We have two additional spectra Q 1232+082 and HE 0027-183
with absorption systems at z_{abs} = 2.3377 and 2.4018

Q 0347-383



Q 0405-443

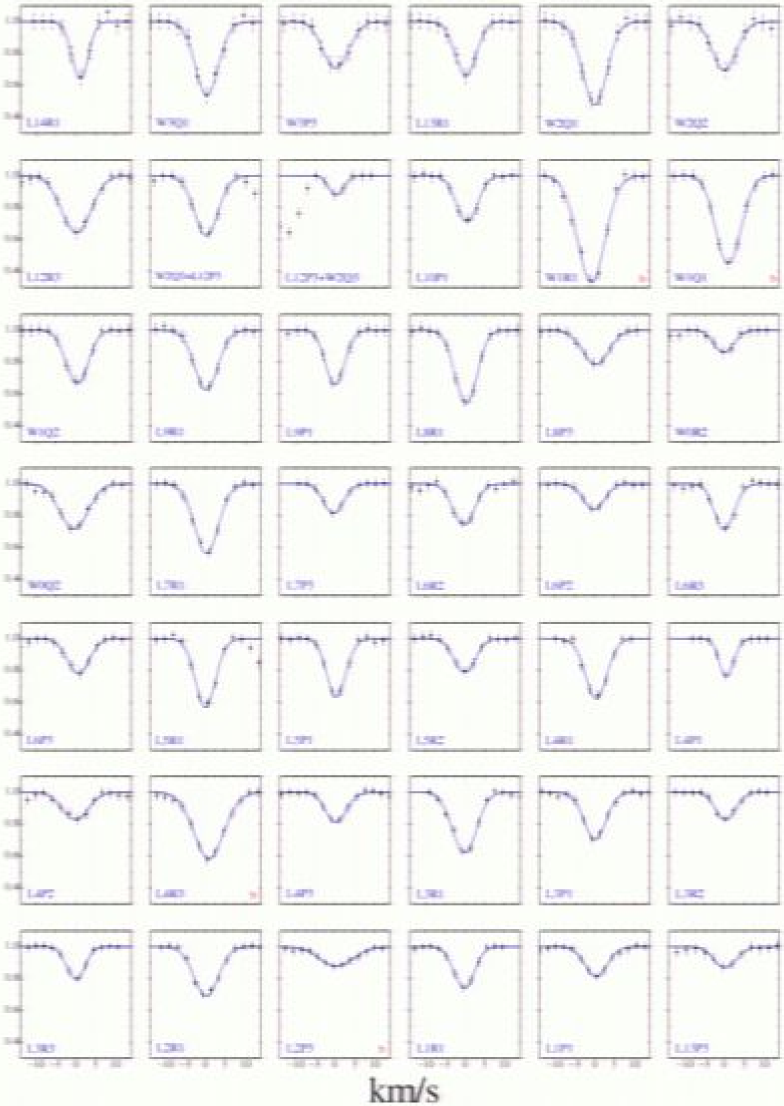


2.

Previously we used Abgrall's atlas (1993) of H_2 laboratory wavelengths which gives errors $\sigma_\lambda \sim 1.5$ mÅ

but now observational accuracy becomes comparable with laboratory one and we need to have more precise H_2 laboratory wavelengths.

Q 0347-383



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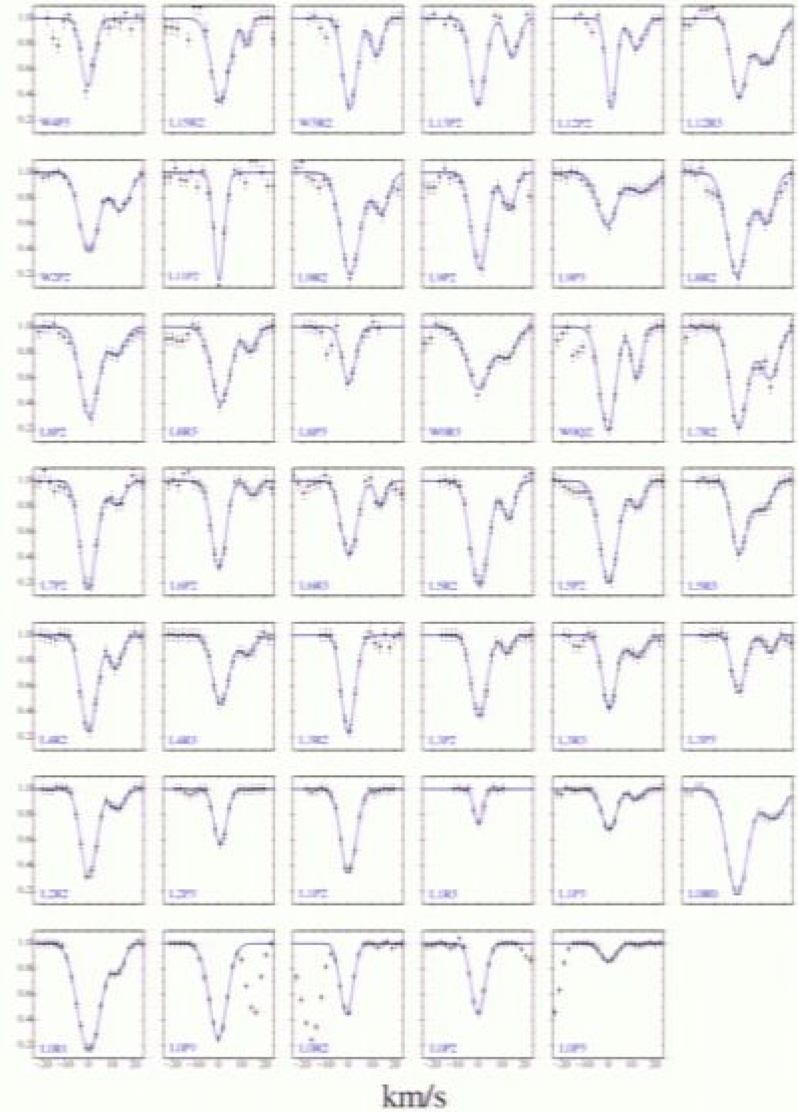


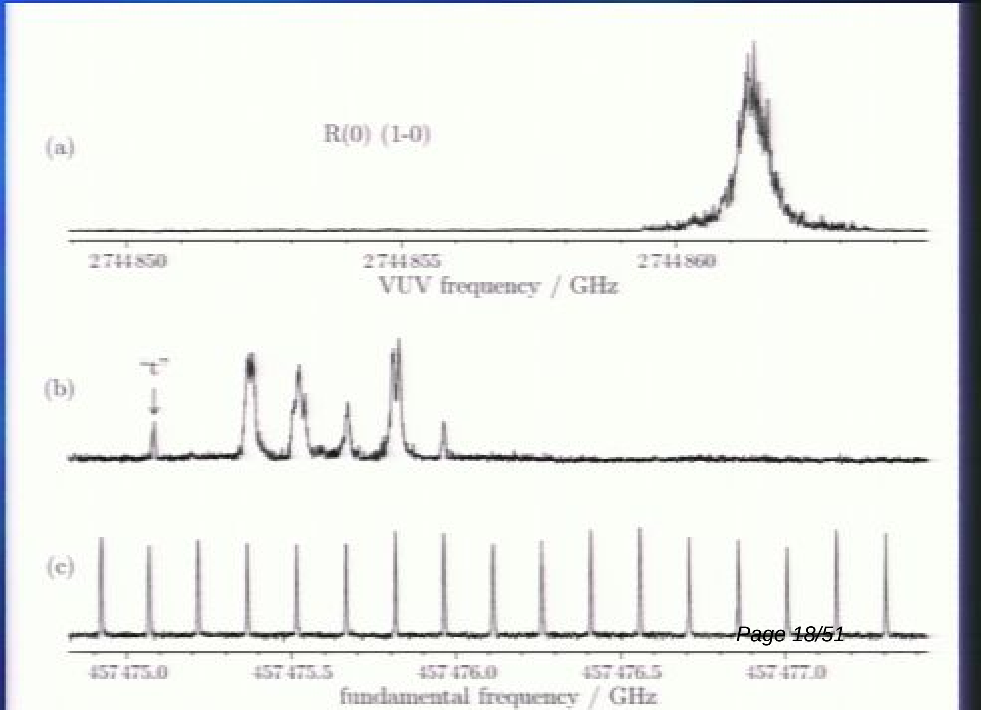
2.

Specially for our H_2 lines observed in the QSO spectra new extremely accurate wavelengths were measured using ultraviolet laser spectroscopy (performed in Amsterdam)

. Philip et al., Can. J. Chem., **82**, 713, 2004

. Reinhold et al., PRL, **96**, 151101, 2006

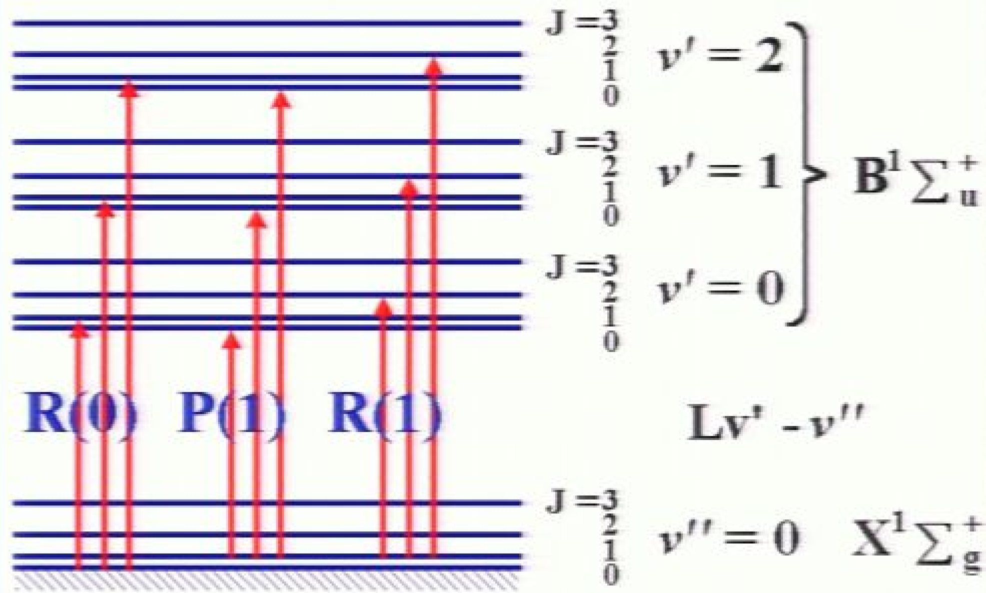
It gives errors $\sigma_\lambda \sim 0.07$ mÅ (i.e. more than 20 times better)



3. How wavelengths change if μ vary ?

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

Sensitivity Coefficients



$$E_{vib} \sim \sqrt{m_e/m_p}\ , \quad E_{rot} \sim (m_e/m_p).$$

Wavelengths of electron-vibro-rotational lines depend on the reduced mass of the molecule. The dependence differs for different transitions. Thus, a measured wavelength λ_i of a line formed in an absorption system at redshift z_{abs} can be written as

$$\lambda_i = \lambda_i^0 \cdot (1 + K_i \cdot \Delta\mu/\mu) \cdot (1 + z_{abs})$$

where K_i defined as

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

3.

In previous work we used standard adiabatic approximation with energy level represented by Dunham formula:

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

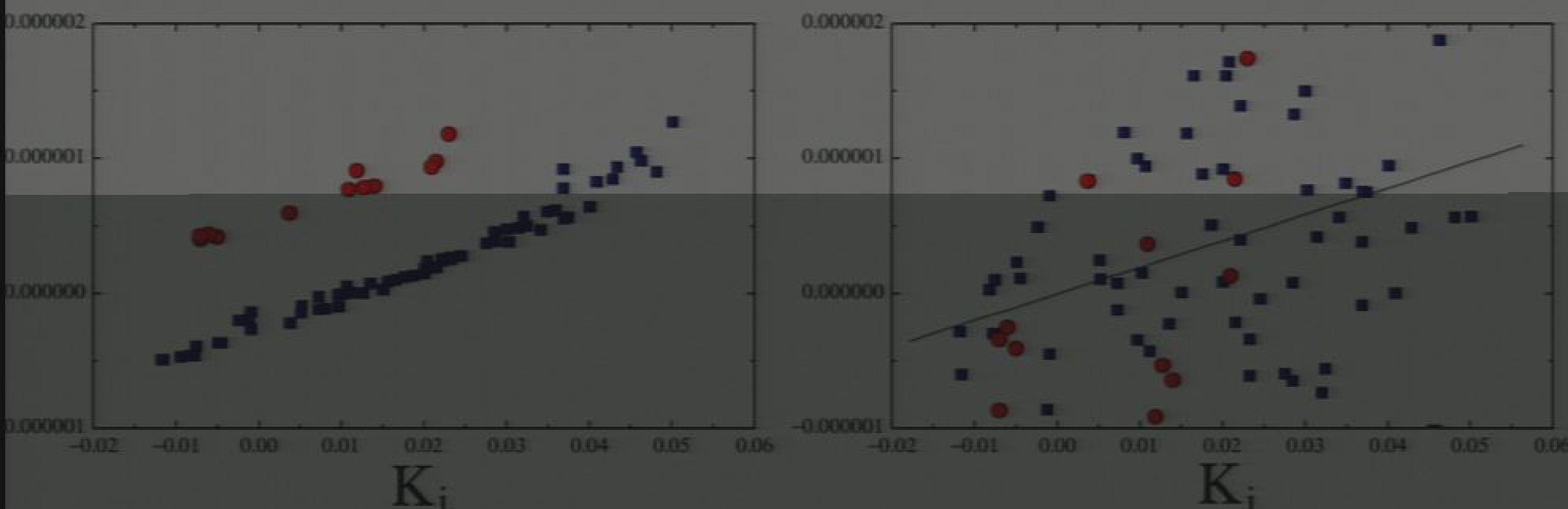
$$Y_{kl}\propto\mu^{-l-k/2}$$

End of slide show, click to exit.

Possible systematic effects

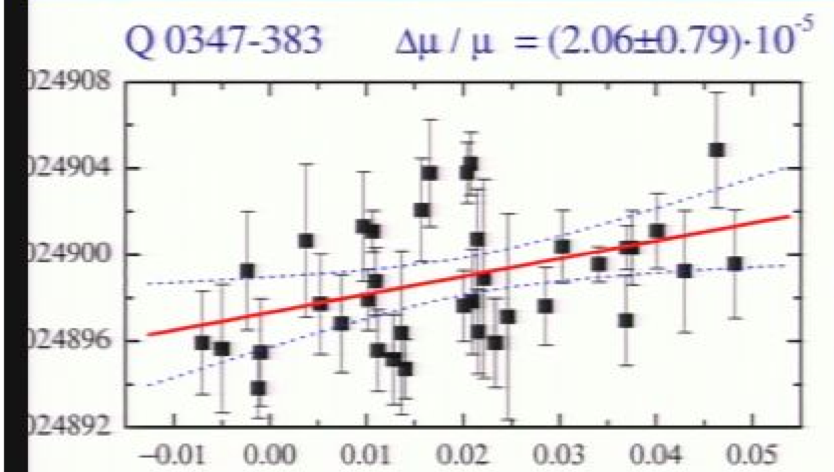
Any effect that could produced a line center shift increasing monotonously with wavelengths (air-vacuum wavelength conversion, Th-Ar calibration, atmospheric dispersion effect etc.)

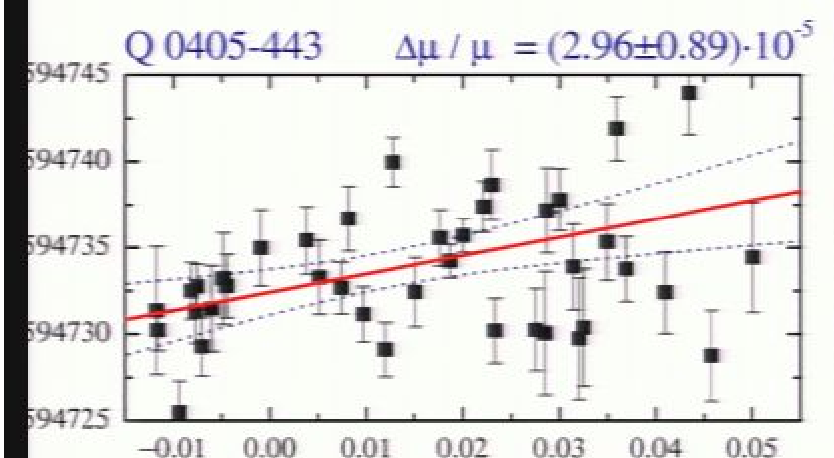
$$\frac{\lambda_i^{abs}}{\lambda_i^{lab}} = (1 + z_{abs})\left(1 + K_i \frac{\Delta\mu}{\mu}\right)$$

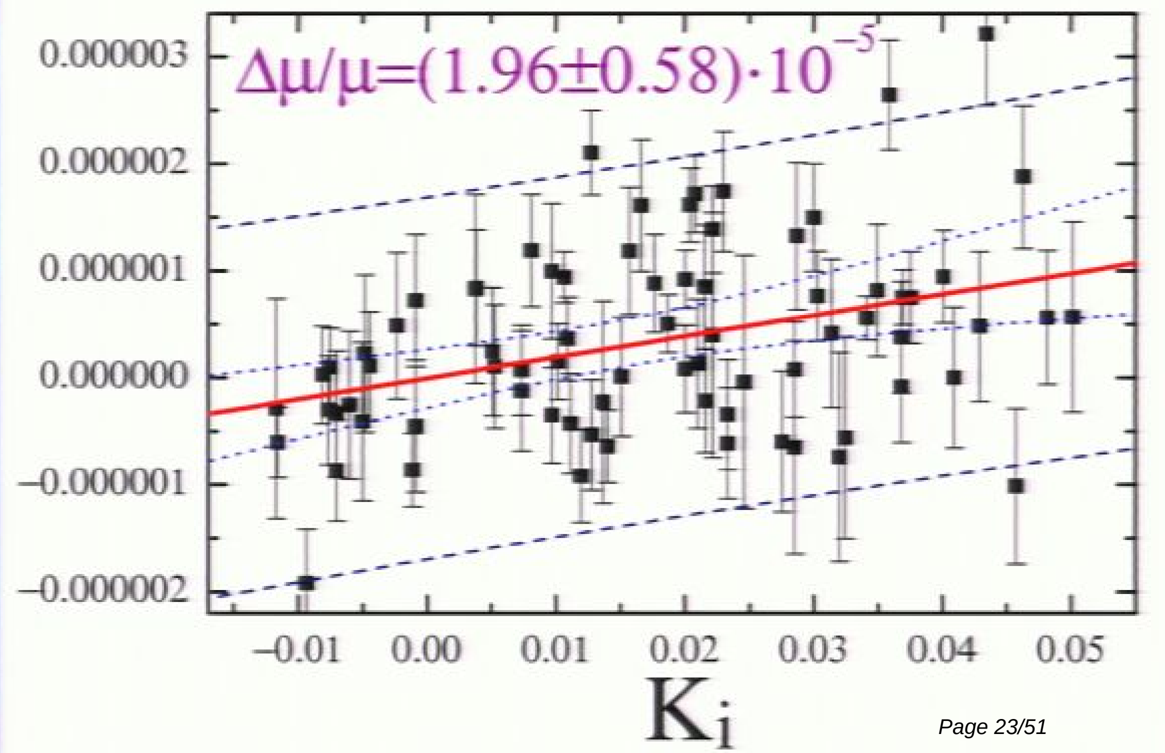


Regression analysis

$$\zeta_i = \frac{z_i - z_{abs}}{1 + z_{abs}}$$







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Now *ab initio* nonadiabatic calculations of the wavelengths λ_i of the individual lines of the Lyman and Werner series of H_2 and corresponding sensitivity coefficients K_i (with accuracy better than 1%) have been performed.

V. Meshkov, A. Stolyarov, A. Ivanchik, and D. Varshalovich

JETP Letters 83, 2006

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So, we have all for the analyses:

$$\lambda_i^{obs}, \quad \lambda_i^{lab}, \quad K_i$$

$$\frac{\lambda_i^{obs}}{\lambda_i^{lab}} = (1 + z_{abs})\left(1 + K_i \frac{\Delta\mu}{\mu}\right)$$

Transition	$\lambda_i (H_2)$	$\lambda_i (D_2)$	$\lambda_i (T_2)$	K_i
L0-0 R(1)	1108.633	1103.351	1101.021	-0.00719
L1-0 R(0)	1092.194	1091.765	1091.565	-0.00055
L2-0 R(0)	1077.137	1080.882	1082.584	+0.00508
L3-0 P(1)	1064.605	1071.312	1074.498	+0.00865

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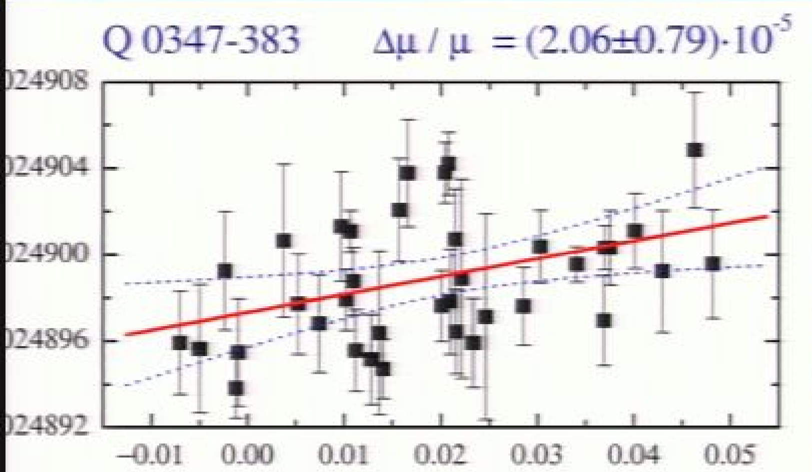
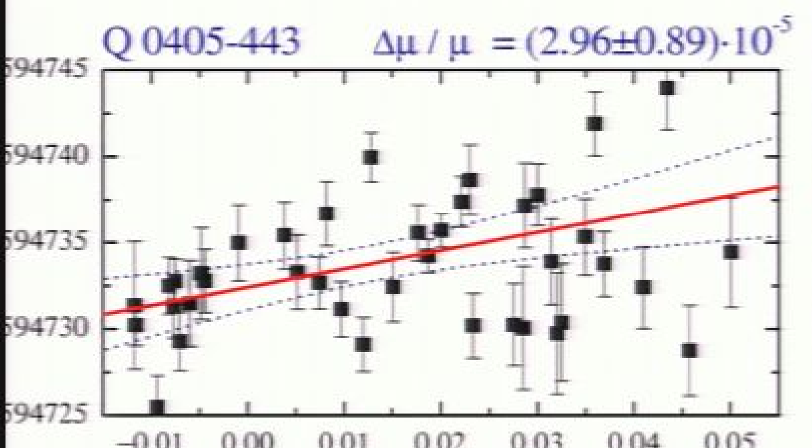
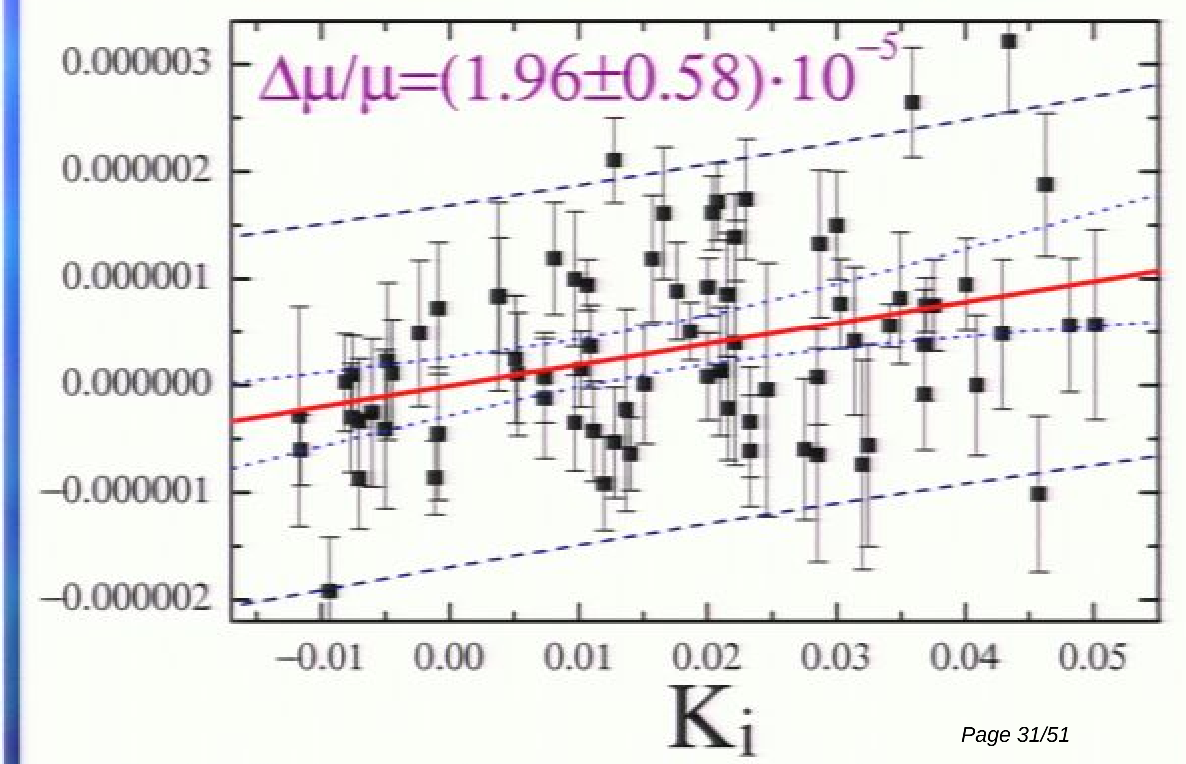
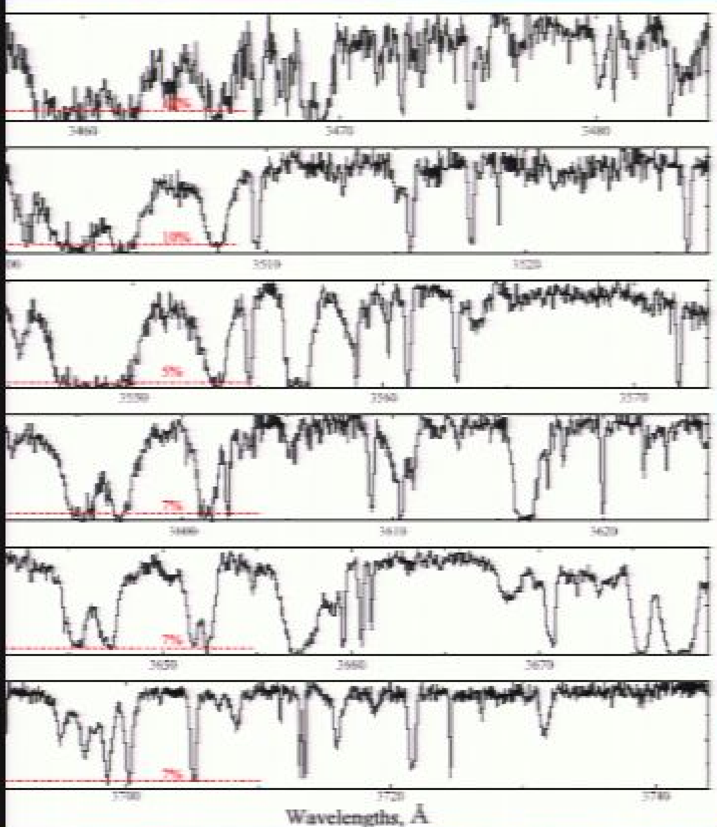


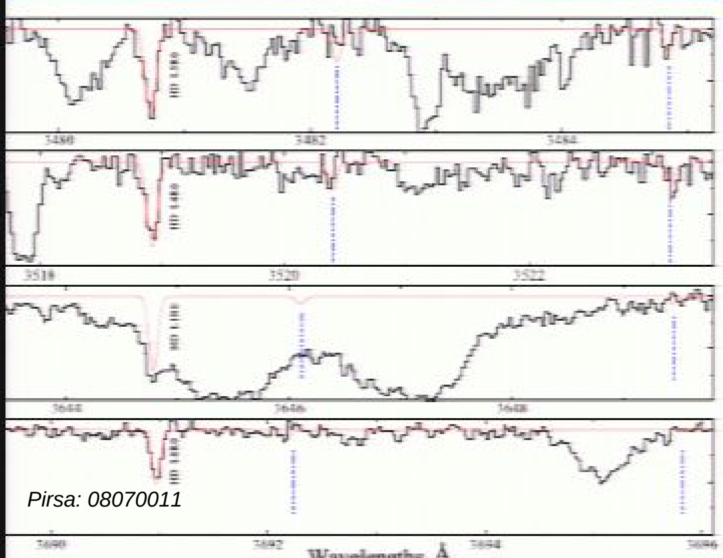


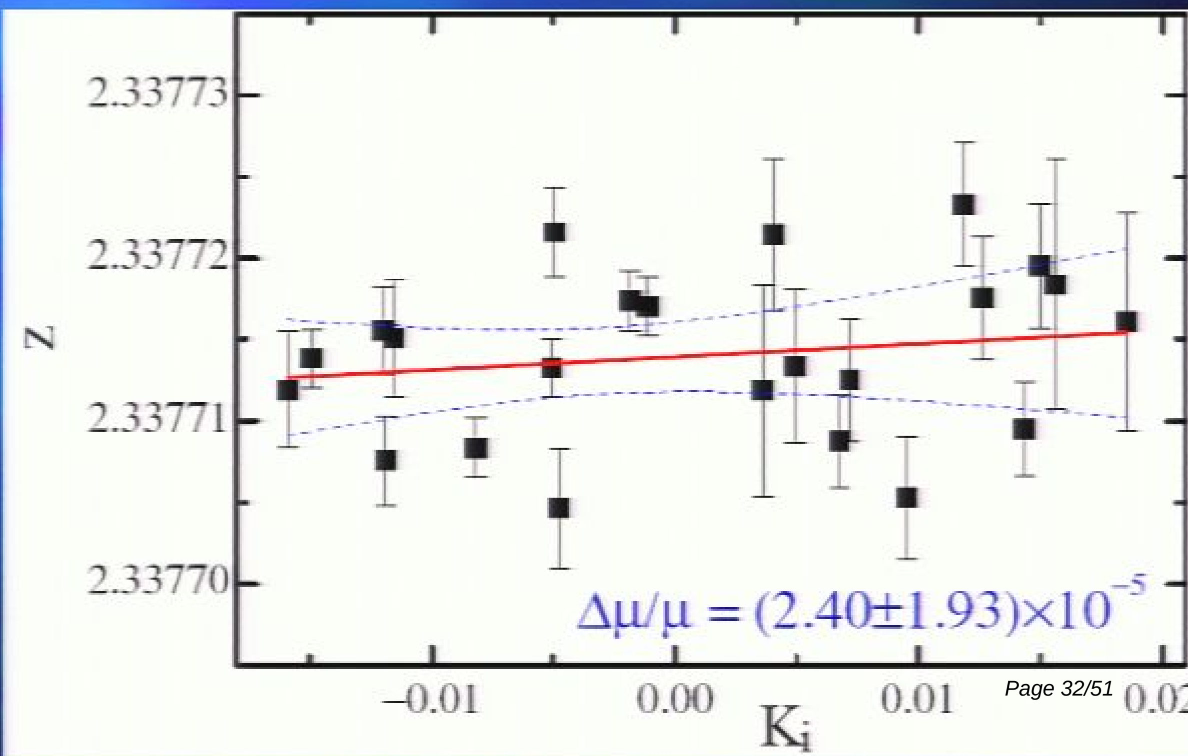


Q1232+082

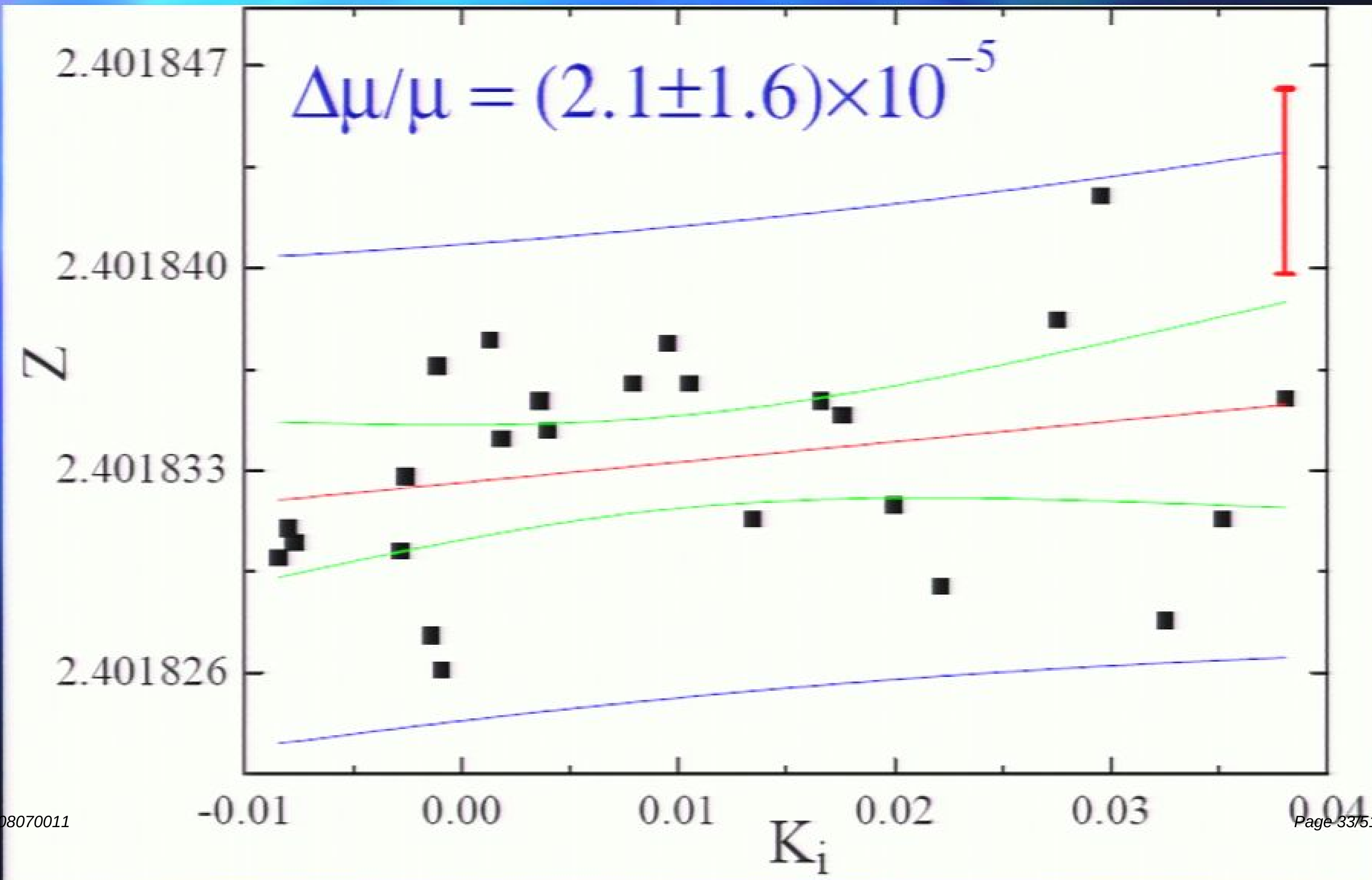
H_2 & HD







HE 0027-183



$\Delta\mu/\mu = (2.1 \pm 1.6) \times 10^{-5}$
2.401847
2.401840
2.401833
2.401826
Z
-0.01
0.00
0.01
0.02
0.03
0.04
K_i

The main question:

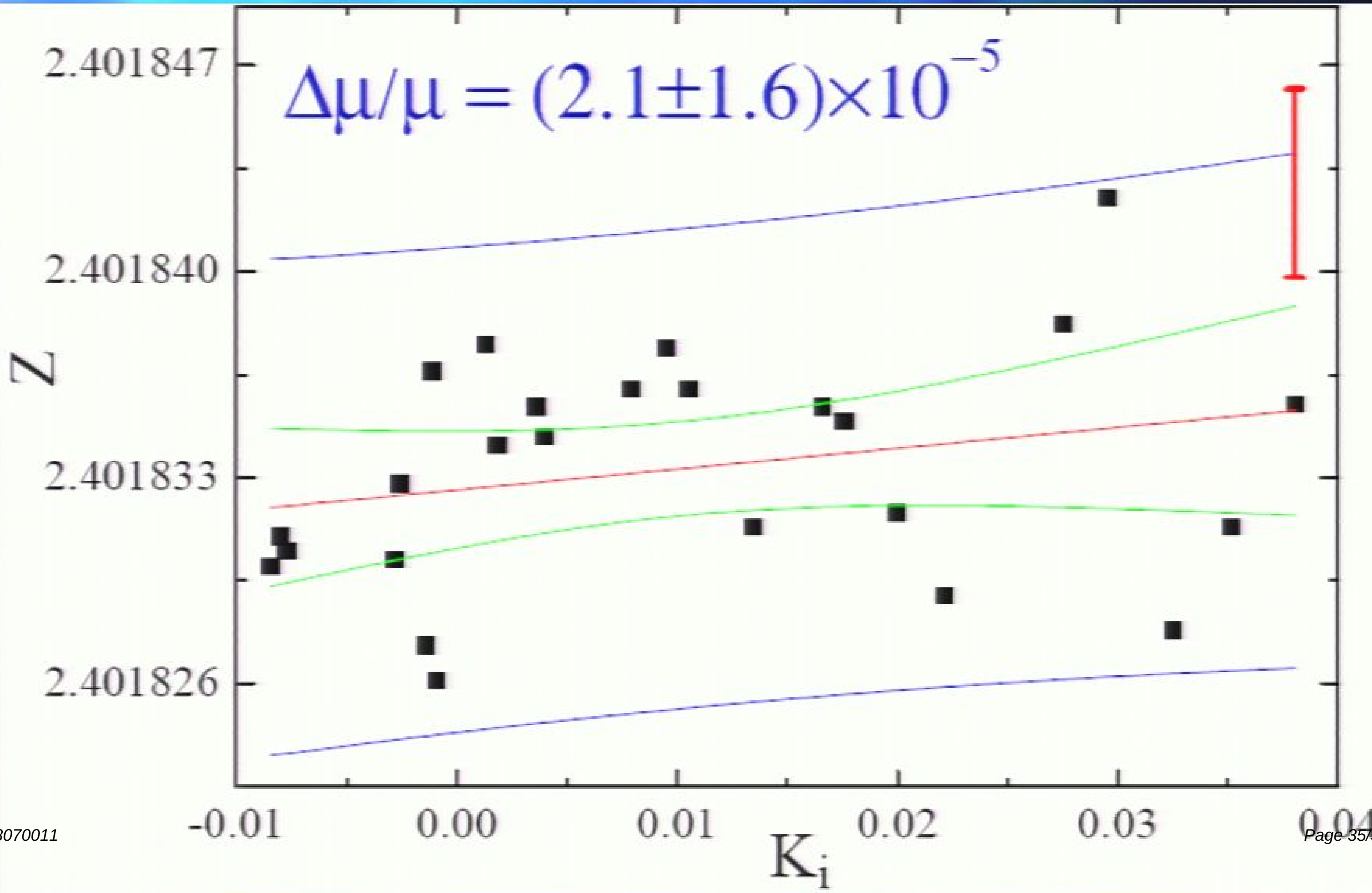
Is it μ-variation

or

unknown systematic effect

?

HE 0027-183



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Today, we do not know it

because …

Possible systematic effects

Any effect that could produced a line center shift increasing monotonously with wavelengths (air-vacuum wavelength conversion, Th-Ar calibration, atmospheric dispersion effect etc.)

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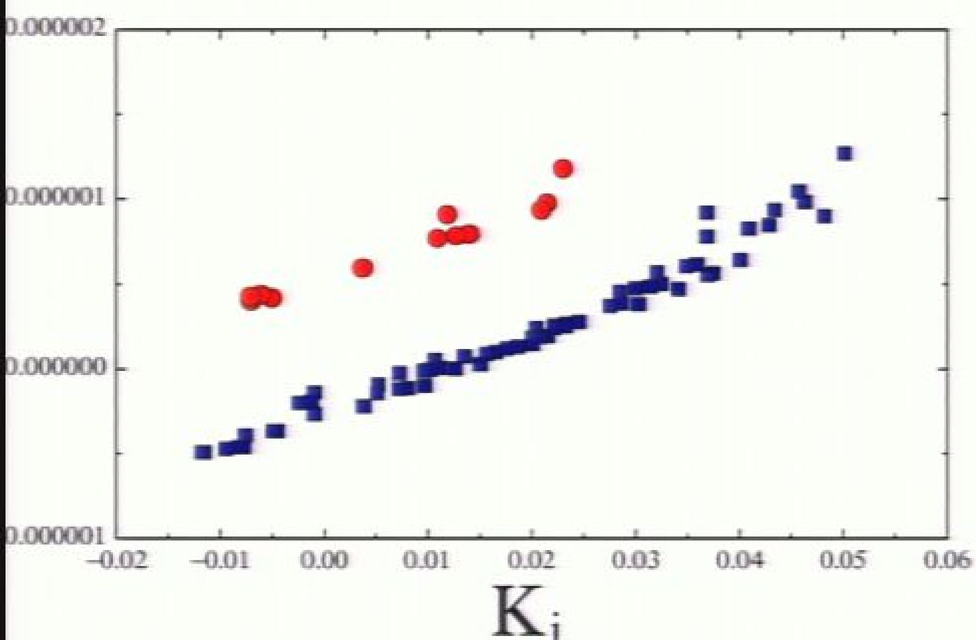

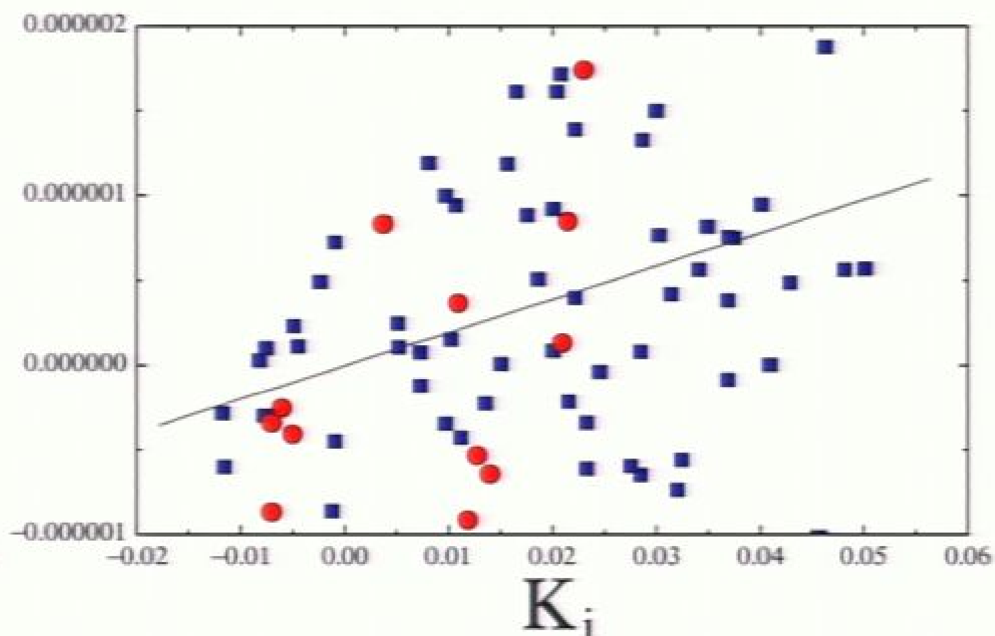

But we know what we have to do …

To distinguish systematic from real effect we have to decrease the dispersion at least two times

we hope that we will be able to answer onto this question in near future 5-10 yr (non-astronomical time scale 12 Gyr)

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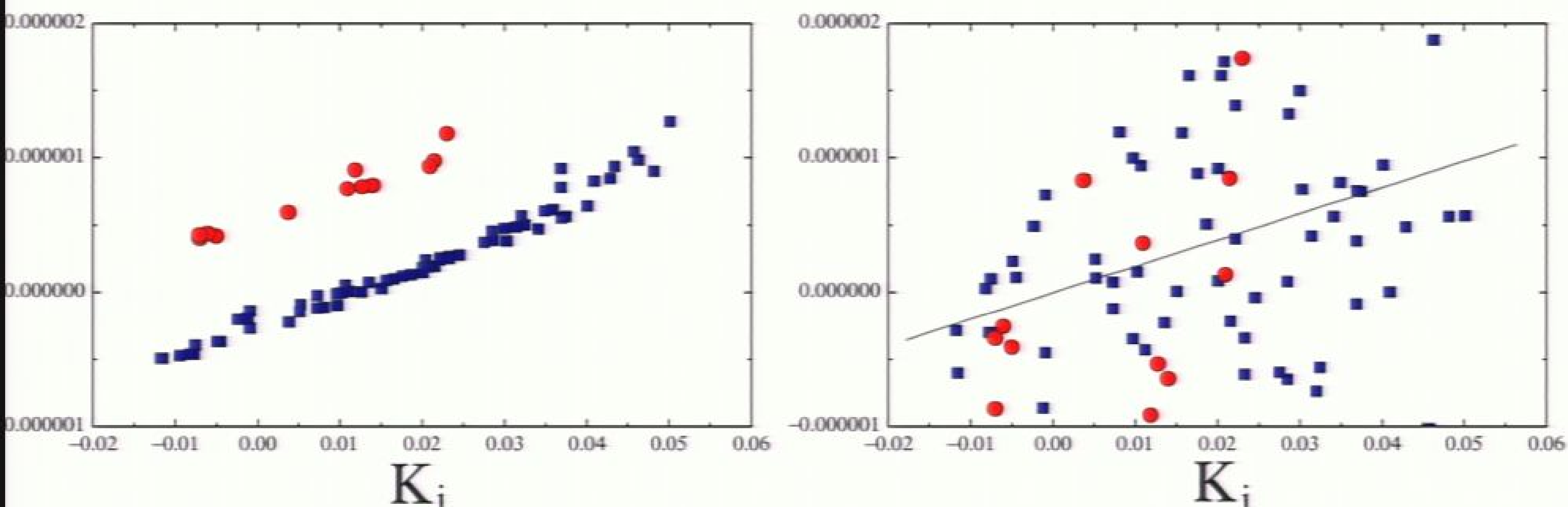

Results

We find a correlation between z_i and K_i that could be interpreted as a variation of μ over 12 Gyr

$$\Delta\mu / \mu = (1.96 \pm 0.58) \times 10^{-5}, \quad 3\sigma$$

! But today, we can not distinguish between real μ-variation and unknown systematic effect. So, the value can be treat as the most stringent limit on possible cosmological μ-variation (at z=3, t=12 Gyr)

Thanks a lot for your attention ☺

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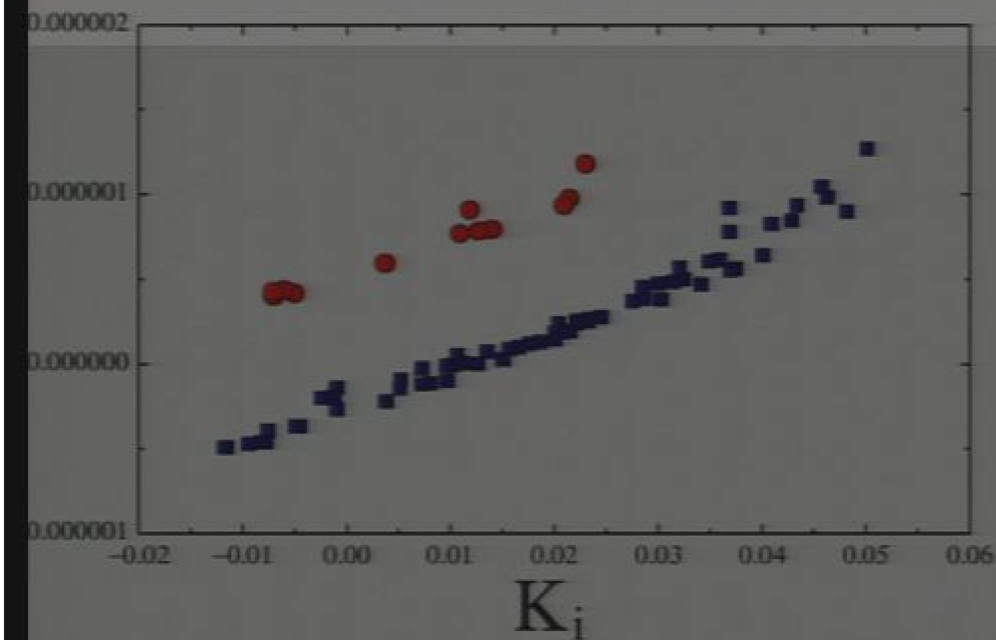

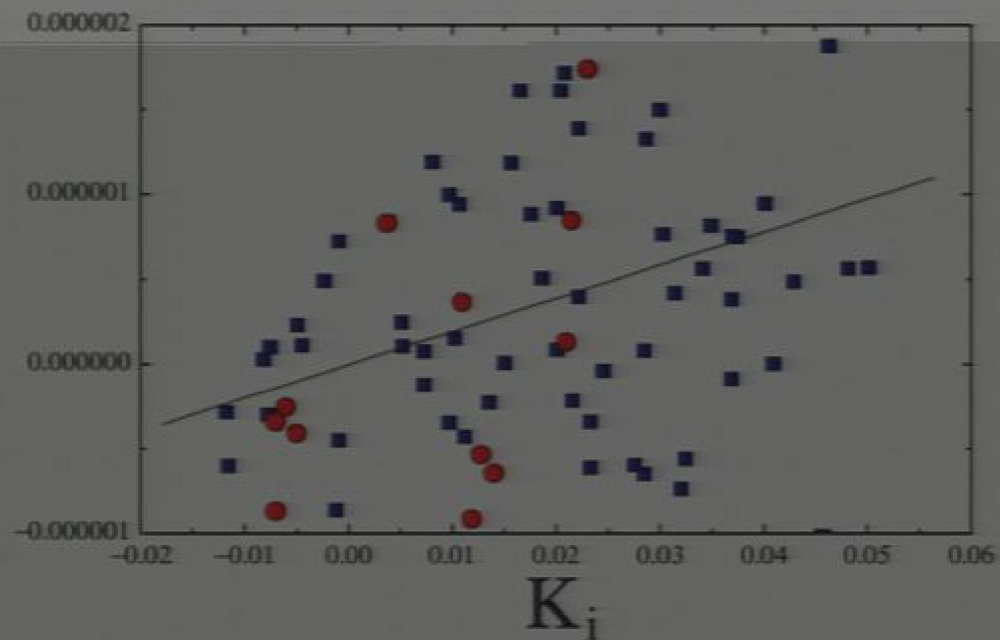

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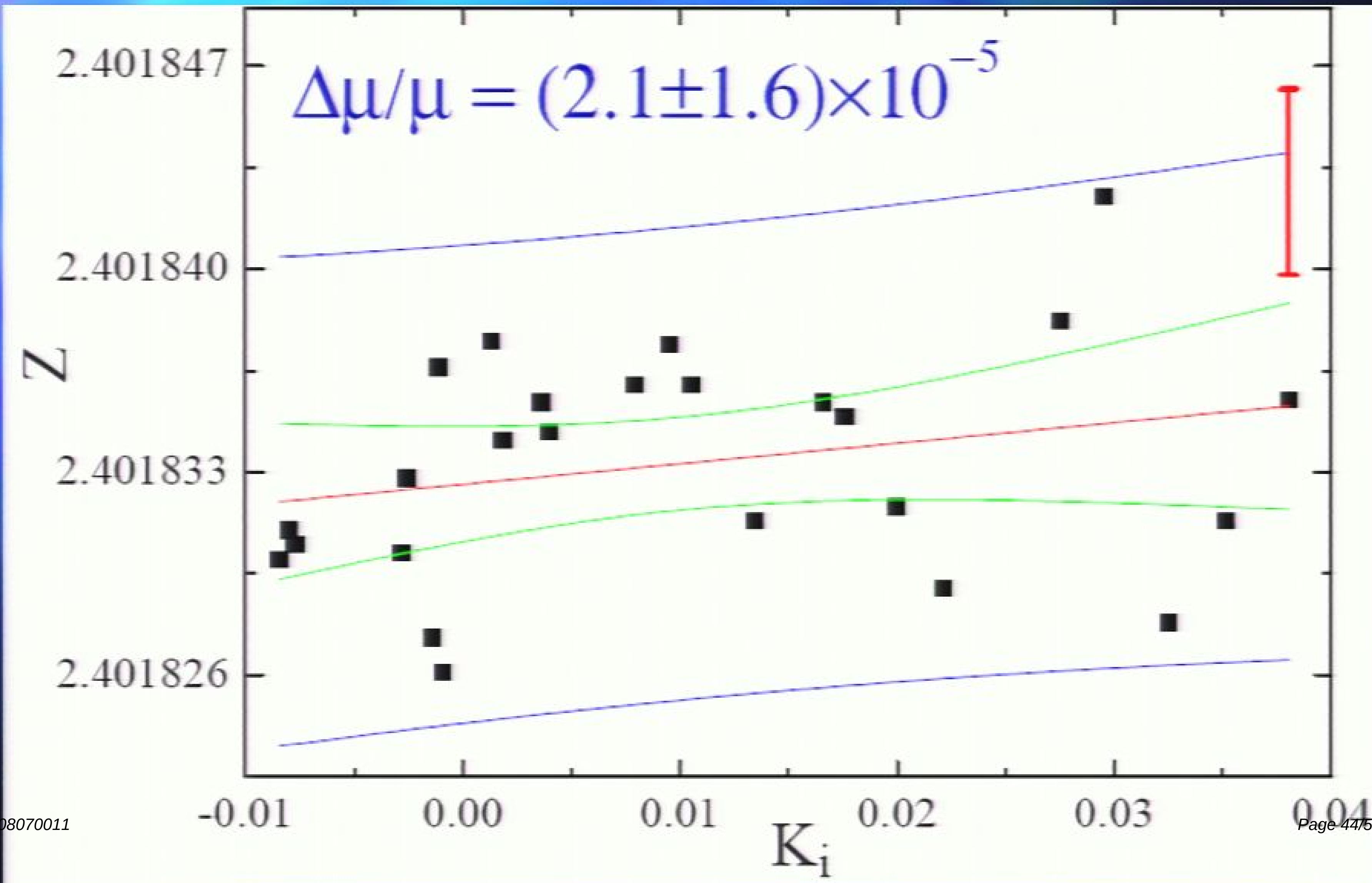

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