Title: Quasar absorption line constraints on variable fundamental constants

Date: Jul 14, 2008 02:40 PM

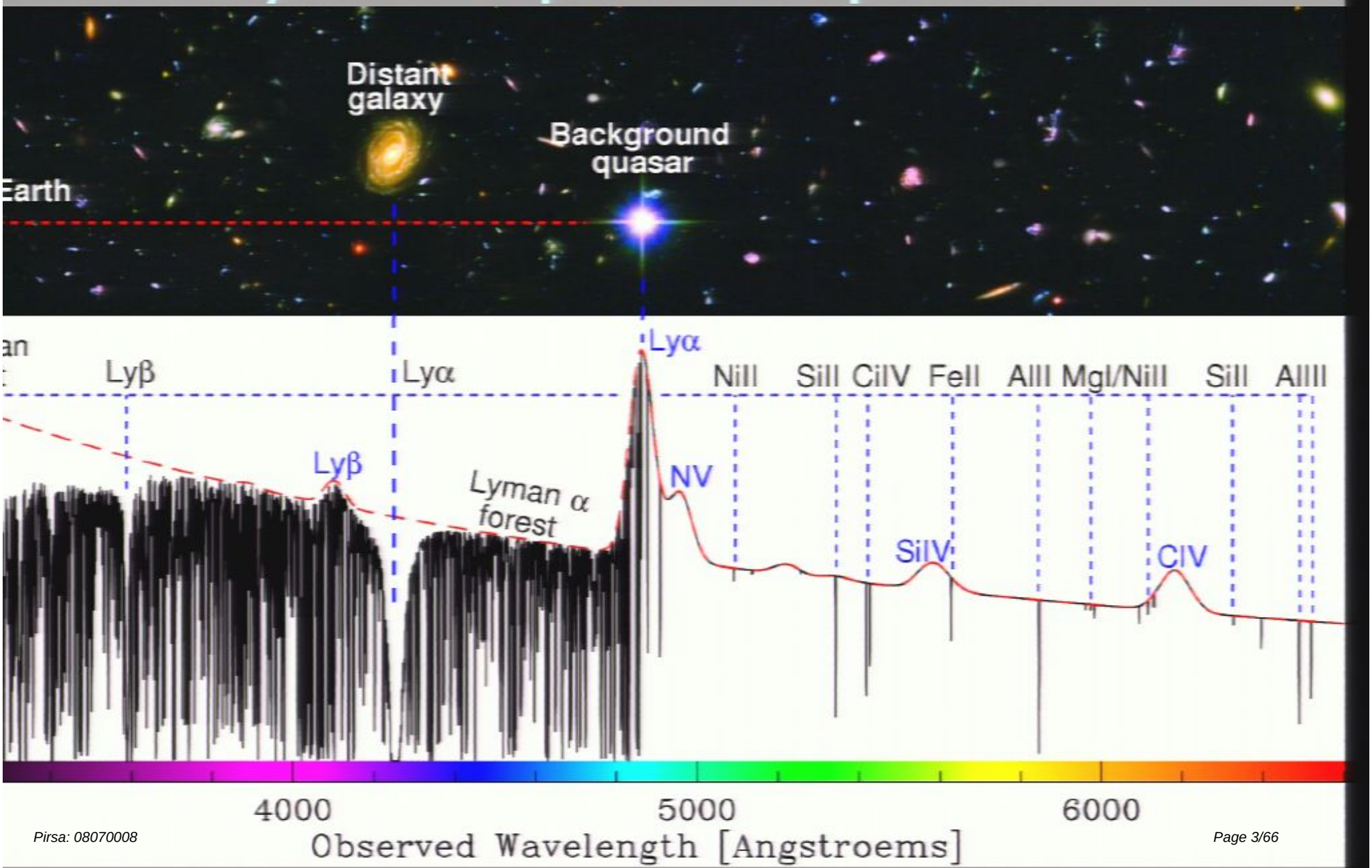
URL: http://pirsa.org/08070008

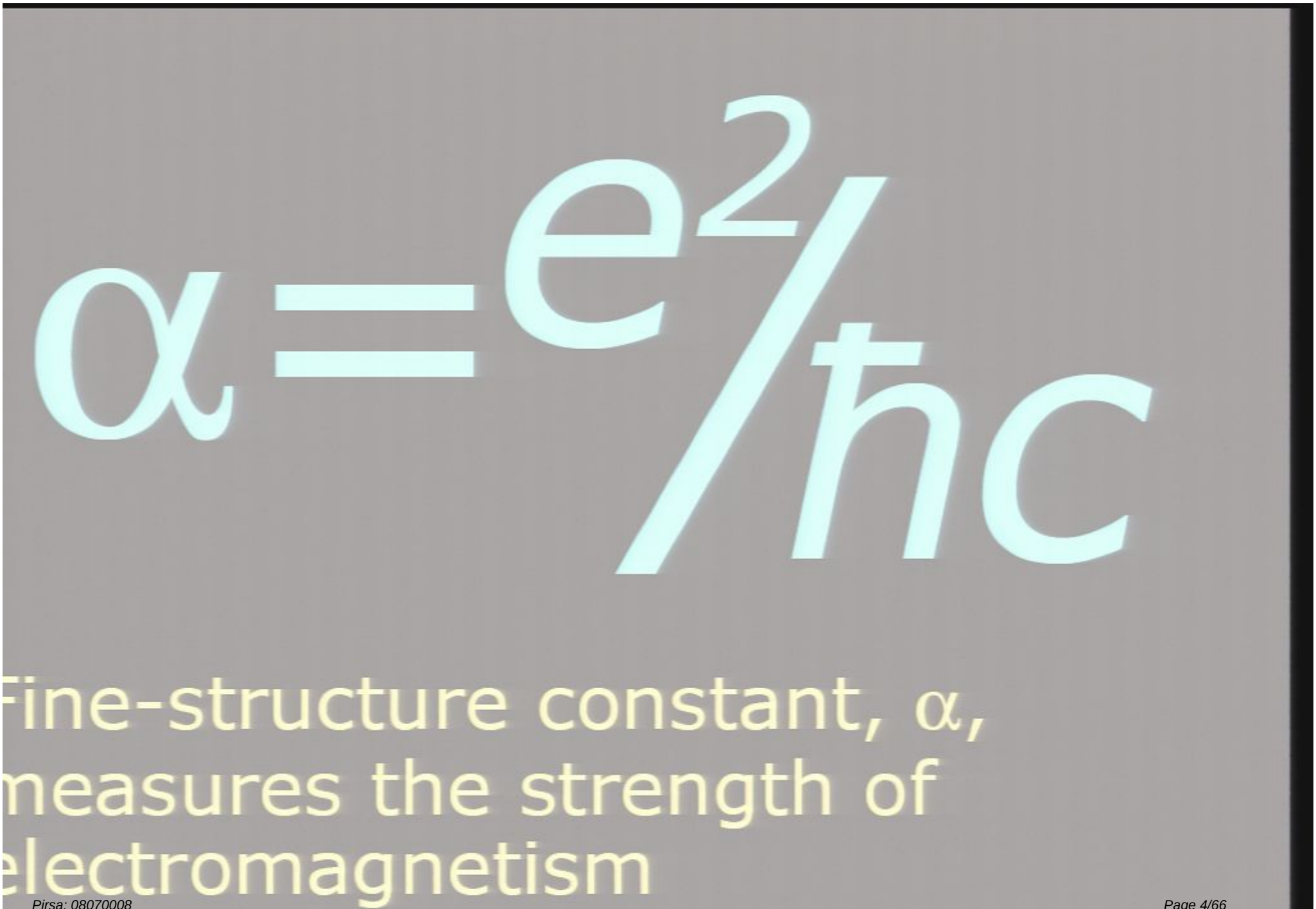
Abstract: I will review the published quasar absorption line constraints on variations in the fine-structure constant, alpha, focusing on the apparent disagreement between those derived from Keck/HIRES and VLT/UVES spectra which have provided evidence for and against alpha variation, respectively. I demonstrate simple yet fundamental flaws in the UVES constraints which preclude reliable comparison with those from HIRES. I will outline our program to obtain a definitive UVES measurement. I will also present several new absorption line constraints on variations in the proton-to-electron mass ratio, mu. For the two molecular hydrogen absorbers from which previous authors found tentative evidence for mu-variation, we find robustly null results. A further two molecular hydrogen absorbers, including an entirely new system, also yield tight, null constraints. Finally, I present new, detailed comparison of a radio absorption system containing ammonia inversion and molecular rotational transitions which yields the strongest current astrophysical constraint on mu-variation, dmu/mu=[mu(z)-mu(lab)]/mu(lab)=[+0.74+/-0.47(stat)+/-0.76(sys)]x10^-6, at redshift z=0.685.

Outline:

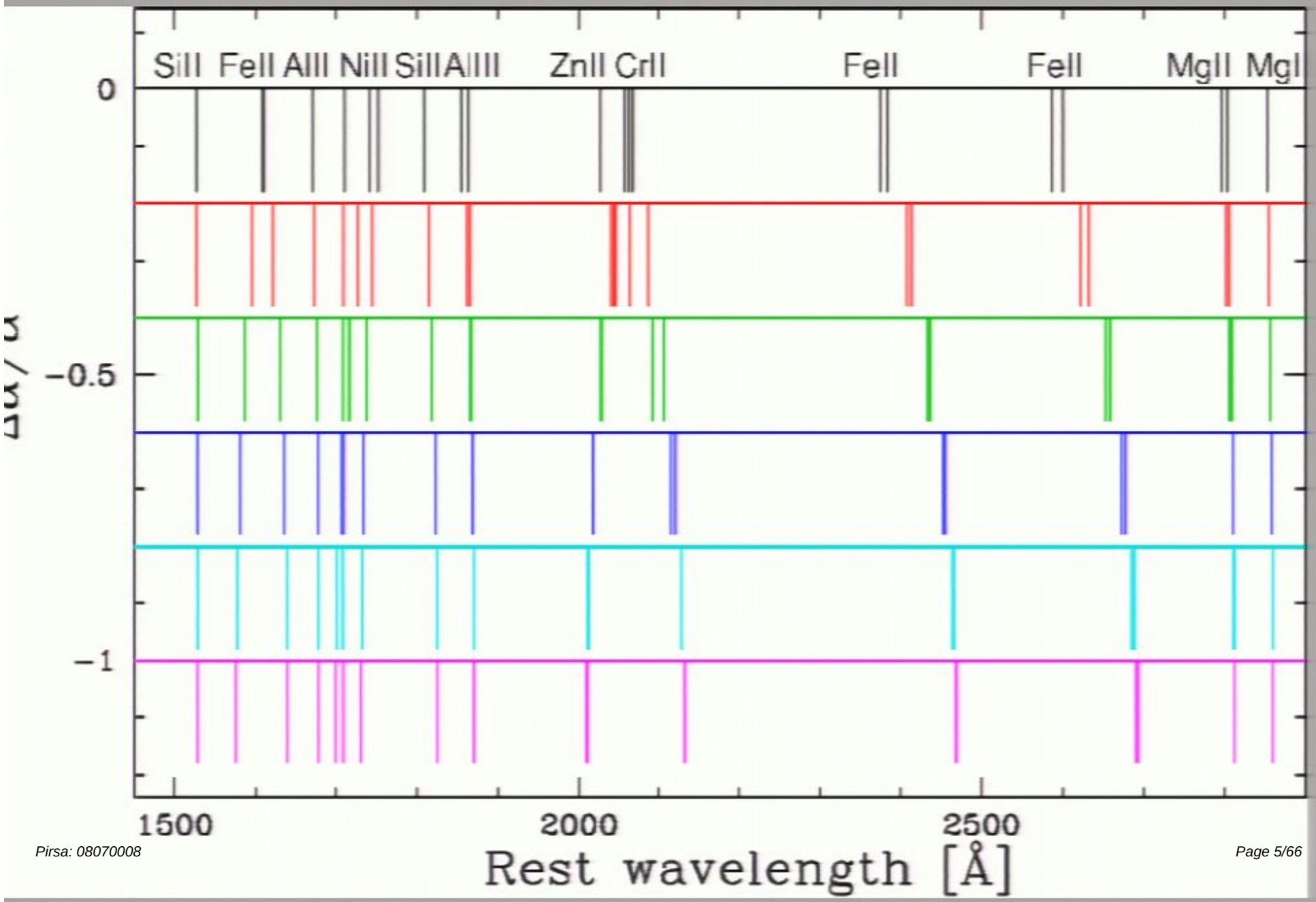
- Keck/HIRES constraints on α: $\Delta\alpha/\alpha \neq 0$?
- VLT/UVES constraints on α: $\Delta\alpha/\alpha = 0$?
- Ammonia constraint(s) on μ: $\Delta\mu/\mu = 0$?
- Future measurements
- New instruments & telescopes
- Astronomical frequency combs – a reality!

natomy of a quasar spectrum:

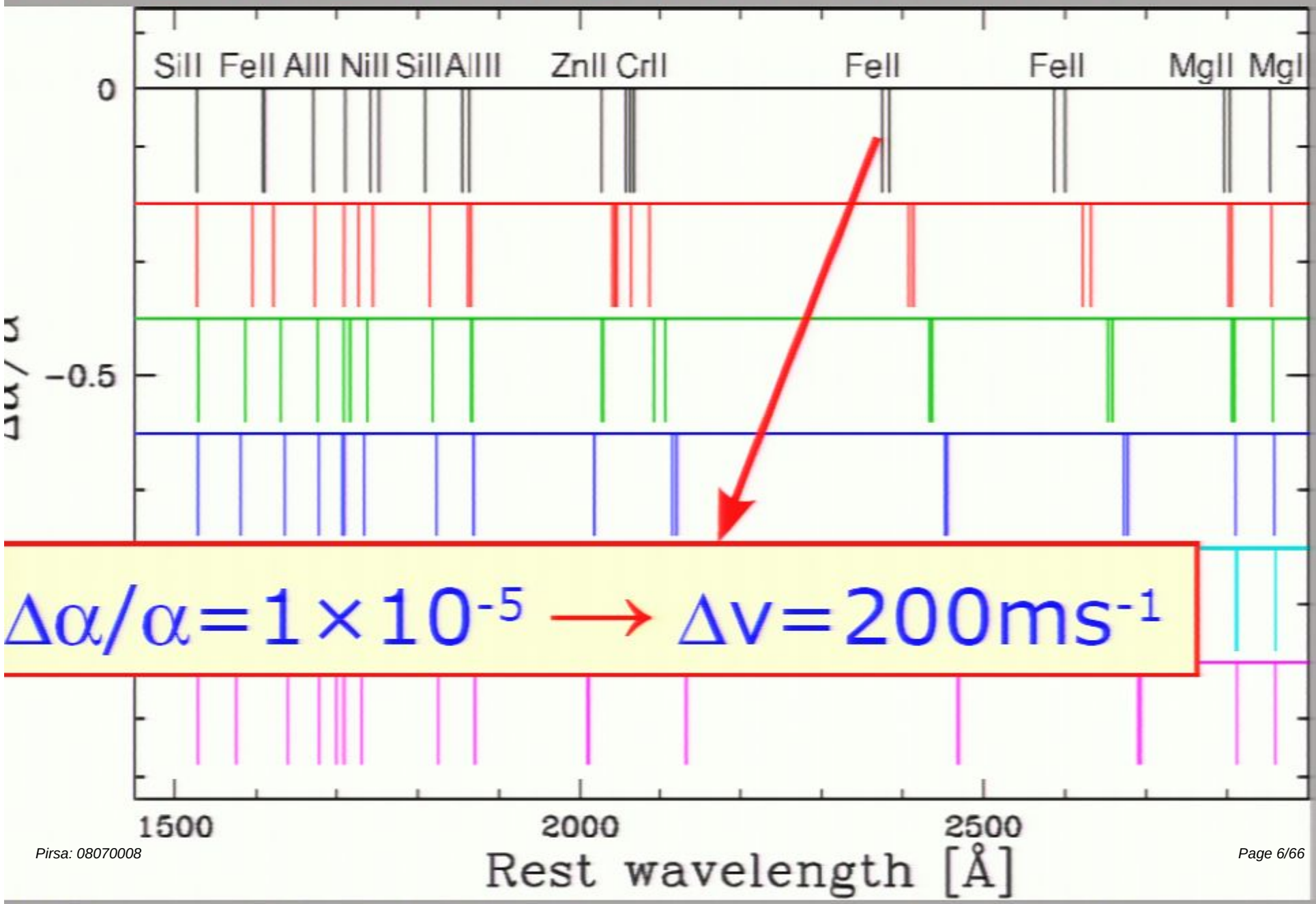



$\alpha = e^2/\hbar c$
Fine-structure constant, α,
measures the strength of
electromagnetism

ine-shifts in the MM method:

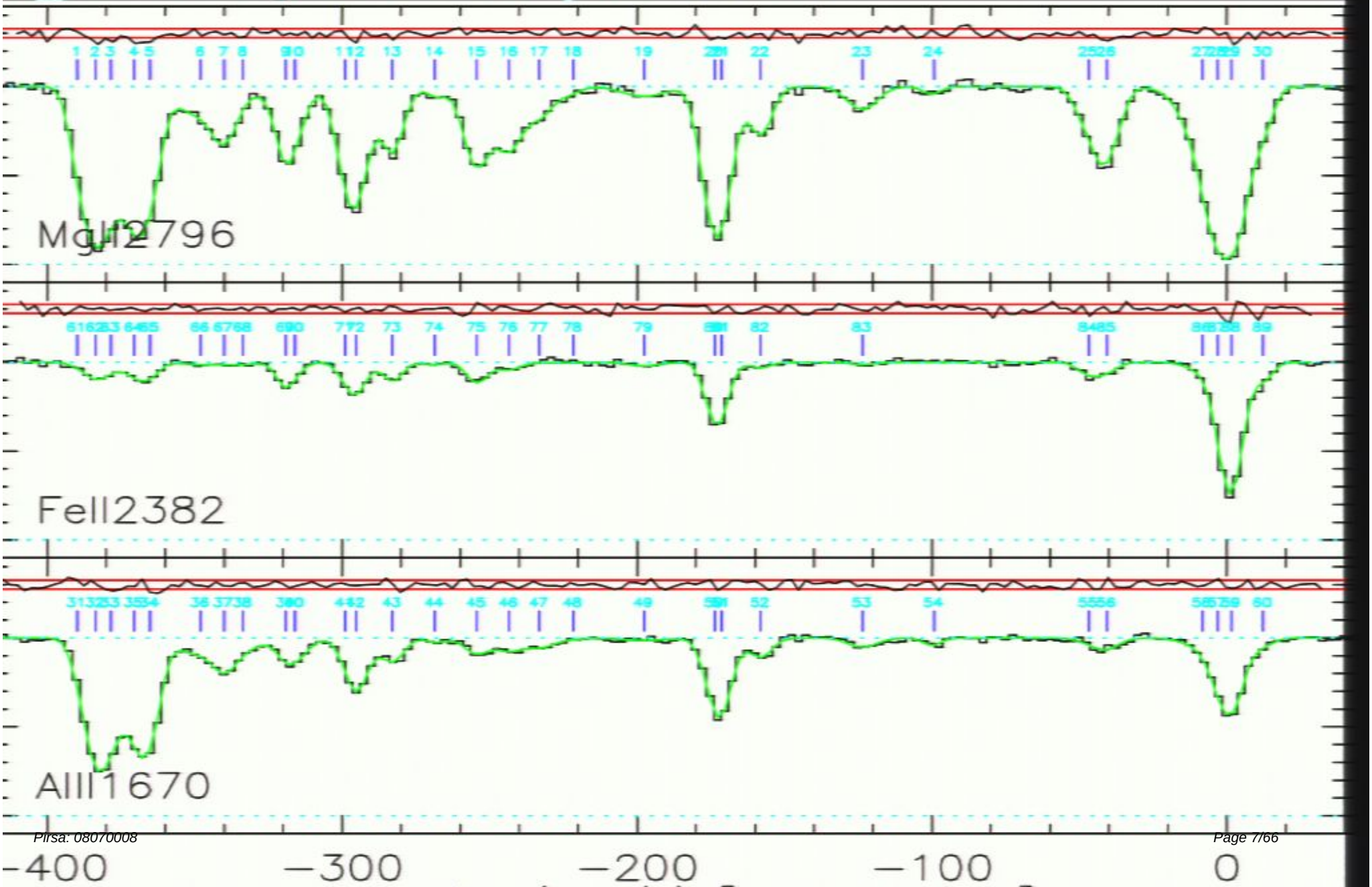


ine-shifts in the MM method:

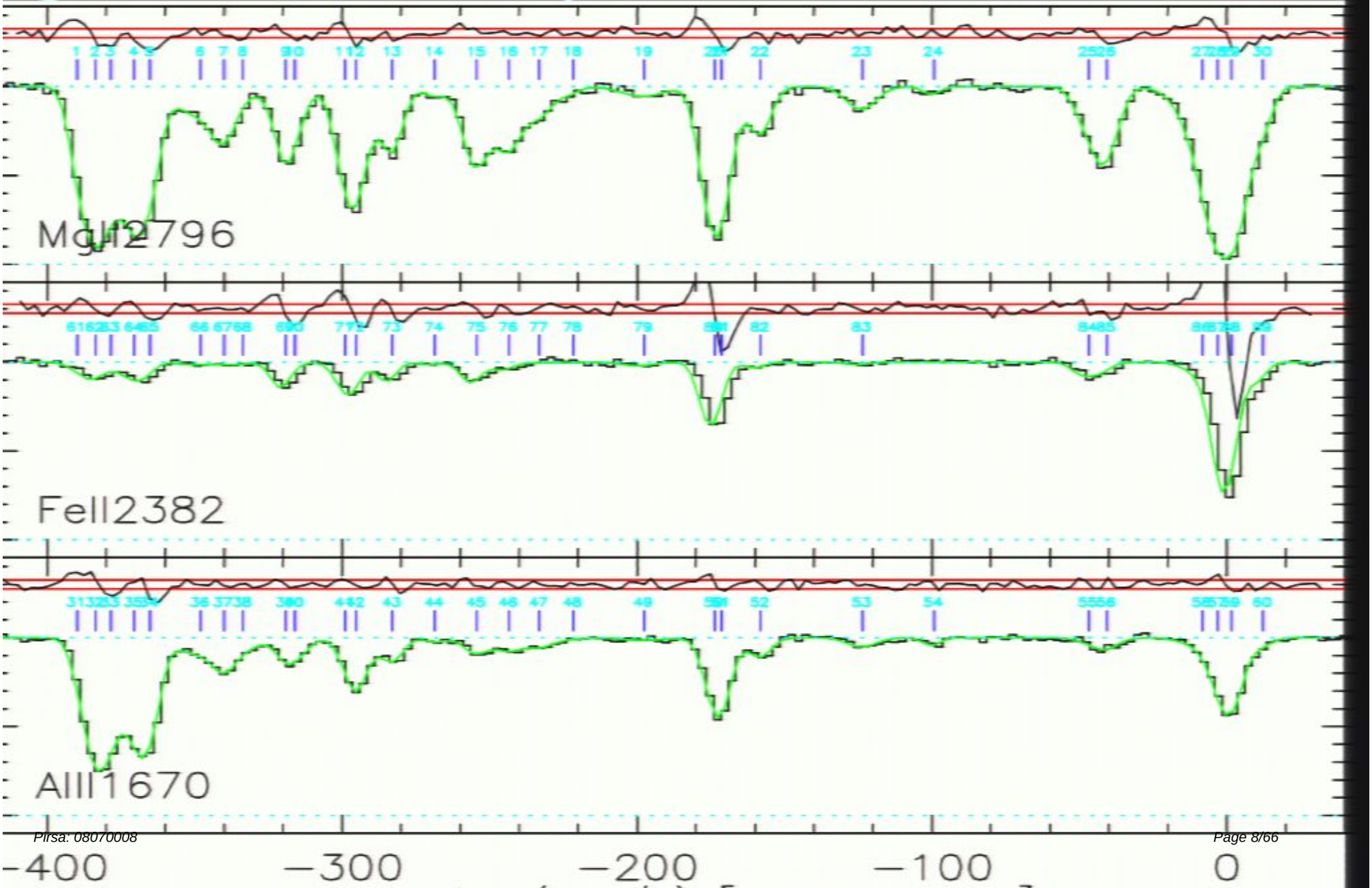


$\Delta\alpha/\alpha = 1\times10^{-5} \rightarrow \Delta v = 200 ms^{-1}$

.g. VLT/UVES profile:

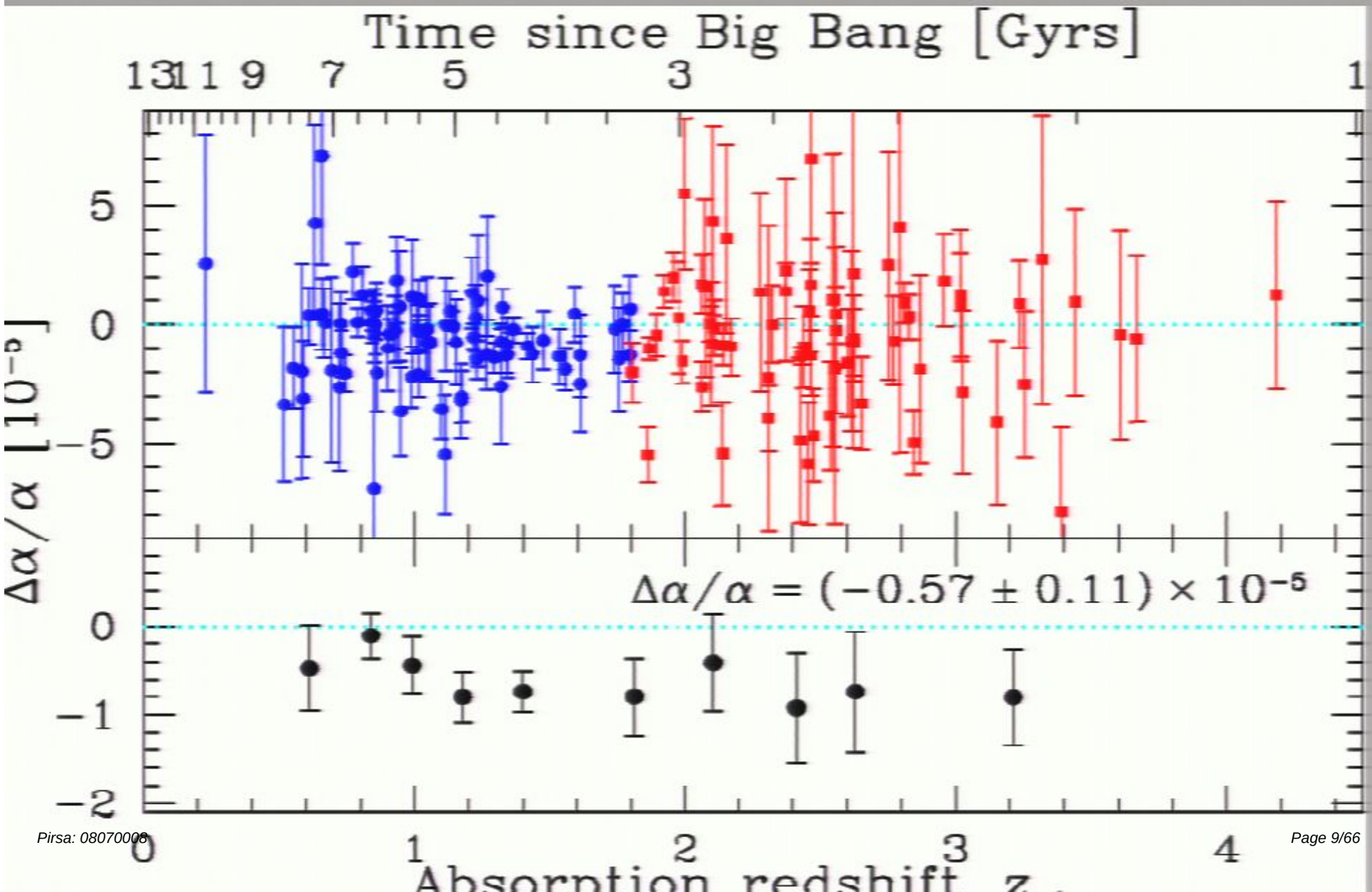


.g. VLT/UVES profile: $\Delta\alpha/\alpha=10^{-4}$

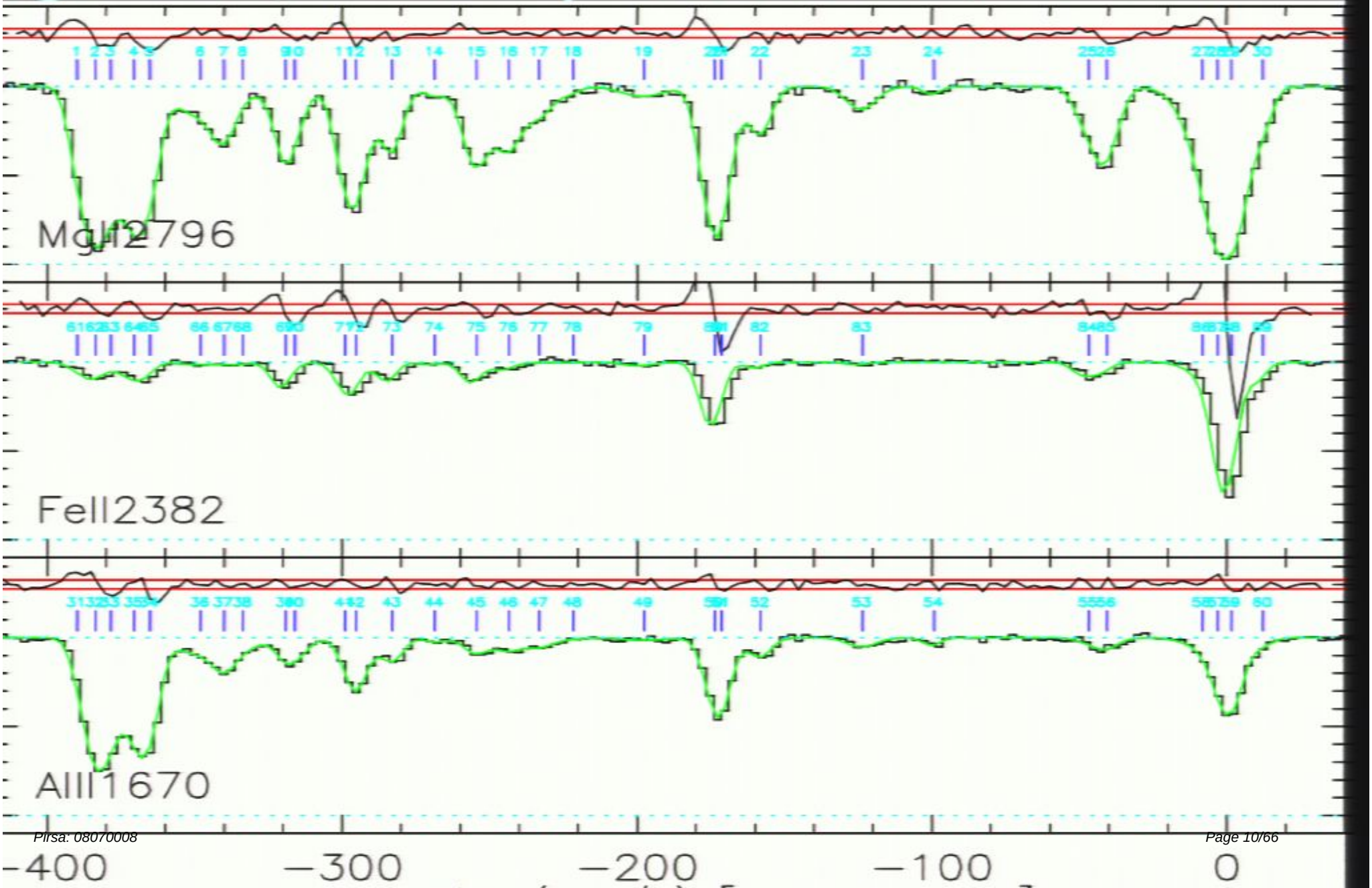


43 Keck/HIRES absorbers:

MTM et al. (LNP, 2004)

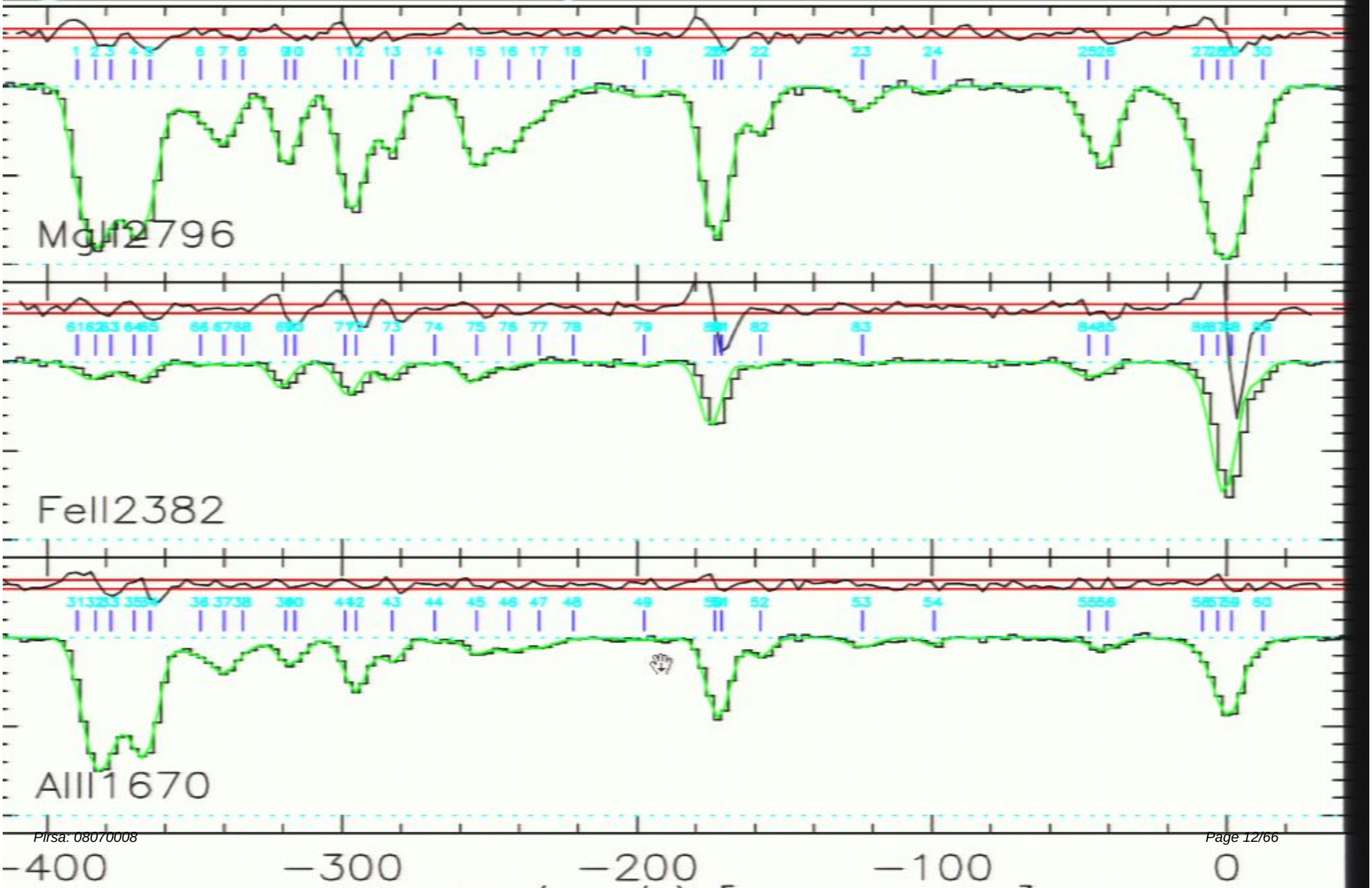


.g. VLT/UVES profile: $\Delta\alpha/\alpha=10^{-4}$

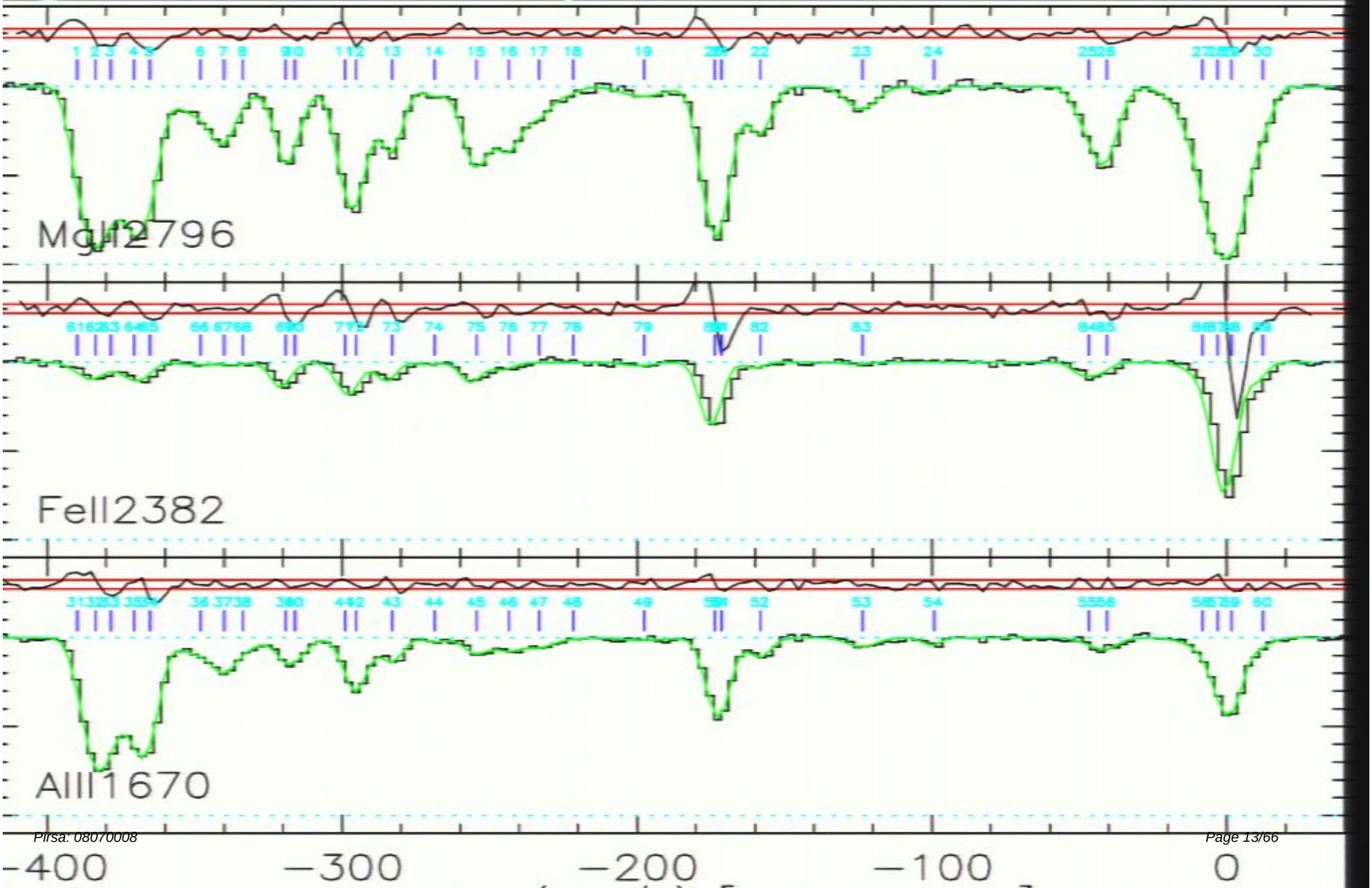



Microsoft
Windows xp
Professional

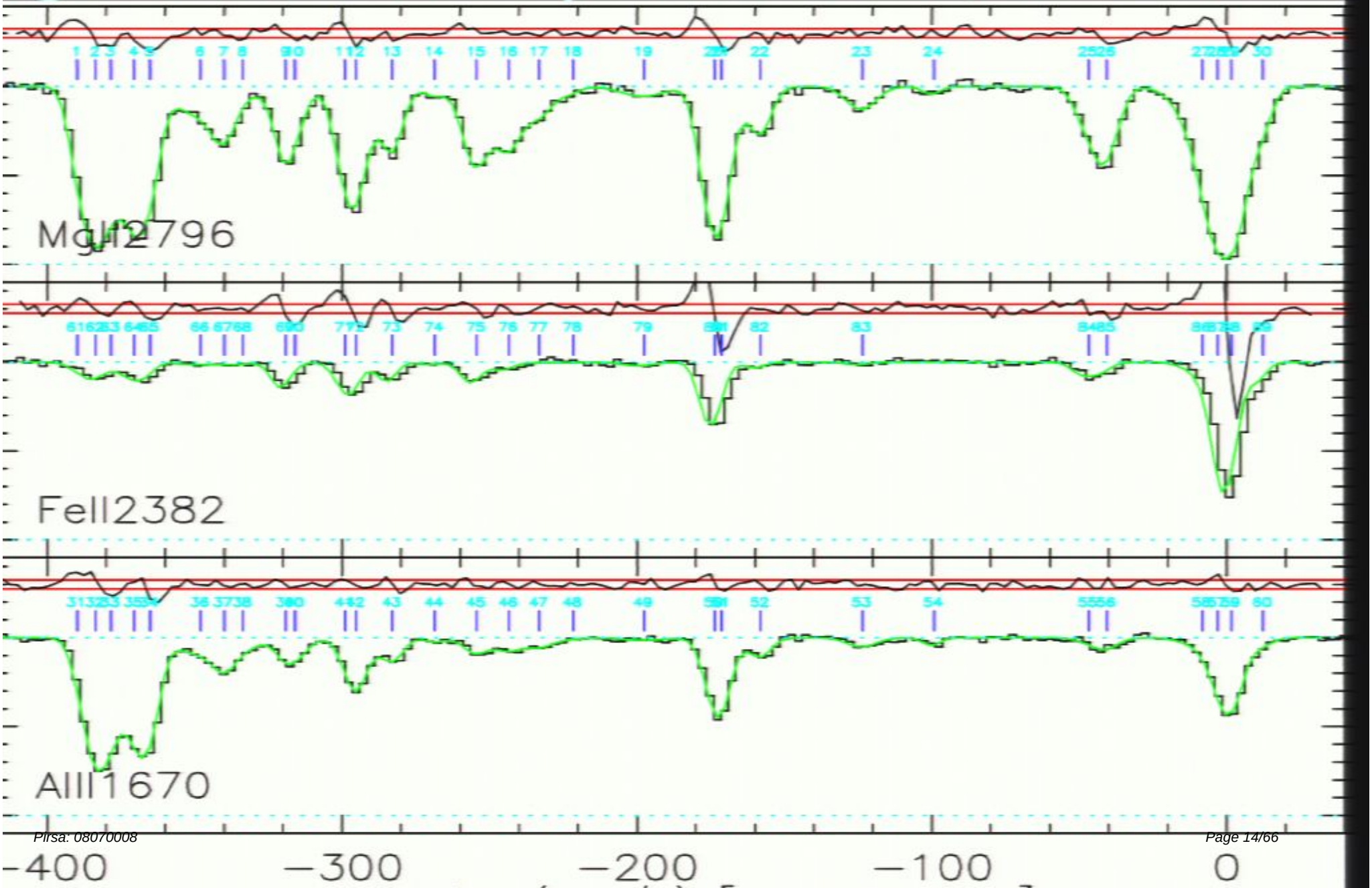
.g. VLT/UVES profile: $\Delta\alpha/\alpha=10^{-4}$



.g. VLT/UVES profile: $\Delta\alpha/\alpha=10^{-4}$

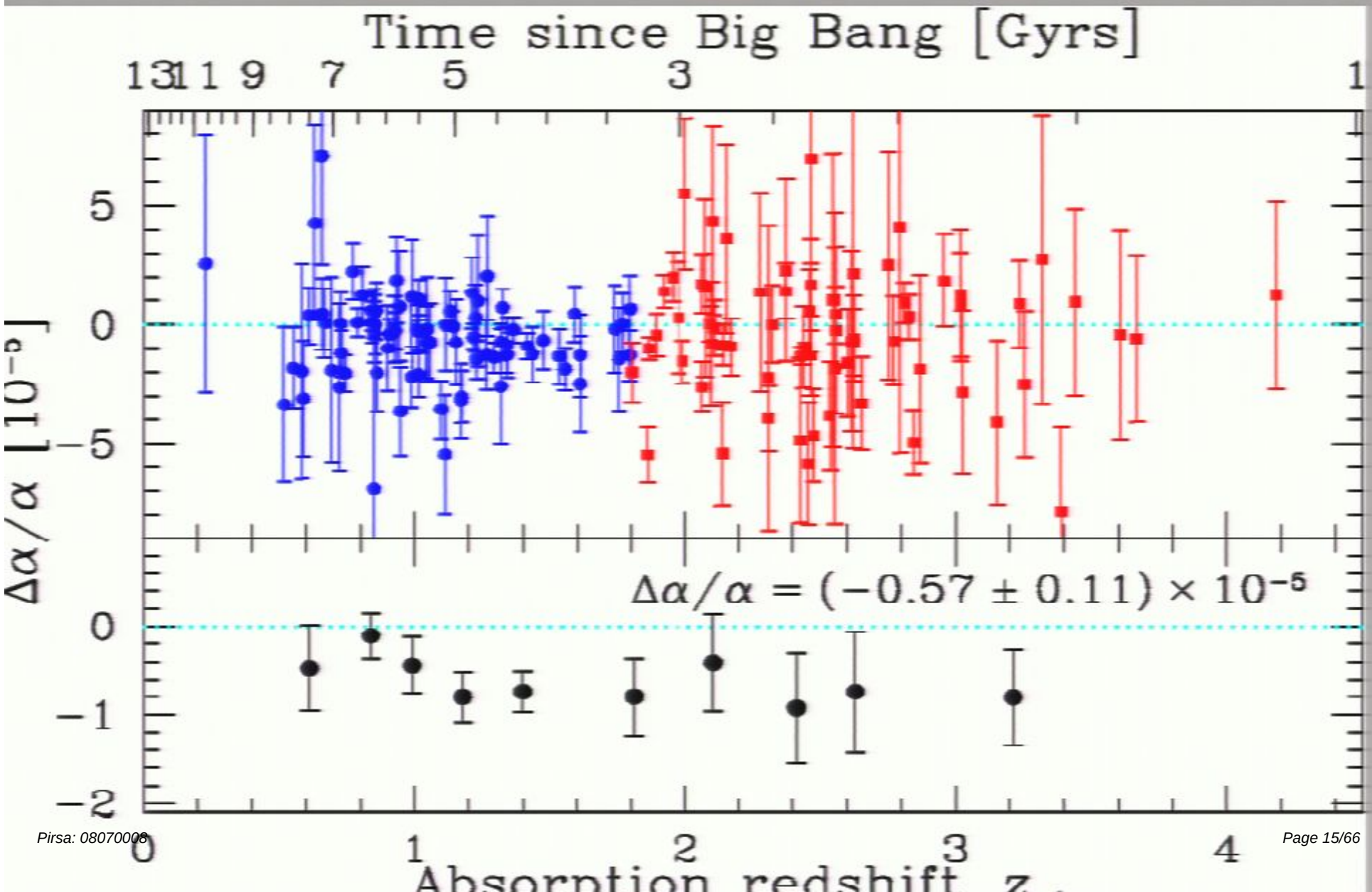


.g. VLT/UVES profile: $\Delta\alpha/\alpha=10^{-4}$

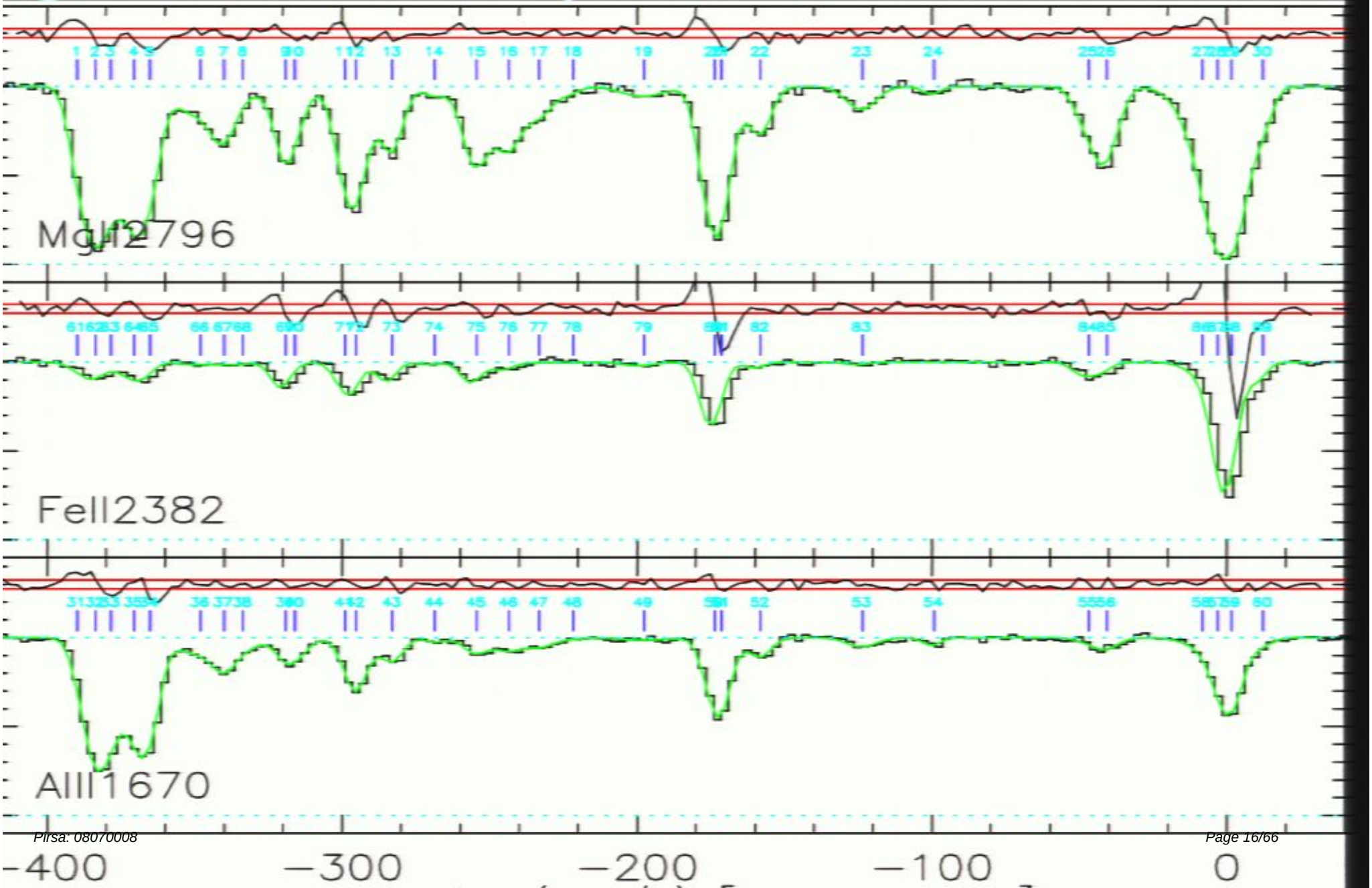


43 Keck/HIRES absorbers:

MTM et al. (LNP, 2004)

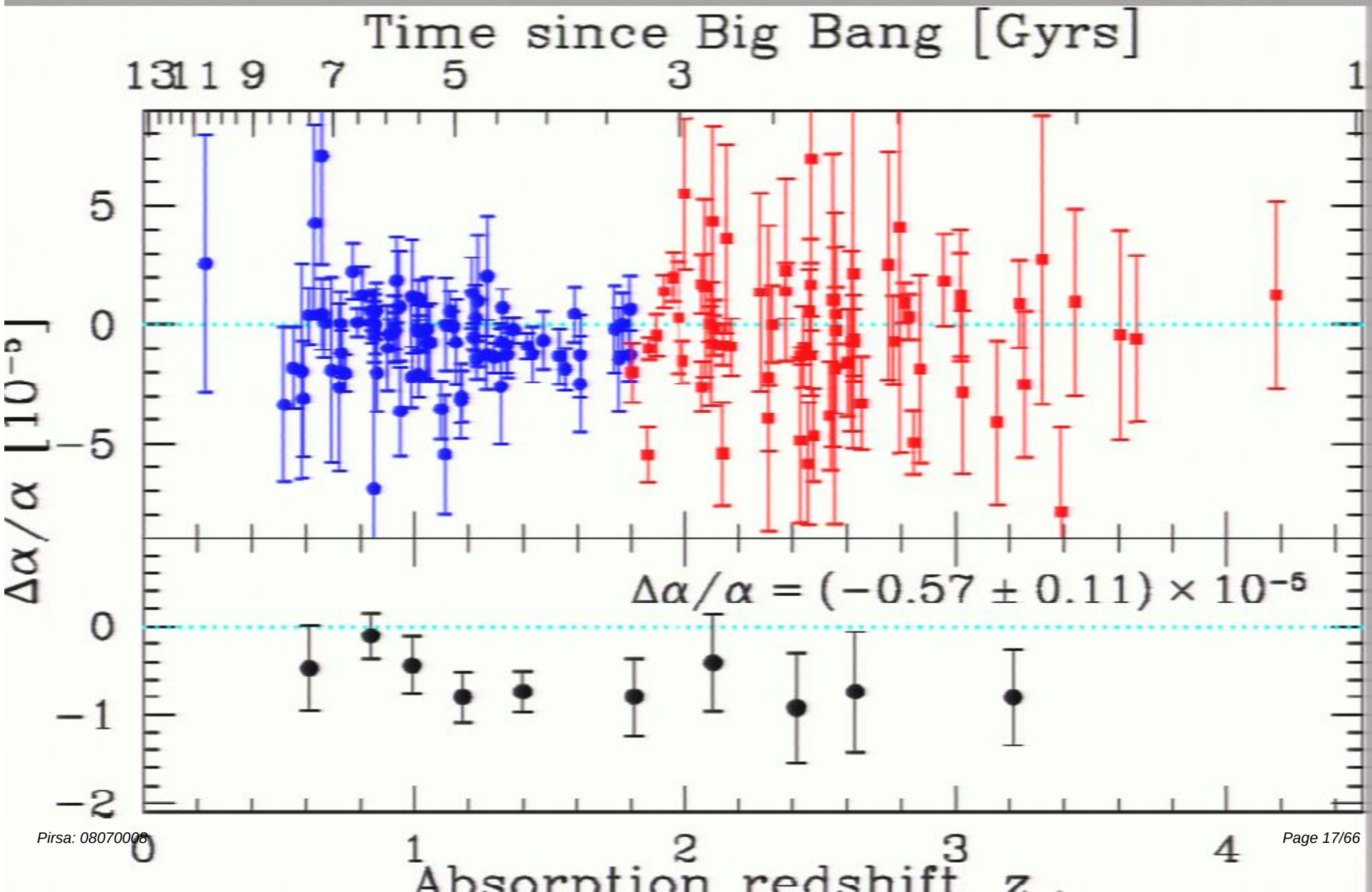


.g. VLT/UVES profile: $\Delta\alpha/\alpha=10^{-4}$



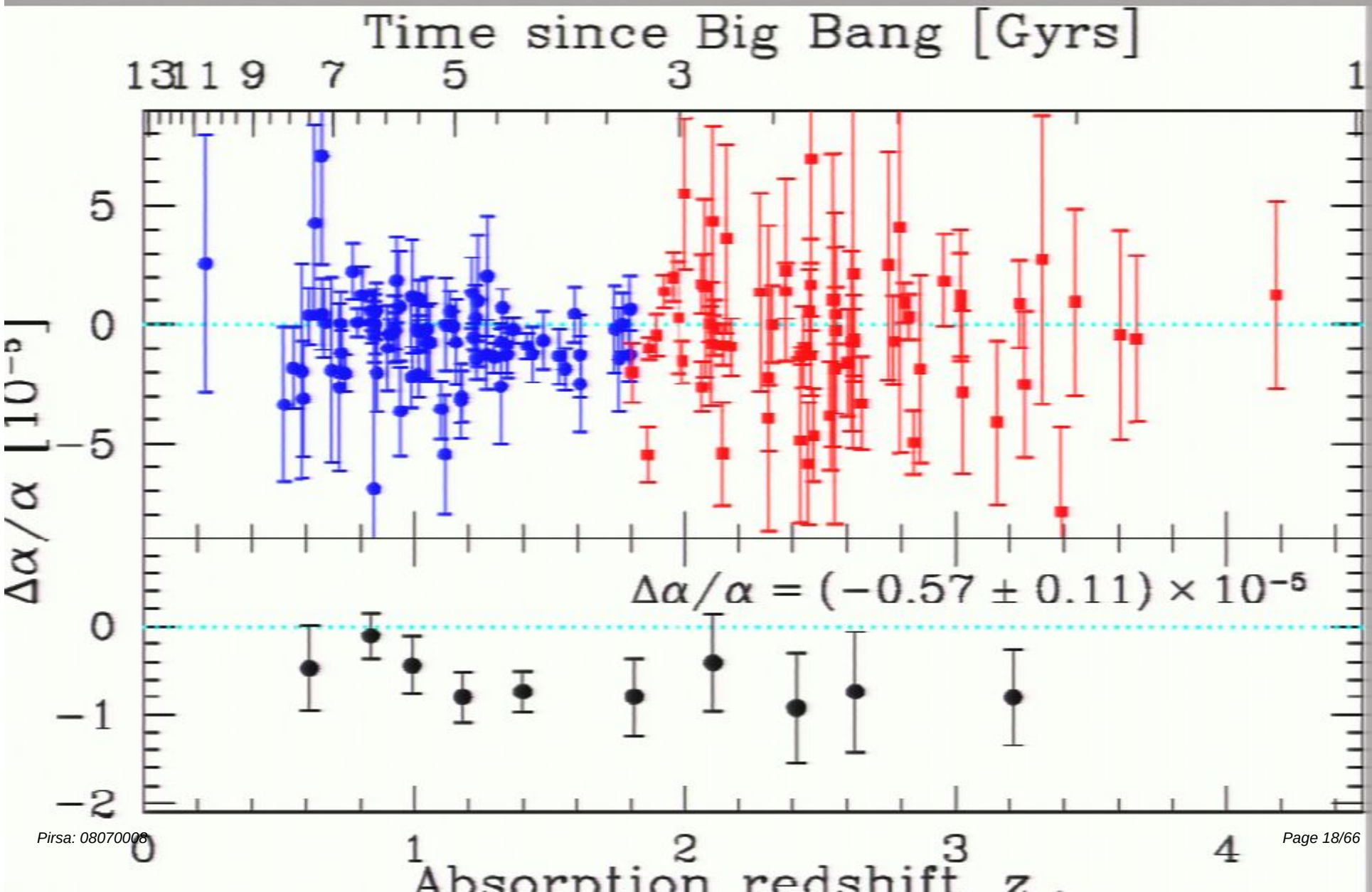
43 Keck/HIRES absorbers:

MTM et al. (LNP, 2004)



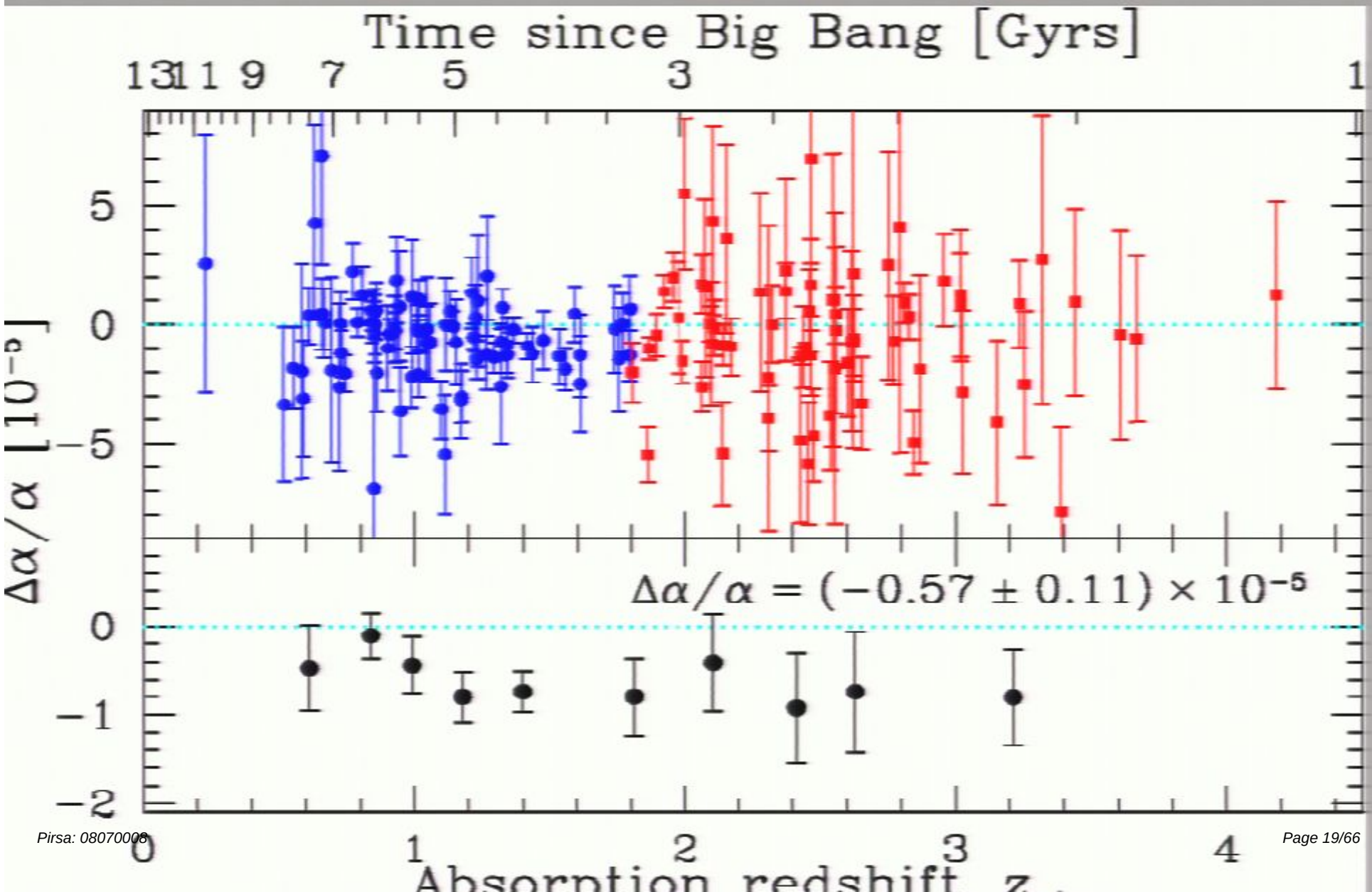
43 Keck/HIRES absorbers:

MTM et al. (LNP, 2004)



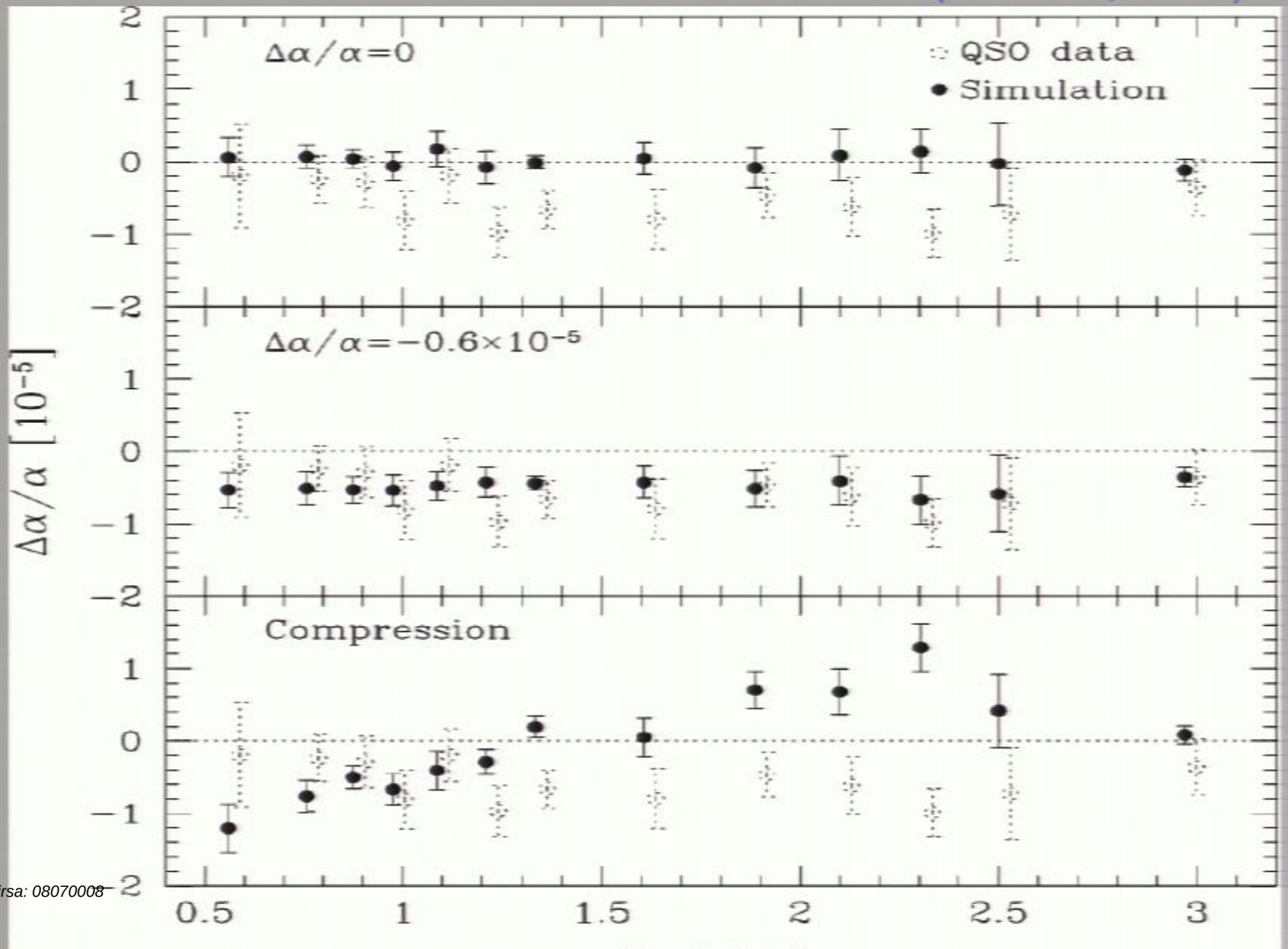
43 Keck/HIRES absorbers:

MTM et al. (LNP, 2004)

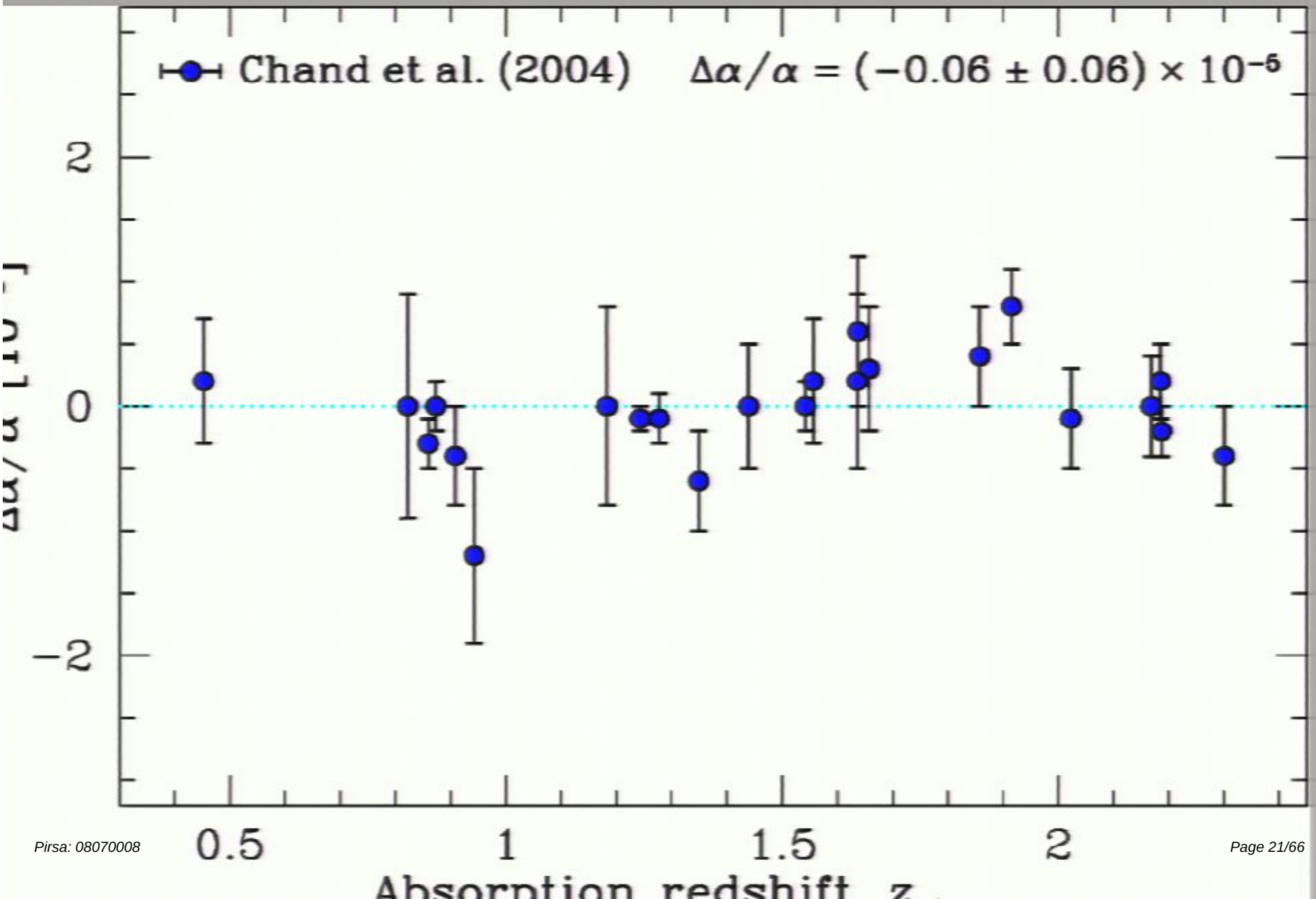


esistant to simple systematics:

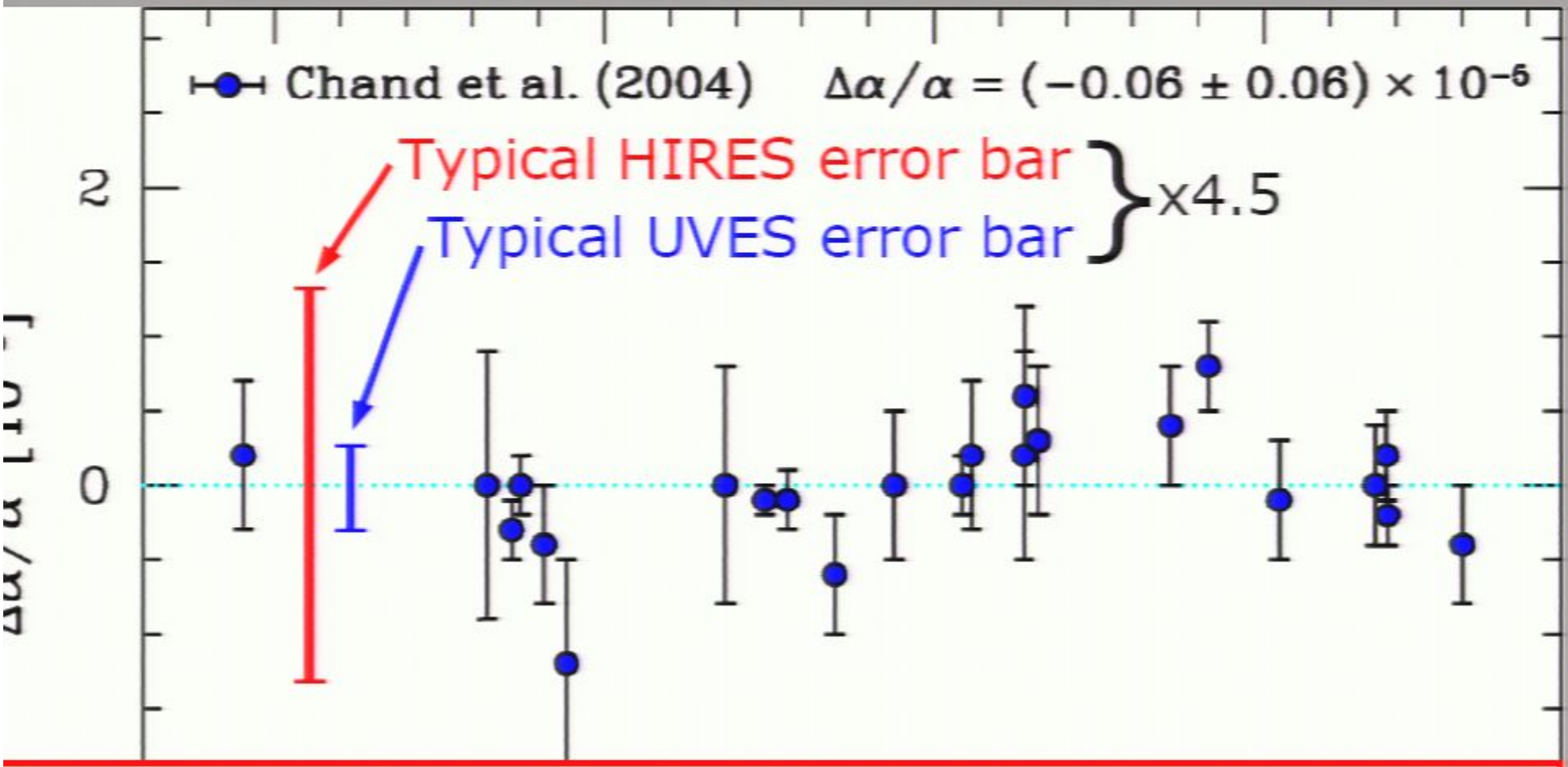
MTM et al. (MNRAS, 2003)



rianand/Chand et al. (2004):



rianand/Chand et al. (2004):



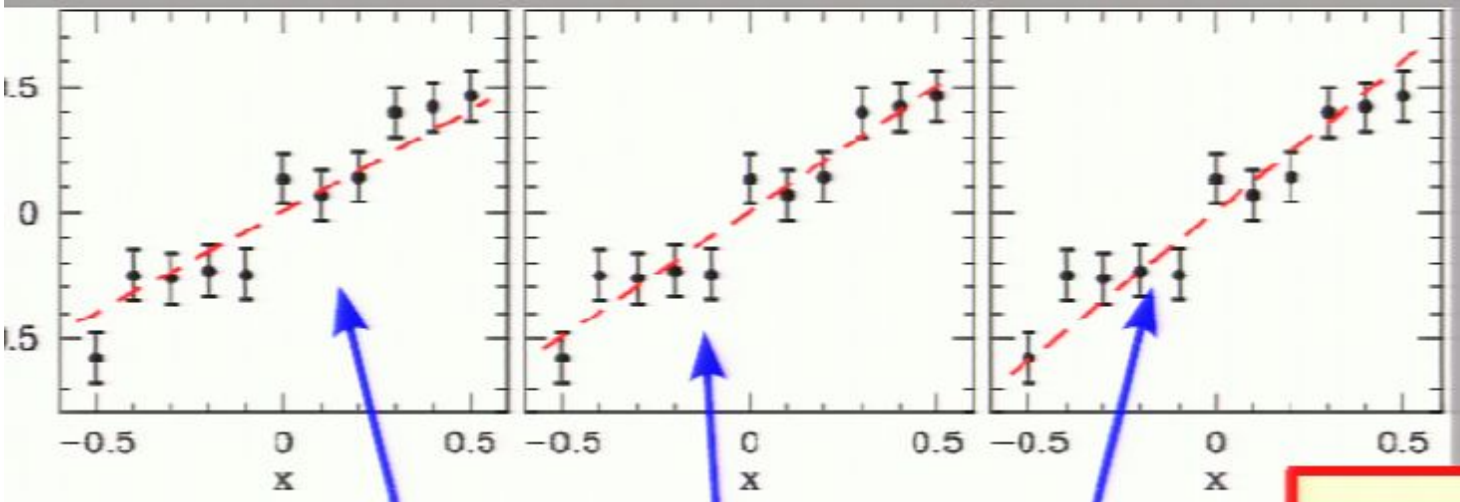
Much smaller error-bars:

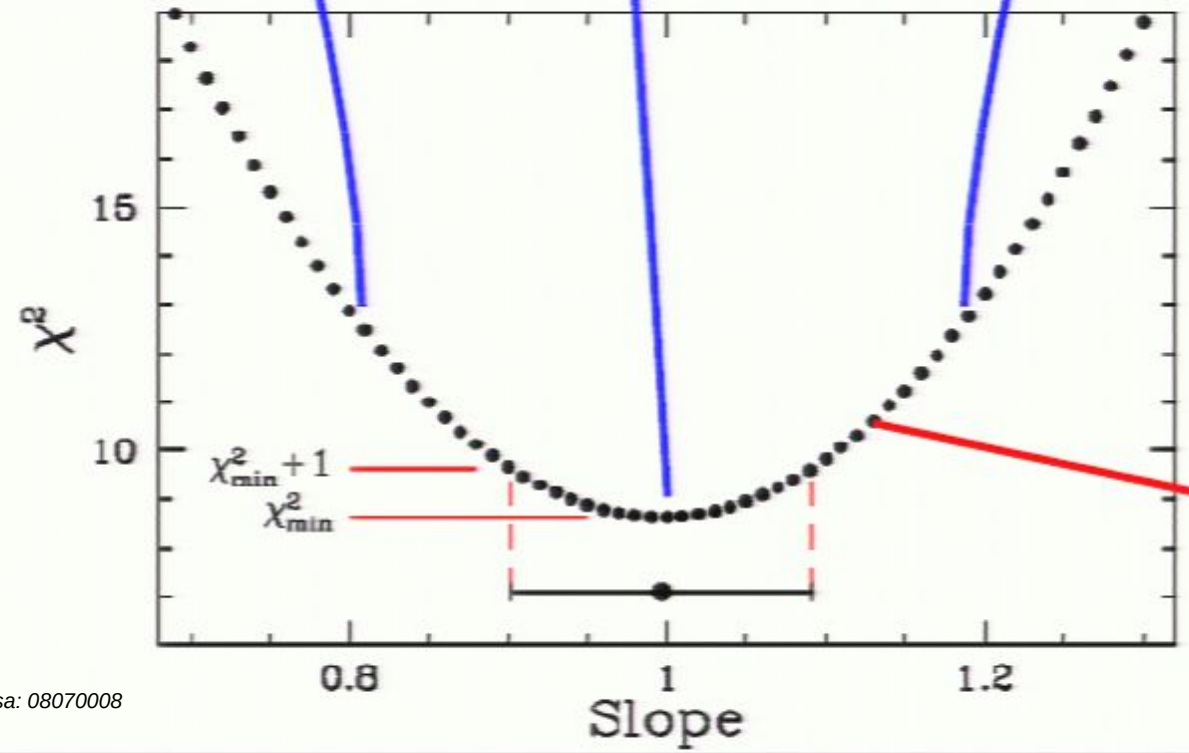
If S/N is ~2× HIRES spectra, error should be

$\sim \frac{1}{2}[0.11\times10^{-5}]\times\sqrt{143/23} = \mathbf{0.14\times10^{-5}}$

Absorption redshift, z

^{2} fitting – a straight line:

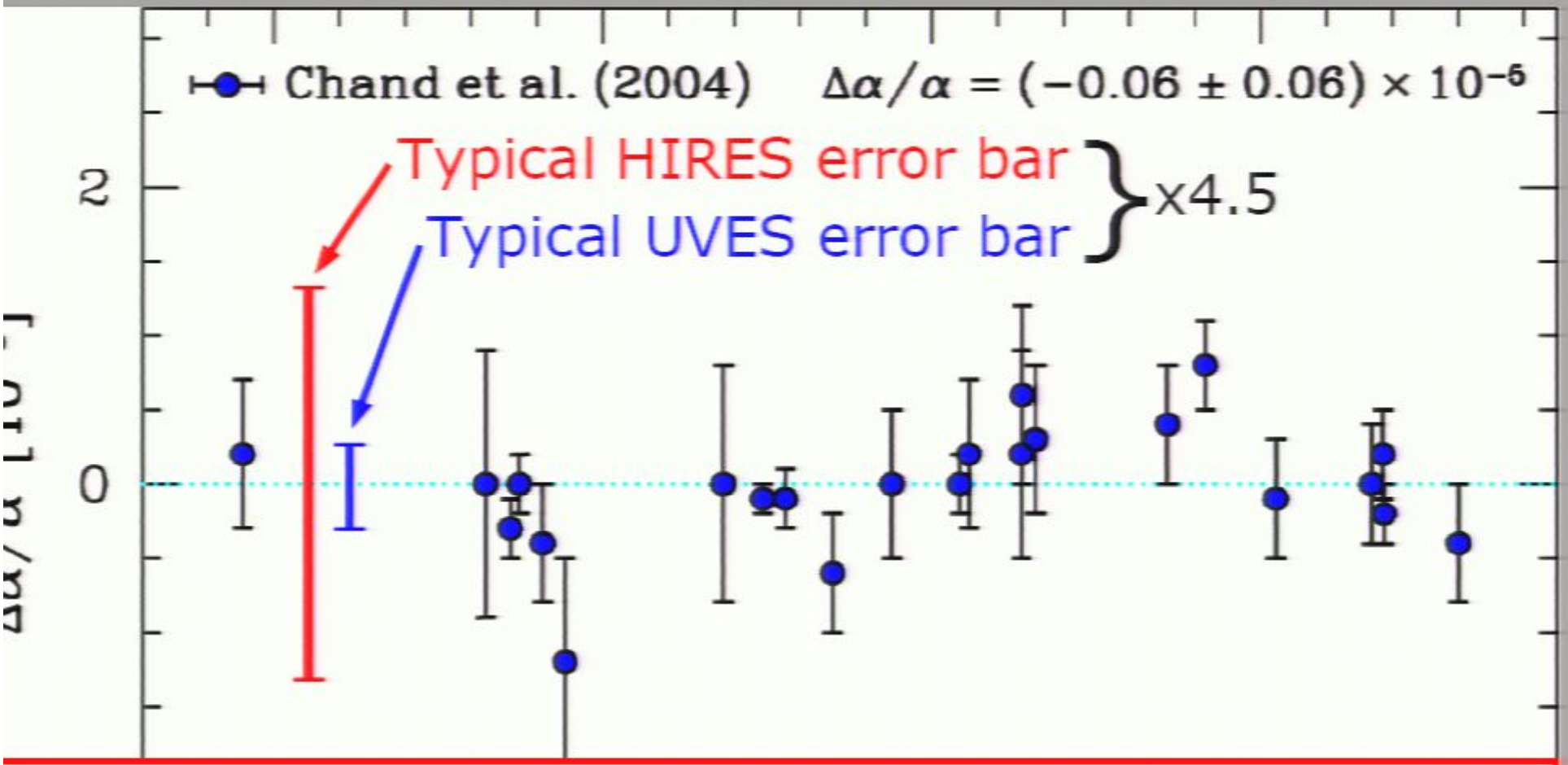




$$\chi^2 \equiv \sum_i \left[\frac{\text{data}_i - \text{model}_i}{\text{error}_i} \right]^2$$

NOTE: χ^2 curve is 'smooth'

rianand/Chand et al. (2004):



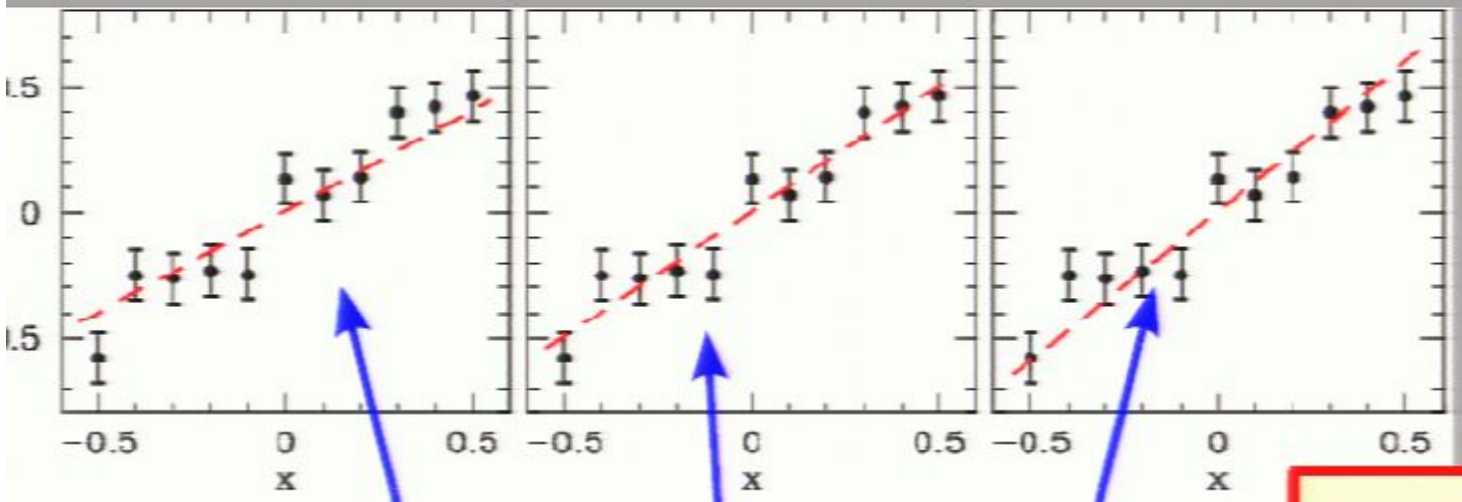
Much smaller error-bars:

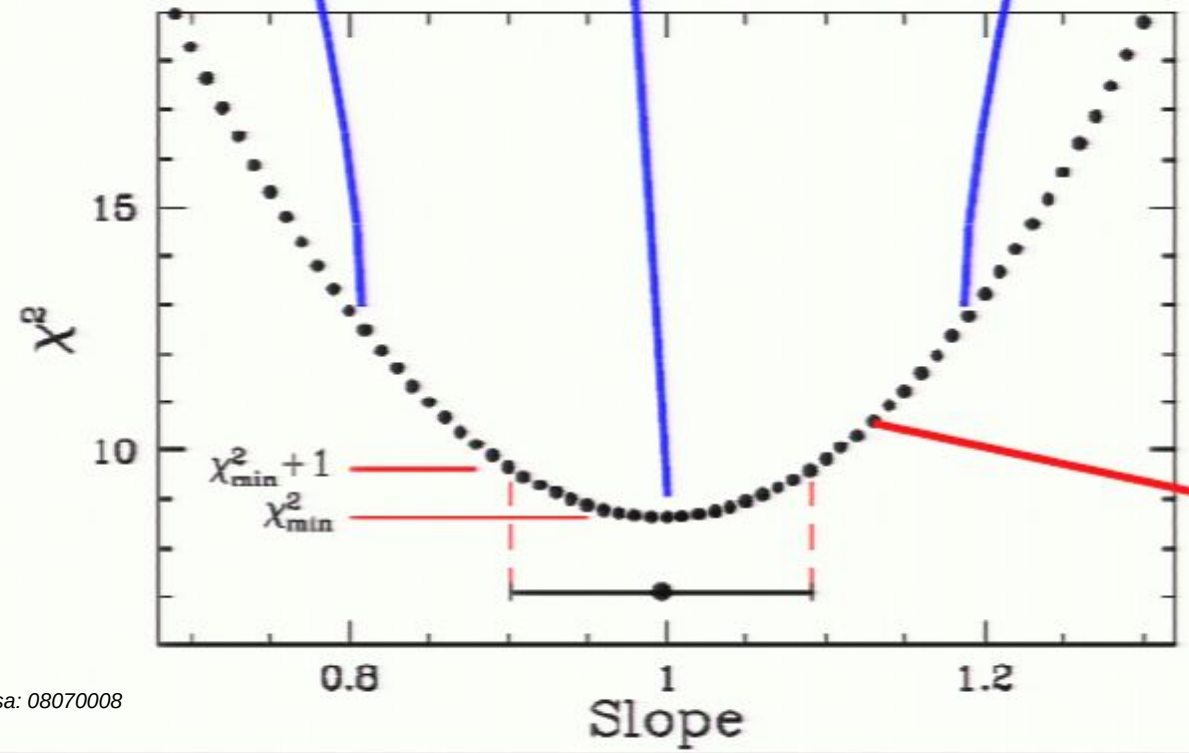
If S/N is ~2× HIRES spectra, error should be

$\sim \frac{1}{2}[0.11\times10^{-5}]\times\sqrt{143/23} = \mathbf{0.14\times10^{-5}}$

Absorption redshift, z

χ^2 fitting – a straight line:





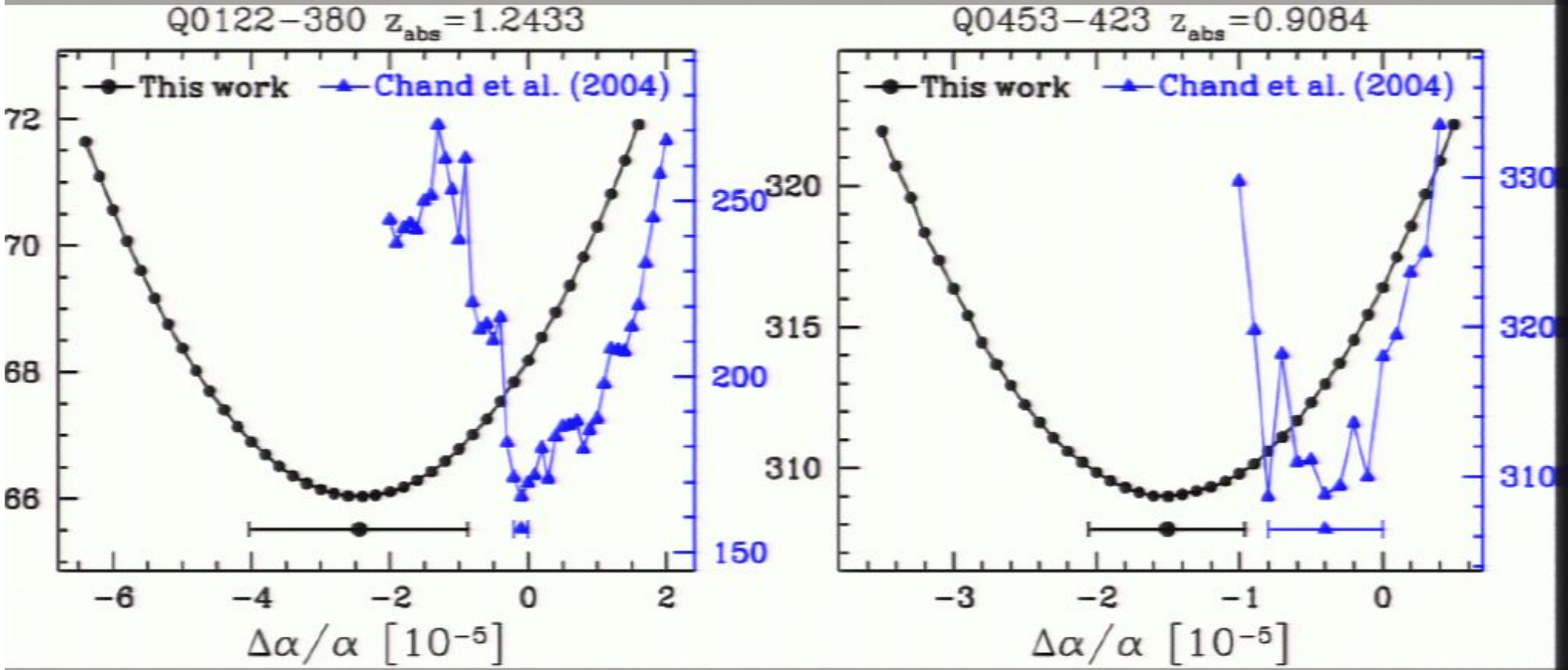
$$\chi^2 \equiv \sum_i \left[\frac{\text{data}_i - \text{model}_i}{\text{error}_i} \right]^2$$

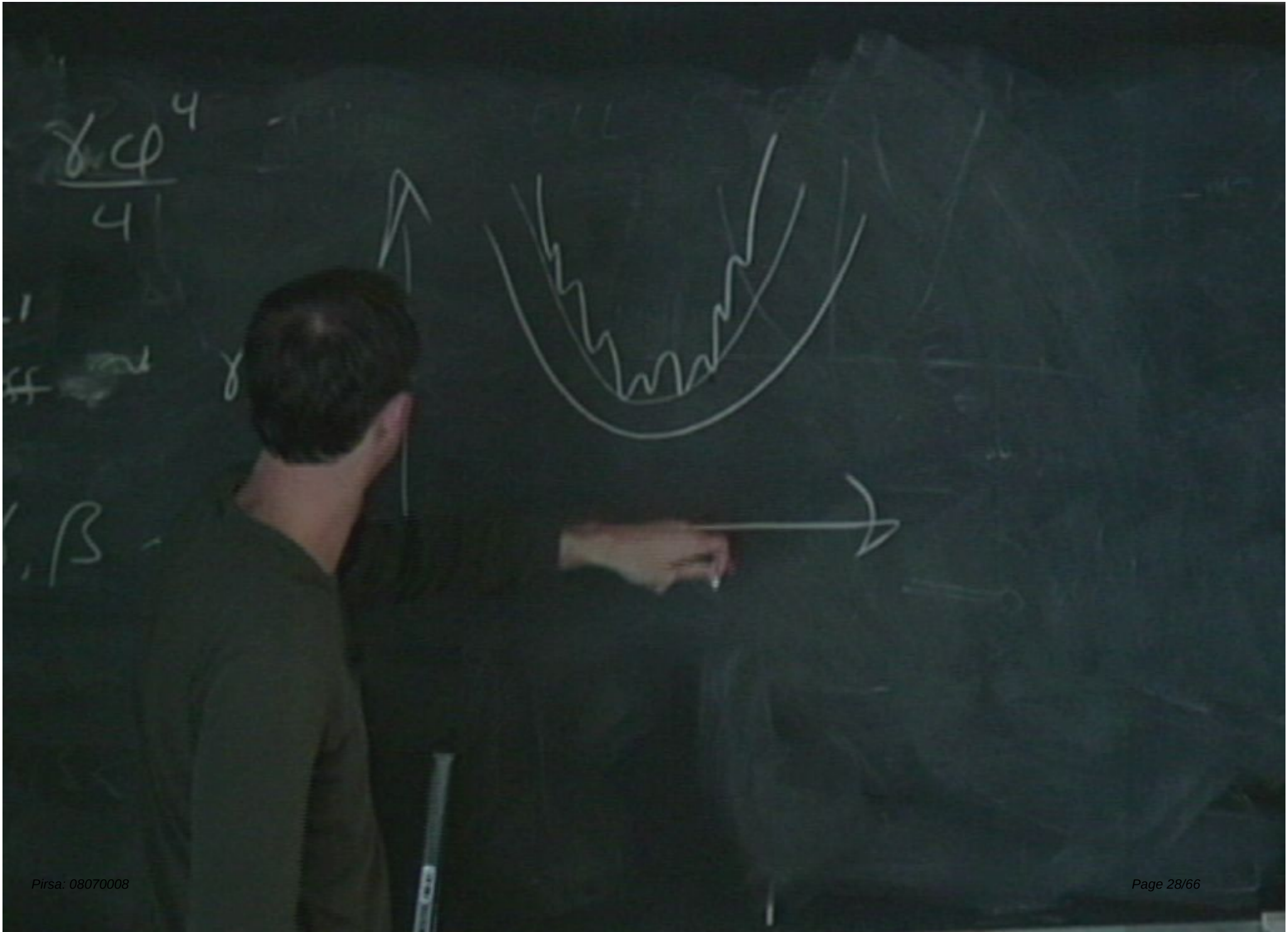
NOTE: χ^2 curve is 'smooth'

^{2} curves should be smooth:

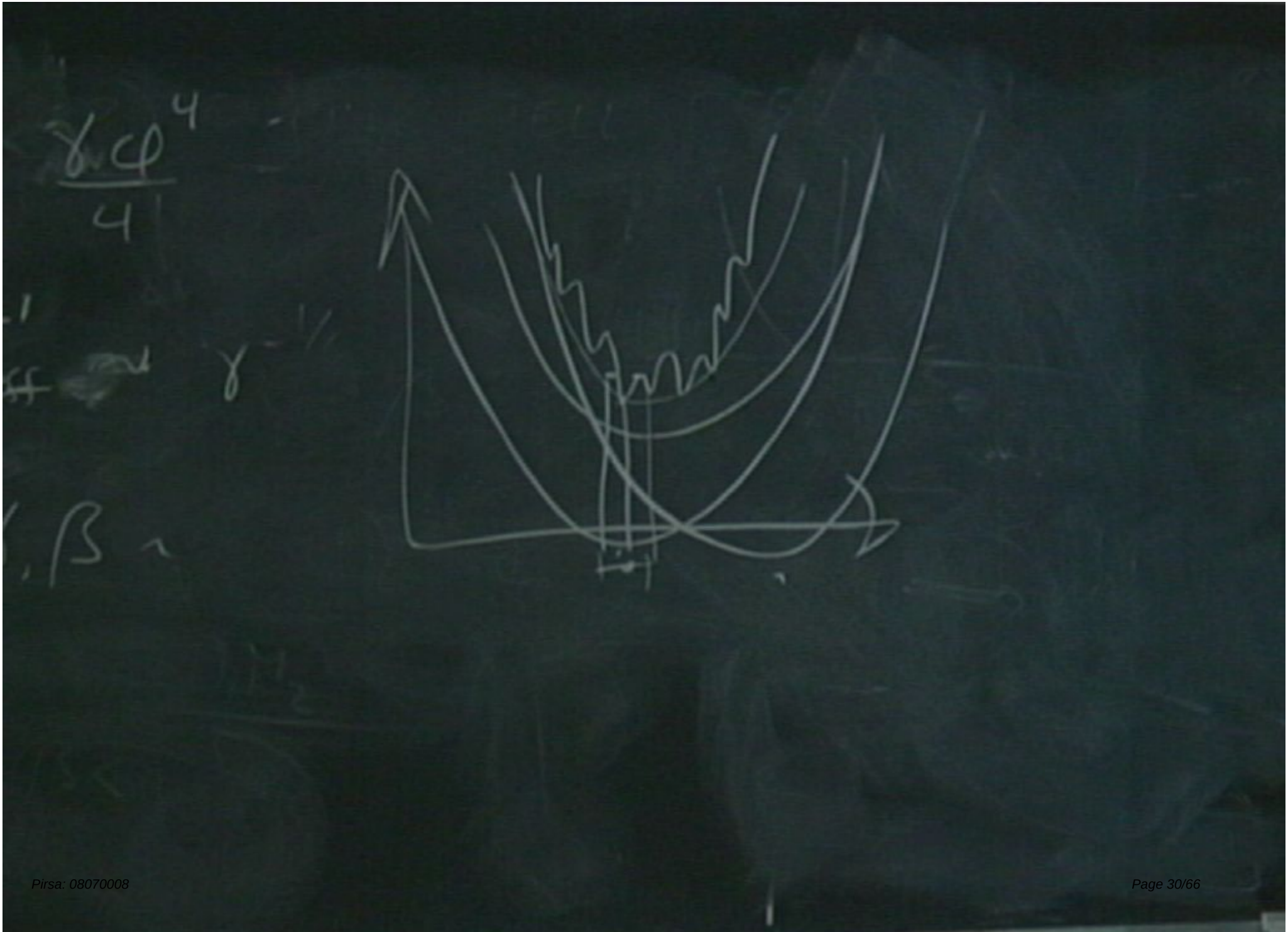
n scales similar to the 1-σ error, the χ^2 curve
UST be SMOOTH and near-parabolic.

MTM, Flambaum, Webb (PRL & MNRAS, 2008)




$\frac{\gamma \cdot \phi^4}{4!}$

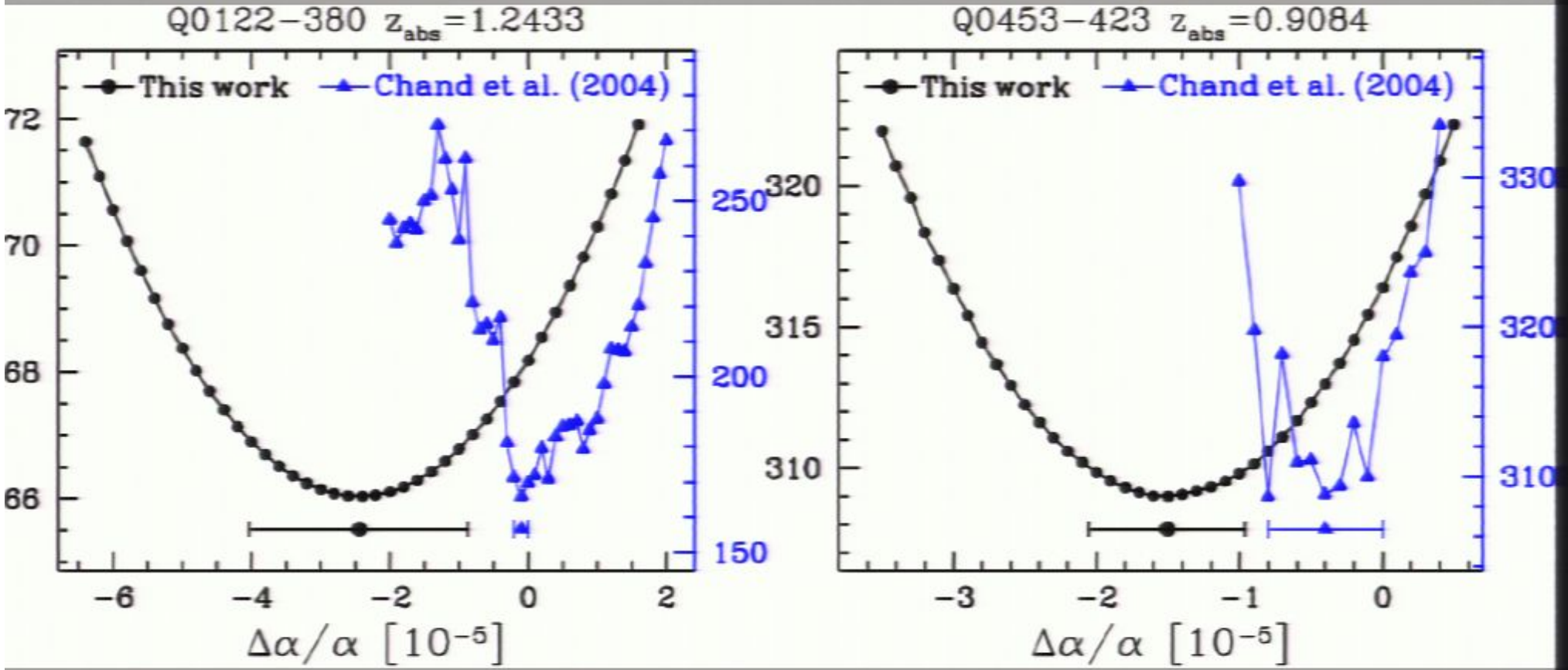

$\frac{\lambda_{ren}\phi^4}{4!}$



^{2} curves should be smooth:

n scales similar to the 1-σ error, the χ^2 curve
UST be SMOOTH and near-parabolic.

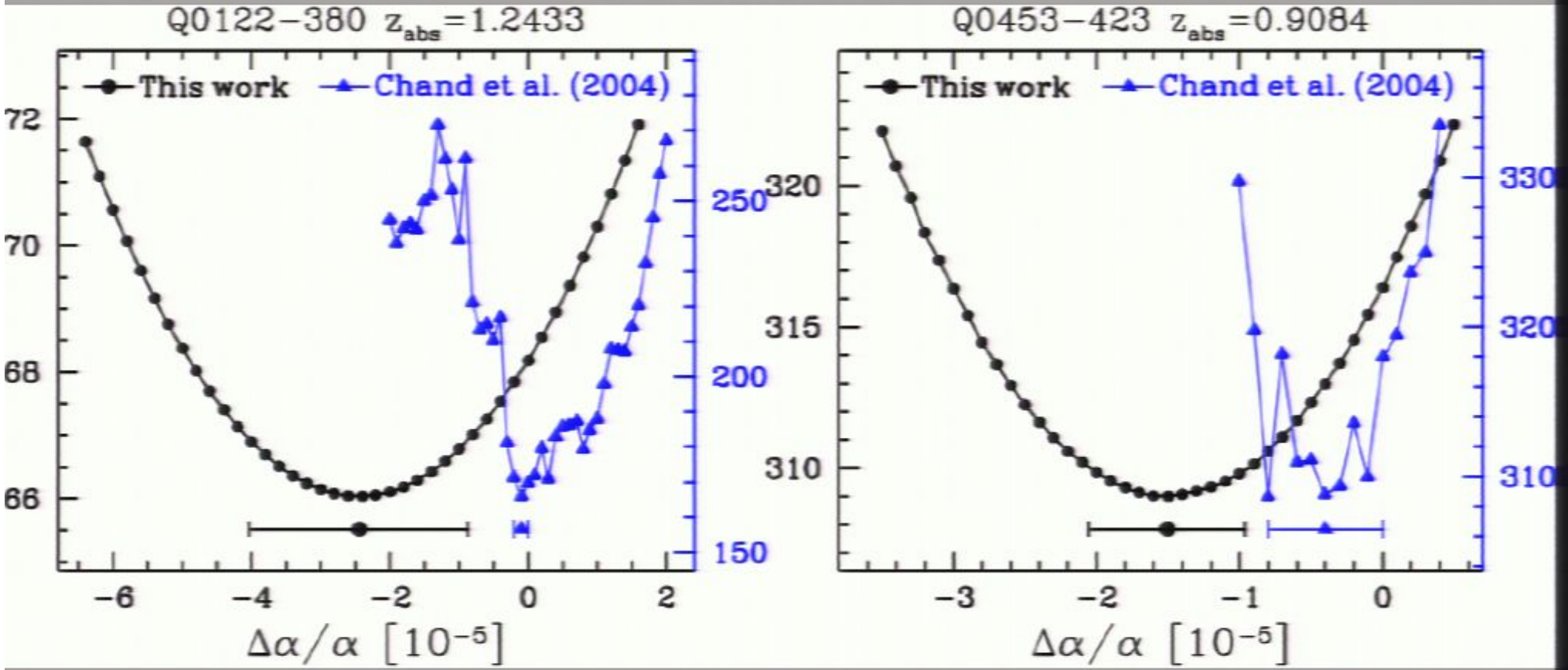
MTM, Flambaum, Webb (PRL & MNRAS, 2008)

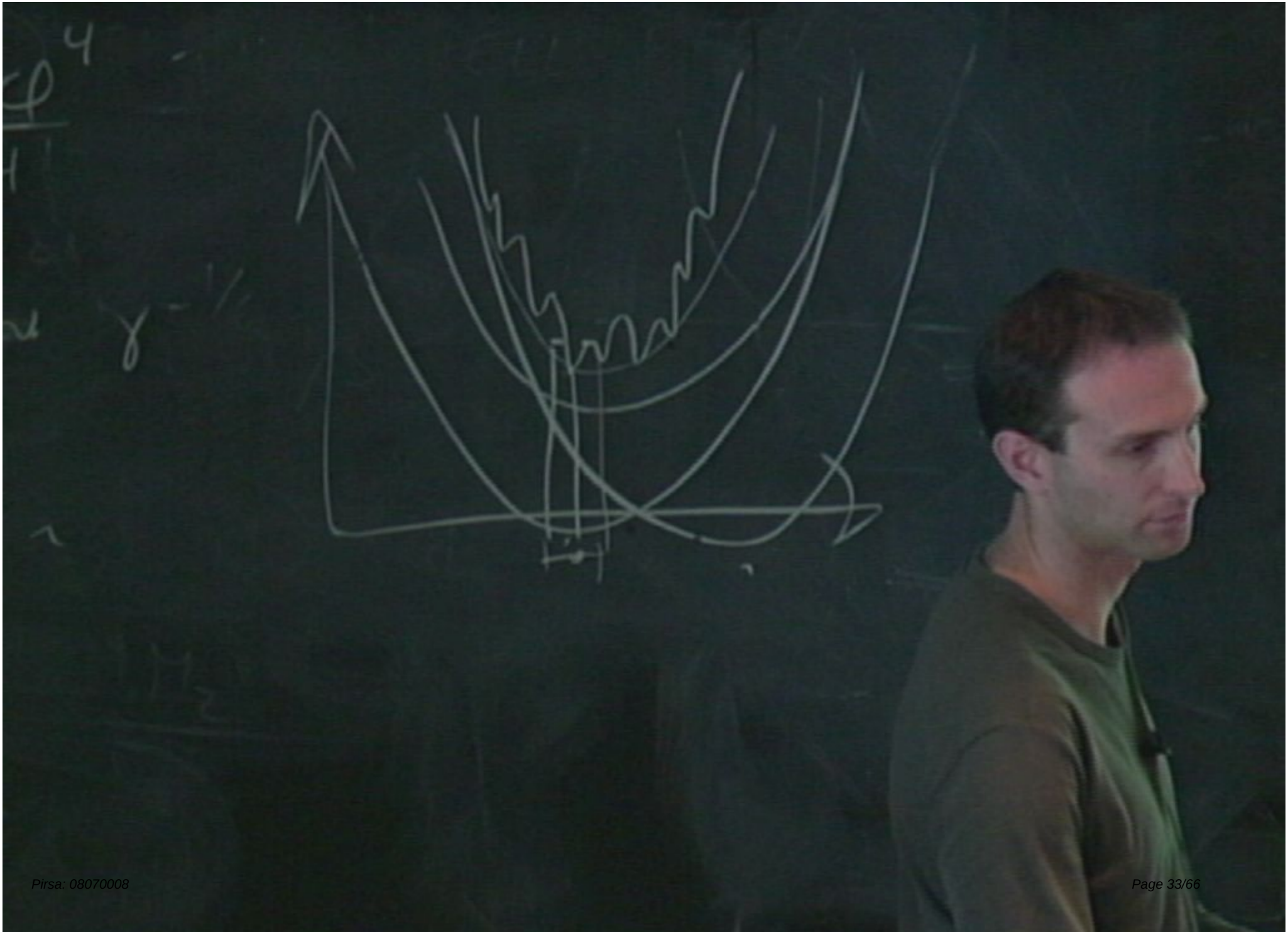


^{2} curves should be smooth:

n scales similar to the 1-σ error, the χ^2 curve *UST* be SMOOTH and near-parabolic.

MTM, Flambaum, Webb (PRL & MNRAS, 2008)

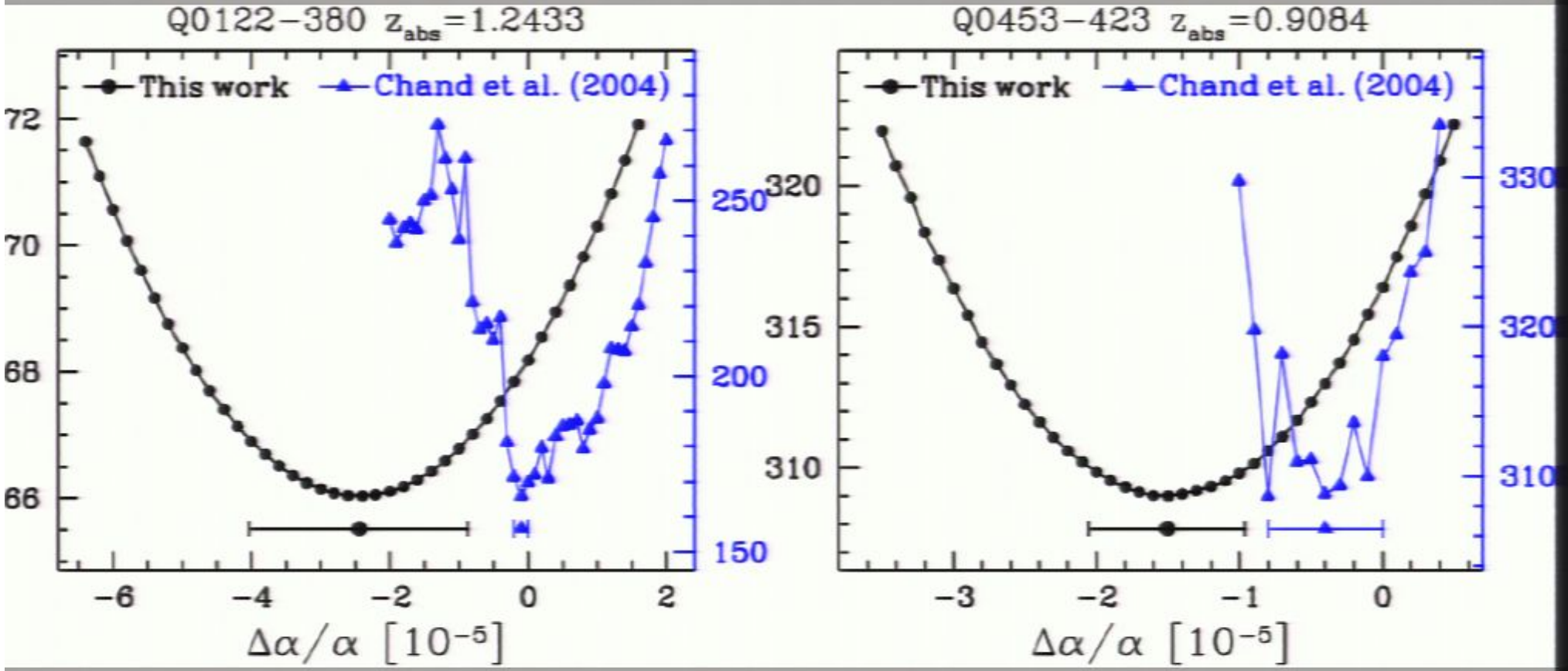




^{2} curves should be smooth:

n scales similar to the 1-σ error, the χ^2 curve
UST be SMOOTH and near-parabolic.

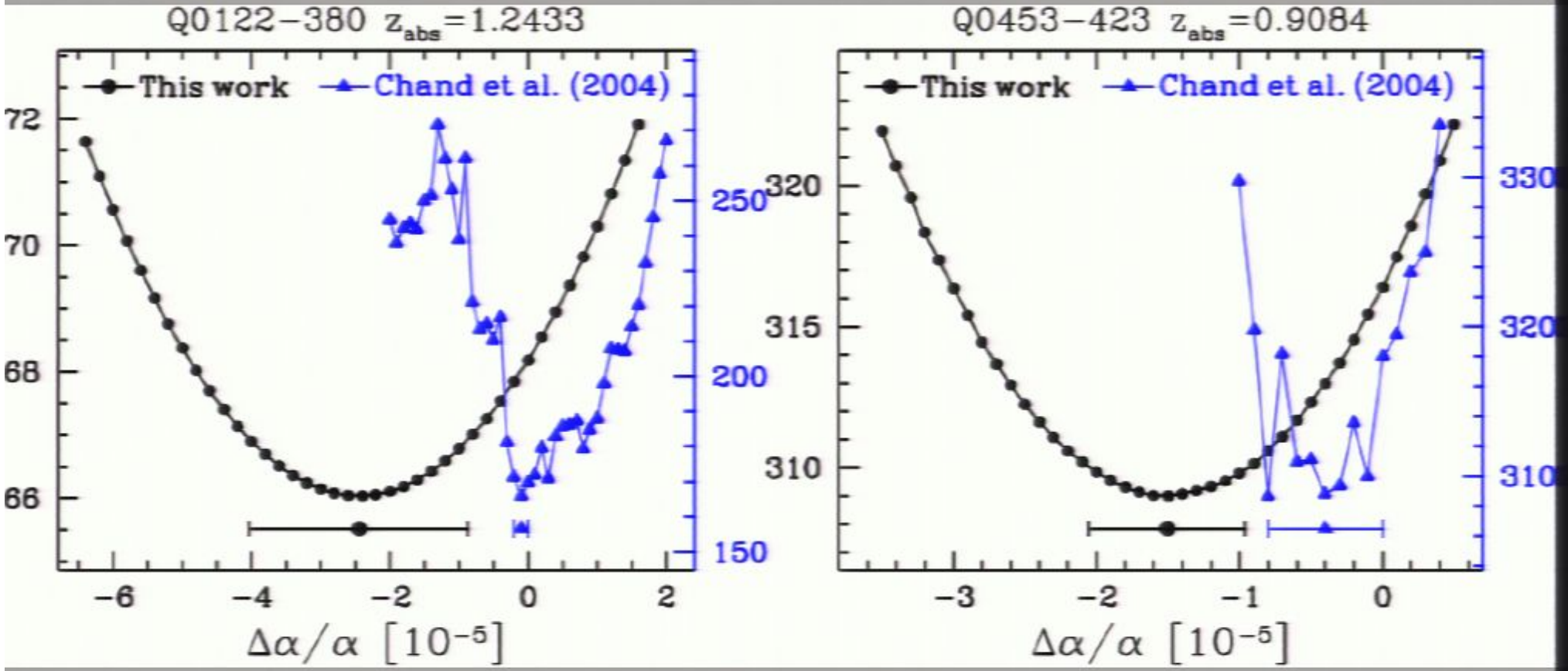
MTM, Flambaum, Webb (PRL & MNRAS, 2008)



^{2} curves should be smooth:

n scales similar to the 1-σ error, the χ^2 curve
UST be SMOOTH and near-parabolic.

MTM, Flambaum, Webb (PRL & MNRAS, 2008)

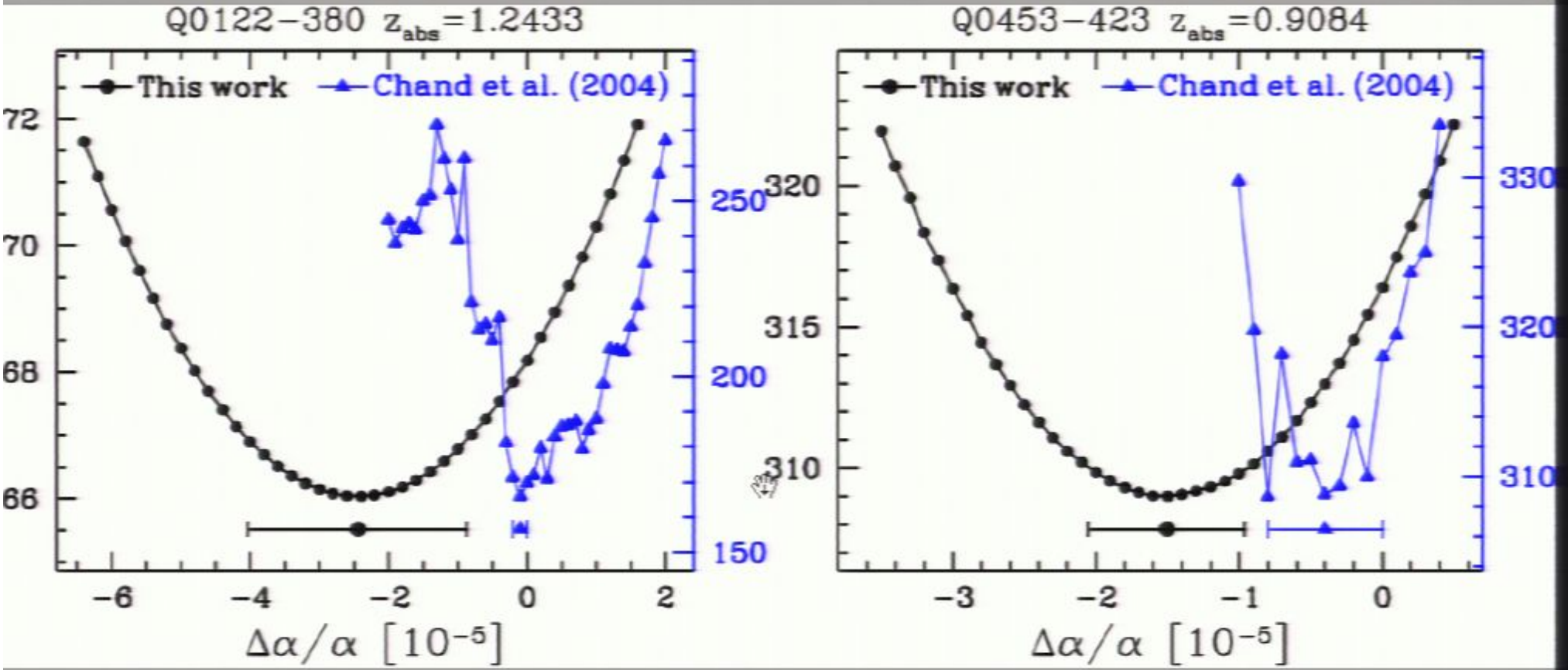


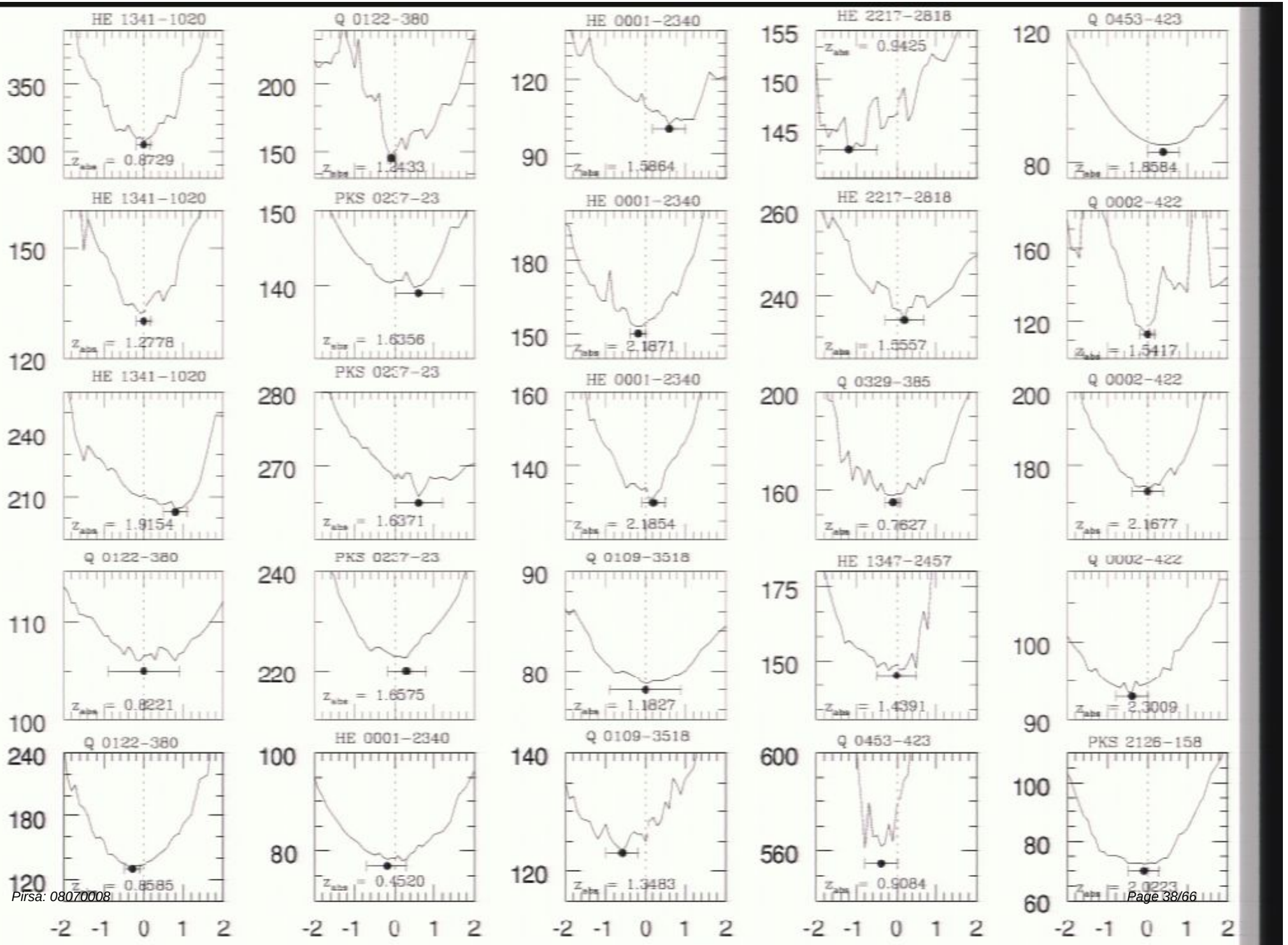

Microsoft
Windows xp
Professional

^{2} curves should be smooth:

n scales similar to the 1-σ error, the χ^2 curve
UST be SMOOTH and near-parabolic.

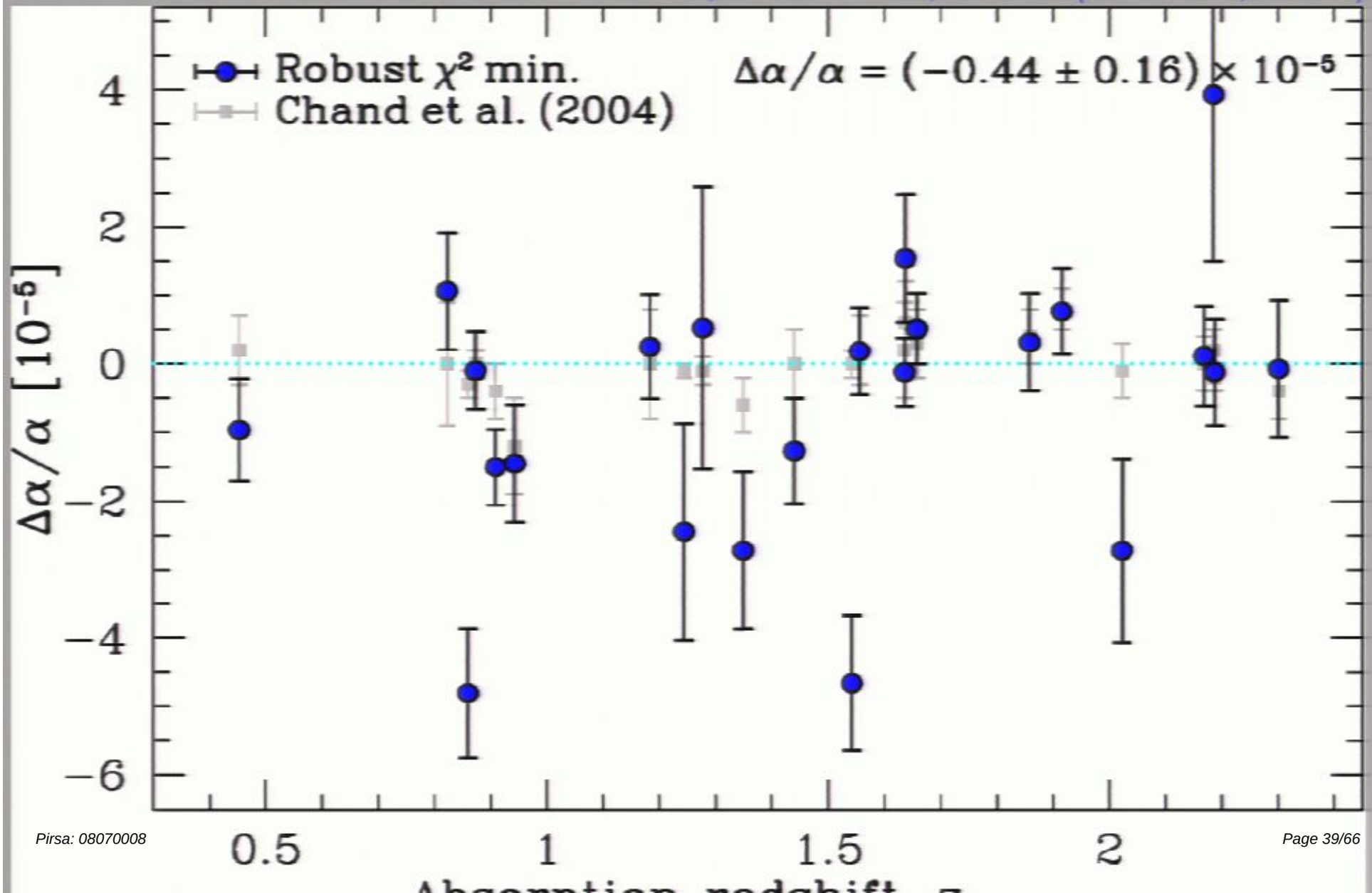
MTM, Flambaum, Webb (PRL & MNRAS, 2008)




HE 1341-1020
z_abs = 0.8729
Q 0122-380
z_abs = 1.2433
HE 0001-2340
z_abs = 1.5864
HE 2217-2818
z_abs = 0.9425
Q 0453-423
z_abs = 1.8584
HE 1341-1020
z_abs = 1.2778
PKS 0237-23
z_abs = 1.6356
HE 0001-2340
z_abs = 2.1871
HE 2217-2818
z_abs = 1.5557
Q 0002-422
z_abs = 1.5417
HE 1341-1020
z_abs = 1.9154
PKS 0237-23
z_abs = 1.6371
HE 0001-2340
z_abs = 2.1854
Q 0329-385
z_abs = 0.7627
Q 0002-422
z_abs = 2.1677
Q 0122-380
z_abs = 0.8221
PKS 0237-23
z_abs = 1.6575
Q 0109-3518
z_abs = 1.1827
HE 1347-2457
z_abs = 1.4391
Q 0002-422
z_abs = 2.3009
Q 0122-380
z_abs = 0.8585
HE 0001-2340
z_abs = 0.4520
Q 0109-3518
z_abs = 1.3483
Q 0453-423
z_abs = 0.9084
PKS 2126-158
z_abs = 2.0223
-2 -1 0 1 2

evise with robust χ^2 minimization:

MTM, Flambaum, Webb (MNRAS, 2008)

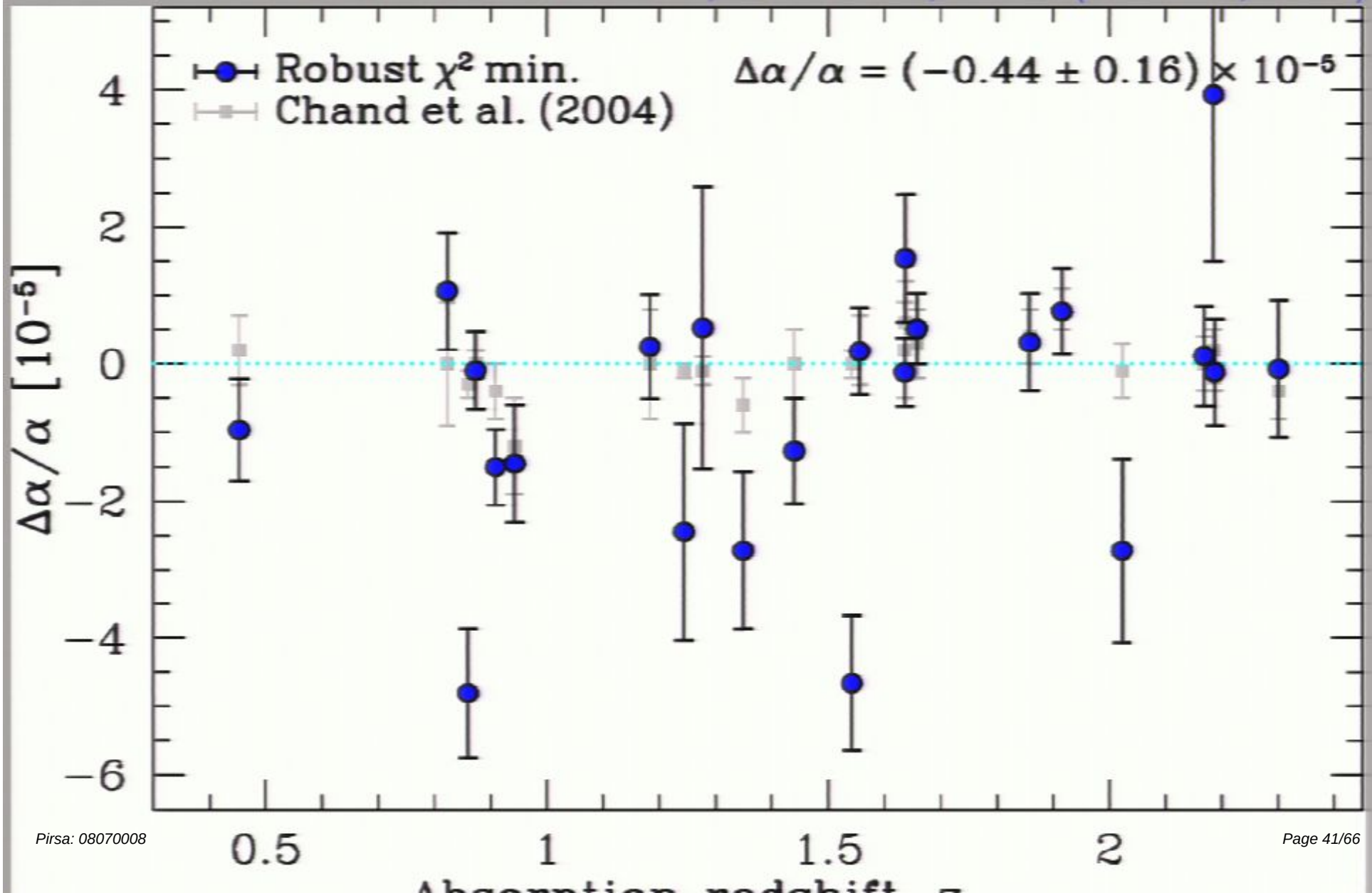


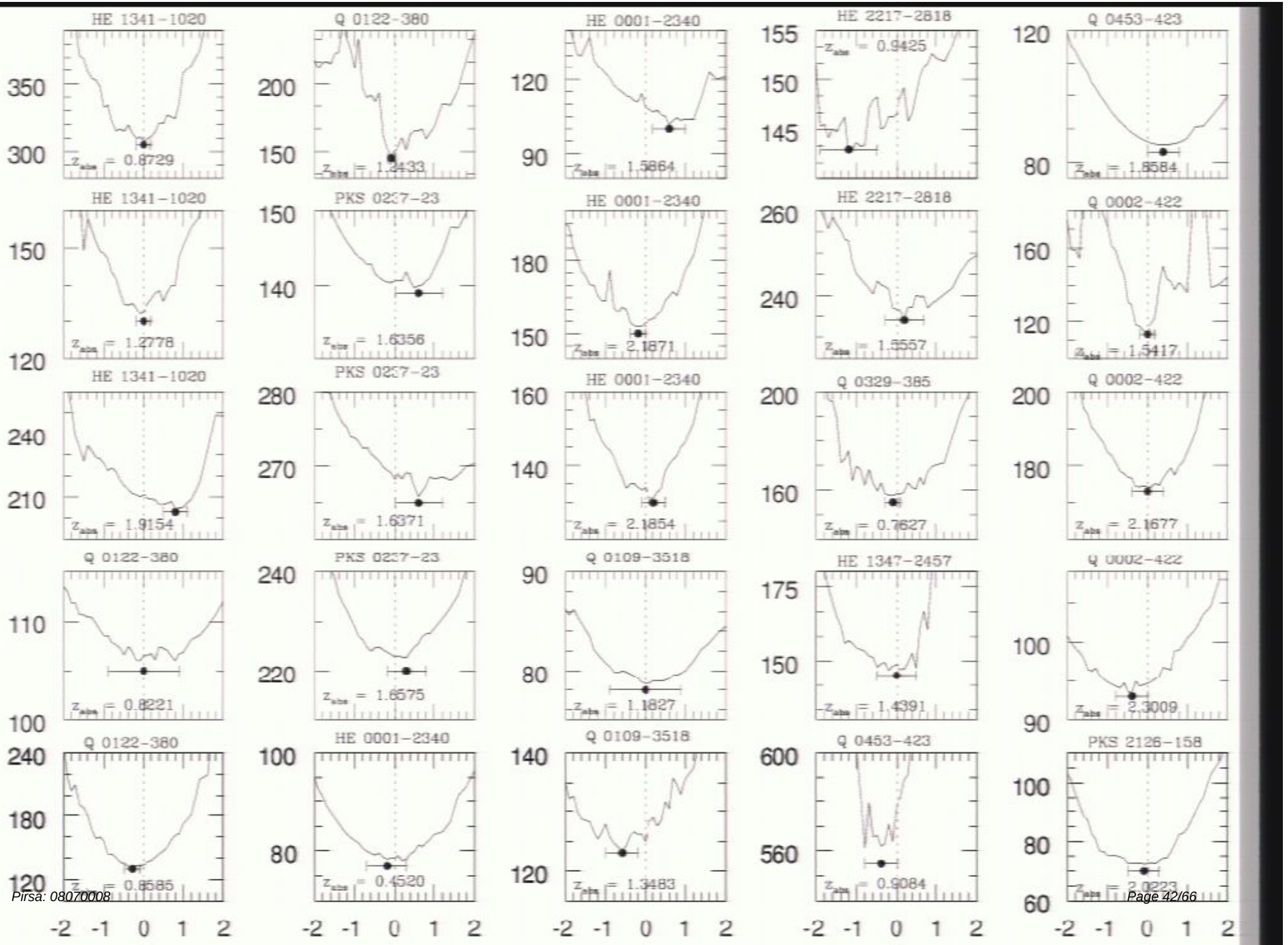
ew VLT/UVES measurements:

- **"UVES SQUAD"**
  UVES Spectroscopic QUasar Absorption Database
  - Uniform reduction of ALL ~500 UVES QSO spectra
  - Repeatable reduction
  - Publicly available
- Initial analysis of >100 high-S/N absorbers
  - 80 spectra already complete
- Predicted precision of $\delta(\Delta\alpha/\alpha) \approx 0.05 \times 10^{-5}$
- Blind analysis
  - Perturb wavelength calib. before profile fitting
  - Apply fit to re-calibrated spectra to obtain $\Delta\alpha/\alpha$

evise with robust χ^2 minimization:

MTM, Flambaum, Webb (MNRAS, 2008)

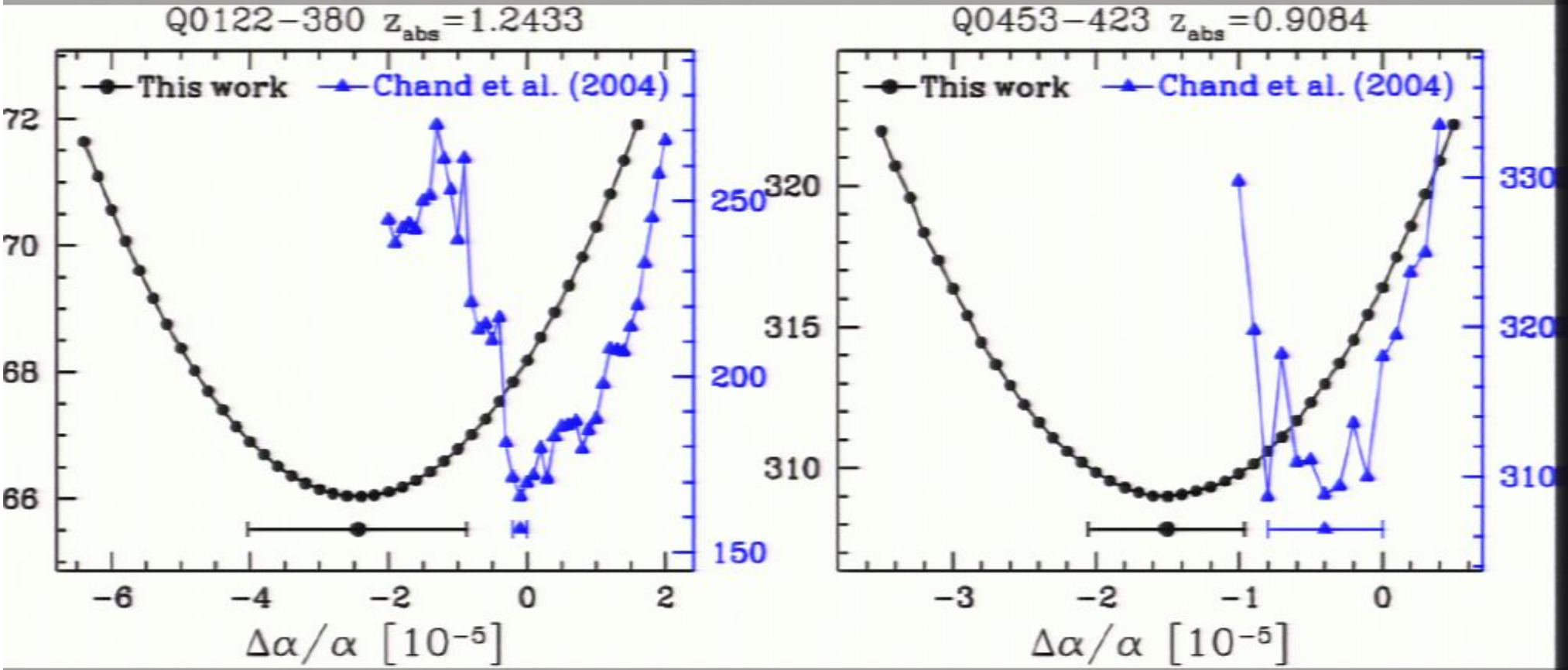



HE 1341-1020
z_abs = 0.8729
Q 0122-380
z_abs = 1.2433
HE 0001-2340
z_abs = 1.5864
HE 2217-2818
z_abs = 0.9425
Q 0453-423
z_abs = 1.8584
HE 1341-1020
z_abs = 1.2778
PKS 0237-23
z_abs = 1.6356
HE 0001-2340
z_abs = 2.1871
HE 2217-2818
z_abs = 1.3557
Q 0002-422
z_abs = 1.5417
HE 1341-1020
z_abs = 1.9154
PKS 0237-23
z_abs = 1.6371
HE 0001-2340
z_abs = 2.1854
Q 0329-385
z_abs = 0.7627
Q 0002-422
z_abs = 2.1677
Q 0122-380
z_abs = 0.8221
PKS 0237-23
z_abs = 1.6575
Q 0109-3518
z_abs = 1.1827
HE 1347-2457
z_abs = 1.4391
Q 0002-422
z_abs = 2.3009
Q 0122-380
z_abs = 0.8585
HE 0001-2340
z_abs = 0.4520
Q 0109-3518
z_abs = 1.3483
Q 0453-423
z_abs = 0.9084
PKS 2126-158
z_abs = 2.0223
-2 -1 0 1 2

^{2} curves should be smooth:

n scales similar to the 1-σ error, the χ^2 curve
UST be SMOOTH and near-parabolic.

MTM, Flambaum, Webb (PRL & MNRAS, 2008)

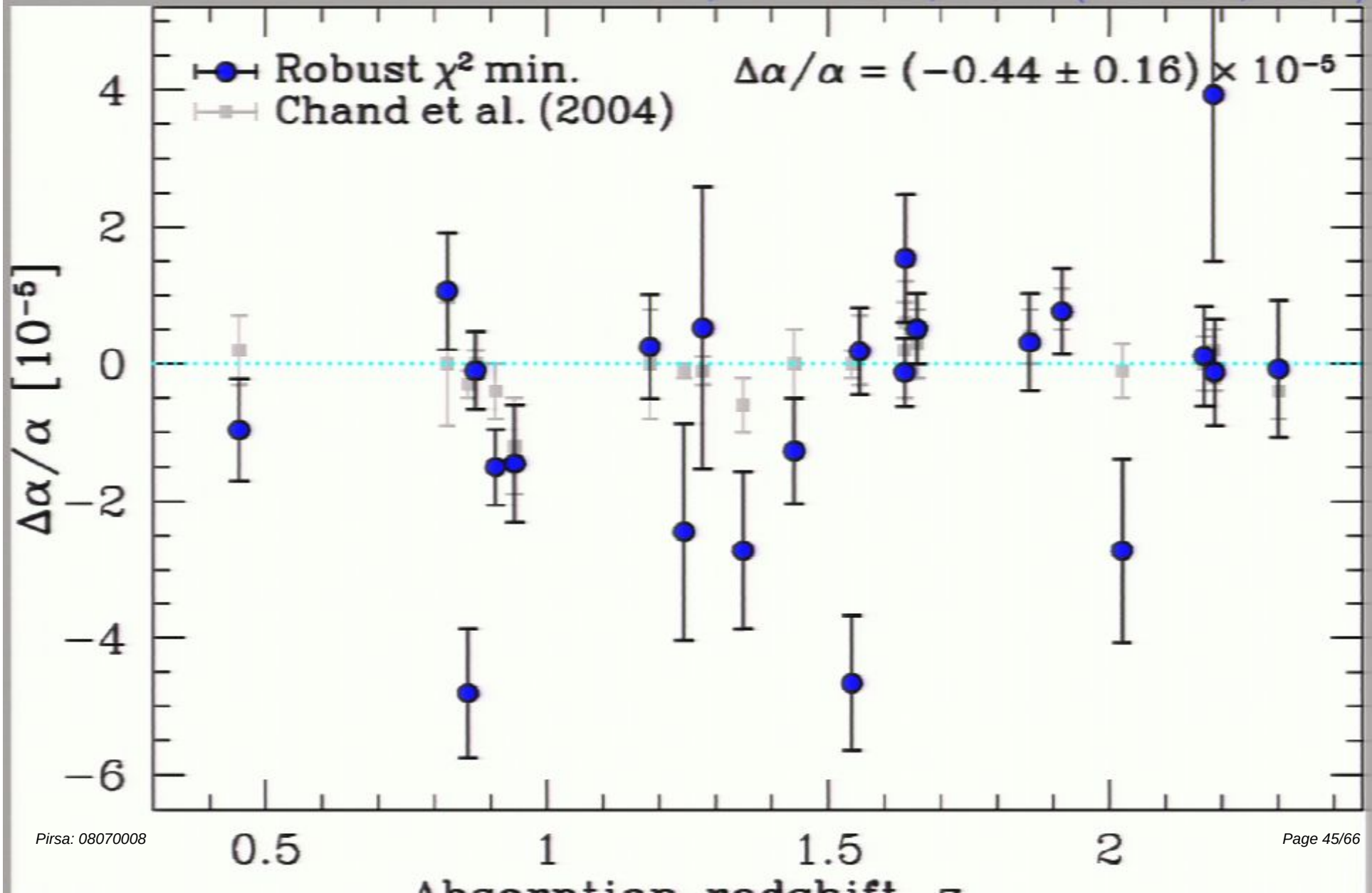


ew VLT/UVES measurements:

- "**UVES SQUAD**"
  UVES Spectroscopic QUasar Absorption Database
  - Uniform reduction of ALL ~500 UVES QSO spectra
  - Repeatable reduction
  - Publicly available
- Initial analysis of >100 high-S/N absorbers
  - 80 spectra already complete
- Predicted precision of $\delta(\Delta\alpha/\alpha) \approx 0.05 \times 10^{-5}$
- Blind analysis
  - Perturb wavelength calib. before profile fitting
  - Apply fit to re-calibrated spectra to obtain $\Delta\alpha/\alpha$

evise with robust χ^2 minimization:

MTM, Flambaum, Webb (MNRAS, 2008)

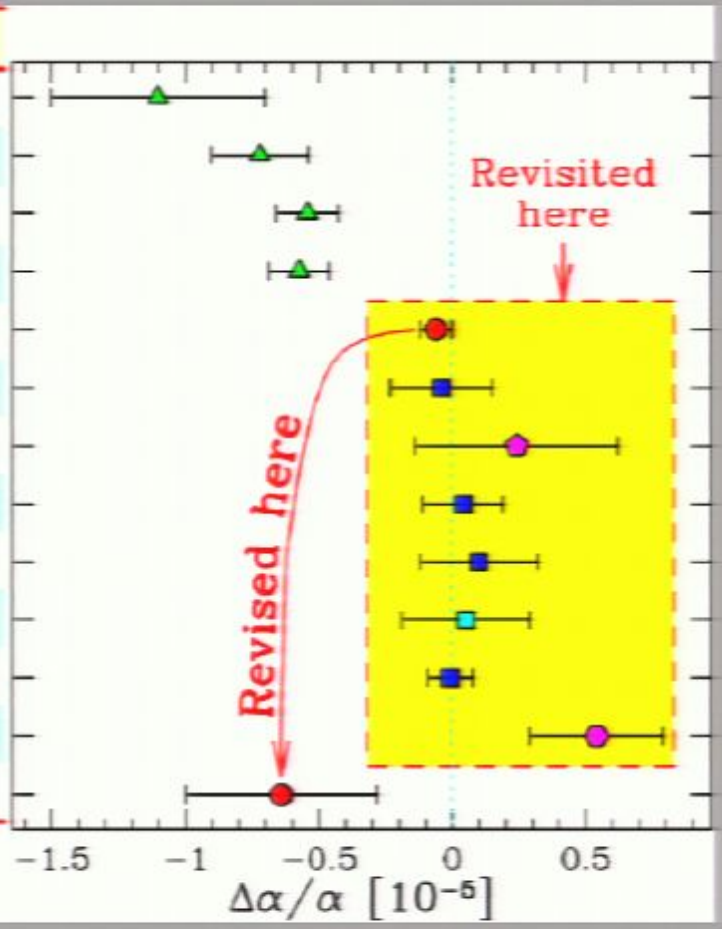


ew VLT/UVES measurements:

- **"UVES SQUAD"**
  UVES Spectroscopic QUasar Absorption Database
  - Uniform reduction of ALL ~500 UVES QSO spectra
  - Repeatable reduction
  - Publicly available
- Initial analysis of >100 high-S/N absorbers
  - 80 spectra already complete
- Predicted precision of $\delta(\Delta\alpha/\alpha) \approx 0.05 \times 10^{-5}$
- Blind analysis
  - Perturb wavelength calib. before profile fitting
  - Apply fit to re-calibrated spectra to obtain $\Delta\alpha/\alpha$

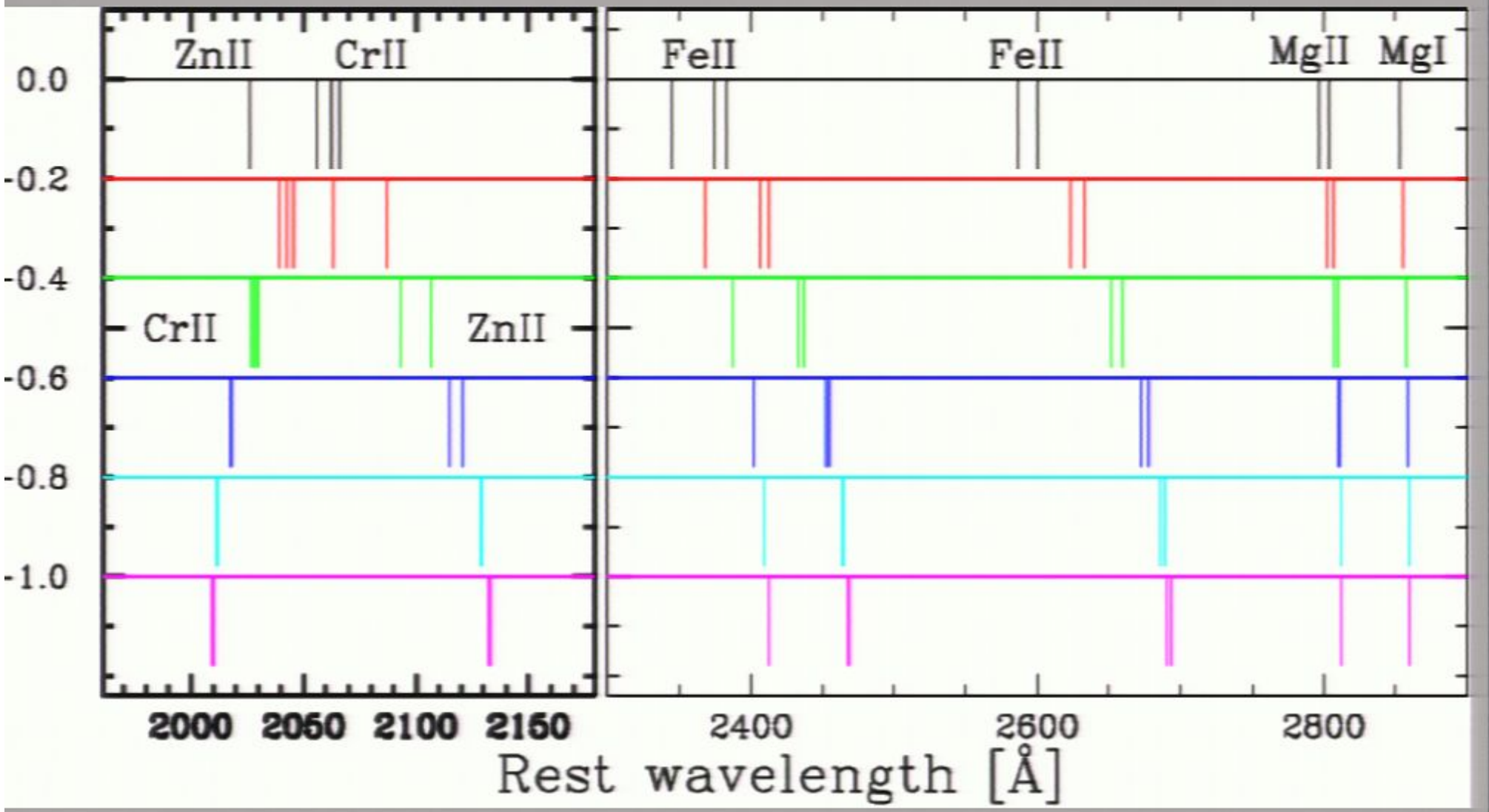
ll current MM constraints:

ument	N_{abs}	z_{abs}	$\Delta\alpha/\alpha$ [10^{-5}]	Reference
ES	30	0.5–1.6	−1.100 ± 0.400	Webb et al. (1999)
ES	49	0.5–3.5	−0.720 ± 0.180	Murphy et al. (2001a)
ES	128	0.2–3.7	−0.543 ± 0.116	Murphy et al. (2003)
ES	143	0.2–4.2	−0.573 ± 0.113	Murphy et al. (2004)
S	23	0.4–2.3	−0.060 ± 0.060	Chand et al. (2004)
S	1	1.151	−0.040 ± 0.190 ± 0.270	Quast et al. (2004)
S	1	1.839	+0.240 ± 0.380	Levshakov et al. (2005)
S	1	1.151	+0.040 ± 0.150	Levshakov et al. (2005)
S	1	1.151	+0.100 ± 0.220	Chand et al. (2006)
PS	1	1.151	+0.050 ± 0.240	Chand et al. (2006)
S	1	1.151	−0.007 ± 0.084 (± 0.100)	Levshakov et al. (2006)
S	1	1.839	+0.540 ± 0.250	Levshakov et al. (2007)
S	23	0.4–2.3	−0.640 ± 0.360	This work

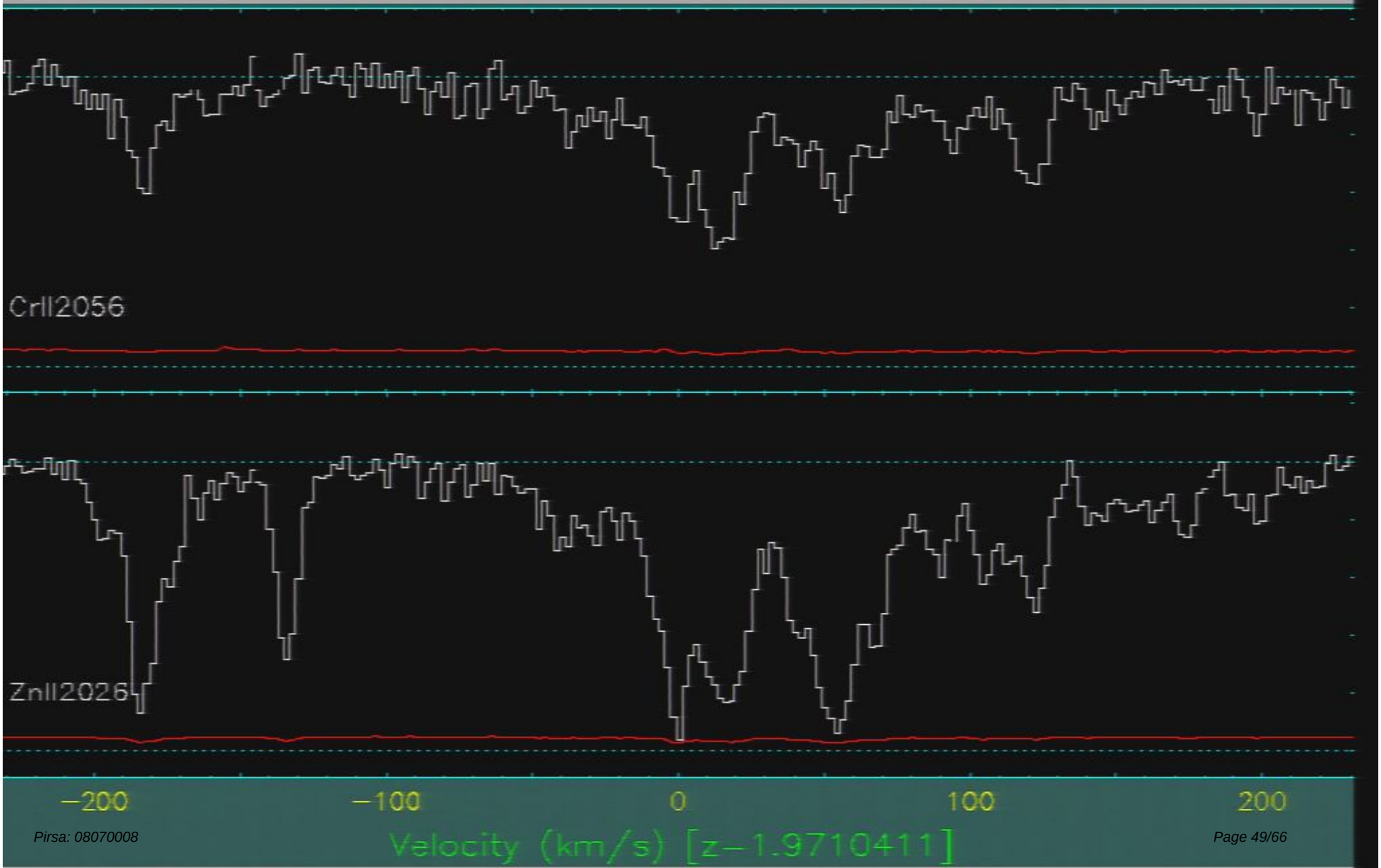


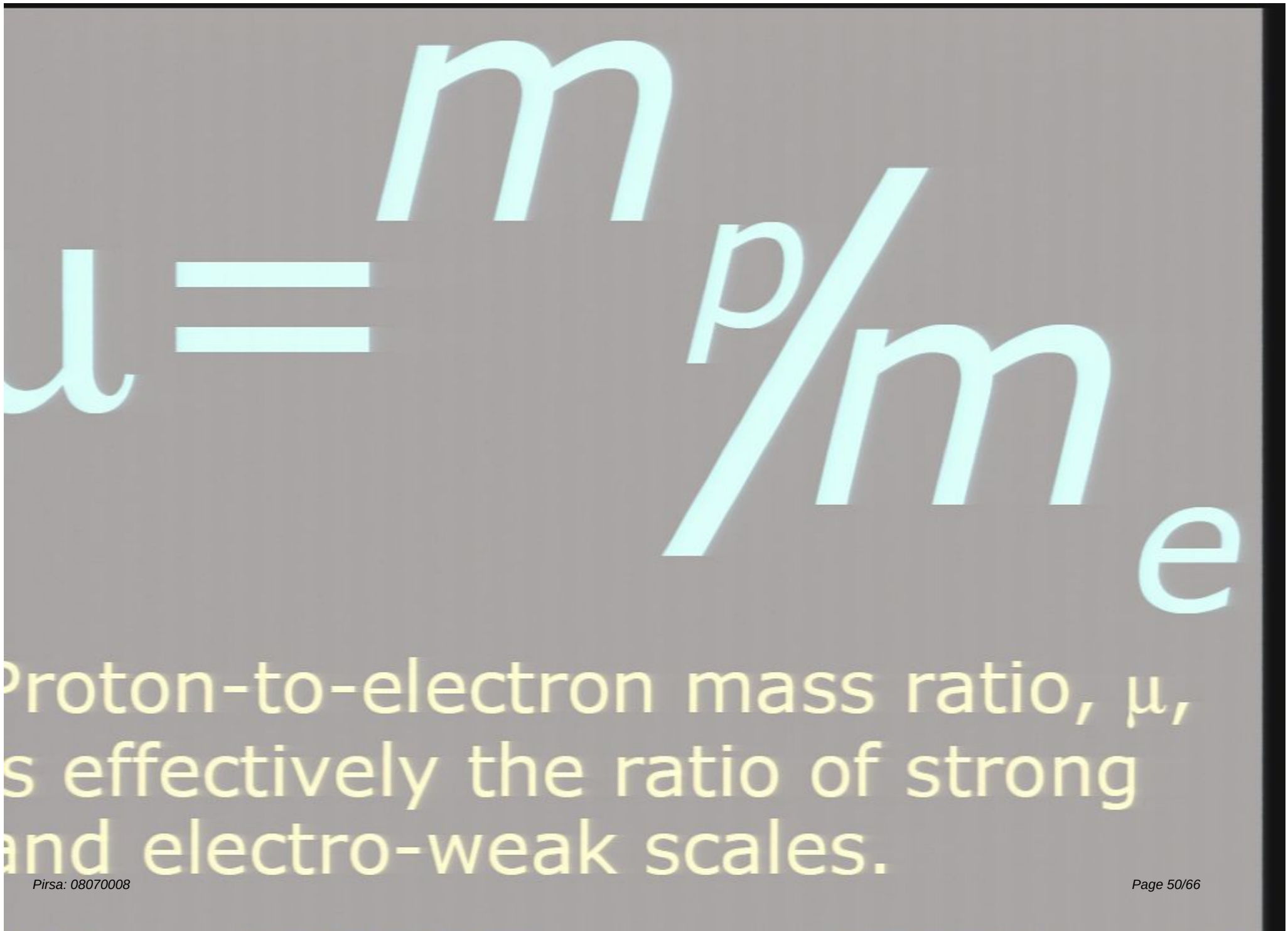
NOTE: Different single absorber constraints are *not* independent

ew Zn/CrII constraints:



ew Zn/CrII constraints:




$\mu = m_p / m_e$
Proton-to-electron mass ratio, μ,
s effectively the ratio of strong
and electro-weak scales.

lolecules and varying μ:

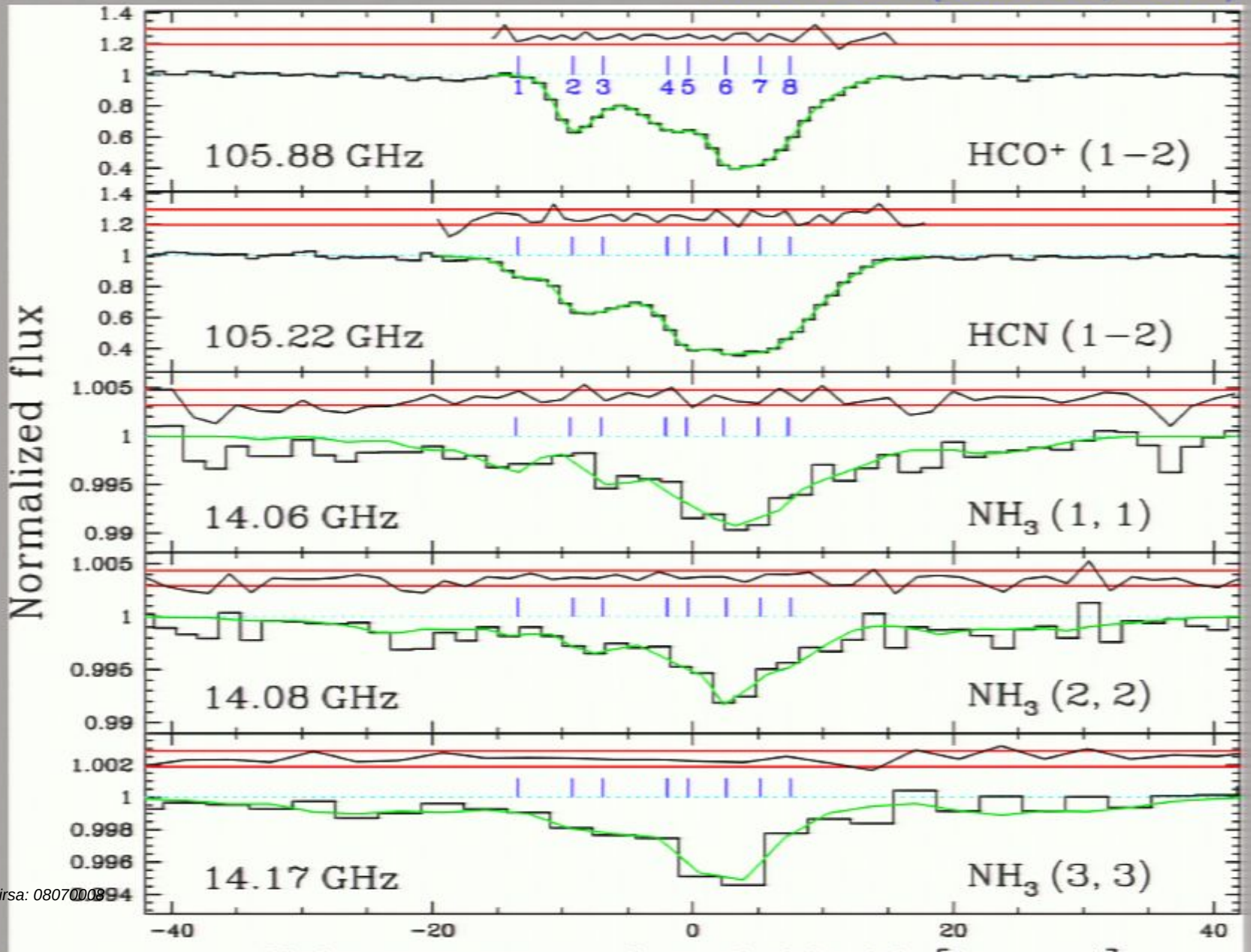
- Transition *i*'s sensitivity to μ-variation:

$$\frac{\Delta v}{c} = \frac{\Delta z_i}{1+z} = K_i \frac{\Delta \mu}{\mu}$$

- H_2 UV transitions: $-0.03 < K_i < +0.04$
  - *See talks by Wim Ubachs and Julian King*
- Ammonia vs. molecular rotational transitions:
  - CO, HCN, HCO^+ @ 8–200GHz: $K_i=1$
  - NH_3 inversion transitions @ 24GHz: $K_i \approx 4.6$!
- Flambaum & Kozlov (2007): For only known NH_3 absorber, $\delta(\Delta\mu/\mu) \approx 2 \times 10^{-6}$ should be possible.

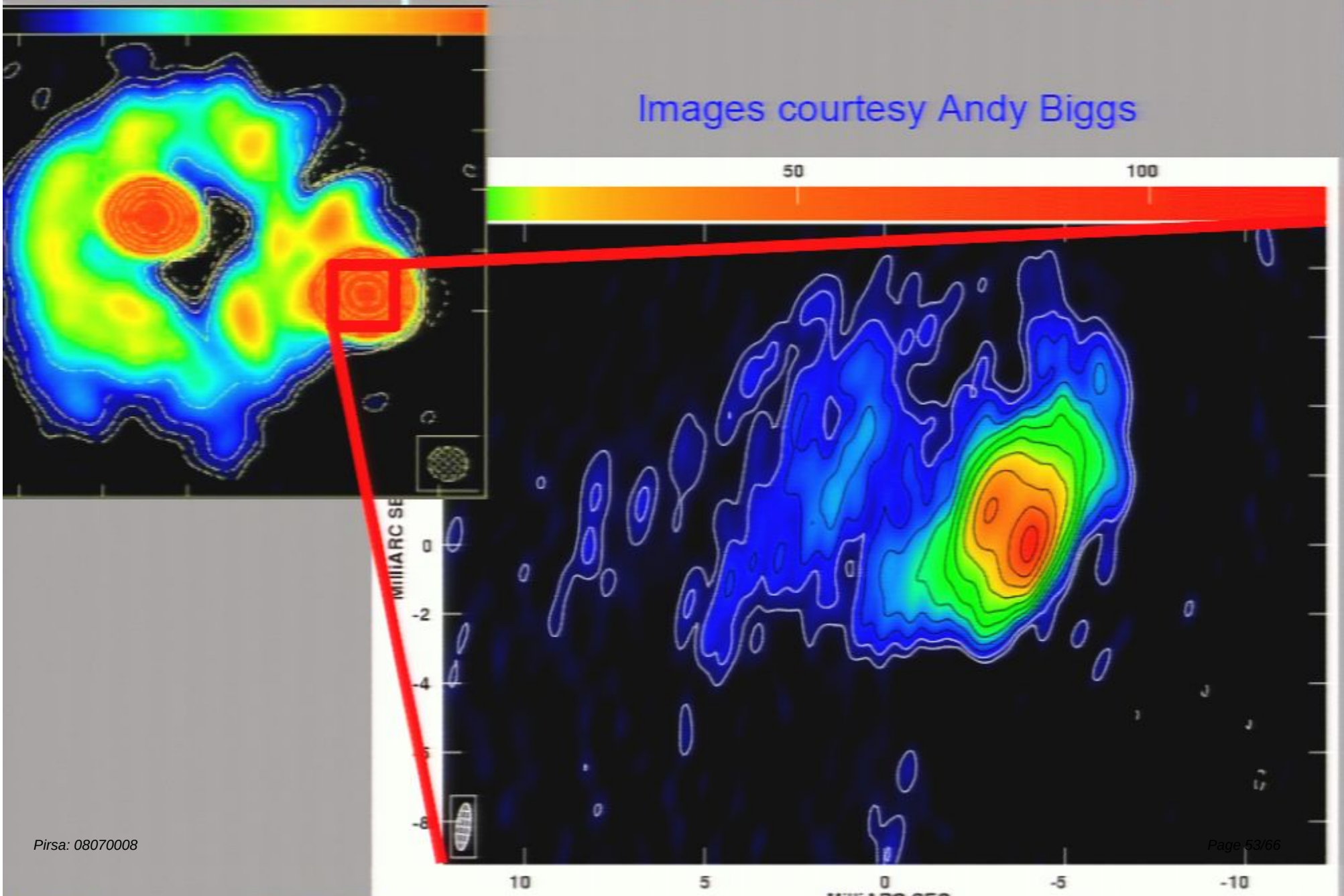
0218+357: New rotational, existing NH_3:

MTM et al. (Science, 2008)



uasars not point sources in radio:

Images courtesy Andy Biggs



ew NH_3 constraints on $\Delta\mu/\mu$:

- New measurement @ z=0.685:

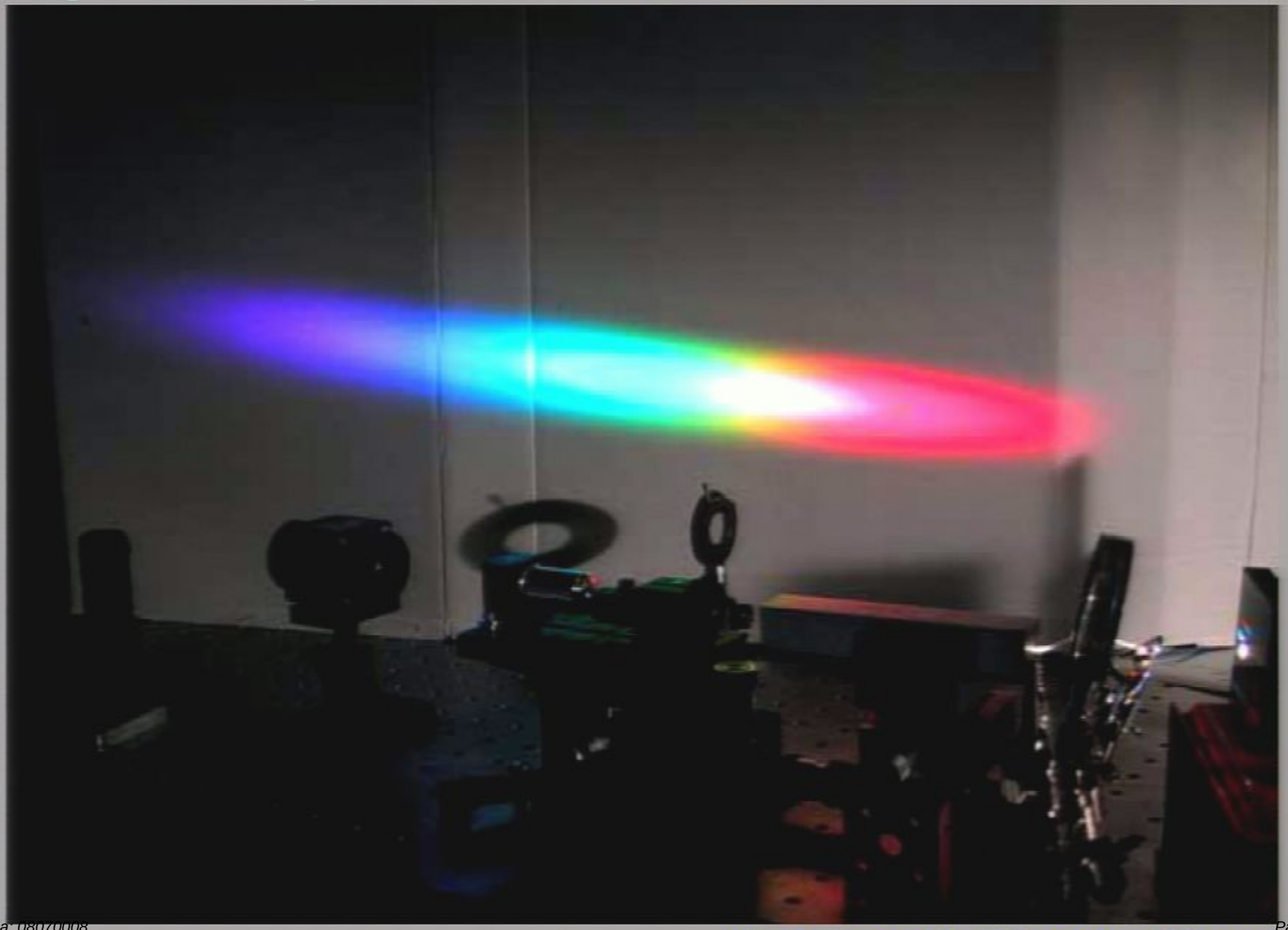
  $$\Delta\mu/\mu = (+0.74 \pm 0.47_{stat} \pm 0.76_{sys}) \times 10^{-6}$$

  - Much-improved rotational spectra
  - Simultaneous fits to all transitions
  - Can reduce *both* stat. and sys. errors with better NH_3 spectra
  - Possible systematic error from background quasar morphology

uture high-precision instruments:

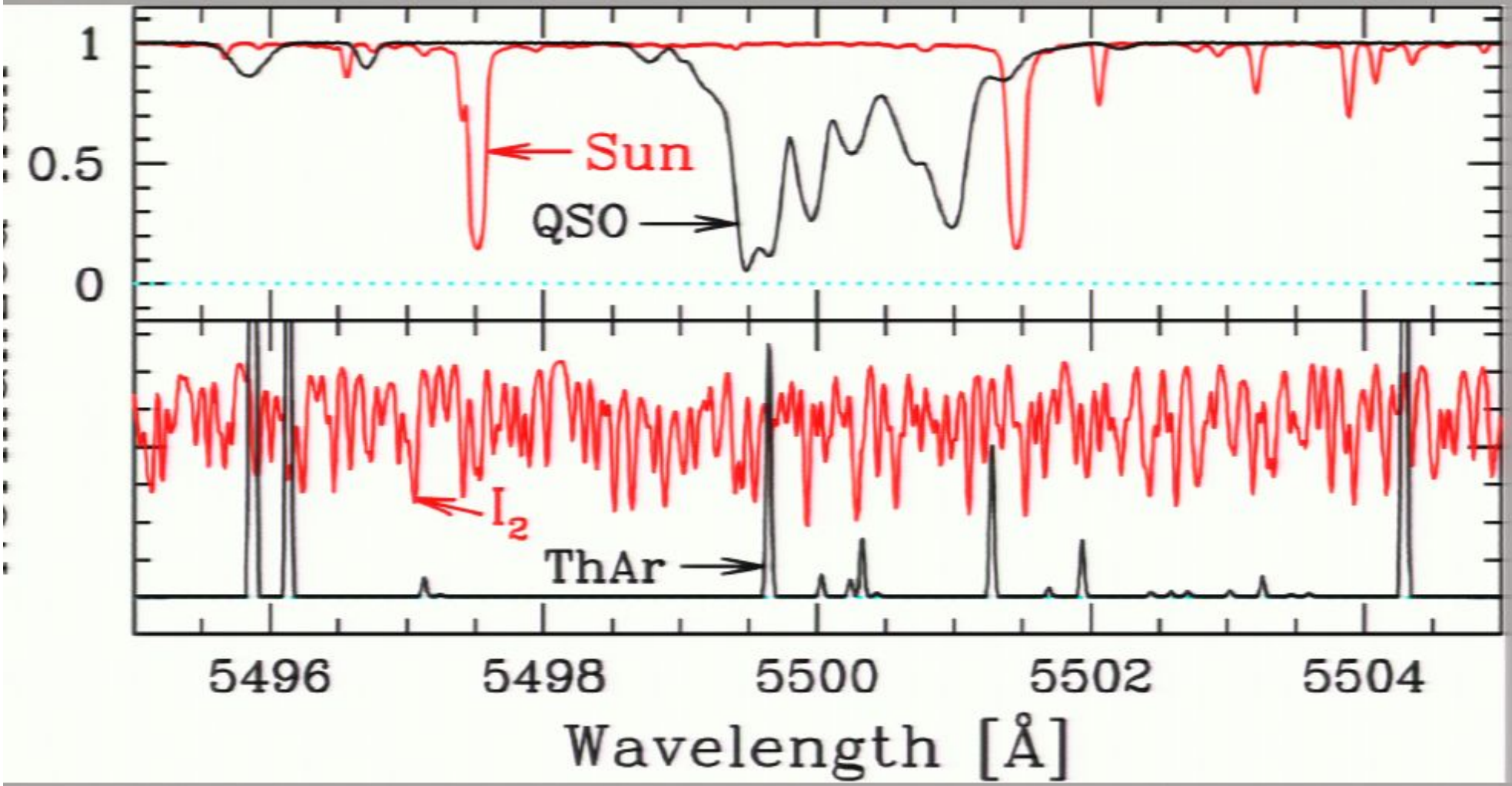
- New VLT concept: **ESPRESSO**
  Echelle Spectrograph for PREcise Super-Stable Observations
  - Vacuum-sealed, in stable coude room
  - Fibre feed, image slicing & beam homogenization
  - Higher resolution (R > 150,000)
  - **Fed by all 4 VLTs!** (or any "available one")
- European ELT concept: **CODEX**
  COsmic Dynamics Experiment
  - 42-m telescope
  - Super-ESPRESSO
  - Aim for cm s^{-1} reproducibility over decades

requency combs:



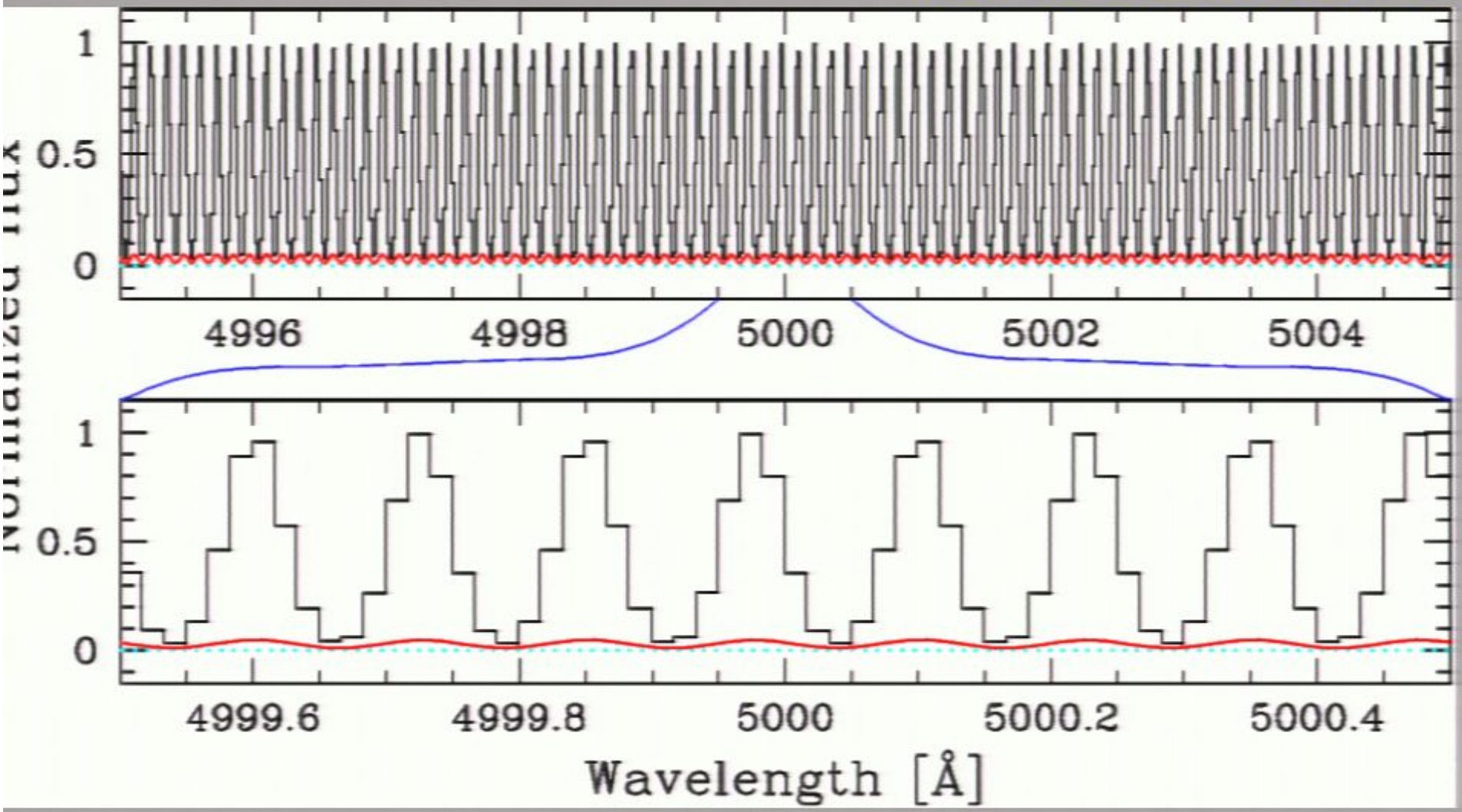
Courtesy H. Giessen (Bonn)

raditional echelle calibration:



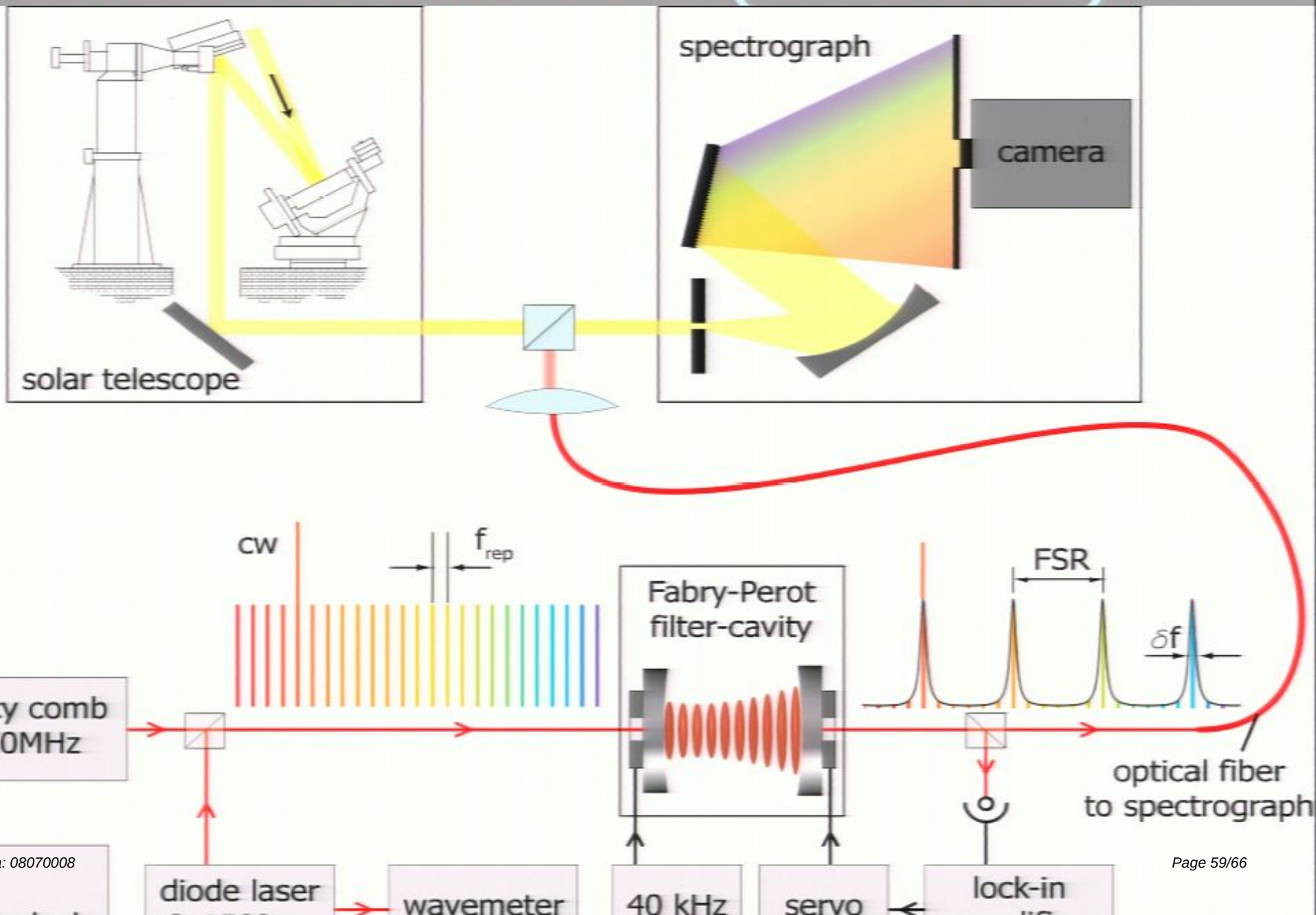
omb echelle simulation:

MTM et al. (MNRAS, 2007)

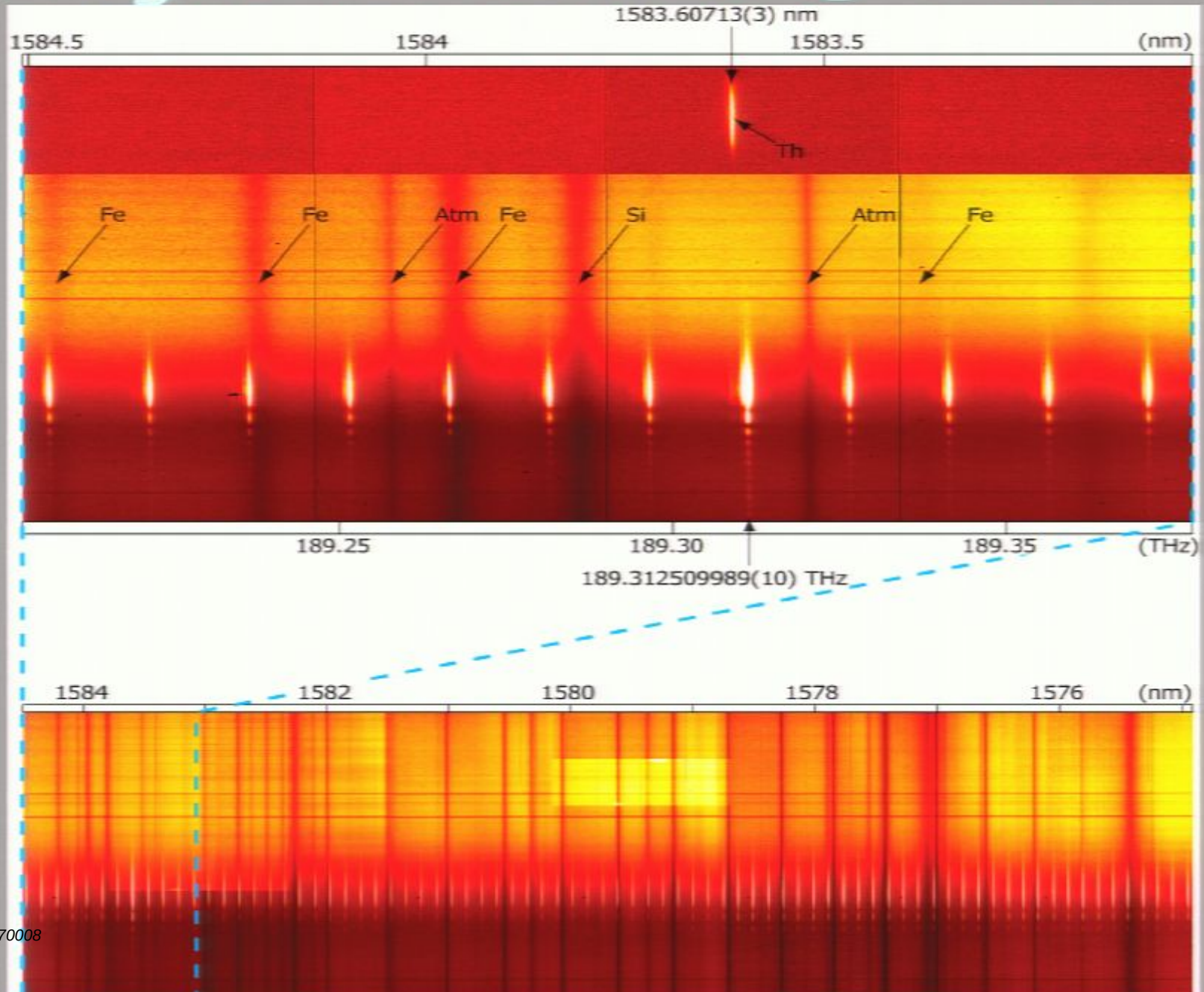


recision integrated over 3800–8200Å is ~1 cm s^{-1}

R comb on the VTT (R=250k):



First light' for combs @ VTT:



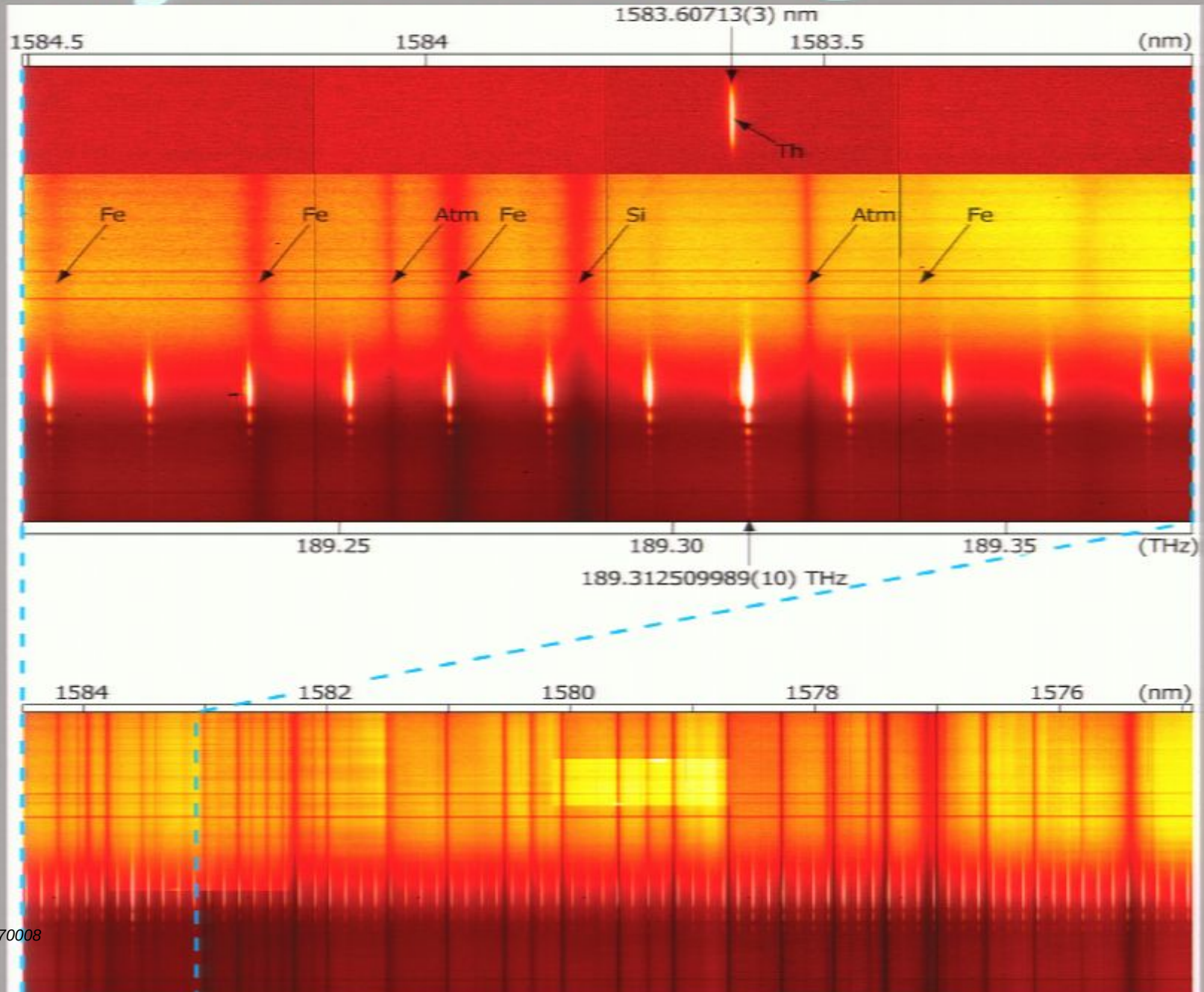
ummary:

- Look out for false positives AND false negatives.
- No robust UVES constraints; large sample soon.
- NH_3 constraint on μ-variation @ z=0.685:

$$\Delta\mu/\mu=(+0.74\pm0.47_{stat}\pm0.76_{sys})\times10^{-6}$$

- Need more NH_3 absorbers (and H_2 absorbers)!
- ESPRESSO & CODEX:
  - Perfect for α (extra λ-coverage would help)
  - Better UV-coverage needed for μ
- Frequency combs: remove calibration uncertainties from varying constants analyses.

First light' for combs @ VTT:



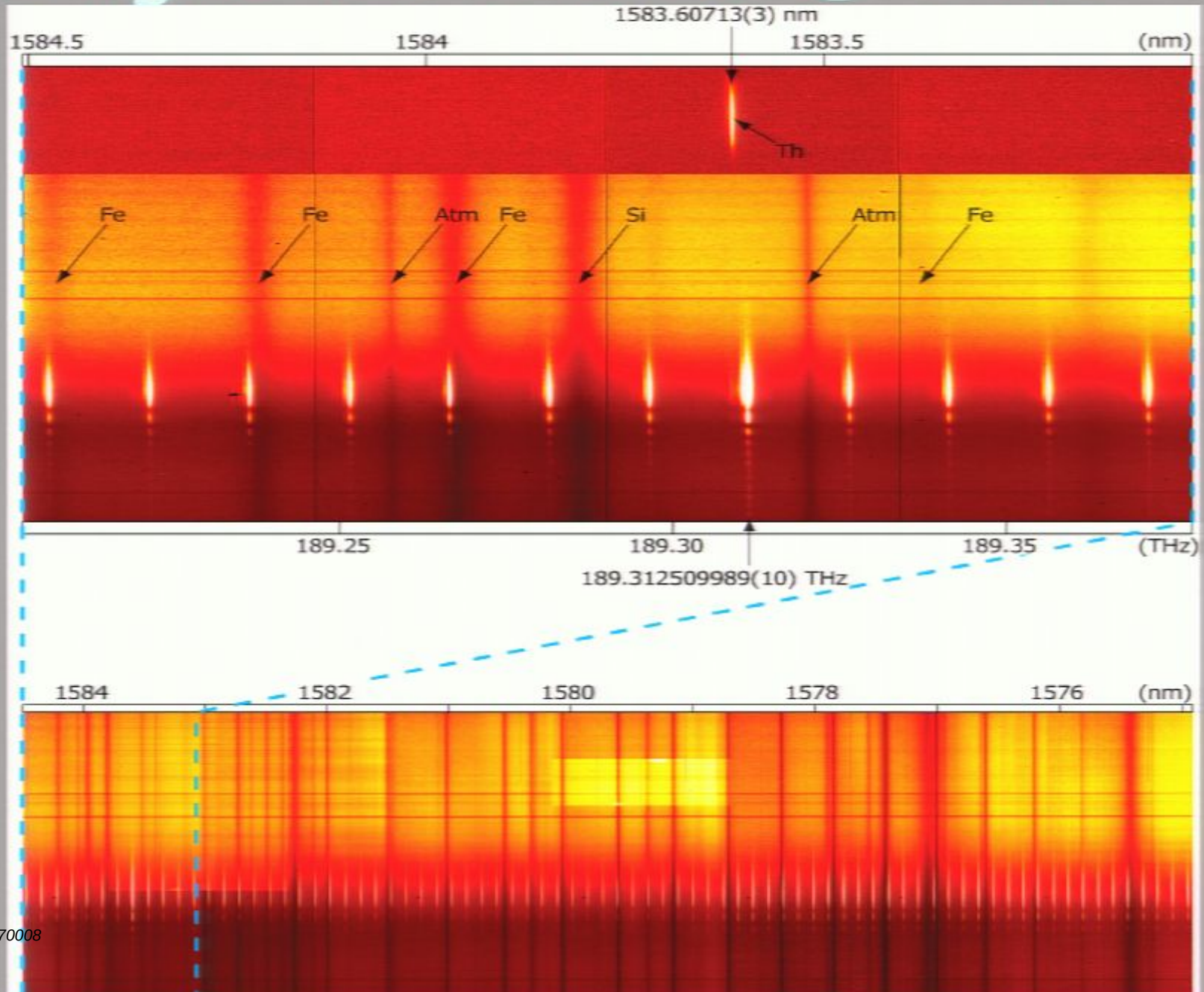
ummary:

- Look out for false positives AND false negatives.
- No robust UVES constraints; large sample soon.
- NH_3 constraint on μ-variation @ z=0.685:

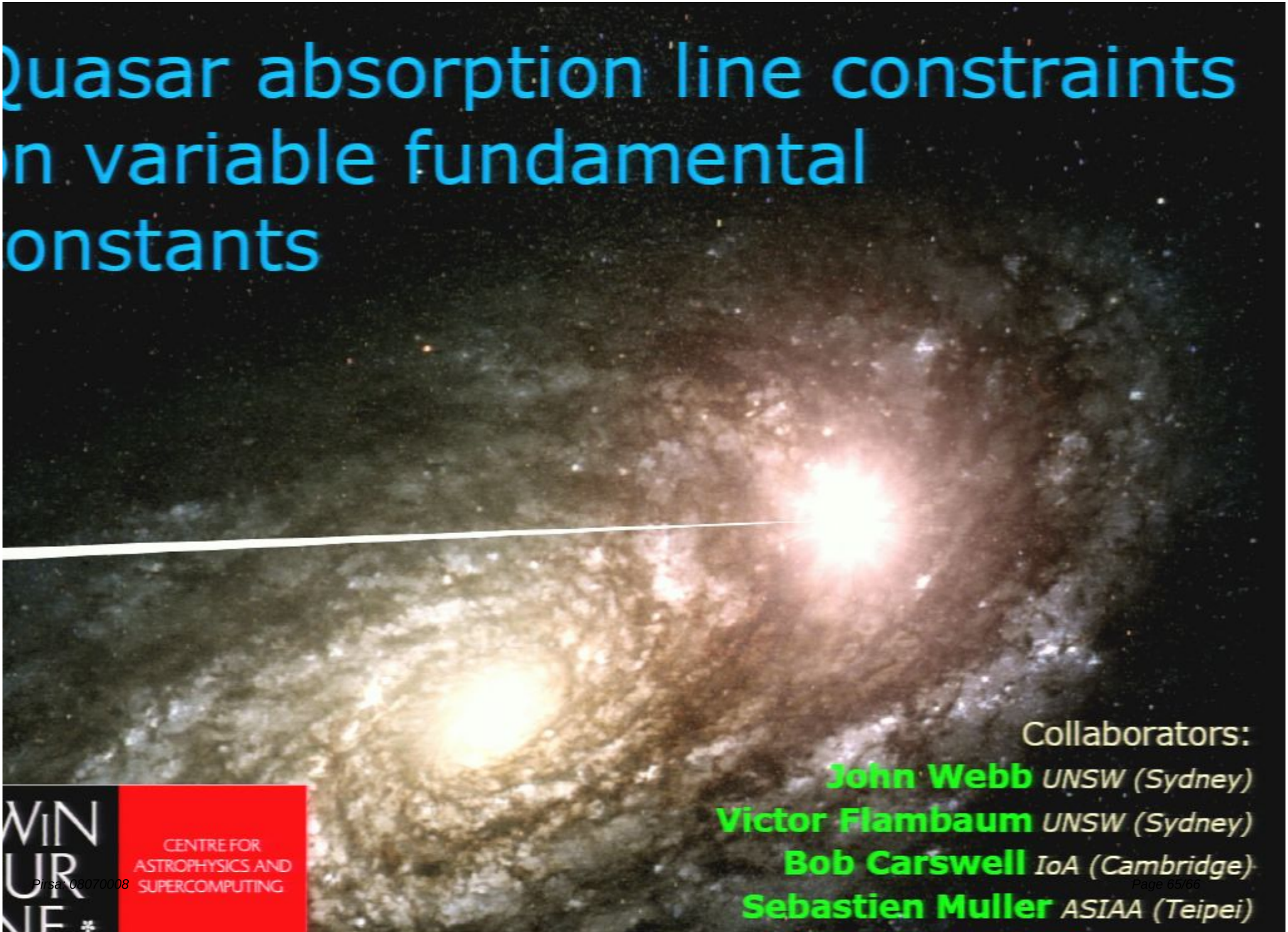
$$\Delta\mu/\mu=(+0.74\pm0.47_{stat}\pm0.76_{sys})\times10^{-6}$$

- Need more NH_3 absorbers (and H_2 absorbers)!
- ESPRESSO & CODEX:
  - Perfect for α (extra λ-coverage would help)
  - Better UV-coverage needed for μ
- Frequency combs: remove calibration uncertainties from varying constants analyses.

First light' for combs @ VTT:



Quasar absorption line constraints on variable fundamental constants



Collaborators:

John Webb *UNSW (Sydney)*

Victor Flambaum *UNSW (Sydney)*

Bob Carswell *IoA (Cambridge)*

Sebastien Muller *ASIAA (Teipei)*

CENTRE FOR ASTROPHYSICS AND SUPERCOMPUTING

natomy of a quasar spectrum: