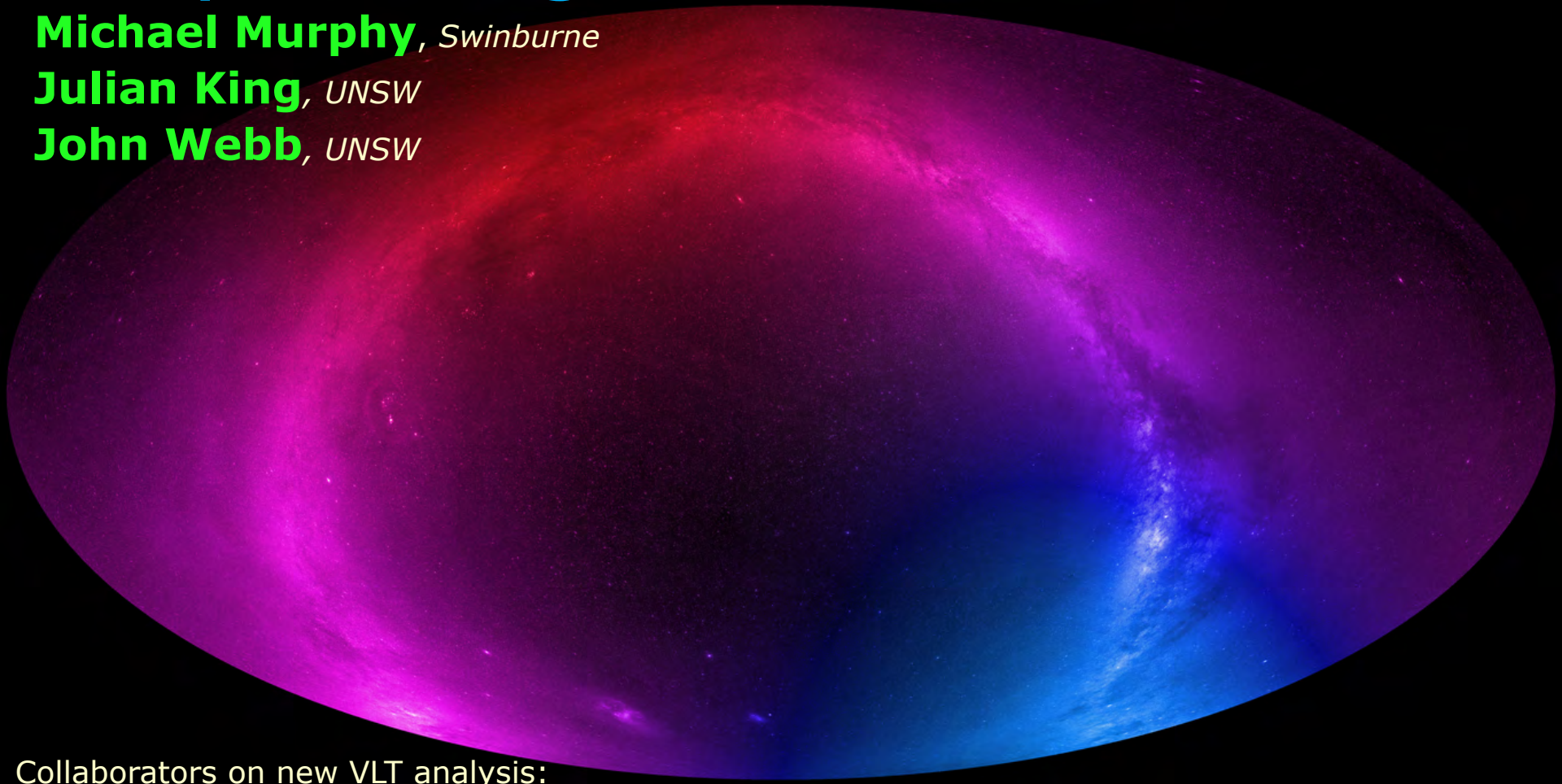
Do the fundamental constants vary throughout the Universe?

Michael Murphy, *Swinburne*
Julian King, *UNSW*
John Webb, *UNSW*



Collaborators on new VLT analysis:
Matthew Bainbridge, Elliott Koch, Michael Wilczynska, Victor Flambaum *UNSW (Sydney)*
Bob Carswell *IoA (Cambridge)*

Collaborators on Keck analysis:
Chris Churchill, Jason Prochaska, Wal Sargent, Art Wolfe

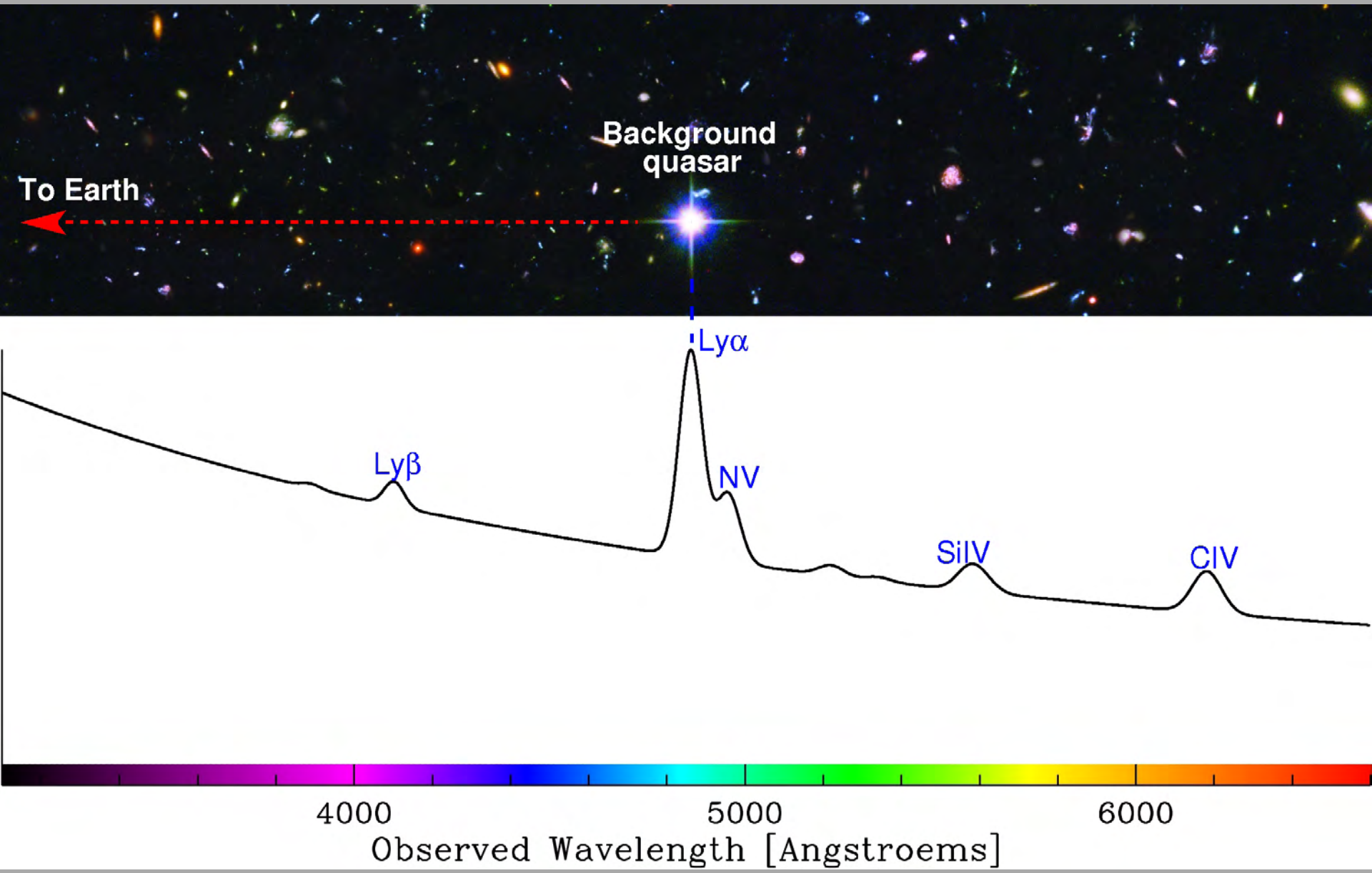
Fundamental? Constants?:

- [Note: Only low-energy limits of constants discussed here]
- Why "fundamental"?
  - Cannot be calculated within Standard Model
- Why "constant"?
  - Because we don't see them changing
  - No theoretical reason – see above
- Best of physics: Relative stability of α ~10^{-17} yr^{-1} (Rosenband et al. 2008)
- Worst of physics: Sign of incomplete theory?

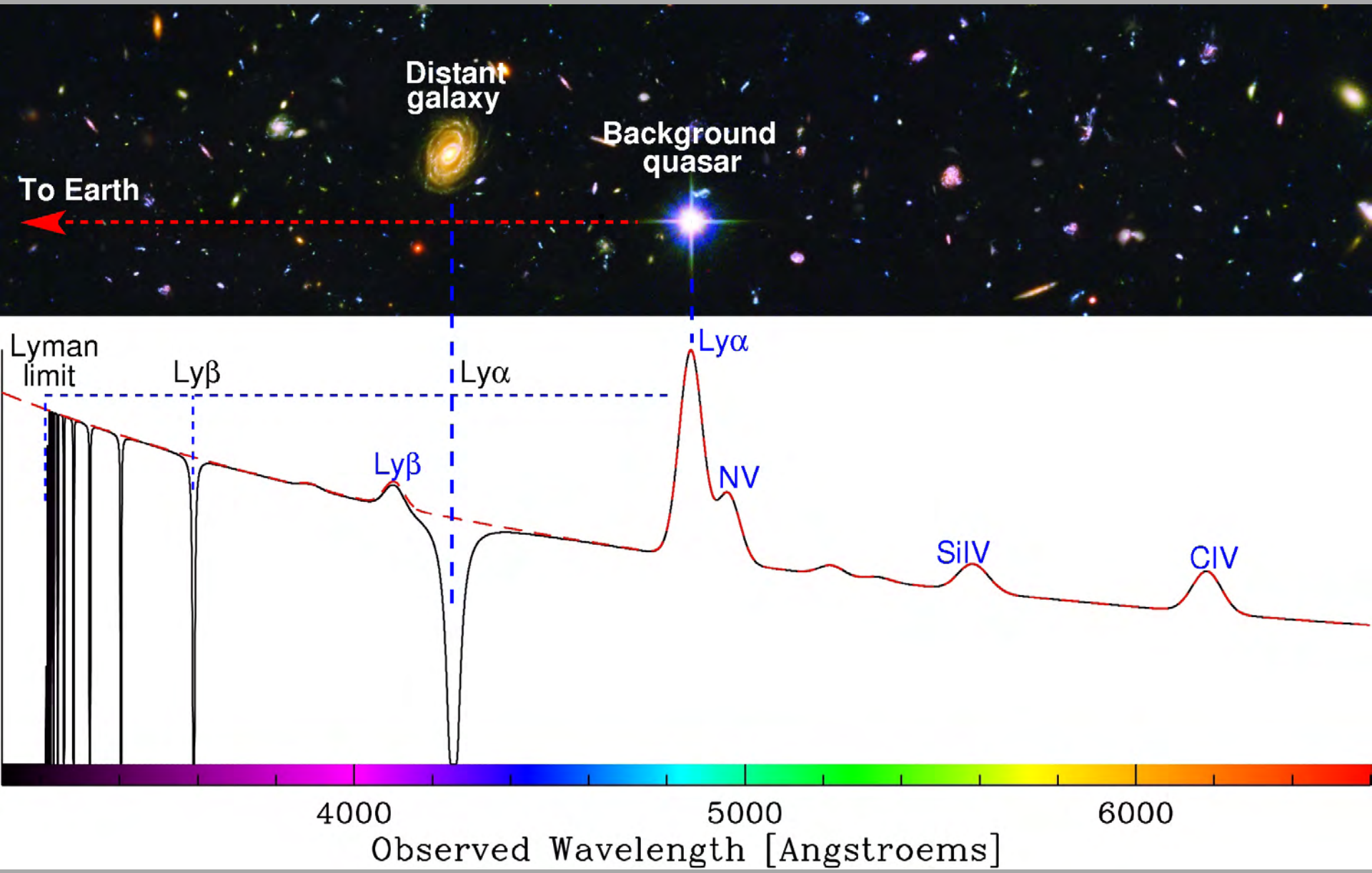
- Constancy based on Earth-bound, human time-scale experiments
- Extension to Universe seems a big assumption

$$\alpha = \frac{e^2}{\hbar c}$$

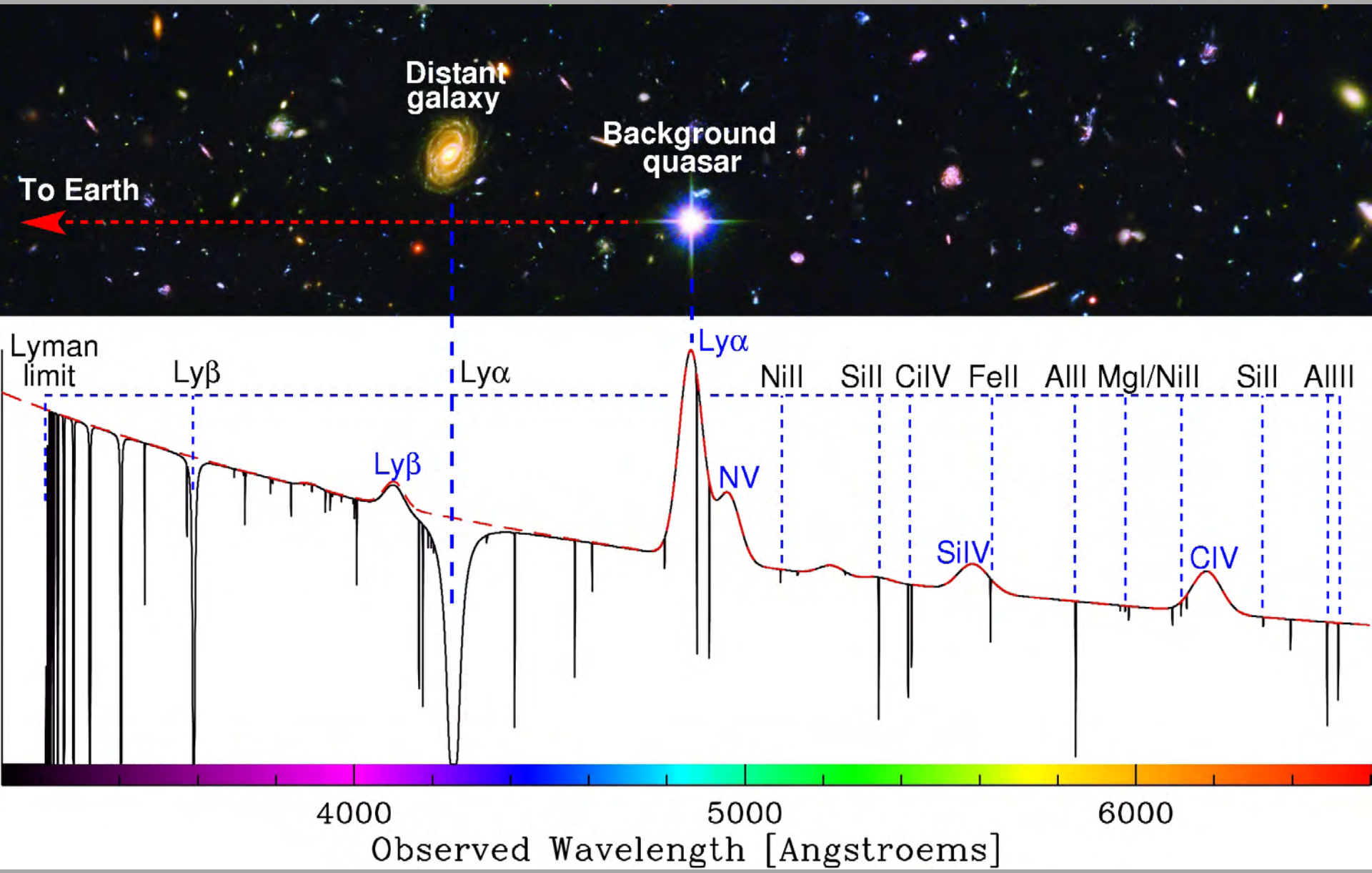
Metal quasar absorbers:



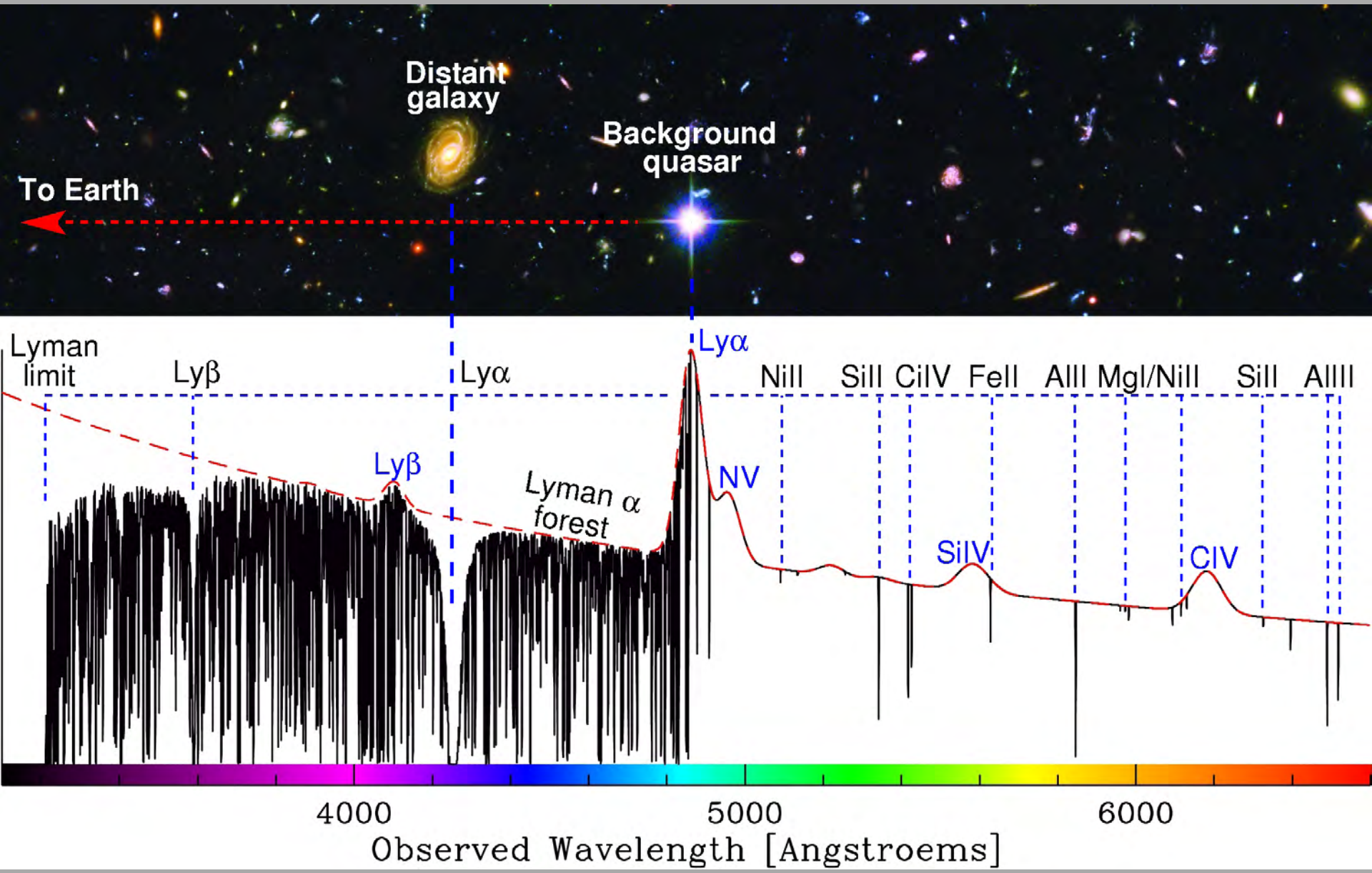
Metal quasar absorbers:



Metal quasar absorbers:



Metal quasar absorbers:



Older than ESO … *just*:

- Savedoff (1956, Nature):
  - Fine-structure doublet *emission* lines in Cyg. A
- Bahcall, Sargent, Schmidt (1967, ApJ):
  - Fine-structure SiIV doublet absorption lines 3C 191

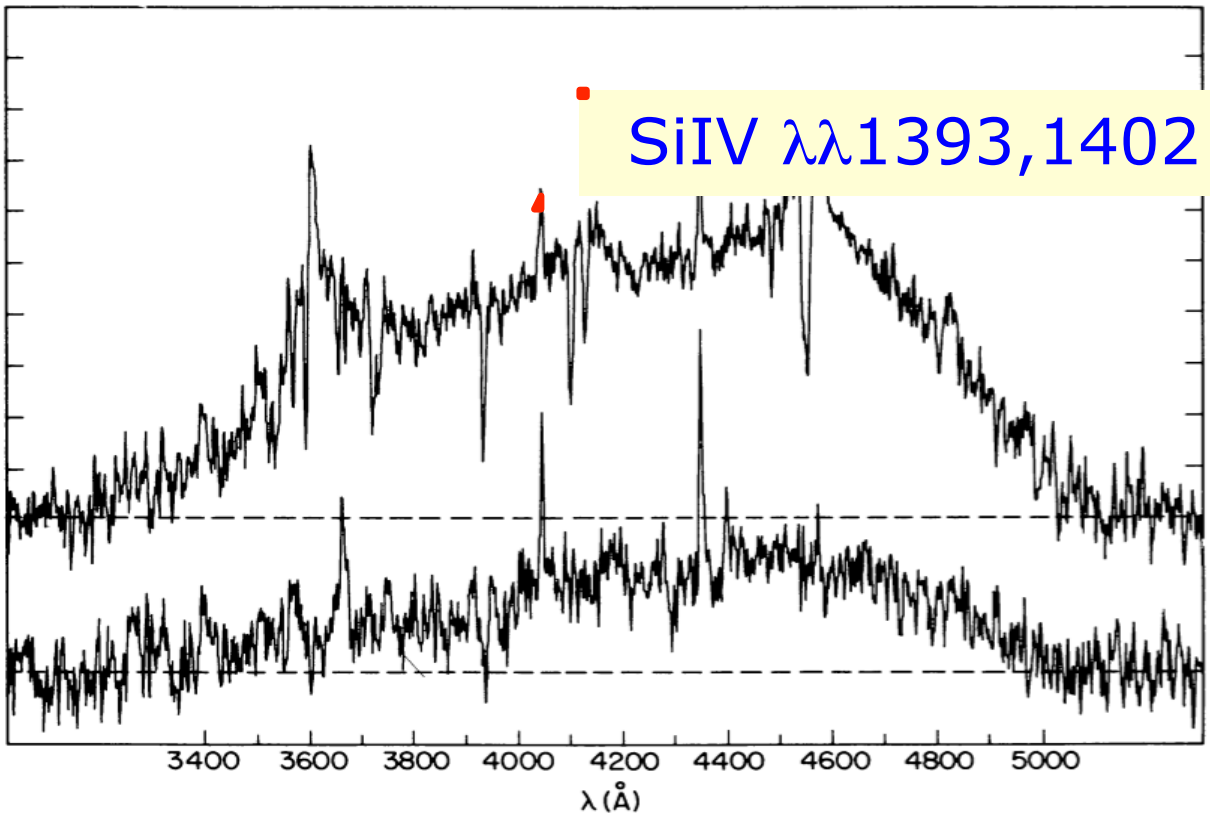


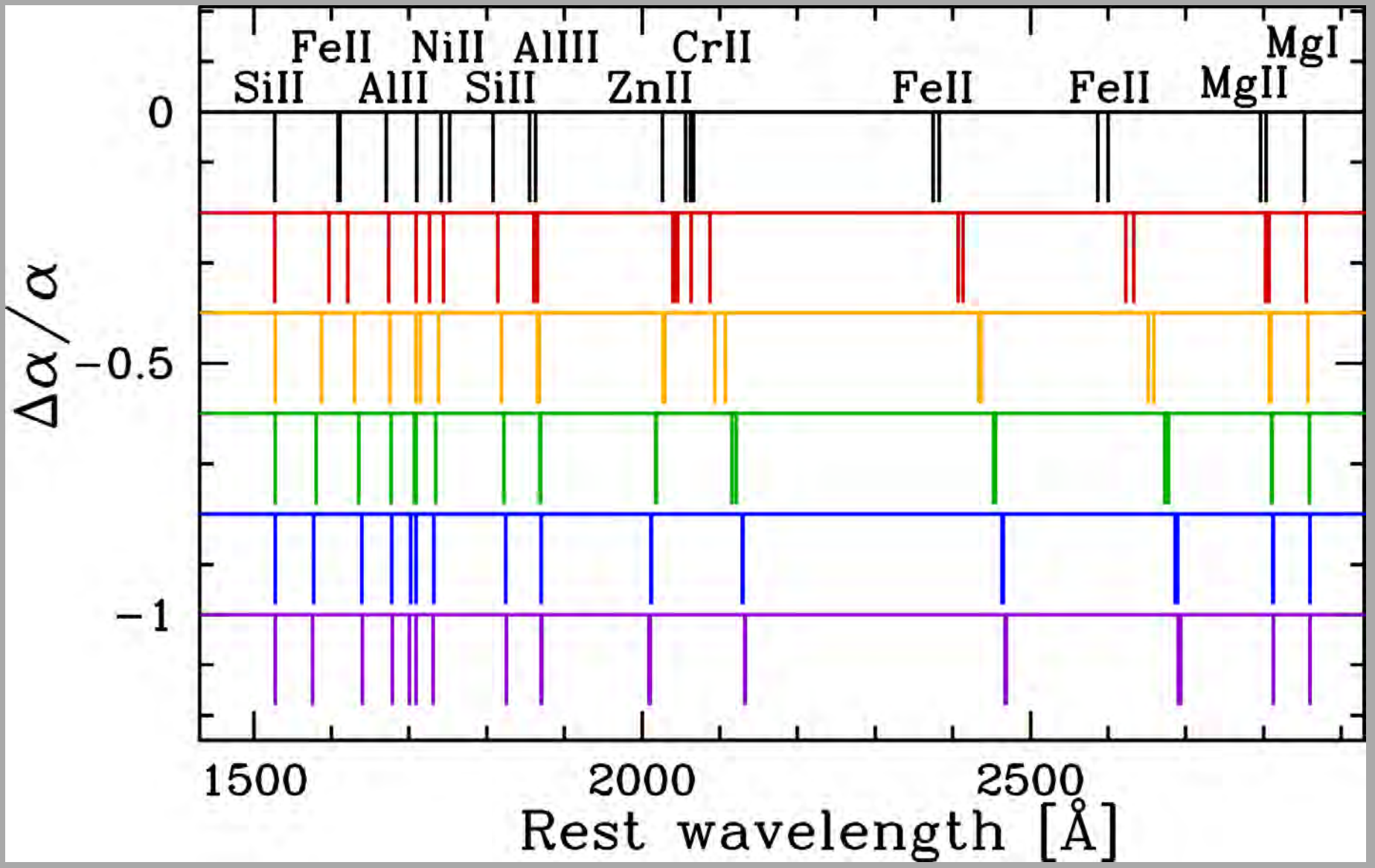
FIG. 1.—Density tracings of the spectrum of 3C 191 and the nearby night-sky spectrum on the same plate are shown. The two tracings have the same vertical magnification but have been shifted by an arbitrary amount. The strong emission lines in the night-sky spectrum are due to mercury city lights.

Webb et al. (1999, PRL):

3 key improvements:

- The "Many Multiplet Method"
  - Order of magnitude increase in sensitivity to $\Delta\alpha/\alpha$
- High-res spectra of many QSOs from Keck
  - C. Churchill, J.X. Prochaska & A. Wolfe, W. Sargent
  - VLT/UVES not on sky yet
- Laboratory wavelength measurements
  - Precision of QSO spectra better than lab accuracy!
  - Thanks to J. Pickering, A. Thorne, U. Litzén, S. Johansson, U. Griesmann, R. Kling and collaborators.

The Many Multiplet (MM) method:



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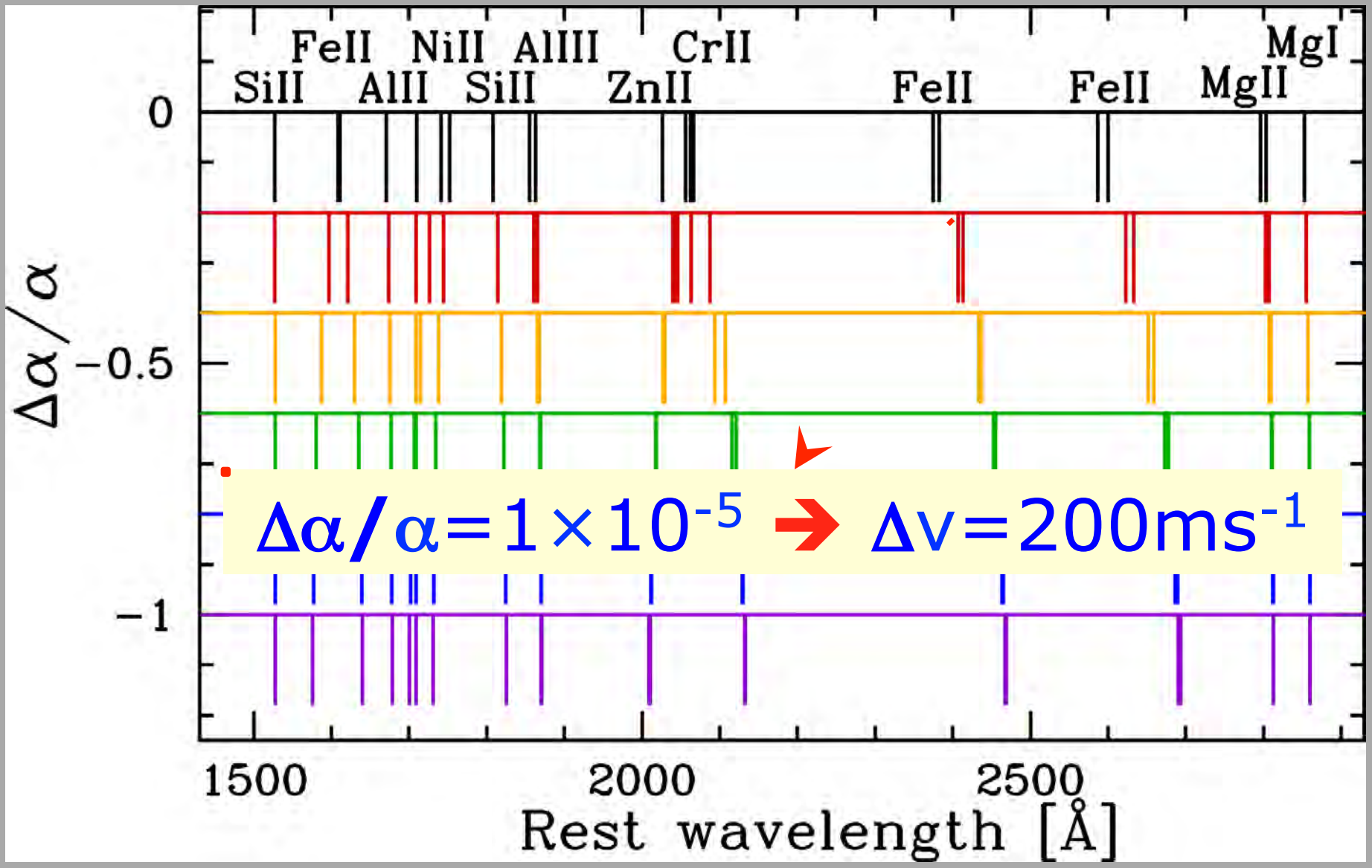
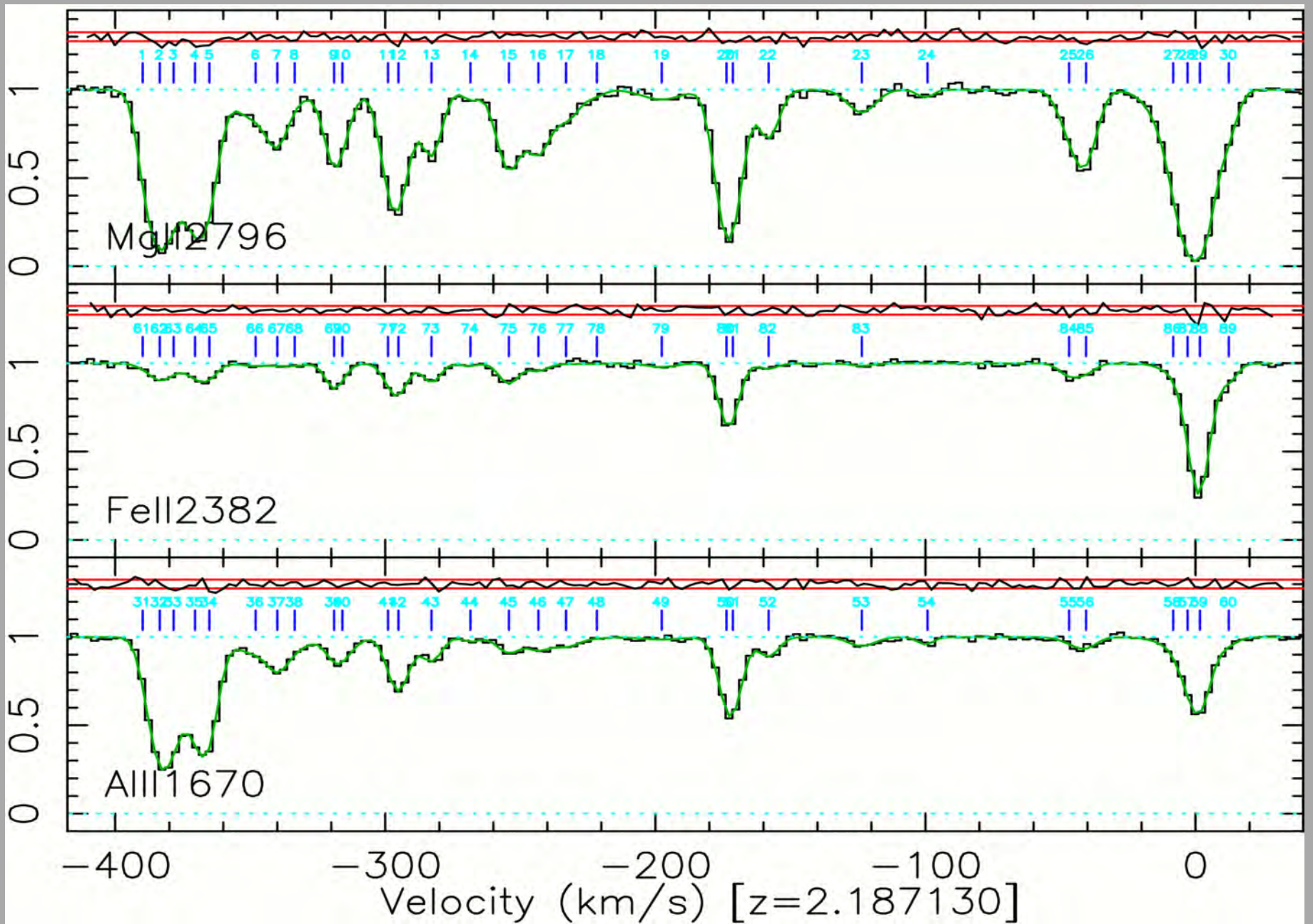
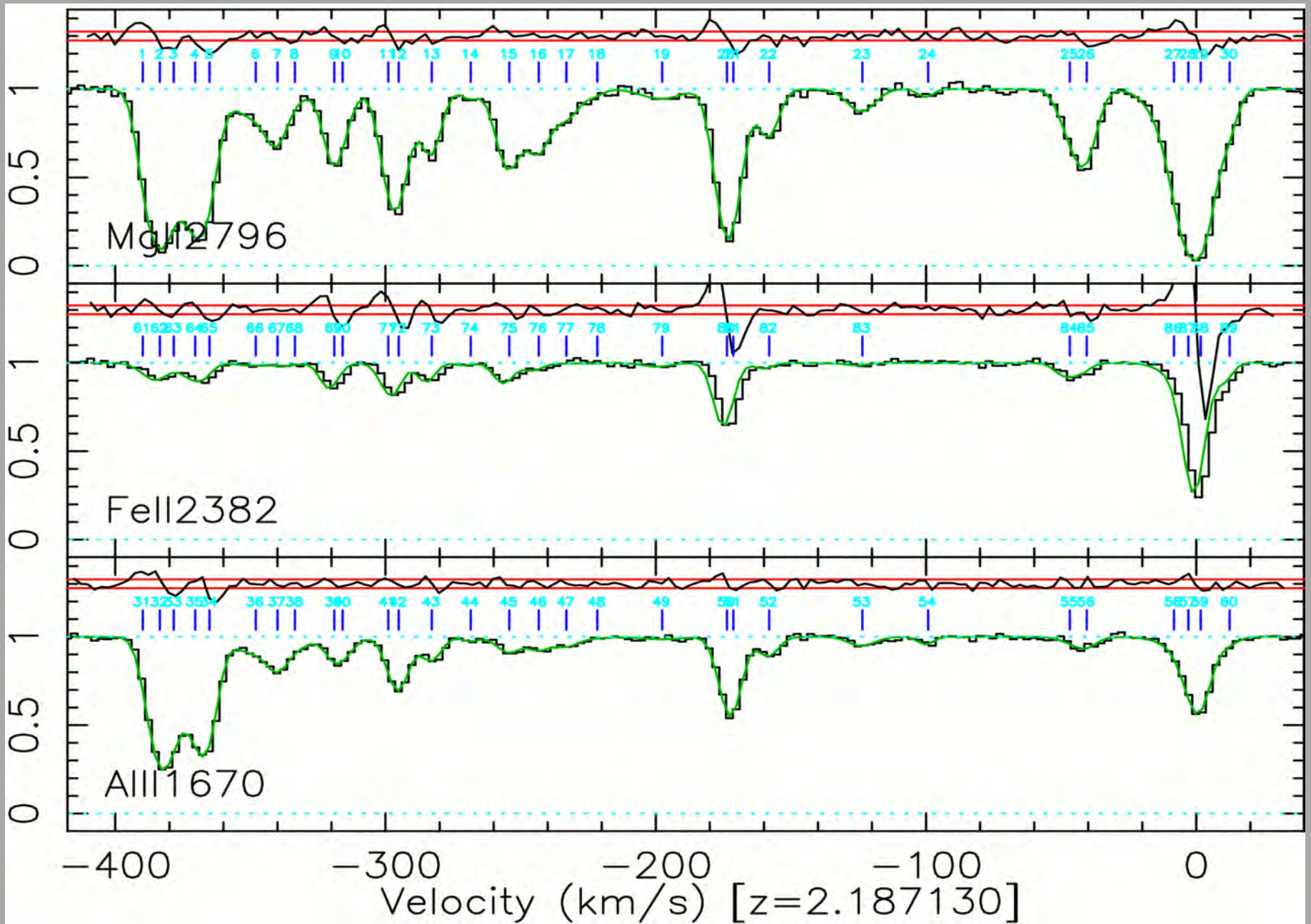


VLT/UVES absorber:

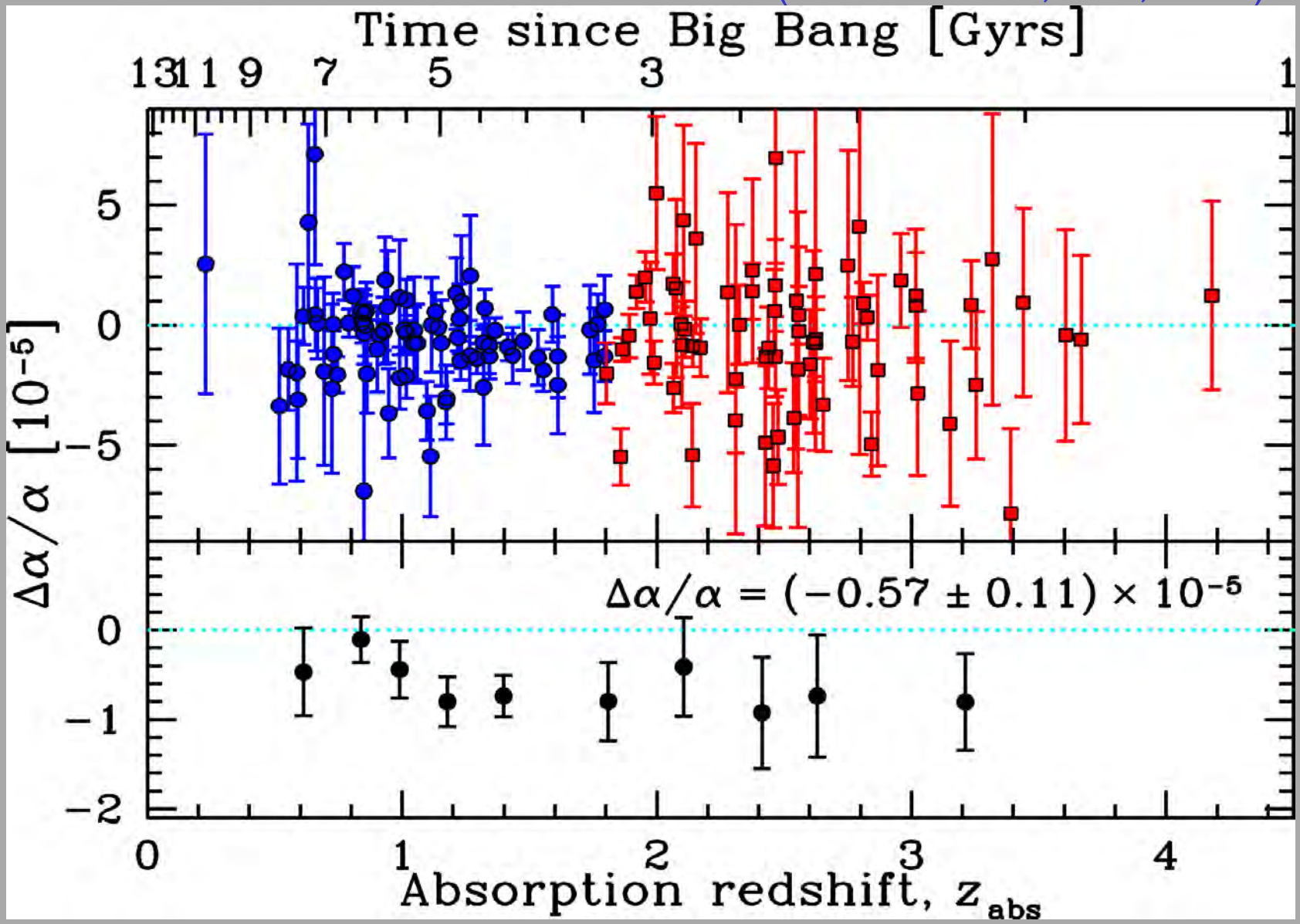


VLT/UVES absorber: $\Delta\alpha/\alpha=10^{-4}$



143 Keck/HIRES absorbers:

MTM et al. (MNRAS 2003; LNP, 2004)

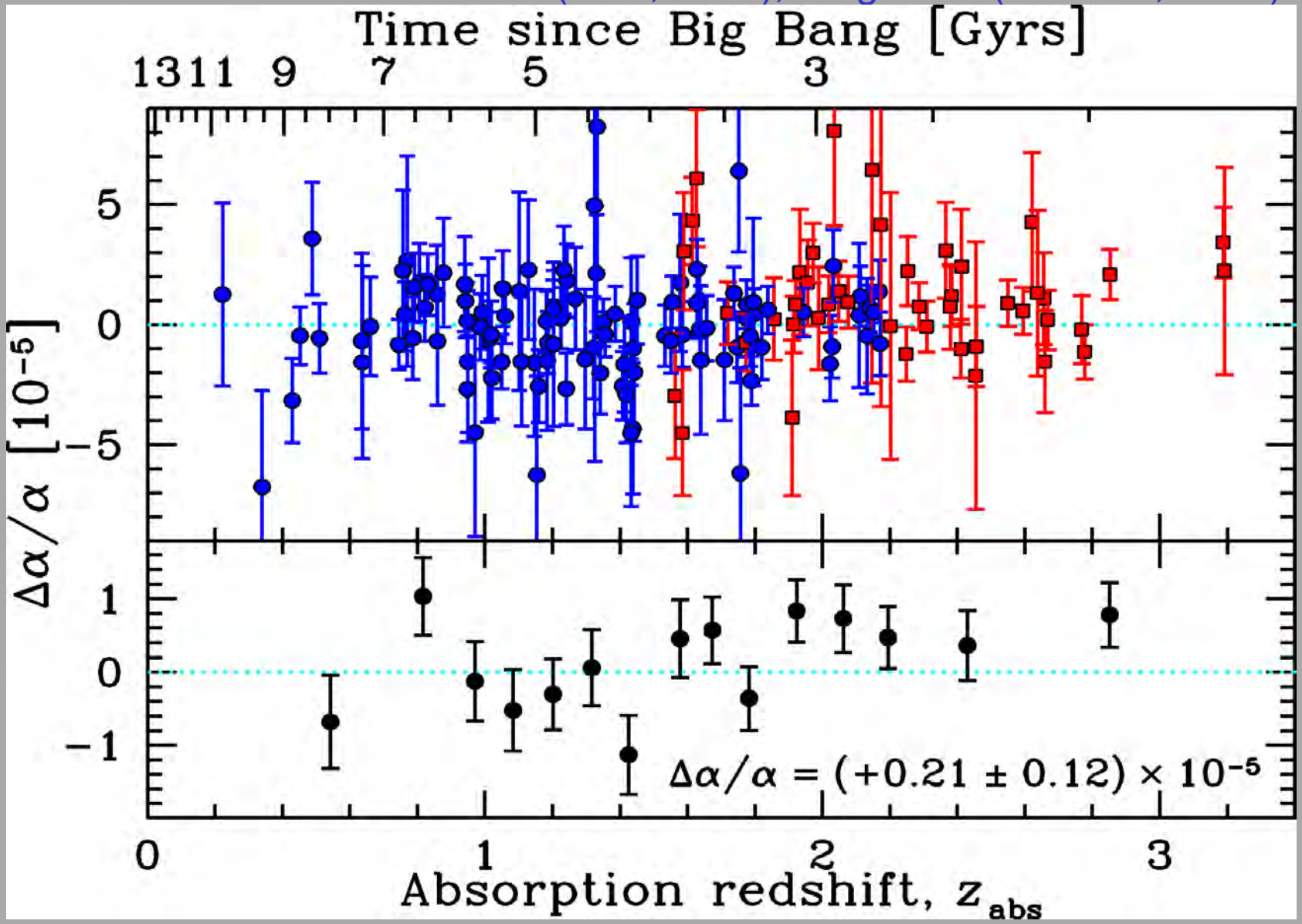


New VLT/UVES measurements:

- **Must check Keck/HIRES results on different telescope/spectrograph.**
- **Summary of VLT sample:**
  $\Delta\alpha/\alpha$ in 153 absorbers (61 QSOs), $0.2<z_{abs}<3.6$.
- More details:
  - **ARCHIVAL SPECTRA** – wavelength calibration!
  - Repeatable reduction of ~450 UVES QSO spectra.
  - Reduced data to be publicly available soon.
  - ~200 absorbers studied, ~100 high-SNR QSOs.

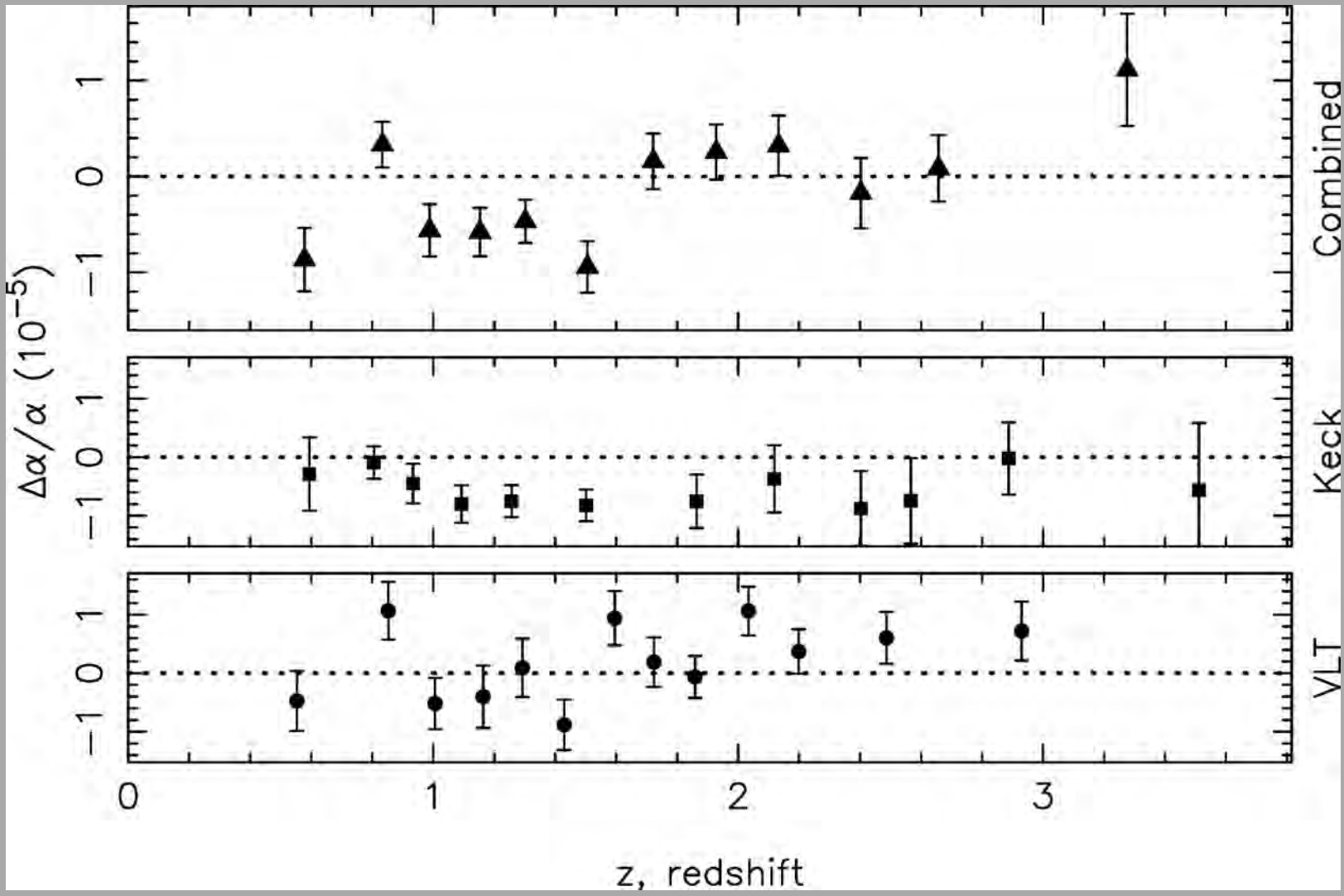
153 VLT/UVES absorbers:

Webb et al. (PRL, 2011), King et al. (MNRAS, 2012)



VLT/UVES vs. Keck/HIRES:

- Keck + VLT
- Keck
- VLT



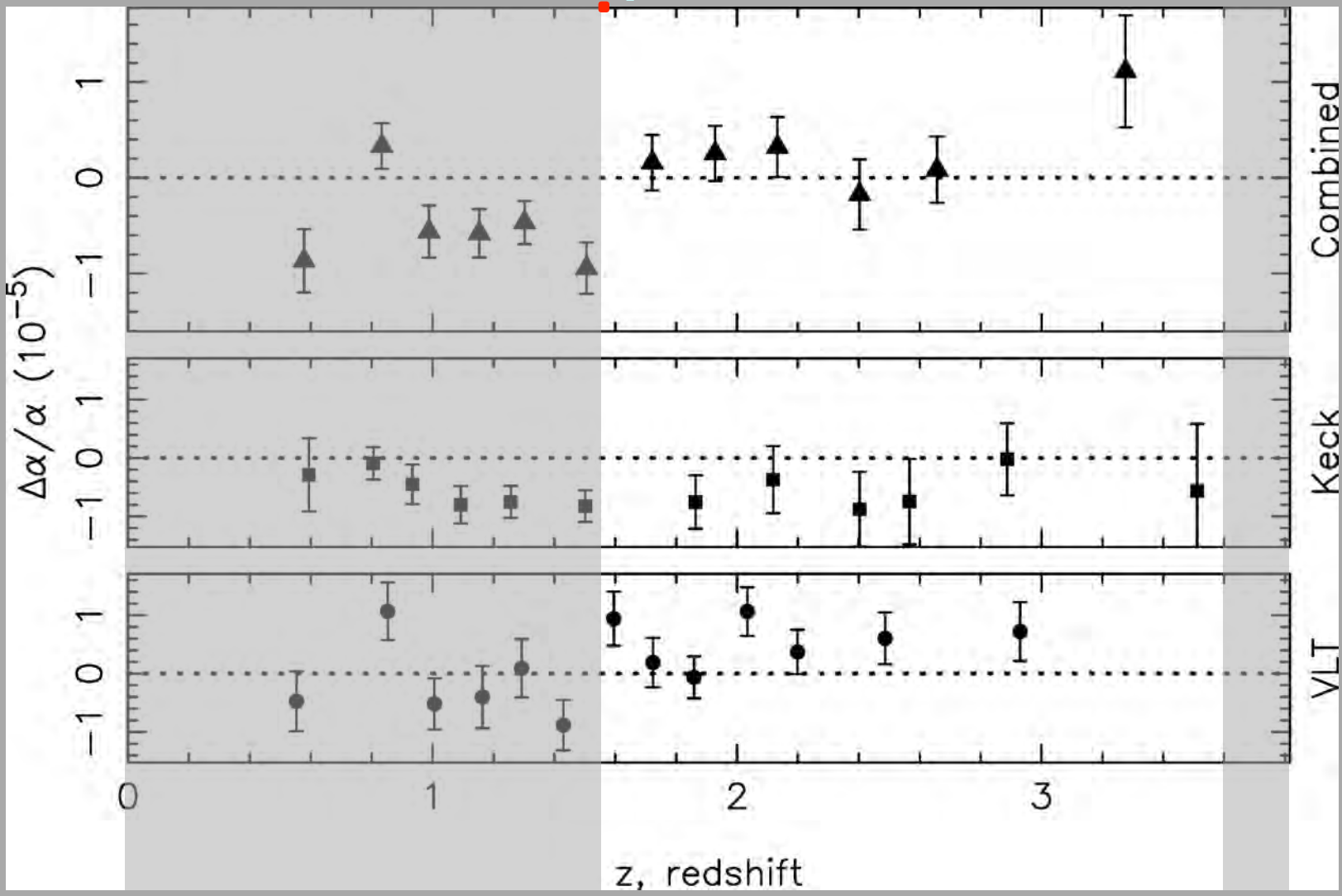
King et al. (MNRAS, 2012)

VLT/UVES vs. Keck/HIRES:

Keck + VLT

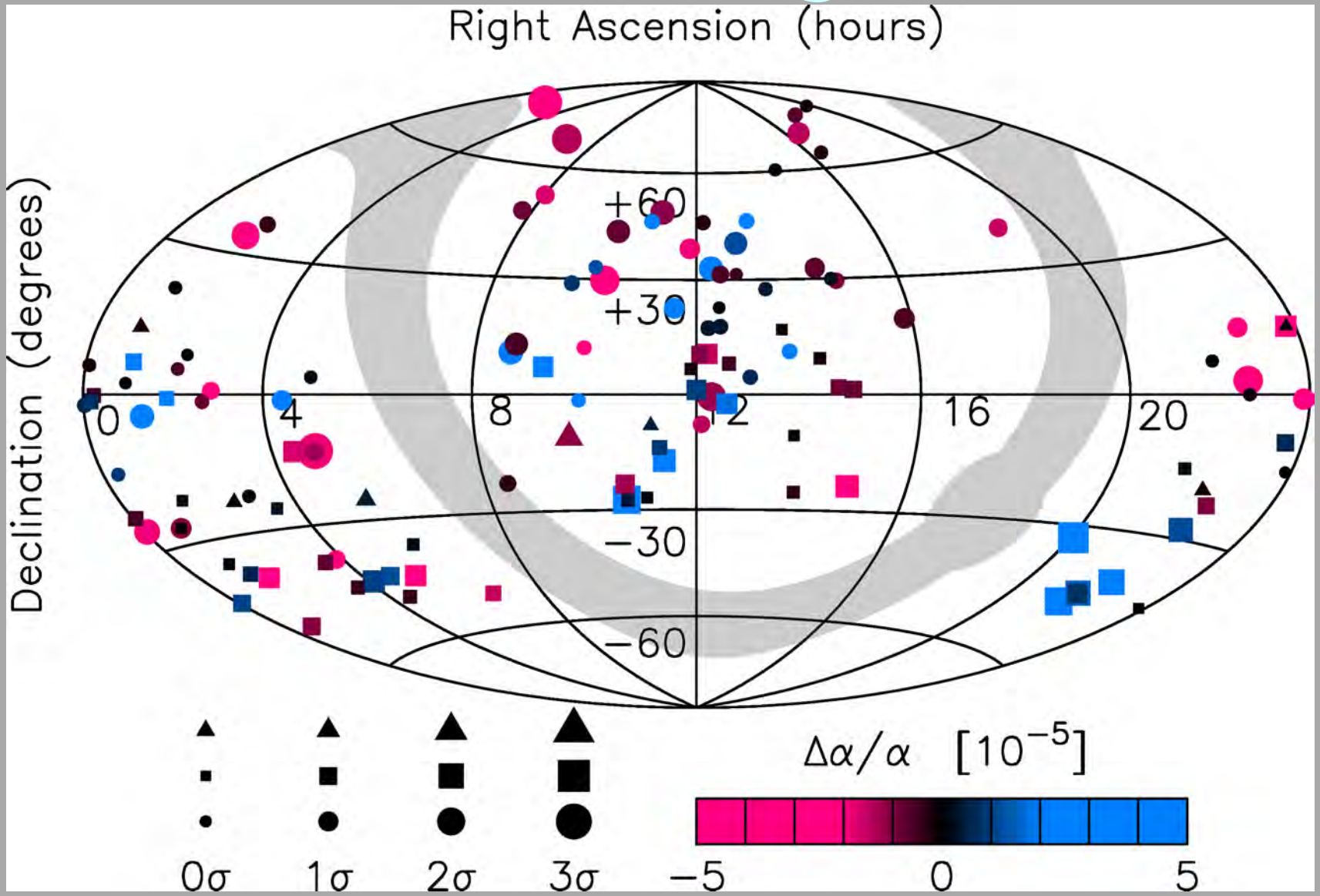
Keck

VLT



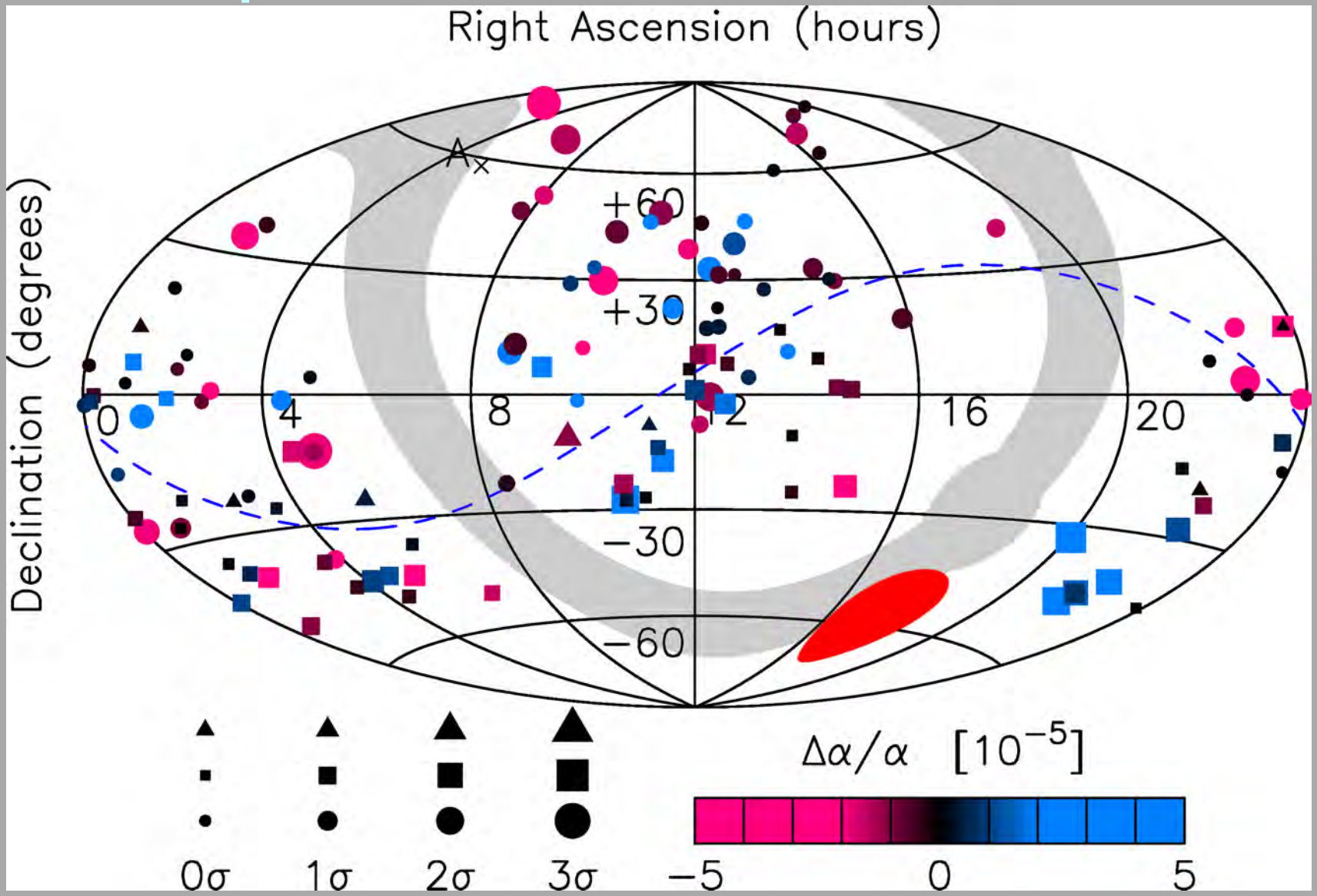
- Keck @ z>1.8: $\Delta\alpha/\alpha=(-0.74\pm0.17)\times10^{-5}$
- VLT @ z>1.8: $\Delta\alpha/\alpha=(+0.61\pm0.20)\times10^{-5}$

$\Delta\alpha/\alpha$ for individual sight-lines:



King et al. (MNRAS, 2012)

An α dipole?:

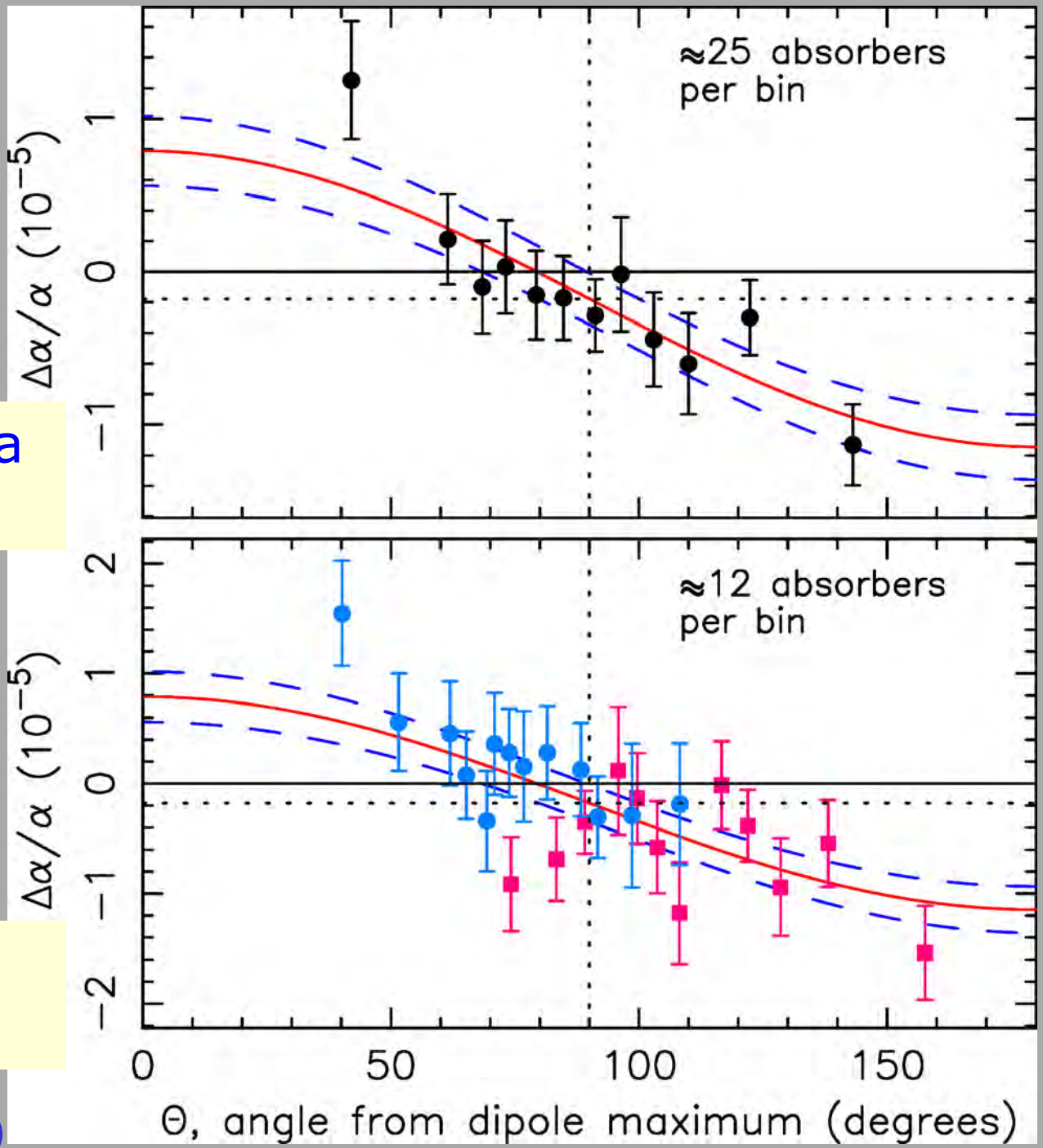


King et al. (MNRAS, 2012)

4.1-σ dipole

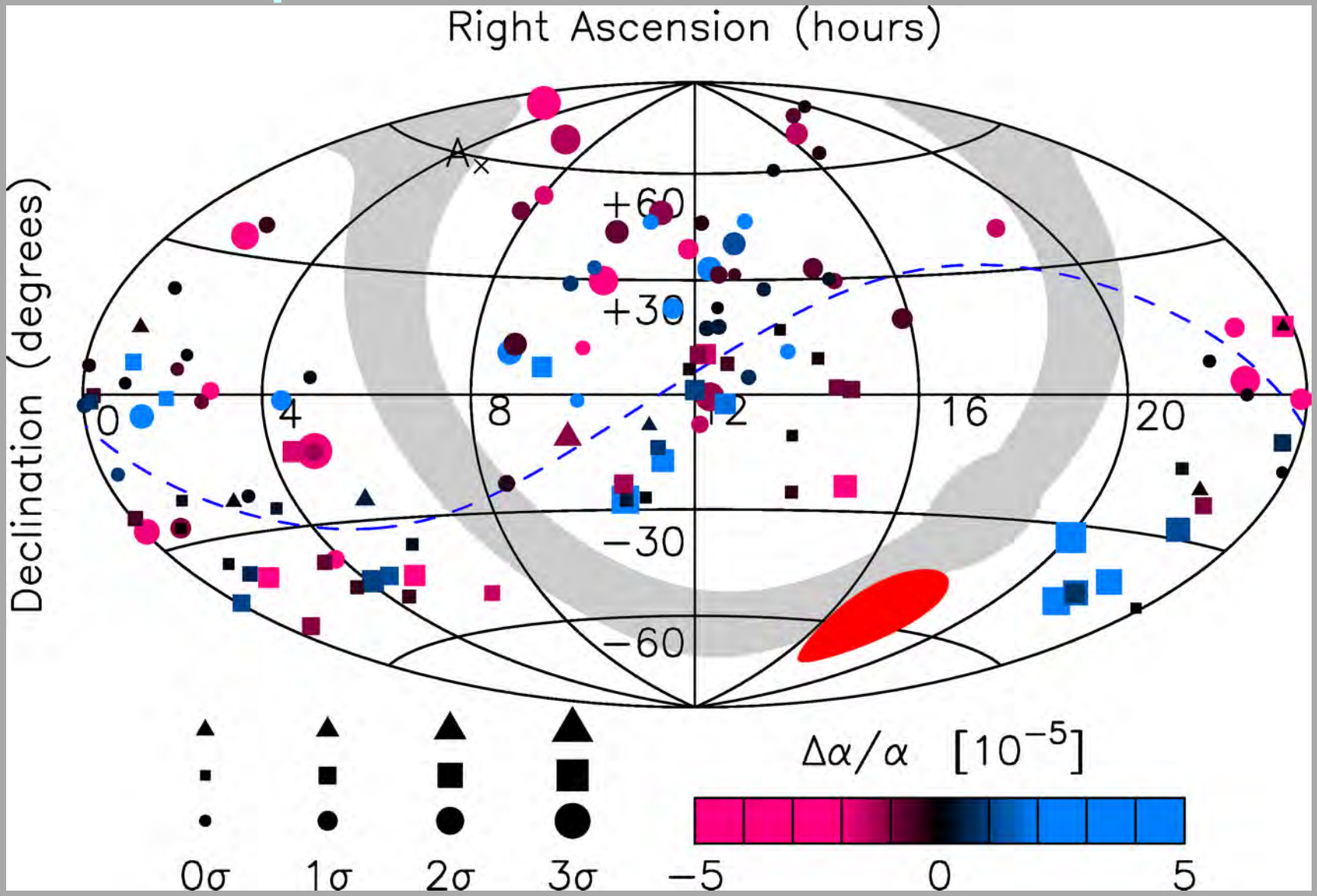
$$\Delta\alpha/\alpha = A\cos\theta + m$$

Keck+VLT data combined



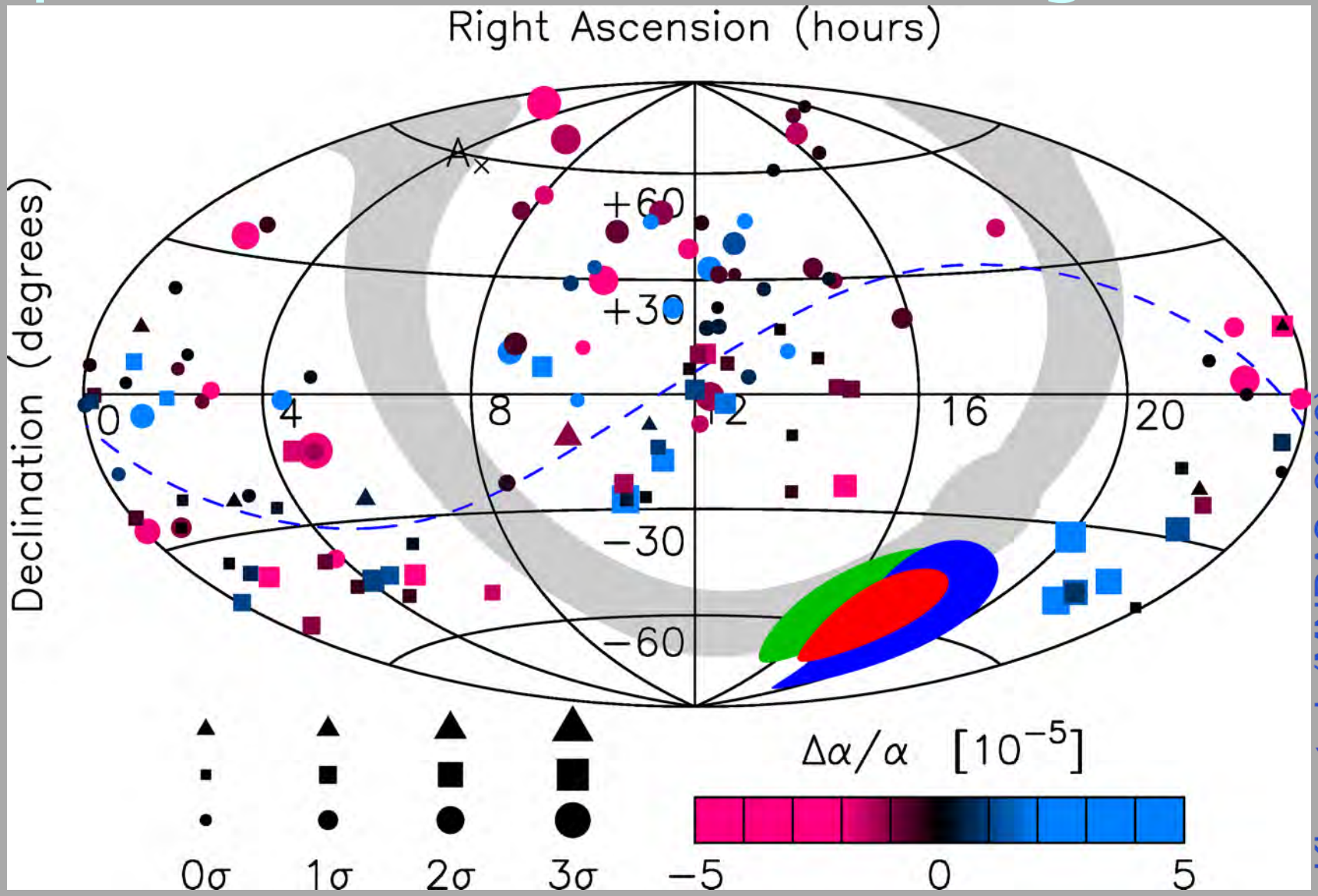
King et al. (MNRAS, 2012)

4.1-σ dipole in α:

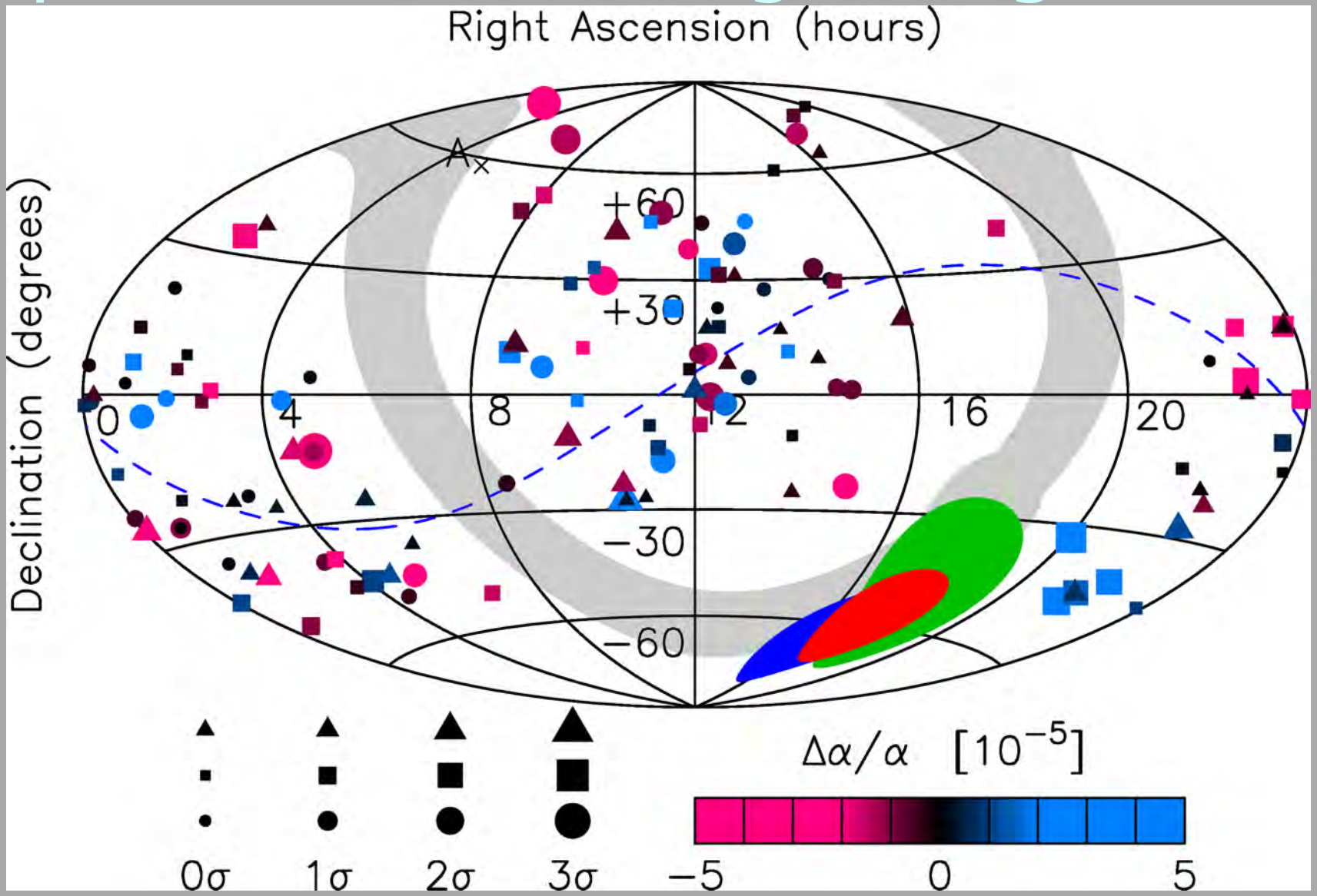


King et al. (MNRAS, 2012)

Dipoles from Keck & VLT agree:



Dipoles from low/high-z agree:



Interpretation:

- Angular + distance dependence ⟶ **Spatial gradient in α throughout Universe**
- Berengut & Flambaum (arXiv:1008.3957):
  - As Earth moves through gradient, α in Galaxy & Solar System will vary
  - Prediction for $\sim 1 \times 10^{-20}$ relative annual modulation of α (cf. current precision $\sim 1 \times 10^{-17}$)
  - Consistent with Oklo & meteoritic constraints

What if it's correct?:

- Standard Model has no explanation
- Need new fundamental theory
  - Gives theory something to aim for
  - Unification?:
    If one constant varies, others probably do too
  - Can String/M-theory make predictions?
- Spatial α gradient $\rightarrow$ anisotropic Universe
- A fundamental Goldilocks zone?
  - "Life wouldn't exist if α were just ~3% different"
  - Spatial α gradient $\rightarrow$ "life wouldn't exist" in sufficiently distant regions of the Universe

Really?:

- Not contradicted by other MM measurements:
  - Only other statistical sample – 23 absorbers: Srianand, Chand et al. (2004, A&A; 2007, PRL)
  - Individual absorbers: e.g. Levshakov, Molaro et al. (2006 & 2007, A&A)
  - All from VLT
  - Consistent with dipole: Berengut & Flambaum (2011, PRD)
- **Most important question is the effect and magnitude of systematic errors.**
- Mg isotopic abundances in low-z absorbers:
  - Higher $^{25,26}Mg/^{24}Mg$ in absorbers → shift $\Delta\alpha/\alpha$ up
  - Doesn't affect low-z dipole though…

EUROPEAN SOUTHERN OBSERVATORY

Organisation Européenne pour des Recherches Astronomiques dans l'Hémisphère Austral
Europäische Organisation für astronomische Forschung in der südlichen Hemisphäre

OBSERVING PROGRAMMES OFFICE • Karl-Schwarzschild-Straße 2 • D-85748 Garching bei München • e-mail: opo@eso.org • Tel.: +49-89-32 00 64 73

APPLICATION FOR OBSERVING TIME LARGE PROGRAMME PERIOD: **85A**

Important Notice:

By submitting this proposal, the PI takes full responsibility for the content of the proposal, in particular with regard to the names of CoIs and the agreement to act according to the ESO policy and regulations, should observing time be granted

1. Title Category: **A–7**

THE UVES LARGE PROGRAM FOR TESTING FUNDAMENTAL PHYSICS

4. Principal Investigator: MOLARO

4a. Co-investigators:

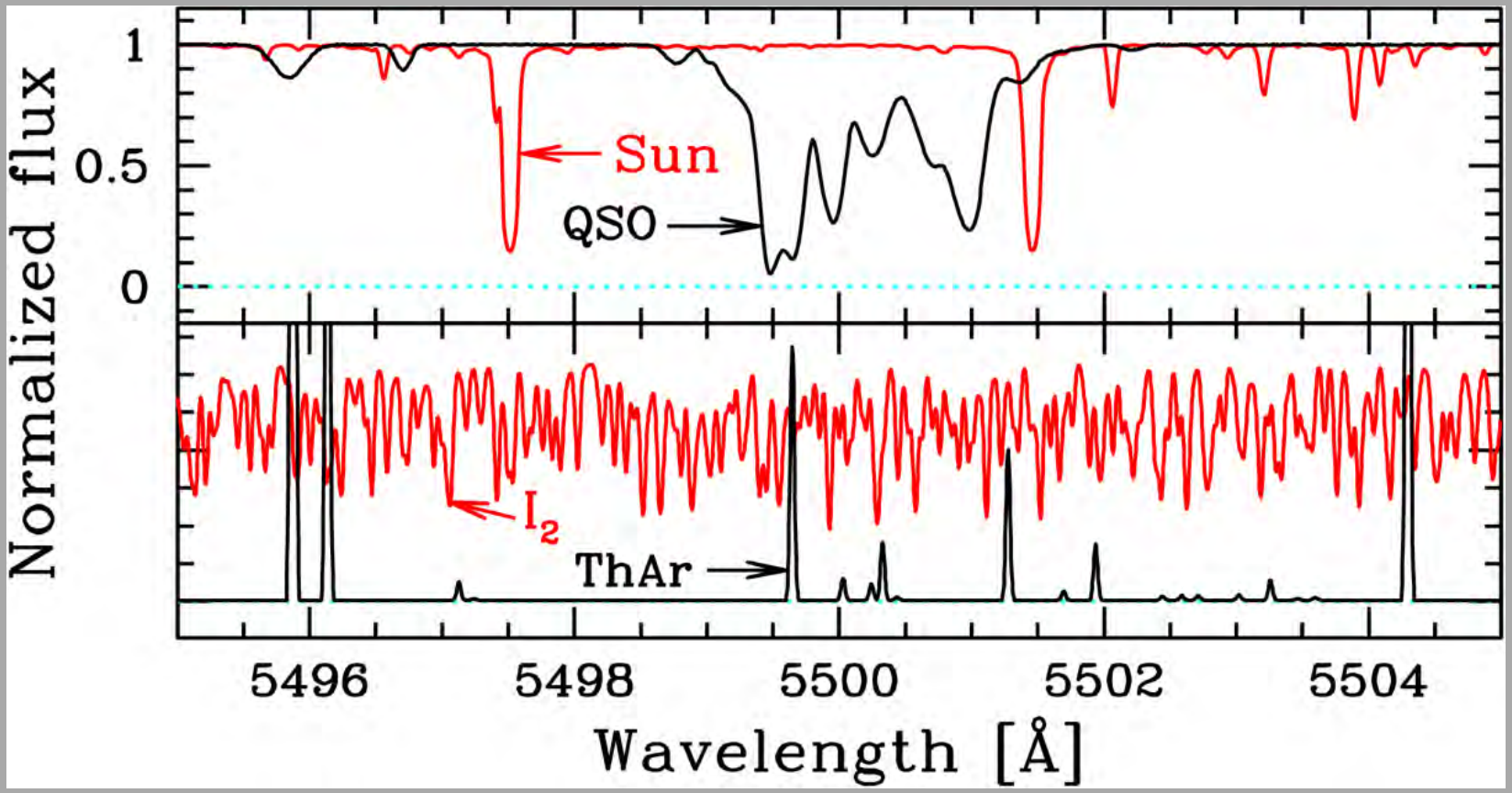
P.	Petitjean	1361
M.	Murphy	2009
S.	Levshakov	1403
D.	Reimers	1311
A.	Srianand	1402
S.	Lopez	1823

Following CoIs moved to the end of the

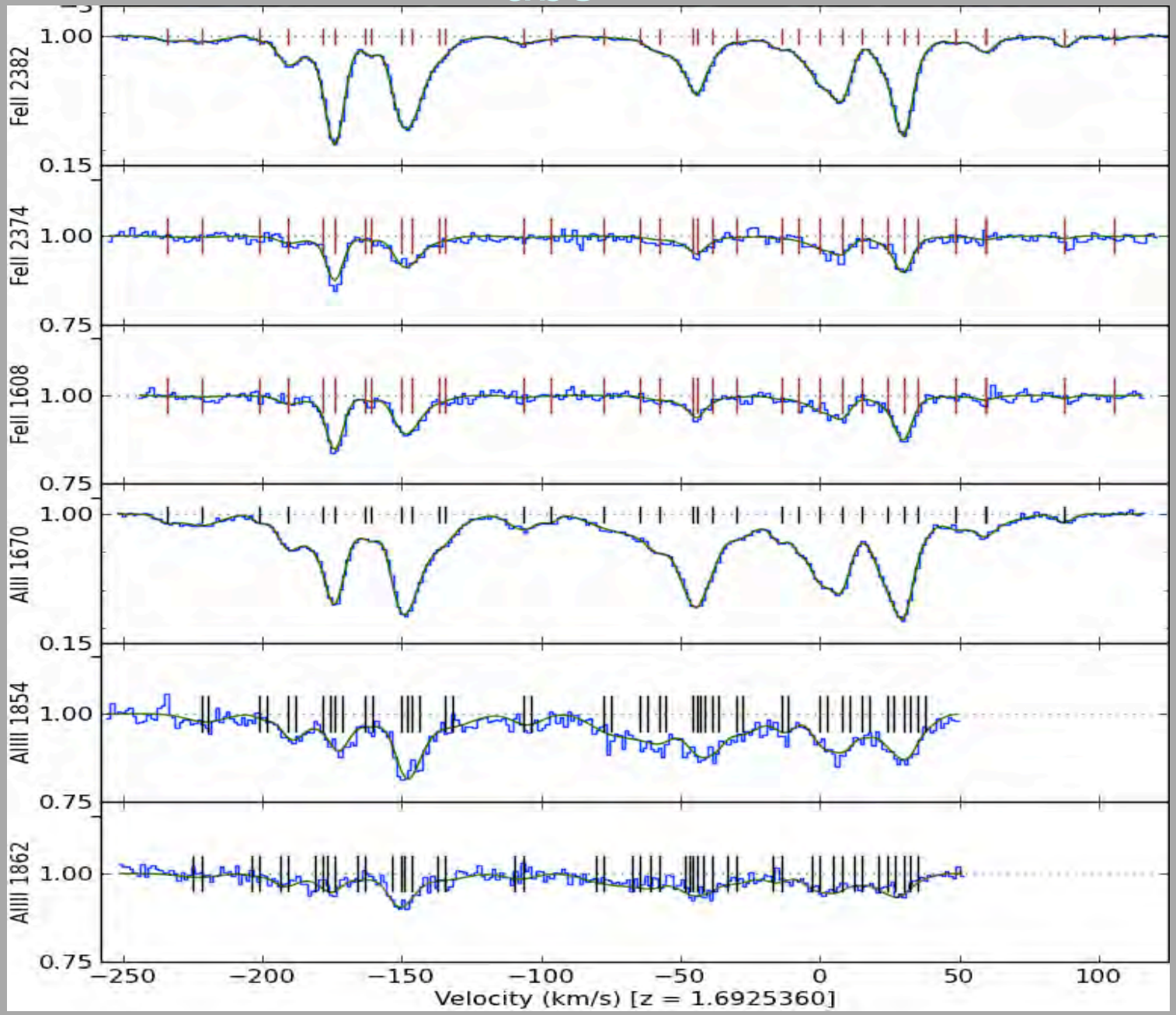
- ~32 nights on VLT/UVES
- Aim: >15 "good" absorbers (13 QSOs) with S/N ≥ 80
- 80% complete so far
- 3 major observational groups involved
- Only large observational program ***dedicated*** to varying constants.

Careful & extra calibrations:

- Frequent, specific ThAr wavelength calibrations:
  - Immediately after QSO exposures to avoid drifts (general) and resets (specific to UVES).
- Iodine cell & asteroid checks on ThAr calibration:



First result at z_{abs}=1.691:



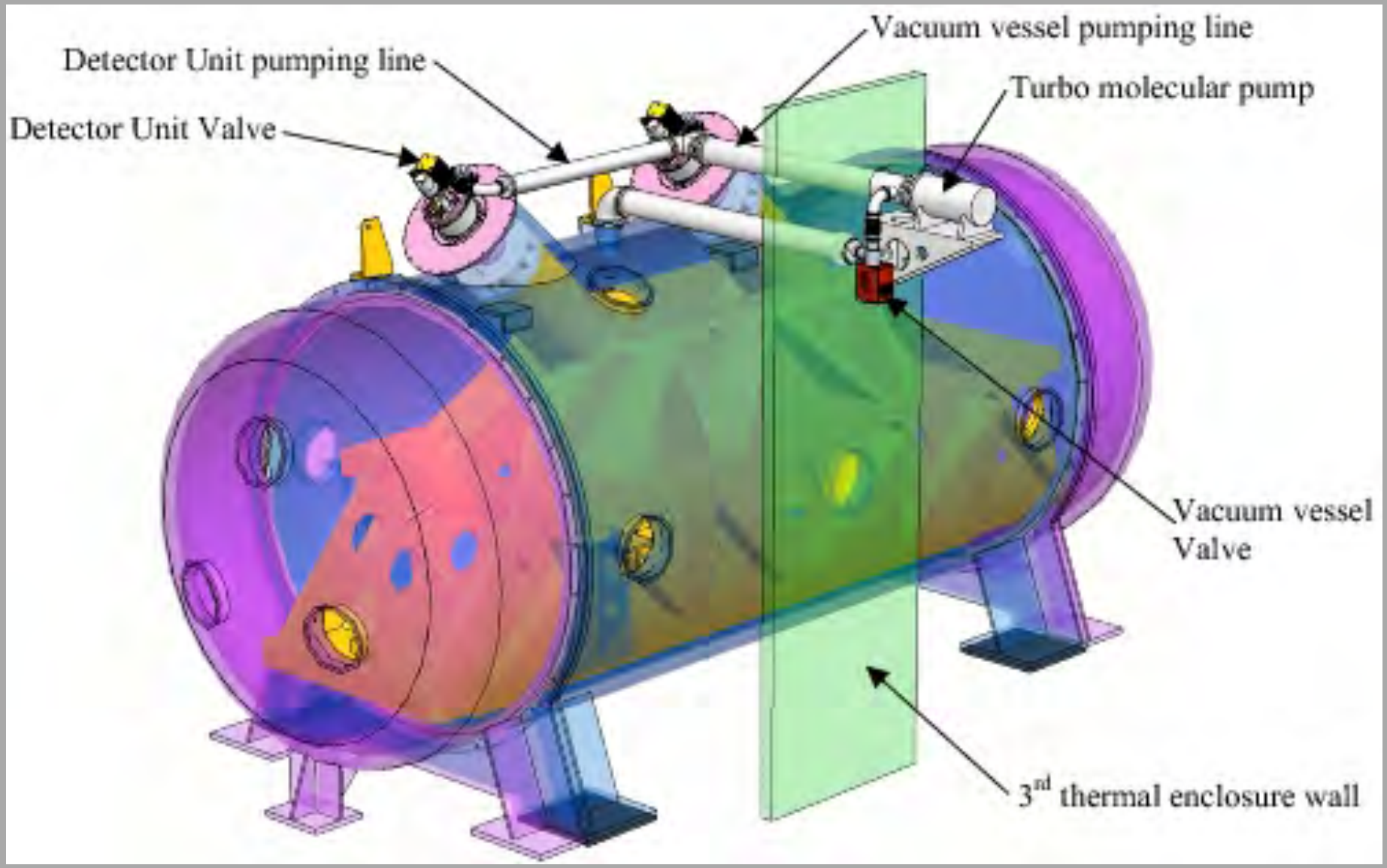
First result at z_{abs}=1.691:

- Preliminary result:

$$\Delta\alpha/\alpha = +0.04 \pm 2.76_{stat} \text{ ppm}$$

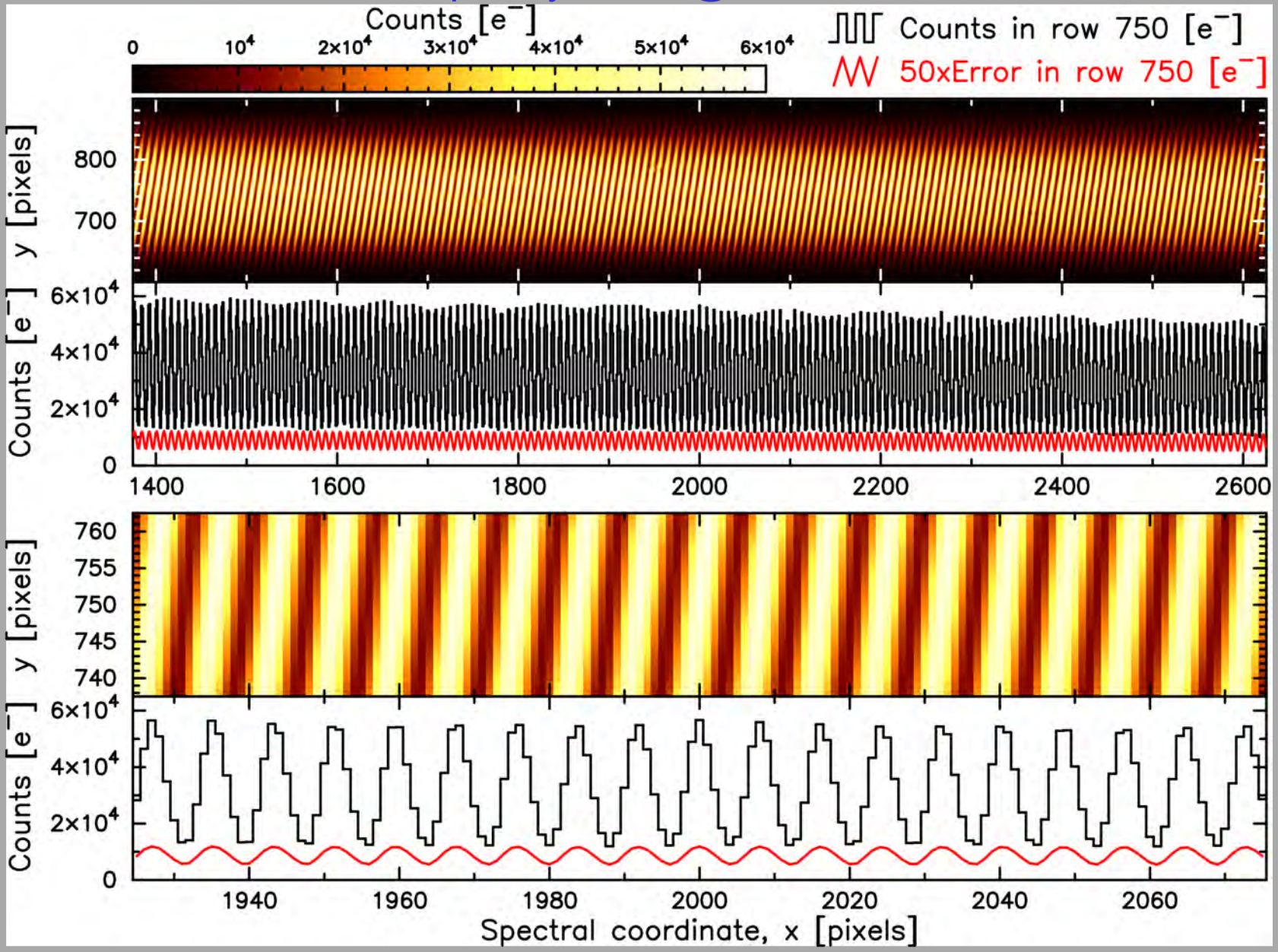
- Systematic error budget still being determined
- Dipole expectation: +5.6 ± 1.5 ppm
- Only one absorber…
- At least 15 more such measurements to come from UVES Large Programme

ESPRESSO @ VLT:

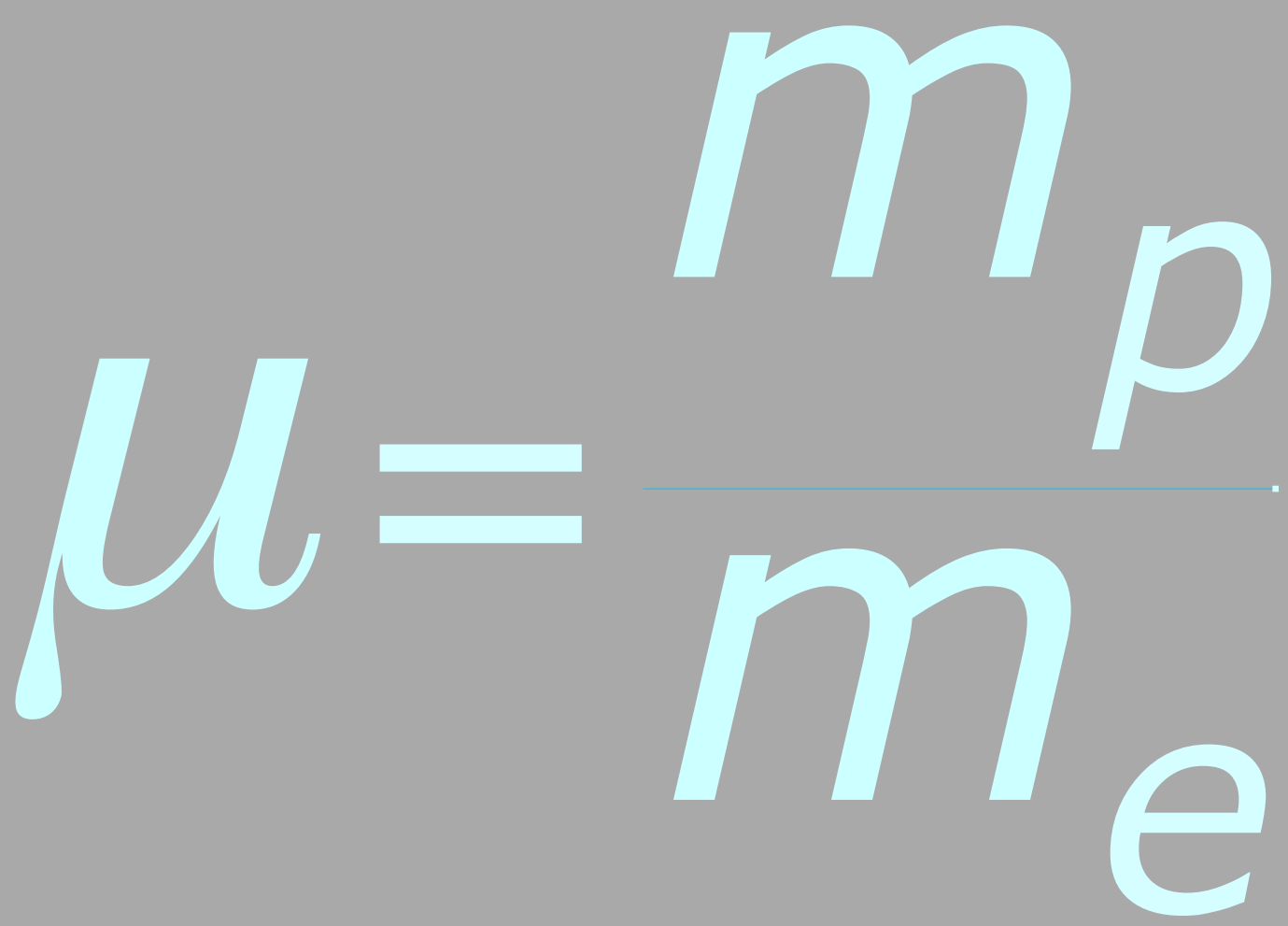


Calibration is key:

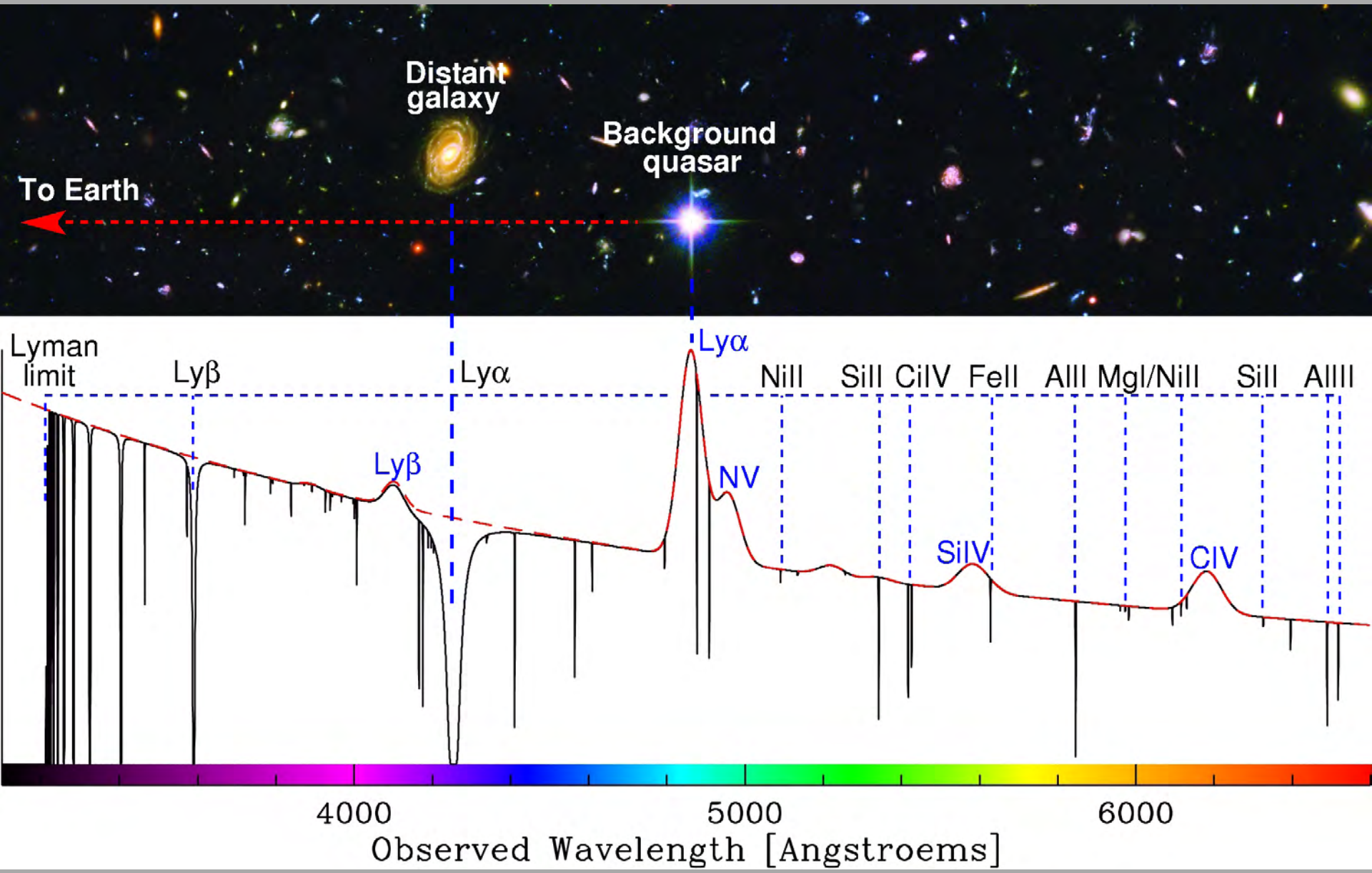
Frequency comb @ AAT/UHRF: 780 nm, R~10^6



MTM et al. (MNRAS, 2012)


$\mu = \frac{m_p}{m_e}$

H_2 quasar absorbers:



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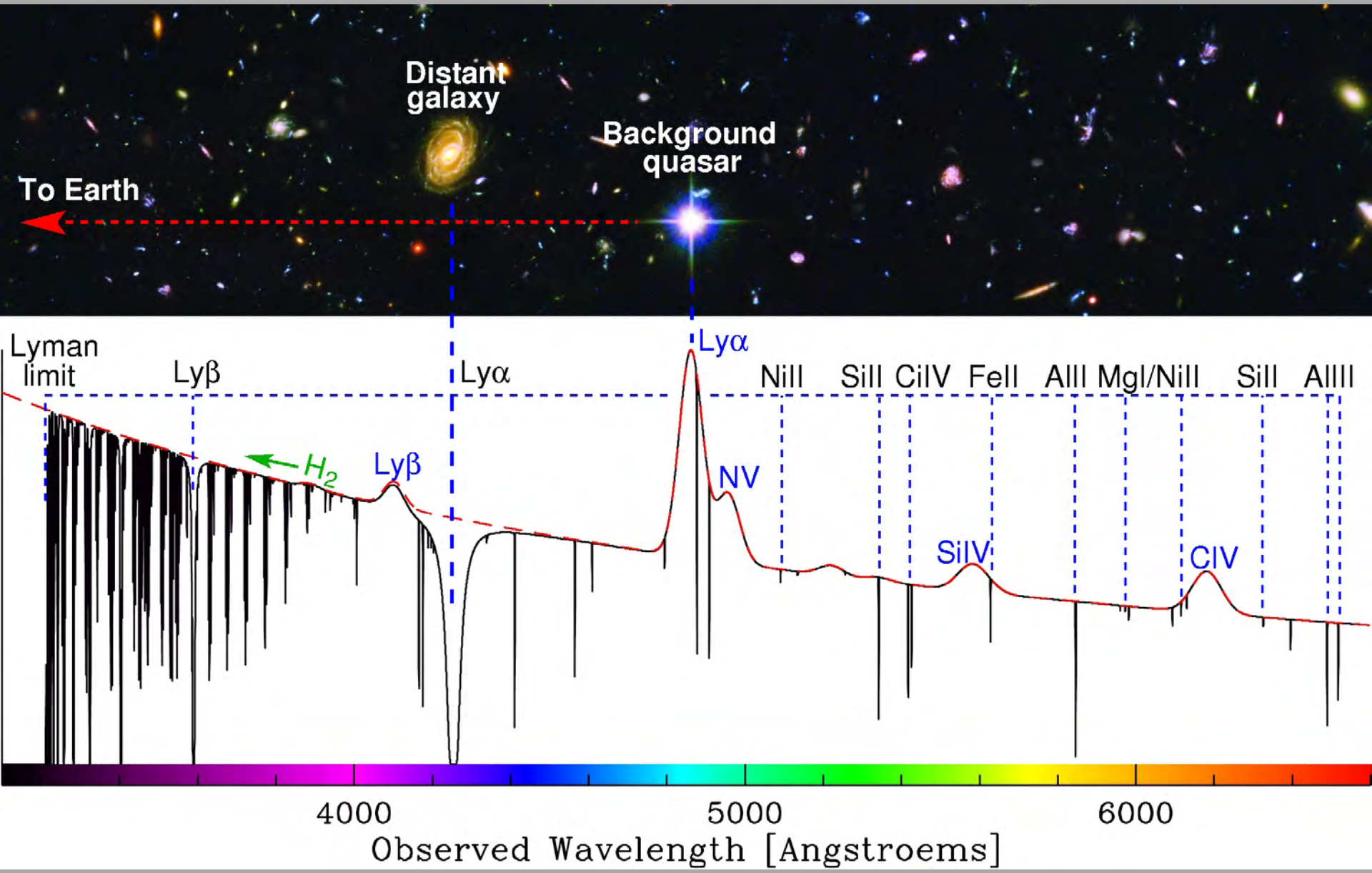
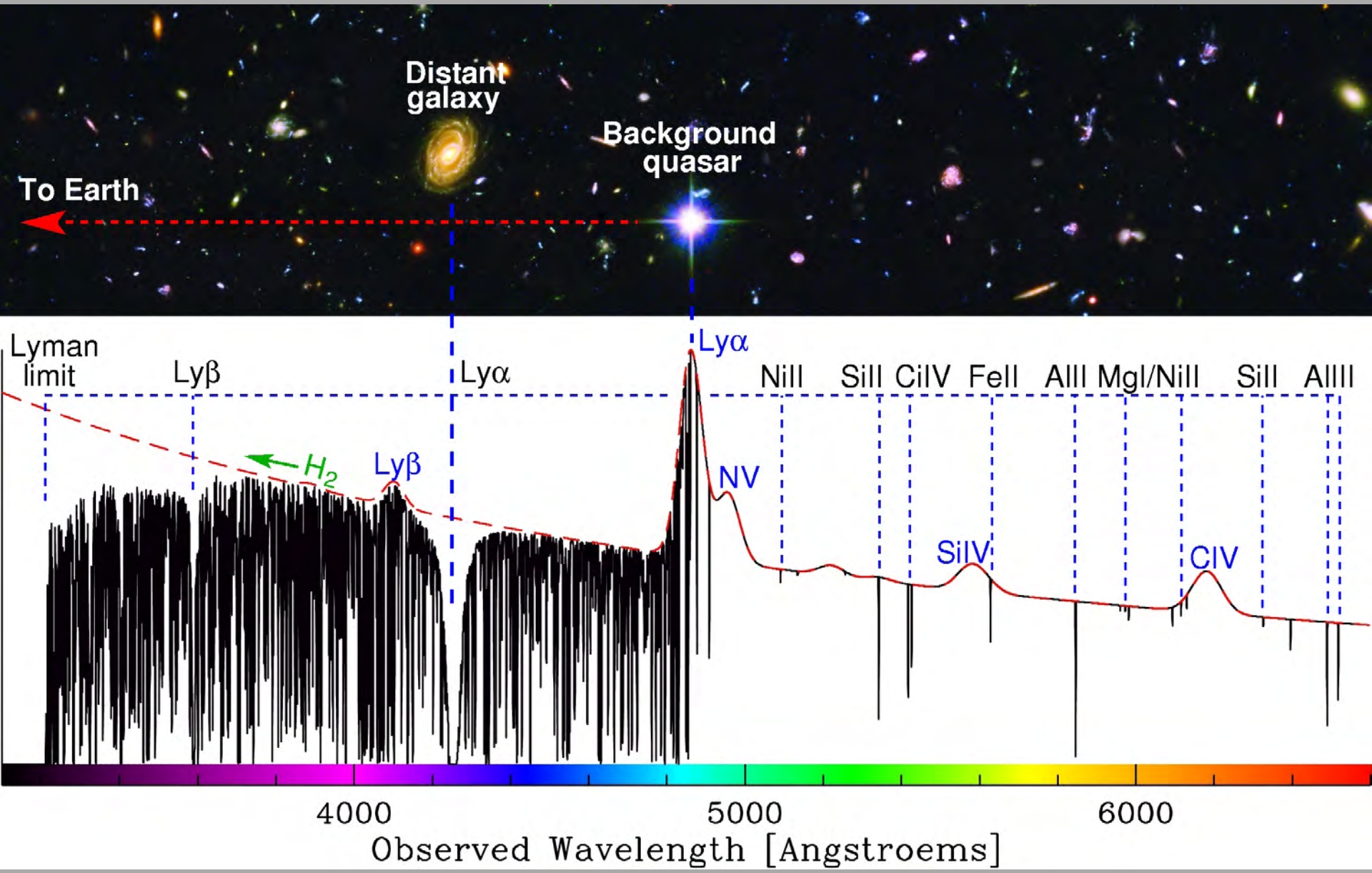
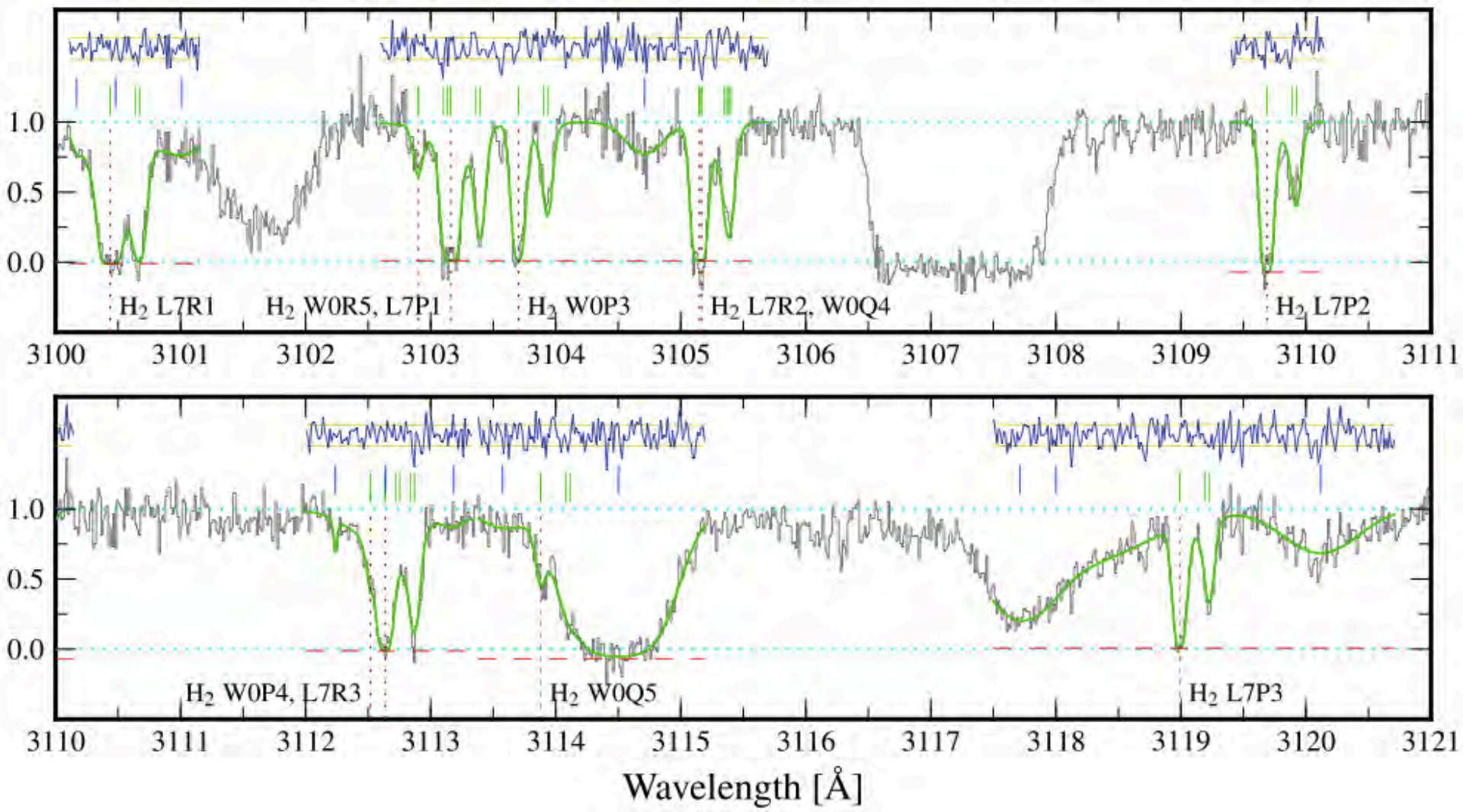


H_2 quasar absorbers:

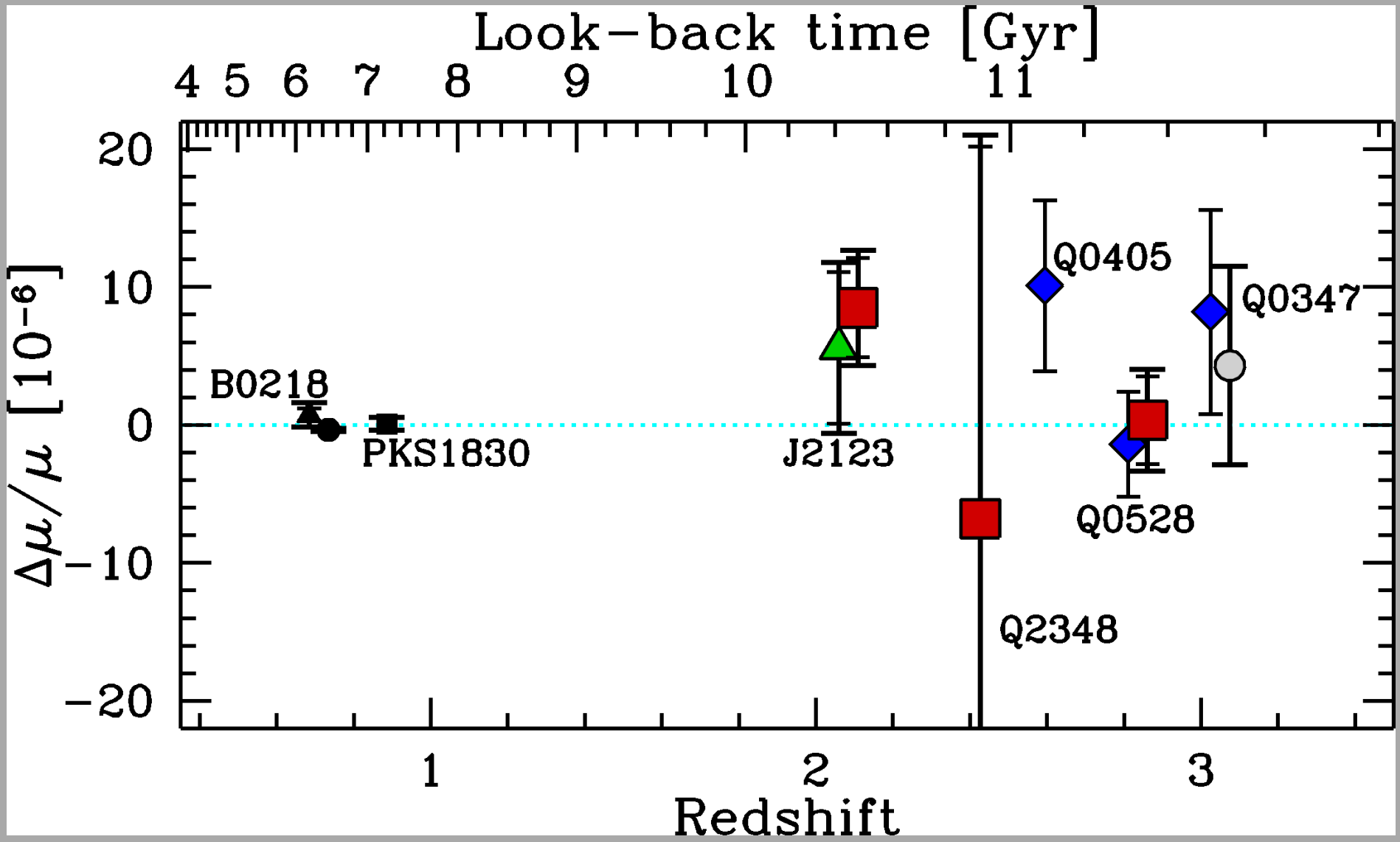


H_2 constraints on $\Delta\mu/\mu$:



Malec et al. (MNRAS, 2010)

Extragalactic values of $\Delta\mu/\mu$:



King et al. (PRL, 2008), Malec et al. (MNRAS, 2010), Van Weerdenburg et al. (2011), King et al. (MNRAS, 2011), Bagdonaite et al. (MNRAS, 2012), Wendt & Molaro (A&A, 2012).

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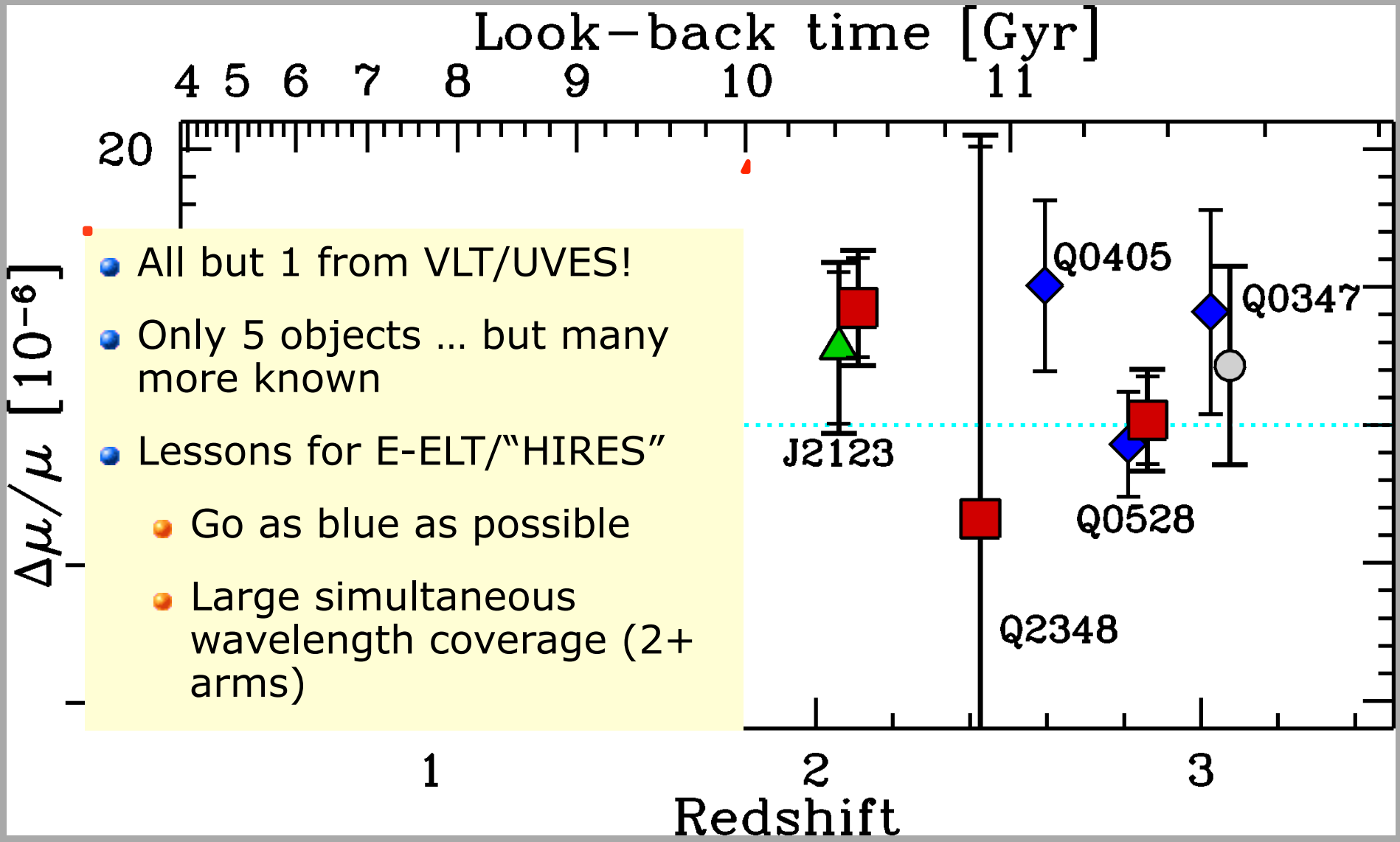

- All but 1 from VLT/UVES!
- Only 5 objects … but many more known
- Lessons for E-ELT/"HIRES"
  - Go as blue as possible
  - Large simultaneous wavelength coverage (2+ arms)

King et al. (PRL, 2008), Malec et al. (MNRAS, 2010), Van Weerdenburg et al. (2011), King et al. (MNRAS, 2011), Bagdonaite et al. (MNRAS, 2012), Wendt & Molaro (A&A, 2012).

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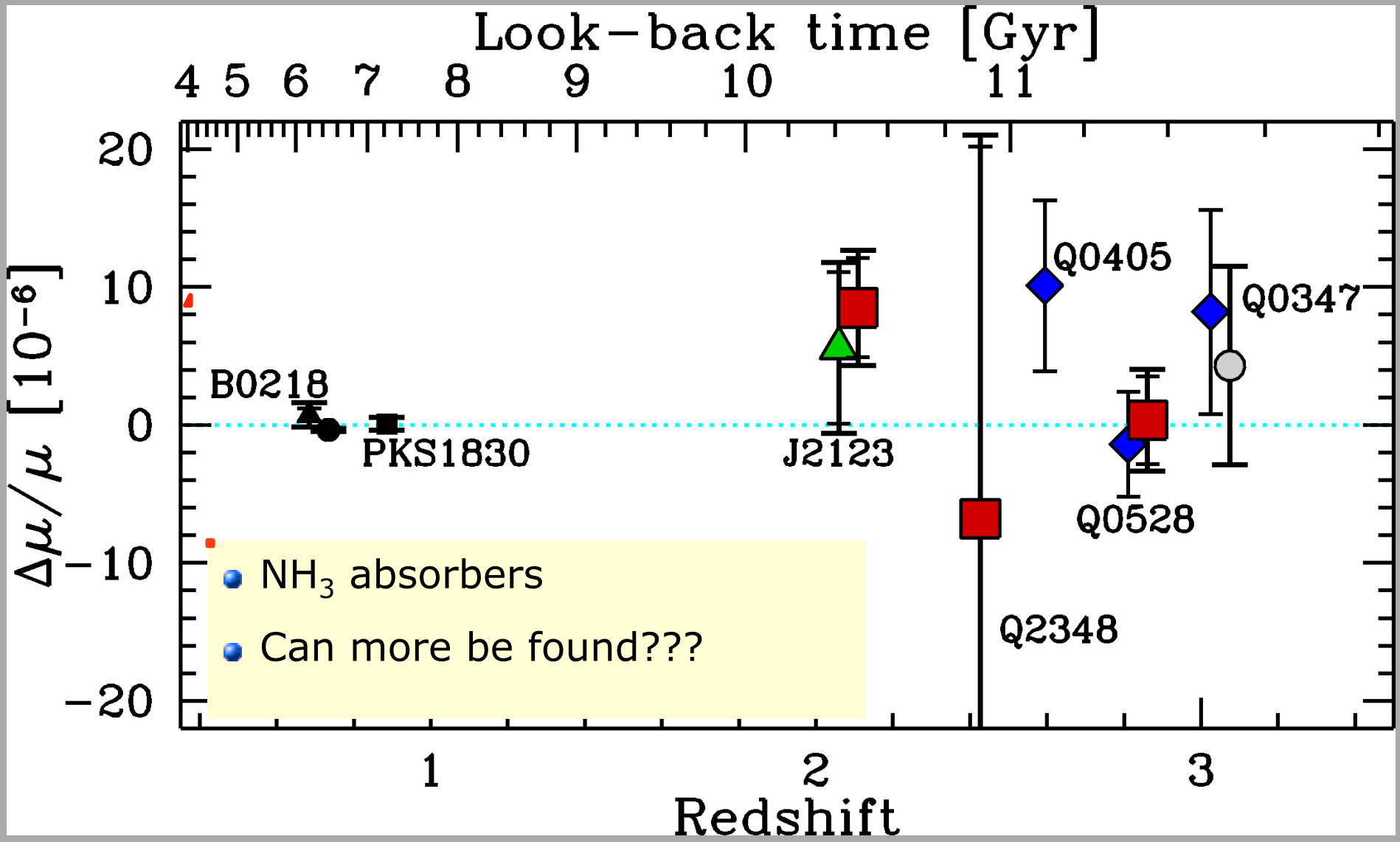

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Conclusions:

- Previous Keck + new VLT results show evidence for spatial variation in α
- Two internal consistencies:
  - Keck and VLT dipoles agree
  - High- and low-z dipoles agree
- No *known* systematics explain the dipole
- ESO Large Programme aims to refute/confirm
- ESPRESSO @ VLT will remove calibration uncertainty entirely