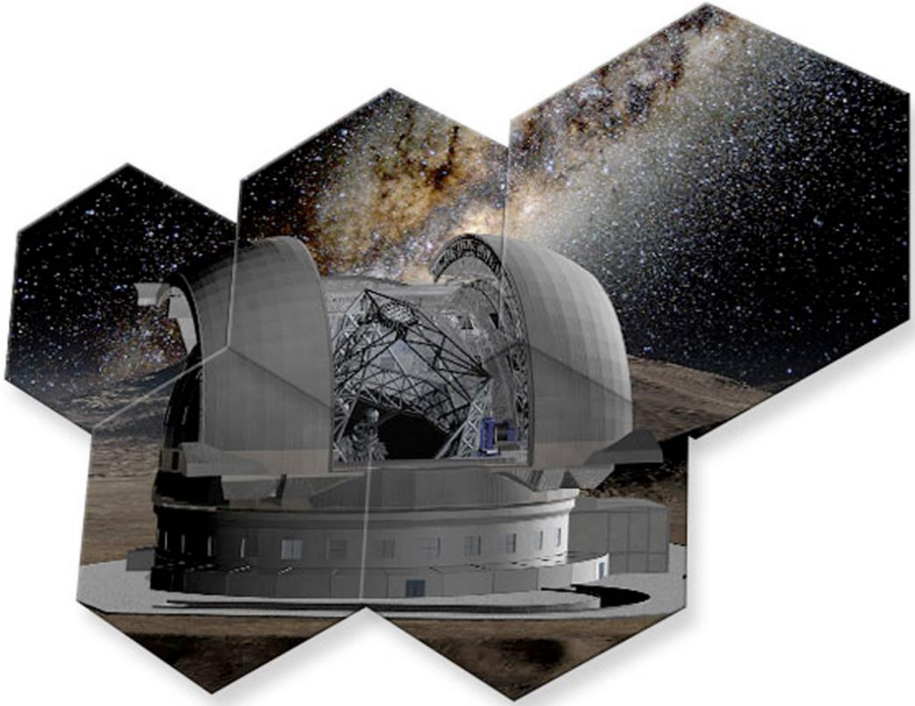
# HIRES – casi scientifici
# Fundamental Physics - Cosmology



Stefano Cristiani
INAF-OATs

*I'm indebted to R. Cooke, V. D'Odorico, J. Liske, G. Lo Curto, C.Martins, M.Murphy, P.Molaro*

# Standard Model – Precision Cosmology

**With the assumptions of homogeneity and isotropy, the concordance model finds a FRW metric with a non zero cosmological constant**

$$H^2 = \frac{8\pi G}{3}\rho - \frac{kc^2}{a^2} + \frac{\Lambda c^2}{3}$$

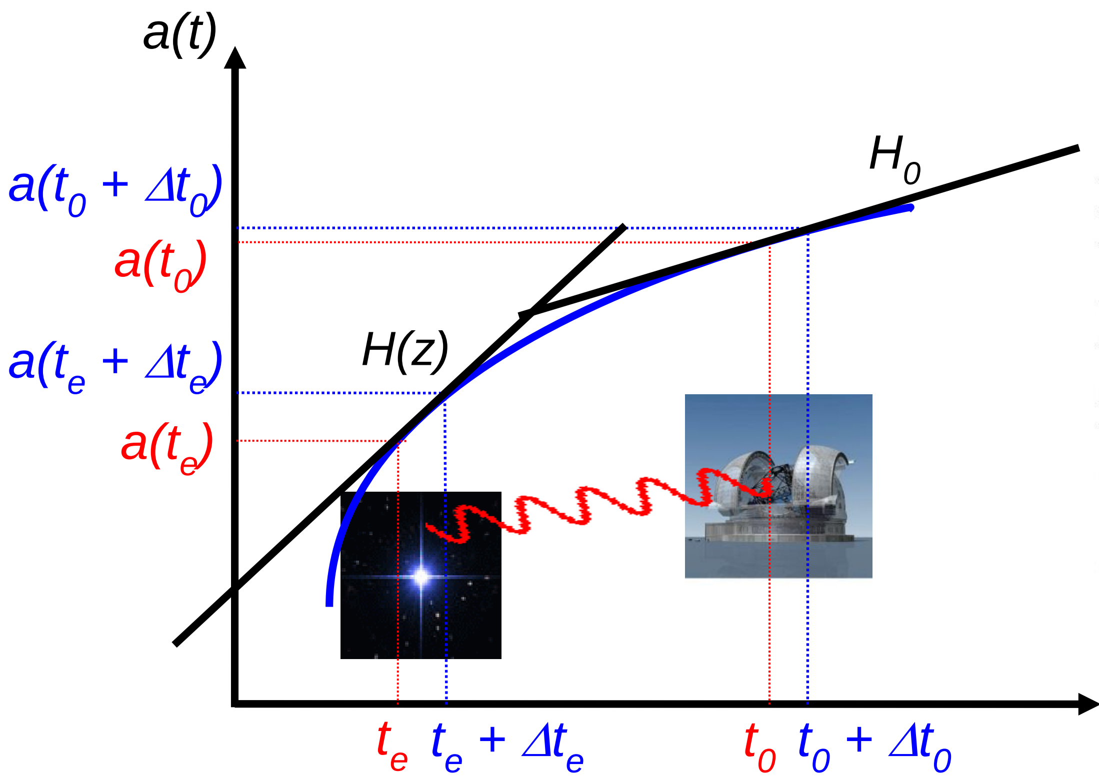
$$H^2(z) = H_o^2\left[(\Omega_b + \Omega_{DM})(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\Lambda\right]$$

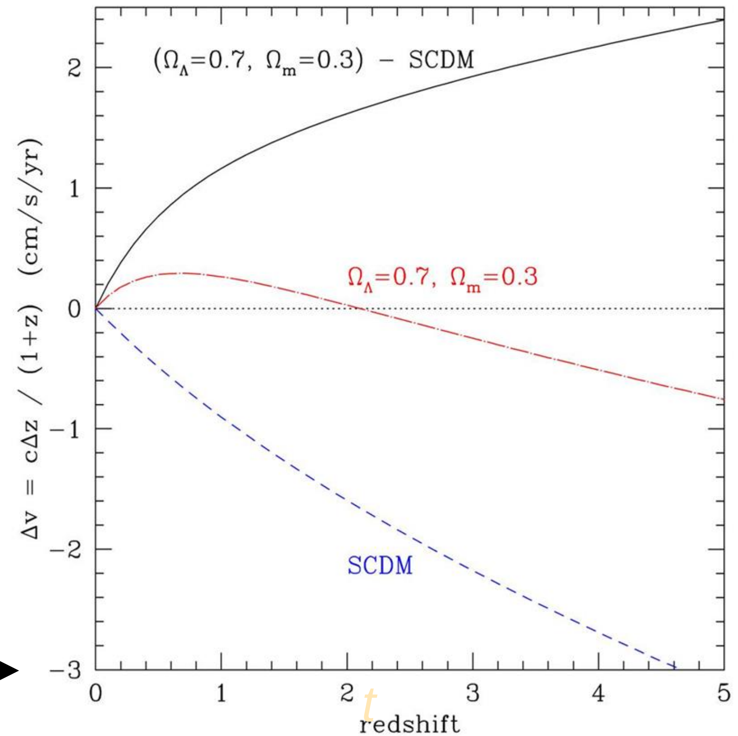
$$\Omega_m = \Omega_b + \Omega_{DM} \simeq 0.31 \quad \Omega_k \sim 0 \;\; \text{(flat space)} \quad \Omega_\Lambda \simeq 0.69$$

$$H_o \simeq 68 \; km/s/Mpc$$

**We do not know what $\Omega_\lambda$ is and how it evolves.**
**Dynamics has never been measured.**
All other experiments, extremely successful such as **High Z SNe search and Planck** measure geometry: dimming of magnitudes and scattering at the recombination surface and clustering (growth of structure).

# Testing General Relativity
# Dynamics: measuring a(t) ← H(z)

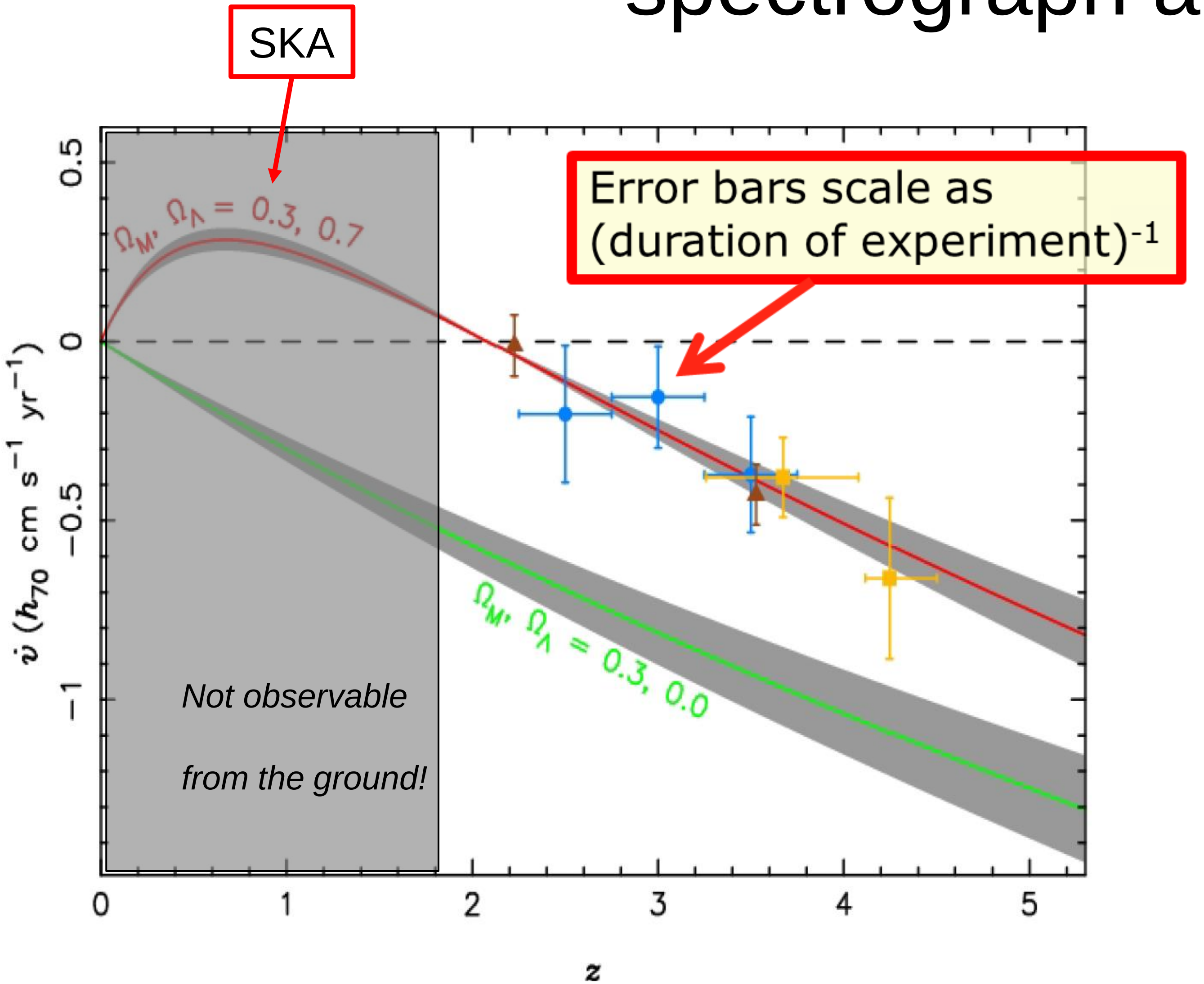



$$\frac{z(t_0+\Delta t_0) - z(t_0)}{\Delta t_0} = \frac{\Delta z}{\Delta t_o} \simeq \frac{dz}{dt_o} = (1+z)\; H_o - H(z)$$

**Sandage Test**
**Cosmic Expansion**

# Feasibility Test with a Rs~$10^5$ spectrograph at the E-ELT




- Different coloured points reflect different targeting strategies
- 4000 hrs on 39-m E-ELT over 21.5 years, *or*
- 1200 hrs on 39-m E-ELT over 40 years

*Pasquini et al. 2005, Liske et al. 2008*

# The QSO Deep Spectrum (UVES)

SC (PI), P. Barai, G. Cupani, V. D'Odorico, F. Fontanot, T.-S. Kim, E. Pomante, M. Viel: INAF-Trieste

G.D. Becker, R.F. Carswell, M.G. Haehnelt: IoA Cambridge

F. Calura, E. Vanzella: INAF-Bologna

J. Miralda-Escude: Universitat de Barcelona

E. Tescari: University of Melbourne

1. Title Category: **A–7**

*Hic sunt Leones*: an ultra-deep quasar spectrum to explore the low-density Universe.

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2. Abstract / Total Time Requested

Total Amount of Time: 0 nights VM, 43 hours SM

We propose to obtain an ultra-deep spectrum of the brightest quasar at $z \sim 3$ accessible from Paranal, HE 0940-1050 ($z_{em} = 3.09$, $V_{mag} = 16.9$), reaching a S/N of $\sim$ 500, 300 and 200 per resolution element in the C IV, Ly-$\alpha$ and O VI forests, respectively (after coadding to the $\sim$ 7h of observation already in the UVES archive). Pushing the spectroscopy of the IGM to unprecedented limits will open new possibilities in several fields: we will extend in particular the measurements of the metal content and the temperature of the IGM to low densities, providing key insight into the epoch and mechanisms of enrichment and significant clues for the understanding of the physics of galactic winds. The temperature measurements will allow us to directly investigate the helium reionization and other possible heating sources of the intergalactic medium, as well as to calibrate out the largest systematic uncertainty in the use of the Ly-$\alpha$ forest as a precision cosmological probe.

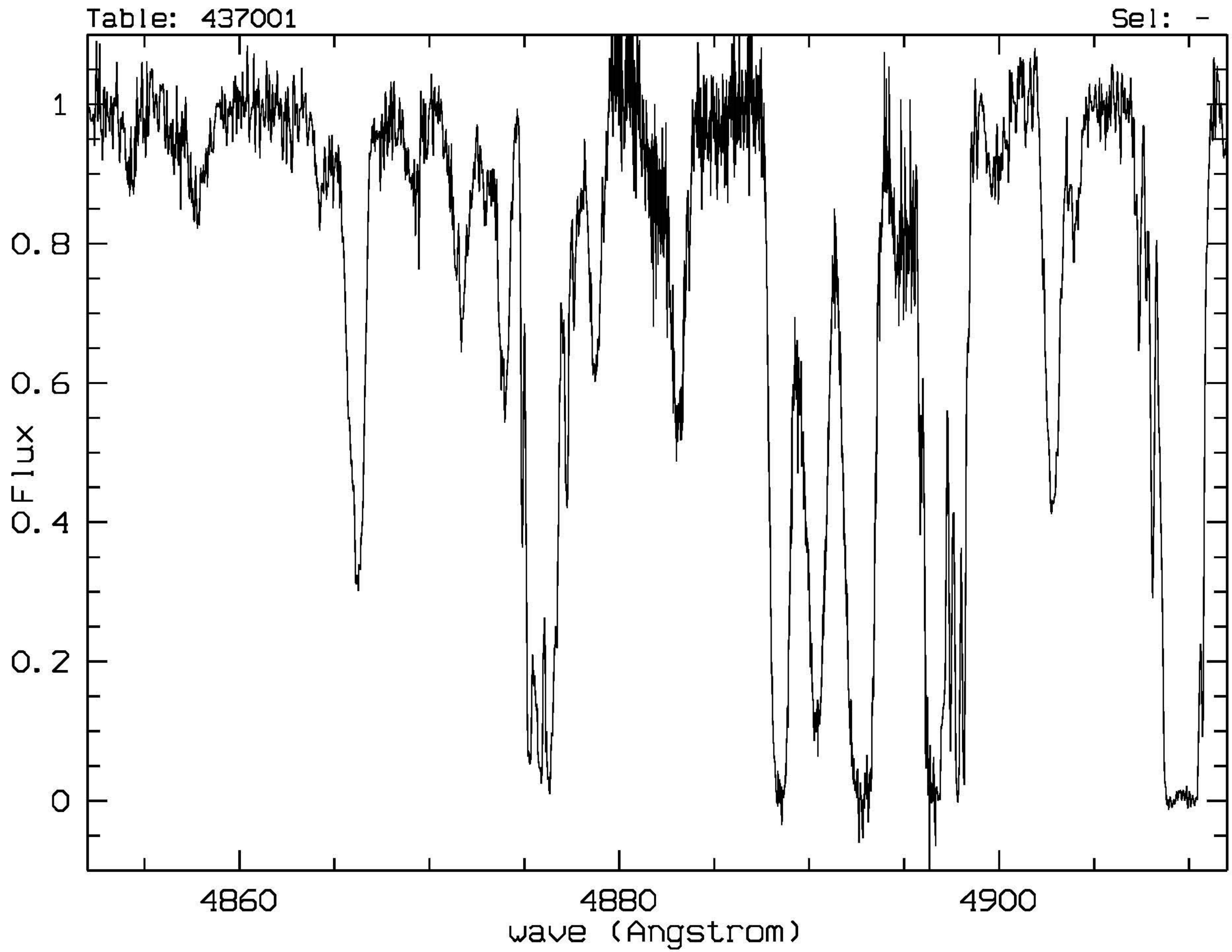
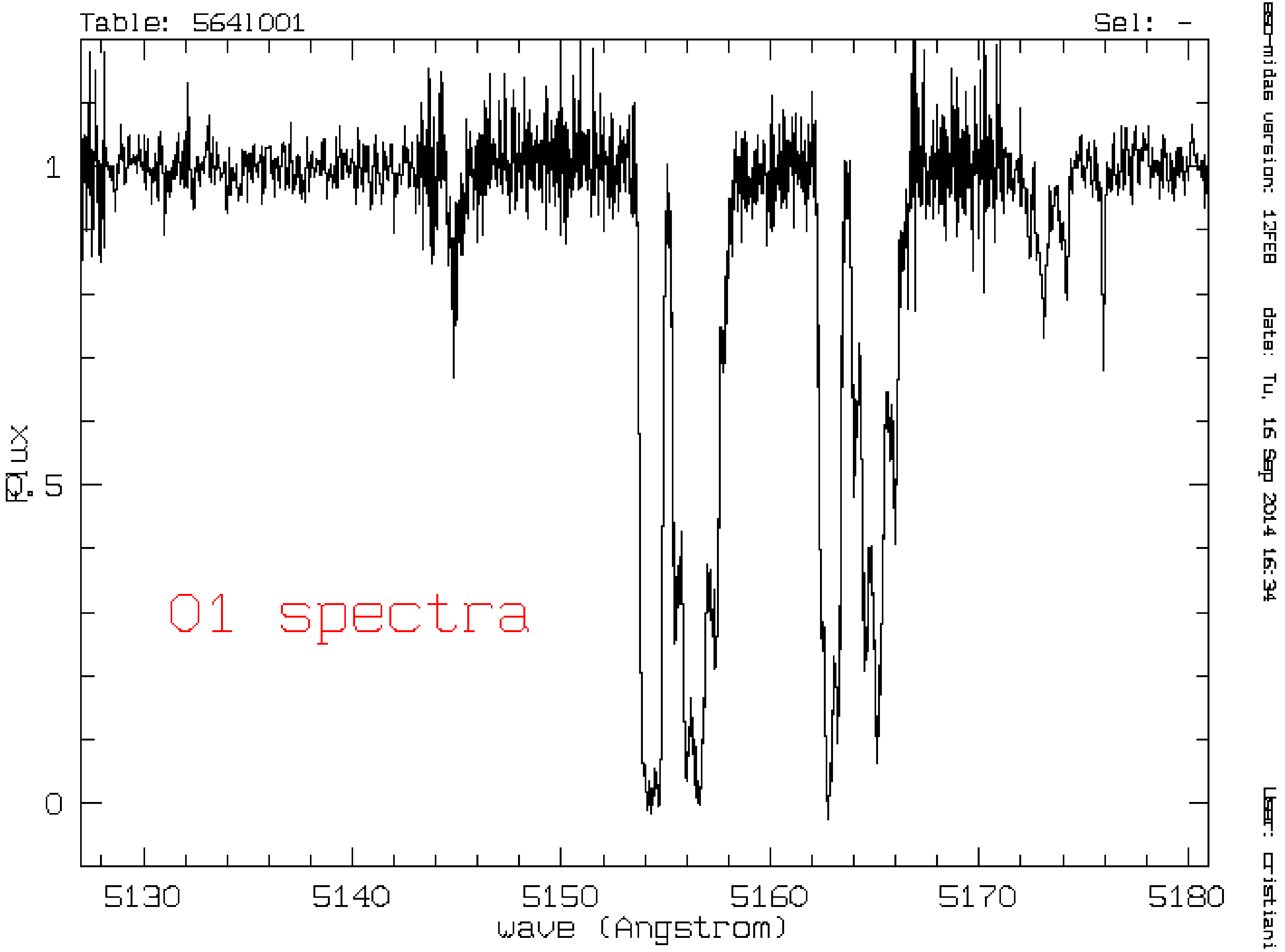


Table: 437001
Sel: -
1
0.8
0.6
0.4
0.2
0
OFlux
4860
4880
4900
wave (Angstrom)




Final s/n = 460 ~sqrt(t) scaling

# Dt ~ 10 yr

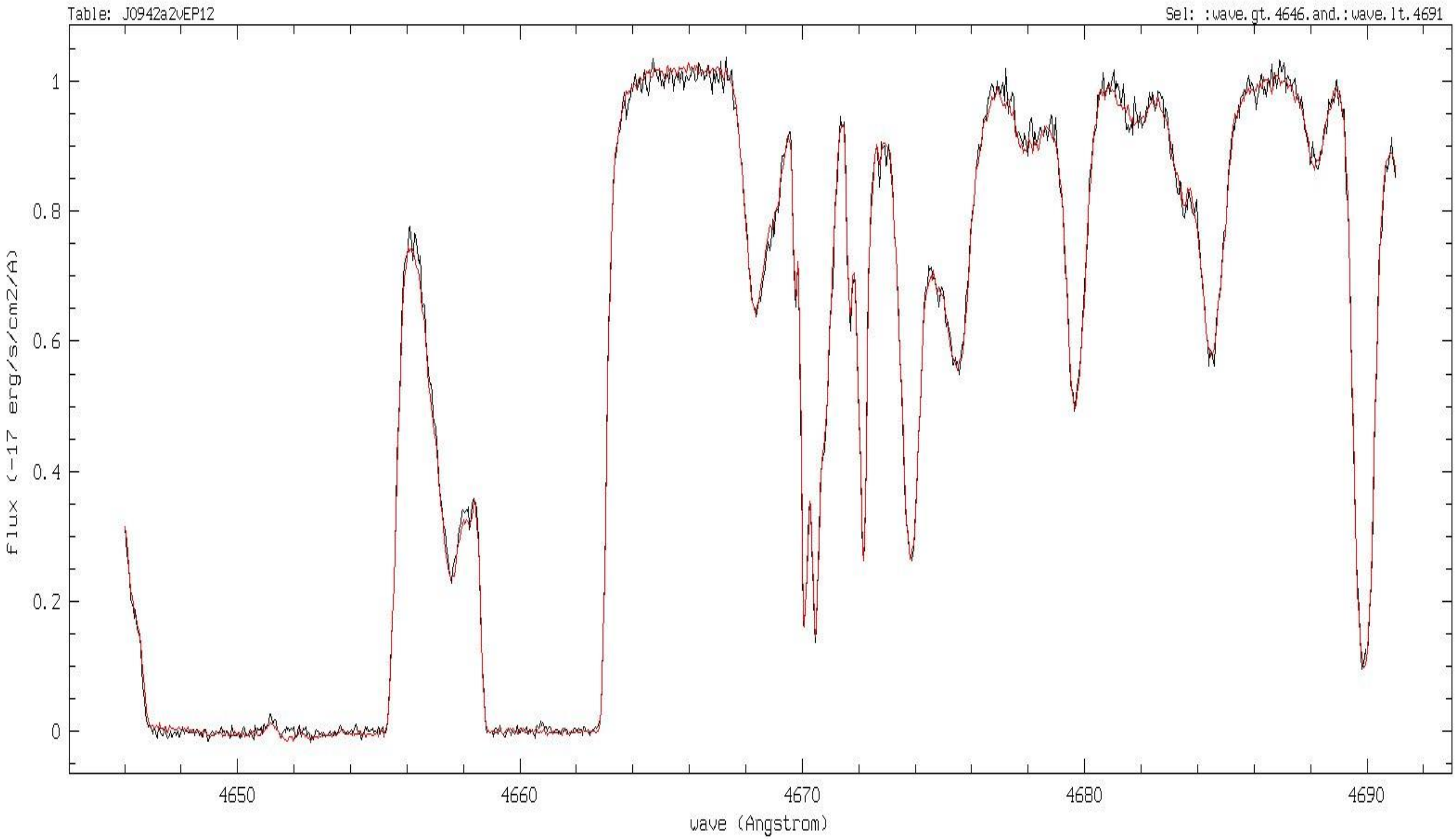
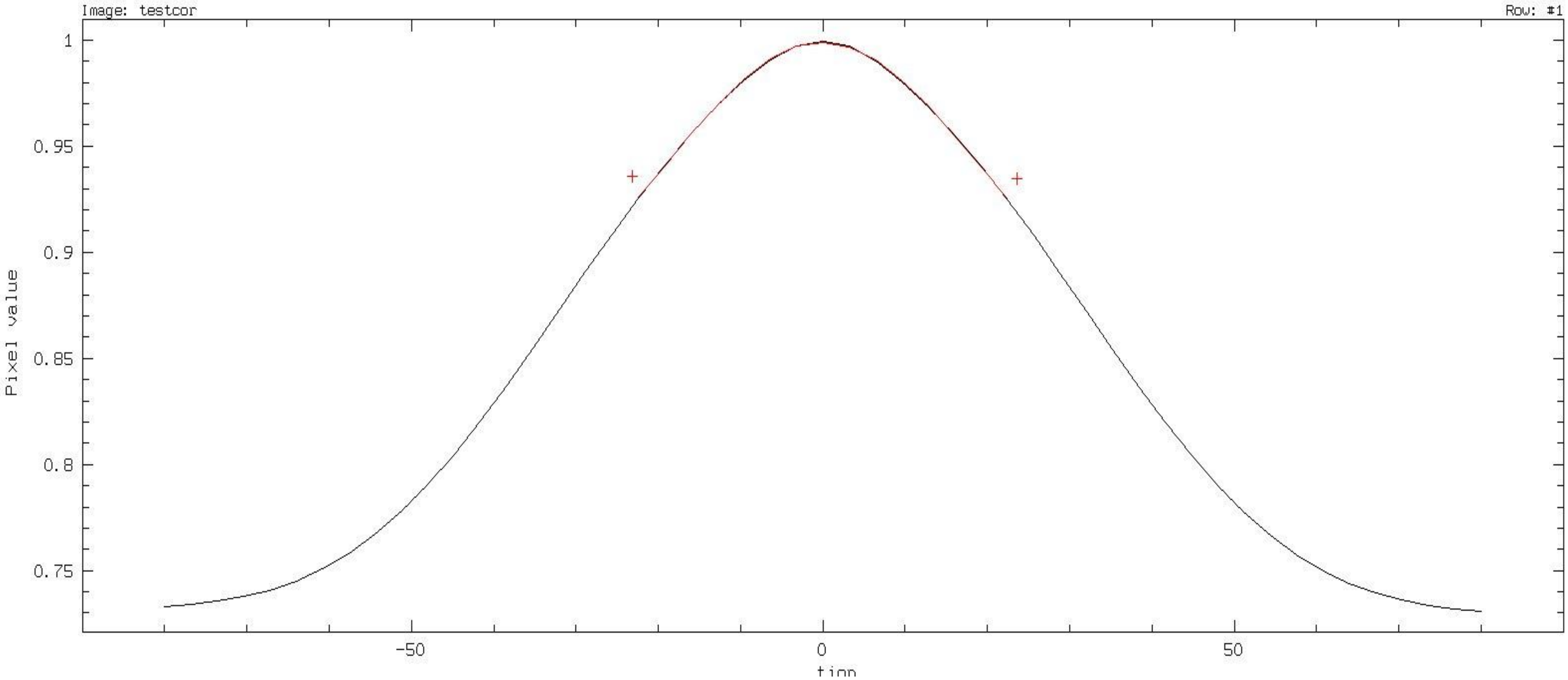


Table: J0942a2vEP12
Sel: :wave.gt.4646.and.:wave.lt.4691
flux (-17 erg/s/cm2/A)
0
0.2
0.4
0.6
0.8
1
4650
4660
4670
4680
4690
wave (Angstrom)

# Dv <~ few x 10 m/s

(cfr. Darling 2012 @ 21cm)



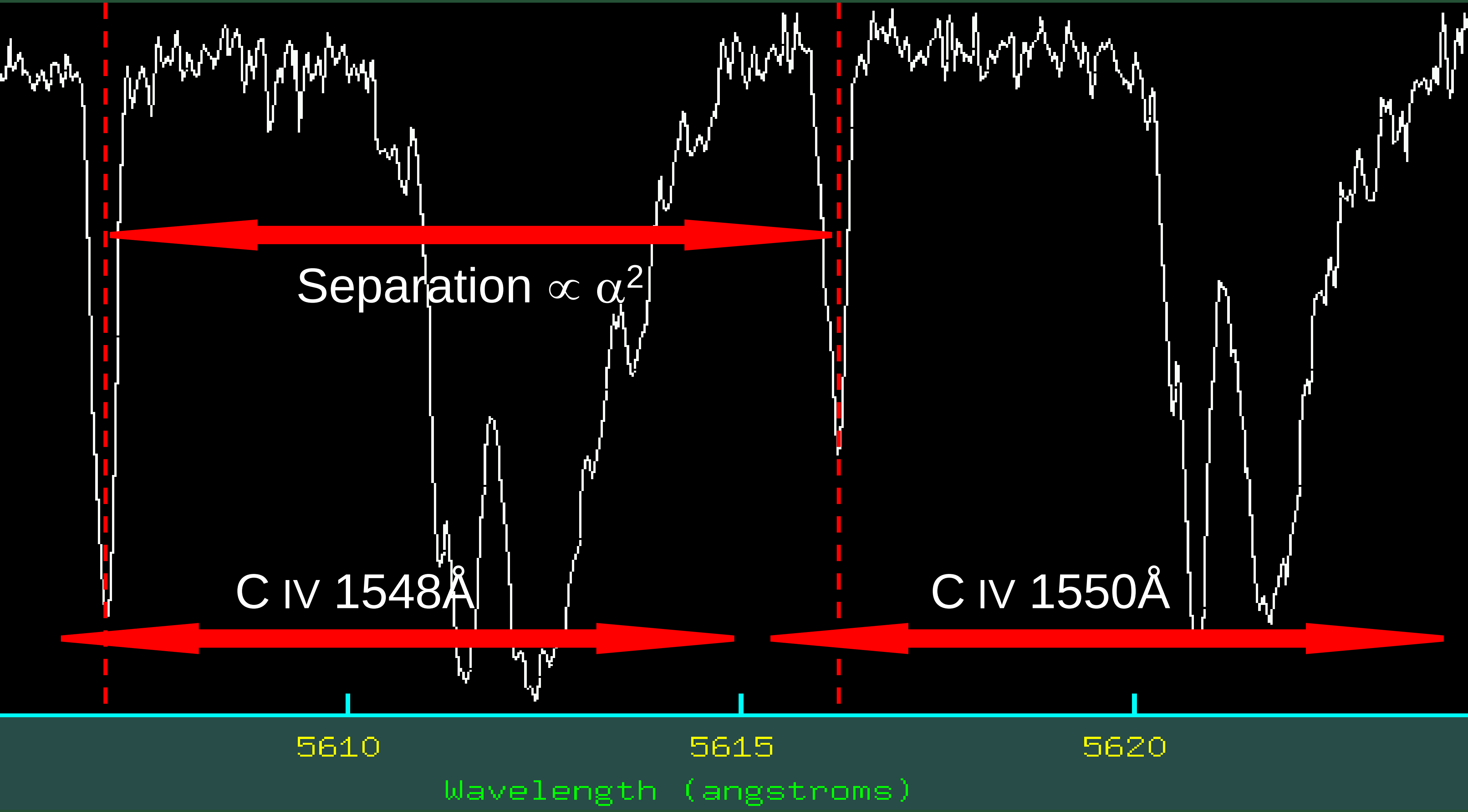
# Fundamental? Constants?:

*See Murphy ESO 50yrs*

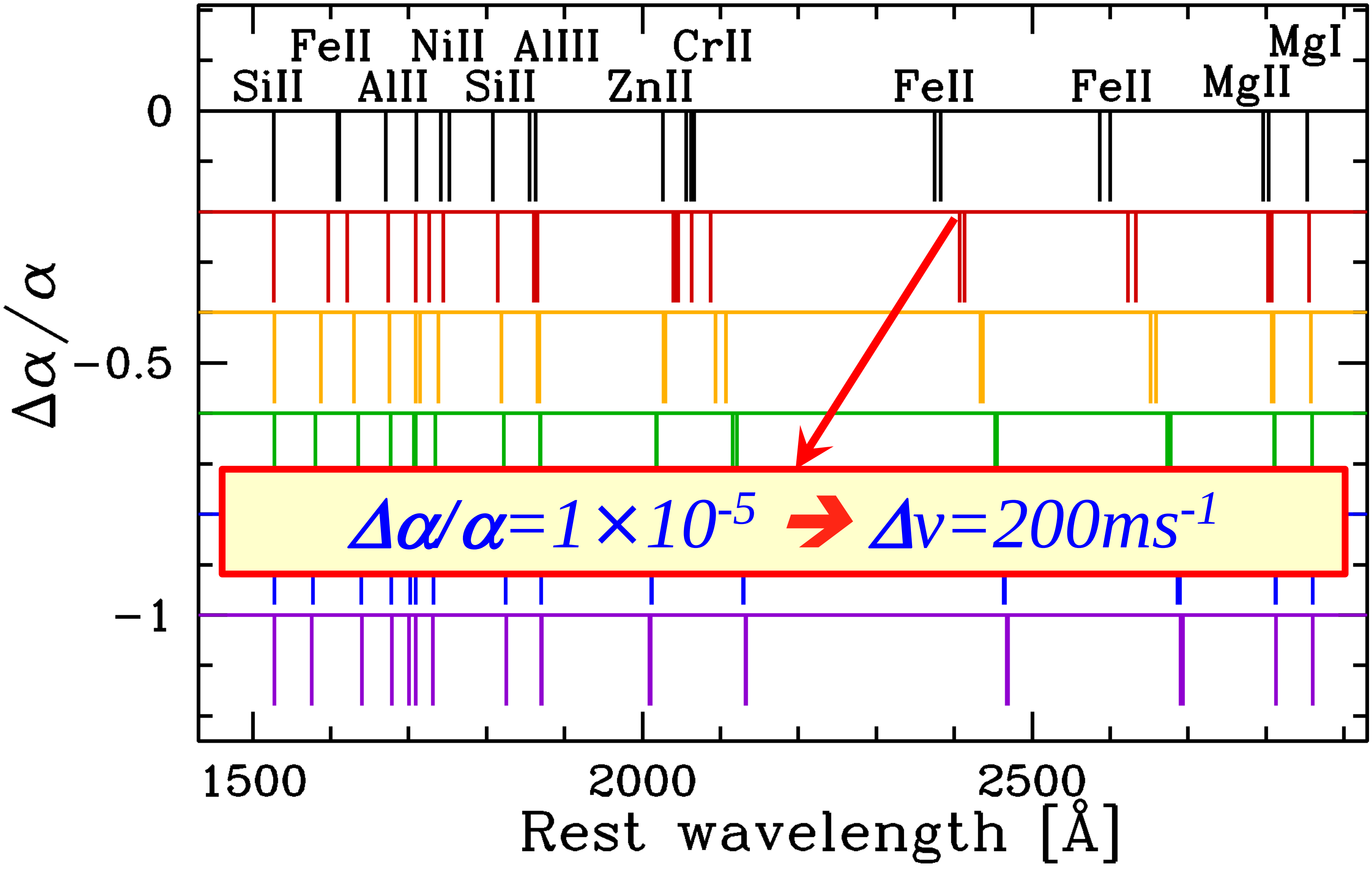
- *[Note: Only low-energy limits of constants discussed here]*
- *Why "fundamental"?*
  - *Cannot be calculated within Standard Model*
- *Why "constant"?*
  - *Because we don't see them changing*
  - *No theoretical reason – see above*
- *Best of physics: Relative stability of $\alpha \sim 10^{-17}\,yr^{-1}$ (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*

# Variation of fundamental constants (α):

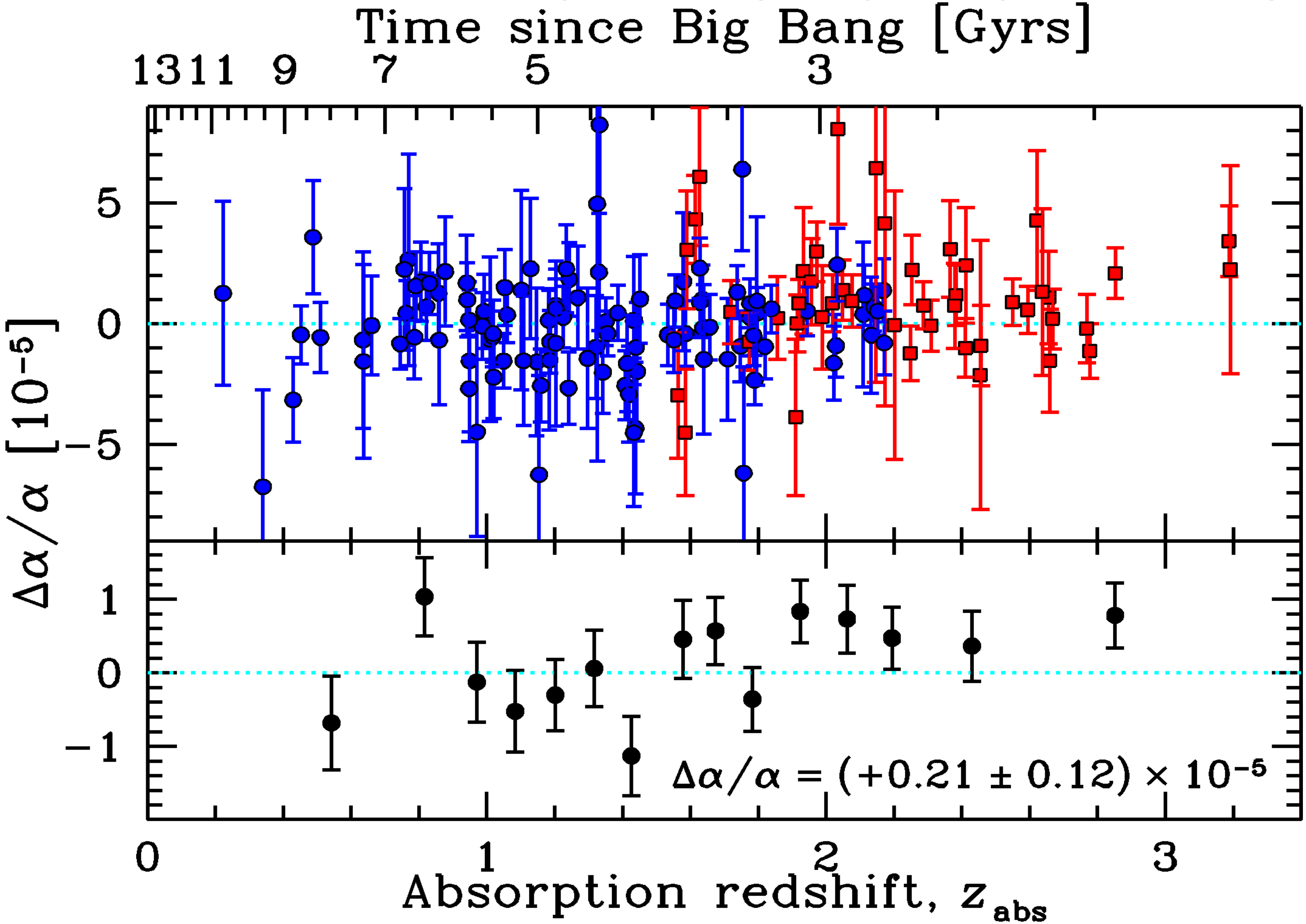


# The Many Multiplet (MM) method:



# 153 VLT/UVES absorbers:

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



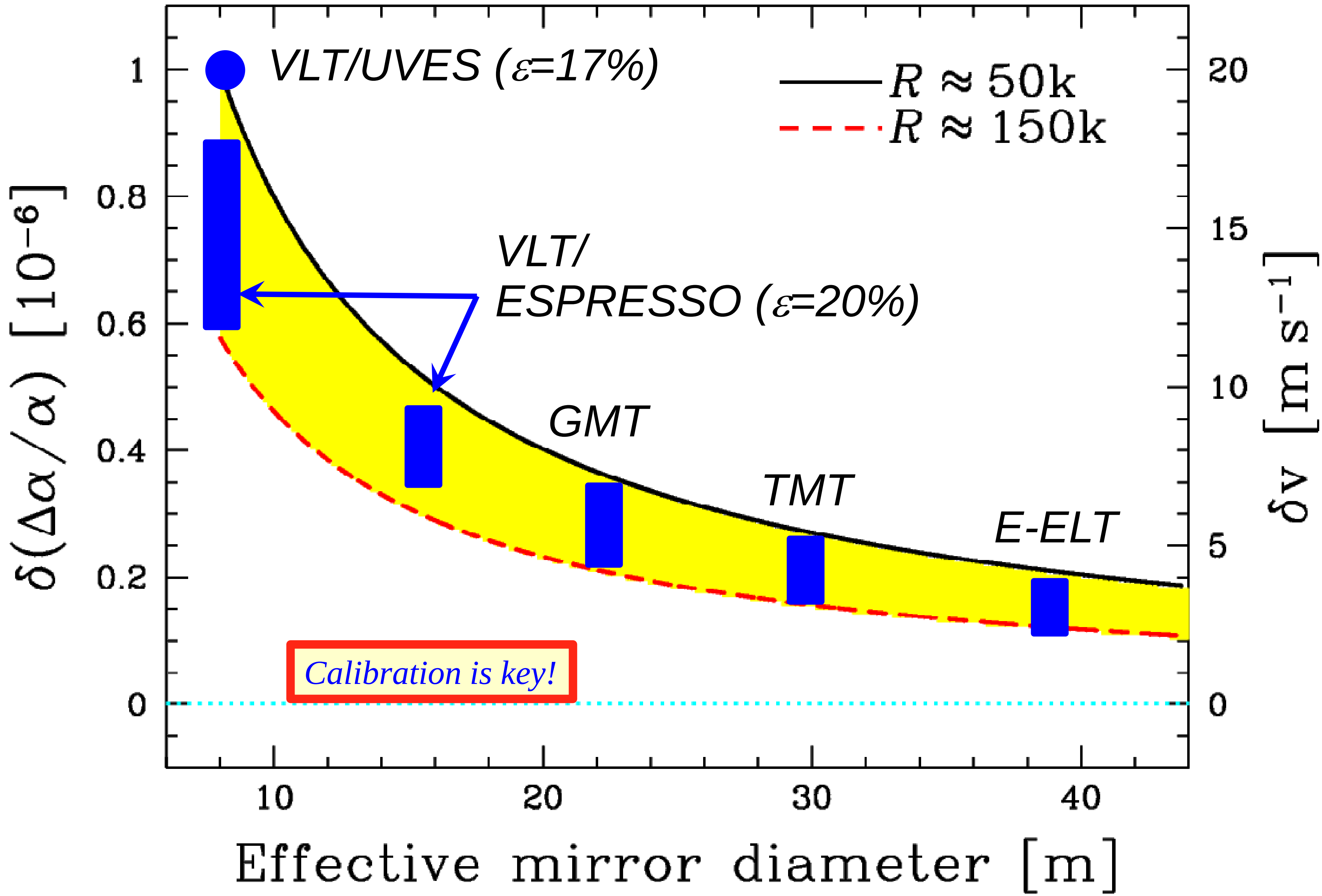
# What if it's correct?:

- *ELTs MUST confirm it!*
- *ELTs MUST characterize variation accurately:*
  - *Does $\alpha$ depend on redshift, density, [other]?*
  - *What are the astrophysical systematics?*

# *What if it's incorrect?:*

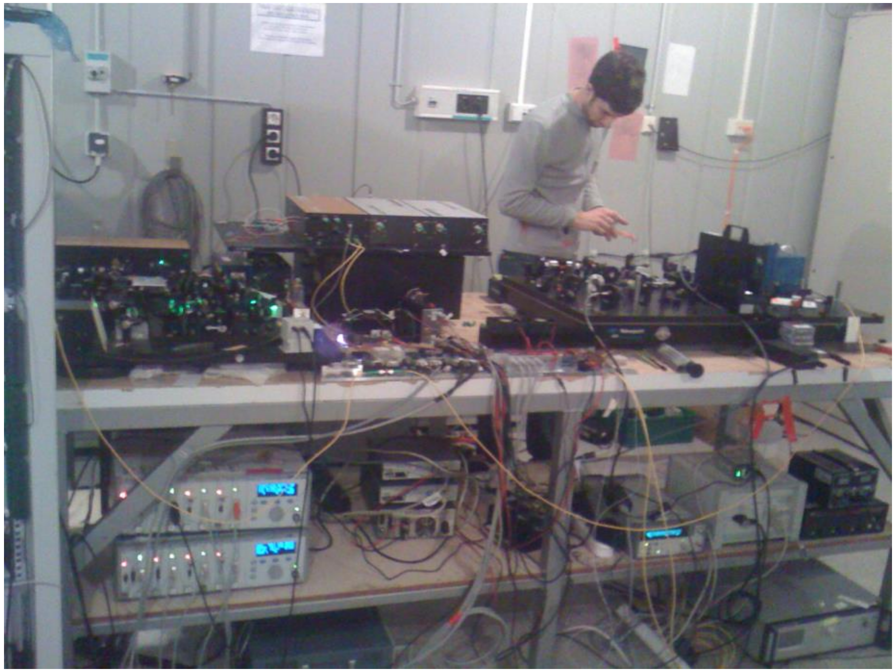
- *VLT/ESPRESSO refutes it*
- *Motivation for new measurements same as now*
- *E-ELT obtains best possible constraints*
- *E-ELT finds new, real effect?*

# Precision from future instruments:

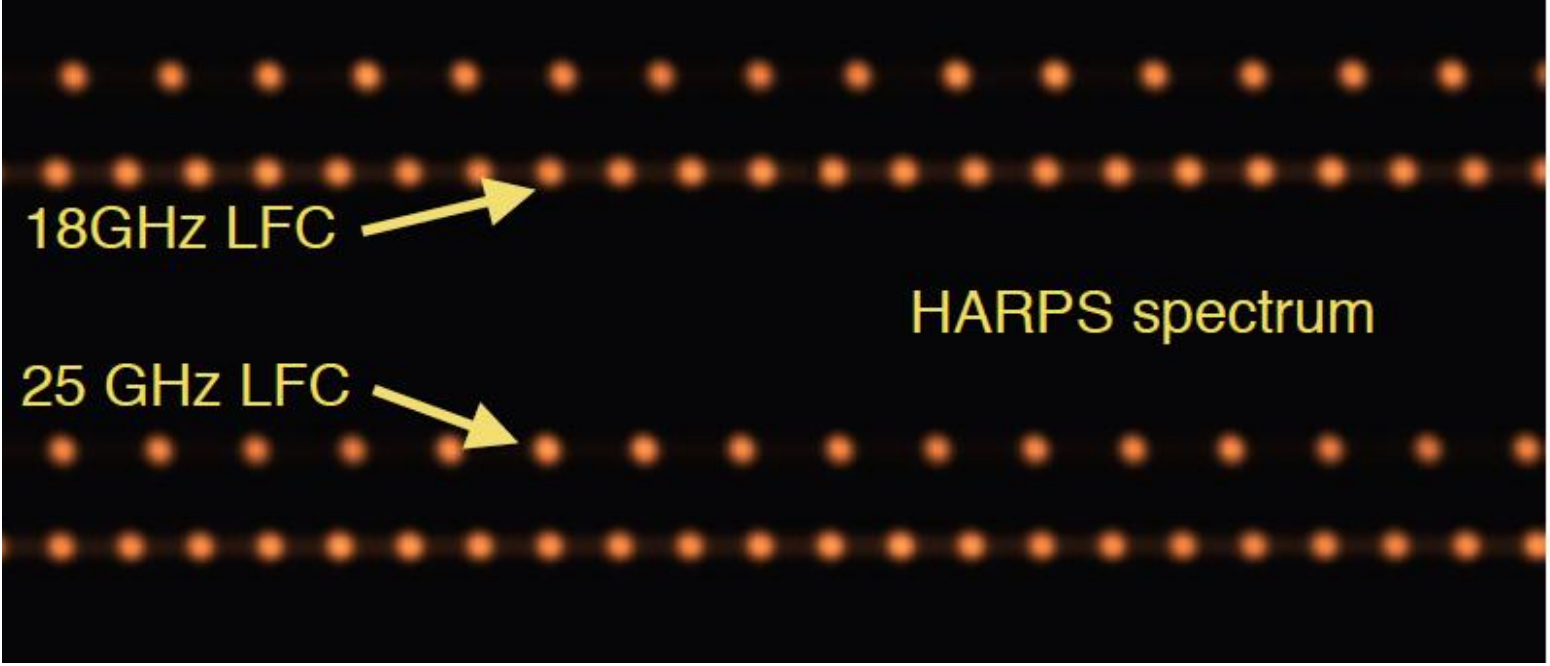


# Laser Frequency Comb for HARPS

The good old times…
(March 2010)



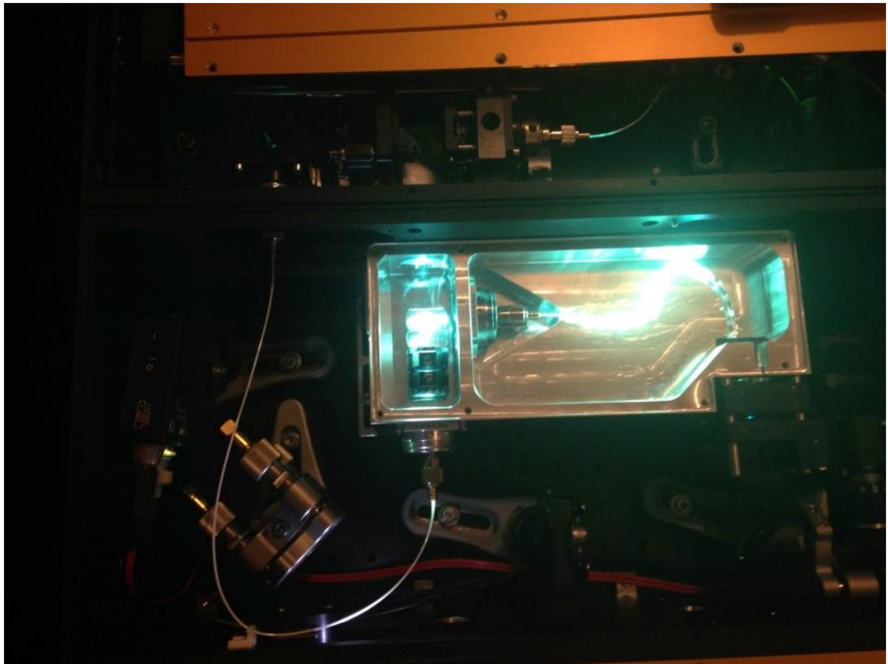
The re-engineered system
(April 2015)



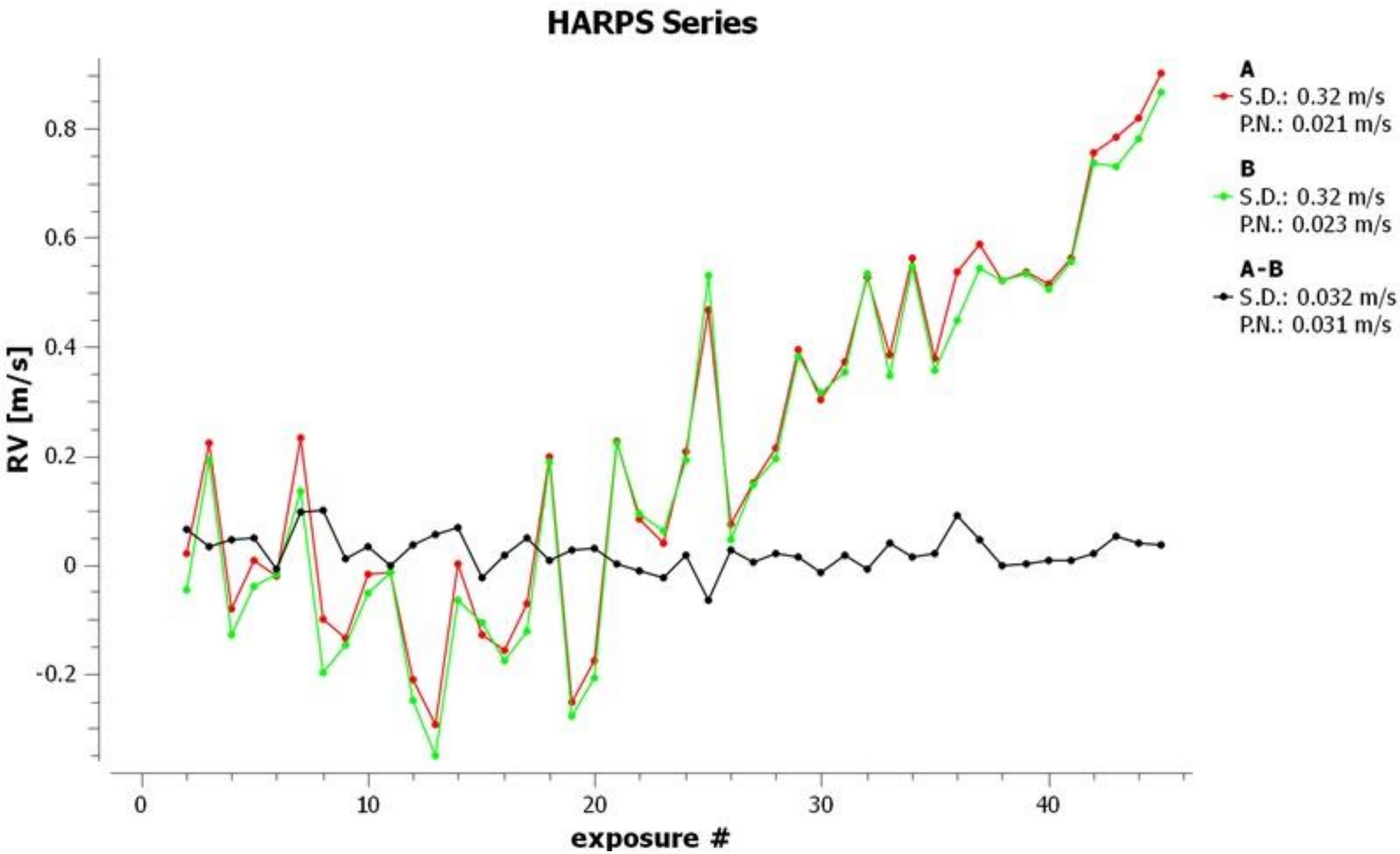

Tests with two LFCs:

- Fully independent systems
- Test precision AND accuracy

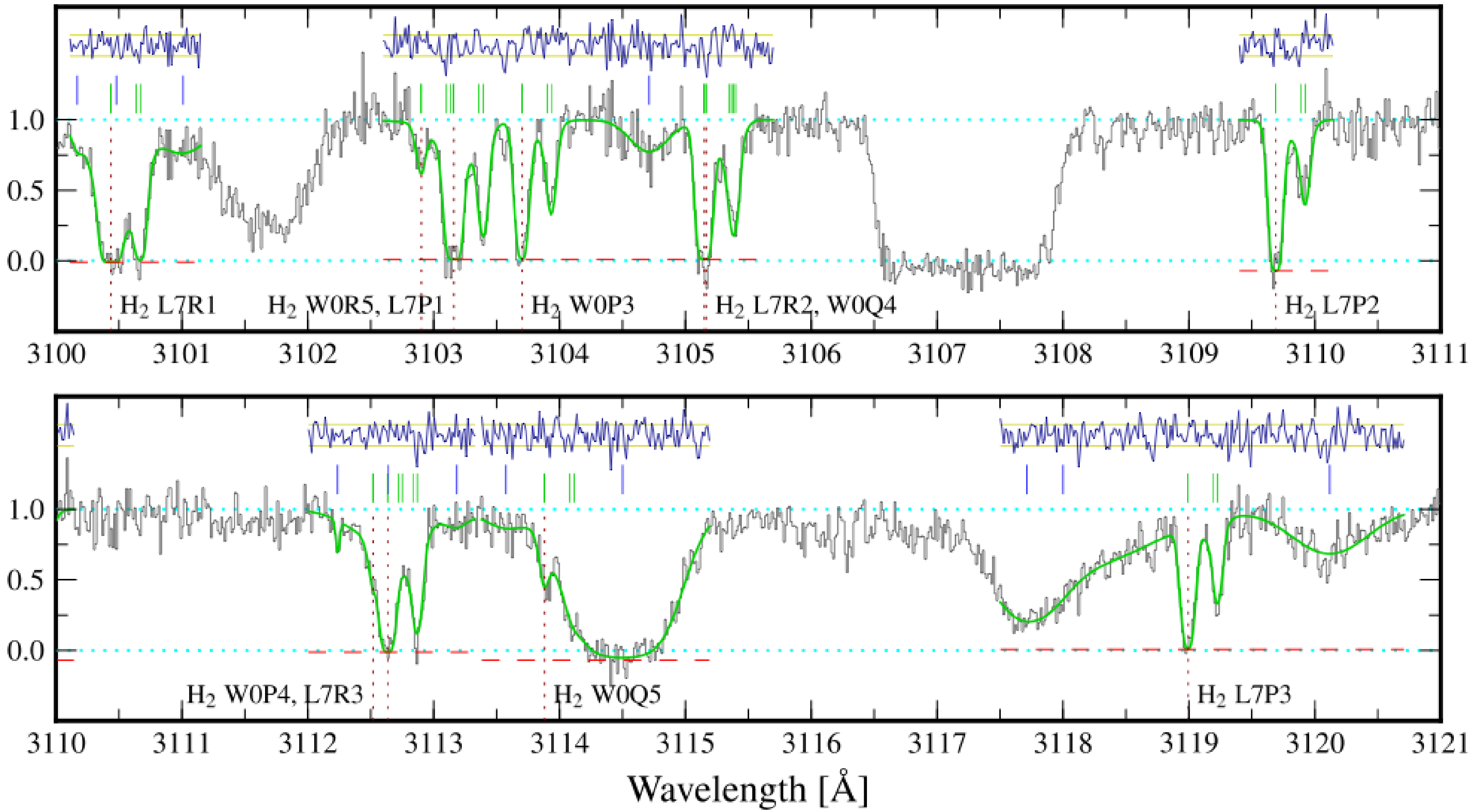
PCF fiber inside its housing
For increased stability and
easier replacement..



Two combs relative drift scatter comparable to photon noise (~2 cm/s)



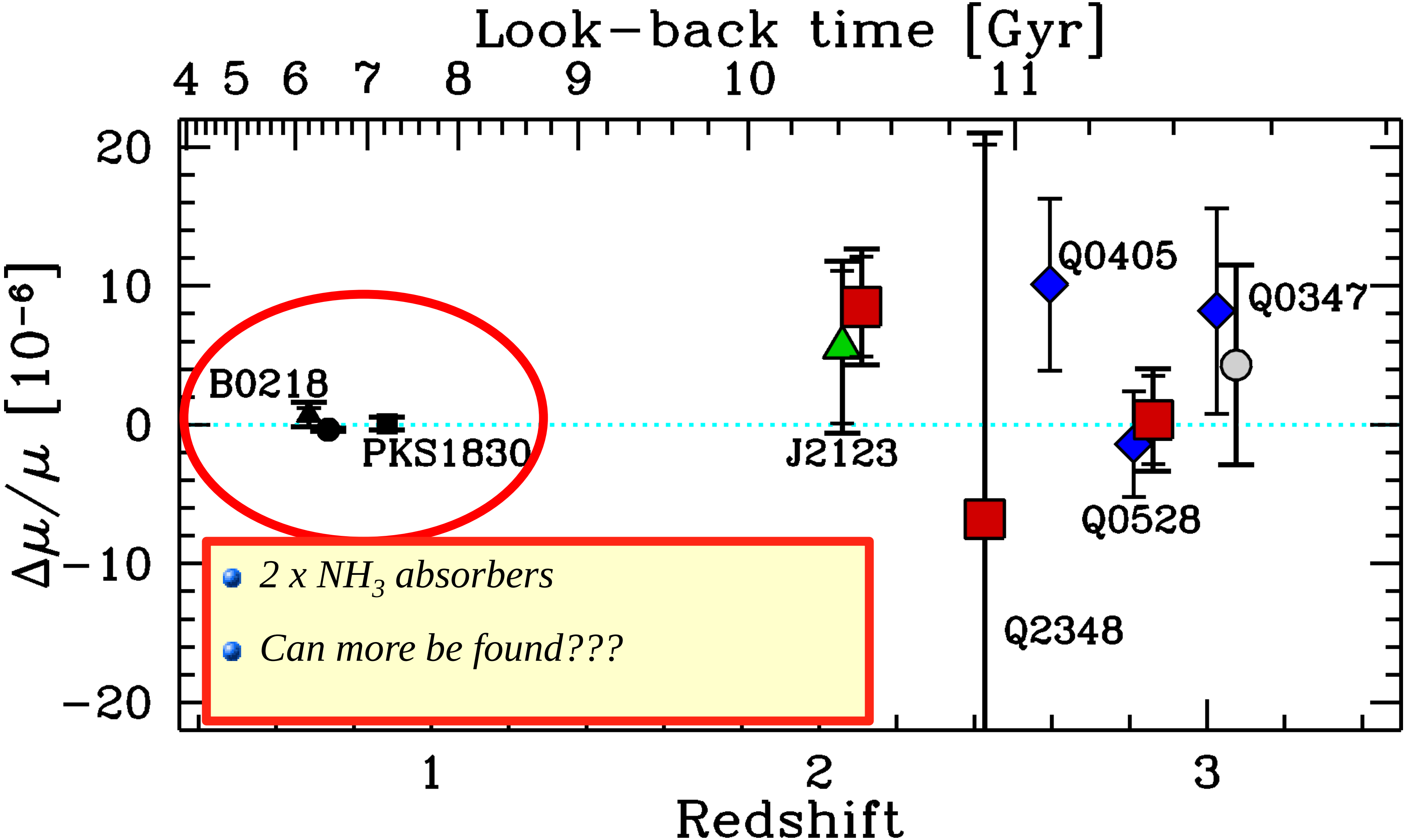
# $H_2$ constraints on $\Delta\mu/\mu$:




J2123-0050

*Malec et al. (MNRAS, 2010)*

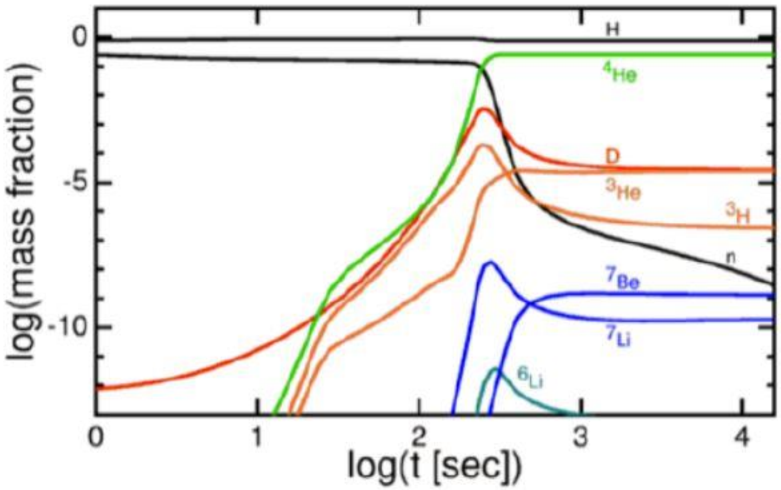
# Extragalactic values of Δμ/μ:

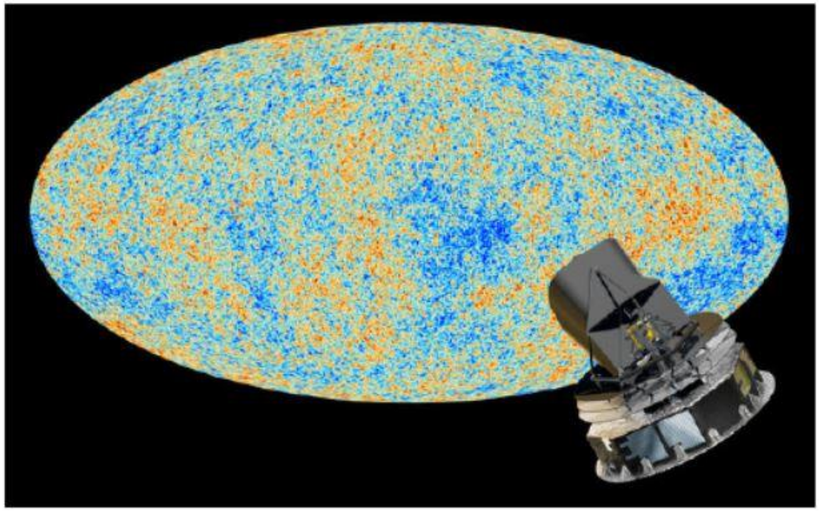


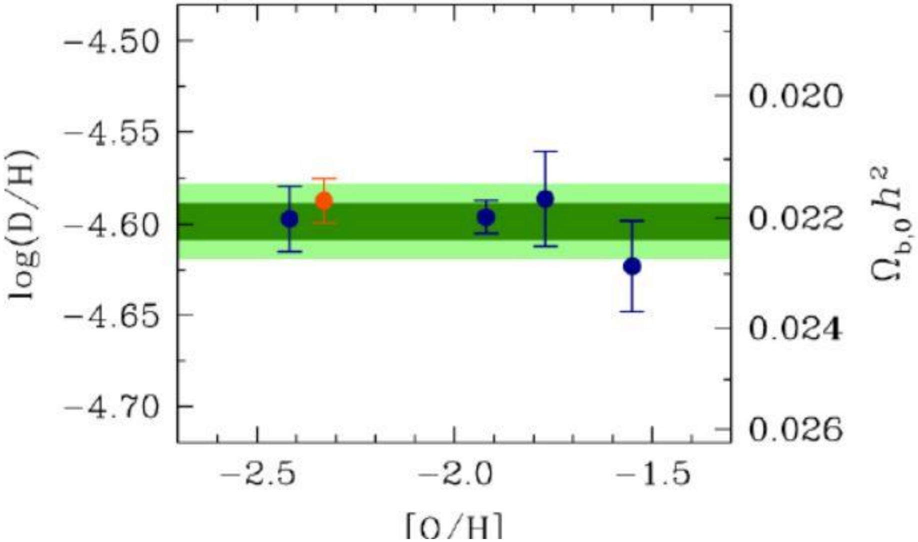

- *2 x $NH_3$ absorbers*
- *Can more be found???*

$H_2$: 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).
NH3: Murphy et al. (Science, 2008), Henkel et al. (A&A, 2009), Kanekar (ApJL, 2011).

# Primordial Deuterium



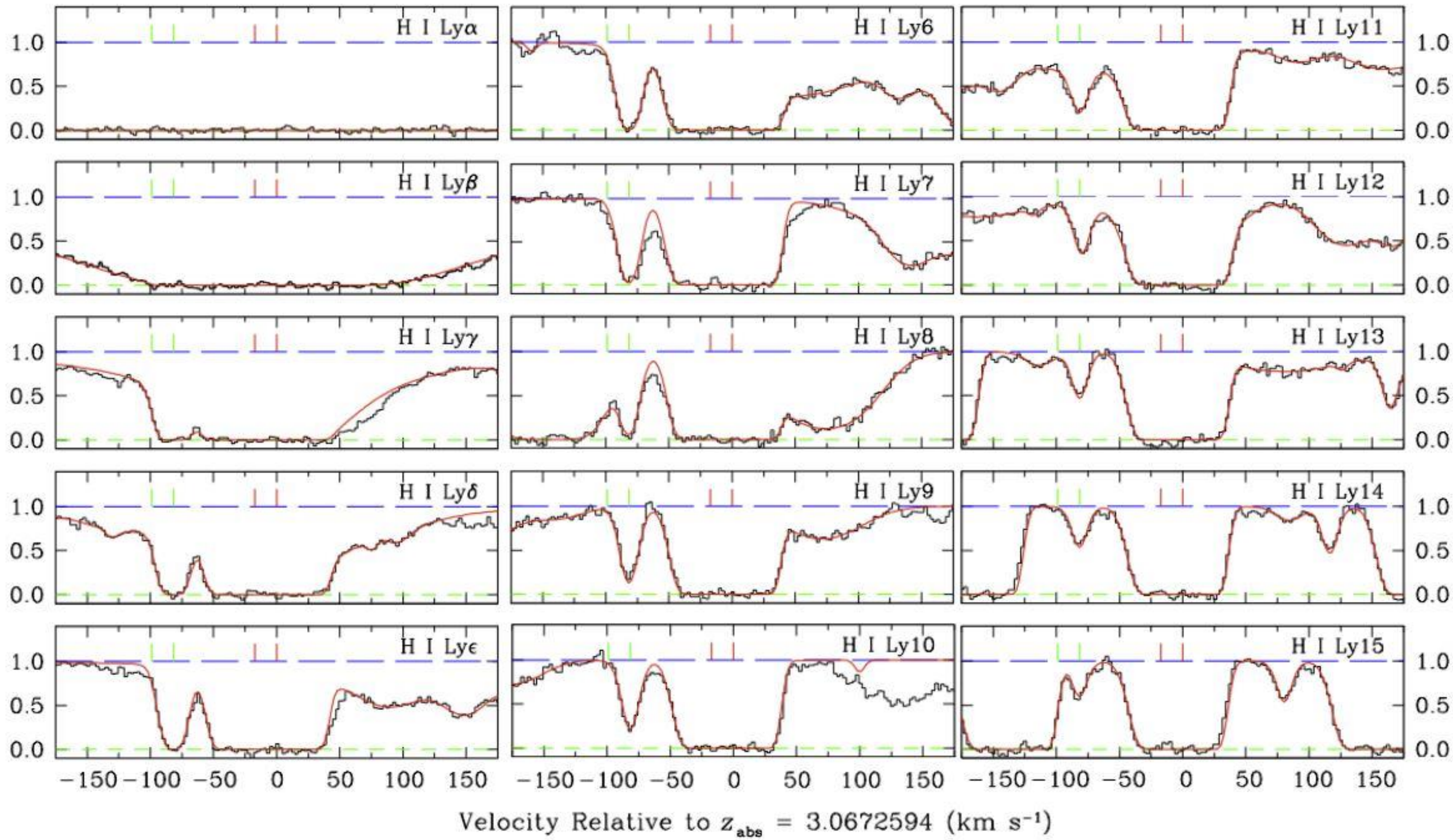





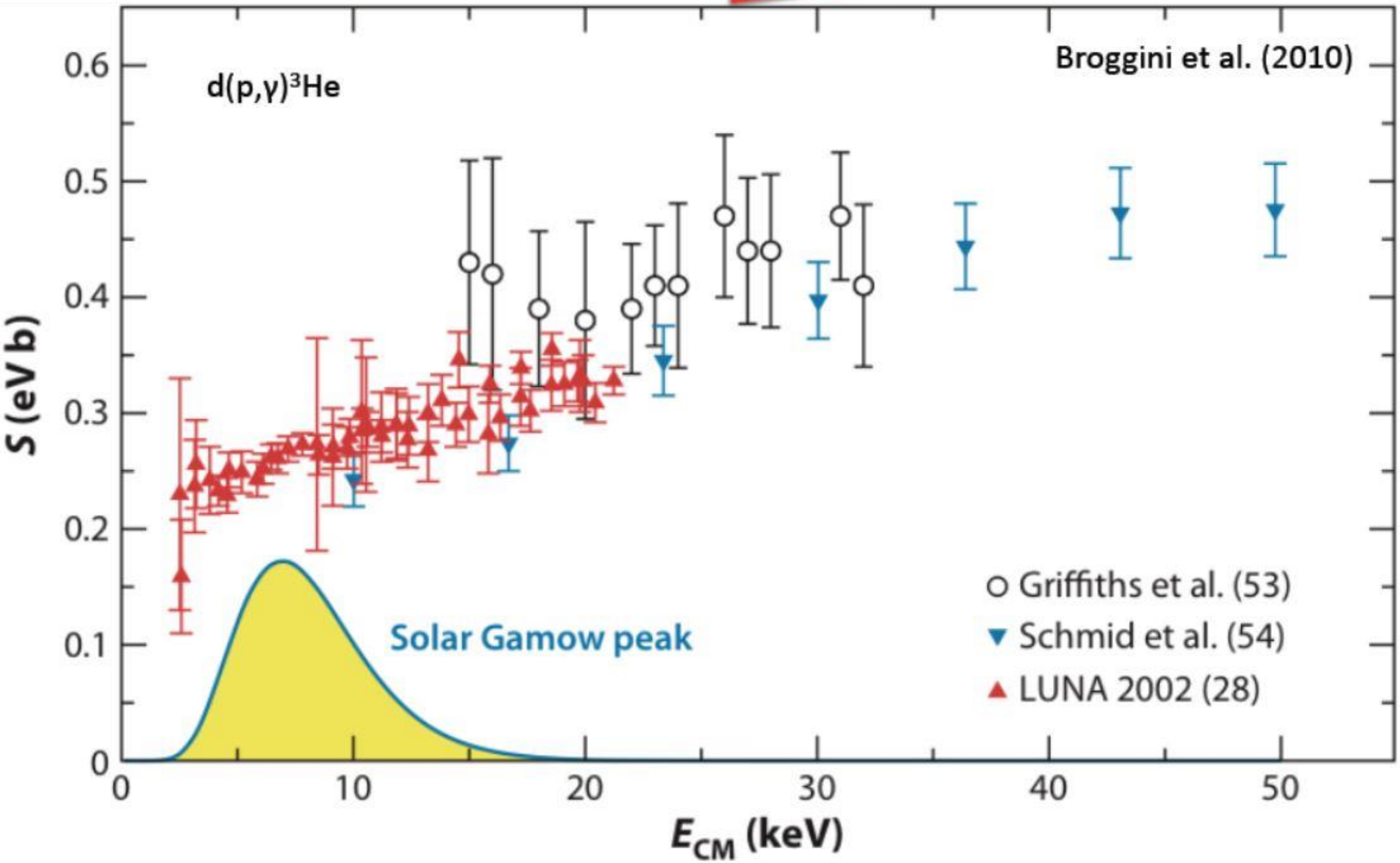

Cooke et al. (2014)
ApJ, 781, 31

# How to observe D/H:
# QSO absorption spectroscopy

Cooke et al. (2014) ApJ, 781, 31



# The current limitation: ~~nuclear reactions~~ Small sample size



# TLR caveat for D

no UV → z>3

z>3 → line crowding complication

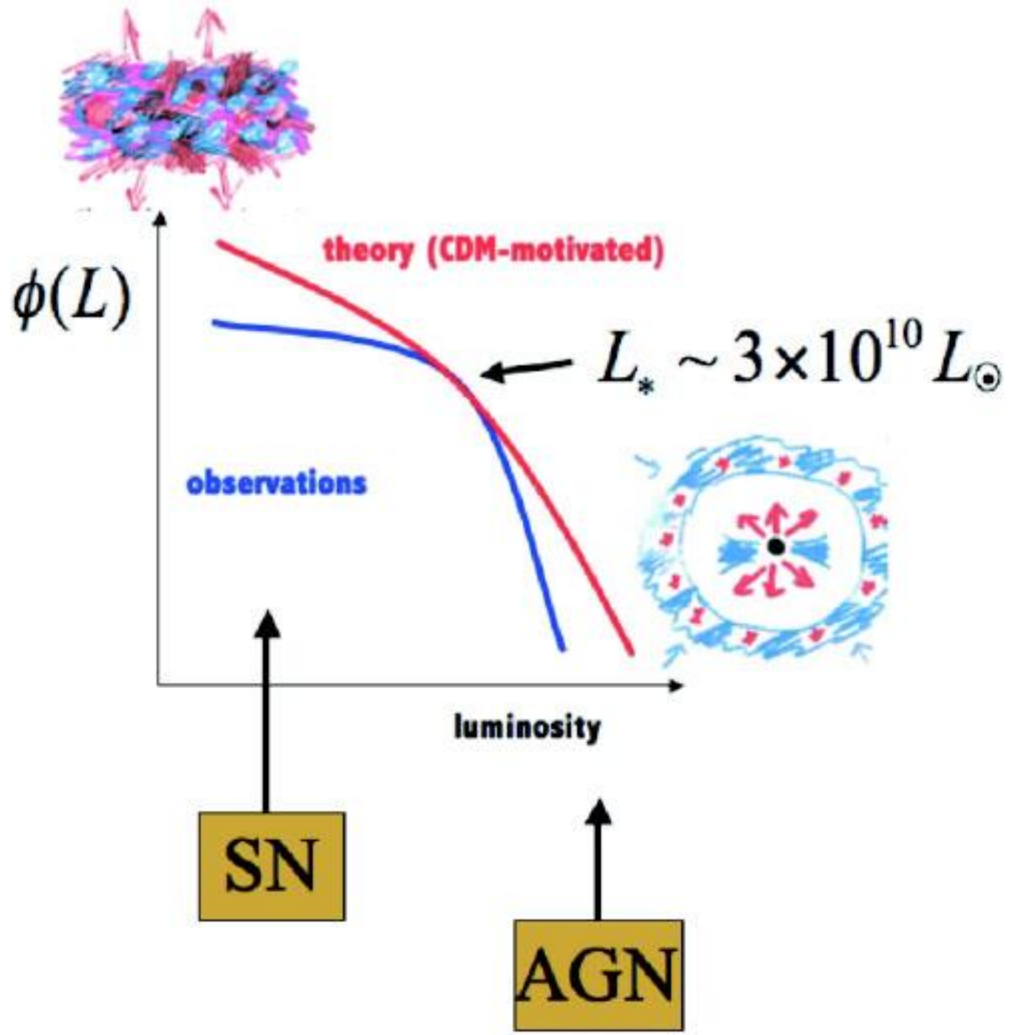
Over the past twenty years our understanding of the Cosmic Web has advanced considerably

temperature, metallicity, kinematics, radiation field, dependence on the underlying cosmological parameters

as a function of **time, spatial scale, density**

# FEEDBACK: the Grail of the last two decades

shapes galaxies,
star formation
history



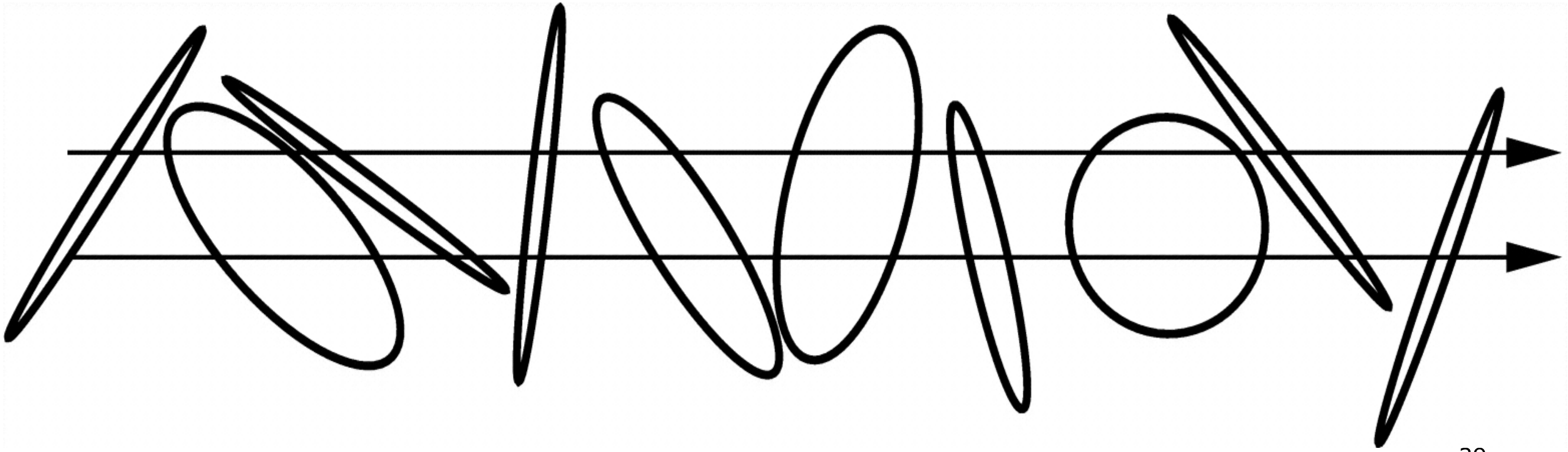
Outflows, winds, superwinds(?)

What can HIRES do more/better?

Fidelity, depth (surface density of targets within reach), resolution

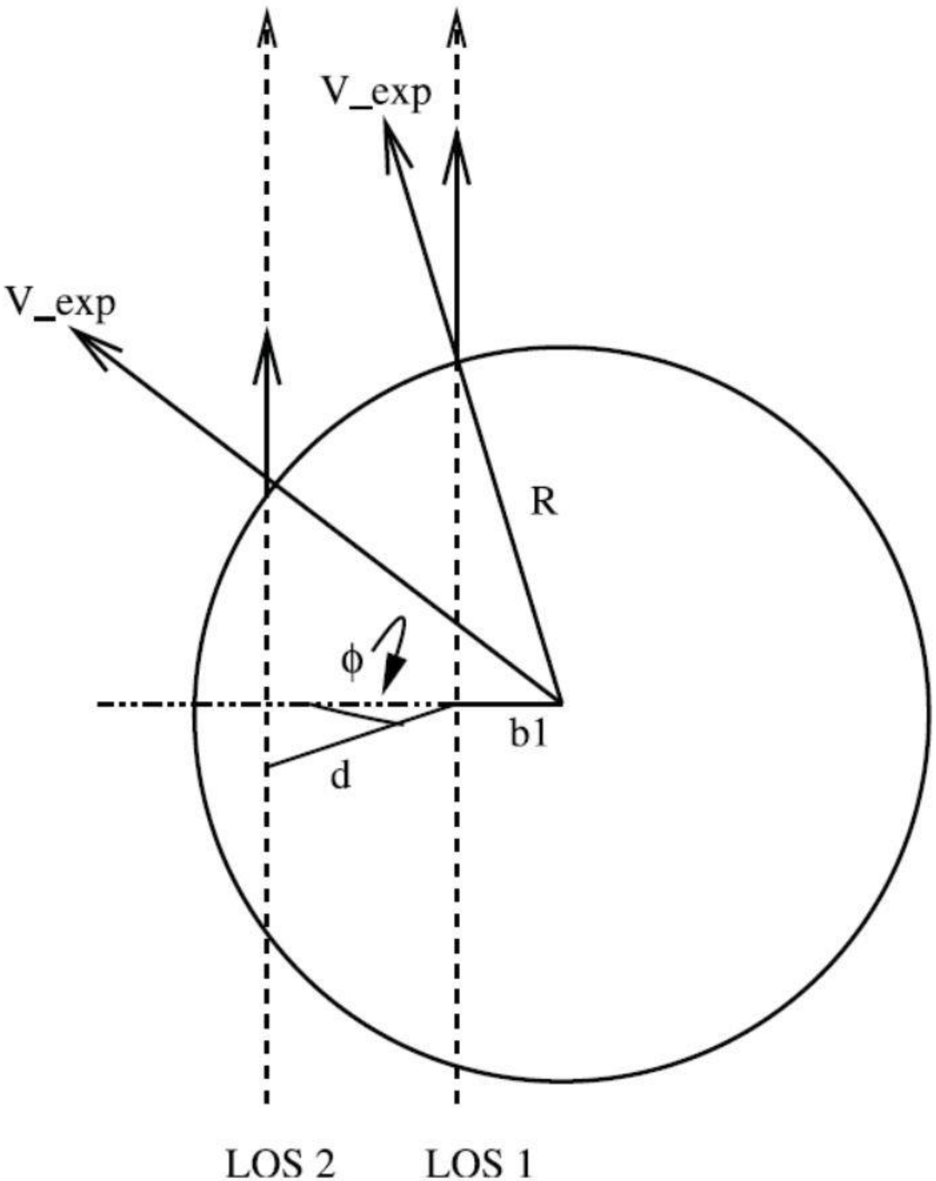
ex. spatial distribution of metals (V.D'Odorico's talk)

# Effects of the winds (entrainment vs outflows/infalls/expansion) as a function of space

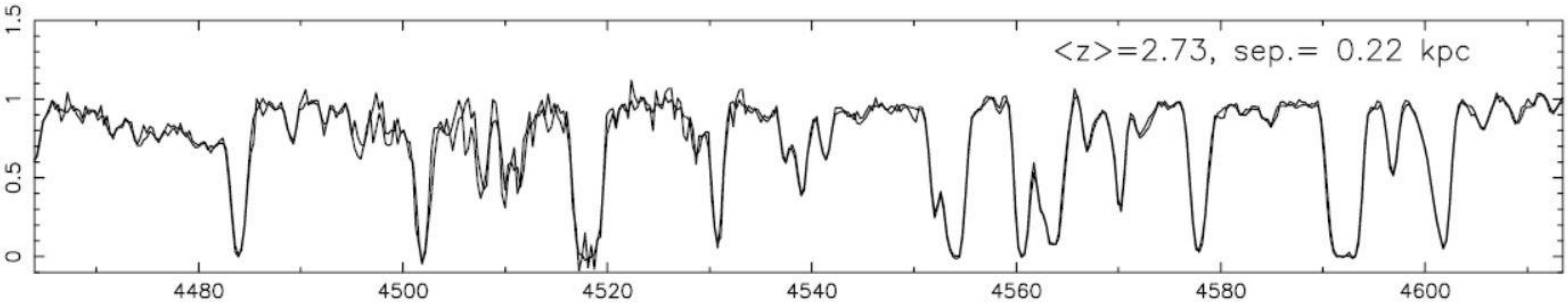


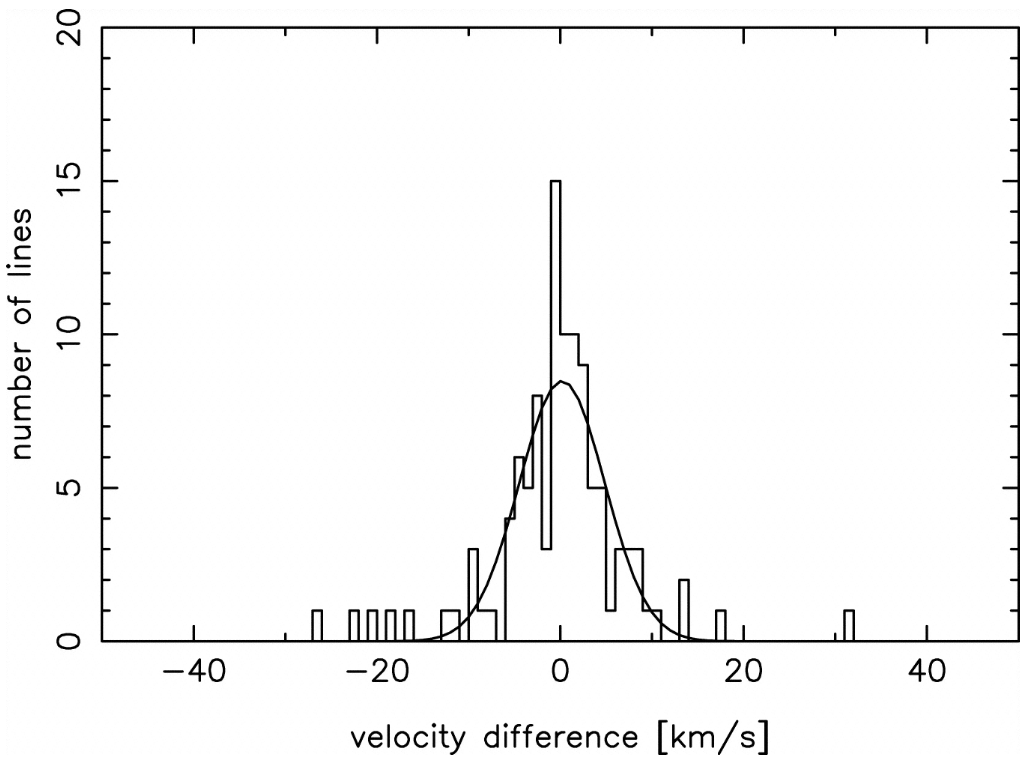
# Scales to probe

0.1-100 kpc



# Present standard @ 0.22 kpc



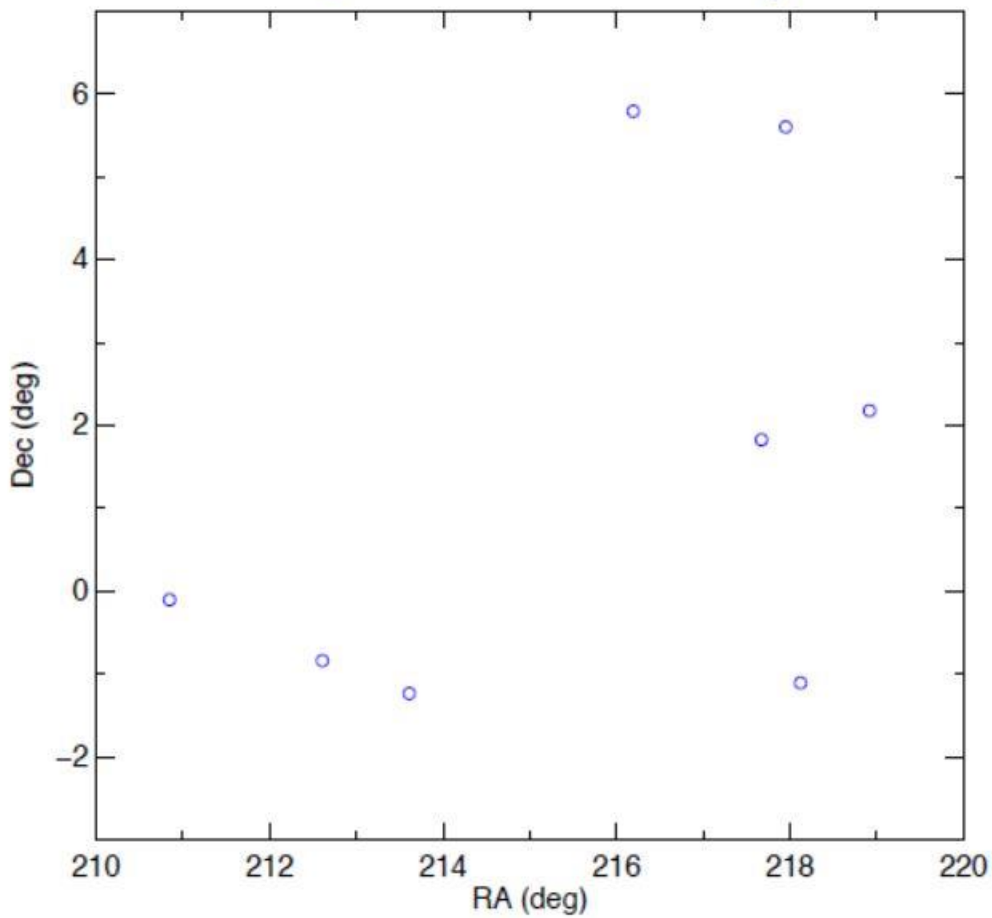



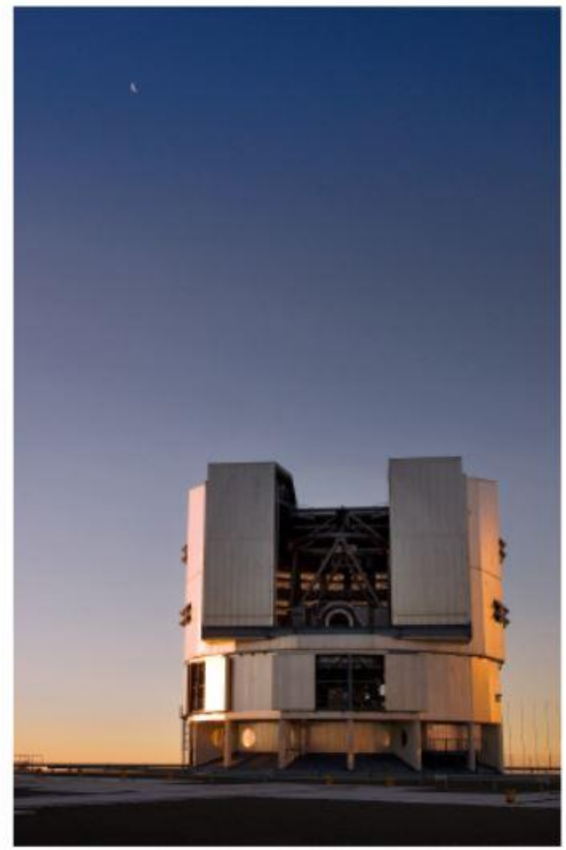
disentangle Hubble expansion, growth of structure (infall), peculiar motions, turbulence, winds

*different  spatial dependence: ex Hubble flow (more important on large scales) vs winds (small scales)*

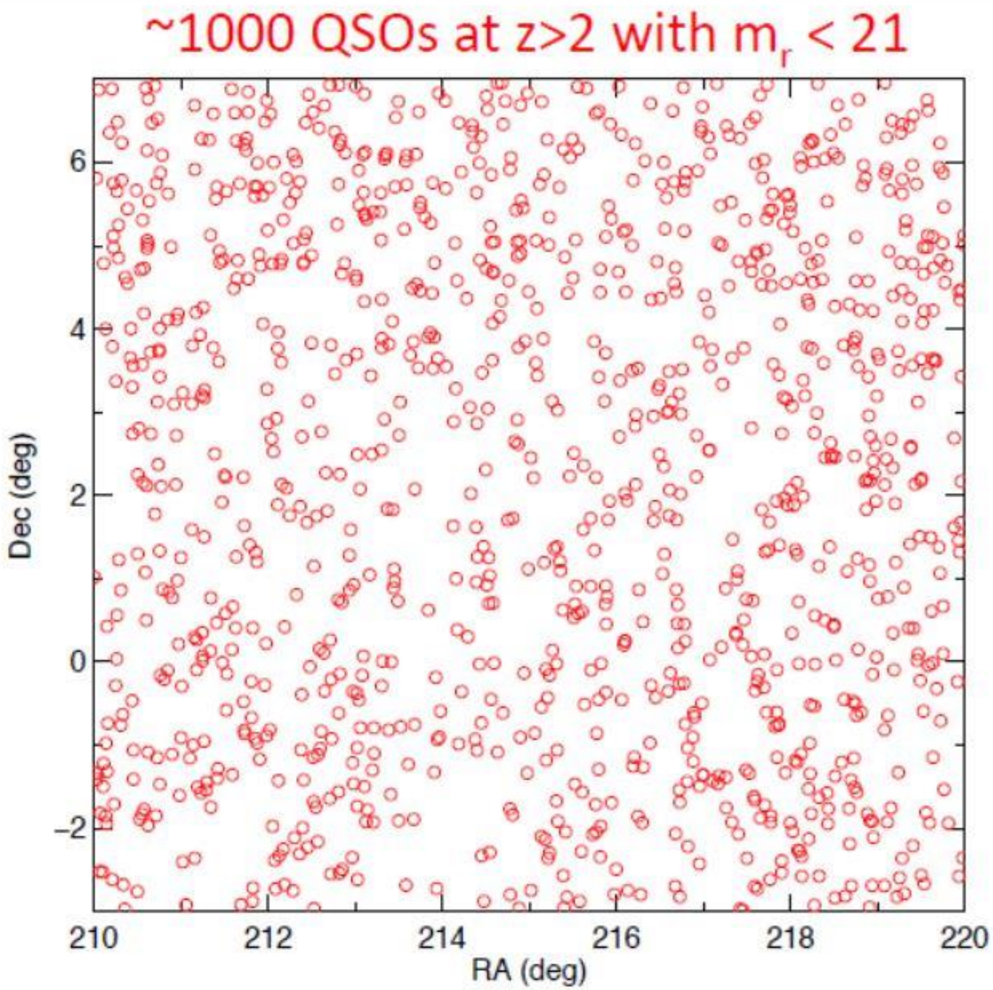
# QSOs that can feasibly be observed with 8-10m class telescopes.

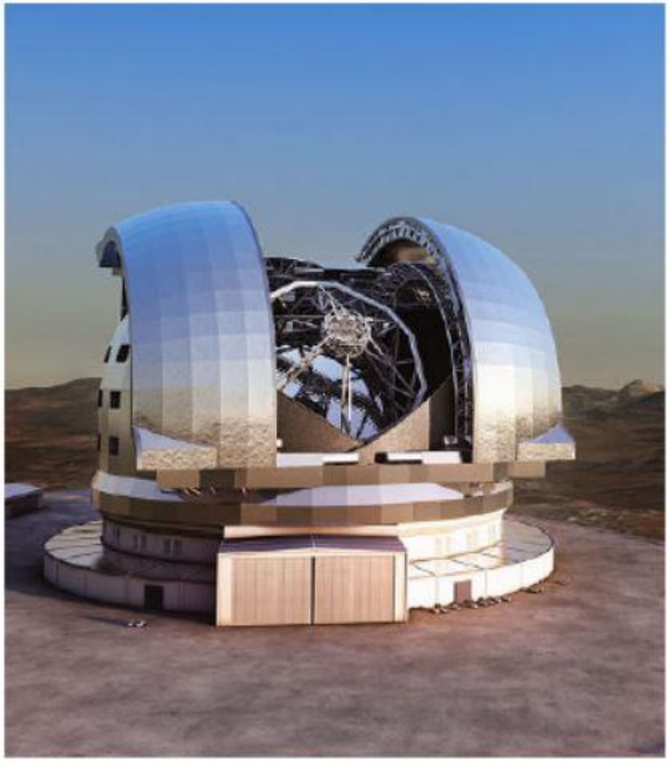
8 QSOs at z>2 with $m_r < 18$



# QSOs that can feasibly be observed with the E-ELT.



# Winds vs. time  (Dt ~ 8 yr)

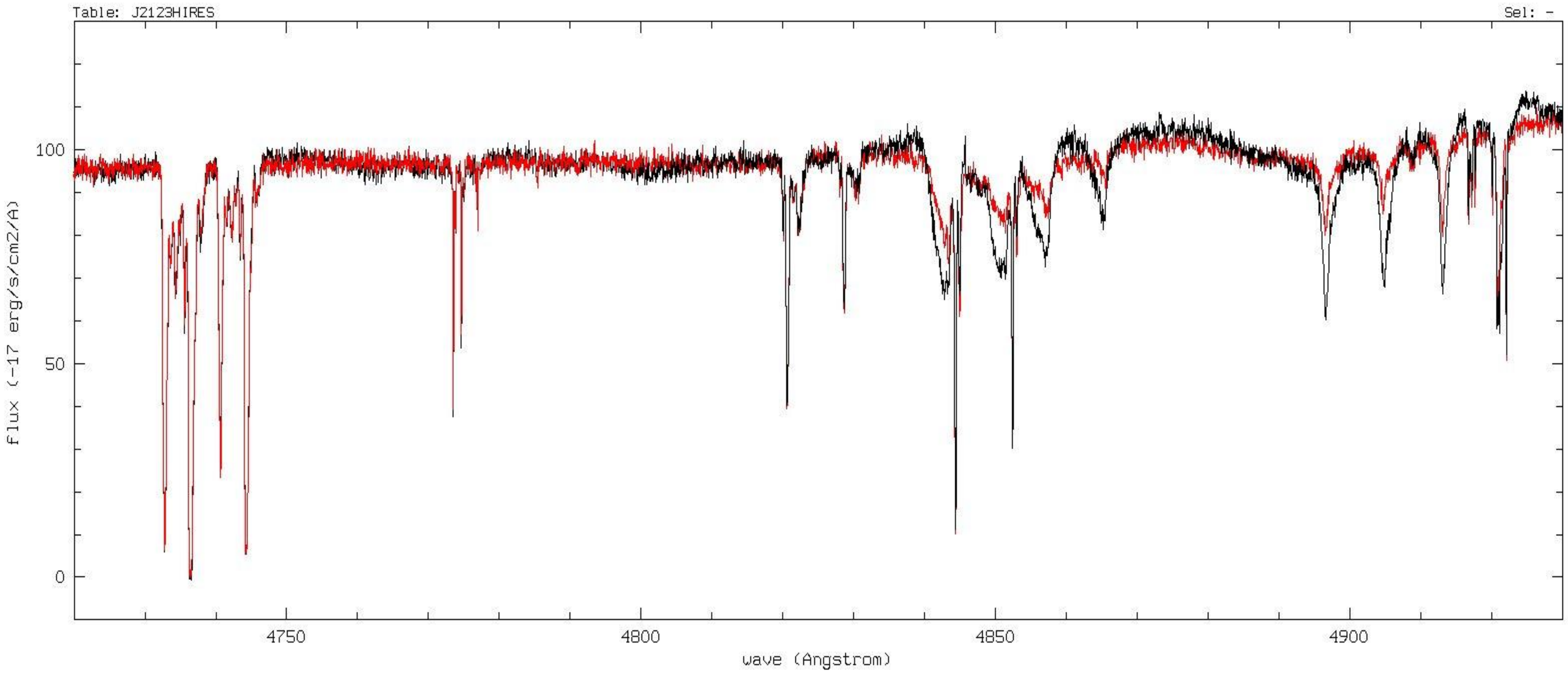


**Table.5.** Summary of science requirements for **fundamental physics** and **cosmology** (**E**=essential; **D**=desirable)

| Science case | | Spectral resolution ($\lambda/\Delta\lambda$) | Wavel. range ($\mu$m) | Wavel. accuracy (m $s^{-1}$) | Stability (m $s^{-1}$) | Multi-plex | Backgr. subtr. | AO / IFU | Polarim. |
|---|---|---|---|---|---|---|---|---|---|
| Fundamental constants & T(CMB) | E | 80,000 | 0.37-0.67 | 2 (relative) | 2 $night^{-1}$ | none | not critical | no | no |
| | D | 100,000 | 0.33-0.8 | 1 (relative) | 1 $night^{-1}$ | none | desirable | no | no |
| Deuterium abundance | E | 50,000 | 0.37-0.7 | 50 | not critical | none | not crit. | no | no |
| | D | 100,000 | 0.33-1.0 | 50 | not critical | none | <1%[a] | no | no |
| Sandage test | E | 100,000 | 0.37-0.67 | 0.02 (absolute) | 0.02 $night^{-1}$ | none | not critical | no | no |
| | D | 150,000 | 0.33-0.8 | 0.01 (absolute) | 0.01 $night^{-1}$ | none | desirable | no | no |

[a] Faint quasars limit.

**Table.3.** Summary of science requirements for the science cases related to **galaxy evolution** and **IGM** (**E**=essential; **D**=desirable)

| Science case | | Spectral resolution ($\lambda/\Delta\lambda$) | Wavel. range ($\mu$m) | Wavel. accuracy ($\lambda/\Delta\lambda$) | Stability | Multi-plex | Backgr. subtr. | AO / IFU | Polarim. |
|---|---|---|---|---|---|---|---|---|---|
| Near pristine gas & reionization | E | 50,000 | 0.6-1.8 | 50,000 | not critical | none | <1% | no | no |
| | D | 100,000 | 0.6-2.4 | 100,00 | not critical | 2[a] | <1% | no | no |
| 3D mapping of the IGM + metallicity | E | 5,000 | 0.4-1.3 | 5,000 | not critical | 5 | <1% | no | no |
| | D | 20,000 | 0.37-1.3 | 20,000 | not critical | 10 | <0.1% | no | no |
| Galaxy evolution | E | 10,000 | 0.4-2.4 | 10,000 | not critical | 5 | <1% | no | no |
| | D | 15,000 | 0.4-2.4 | 15,000 | not critical | 10 | <1% | no | no |
| Low mass Black Holes | E | 100,000 | 1-2.4 | not critical | not critical | none | not crit. | AO+ IFU | no |
| | D | 100,000 | 0.5-2.4 | not critical | not critical | none | not crit. | AO+ IFU | no |

[a] QSO pairs.