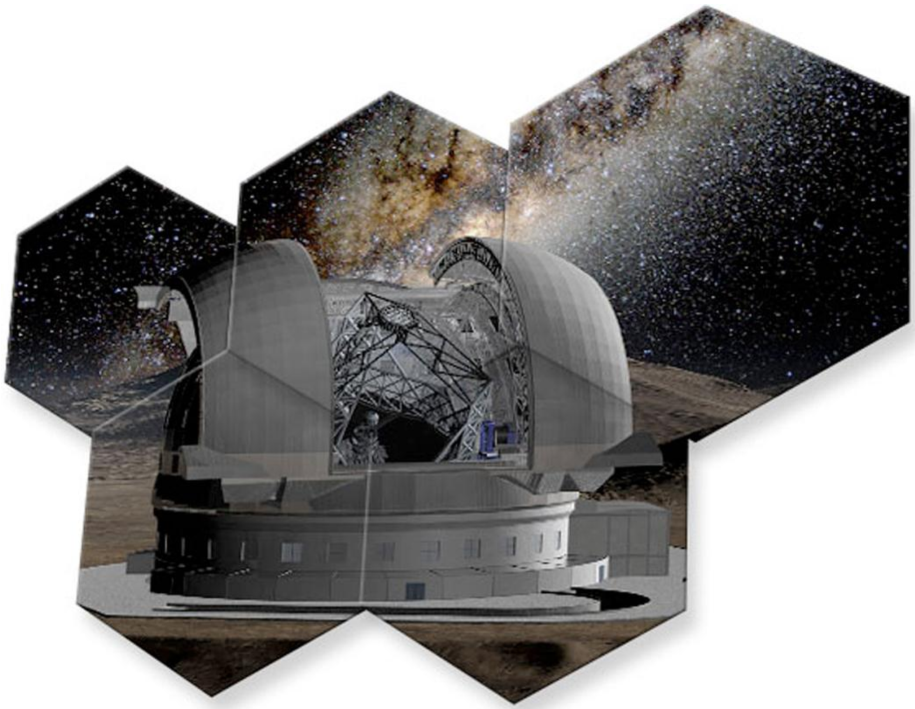
The Intergalactic Medium as a Cosmological Probe



Stefano Cristiani
INAF-Trieste Observatory

A meeting in March 1999 – Chile – VLT inauguration

C.R. – *You spent billions for your telescopes, if you don't win a couple of Nobel prizes in the next few years, you'll have failed…*

Be bold, and attack the fundamental questions of Physics (e.g. the observations of SN Ia for the discovery of the accelerating expansion of the Universe).

IGM Cosmology

- Cosmological parameters
- Particles and Dark Matter
- Testing General Relativity
- The Fundamental Constants of Physics

Special thanks to M.Murphy, P.Molaro, M.Viel, J.Liske, R.Maiolino and the HIRES team

[Usual Disclaimer: the science of 2022+ will not be the science that we would do today with the facilities of 2022]

The (simple) physics of the Cosmic Web

~90 % of the baryons at z=3 are in the IGM (Lyman-α forest)

neutral hydrogen (HI) is determined by ionization balance between recombination of e and p and HI ionization from UV photons

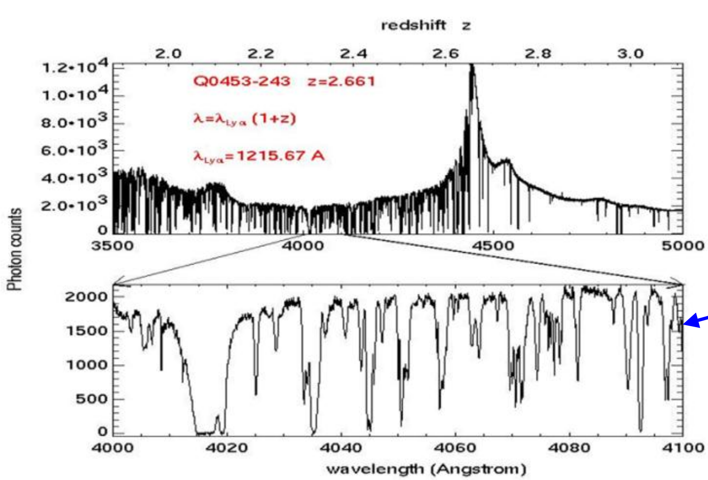
Recombination coefficient depends on T(gas)

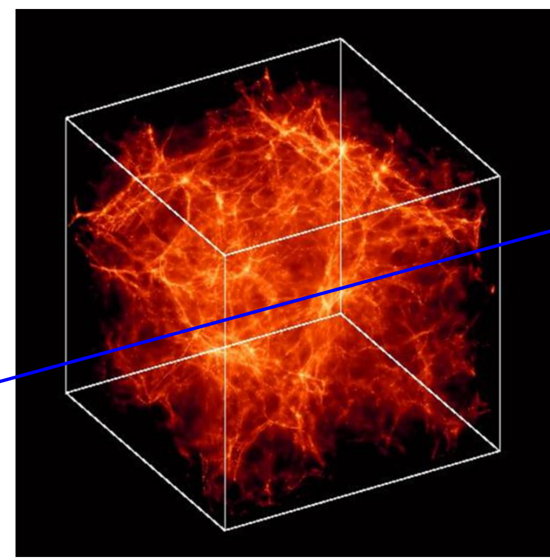
$$\rho_{HI} \propto \rho_{gas}^2$$

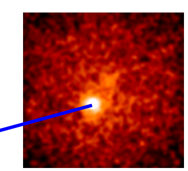
Neutral hydrogen traces overall gas distribution, which traces dark matter on large scales, with additional pressure effects on small scales

Density and temperature are correlated, modeled as a power law with slope γ and amplitude To

$$T = T_0 (1+\delta)^{\gamma}$$

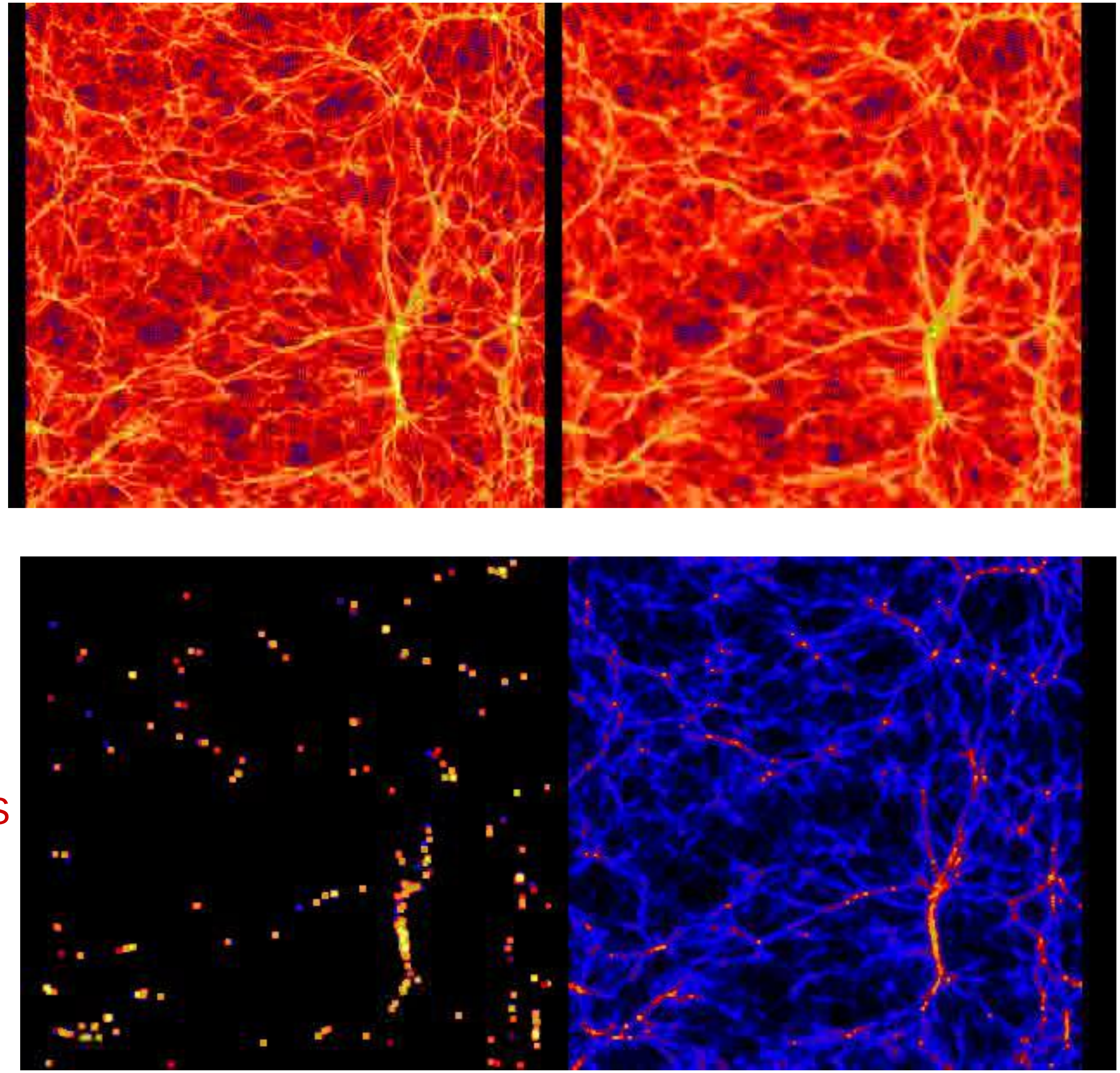






$\Omega_m = 0.26$ $\Omega_\Lambda = 0.74$ $\Omega_b = 0.0463$ H = 72 km/sec/Mpc - 60 Mpc/h

COSMOS computer – DAMTP (Cambridge)



$\delta_{IGM} \sim \delta_{DM}$ at scales larger than the Jeans length ~ 1 com Mpc

flux = $\exp(-\tau) \sim \exp[-(\delta_{IGM})^{1.6}\, T^{-0.7}]$

Courtesy M.Viel

cosmoIGM: science

COSMOLOGY

IGM as a tracer of the large scale structure of the universe: tomography of IGM structures; systematic/statistical errors; sinergies with other probes – IGM unique in redshift and scales

cosmoIGM

IGM as a probe of fundamental physics: dark matter at small scale; neutrinos; coldness of dark matter; fundamental constants; cosmic expansion

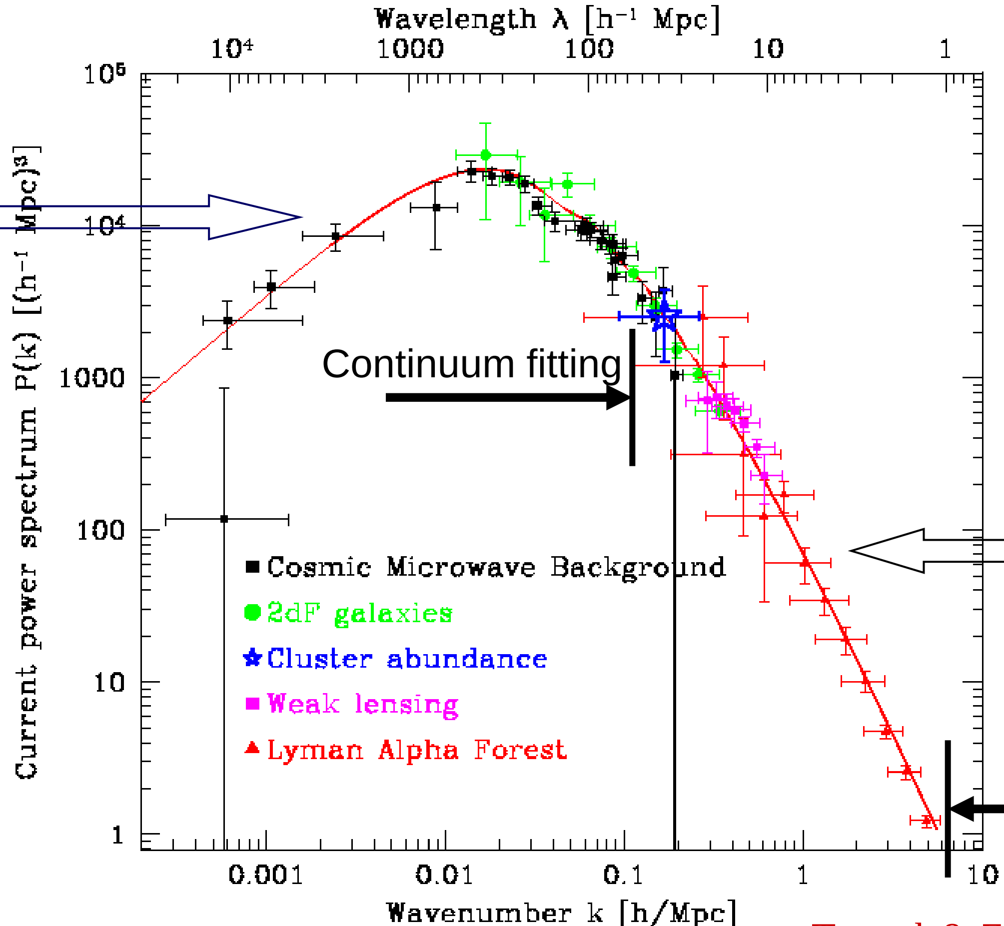
PARTICLE PHYSICS

Galaxy/IGM interplay: metal enrichment and galactic feedback; impact on the cosmic web and metal species; the UV background; the temperature of the IGM

GALAXY FORMATION

The primordial dark matter power spectrum

CMB physics
z = 1100
dynamics



Lyα physics
z < 6
dynamics
+
termodynamics

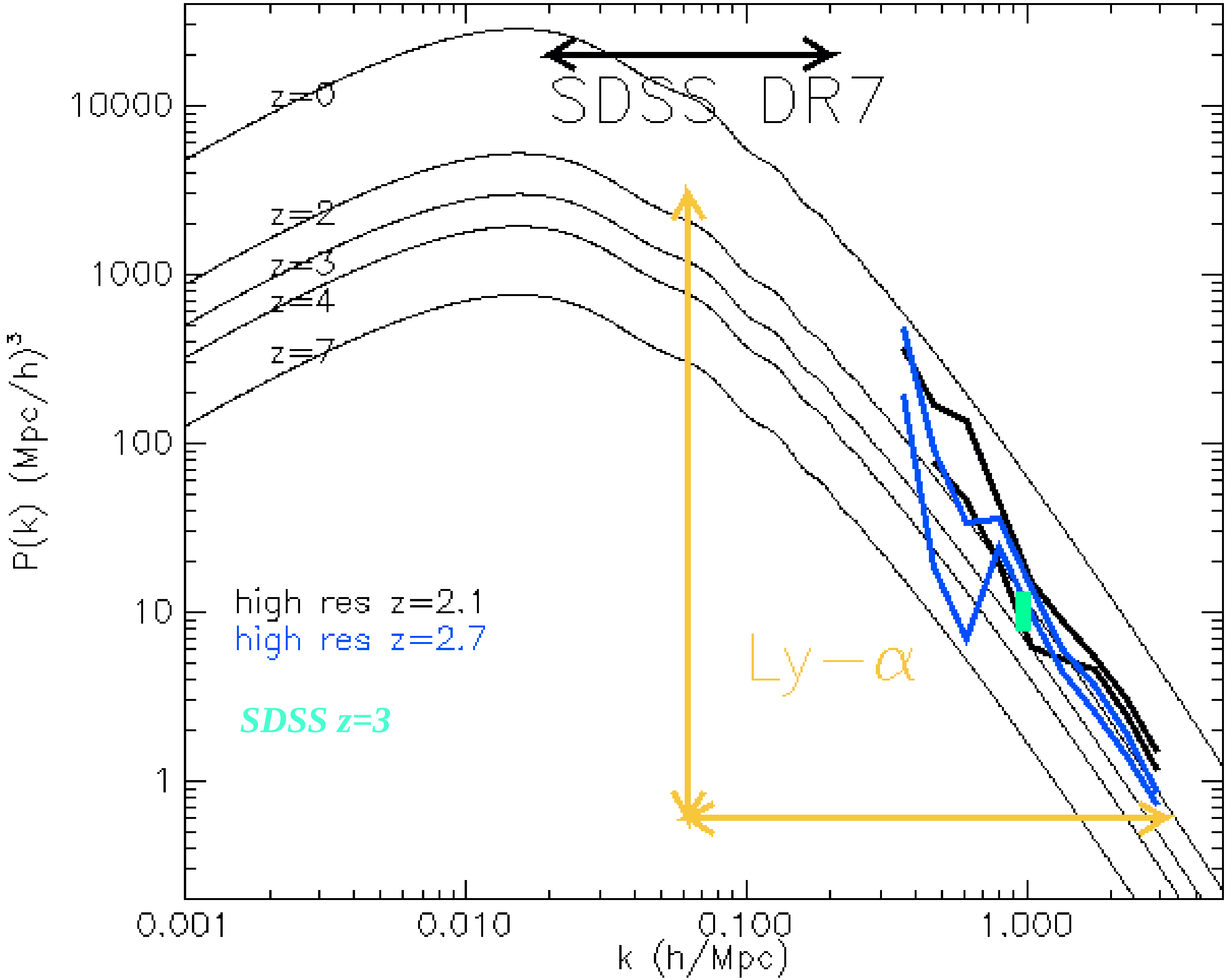
Temperature, metals, noise

Tegmark & Zaldarriaga 2002

CMB + Lyman α → Long lever arm

Relation: $P_{FLUX}(k)$ - $P_{MATTER}(k)$

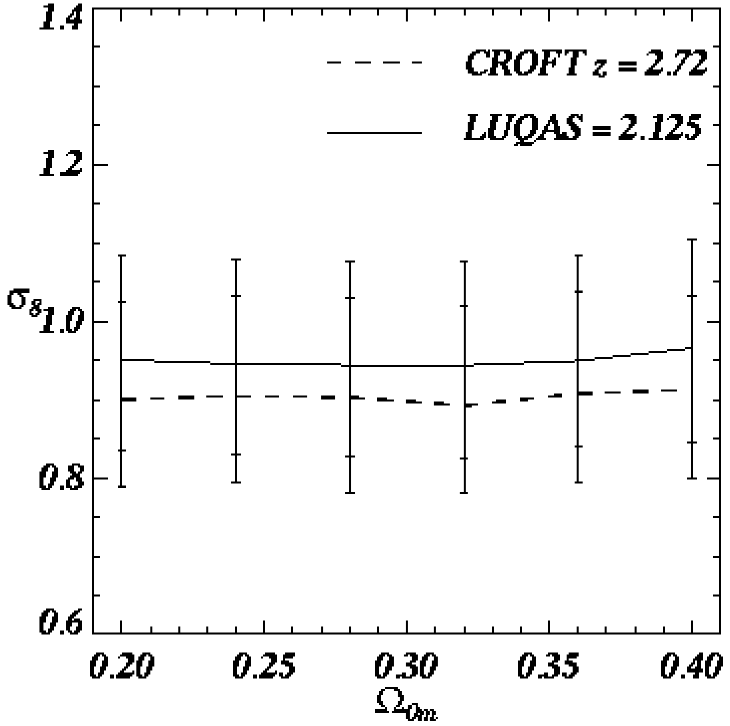
Constrain spectral index and shape



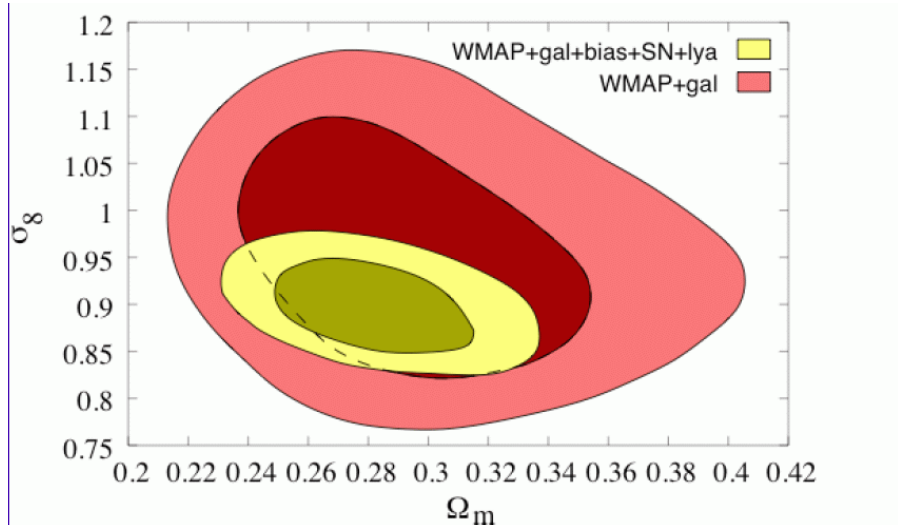
e.g. Kim, Viel, Haehnelt, Carswell, Cristiani 2004

Cosmological implications: combining the forest data with CMB

Viel, Haehnelt, Springel 2004



SDSS Seljak et al. 2004



$n = 1.01 \pm 0.02 \pm 0.06$

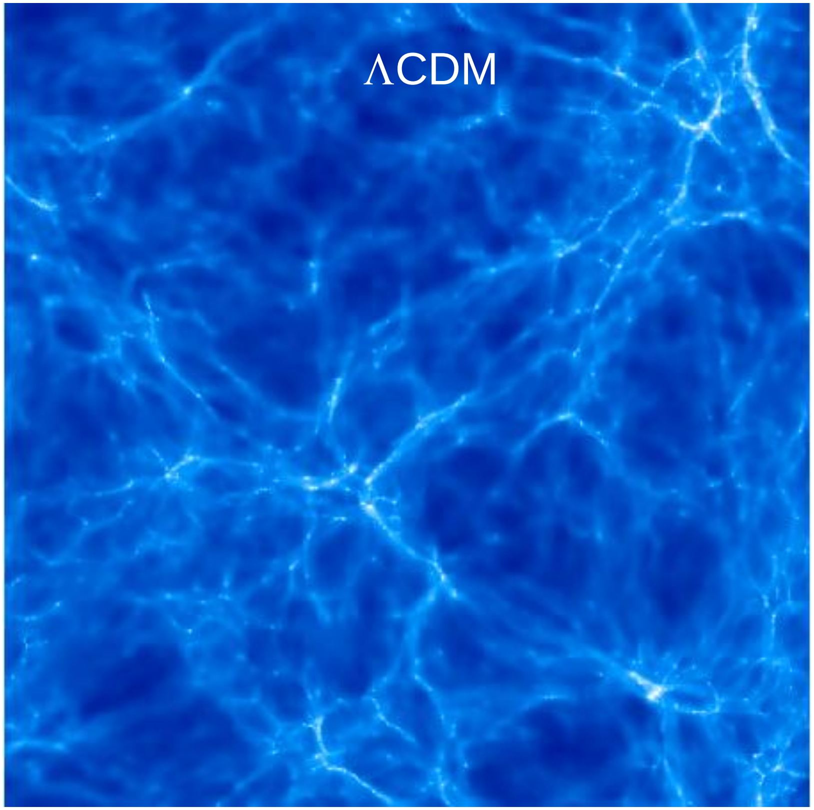
$\sigma_8 = 0.93 \pm 0.03 \pm 0.09$

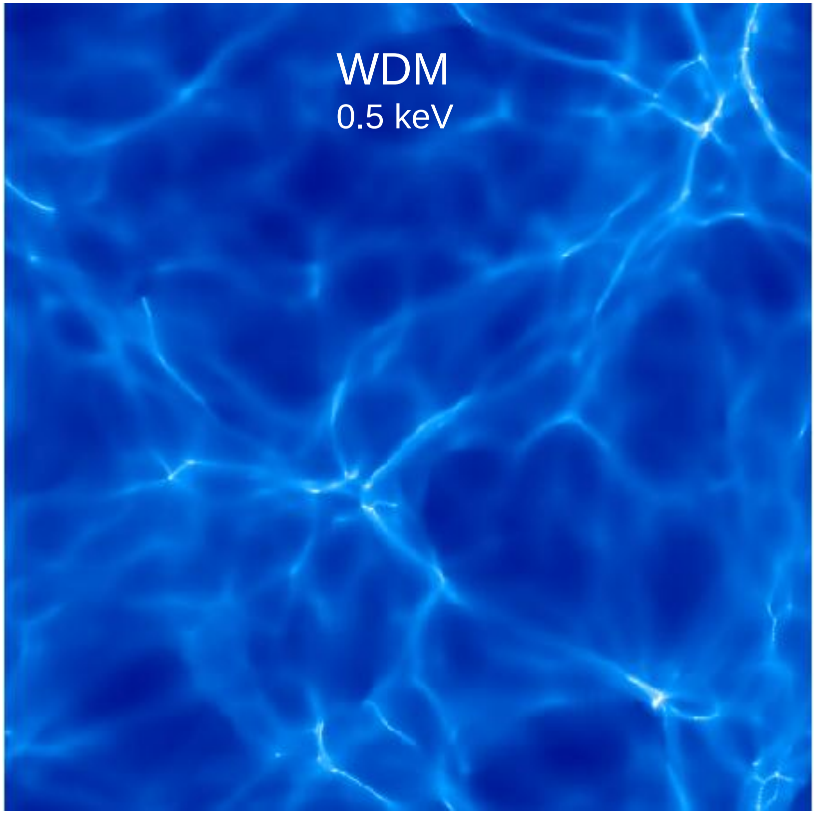
Systematic error

Statistical error

M(ν) now in the range 0.05 – 0.3 eV

Cosmological implications: Warm Dark Matter particles





30 comoving Mpc/h z=3

In general

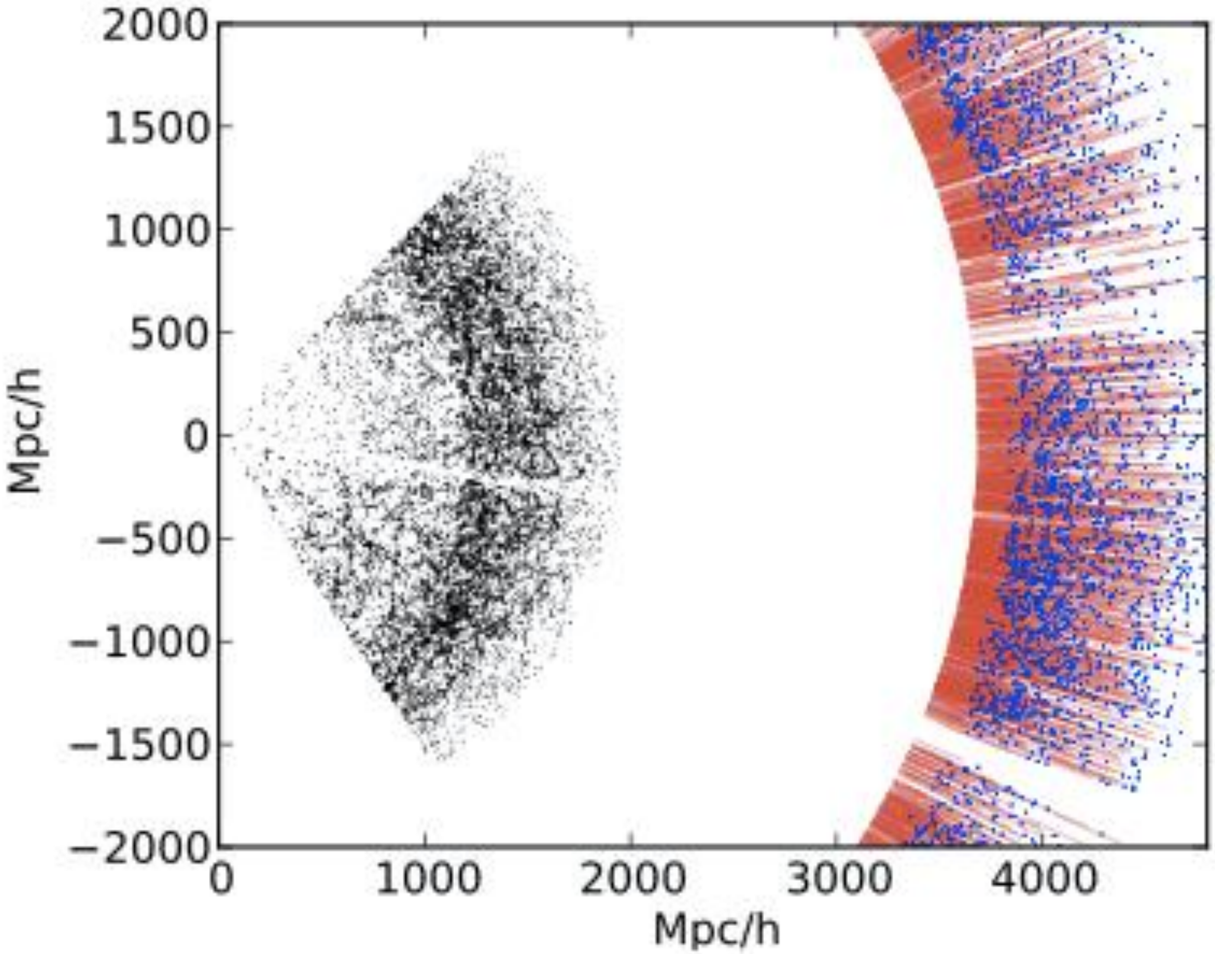
m(sterile neutrino) > 28 keV (2σ)

if light gravitinos

m(WDM) > 4 keV (2σ)

Viel + 2008, Seljak+ 2006, Boyarsky + 2009

The BOSS/SDSS-III perspective: 3D flux power



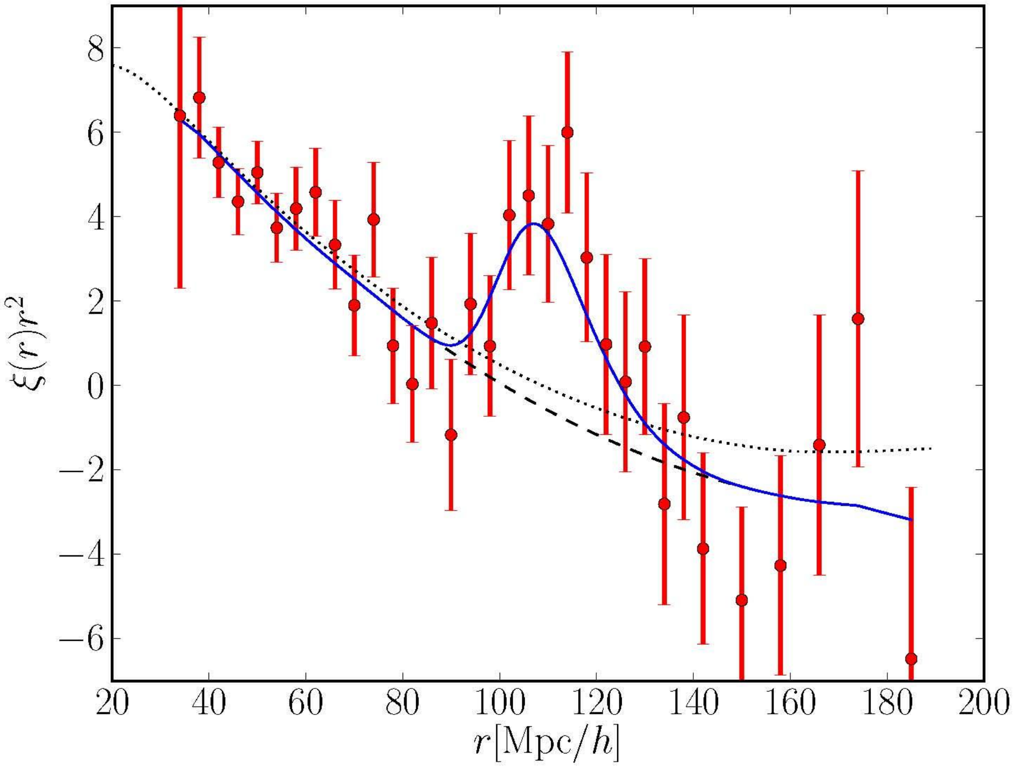
Slosar et al. 2011 (BOSS collaboration)

Present perspectives: BAO

Importance of transverse direction:
Viel et al 2002;
White 2003;
McDonald & Eisenstein 2007;
Slosar et al. 2009

about< 20 QSOs per square degree with BOSS

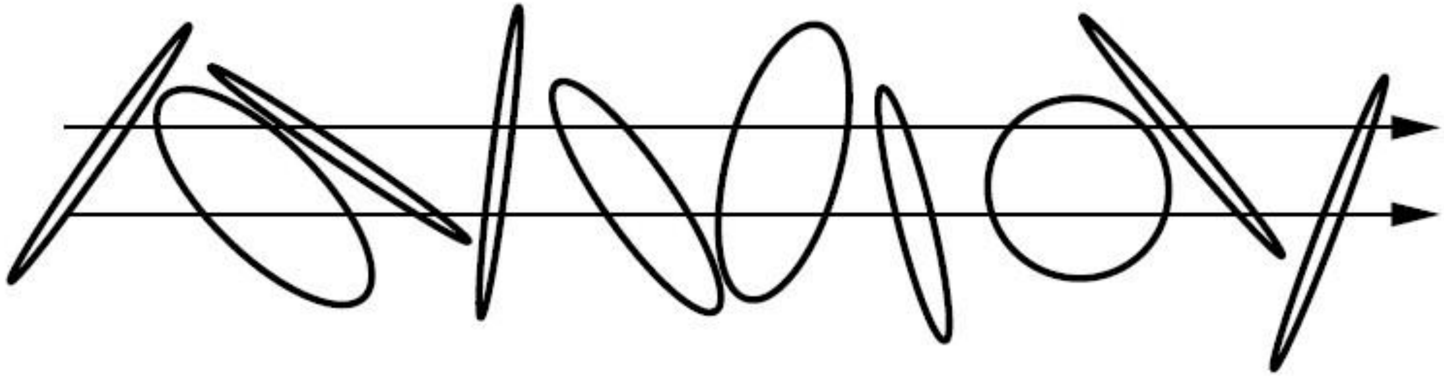
z(eff) = 2.4



Slosar et al. 2013

The small-scale Structure of the IGM

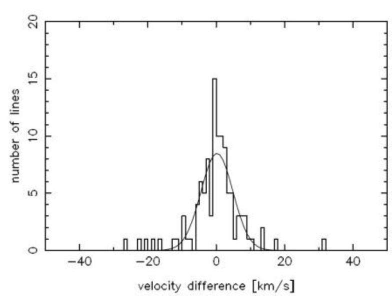
1-200 kpc

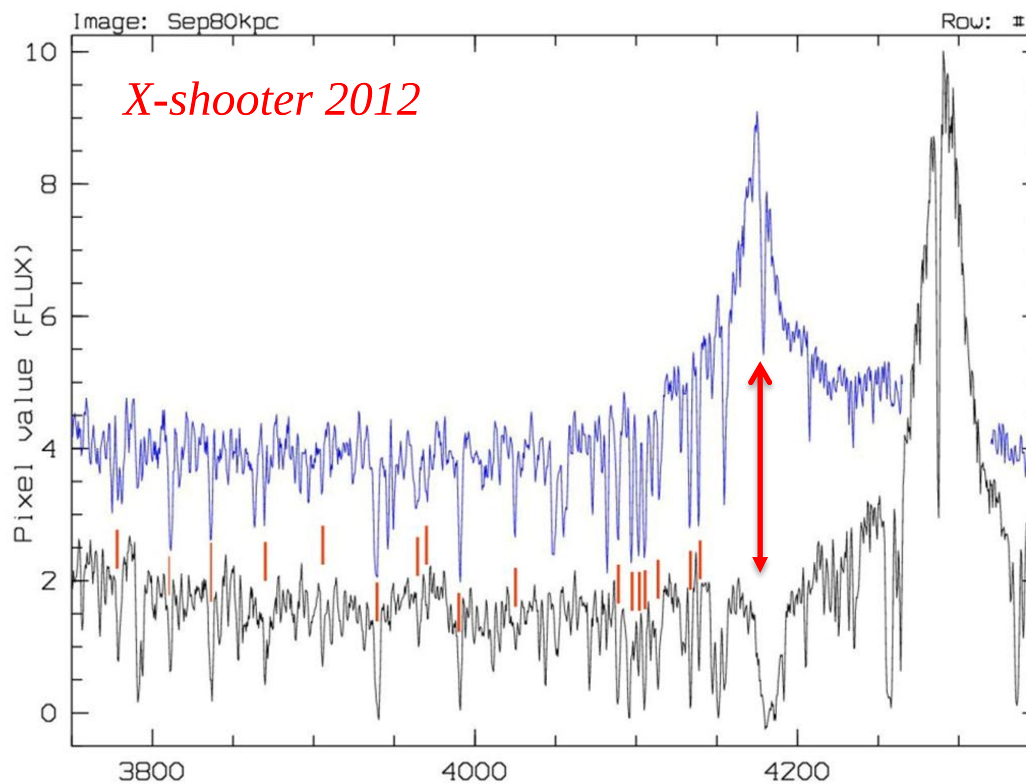


Multiple LOS

expansion-collapse in the cosmic web

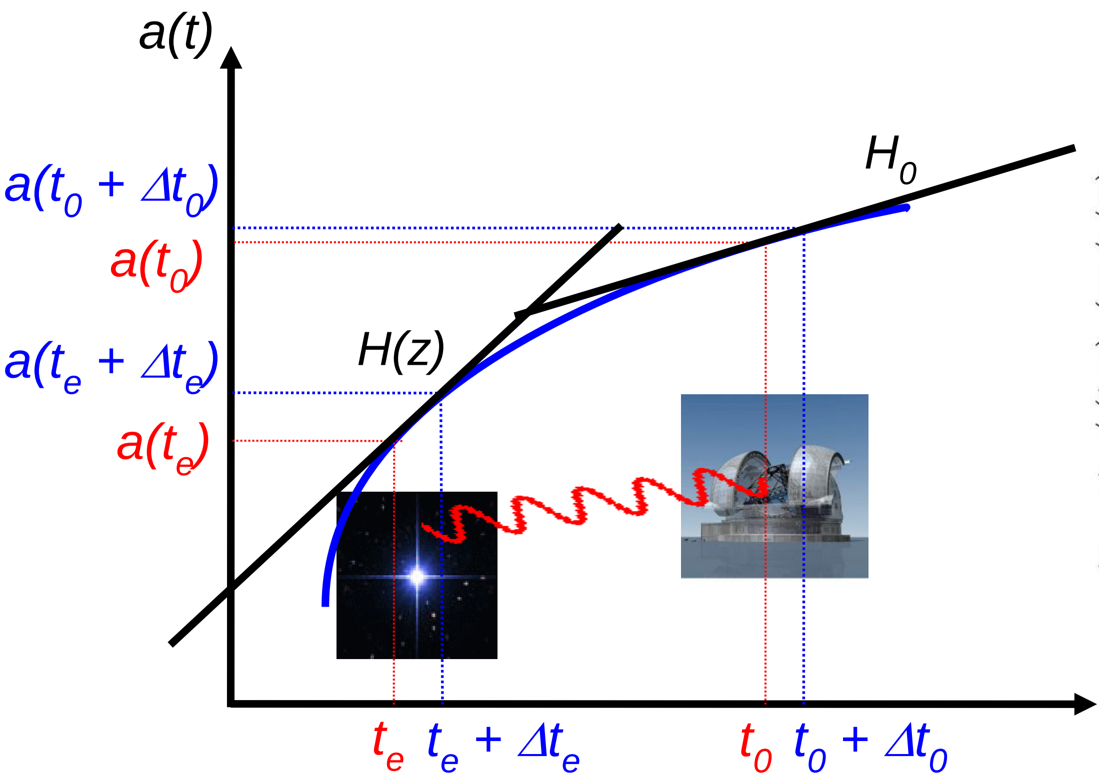
winds

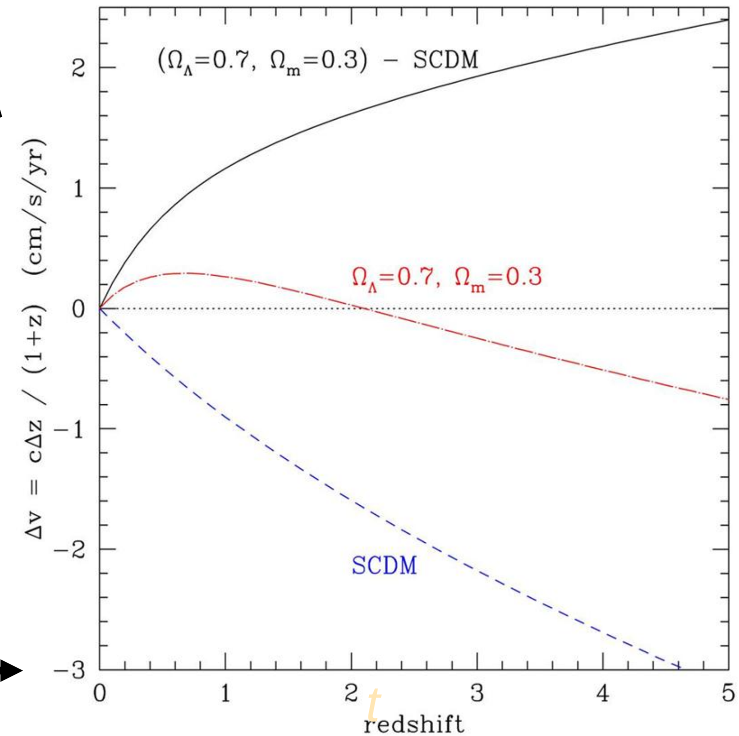




Rauch, Becker, Viel et al. 2005

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





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

A small signal ..

this is for 10^7 years… Having much less time at our disposal the shift is much smaller.. Why can we conceive to detect it NOW?

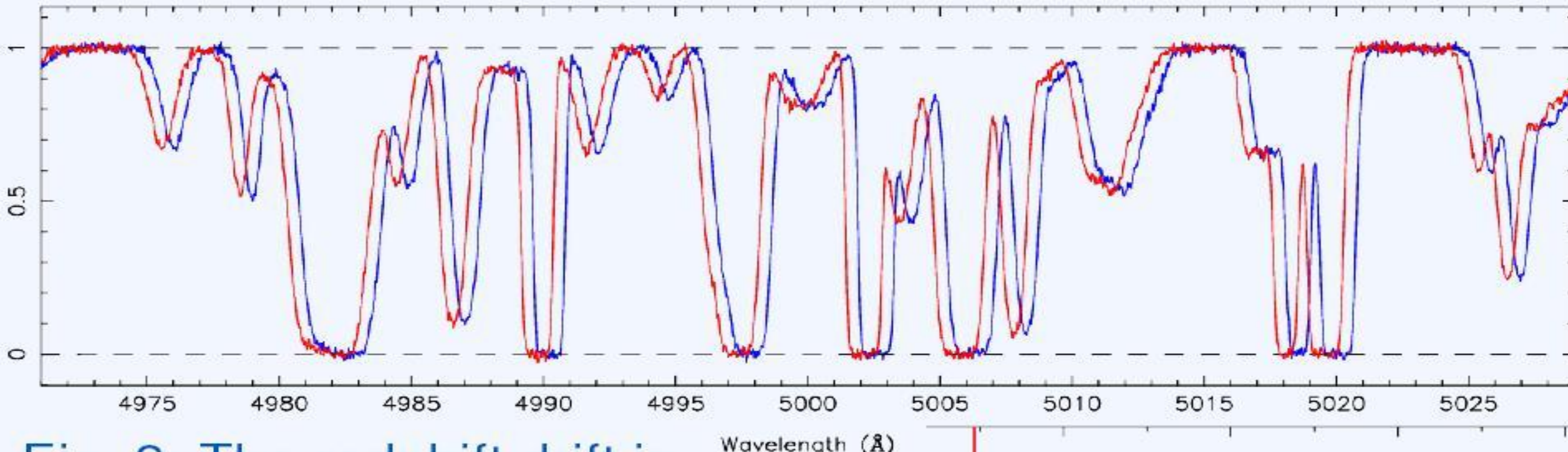


Fig. 2: The redshift drift in a simulated Lyα forest spectrum for Δt = 10^7 yr.

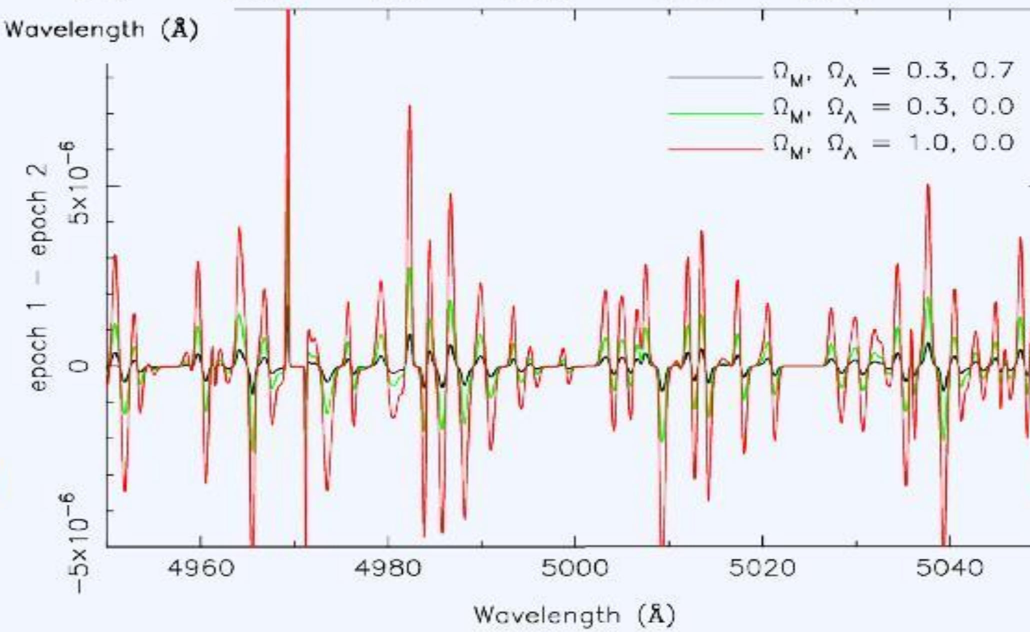
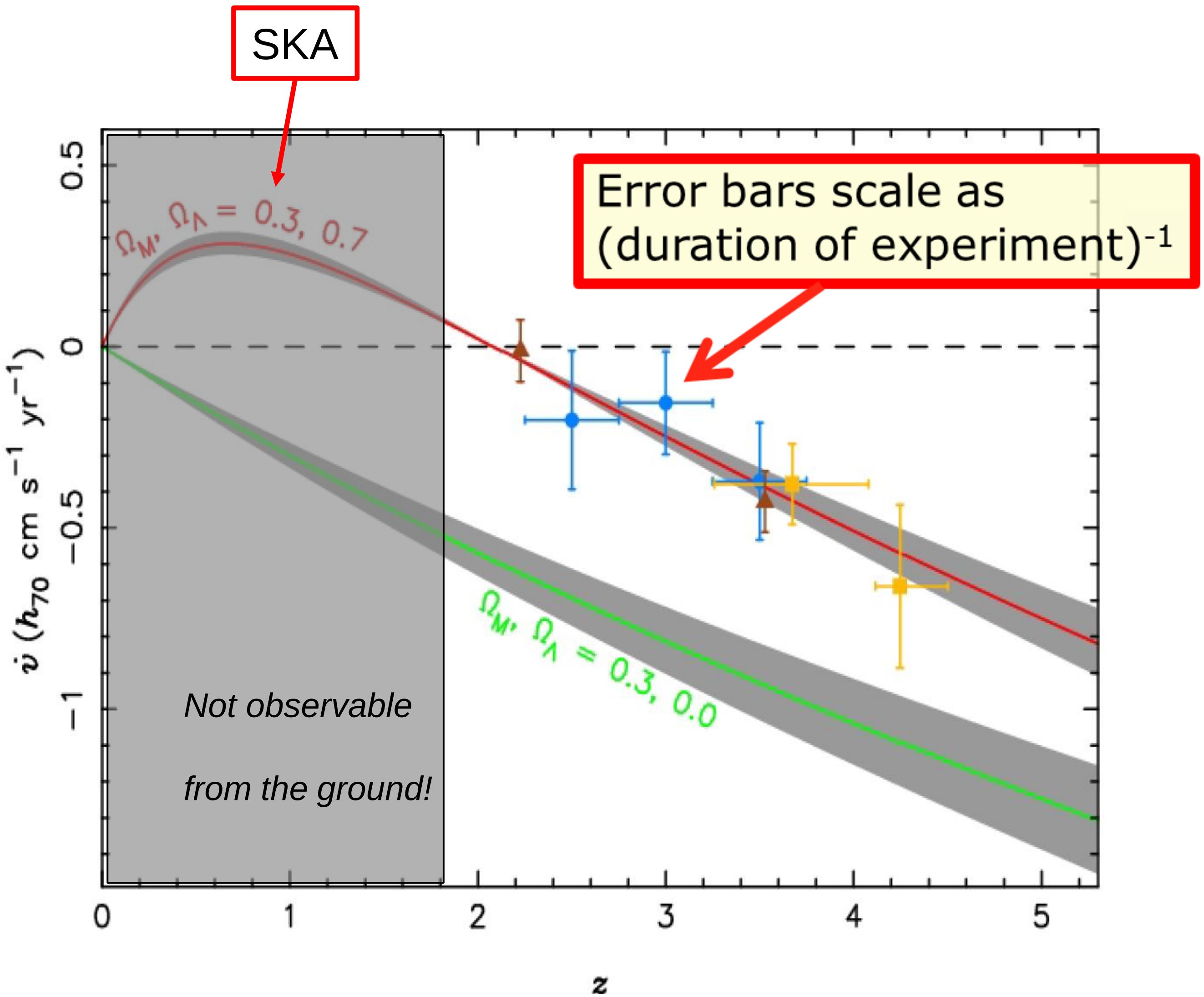


Fig. 3: The difference of two simulated noiseless Lyα forest spectra taken Δt = 10 yr apart.

Feasibility Test with a Rs~10^5 spectrograph



- 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, Cristiani et al. 2007, Liske et al. 2008

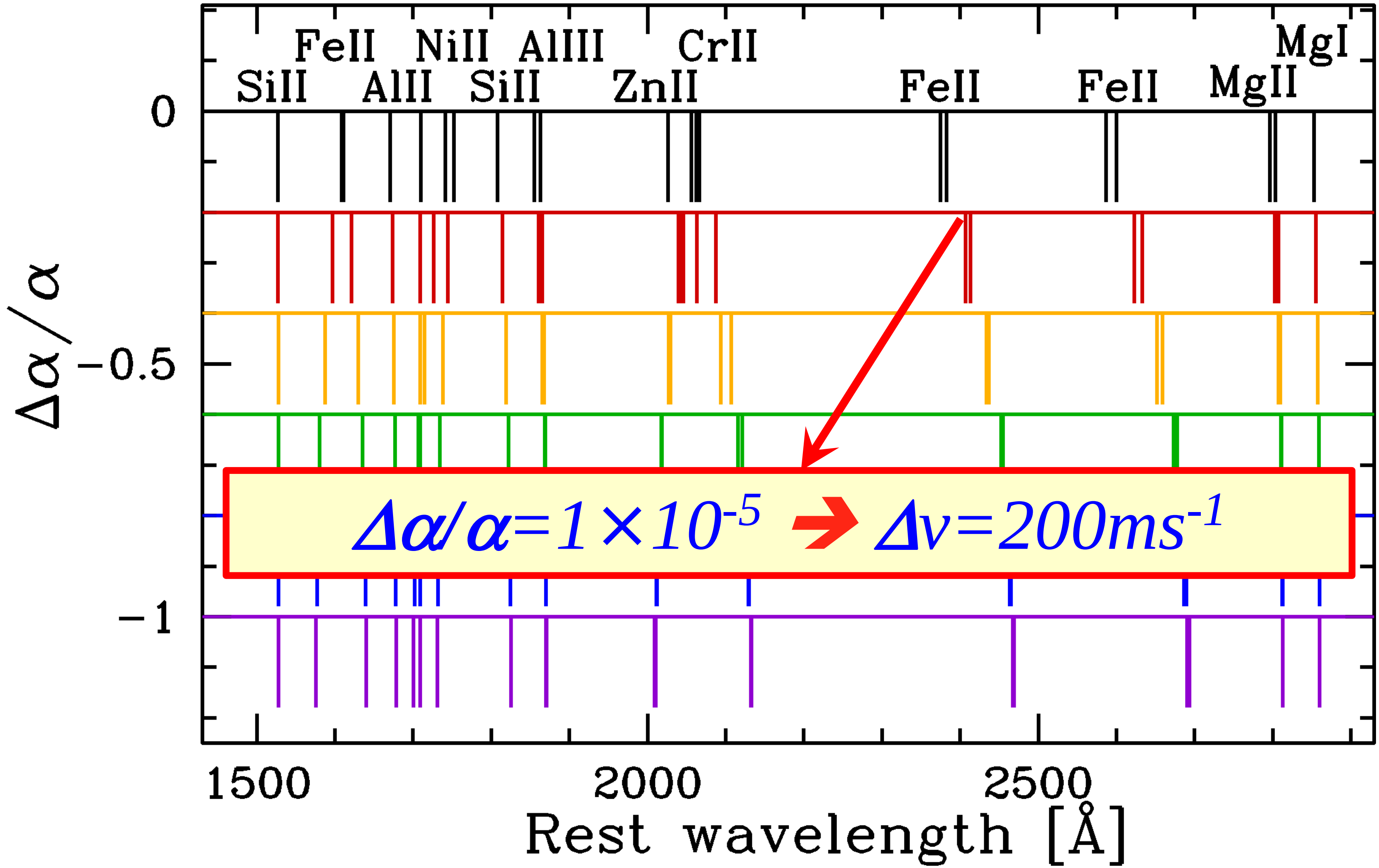
Fundamental? Constants?:

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?*

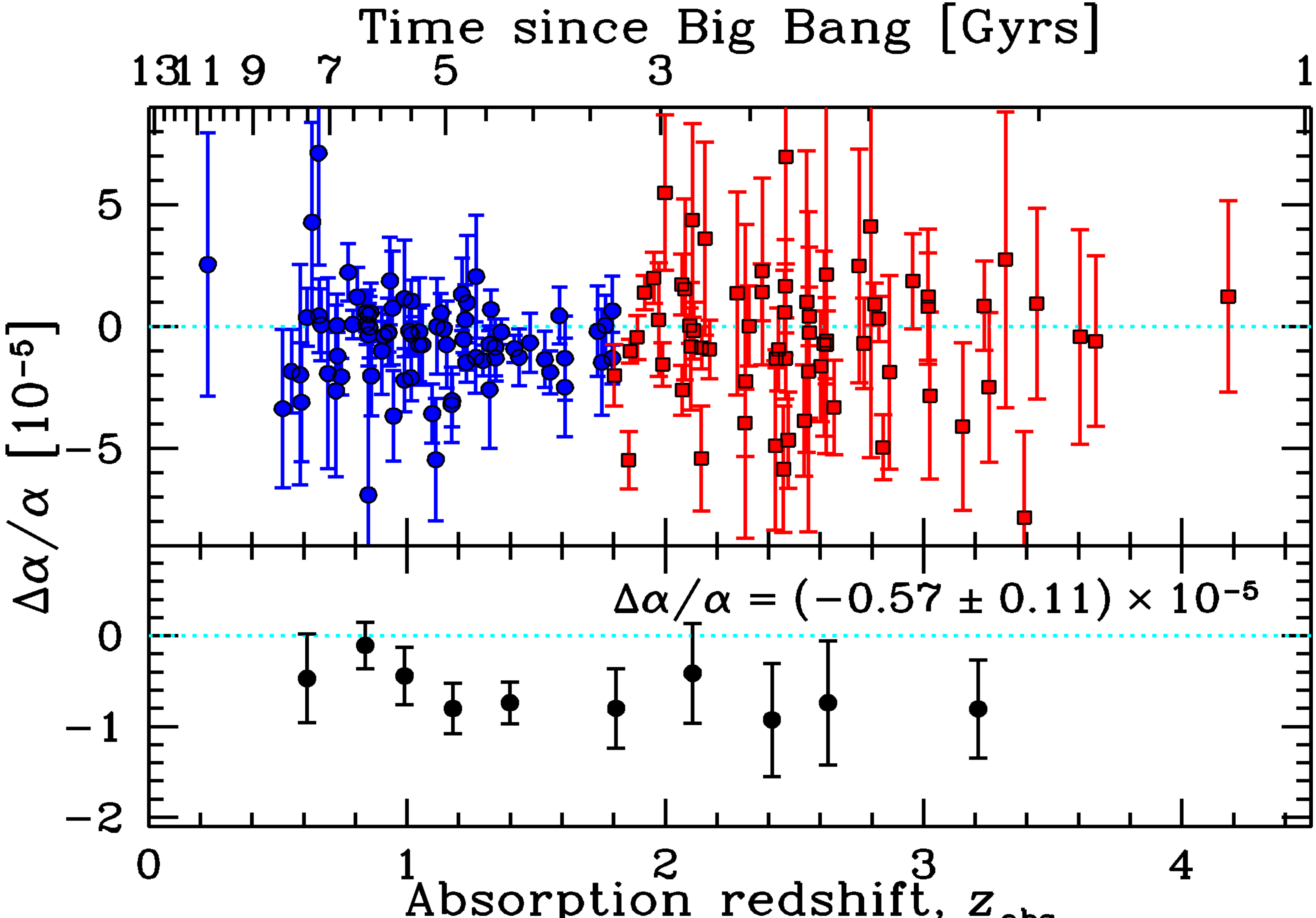
- *Constancy based on Earth-bound, human time-scale experiments*
- *Extension to Universe seems a big assumption*

The Many Multiplet (MM) method:



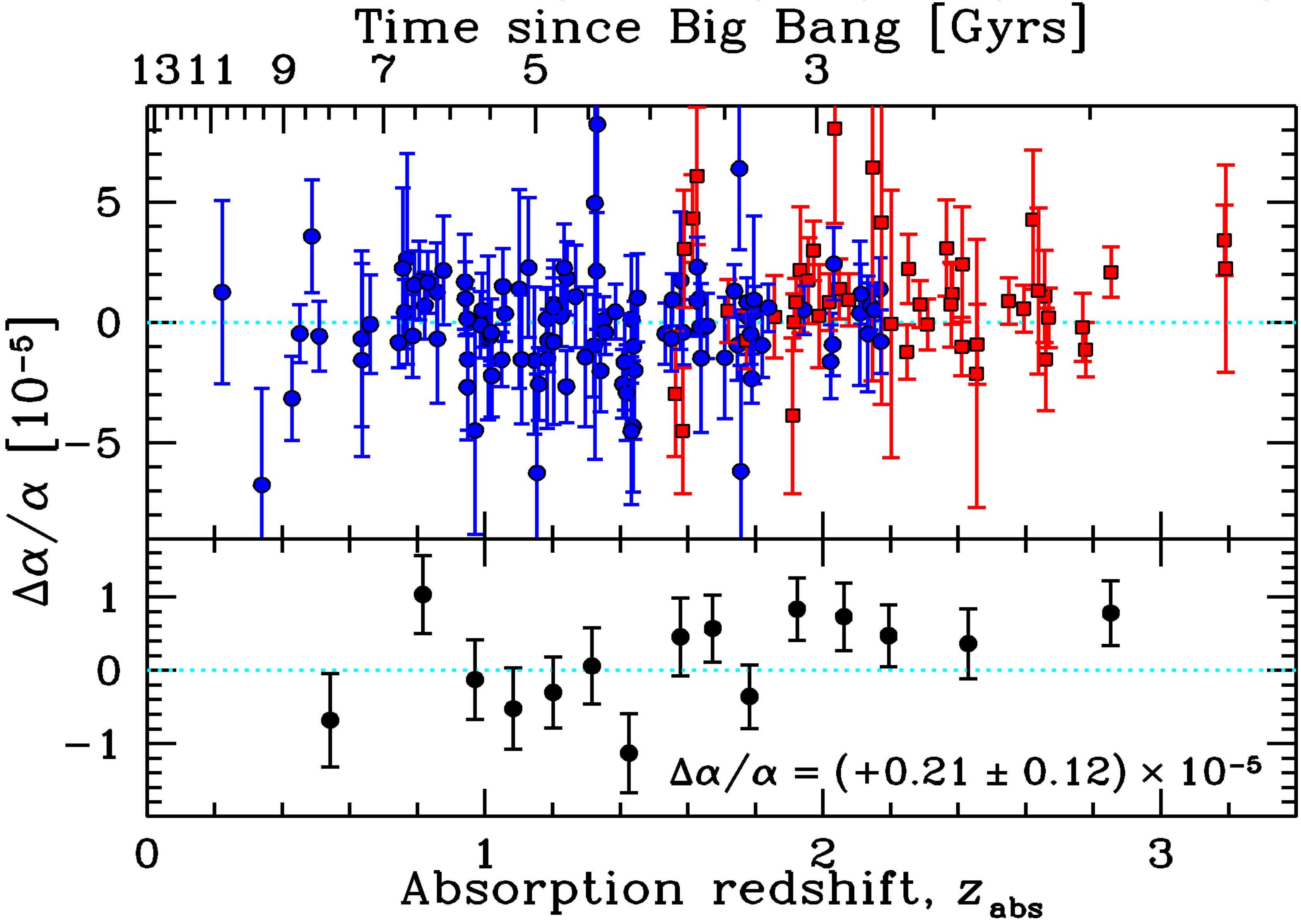
143 Keck/HIRES absorbers:

MTM et al. (MNRAS 3003; LNP, 2004)

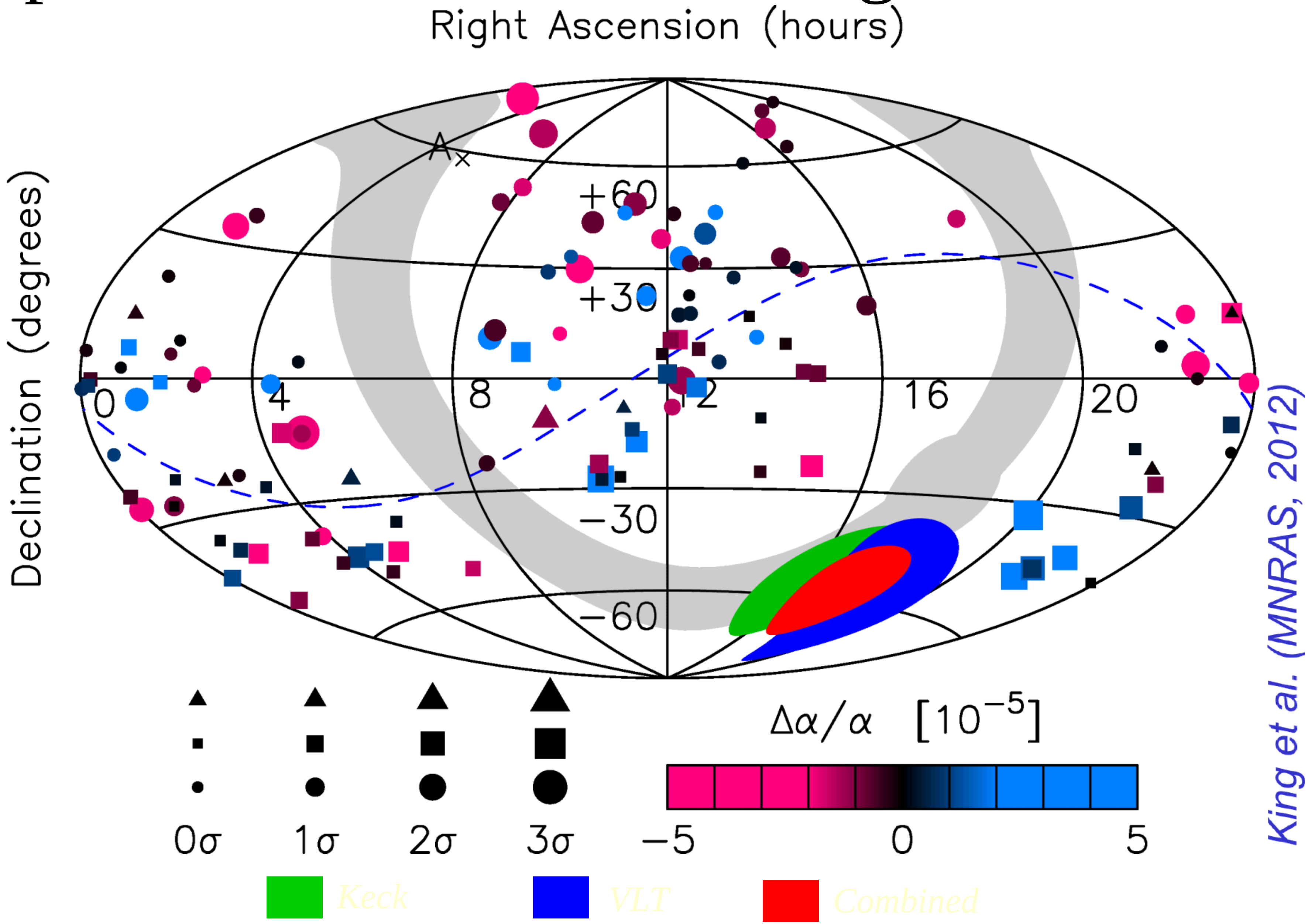


153 VLT/UVES absorbers:

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



Dipoles from Keck & VLT agree:



Update

Absorbers toward QSO HE2217-2818 reveal no evidence for variation in α at the 3 ppm level (1σ)

(the expectation from the dipole being 3.2-5.4 ±1.7 ppm)

Molaro et al 2013

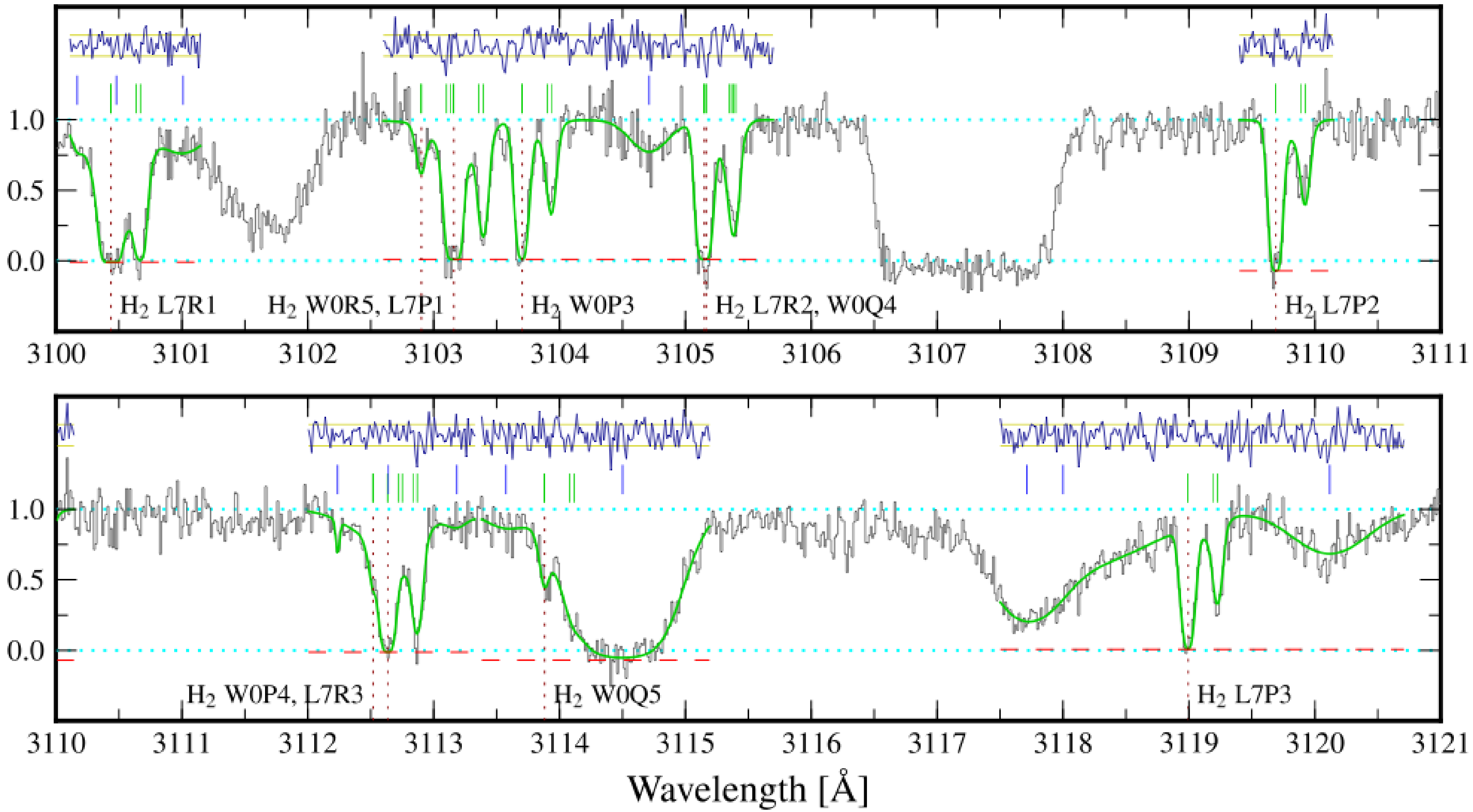
What if it's correct?:

- *ELTs MUST confirm it!*
- *ELTs MUST characterize variation accurately:*
  - *Does α 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?*

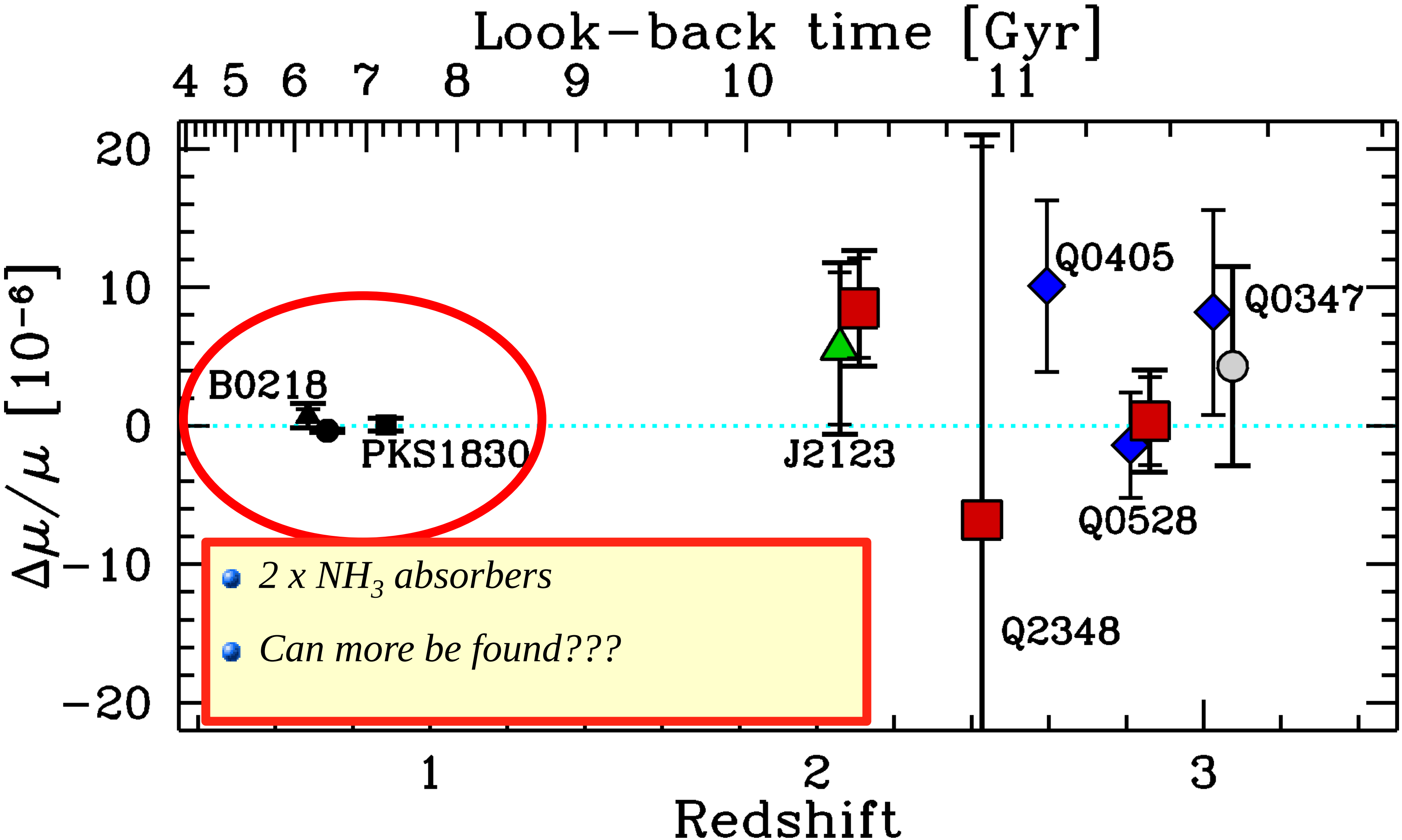
H_2 constraints on $\Delta\mu/\mu$:



J2123-0050

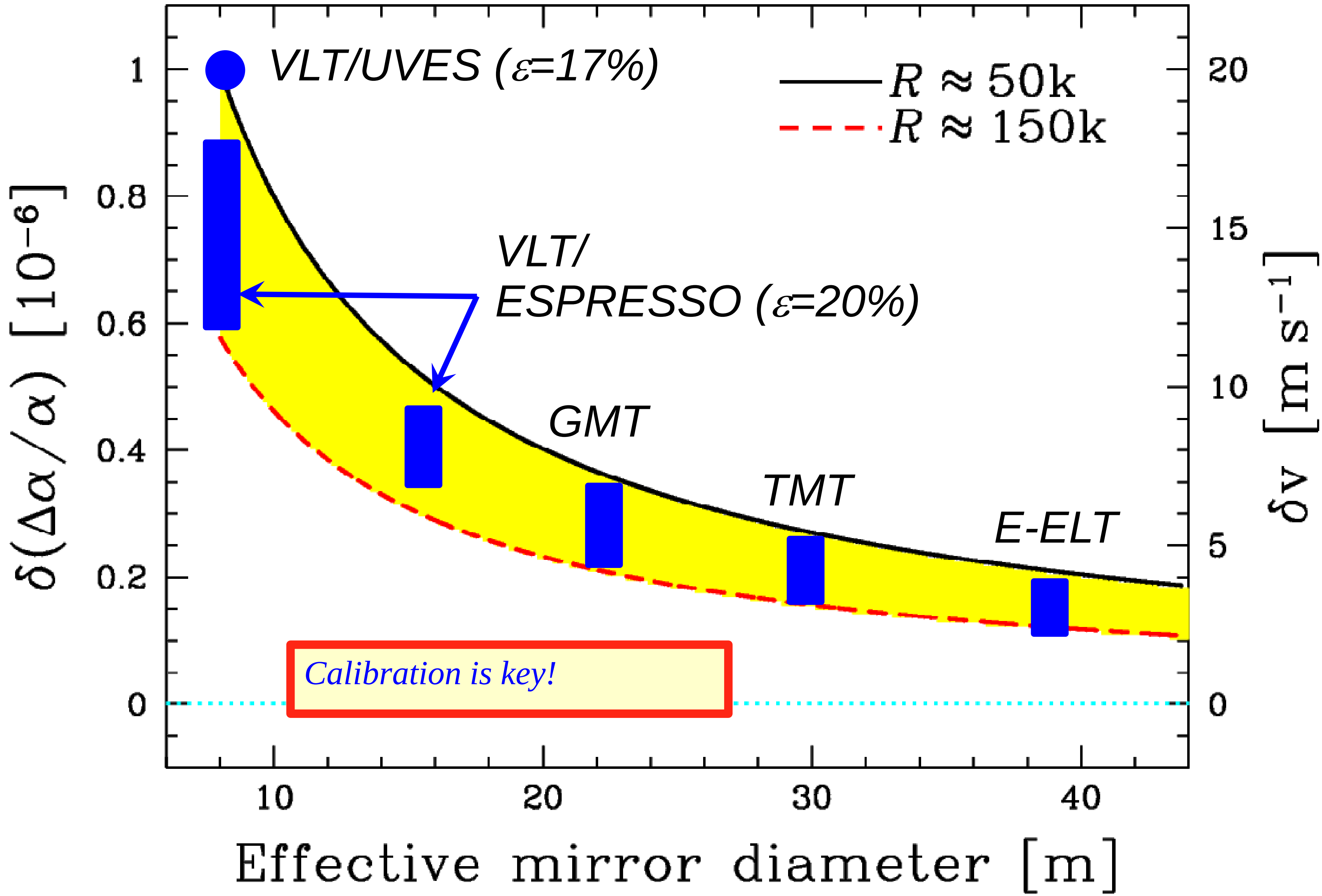
Malec et al. (MNRAS, 2010)

Extragalactic values of Δμ/μ:



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).

Precision from future instruments:



Sandage test requirements:

	Aspect/parameter	Requirement
★	Spectral resolution	$R \geq 100$k, mainly for precise λ calibration
★	Spectral coverage	**350nm (important)** $< \lambda <$ 670nm
	Spectral sampling	≥3 pix per FWHM
	Multiplexing	1
★	Wavelength calibration	Freq. comb.; 2 cm s^{-1} *absolute*
★	Stability	2 cm s^{-1} $night^{-1}$ if absolutely calibrated
★	Entrance interface	Fibre (crucial), scrambling $\varepsilon > 2000$
	Exposure time	15 min $< T_{exp} <$ 120 min
★	Total throughput	**$\varepsilon \geq 20\%$**
	Source size	Point source
	Typical object magnitudes	15–17
	Sky subtraction	Yes
	Background	Dark time
	Target density	Very low (~50 over hemisphere)
	Adaptive optics	Not essential
	Field of view	~few arcseconds

$\Delta\alpha/\alpha$ requirements:

Aspect/parameter	Requirement
Spectral resolution	R ~ 100k
Spectral coverage	**370nm** < λ < 800nm (680nm is OK)
Spectral sampling	≥4 pix per FWHM
Multiplexing	1
★ Wavelength calibration	Freq. comb preferred; 2 cm s^{-1} *relative*
Stability	1 m s^{-1} $night^{-1}$
Entrance interface	Fibre (crucial), scrambling ε > 100
Exposure time	15 min < T_{exp} < 120 min
Total throughput	
Source size	Point source
Typical object magnitudes	15–18
Sky subtraction	Preferred
Background	Bright is OK (then need sky subtraction)
Target density	Low (~500 over hemisphere)
Adaptive optics	Not essential
Field of view	~few arcseconds

Δμ/μ requirements:

Aspect/parameter	Requirement
Spectral resolution	$R \geq$ 100k
★ Spectral coverage	**330nm (370nm crucial)** < λ < 670nm
Spectral sampling	≥4 pix per FWHM
Multiplexing	1
★ Wavelength calibration	Freq. comb preferred; 2 cm s^{-1} *relative*
Stability	1 m s^{-1} $night^{-1}$
Entrance interface	Fibre (crucial), scrambling ε > 100
Exposure time	15 min < T_{exp} < 120 min
Total throughput	
Source size	Point source
Typical object magnitudes	16–19
Sky subtraction	Yes
Background	Dark
Target density	Very low (~50 over hemisphere)
Adaptive optics	Not essential
Field of view	~few arcseconds

VLT papers use data generated by VLT instruments, including visitor instruments for which observing time is recommended by the ESO OPC (Observing Programmes Committee), e.g, VLT Ultracam. Instrument-level data for the VLT are available since the beginning of operations, i.e., from publication year 1999 onwards.

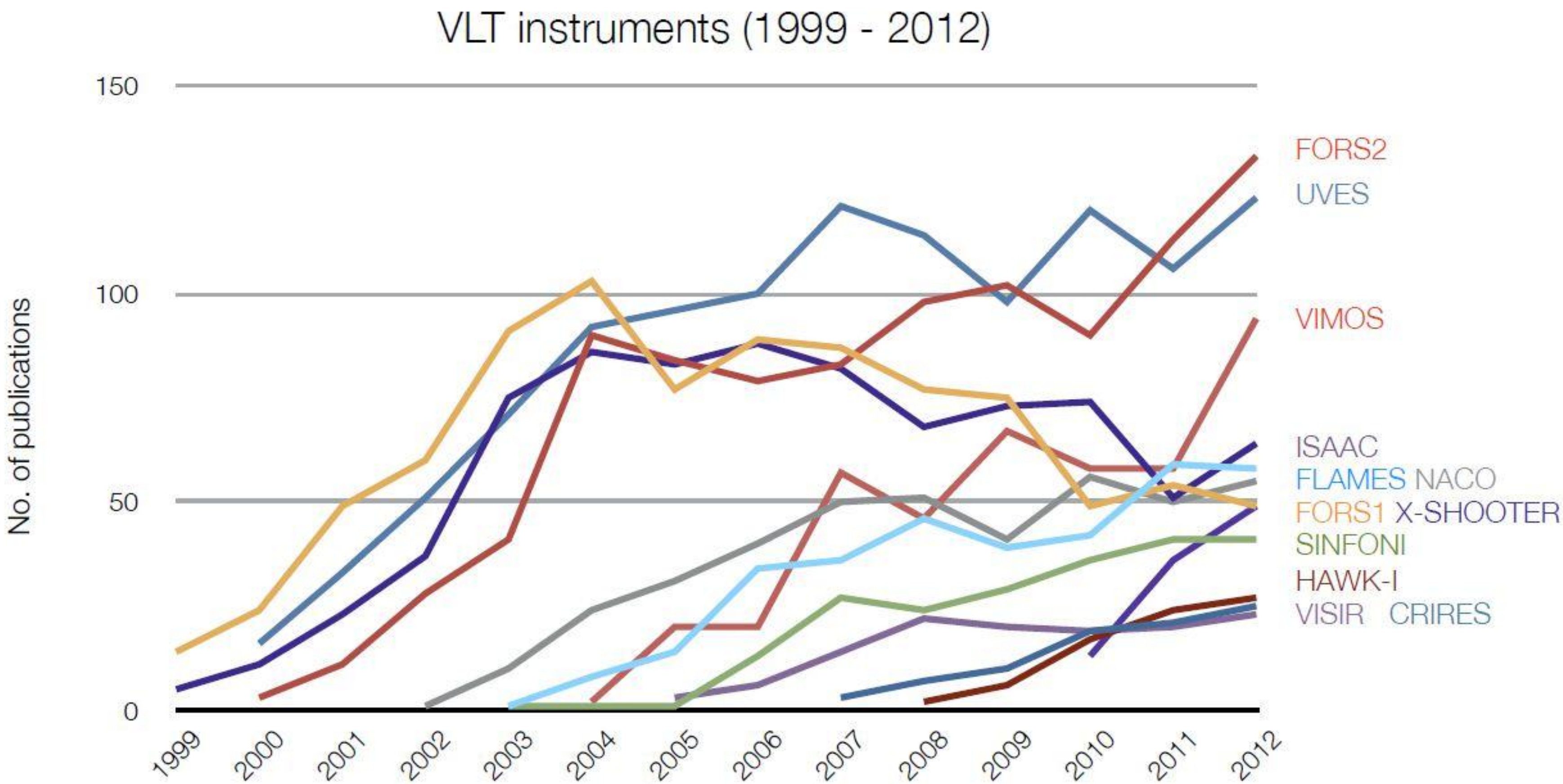


Fig. 4: Refereed publications using data from VLT instruments

FLAMES = FLAMES/UVES + FLAMES/GIRAFFE
NACO = NAOS + CONICA
SINFONI = SPIFFI + MACAO

Grothkopf & Meakins 2013