Past, present and future of IGM cosmology: from CASPEC to ESPRESSO and beyond

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Disclaimer/apologies: citations are incomplete – only 15min, including questions.

IGM - Absorption Lines – Why?

What were the physical conditions of the primordial Universe?

What fraction of the matter was in a diffuse medium and how early did it condense in clouds?

Where are most of the baryons at the various redshifts?

How early and in what amount have metals been produced?

Which constraints on cosmology & types of DM (e.g. ν) are derived from the IGM LSS?

What was the typical radiation field, how homogenous, and what was producing it?

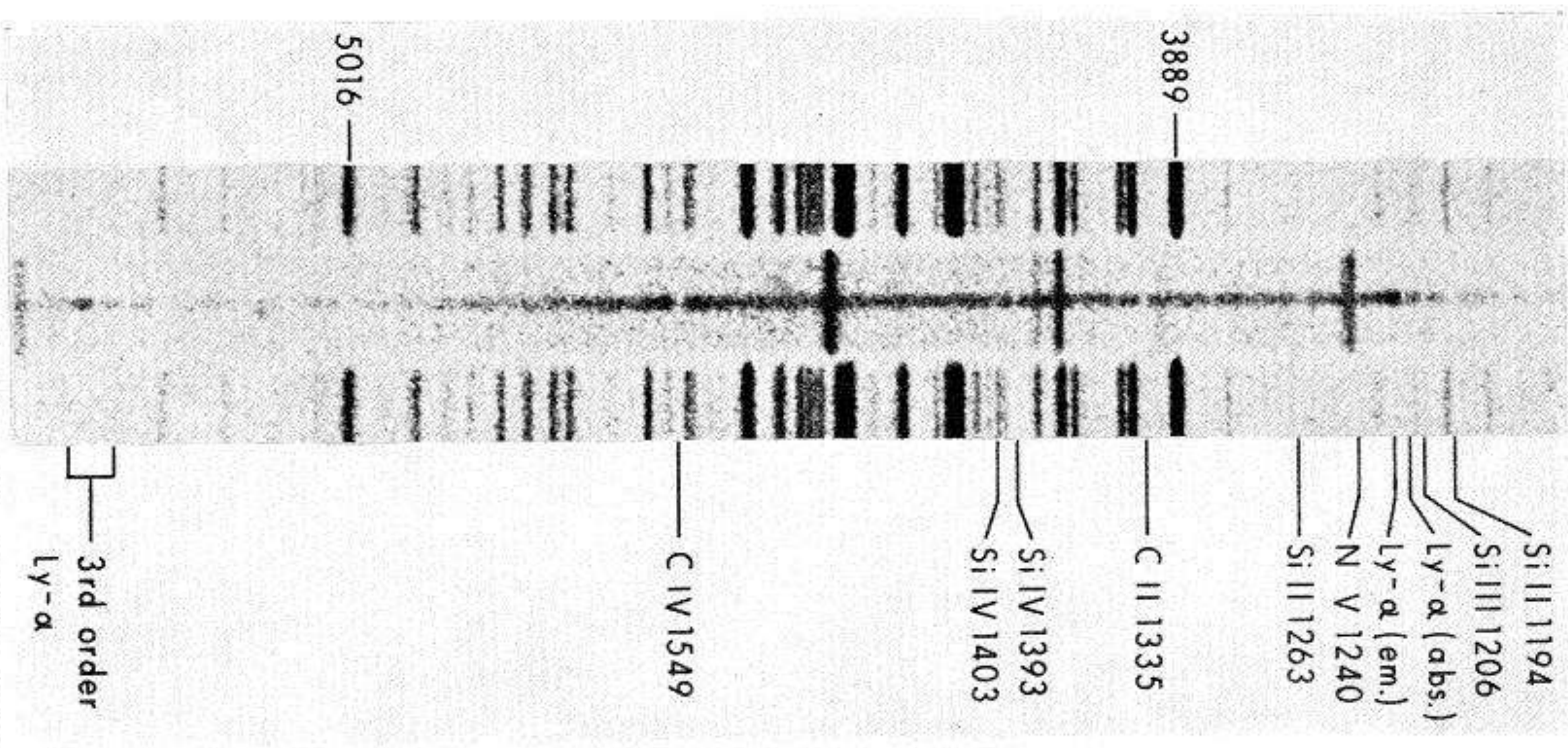
When and how, after the Dark Ages following recombination, did the Universe get reionized?

Does the SBBN correctly predict primordial element abundances and CMB T evolution?

Do fundamental constants of physics (e.g. α, μ) vary with time?

1965: Bahcall and Salpeter predict QSO absorption lines

1966: Burbidge et al. 3C191 – detected!



ig. 2 —Lick spectrum of 3C 191 obtained in February, 1966, with the prime-focus spectrograph on 120-inch telescope. The comparison spectrum shown is that of He + Ar.

due to gas emitted by the QSO itself or originated by intervening material?

1969: Bahcall & Spitzer: most absorption systems with metals produced by the halos of normal galaxies

The Lyman Forest: 4C 05.34 (Lynds, 1971)

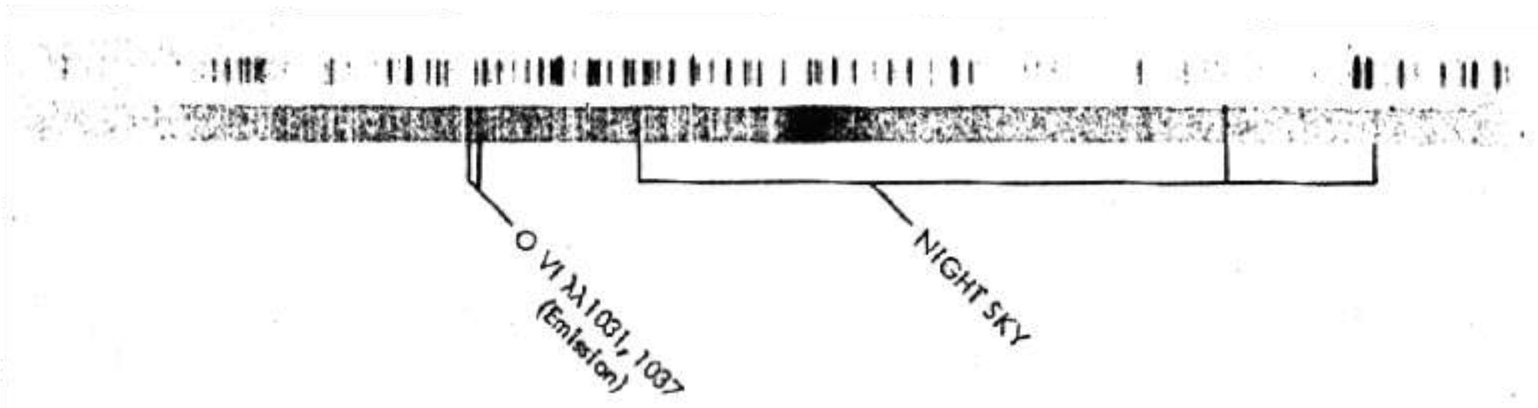


FIG. 1.—A spectrogram illustrating the numerous absorption lines in 4C 05.34. The strong emission line in the center is Lα. The O VI emission lines and several airglow features are also indicated. The comparison spectrum is He + Ar + Ne.

One of the first QSOs with z > 2.5. The region bluewards of the Lyman-emission accessible to ground observations.

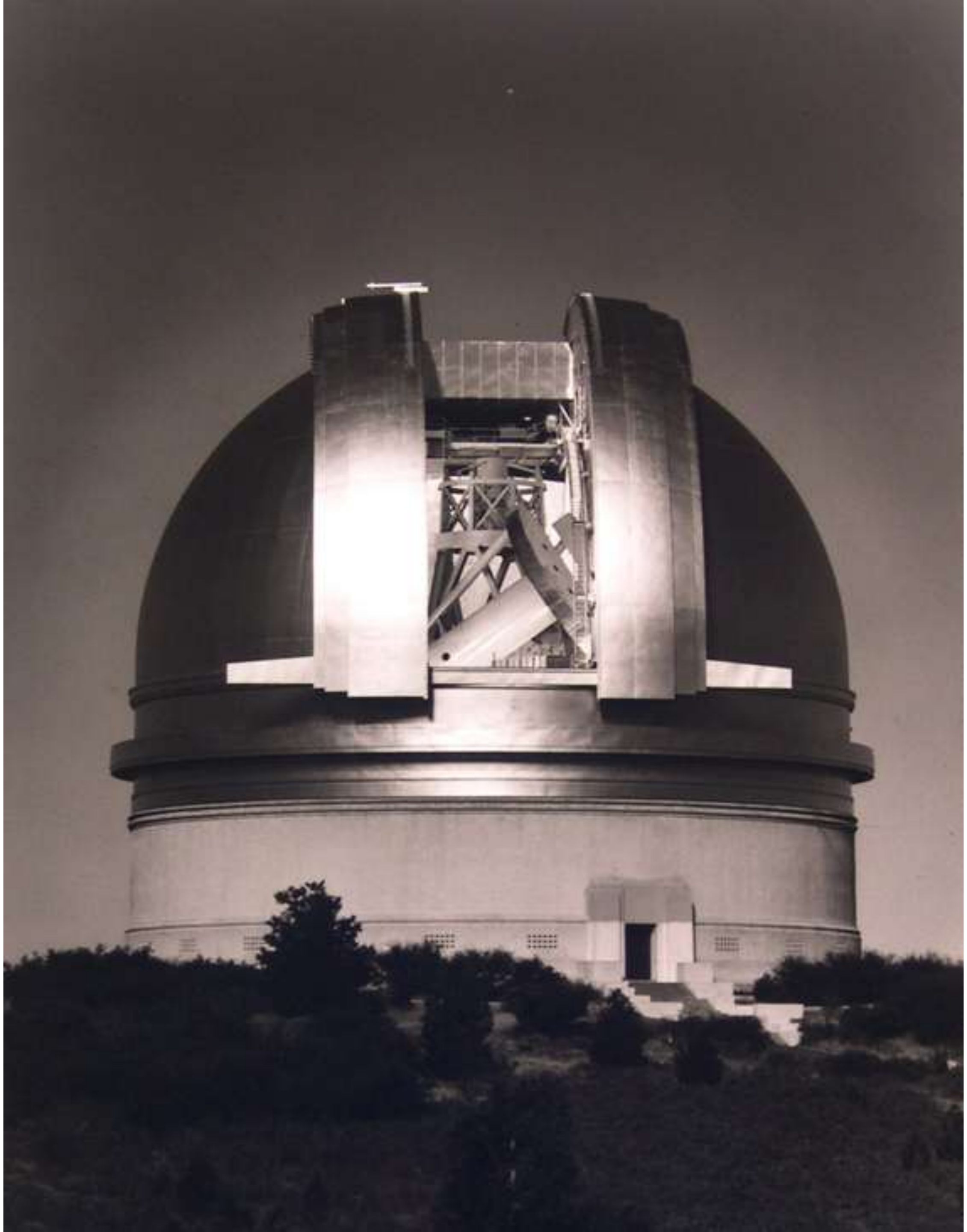
A “forest” of absorption lines, much more numerous than in the region longward the Lyman- emission.

→ **intervening Lyman-α absorbers.**

the sheer number of Lyman- forest lines strongly supported the idea that galactic and intergalactic gas, and not only material intrinsic to the QSO, is the source of most QSO absorption lines.

P200” + IPCS

e.g. Young, Sargent, Boksenberg 1982



...or the AAT

YBS 1979

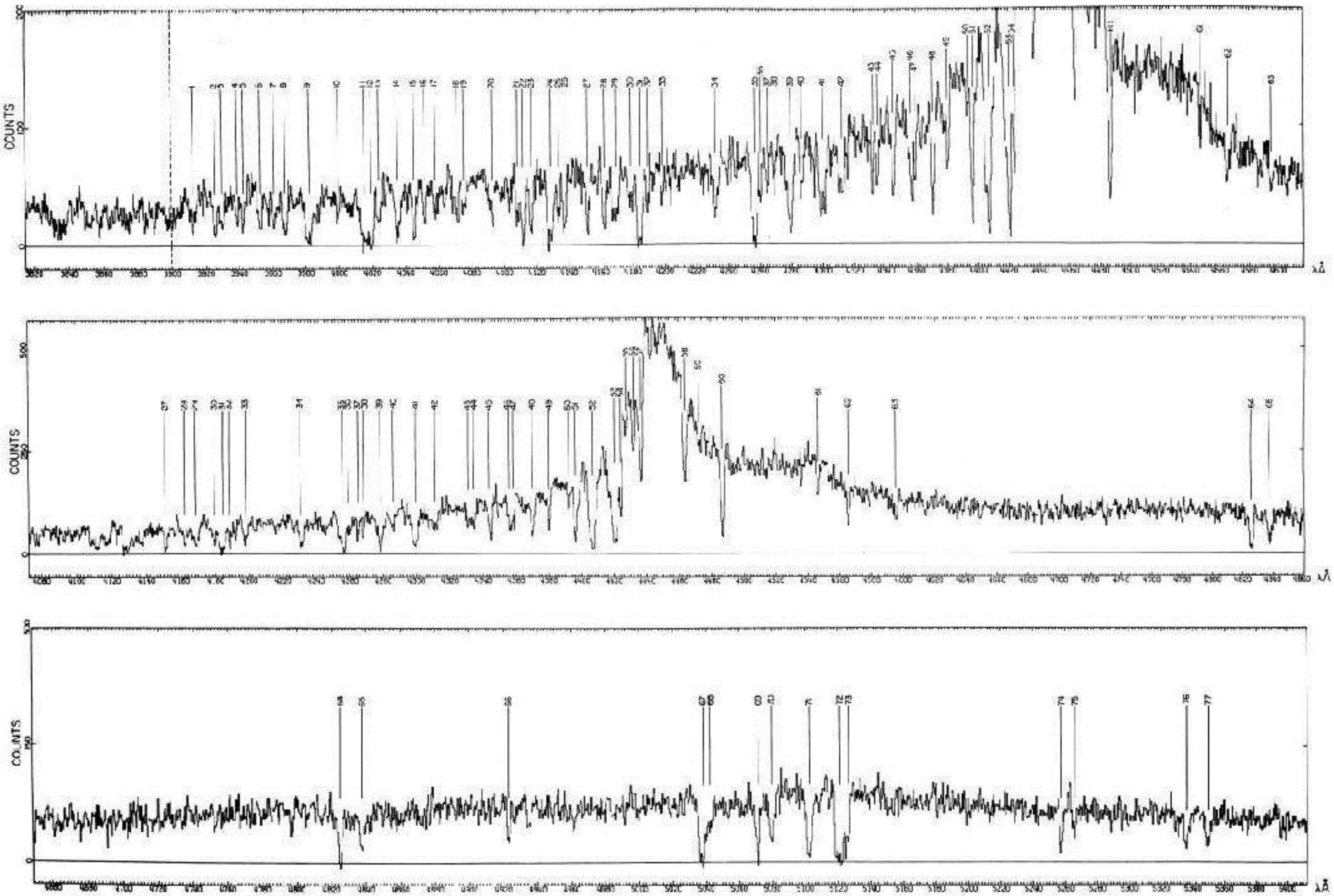


FIG. 2.—Spectrum of Q0453−423, showing three overlapping independent observations covering the range 3815 Å–5412 Å. Each bin is 25.78 km s⁻¹. The zero intensity level in each observation is indicated by a horizontal solid line. The vertical dashed line at 3900 Å shows the lower limit of usable data. The 77 absorption lines listed in Table 4 are marked and labeled.

Astron. Astrophys. 133, 374–386 (1984)

ASTRONOMY AND ASTROPHYSICS

The evolution and origin of the sharp metal-rich absorption lines in QSO spectra

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Summary. Using all high resolution data on QSO spectra available to date, we have constructed large unbiased homogeneous samples of sharp metal-rich absorption systems. In an unbiased sample of 47 QSOs there are 47 C IV doublets and only 7 Mg II doublets. Including homogeneous data on a priori known optical (and for the lowest redshifts Ca II and Na I). Very few far UV observations attempting to detect C IV at the same redshift have been made due to the low sensitivity of the UV satellite IUE (see e.g. Bergeron and Kunth, 1983a). If absorption systems are really associated with ordinary galaxies, a comparison with our Galaxy

Table 2a. C IV λλ 1548, 1550 absorption lines: extension of the YSB unbiased sample

+ SYB 82, Sargent, Young, Schneider 82, Carswell+ 82, Wright 82, Shaver+ 82, 83

QSO	z_e	z_{min}	z_{max}	z_a	W_r λ1548	W_r λ1550	S	Res Å	ref
0028+003	1.730	1.33	1.70	......	....	....		2.5	1
0029+003	2.222	1.60	2.11	1.7334	1.02	1.10	*	2.5	1
				1.9984	0.53	0.40	*		

Weymann, Carswell, Smith, 1981, ARAA,
Absorption lines in the spectra of quasistellar objects

A Turning Point: CASPEC + CCD commissioning - 1983

- first ESO-designed spectrograph for the 3.6m telescope. Echelle format, suited for 2D detectors
- based on excellent French optical design.
- (problems with the SEC Vidicon detector) proposal to use RCA 512x320 pix CCD system with fast optical camera for first light at telescope.
- Configuration well matched to the relatively poor seeing of 3.6m. Competitive for faint work at 20000 resolution, with 90nm spectral coverage
- very smooth and successful implementation
- limited on the faint limit by the CCD r.o.n.
- Providing an unique capability to European astronomers for stellar and extragalactic work

Instrumentation

ESO Annual Report 1983

The Cassegrain Echelle Spectrograph CASPEC was installed at the 3.6 m telescope with for the moment a CCD detector. A photon counting system with microchannel plate and multianode read-out has been ordered and should become available later in 1984. The first results show that the instrument fully lives up to expectations. Spectra have been obtained with a resolution of 20,000 and a signal-to-noise ratio of 50 of stars of V magnitude 13.5 in 1 hour.

the MAMA device never made to regular operation on the instrument. CASPEC was operated with CCDs till its retirement more than 10 years later.

Courtesy S.D'Odorico

Webb + 1988

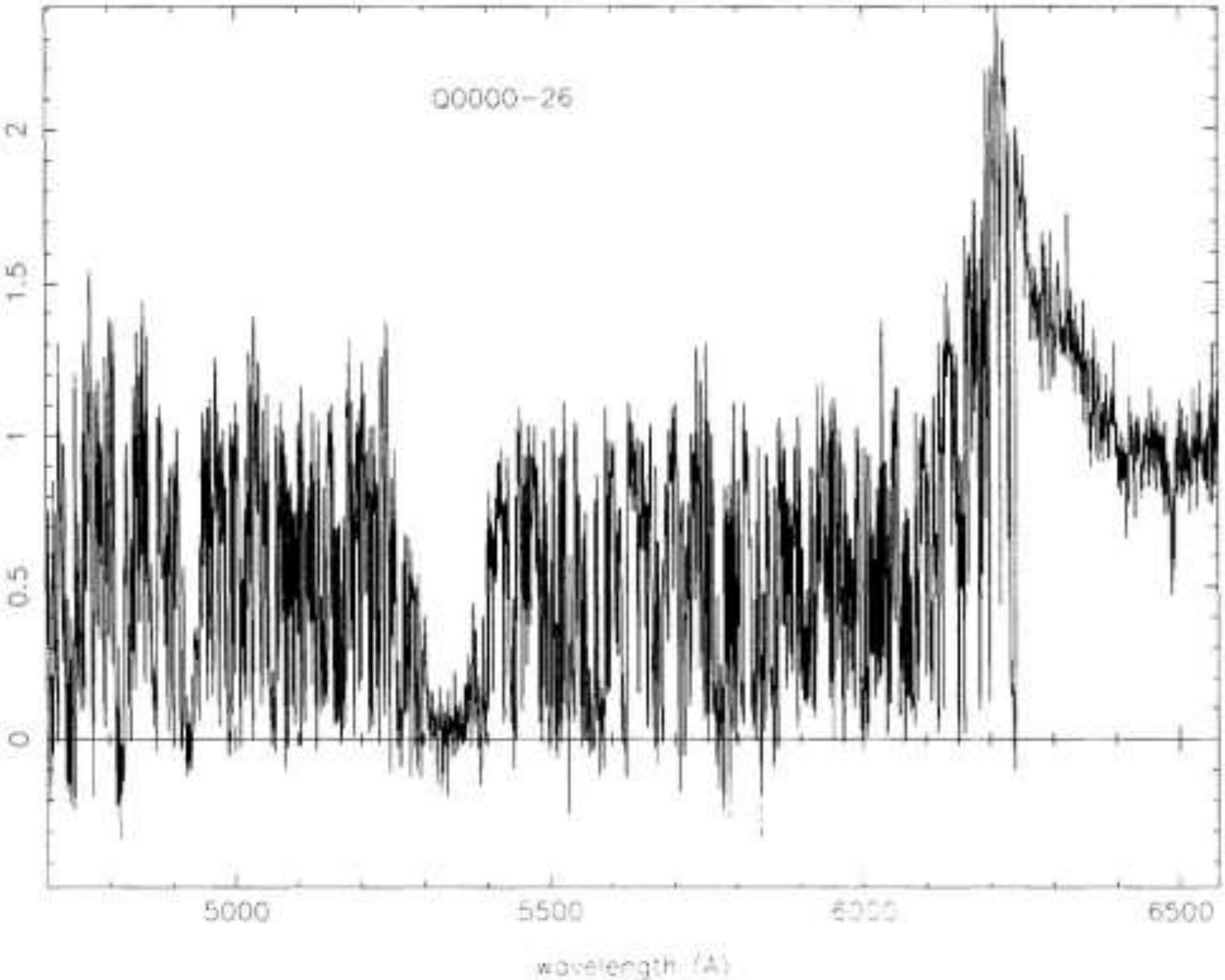


Figure 1: *The spectrum of Q0000-26 obtained using CASPEC on the ESO 3.6-m telescope. The dense Lyα forest, extending right up to the Lyα emission line at 6230 Å is clearly evident.*

Astron. Astrophys. 175, L1–L4 (1987)

ASTRONOMY
AND
ASTROPHYSICS

Letter to the Editor

Observation of the H II galaxy giving origin to the $z = 0.3930$ absorption system of the QSO 1209+107

S. Cristiani [1,2]

EFOSC

LETTER

Direct CCD images were taken in the Gunn R system on April 15 and 16, 1986; with a seeing of 1.5 and 1.3 arcsec respectively. Dark exposures and flat field exposures taken on the night sky were used to correct the raw images. The result is shown in Fig.1.

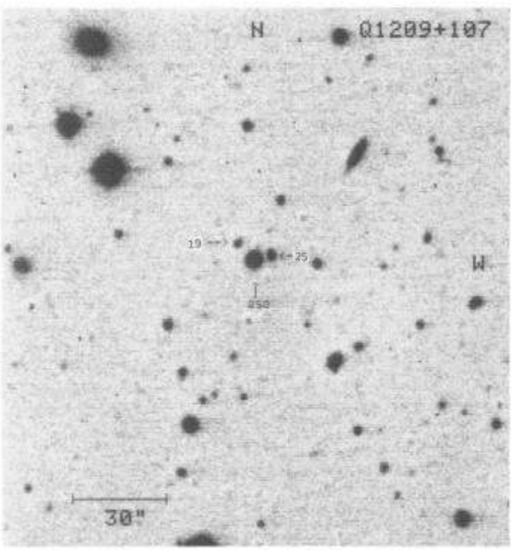


Fig.1.: the field of Q1209+107. CCD exposures taken in the Gunn R system

On April 16, spectra of the objects #14, #19 and #25 (see Table 1) were taken with the same instrument at the dispersion of 230 Å/mm, in the wavelength region 3500-7000 Å. The slit was 1.5 arcsec wide, corresponding to a resolution of 15 Å. Objects #19 and #25 were observed on the same frame, rotating the spectrograph to a position angle of 252 deg. Raw spectra were corrected using dark exposures and flat field images taken with an internal halogen lamp, then wavelength calibrated, using comparison spectra of Helium and Argon lamps, and finally flux

4. Photometry and spectroscopy

In Table 1 astrometry and photometry for 51 objects contained in a 160x160 arcsec field around the QSO (shown in Fig.1) are given together with a "point-like" or "extended" classification, according to the INVENTORY package of MIDAS.

There are 14 resolved objects, of which #19 is the closest to the QSO, at a distance of 7.1±0.1 arcseconds.

Table 1. Photometry of the field of Q1209+107

ID	DA	DD	GR	GI	GZ	ELON	PA	XFW	YFW
1	78.2	3.3	22.7	-	-	.06	5	1.4	2.0
2	74.2	-1.4	20.6	-	-	.24	55	2.7	2.1
3	72.7	-69.1	22.3	-	-	-	-	1.3	1.5
4	66.1	-74.8	23.0	-	-	.07	150	1.6	1.6
5	60.7	-31.5	23.4	-	-	-	-	1.3	1.4
6	52.0	43.9	23.1	-	-	-	-	1.4	1.4
7	51.1	65.2	18.1	-	-	.10	65	1.7	1.6
8	42.9	7.7	21.8	21.4	-	-	-	1.4	1.3
9	33.6	45.2	23.2	-	-	-	-	1.4	1.5
10	27.6	-19.0	21.2	21.3	-	-	-	1.4	1.4
11	27.0	29.4	22.0	-	-	.04	80	1.6	1.6
12	24.1	36.3	22.9	-	-	-	-	1.4	1.5
13	23.8	-64.4	21.2	-	-	-	-	1.4	1.5
14	23.0	-33.4	21.6	-	-	-	-	1.5	1.5
15	20.7	-49.8	18.4	17.3	16.7	-	-	1.5	1.5
16	16.8	-42.1	22.2	-	-	-	-	1.4	1.5
17	13.0	-40.3	22.9	-	-	-	-	1.2	1.6
18	6.9	-28.8	22.7	-	-	.10	160	1.6	1.6

To check wether a galaxy closer on the sky from Q1209+107 than object #19 is hidden in the image of the QSO itself, a point source profile, derived from the stars on the same CCD frame has been subtracted to the quasar. This procedure shows that there is no other object of equal or brighter magnitude and similar angular size to that of #19 at a distance larger than 2 arcsec from the quasar. The nature of three objects, #14, #19 and #25, was investigated spectroscopically: #14 and #25 turned out to be stars. The spectrum of object #19, integrated over 1.5x2.0 arcsec is shown in Fig.2.

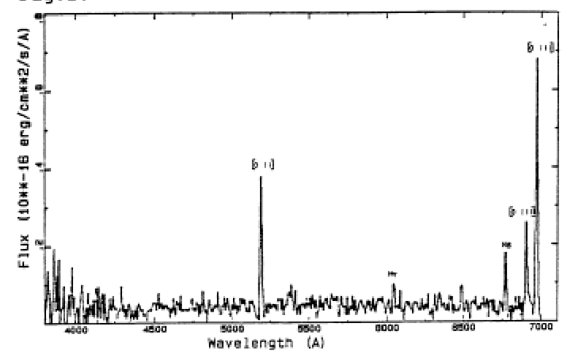


Fig.2: Flux-reduced spectrum of object #19.

Several emission lines are detected, all unresolved. Their wavelengths, intensities and redshifts are listed in Table 2.

Table 2. Emission lines observed in the spectrum of galaxy 19.

Rest. λ(Å)	Ident.	Inten.	Redshift
3727.5	[OII]	4.2	0.3918
4340.5	Hγ	0.6	0.3924
4861.3	Hß	1.5	0.3924
4958.9	[OIII]	3.6	0.3921
5006.8	[OIII]	8.8	0.3921
			0.3922±0003

…ies are given in units of …/s/cm^2. The internal error on …y measurements is 0.2 · 10^{-16} …2.

… measured redshift for the object 19 …3922±0.0003, equal within two sigmas …edshift z=0.3930 of the absorption …measured by Young et al. (1982) in …trum of Q1209+107.
… spectrum of object 19 is typical of …alaxies, i.e., galaxies with …

5. Di…
T… observ… redshi… emissi… veloci… rest … origin… associ… possib…
T… to the… a Hubb… spectr… same r… absorp…
T… detect… arcsec… Howeve… distri… field,… anothe… center… high … confir…
I… demons… absorb… Z=0.39… the HI… from t…
A… Burbid… the BL… system… the sp… object… of the… was o… spectr… materi… system… consid…
a… b… the BL…
S… more … becaus… nebulo… than t… lumino…
T… Q1209+… case o… two … lumino… within… that t… the c… the em… the a… nebulo… a mod… unless… explan…

Lyα

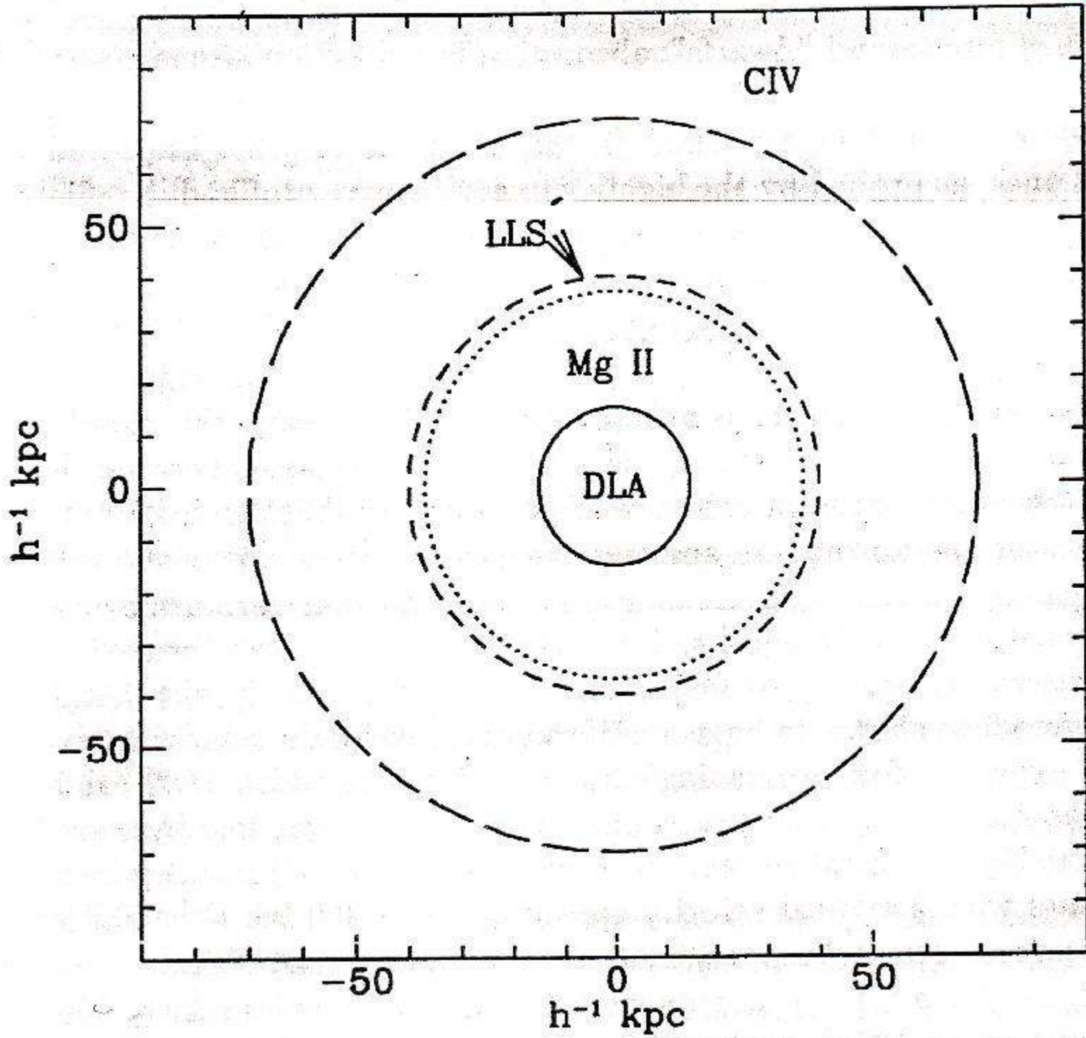


Fig. 1. Schematic diagram illustrating an over–simplified view of the structure of an "L^*" galaxy as deduced solely from the statistics of the various classes of metal line absorption systems. Note that the Mg II and Lyman limit selected systems have the same cross-section, and that the damped Lyman α systems have a cross–section which is only a few percent of the total.

Identifying the absorbers: from N(z) to N(V) and σ

$$N_{co}(V)\ \sigma = N(z)\ \frac{H_o}{c}\ \frac{E(z)}{(1+z)^2}$$

J.Bergeron +

1995MNRAS.273.1016C

1020 *S. Cristiani et al.*

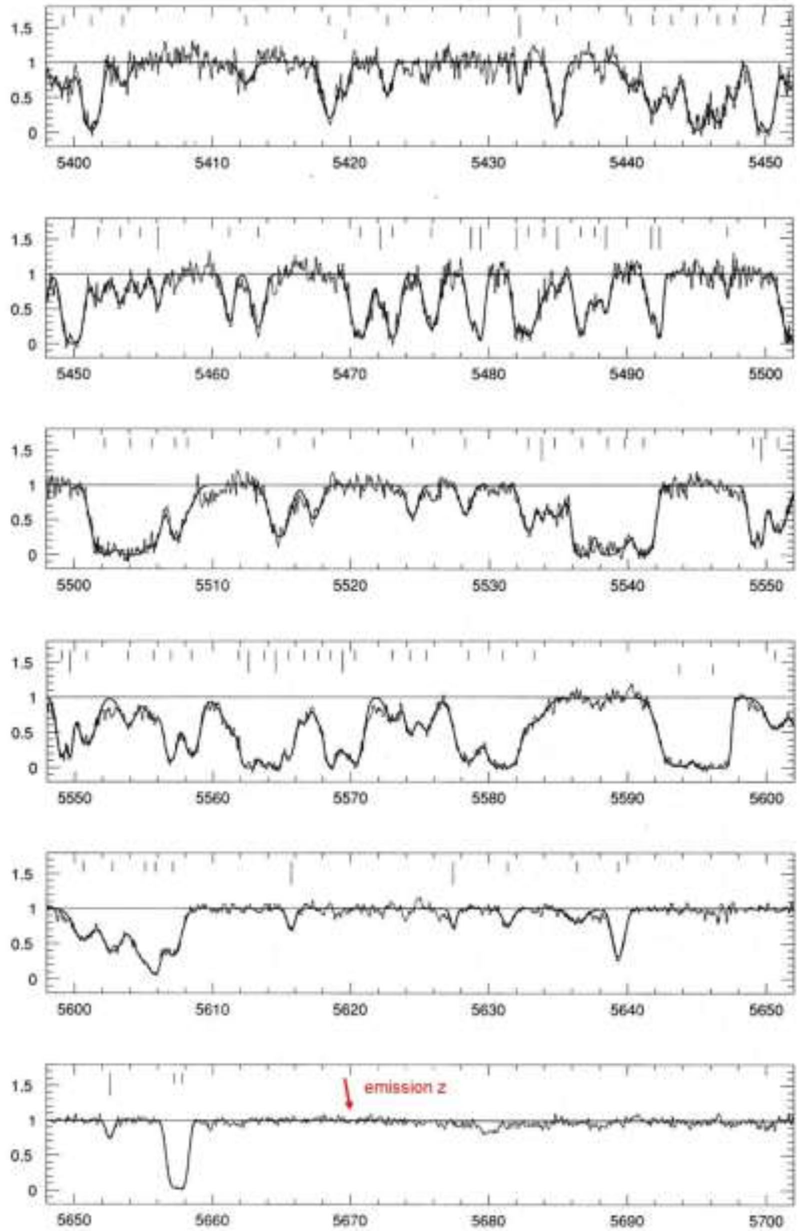


Figure 1 – *continued*

EMMI echelle spectra

←Q0055-269

Early-mid 90's

The UV background via the proximity effect

(MaxLik: Giallongo, SC+ 1996)

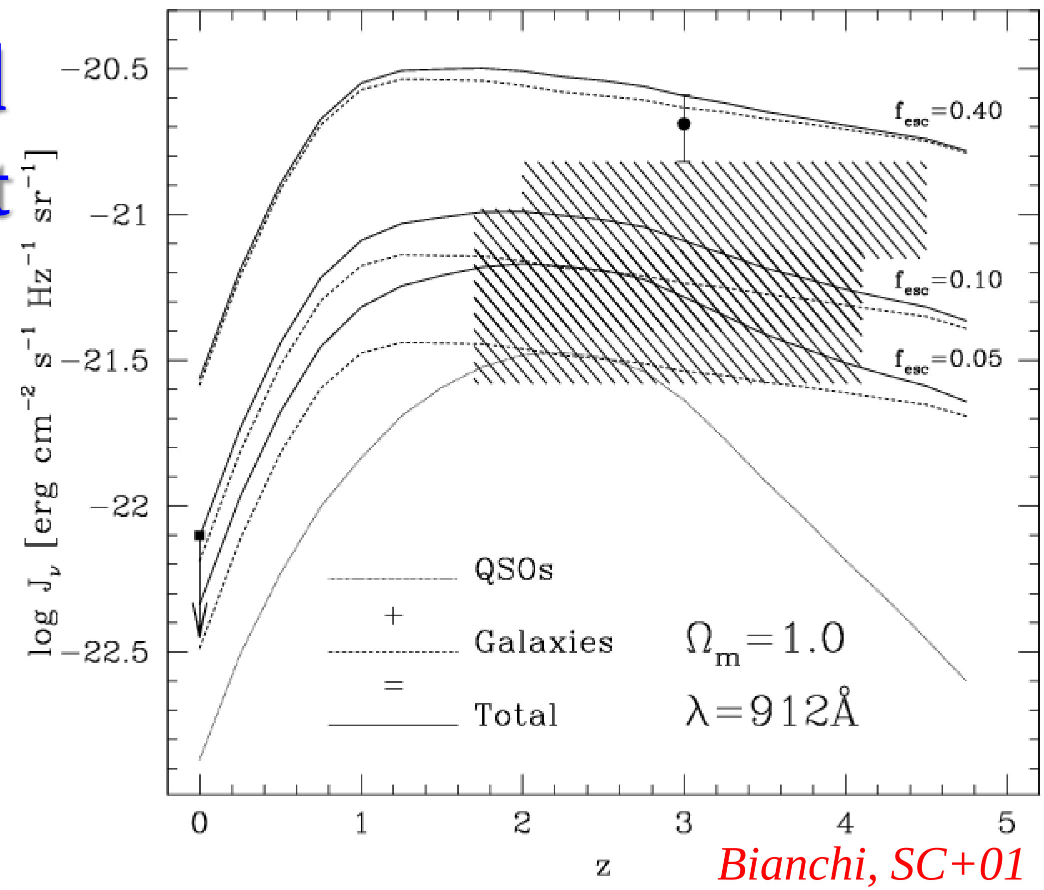
$$N_{HI} = \frac{N_\infty}{1+\omega} \qquad \omega(z) = \frac{F}{4\pi J}$$

Conservation Law

$$f(N) = g(N_\infty)dN_\infty/dN = g(N_\infty)(1+\omega)$$

$$\frac{\partial^2 n}{\partial z \partial N_{HI}} = A_o(1+z)^\gamma (1+\omega)^{1-\beta_f} \begin{cases} N_{HI}^{-\beta_f} & N_{HI} < N_{break} \\ N_{HI}^{-\beta_s} N_{break}^{\beta_s-\beta_f} & N_{HI} \geq N_{break} \end{cases}$$

N$_l$	γ	β_f	$\log N_{\infty,b}$	β_s	$\log J$	
1128	2.49±0.21	1.10±0.07	14.00±0.02	1.80±0.03	-21.21±0.07	
	2.65±0.21	1.34±0.07	13.98±0.04	1.80±0.03	-21.32±0.08	–



Bianchi, SC+01

$J_{22} = 5 \pm 1$

The Lyman-forest IGM revolution

High-res, high S/N spectra → clustering, metallicity (Cowie+ 95)

Increasing clustering with increasing NHI (i.e. density contrast)

Cristiani, D'Odorico, Giallongo et al, 1995,1997

Clustering properties of Lyman α clouds 211

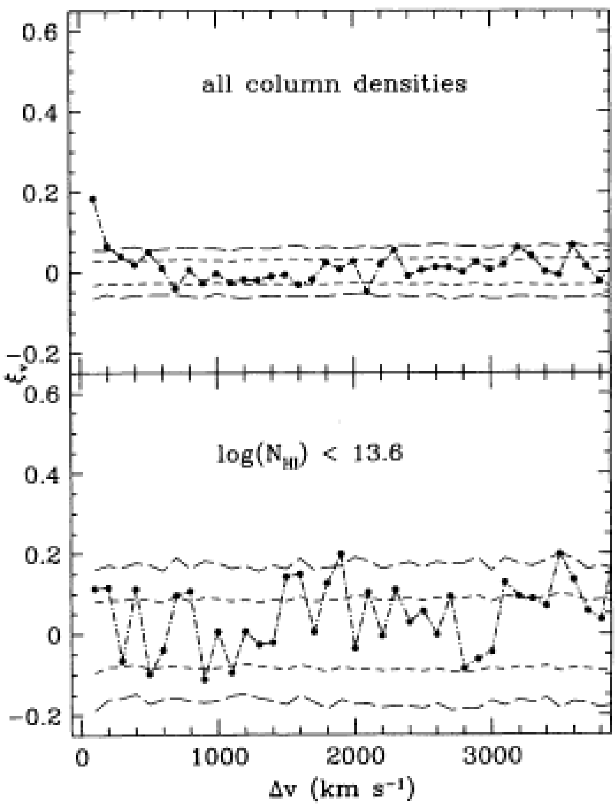


Figure 1. Two-point correlation function in the velocity space.

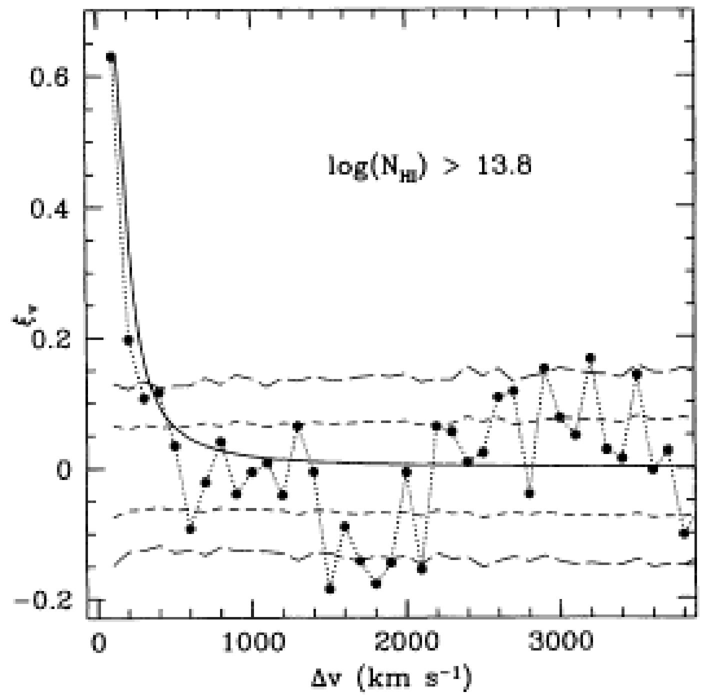
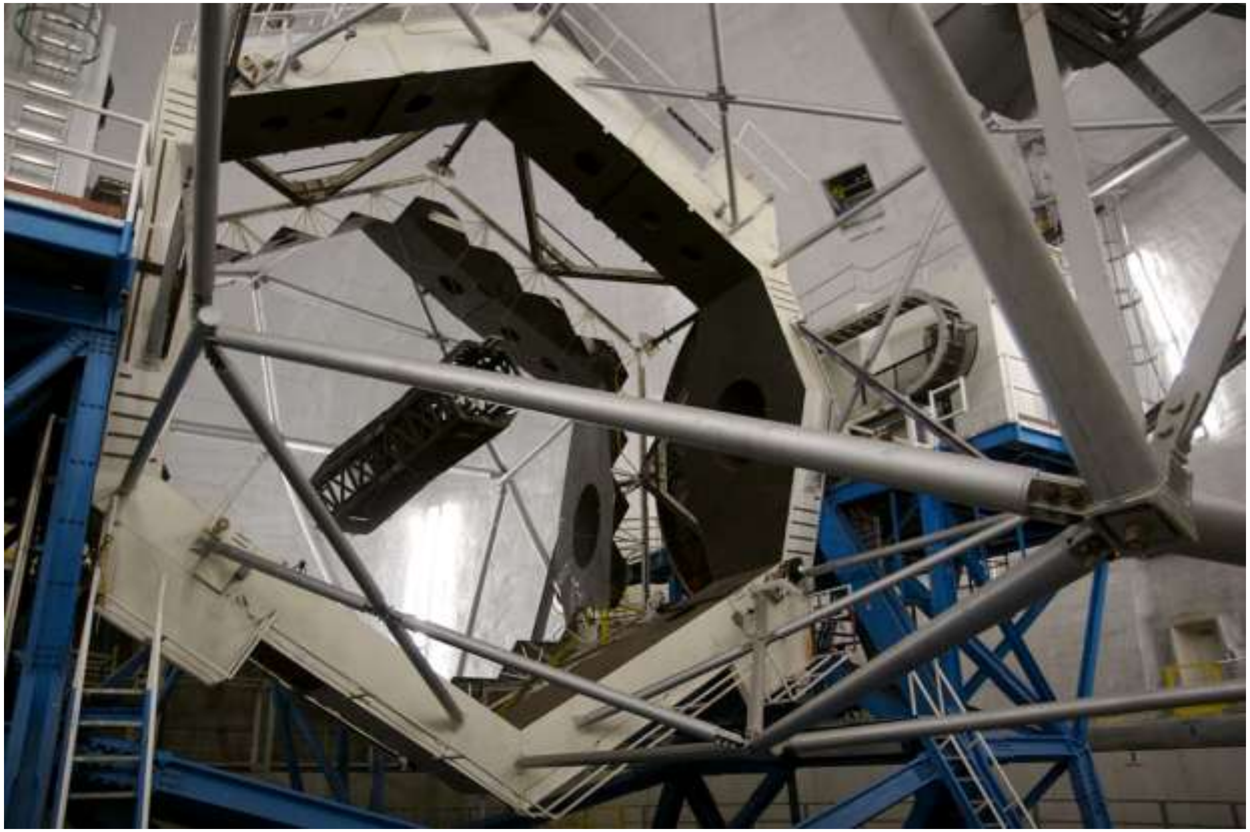
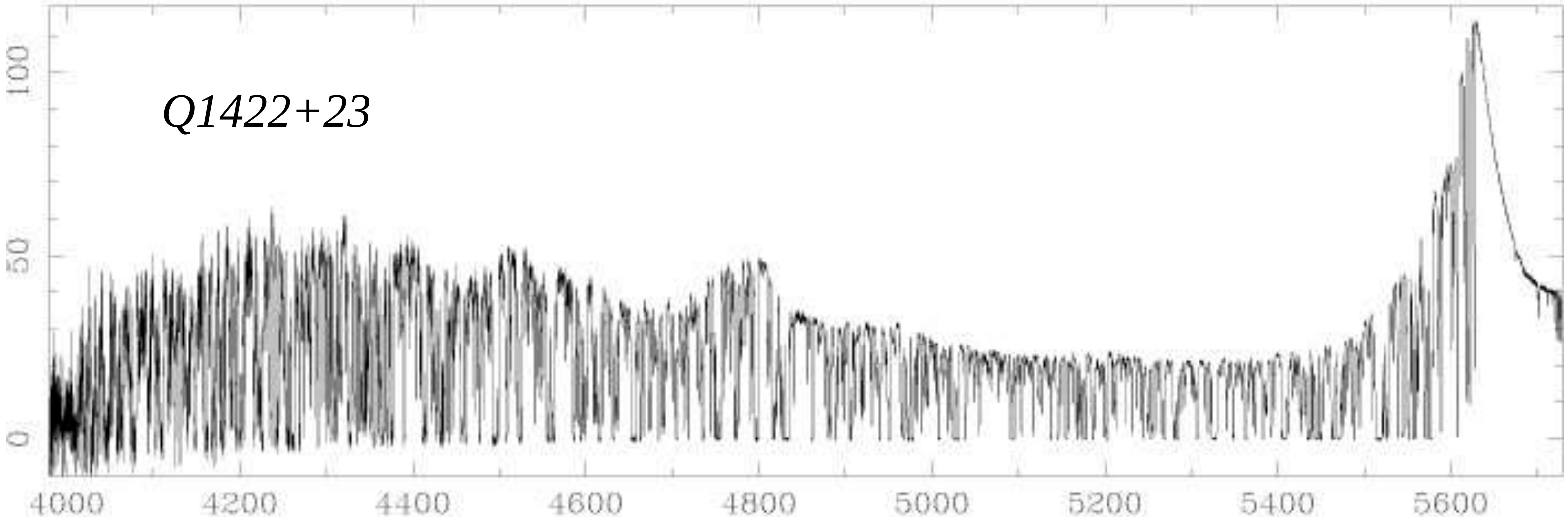


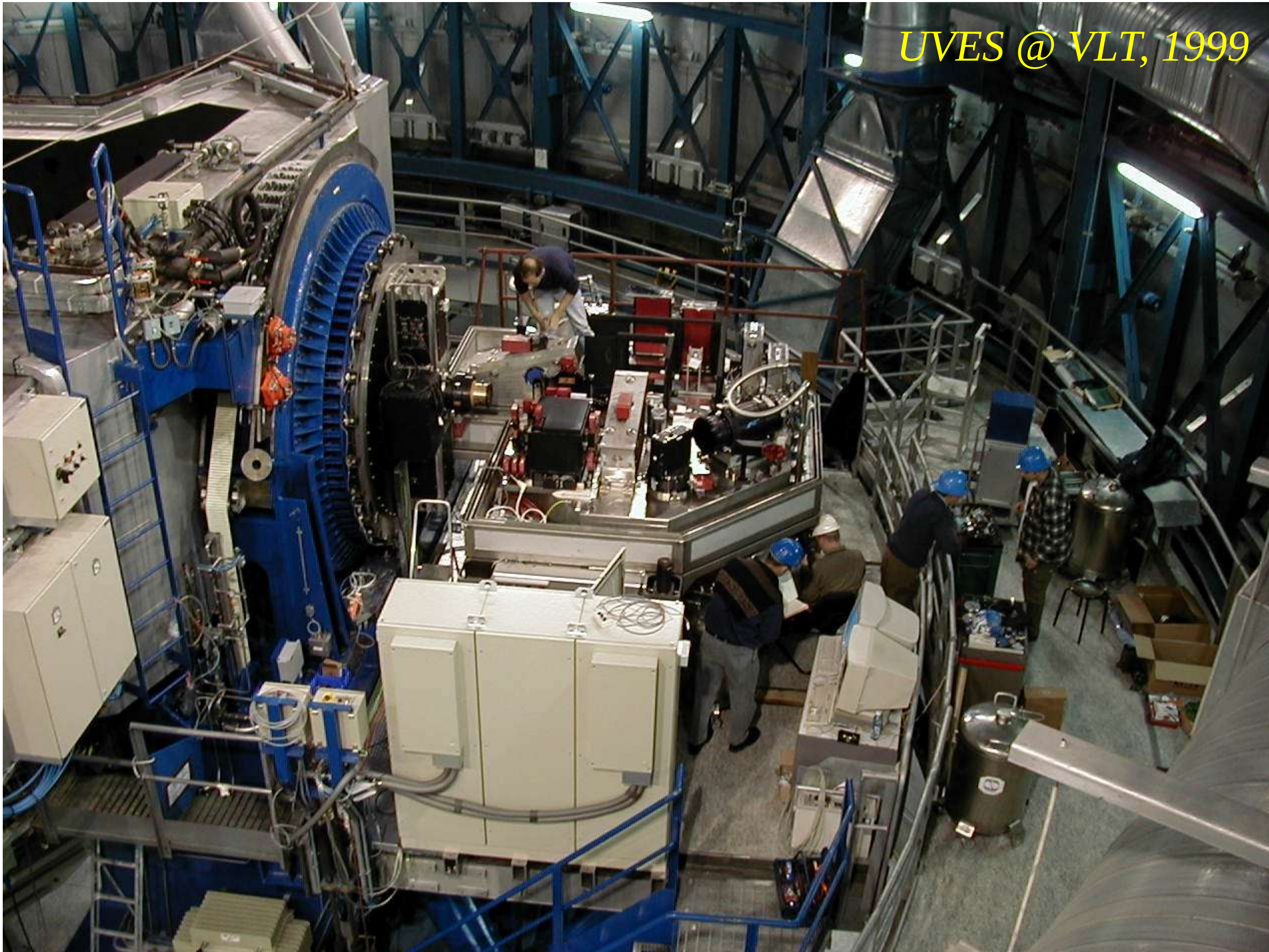
Figure 2. Two-point correlation function in velocity space for lines with column densities $> 10^{13.8}$ cm^{-2}. Confidence limits are as in Fig. 1. The continuous line shows the model described in Section 4, equation (4), with $\gamma = 1.77$, $\sigma = 50$ km s^{-1}, $r_{cl} = 180\ h_{50}^{-1}$ kpc and $r_0 = 250\ h_{50}^{-1}$ kpc at $z = 3$.

HIRES
@ Keck!

1995

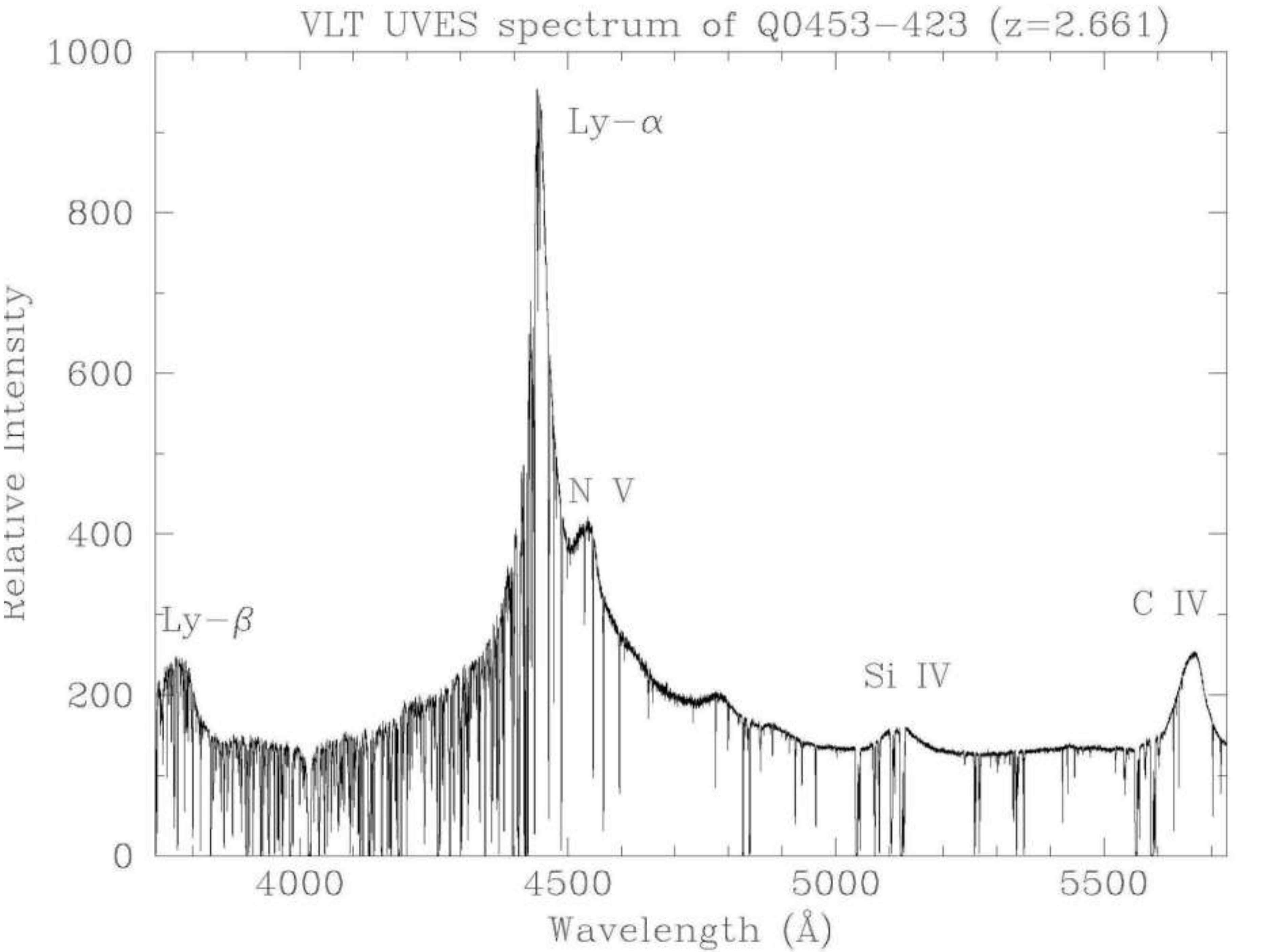





UVES @ VLT, 1999

Echelle Spectrum of QSO HE2217-2818 (330 - 450 nm)   (VLT KUEYEN + UVES)

ESO PR Photo 37d/99 (5 October 1999)


VLT UVES spectrum of Q0453−423 (z=2.661)
Ly−α
N V
Ly−β
Si IV
C IV
Relative Intensity
Wavelength (Å)
0
200
400
600
800
1000
4000
4500
5000
5500

The Large Programme "Cosmic Evolution of the IGM"

Metal enrichment, clustering properties and main heating process of the intergalactic medium can be probed by analyzing the numerous Lyman "forest" lines in the spectra of distant quasars and their associated, absorption metal lines. Constraints can then be placed on the scenarii of structure formation, the origin of metals and how they have been expelled in the intergalactic medium, and the spectral shape of the metagalactic UV flux.

J. Bergeron[1], P. Petitjean[1,2],
B. Aracil[3], C. Pichon[1],
E. Scannapieco[4], R. Srianand[5],
P. Boissé[1], R. F. Carswell[6],
H. Chand[5], S. Cristiani[7],
A. Ferrara[8], M. Haehnelt[6],
A. Hughes[1], T.-S. Kim[6],
C. Ledoux[9], P. Richter[10],
M. Viel[6]

ESO Messenger 118, 40

The history of the Universe in its formative stages is recorded in the ubiquitous intergalactic medium (IGM), which contains almost all of the residual baryonic material from the Big Bang. During the epoch of structure formation, the IGM became highly inhomogeneous and acquired peculiar motions under the influence of gravity. It was the source of gas that accreted, and then cooled to form stars, and was also the sink for the metal-enriched gas and radiation produced by the population of primordial objects. Absorption lines in quasar spectra thus trace not only the chemical composition of the IGM, but also the density fluctuations in the early Universe and the background UV flux.

The IGM is revealed through numerous H I absorption lines in the spectra of remote quasars, the so-called Lyman-α forest. Numerical simulations and analytical modelling of a warm (~10^4 K) photoionised IGM within a cosmological context successfully reproduce many observational properties of the Lyman-α forest: the column density distribution, the Doppler parameter distribution, the flux decrement distribution and

From Early Models of the IGM…

Discrete Clouds

- Clouds →Voigt Profiles →Too Low Density & Too high ionization → No star formation
- No metals, No clustering, too many → unrelated to galaxies

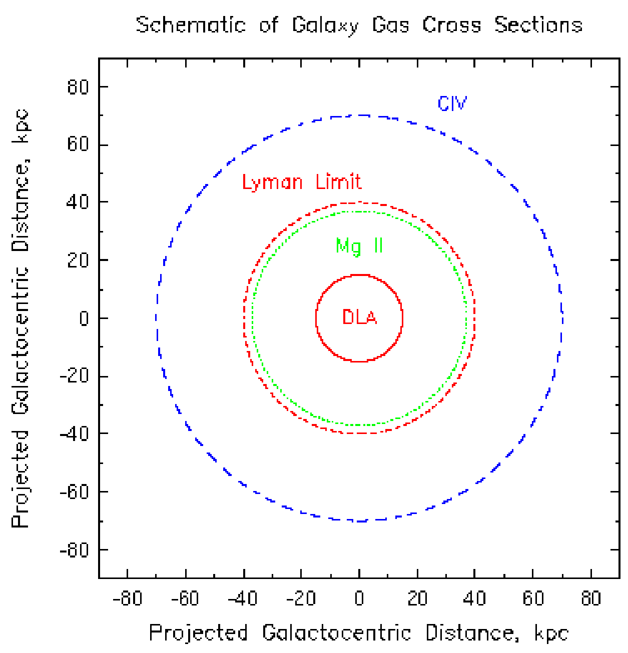
Pressure confined by a hotter and more tenuous ICM

PROBLEMS

- COBE (1989) limits

on hot intra-cloud medium

- Range in N_{HI} - very large
- N(z)
- How did the clouds form??

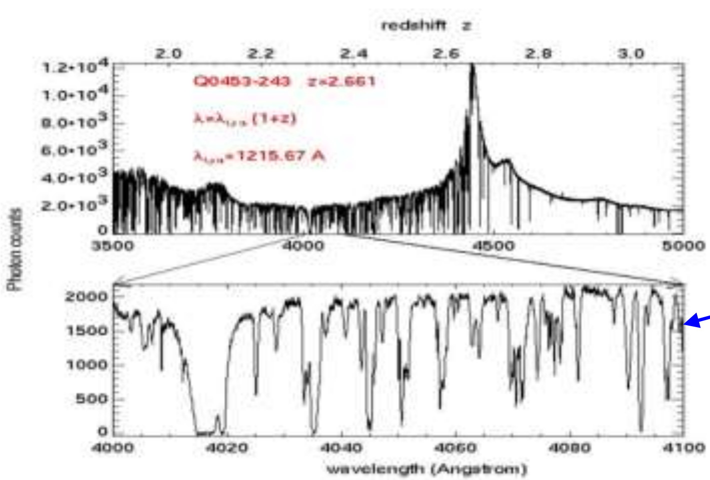


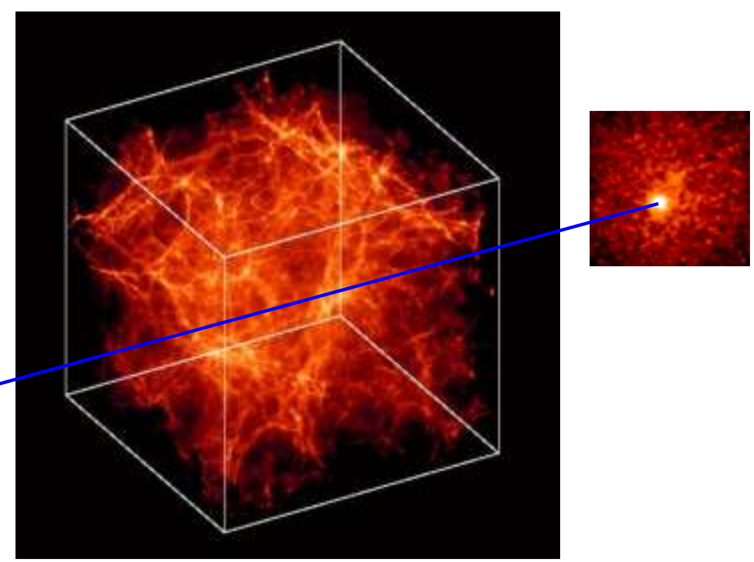
…to a new IGM paradigm: <u>the Cosmic Web</u>

THE RISE OF DM MODELS – minihalos (Rees 86)

Cosmological Hydro simulations

- large number of collapsed DMH - too small to form stars and turn into galaxies
- Warm photoionized IG gas sinks into mini-halos or accretes onto DM filaments and sheets
- thermal gas Press. prevents further collapse (i.e.no star formation)
- visible only in absorption



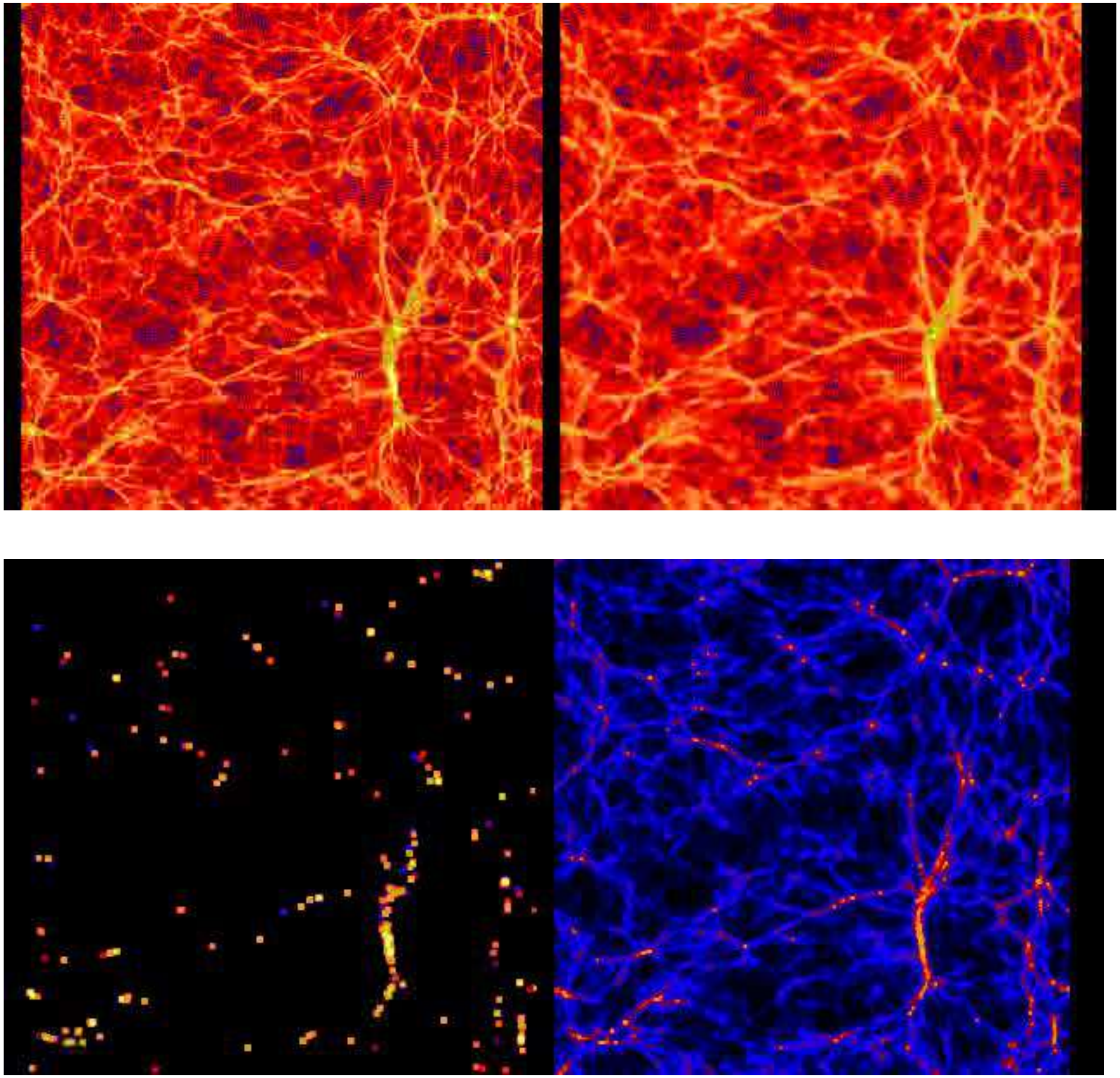


$\Omega_m = 0.26$ $\Omega_\Lambda = 0.74$ Ω_b=0.0463   H = 72 km/sec/Mpc   - 60 Mpc/h

COSMOS computer – DAMTP (Cambridge)

DM

GAS



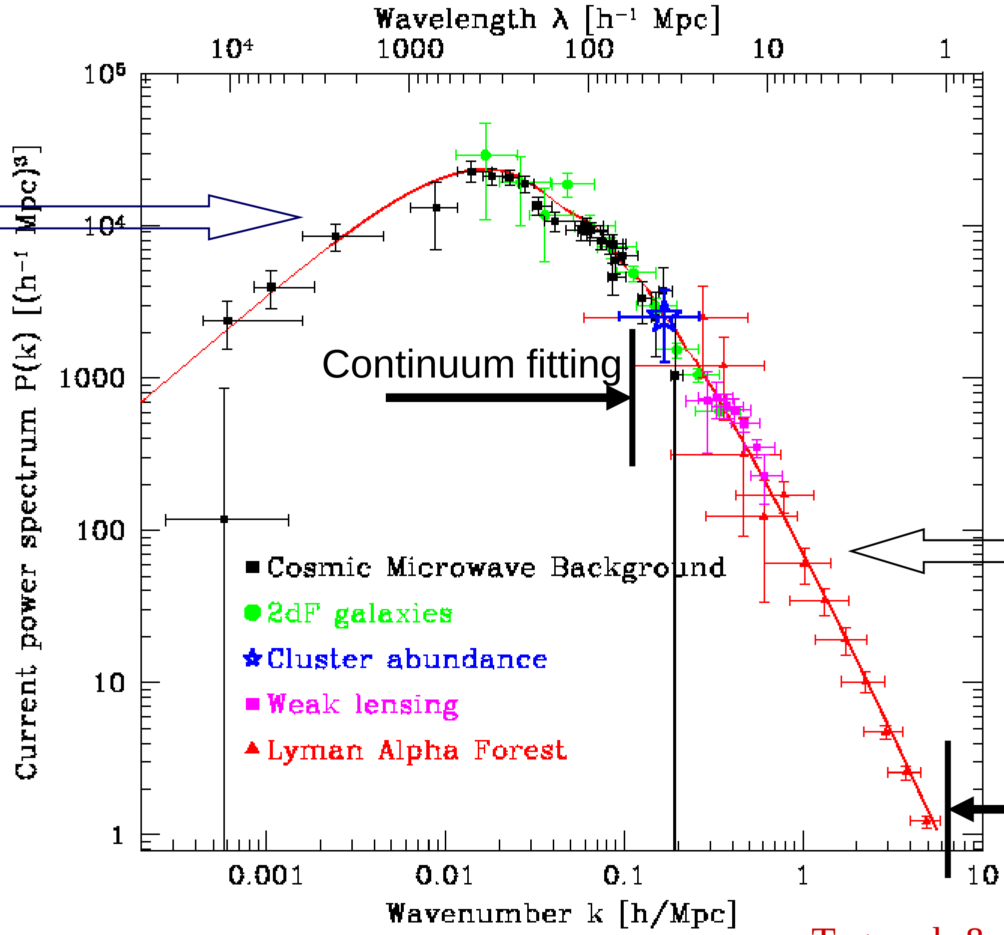
STARS

NEUTRAL HYDROGEN

Courtesy M.Viel

GOAL: the primordial dark matter power spectrum

CMB physics
$z = 1100$
dynamics



Lyα physics
$z < 6$
dynamics
+
termodynamics

Temperature, metals, noise

Tegmark & Zaldarriaga 2002

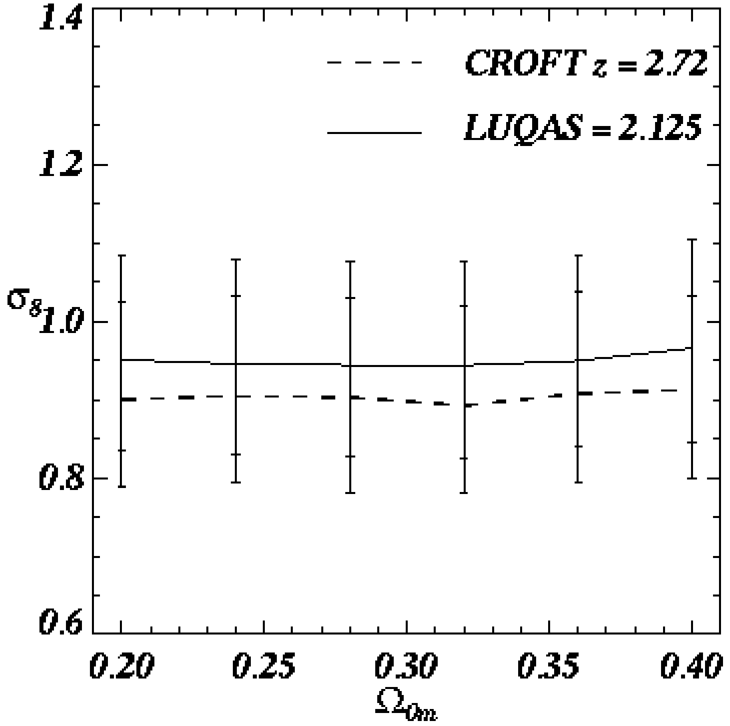
CMB + Lyman α → Long lever arm

Constrain spectral index and shape

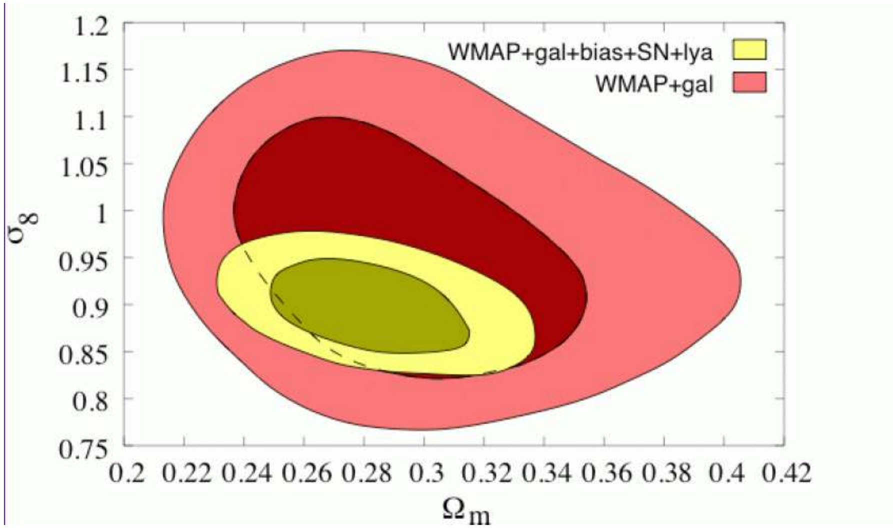
Relation: P_{FLUX} (k) - P_{MATTER} (k)?

Cosmological implications: combining the forest data with CMB

Viel, Haehnelt, Springel 2004



SDSS Seljak et al. 2004



$n = 1.01 \pm 0.02 \pm 0.06$

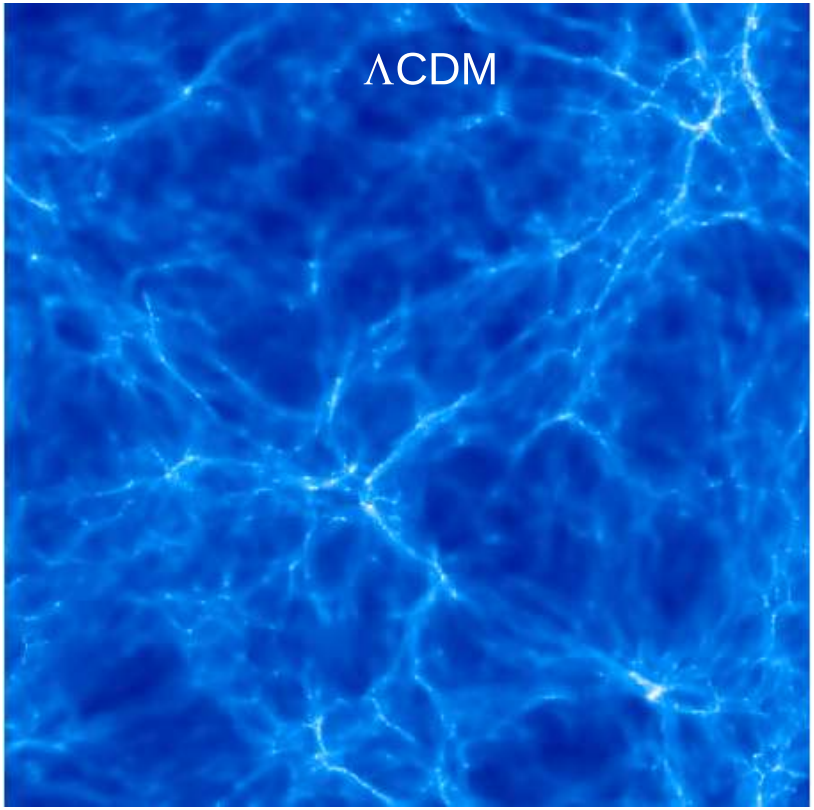
$\sigma_8 = 0.93 \pm 0.03 \pm 0.09$

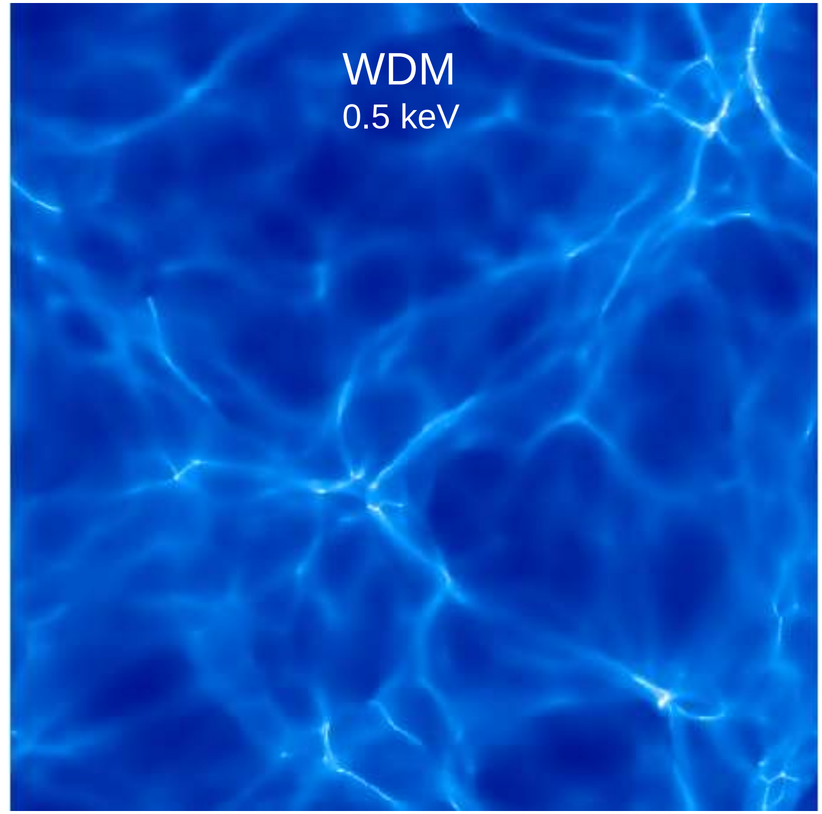
Systematic error

Statistical error

e.g. the **Large sample of UVES QSO Absorption Spectra (LUQAS)**
Kim, Viel, Haehnelt, Carswell, Cristiani 2004

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

Ly-alpha forest as a tracer of dark matter

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

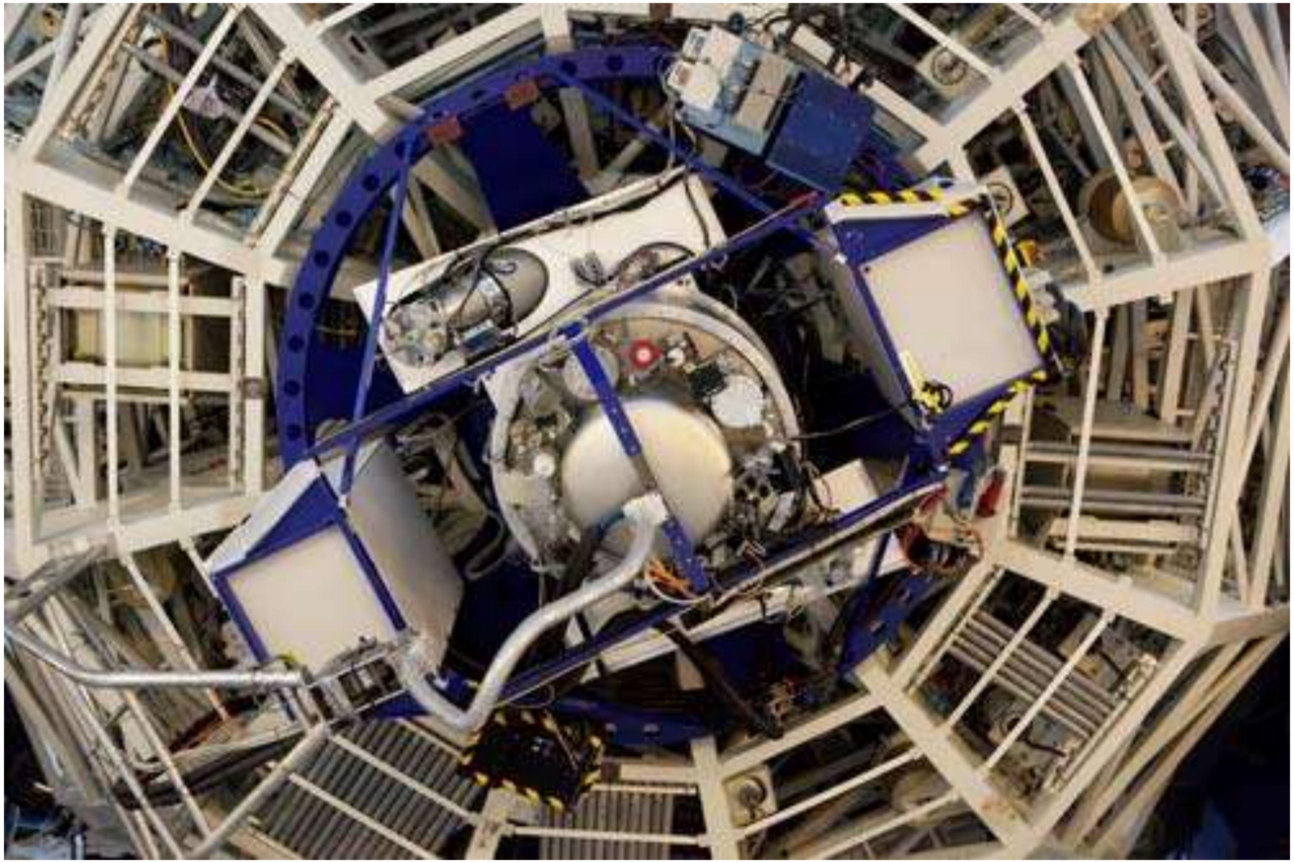
Density and temperature are correlated, modeled as a power law with slope γ and amplitude To

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

The astrophysics uncertainties in the model can be parametrized with γ, To and mean flux F (UV background) as a function of z

They all have external constraints; (main problem is mean flux constraint, which is poorly determined)

Sensitivity and IR: X-shooter

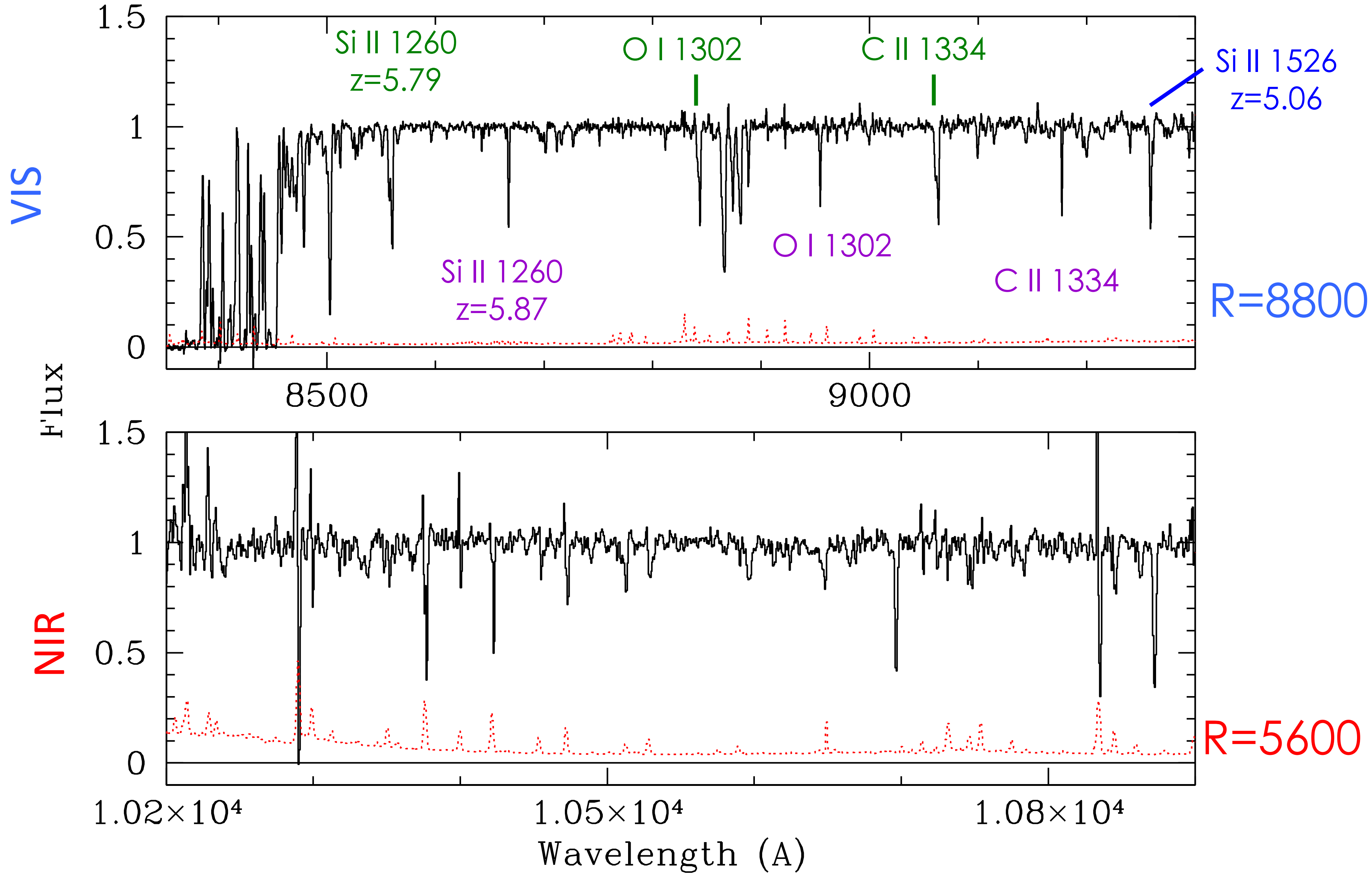


LP: QSOs and their absorption lines: a legacy survey of the high-z Universe (2012)

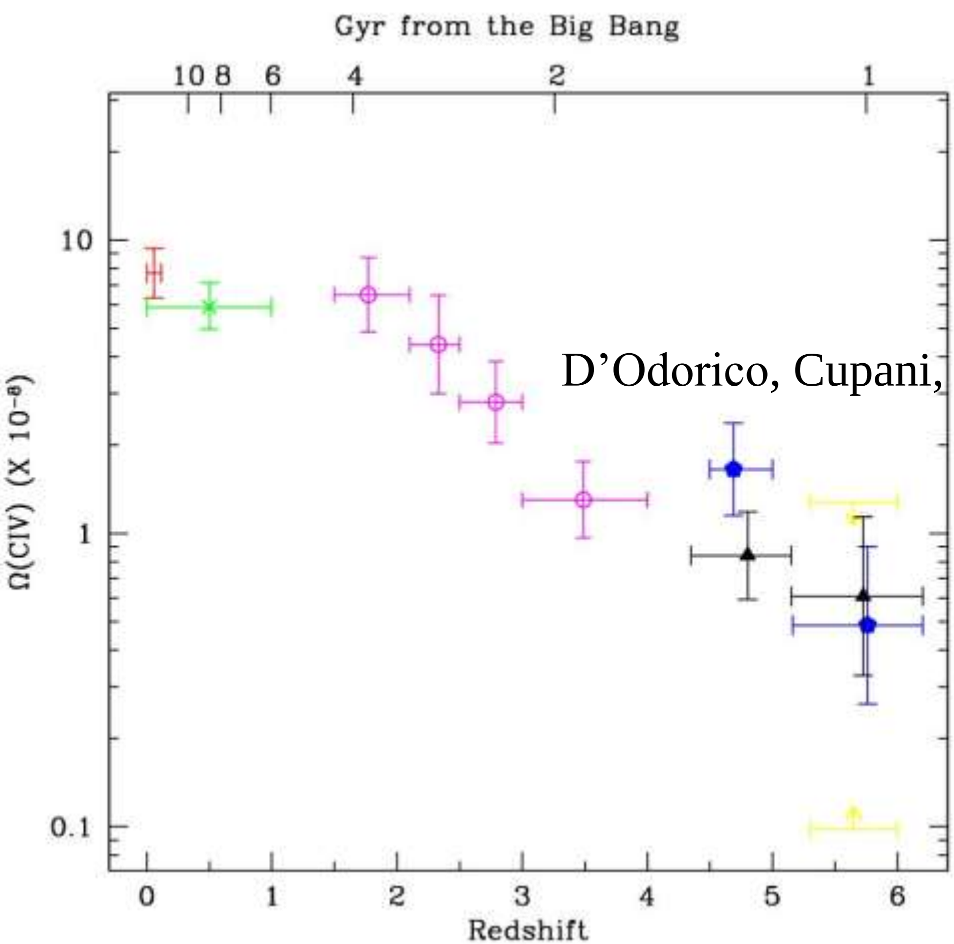
100 h **(P.I. S.Lopez + Cristiani, Cupani, V.D'Odorico, Viel, Christensen, Dessauges, Ellison, Becker, Haehnelt, Menard, Paris, Prochaska, Hamann, Worseck)**

V.D'Odorico + 2010

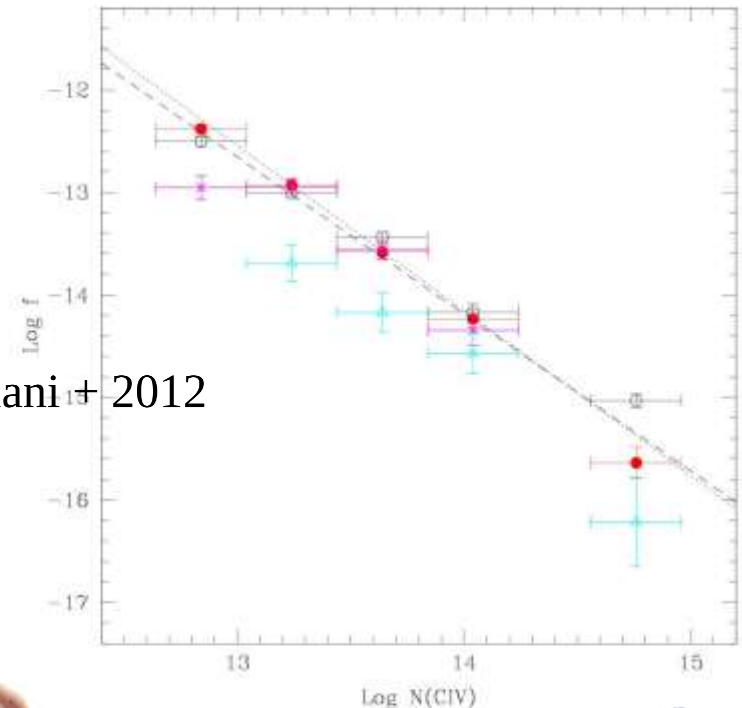
X-shooter spectrum: J0818+1722 (z_{em} = 6.00, J_{vega} = 18.5)

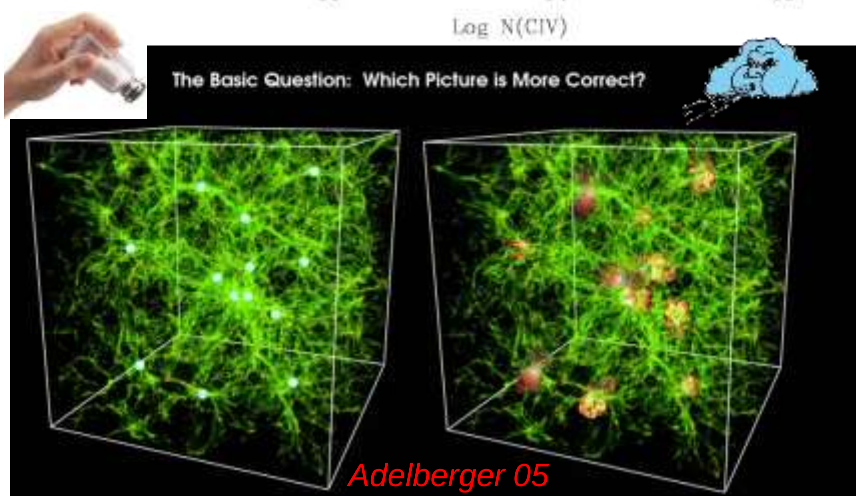


Metal pollution in the Universe



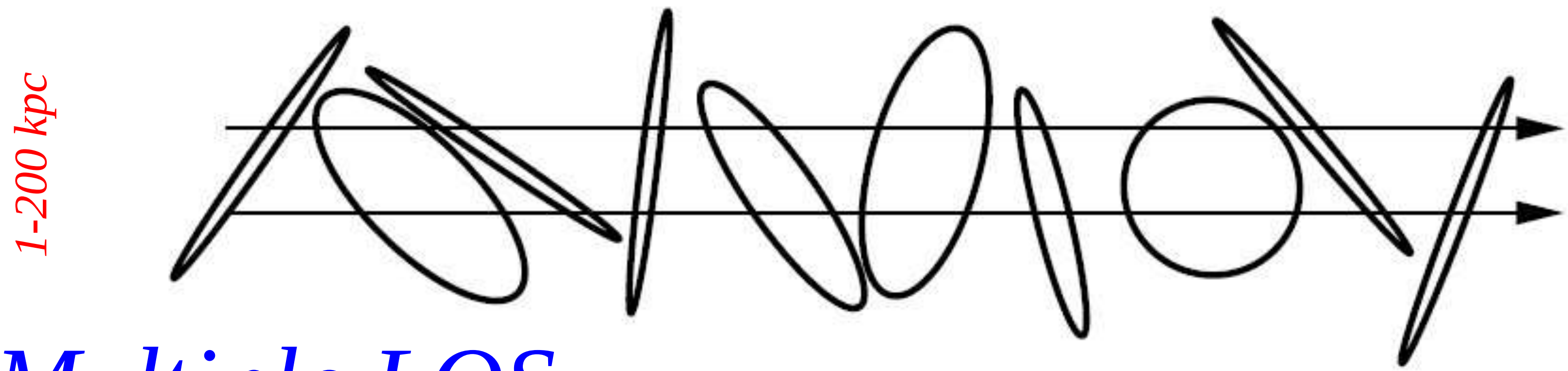
D’Odorico, Cupani, Cristiani + 2012





An archaeological record of past star formation

The small-scale Structure of the IGM

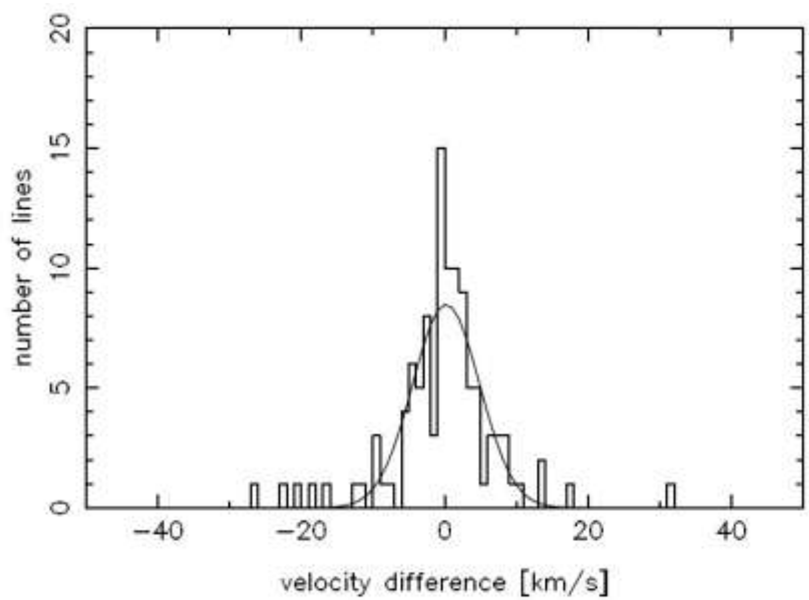


Multiple LOS

expansion-collapse in the cosmic web

winds

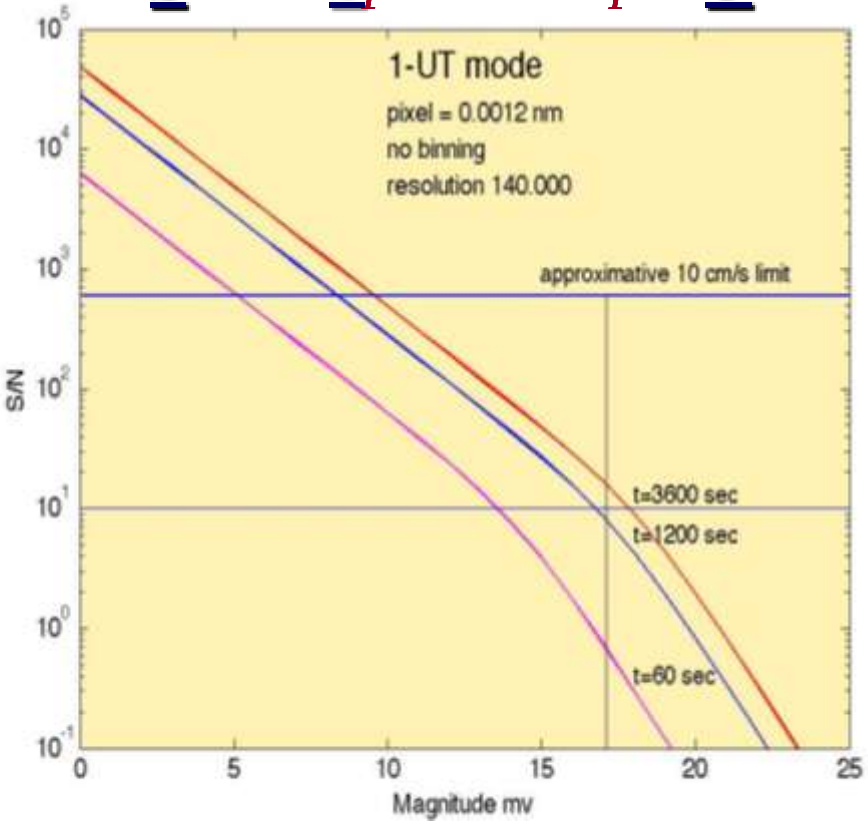
Rauch, Becker, Viel et al. 2005

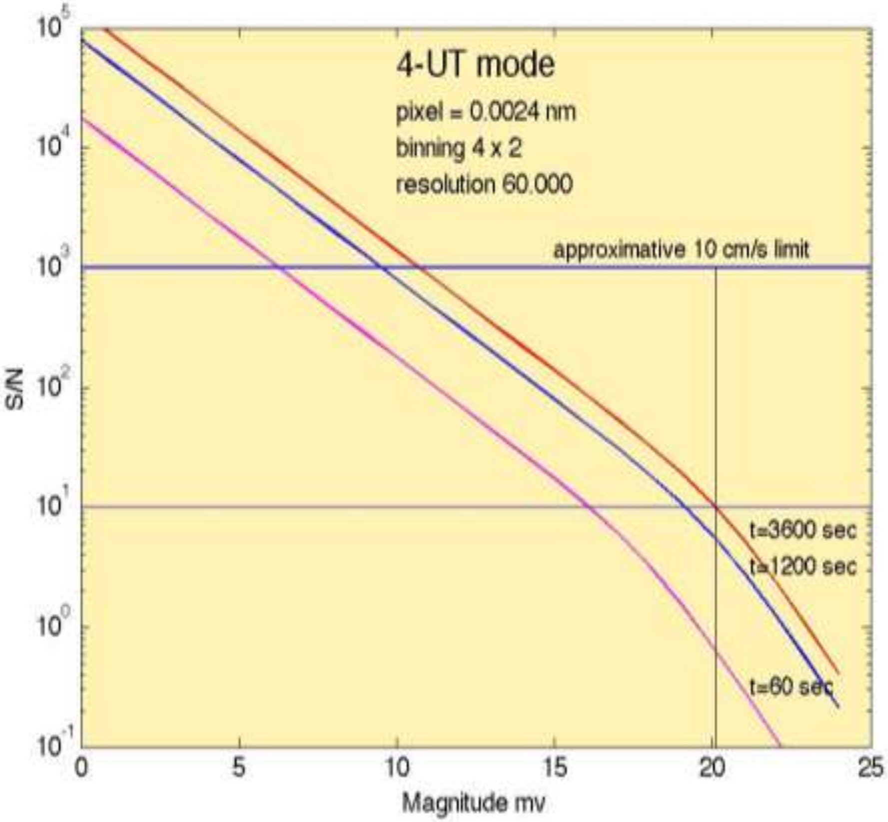


Sensitivity + Stability:

***E**chelle **SP**ectrograph for **R**ocky **E**xoplanets*

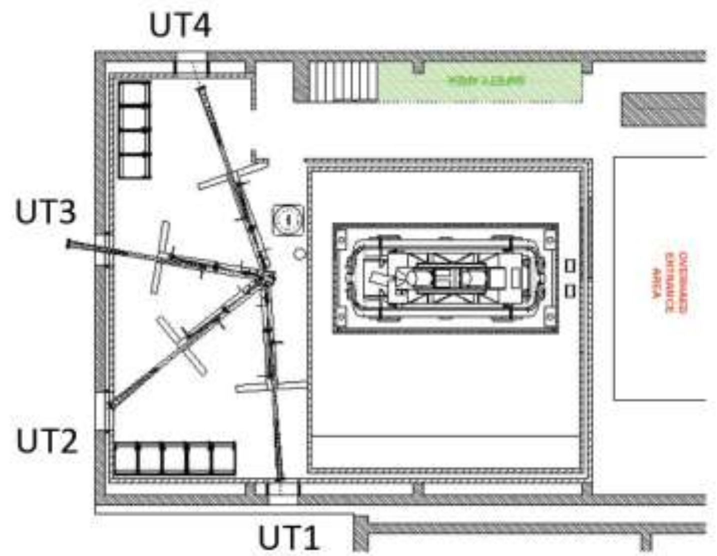
*and **S**table **S**pectroscopic **O**bservations*

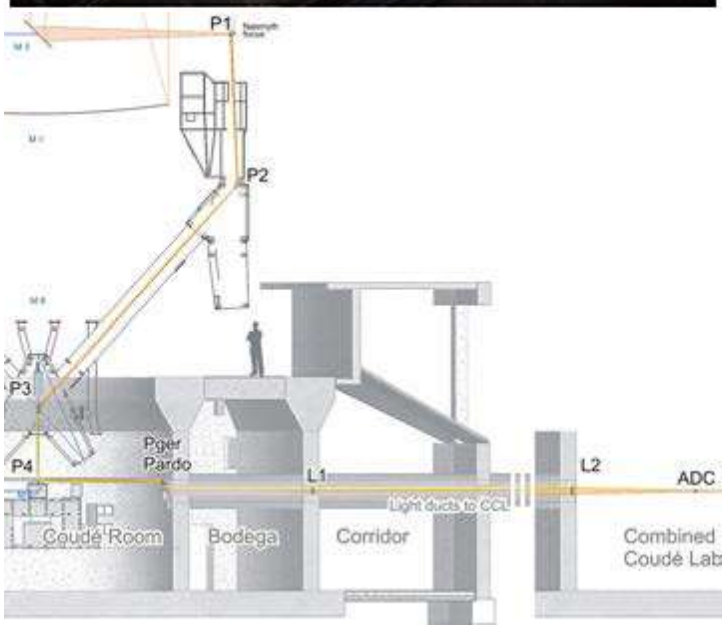


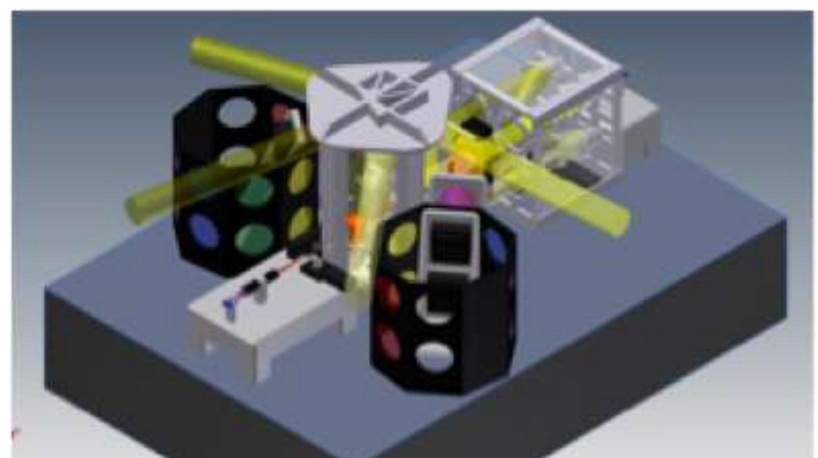


ESPRESSO @ the CCL of VLT

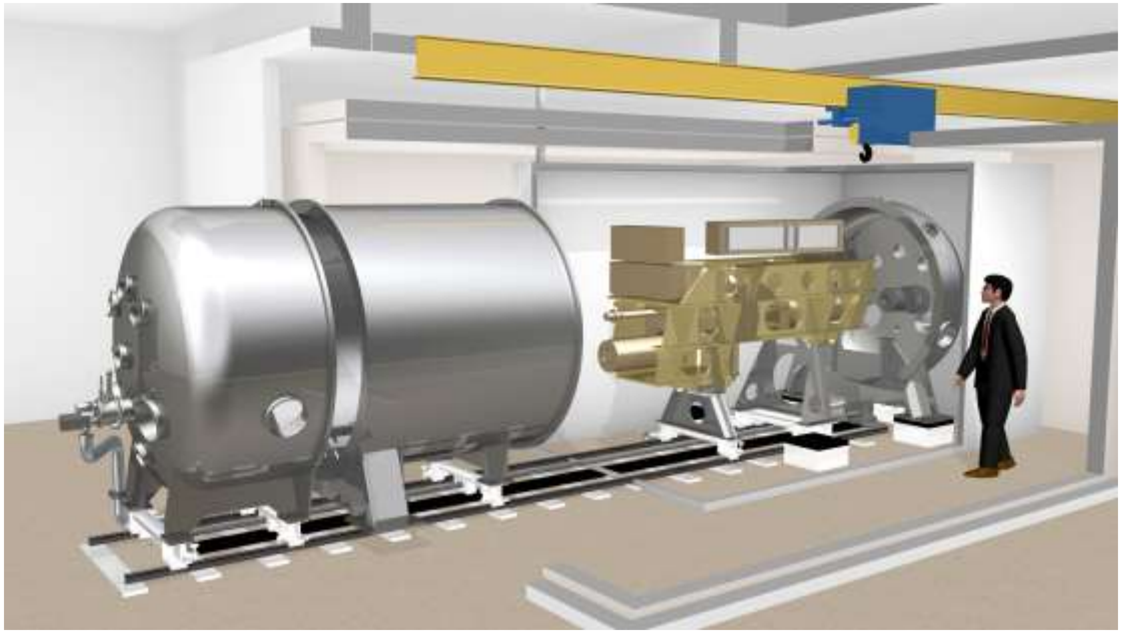
Distances to Combined Lab
UT 1 – 69 m
UT 2 – 48 m
UT 3 – 63 m
UT 4 – 63 m







ESPRESSO: designed for stability



ΔRV =1 m/s

ΔT =0.01 K

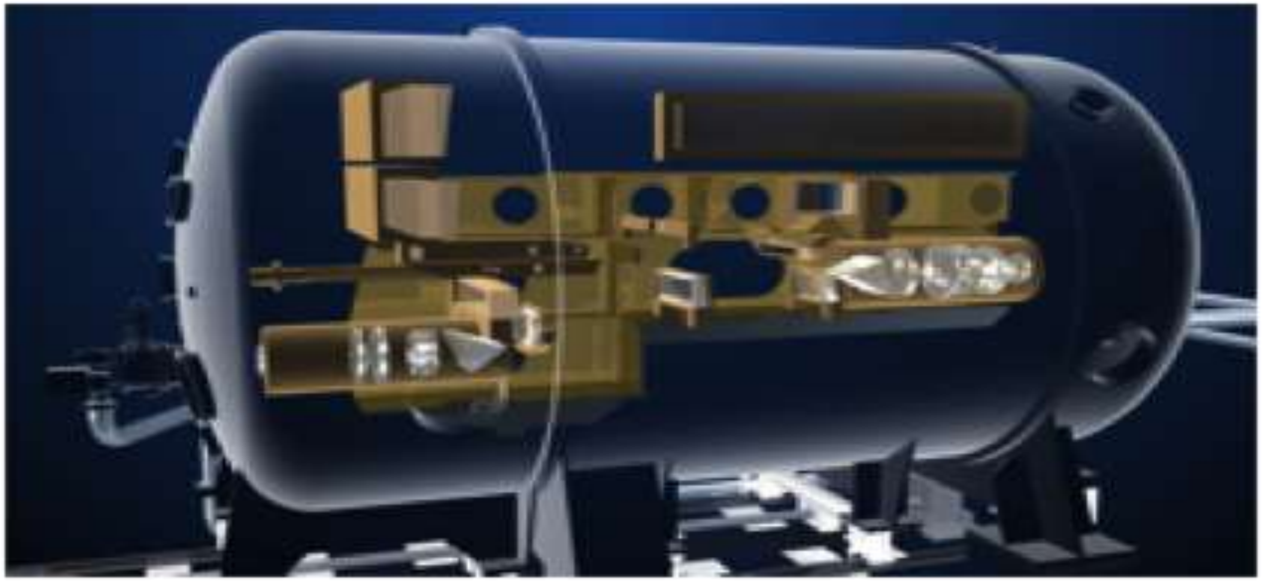
Δp=0.01 mBar

ΔRV =1 m/s

Δλ=0.00001 A

15 nm

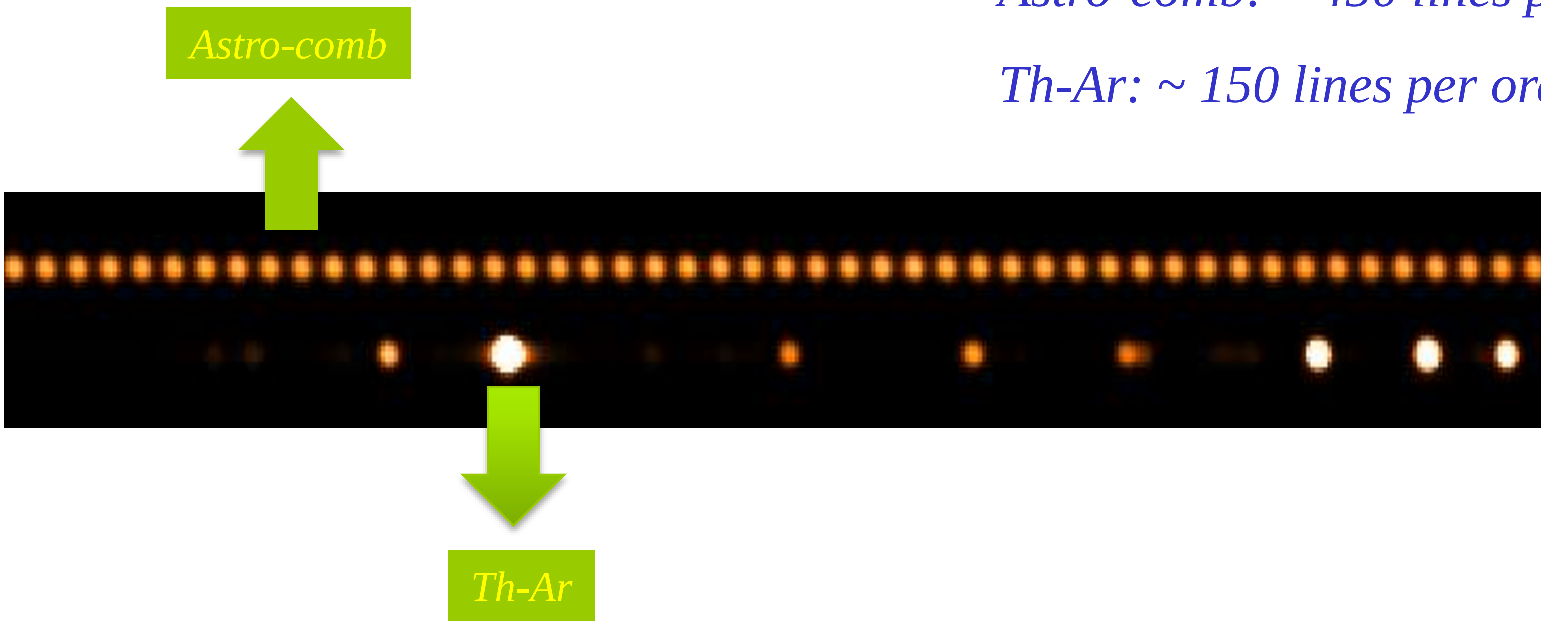
1/1000 pixel



Laser Frequency Comb

Astro-comb: ~ 450 lines per order

Th-Ar: ~ 150 lines per order



*Measure RV of 61 Vir using 30 wavelength calibration files on **one** stellar spectrum*

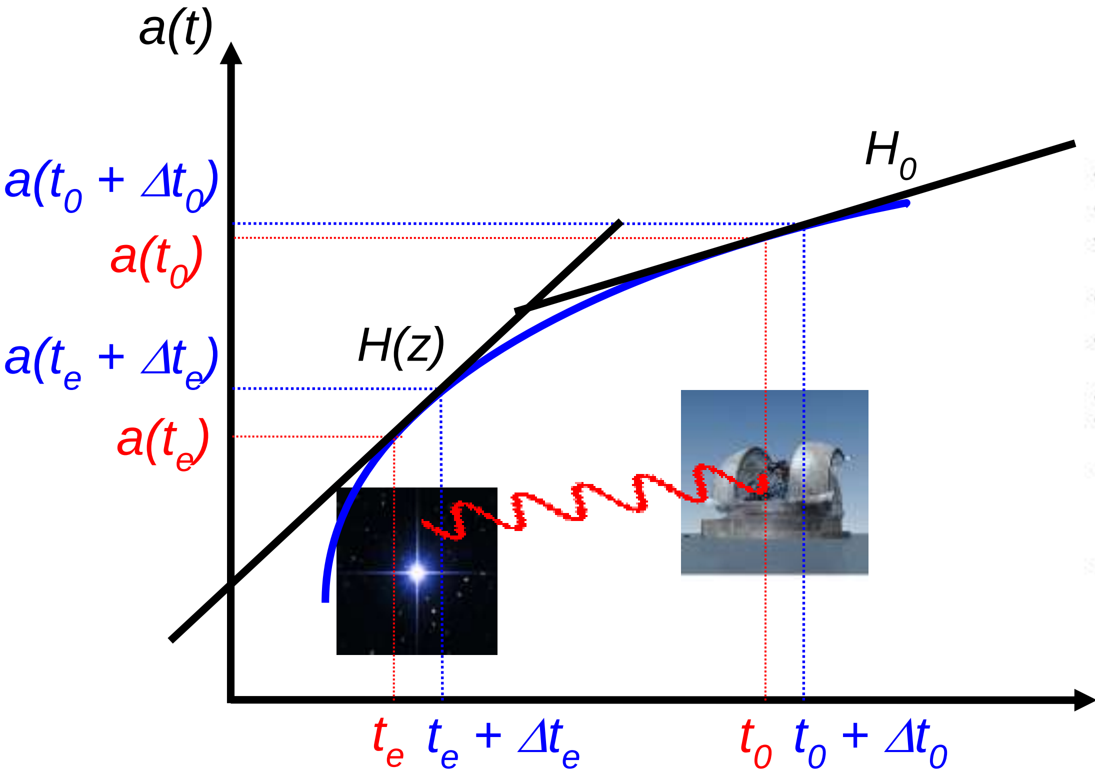
	Comb RV mean	Th RV mean	Comb RV RMS	Th RV RMS
1 order	-7.73132km/s	-7.66583km/s	7.7cm/s	220cm/s
72 orders	-	-7.69770km/s	0.9/0.8cm/s *	24cm/s

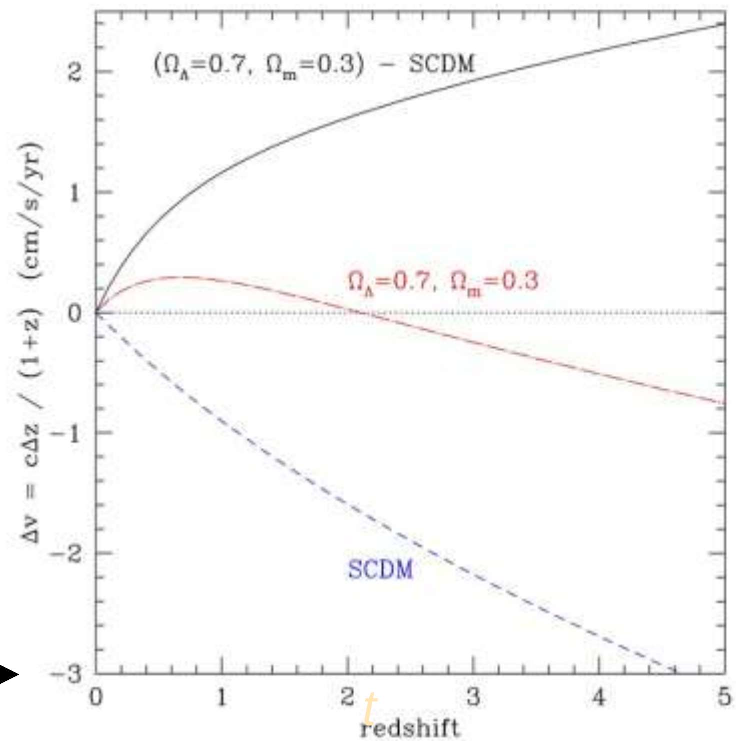
** Extrapolation to 72 orders*

Testing General Relativity

$$G_{\mu\nu} + g_{\mu\nu}\Lambda = 8\pi T_{\mu\nu}$$

Dynamics: measure 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?

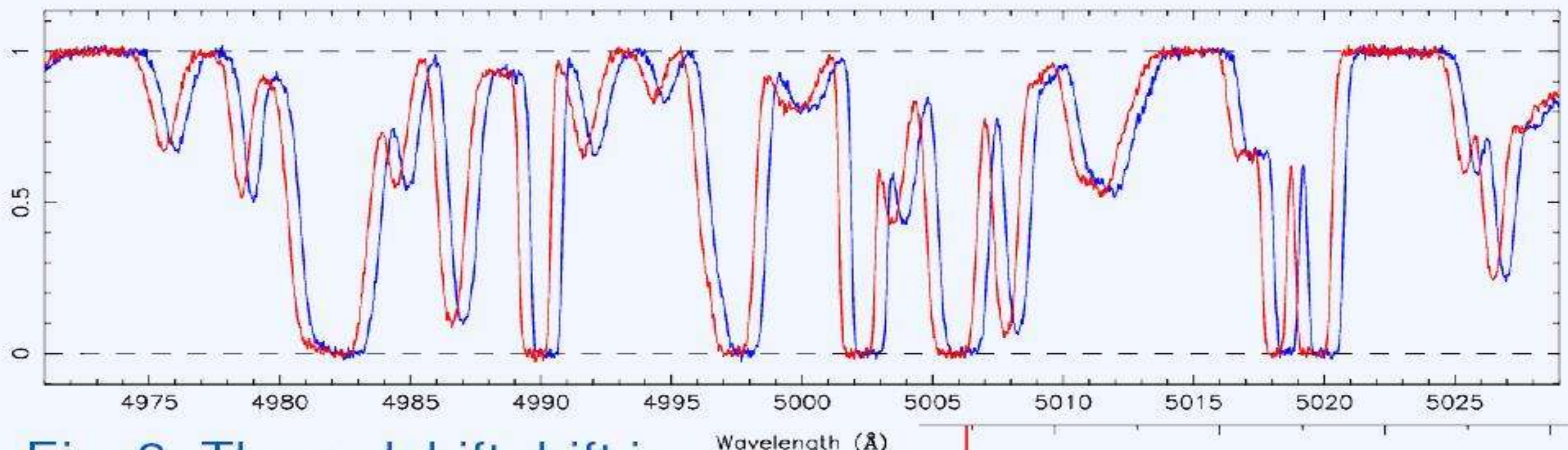


Fig. 2: The redshift drift in a simulated Lyα forest spectrum for $\Delta t = 10^7$ yr.

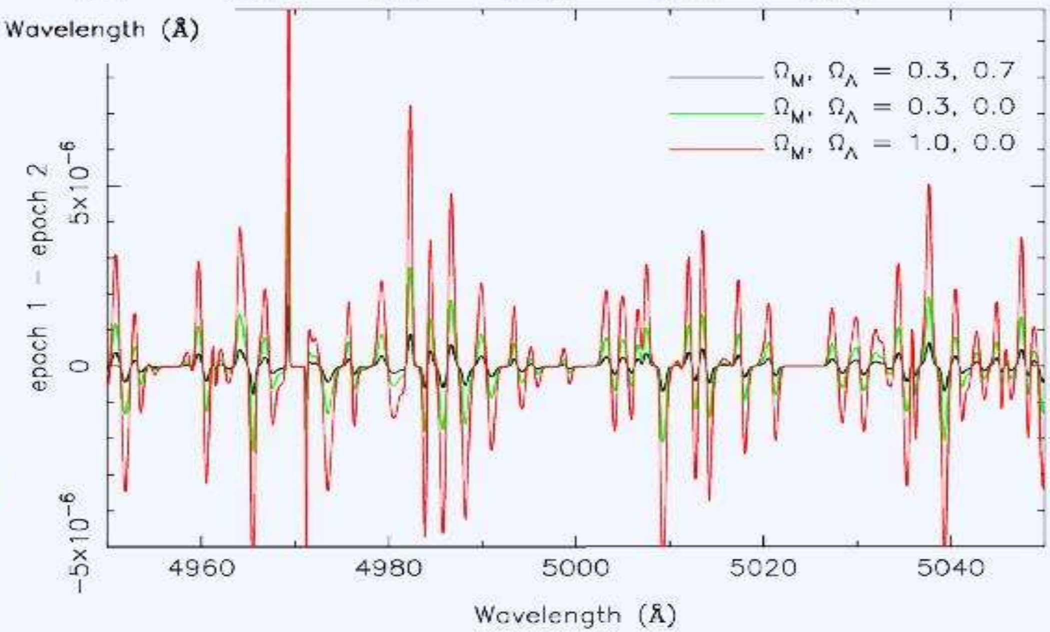
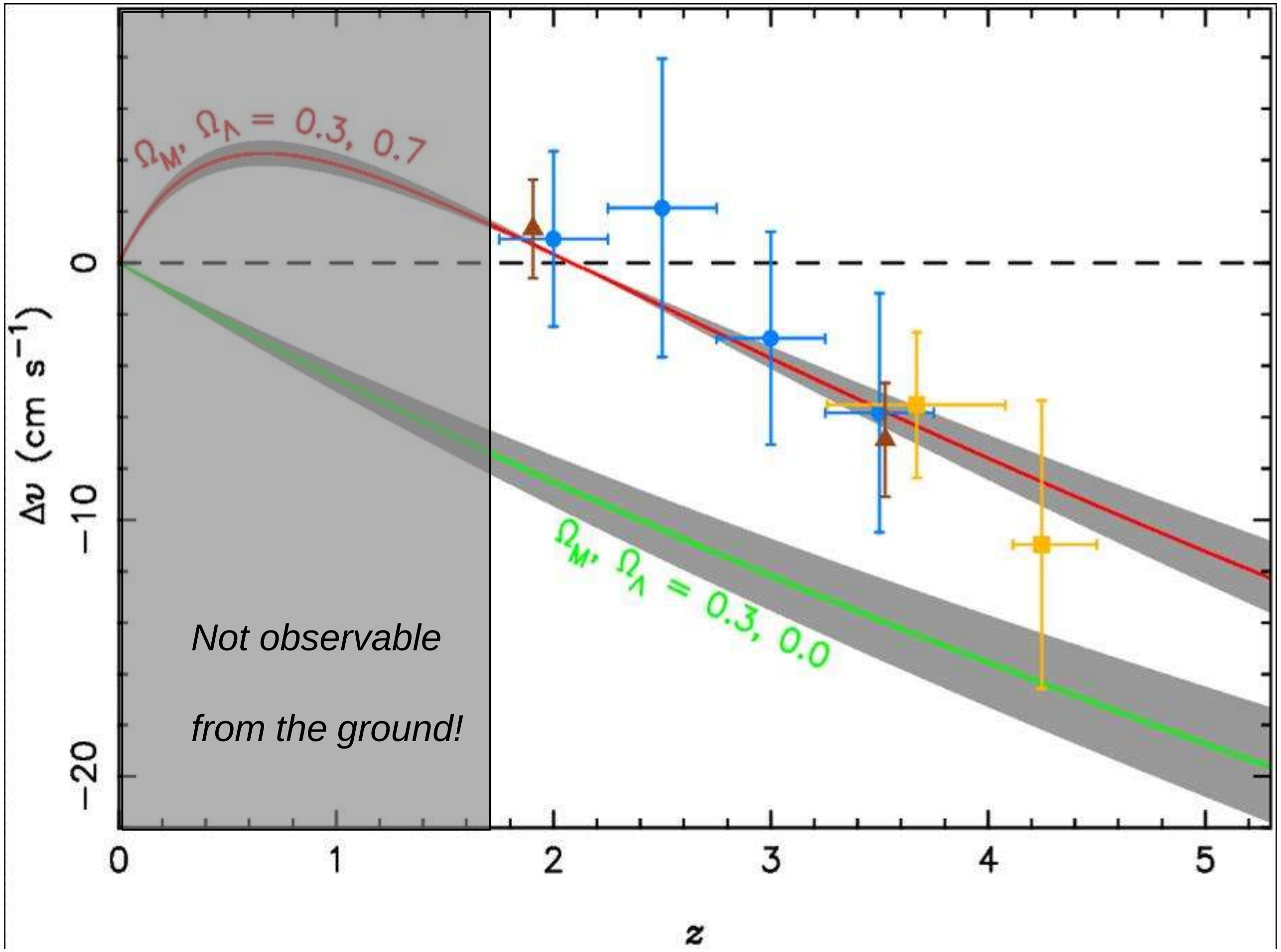


Fig. 3: The difference of two simulated noiseless Lyα forest spectra taken $\Delta t = 10$ yr apart.

Cosmic Dynamics & EXoplanets = CODEX



~30 pairs of Lyα forest spectra randomly distributed in range

$2 < z_{QSO} < 4.5$

S/N ≥ 2000

$\Delta t \approx 30$ yr

~2000+2000 hours

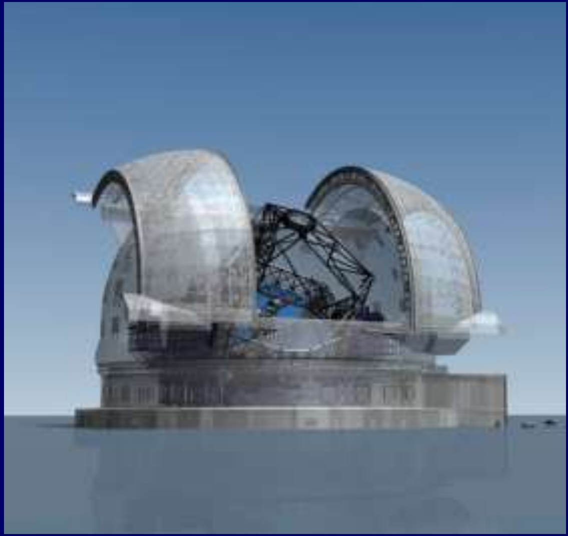
Pasquini et al. 2005

Cristiani et al. 2007

Liske et al. 2008

‘*L'astronomie est bien l’école de la patience.*’ (letter by Danjon to Oort, 21 Sep1962)

We have at least another 50 years of fun ahead!



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