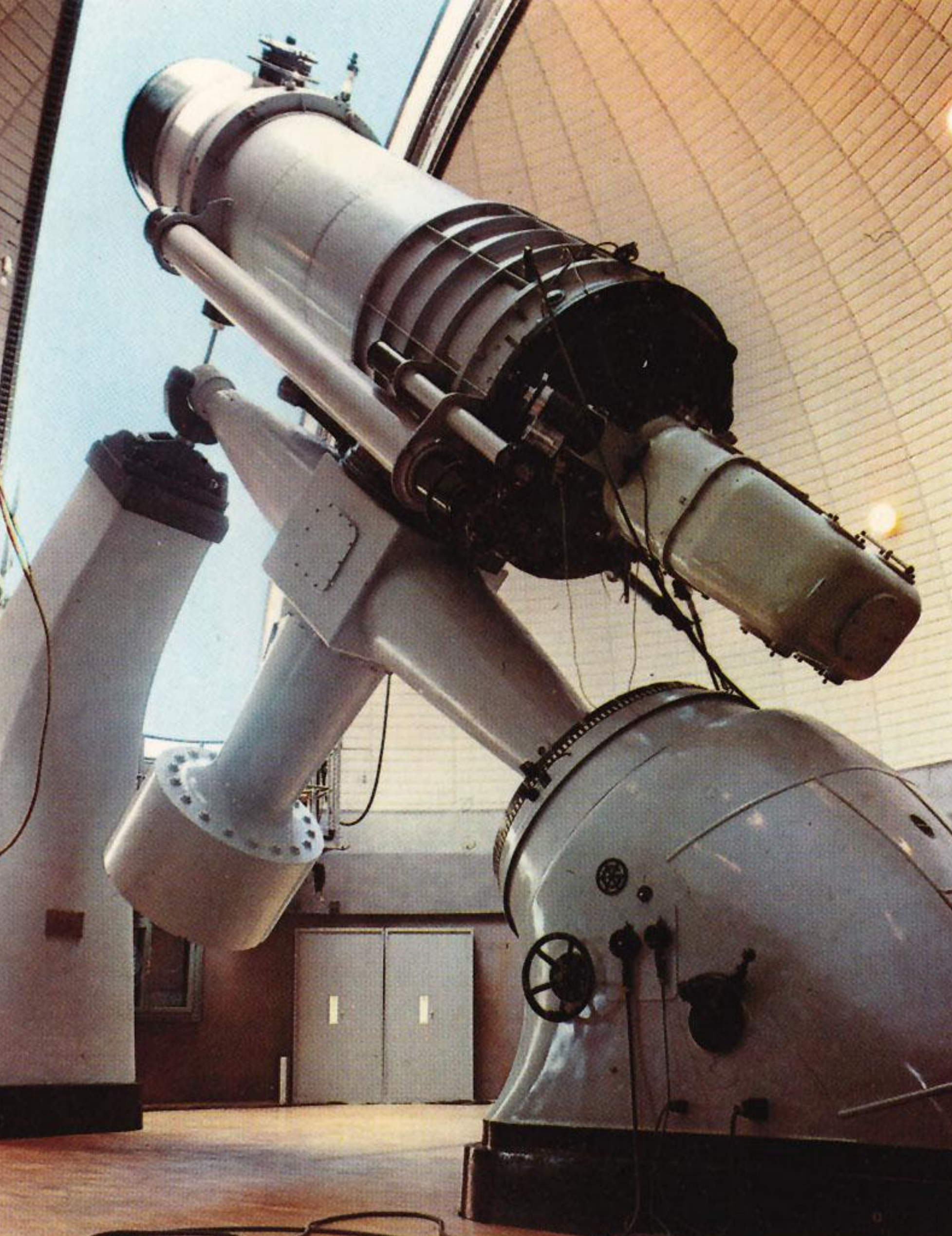
30 years of hi-res spectroscopy: from CASPEC to CODEX

(an IGM personal perspective)

Stefano Cristiani

INAF-Trieste Observatory

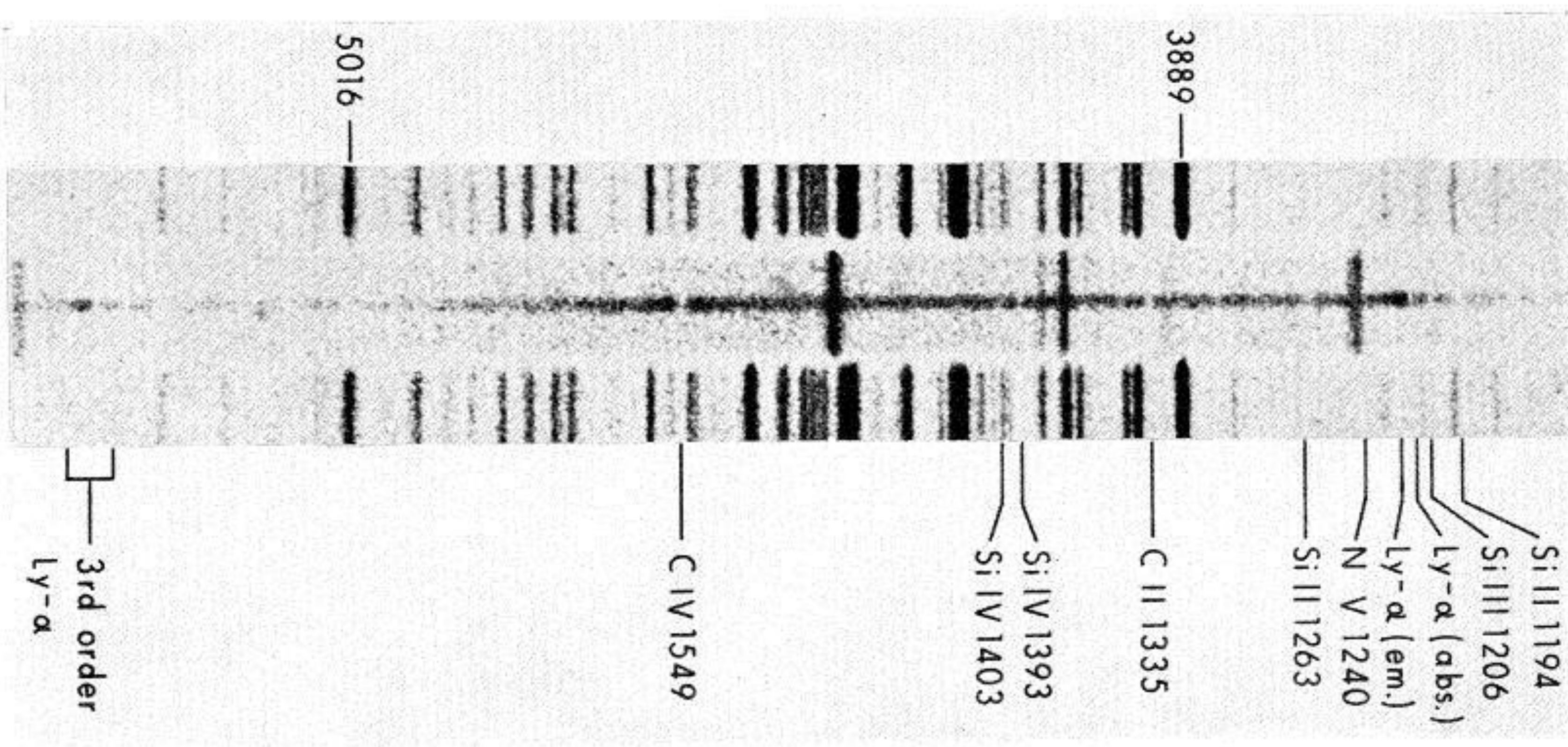


ASIAGO - OSSERVATORIO ASTROFISICO
DELL'UNIVERSITÀ DI PADOVA m. 1050
TELESCOPIO GALILEO da cm. 122

Early 80s

Ekar 182 cm

3C191 – QSO absorption lines detected! (Burbidge et al. 1966)



ɪɢ. 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)

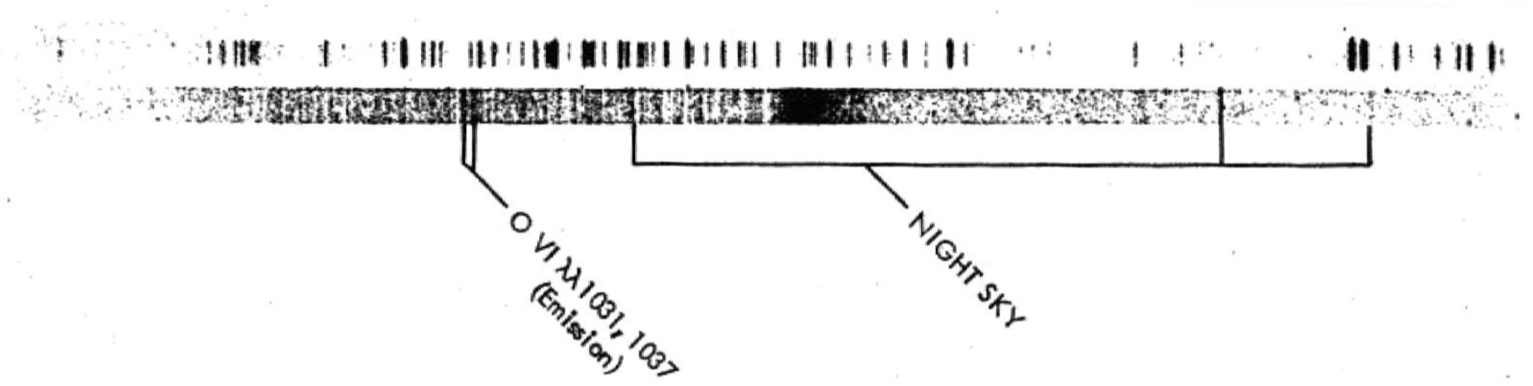


FIG. 1.—A spectrogram illustrating the numerous absorption lines in 4C 05.34. The strong emission line in the center is Lα. The O VI emission lines and several airglow features are also indicated. The comparison spectrum is He + Ar + Ne.

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.

UNIVERSITÁ DEGLI STUDI DI PADOVA

FACOLTA' DI SCIENZE MM. FF. NN.

ISTITUTO DI ASTRONOMIA

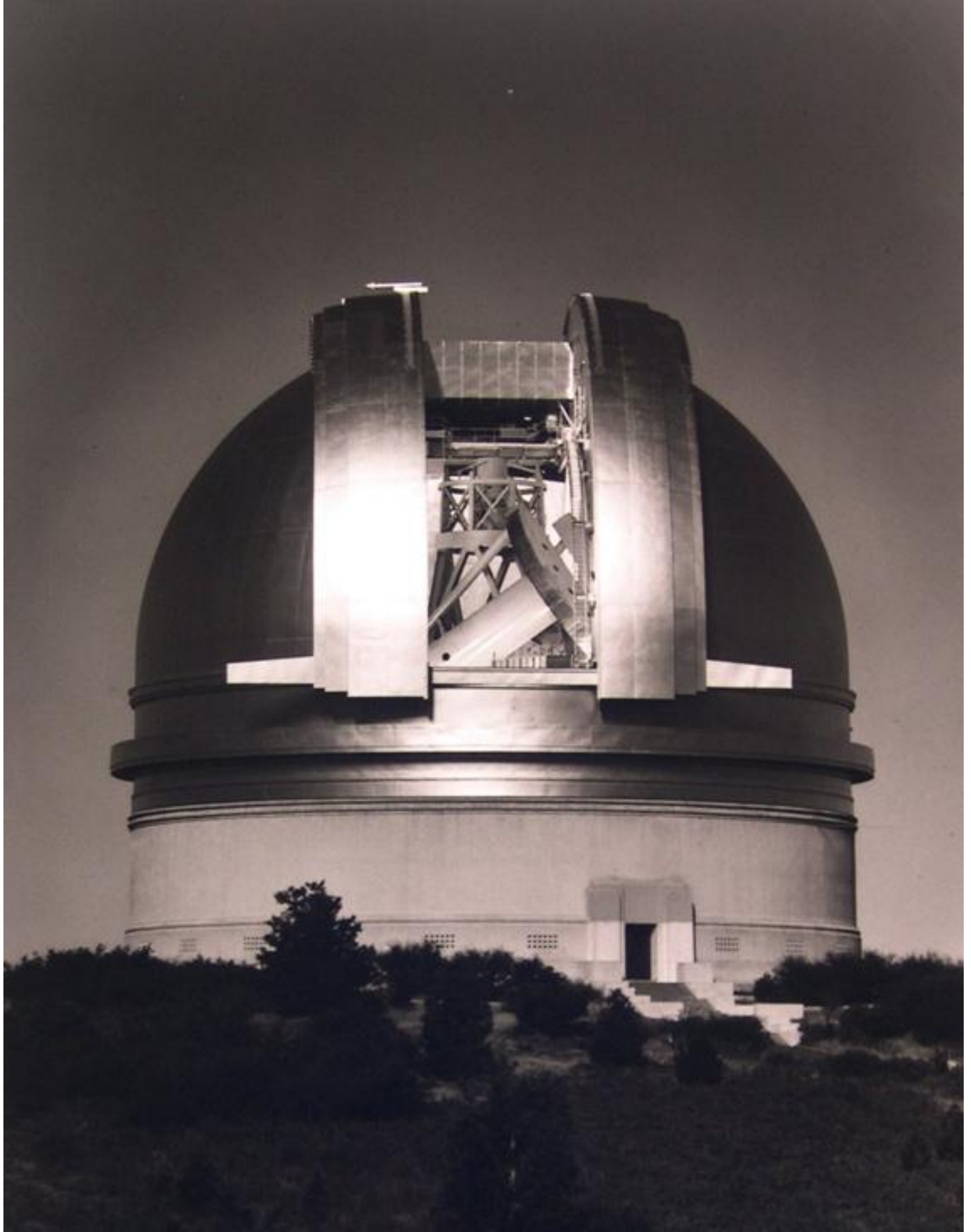
TESI DI LAUREA

Righe di assorbimento negli spettri degli Oggetti Quasi-Stellari

Absorption lines in the spectra of quasi-stellar objects (~1982)

P200” + IPCS

e.g. Young, Sargent, Boksenberg 1982



...or the AAT

YBS 1979

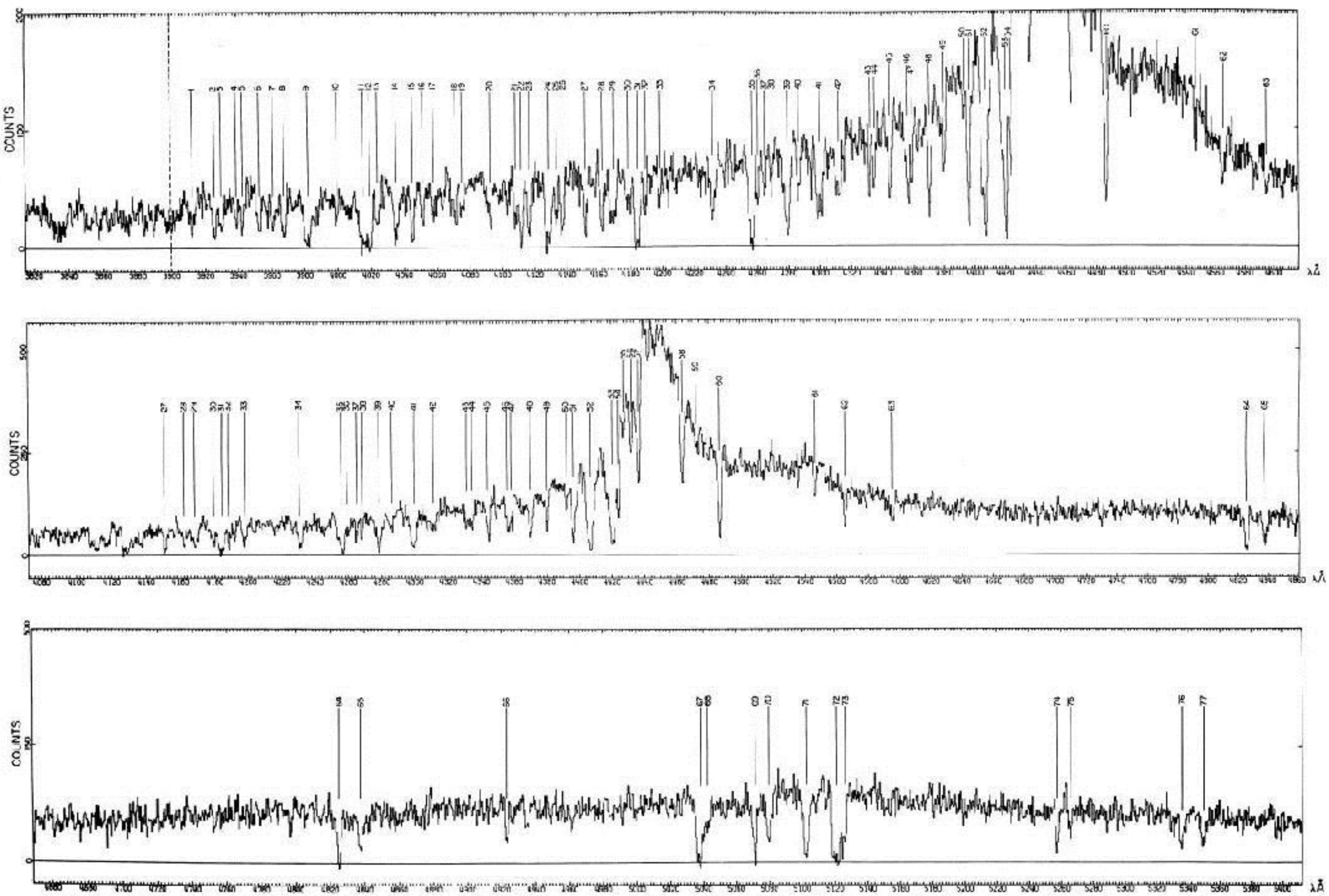


FIG. 2.—Spectrum of Q0453−423, showing three overlapping independent observations covering the range 3815 Å–5412 Å. Each bin is 25.78 km s^{-1}. The zero intensity level in each observation is indicated by a horizontal solid line. The vertical dashed line at 3900 Å shows the lower limit of usable data.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

INTRINSIC — EXTRINSIC

INTRINSIC		EXTRINSIC	
broad	sharp	sharp	Ly-α
	$\Delta v < 3000$ km/s	$\Delta v > 3000$ km/s	

INTRINSIC (sharp, $\Delta v < 3000$ km/s) and EXTRINSIC sharp ($\Delta v > 3000$ km/s) → METALS

EXTRINSIC Ly-α → NO METALS ?

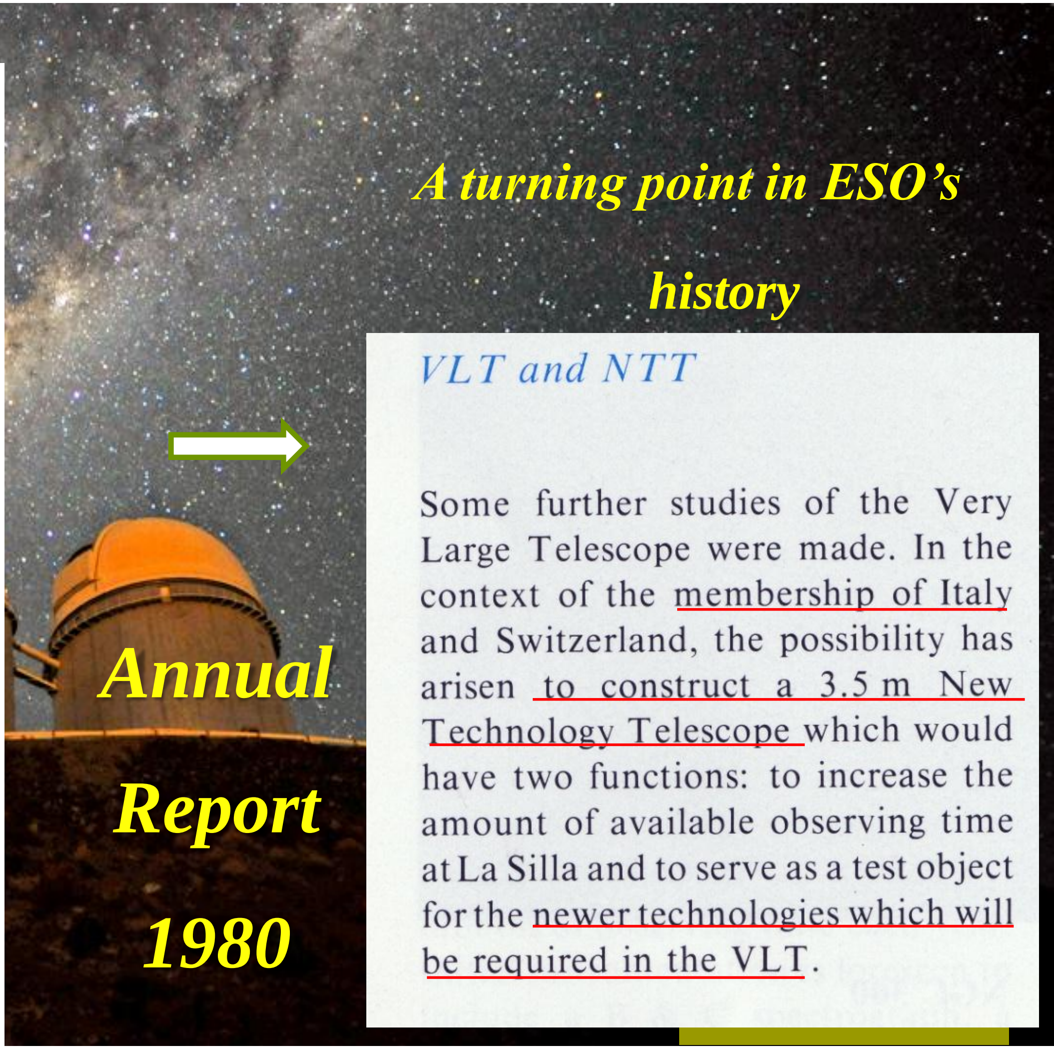
METALS	NO METALS ? (~1995 > $[C/H] \cong -3$)
Mg II	Ly limit ($\log N(HI) > 17$)
C IV	
Si IV	Damped ($\log N(HI) > 20$)
CLUSTERING	NO CLUSTERING? (~1995 > yes!)
Galaxies	IGM clouds?

In the early 80's ESO was very much child of a lesser God with respect to other Observatories with 4-5 m telescopes

The 3.6m at la Silla had started operation in 1978. Main instrument was a B & C spectrograph with the 1D IDS.

Other detectors in use at La Silla:

- photographic plates,
- Mc Mullan Camera for imaging
- Reticon 1D array,
- first ESO CCD camera for imaging at the Danish 1.5m,
- 1 pixel IR sensors
- as occasional visitor at the 3.6m, Boksenberg's IPCS



VLT and NTT

Some further studies of the Very Large Telescope were made. In the context of the membership of Italy and Switzerland, the possibility has arisen to construct a 3.5 m New Technology Telescope which would have two functions: to increase the amount of available observing time at La Silla and to serve as a test object for the newer technologies which will be required in the VLT.

Courtesy S.D'Odorico

Table 1. Journal of observations.

Date	Telescope	Instrument	Exp. time	Range (Å)	FWHM Res. (Å)
TOL 1037-271					
23 Dec 1983	2.2m	B&C+CCD RCA	2 X 45 min	3800-5500	5
24 Dec 1983	2.2m	B&C+CCD RCA	90 min	3600-5300	5
25 Dec 1983	2.2m	B&C+CCD RCA	60 min	4100-5800	5
24 Dec 1984	3.6m	B&C + RPCS	2 X 40 min	3680-4780	1.2
26 Dec 1984	3.6m	B&C + RPCS	40 min	3690-4760	1.2
27 Dec 1984	3.6m	B&C + RPCS	40 min	3670-4785	1.2
28 Dec 1984	3.6m	B&C + RPCS	40 min	3670-4785	1.2
7 Jan 1985	2.2m	B&C + RPCS	47 min	4495-6040	1.7
7 Jan 1985	2.2m	B&C + RPCS	43 min	4495-6040	1.7
8 Jan 1985	2.2m	B&C + RPCS	45 min	4420-6040	1.7
Galaxy TOL 1037-271					
Date	Telescope	Instrument	Exp. time	Range (Å)	FWHM Res. (Å)
15 Apr 1986	3.6m	EFOSC	45 min	3500-7000	10
Galaxy TOL 1038-272					
Date	Telescope	Instrument	Exp. time	Range (Å)	FWHM Res. (Å)
8 May 1985	2.2m	B&C + PCD	40 min	3600-6800	5
TOL 1038-272					
Date	Telescope	Instrument	Exp. time	Range (Å)	FWHM Res. (Å)
30 Apr 1984	3.6m	B&C+CCD RCA	2 X 60 min	3800-4400	1.8
30 Apr 1984	3.6m	B&C+CCD RCA	53 min	3800-4400	1.8
26 Dec 1984	3.6m	B&C + RPCS	2 X 40 min	3690-4760	1.2
27 Dec 1984	3.6m	B&C + RPCS	2 X 40 min	3670-4785	1.2
28 Dec 1984	3.6m	B&C + RPCS	2 X 40 min	3670-4785	1.2
7 Jan 1985	2.2m	B&C + RPCS	64 min	4495-6040	1.7
10 Jan 1985	2.2m	B&C + RPCS	44 min	4400-6000	1.7
10 Jan 1985	2.2m	B&C + RPCS	42 min	4400-6000	1.7
10 Jan 1985	2.2m	B&C + RPCS	43 min	4400-6000	1.7

telescopes and detectors have been used, creating some difficulties for a homogeneous treatment of the data.

The raw data were sky-subtracted and corrected for pixel-to-pixel sensitivity variations by division by a suitably normalized exposure of the spectrum of an incandescent source. Wavelength calibration was carried out by comparison with exposures of a He–Ar lamp. Relative flux calibration was finally achieved by observations of standard stars listed by Oke (1974) and Stone (1977).

The reduction process used the standard IHAP facilities (Middelburg & Crane 1979) available at ESO La Silla and in the ESO computer centre at La Serena, and the MIDAS environment of the VAX 11/750 at La Silla.

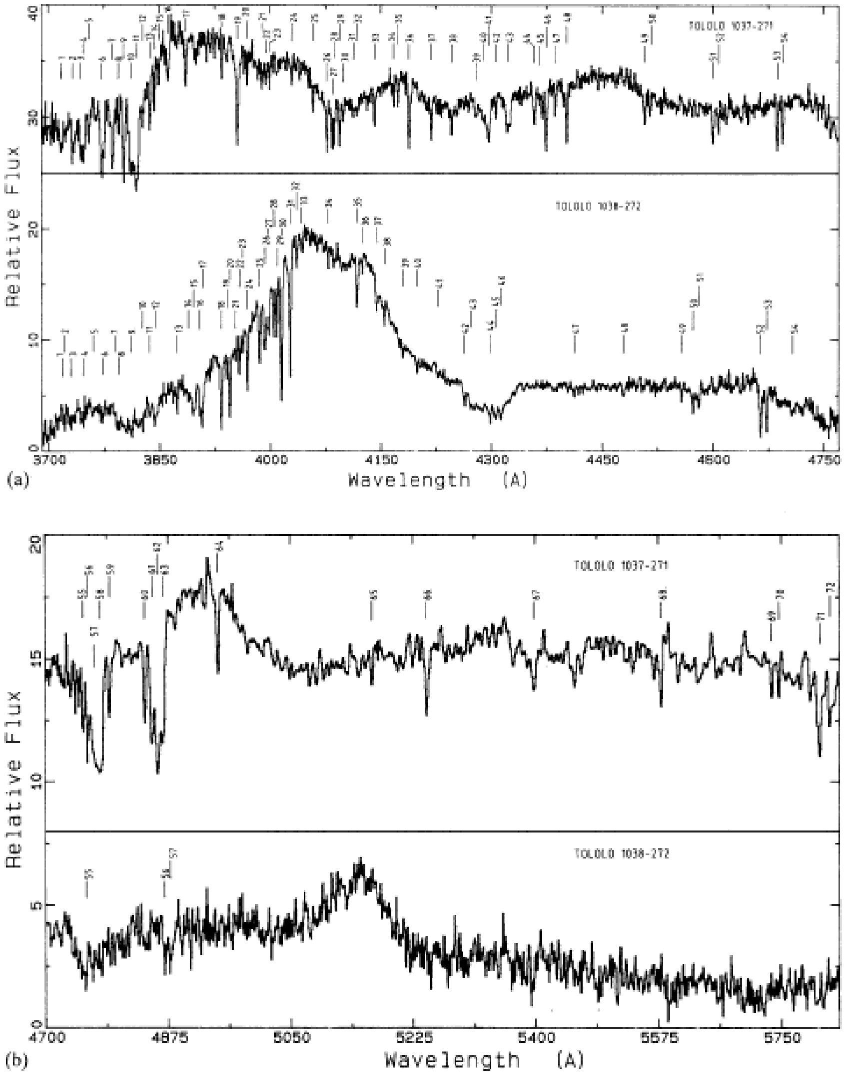


Figure 1. (a, b) Composite spectrum of TOL 1037−271 and of TOL 1038−272.

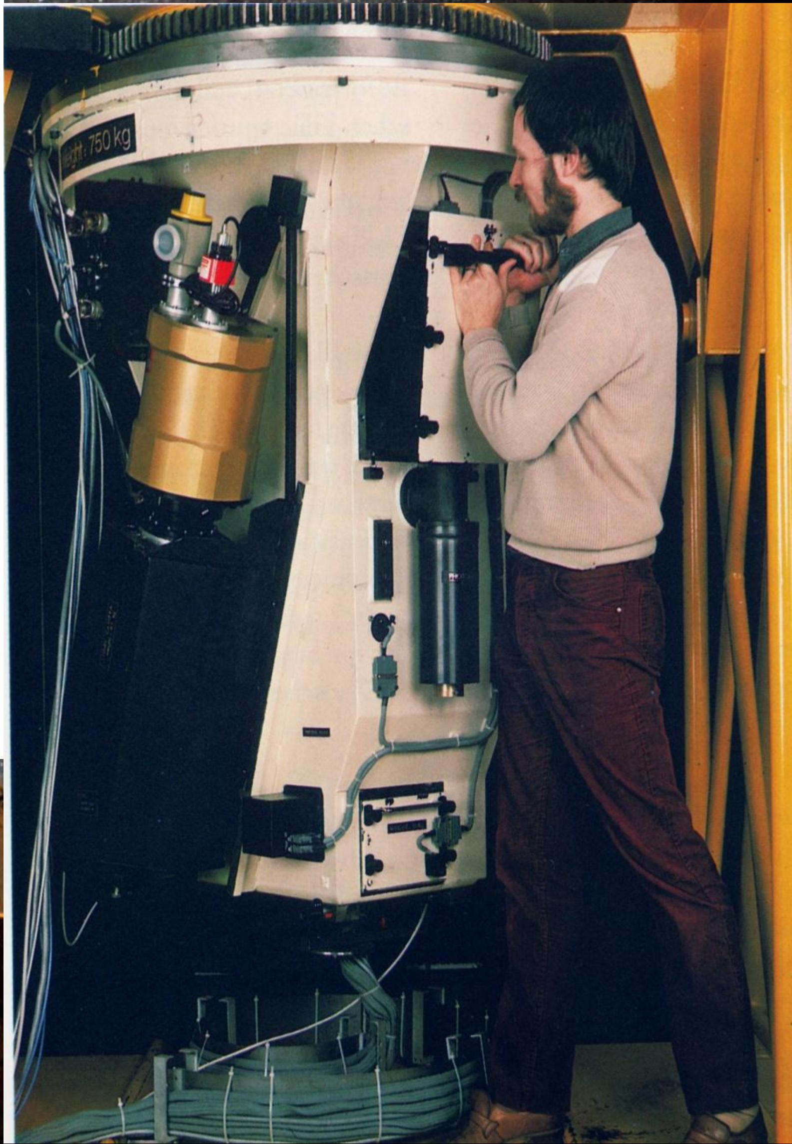
The spectra of the two quasars, representing weighted means of the data summarized in Table 1, are shown in Fig. 1.

3 Emission redshifts and absorption systems*

The galaxy close to TOL 1037−271 (A in Plate 1) showed several emission lines (Table 2)

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

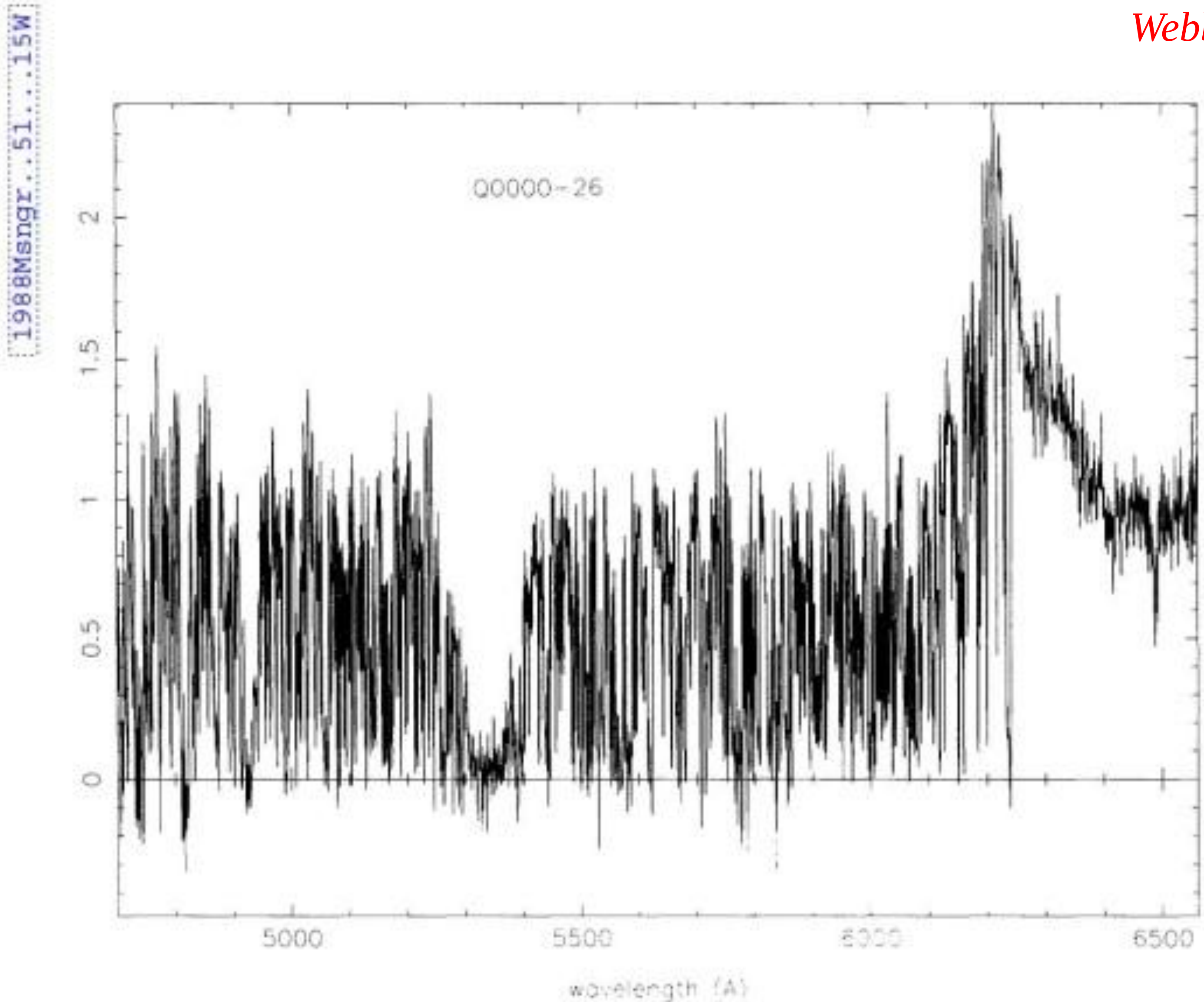
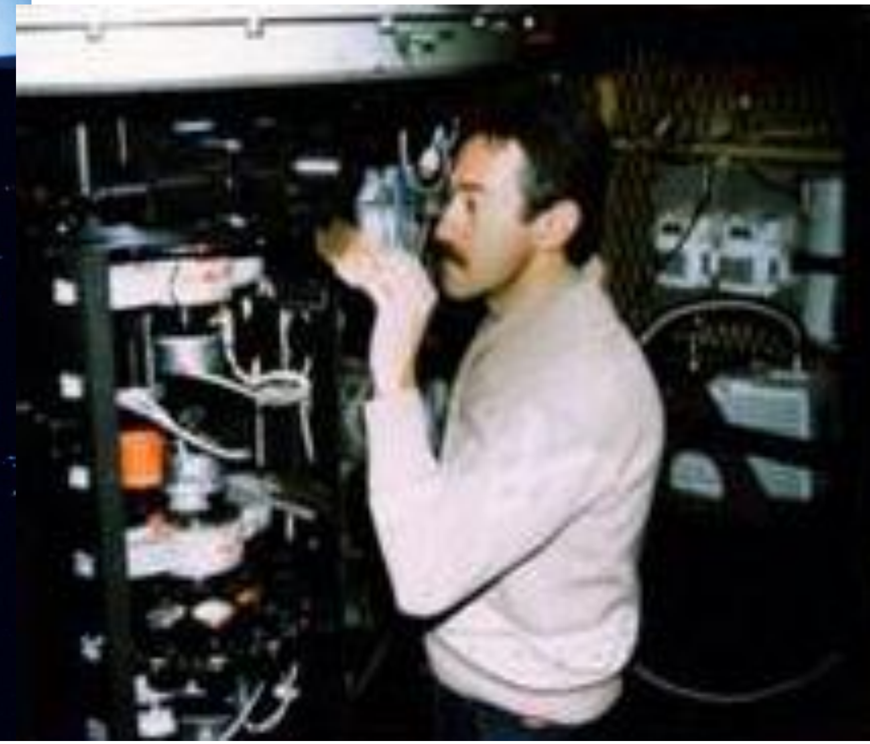


Figure 1: *The spectrum of Q0000-26 obtained using CASPEC on the ESO 3.6-m telescope. The dense Lyα forest, extending right up to the Lyα emission line at 6230 Å is clearly evident.*

EFOSC: 1985



OBSERVATIONS OF QSOs AND RELATED OBJECTS WITH EFOSC, THE ESO FAINT OBJECT SPECTROGRAPH AND CAMERA

1986 IAUS 119 57

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EFOSC is a standard ESO instrument operating at the Cassegrain focus of the 3.6 m telescope since April 1st, 1985. A description of its optical design and operating modes is given in Enard and Delabre (1982) and Dekker and D'Odorico (1985). Briefly, it is a focal reducer with spectroscopic capability. The collimator produces a collimated beam with a diameter of 40 mm which passes through a filter and/or grism. The f/2.5 camera focusses the beam on the detector which is at present a thinned, back-illuminated RCA CCD with 320×512 pixels. The pixel size is

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]

LETTER

EFOSC

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.

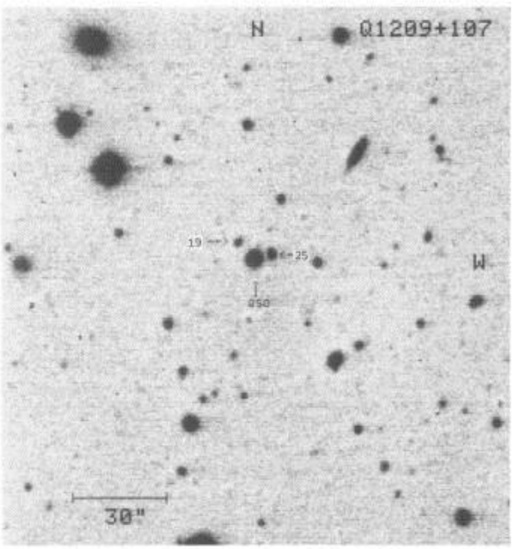

Fig.1.: the field of Q1209+107. CCD exposures taken in the Gunn R system

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
19	5.1	4.9	21.9	-	-	.17	145	1.5	1.6
20	3.8	-41.1	22.3	-	-	-	-	1.4	1.5
21	1.8	57.4	22.7	-	-	-	-	1.5	1.4
22	1.7	40.2	21.1	21.0	-	-	-	1.5	1.5
23	0.0	0.0	18.1	17.9	17.7	-	-	1.5	1.5
24	-1.3	-79.8	22.3	21.4	-	-	-	1.2	1.5
25	-5.5	1.3	20.9	19.6	18.9	-	-	1.4	1.4
26	-8.6	17.7	21.4	21.3	-	-	-	1.5	1.5
27	-16.7	-18.9	22.7	-	-	-	-	1.4	1.5
28	-20.1	-1.2	21.2	21.2	-	-	-	1.4	1.4
29	-24.3	54.1	23.0	-	-	-	-	1.5	1.2
30	-25.3	-30.1	20.1	20.1	19.4	.19	140	1.8	1.8
31	-26.0	-11.6	23.4	-	-	.08	95	1.5	1.8
32	-28.1	66.8	19.0	18.4	18.1	-	-	1.5	1.5
33	-32.3	-51.4	21.3	21.0	-	-	-	1.3	1.5
34	-33.0	-25.7	21.7	21.6	-	-	-	1.5	1.5
35	-33.1	31.7	19.9	19.4	19.3	.67	145	2.3	3.5
36	-37.5	60.6	22.8	-	-	-	-	1.6	1.2
37	-40.7	-62.9	22.0	-	-	-	-	1.4	1.6
38	-41.2	-1.9	22.7	-	-	-	-	1.4	1.6
39	-44.7	-71.4	22.9	-	-	-	-	1.5	1.5
40	-45.0	3.6	23.2	-	-	-	-	1.7	1.3
41	-52.7	-19.1	22.1	-	-	-	-	1.4	1.5
42	-55.4	6.6	22.0	-	-	.28	165	1.5	1.7

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.

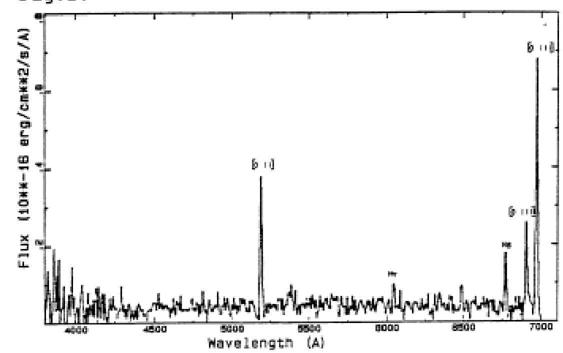

Fig.2: Flux-reduced spectrum of object #19.

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.

Obs. λ(Å)	Rest. λ(Å)	Ident.	Inten.	Redshift
5188.0	3727.5	[OII]	4.2	0.3918
6043.5	4340.5	Hγ	0.6	0.3924
6769.0	4861.3	Hβ	1.5	0.3924
6903.4	4958.9	[OIII]	3.6	0.3921
6970.1	5006.8	[OIII]	8.8	0.3921
				0.3922±0003

Intensities are given in units of 10^{-16} erg/s/cm^2. The internal error on intensity measurements is $0.2 \cdot 10^{-16}$ erg/s/cm^2.

The measured redshift for the object 19 is z=0.3922±0.0003, equal within two sigmas to the redshift z=0.3930 of the absorption system measured by Young et al. (1982) in the spectrum of Q1209+107.

The spectrum of object 19 is typical of HII galaxies, i.e., galaxies with

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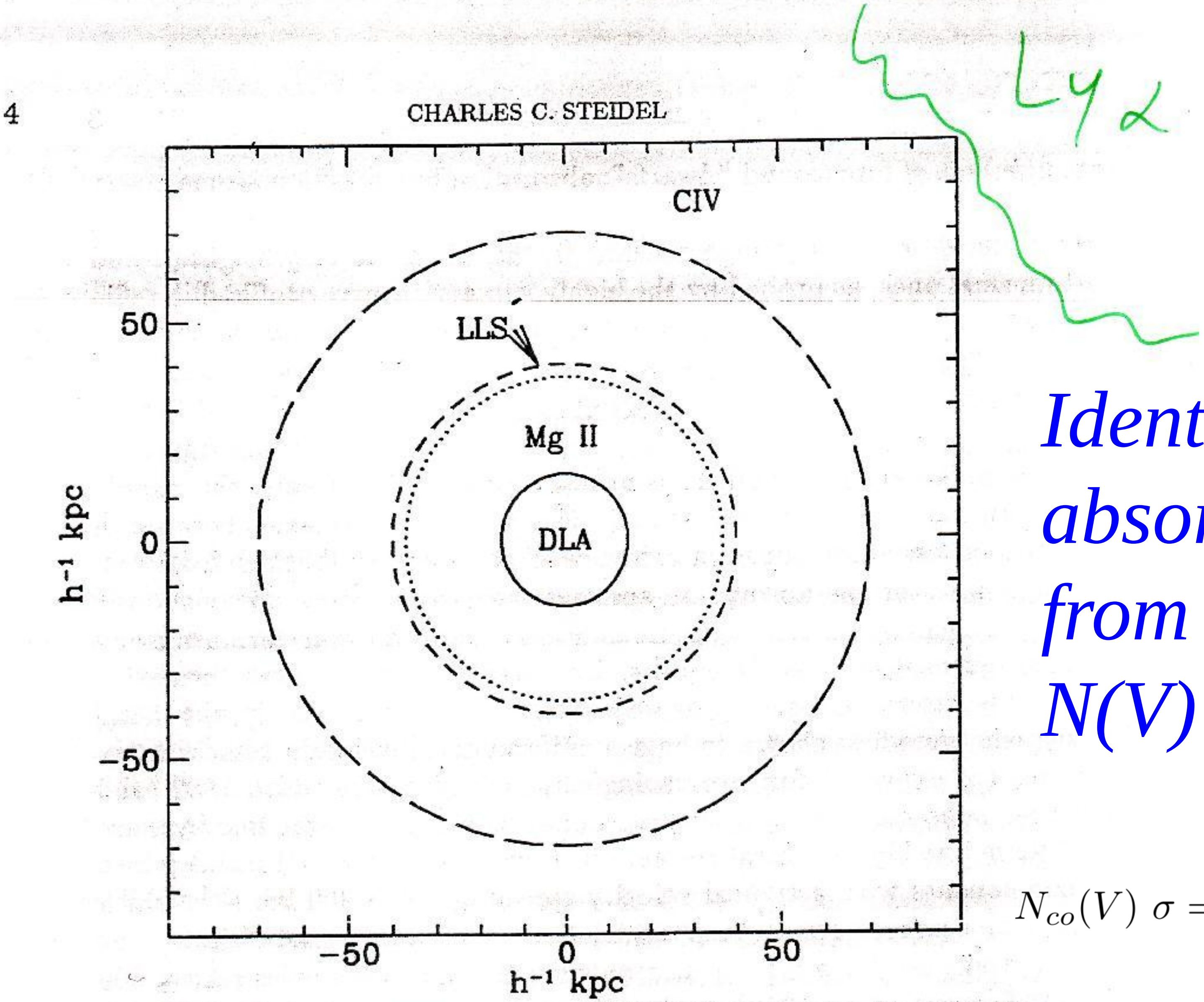
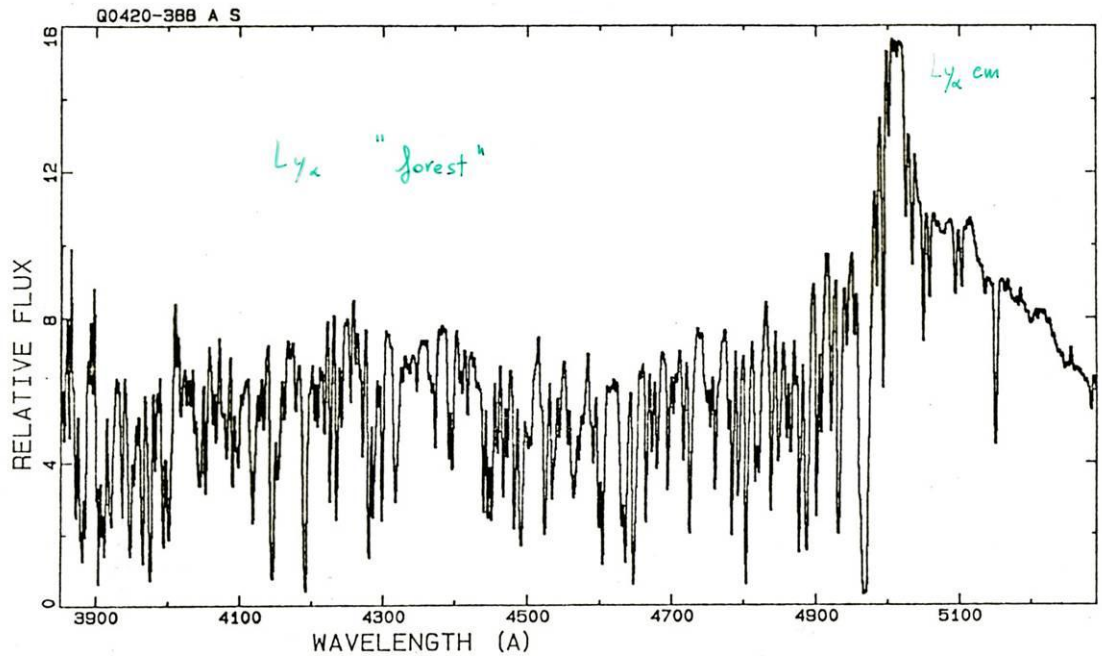


Fig. 1. Schematic diagram illustrating an over–simplified view of the structure of an "L^*" galaxy as deduced solely from the statistics of the various classes of metal line absorption systems. Note that the Mg II and Lyman limit selected systems have the same cross-section, and that the damped Lyman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



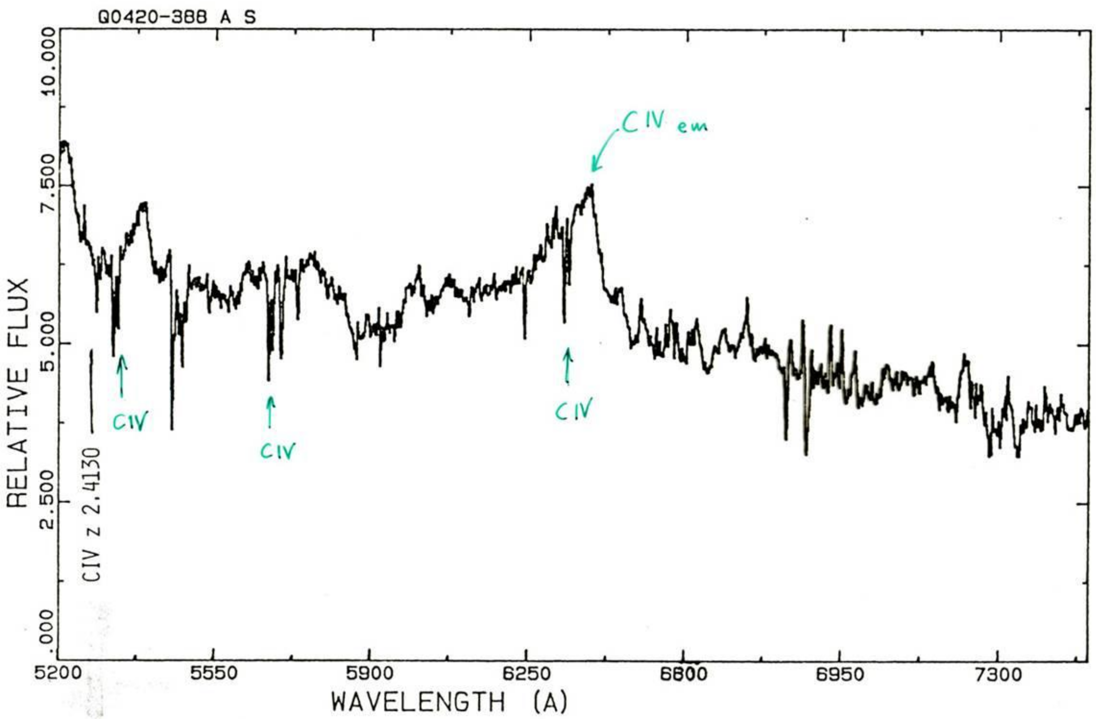


FIG. 4B

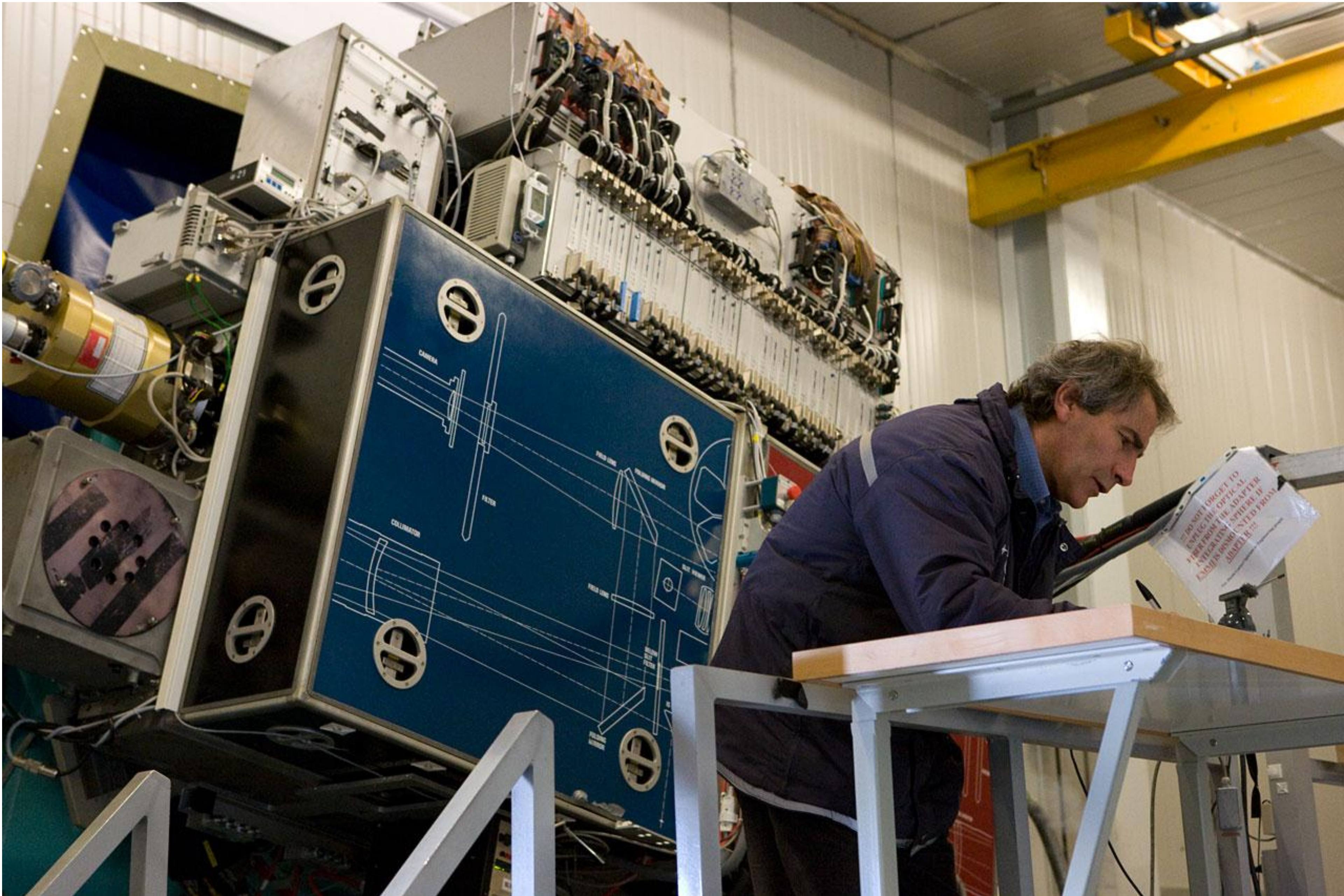
EFOSC echelle

Lyman Forest

vs.

Metal lines

EMMI @ NTT: MORE ECHELLE!



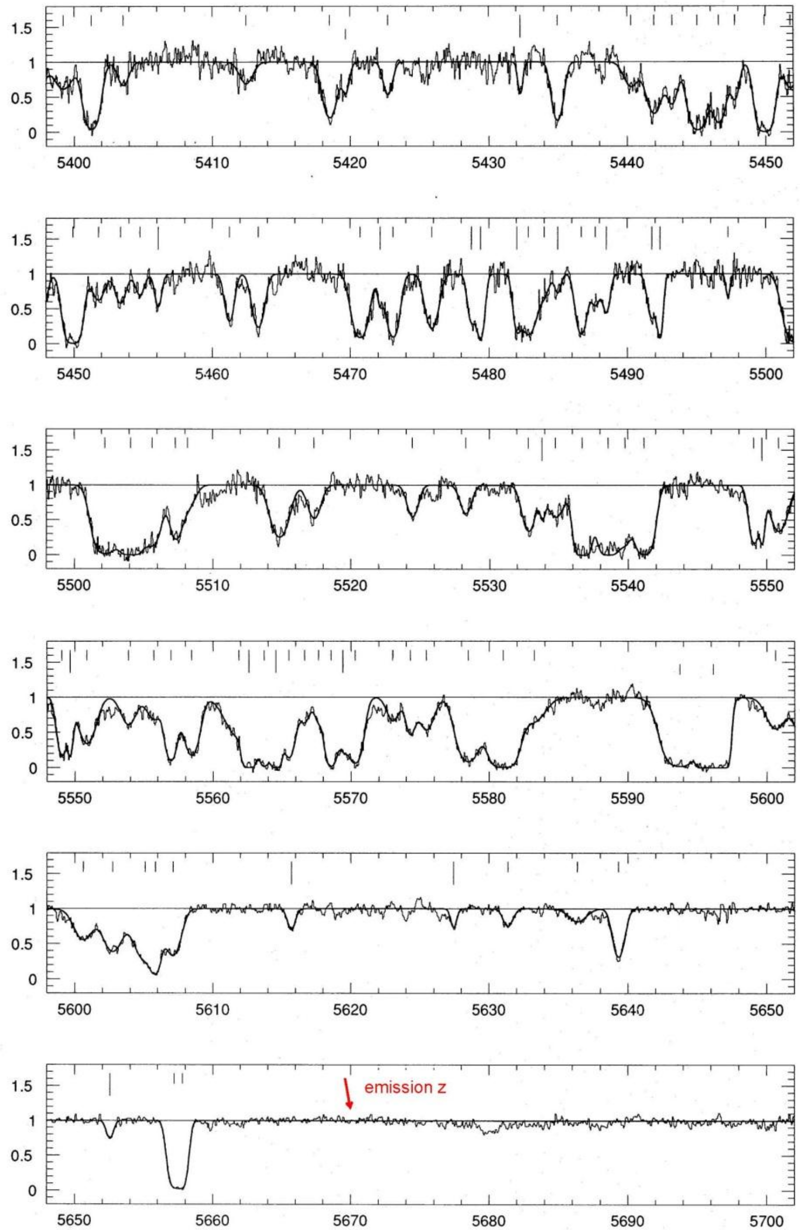


Figure 1 – *continued*

EMMI spectrum

Q0055-269

Early-mid 90's

The Lyman-forest 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

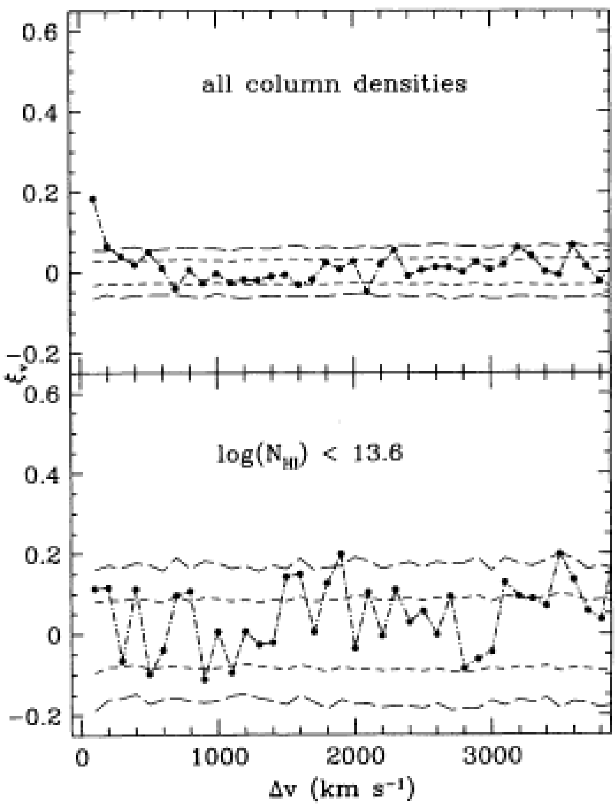


Figure 1. Two-point correlation function in the velocity space.

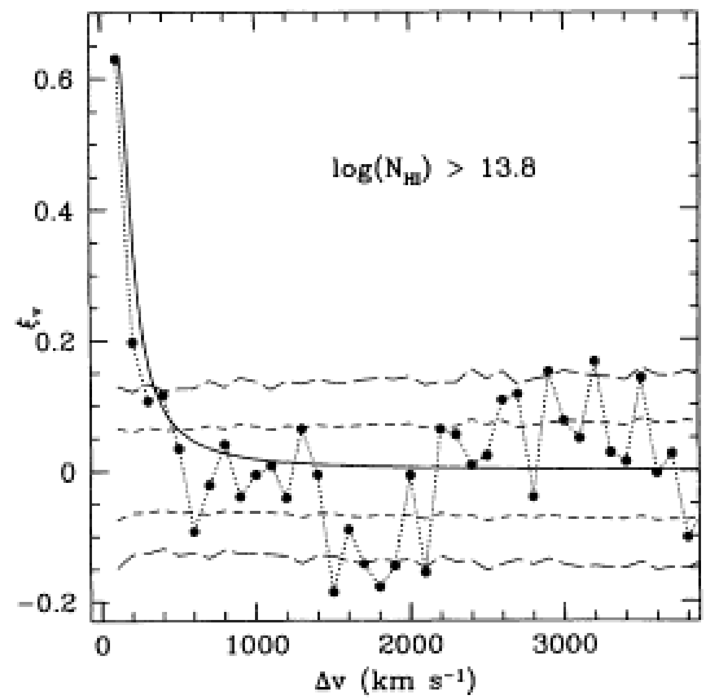
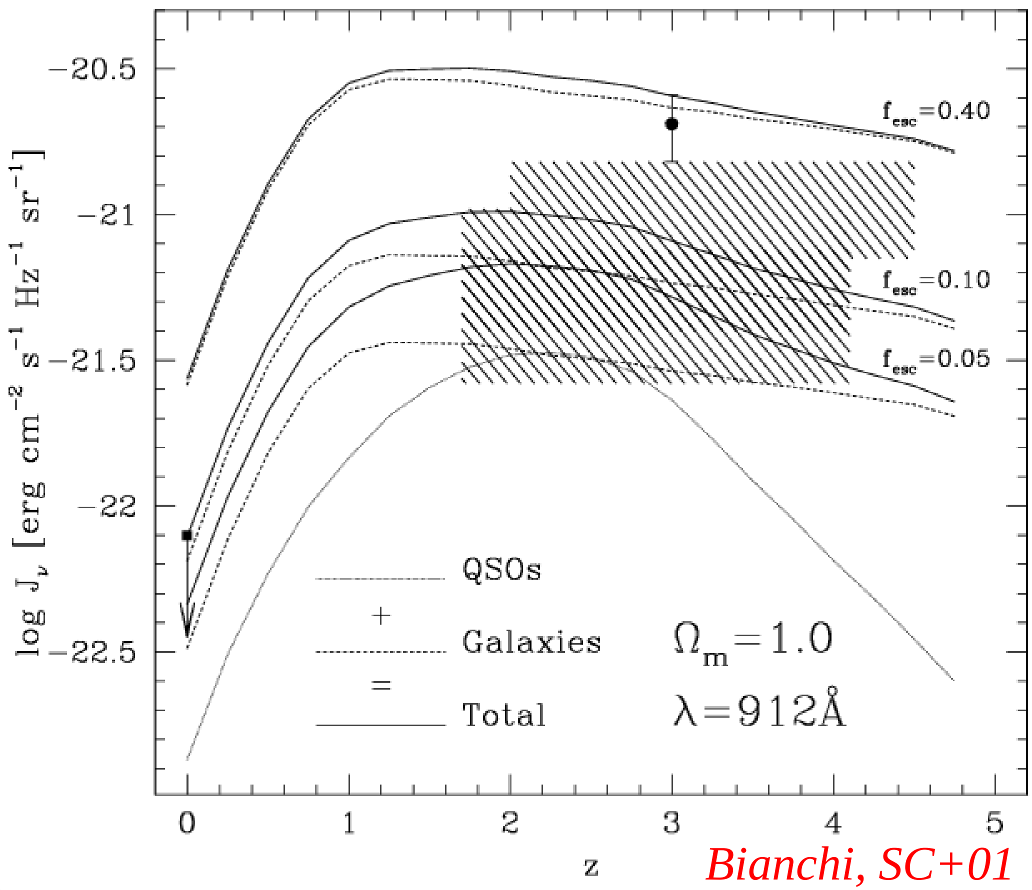


Figure 2. Two-point correlation function in velocity space for lines with column densities $> 10^{13.8}$ cm^{-2}. Confidence limits are as in Fig. 1. The continuous line shows the model described in Section 4, equation (4), with $\gamma = 1.77$, $\sigma = 50$ km s^{-1}, $r_{cl} = 180\ h_{50}^{-1}$ kpc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

The UV background
via the proximity effect

(MaxLik: Giallongo, SC+ 1996)

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



Bianchi, SC+01

Conservation Law

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

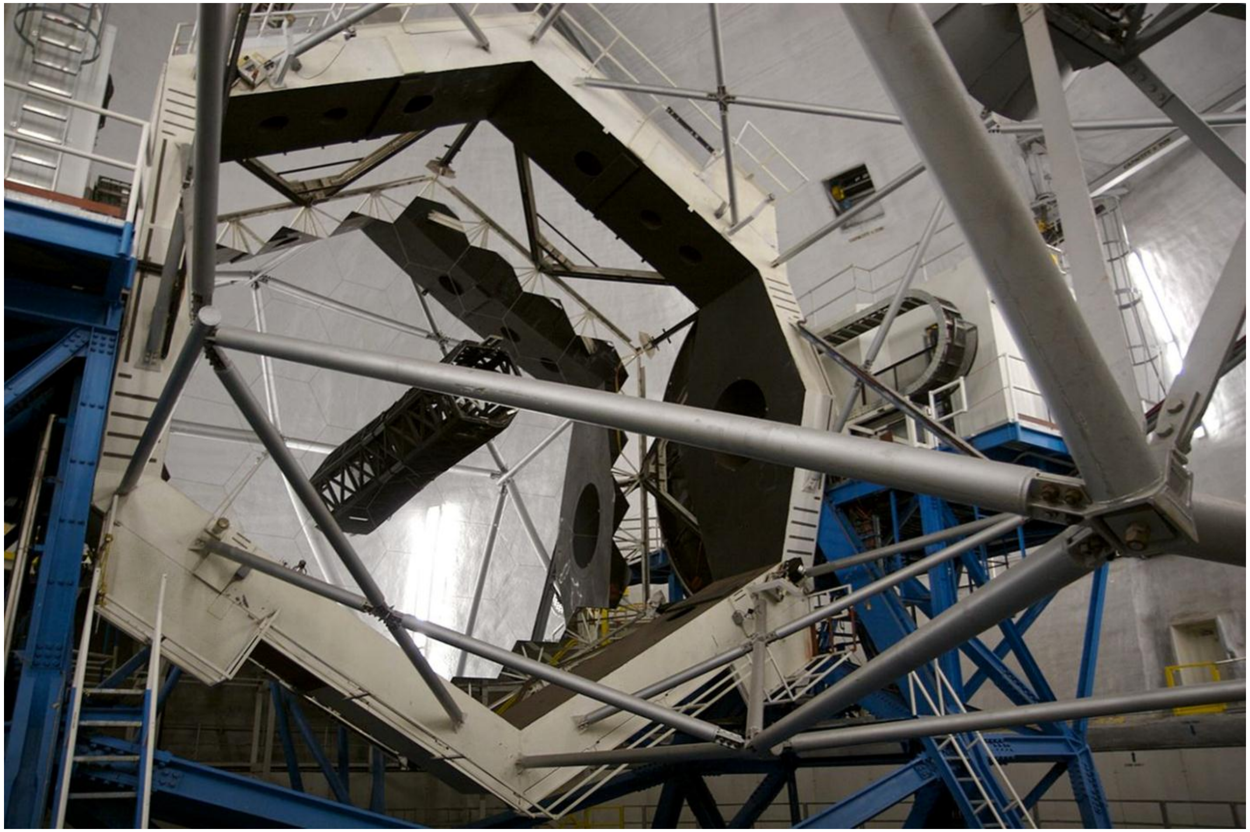
$$\frac{\partial^2 n}{\partial z \partial N_{HI}} = A_o(1+z)^\gamma(1+\omega)^{1-\beta_f} \begin{cases} N_{HI}^{-\beta_f} & N_{HI} < N_{break} \\ N_{HI}^{-\beta_s} N_{break}^{\beta_s-\beta_f} & N_{HI} \geq N_{break} \end{cases}$$

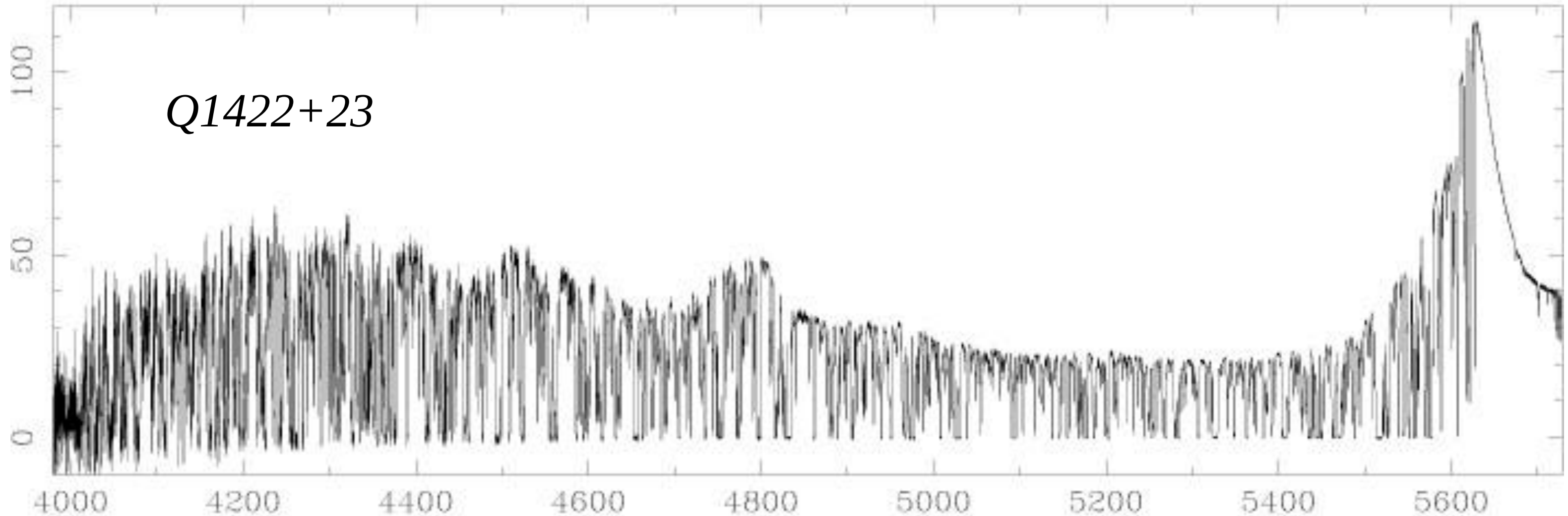
N_l	γ	β_f	$\log N_{\infty,b}$	β_s	$\log J$	
1128	2.49±0.21	1.10±0.07	14.00±0.02	1.80±0.03	-21.21±0.07	
	2.65±0.21	1.34±0.07	13.98±0.04	1.80±0.03	-21.32±0.08	–

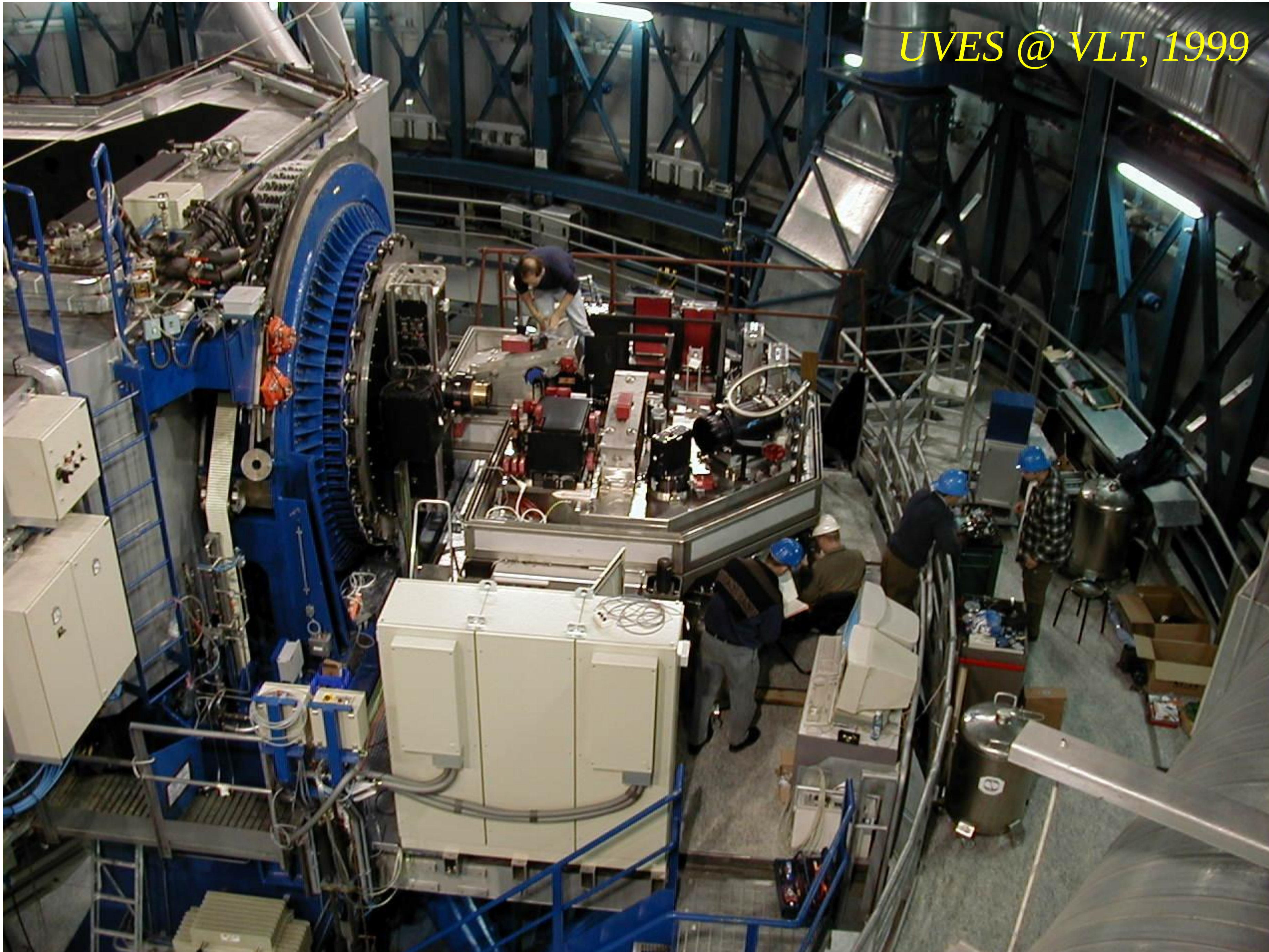
$J_{22} = 5 \pm 1$

HIRES
@ Keck!

1995

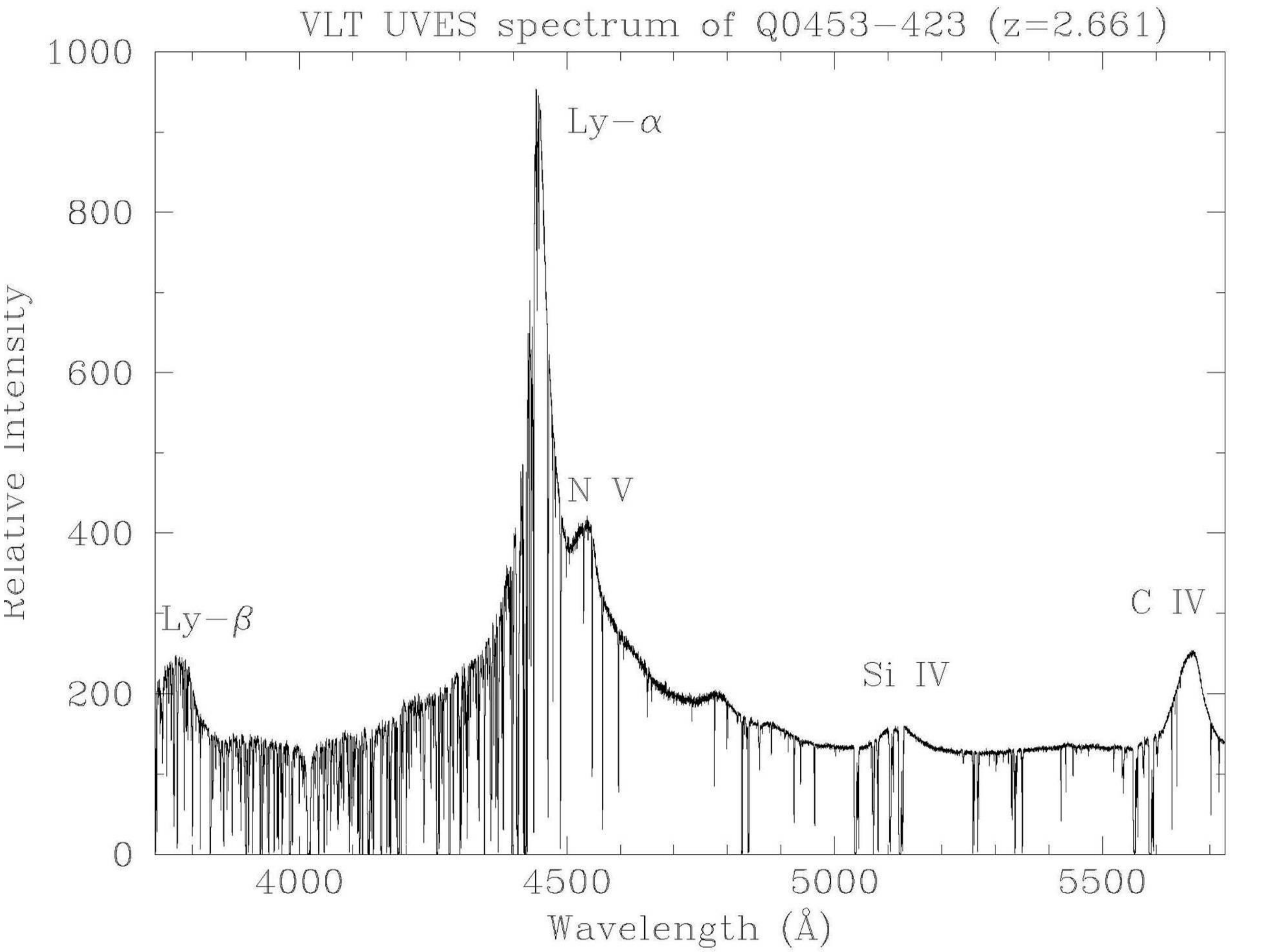





UVES @ VLT, 1999

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)
1000
800
600
400
200
0
4000
4500
5000
5500

…from Lyman Forest Early Models

Discrete Clouds

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

<u>Pressure confined by a hotter and more tenuous ICM</u>

PROBLEMS

- COBE (1989) limits on hot intra-cloud medium
- Range in NHI- very large
- N(z)
- How did the clouds form??

…to a new Ly Forest paradigm: the cosmic Web

THE RISE OF DM MODELS – minihalos (Rees 86)

Cosmological Hydro simulations

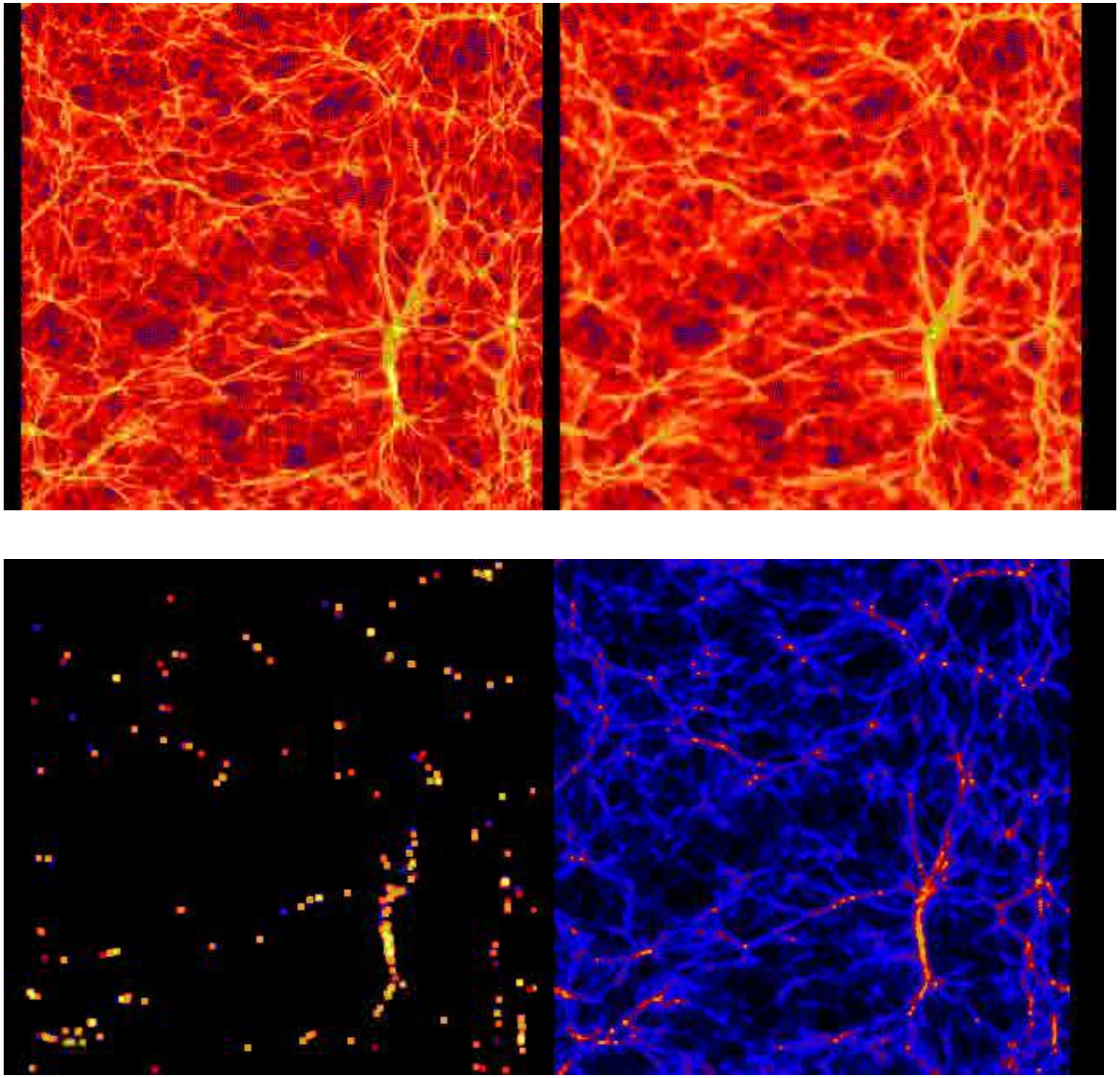
- large number of collapsed DMH too small to form stars and turn into galaxies
- Warm photoionized IG gas sinks into mini-halos or accretes onto DM filaments and sheets
- thermal gas pressure prevents further collapse (i.e. no star formation)
- visible only in absorption

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

COSMOS computer – DAMTP (Cambridge)

DM

GAS



STARS

NEUTRAL HYDROGEN

Courtesy M.Viel

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

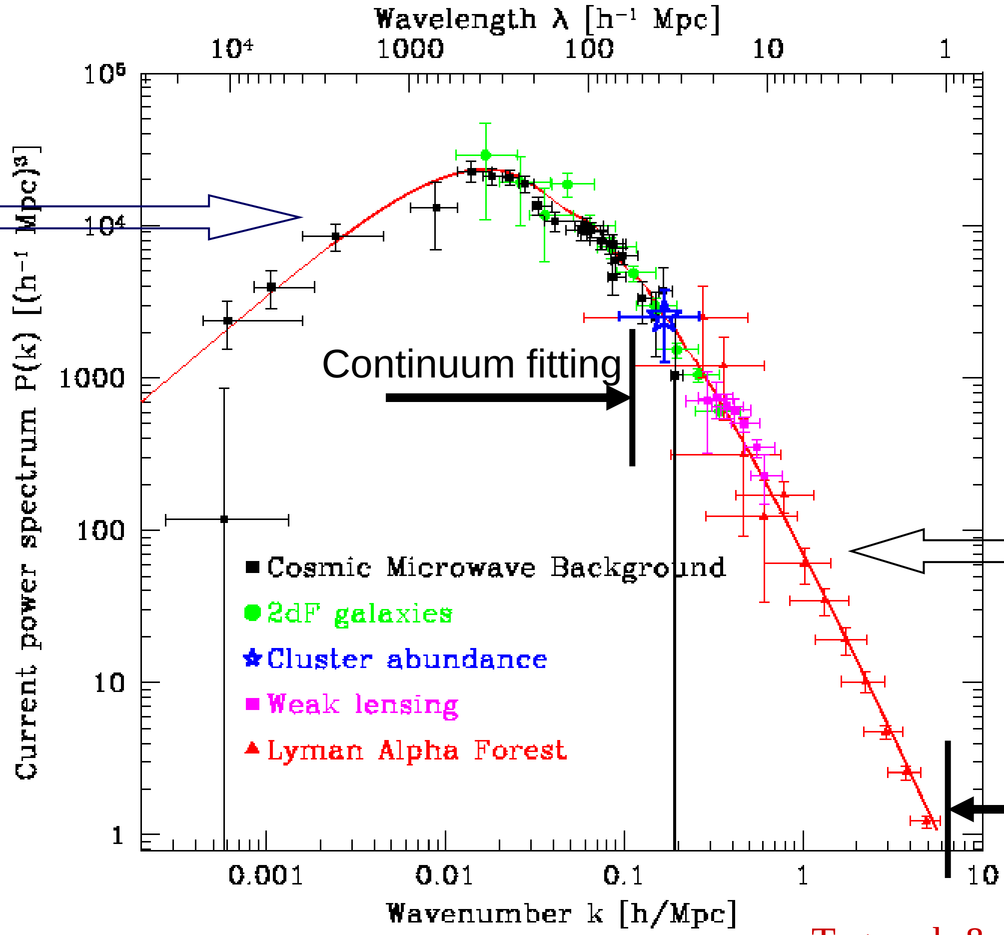
$$T = T_0(1+\delta)^\gamma$$

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)

GOAL: the primordial dark matter power spectrum

CMB physics
z = 1100
dynamics



Lyα physics
z < 6
dynamics
+
termodynamics

Temperature, metals, noise

Tegmark & Zaldarriaga 2002

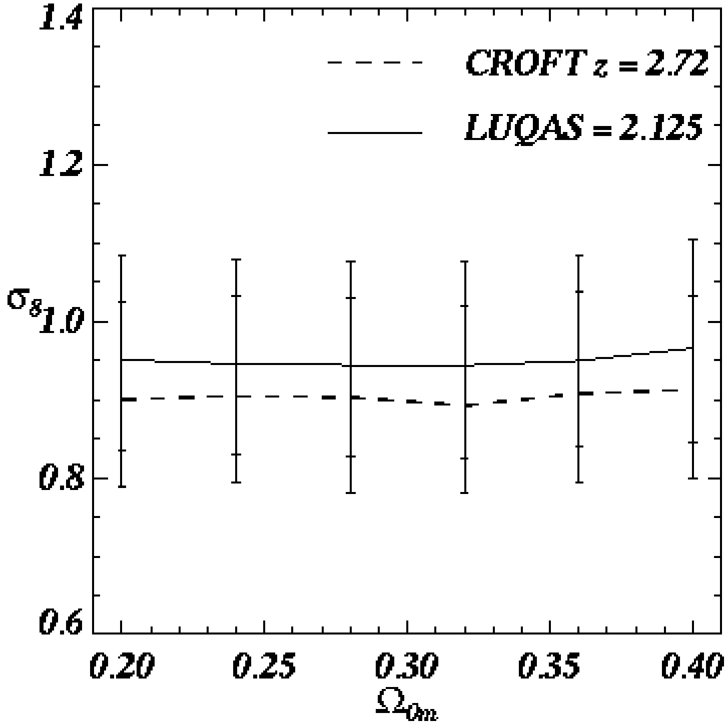
CMB + Lyman α → Long lever arm

Constrain spectral index and shape

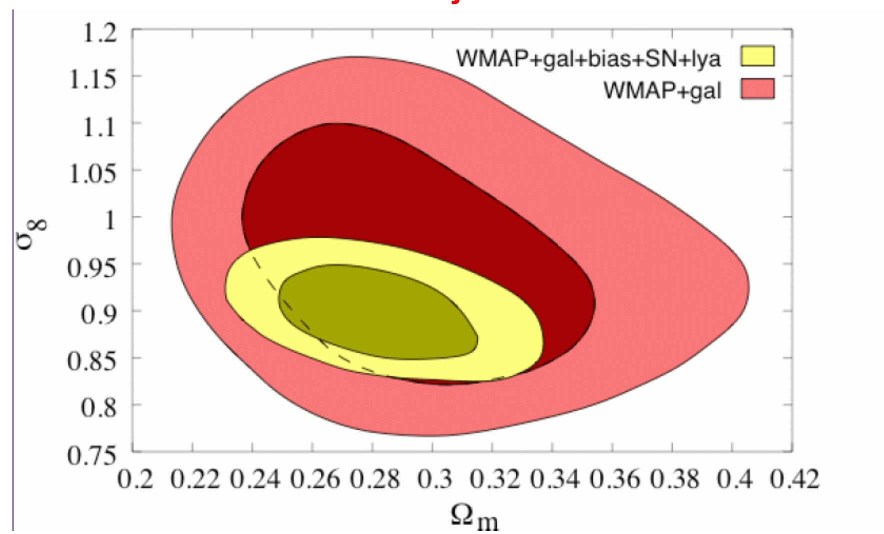
Relation: P_{FLUX} (k) - P_{MATTER} (k)?

Cosmological implications: combining the forest data with CMB

Viel, Haehnelt, Springel 2004



SDSS Seljak et al. 2004



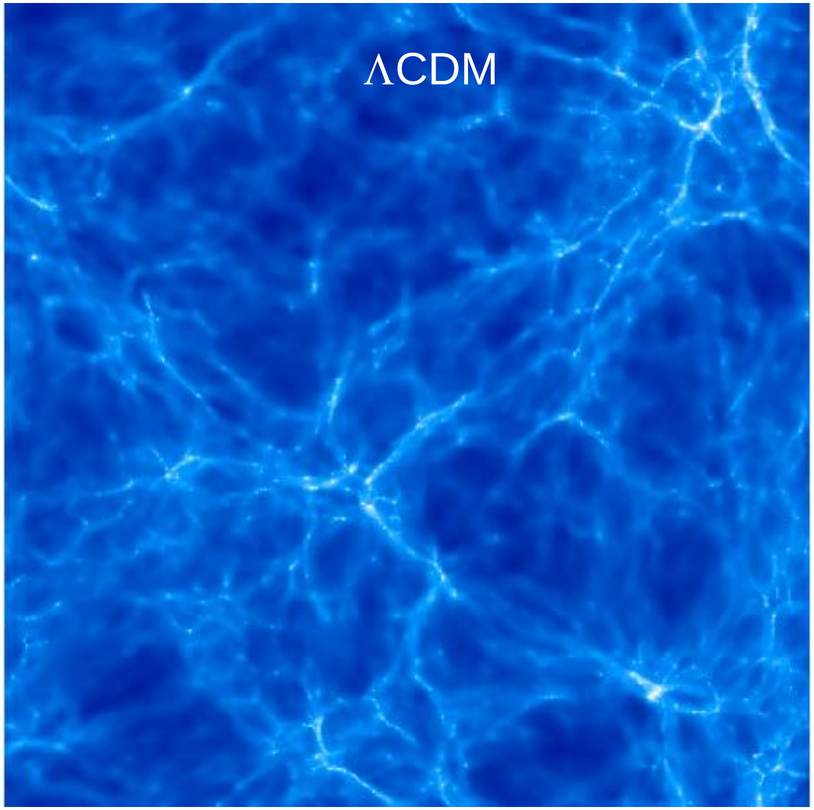
$$n = 1.01 \pm 0.02 \pm 0.06$$
$$\sigma_8 = 0.93 \pm 0.03 \pm 0.09$$

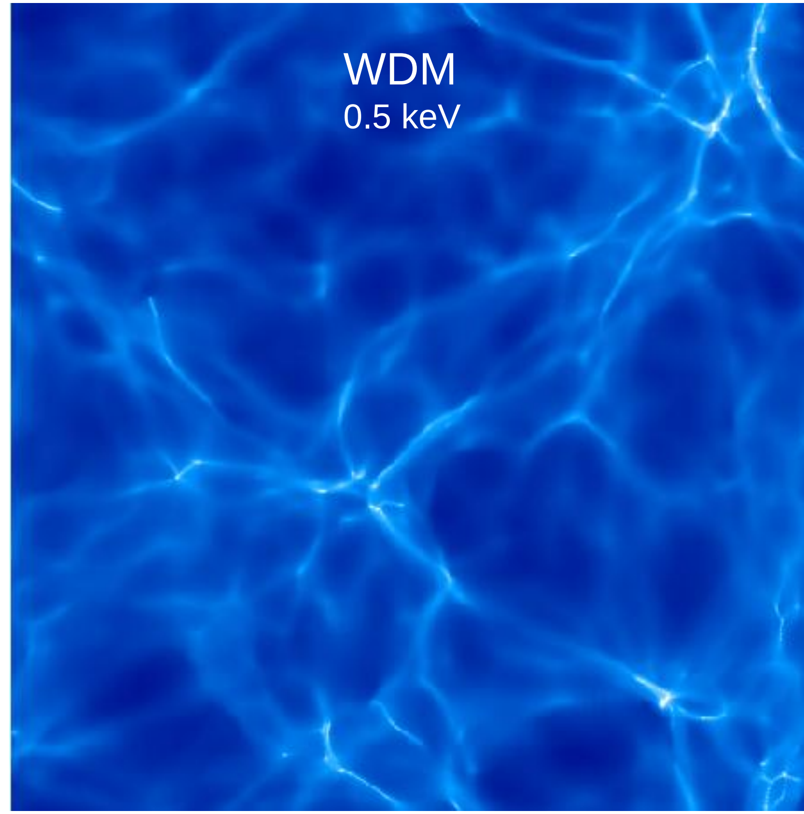
Systematic error

Statistical error

Note that the flux bispectrum analysis agrees with these values
Viel, Matarrese, Heavens, Haehnelt, Kim, Springel, Hernquist, 2004

Cosmological implications: Warm Dark Matter particles





30 comoving Mpc/h z=3

In general

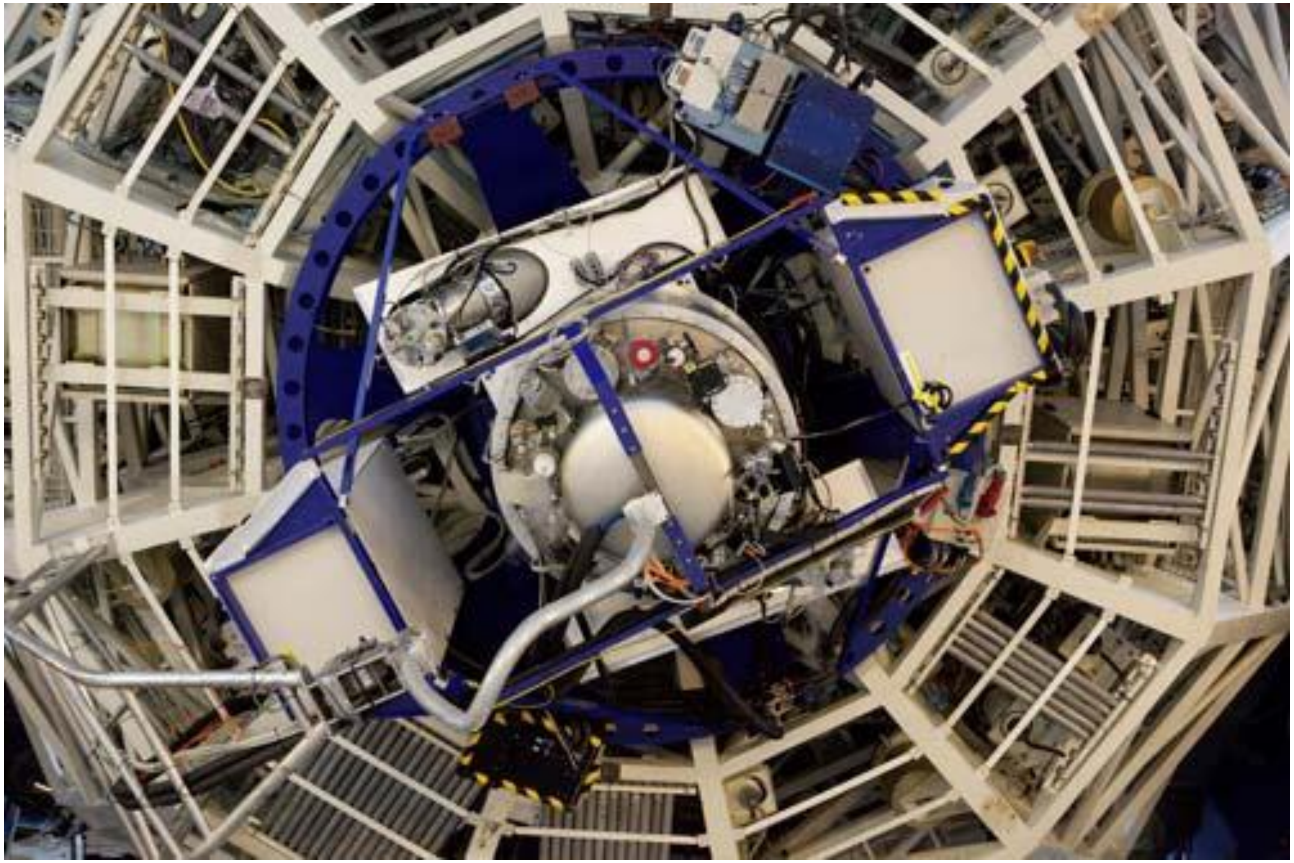
m(sterile neutrino) > 28 keV (2σ)

if light gravitinos

m(WDM) > 4 keV (2σ)

Viel + 2008

X-shooter

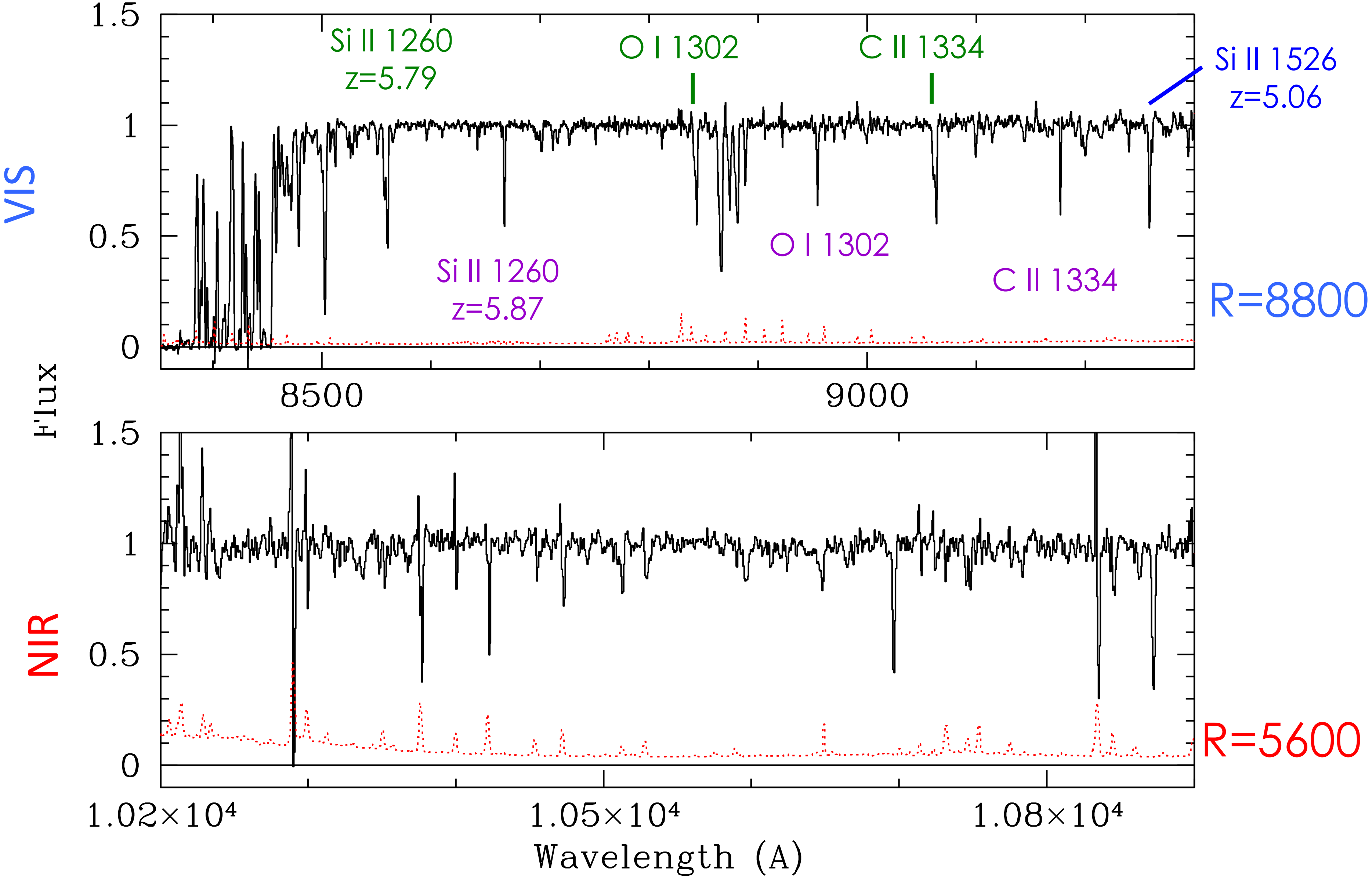


LP: QSOs and their absorption lines: a legacy survey of the high-z Universe (2012)

100 h (P.I. S.Lopez + Cristiani, Cupani, V.D'Odorico, Viel…)

V.D'Odorico +

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



Cosmology - Standard Model

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

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

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

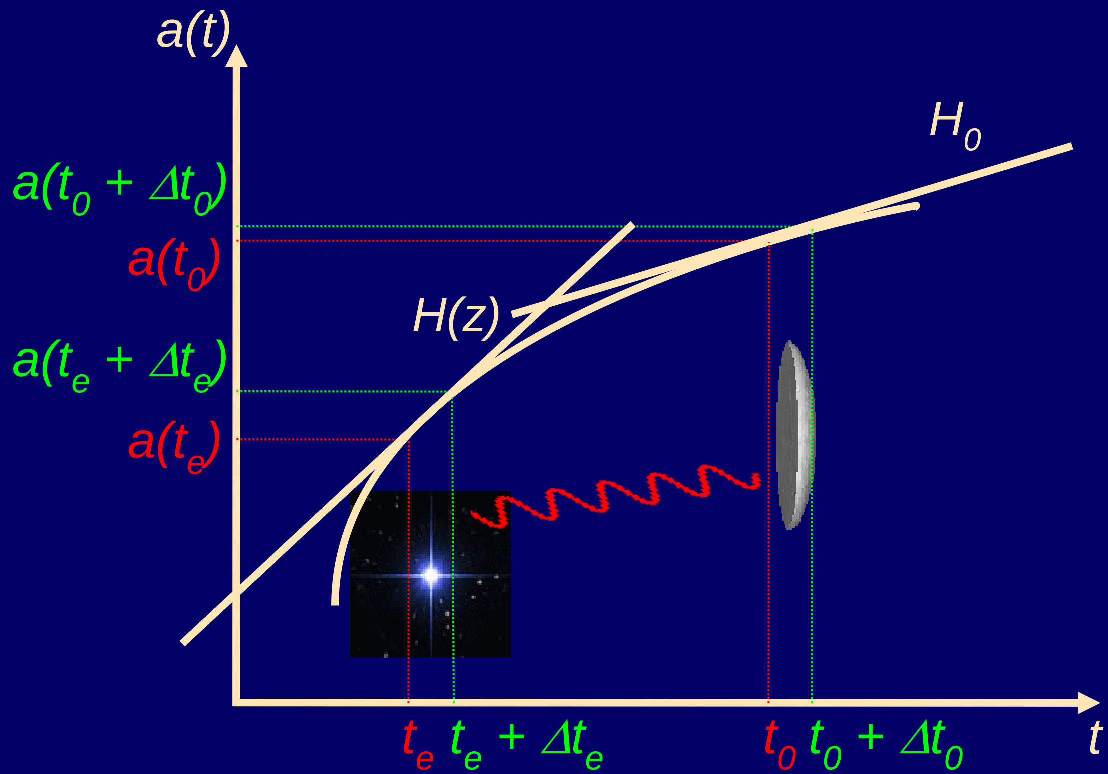
$$\Omega_b \simeq 0.046 \quad \Omega_{DM} \simeq 0.227 \quad \Omega_k \sim 0 \quad \text{(flat space)} \quad \Omega_\Lambda \simeq 0.728$$

We do not know what Ω_λ is and how it evolves.

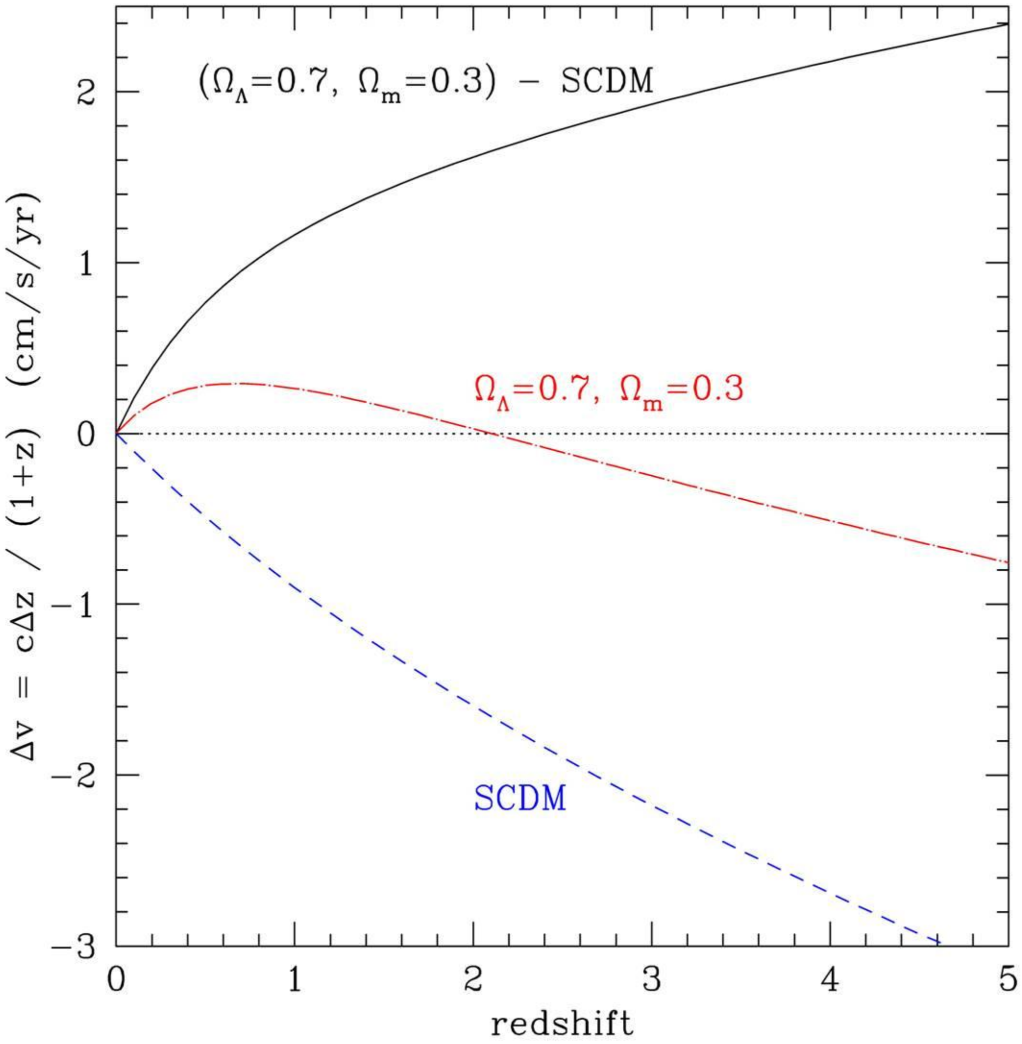
Dynamics has never been measured.

All other experiments, extremely successful such as **High Z SNe search, WMAP, BAOs** ecc. measure **geometry**: dimming of magnitudes and scattering at the recombination surface and clustering (growth of structure).

Dynamics: measuring a(t) ← H(z)



$$\frac{z(t_0 + \Delta t_0) - z(t_0)}{\Delta t_0} = \frac{\Delta z}{\Delta t_0} \approx \frac{dz}{dt_0} = (1+z)H_0 - H(z)$$



Liske et al. 2008

The Signal is SMALL!

$$\dot{z} = (1+z)H_0 - H(t_e)$$

The change in sign is the signature of the non zero cosmological constant

A small signal ..

But 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?

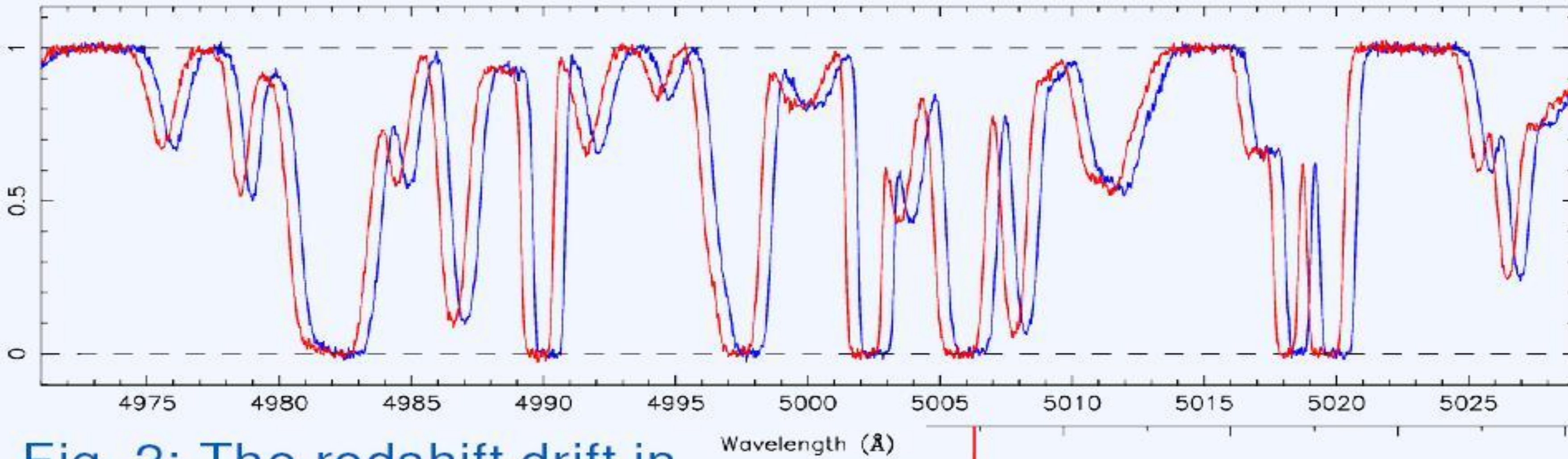


Fig. 2: The redshift drift in a simulated Lyα forest spectrum for Δt = 10^7 yr.

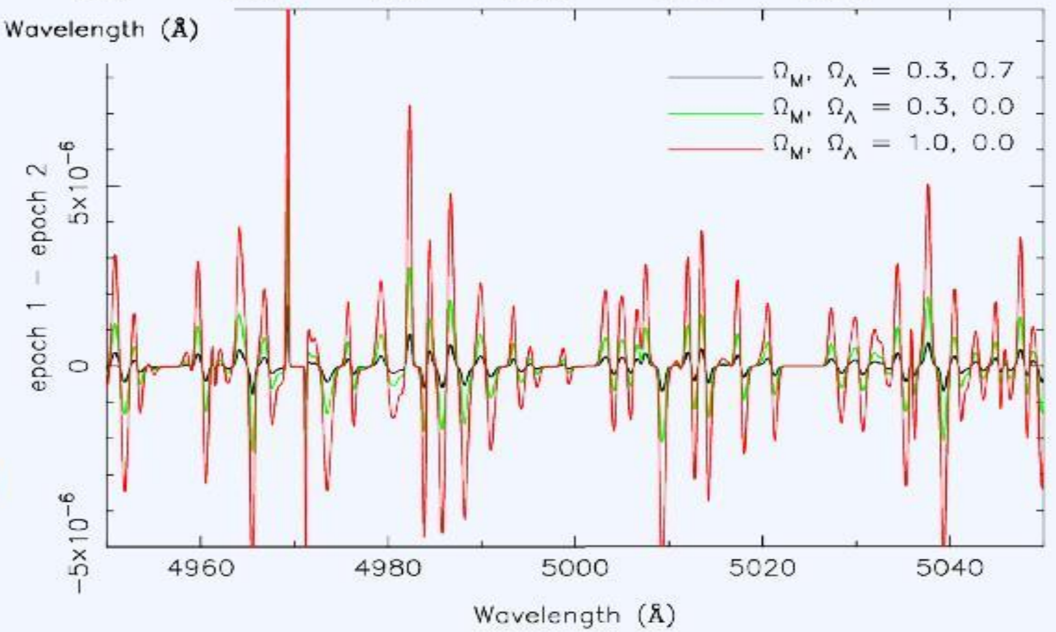
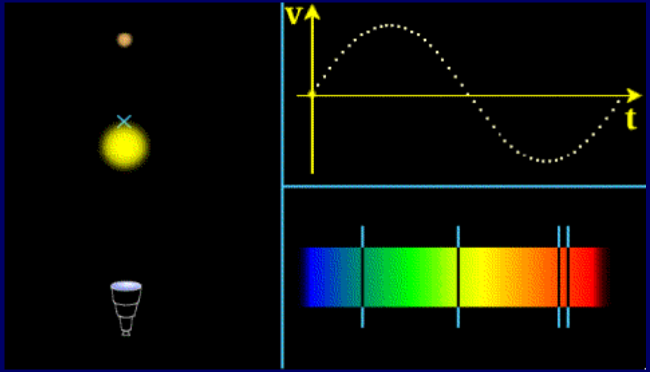


Fig. 3: The difference of two simulated noiseless Lyα forest spectra taken Δt = 10 yr apart.

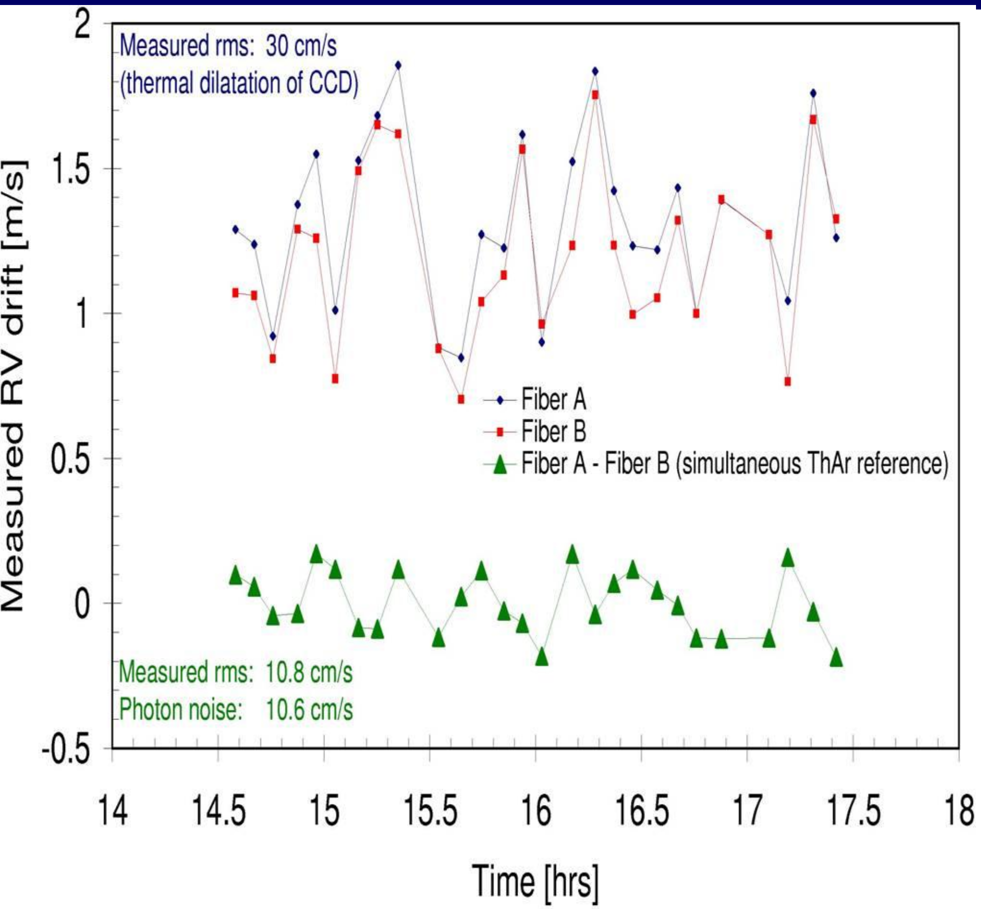
The HARPS Experience

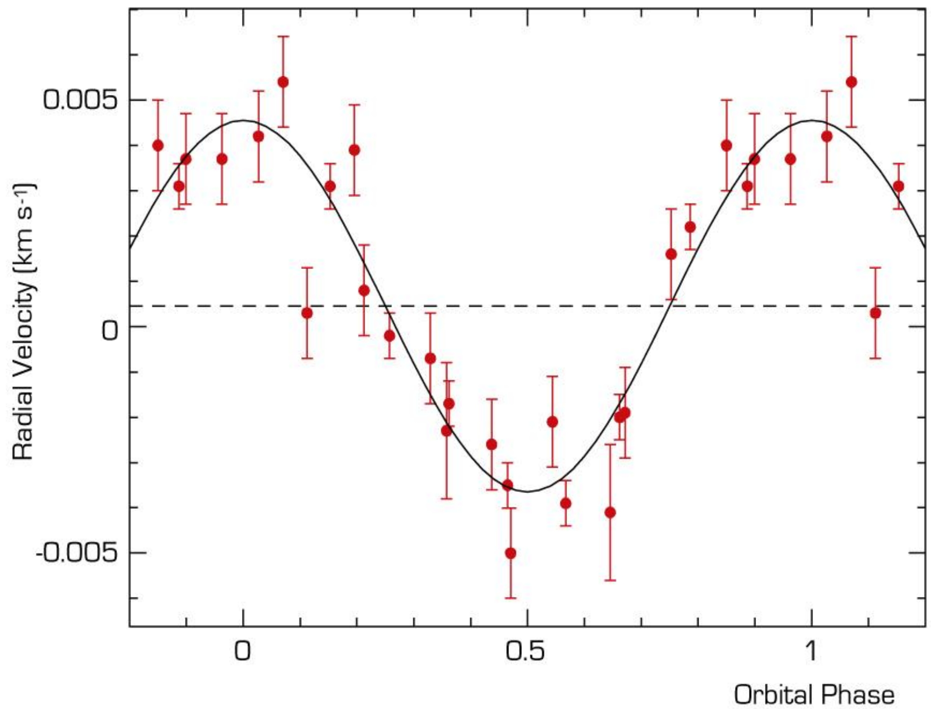
extra-solar planets

Th-Th < 10 cm/sec



O-C < 80 cm/sec





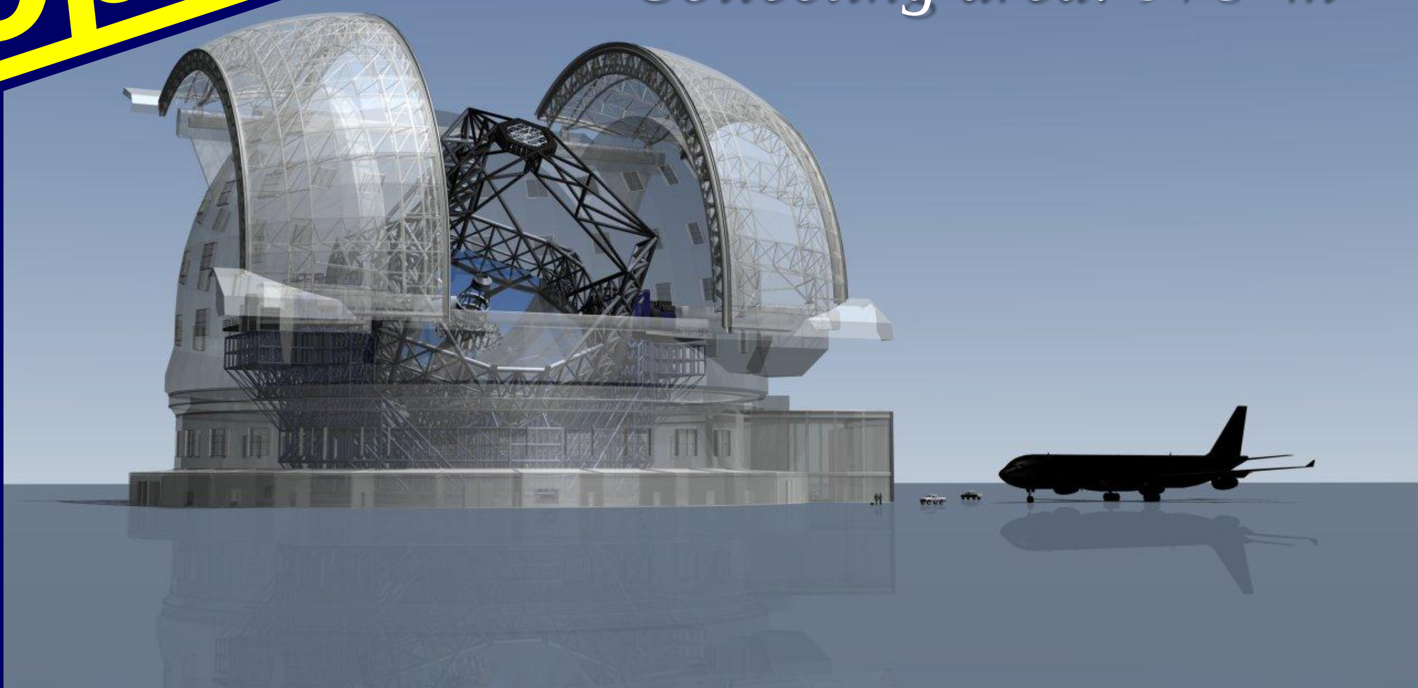
"Velocity Curve" of mu Arae

ESO PR Photo 25d/04 (25 August 2004)

COsmic Dynamics & EXoplanets

@ E-ELT

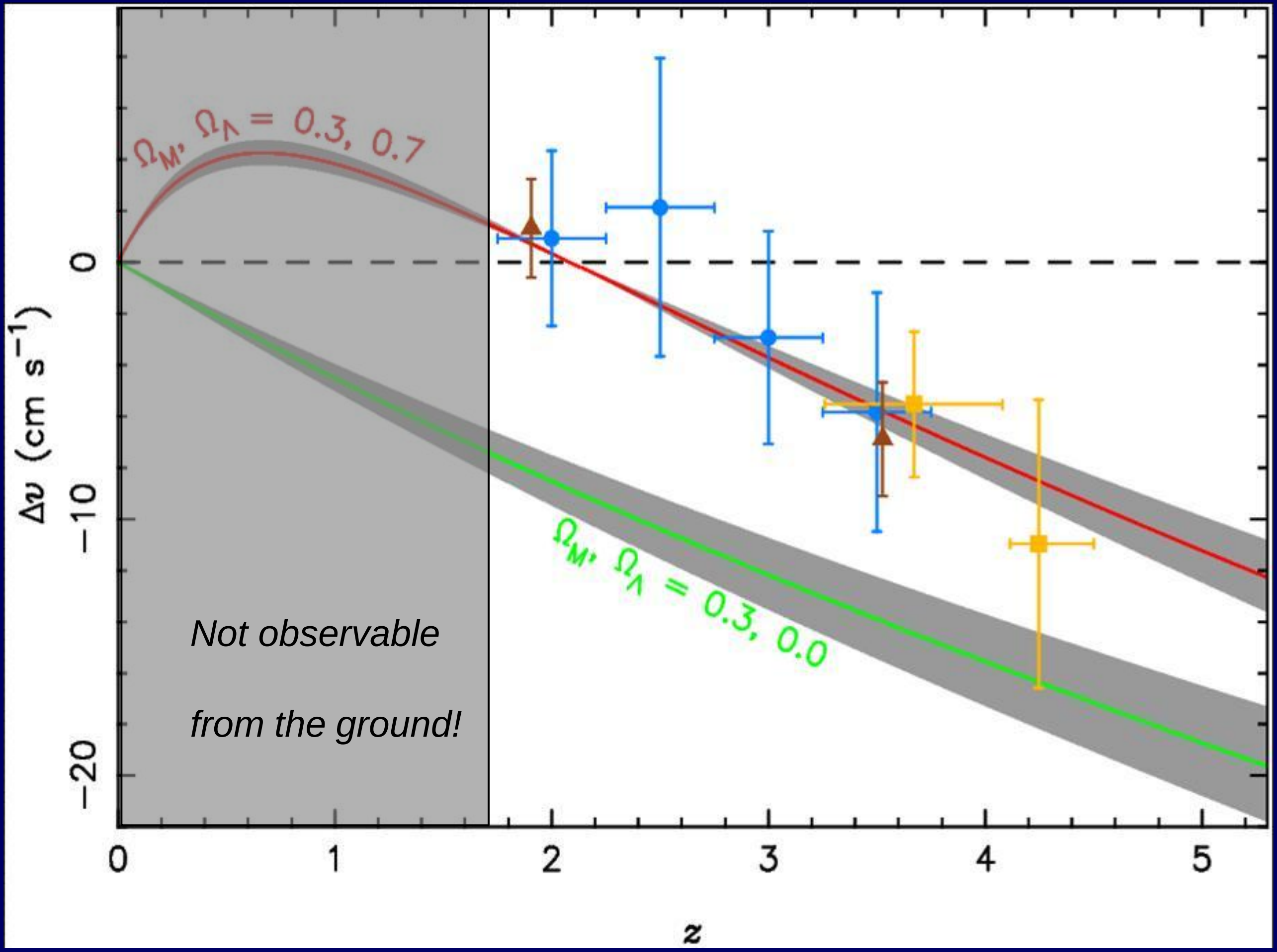
Collecting area: 978 m^2



A simulated measurement

Cristiani et al. 2007

Liske et al. 2008



30 pairs of Lyα forest spectra randomly distributed in range

$2 < z_{QSO} < 4.5$

S/N = 2000

Δt = 30 yr

2000+2000 hours

One giant leap from HARPS (3.6m) & HARPS-N (TNG)?

Need for a prototype

Better… a **precursor**

ESPRESSO

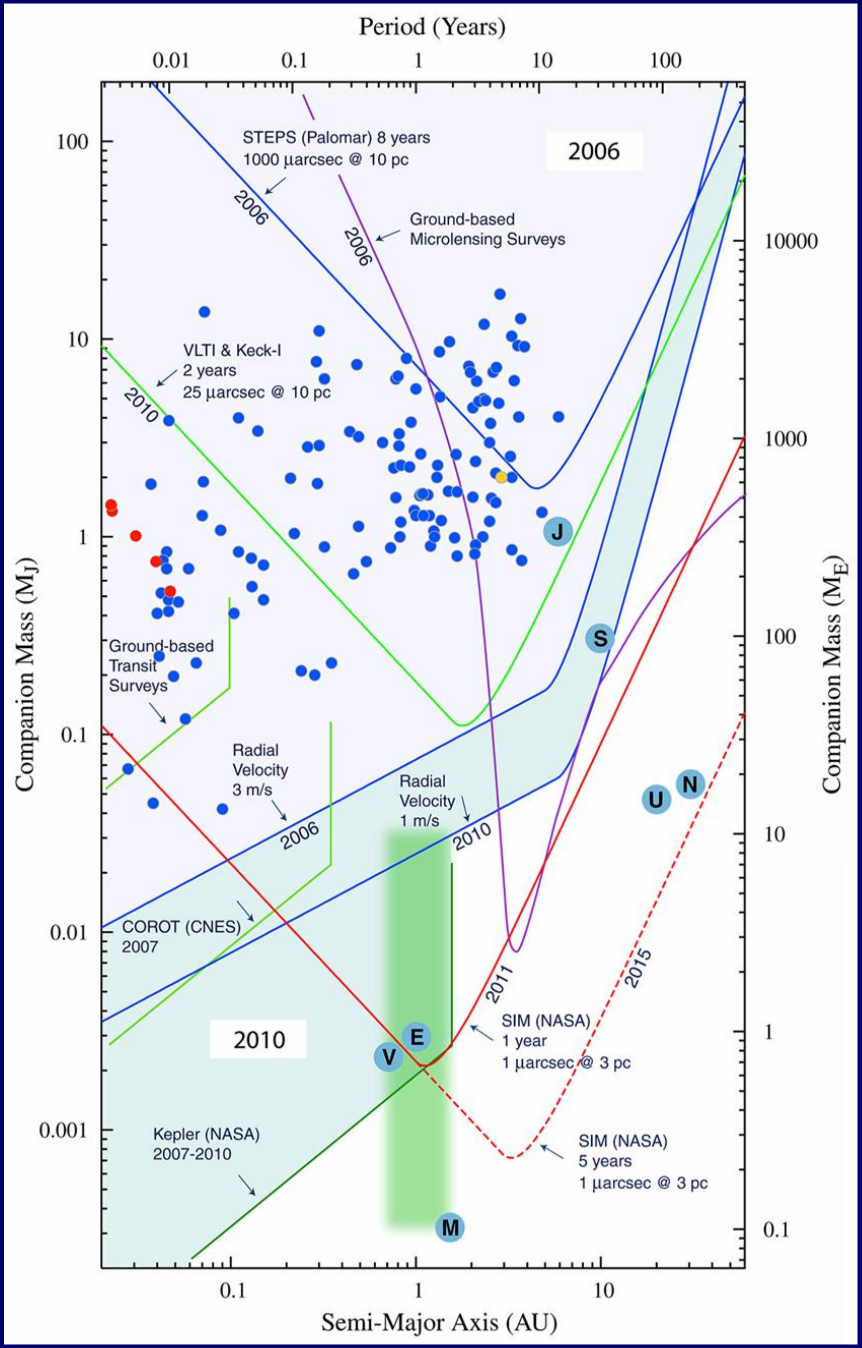
Echelle **SP**ectrograph for **R**ocky **E**xoplanets and **S**table **S**pectroscopic **O**bservations

@ the ESO VLT – one mode @ the incoherently combined focus of the 4 UTs

ESPRESSO & CODEX Science

Terrestrial extra-solar planets

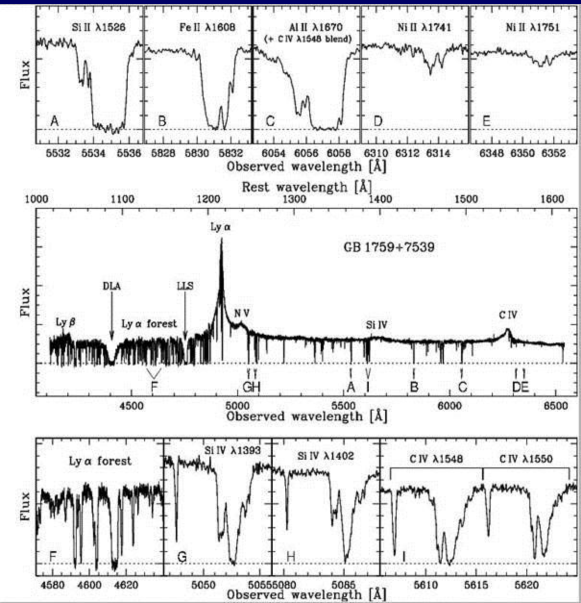
- search and characterization of rocky exoplanets in the habitable zone of quiet, nearby G to M-dwarfs.
- Radial velocity follow-up of earth-mass planet candidates discovered through other techniques (astrometry, transits).
- Different environments and formation histories (GCs, DGs)
- Difficulty: “seeing” the planet through the noise of stellar activity

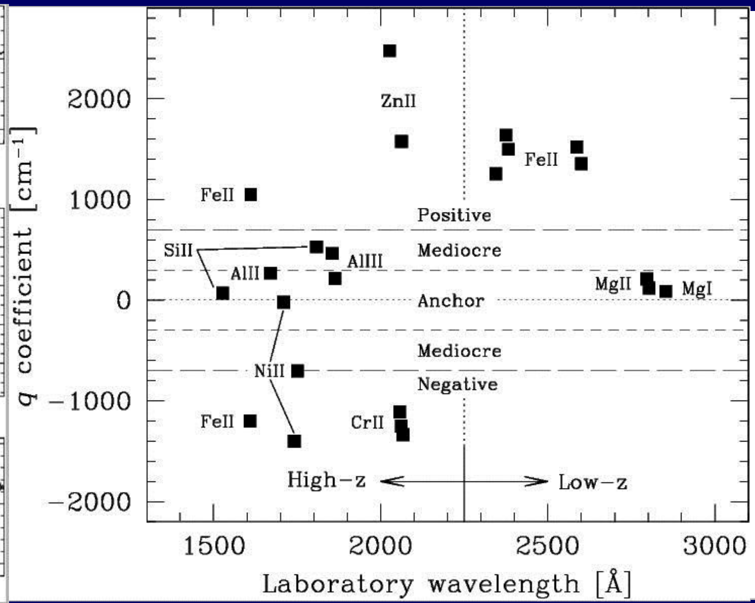


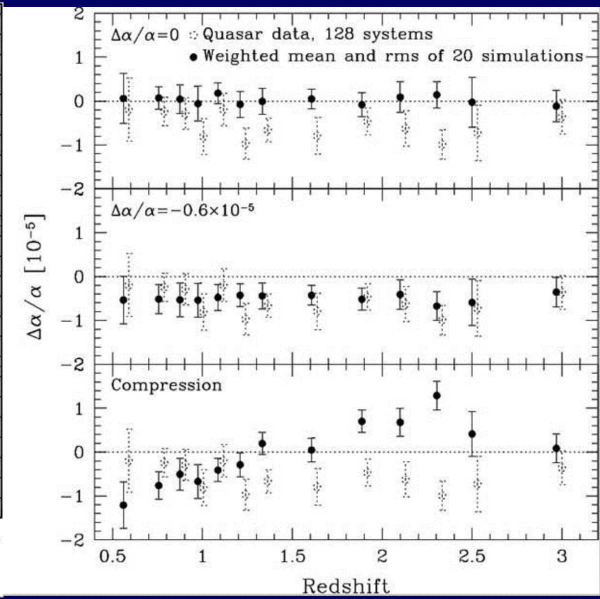
Espresso Science

Cosmological variation of the fine structure constant, m_e/m_p ratio

– Accuracy in $\Delta\alpha/\alpha \sim 10^{-7}$







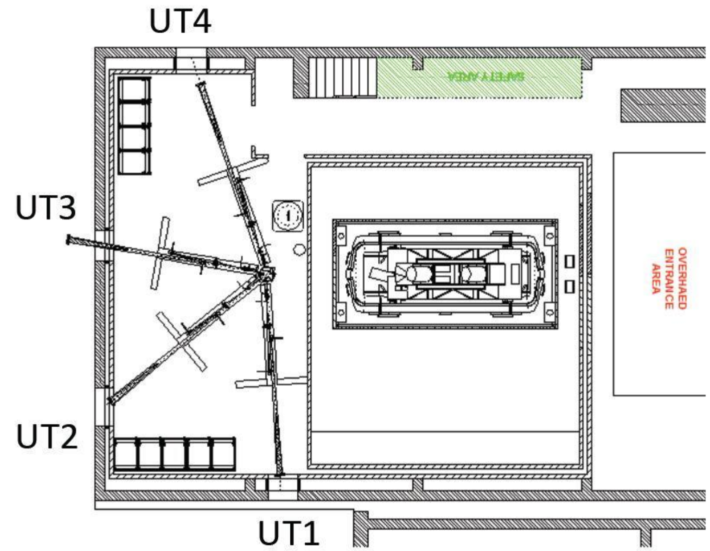
See Molaro+ 09

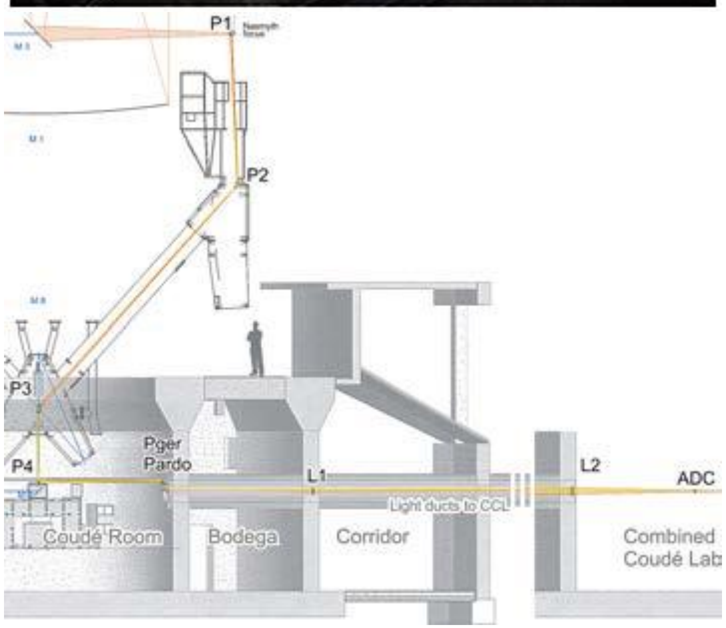
ESPRESSO – Science +

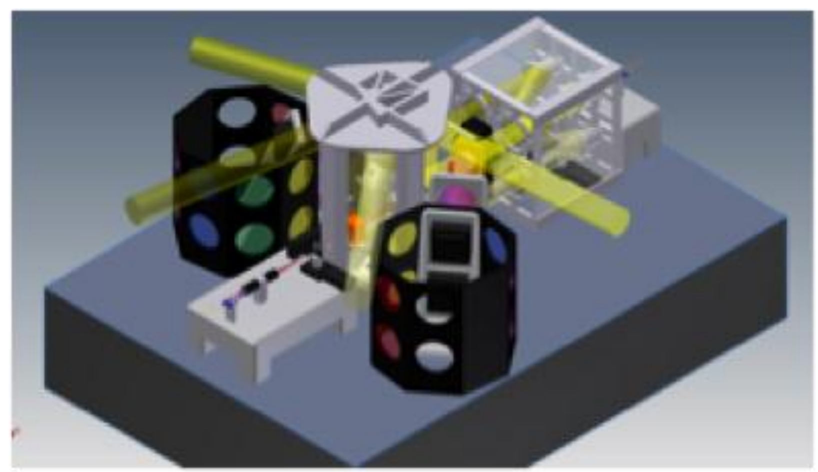
- ✓*Chemical composition of stars in local galaxies*
- ✓*Investigation of metal-poor stars*
- ✓*Stellar oscillations, asteroseismology*
- ✓*Diffuse stellar bands in the interstellar medium*
- ✓*Chemical enrichment of IGM*
- ✓*Galactic winds and tomography of the IGM*
- ✓*Chemical properties of protogalaxies*
- ✓*Cosmology*

The 4 VLT Telescopes and the CCL

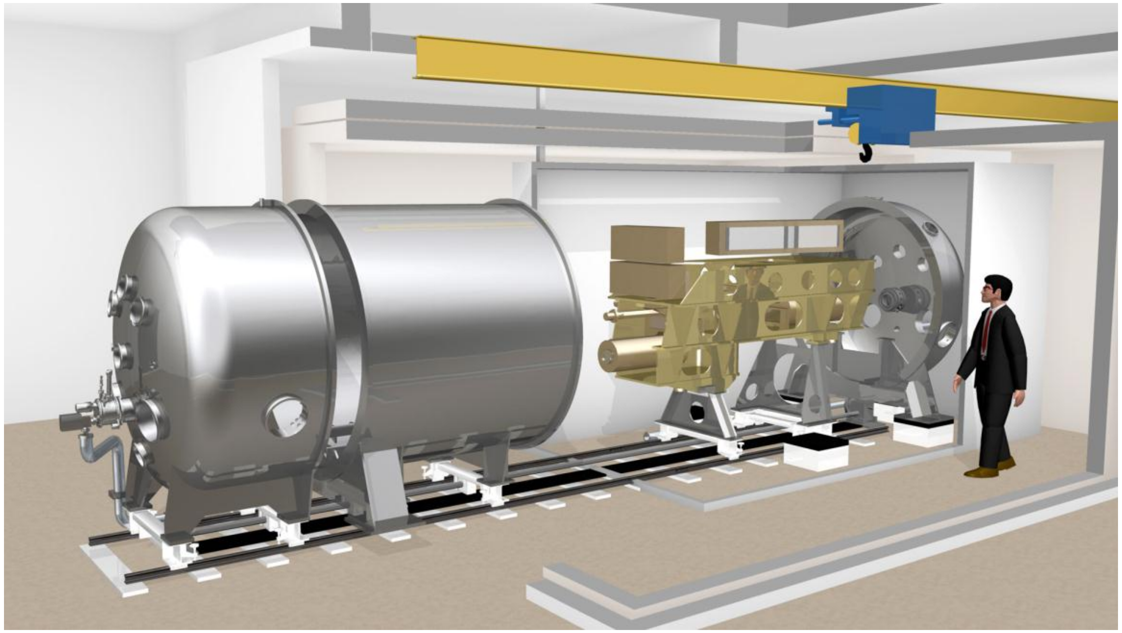
Distances to Combined Lab
UT 1 – 69 m
UT 2 – 48 m
UT 3 – 63 m
UT 4 – 63 m







Designed for stability



ΔRV =1 m/s

ΔT =0.01 K

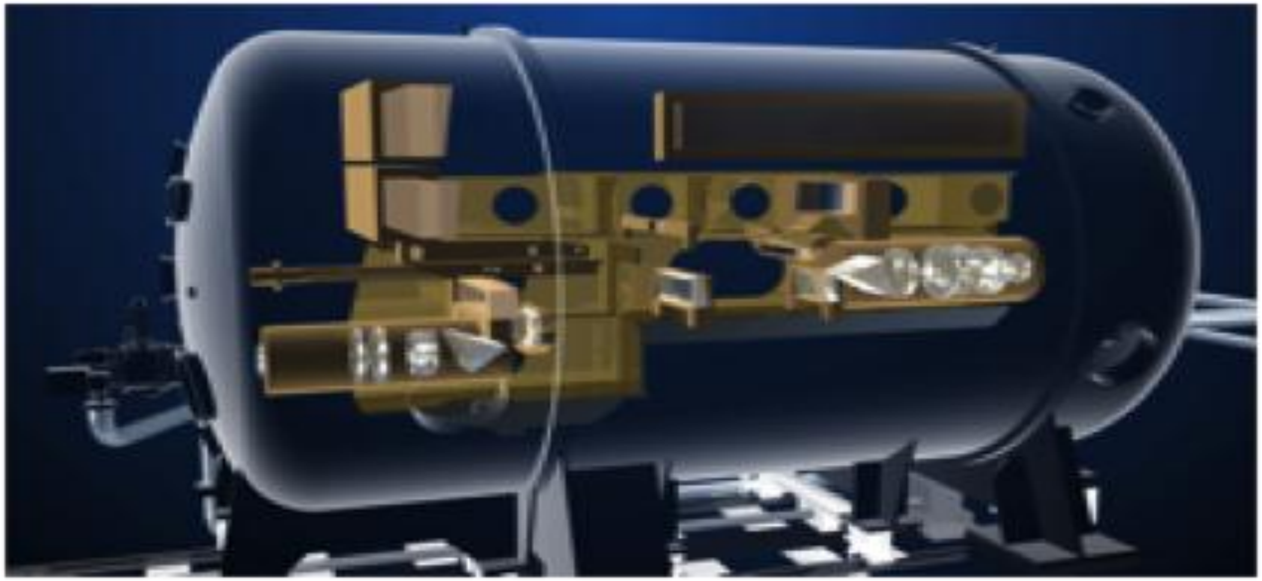
Δp=0.01 mBar

ΔRV =1 m/s

Δλ=0.00001 A

15 nm

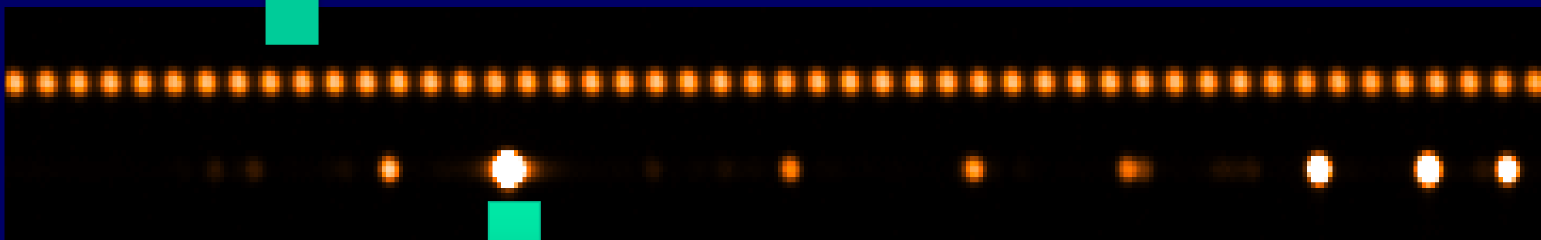
1/1000 pixel



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*

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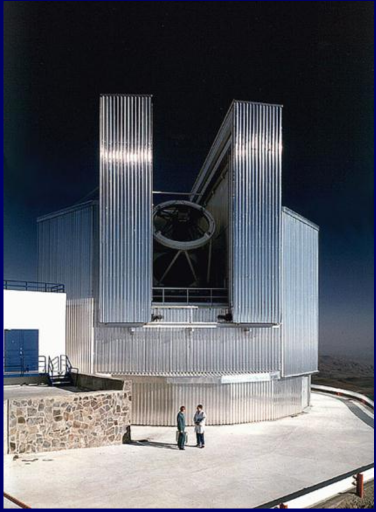

We have at least another 30 years of fun ahead!