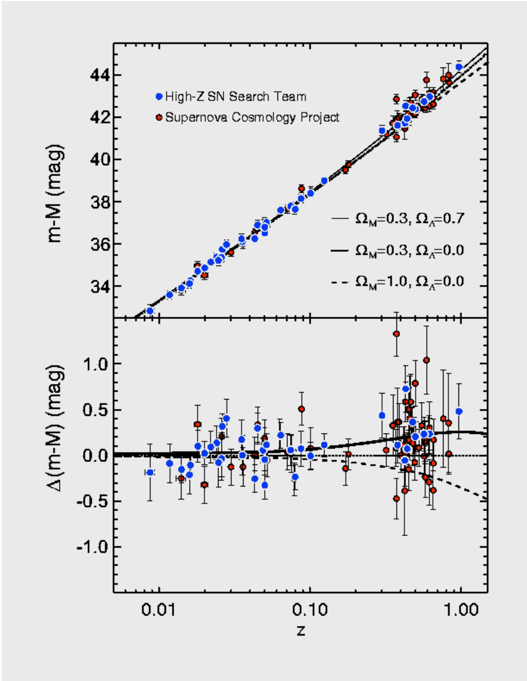
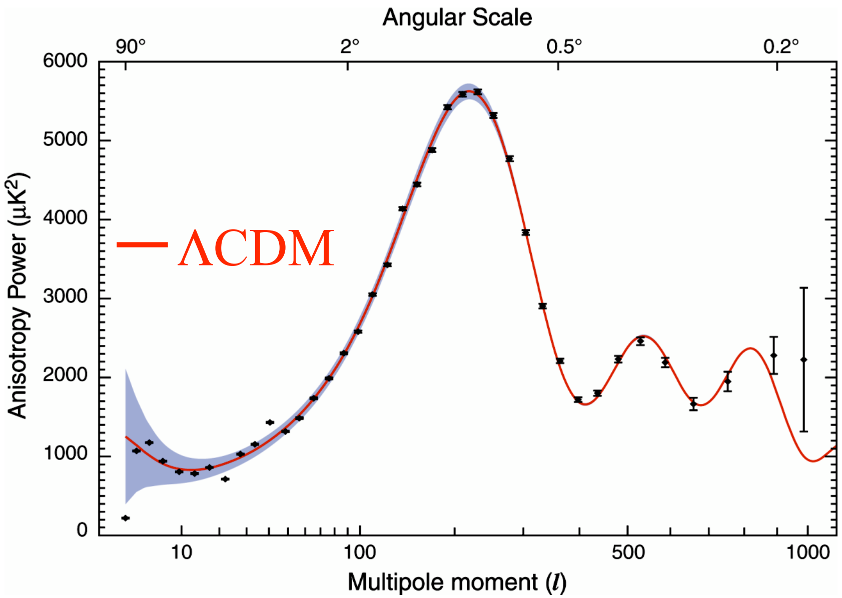
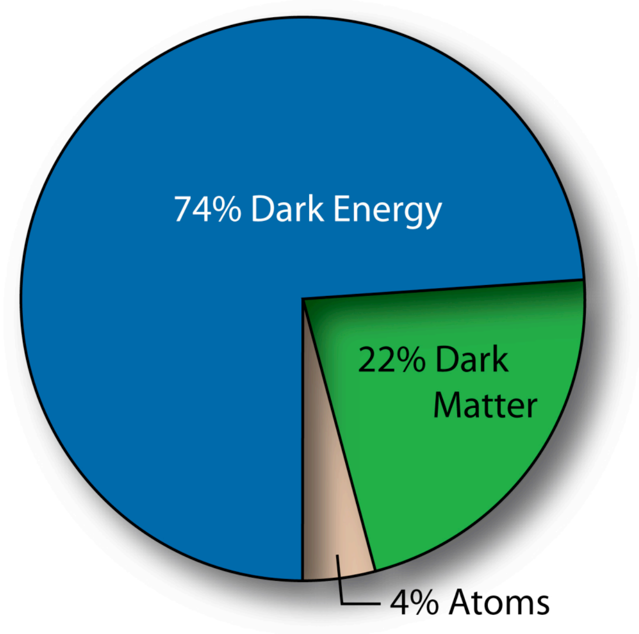
Measuring the redshift drift of the Lyα forest
-
a direct measurement of the dynamical evolution of the Universe


High-Z SN Search Team
Supernova Cosmology Project
Ω_M=0.3, Ω_Λ=0.7
Ω_M=0.3, Ω_Λ=0.0
Ω_M=1.0, Ω_Λ=0.0
m-M (mag)
Δ(m-M) (mag)
z


Angular Scale
90°
2°
0.5°
0.2°
Anisotropy Power (μK^2)
ΛCDM
Multipole moment (l)


74% Dark Energy
22% Dark Matter
4% Atoms

“It should be possible to choose between various models of the expanding universe if the deceleration of a given galaxy could be measured. Precise predictions of the expected change in $z=d\lambda/\lambda_0$ for reasonable observing

times (say 100 years) is exceedingly small. Nevertheless, the predictions are interesting, since they form part of the available theory for the evolution of the universe”

Sandage 1962 ApJ 136,319

1. Title Category: **A–8**

Monitoring the redshift-drift of the Lyman-alpha forest – a direct measurement of the dynamical evolution of the Universe

2. Abstract / Total Time Requested

Total Amount of Time: 3660h Total Number of Semesters: 30

We propose to monitor the redshift drift of the Lyα forest and associated metal lines of a sample of high (1000-3300) S/N spectra of 30 very bright QSOs in the redshift range $2 < z < 4.5$ with the ultra-stable high resolution optical spectrograph on the E-ELT for a period of 15 yrs. The redshift drift is sensitive to the difference of the expansion rate today and the expansion rate at the redshift of the absorbing structures and is directly related to the acceleration of the Universe. With the proposed observations we can achieve an overall measurement accuracy of 3.2 cm/s. By monitoring the drift of the Lyα forest over a wide redshift range we will measure the instantaneous expansion rate of the Universe today and the expansion rate at high redshift. The measurement of the expansion rate and its evolution at high redshift will be an important test of General Relativity. The measurement of the instanteneous expansion rate will test whether the Universe expands today at the rate expected from other astronomical measurements which generally constitute measurements of the expansion rate averaged over hundred Myrs or more. The observations proposed can be used as a first epoch measurement for more accurate measurements by future generation of astronomers and will thus leave a long lasting legacy. The acquired spectra will represent a unique resource for a wide range of QSO absorption line studies.

3. Run	Period	Instrument	Time	Month	Moon	Seeing	Sky Trans.	Obs.Mode
A	80	UVES	122h	any	d	$\leq 0.8''$	PHO	s
B	81	UVES	122h	any	d	$\leq 0.8''$	PHO	s
C	82	UVES	122h	any	d	$\leq 0.8''$	PHO	s
D	83	UVES	122h	any	d	$\leq 0.8''$	PHO	s
E	83	UVES	122h	any	d	$\leq 0.8''$	PHO	s
F	83	UVES	122h	any	d	$\leq 0.8''$	PHO	s
G	83	UVES	122h	any	d	$\leq 0.8''$	PHO	s
H	83	UVES	122h	any	d	$\leq 0.8''$	PHO	s
I	83	UVES	122h	any	d	$\leq 0.8''$	PHO	s
J	83	UVES	122h	any	d	$\leq 0.8''$	PHO	s
K	83	UVES	122h	any	d	$\leq 0.8''$	PHO	s
L	83	UVES	122h	any	d	$\leq 0.8''$	PHO	s

Following runs moved to box 3a, last page...

4. Principal Investigator: **L. Pasquini** (ESO, D, lpasquin@eso.org)

Col(s): M. Haehnelt (IoA, UK), on behalf of the CODEX team (OTHER, OTHER), and the ESO-ELT SWG (OTHER, OTHER)

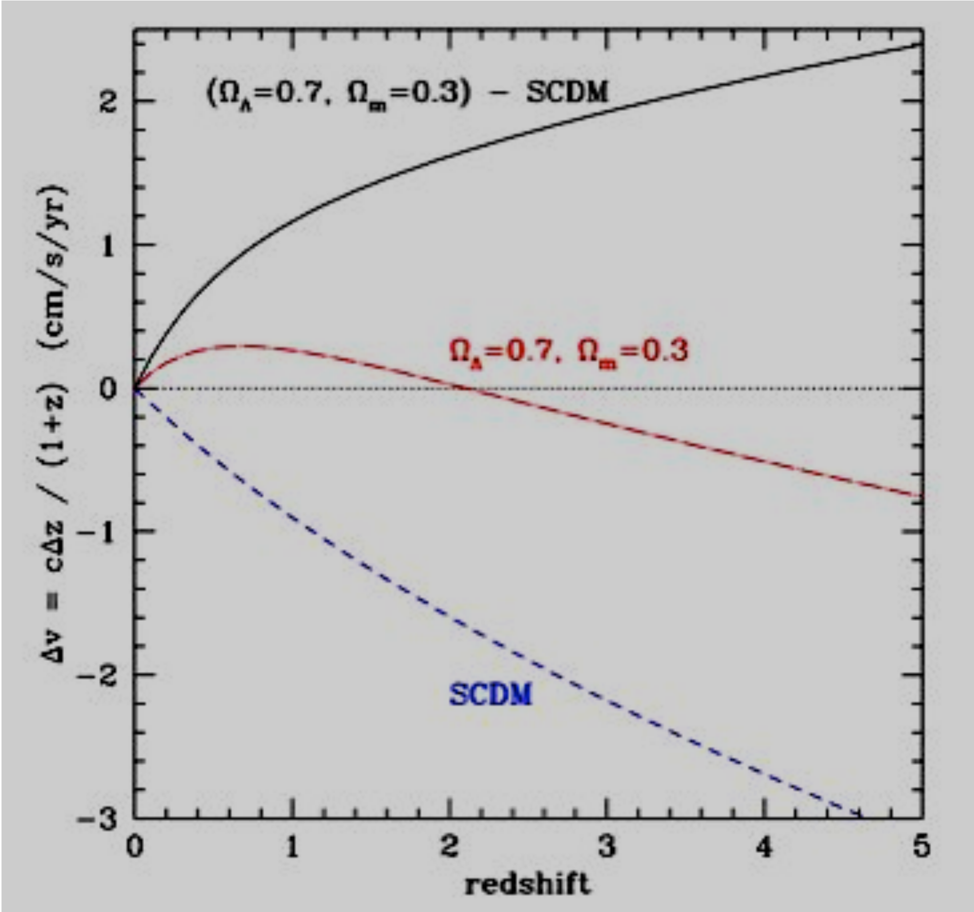
Measuring $\dot{z}$

$$dz = \frac{\partial z}{\partial t_0} dt_0 + \frac{\partial z}{\partial t_e} dt_e$$

$$\dot{z} = \frac{dz}{dt_0} = \frac{\partial z}{\partial t_0} + \frac{\partial z}{\partial t_e}\frac{dt_e}{dt_0} = \frac{\dot{a}(t_0)}{a(t_e)} - \frac{\dot{a}(t_e)}{a(t_e)}\frac{a(t_0)}{a(t_e)}\frac{1}{1+z}$$

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

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

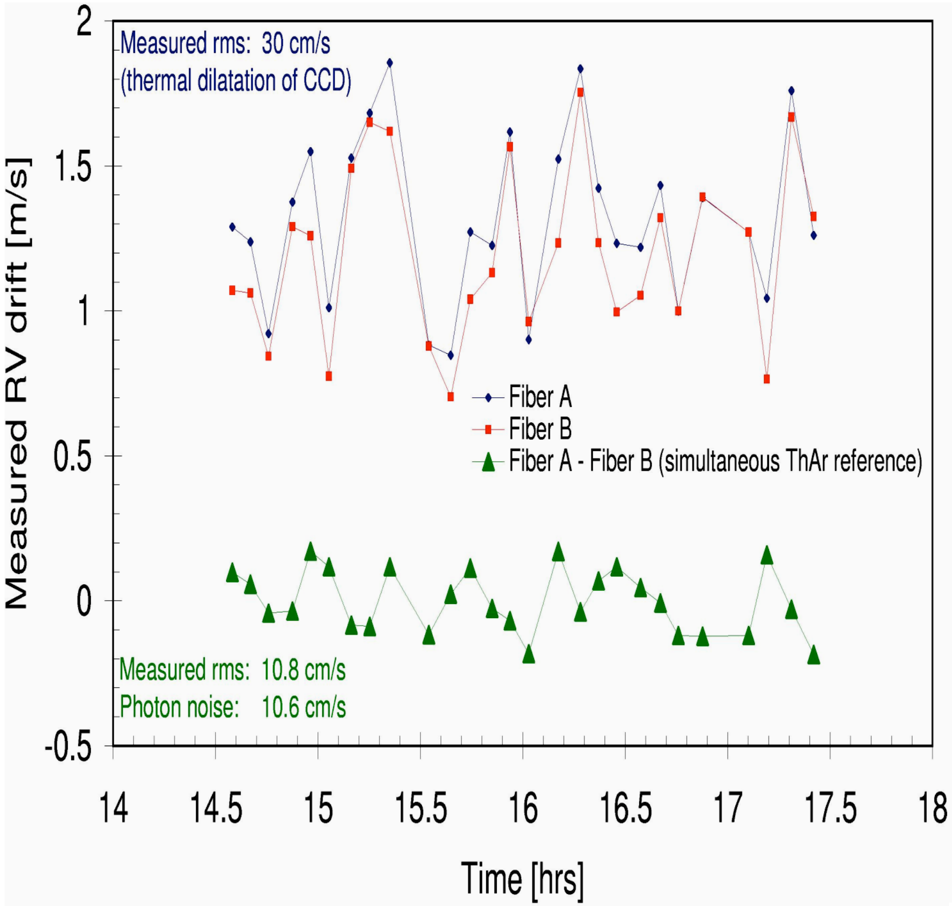


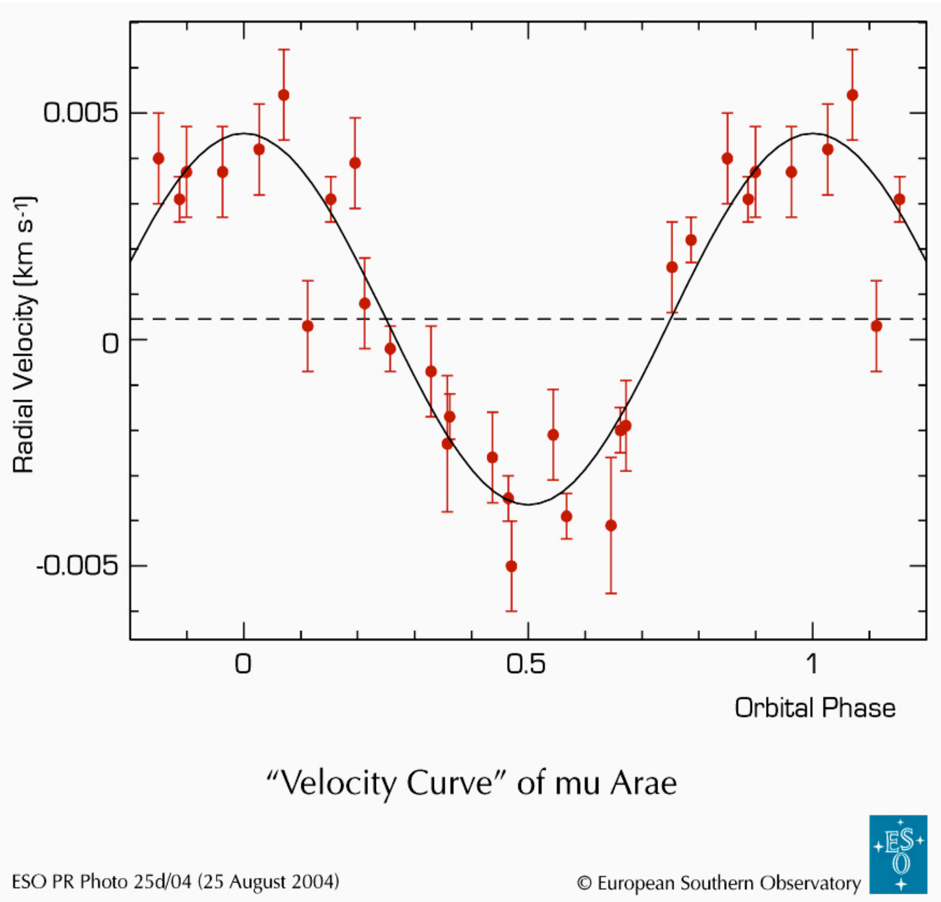
The Signal
is SMALL!

The HARPS Experience

Th-Th < 10 cm/sec

O-C < 80 cm/sec





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Received ; accepted To be inserted later

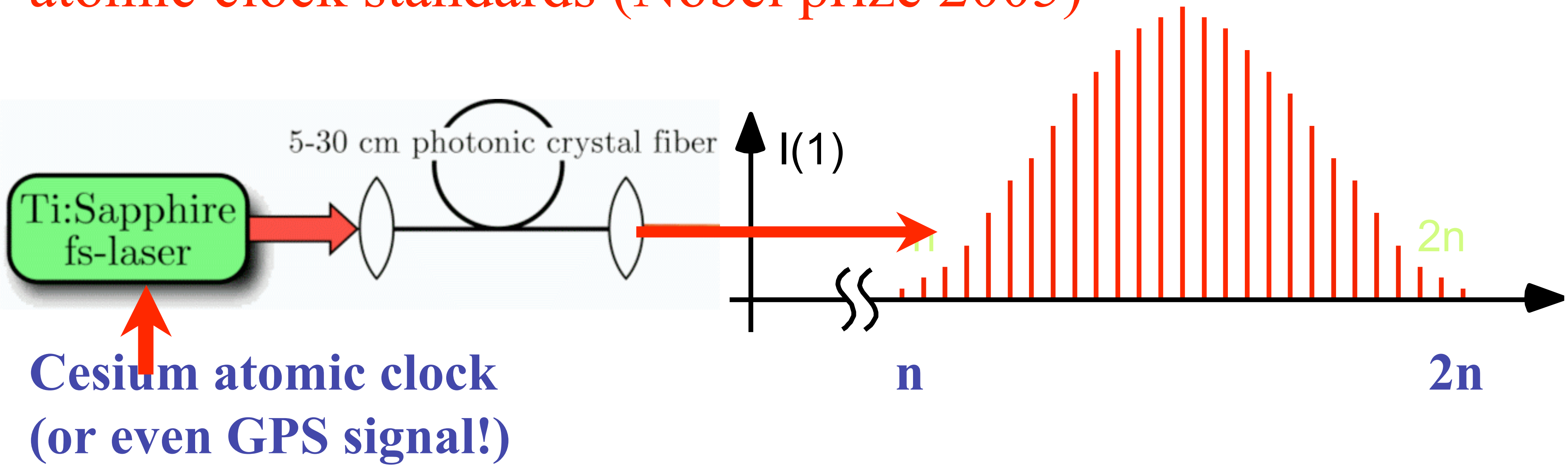
Abstract. This Letter reports on the detection of two super-Earth planets in the Gl 581 system, already known to harbour a hot Neptune. One of the planets has a mass of 5 $M_\oplus$ and resides at the "warm" edge of the habitable zone of the star. It is thus the known exoplanet which most resembles our own Earth. The other planet has a 7.7 $M_\oplus$ mass and orbits at 0.25 AU from the star, close to the "cold" edge of the habitable zone. These two new light planets around an M3 dwarf further confirm the formerly tentative statistical trend for i) many more very low-mass planets being found around M dwarfs than around solar-type stars and ii) low-mass planets outnumbering Jovian planets around M dwarfs.

Key words. stars: individual: Gl 581, stars: planetary systems – techniques: radial velocities – techniques: spectroscopy

Spectrograph builders are confident that they can reach wavelength accuracy of 1cm/s over long periods of time.

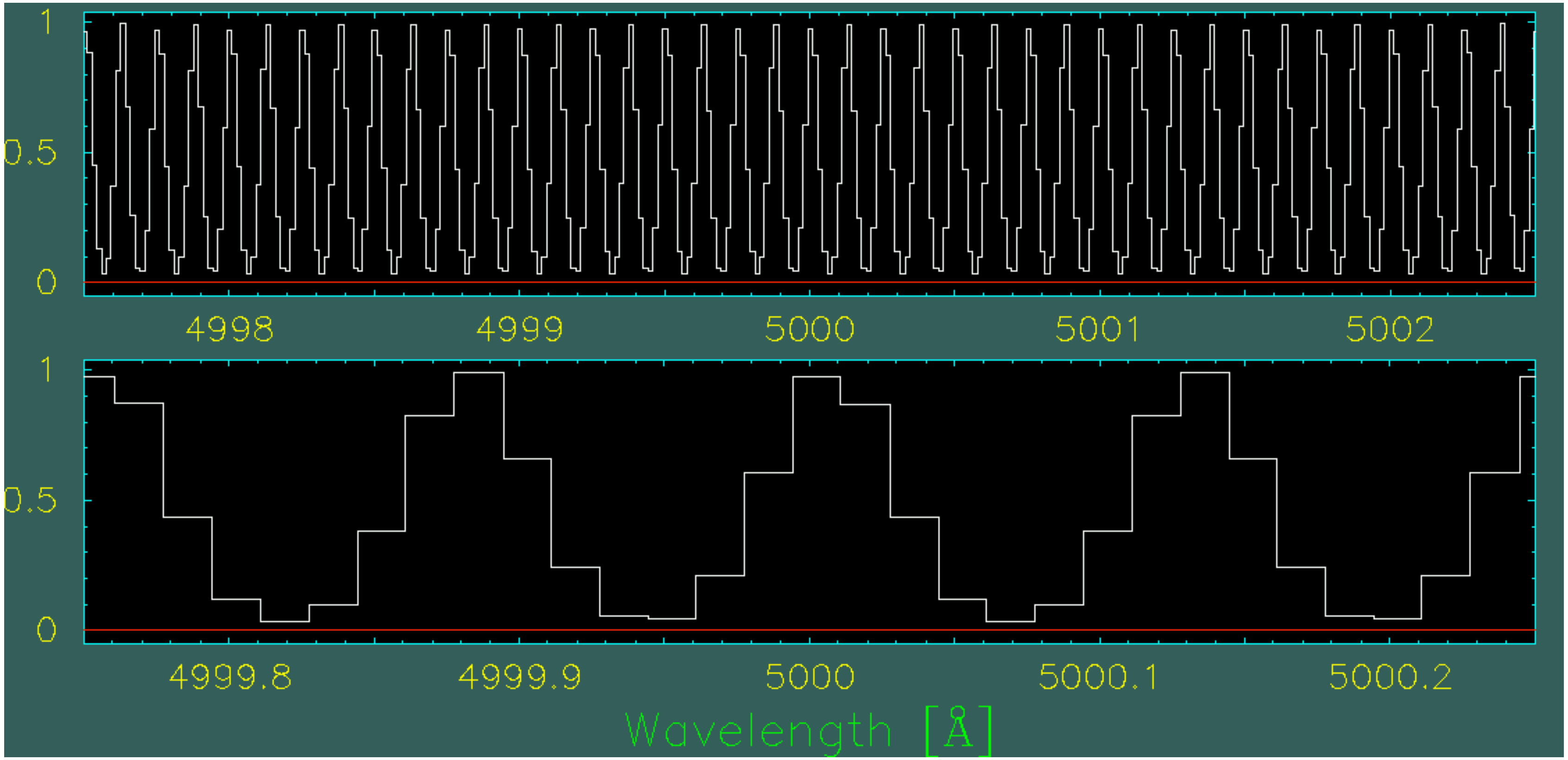
Novel Calibration System: Laser Frequency Comb

Metrology labs recently revolutionized by introduction of femtosecond-pulsed, self-referenced lasers driven by atomic clock standards (Nobel prize 2005)



❖Result is a reproducible, stable "comb" of evenly spaced lines who's frequencies are known *a priori* to better than 1 in 10^{12}

Comb spectrum simulation with
R =100k, $\Delta\nu$=15GHz, λ=5000Å



Detailed study carried out by ESO in colloboration with Max Planck Institute for Quantum Optics.

Spectrograph builders are confident that they can reach wavelength accuracy of 1cm/s over long periods of time.

Redshift drift measurements will then be photon-noise limited.

Need spectra of bright objects with many sharp features.

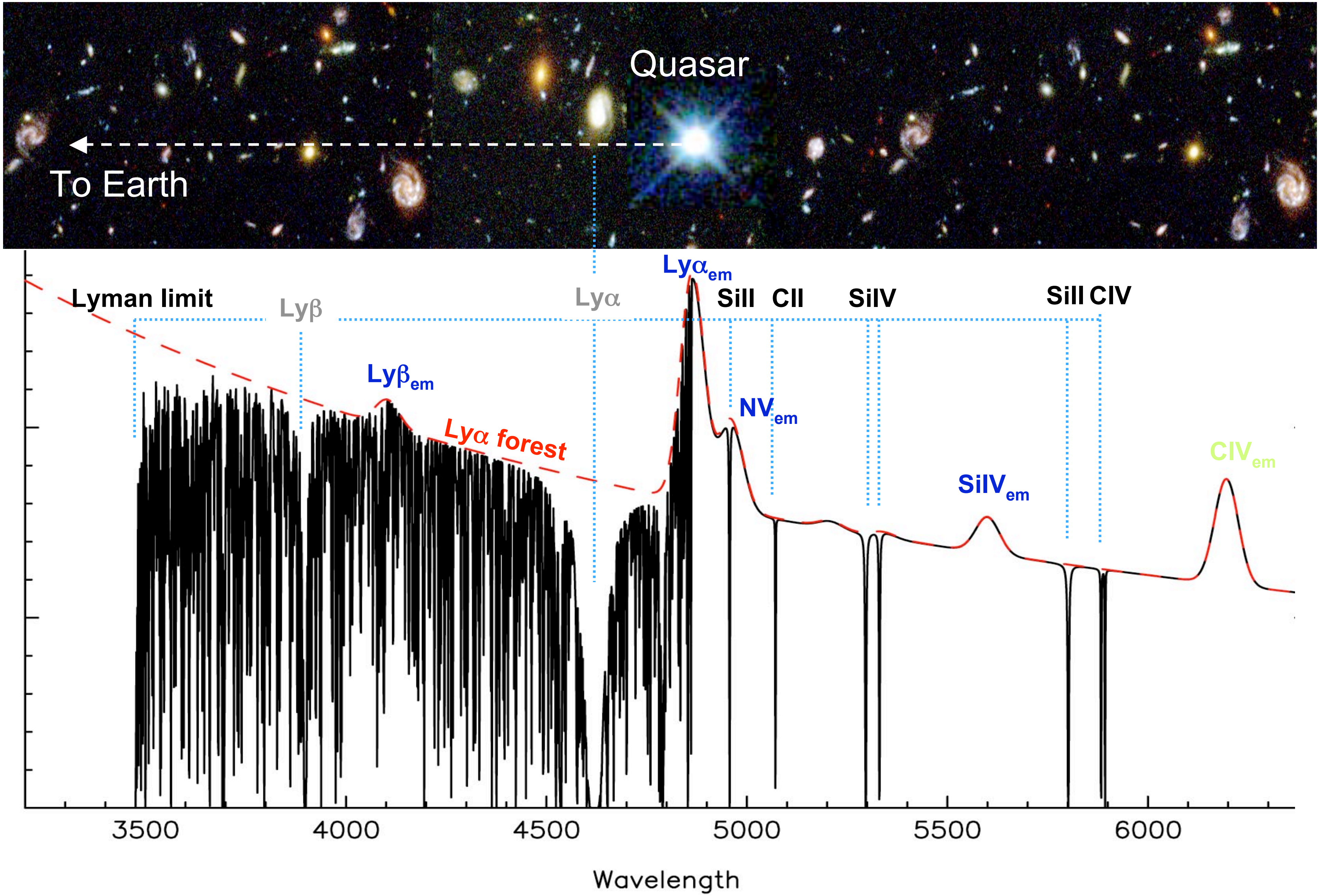
Where too look?

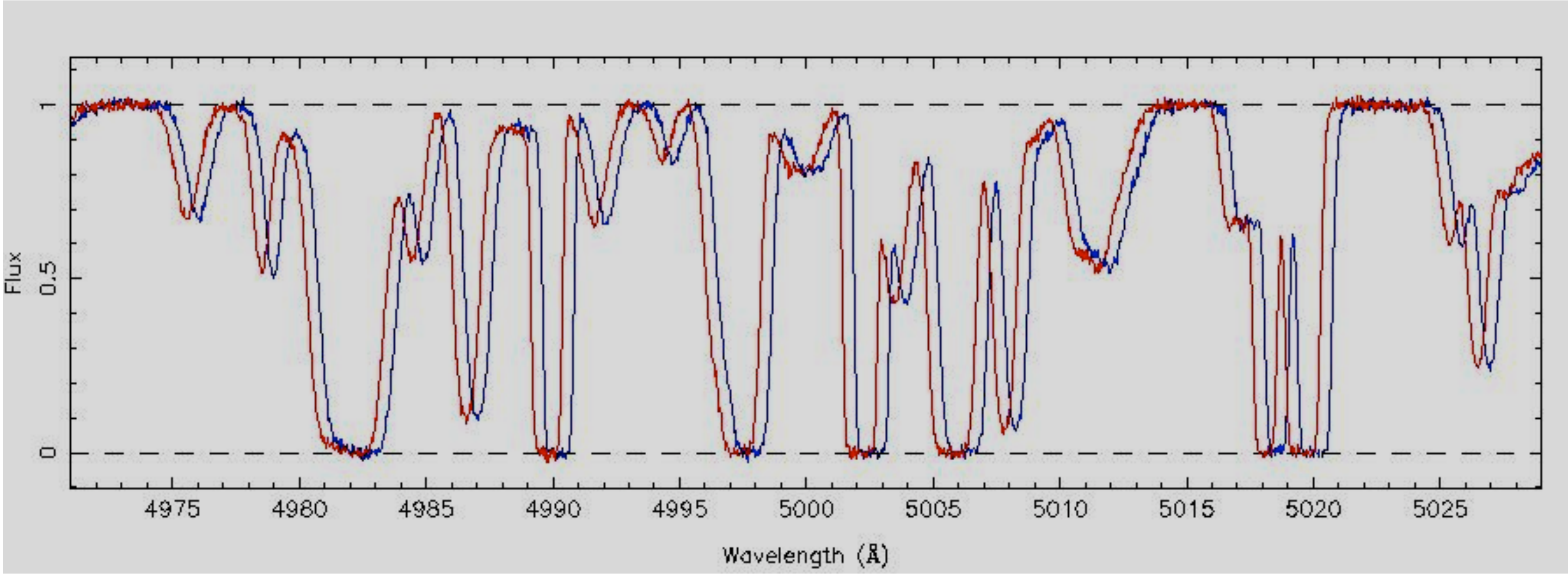
Masers : in principle good candidates: lines are very narrow and measurements accurate: they sit, however, at the center of deep potential wells: large peculiar motions, larger than the cosmic signal are expected

Radio Galaxies with ALMA : as for Masers, local motions of the emitters swamp the cosmic signal.

Lyα forest: Absorption from the many intervening lines in front of high redshift QSOs are the most promising candidates. Simulations and observations have shown that the Lyα forest are produced by density fluctuations of a warm IGM which traces the Hubble flow very well

QSO absorption lines

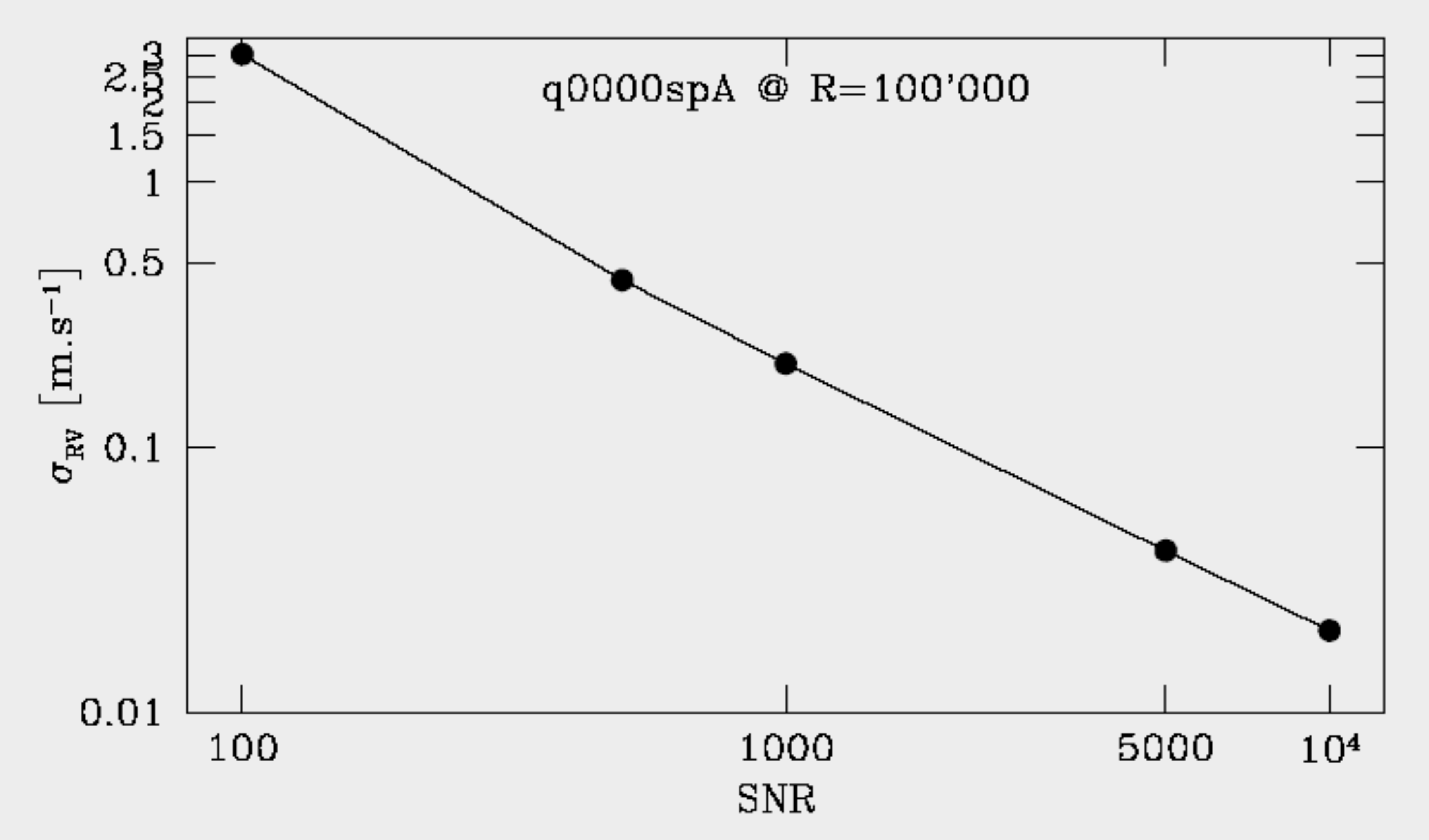


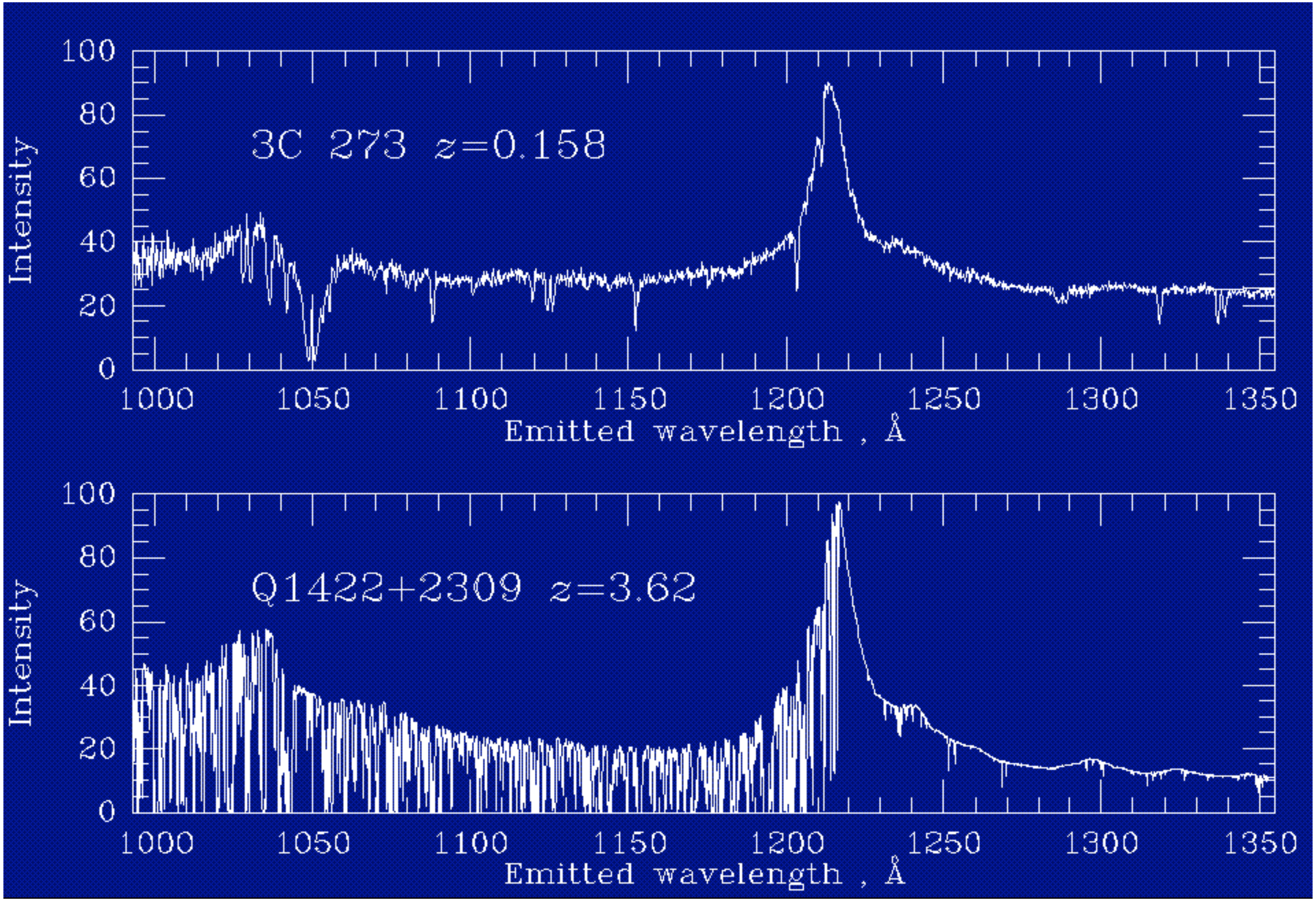


But this is for 10^7 years… Having much less time at our disposal the shift is much smaller.

Results of simulation (1): real spectrum

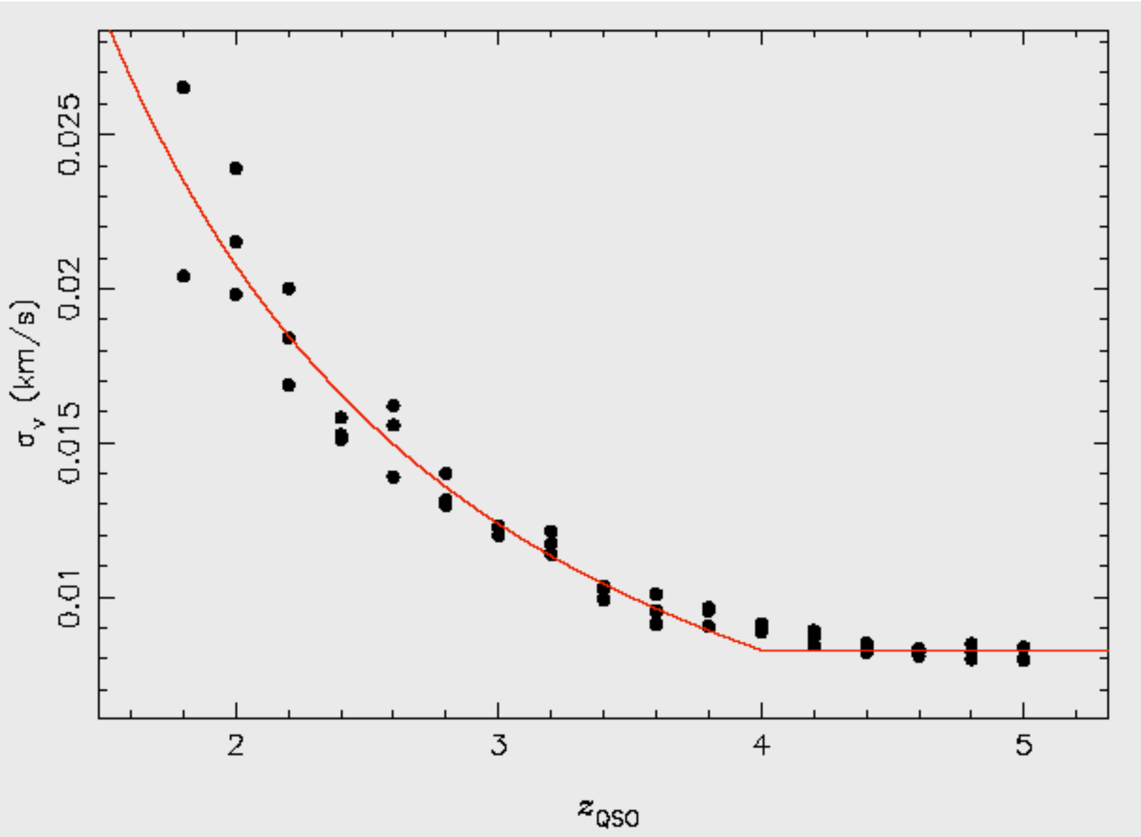
Dependence on cumulative S/N/pixel (0.015 A)





The forest thickens with increasing redshift.

Simulations of the z dependence of the measurement accuracy



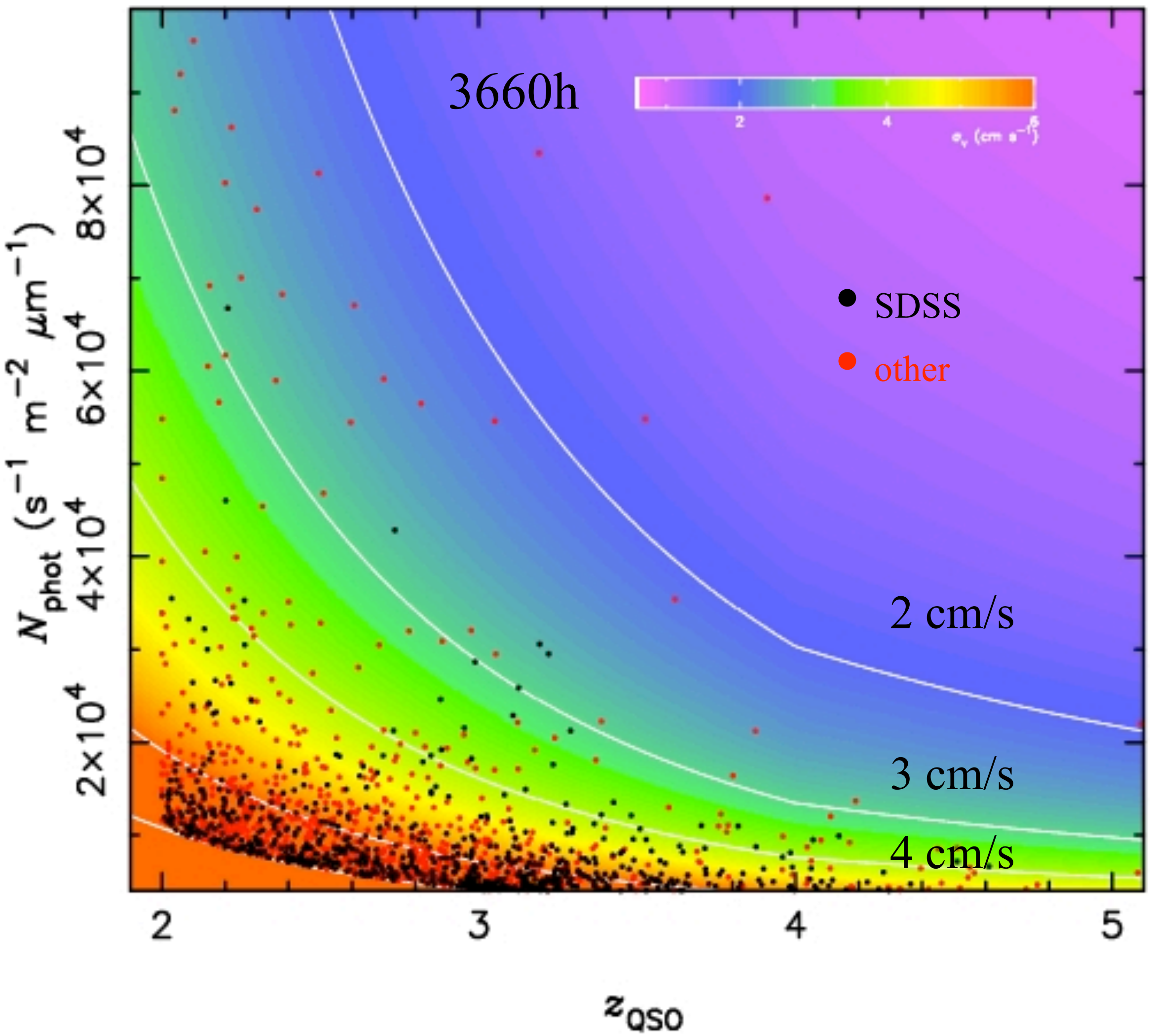
For fixed photon flux accuracy first increases with increasing redshift due to the larger number of lines and then saturates when lines start to overlap.

The simulation results for the accuracy in the photon-noise limited case can be summarized into a simple scaling law

$$\sigma_v = 1.4*(2350/(S/N))(30/N_{QSO})^{0.5}\ (5/(1+Z))^{1.8}\ \text{cm/sec}$$

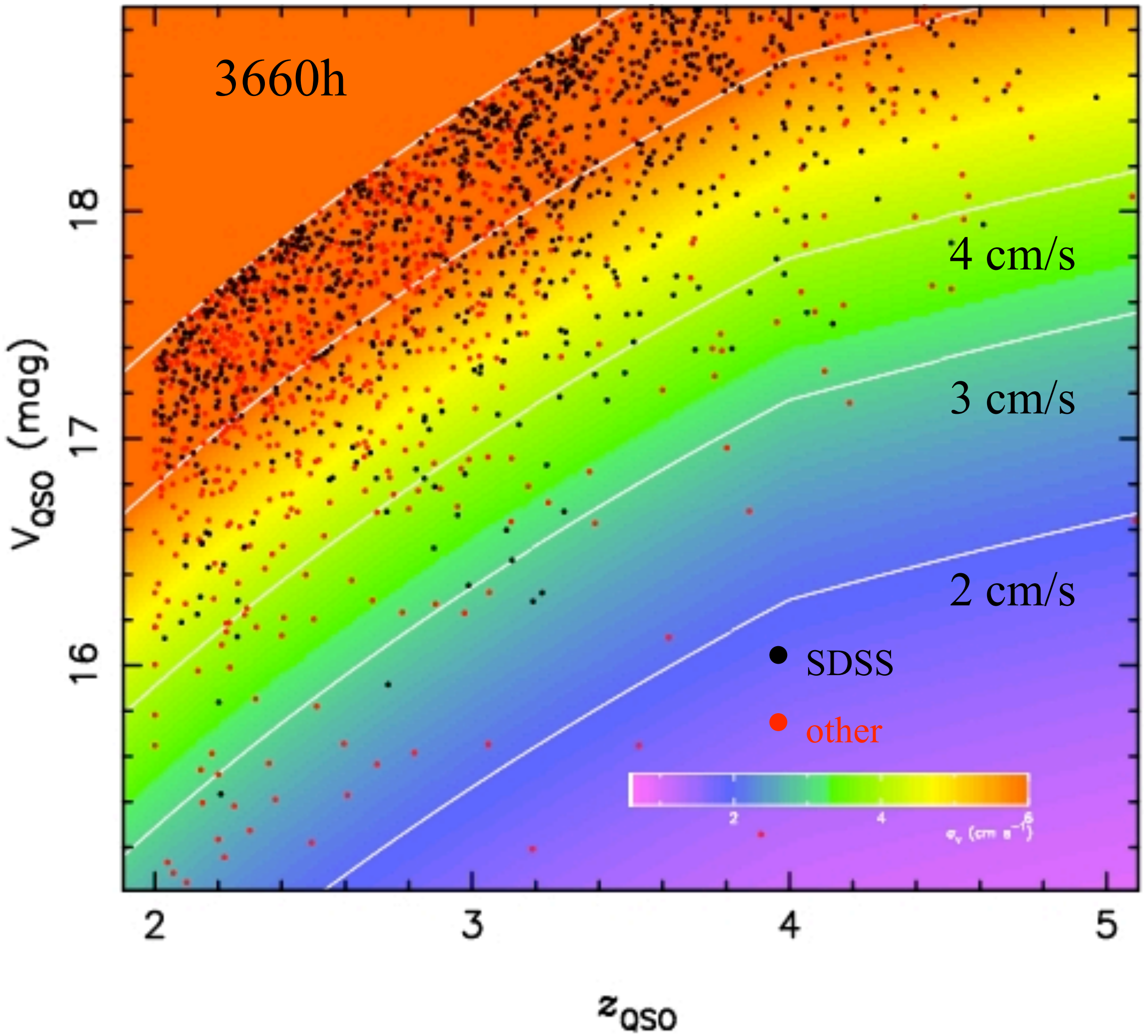
for a pixel size of 0.0125 Angstrom. The contribution from metal lines associated with the Lyα forest is included.

How well can we do with known QSOs?



S/N has been verified with adapted results from ELT exposure time calculator.
The exposure time calculator in its present form is not directly suitable for a seeing limited high-resolution spectrograph.

How well can we do with known QSOs?



S/N has been verified with adapted results from ELT exposure time calculator.
The exposure time calculator in its present form is not directly suitable for a seeing limited high-resolution spectrograph.

A compromise between sample size redshift coverage and total number of photons collected:

30 bright <u>known</u> QSOs accessible in the southern hemisphere

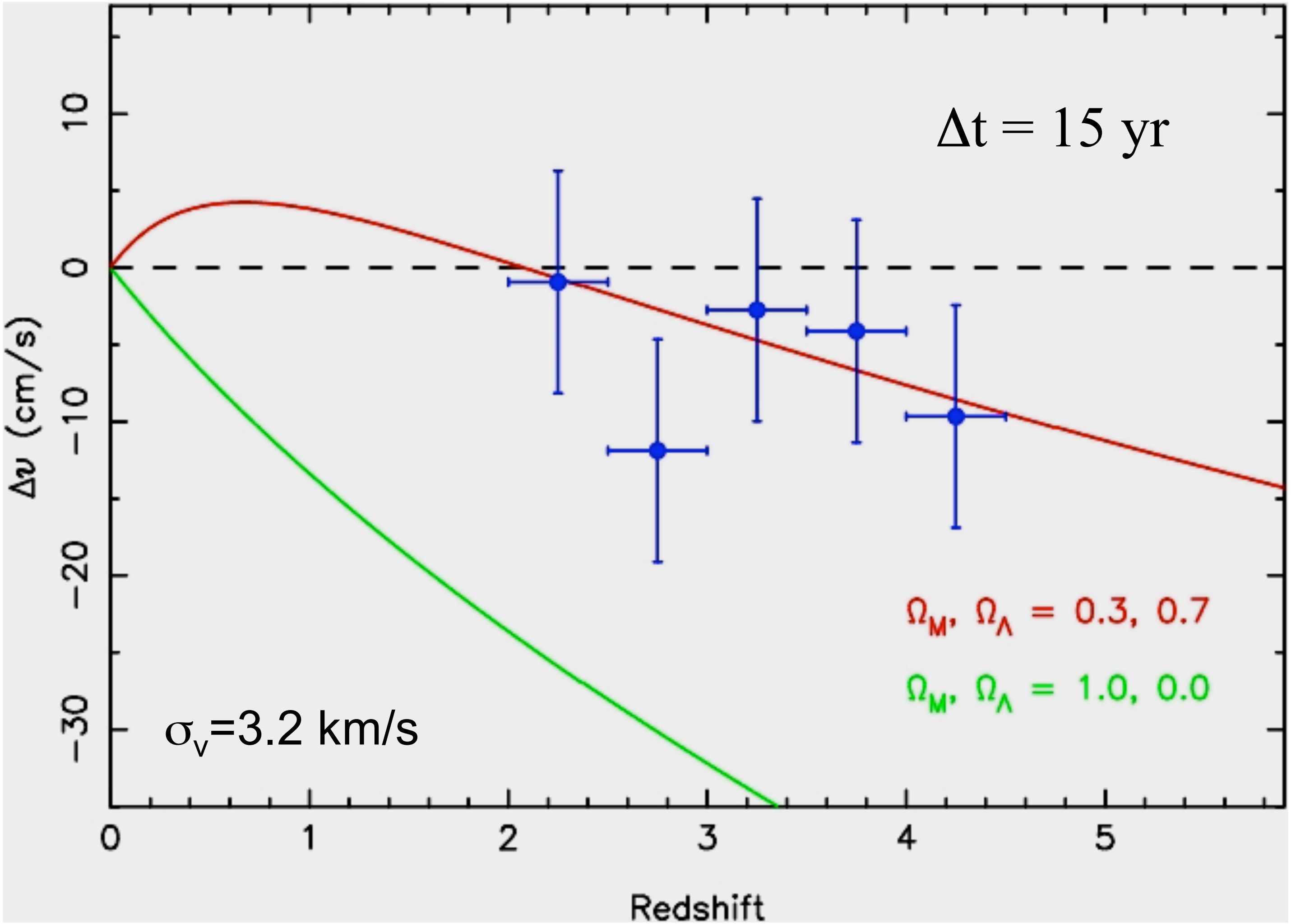
Redshift	Average Mag.	N Obj	S/N per QSO	Tot exp (hours)
2 - 2.25	14.96	3	3275	234
2.25-2.5	15.56	3	2856	313
2.5-2.75	16.13	3	2454	415
2.75 - 3.00	16.35	3	2231	376
3.0 - 3.25	16.10	3	1993	272
3.25- 3.50	17.07	3	1793	483
3.5 - 3.75	16.85	3	1620	369
3.75 - 4.00	17.06	3	1620	342
4.00 - 4.25	17.15	3	1124	288
4.25 - 4.5	17.97	3	1031	566

Total exposure time: 3658h

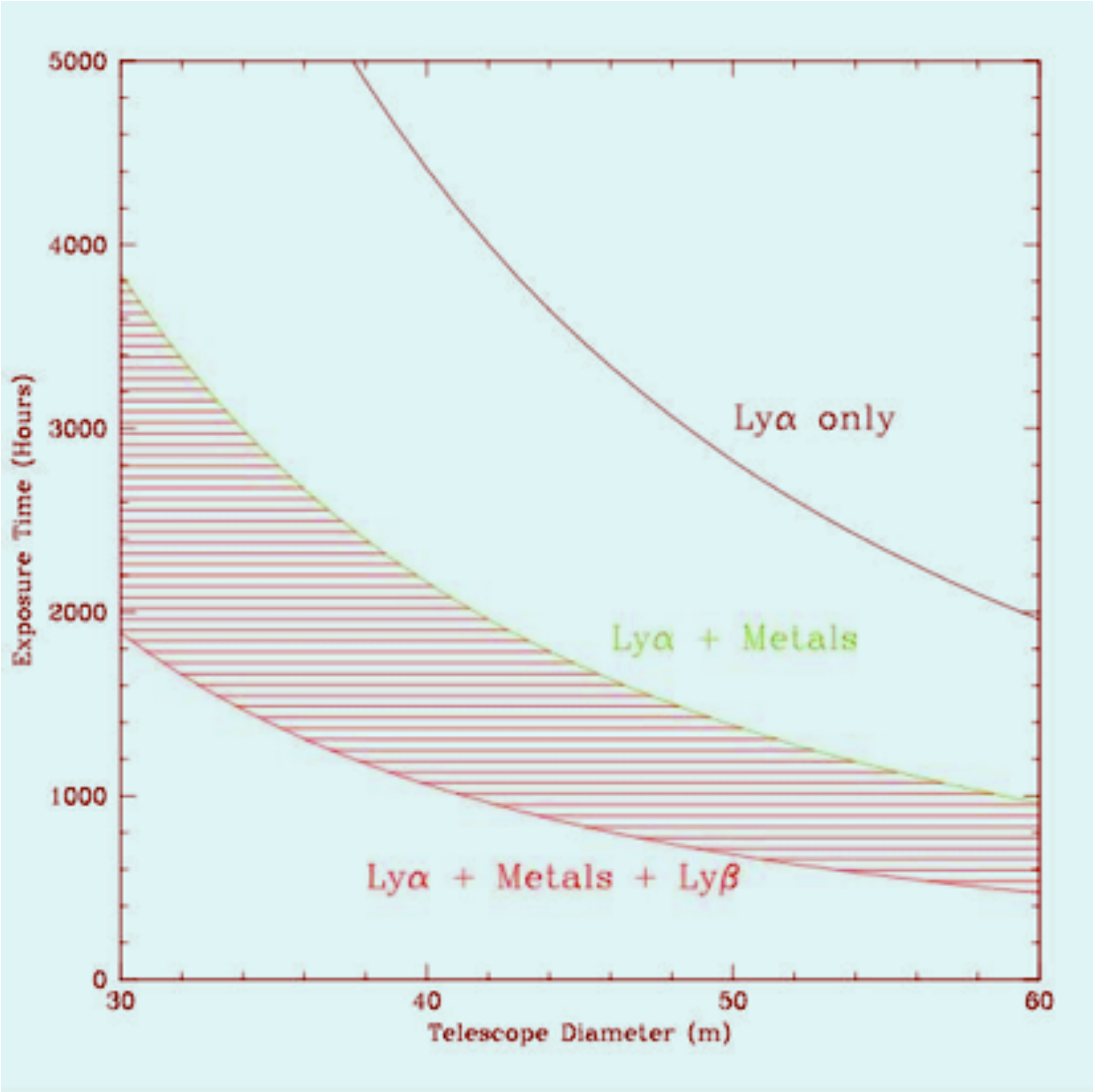
12. List of targets proposed in this programme

Run	Target/Field	α(J2000)	δ(J2000)	ToT	Mag.	Diam.	Additional info
A	PG 1247+268	12 50 05.70	+26 31 07.0	88	g=15.01		z=2.042
A	PKS 0858-279	09 00 40.00	-28 08 20.0	51	g=14.56		z=2.152
A	B2 1225+31	12 28 24.80	+31 28 38.0	95	r=15.32		z=2.219
A	Q 0049-3936	00 52 09.20	-39 19 45.0	97	r=15.43		z=2.300
A	CTS A33.02	05 54 45.70	-33 05 17.0	117	r=15.71		z=2.360
A	Q 0147-3855	01 49 25.30	-38 40 19.0	99	r=15.55		z=2.380
A	KP 1623.9+26.8	16 25 57.70	+26 44 44.0	77	r=15.53		z=2.607
A	CSO 38	10 11 55.70	+29 41 41.0	182	r=16.48		z=2.620
A	PHL 957	01 03 11.30	+13 16 17.0	156	r=16.38		z=2.686
A	TEX 1835-345	18 38 28.70	-34 27 33.0	133	r=16.31		z=2.780
A	CTS C15.05	23 50 34.30	-43 26 00.0	124	r=16.34		z=2.885
A	SDSS J12006+312631	12 00 06.25	+31 26 30.9	119	r=16.40		z=2.989
A	HE 0940-1050	09 42 53.60	-11 04 26.0	108	r=16.36		z=3.054
A	Q 0016-357	00 18 40.60	-35 29 13.0	34	r=15.22		z=3.190
A	CTS G18.01	00 41 31.50	-49 36 12.0	130	r=16.73		z=3.240
A	SDSS J09422+042244	09 42 02.05	+04 22 44.5	194	r=17.20		z=3.276
A	CTQ 1061	10 48 56.70	-16 37 10.0	130	r=16.85		z=3.370
A	SDSS J111119+13364	11 11 19.11	+13 36 03.9	159	i=17.17		z=3.481
A	SDSS J120148+120630	12 01 47.91	+12 06 30.3	177	i=17.31		z=3.510
A	B 1422+231	14 24 38.10	+22 56 01.0	48	i=15.99		z=3.620
A	SDSS J162117-004251	16 21 16.92	-00 42 50.9	144	i=17.25		z=3.703
A	SDSS J16004+0028	16 00 26.10	+00 28 34.0	123	i=17.13		z=3.764
A	1208+1011	12 10 57.00	+09 54 27.0	88	i=16.80		z=3.803
A	SDSS J16399+282447	16 39 09.11	+28 24 47.2	131	i=17.24		z=3.819
A	Q 0000-26	00 03 23.00	-26 03 18.0	94	i=17.11		z=4.111
A	PSS J1326+0743	13 26 11.90	+07 43 58.0	117	i=17.39		z=4.170
A	PSS J0926+3055	09 26 36.30	+30 55 05.0	77	i=16.96		z=4.190
A	SDSS J083839+285853	08 38 39.17	+28 58 52.7	197	i=18.10		z=4.363
A	SDSS J13096+1125	13 09 41.40	+11 25 39.0	141	i=17.76		z=4.395
A	BR J0419-5716	04 19 50.90	-57 16 14.0	228	i=18.06		z=4.461

That is what we get



Can be improved with brighter QSOs (new surveys, variability) and the use of the Lyβ forest.



V=16.5
14 % efficiency

CODEX @ E-ELT

ESO:

G. Avila, B. Delabre, H. Dekker, S. D'Odorico,
J. Liske, L. Pasquini, P. Shaver, A. Manescau

Observatoire Geneve :

M. Dessauges-Zavadsky, M. Fleury, C. Lovis, M. Mayor, F. Pepe,
D. Queloz, S. Udry

INAF-Trieste:

P. Bonifacio, S. Cristiani, V. D'Odorico, P. Molaro, M. Nonino, E. Vanzella,
M. Viel

Institute of Astronomy Cambridge:

B. Carswell, M. Haehnelt, M. Murphy

Instituto de Astrofisica Canarias:

R. Garcia-Lopez, R. Rebolo, M.R. Zapatero

Others:

F. Bouchy (Marseille), S. Borgani (Daut-Ts), A. Grazian (Roma), S. Levshakov (St-Petersburg), L. Moscardini (OABo-INAF), S. Zucker (Tel Aviv), T. Wilklind (ESA)

QUESTIONS

- wavelength range
- diameter
- seeing limited vs GLAO

Why should we do it?

Robertson-Walker metric

$$ds^2 = c^2 dt^2 - R^2(t)\left[\frac{dr^2}{1-kr^2} + r^2(d\Theta^2 + \sin^2\Theta\, d\Phi^2)\right]$$

$k = 0$ flat space

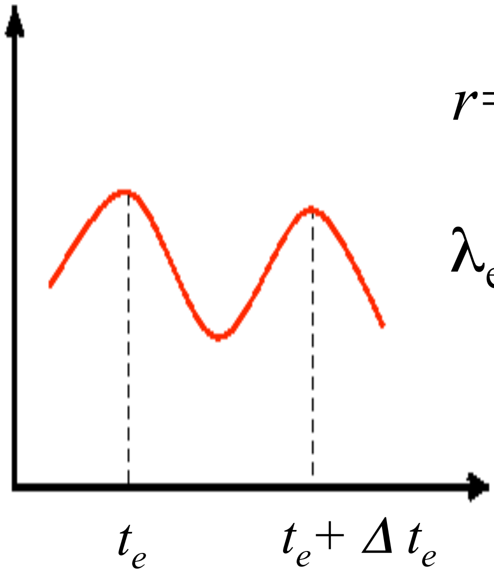
$k = 1$ spherical

$k = -1$ hyperbolical

R-W metric is maximally symmetric. It is the simplest metric that describes a homogeneous and isotropic Universe.

Cosmological redshifts

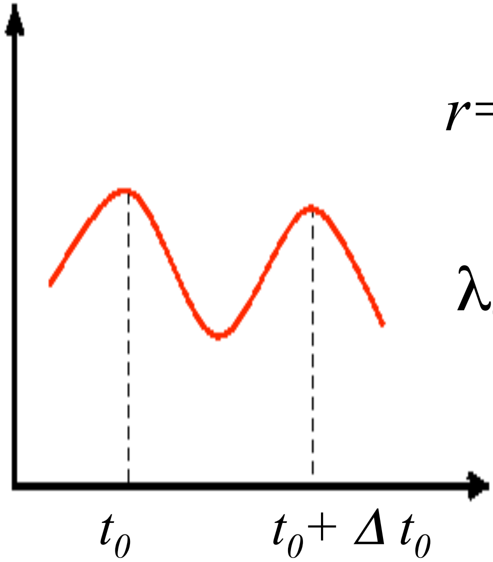
emitted



$r = r_e$

$\lambda_e = c\,\Delta t_e$

received



$r = r_0$

$\lambda_0 = c\,\Delta t_0$

$$z = \frac{\lambda_0 - \lambda_e}{\lambda_e}$$

$$1 + z = \frac{\lambda_0}{\lambda_e}$$

photons:

radial light path $d\Theta = d\Phi = 0$

$$ds^2 = 0 = c^2 dt^2 - R^2(t)\frac{dr^2}{1-kr^2}$$

Photons travel from r_e to $r_0 = 0$:

$$\int_{t_e}^{t_0} \frac{dt}{R(t)} = \frac{1}{c}\int_{r_e}^{0} \frac{dr}{\sqrt{1-kr^2}} = \int_{t_e+\Delta t_e}^{t_0+\Delta t_0} \frac{dt}{R(t)}$$

$$\int_{t_e}^{t_0} \frac{dt}{R(t)} = \int_{t_e+\Delta t_e}^{t_0+\Delta t_0} \frac{dt}{R(t)}$$

To first order in Δt:

$$\frac{\Delta t_0}{R(t_0)} = \frac{\Delta t_e}{R(t_e)}$$

$$\longrightarrow \qquad 1 + z = \frac{\lambda_0}{\lambda_{\mathrm{e}}} = \frac{\Delta t_0}{\Delta t_{\mathrm{e}}} = \frac{R(t_0)}{R(t_{\mathrm{e}})}$$

$$\boxed{1 + z = \frac{R(t_0)}{R(t_{\mathrm{e}})}}$$

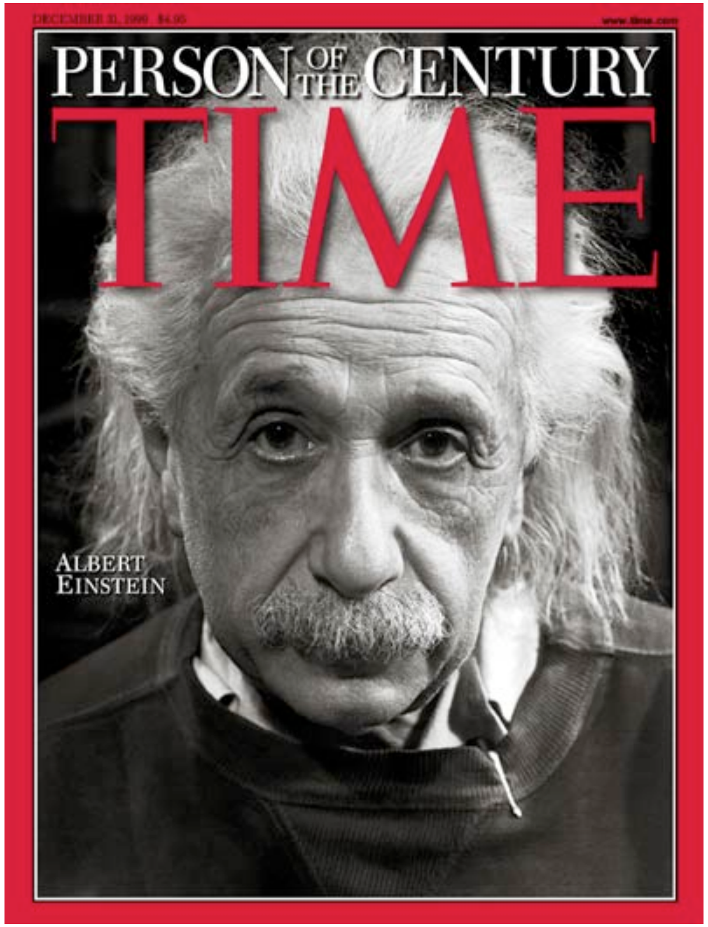
$$\dot{z} = (1+z)\left(\frac{\dot{R}}{R}\right)_{t=t_0} - \left(\frac{\dot{R}}{R}\right)_{t=t_e}$$

Redshift drift maps the expansion history without any further model assumptions and without reference to a theory of gravity.

Luminosity distances

$$D_L(z_e) = \frac{c}{H_0} \frac{(1+z_e)}{\sqrt{|1-\Omega_{\text{tot}}|}} \left\{ \begin{matrix} \sin \\ 1 \\ \sinh \end{matrix} \right\} \left(\sqrt{|1-\Omega_{\text{tot}}|} \int_0^{z_e} \frac{H_0 \; dz}{H(z)} \right) \qquad \left\{ \begin{matrix} \text{spherical} \\ \text{flat} \\ \text{hyperbolical} \end{matrix} \right\}$$

Involves integral over z and need to know curvature.



Geometry of space time ↔ **Gravity**

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

cosmological constant

General Relativity → Friedmann equation

$$H^2 = \left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi G}{3}\rho - \frac{k\,c^2}{R^2} + \frac{\Lambda\,c^2}{3} \qquad \rho = \rho_{\mathrm{mat}} + \rho_{\mathrm{rad}}$$

$$H^2(t) = H_0{}^2\left(\Omega_{\mathrm{mat},0}\,(1+z)^3 + \Omega_{\mathrm{rad},0}\,(1+z)^4 + \Omega_{\mathrm{k},0}\,(1+z)^2 + \Omega_{\Lambda,0}\right)$$

$$\Omega_{\mathrm{k},0} = 1 - \Omega_{\mathrm{mat},0} - \Omega_{\mathrm{rad},0} - \Omega_{\Lambda,0}$$