A dynamical measurement of the expansion history of the Universe: simulation results

Joe Liske

E-ELT Science Office

Cosmic Dynamics

- One of 9 “prominent” science cases chosen by the Science Working Group for the Design Reference Mission

- DRM proposal prepared by L.Pasquini and M.Haehnelt
- Simulations and results described in detail in DRM report
- Proposal and DRM report public on E-ELT Science web pages

The Science Case

- The Hubble expansion is a cornerstone of modern cosmology.
- Surprise: the expansion is accelerating! Good evidence from SNIa that a period of decelerated expansion was followed 'recently' by a period of acceleration.
- The source of the acceleration is entirely unknown. Most explanations so far proposed require new physics.
  Dark energy: cosmological constant, quintessence, etc.
  Modification of gravity: Cardassian expansion, DGP, etc.

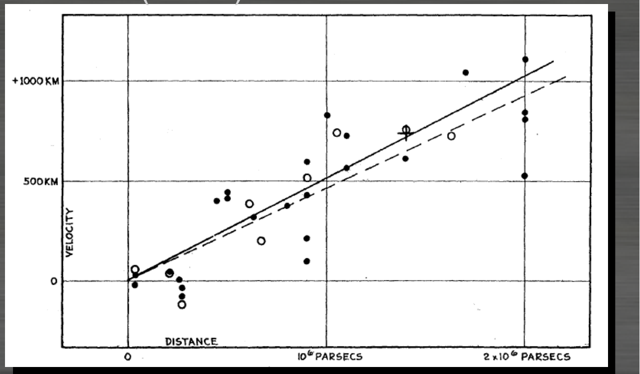
➝ Intense interest in the expansion history.
  Best current methods of measuring H(z):
  - SNIa
  - Weak lensing
  - Baryon Acoustic Oscillations (BAO)

  None is entirely 'clean' or direct. They require
  - A prior on spatial curvature
  - Detailed understanding of the linear growth of density perturbations → model-dependent

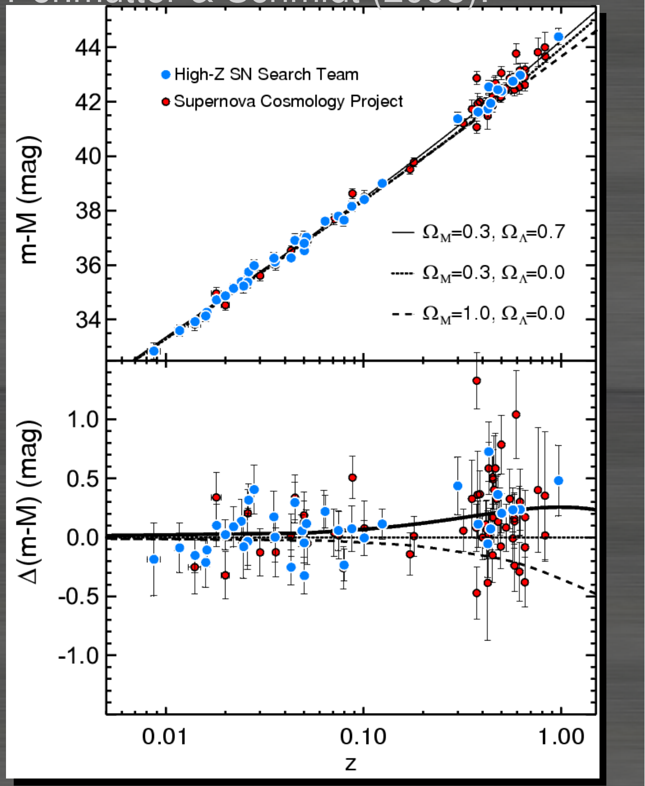
  All are geometric methods and/or use the dynamics of localised density perturbations.

- Direct observations of the dynamics of the global FRW metric do not exist.

Hubble (1929):



Perlmutter & Schmidt (2003):



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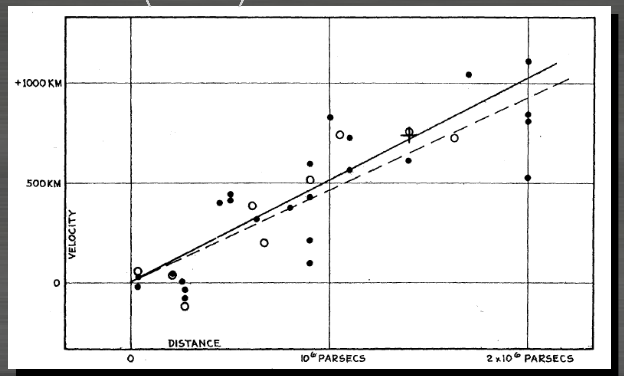

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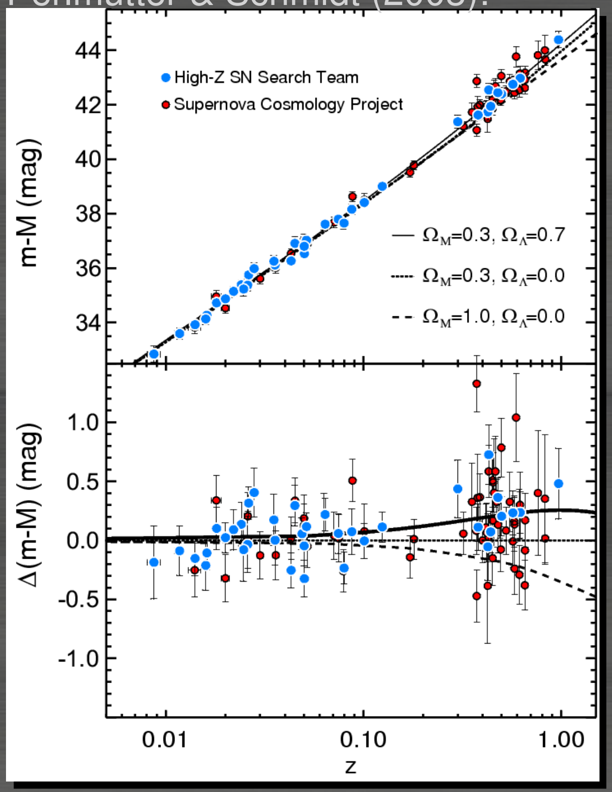


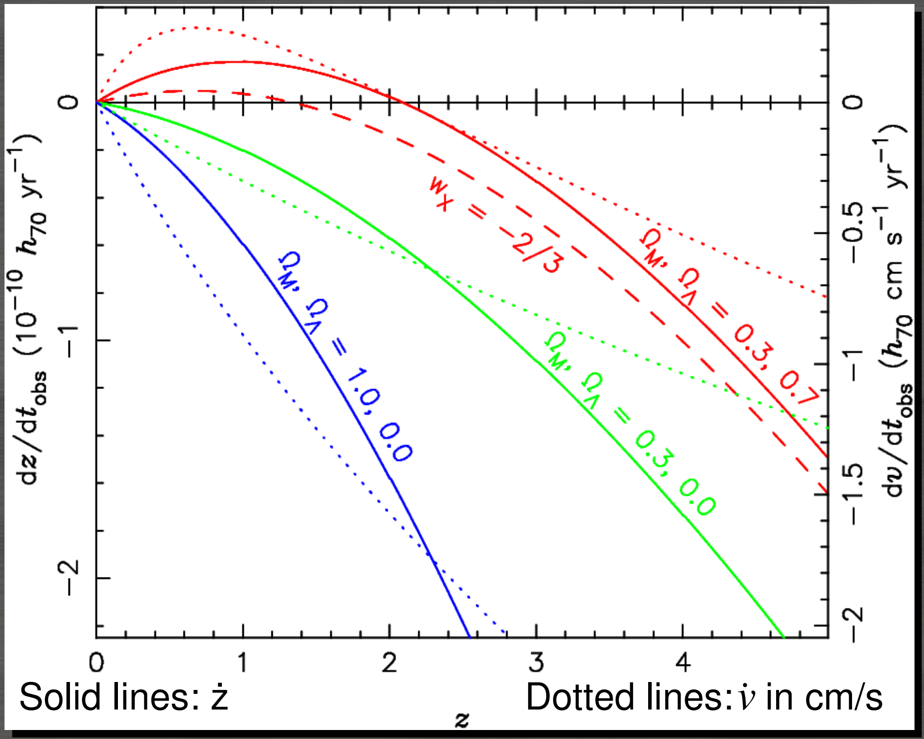
Cosmic Dynamics

The de- or acceleration of the universal expansion rate between epoch z and today causes a small drift in the observed redshift as a function of time:

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

Measuring ż(z):

- Allows us to watch, in real time, the universe changing its expansion rate.
- Most direct and model-independent route to the expansion history and acceleration.
- First non-geometric measurement of the global FRW metric.
- Independent confirmation and quantification of accelerated expansion.
- H(z) determination in a redshift range inaccessible to other methods.



Size of the signal

If $\Delta t = 10$ years then:

- $\Delta z \sim 10^{-9}$
- $\Delta\lambda = \lambda_{rest}\, \Delta z$

  $\sim 10^{-6}$ Å

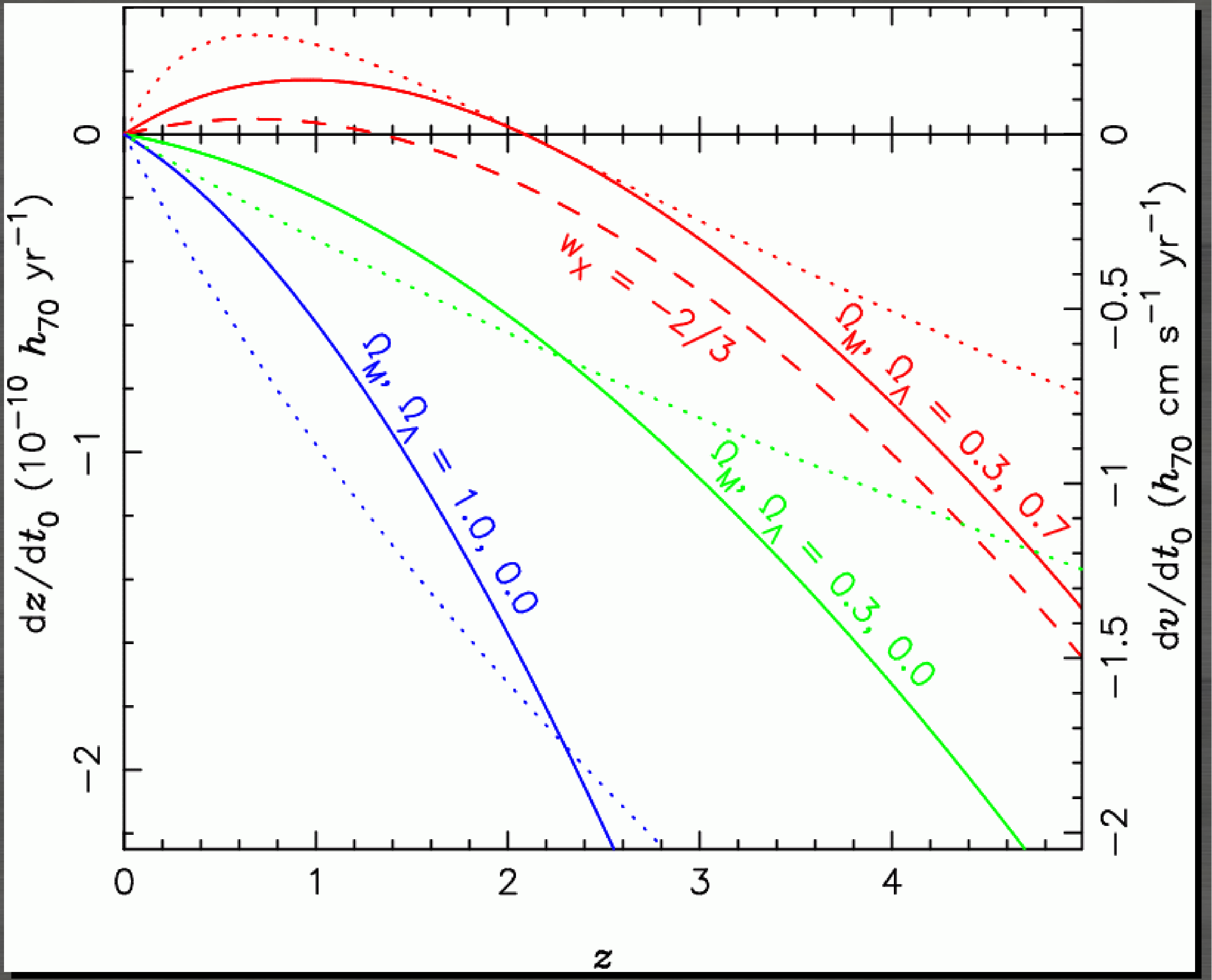
  $\sim 10^{-4}$ pixel

  ~ 1 nm on CCD
- $\Delta v = c\, \Delta z/(1+z)$

  ~ 6 cm/s

→ Tiny signal!

BUT: HARPS has already achieved a long-term accuracy of better than 1 m/s.

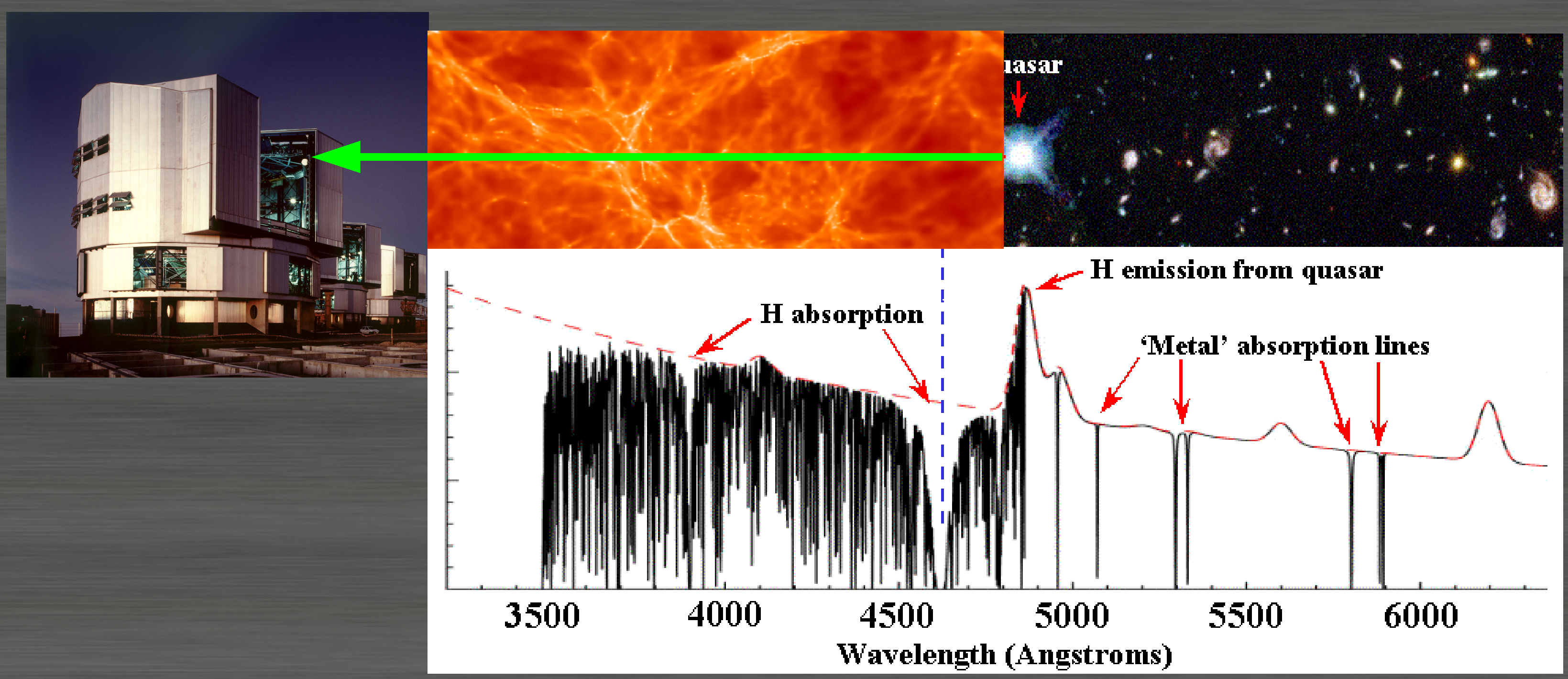


Measuring Cosmic Dynamics

Measuring the redshift drift requires:

- E-ELT
- High-resolution, extremely stable spectrograph: CODEX
- ~20 yr long spectroscopic monitoring campaign.

Best place to observe the redshift drift: QSO absorption lines



by John Webb

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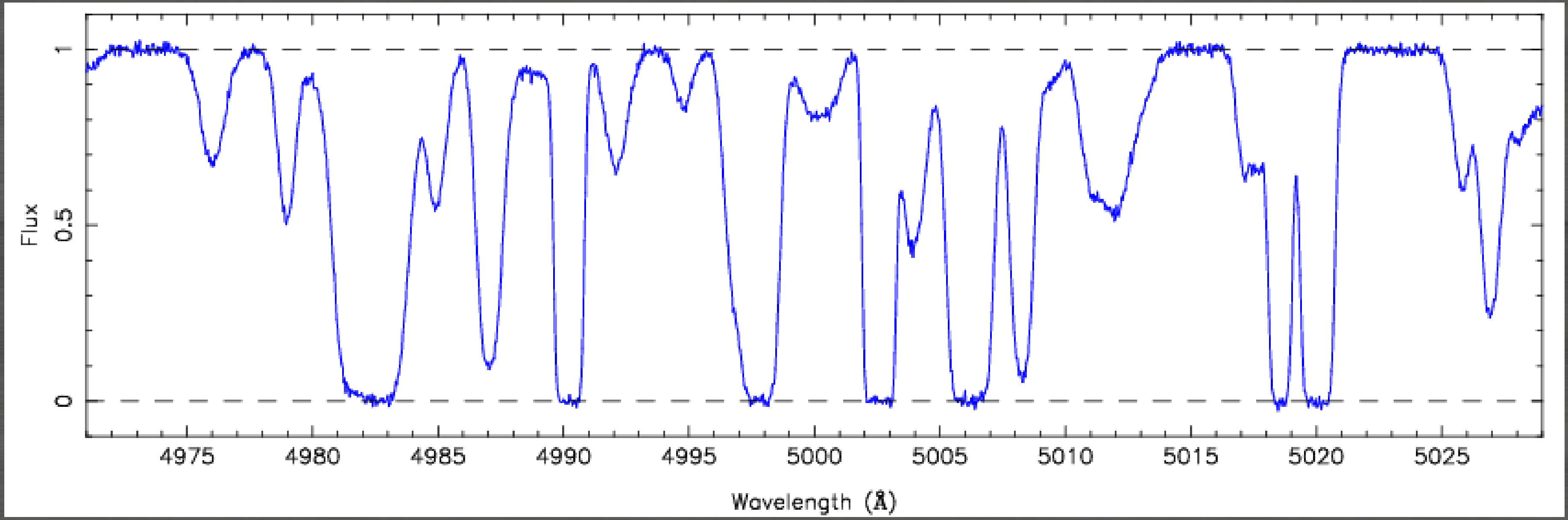

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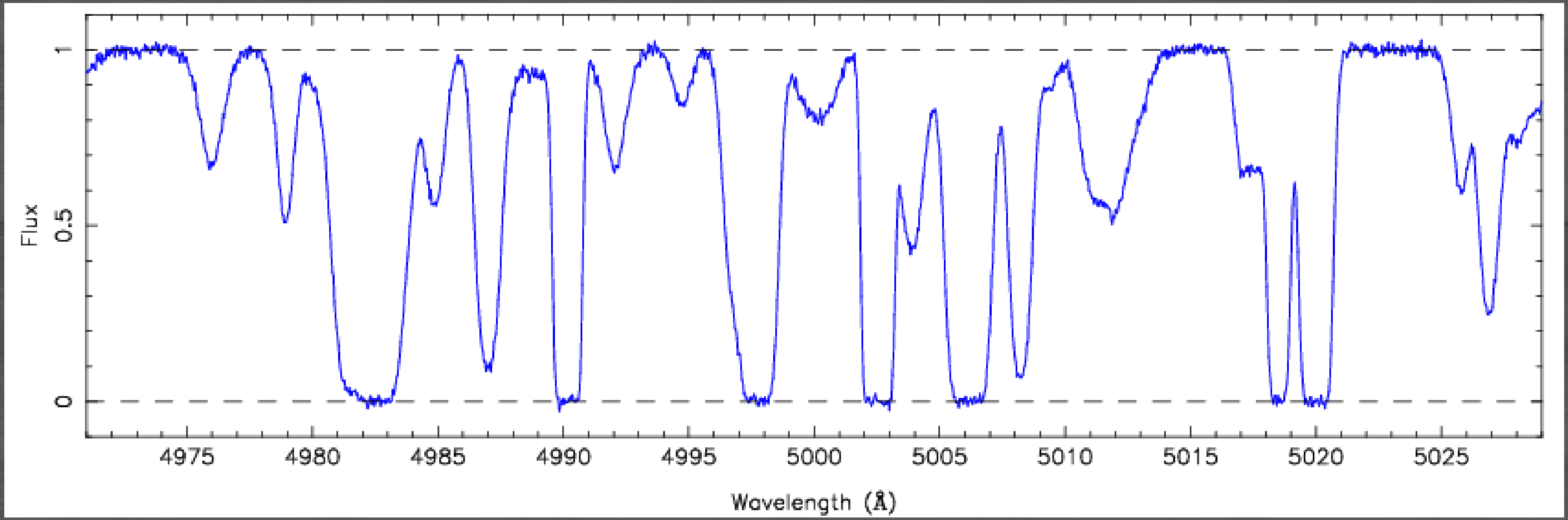

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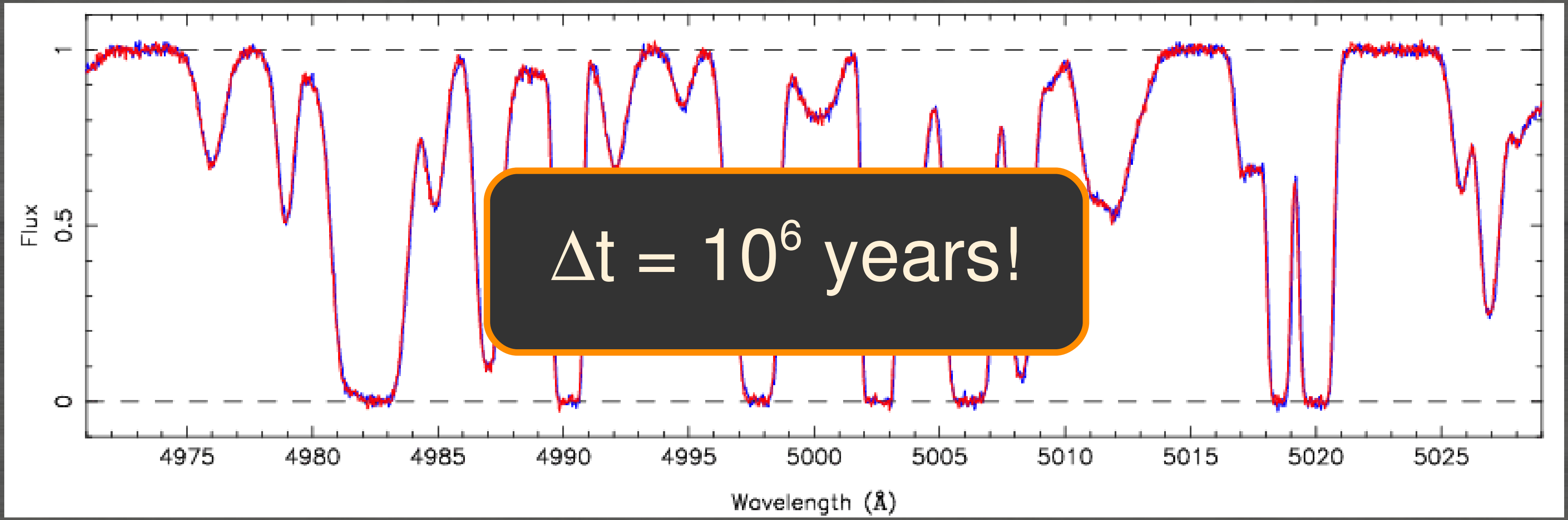
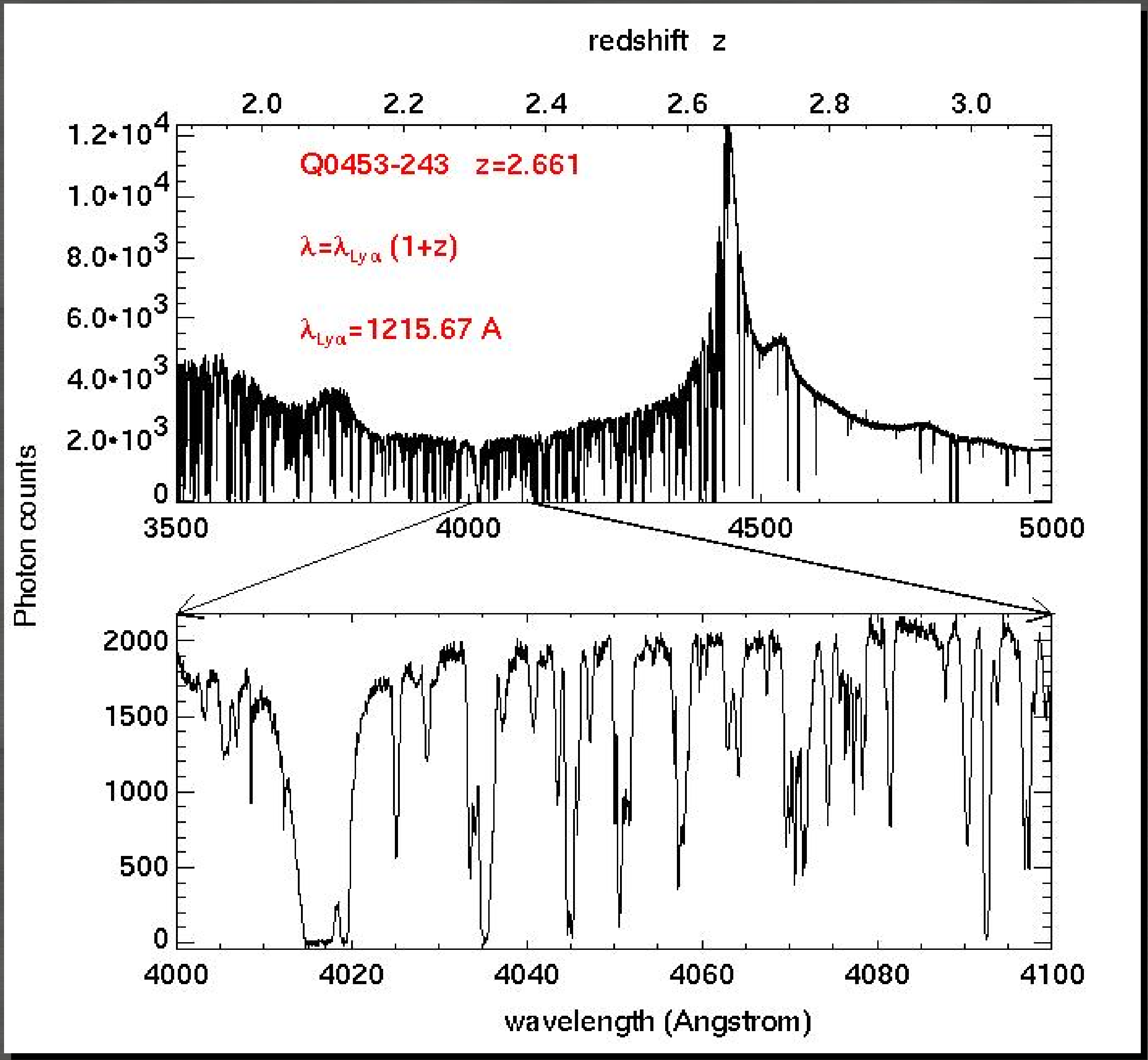


The Lyman α forest

- ✔ QSOs are the brightest sources at any redshift.
- ✔ QSOs exist over all redshifts, $0 < z < 6$.
- ✔ Each line of sight to a background QSO shows $\sim 10^2$ Lyα lines.
- ✔ The Lyα forest is an excellent tracer of the Hubble flow (small peculiar motions).
- ✗ Line widths are 15-50 km/s. (Metal line widths are of order 1 km/s but reside in deeper potential wells).



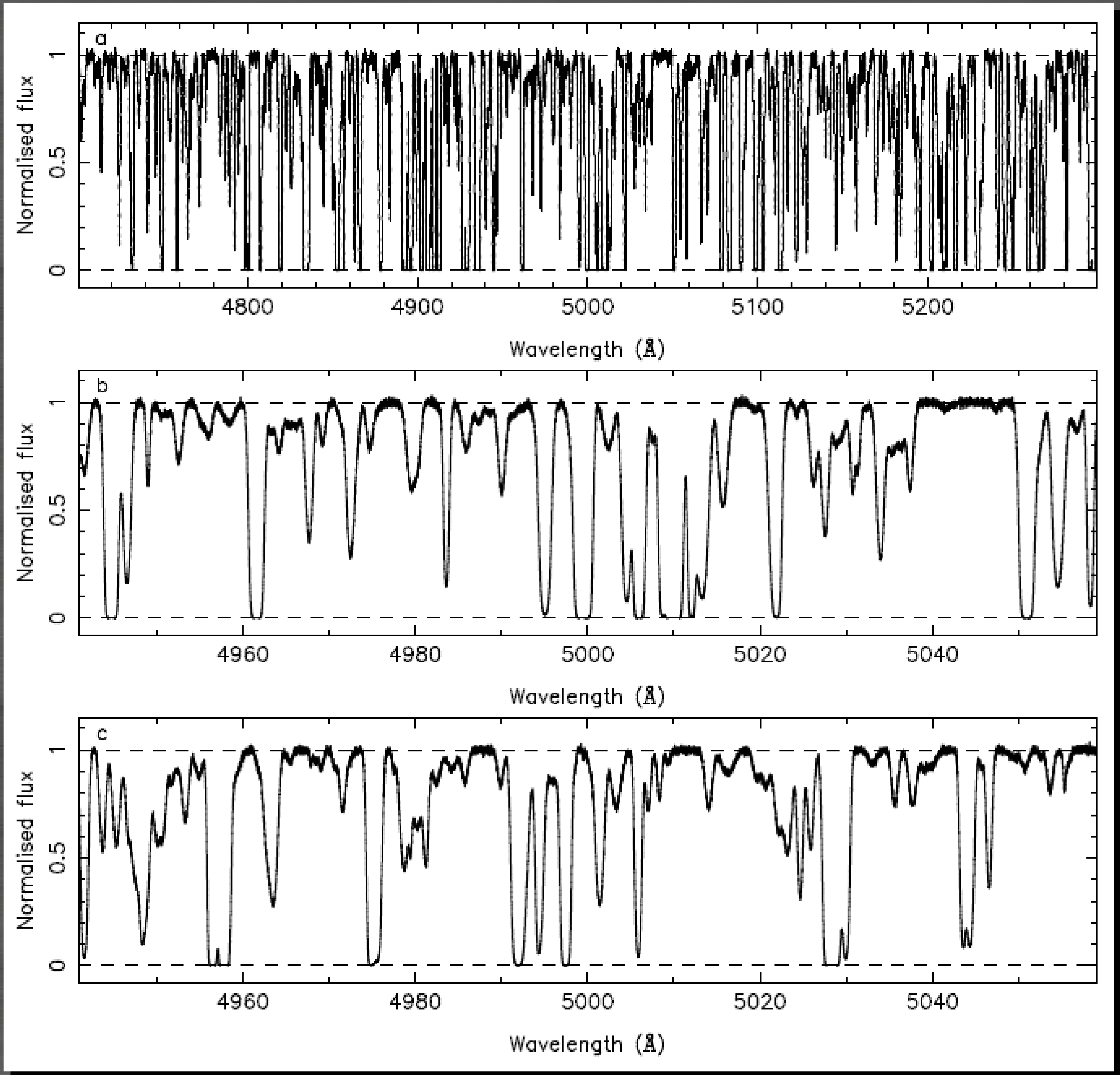
Simulation goals

- Determine how the properties of the Lyα forest translate to radial velocity shift accuracy, and how this scales with S/N and redshift.
- Determine how much this accuracy can be improved by including other parts of a QSO's absorption spectrum – Lyβ forest and metal lines.
- Quantify the impact of a realistic distribution of observing time.
- Using the above results and assuming the known population of QSOs predict the overall accuracy of a redshift drift experiment.
- Predict possible constraints on cosmological parameters.

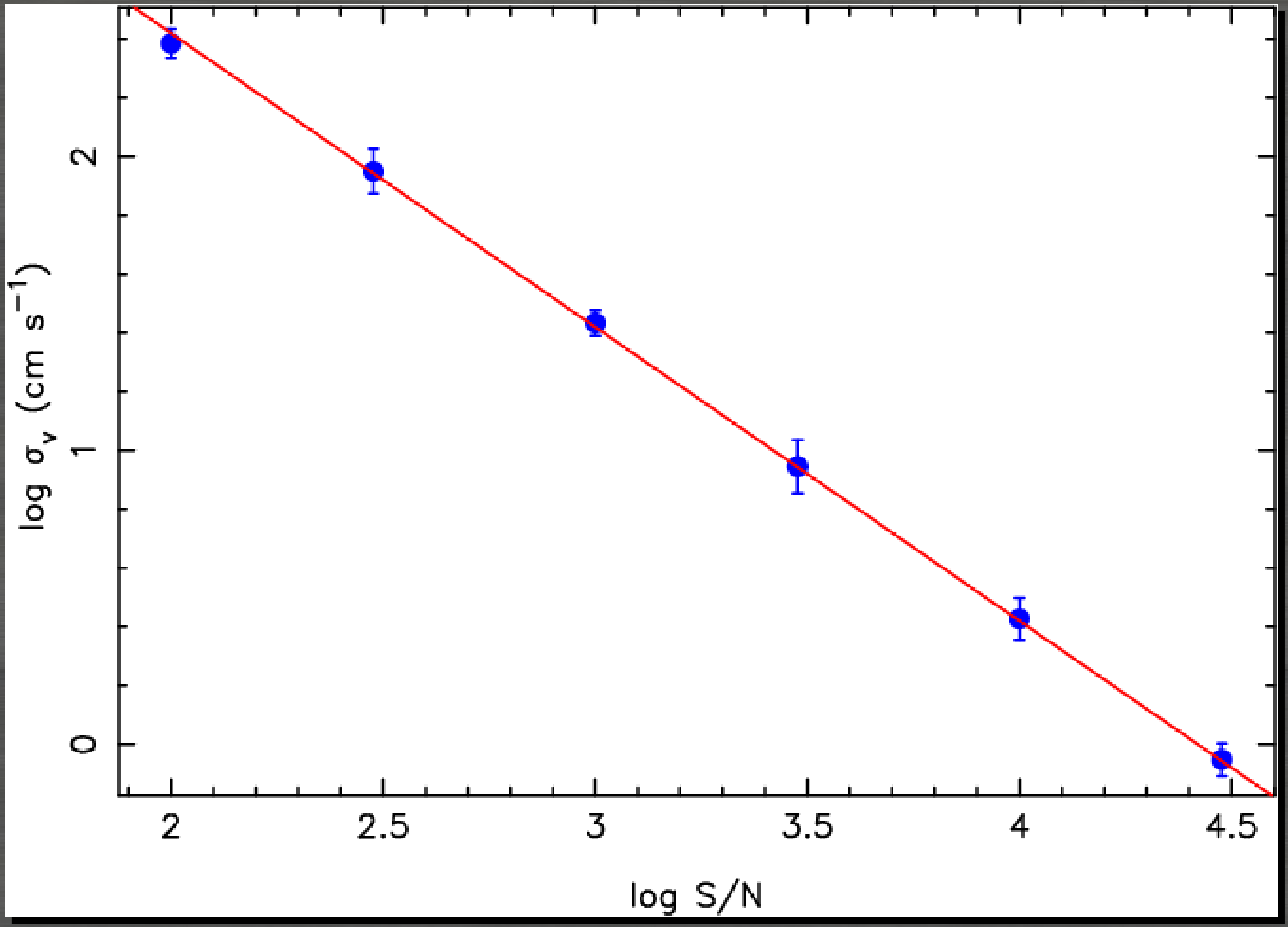
Simulated spectra

- Normalised spectra are generated from absorption line lists at any desired resolution, pixel size, S/N.
- Assumes object photon noise only (no sky noise).
- Line lists: either from high-resolution observations or drawn from known parameter distributions (MC sims):

$$f(z, N, b) \propto (1+z)^{\gamma} N^{-\beta} gauss(b)$$



Sensitivity to radial velocity shifts



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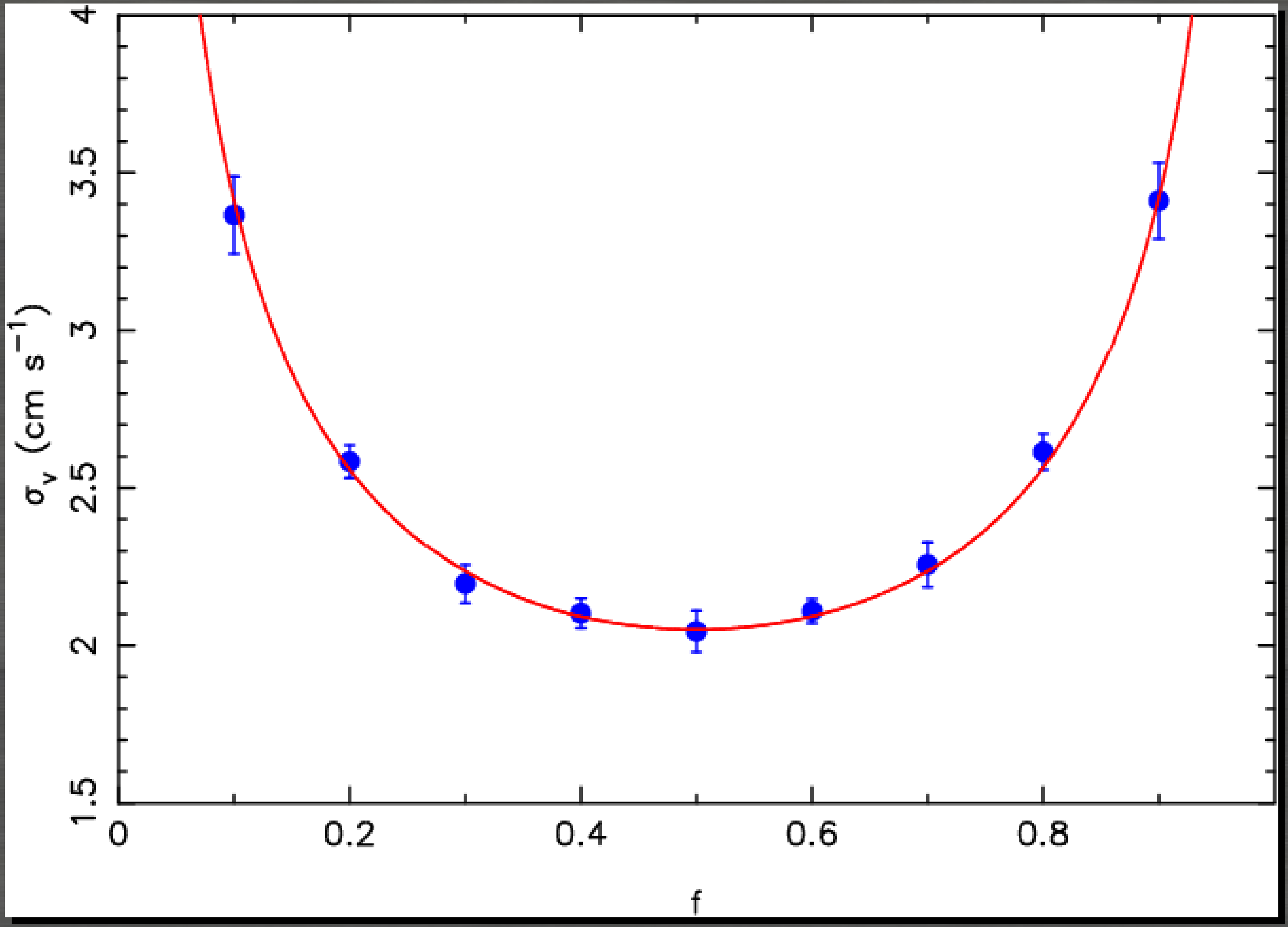

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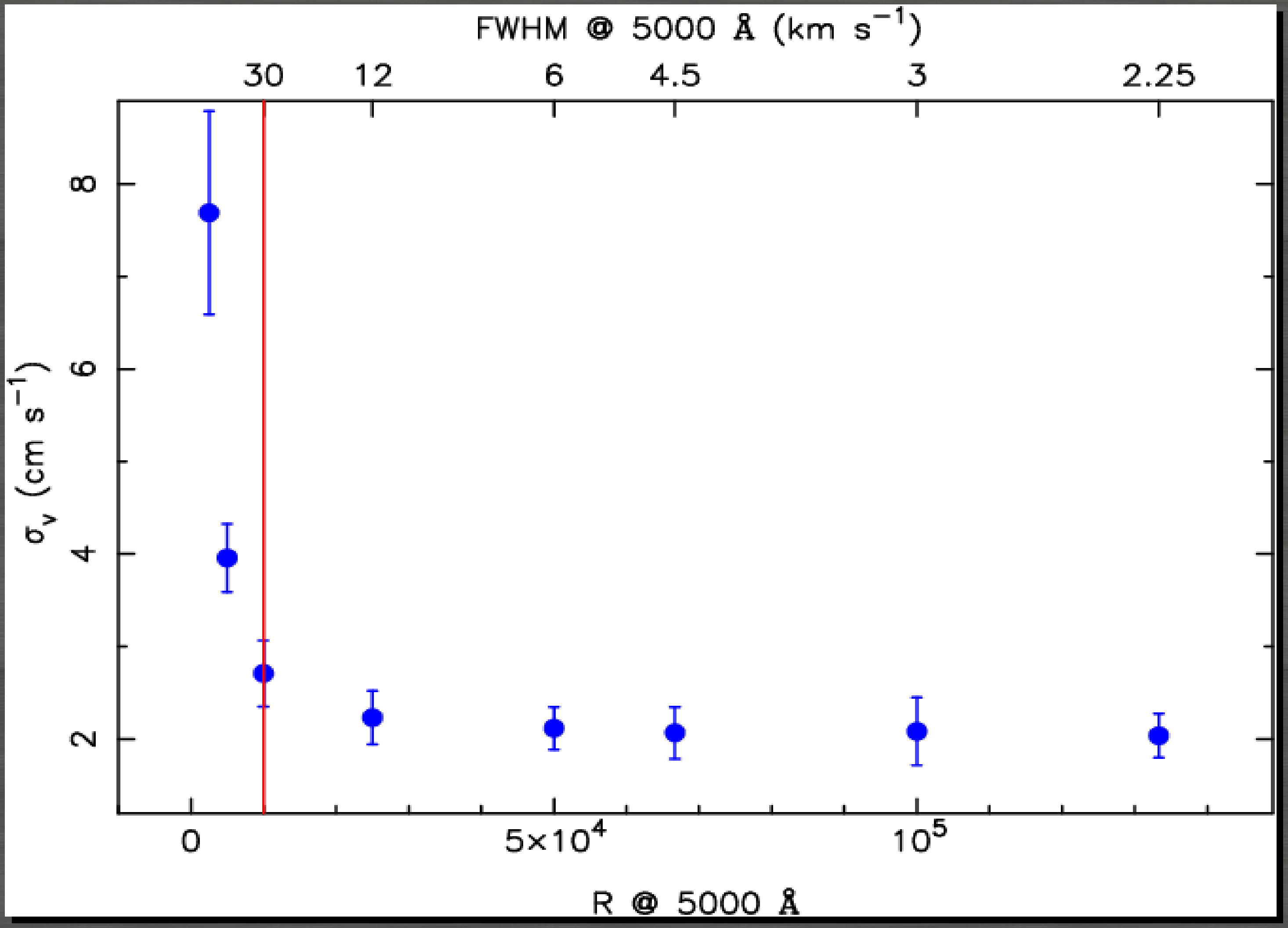
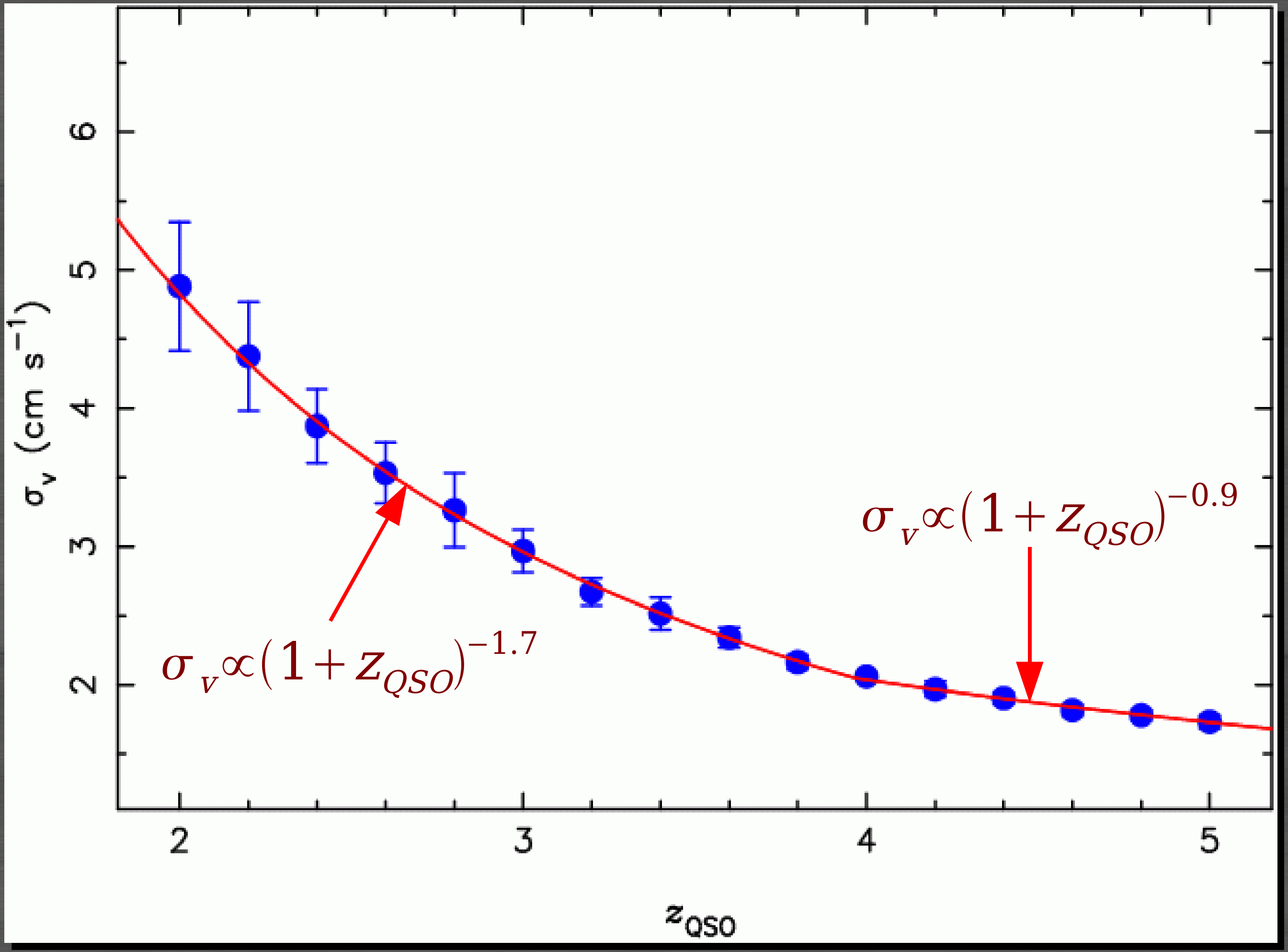


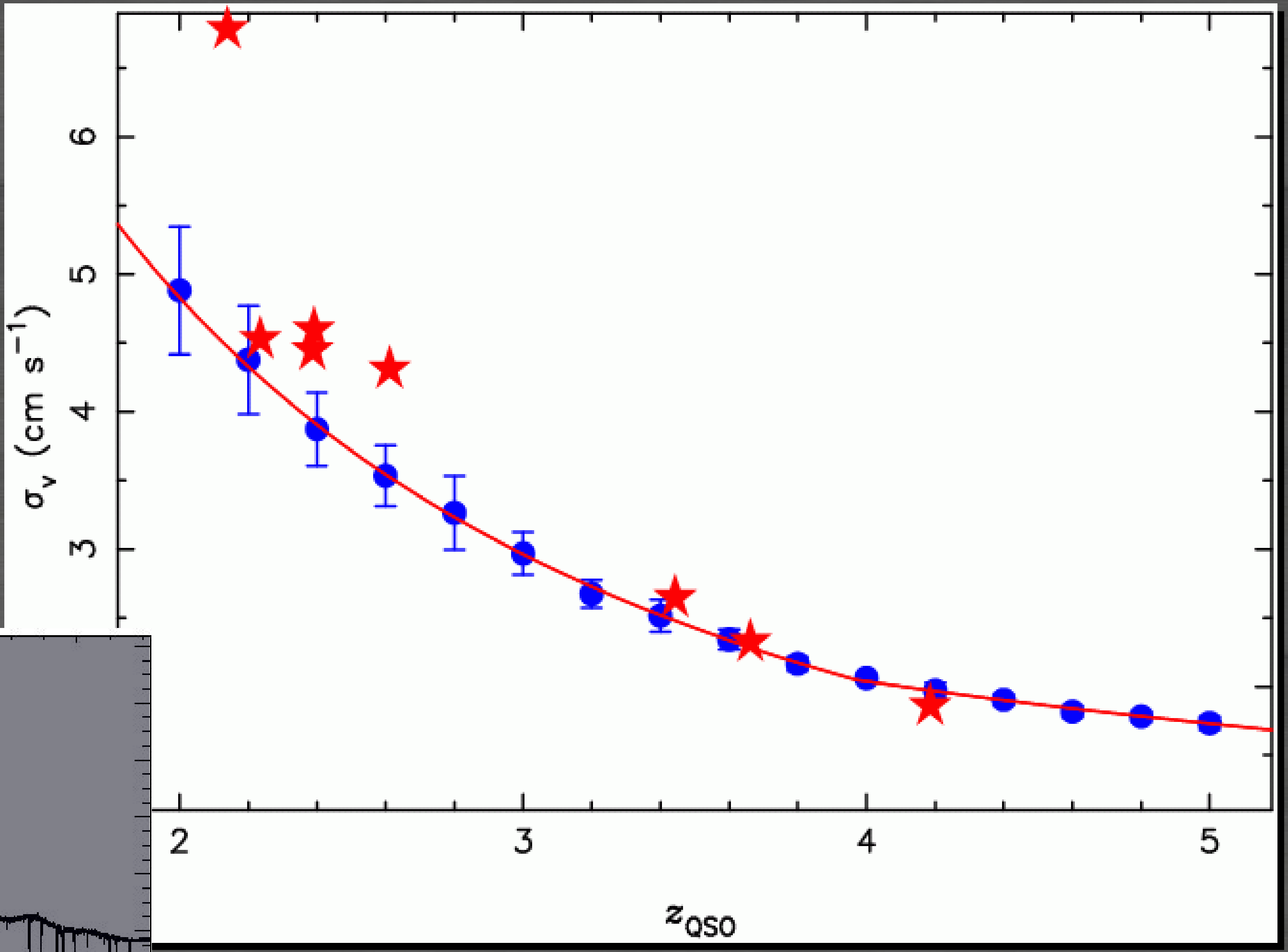
Sensitivity to radial velocity shifts

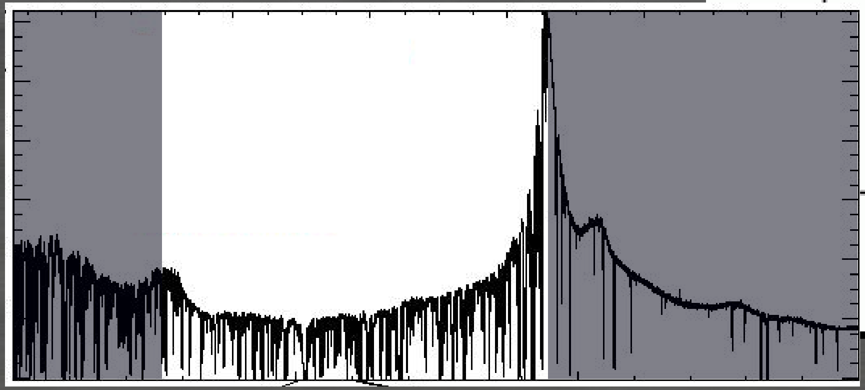
- MC simulations: based on statistics of absorption line parameters.



Sensitivity to radial velocity shifts

- Real absorption line lists: derived from high-reslution, high-S/N UVES VLT spectra (Kim et al. 2001, 2002)





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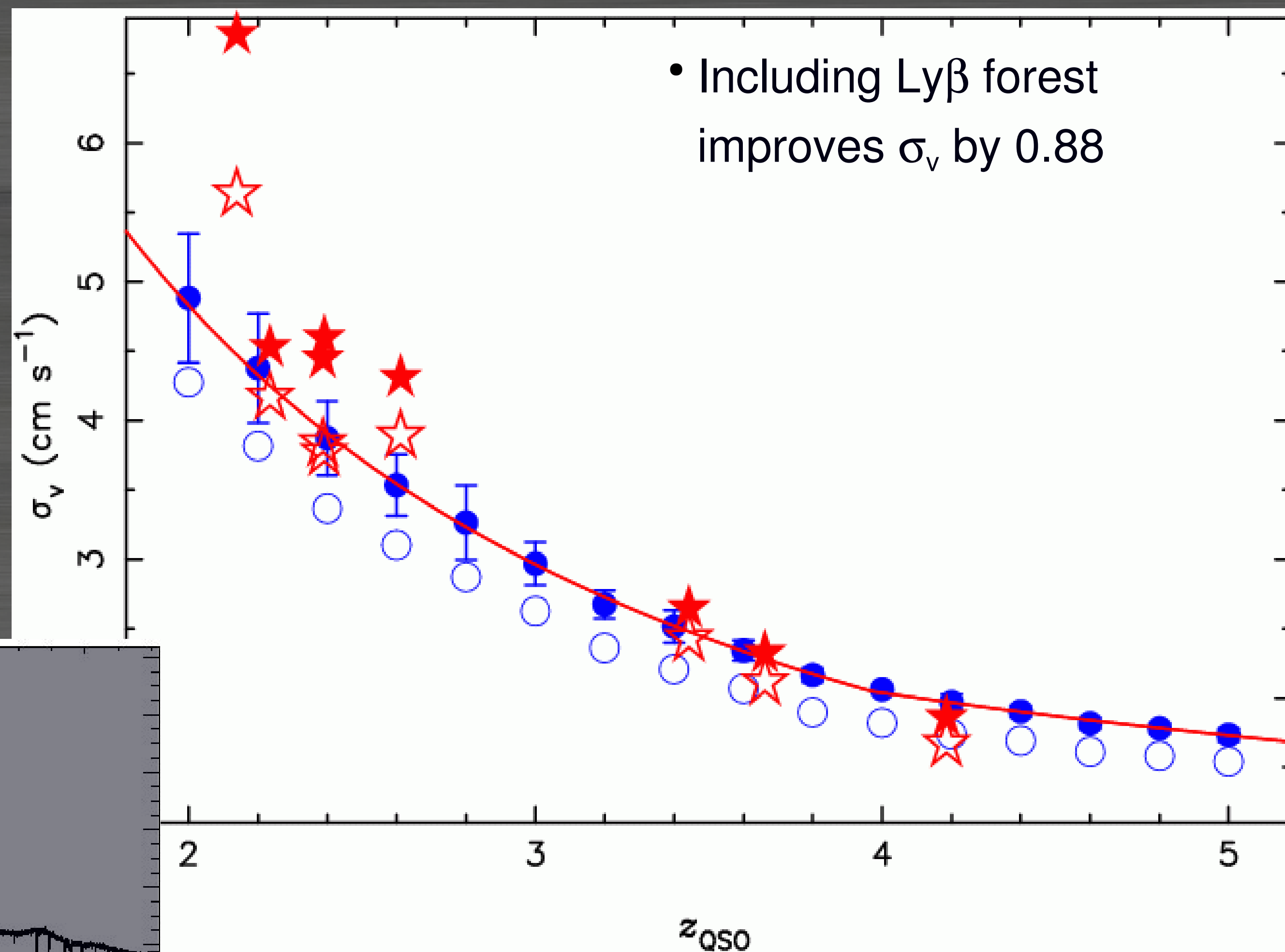

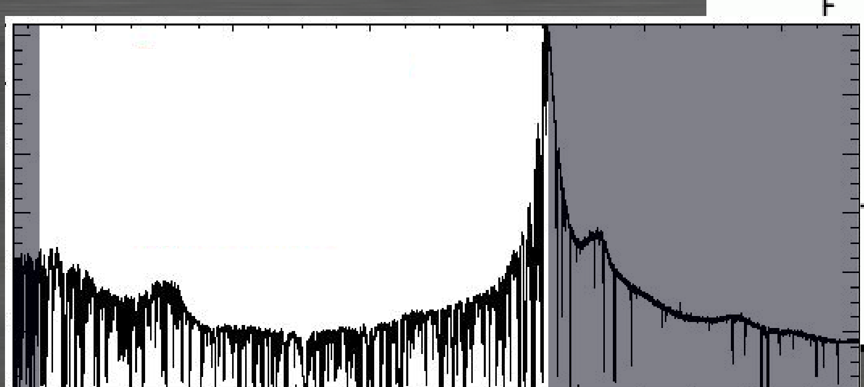

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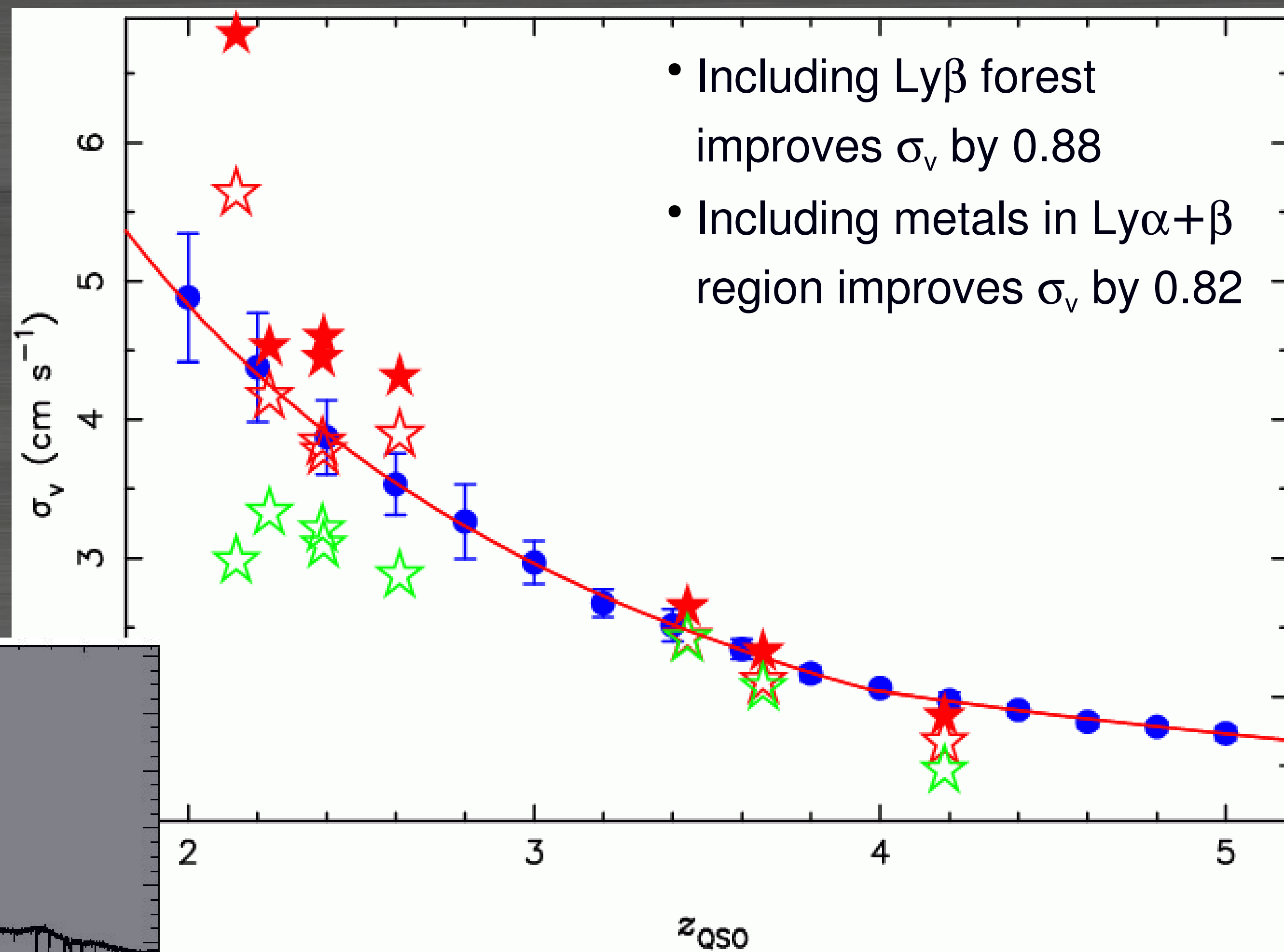

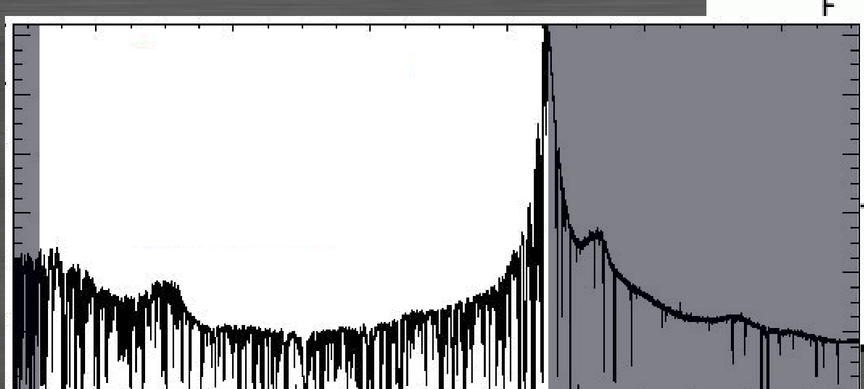

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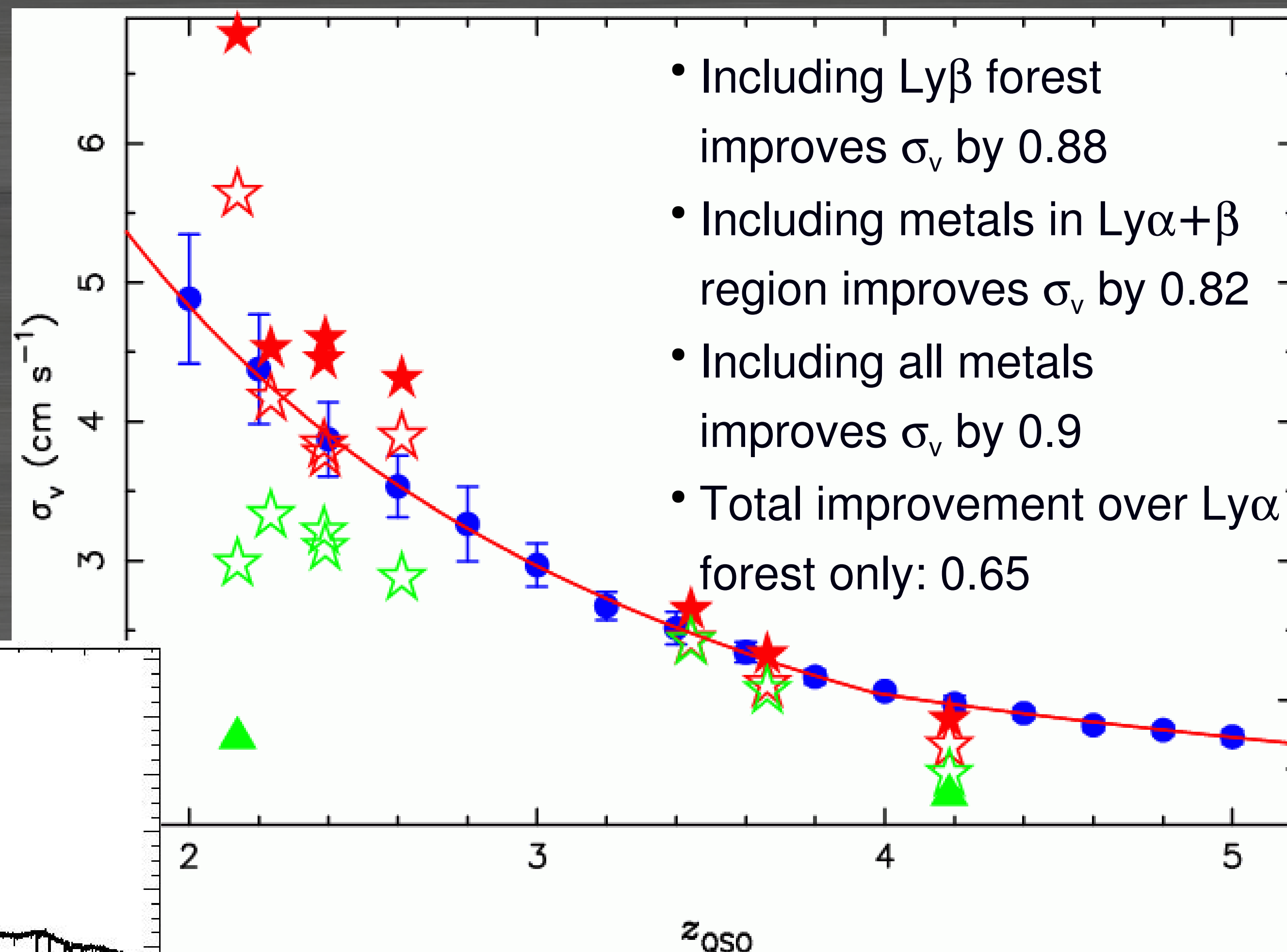
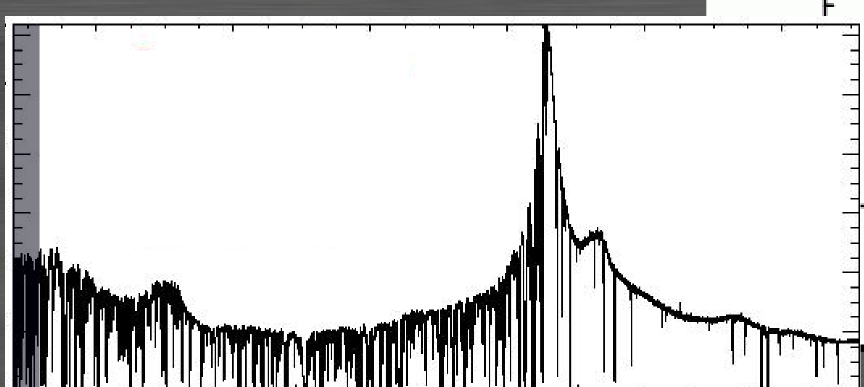




Scaling relation

Using the Lyα forest what radial velocity accuracy can we achieve for a given S/N ? How does the sensitivity depend on redshift?

$$\sigma_v = 1.35 \left[\frac{S/N}{3350}\right]^{-1} \left[\frac{N_{QSO}}{30}\right]^{-\frac{1}{2}} \left[\frac{1+z_{QSO}}{5}\right]^{-1.7} g(N_e, f_{1\ldots N_e})\, cm/s$$

where S/N is the total S/N per 0.0125 Å pixel (4 pixel per resolution element at R = 100 000) accumulated over all N_e epochs, for each spectrum. g ≈ 1.1 is a 'form factor' that depends on the number of epochs and their distribution within the time span of the experiment.

Can we collect enough photons?

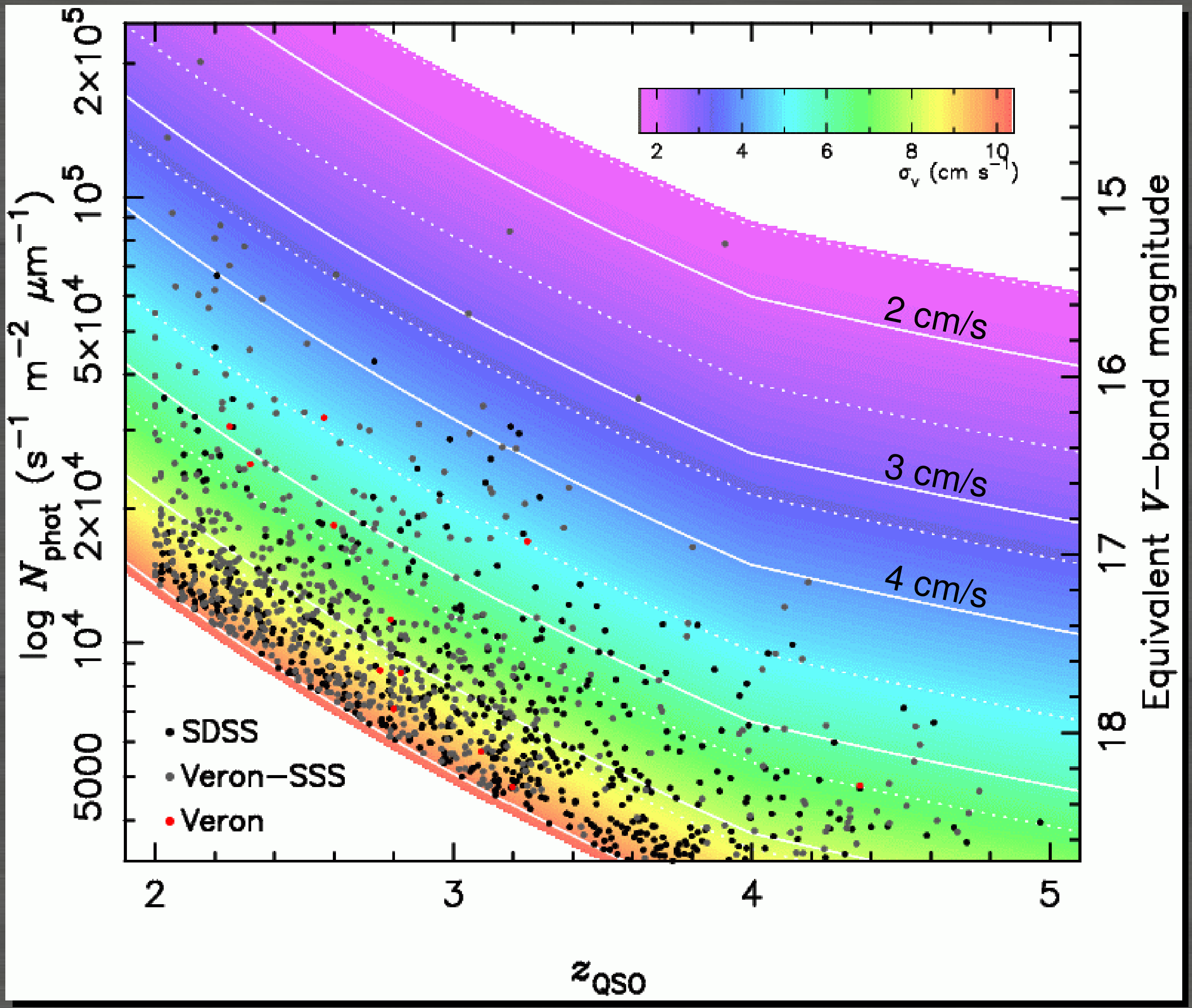
Can we collect enough photons to achieve the required radial velocity accuracy?

QSOs from latest compilations (including SDSS):

Lines of constant σ_v assume:

D = 42 m
efficiency = 25%
t_{exp} = 2000 h

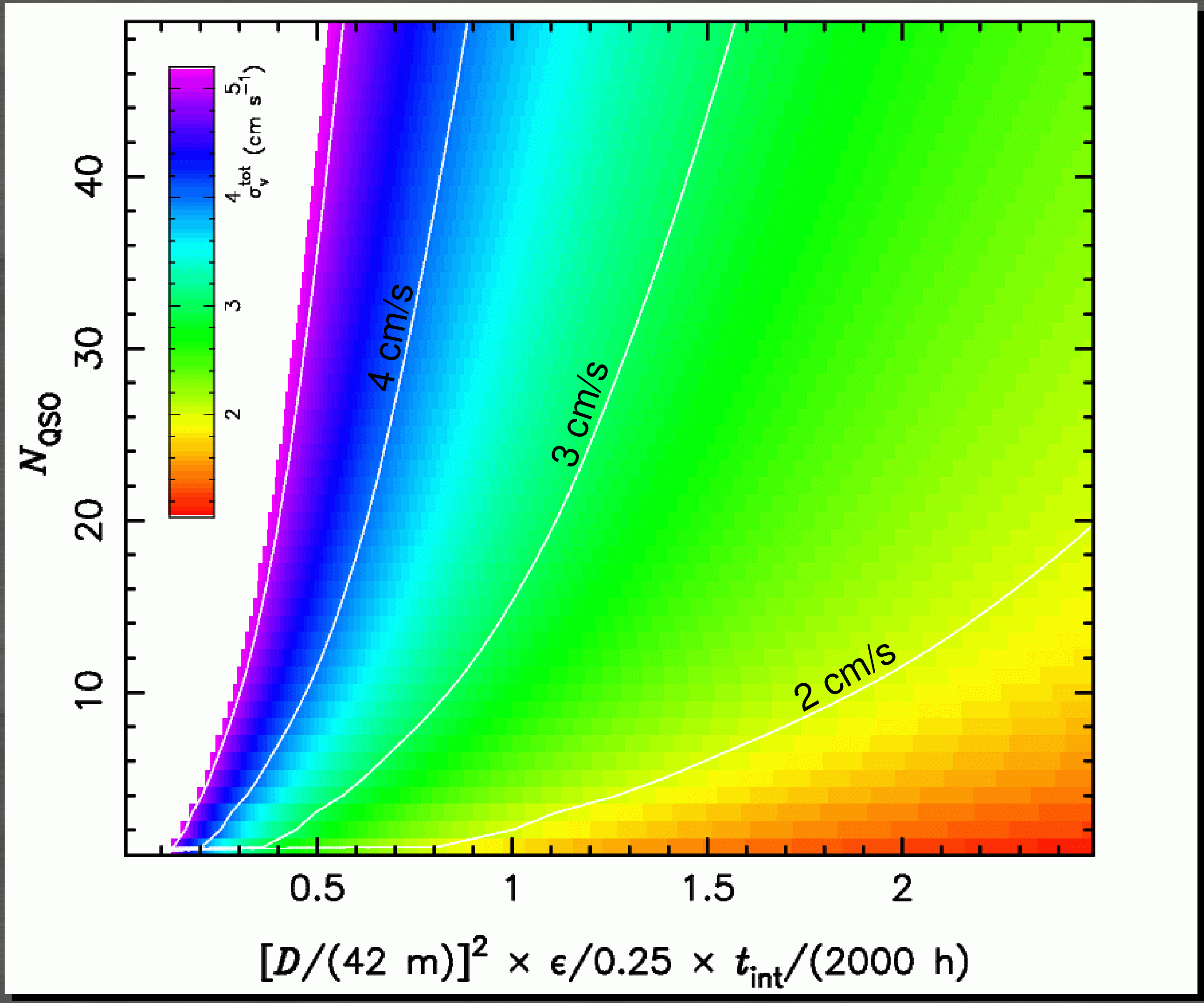
Yes: 18 known QSOs with 2 < z < 5 are bright enough to achieve a radial velocity accuracy of 4 cm/s using 2000 hours on a 42-m ELT.



Liske et al. (2008)

Total achievable accuracy

A total, overall radial velocity accuracy of 2-3 cm/s is well within reach of the E-ELT targeting 10-20 QSOs.



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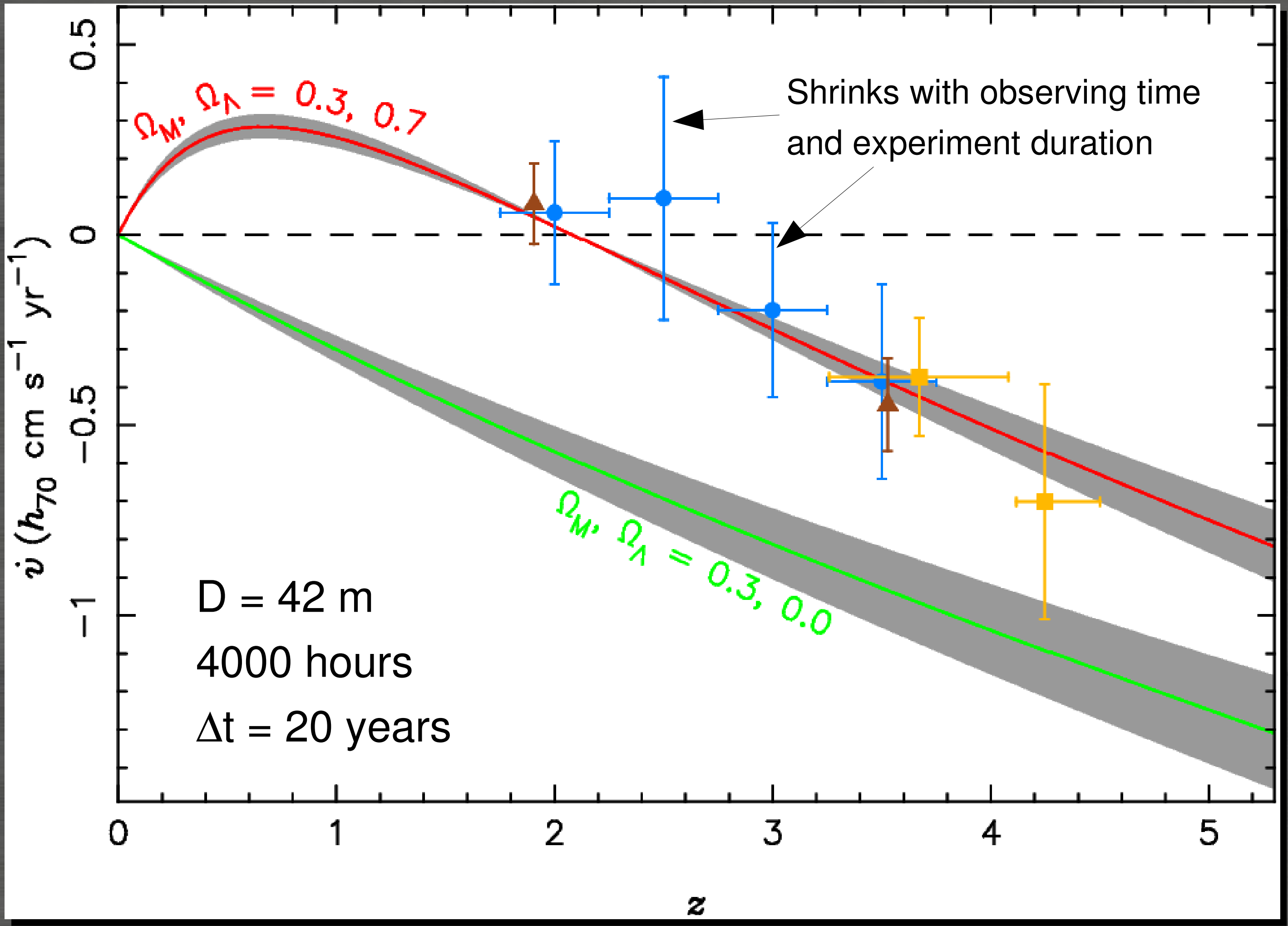
Simulation results

Photon-noise limited simulations:

4000 hours on a 42-m ELT over 20 years will deliver any *one* of these sets of points.

Different sets correspond to different target selection strategies.



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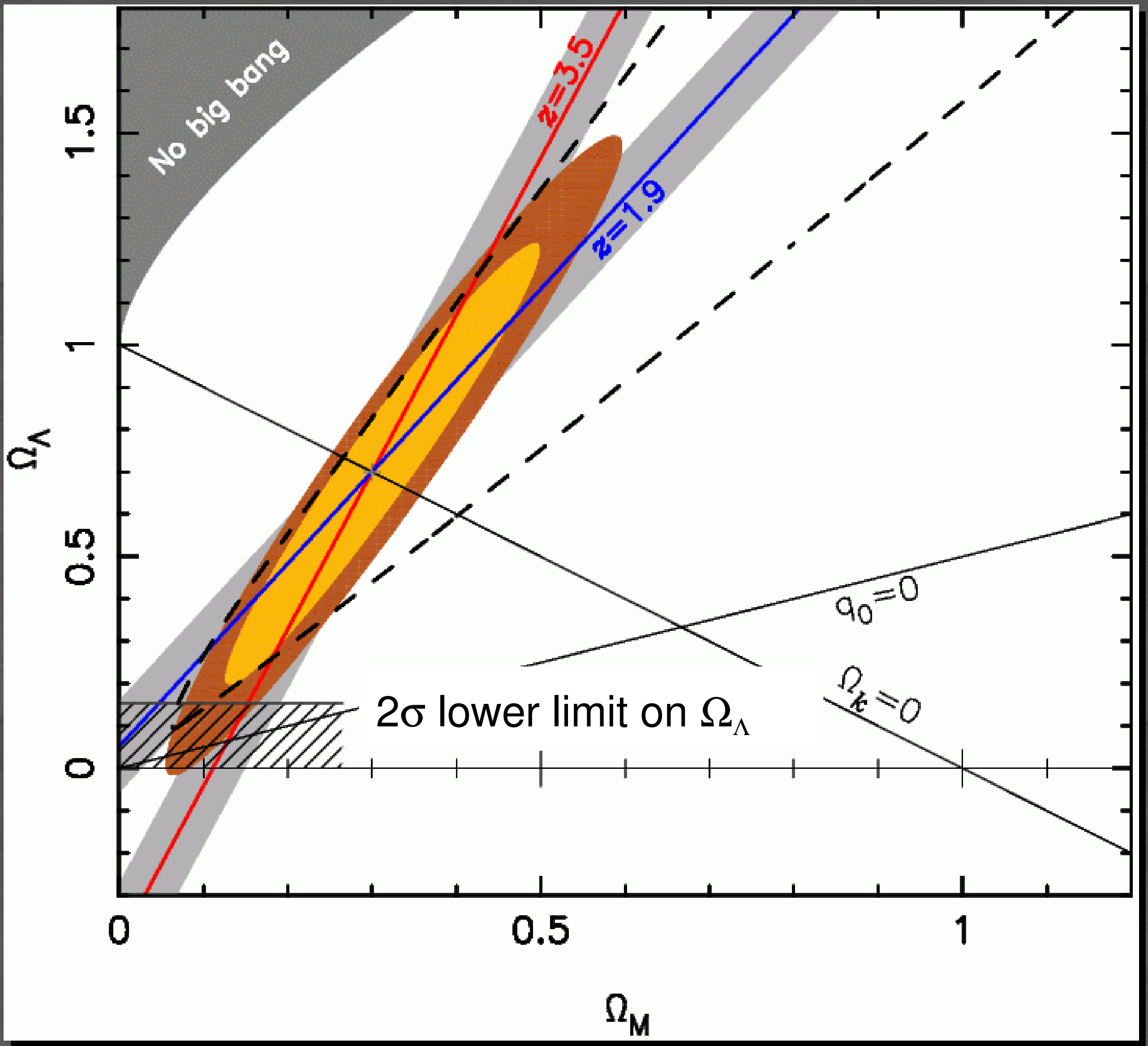
Simulation results

- 4000 hours over 20 years will unequivocally prove the existence of dark energy without assuming flatness, using any other cosmological constraints or making any other astrophysical assumption whatsoever.
- Provides independent confirmation of SNIa results, using a different method and a complementary redshift range.



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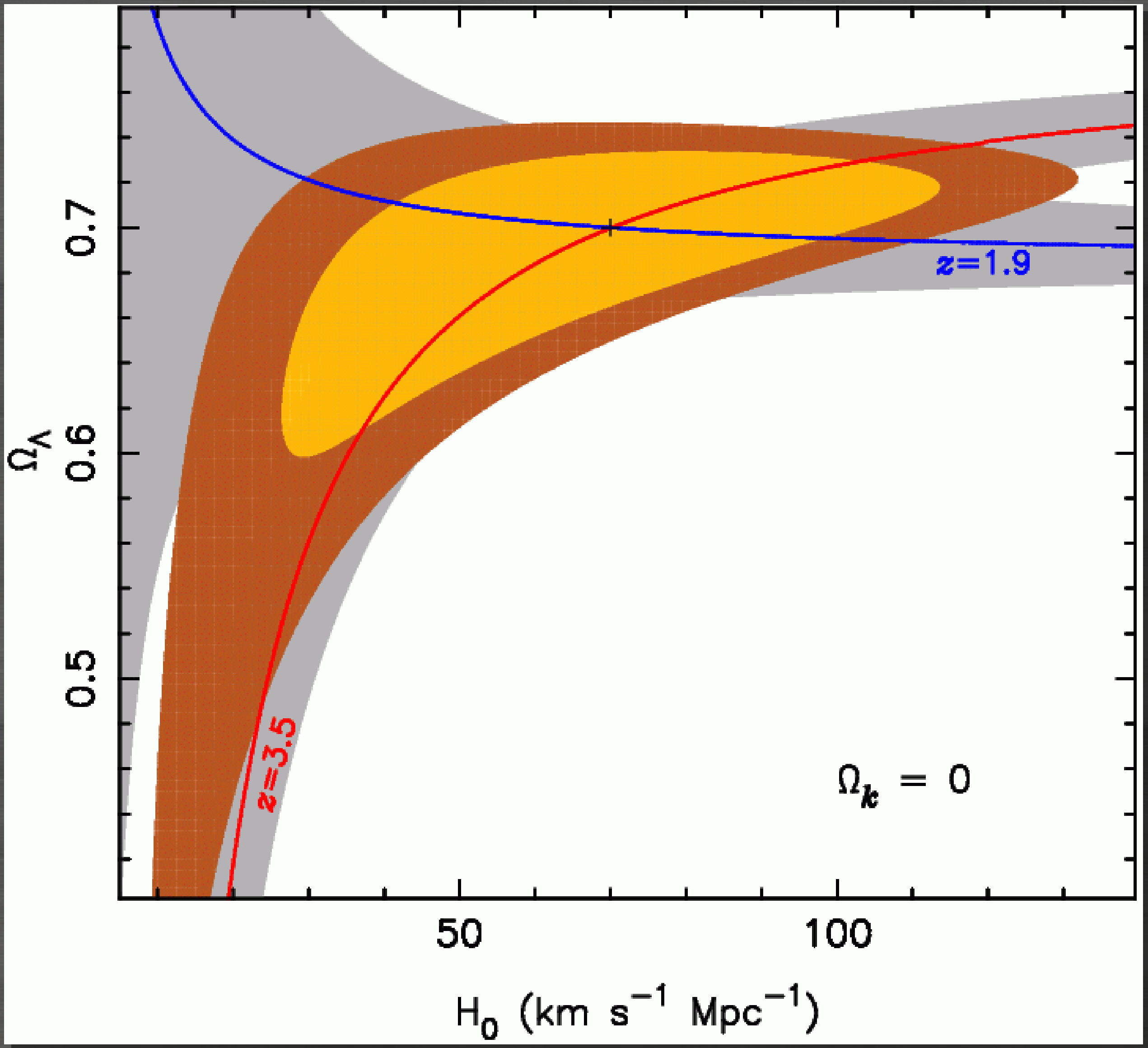

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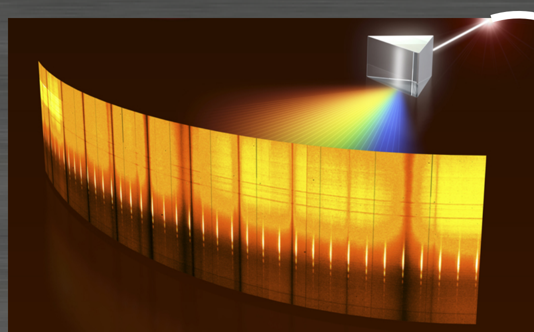
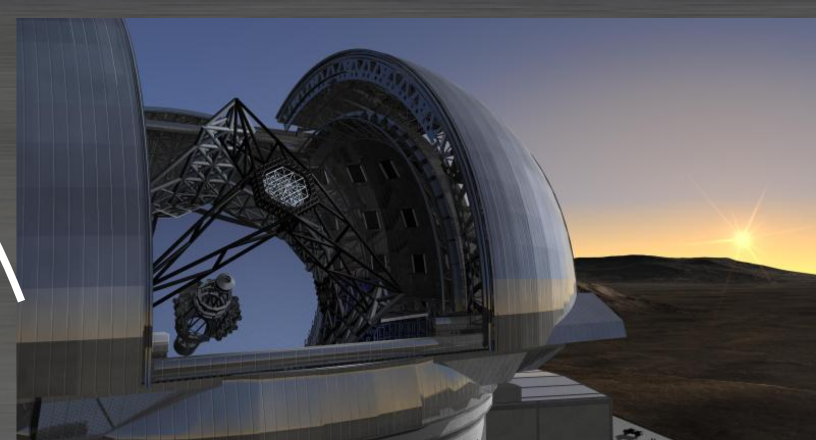
Summary

- The E-ELT will be the first telescope capable of detecting the redshift drift and of providing us with the first observation of the dynamics of the global FRW metric.
- A redshift drift experiment on the E-ELT can detect the difference between $(\Omega_M, \Omega_\Lambda)$ = (0.3,0.7) and (0.3,0.0) at 3σ significance in 15 yr, using 20 QSOs and 2500 h of observing time.
- $D^2 \times$ system throughput (photon collecting power) is the most crucial parameter $\rightarrow$ do **not** build a smaller telescope; coatings; need to optimise throughput of instrument.
- Calibration requirement: the error on radial velocity measurements must remain photon noise dominated over the duration of the experiment.
- Results depend on precise QSO sample available $\rightarrow$ need to search for (and monitor) more bright QSOs, especially in the south (VISTA, LSST).





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