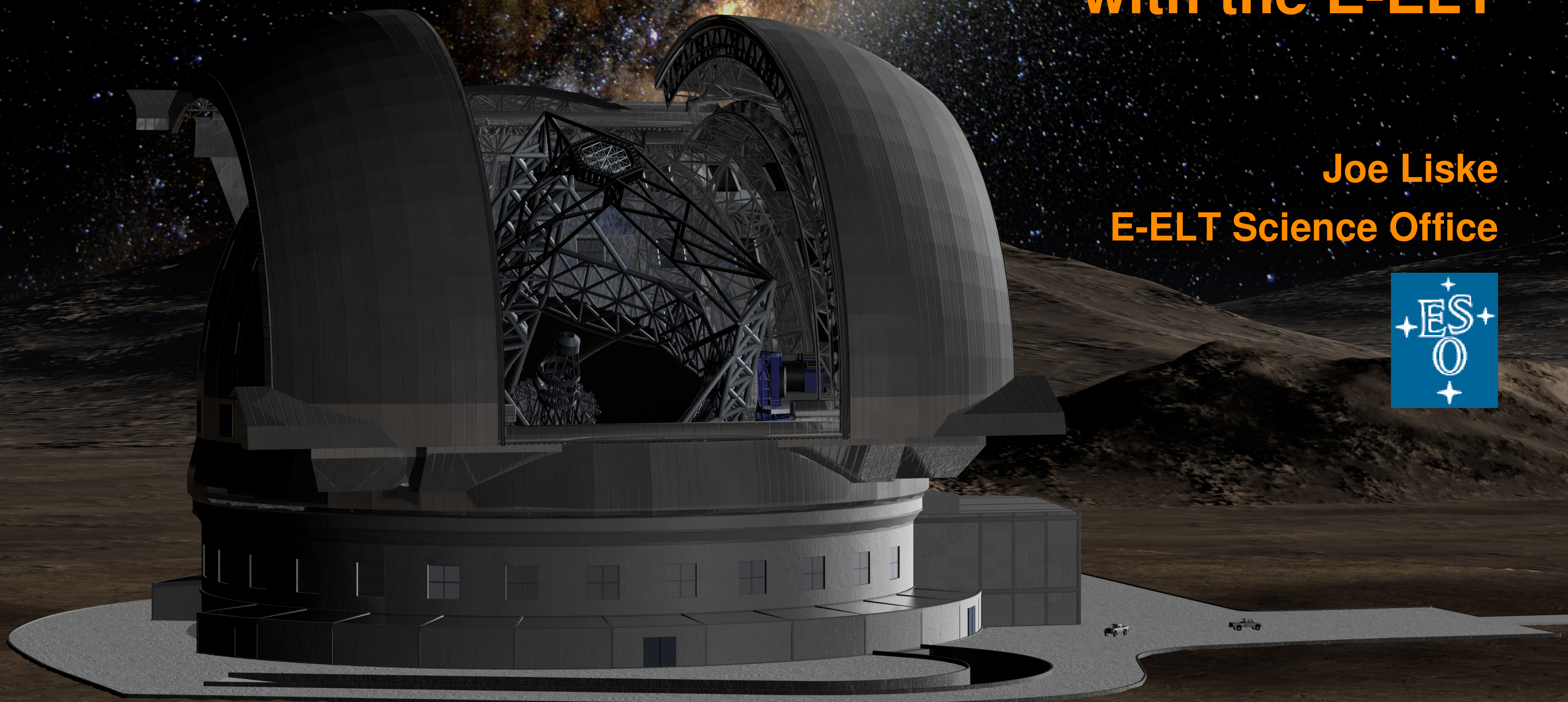
Cosmological Dynamics:

A Direct Measurement of the Expansion History of the Universe with the E-ELT



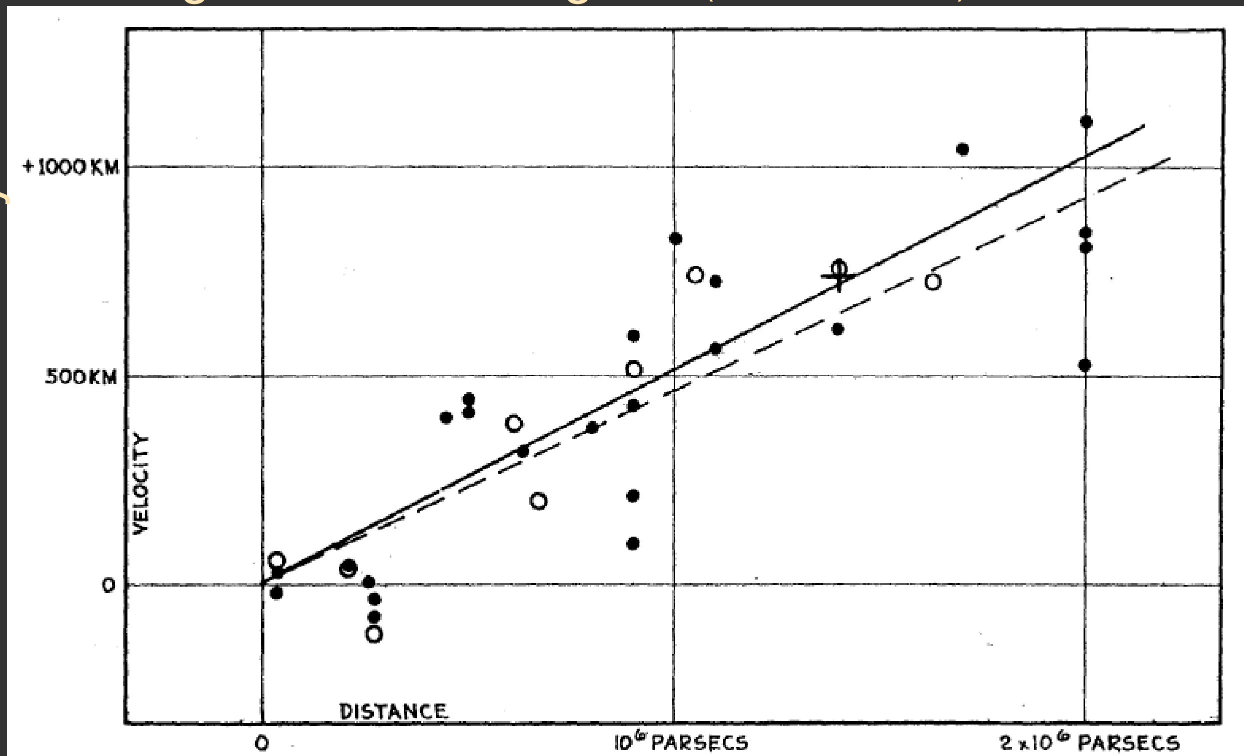
Joe Liske

E-ELT Science Office

Universal Expansion

The original Hubble diagram (Hubble 1929):

Recession velocity

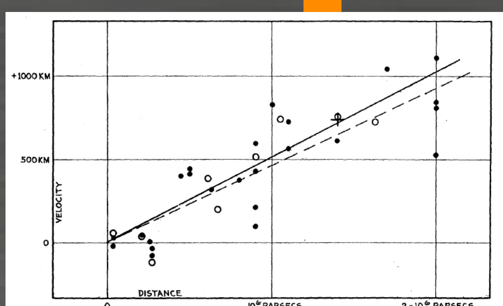


Distance

All distant galaxies are found to recede from us.

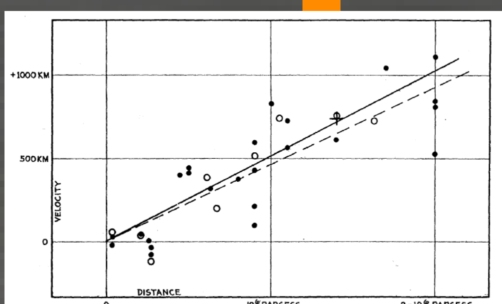
Hubble's Law: $v = H_0\, d$ → **The universe expands!**

Relativistic Big Bang Cosmology

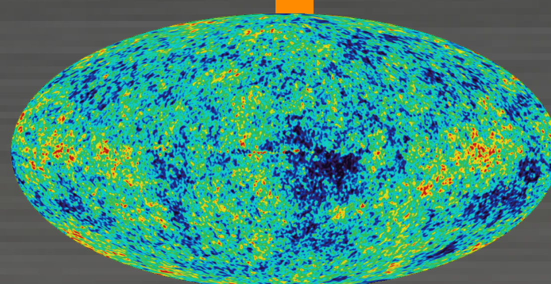


Expansion

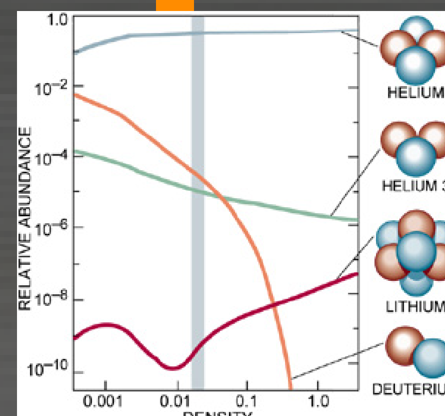
Relativistic Big Bang Cosmology



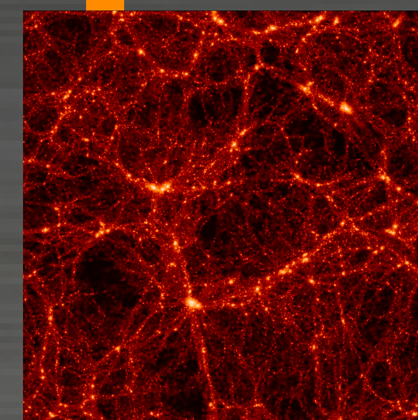
Expansion



Cosmic Microwave Background



Abundance of light elements



Structure formation

Which of the solutions of the Friedmann equation corresponds to reality?

$$G_{\mu\nu} = \frac{8\pi G}{c^4} T_{\mu\nu}$$

Or in other words:

What is the stress-energy tensor of the universe?

For each mass/energy component i, what is Ω_i, w_i (and what is H_0)?

Density parameter (Ω_i) — Equation of state parameter (w_i)

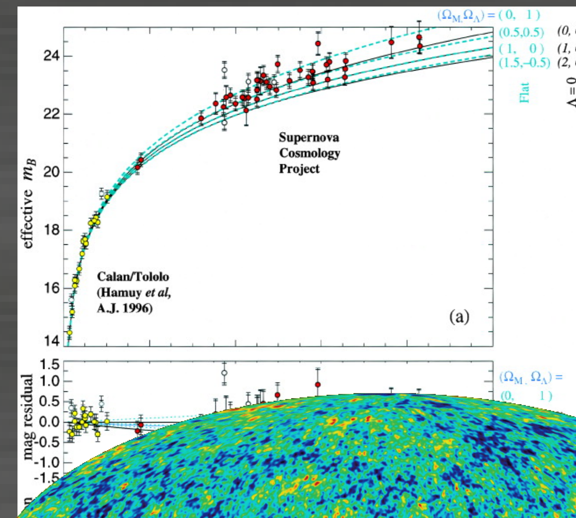
How can these be measured?

- Geometry
- Expansion history
- Clustering

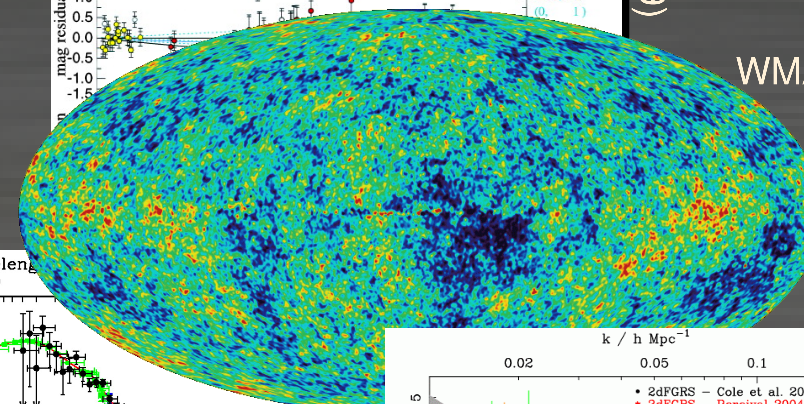
Which of the solutions of the Friedmann equation corresponds to reality?

Answers have already been provided by:

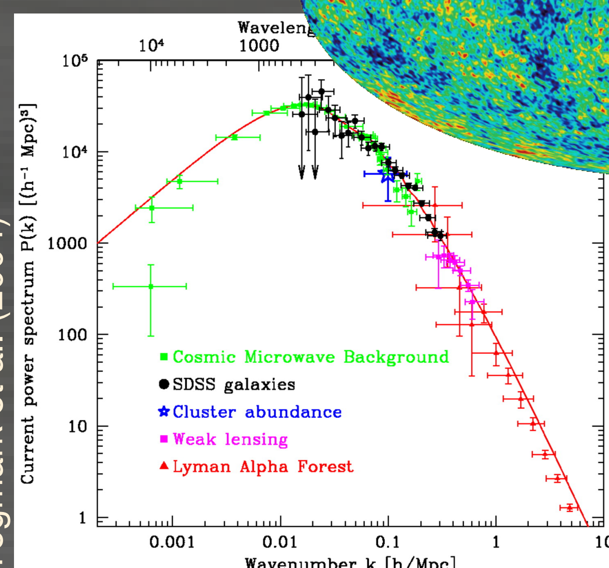
- Cosmic Microwave Background
- Supernovae type Ia
- Large scale structure of galaxies and intergalactic medium
- Galaxy clusters
- Weak lensing



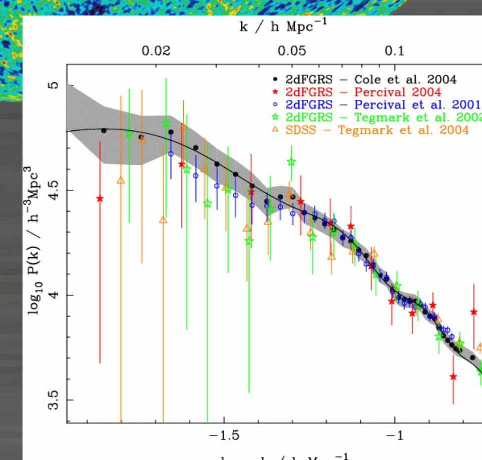
Perlmutter et al. (1999)



WMAP

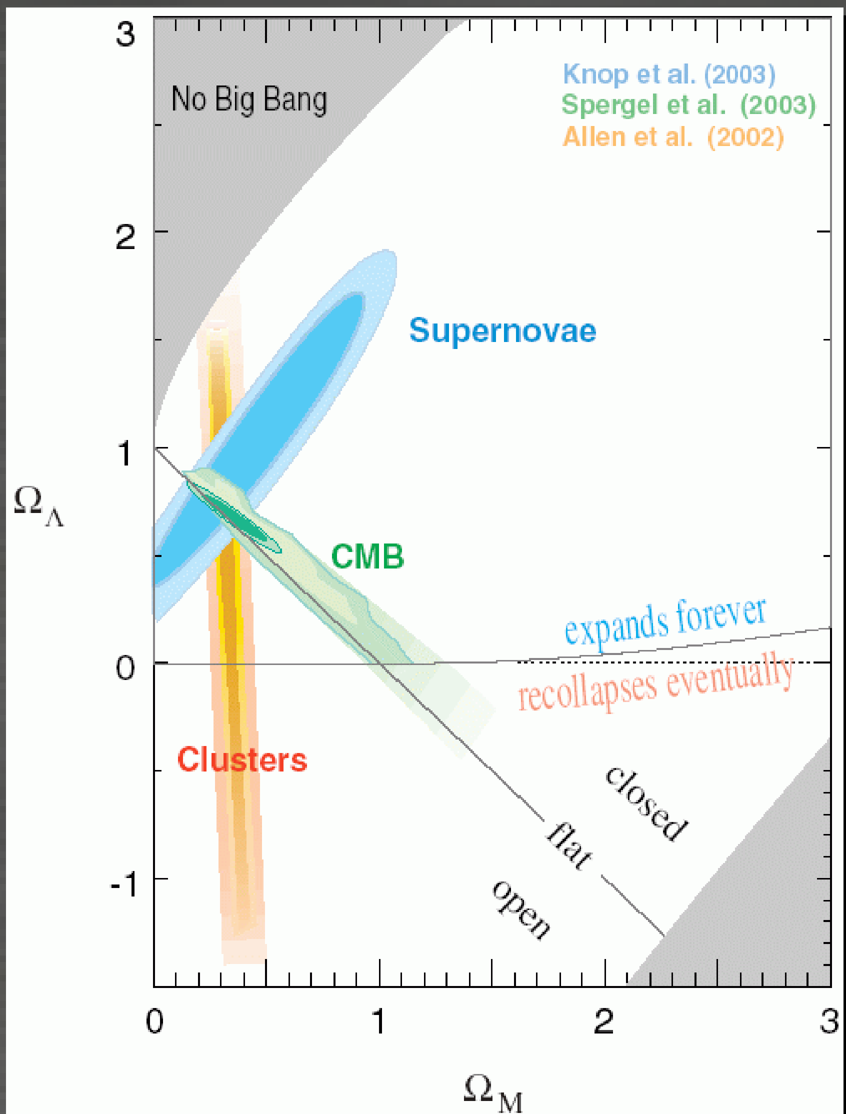


Tegmark et al. (2004)

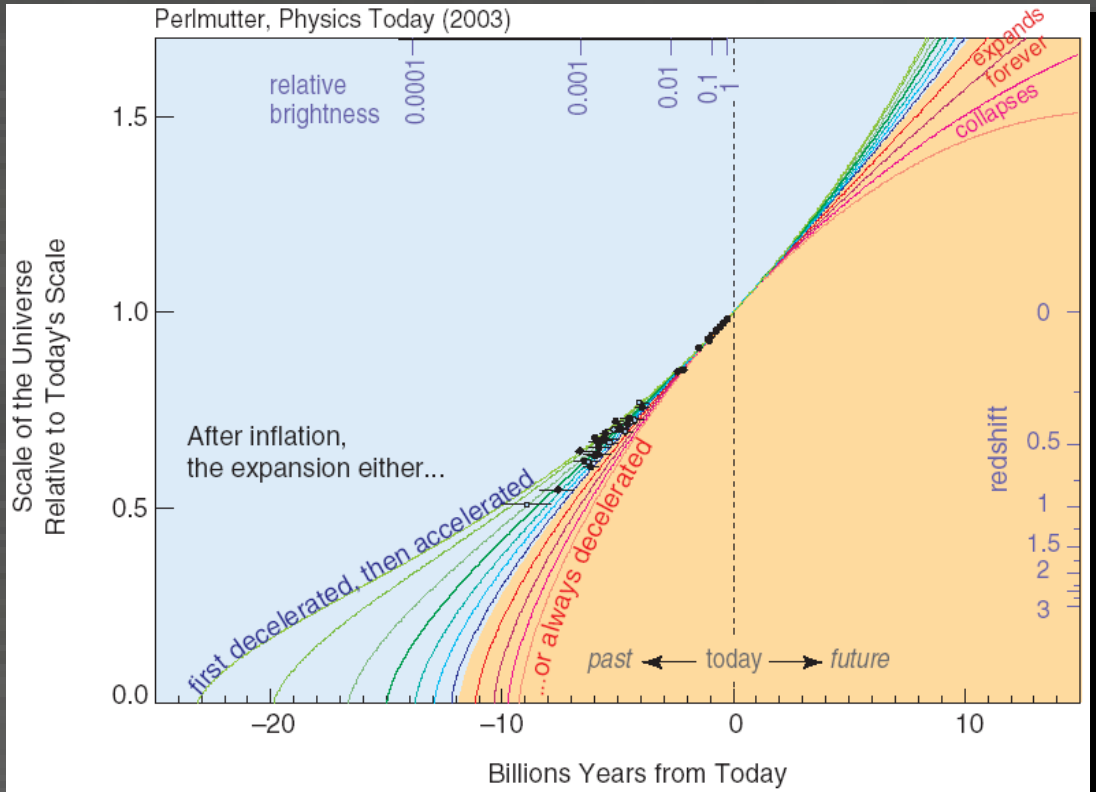


Cole et al. (2005)

Surprise:
the expansion is accelerating!



- Good evidence from SNIa that universe underwent a period of decelerated expansion, followed 'recently' by a period of acceleration.
- Existence of an additional mass/energy component supported by CMB.



Surprise: the expansion is accelerating!

The source of the acceleration is entirely unknown. A large number of explanations have been proposed, many requiring new physics, including:

- Modification of the stress-energy tensor:
  - Cosmological constant $w = -1$
  - Quintessence $-1 < w(z) < 0$
  - Phantom energy $w(z) < -1$
  - ...

- Modification of the theory of gravity
  - f(R)
  - Non-minimal couplings
  - Brane world scenarios (Cardassian, DGP, ...)
  - ...

- Modification of the Copernican Principle:
  - Inhomogeneous models without DE can reproduce past light-cone observations of FRW models with DE (LTB, void models, ...)
  - Backreaction (averaging and evolution do not commute)

Surprise: the expansion is accelerating!

- The observed acceleration of the expansion is the primary smoking gun that something funny is going on.

→ Intense interest in expansion history, H(z). Best ways to measure H(z):

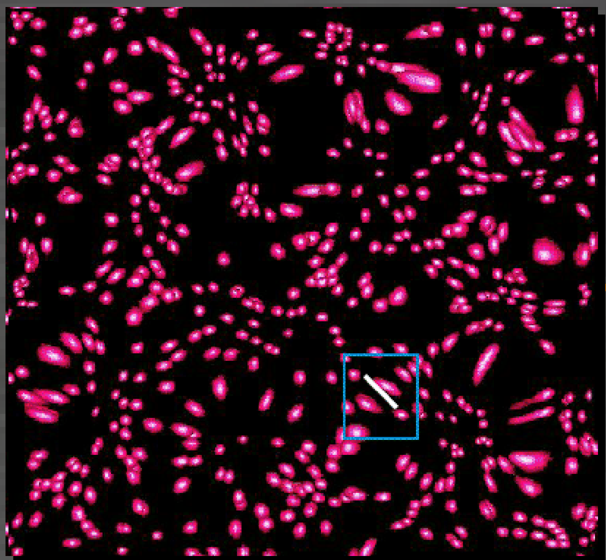
- SNIa
- Weak lensing
- Baryon Acoustic Oscillations (BAO)

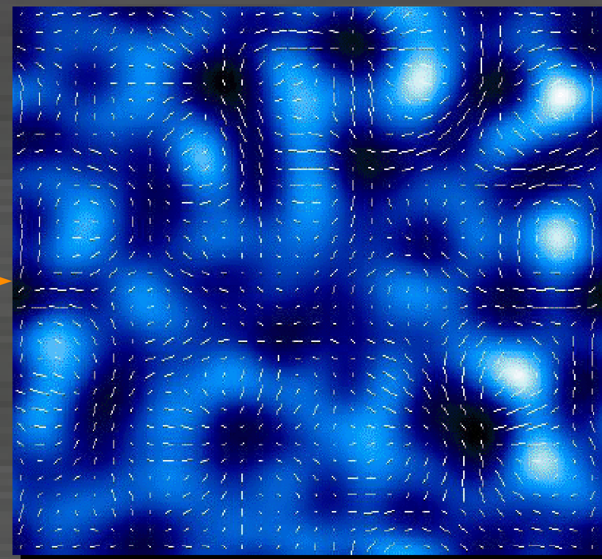
$$d \propto \int 1/H(z)\; dz$$

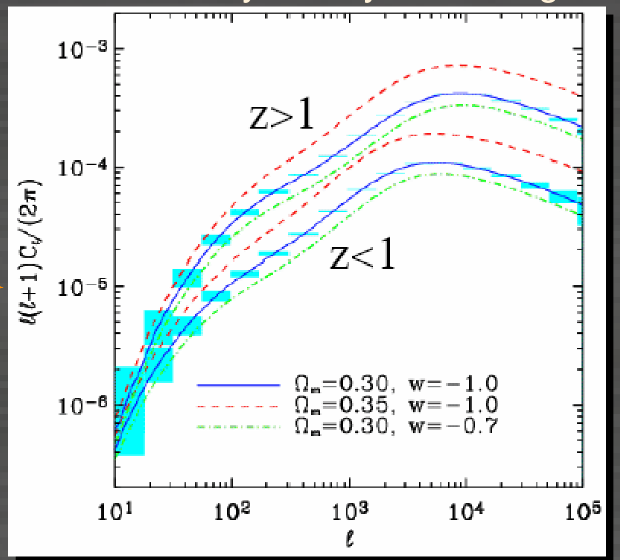
$$\delta = f(H(z))$$

Weak lensing

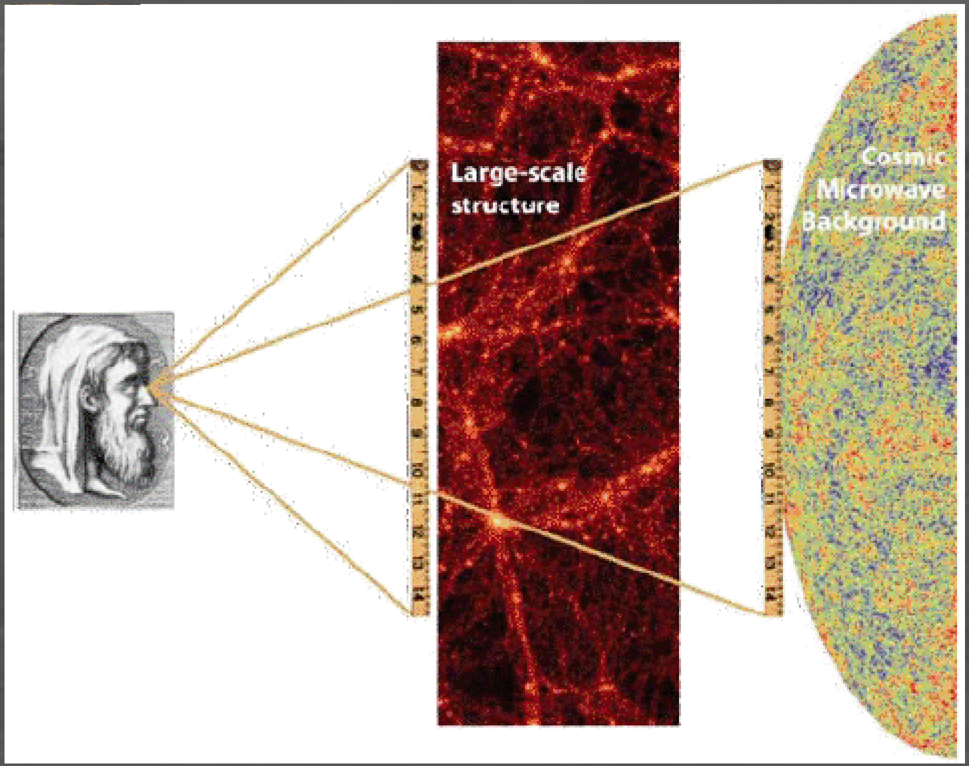
by S. Lilly / A. Refrigier



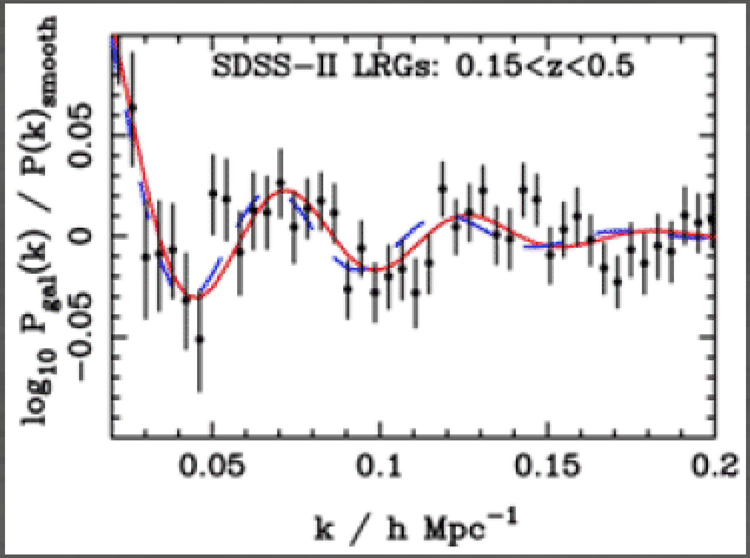




- The weak lensing power spectrum depends on:
  - the shape of the density fluctuation power spectrum,
  - D_A in the lensing equation for the lensing amplitude,
  - D_A to set the angular scale,
  - the growth factor g(z).



Percival et al. (2009)



Baryon Acoustic Oscillations

- The decoupling of the CMB photons freezes the acoustic oscillations in the photon-baryon fluid and imprints the sound horizon scale onto the CMB and galaxy power spectra.
- Provides $D_A(z)$, $H(z)$, AP test.
- Get RSD for free to break degeneracy between DE and modified gravity models with the same $H(z)$.

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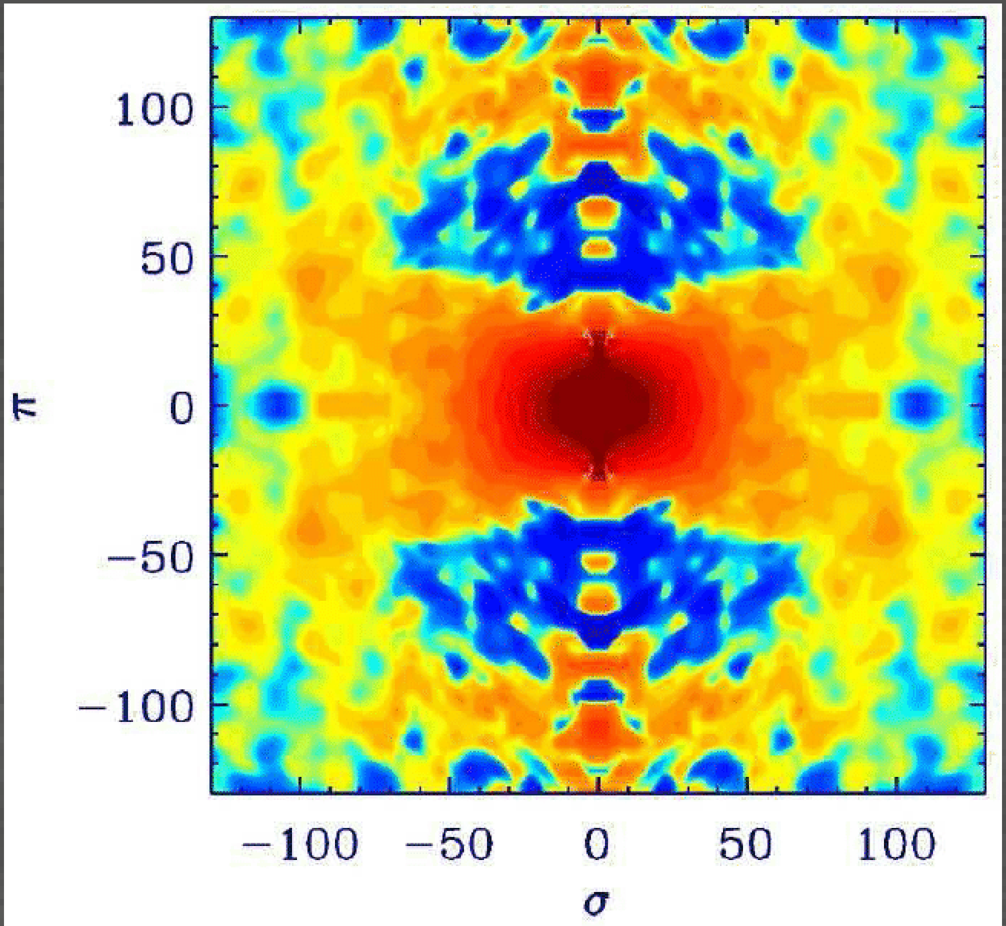

Gaztanaga et al. (2009)

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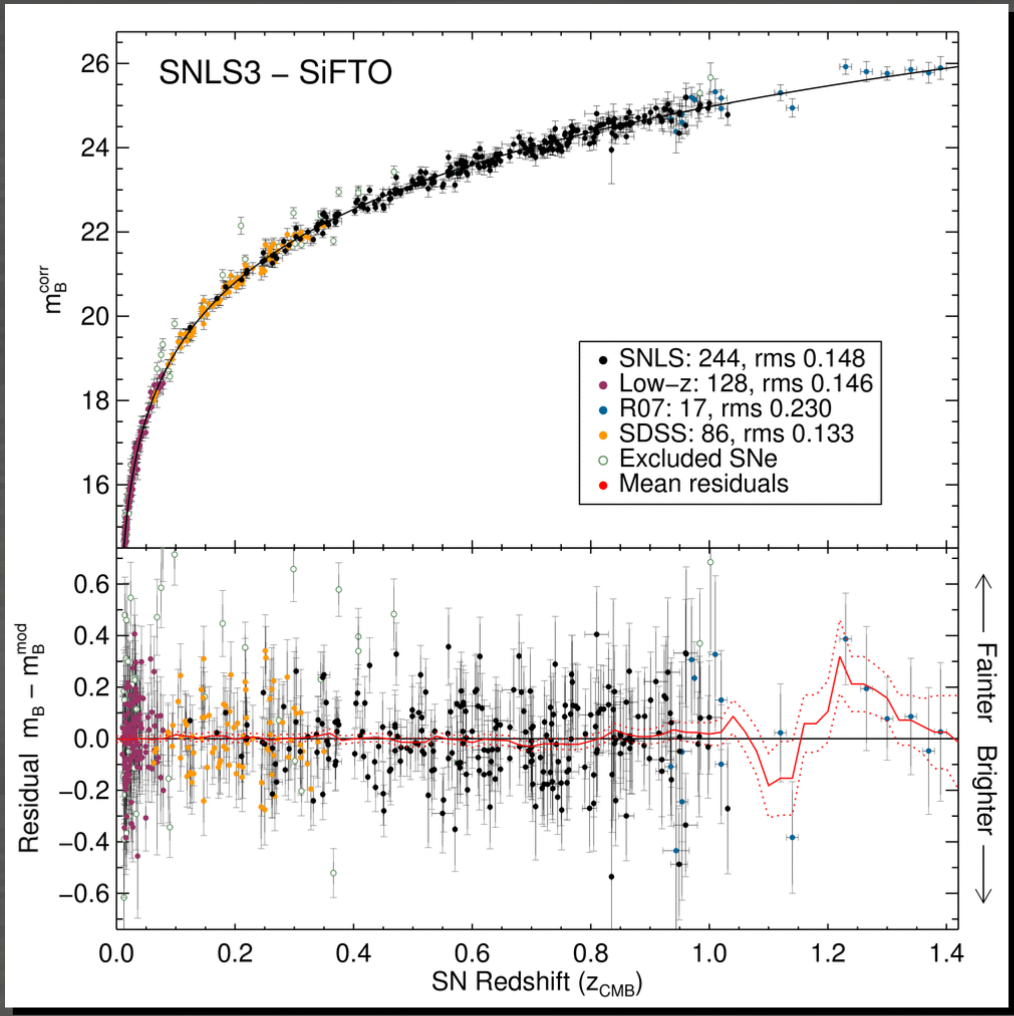
Supernovae Ia

- SNe Ia are standardisable candles which hence provide $D_L(z)$.
- Current datasets give ~500 SNe to z ~ 1 and constrain w to 5% accuracy (stat).
- Many new experiments running or planned but these will remain at z < 2.

Preliminary 3rd year SNLS Hubble diagram:



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  - SNIa
  - Weak lensing
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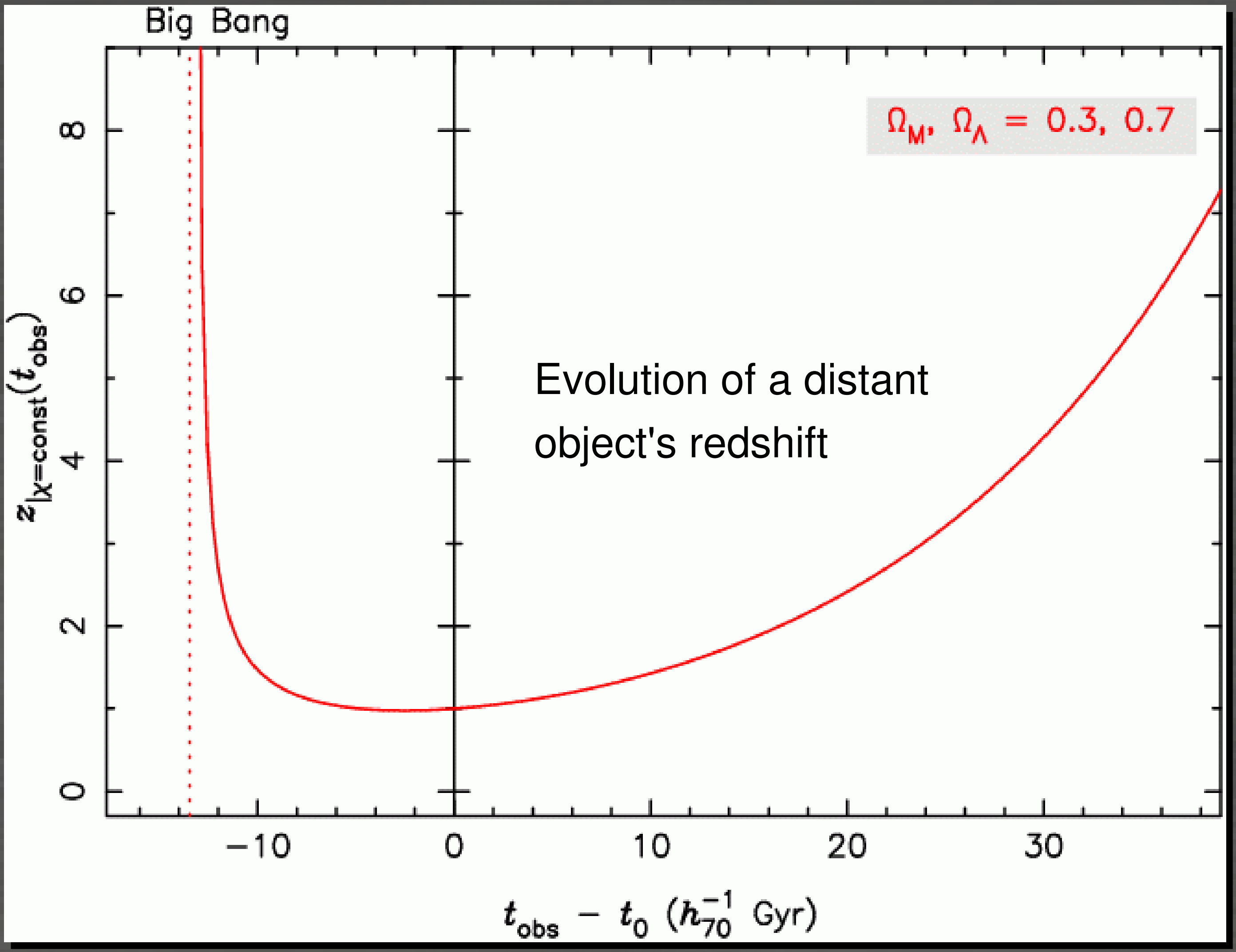
These methods are essentially geometric in nature and/or probe the dynamics of localised density perturbations.

A measurement of the ***global dynamics*** has never been attempted. This would offer a direct, entirely model-independent route towards H(z).

Evolving redshifts

$$1+z = \frac{a(t_{obs})}{a(t_{em})}$$

The evolution of an object's redshift with time contains the entire expansion history.



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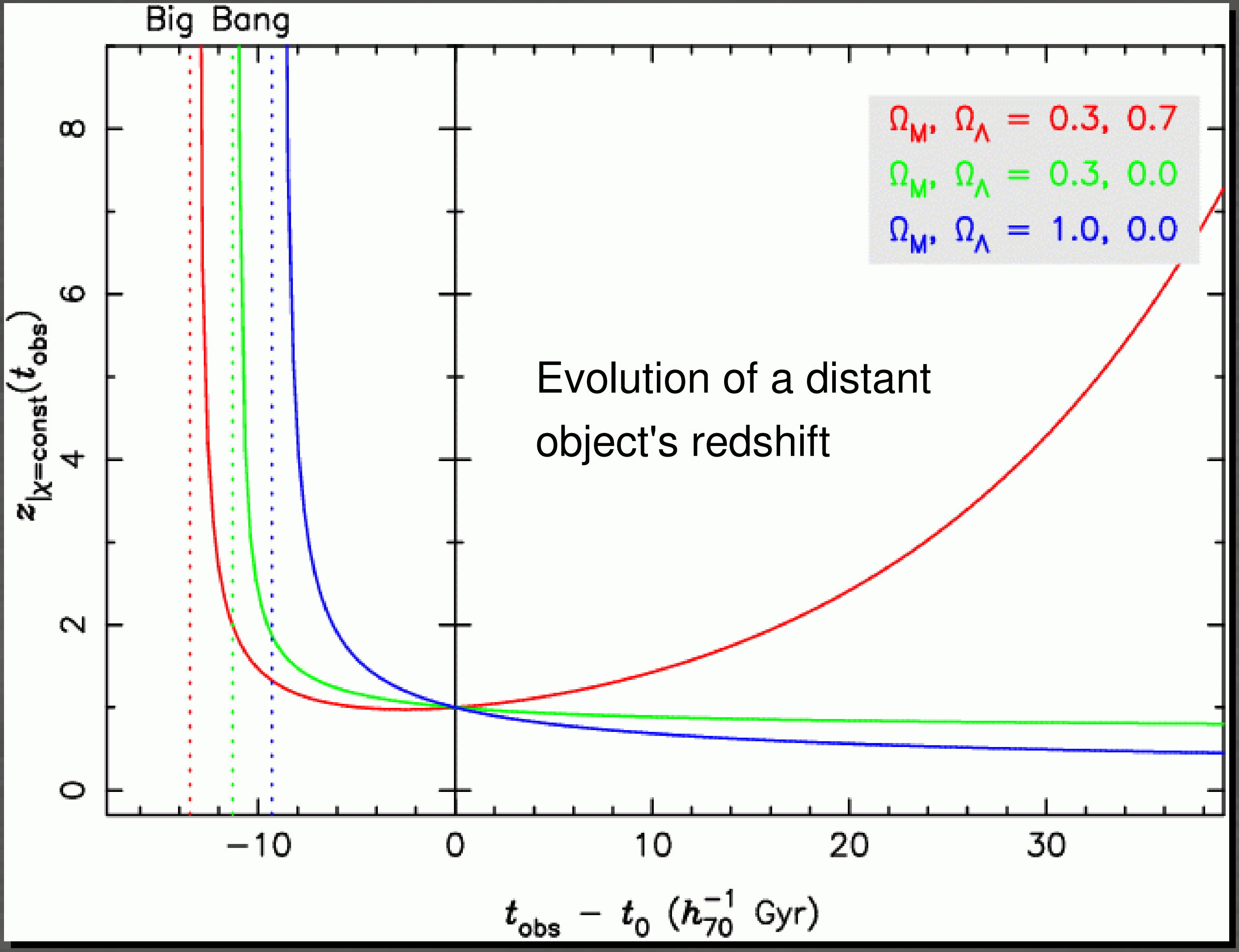

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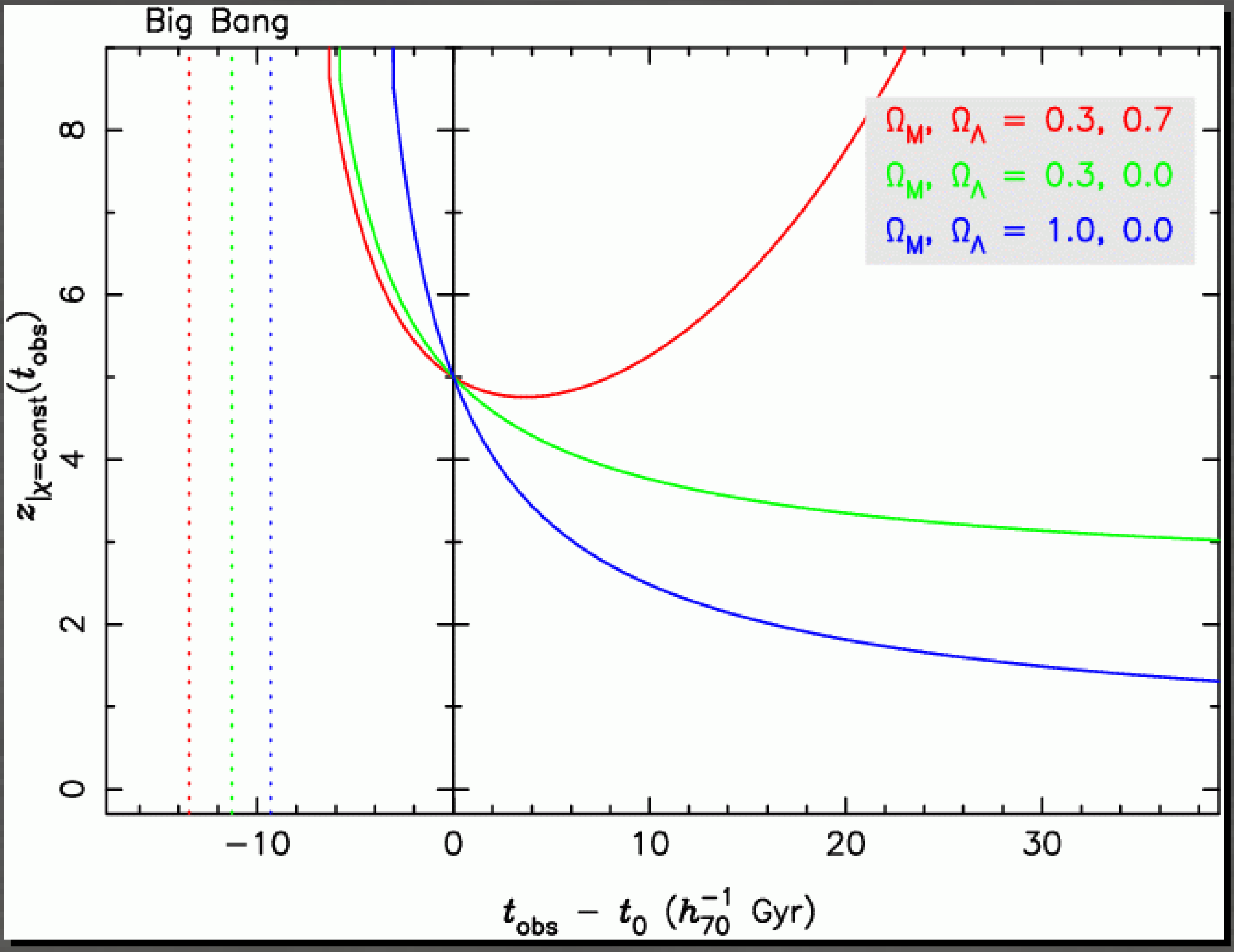


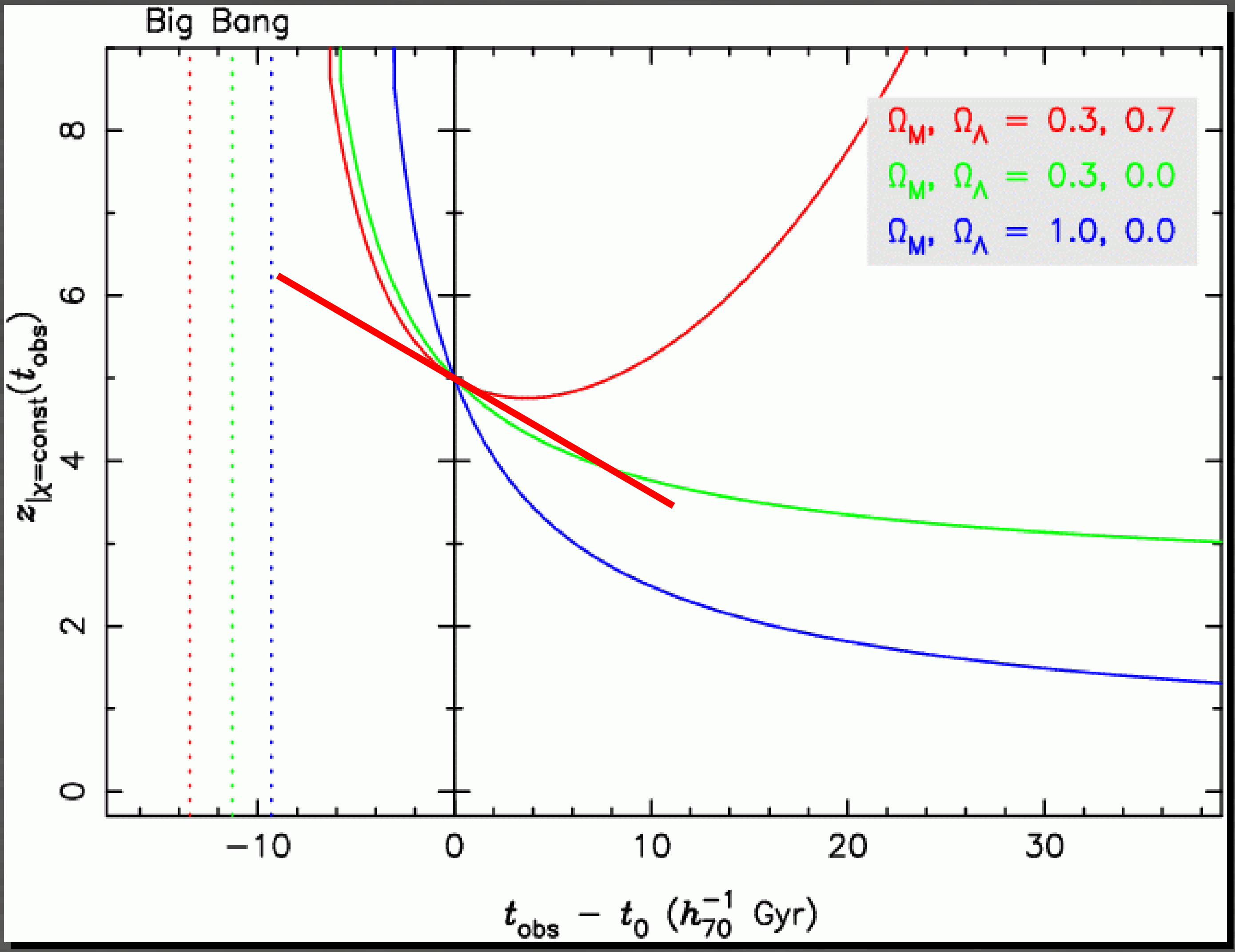
Evolving redshifts

To use $z(t_{obs})$ to reconstruct the expansion history we need to observe for Gyrs!

Alternative: measure

$$\frac{dz}{dt_{obs}}$$

dz/dt = change of redshift as a fuction of time.



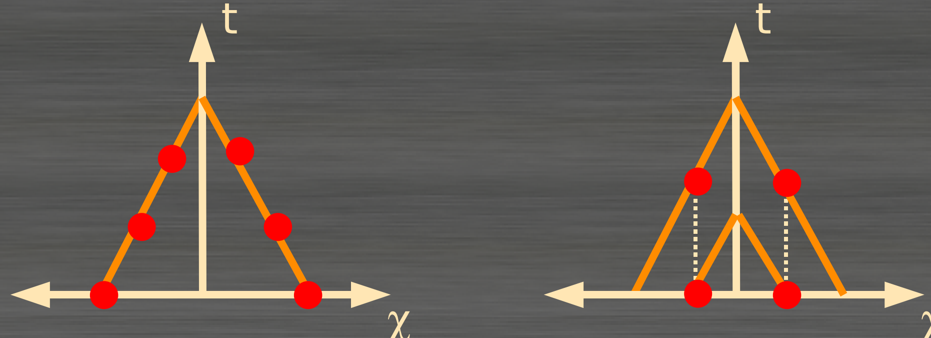
Redshift Drift

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:

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

Two remarkable features:

- For this equation to be valid you only need:
  - gravity can be described by a metric theory
  - homogeneity and isotropy
- The redshift drift does not deduce the evolution of the expansion by mapping out our present-day past light-cone but directly measures the evolution by comparing our past light-cones at different times.



Direct Dynamical Measurement of the Expansion History

It is possible to obtain a **direct, model-independent, purely dynamical** measurement of the expansion history by simply monitoring the redshifts of cosmological sources. The change of these redshifts as a function of time is a direct signal of the de/acceleration of the universe's expansion and hence of its dynamics.

Sandage (1962):
“It should be possible to choose between various models of the expanding universe if the deceleration of a given galaxy could be measured.“

Since then:
McVittie (1965), Weinberg (1972), Ebert & Trümper (1975), Davis & May (1978), Rüdiger (1980), Lake (1981), Rüdiger (1982), Phillipps (1982), Lake (1982), Partovi & Mashhoon (1984), Teuber (1986), Loeb (1998), Peacock (1999), Nakamura & Chiba (1999), Gudmundsson & Björnsson (2002), Freedman (2002), Zhu & Fujimoto (2004), Davis & Lineweaver (2004), Seto & Cooray (2006), Corasaniti et al. (2007), Lake (2007), Uzan et al. (2007), Balbi & Quercellini (2007), Zhang et al. (2007), Uzan et al. (2007), Liske et al. (2008)

Size of the signal

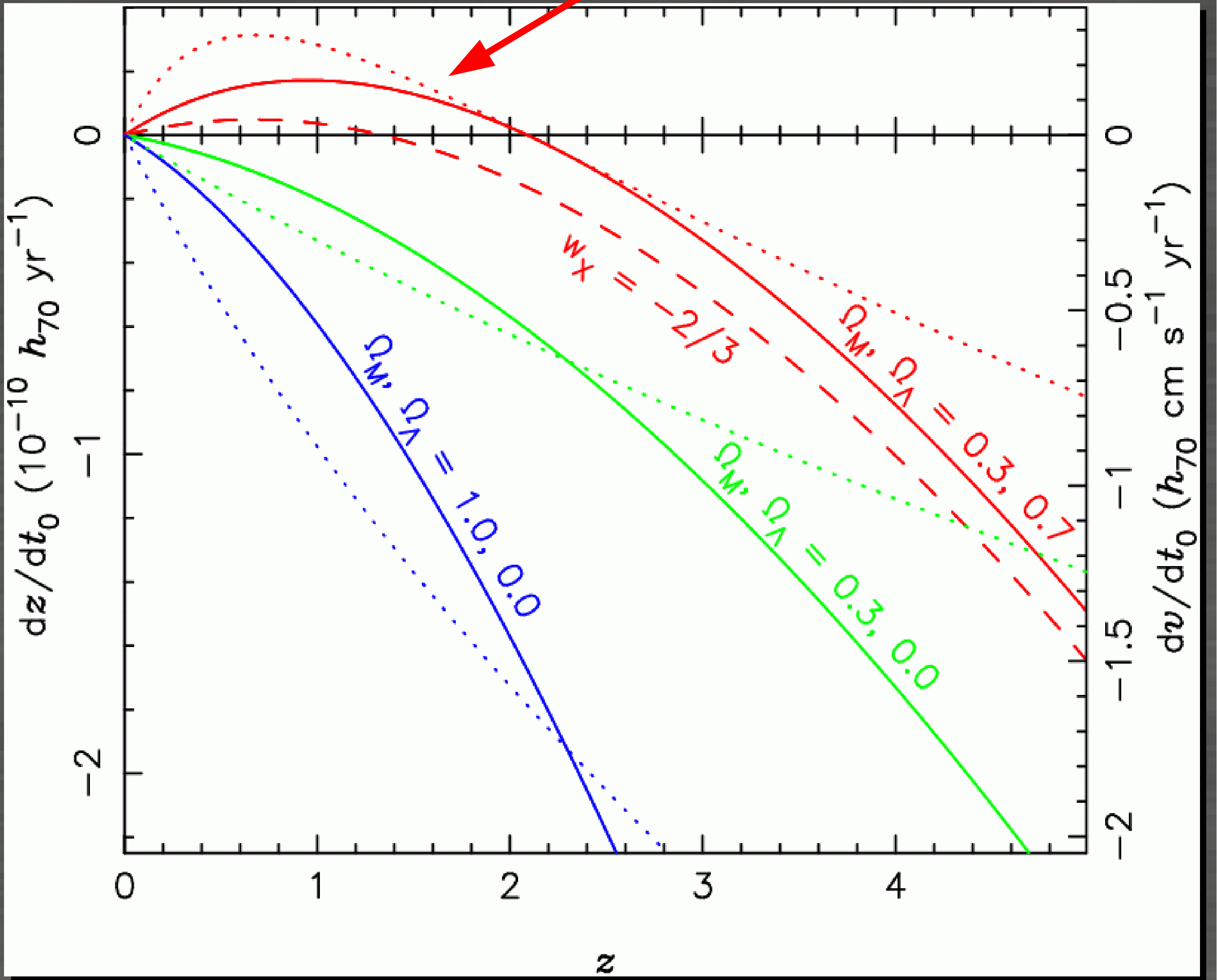
If Δt = 10 years then:

- $\Delta z \sim 10^{-9}$
- $\Delta\lambda = \lambda_{rest}\, \Delta z$
  $\sim 10^{-6}$ 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 ~1 m/s with ~10 cm/s accuracy over a few hours.

Signature of $\Lambda > 0$



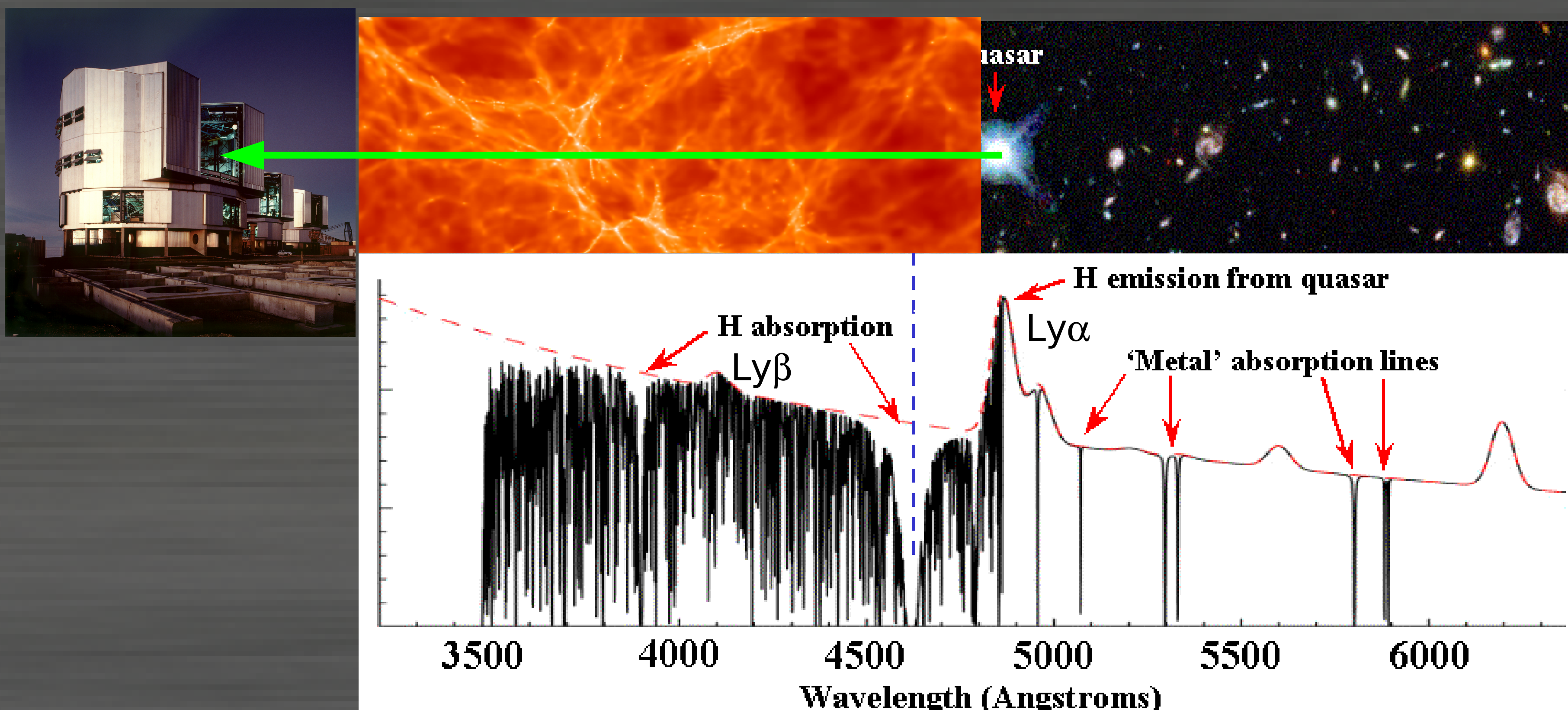
How can we measure the redshift drift?

The accuracy with which a velocity shift of a spectrum can be determined depends on:

- The number and sharpness of available spectral features.
- The S/N at which they are recorded, i.e.
  - the brightness of the source(s),
  - the size of the telescope,
  - the total system efficiency,
  - the exposure time.

Measuring dz/dt in the IGM

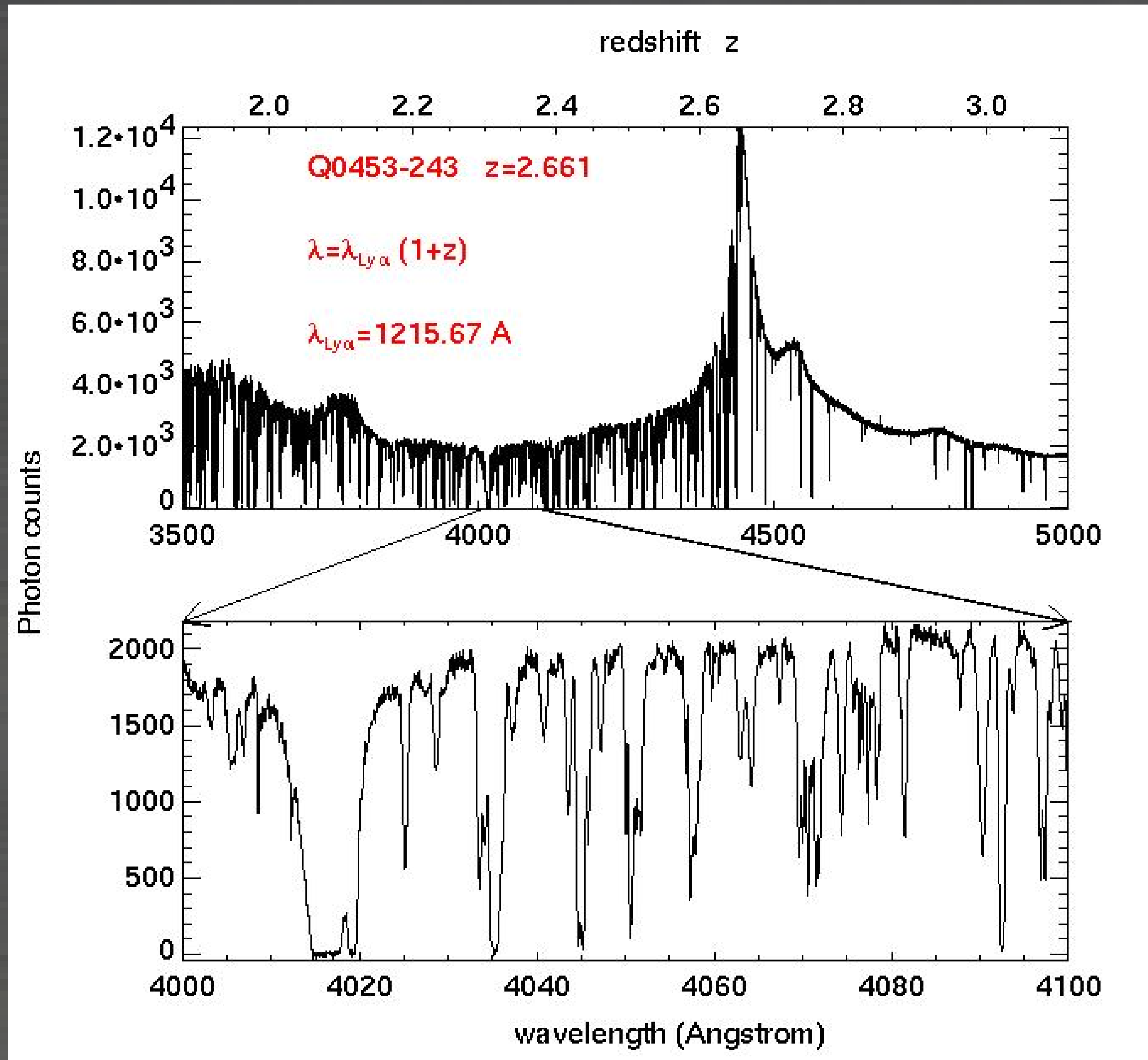
First proposed by Loeb (1998).



by John Webb

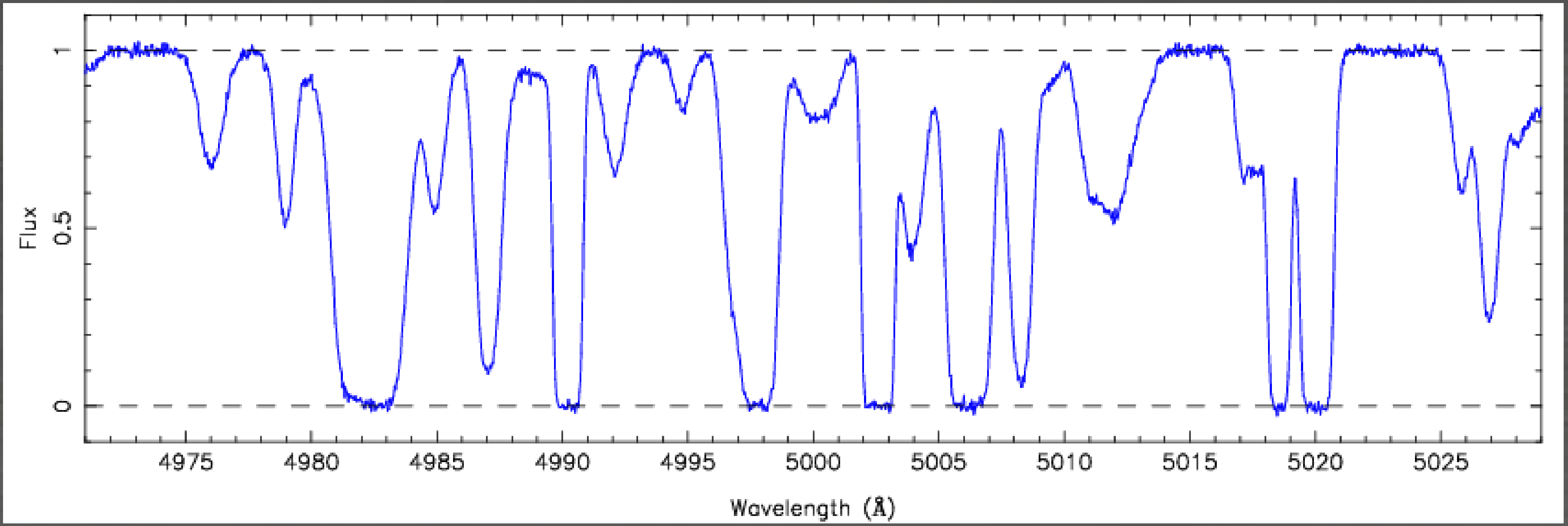
The Lyman α Forest

- ✔ 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).



Observing dz/dt in the Lyα Forest

Simulation of the Lyα forest at z ~ 3:



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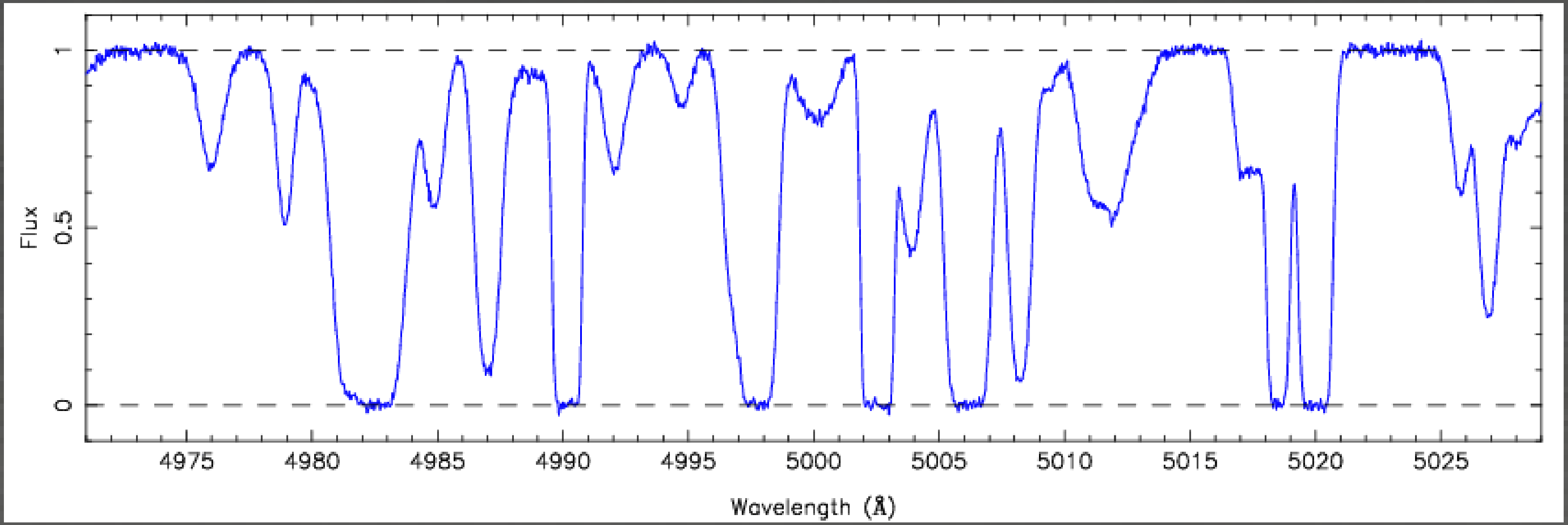

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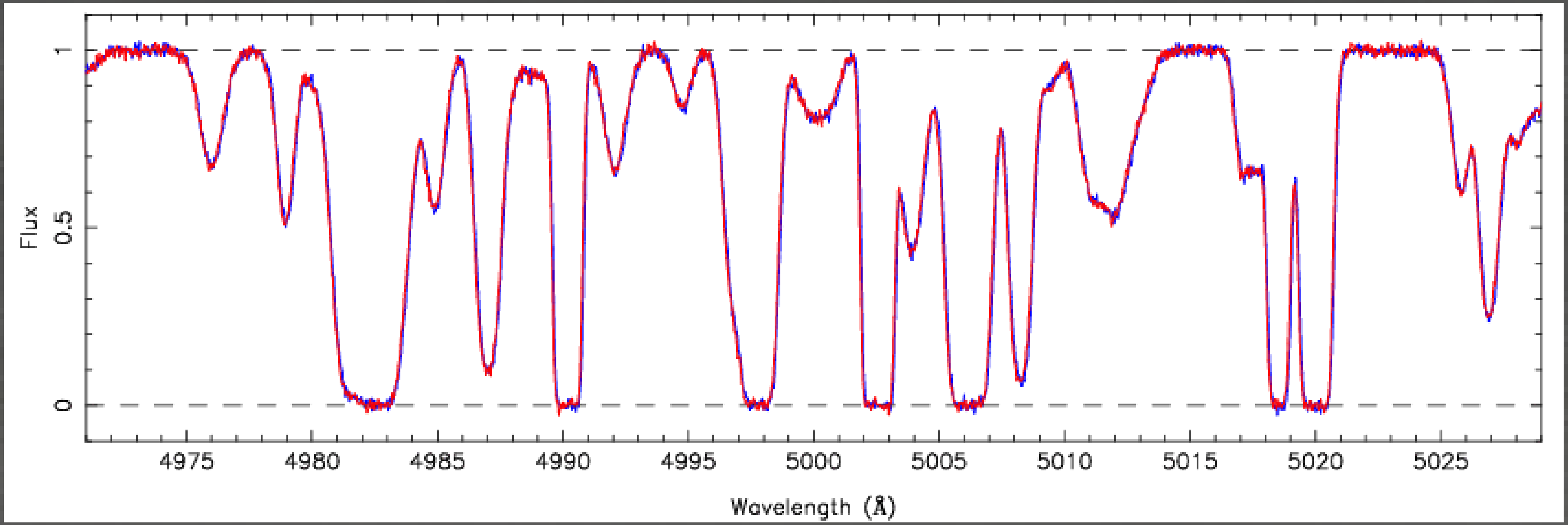
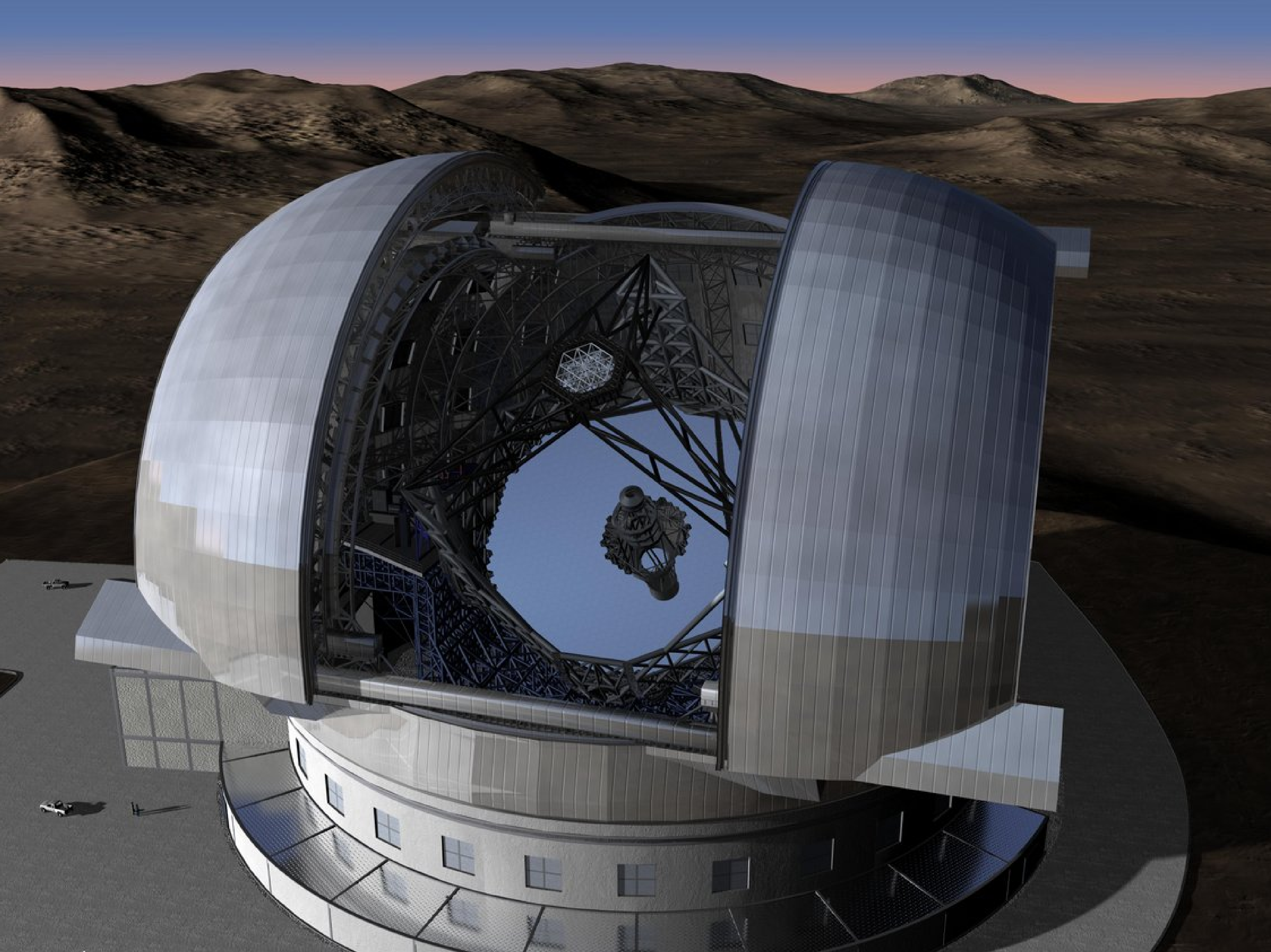
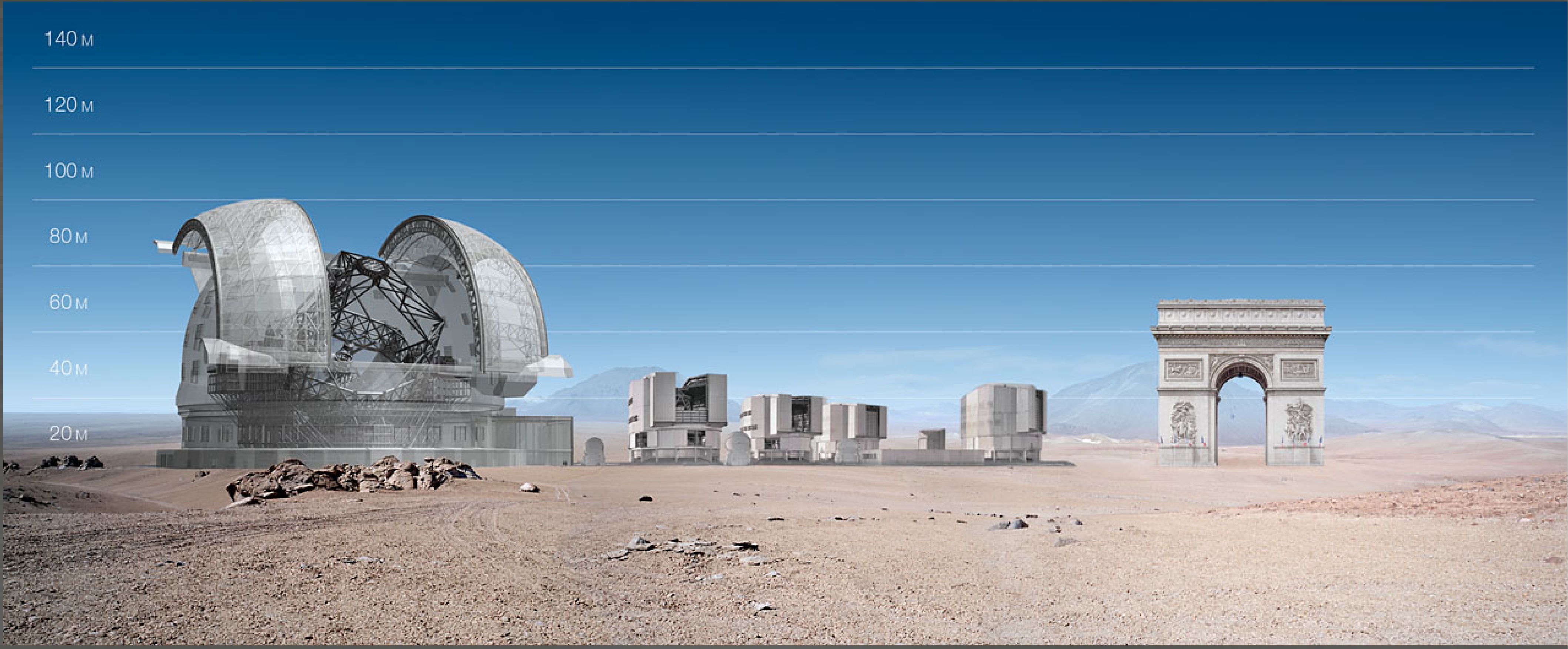


$\Delta t = 10^6$ years!



The European Extremely Large Telescope: The World's Biggest Eye on the Sky

- World's largest optical-infrared telescope: 42 m segmented primary mirror
- Adaptive optics built in
- Diffraction-limited performance
- 10 arcmin field of view
- Site: Cerro Armazones (near the VLT)



Are there enough photons in the sky?

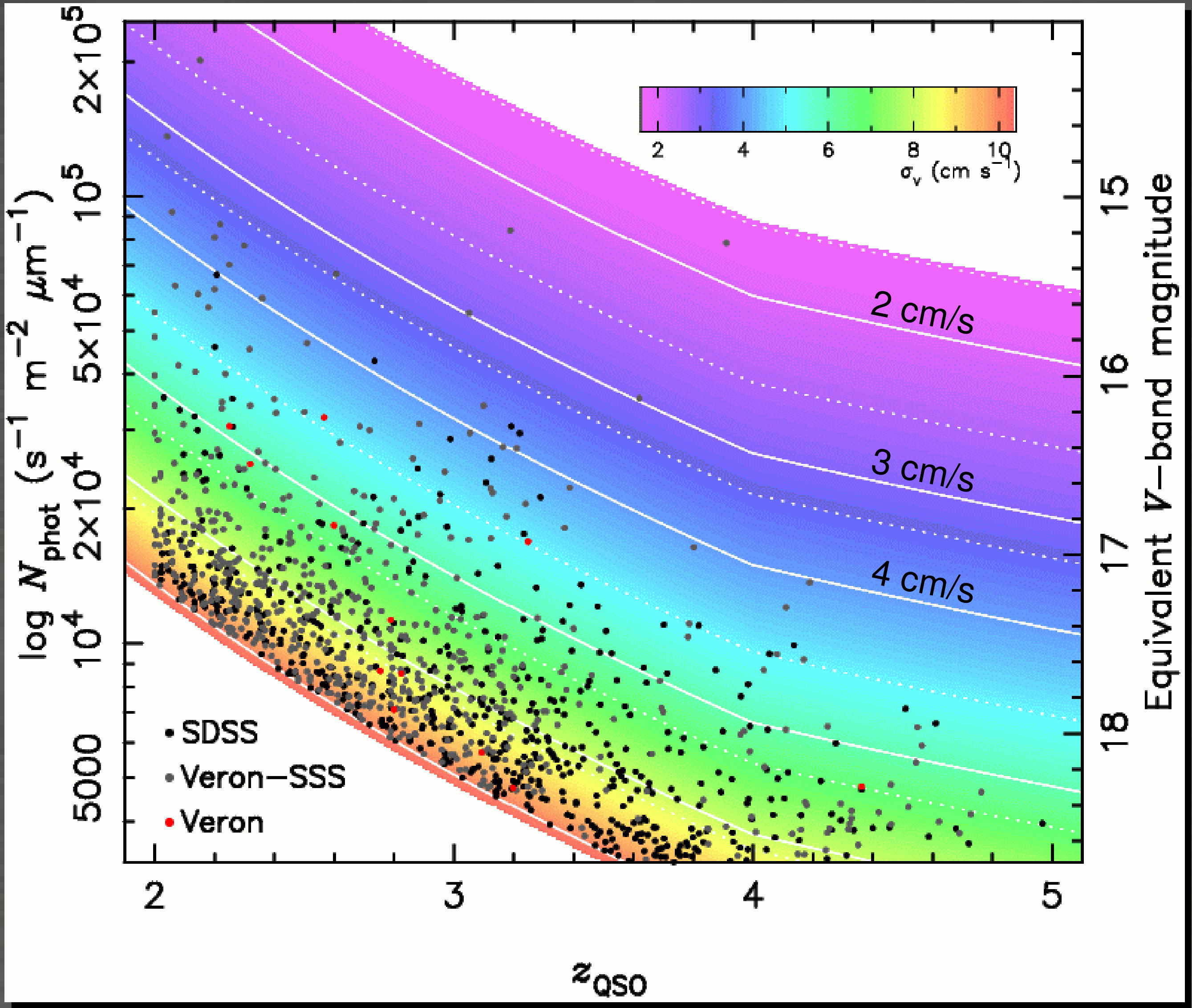
Can we collect enough photons to achieve the required radial velocity accuracy?

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.

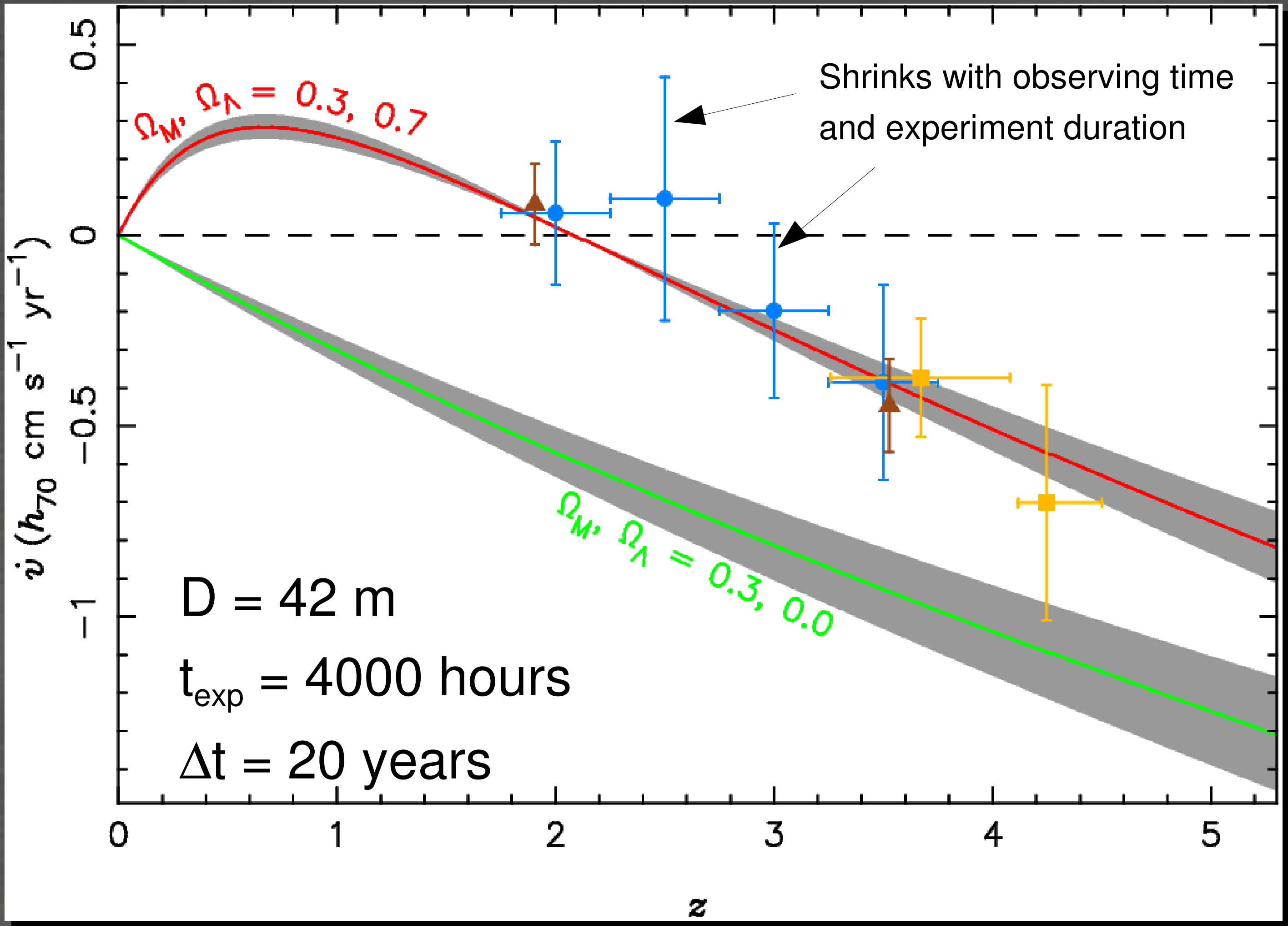


Liske et al. (2008)

Simulation Results

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

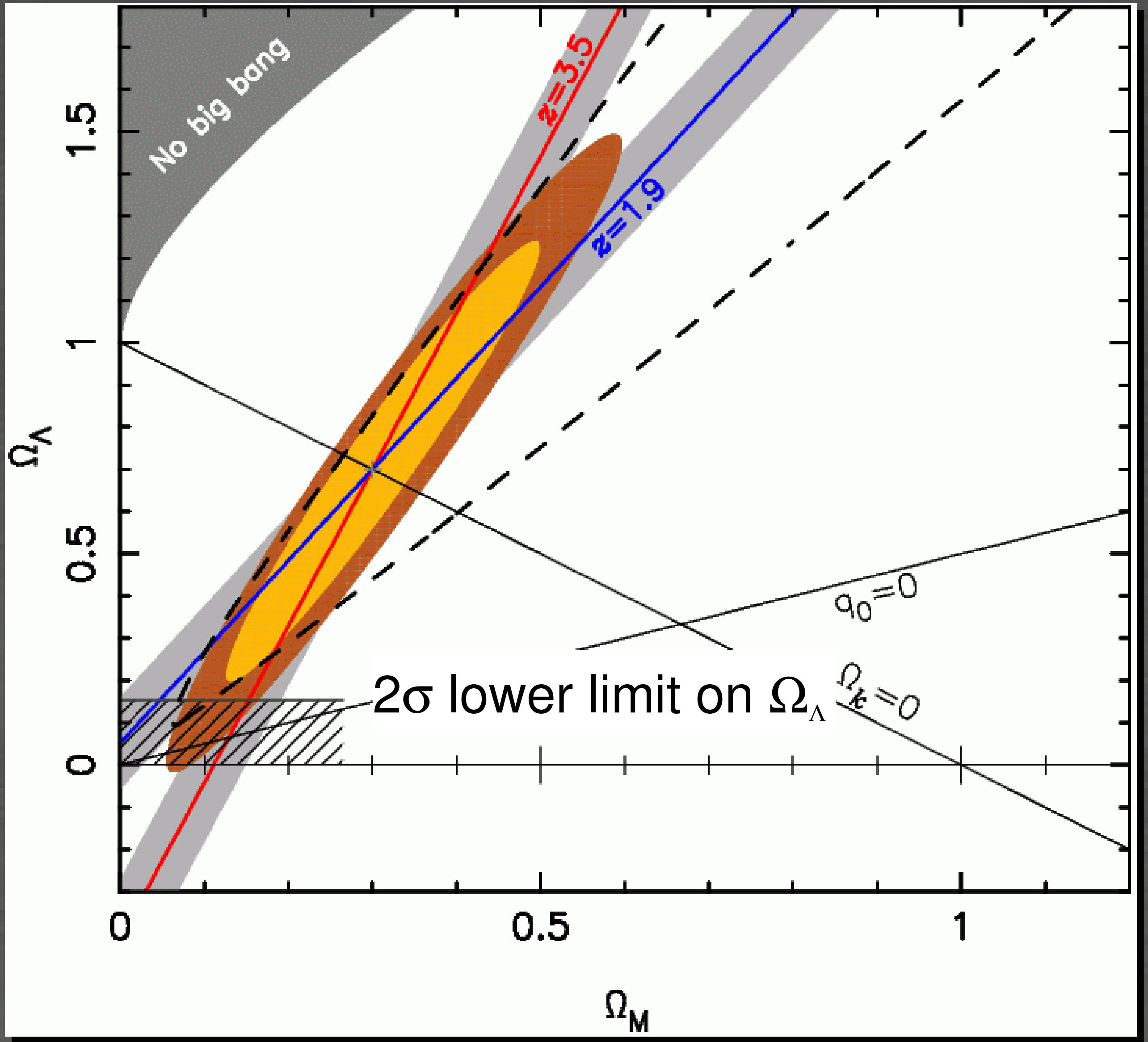
Different sets correspond to different target selection strategies.



Liske et al. (2008)

Constraints on Cosmology

- 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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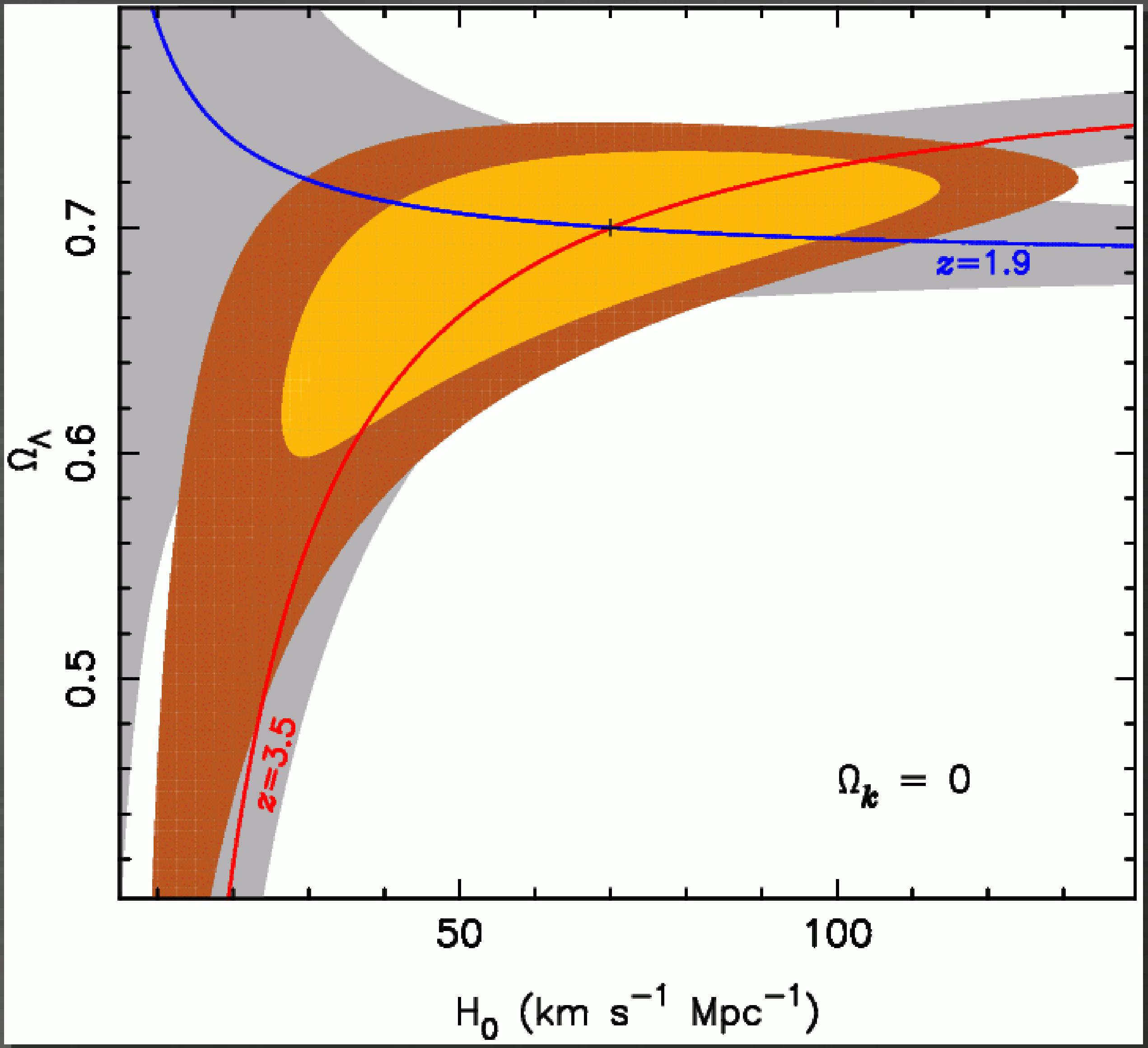

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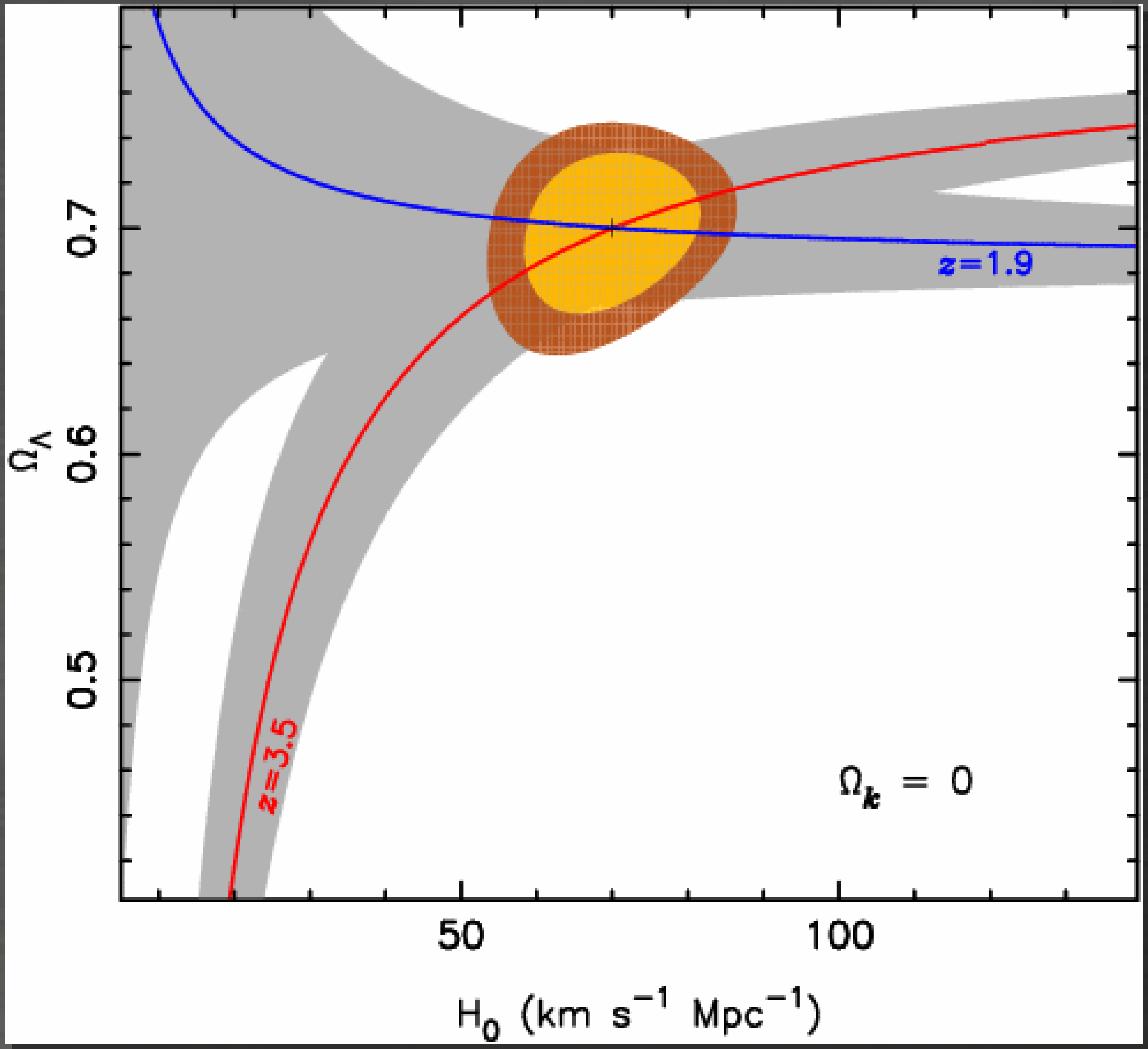
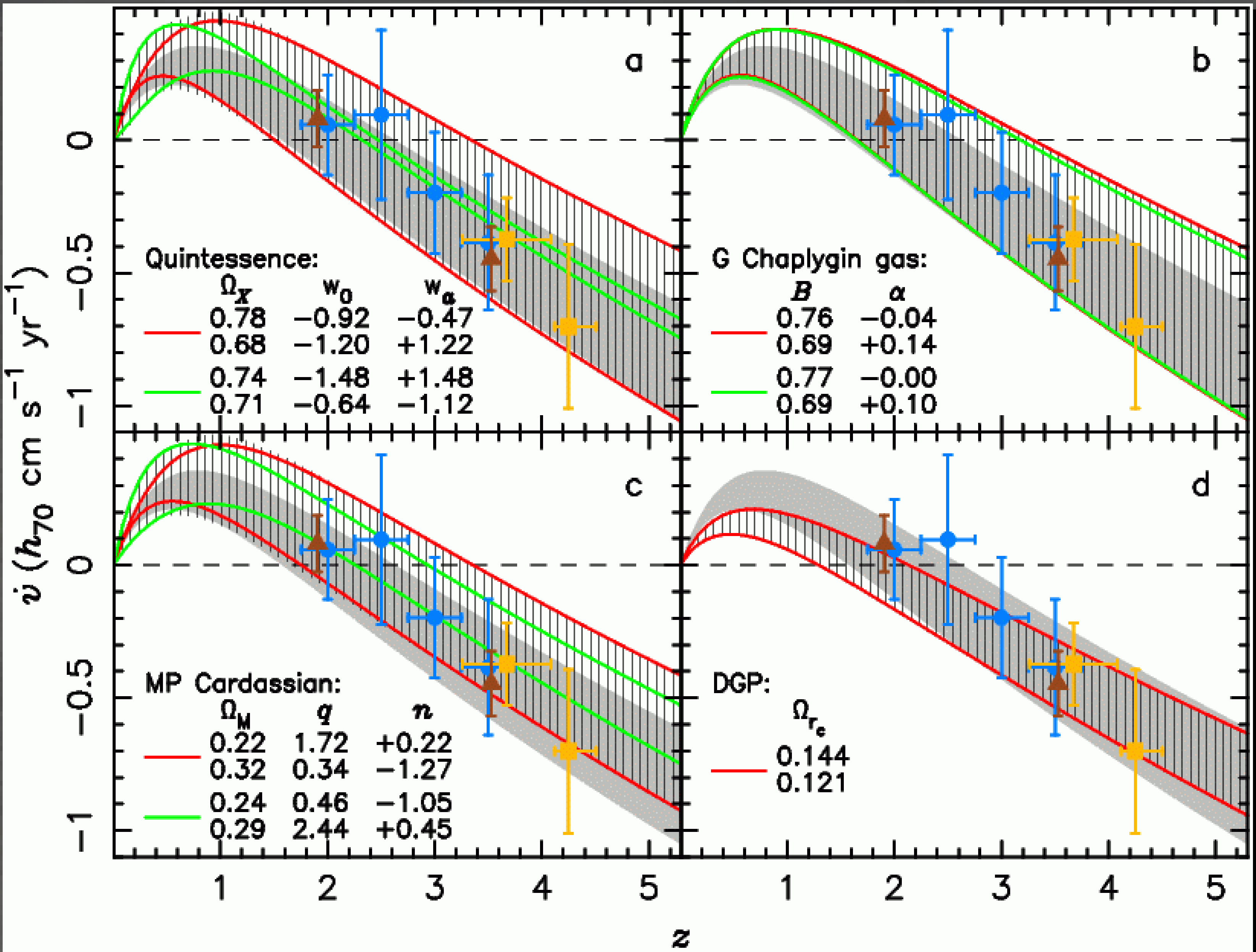


Liske et al. (2008)

Constraints on non-standard models

Assuming flatness and a fixed H_0 the hashed regions show the allowed dz/dt ranges after the models have been constrained by SNIa, CMB and BAO data (Davis et al. 2007).



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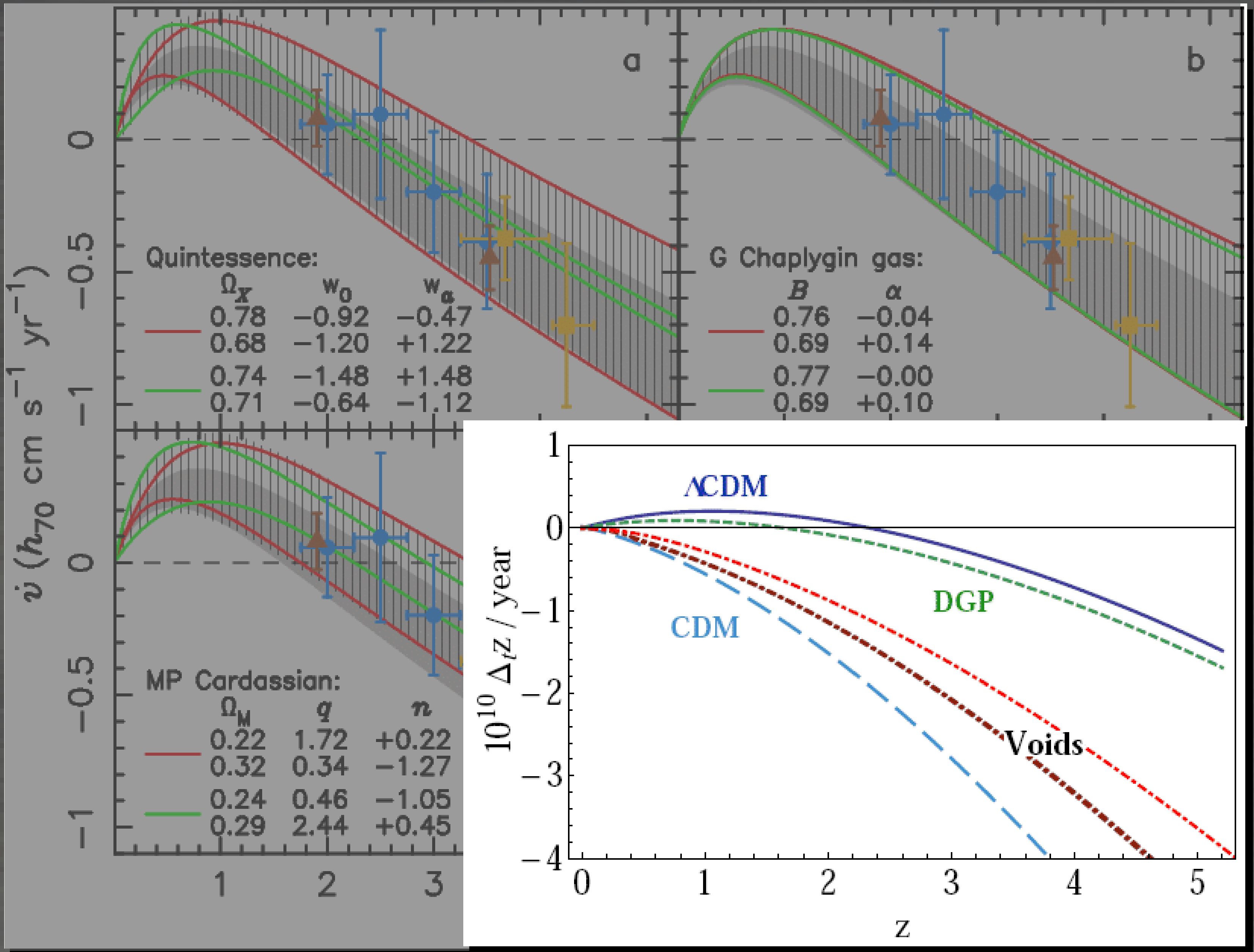


Quartin & Amendola (2009)

Summary

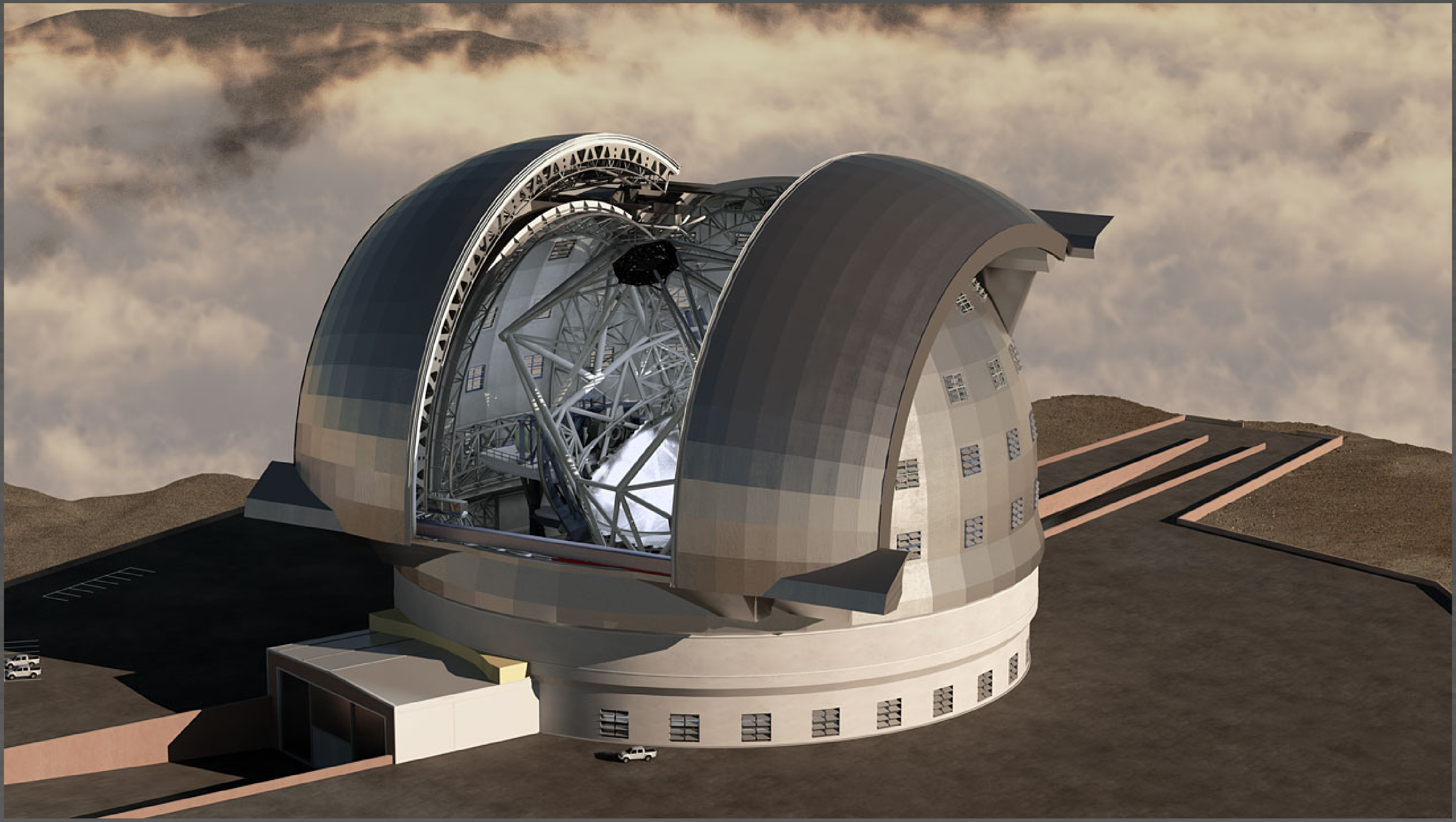
- The acceleration of the universal expansion is one of the most fundamental problems in cosmology and even all of physics.
- The evolution of the redshift of cosmological sources as a function of time is a direct, dynamical signal of the de/acceleration of the universe's expansion.
- E-ELT will offer us the first opportunity to measure the redshift drift (over a timescale of ~20 years), resulting in a unique measurement of the expansion history:
  - 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.
  - Requires no priors and is independent of other cosmological experiments.
  - Independent confirmation and quantification of accelerated expansion.
  - H(z) determination in a cosmic epoch inaccessible to other methods.
  - Does not involve or rely on any astrophysics (such as the [unknown] evolution of the sources used).
  - Extraordinary legacy value!.

E-ELT

=

Extremely-Exciting Long Term

science



4000 h is an impressive time request for any telescope. However:

- The total time is distributable

  4000 h / 20 yr = 20 nights per year

- Comparable to past investment

  VLT/UVES and Keck/HIRES have each invested ~100 nights on QSO spectroscopy.

- Synergy with other ELTs

  Assuming appropriate instrumentation, data from all ELTs could be combined.

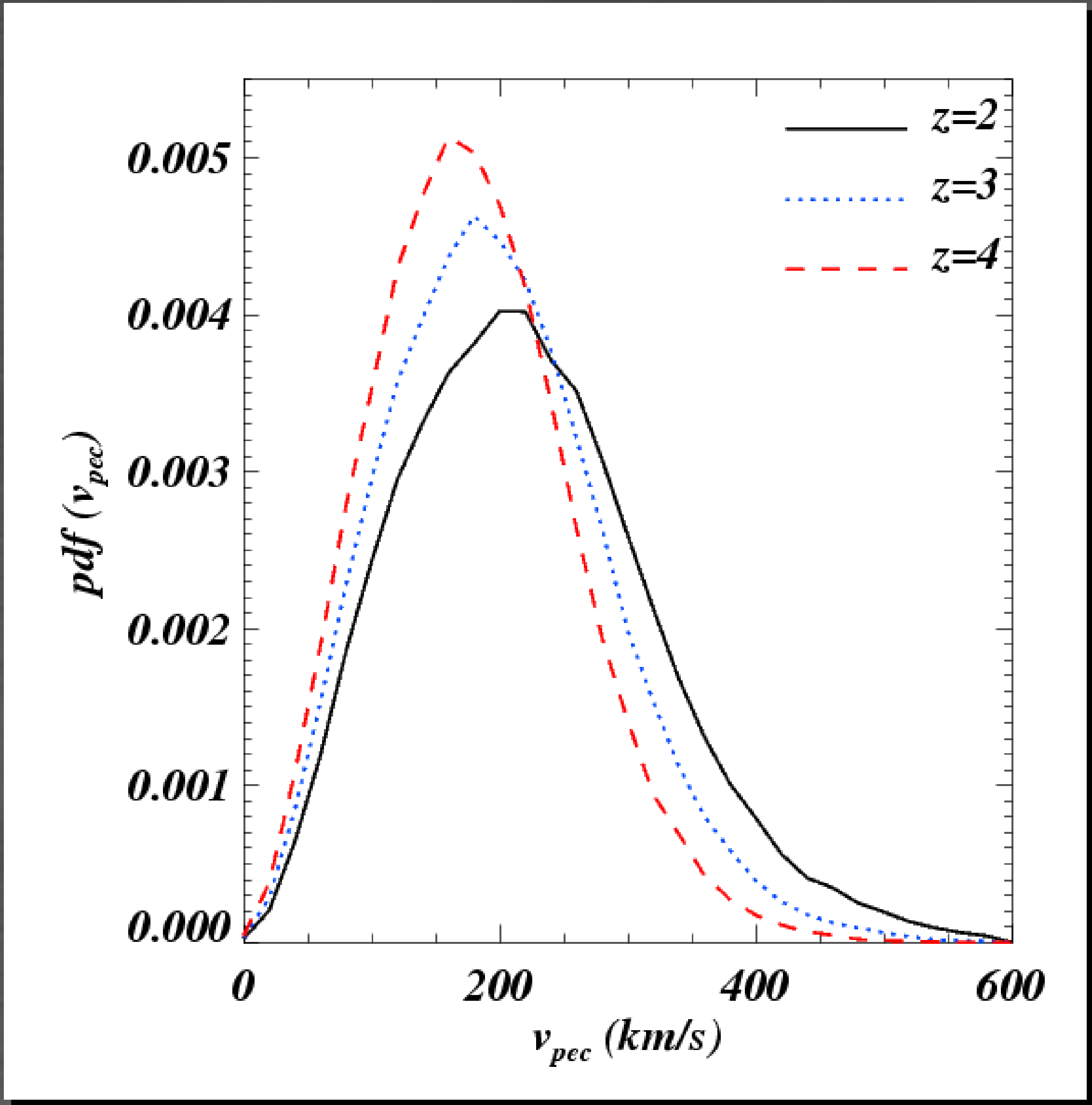
- Immediate science with the same data
  - Cosmological variation of fundamental constants
  - Metallicity evolution of the low-density IGM
  - Tomography of the IGM
  - Power spectrum of Lyα forest
  - Primordial deuterium abundance

See conference on *Precision Spectroscopy in Astrophysics,* Aveiro, Sep 2006

The Lyman α Forest

? How well does the Lyα forest trace the Hubble flow? Investigate this issue using hydrodynamical simulations:

GADGET-2, 400^3 DM and gas particles (B2 of Viel, Haehnelt & Springel 2004), extract physical v_{pec} and a_{pec} along 1000 random LOS.



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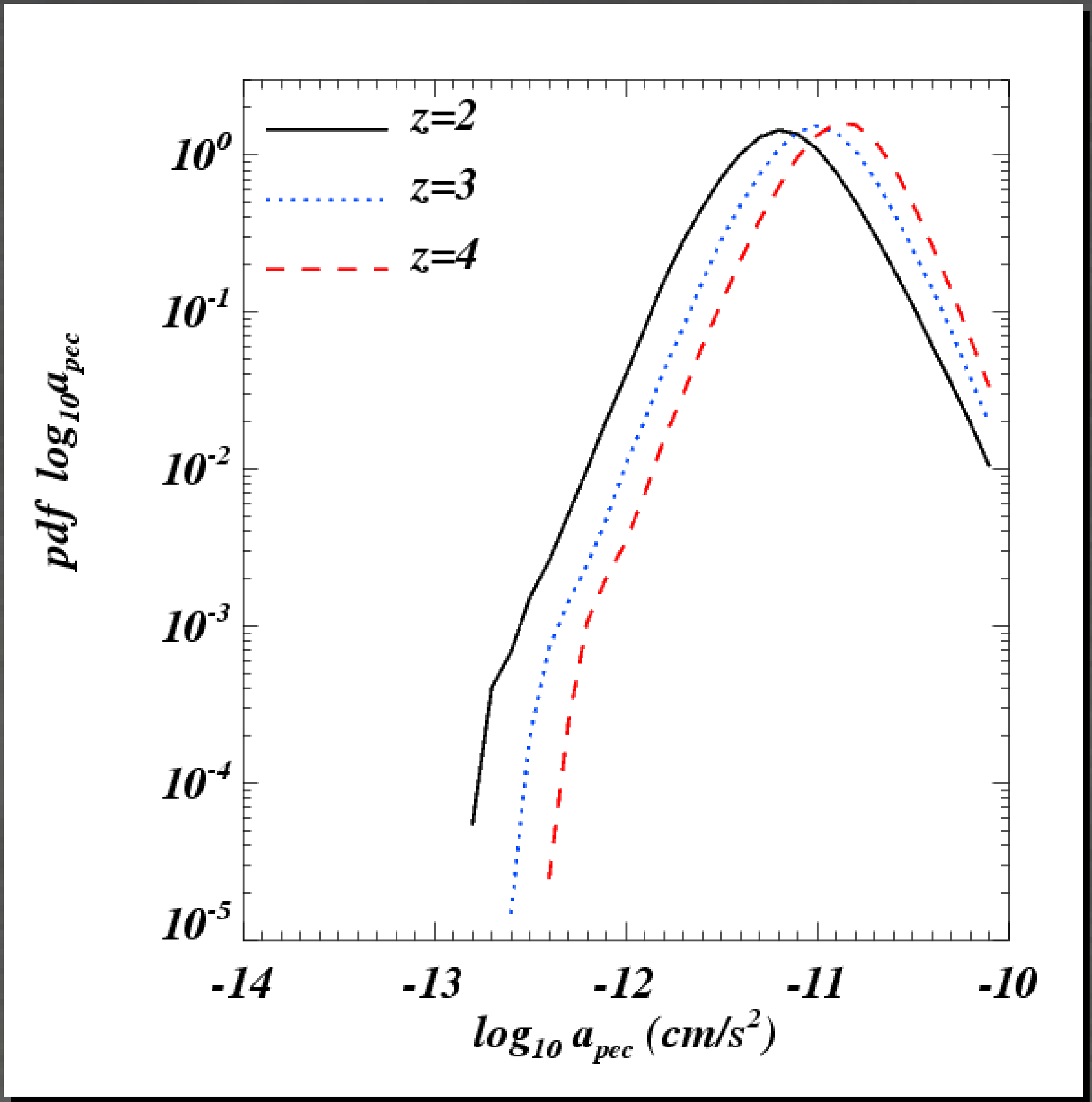
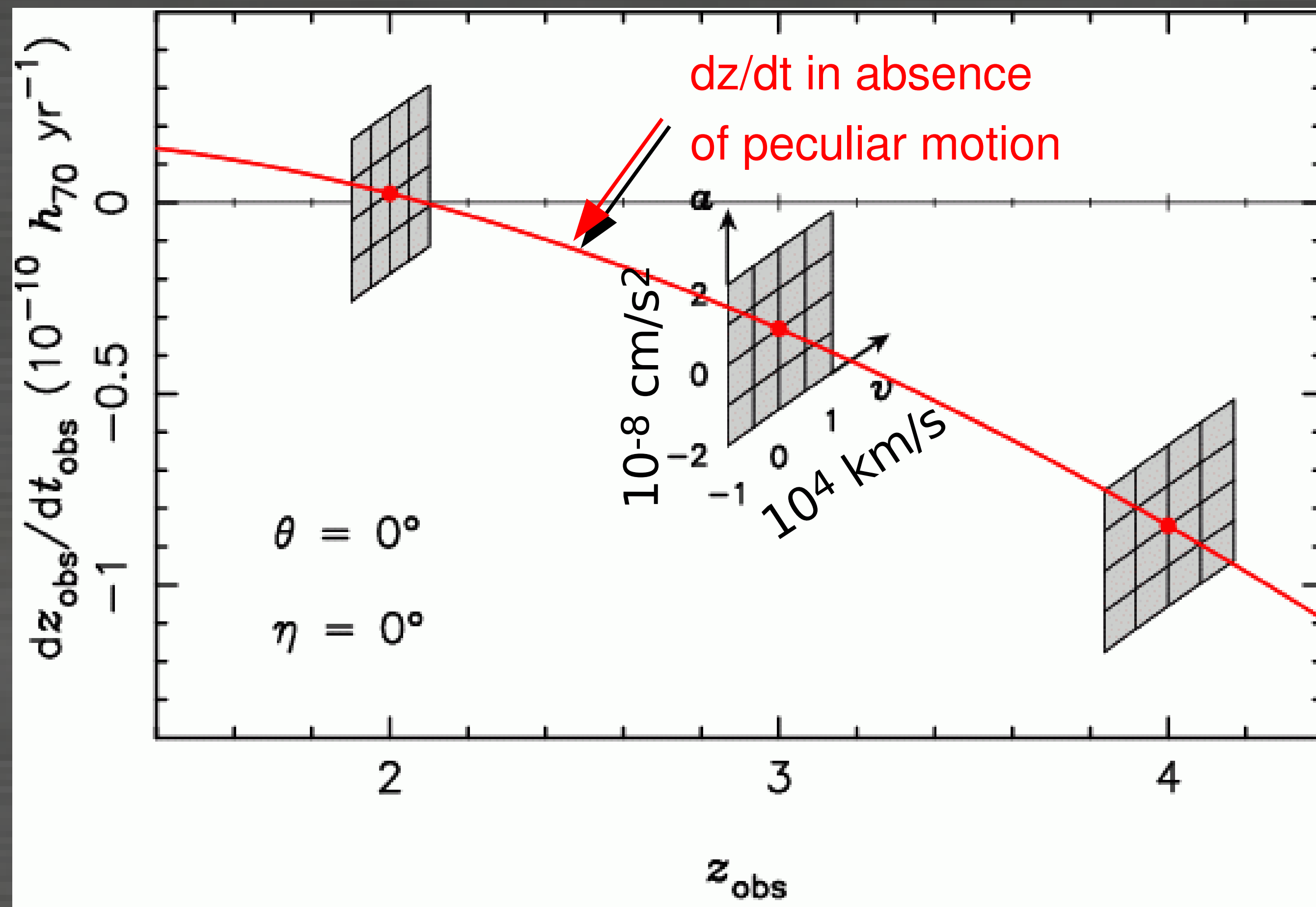


Effect of peculiar motion

- The effect of peculiar motion should be compared to the size of the error on an *individual* $\dot{z}$ measurement.

- Peculiar motion is only problematic when using a small number of high-precision measurements.

- No problem when using QSO absorption lines, even if the absorbing gas lies in a deep potential well.



→ The Lyα forest traces the Hubble flow!

Earth's peculiar motion

Correction from observed to barycentric redshift:

$$1+z_b = (1+z)\left(1 - \frac{\Phi_{obs}}{c^2} - \frac{\vec{v}_{obs}^{\,2}}{2c^2}\right)\left(1 + \frac{\vec{k}\cdot\vec{v}_{obs}}{c}\right)$$

Parameter	Induced error on correction in cm/s	
Earth orbital velocity		
• Solar system ephemerides	< 0.1	
Earth rotation		
• Geoid shape	~ 0.5	
• Observatory coordinates	< 0.1	
• Observatory altitude	< 0.1	
• Precession/nutation corrections	< 0.1	
Target coordinates		
• RA and Dec	< 1	70 mas → 1 cm/s
• Proper motion	0	
• Parallax	0	
Relativistic corrections		
• Local gravitational potential	< 0.1	
Timing		
• Flux-weighted time of observation	?	0.6 s → 1 cm/s
Correction to cosmological reference frame	~ 0.5	GAIA

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?

Answer from Monte Carlo simulations:

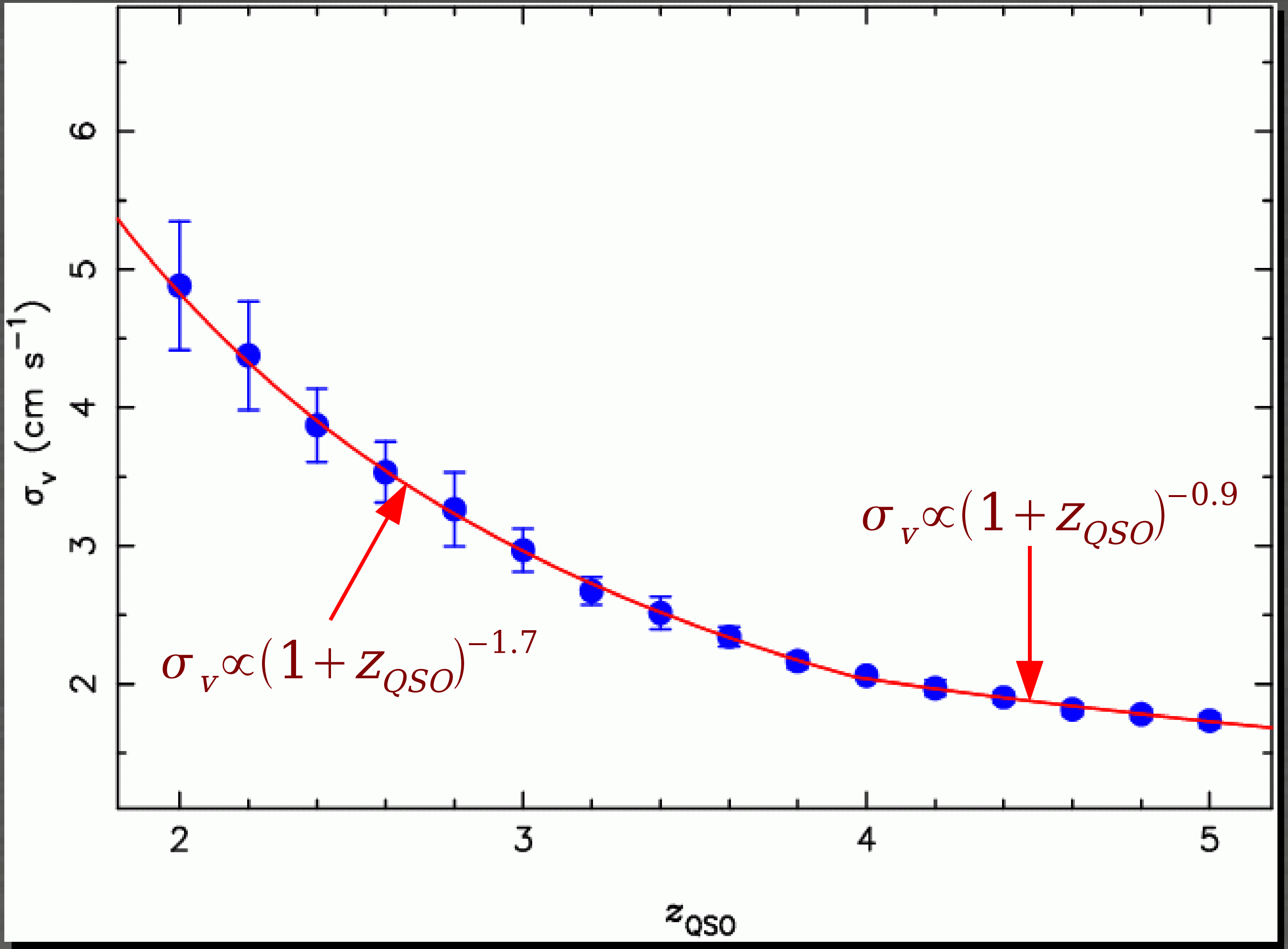
$$\sigma_v = 1.35 \left[\frac{S/N}{3350}\right]^{-1} \left[\frac{N_{QSO}}{30}\right]^{-\frac{1}{2}} \left[\frac{1+z_{QSO}}{5}\right]^{-1.7} g(N_e, f_{1\ldots N_e})\, cm/s$$

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.

Sensitivity to radial velocity shifts

What radial velocity accuracy can we achieve using the Lyα forest? How does the sensitivity depend on redshift?

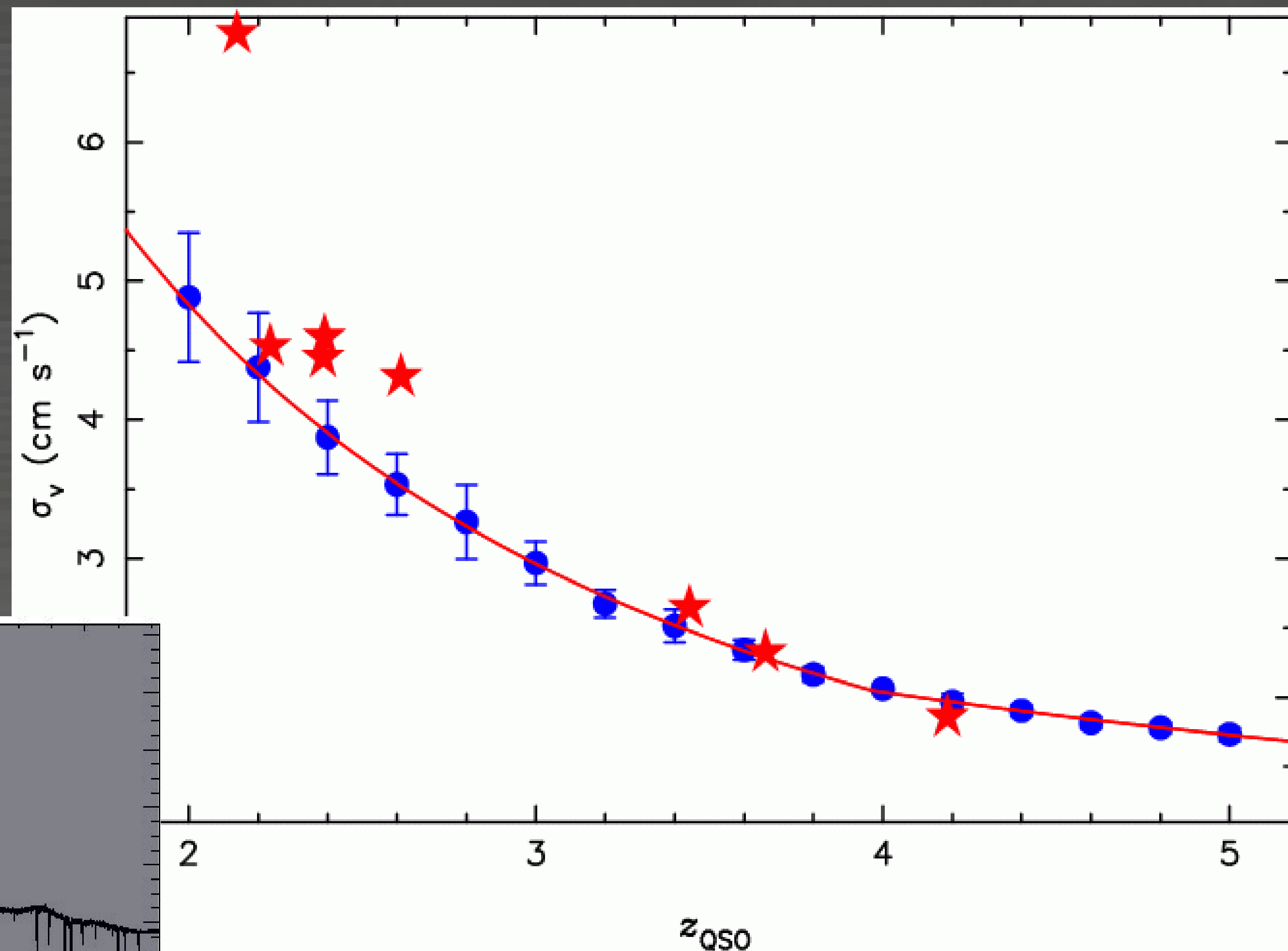
MC simulations: based on statistics of absorption line parameters.

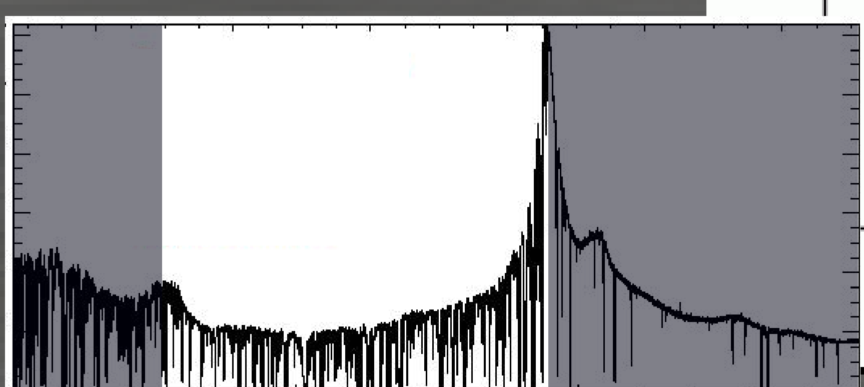


Sensitivity to radial velocity shifts

What radial velocity accuracy can we achieve using the Lyα forest? How does the sensitivity depend on redshift?

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





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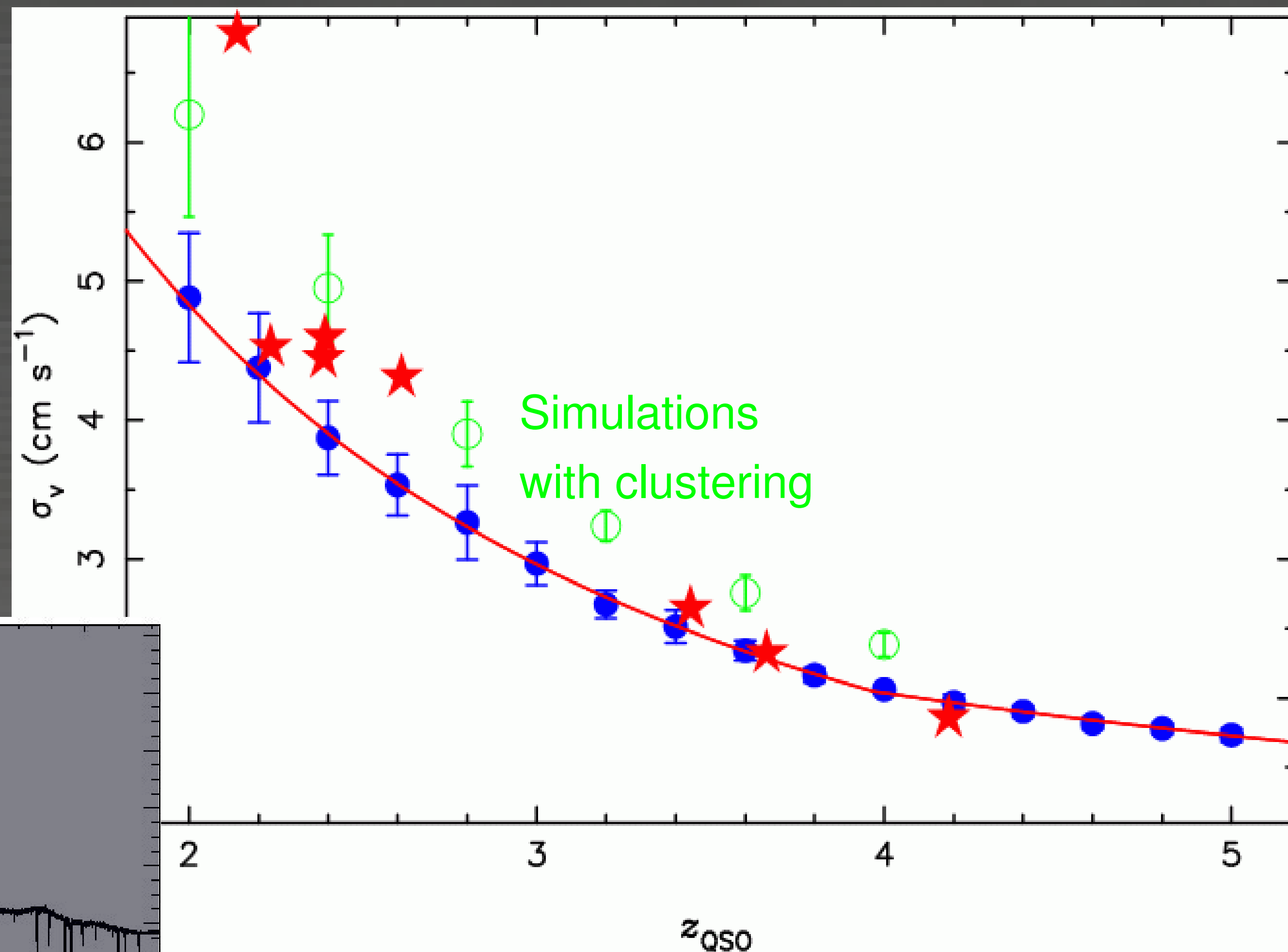

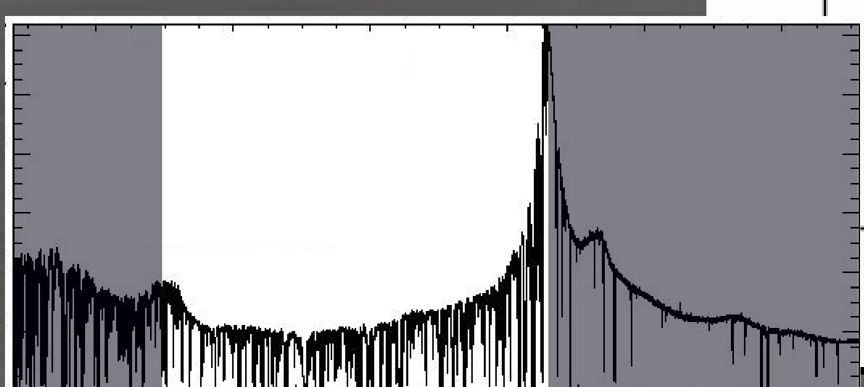

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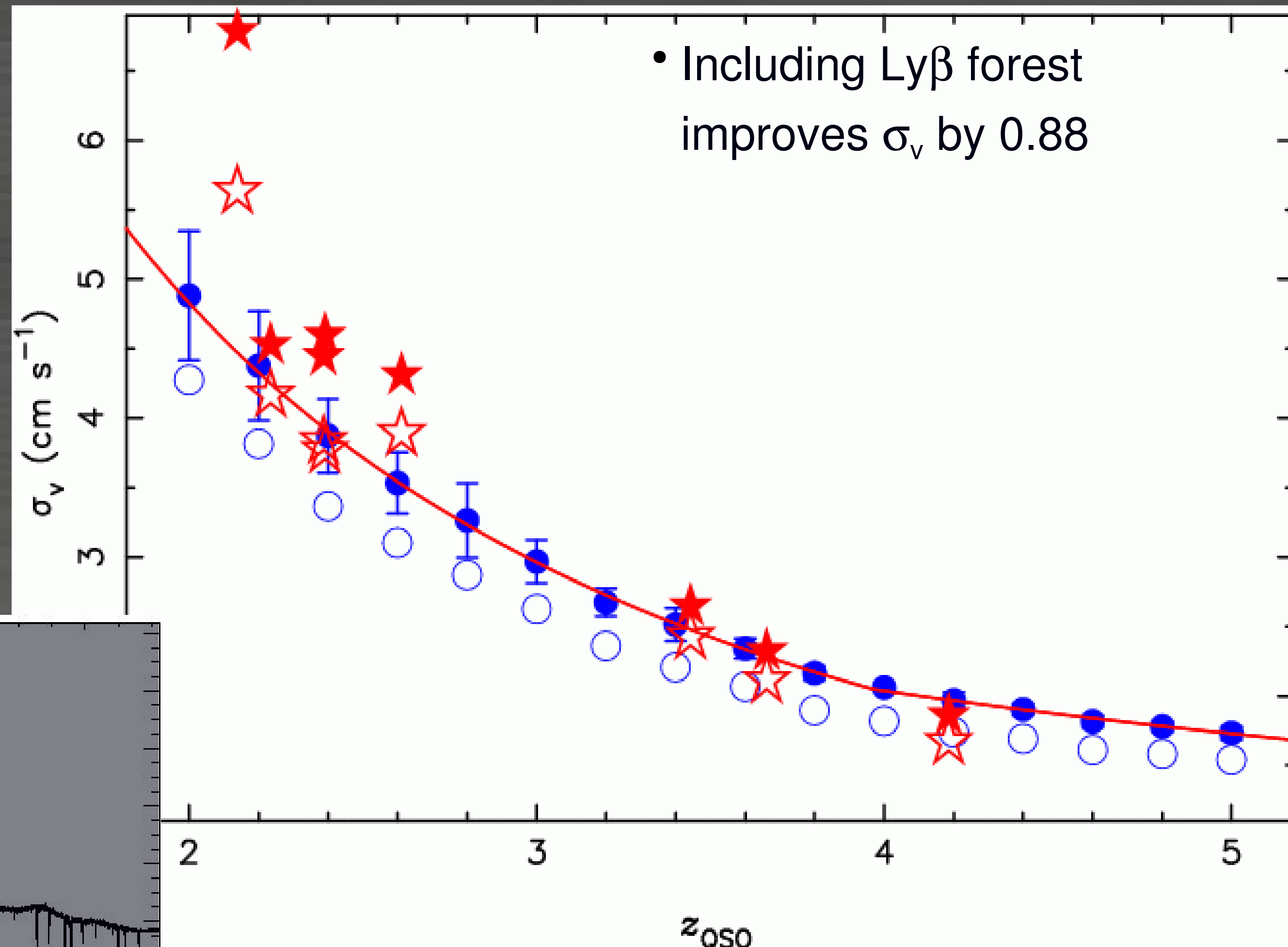

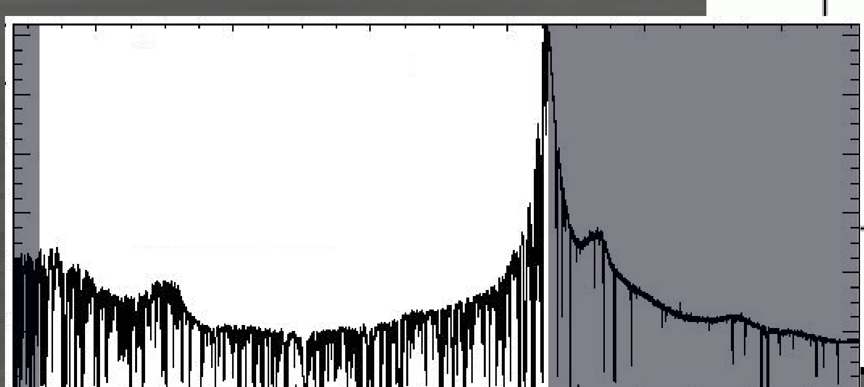

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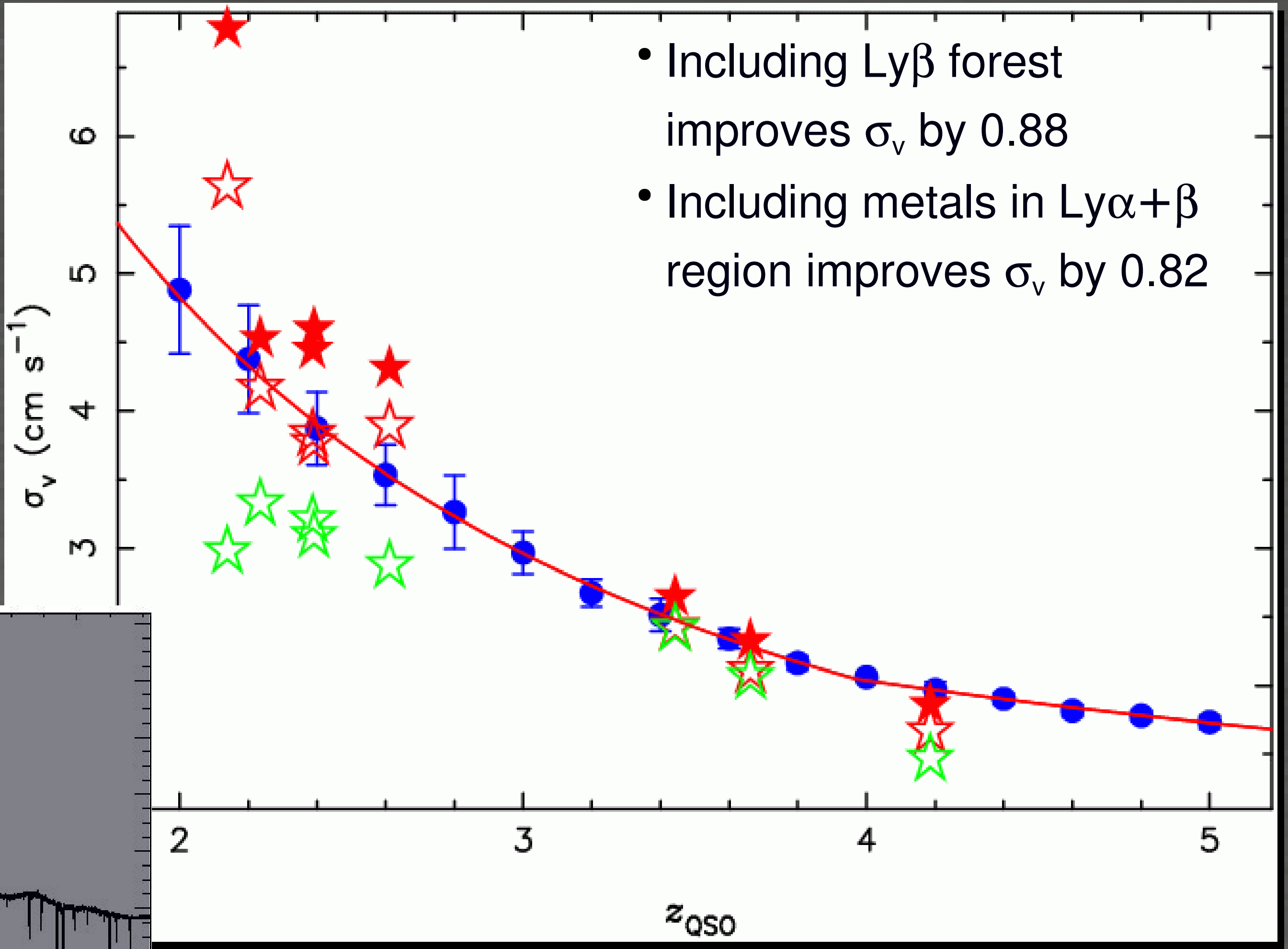

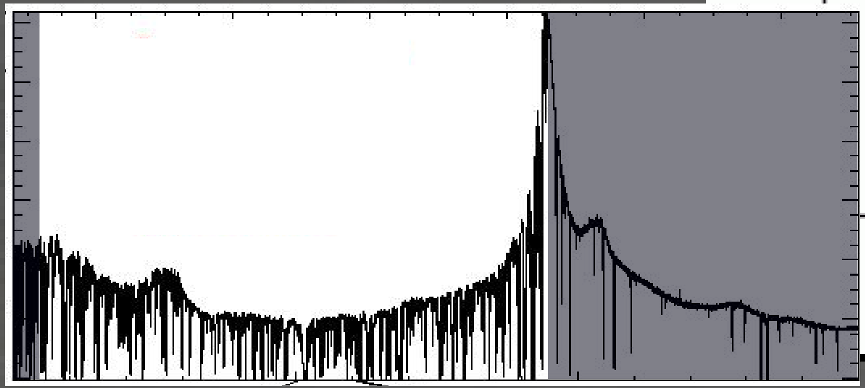

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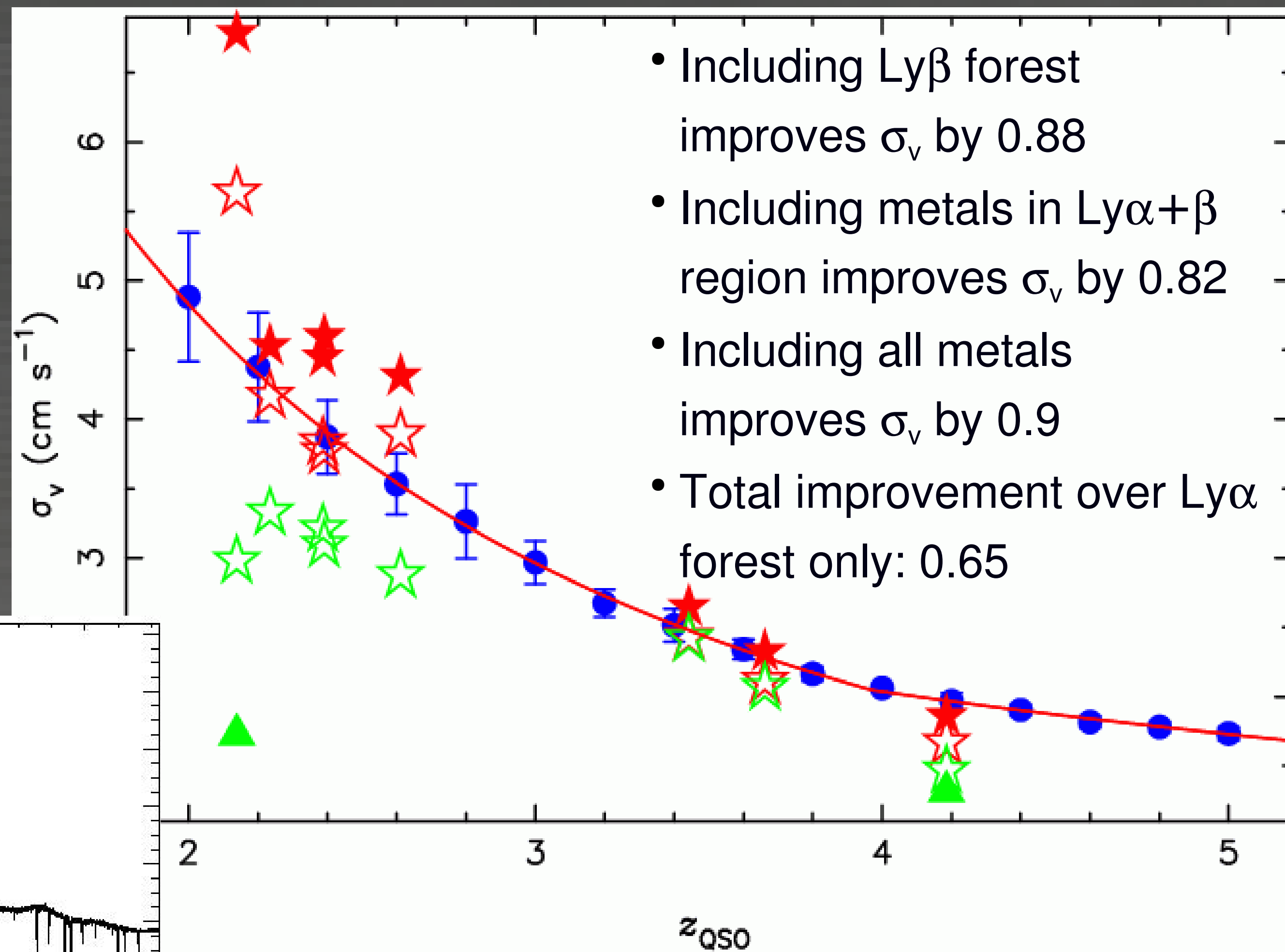
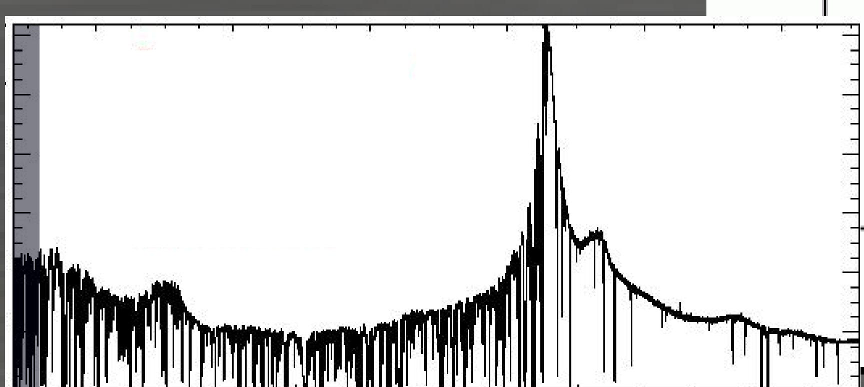


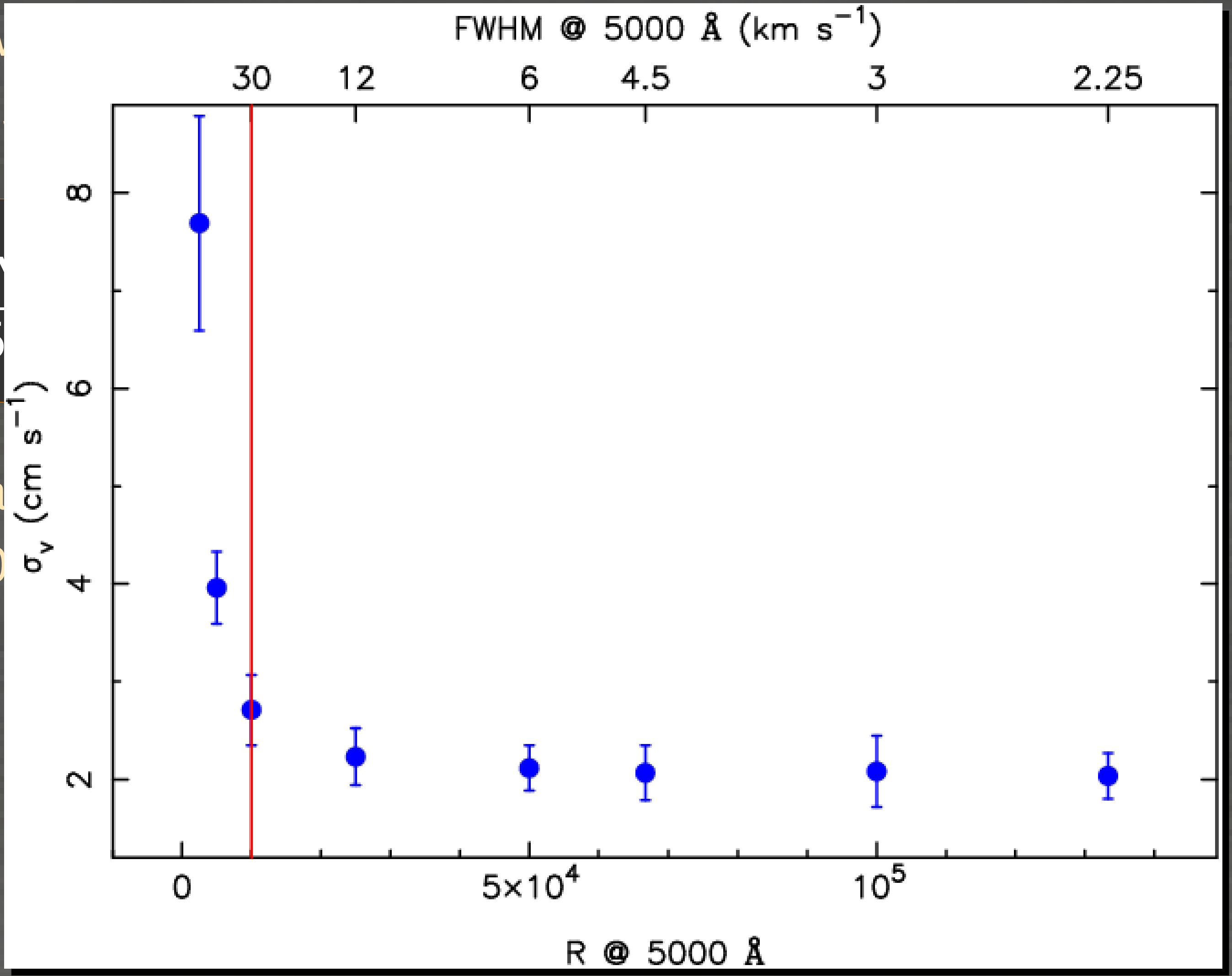


Scaling relation

Using the Lyα forest v
given S/N ? How doe

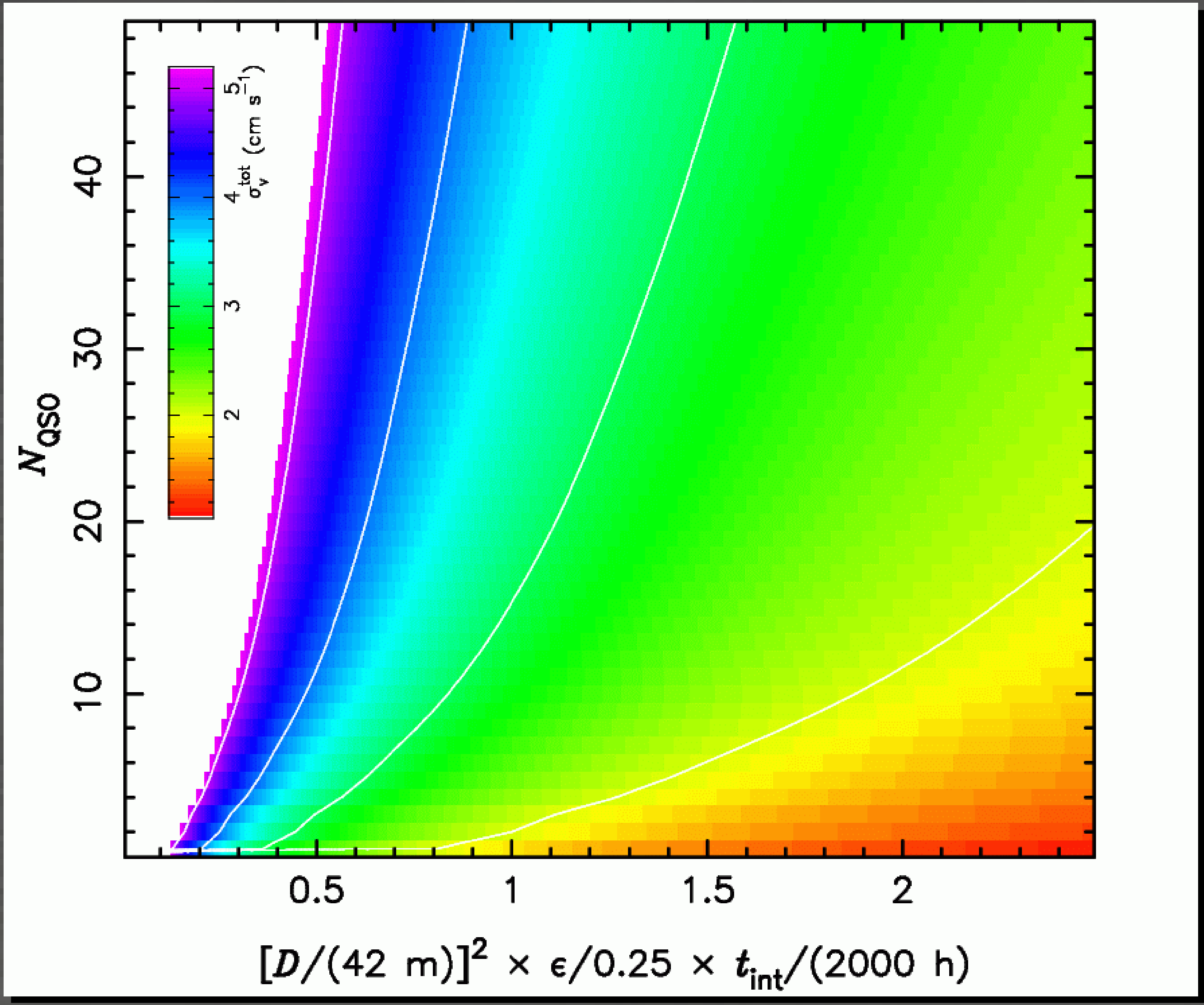
$$\sigma_v = 1.35 \left[\frac{S/N}{335} \right.$$

where S/N is the tota
element at R = 100 0
spectrum.



Are there enough photons in the sky?

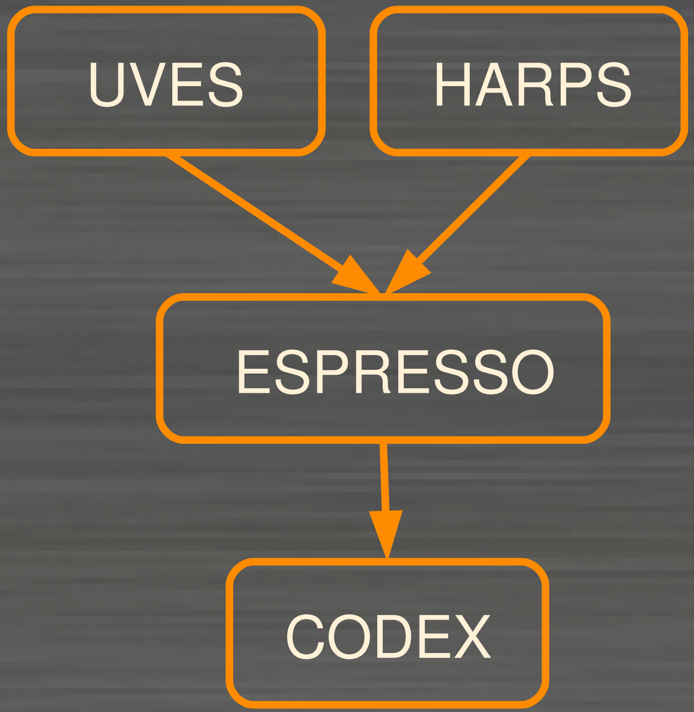
A total, overall radial velocity accuracy of 2-3 cm/s is well within reach of an ELT targeting 10-20 QSOs.



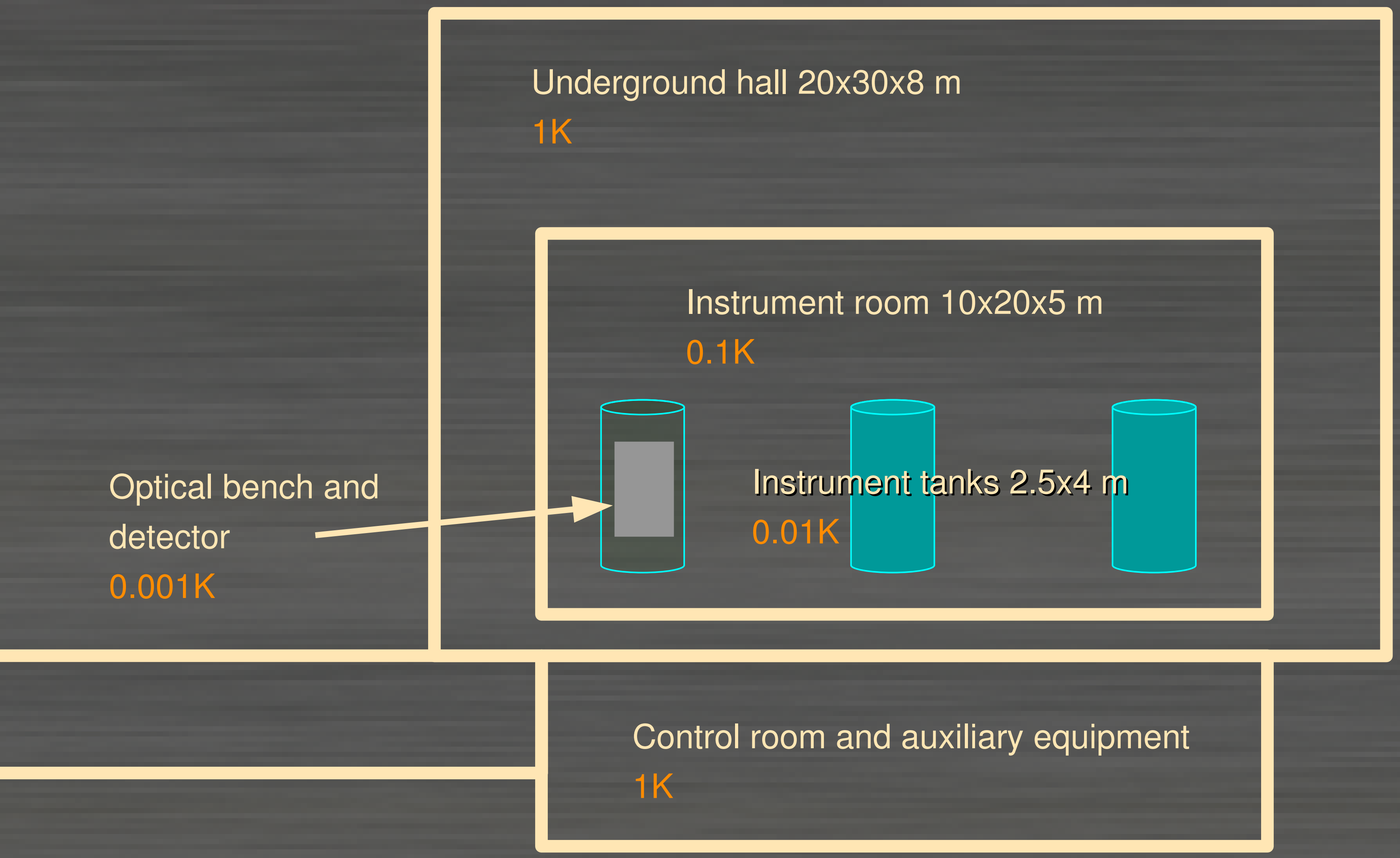
Liske et al. (2008)

Improving radial velocity accuracy

- Light scramblers to reduce effects of guiding errors
- Simultaneous wavelength calibration
- Wavelength calibration with laser frequency comb
- Fully passive instrument, zero human access
- Instrument in vacuum tank
- High precision control of detector temperature
- Underground facility with nested environments
- Precise flux-weighted timing of observations
- Precursor instrument @ VLT: ESPRESSO

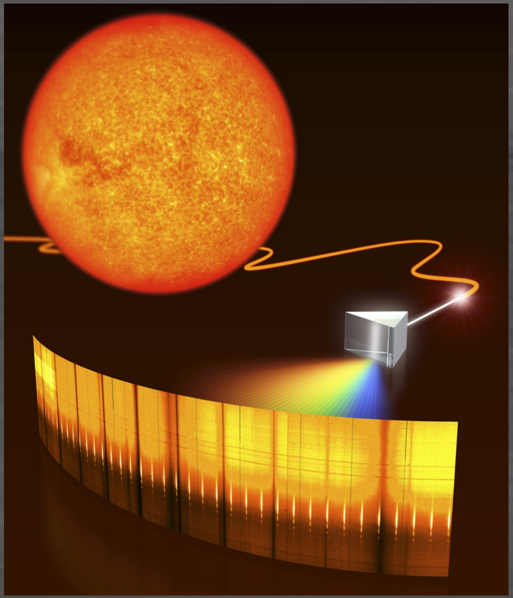


CODEX laboratory floor plan



The HARPS instrument tank

Wavelength Calibration



- Classical method: ThAr comparison spectra.

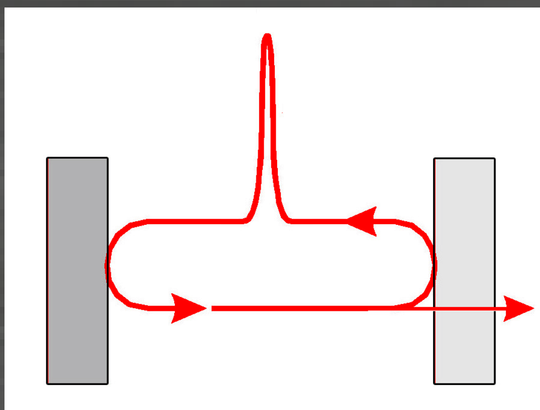
  Problems:
  - Long-term stability
  - Varying line density and intensity along the optical spectrum.
  - Blends

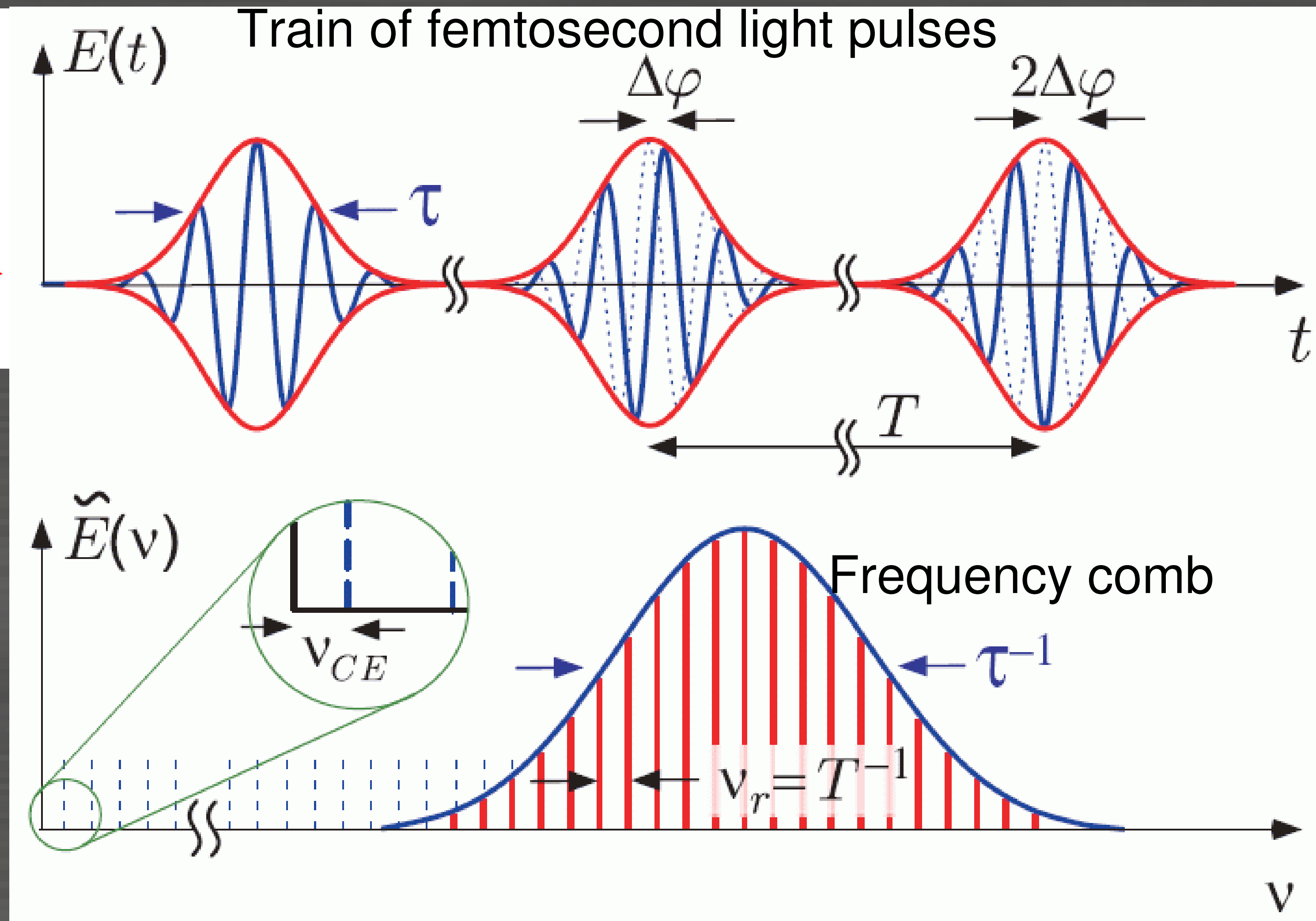
- Relatively new alternative: observe object spectrum through an iodine cell.

  Problems:
  - Long-term stability?
  - Blends
  - Loss of flux!

- System pursued for CODEX: the frequency comb
  - Optical or NIR laser producing a train of monochromatic femtosecond light pulses.
  - Pulse repetition rate is controlled by an atomic clock.
  - Produces a spectrum of evenly spaced δ-functions (frequency comb) whose absolute wavelengths are known to a precision limited only by the atomic clock.

Frequency Comb





$$\nu_n = n\nu_r + \nu_{CE}$$

Zero offset and line spacing known with absolute precision limited by atomic clock.

by Thomas Udem

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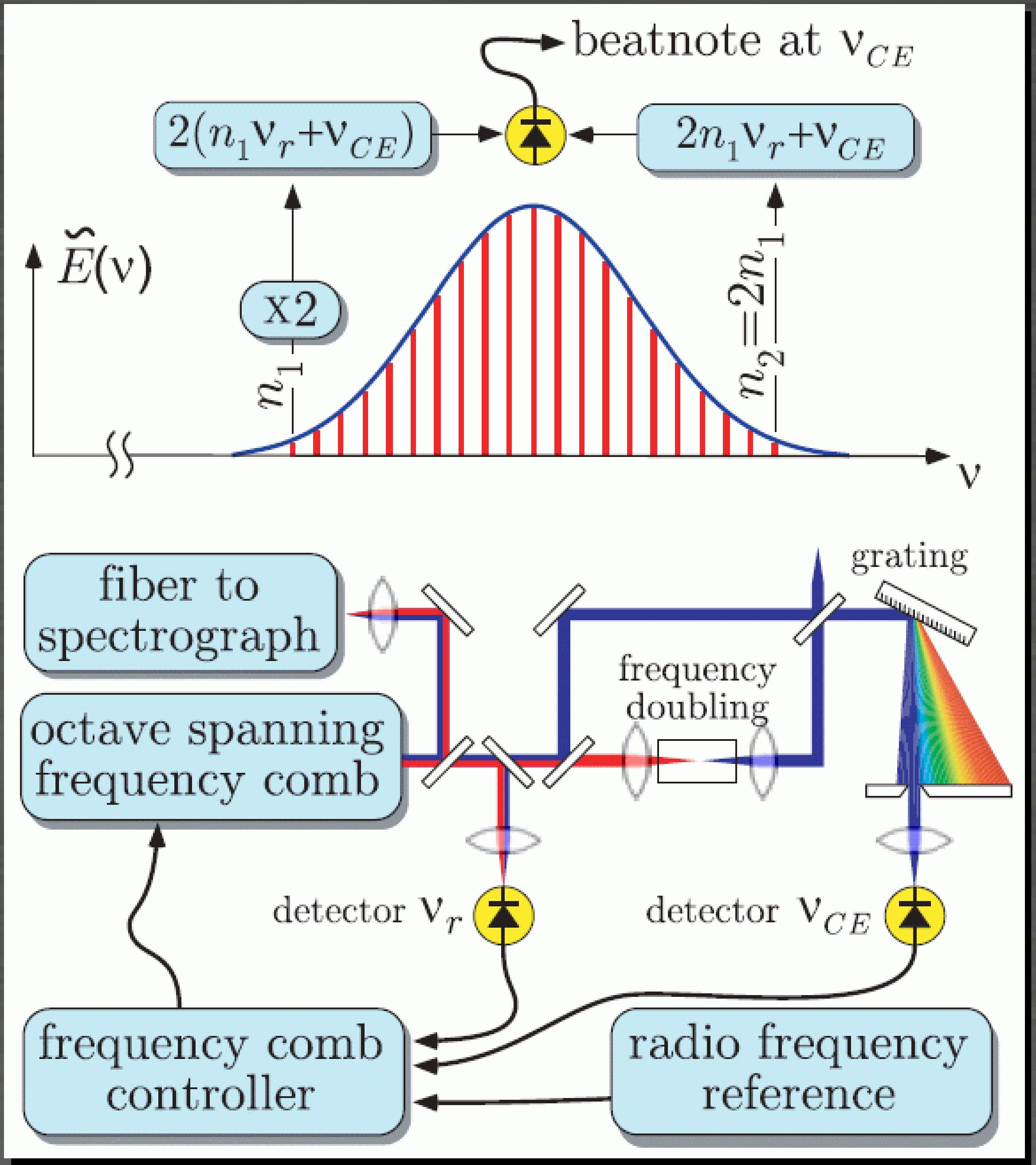
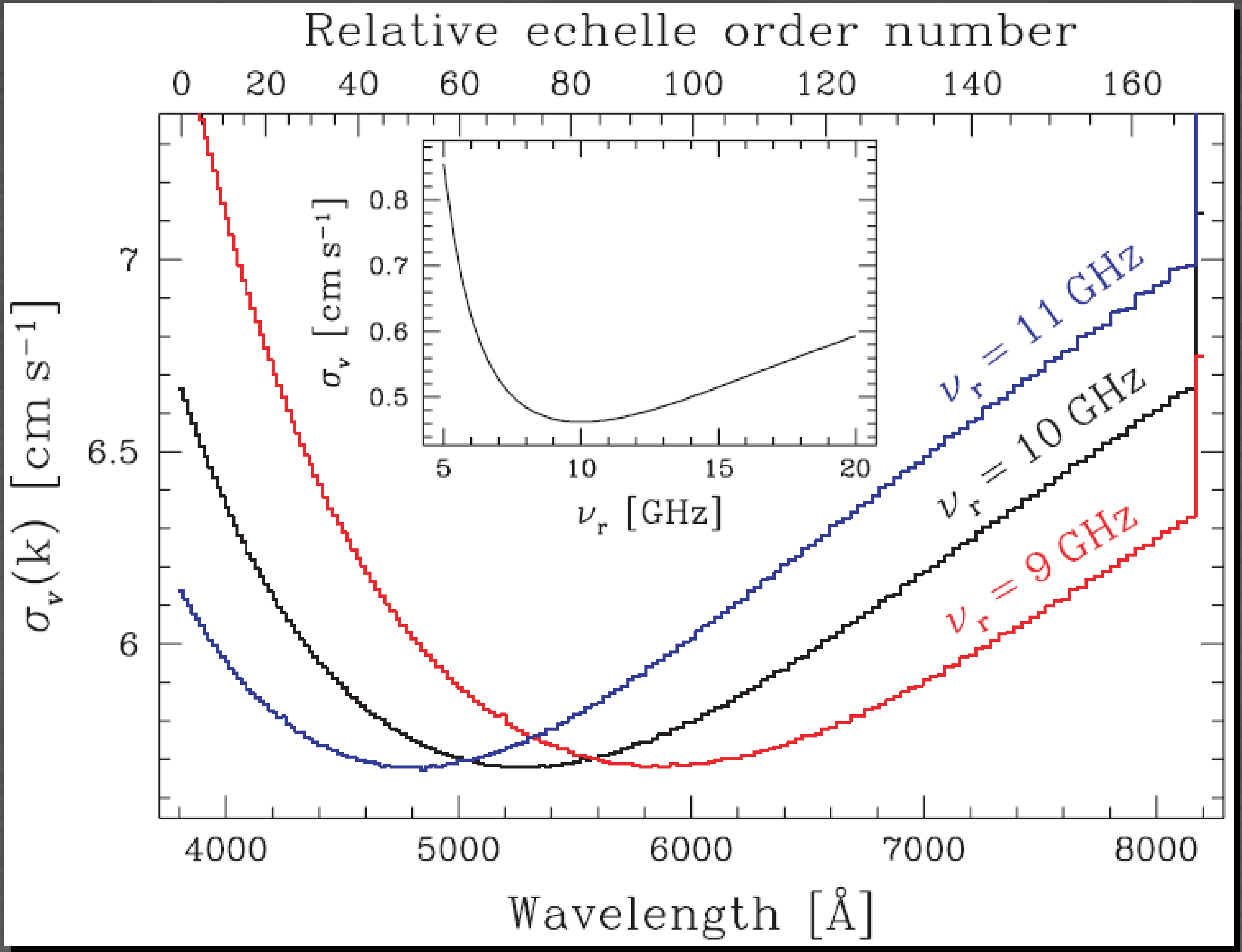


by Thomas Udem

Simulation Results

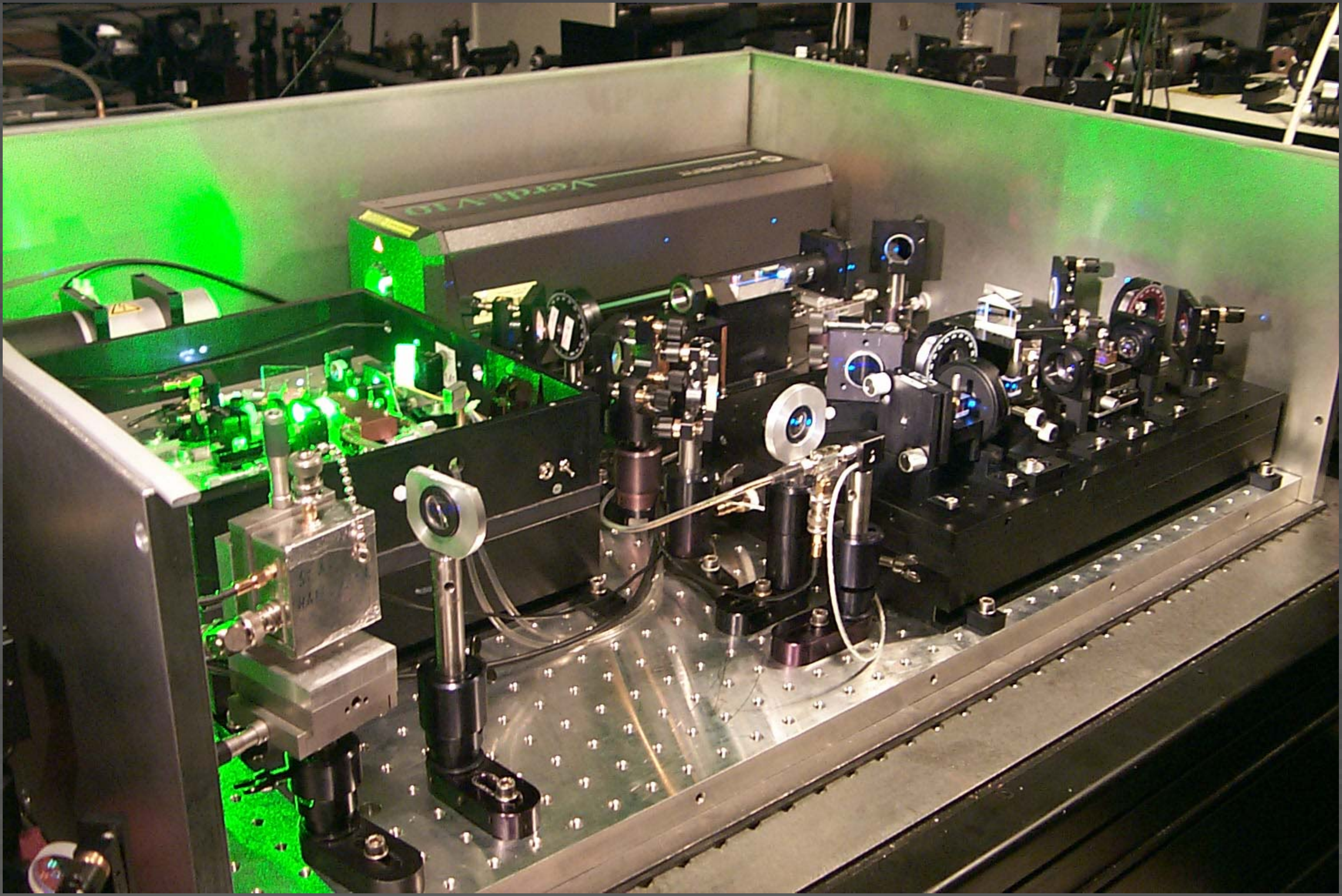
Photon-limited wavelength calibration precision is ~0.5 cm/s.

Optimal pulse repetition rate is 10-20 GHz.



Murphy et al. (2007)

Wavelength Calibration



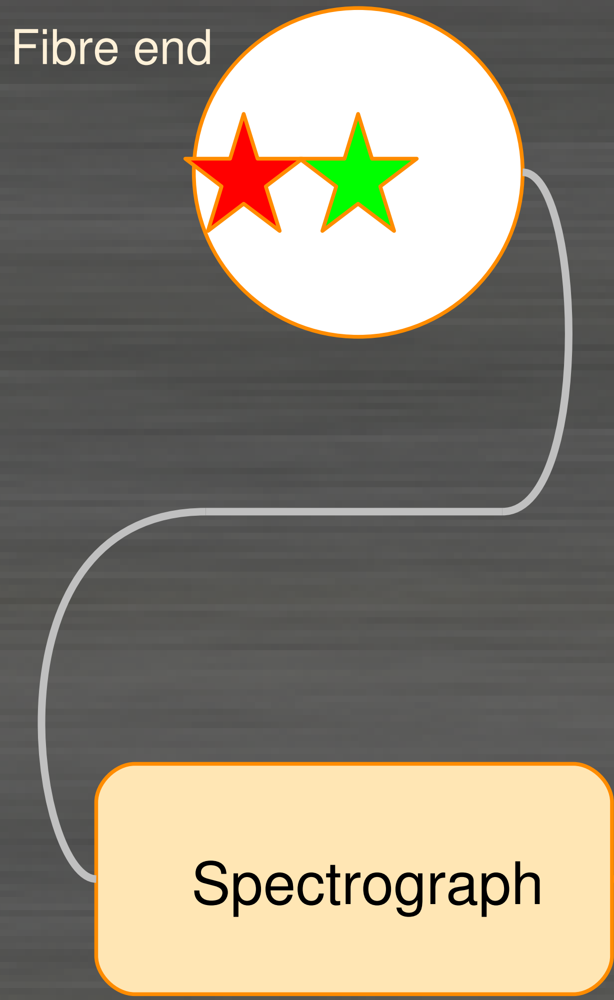
Thomas Udem (MPQ)

Wavelength Calibration

Desired characteristic	ThAr	I_2 cell	Comb
From fundamental physics	✔	✔	✔
Individually unresolved	Mostly	✔	✔
Resolved from each other	✘	✘	?
Uniformly spaced	✘	✘	✔
Cover optical range	✔	✘	?
Uniform intensity	✘	✘	?
Long-term stability	✘	?	✔
Maintain object S/N	✔	✘	✔
Exchangeable	✔	✔	✔
Easy to use	✔	✔	?
Reasonably low cost	✔	✔	?

Murphy et al. (2007)

Scrambling

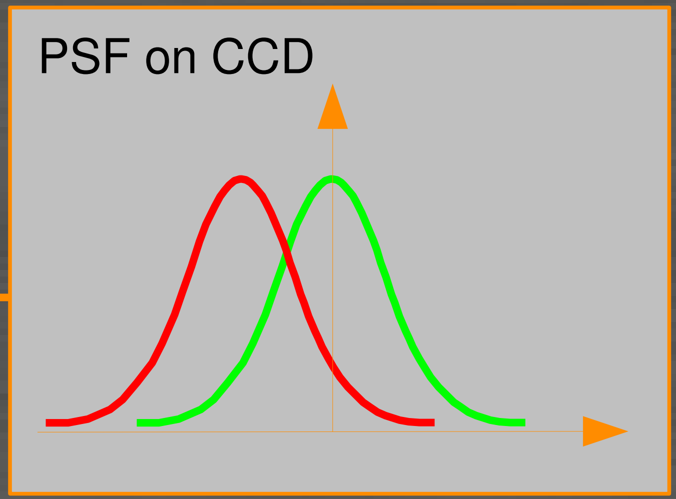


Telescope delivers pointing accuracy of ~0.05 arcsec.
At R = 150,000 this corresponds to 100 m/s.

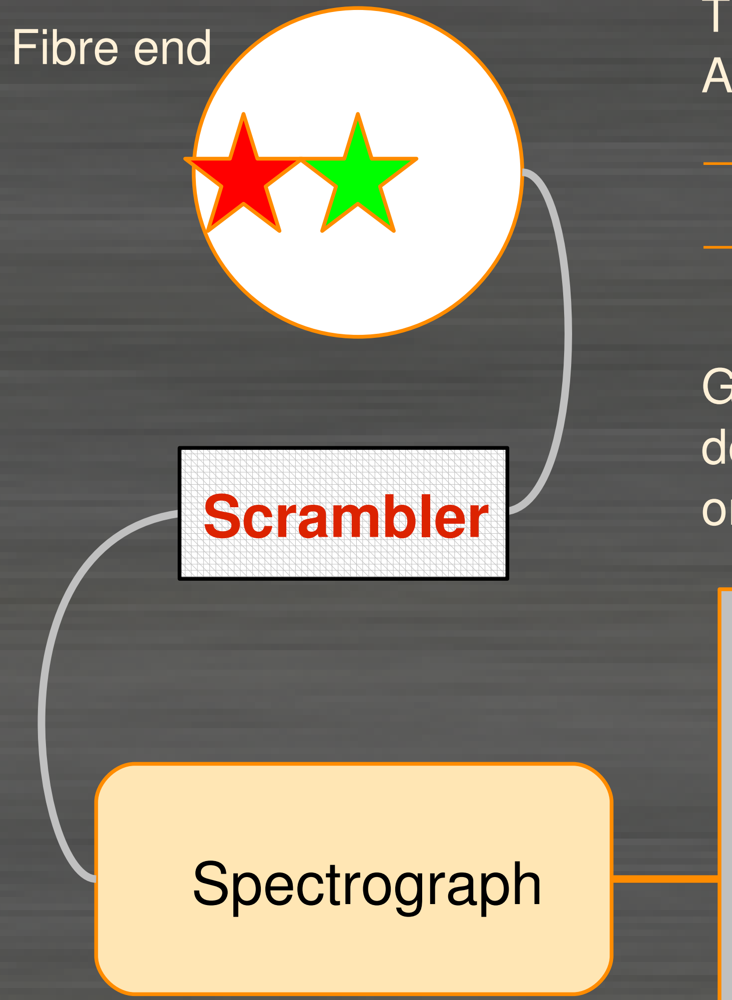
→ Need a scrambling gain of ~5000 to reach 2 cm/s.

→ A dedicated scrambling device in addition to the fibre is required.

Goal: a photon's position on the CCD must only depend on λ, but should be independent of its position on the entrance aperture.



Scrambling



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