Precision Cosmology in the E-ELT Era

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Precision Measurements for not very precise Cosmology in the E-ELT Era

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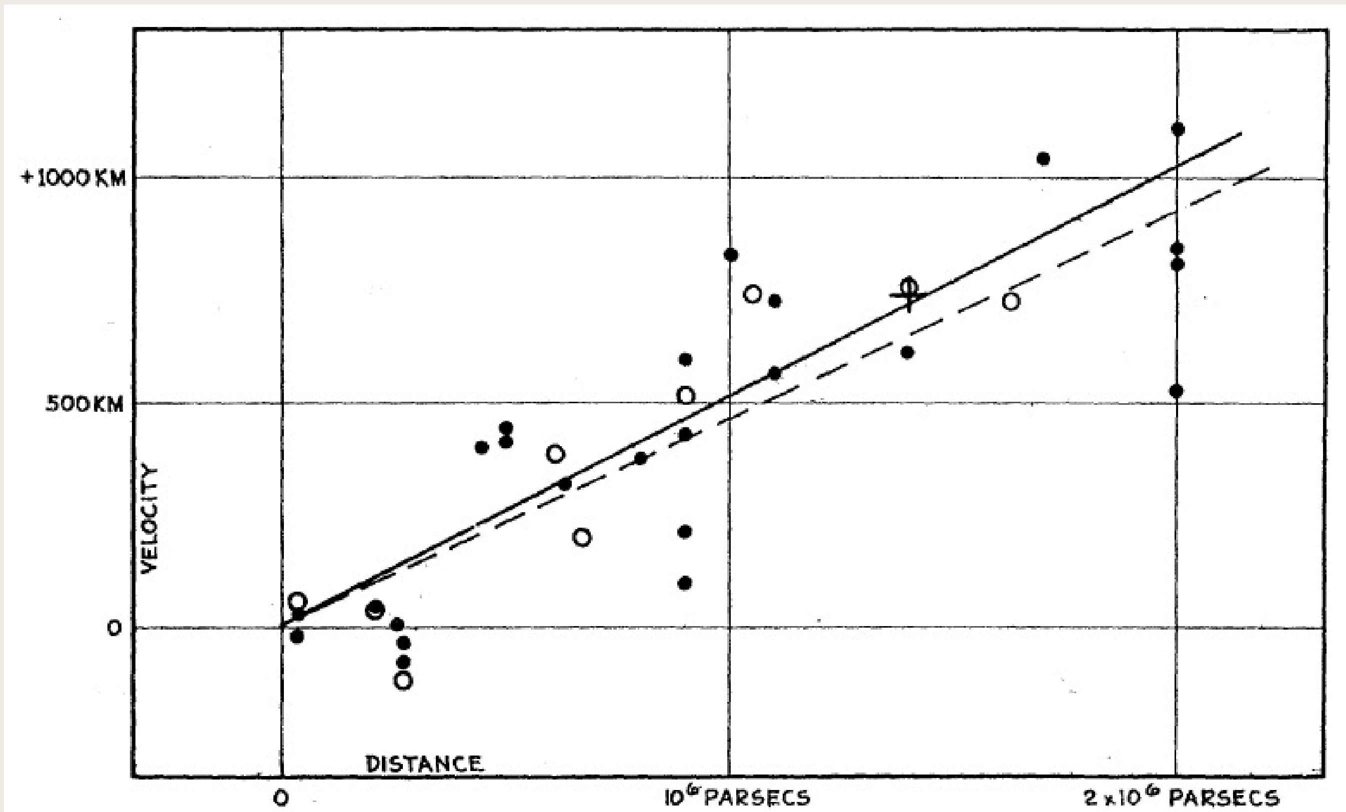
1929: Universal Expansion

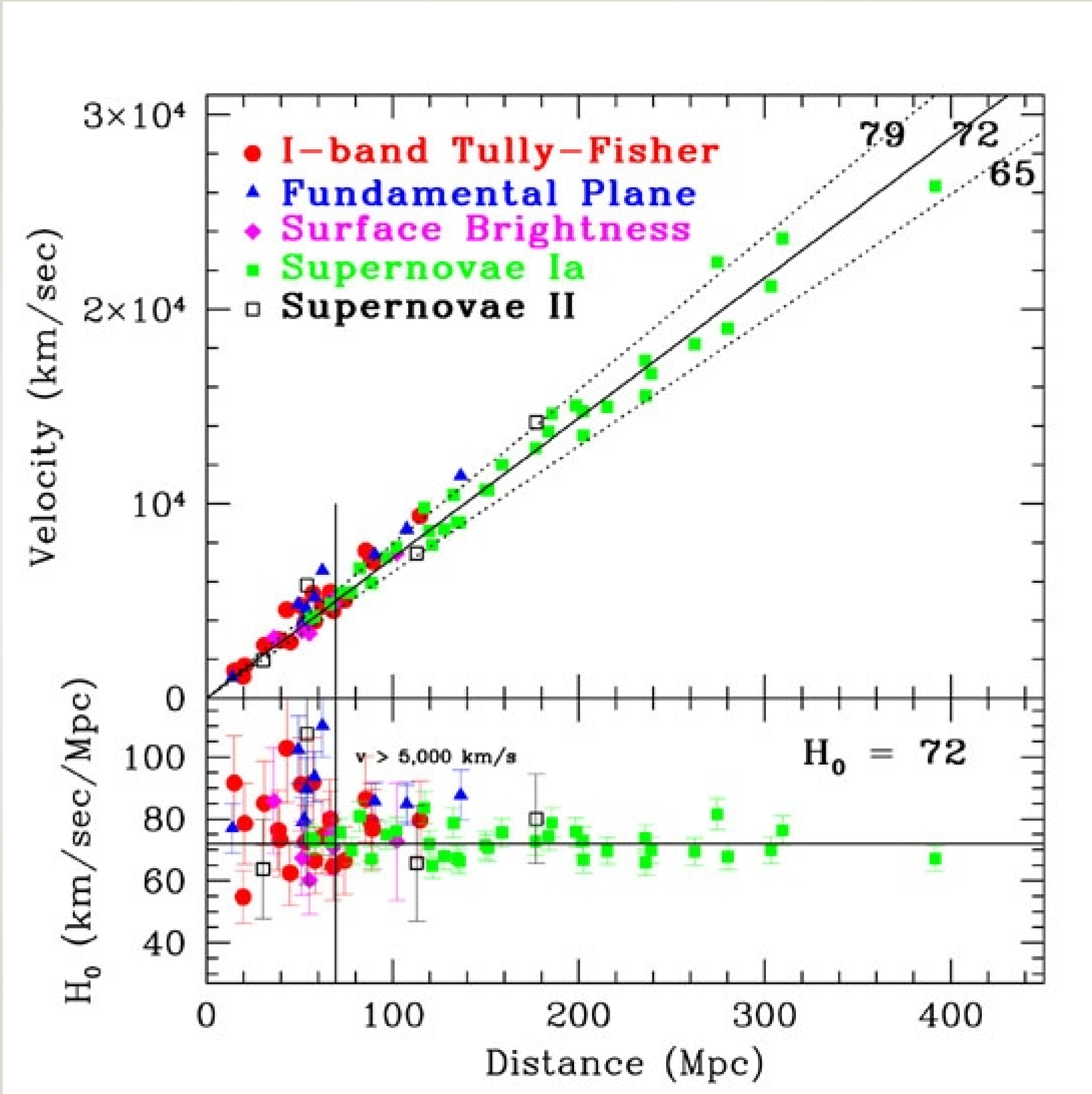
The original Hubble diagram (Hubble 1929):

Recession velocity

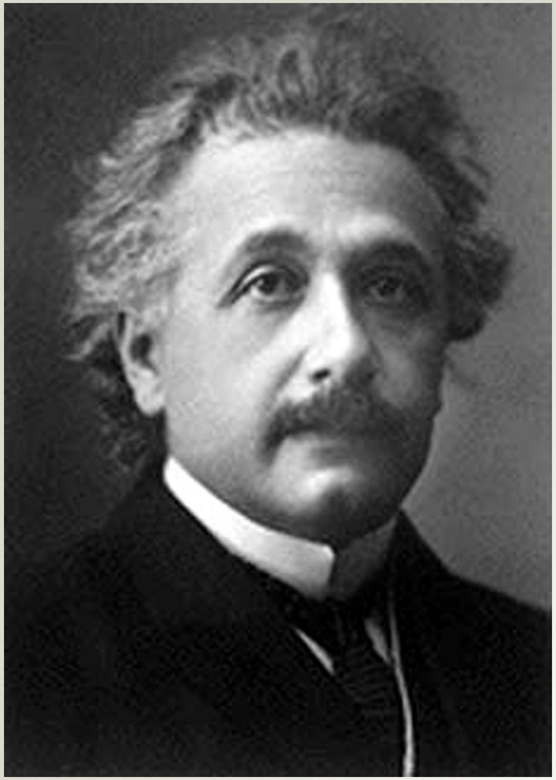


Distance

All distant galaxies are found to recede from us.
Hubble's Law: $v = H_0 d$ → The Universe expands!

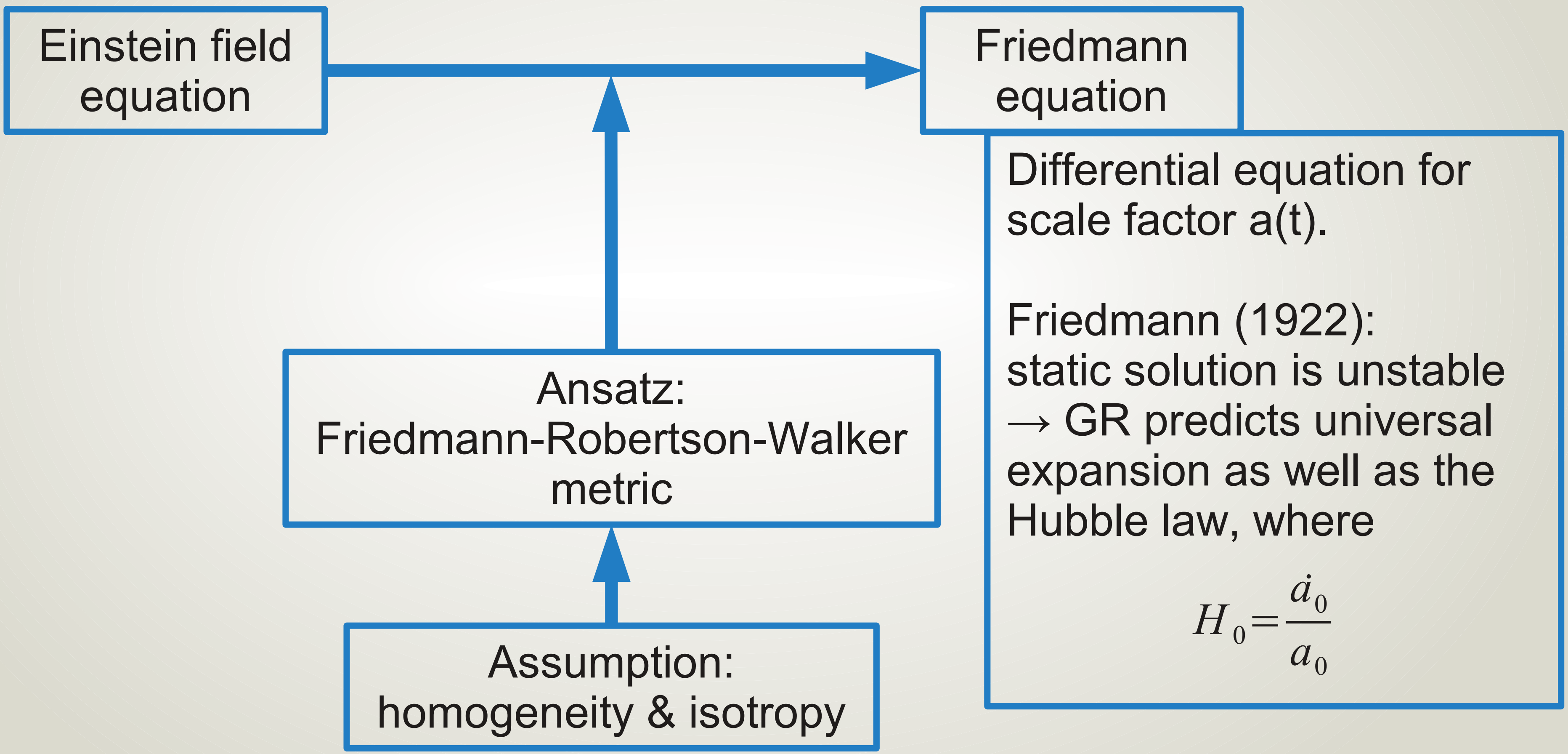


HST Key Project, Freedman et al.

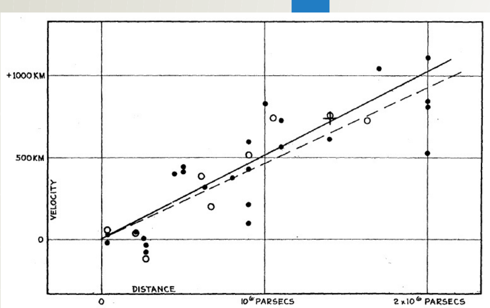


1916: Einstein's Theory of General Relativity

Relativistic Cosmology

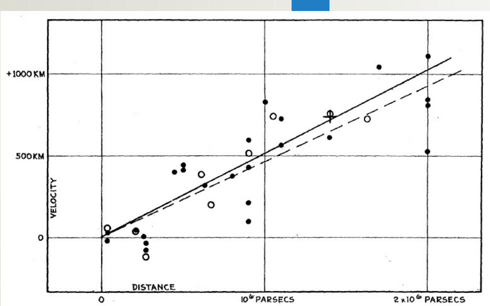


Relativistic Big Bang Cosmology

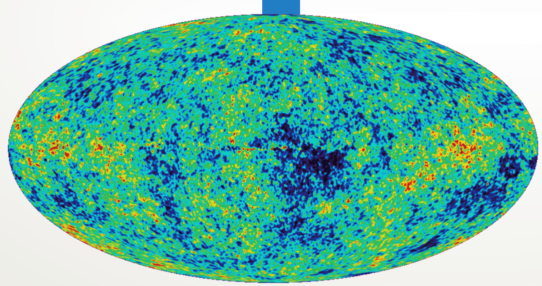


Expansion

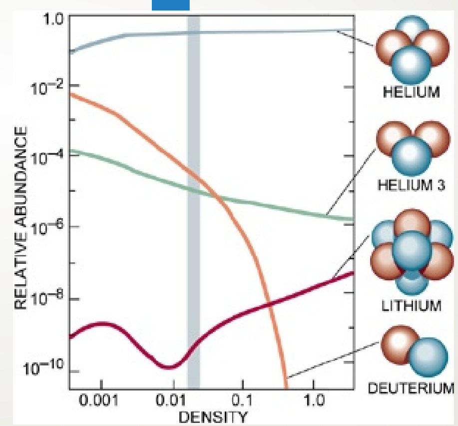
Relativistic Big Bang Cosmology



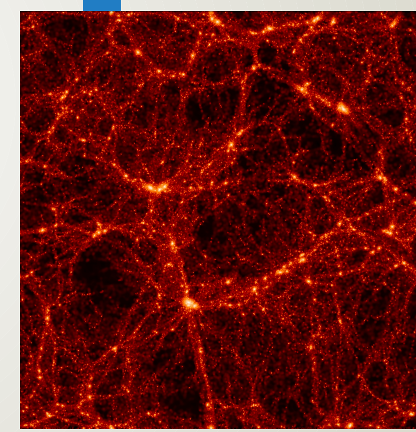
Expansion



Cosmic Microwave Background



Abundance of light elements



Structure formation

Relativistic Cosmology

FRW metric:

$$ds^2 = -c^2\,dt^2 + a^2(t)[d\chi^2 + \Sigma^2(\chi)(d\theta^2 + \sin^2\theta\,d\phi^2)]$$

$$\Sigma(\chi) = \begin{cases} \sin\chi & k = +1 \\ \chi & k = 0 \\ \sinh\chi & k = -1 \end{cases}$$

Friedmann equation:

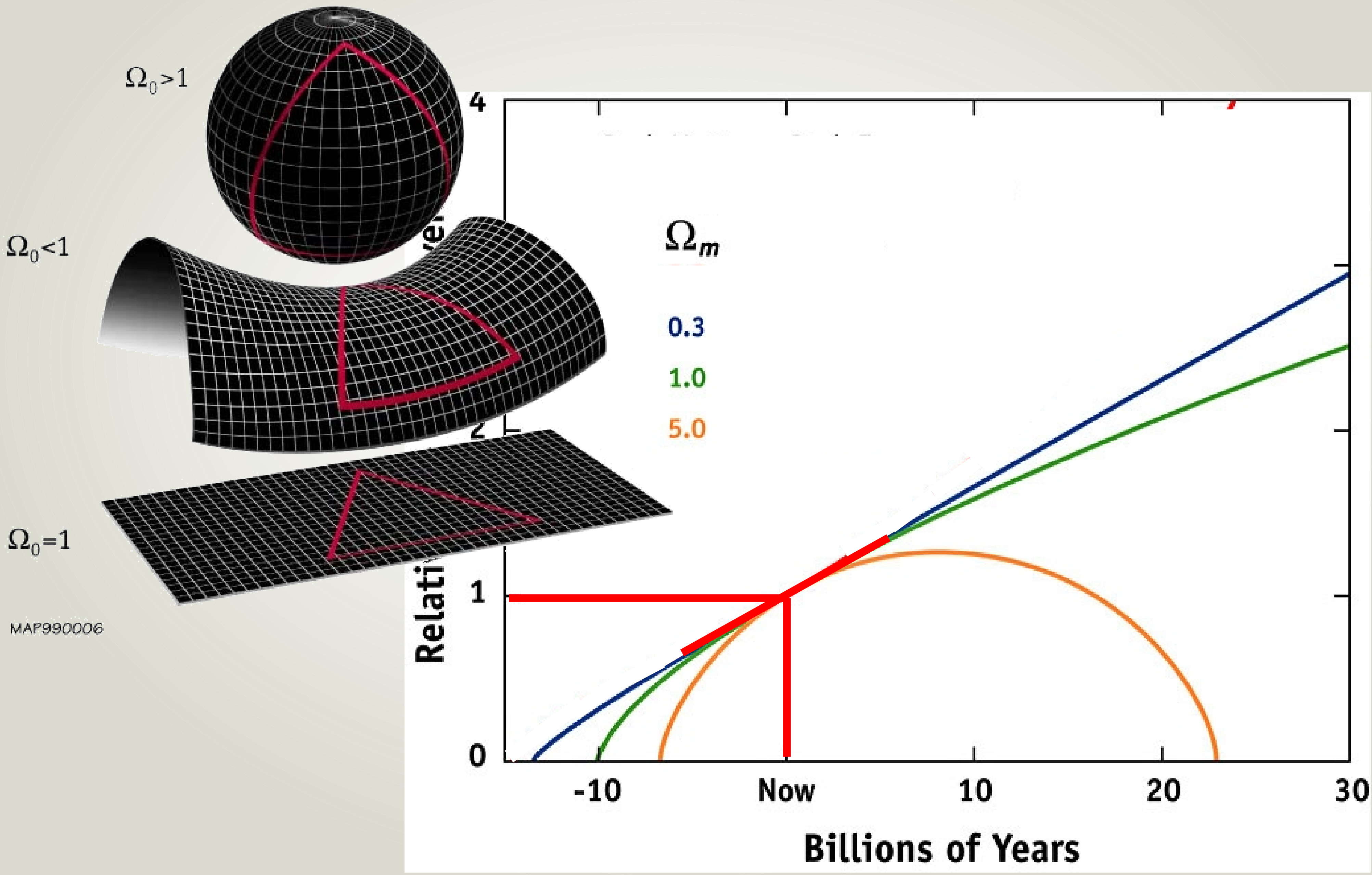
$$H(z) = H_0\left[\sum_i \Omega_i (1+z)^{3(1+w_i)} + \Omega_k (1+z)^2\right]^{\frac{1}{2}}$$

$$H = \frac{\dot{a}}{a}, \quad 1+z = \frac{a_0}{a}$$

Equation of state:

$$p_i = w_i c^2 \rho_i$$

Relativistic Cosmology



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 — Equation of state parameter

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

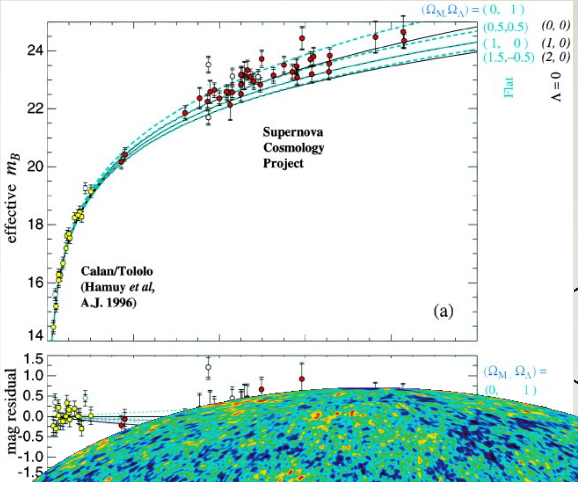
How can these be measured?

- Geometry
- Expansion history
- Clustering, evolution and dynamics of density perturbations

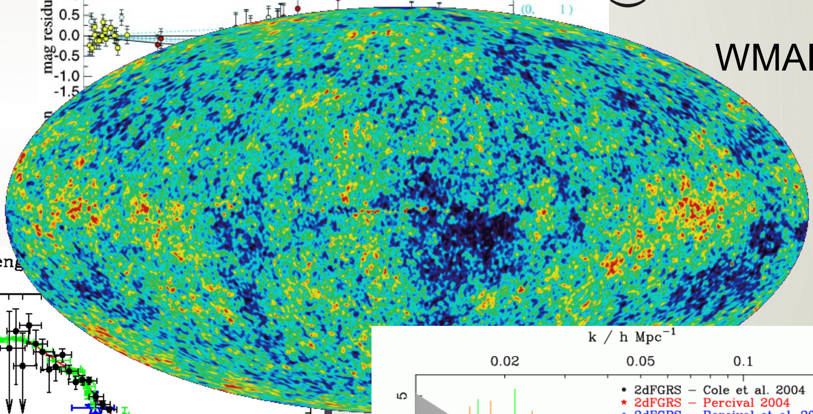
Precision Cosmology

Past decades: development of a wide array of observations to constrain the cosmological model:

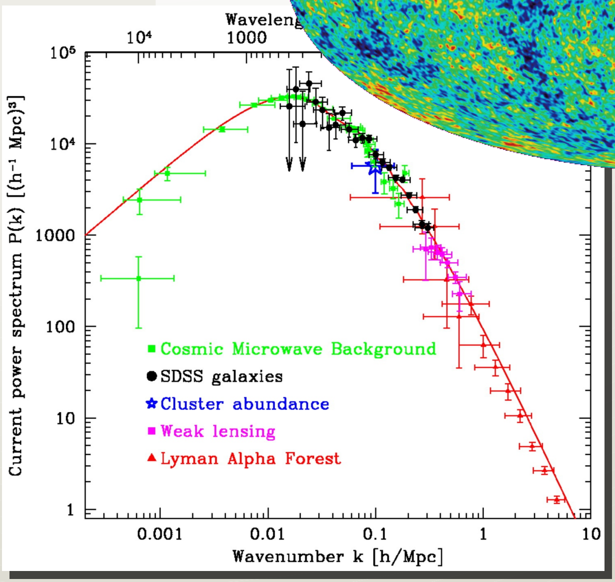
- Cosmic Microwave Background
- Supernovae type Ia
- Large scale structure of galaxies and intergalactic medium
- Galaxy cluster abundance
- Weak lensing



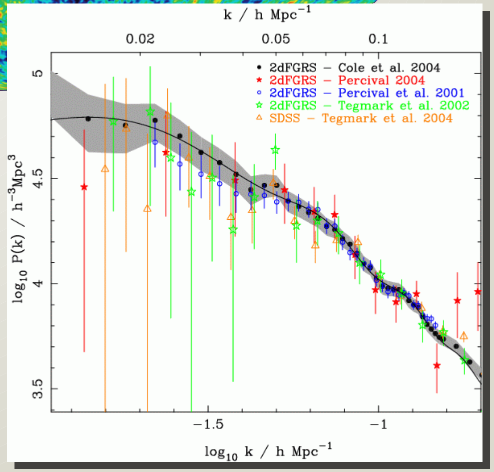
Perlmutter et al. (1999)



WMAP



Tegmark et al. (2004)



Cole et al. (2005)

Surprise: Accelerated Expansion

- Good evidence from SNIa that a period of decelerated expansion was followed 'recently' by a period of acceleration.

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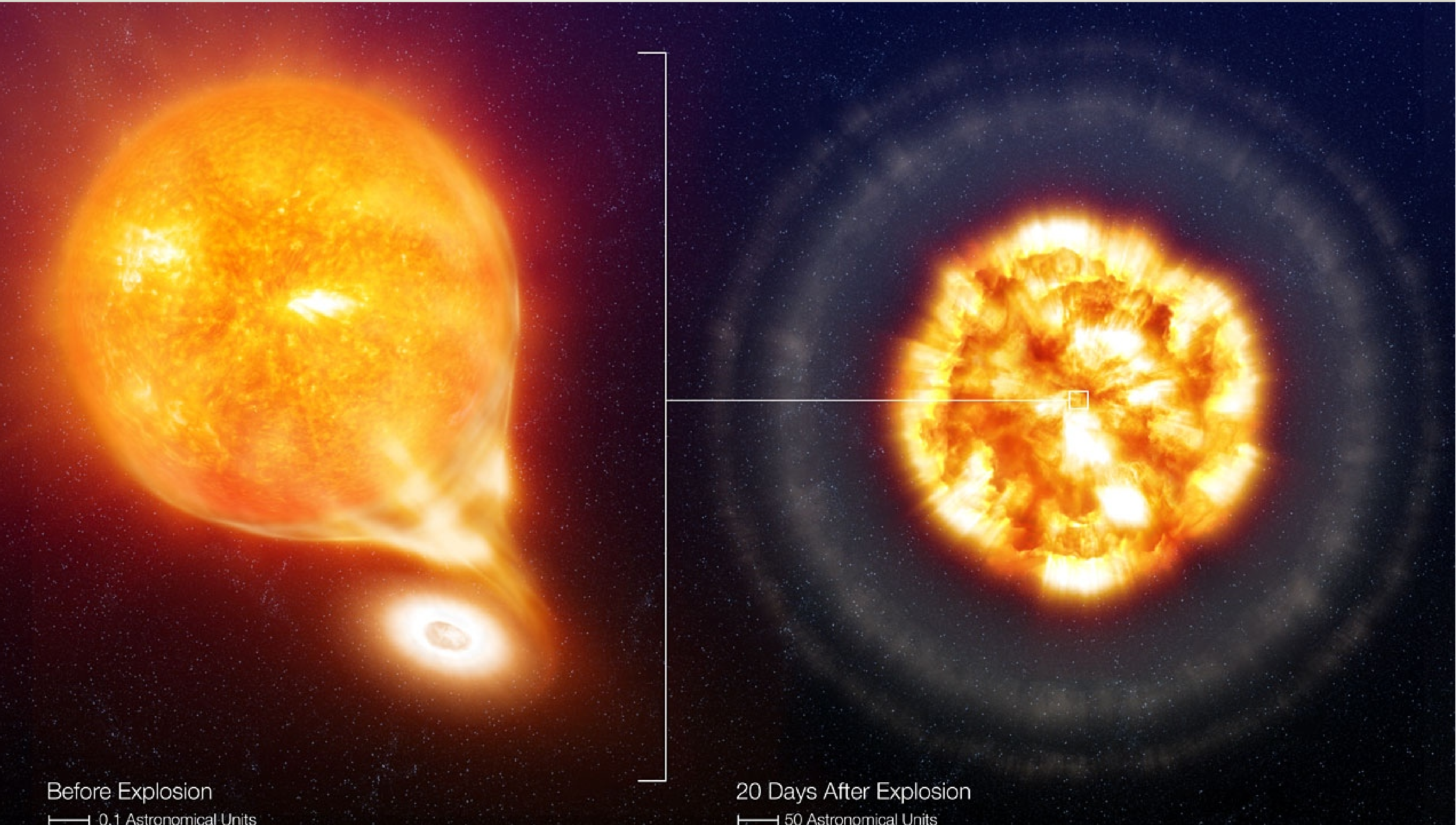

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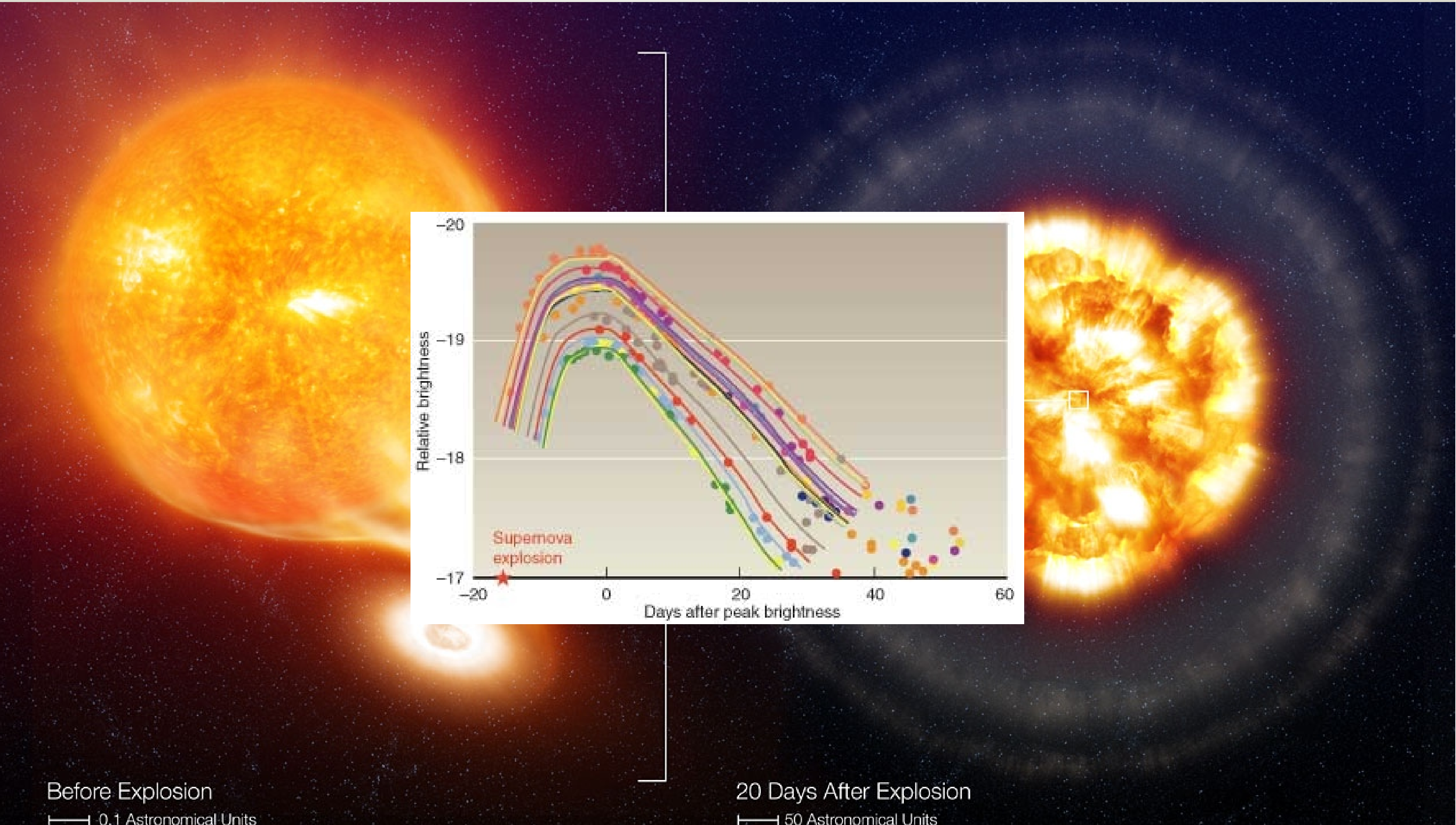

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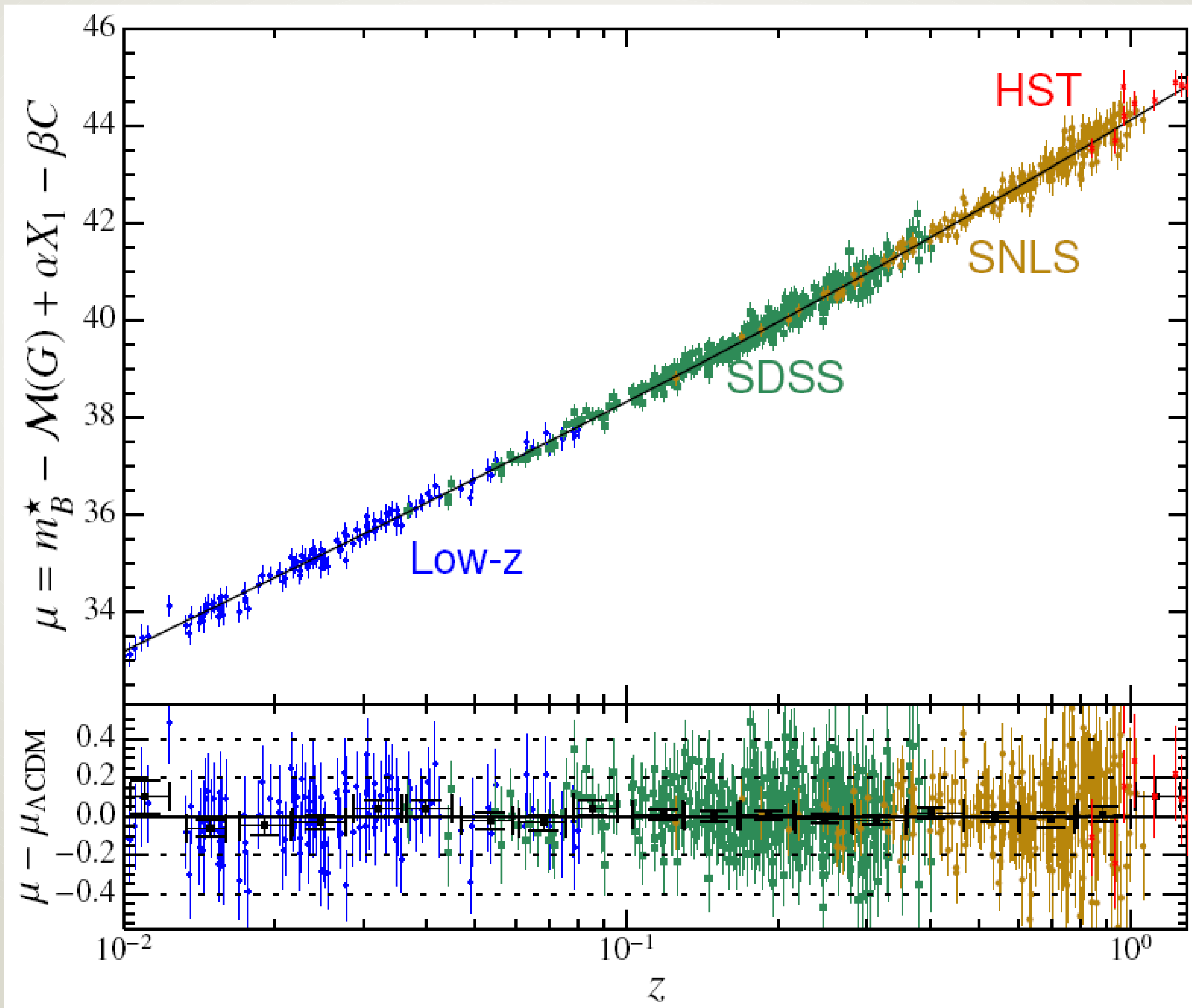

Betoule et al. (2014)

Surprise: Accelerated Expansion

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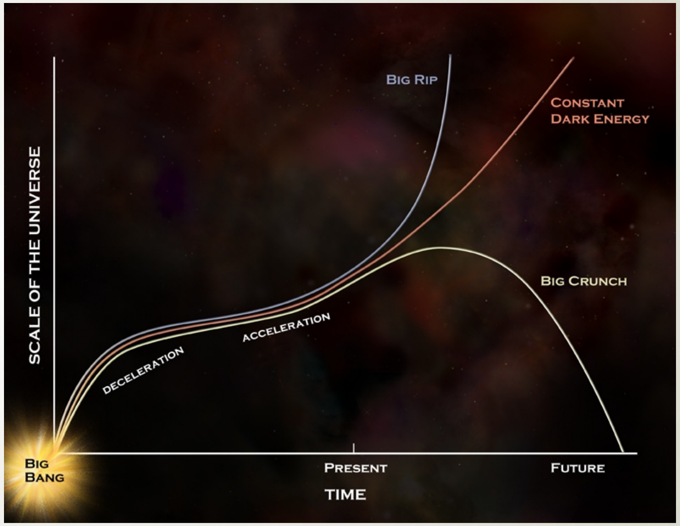
- The source of the acceleration is entirely unknown.
  Most explanations so far proposed require new physics.



Dark energy:

- Cosmological constant $w = -1$
- Quintessence $-1 < w(z) < 0$
- Phantom energy $w(z) < -1$
- ...

Modification of gravity:

- f(R)
- Non-minimal couplings
- Braneworld scenarios (DGP, Cardassian, ...)
- ...

Modification of Copernican Principle:

- Inhomegeneous models without DE can reproduce past light-cone observations of FRW models with DE (LTB, void models, ...)
- Backreaction (averaging and evolution do not commute)

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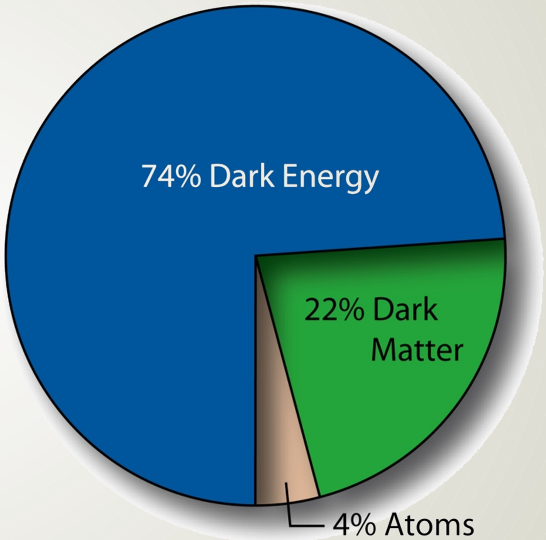

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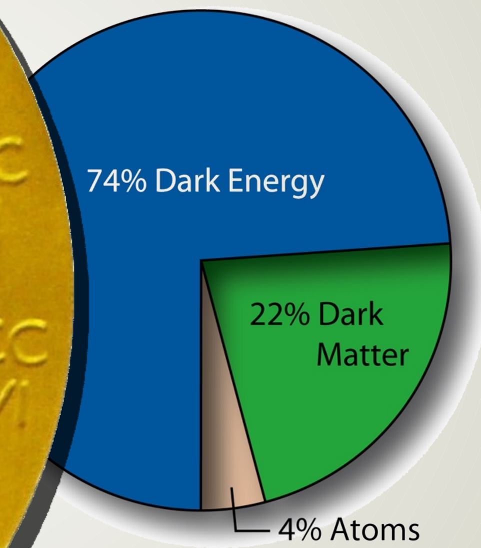

Nobel Prize for Physics 2011


Saul Perlmutter


Brian Schmidt


Adam Riess

Accelerated Expansion

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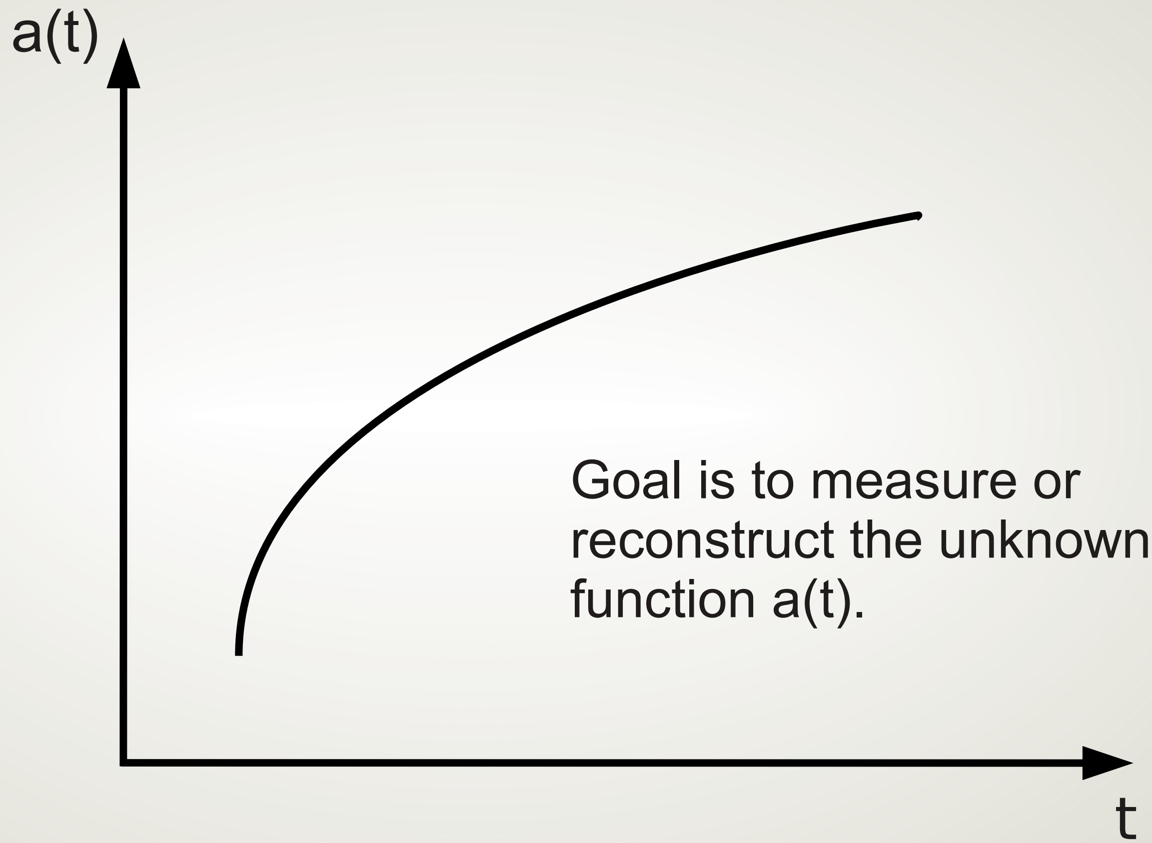

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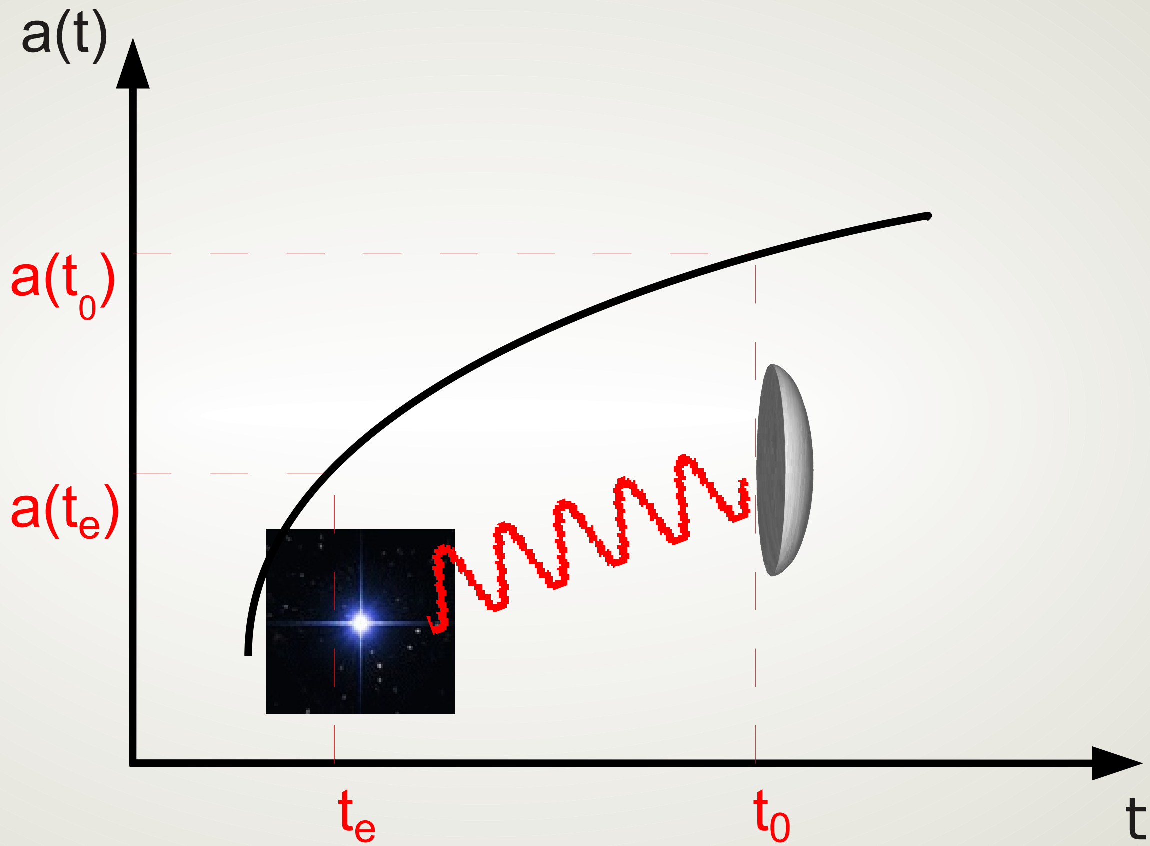
$$1+z = \frac{a(t_0)}{a(t_e)}$$



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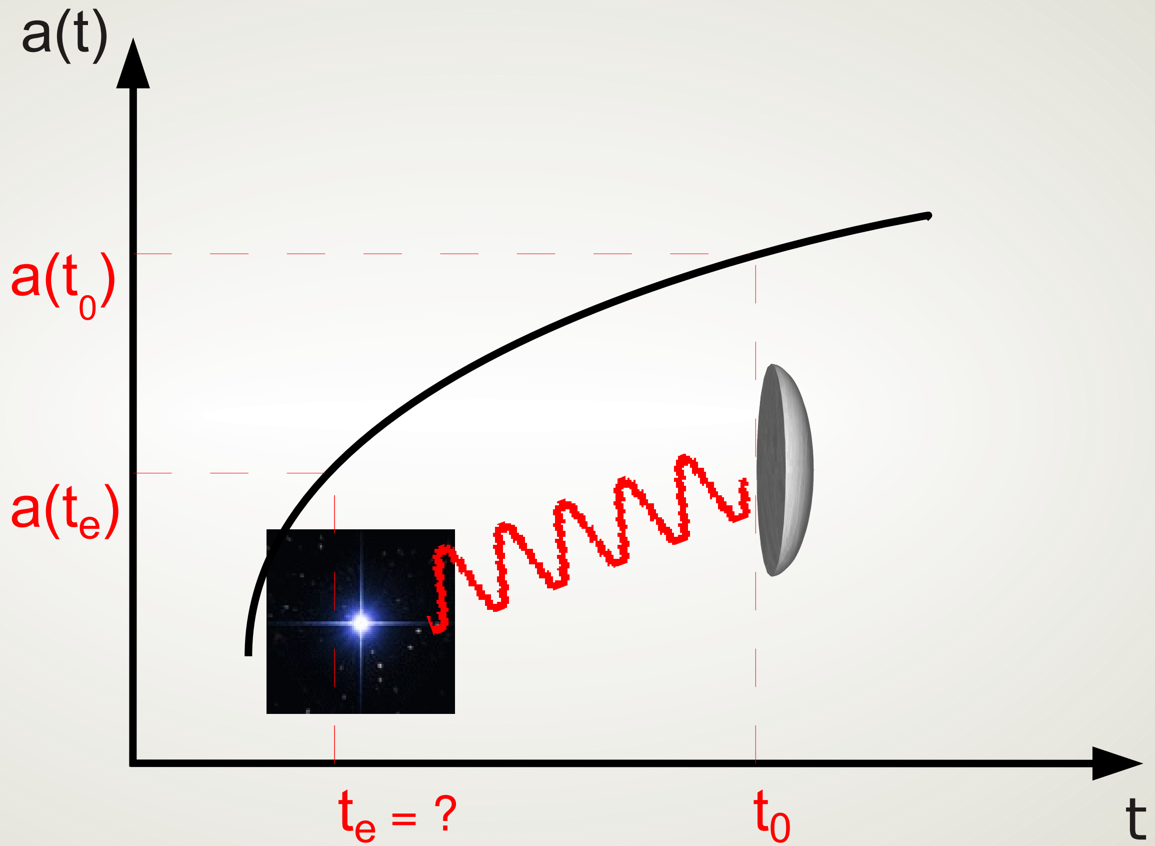

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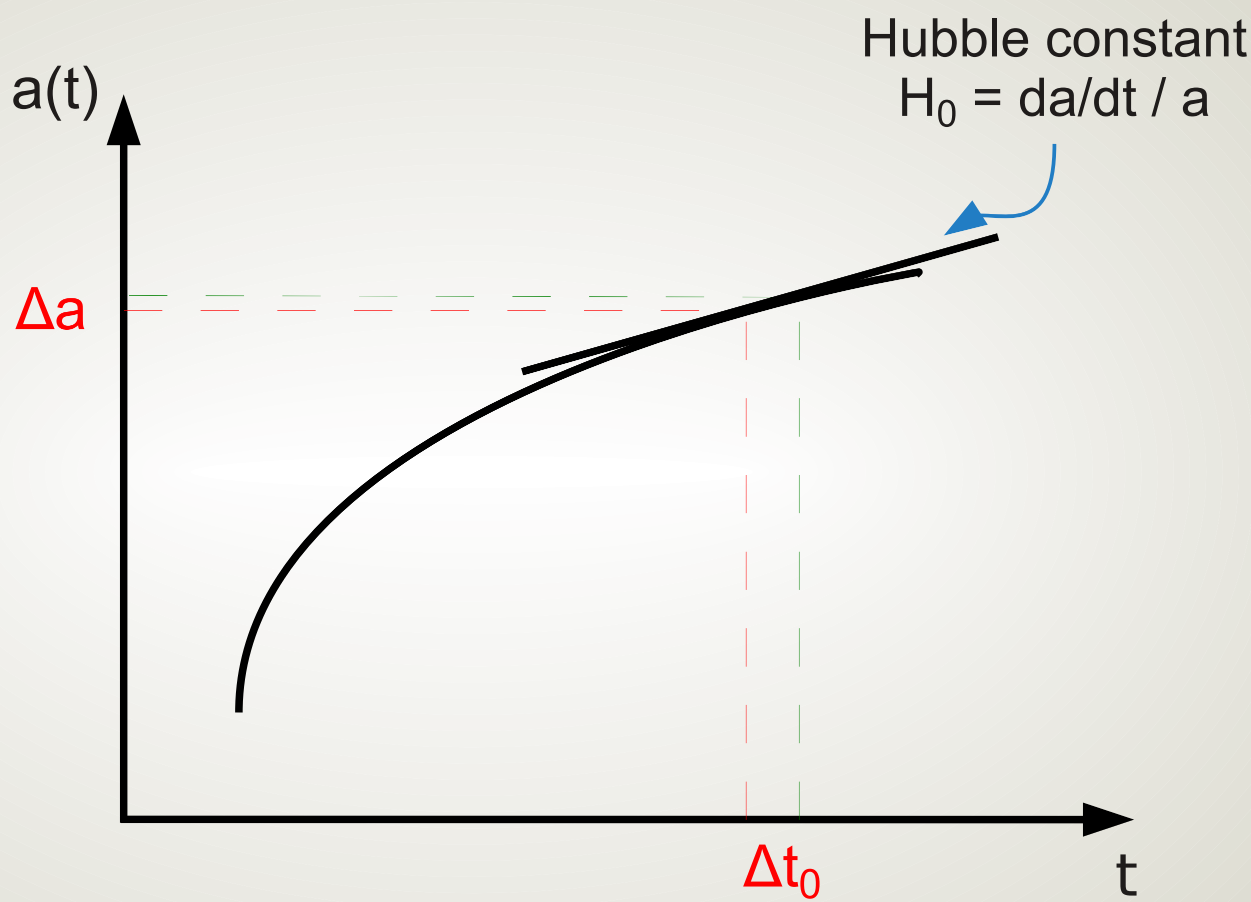

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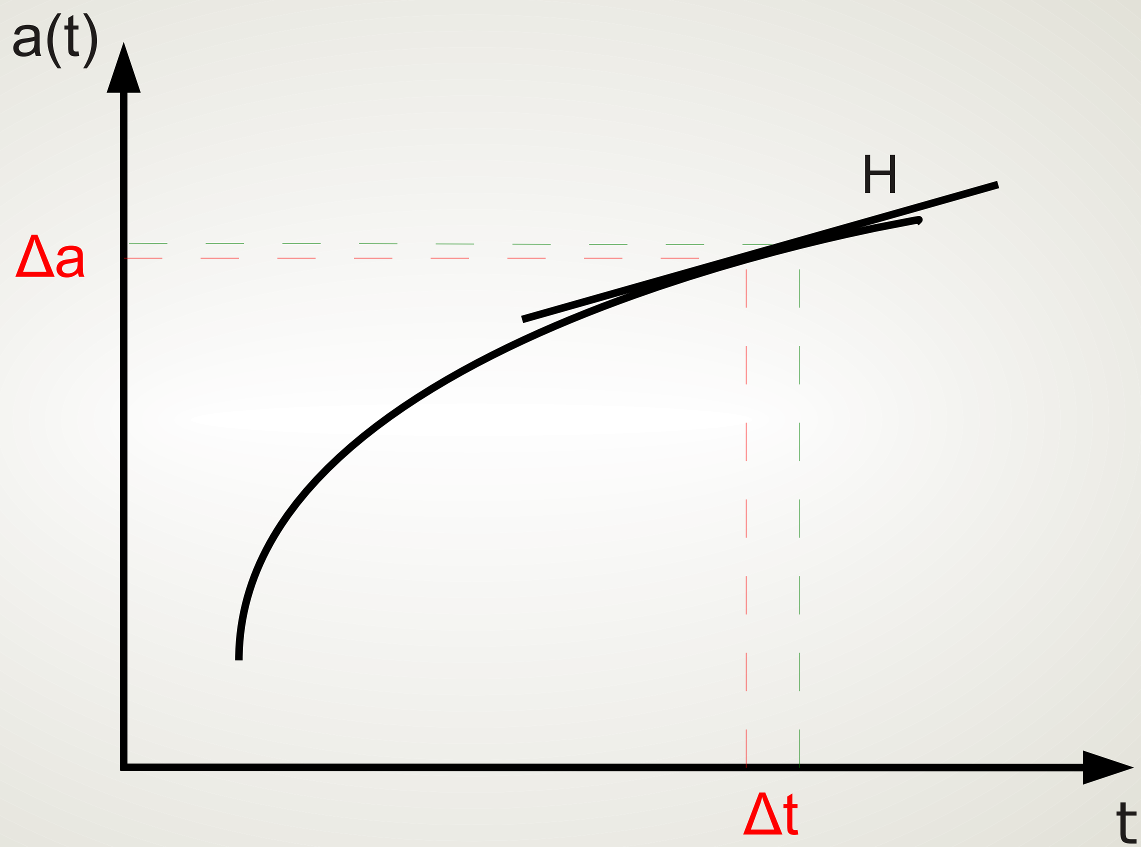

A measurement of H(z) allows the reconstruction of a(t).

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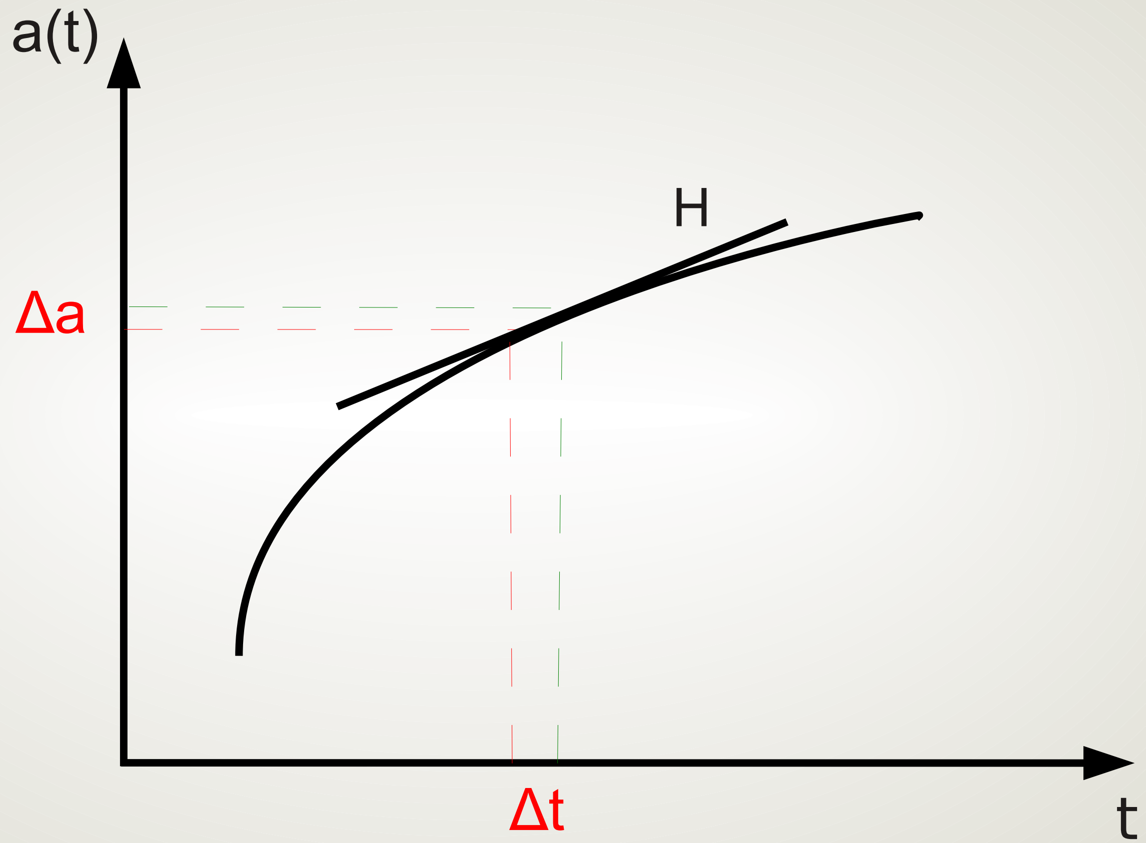

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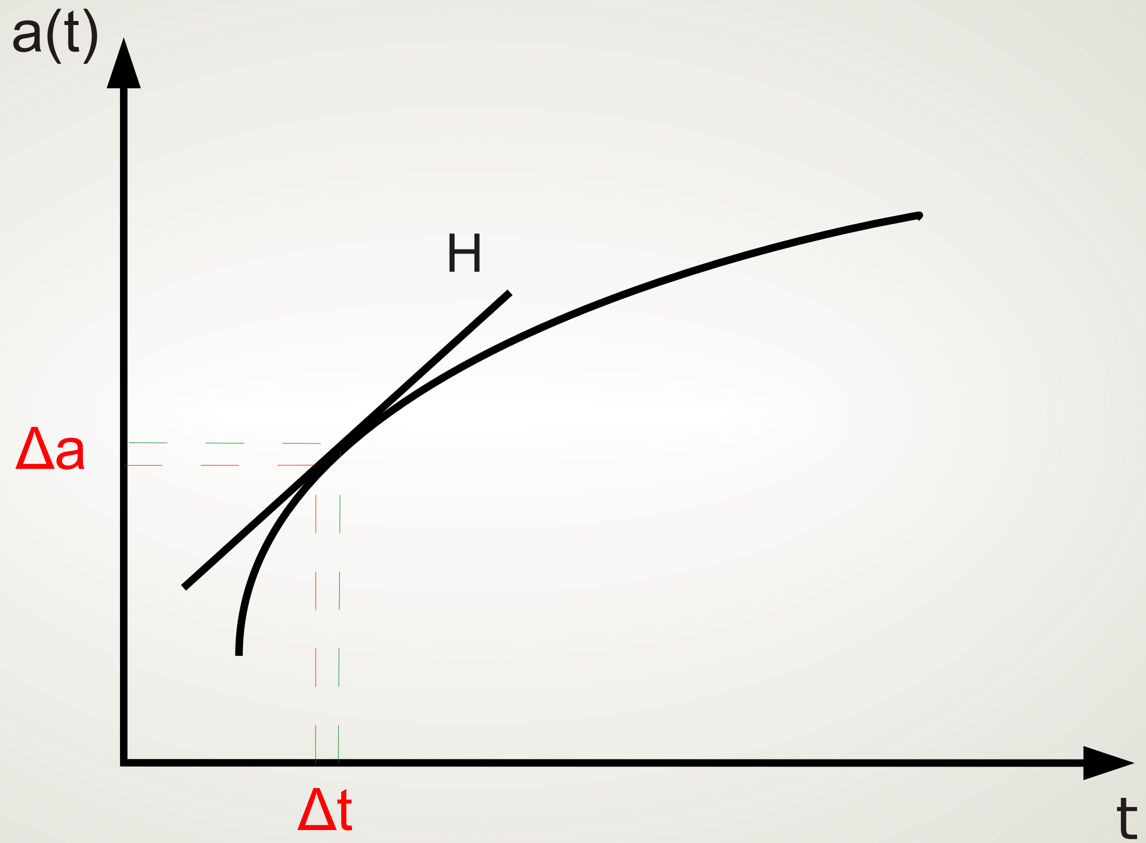
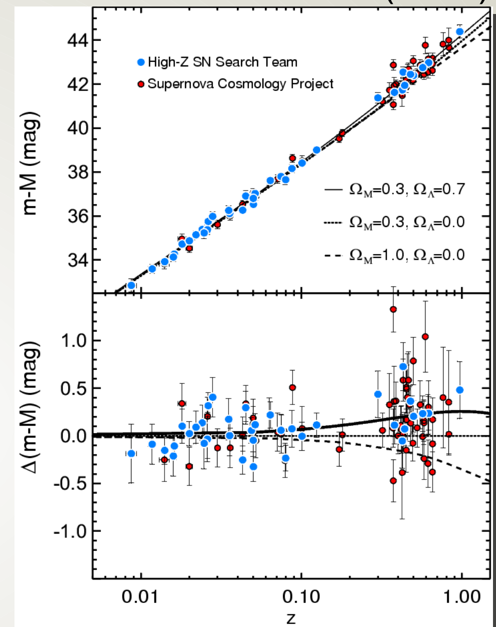


A measurement of H(z) allows the reconstruction of a(t).

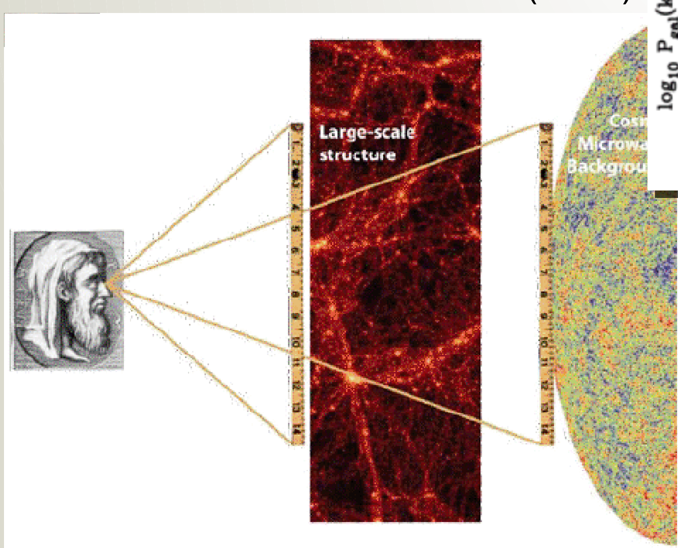
Accelerated Expansion

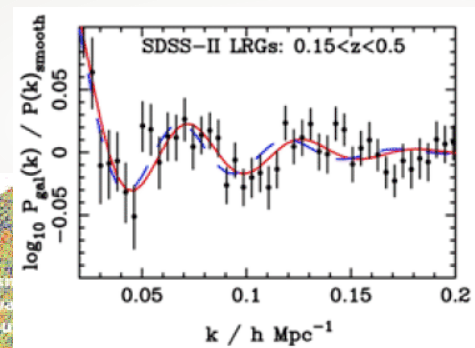
- Intense interest in the expansion history. Best current methods of measuring H(z):
  - SNIa
  - Weak lensing
  - Baryon Acoustic Oscillations (BAO)
  - Redshift Space Distortions (RSD)

Perlmutter & Schmidt (2003)

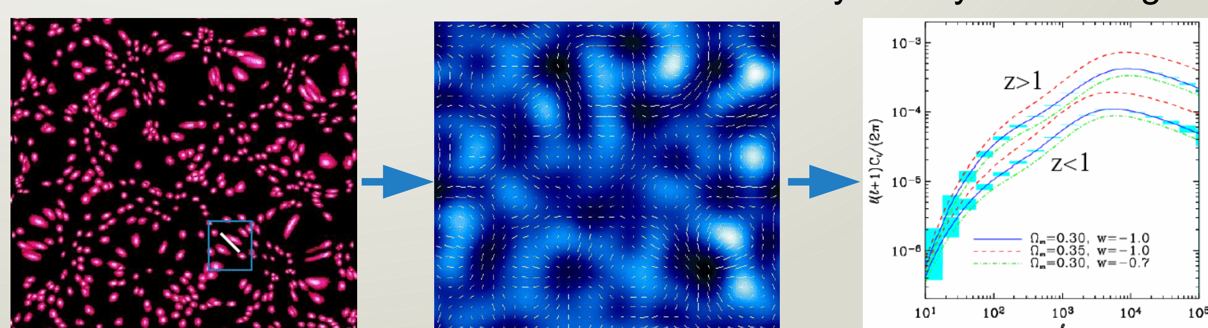


Percival et al. (2010)





by S. Lilly / A. Refregier



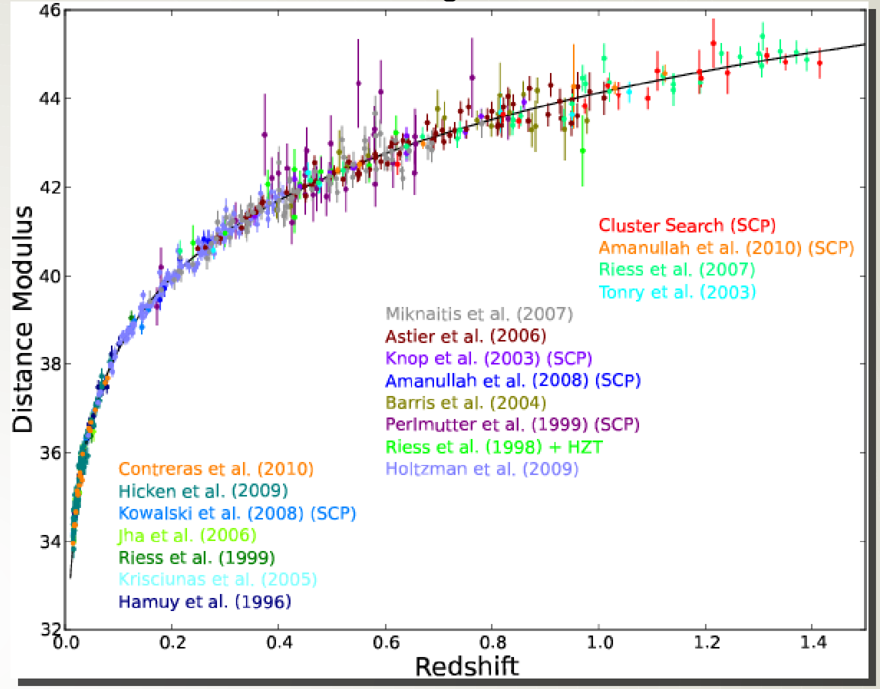
Supernovae Ia

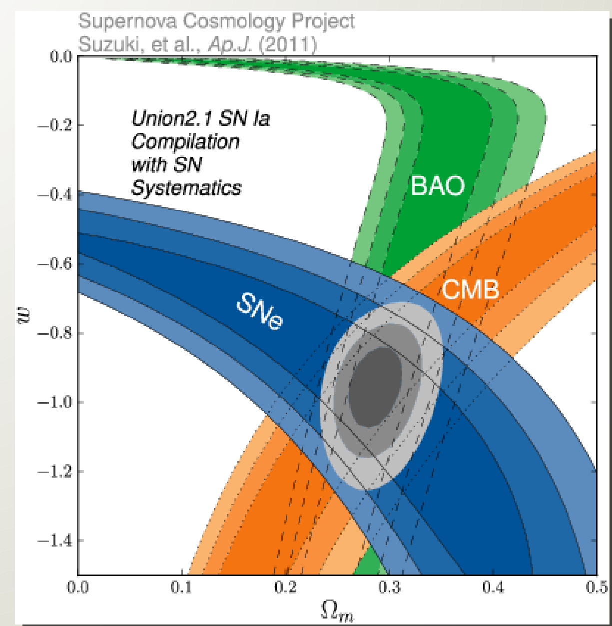
- SNe Ia are standardisable candles which hence provide $D_L(z) \sim \int 1/H(z)$.

- Current datasets give ~850 Sne Ia to z ~ 1.5 and constrain w to within ~10 %.

- Many new experiments running or planned but going to high redshifts is hard (no Sne Ia at z > 2). Secondary parameters? Evolution?

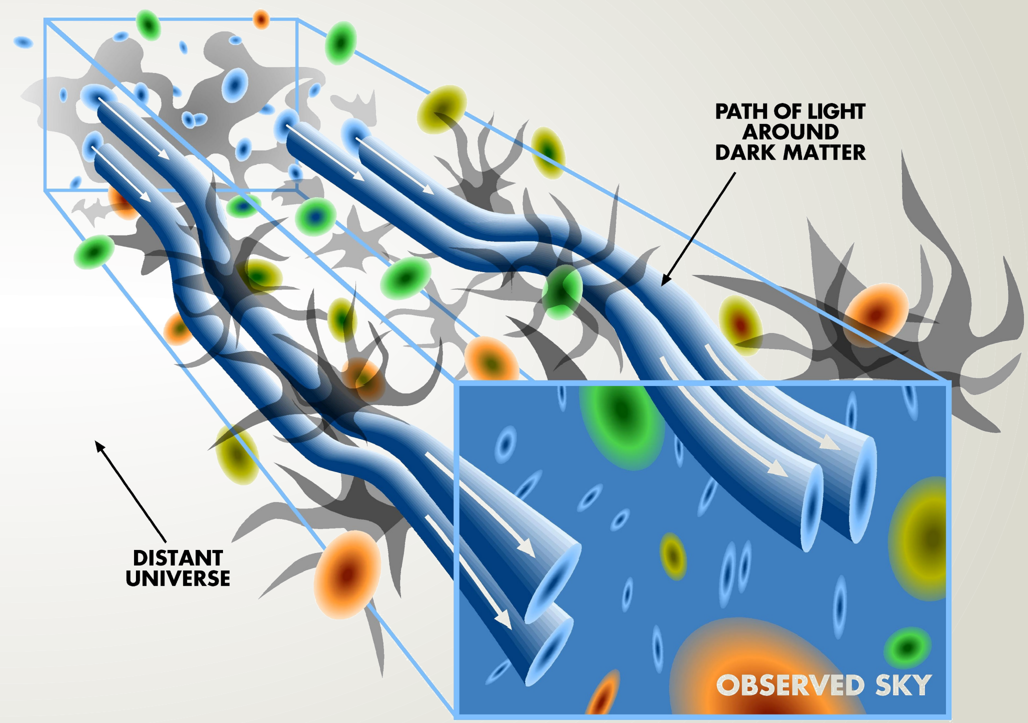
SCP Union2.1 Hubble diagram:





Weak Lensing, Cosmic Shear

- Gravitational lensing by large-scale structure distorts the images of background galaxies.



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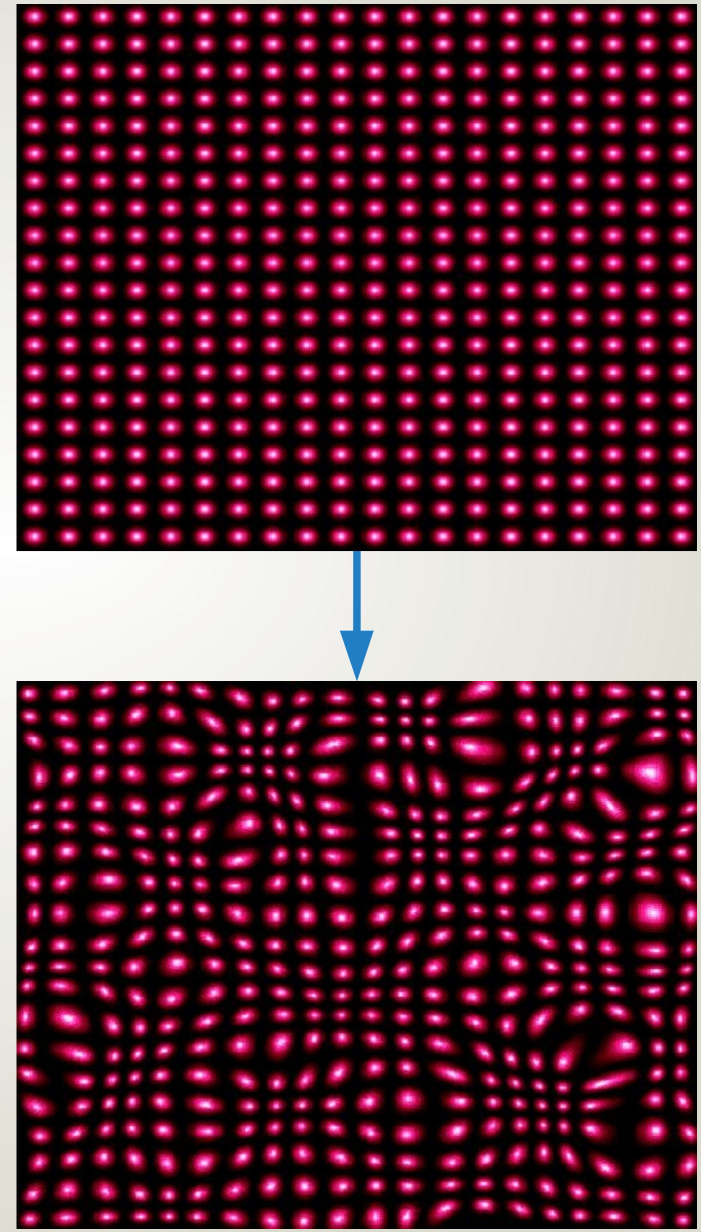

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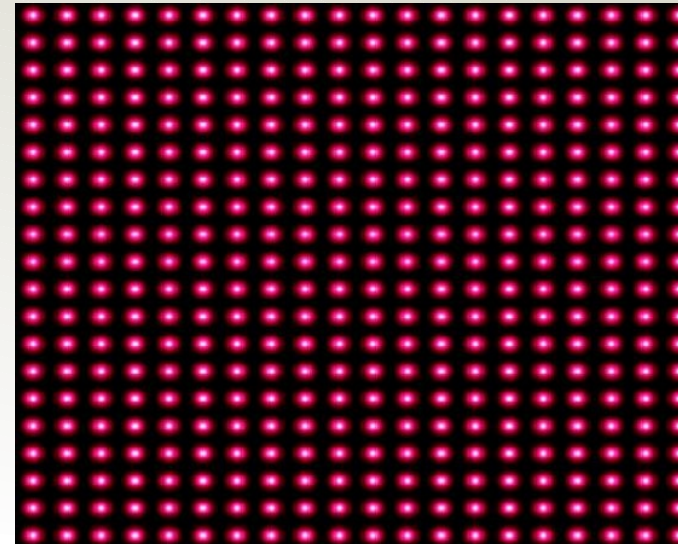

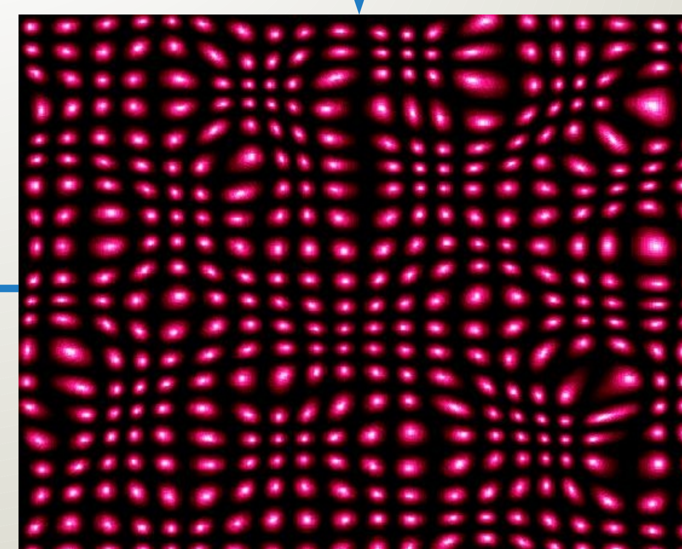

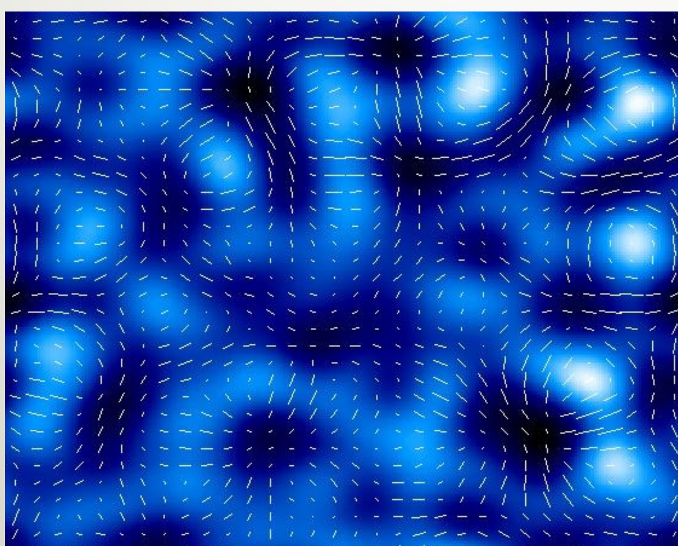

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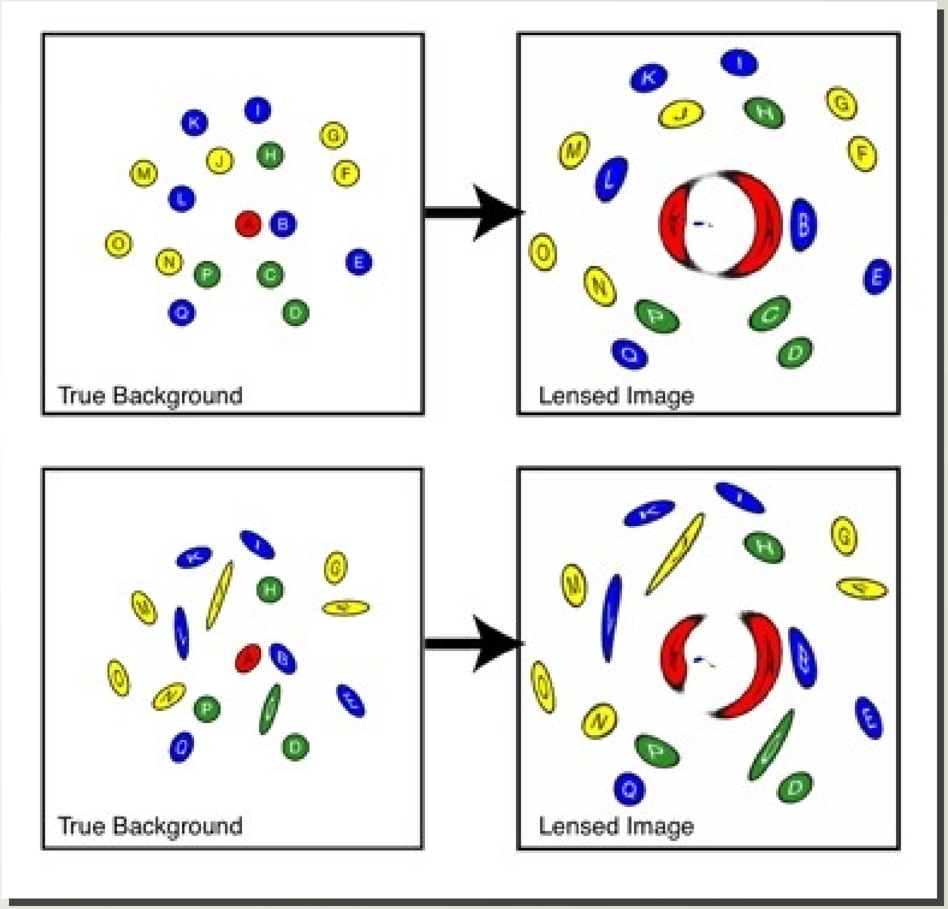

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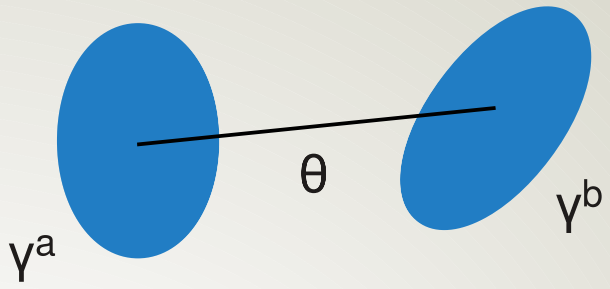
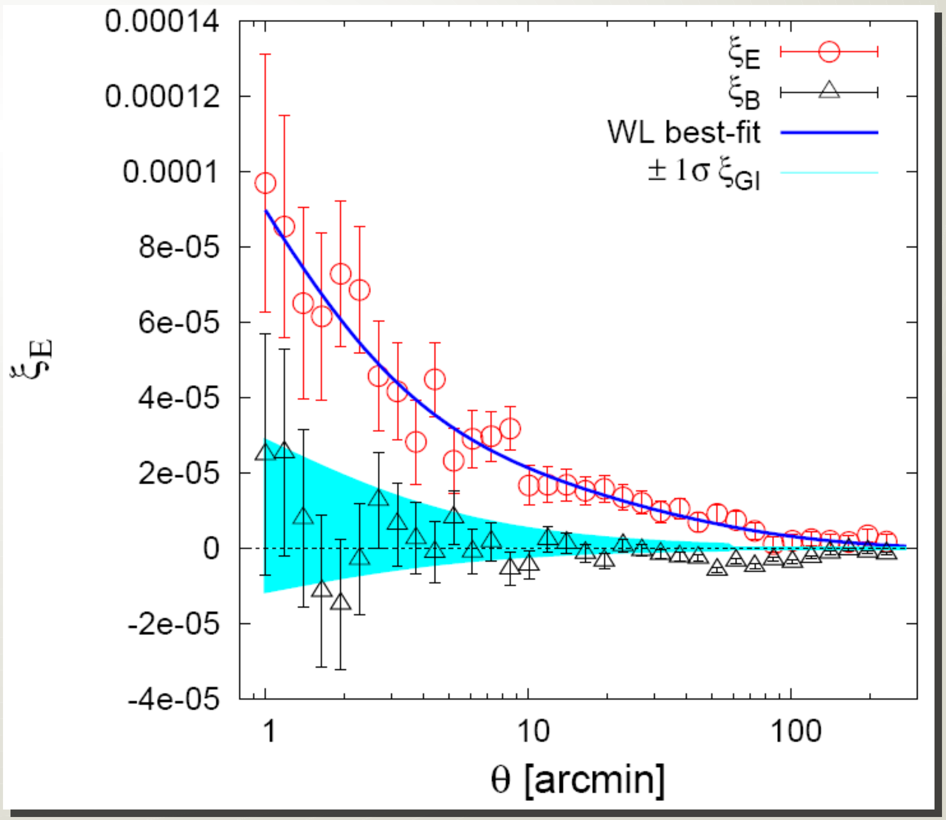
- Use ellipticities of large samples of galaxies to estimate shear correlation function (or power spectrum).



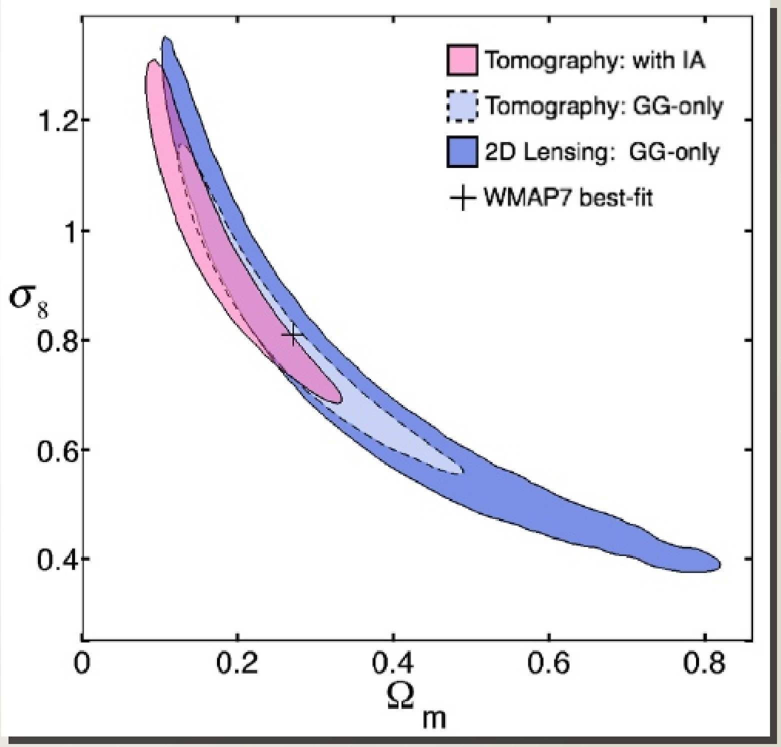


CFHTLS, Fu et al. (2008)

Weak Lensing, Cosmic Shear

$$P_\kappa(l,\chi_s) = \frac{9H_0^4\Omega_m^2}{4c^4}\int_0^{\chi_s} d\chi \frac{(\chi_s-\chi)^2}{\chi_s^2}\frac{P_\delta(l/\chi,\chi)}{a(\chi)^2}$$

- The shear power spectrum is sensitive to:
  - Matter density Ω_M
  - Amplitude of DM power spectrum σ_8
  - Growth of structure → DE, break degeneracy between DE and modified gravity
  - Source distances → DE
  - Expansion history → DE



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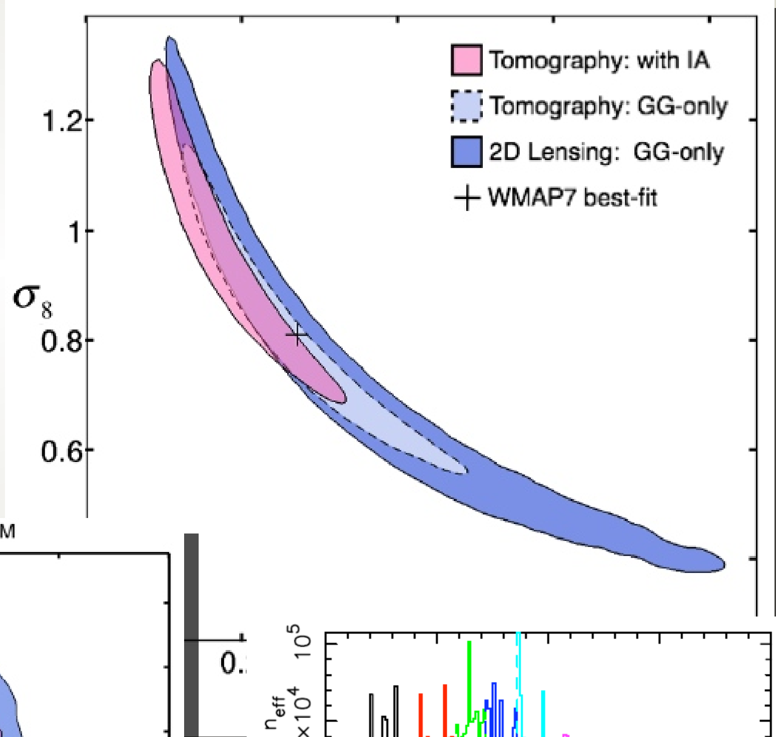
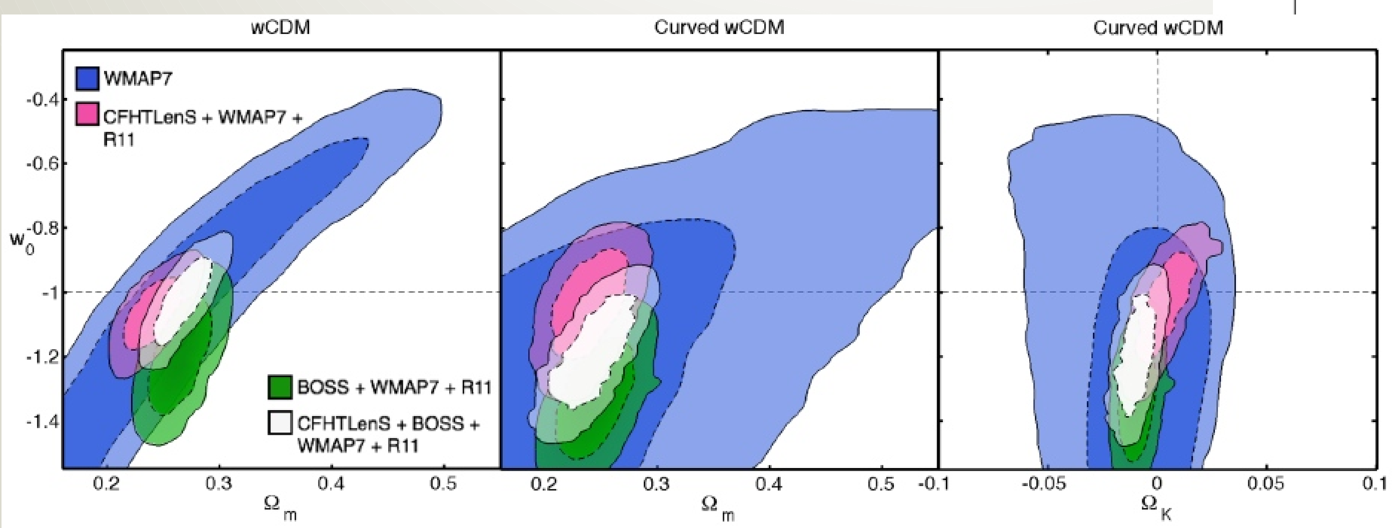
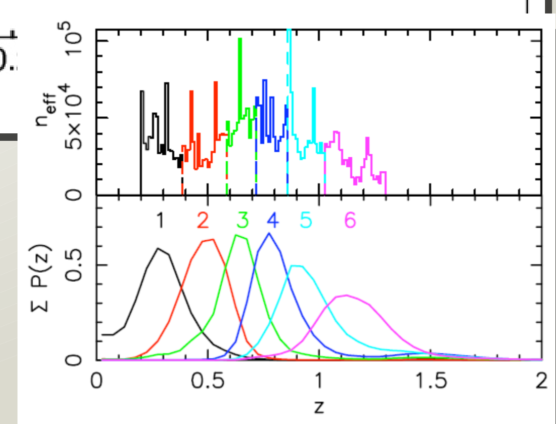
- Redshift information helps → tomography







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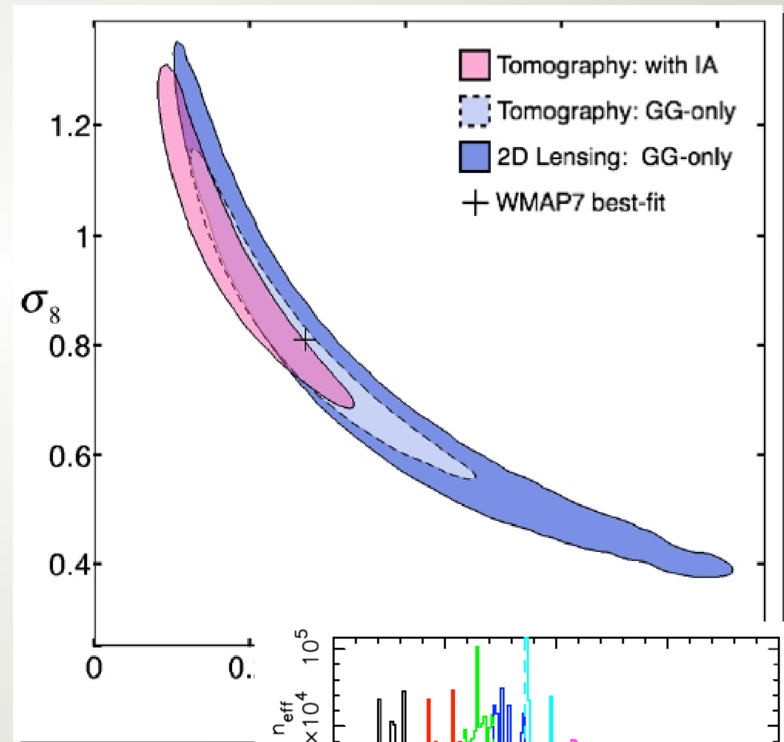
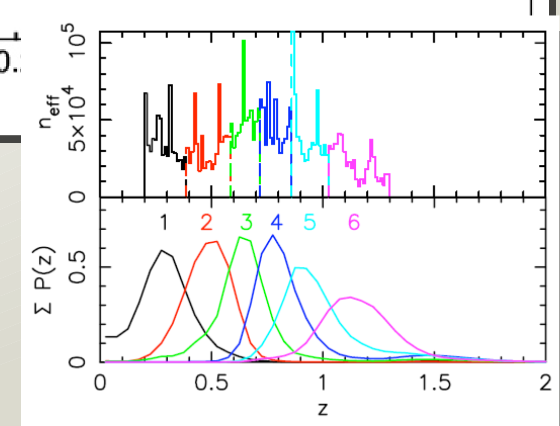
- Redshift information helps → tomography
- This is hard! Need:
  - huge imaging surveys
  - in multiple bands (for photo-z)
  - excellent control of PSF in at least one band
  - shape measurements
  - deal with intrinsic galaxy alignments

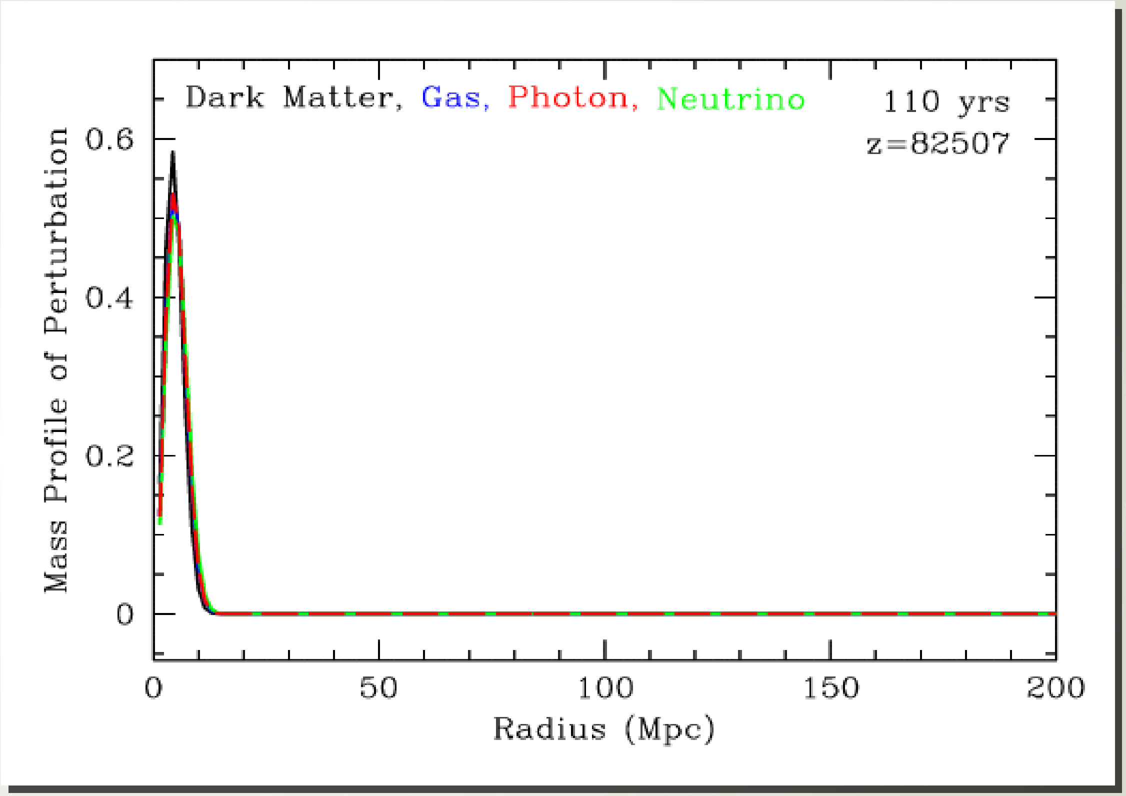




Baryon Acoustic Oscillations

Origin of acoustic peaks in CMB and galaxy power spectra (from D. Eisenstein and W. Hu)

- Consider initial point-like density perturbation in the early Universe.



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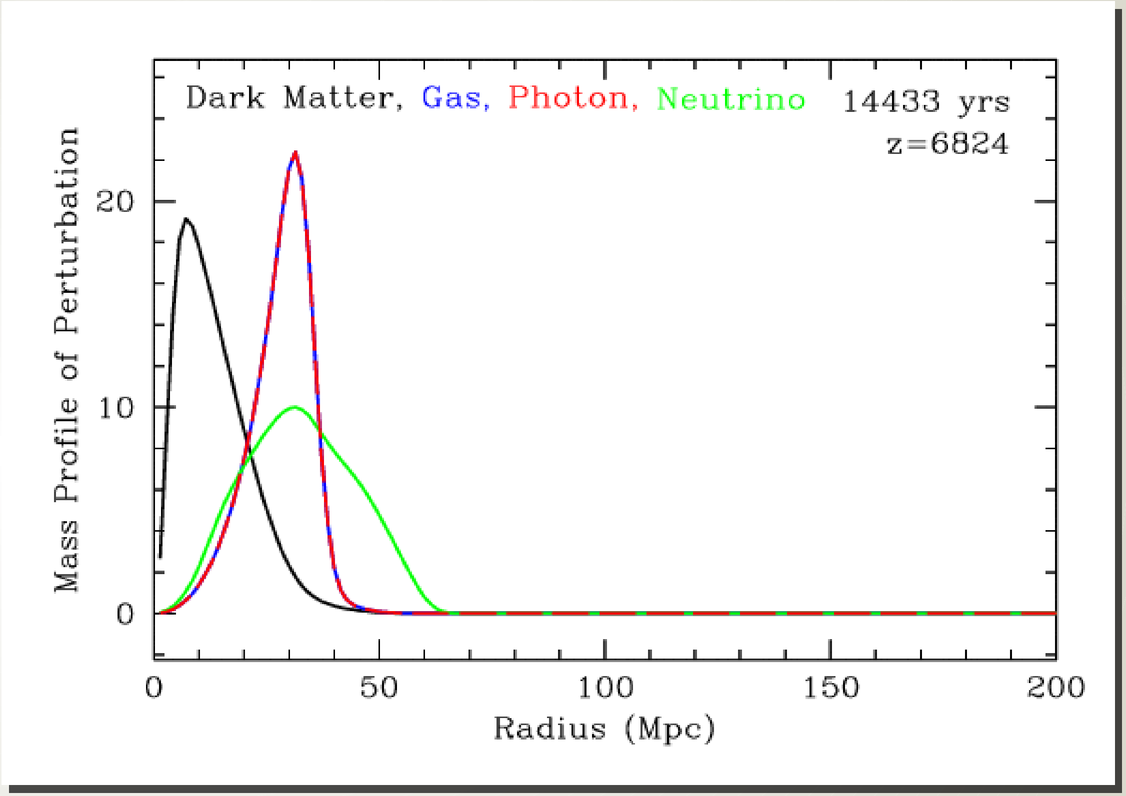
- As it evolves:
  - Neutrinos free-stream
  - CDM attracts more CDM
  - Hot photon-gas fluid has huge pressure → wave travels outward at speed of sound (acoustic wave)



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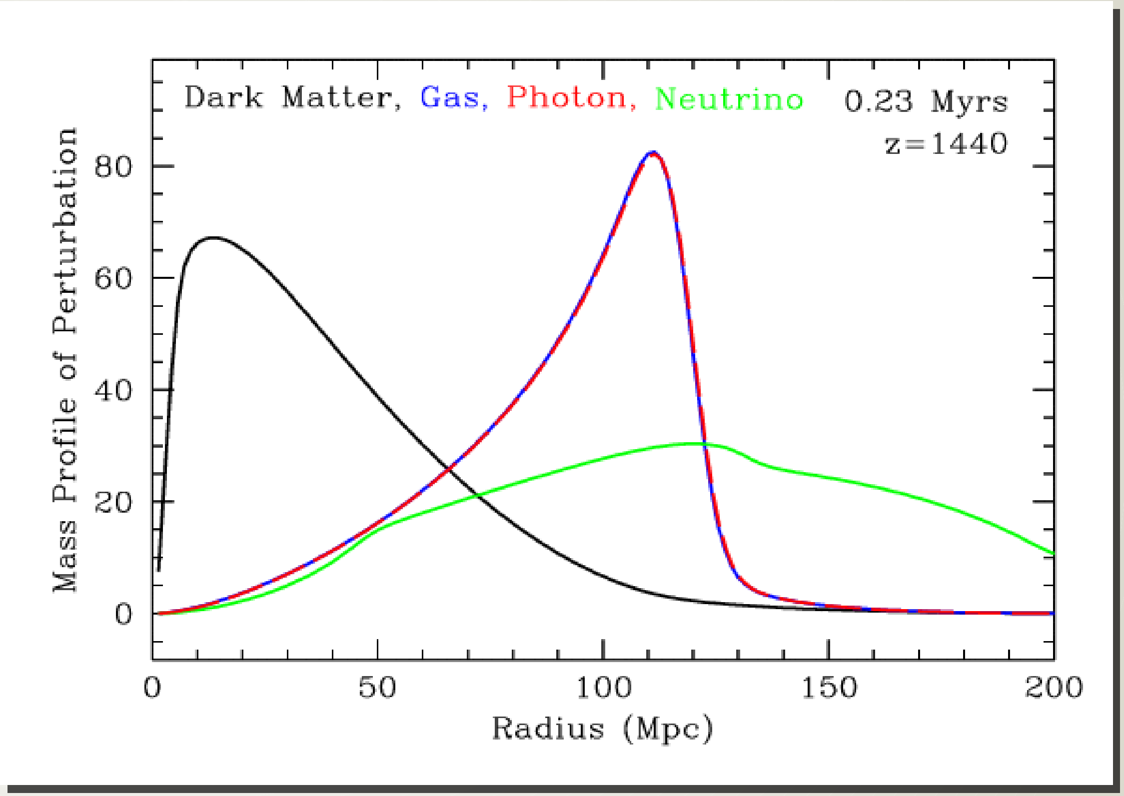

Baryon Acoustic Oscillations

Origin of acoustic peaks in CMB and galaxy power spectra (from D. Eisenstein and W. Hu)

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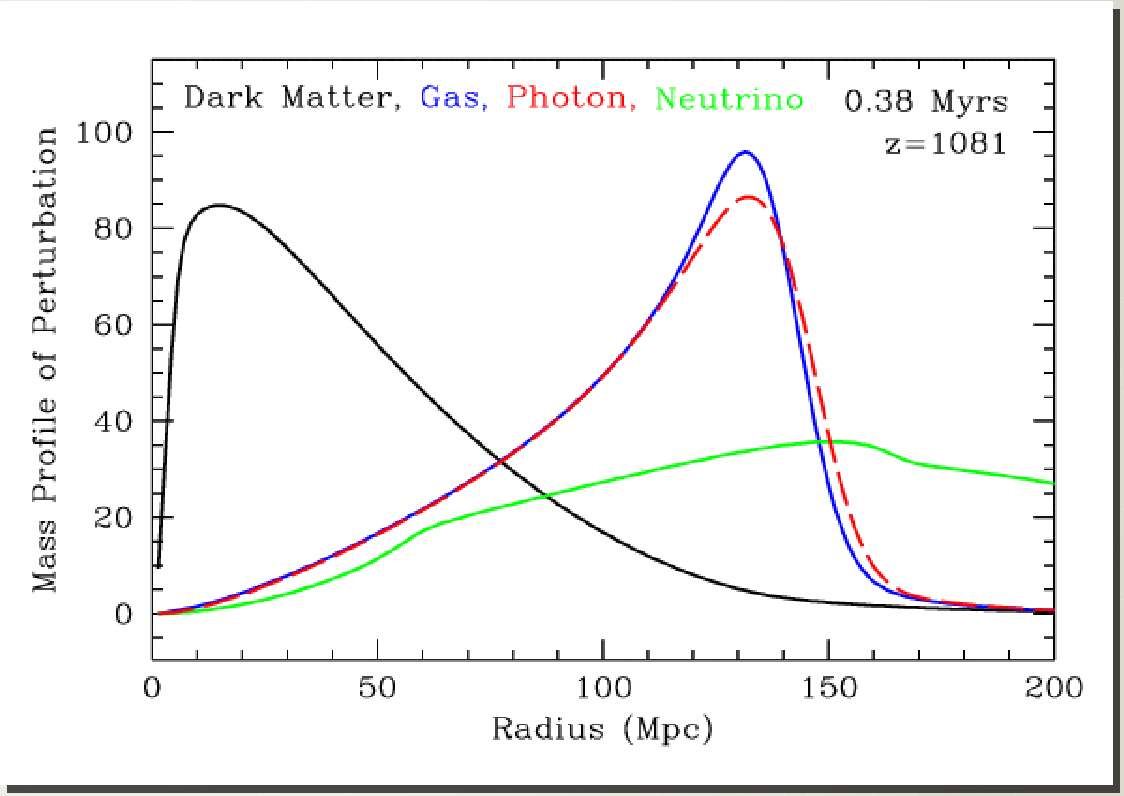

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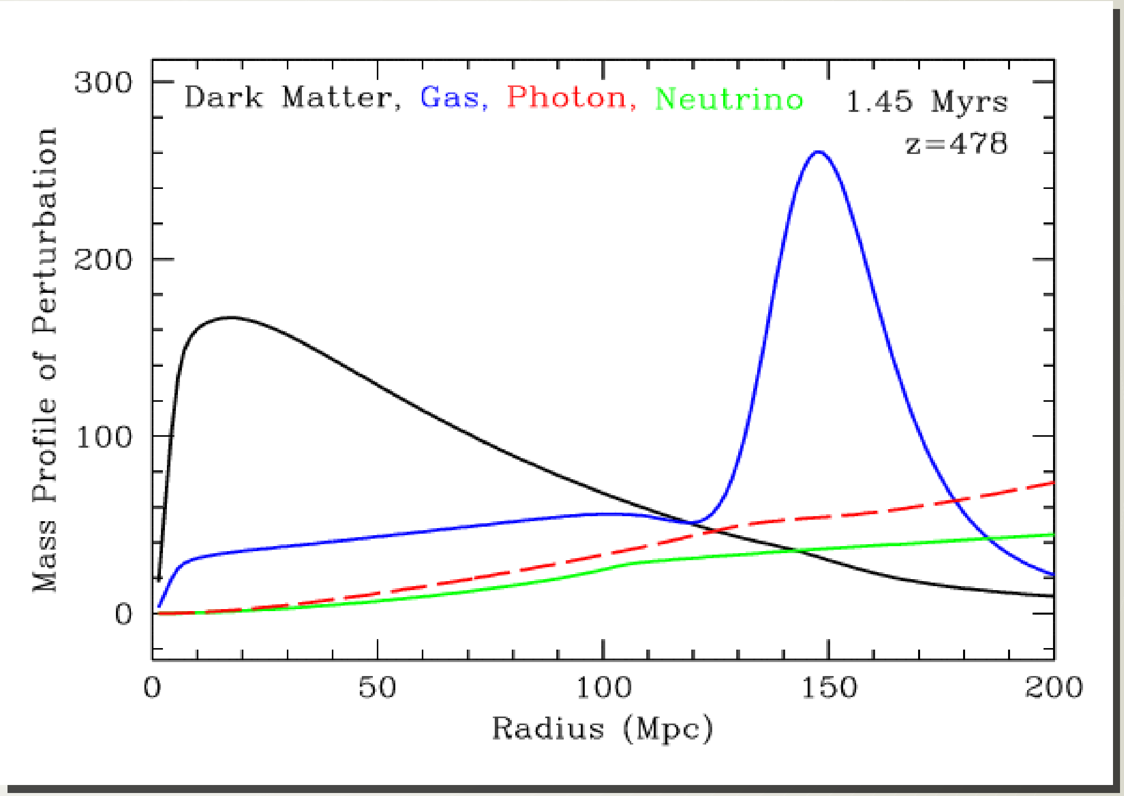

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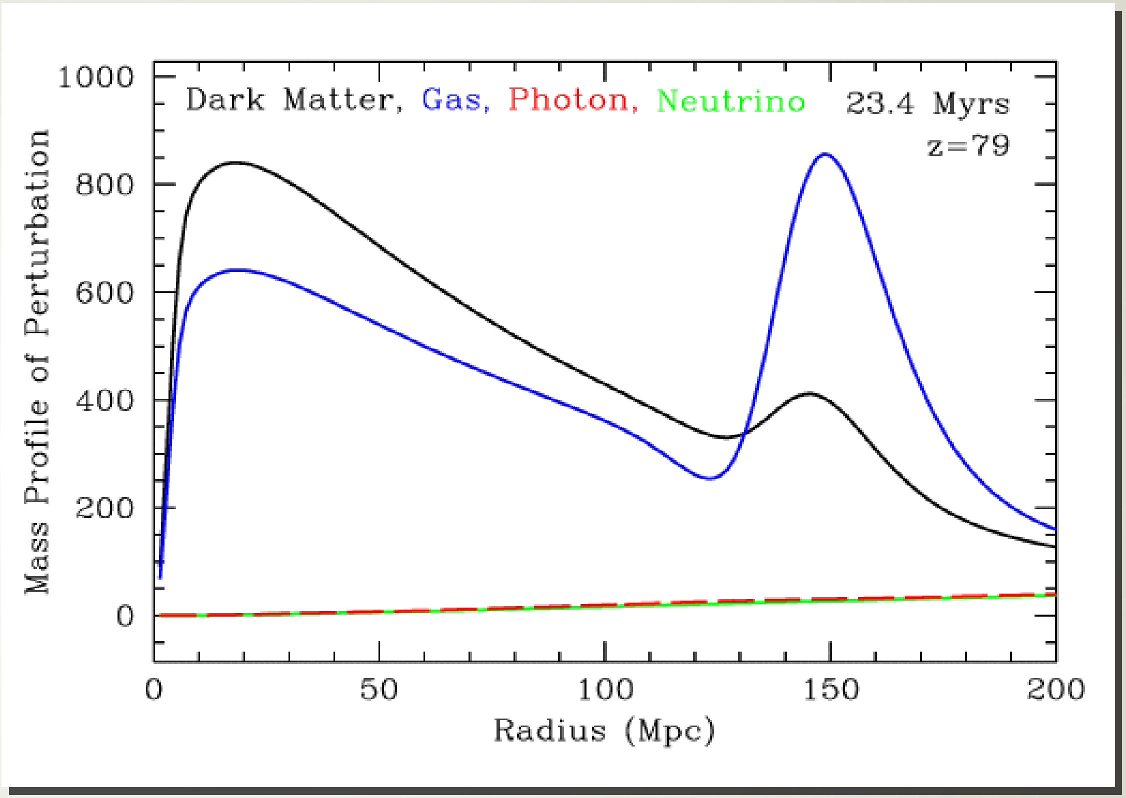

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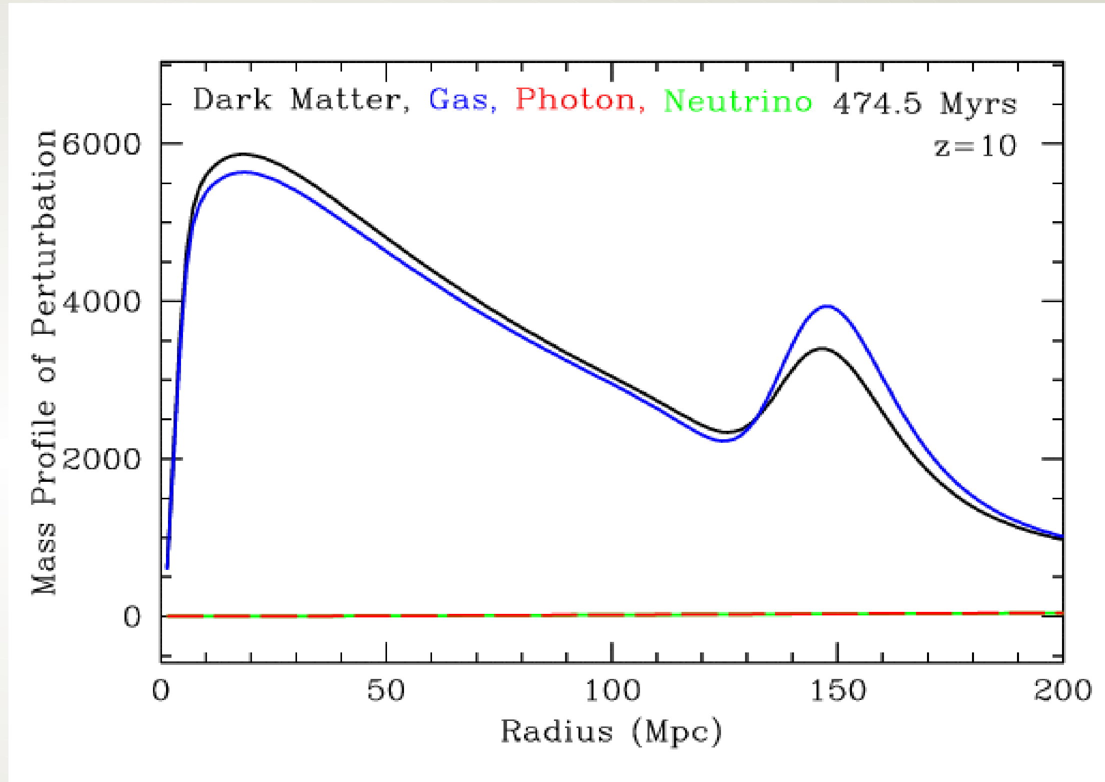
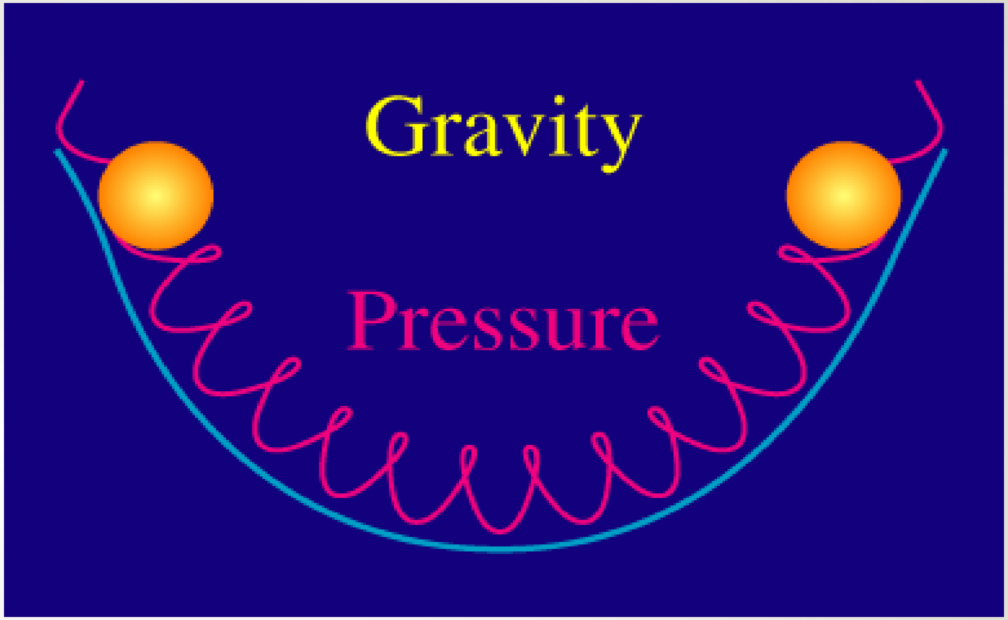


- An overdensity of both baryons and CDM remains at the location of the initial density perturbation as well as at a distance of $c_s * t_{recomb}$ → these act as seeds for galaxy formation → a preferred scale is imprinted on the galaxy distribution.

Baryon Acoustic Oscillations

Origin of acoustic peaks in CMB and galaxy power spectra (from D. Eisenstein and W. Hu)

- But it's a wave! So far only considered a single crest.



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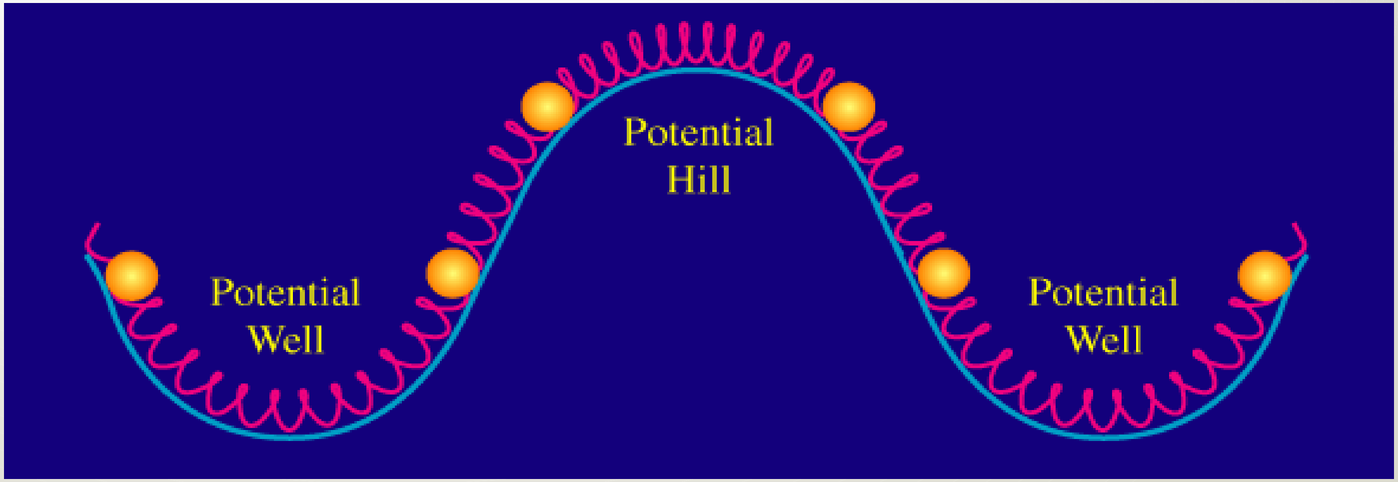

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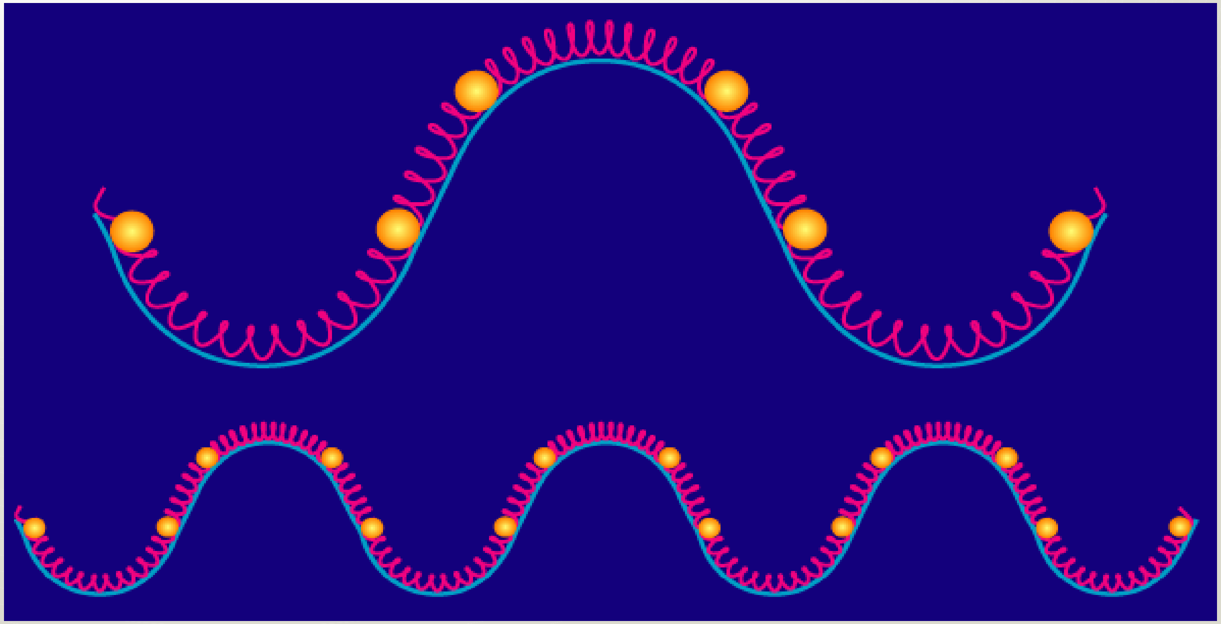

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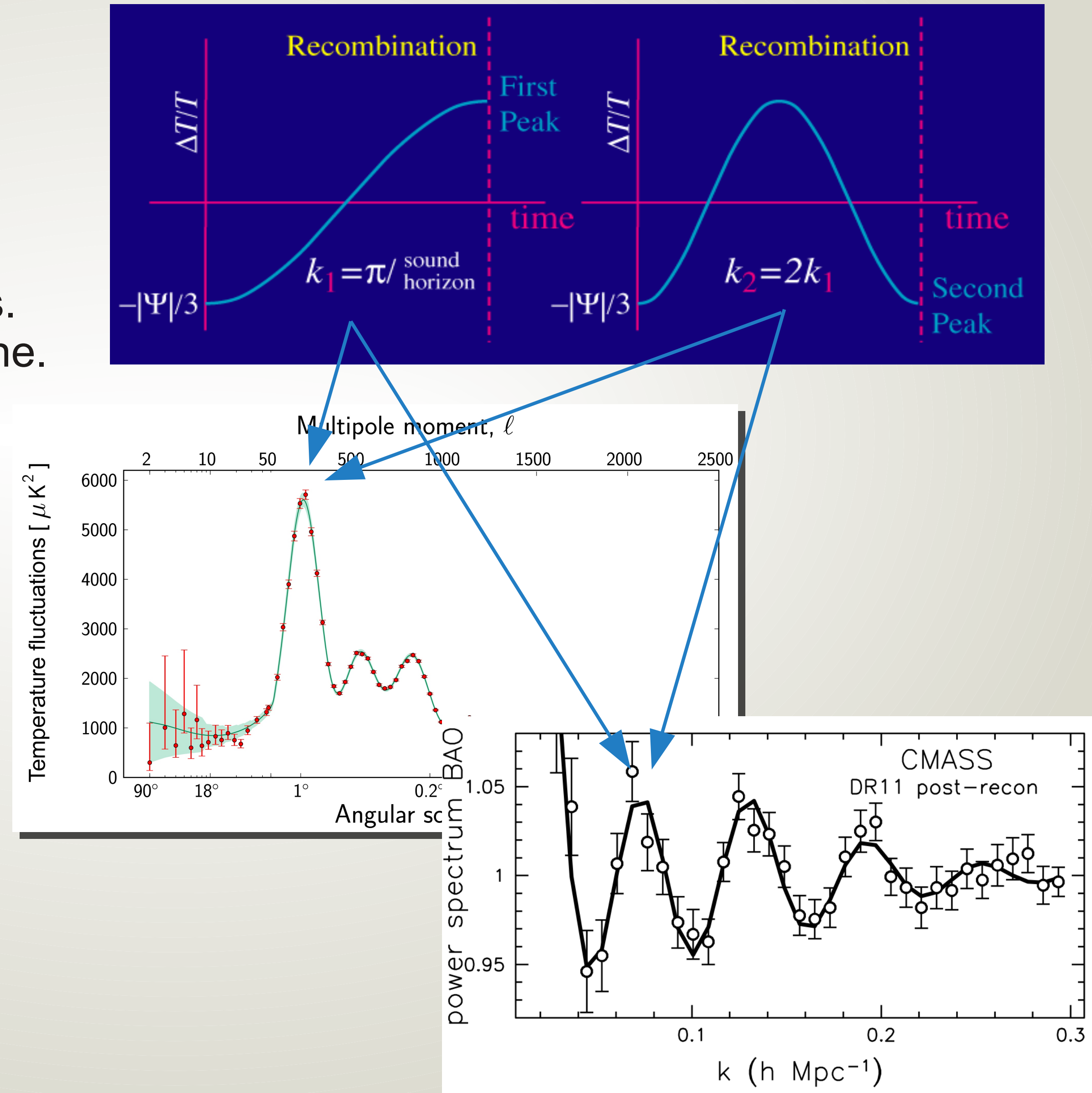
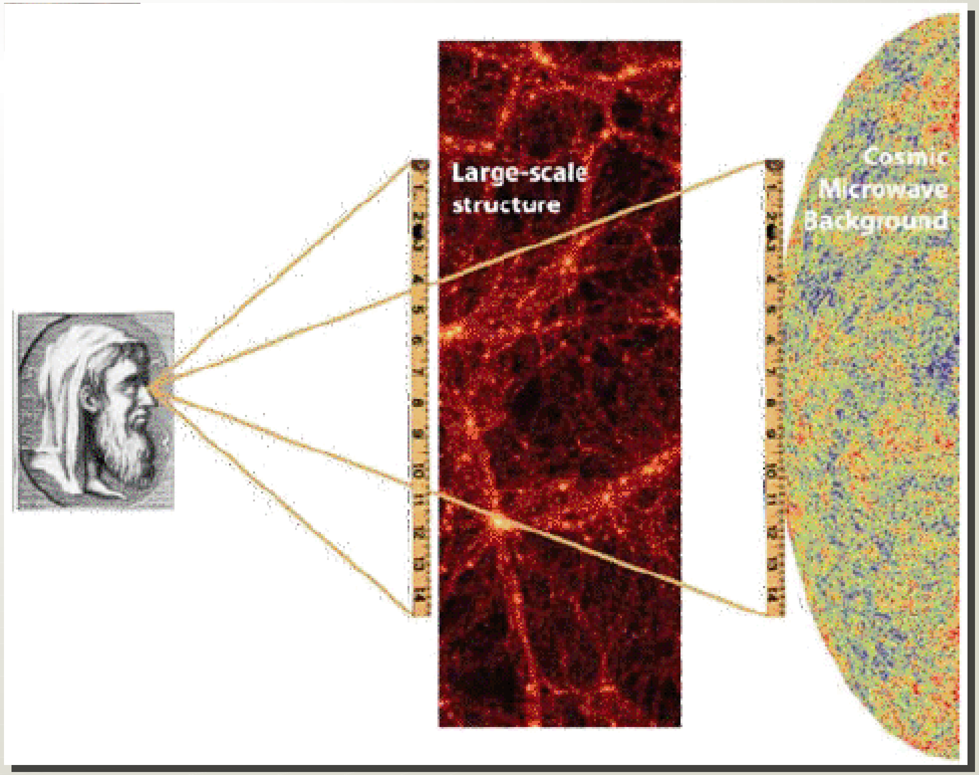
- And there are many perturbations. So far only considered a single one.
- In fact, there's a spectrum of perturbations with some power spectrum.
- All modes that are multiples of $c_s{}^*t_{recomb}$ are enhanced.



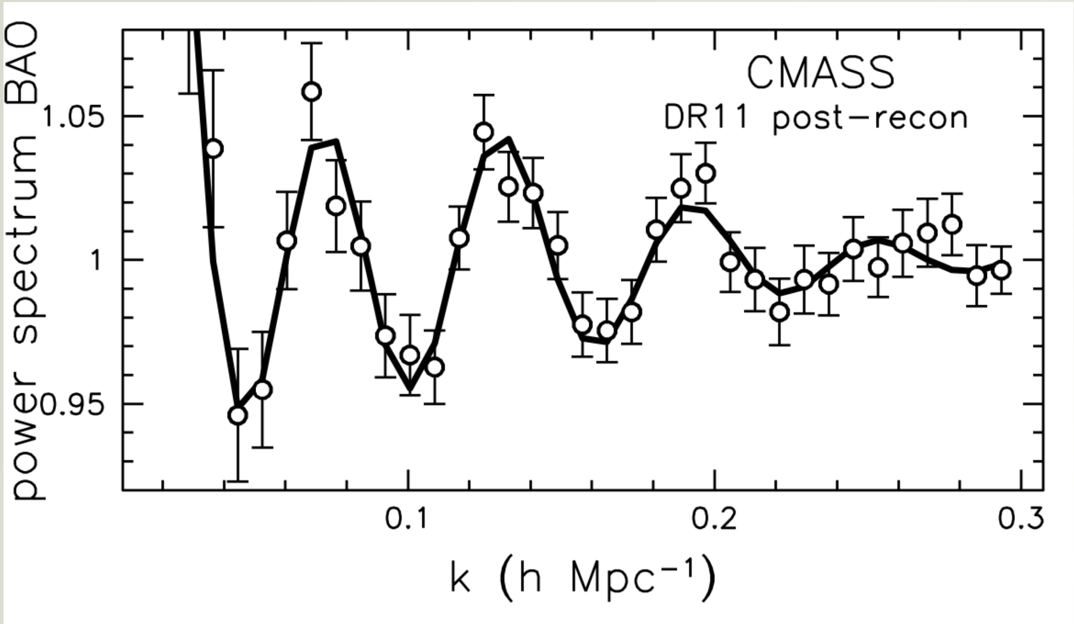
Baryon Acoustic Oscillations

- Geometrical large-angle standard ruler test.
- The ruler itself is based on clean, linear-regime physics at the recombination epoch which is very sensitively probed by the CMB and well understood.
- Provides $D_A(z)$, $H(z)$, $D_V(z)$ (Alcock-Pacinski test).
- Not sensitive to galaxy evolution, dust, etc.
- Does not require precise measurements. Basic galaxy photometry and spectroscopy is enough,
- Works best at $1 < z < 3$.
- Get RSD for free.

- Requires huge samples, i.e. Surveys: volumes of > 1 Gpc^3
- Needs spectroscopy.
- Works best at $1 < z < 3$.



BAO Current Results



BOSS, Anderson et al. (2014)

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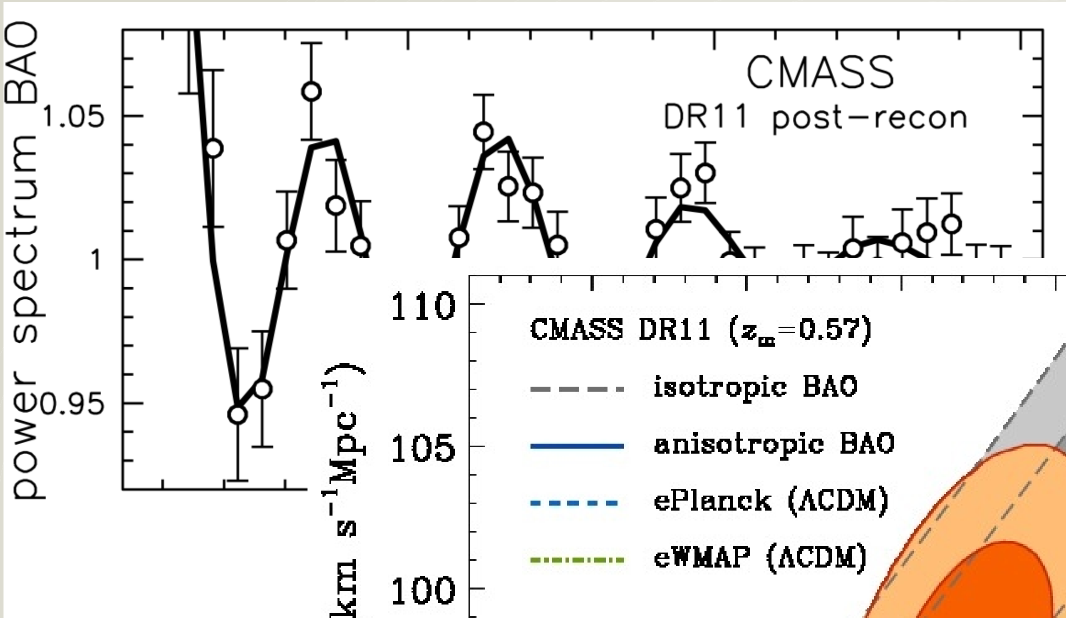

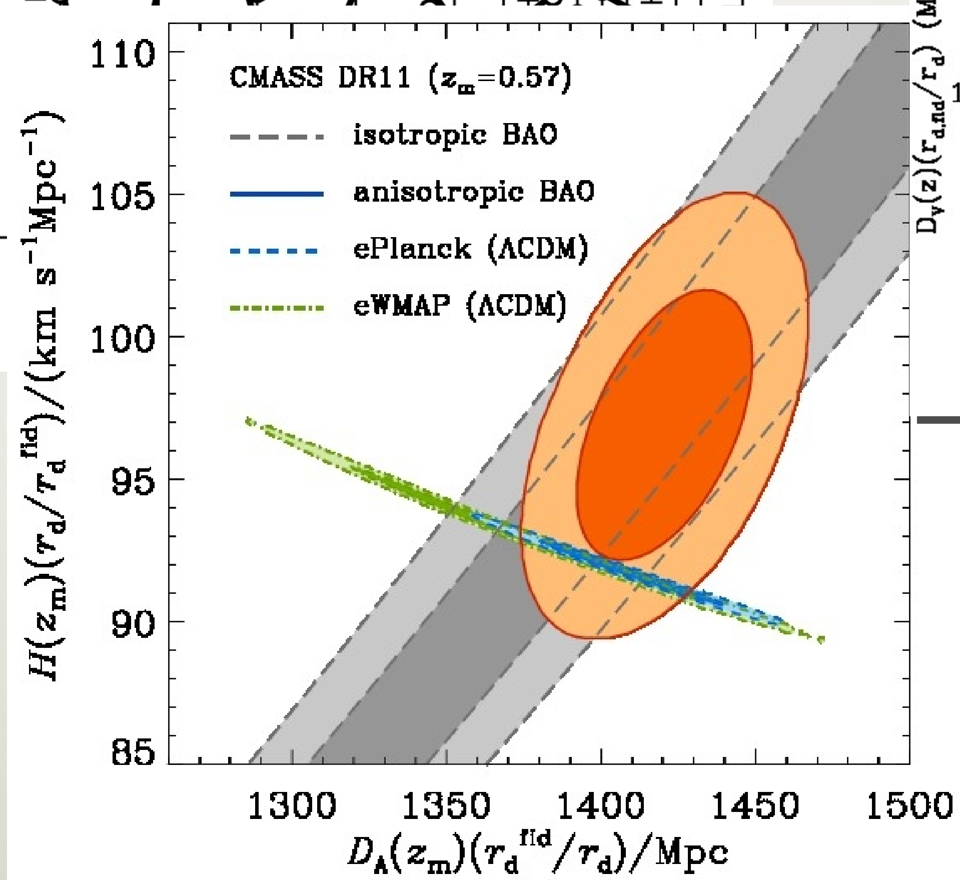

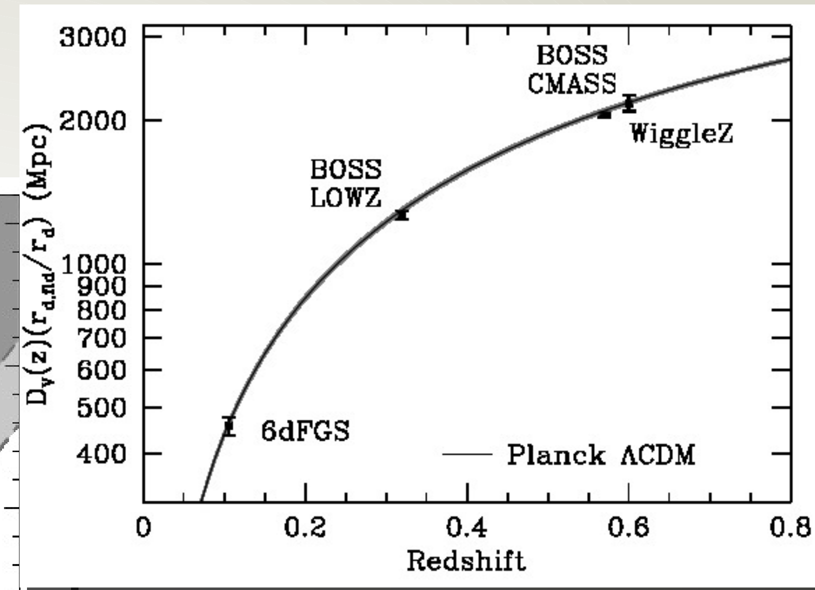

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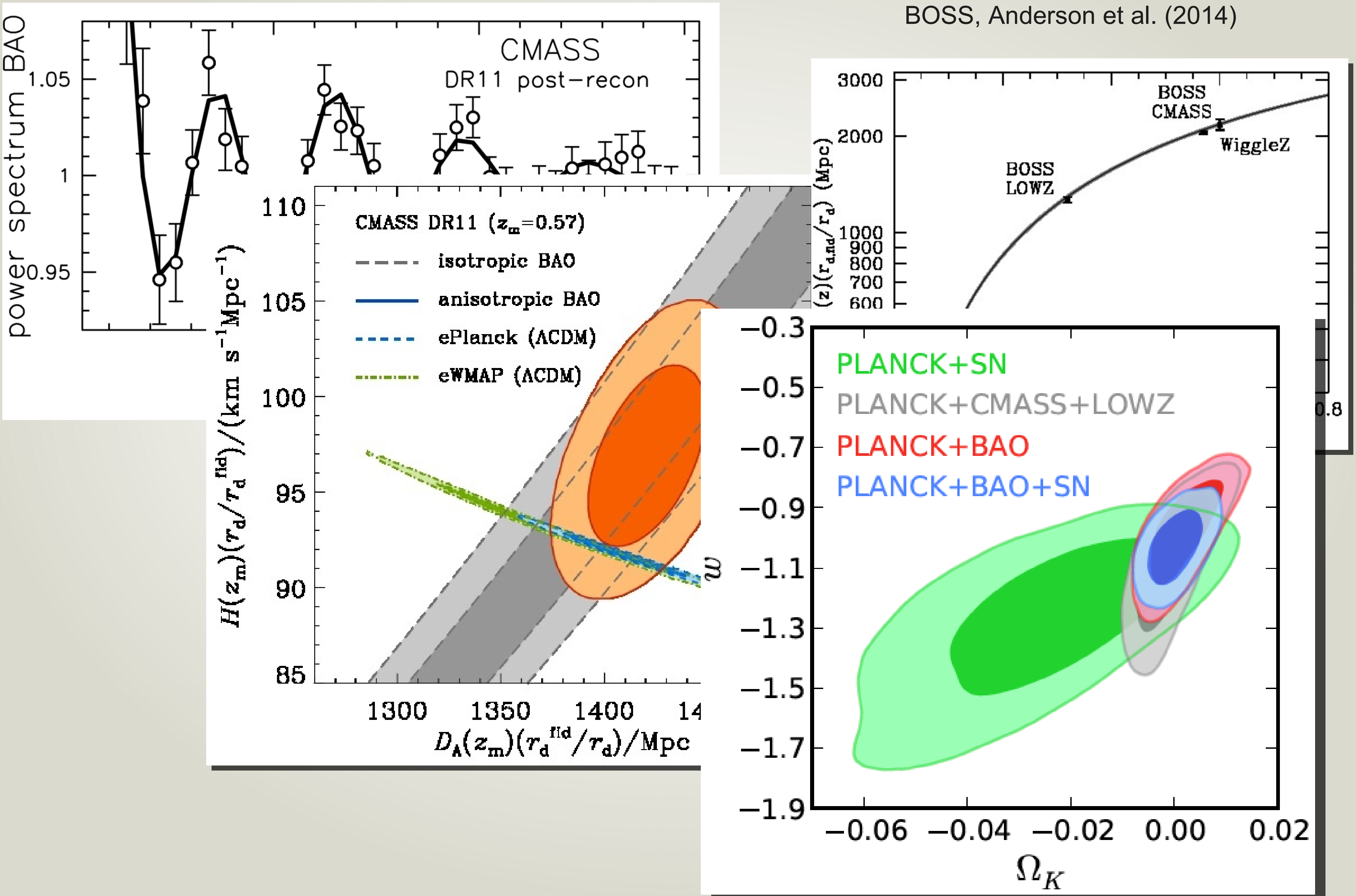
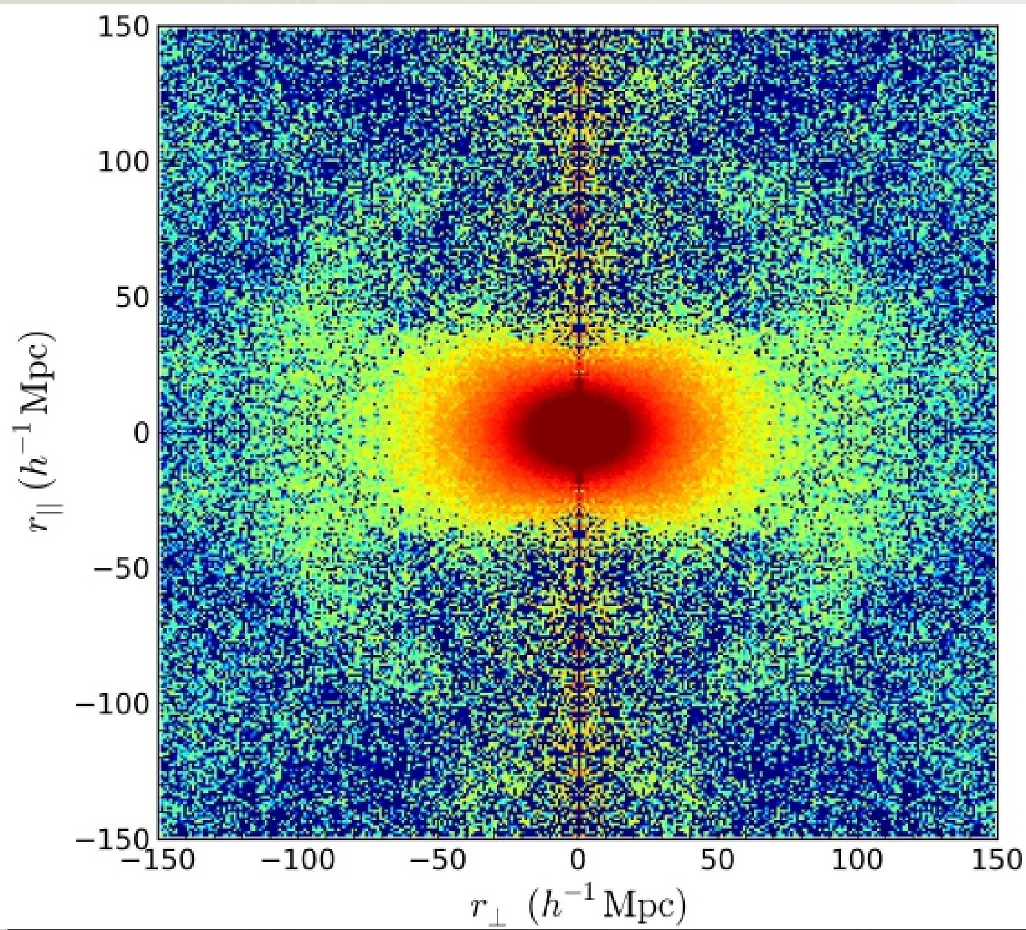


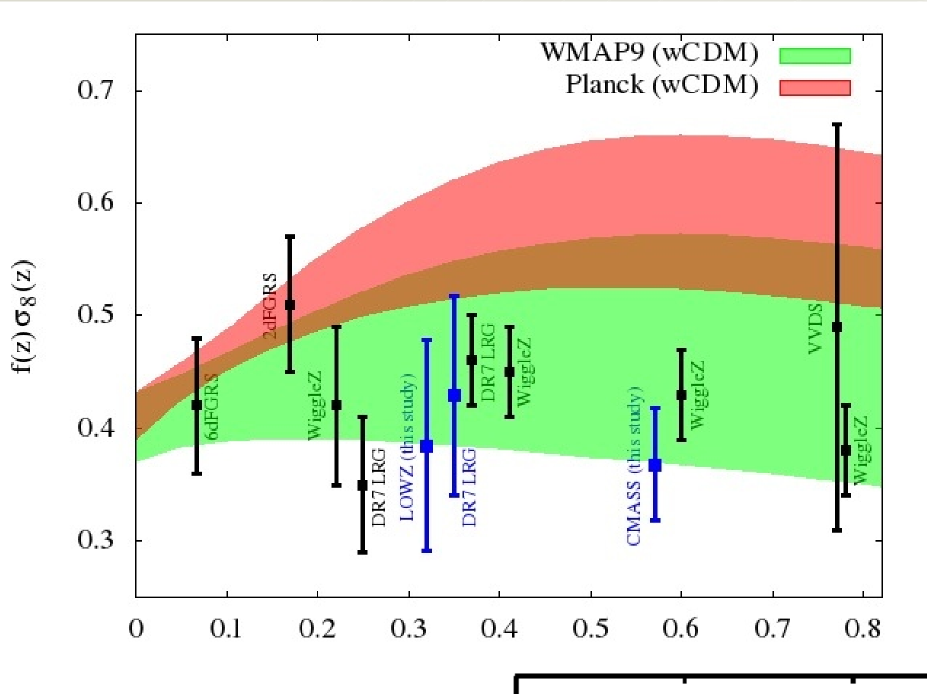
Redshift Space Distortions



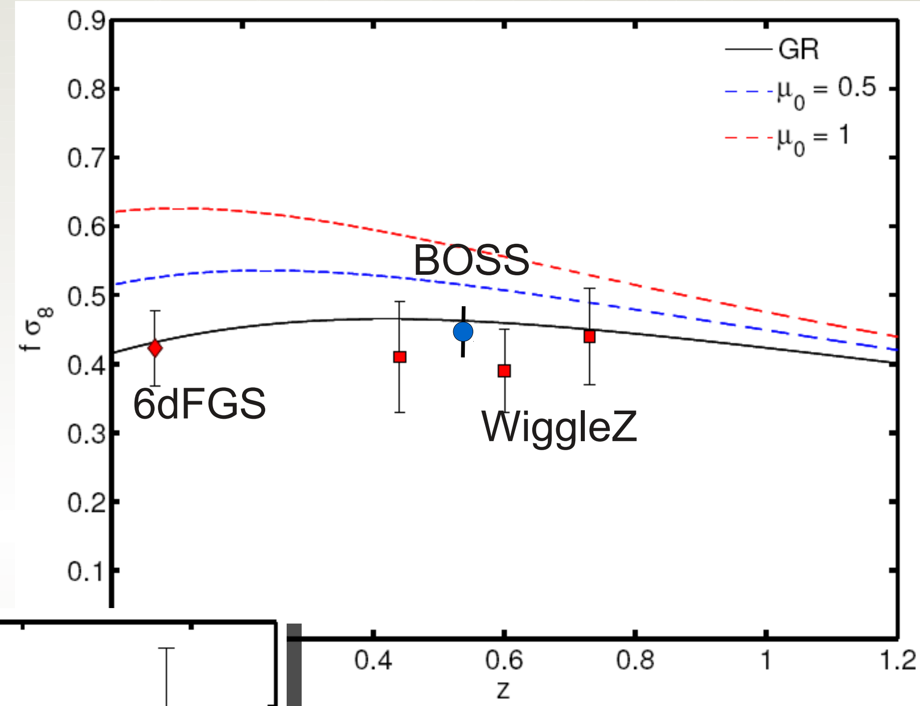
Samushia et al. (2013)

- Measured redshifts include not only the Hubble flow but also peculiar velocities:
  - on small scales: finger-of-God effect in collapsed structures
  - on large scales: infall into high-density regions and outflow from low-density regions (Kaiser effect)
- Creates anisotropy between the LOS and transverse correlation functions.
- Anisotropy constrains σ_8*dlnG/dlna, i.e. the growth of structure.
- Breaks the degeneracy between DE and modified gravity models with the same H(z).
- Again need big redshift surveys, but get them 'for free' with BAO surveys.

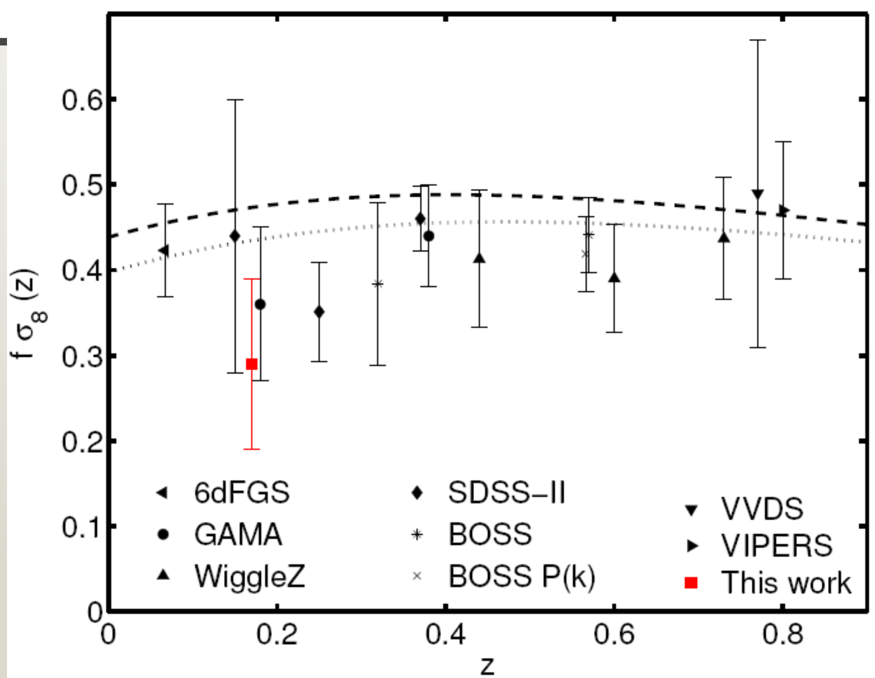
RSD Current Results



Chuang et al. (2014)



Simpson et al. (2013)



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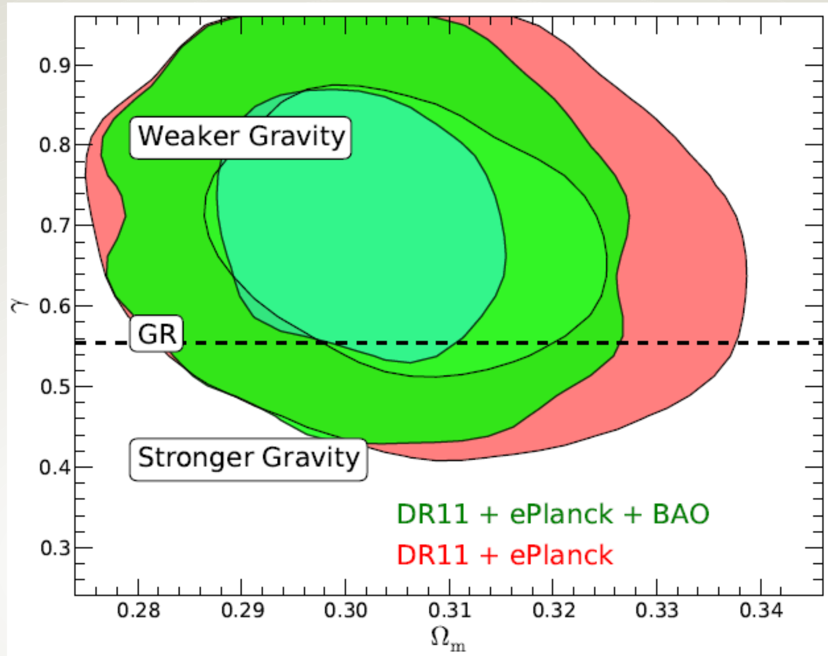

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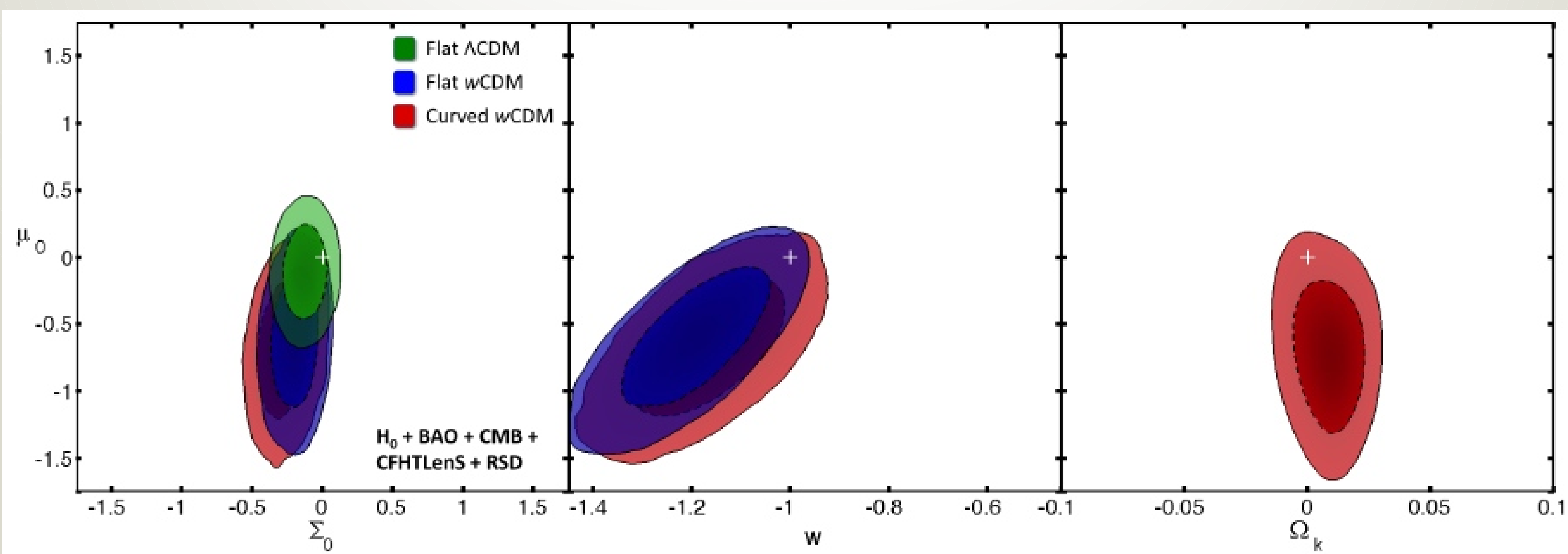

Simpson et al. (2013)

Accelerated Expansion

- Intense interest in the expansion history. Best current methods of measuring H(z):
  - SNIa
  - Weak lensing
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DES
eBOSS
HETDEX
4MOST
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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).

Observing the Expansion

A photon emitted by some object at comoving distance χ at time t_{em} and observed at t_{obs} suffers a redshift of:

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

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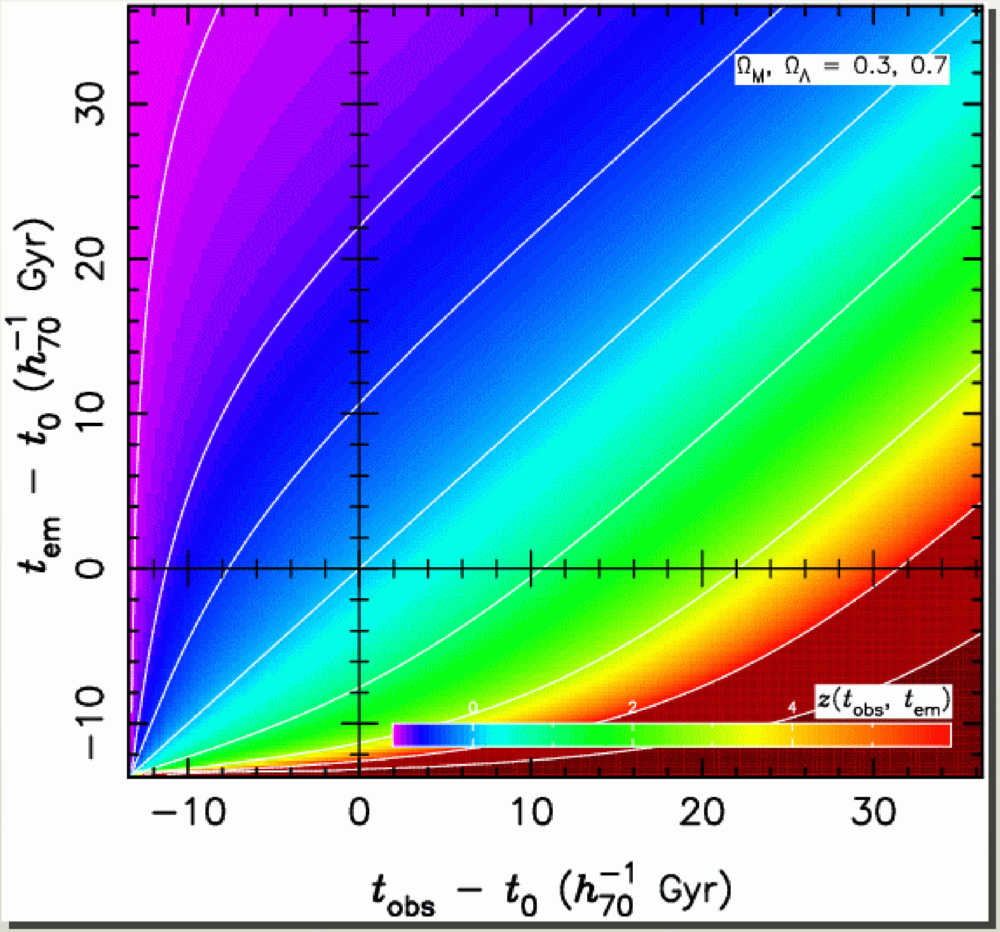

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Three ways to look at this equation:

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

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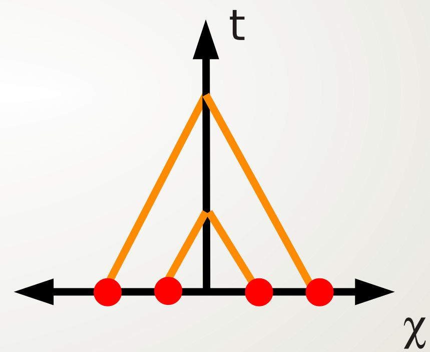
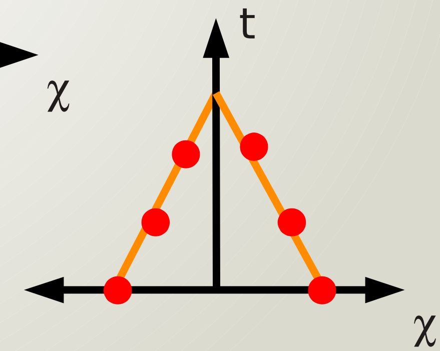
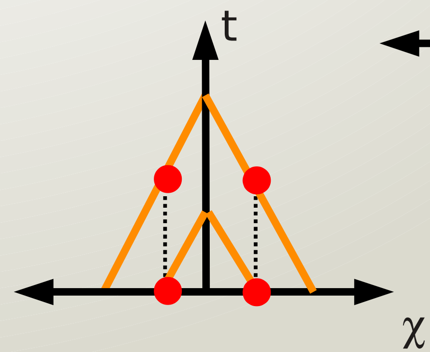
3. $$1+z(t_{obs}) = \frac{a(t_{obs})}{a(t_{em})}$$ χ const







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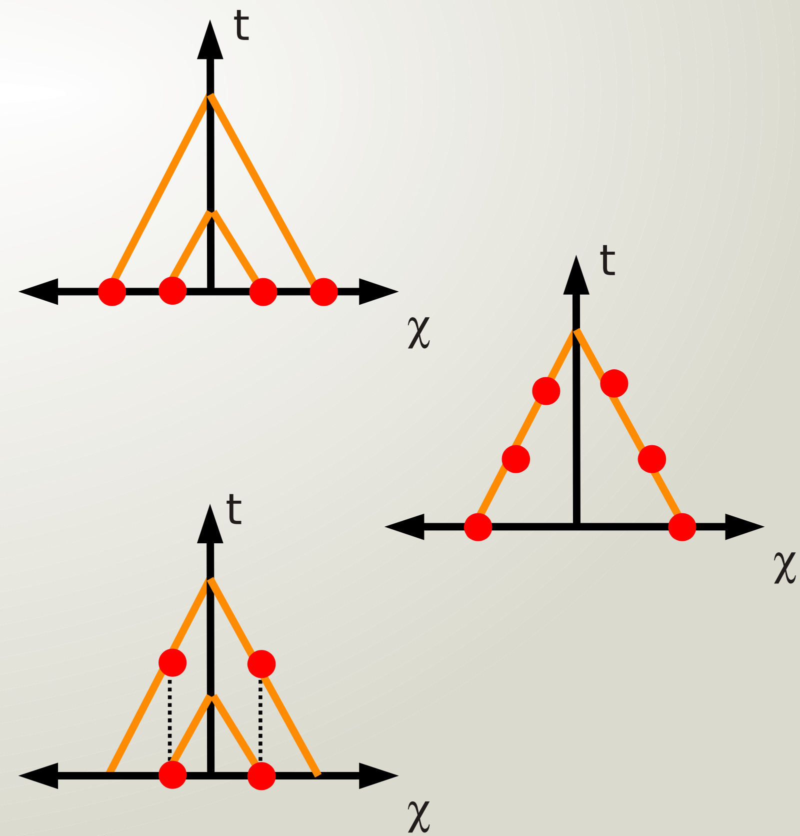

Evolving redshifts

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

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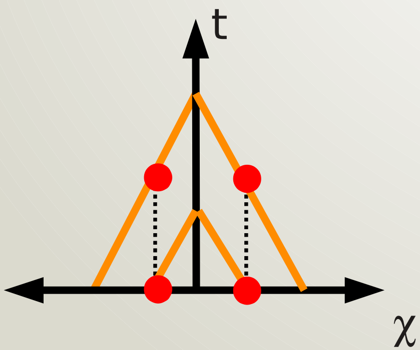

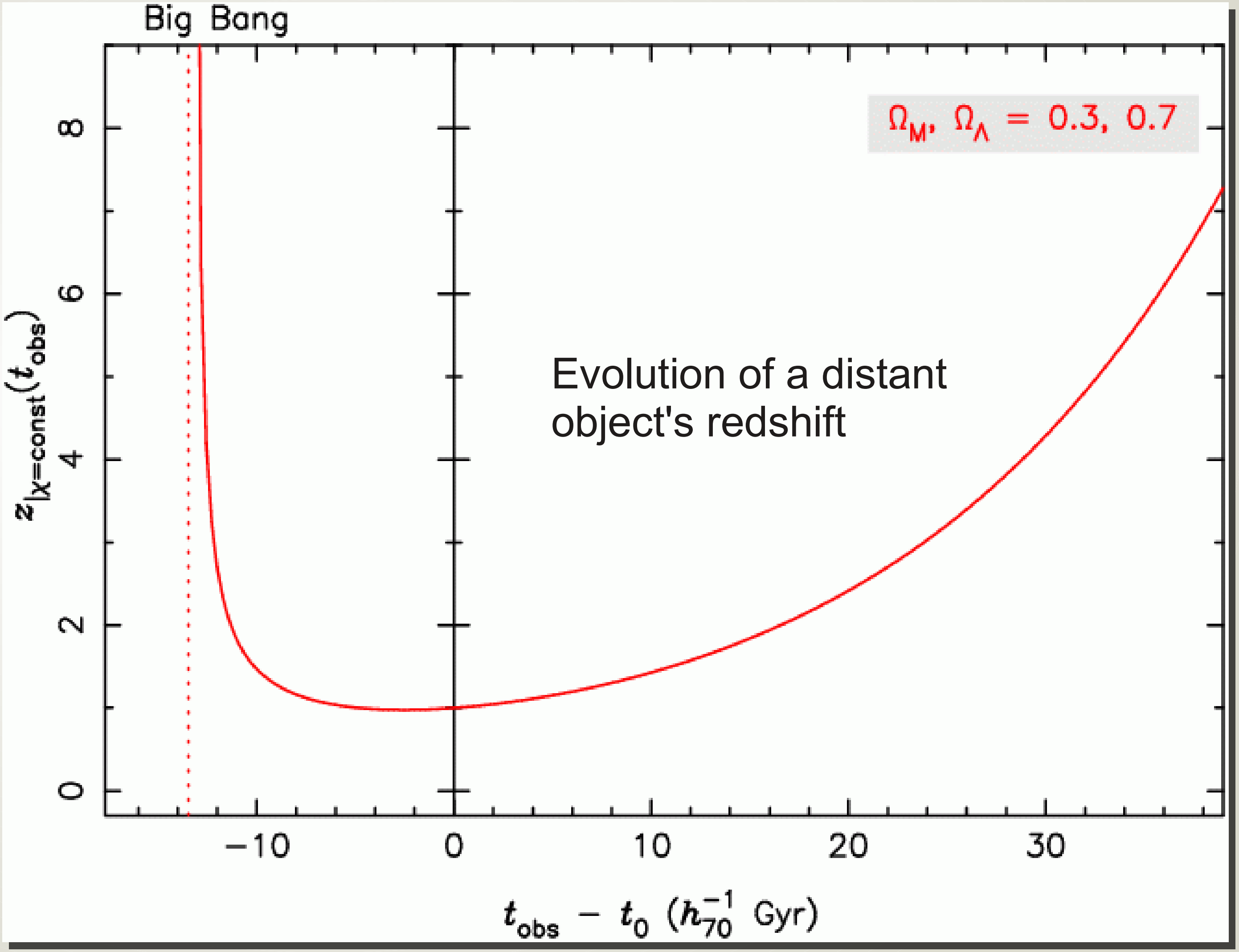

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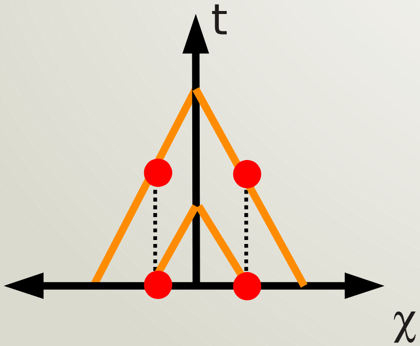

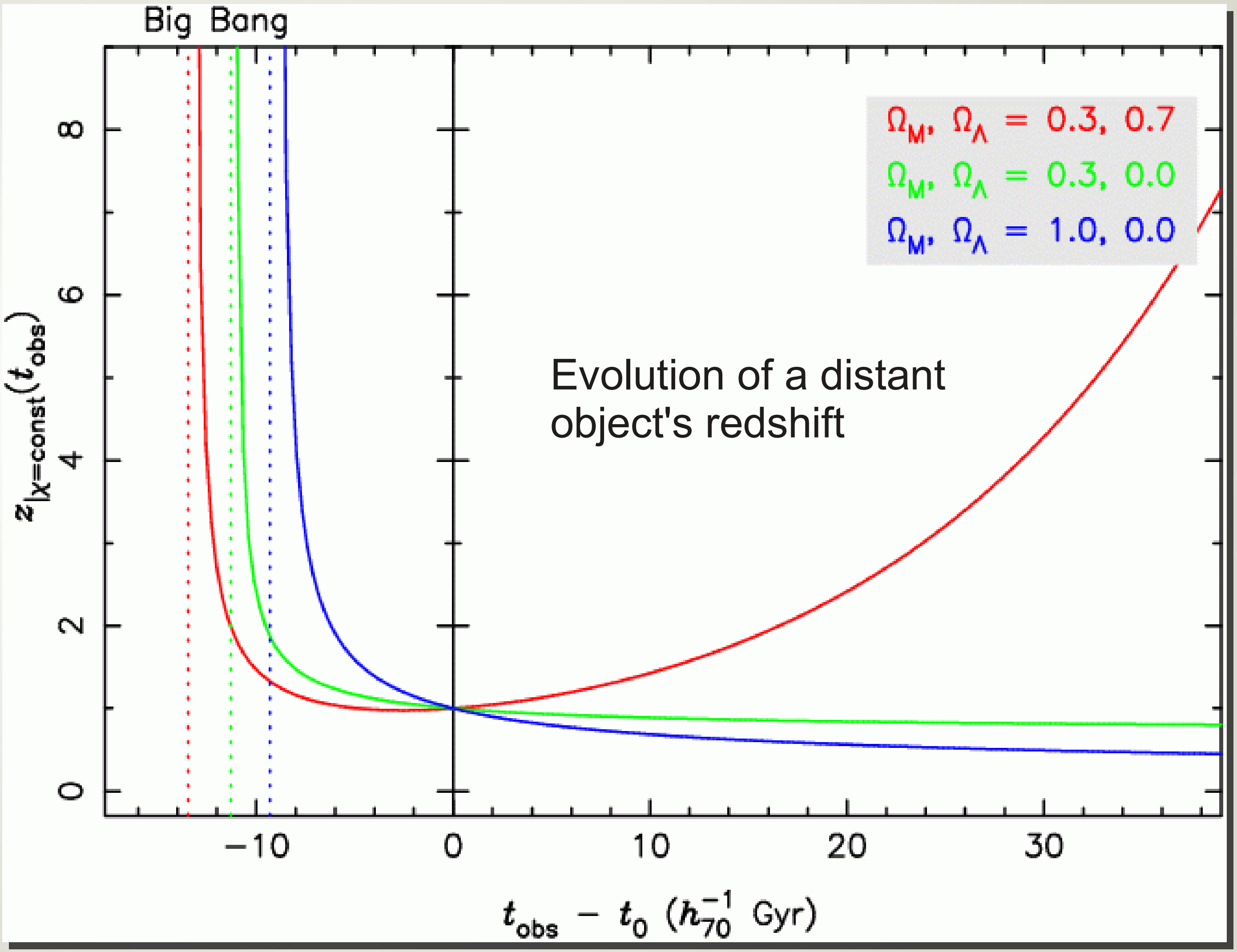

Evolution of a distant object's redshift

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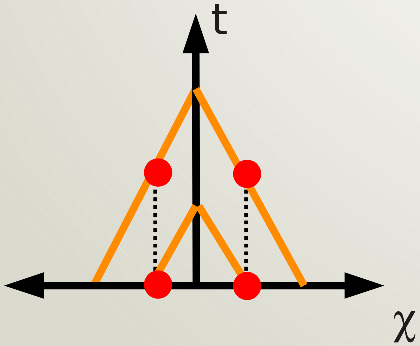
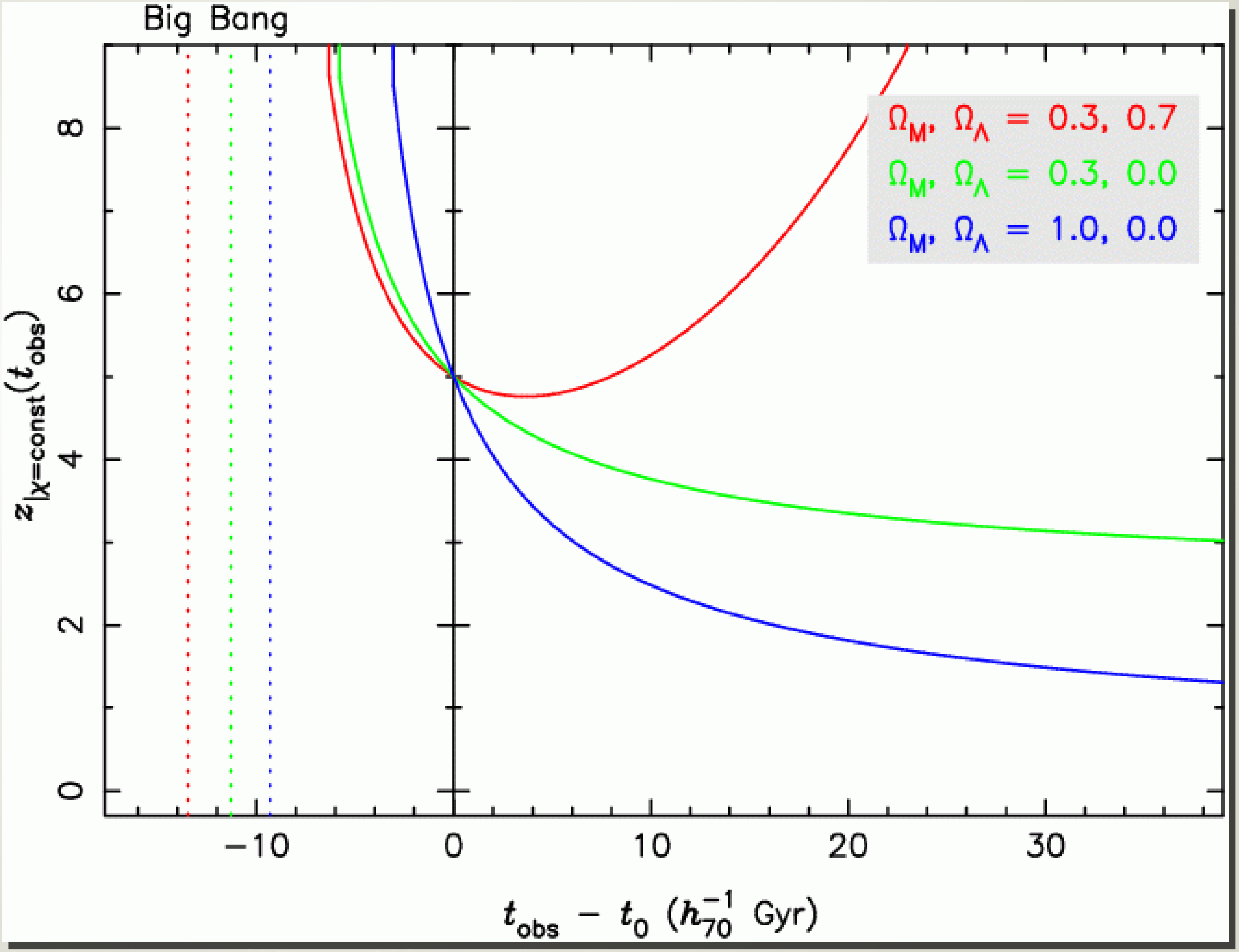


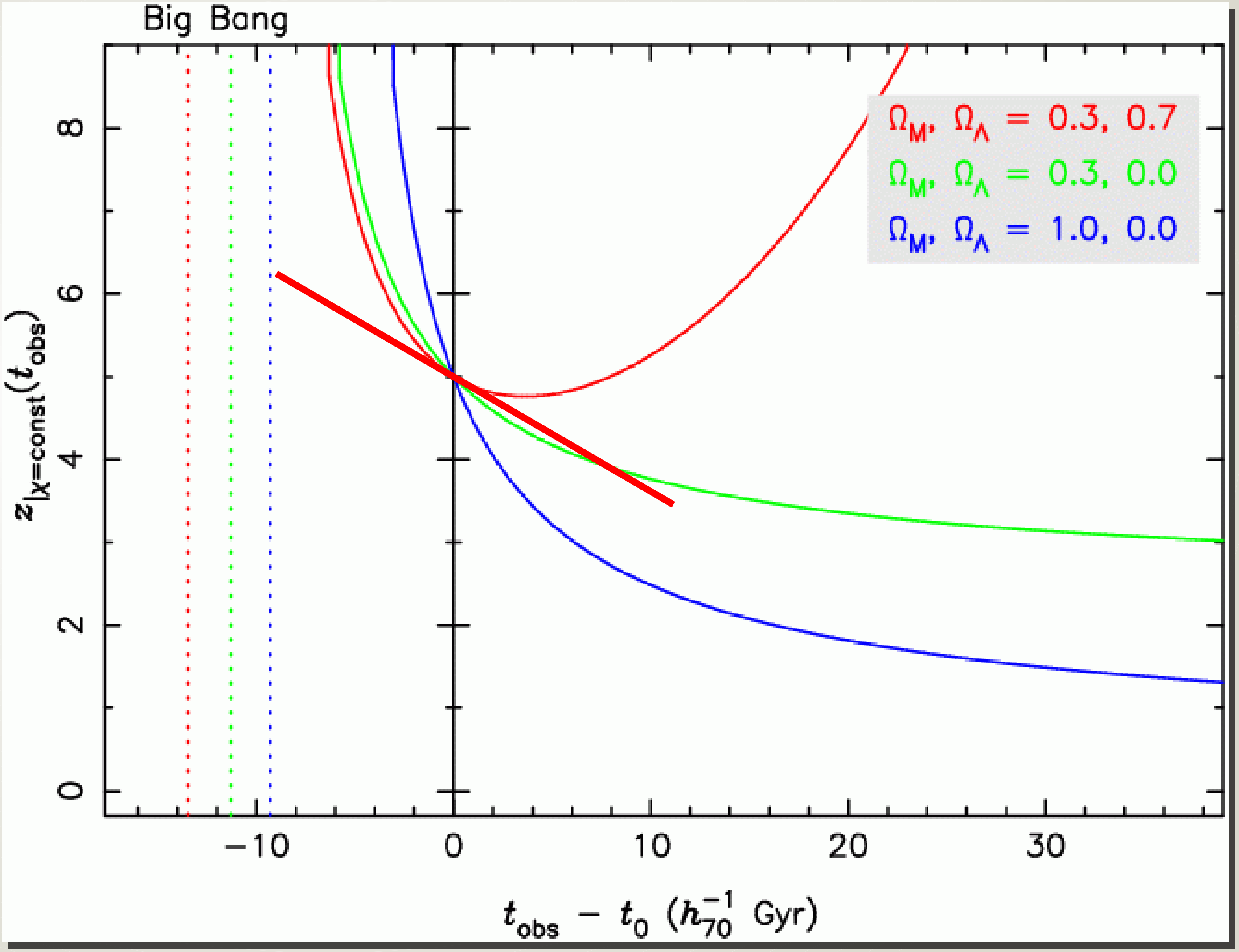


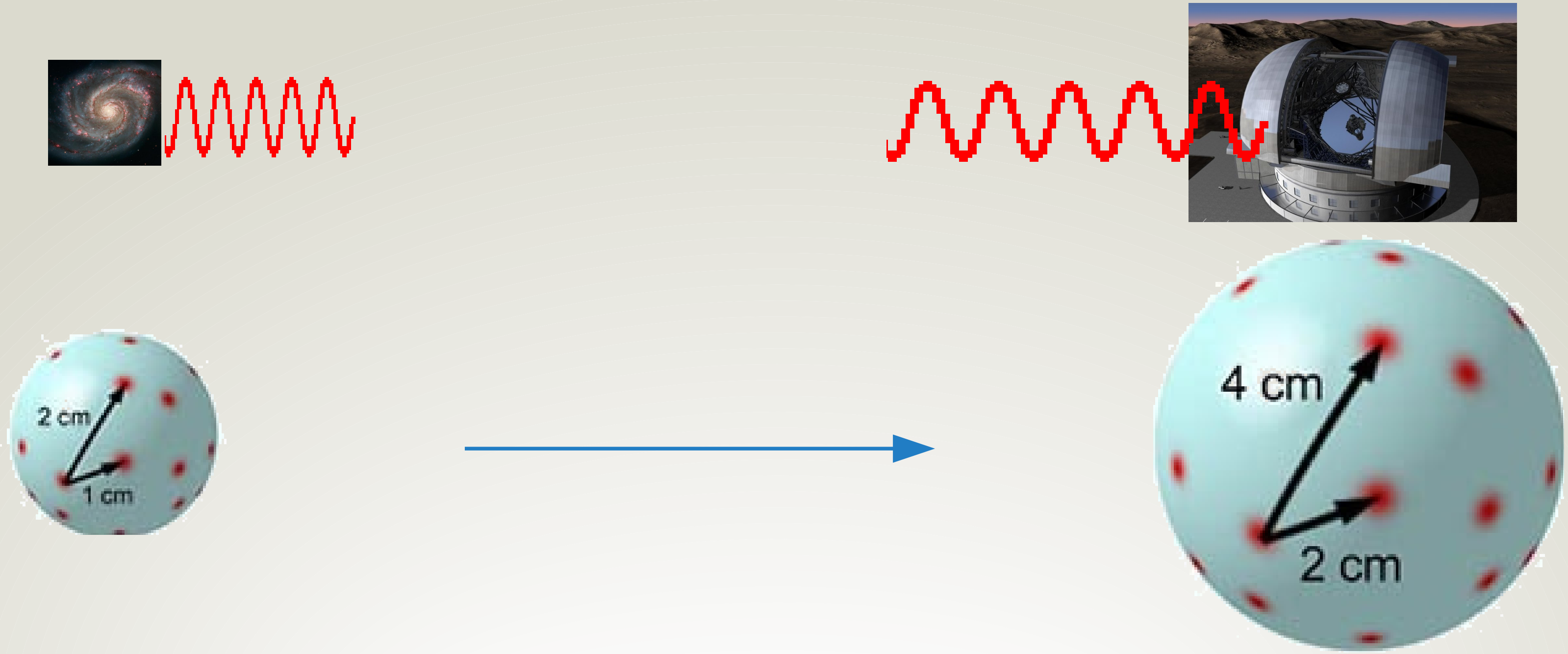
Evolving redshifts

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

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

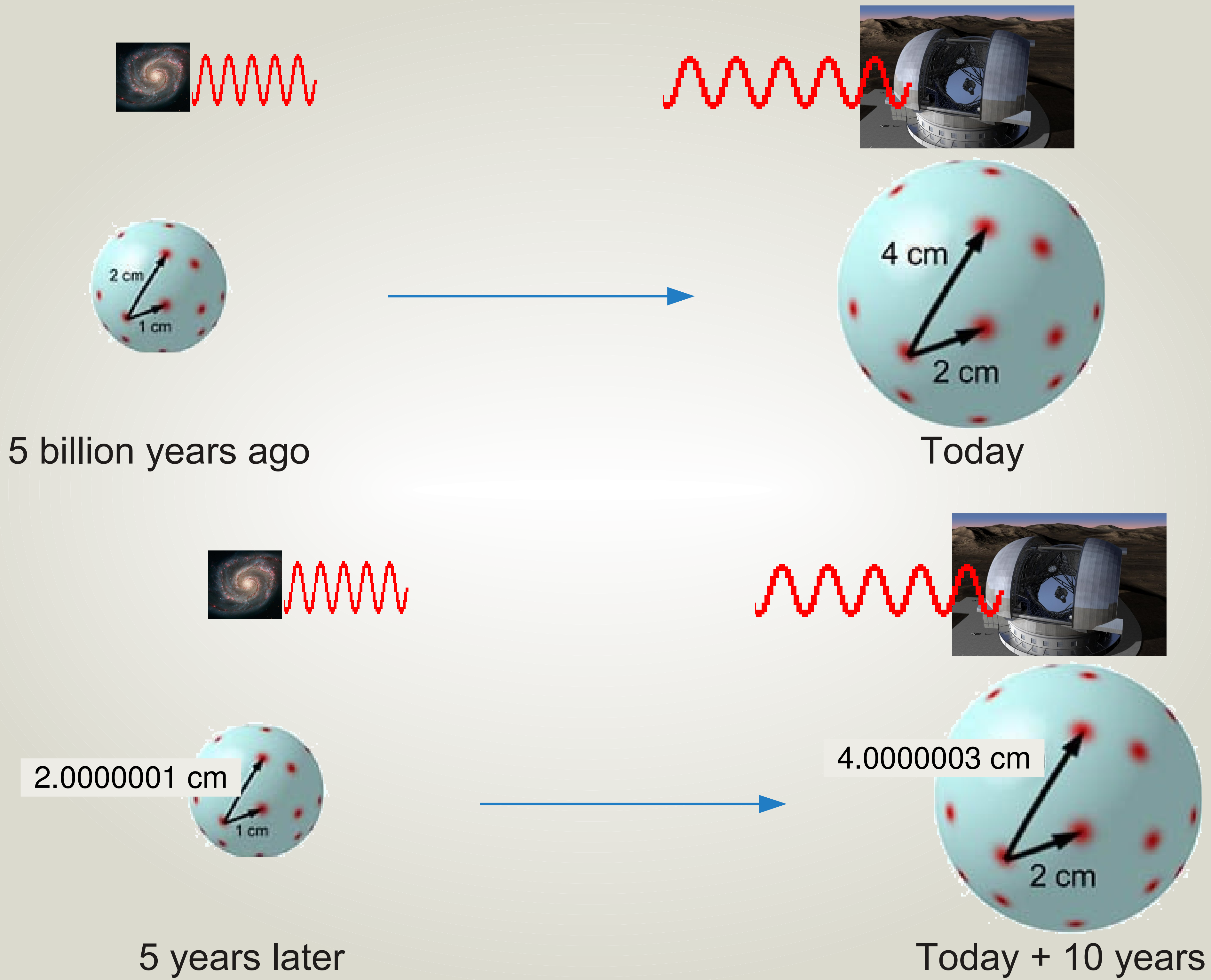
dz/dt = change of redshift as a fuction of time.

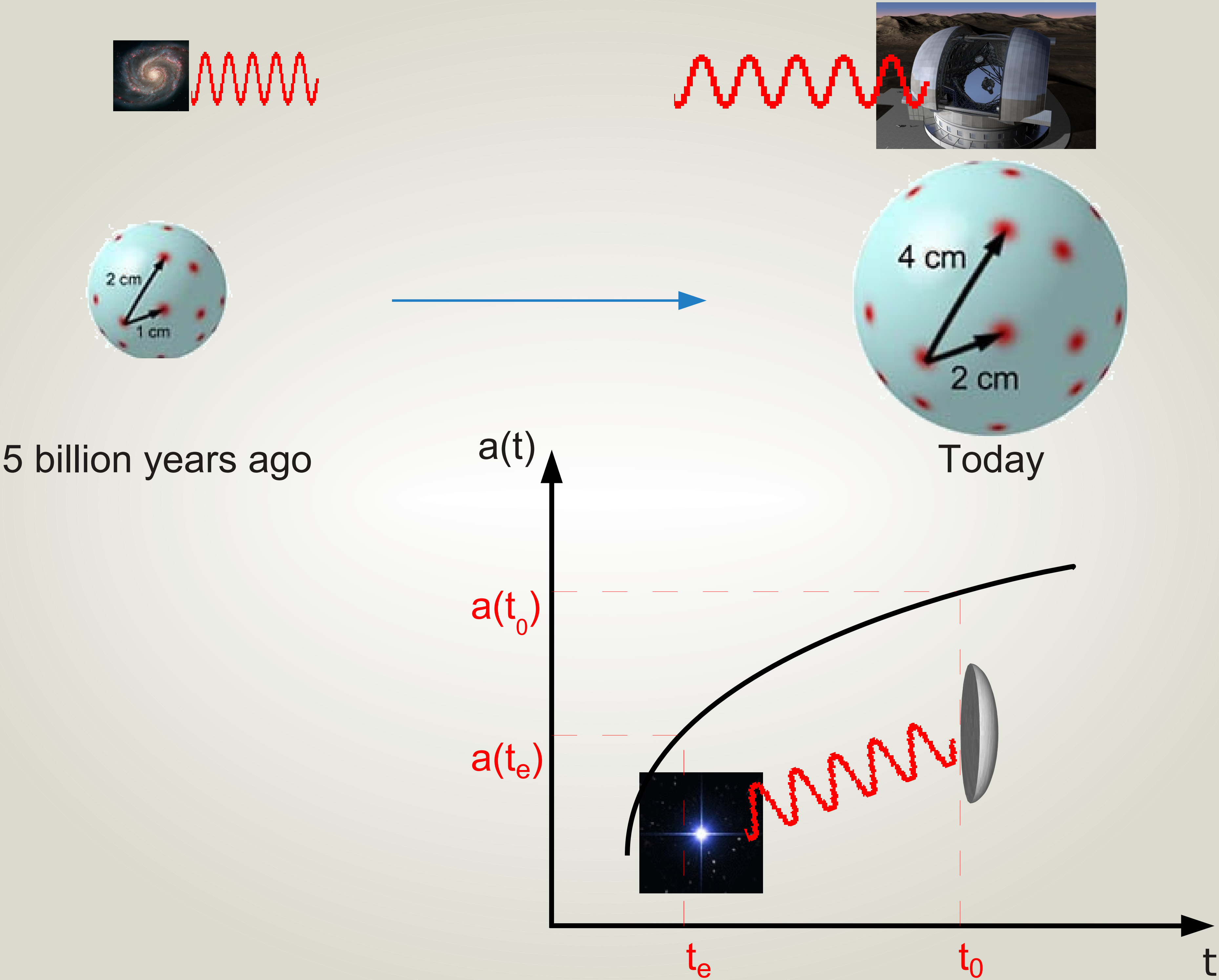


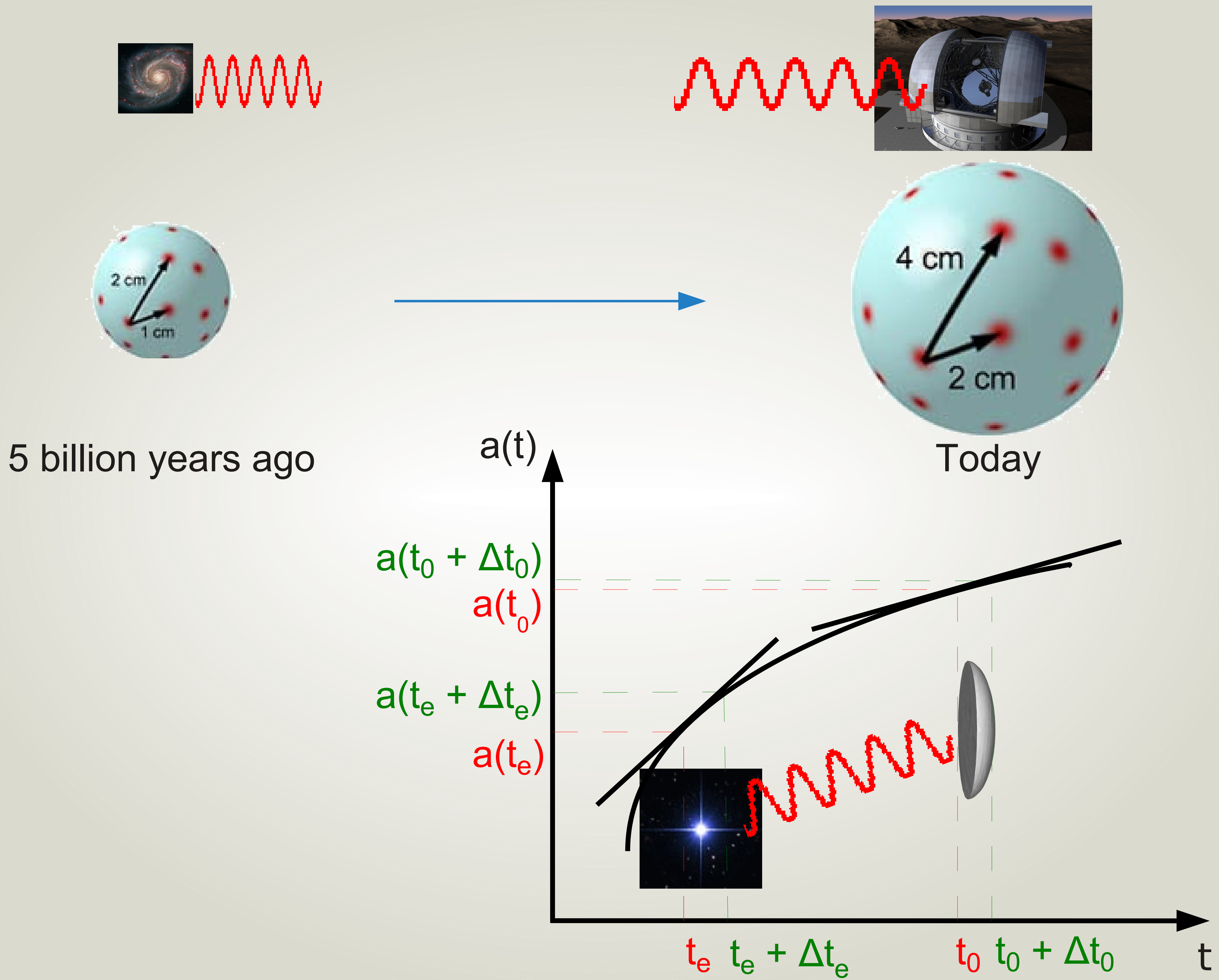


5 billion years ago

Today


2 cm
1 cm
4 cm
2 cm
5 billion years ago
Today
2.0000001 cm
1 cm
4.0000003 cm
2 cm
5 years later
Today + 10 years


2 cm
1 cm
4 cm
2 cm
5 billion years ago
Today
a(t)
a(t_0)
a(t_e)
t_e
t_0
t



2 cm
1 cm
4 cm
2 cm
5 billion years ago
Today
a(t)
a(t0 + Δt0)
a(t0)
a(te + Δte)
a(te)
te
te + Δte
t0
t0 + Δt0
t

What is dz/dt_0?

$$1+z = \frac{a(t_0)}{a(t_e)}$$

$$\frac{d}{dt_0}\left[1+z = \frac{a(t_0)}{a(t_e)}\right]$$

$$\frac{dz}{dt_0} = \frac{\dot{a}(t_0)}{a(t_e)} - \frac{a(t_0)}{a(t_e)^2}\,\dot{a}(t_e)\,\frac{dt_e}{dt_0}$$

$$= (1+z)\,\frac{\dot{a}(t_0)}{a(t_0)} - (1+z)\,\frac{\dot{a}(t_e)}{a(t_e)}\,\frac{1}{1+z}$$

$$\boxed{\frac{dz}{dt_0} = (1+z)\,H_0 - H(z)}$$

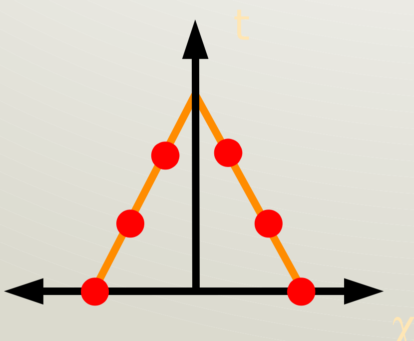
Cosmic Dynamics

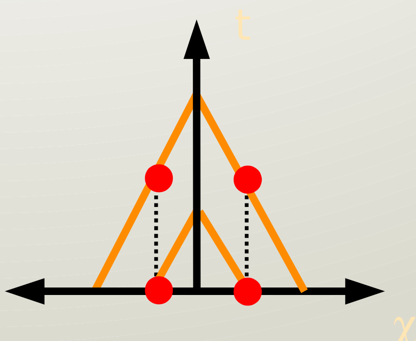
The de- or acceleration of the universal expansion rate between epoch z and today causes a small drift in the observed redshift as a function of time:

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

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.





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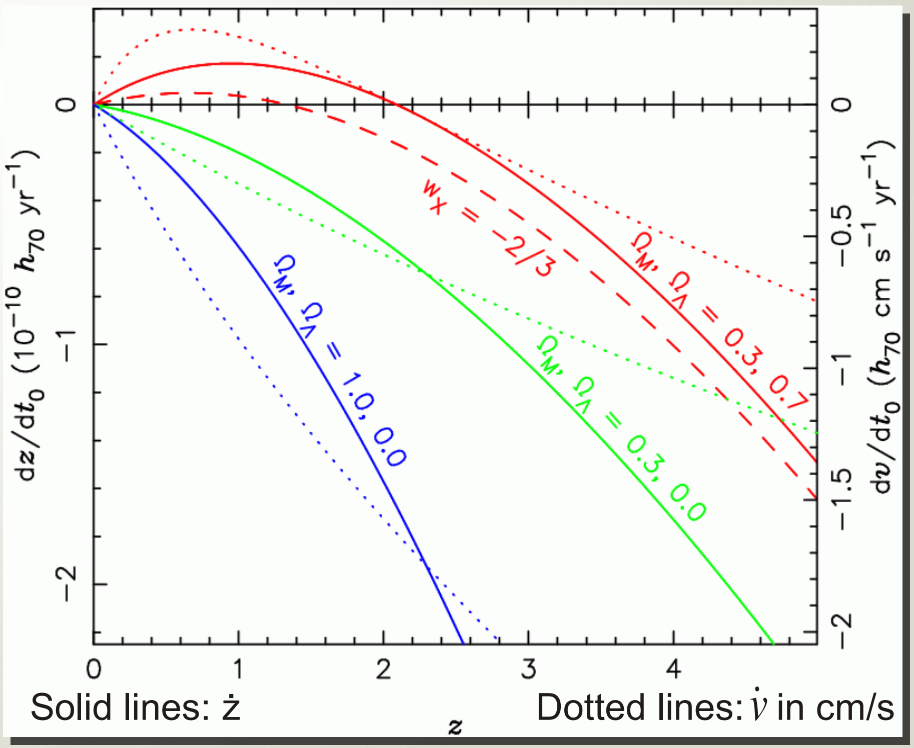
$$\dot{z} = (1+z)H_0 - H(z)$$

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.
- Tests whether the geometry and dynamics of spacetime are determined by the 'same' stress-energy tensor.
- Independent confirmation and quantification of accelerated expansion.
- H(z) determination in a redshift range inaccessible to other methods.



Size of the signal

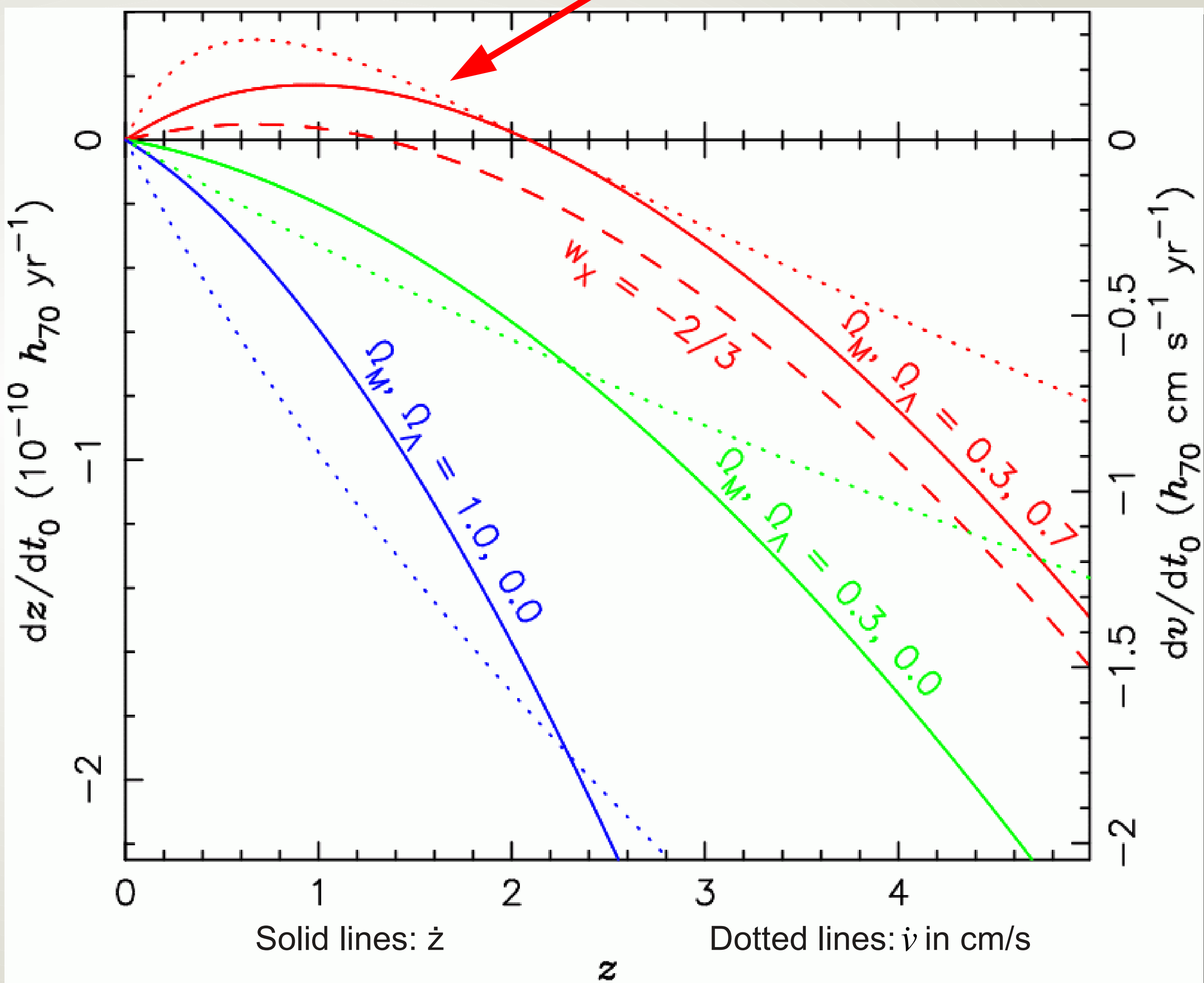
If Δt = 10 years then:

- $\Delta z \sim 10^{-9}$
- $\Delta\lambda = \lambda_{rest}\,\Delta z$
  $\sim 10^{-6}$ 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 $\Lambda > 0$



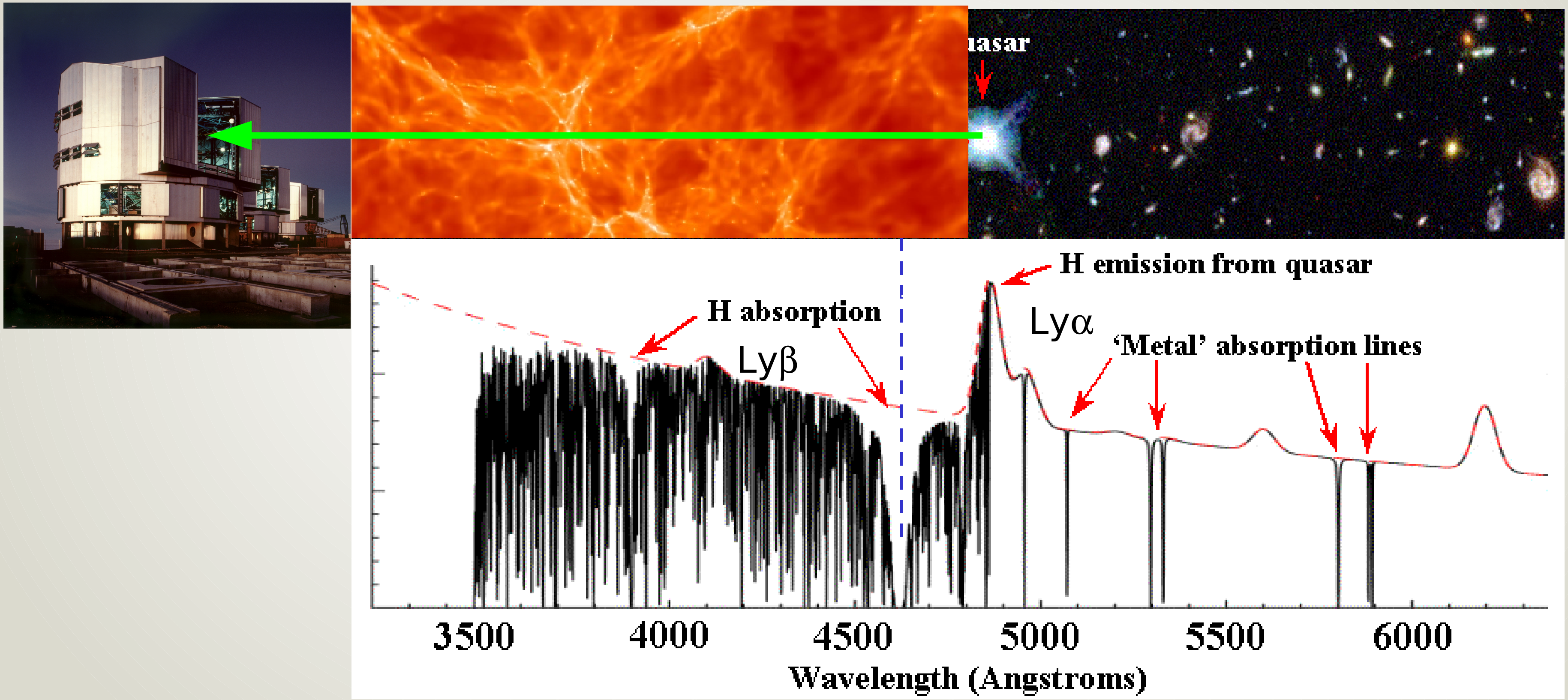
Solid lines: $\dot{z}$ Dotted lines: $\dot{v}$ in cm/s

How can we measure the redshift drift?

The precision 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



by John Webb

The Lyman α Forest

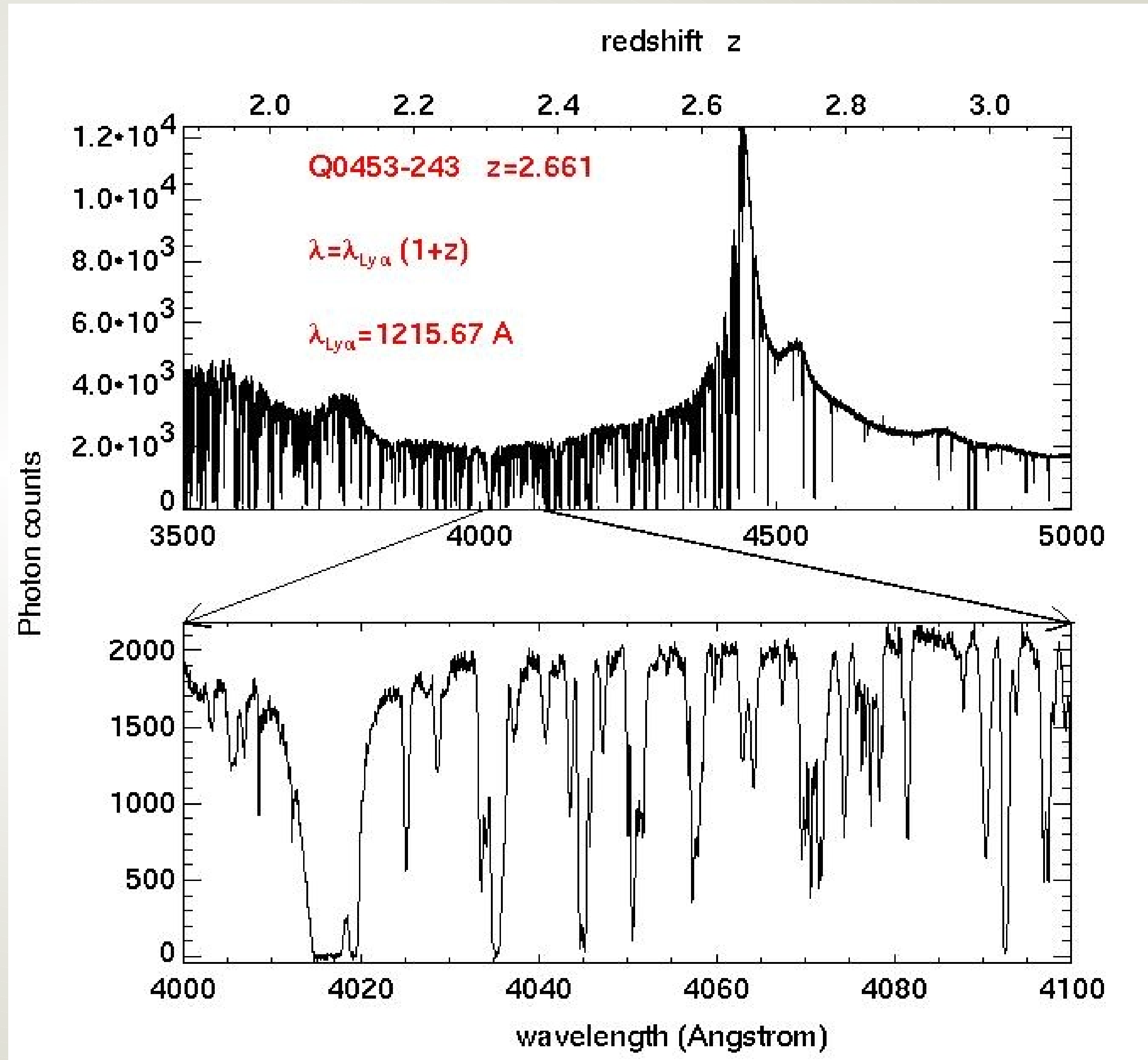
✔QSOs are the brightest sources at any redshift.

✔QSOs exist over all redshifts, 0 < z < 6.

✔Each line of sight to a background QSO shows ~10^2 Lyα lines.

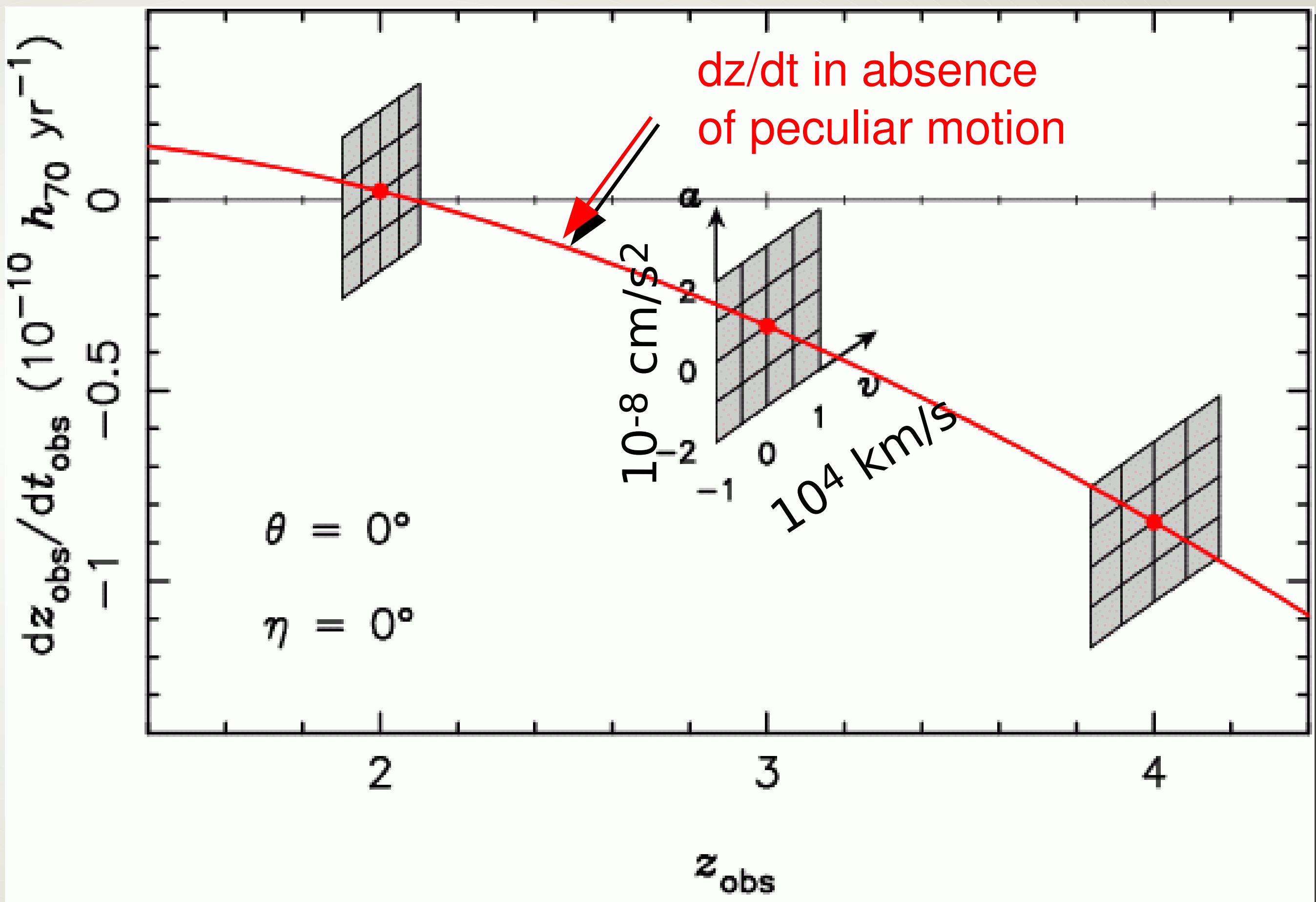
✔The Lyα forest is an excellent tracer of the Hubble flow (small peculiar motions).

✗ Line widths are 15-50 km/s. (Metal line widths are of order 1 km/s but reside in deeper potential wells).



Effect of peculiar motion

- The effect of peculiar motion should be compared to the size of the error on an *individual* ż 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.

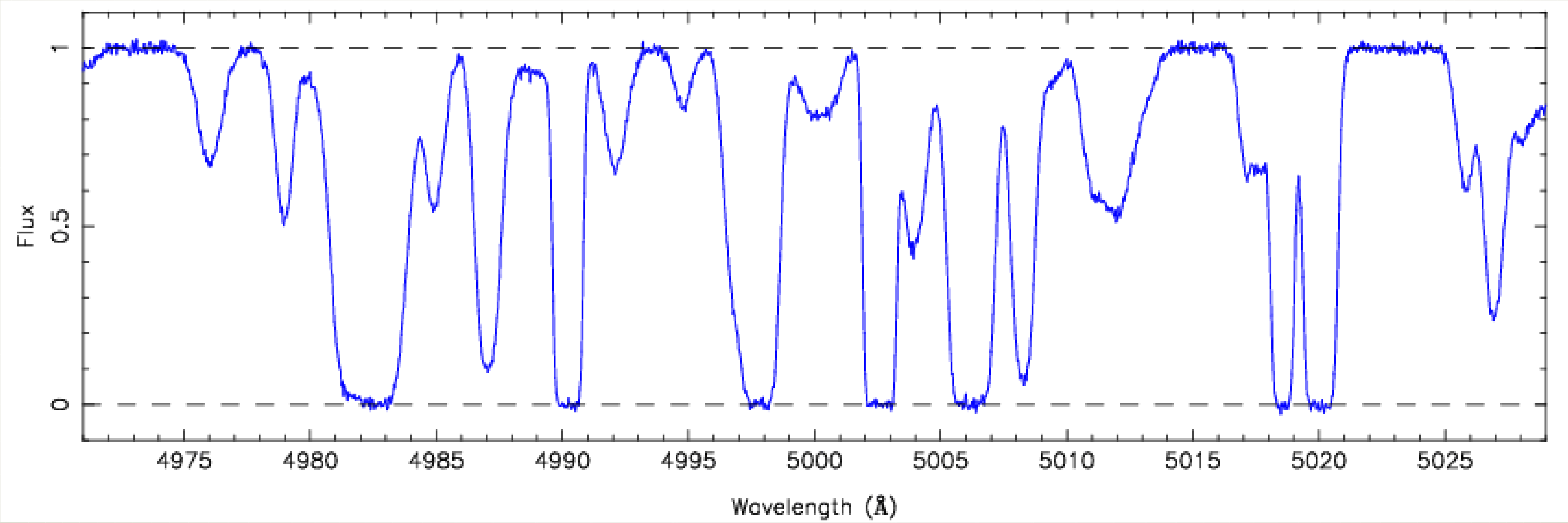


Liske et al. (2008)

→ The Lyα forest traces the Hubble flow!

Observing dz/dt in the Lyα Forest

Simulation of the Lyα forest at z ~ 3:



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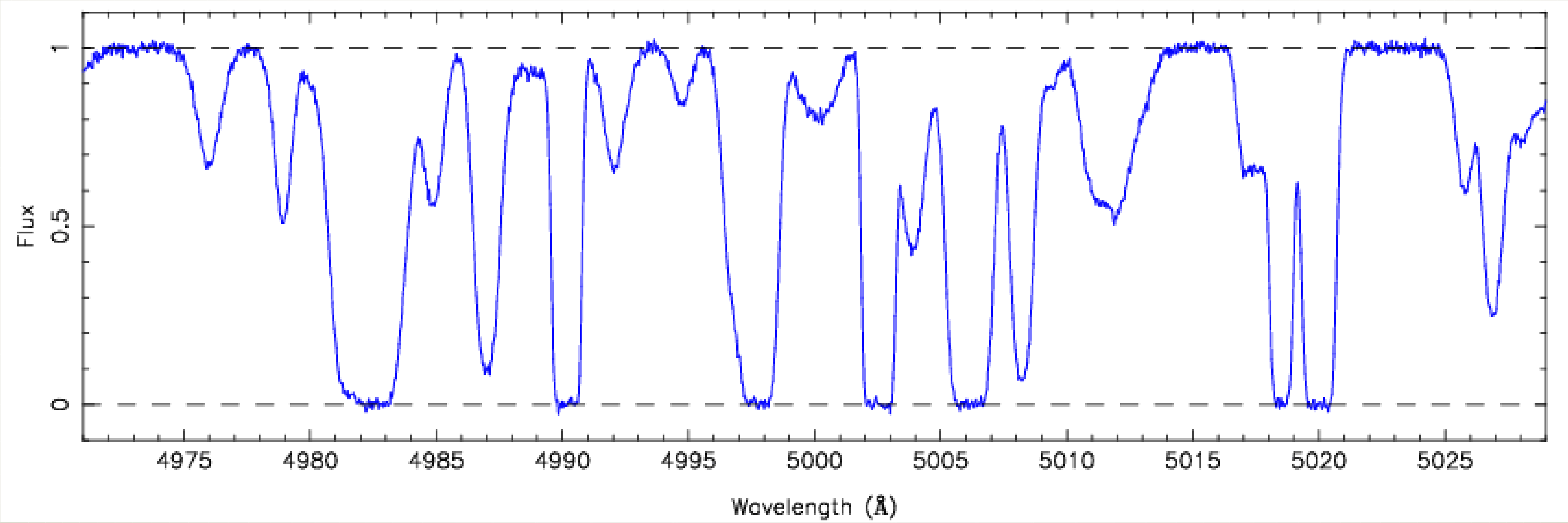

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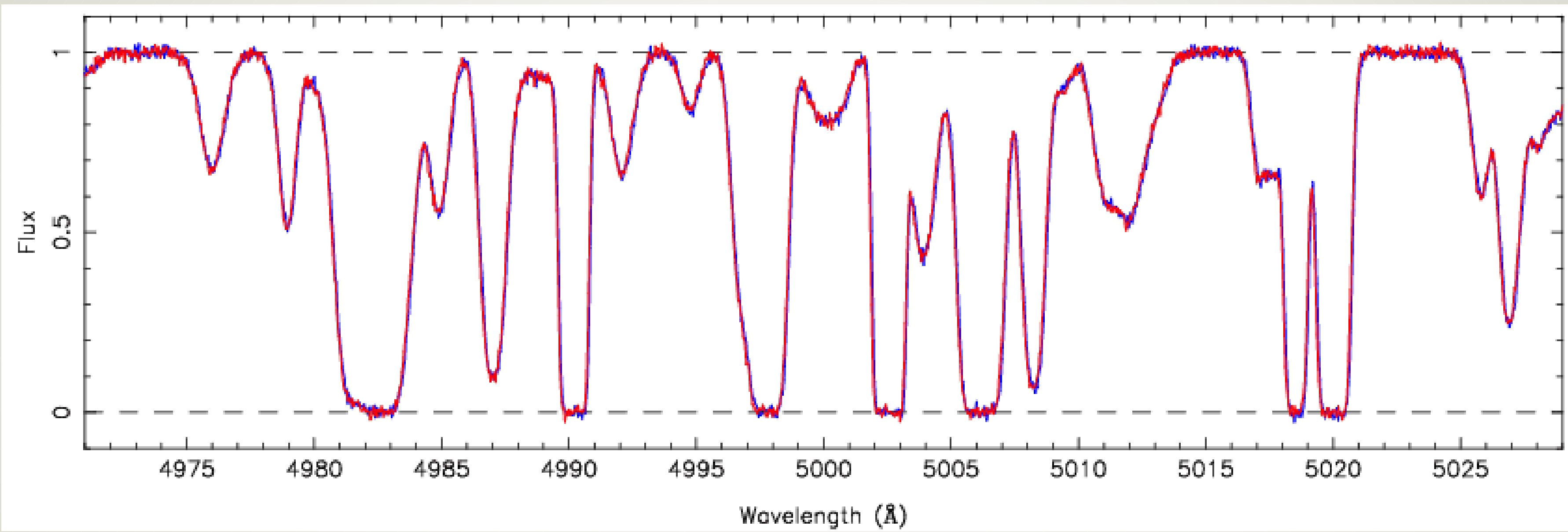

$\Delta t = 10^6$ years!

How can we measure the redshift drift?

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Can we collect enough photons?

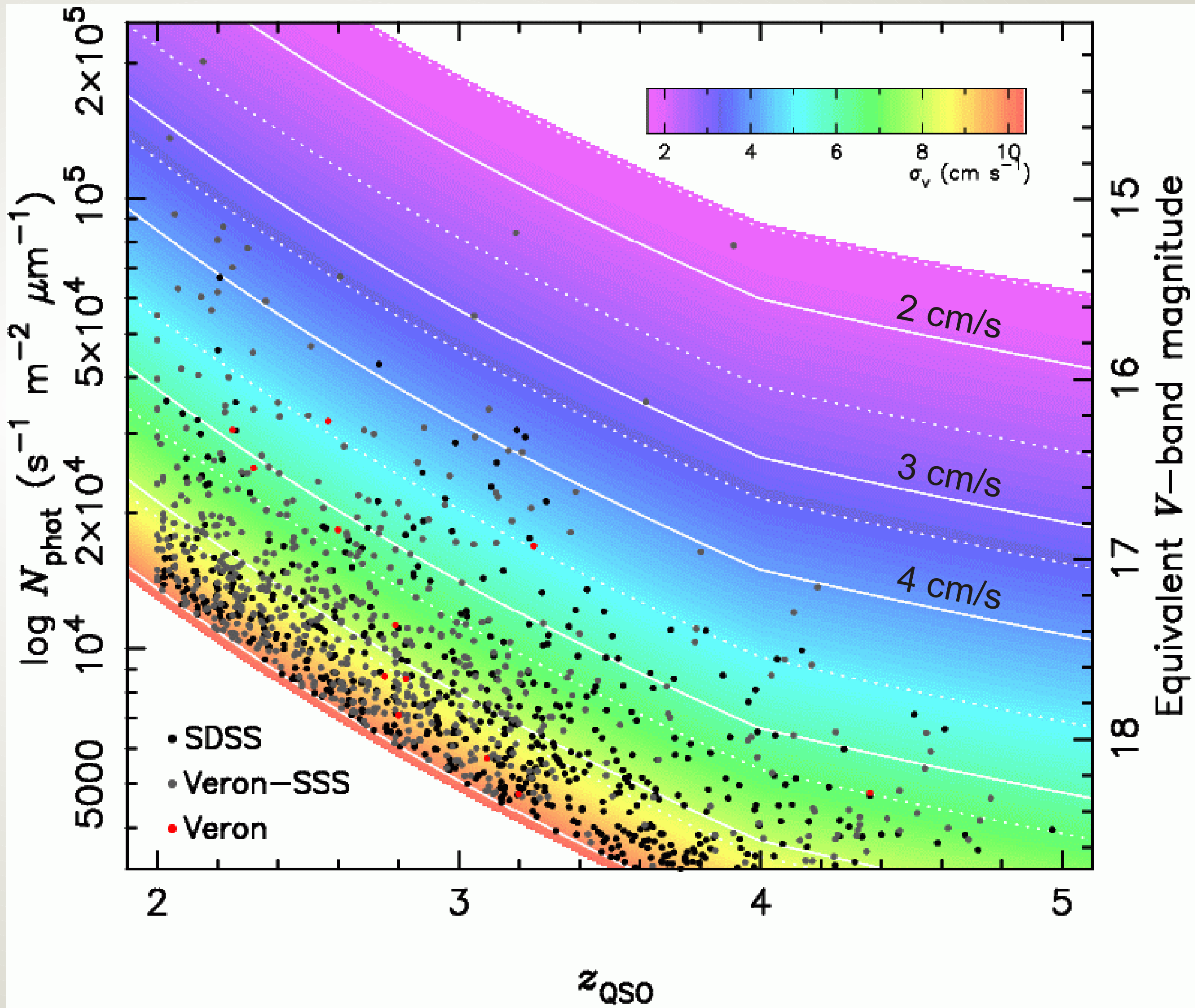
Can we collect enough photons to achieve the required radial velocity accuracy?

QSOs from latest compilations (including SDSS):

Lines of constant σ_v assume:

D = 39 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 39-m ELT.

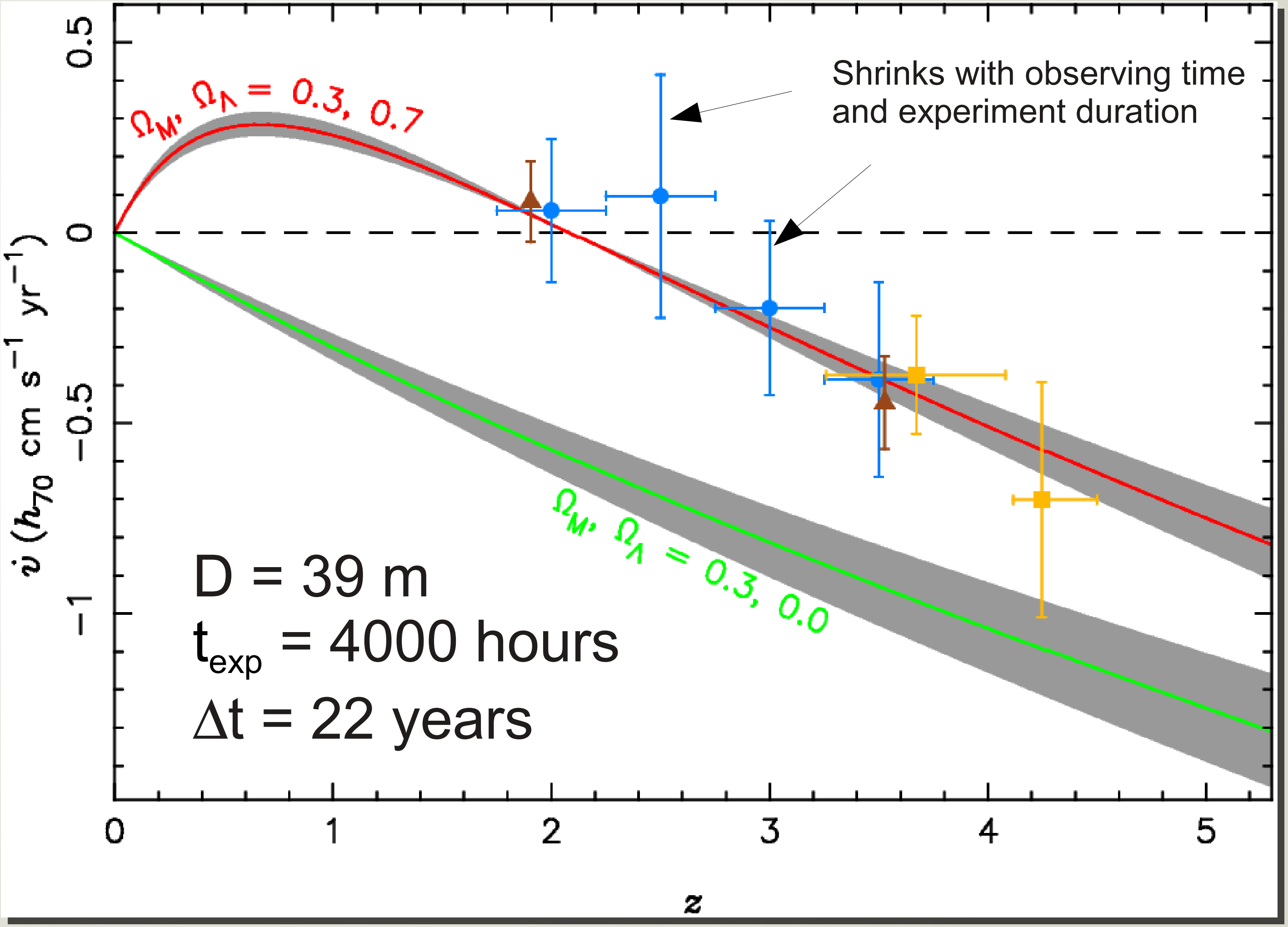


Liske et al. (2008)

Simulation Results

4000 h on a 39-m ELT over 22 years will deliver any *one* of these sets of points.

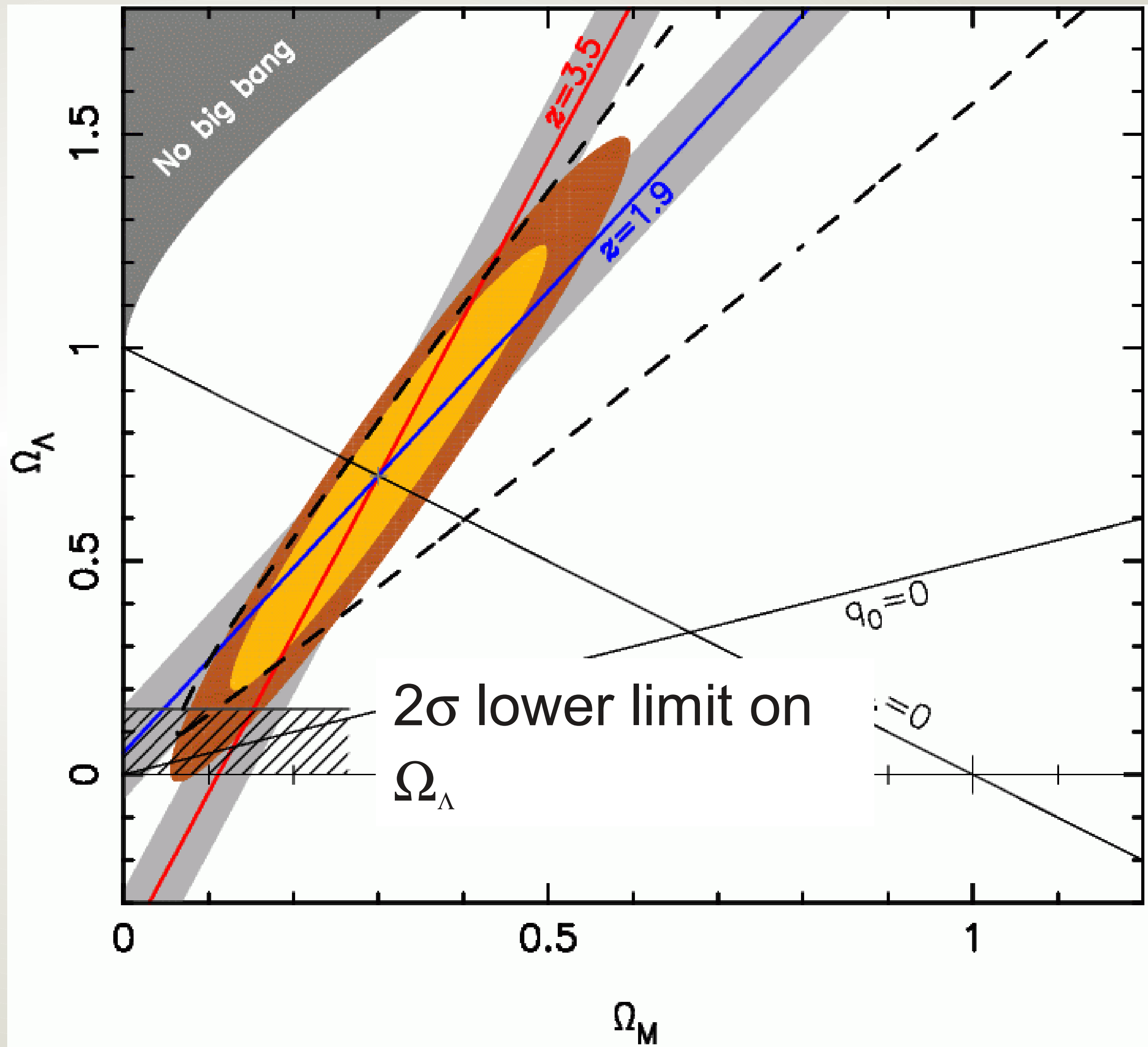
Different sets correspond to different target selection strategies.



Liske et al. (2008)

Constraints on Cosmology

- 4000 hours over 22 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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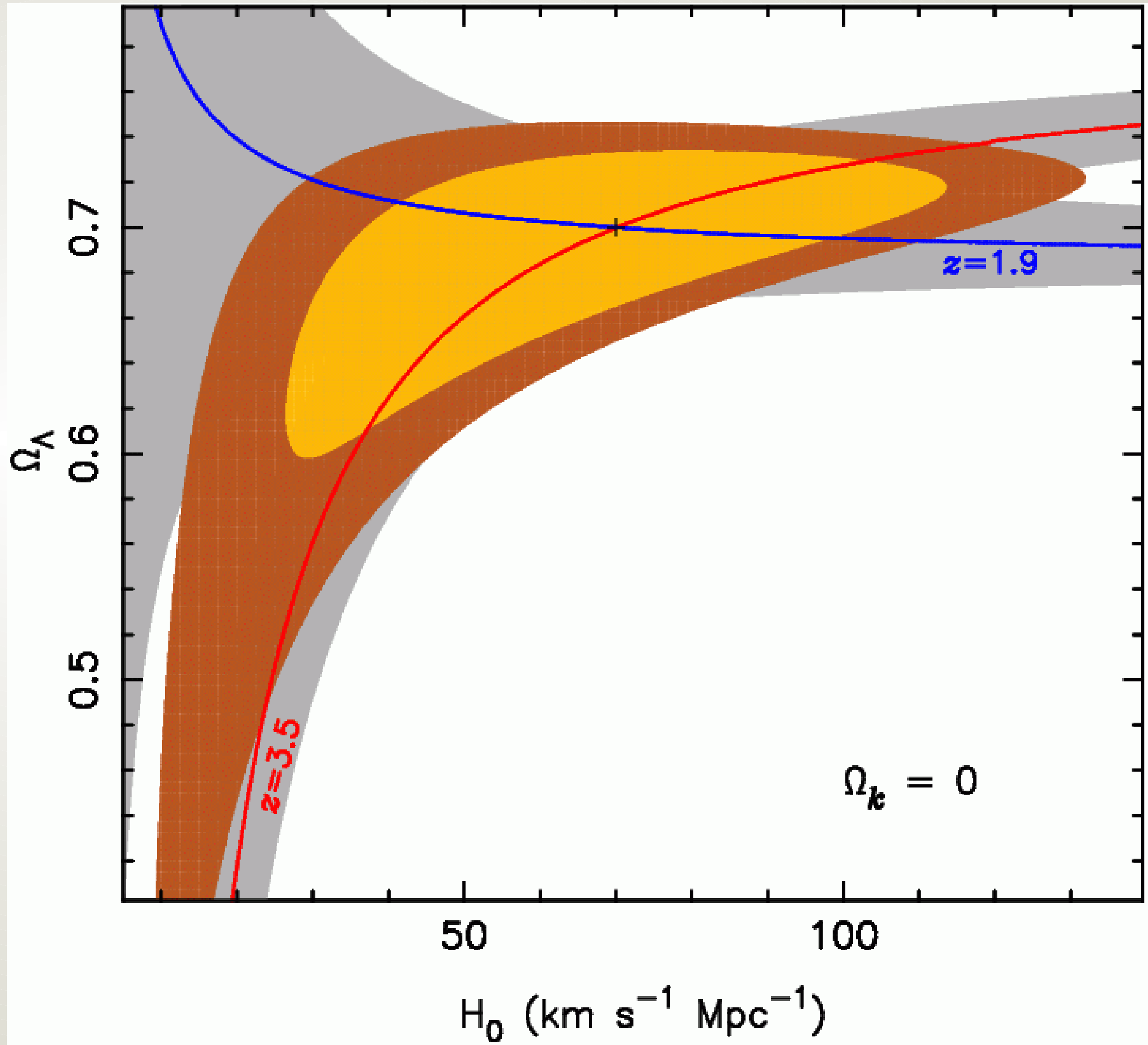

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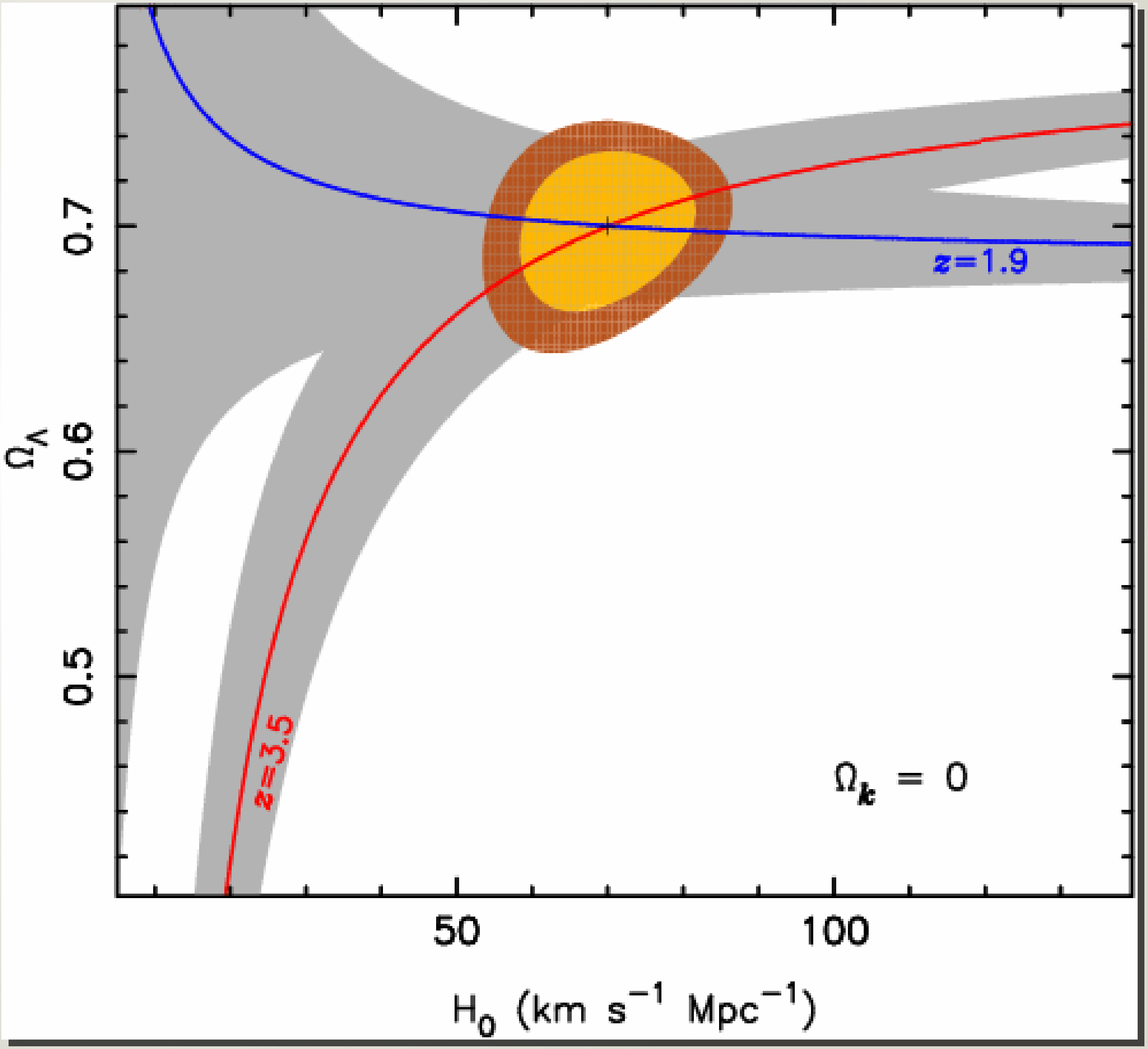
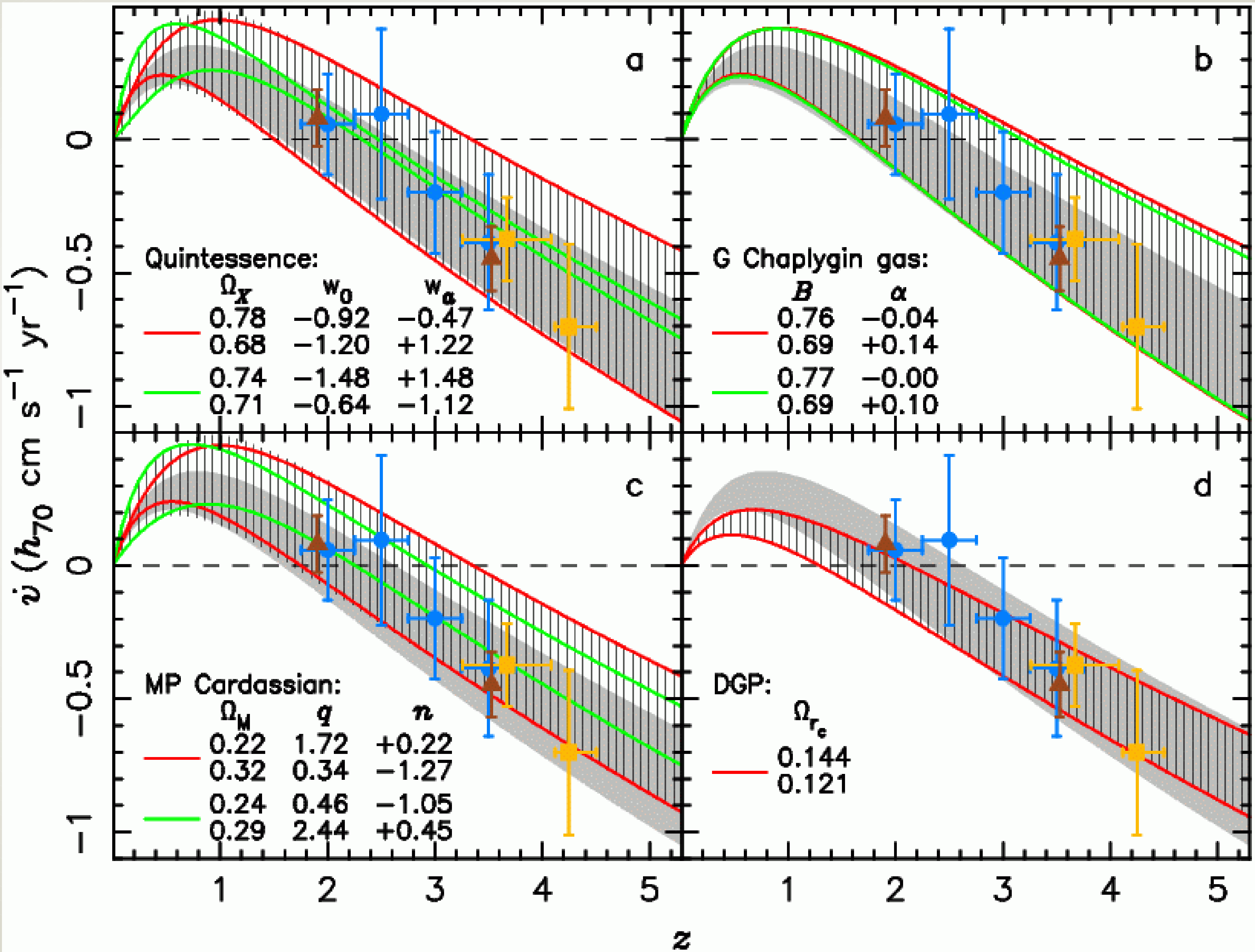


Liske et al. (2008)

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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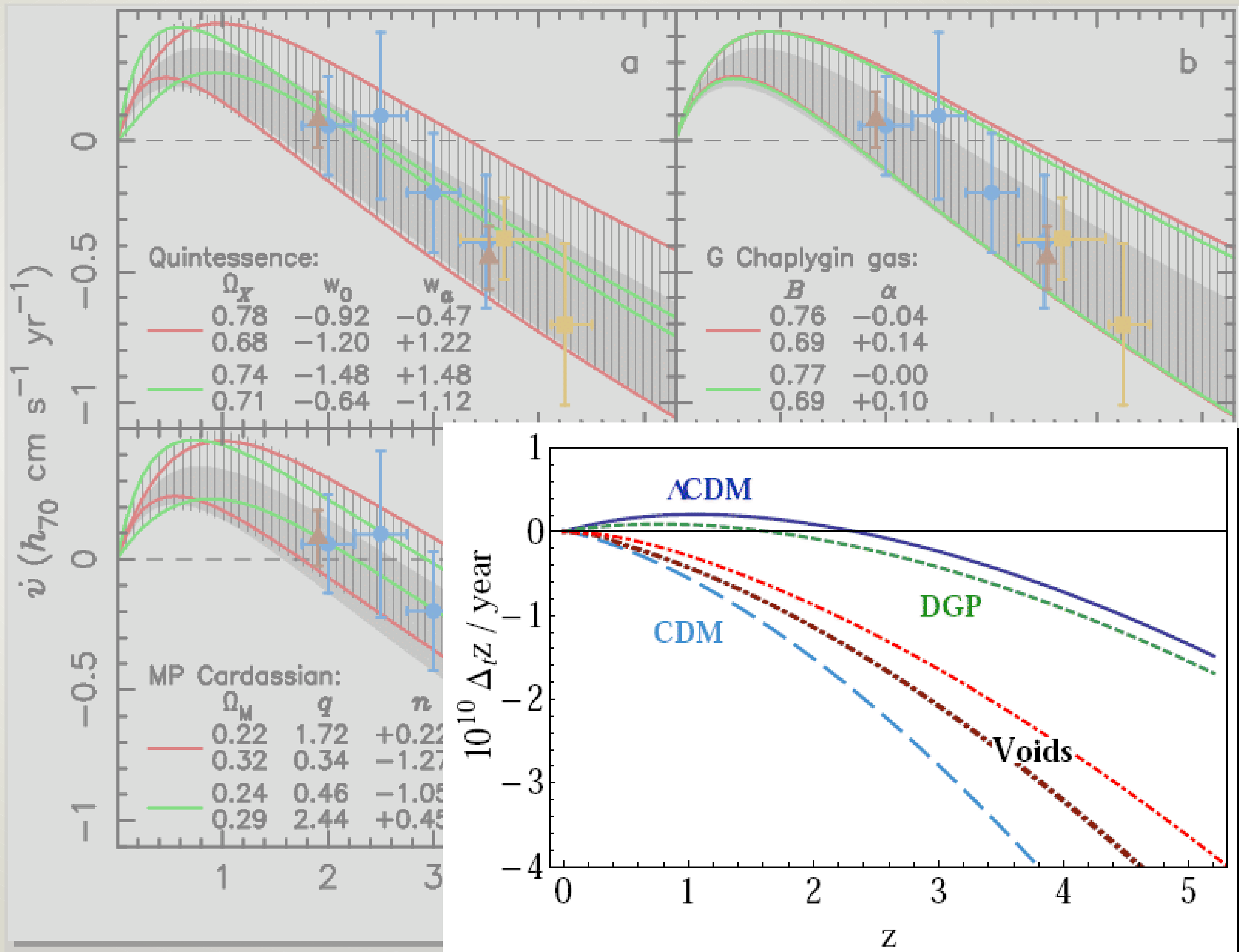
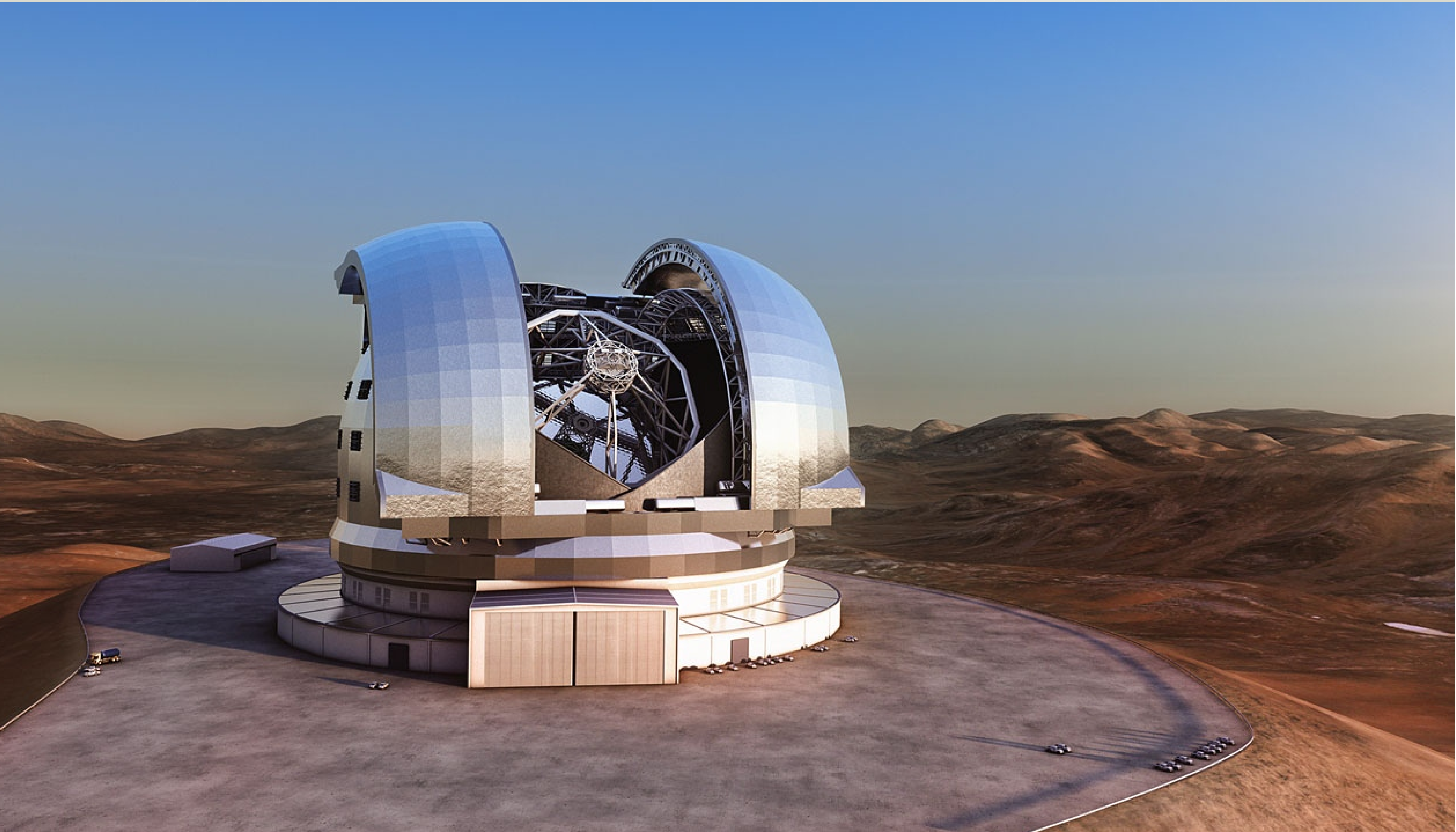


Quartin & Amendola (2009)

Redshift Drift Summary

- 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.
- The E-ELT will offer us the first opportunity to measure the redshift drift (over a timescale of ~20 yrs), 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).
  - Keeps on giving: signal grows linearly with time → very cost effective.

E-ELT
=
Extremely Exciting Long Term
science



Is it affordable?

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

- The total time is distributable (to some extent)
  4000 h / 20 yr = 20 nights per year
- Comparable to past investment
  VLT/UVES has invested ~3000 hours 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
  - $T_{CMB}(z)$
  - Primordial deuterium abundance
  - Metallicity evolution of the low-density IGM
  - Tomography of the IGM

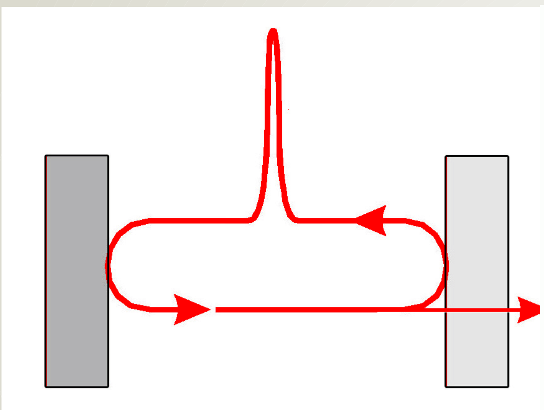
Wavelength Calibration

Desired characteristic	ThAr	I_2 cell	LFC
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	✔	✔	✔

Adapted from Murphy et al. (2007)

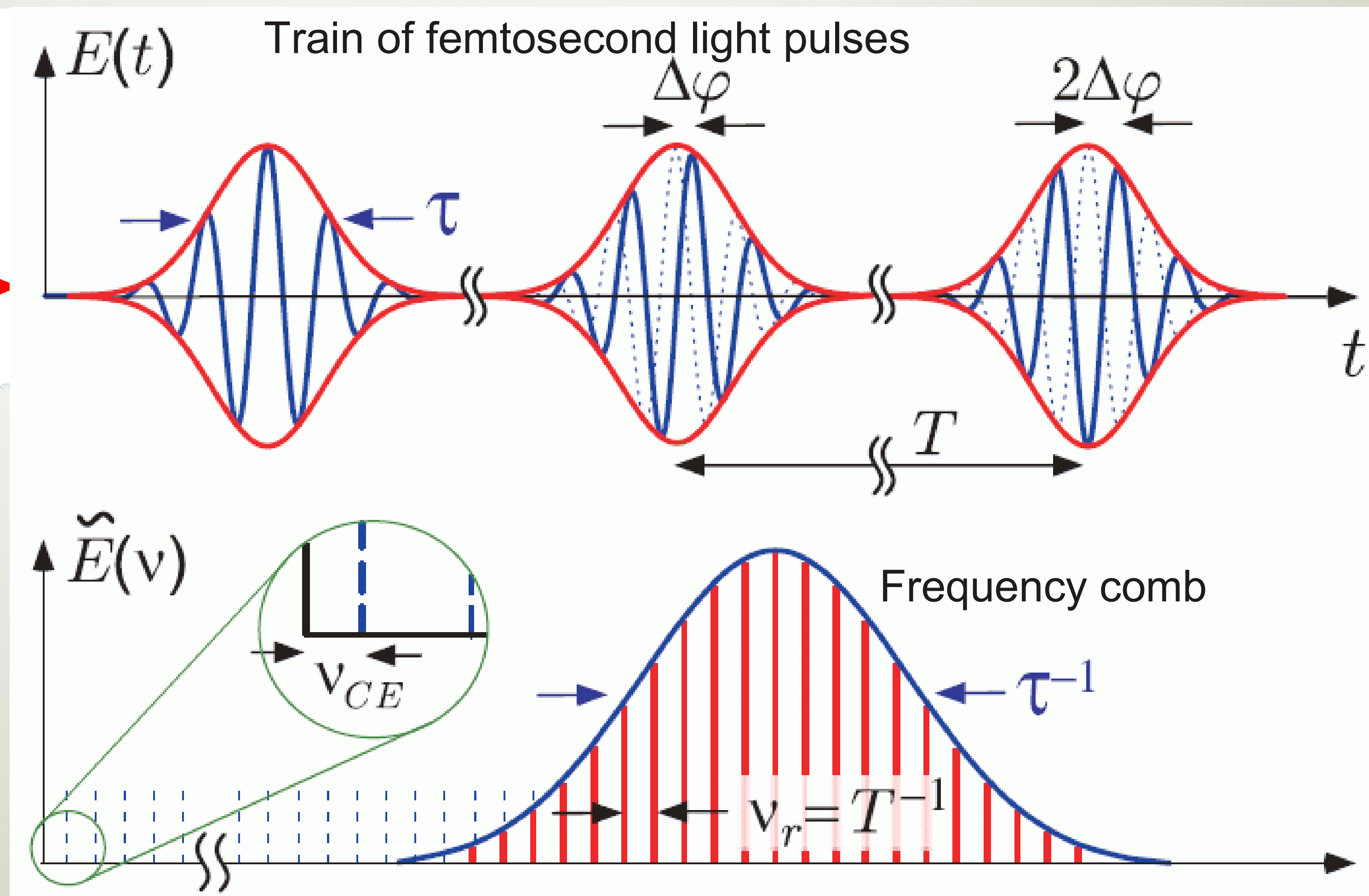
Laser Frequency Comb

- 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.



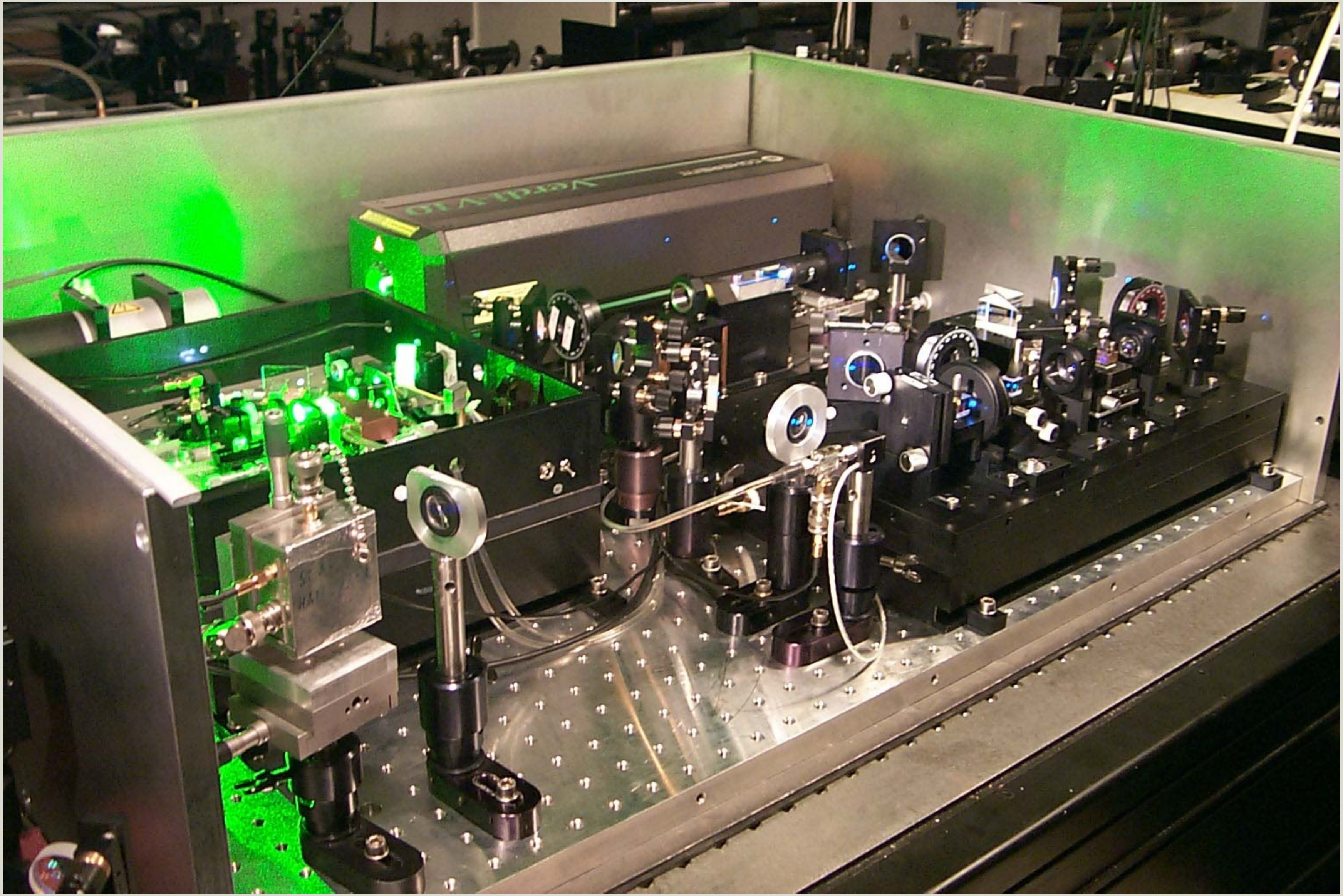
$$\nu_n = n\nu_r + \nu_{CE}$$

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



by Thomas Udem (MPQ)

Laser Frequency Comb

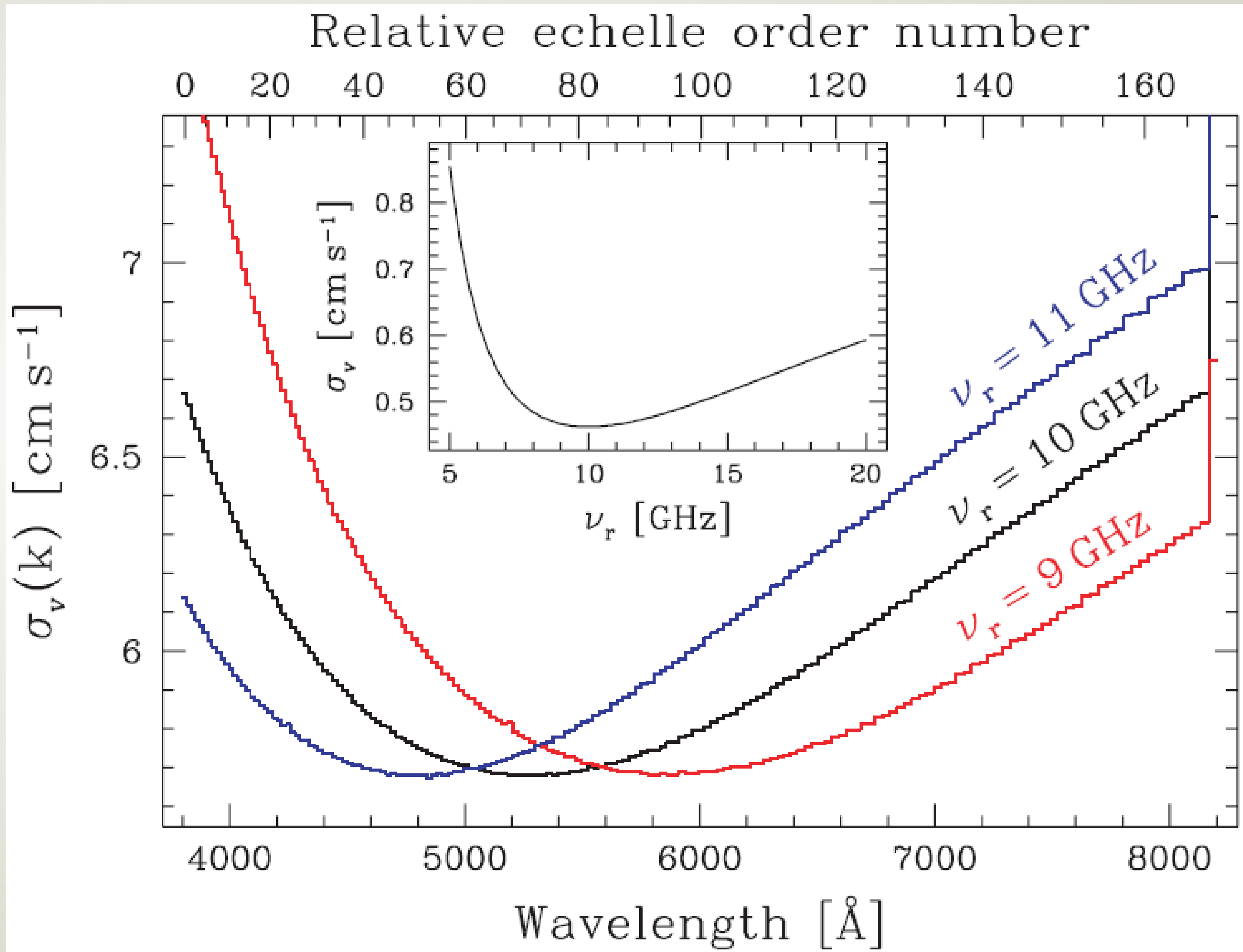


Thomas Udem (MPQ)

Simulation Results

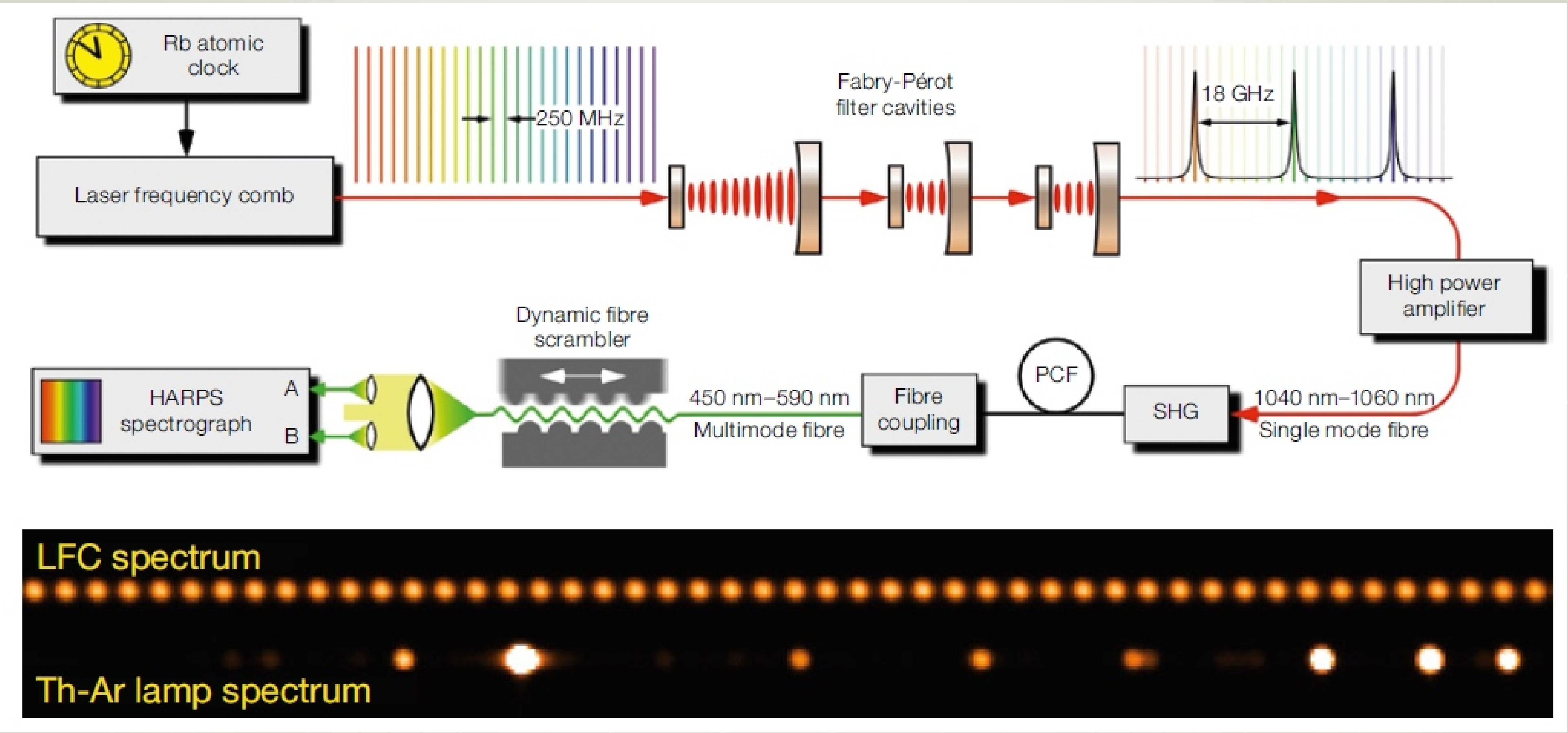
Photon-limited wavelength calibration precision is ~0.5 cm/s.

Optimal pulse repetition rate is 10-20 GHz.



Murphy et al. (2007)

LFC on HARPS @ ESO 3.6 m



Lo Curto et al. (2012)

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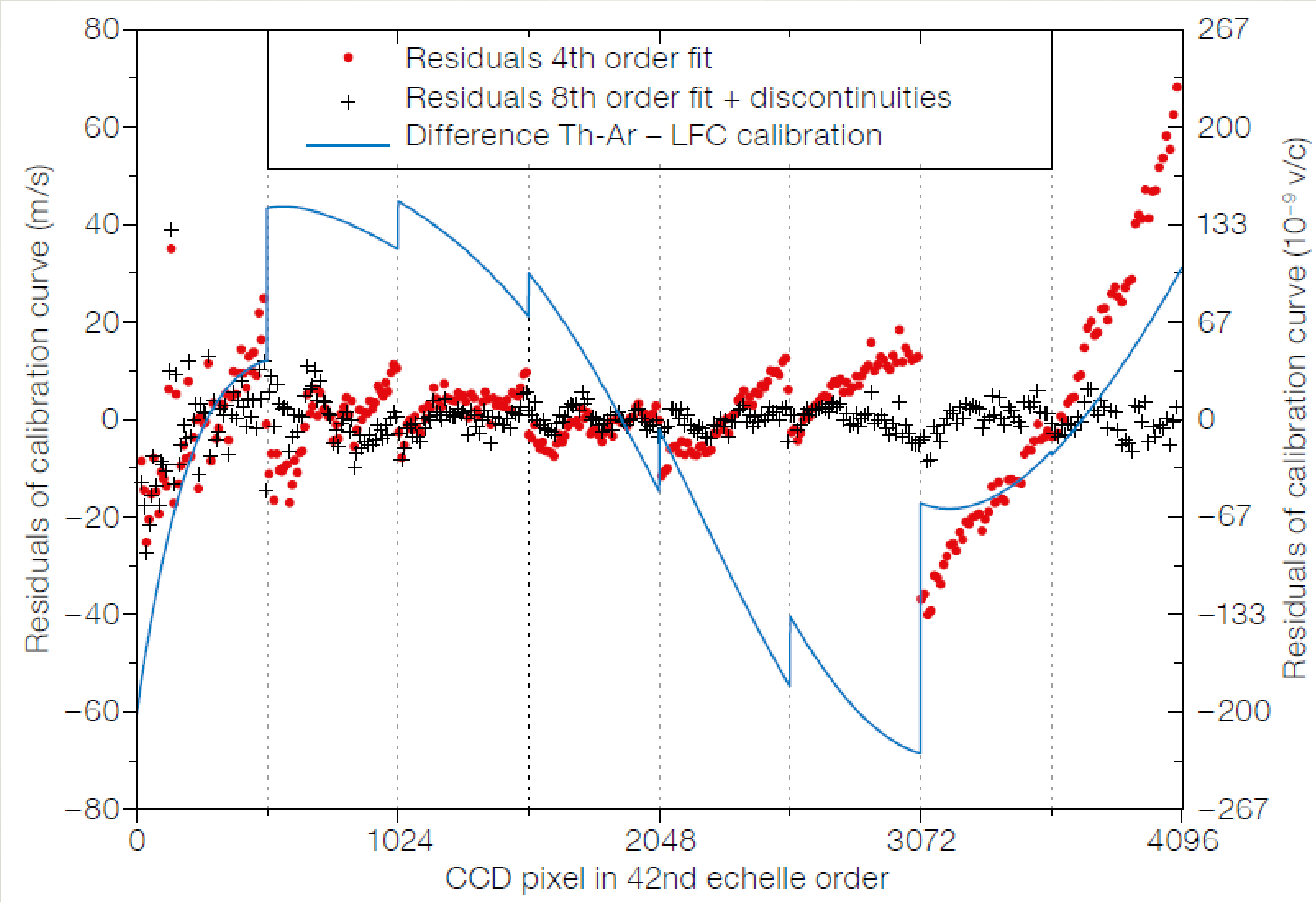

Lo Curto et al. (2012)