Precision Cosmology in the E-ELT Era

Jochen Liske

hamburger sternwarte

Fachbereich Physik | Universität Hamburg

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

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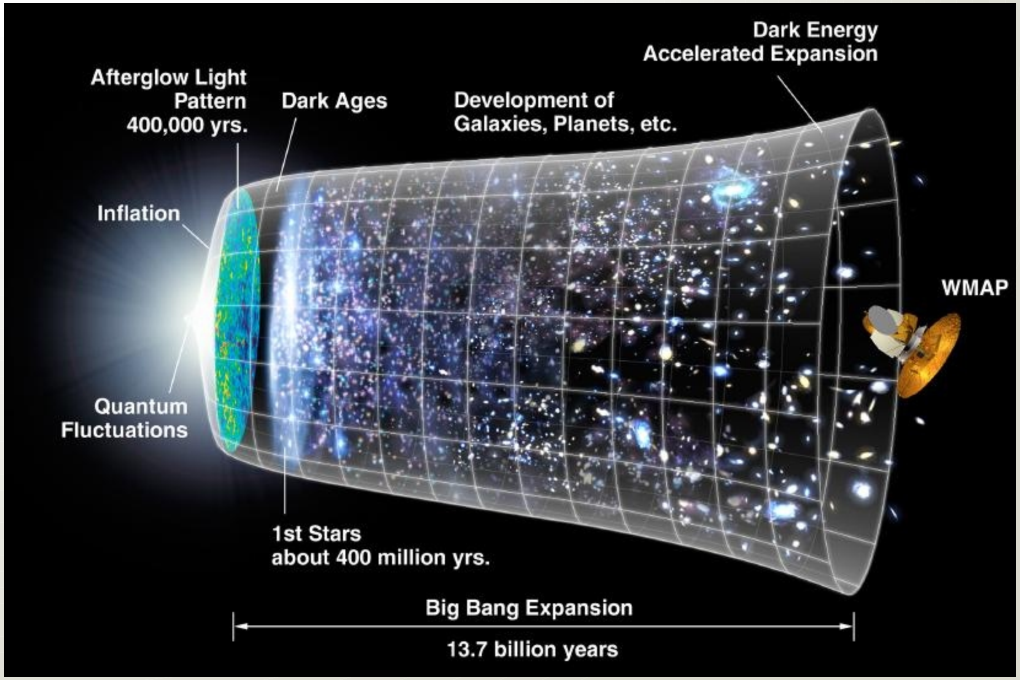
Cosmological Topics

- The background model
  - What is the correct model for the geometry and evolution of the background space-time?
  - What is the source of the observed acceleration of the expansion?
  - What is the nature of Dark Matter?
  - Consistency tests
- The perturbations
  - Structure formation
  - Galaxy formation and evolution
  - Reionization
  - IGM evolution
- Did inflation happen?
- Fundamental physics
  - Are constants constant?
  - Testing GR with MW Black Hole
  - Quantum optics



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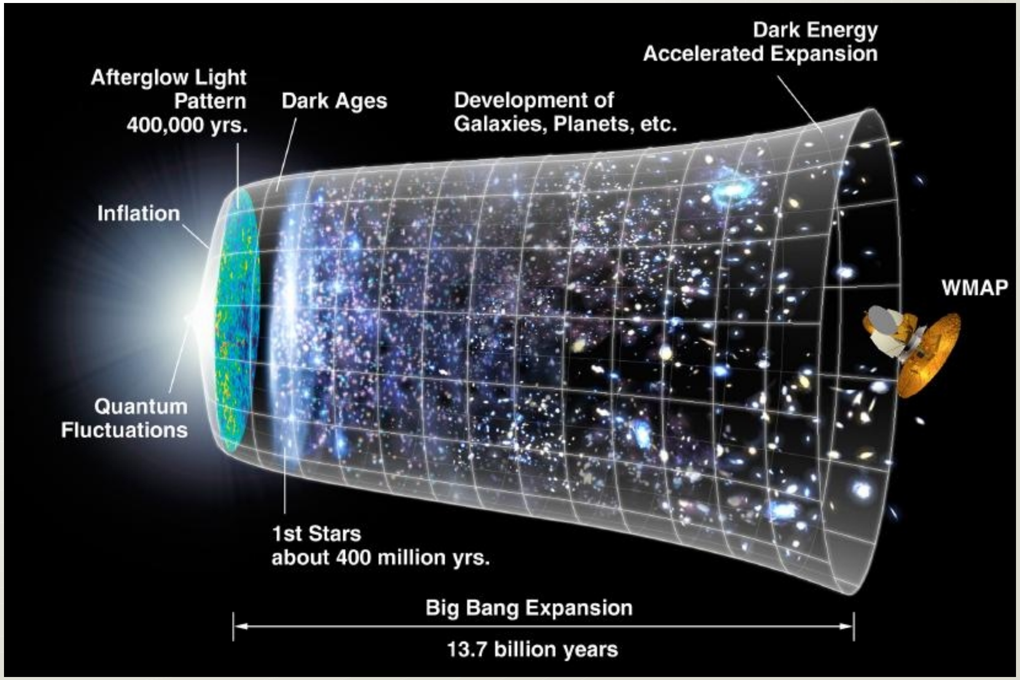
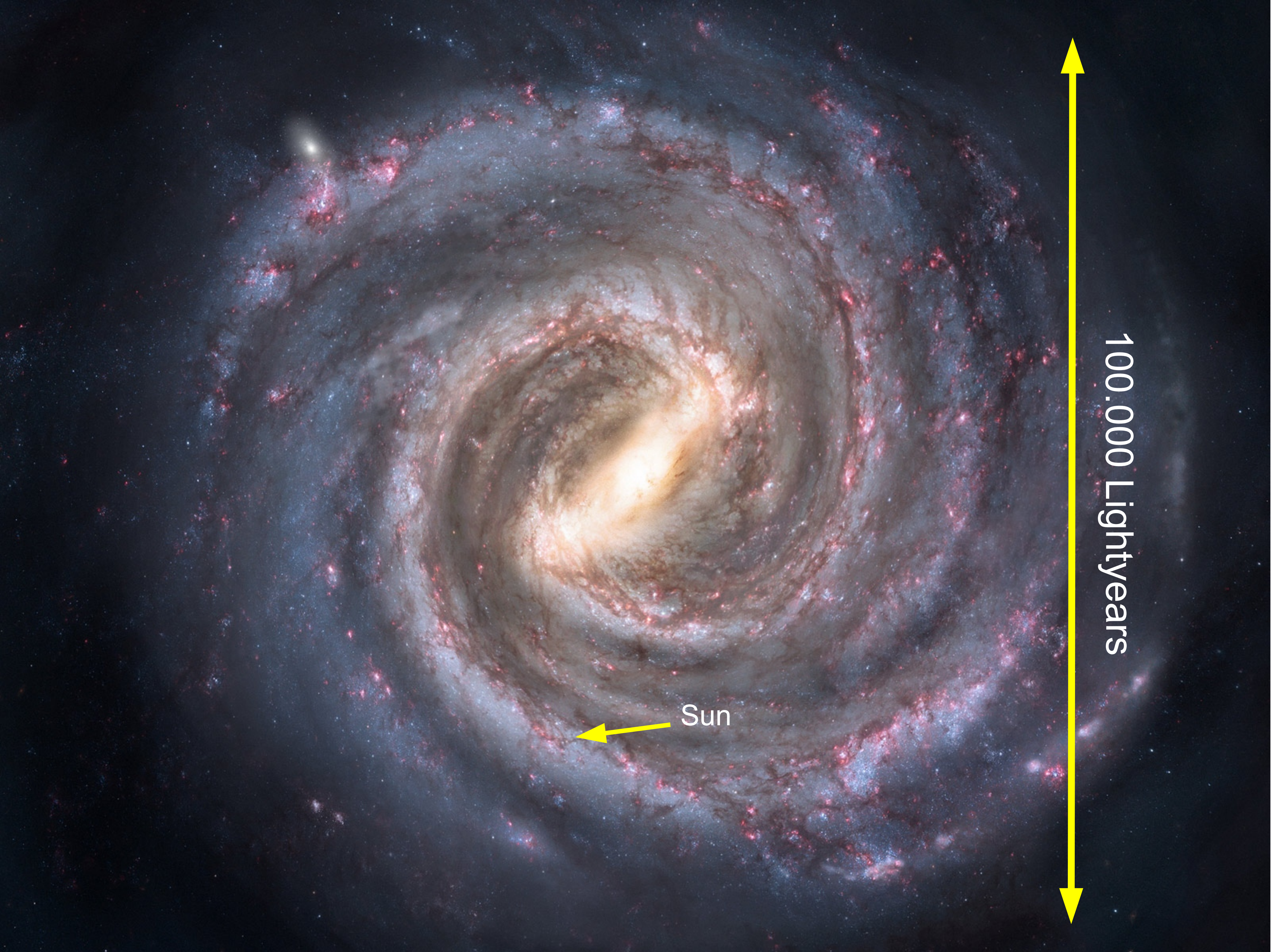
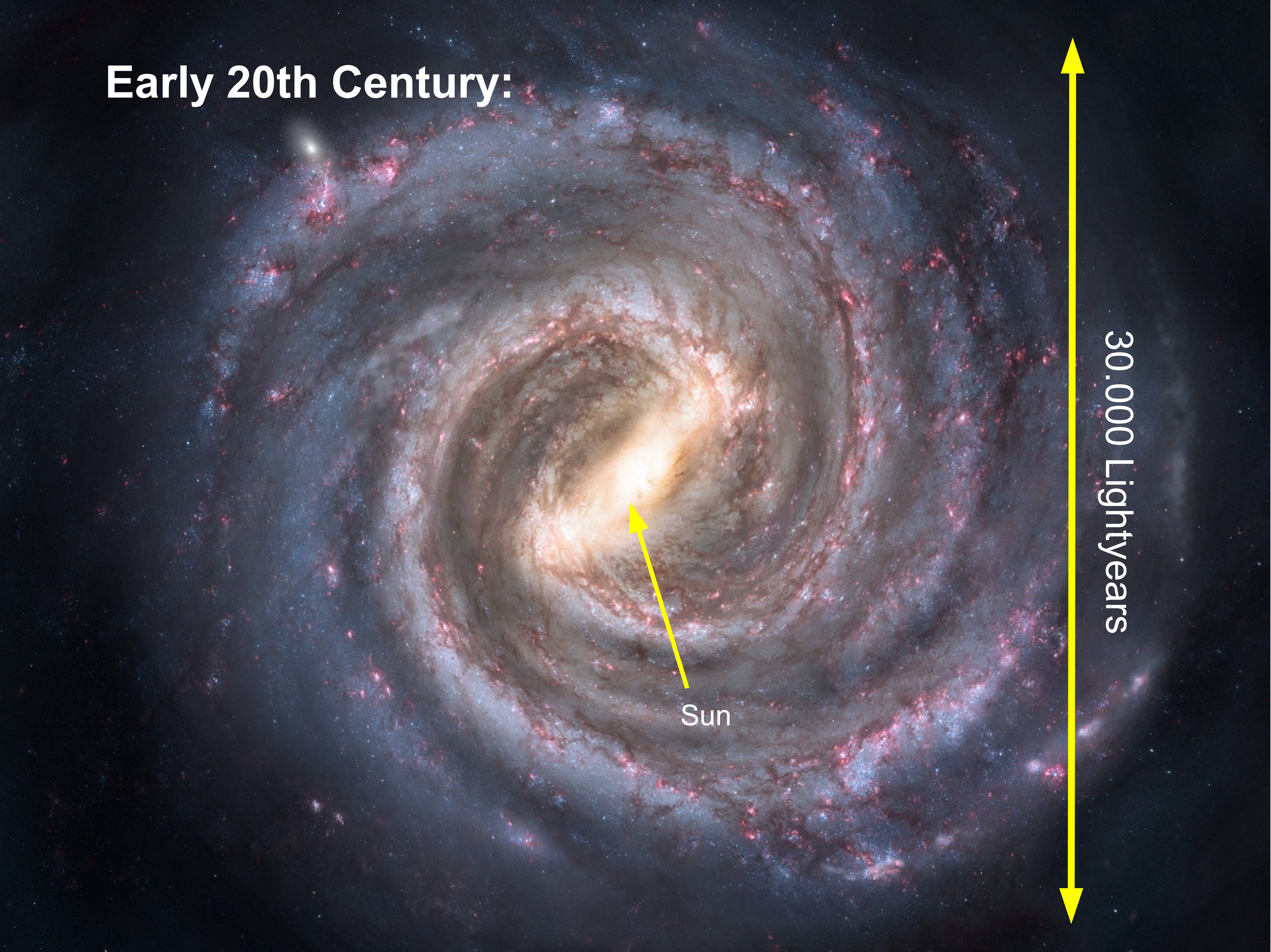




100.000 Lightyears
Sun


Early 20th Century:
30.000 Lightyears
Sun

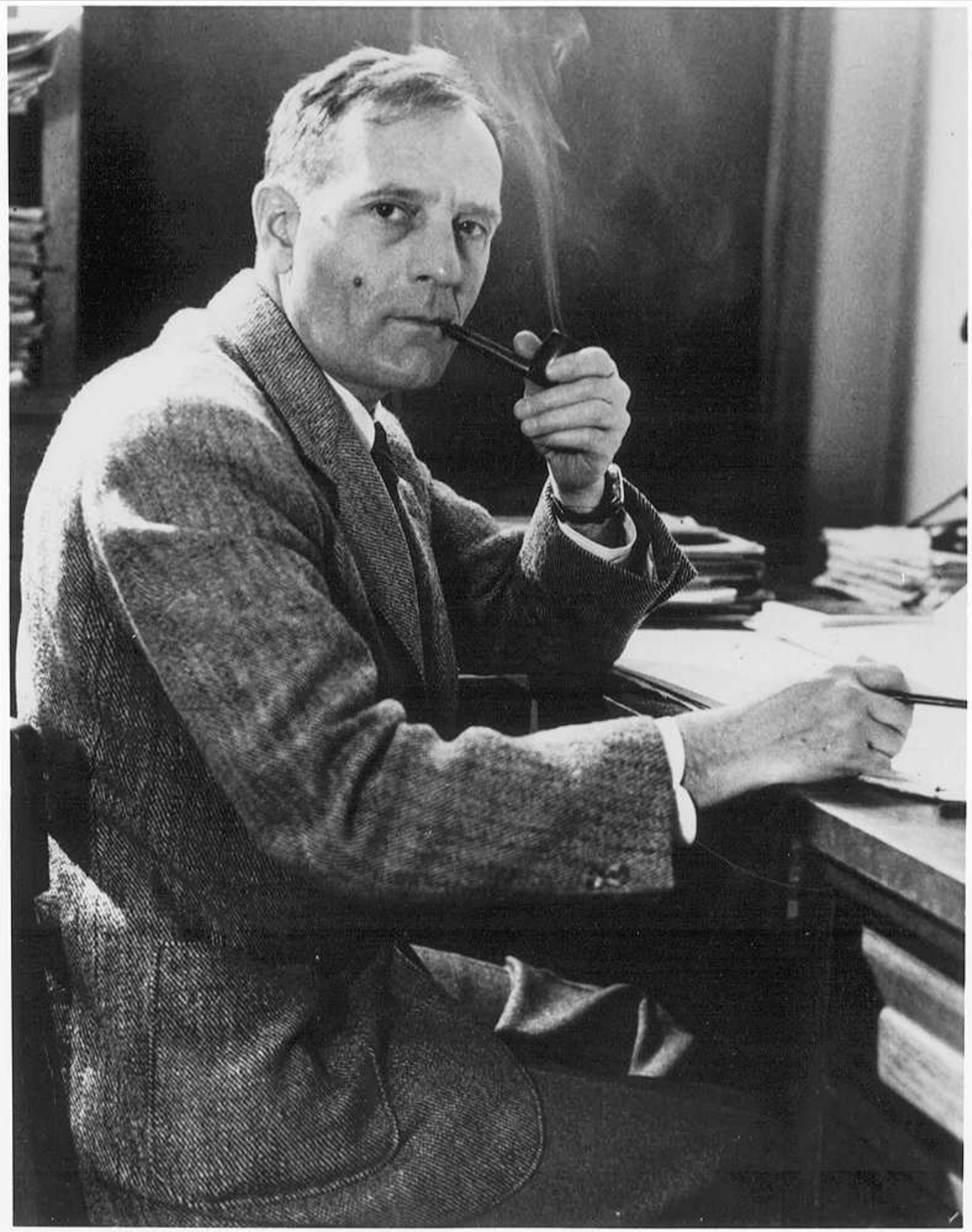
1920: The Great Debate

Harlow Shapley:
- MW is larger than previously thought
- Sun not at the centre
- Milky Way = Universe

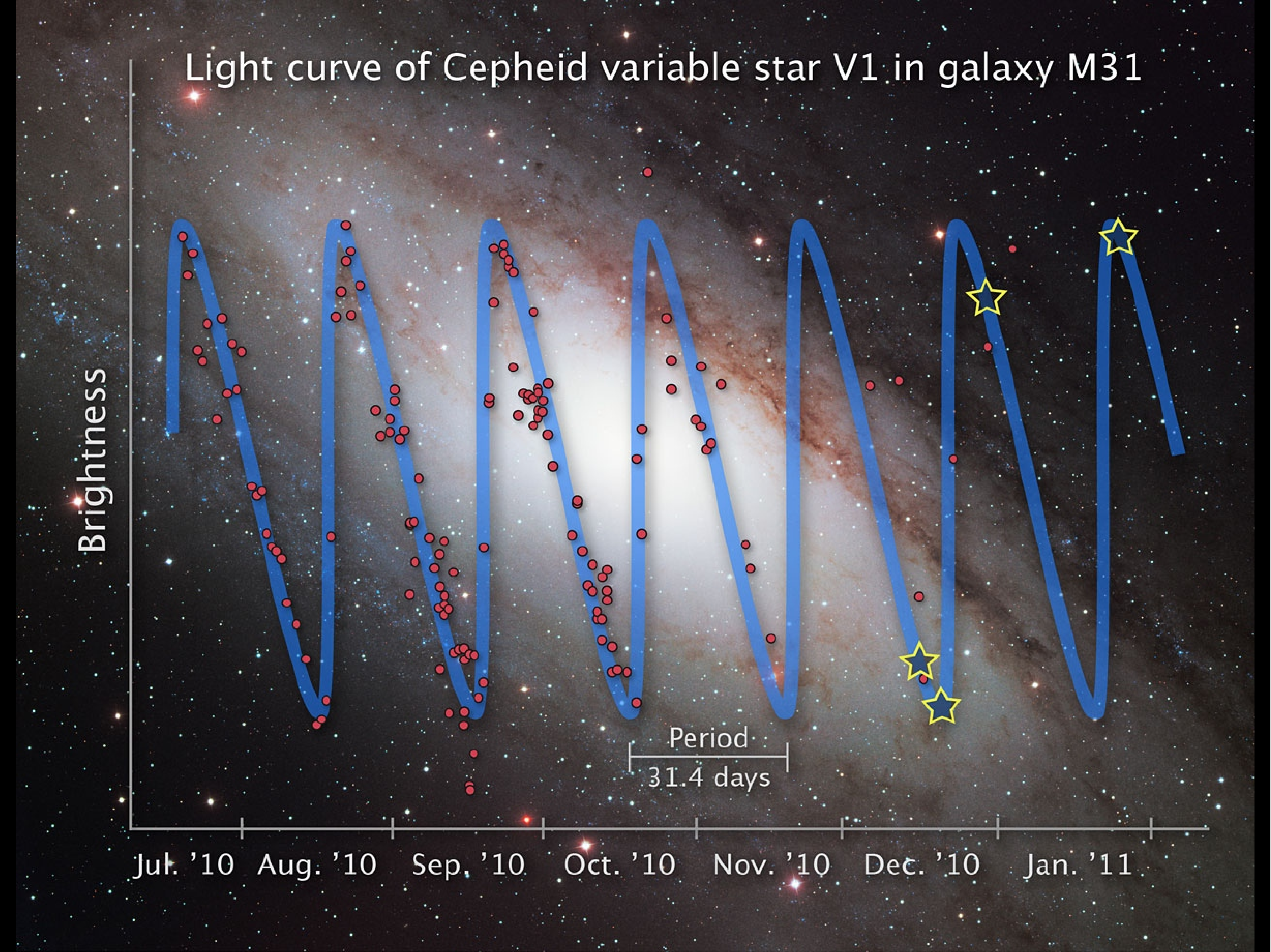
Heber Curtis:
- Represented old picture of MW
- But: Milky Way ≠ Universe

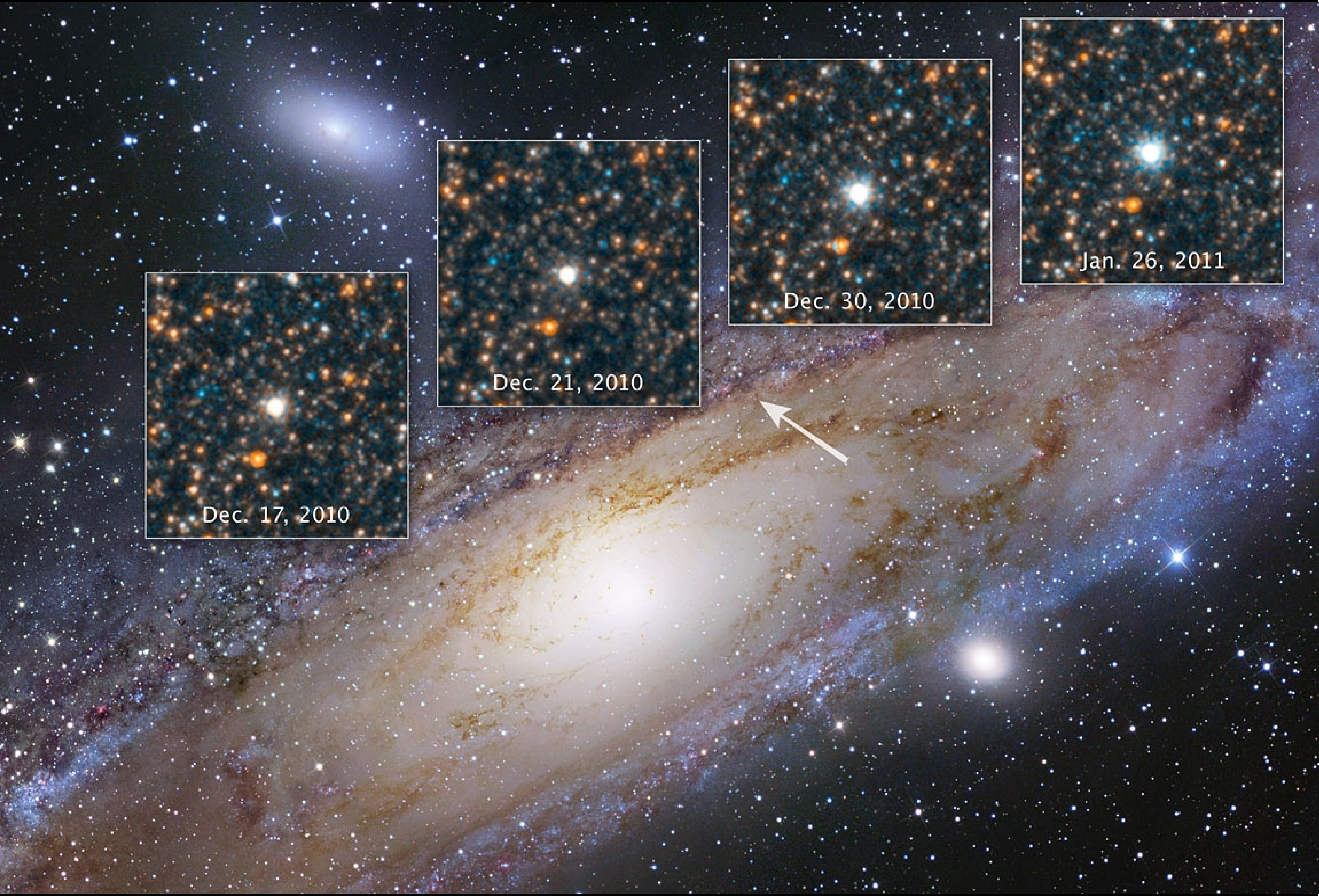

Image of Andromeda Galaxy from 1899

Hubble, the Man



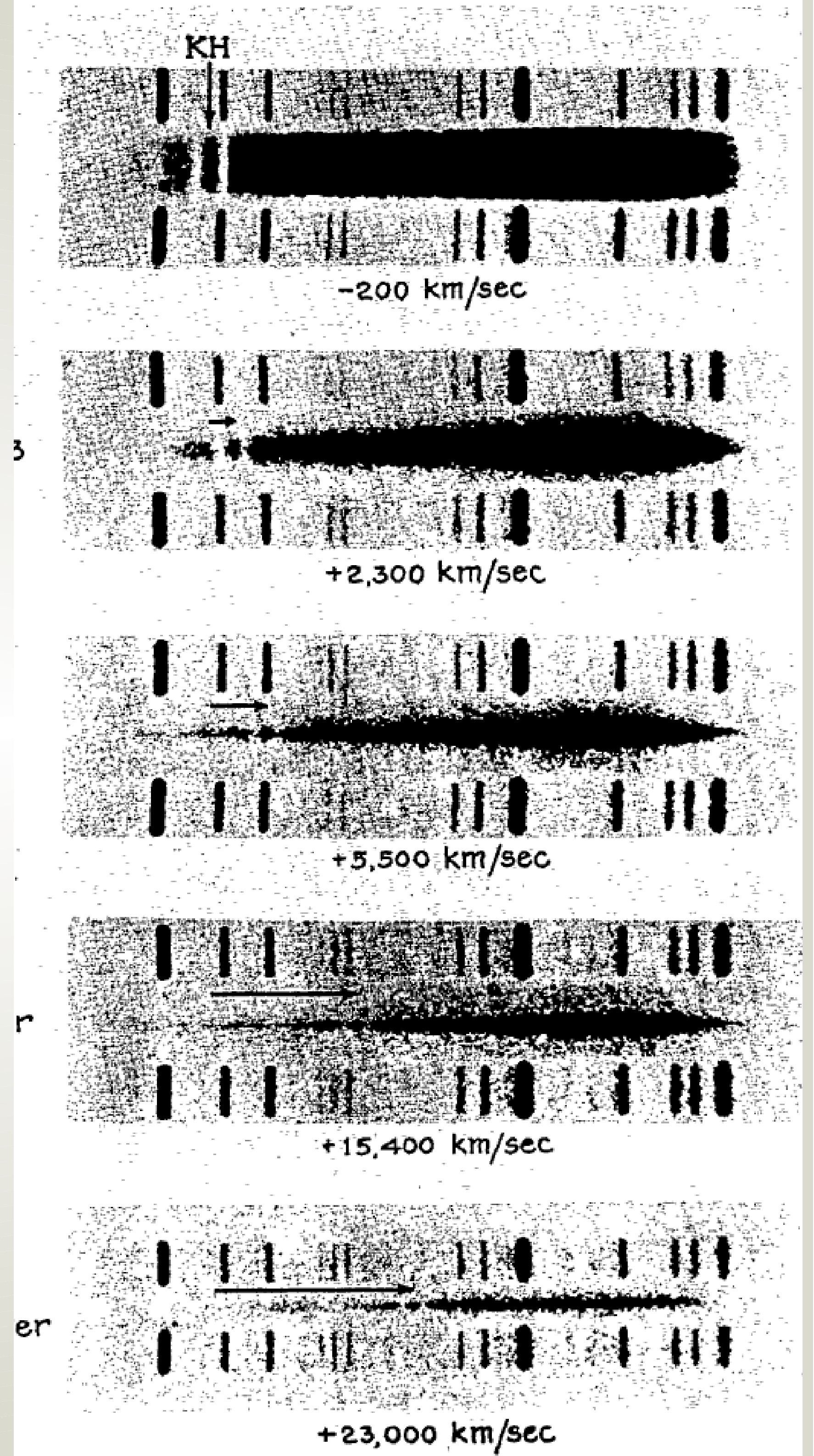
100" Hooker Telescope

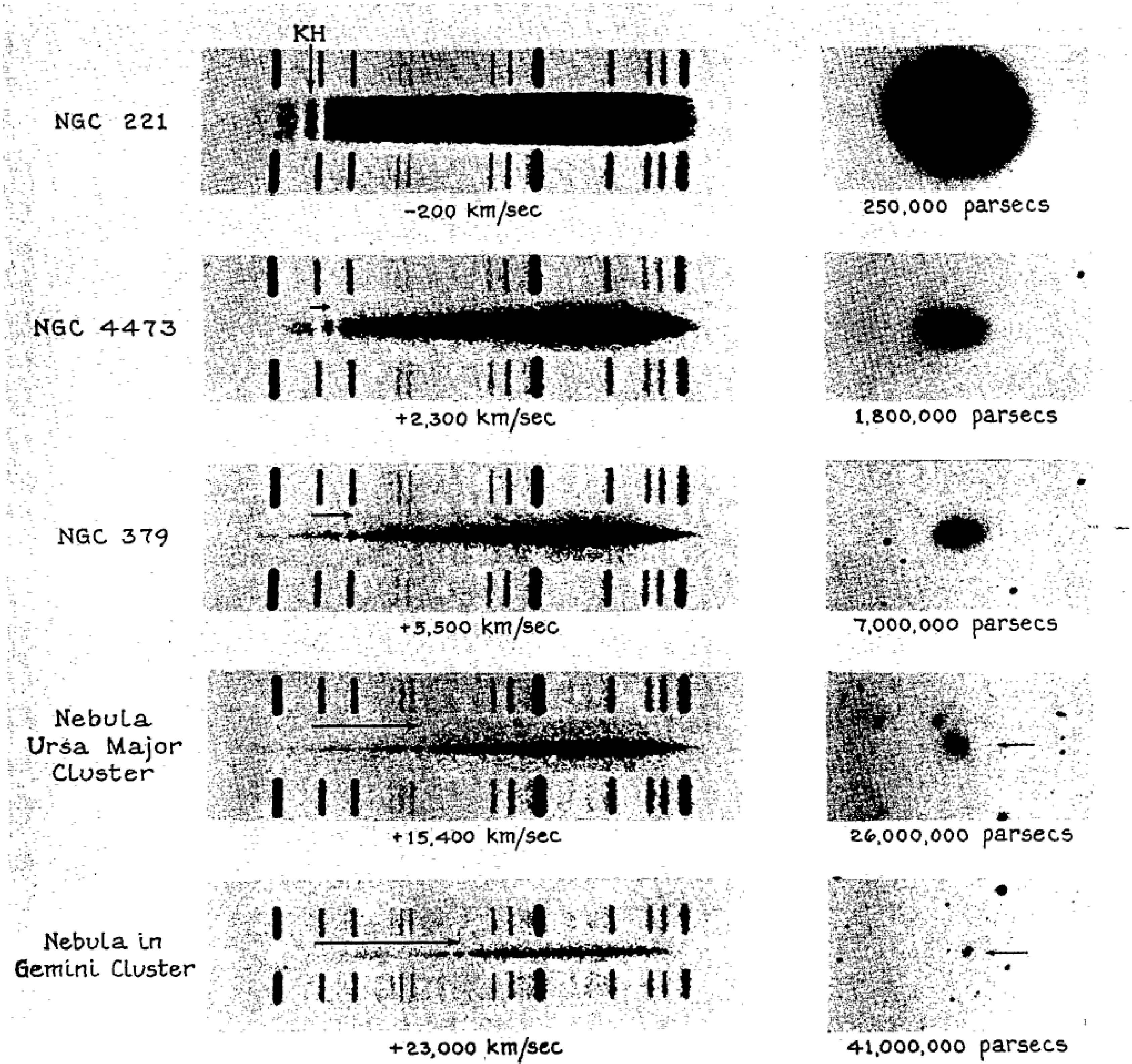

Light curve of Cepheid variable star V1 in galaxy M31
Brightness
Period
31.4 days
Jul. '10
Aug. '10
Sep. '10
Oct. '10
Nov. '10
Dec. '10
Jan. '11



Dec. 17, 2010
Dec. 21, 2010
Dec. 30, 2010
Jan. 26, 2011

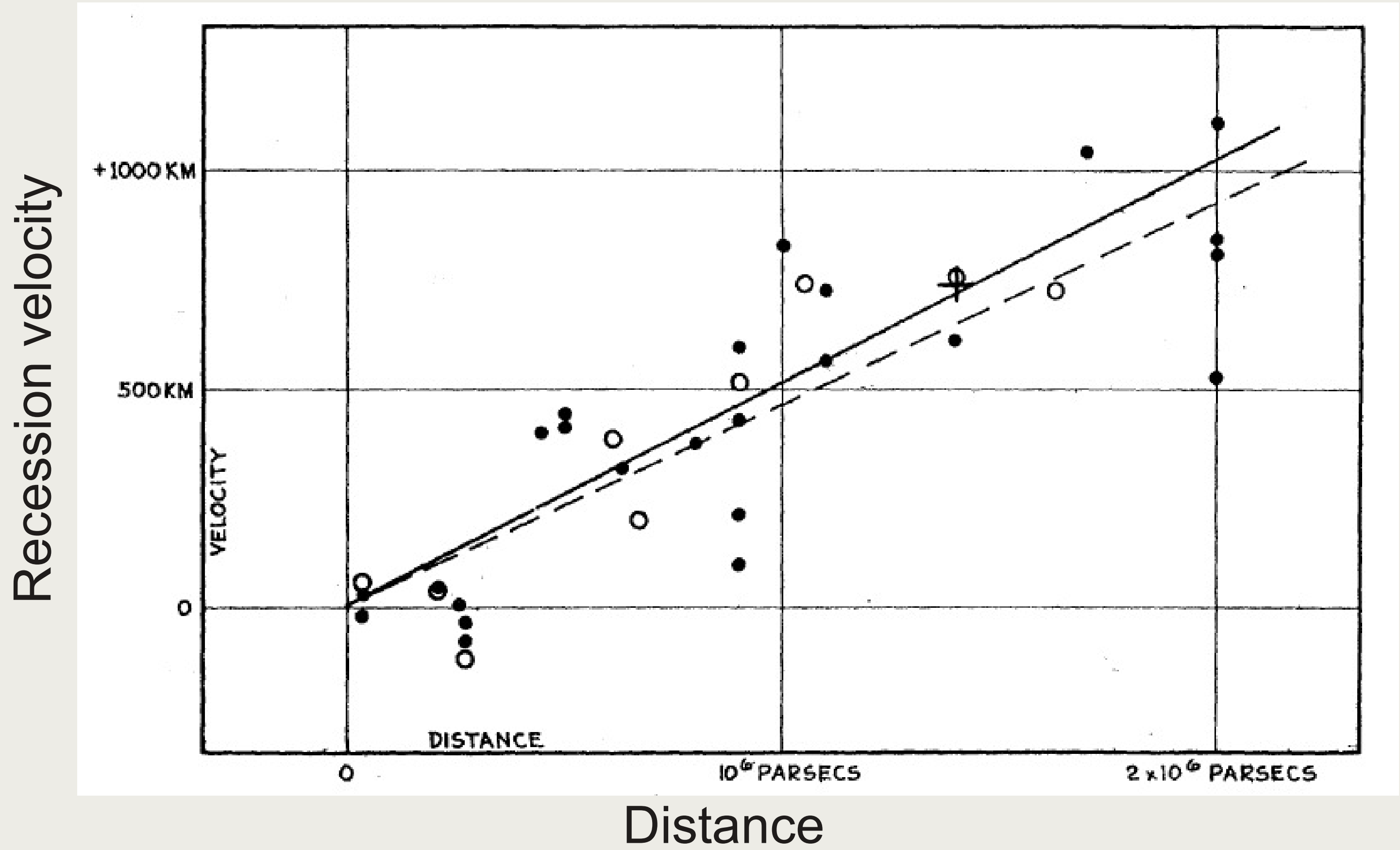
1912: Vesto Slipher discovers the redshift of spiral nebulae




KH
NGC 221
-200 km/sec
250,000 parsecs
NGC 4473
+2,300 km/sec
1,800,000 parsecs
NGC 379
+5,500 km/sec
7,000,000 parsecs
Nebula Ursa Major Cluster
+15,400 km/sec
26,000,000 parsecs
Nebula in Gemini Cluster
+23,000 km/sec
41,000,000 parsecs

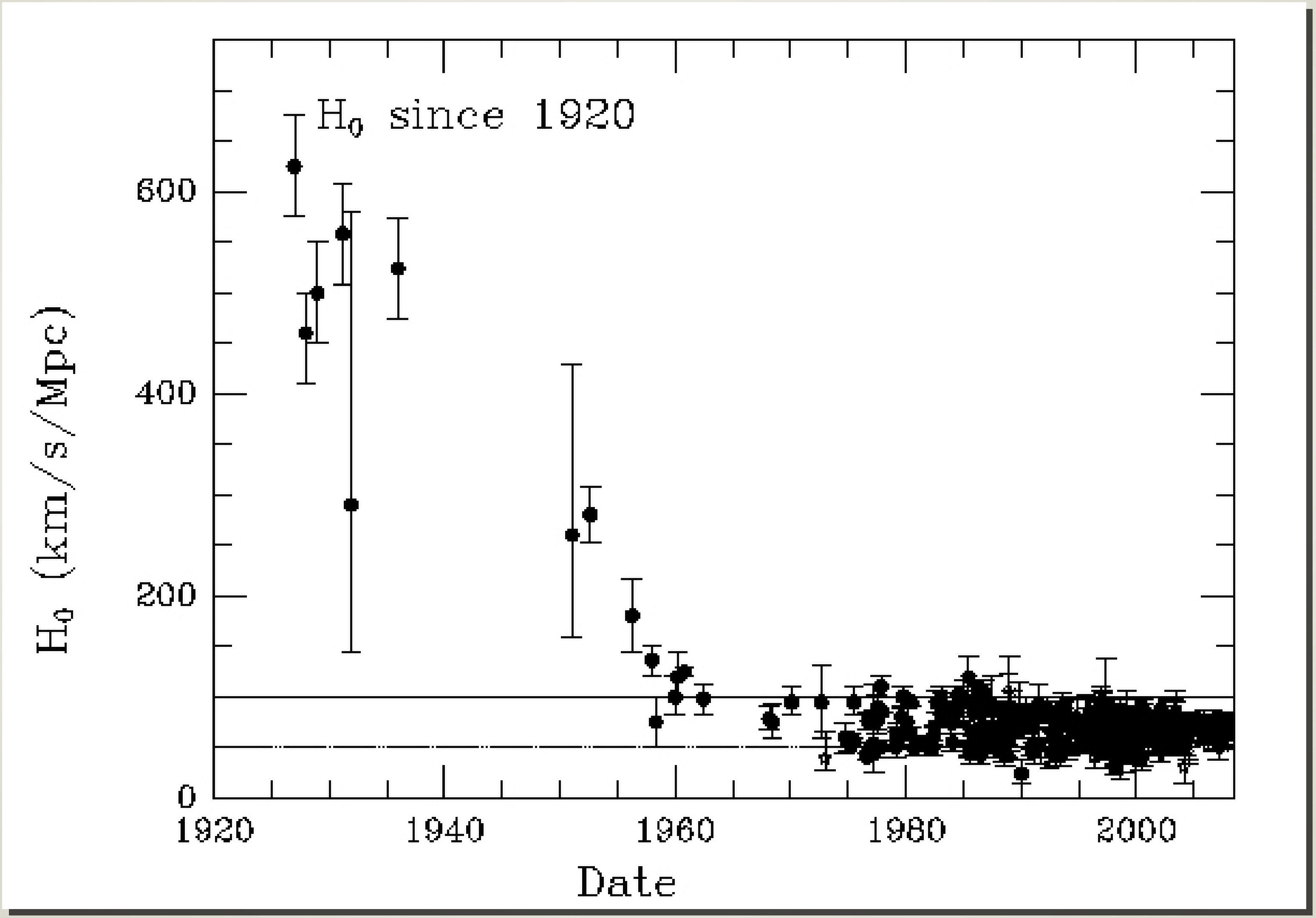
1929: Universal Expansion

The original Hubble diagram (Hubble 1929):



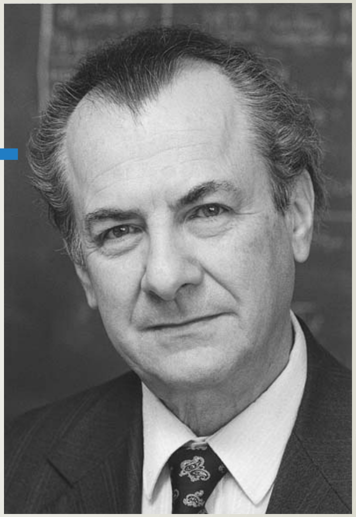
All distant galaxies are found to recede from us.
Hubble's Law: $v = H_0 d$ → The Universe expands!

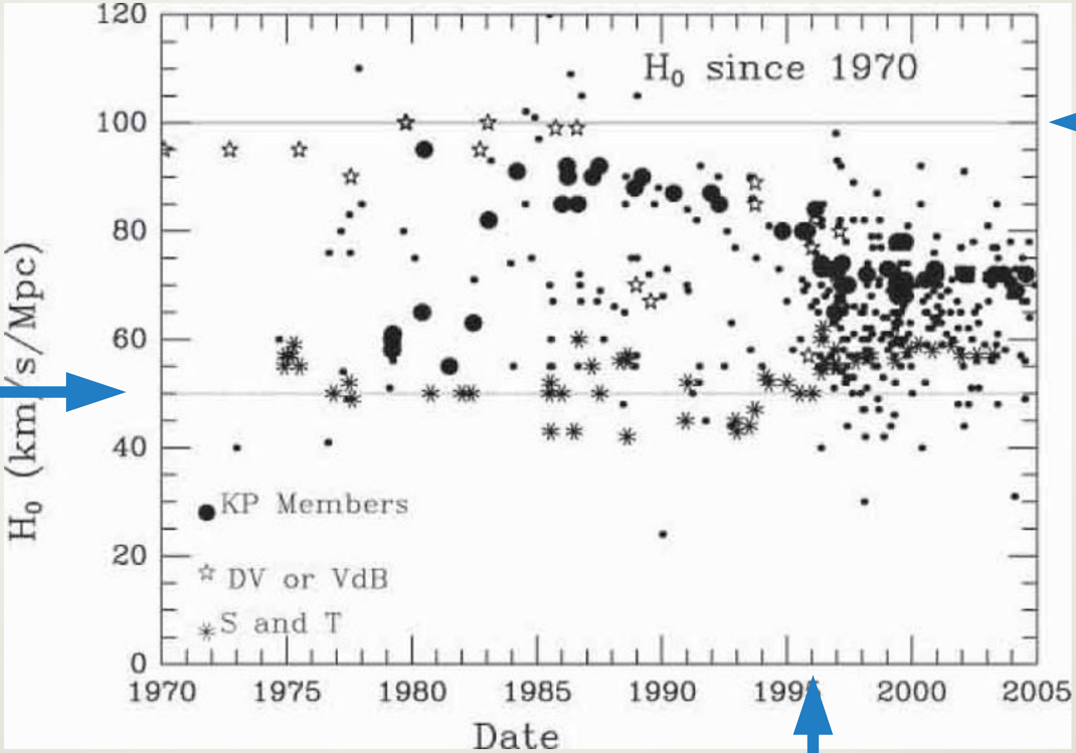
Hubble, the Constant

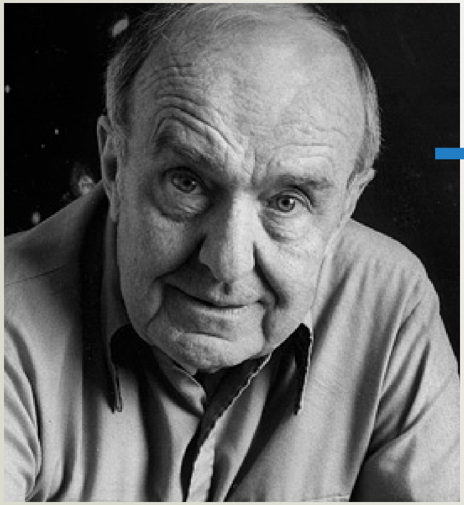


Hubble, the Constant

Gerard de Vaucouleurs: H_0 = 100 km/s/Mpc



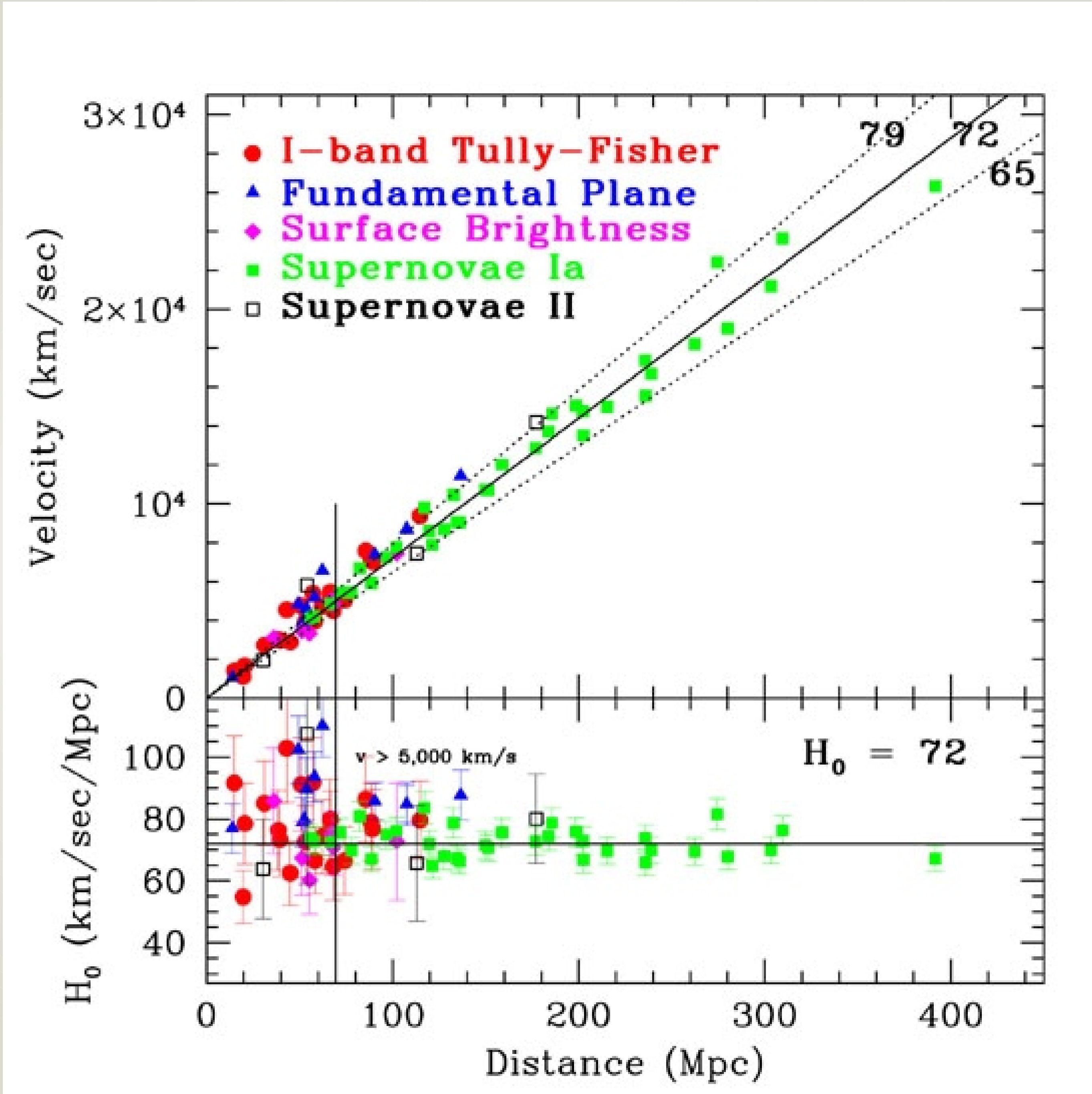




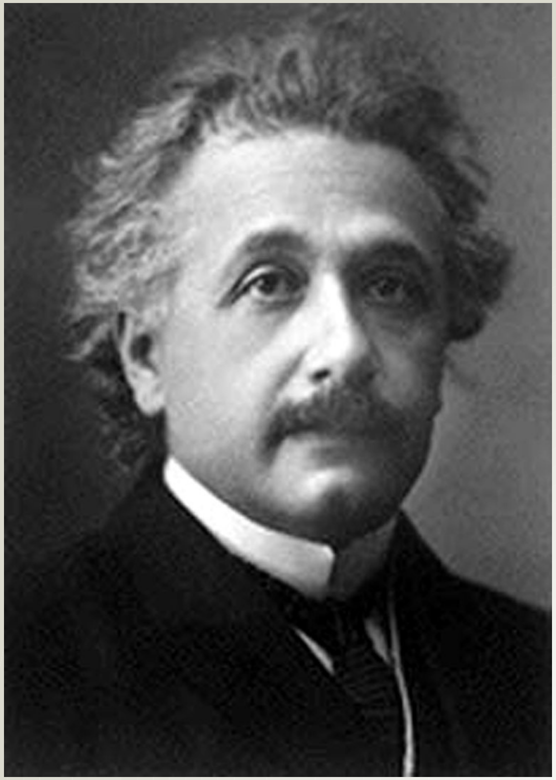
Allan Sandage: H_0 = 50 km/s/Mpc

1996: the Great Debate – Part 2


Hubble,
the Telescope

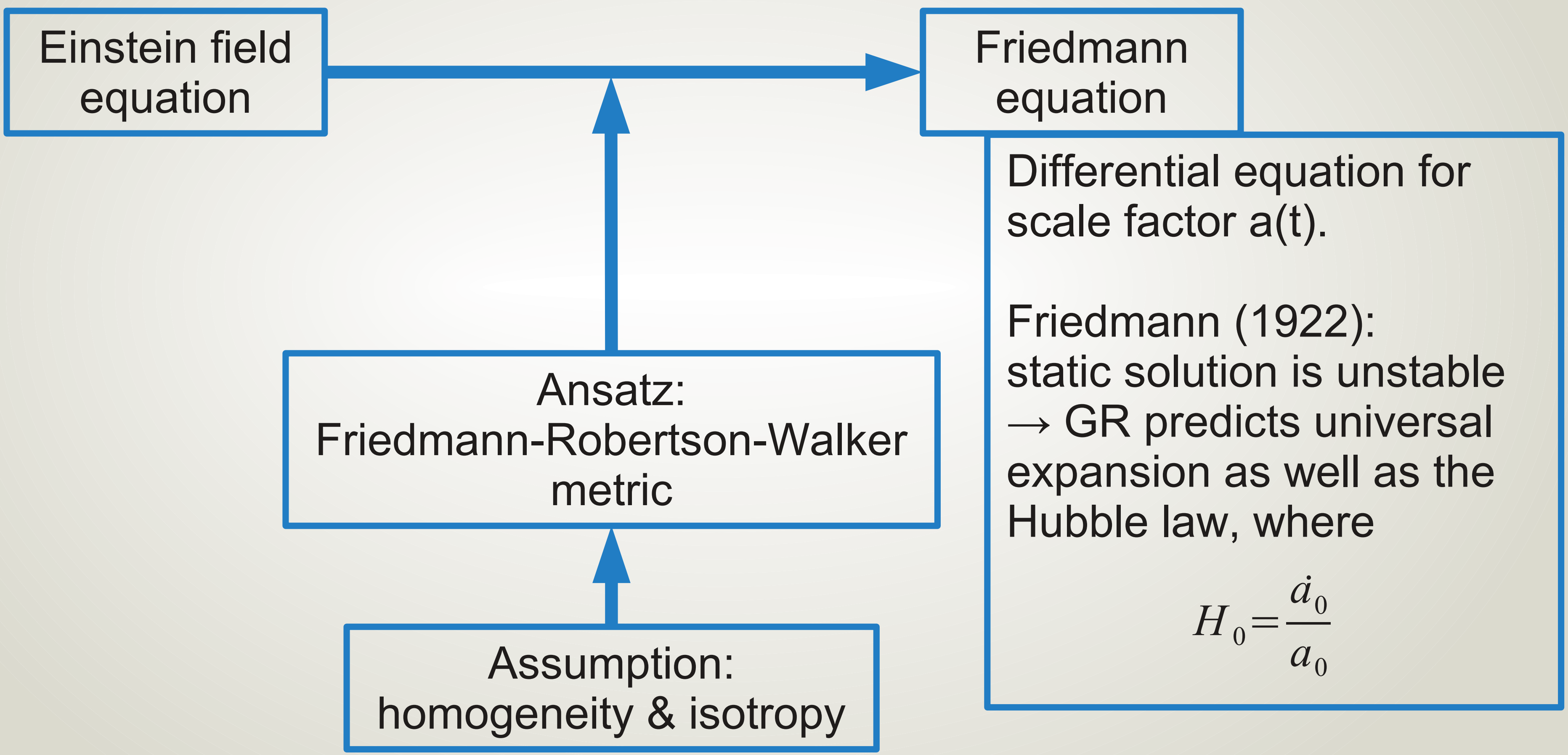


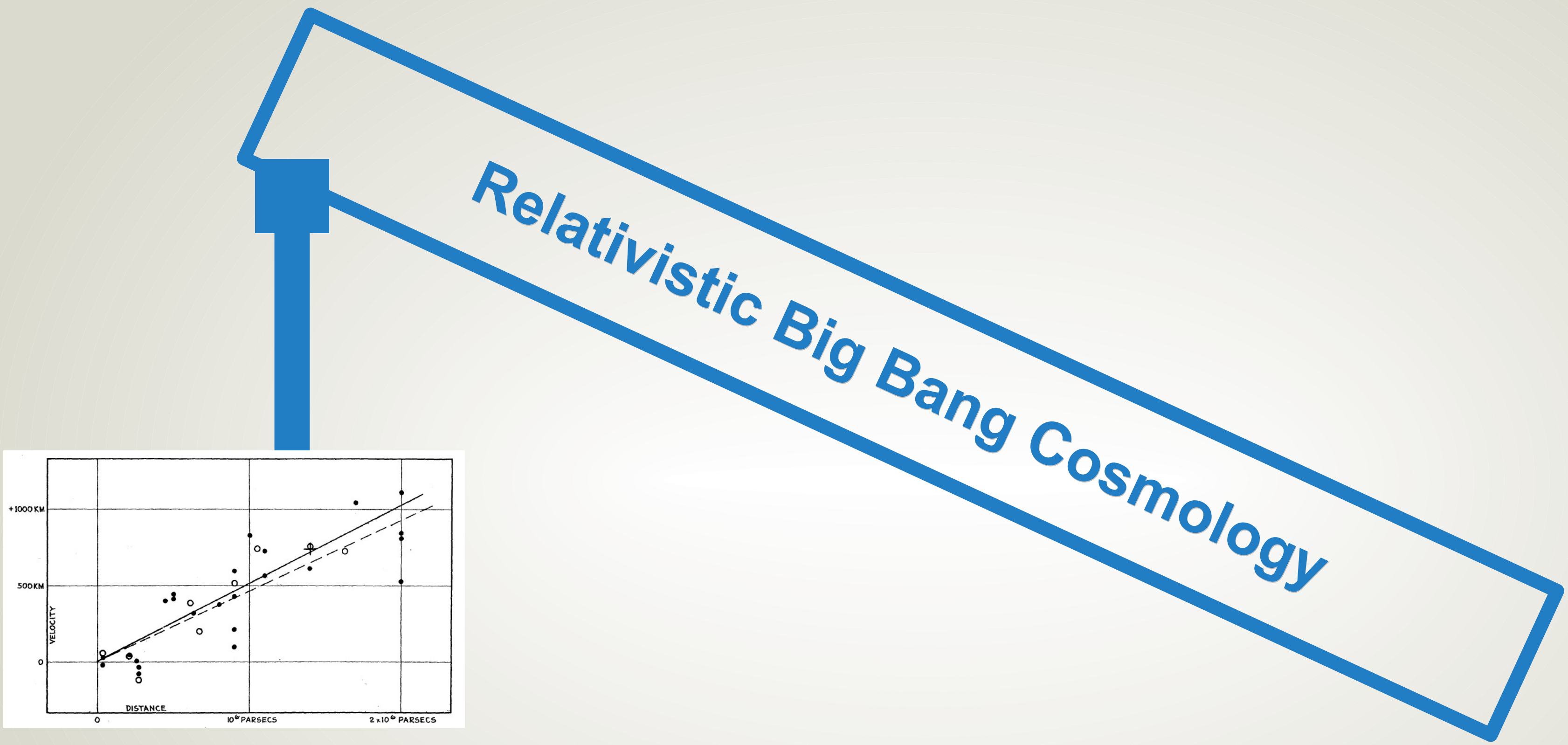
HST Key Project, Freedman et al.



1916: Einstein's Theory of General Relativity

Relativistic Cosmology

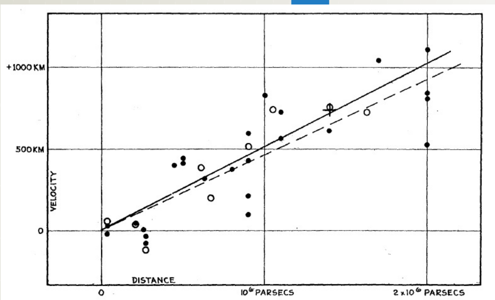




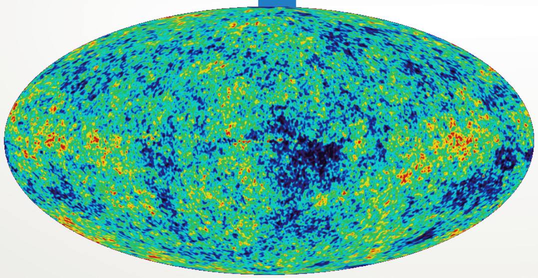
Relativistic Big Bang Cosmology
+1000 KM
500 KM
0
VELOCITY
DISTANCE
0
10⁶ PARSECS
2 x 10⁶ PARSECS

Expansion

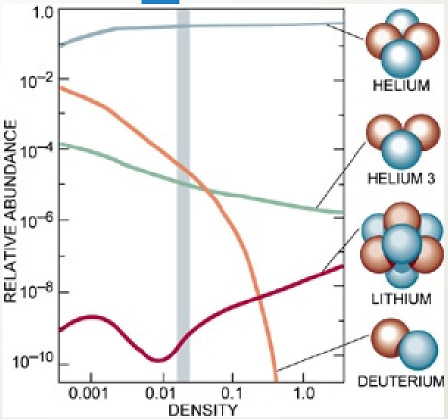
Relativistic Big Bang Cosmology



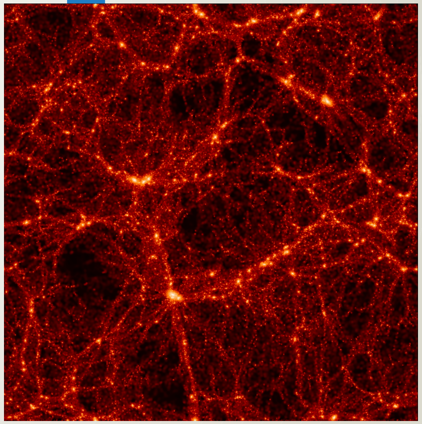
Expansion



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:

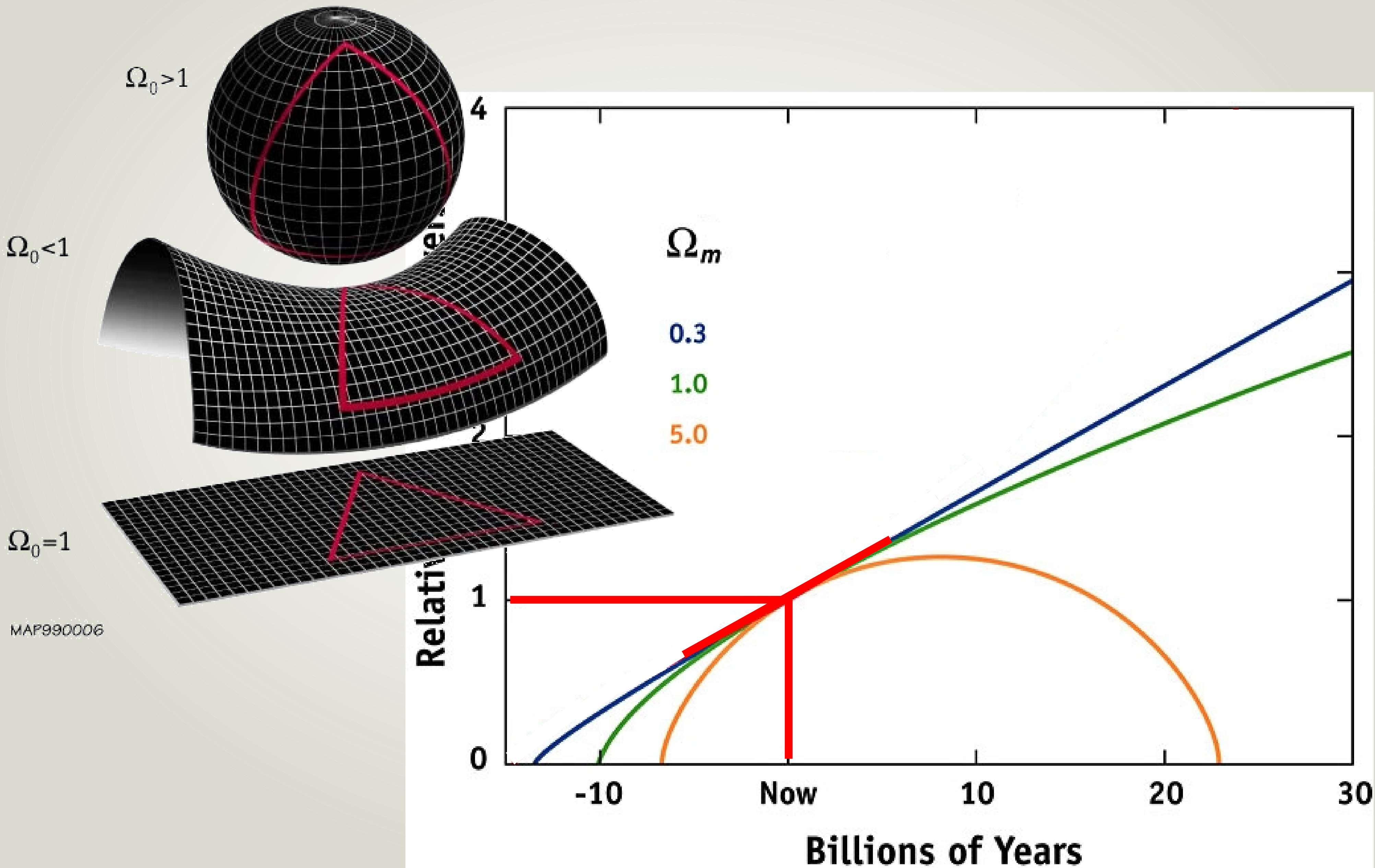
$$H(z) = H_0 \left[\sum_i \Omega_i (1+z)^{3(1+w_i)} + \Omega_k (1+z)^2 \right]^{\frac{1}{2}}$$

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

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 (Ω_i) — Equation of state parameter (w_i)

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Density parameter — Equation of state parameter

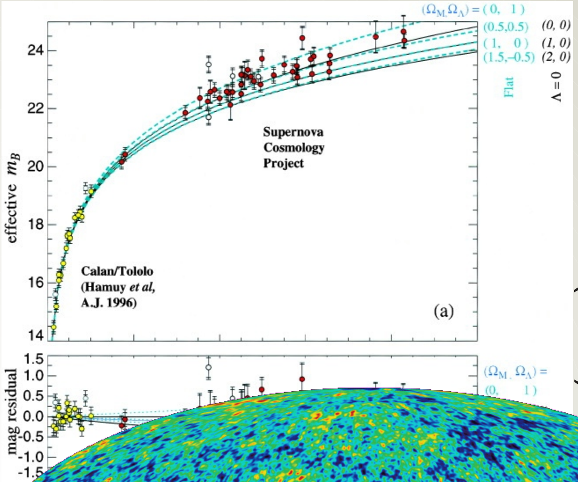
How can these be measured?

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

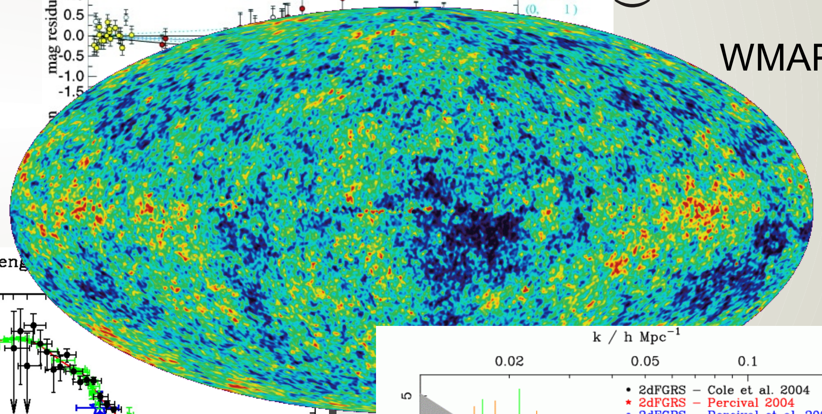
Precision Cosmology

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

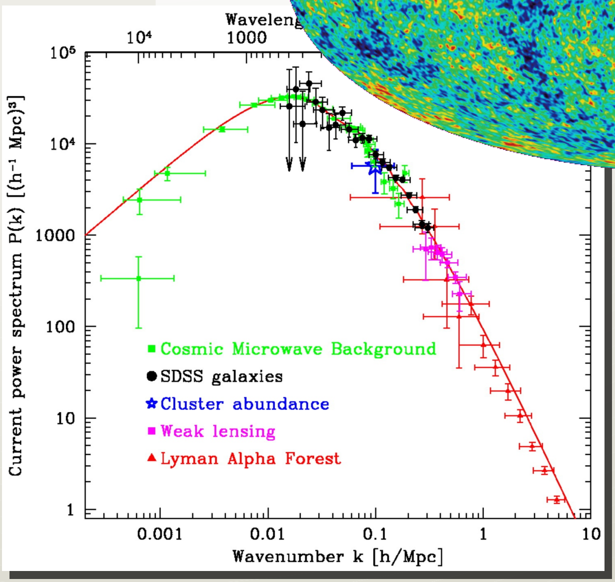
- Cosmic Microwave Background
- Supernovae type Ia
- Large scale structure of galaxies and intergalactic medium
- Galaxy cluster abundance
- Weak lensing



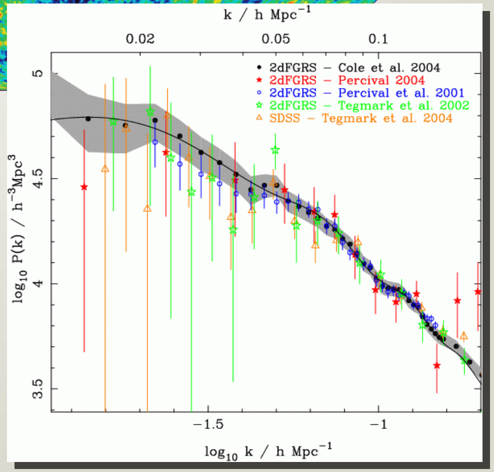
Perlmutter et al. (1999)



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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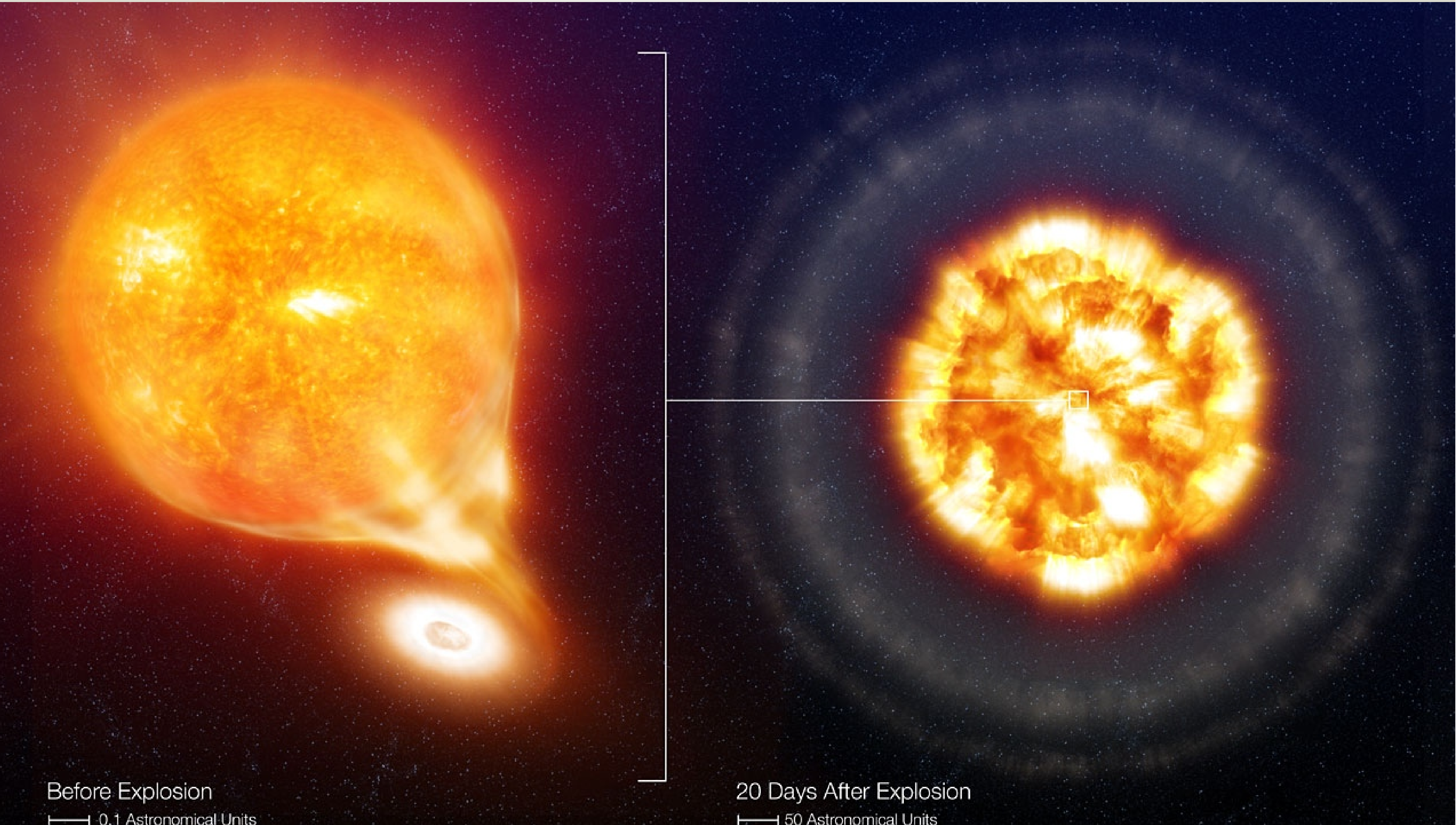

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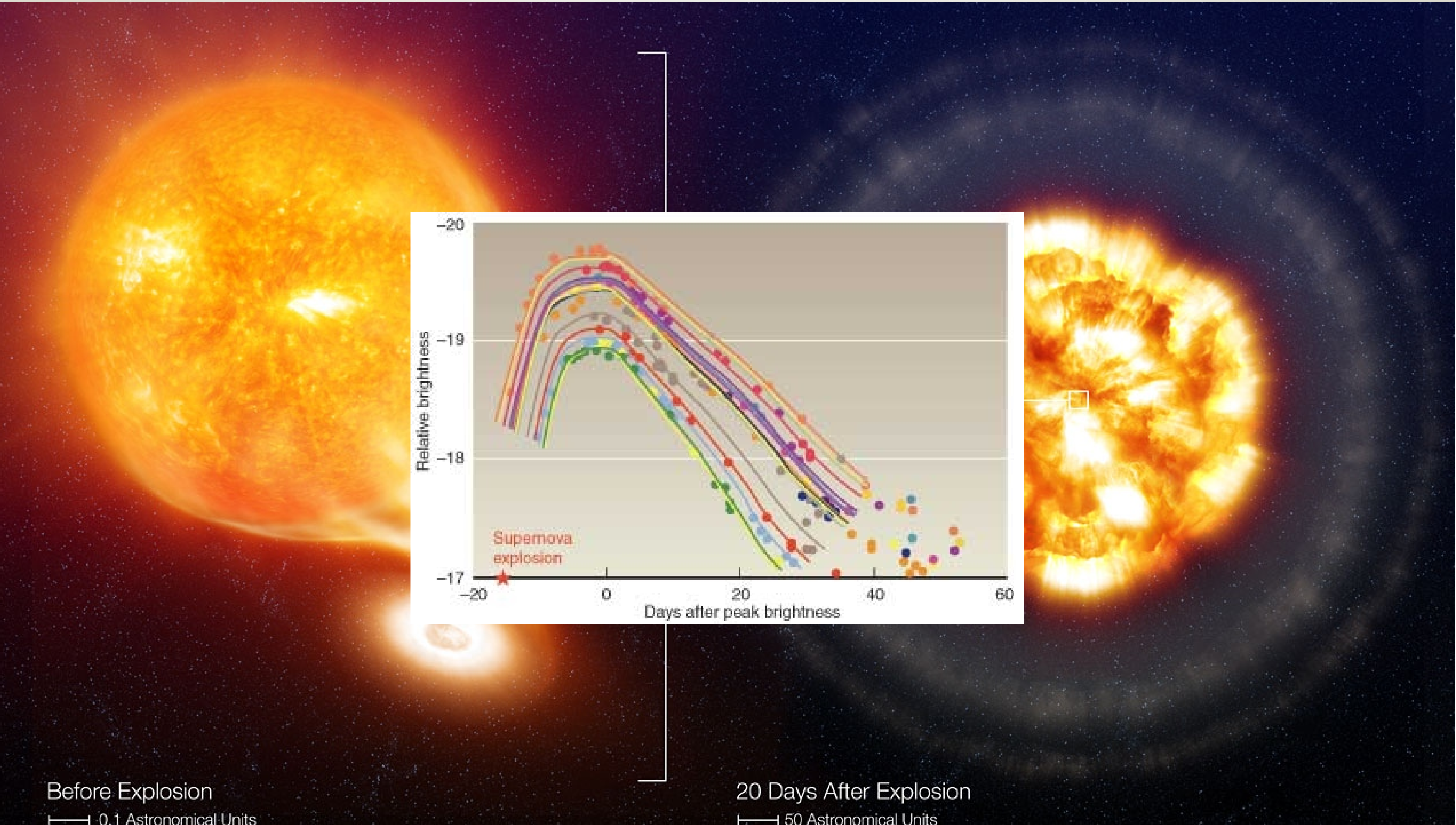

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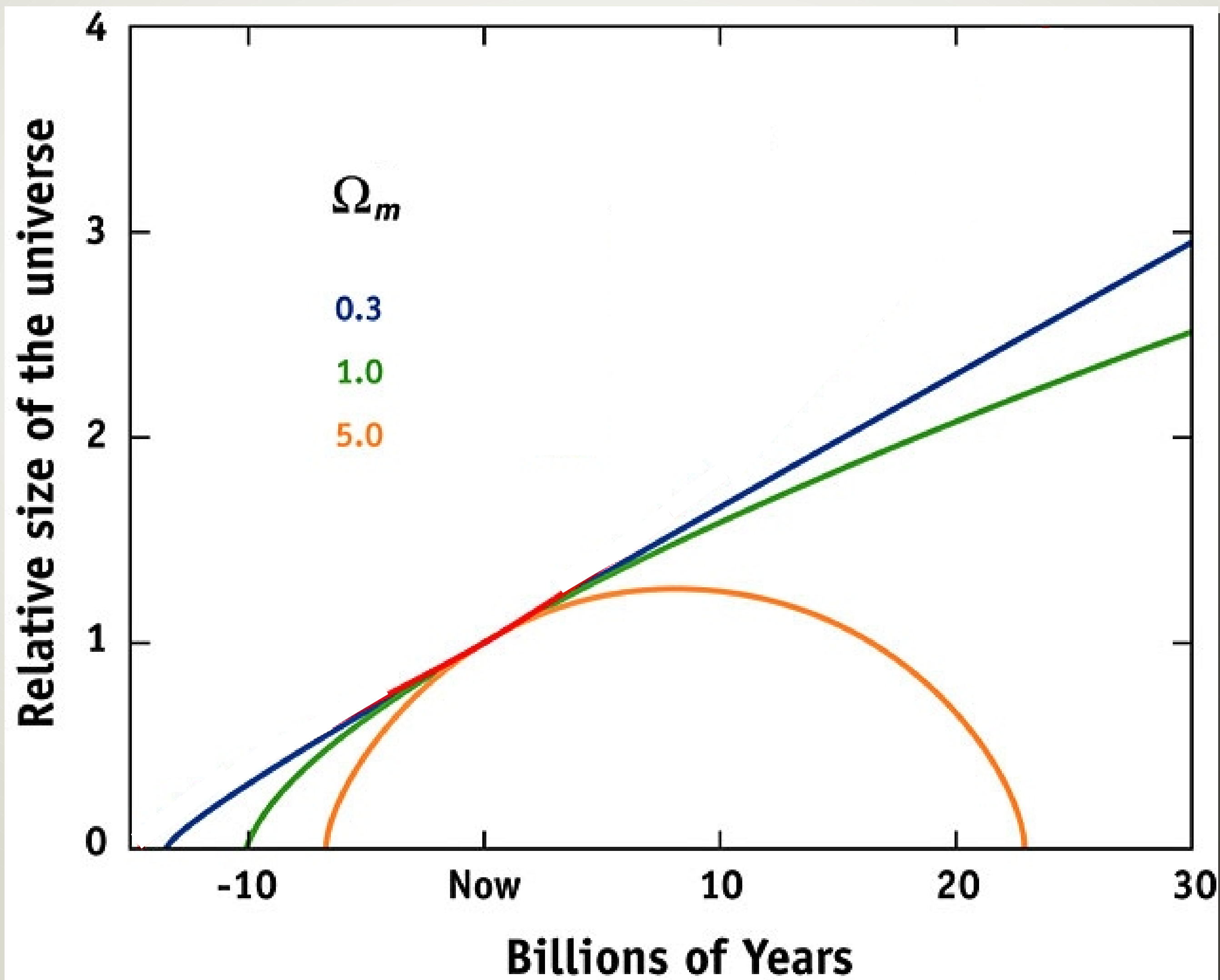

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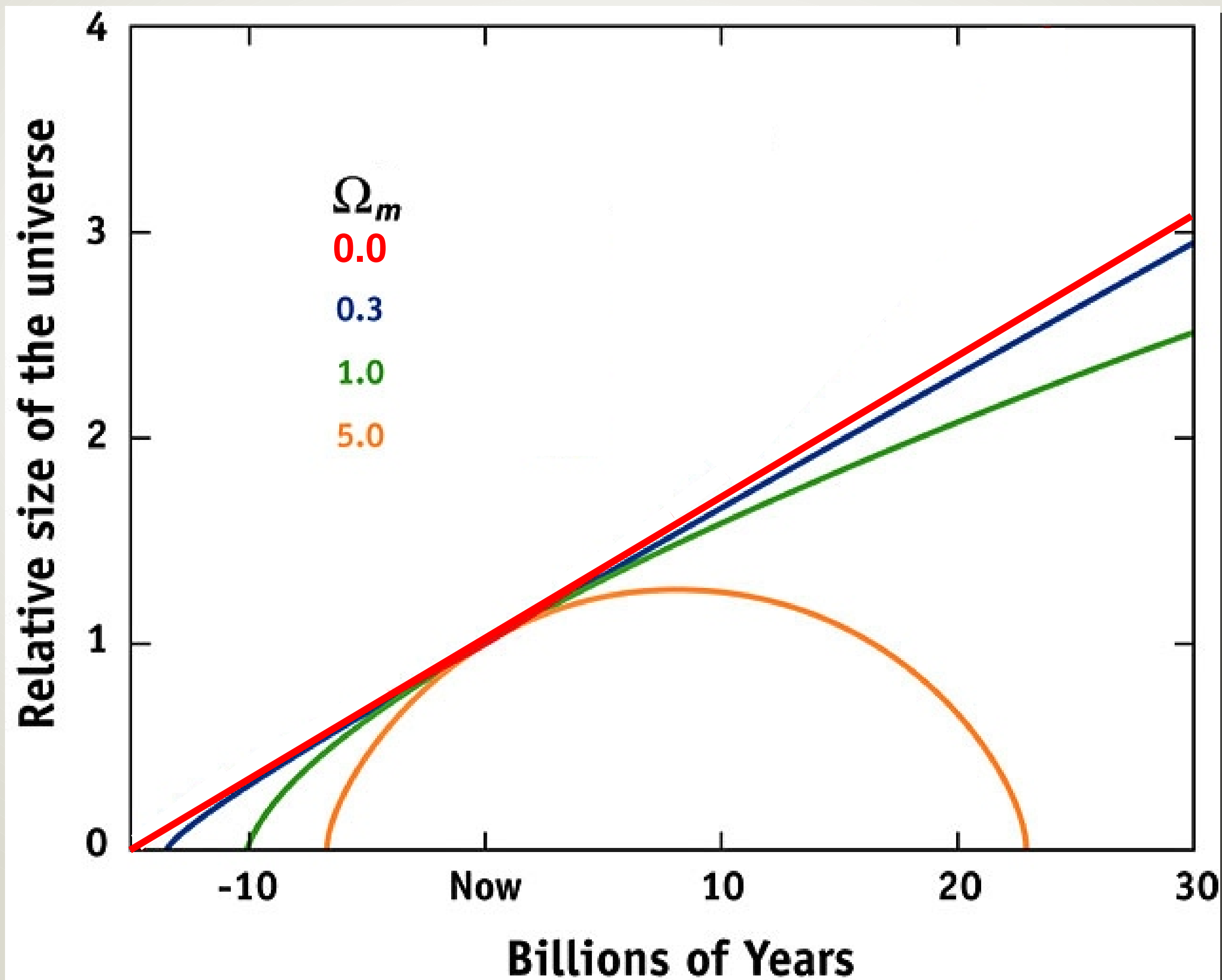

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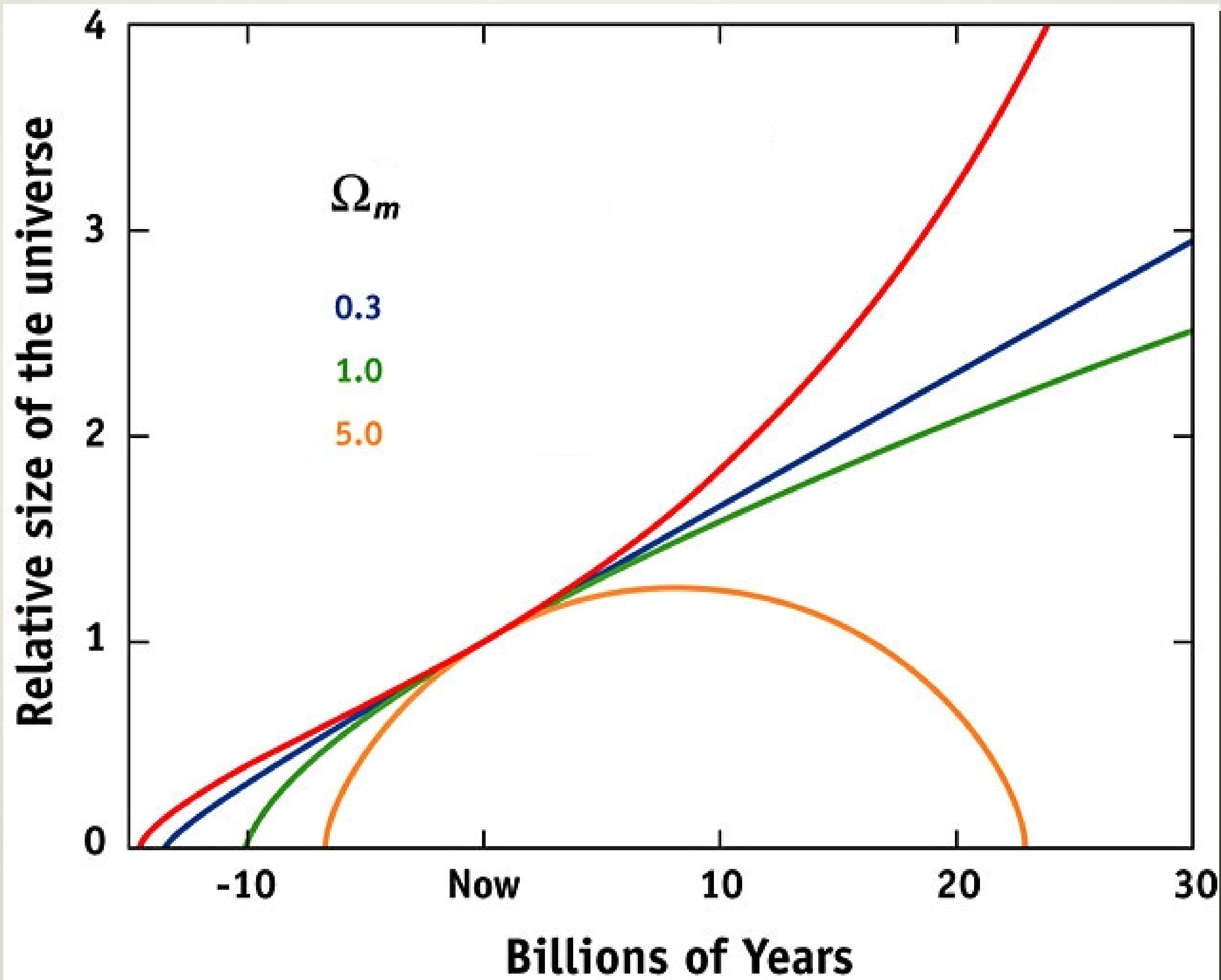

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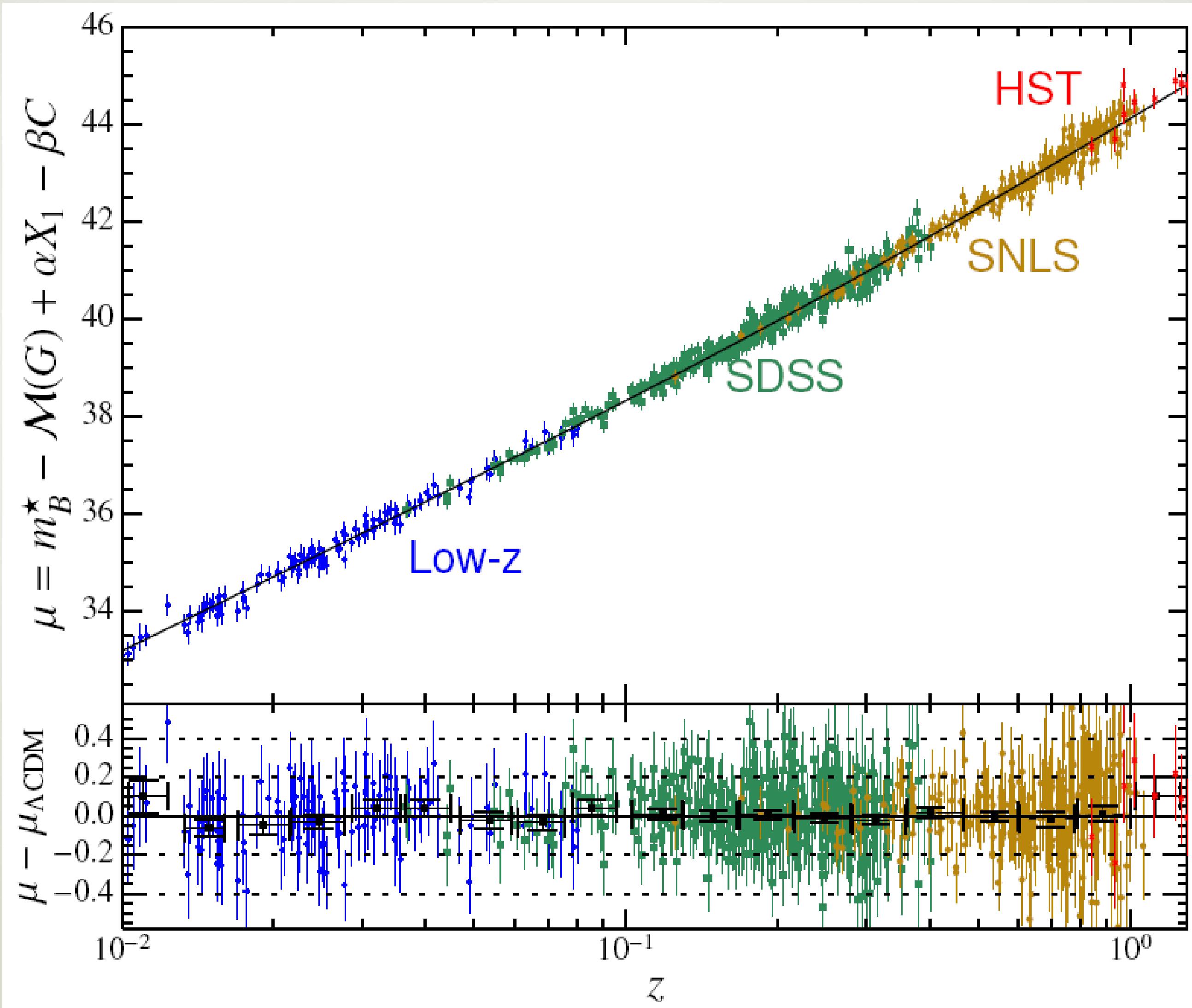

Betoule et al. (2014)

Surprise: Accelerated Expansion

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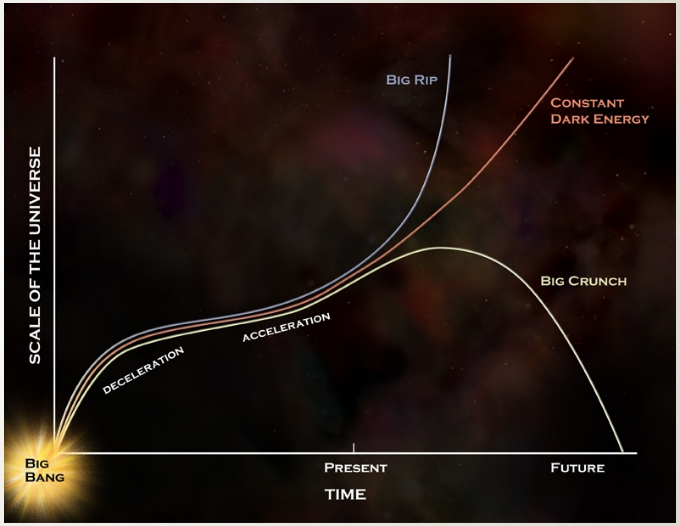
- The source of the acceleration is entirely unknown.
  Most explanations so far proposed require new physics.



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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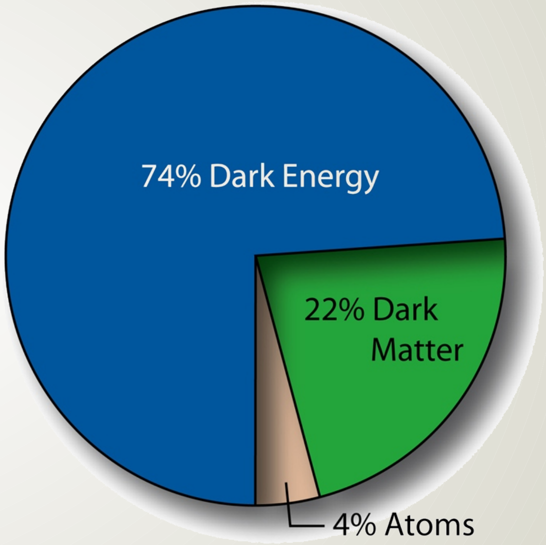

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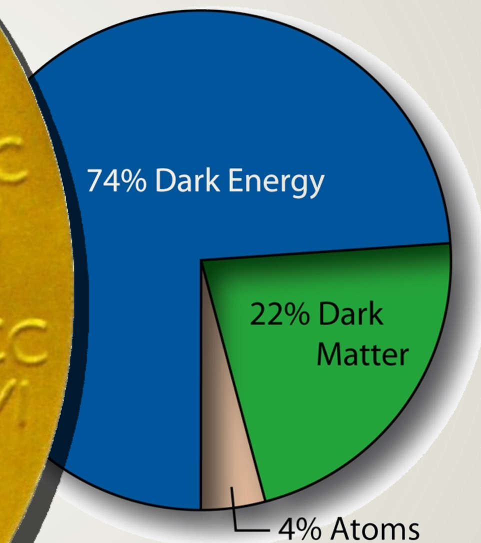

Nobel Prize for Physics 2011


Saul Perlmutter


Brian Schmidt


Adam Riess

Accelerated Expansion

- Intense interest in the expansion history.

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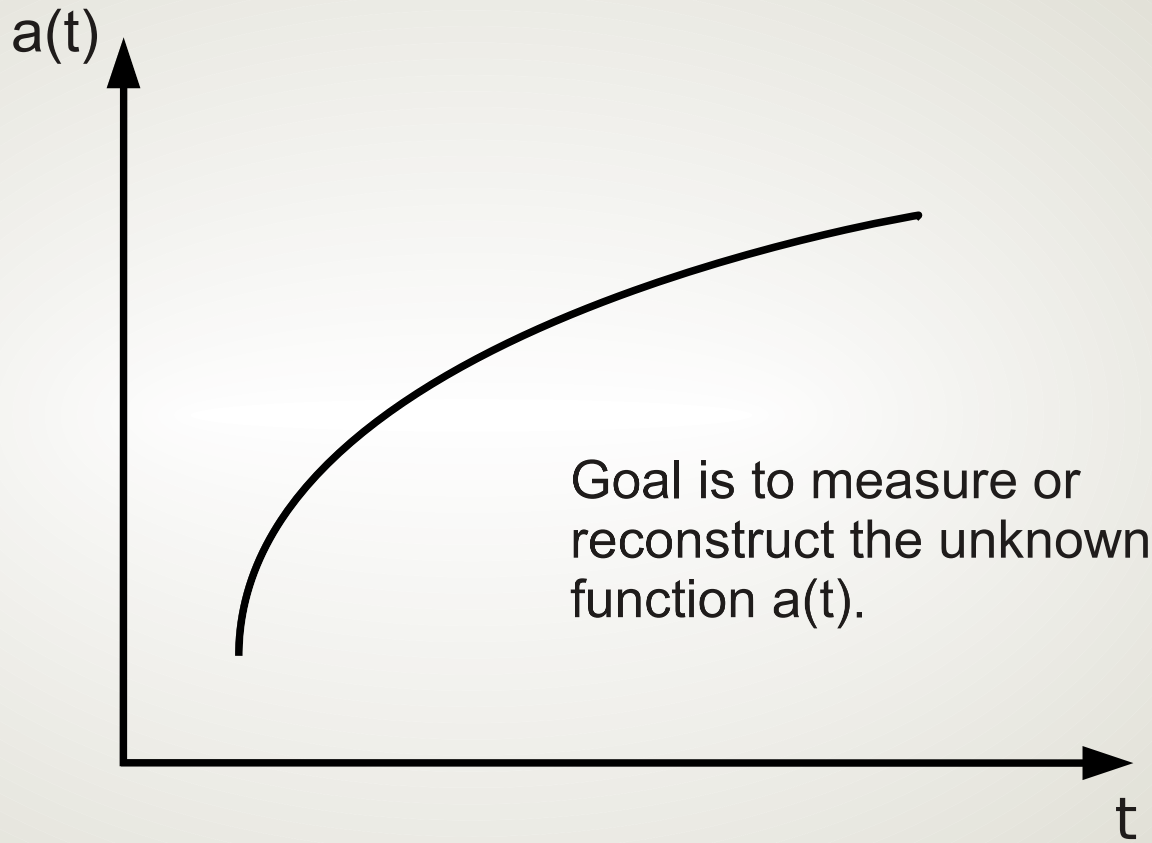
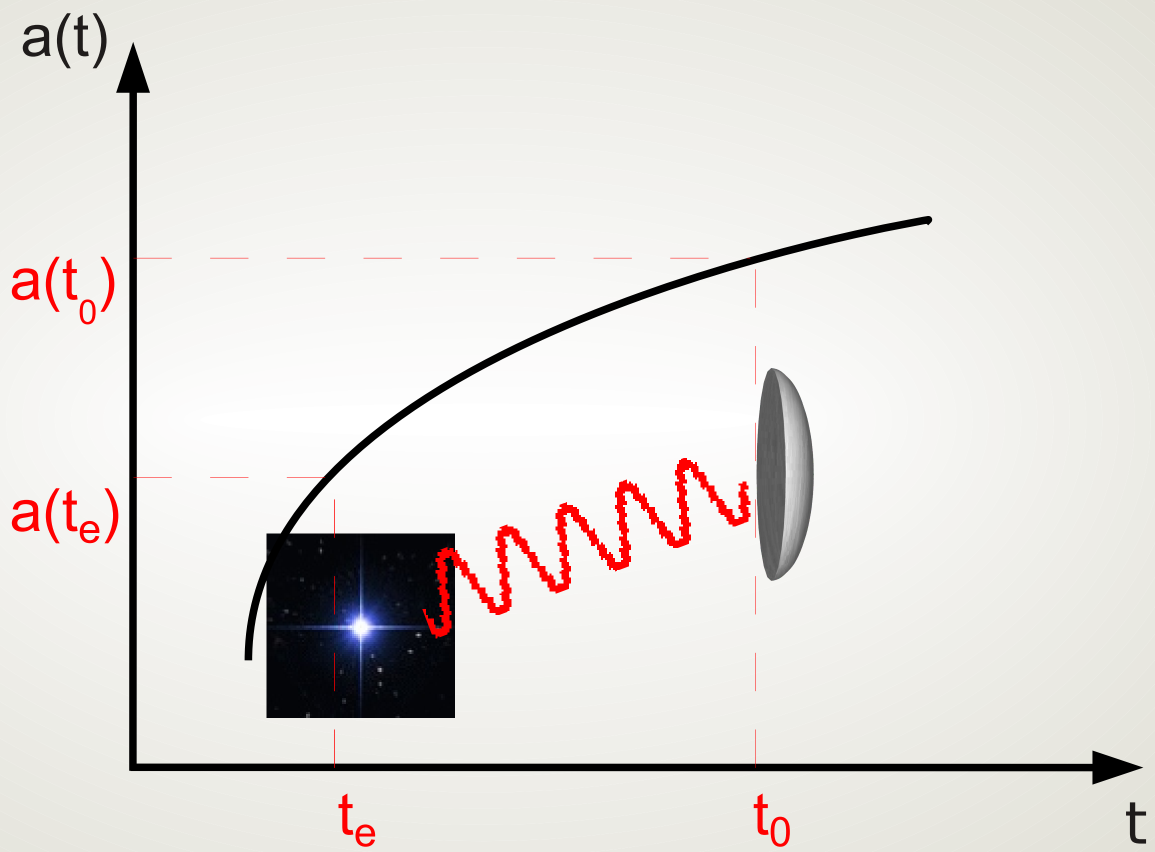


Goal is to measure or reconstruct the unknown function a(t).

Accelerated Expansion

➔ Intense interest in the expansion history.

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



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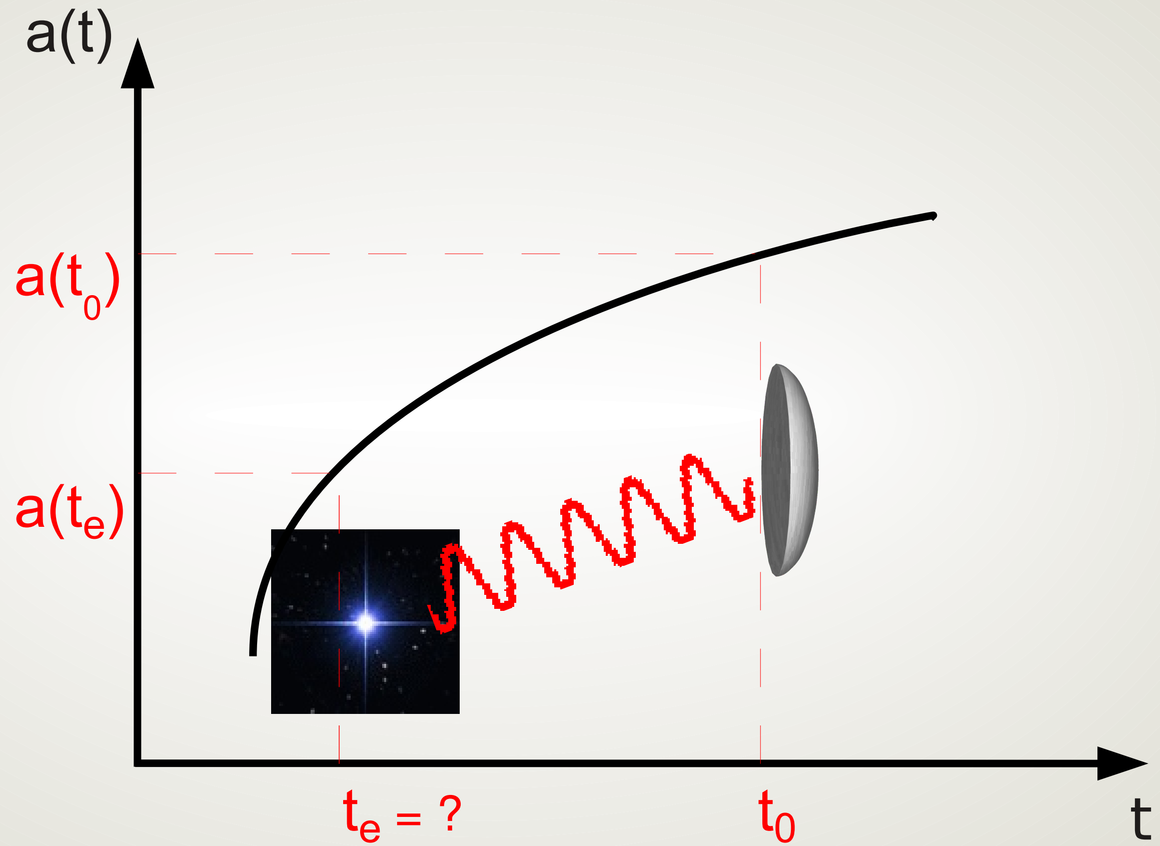

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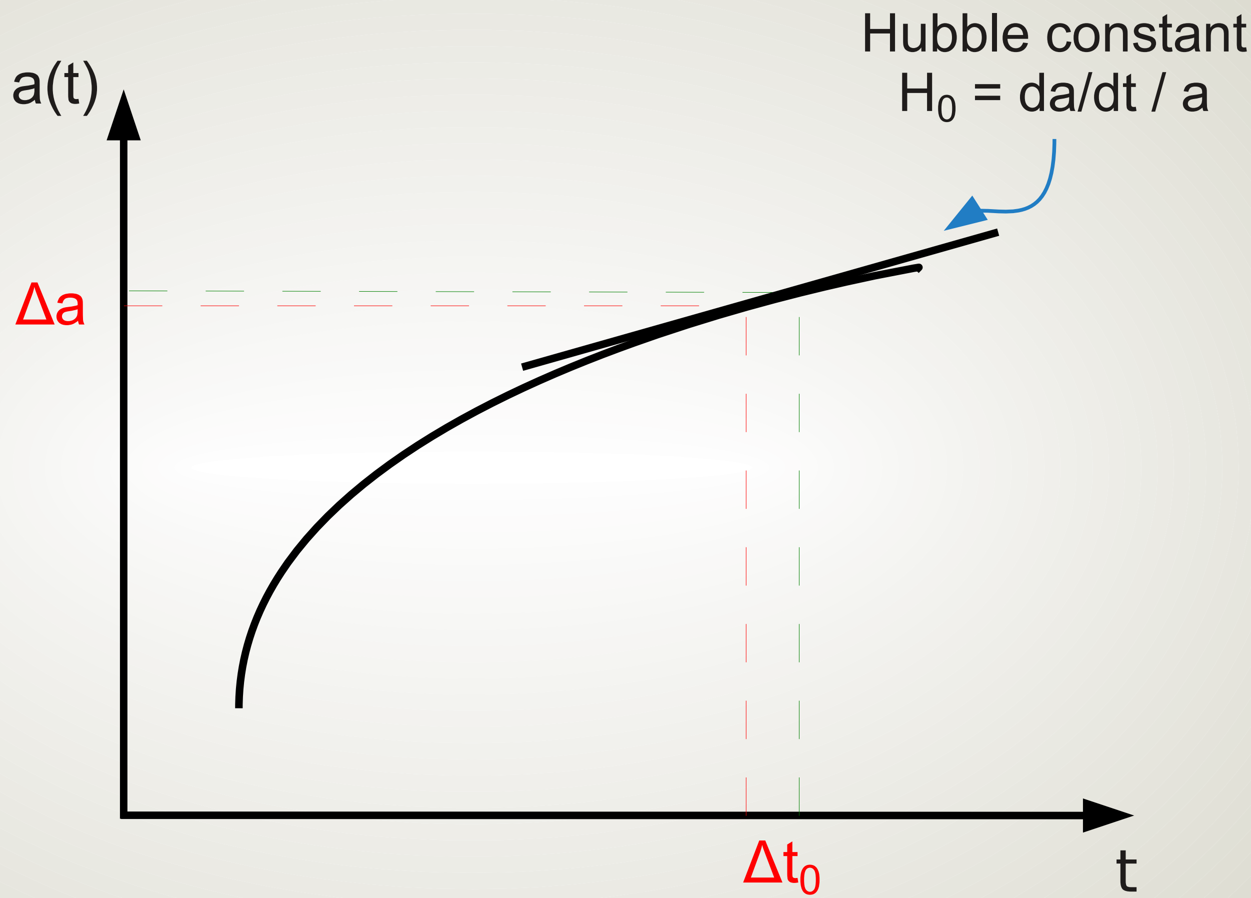

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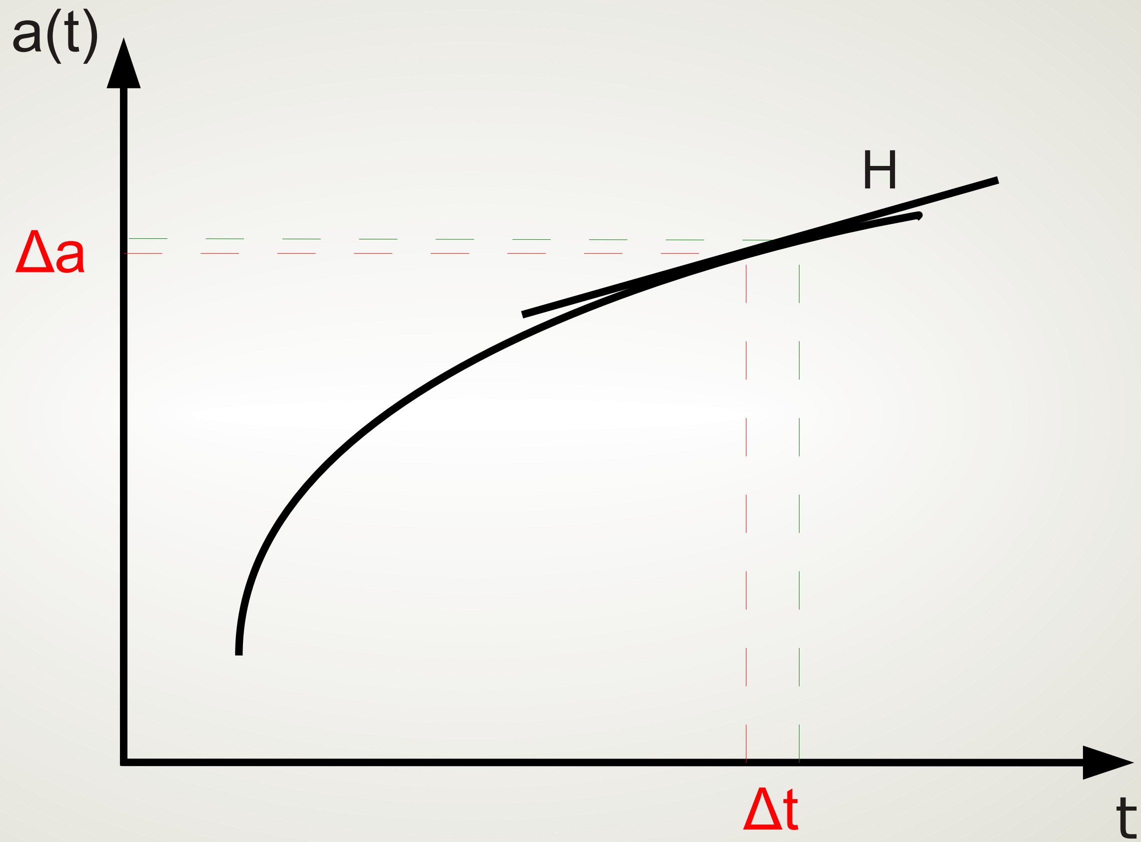

A measurement of H(z) allows the reconstruction of a(t).

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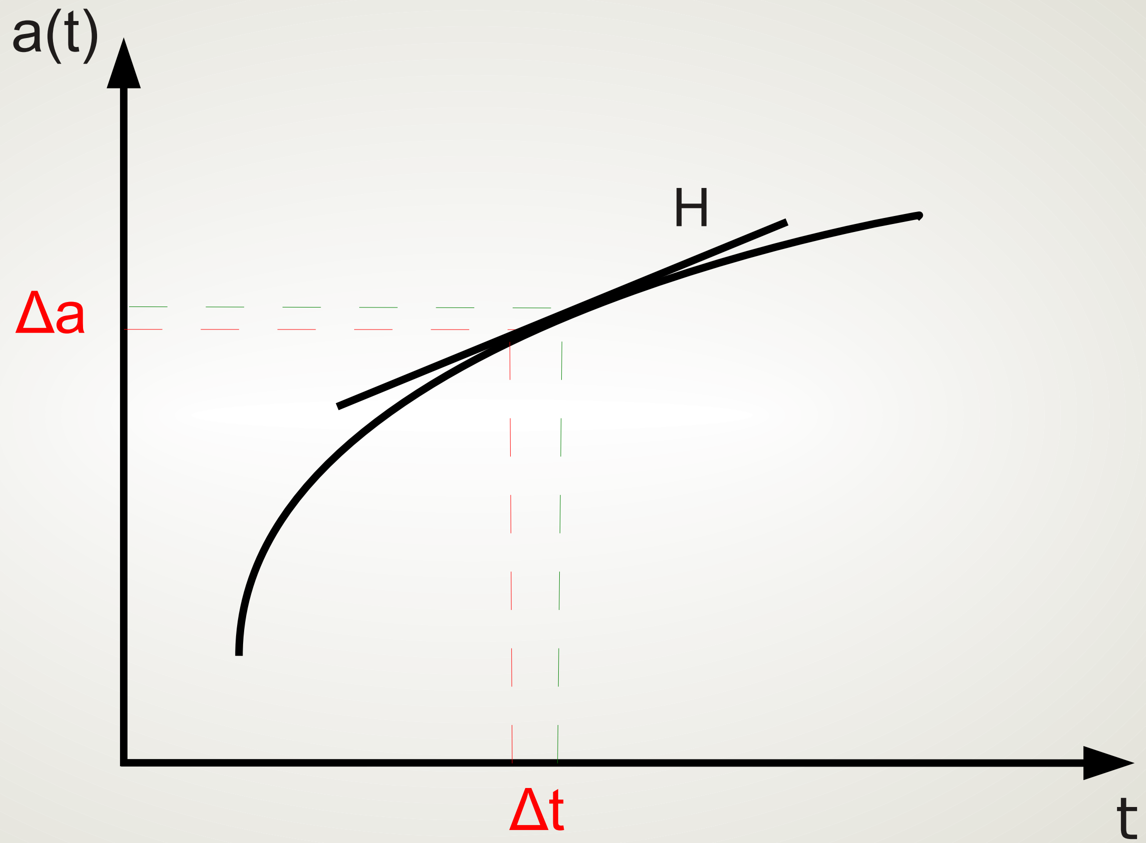

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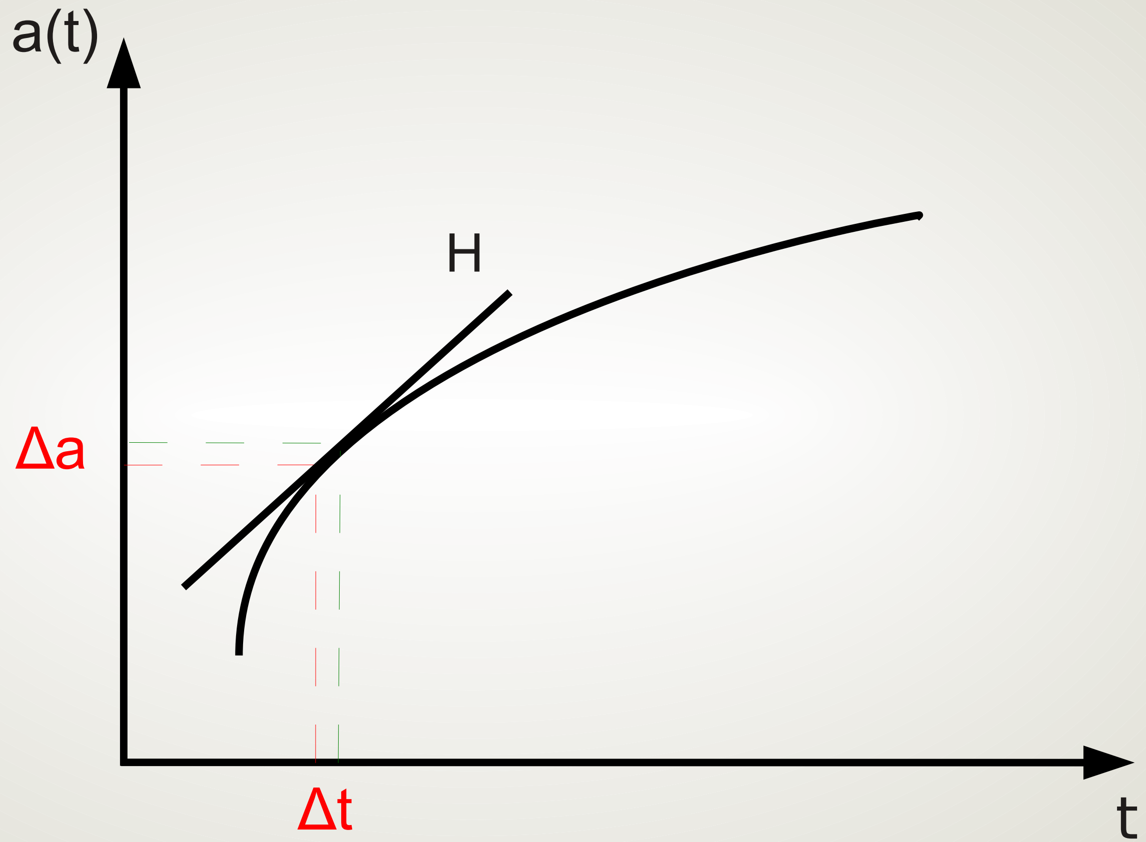
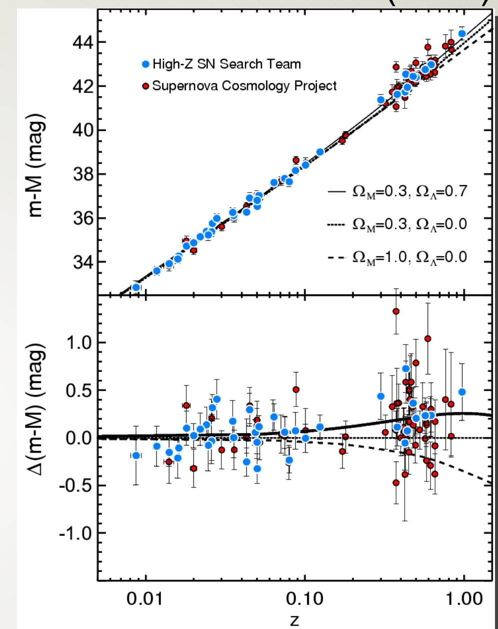


A measurement of H(z) allows the reconstruction of a(t).

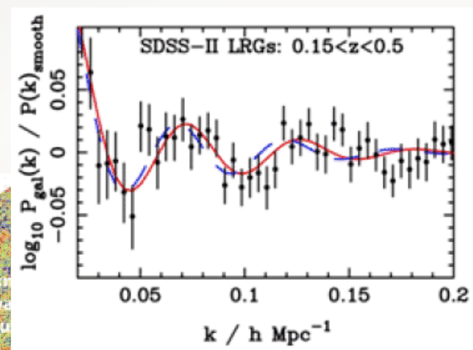
Accelerated Expansion

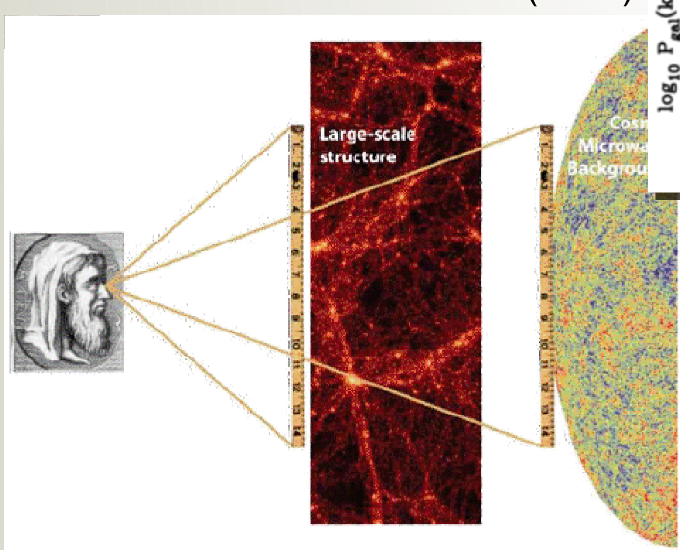
- Intense interest in the expansion history. Best current methods of measuring H(z):
  - SNIa
  - Weak lensing
  - Baryon Acoustic Oscillations (BAO)
  - Redshift Space Distortions (RSD)

Perlmutter & Schmidt (2003)

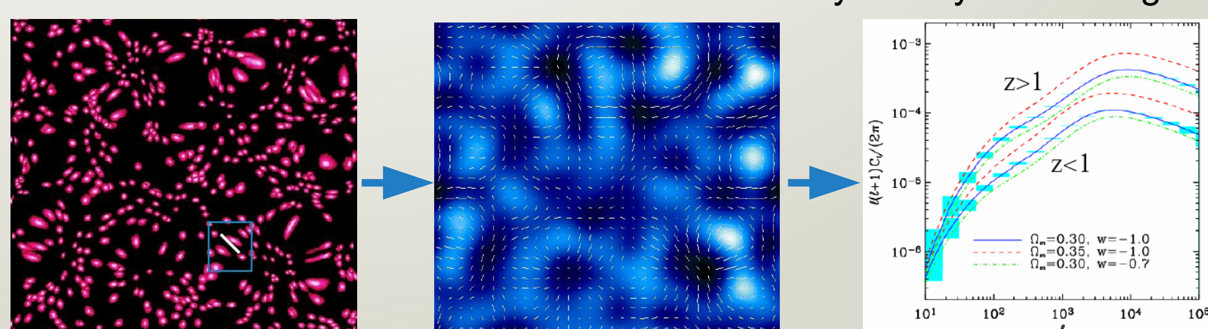


Percival et al. (2010)





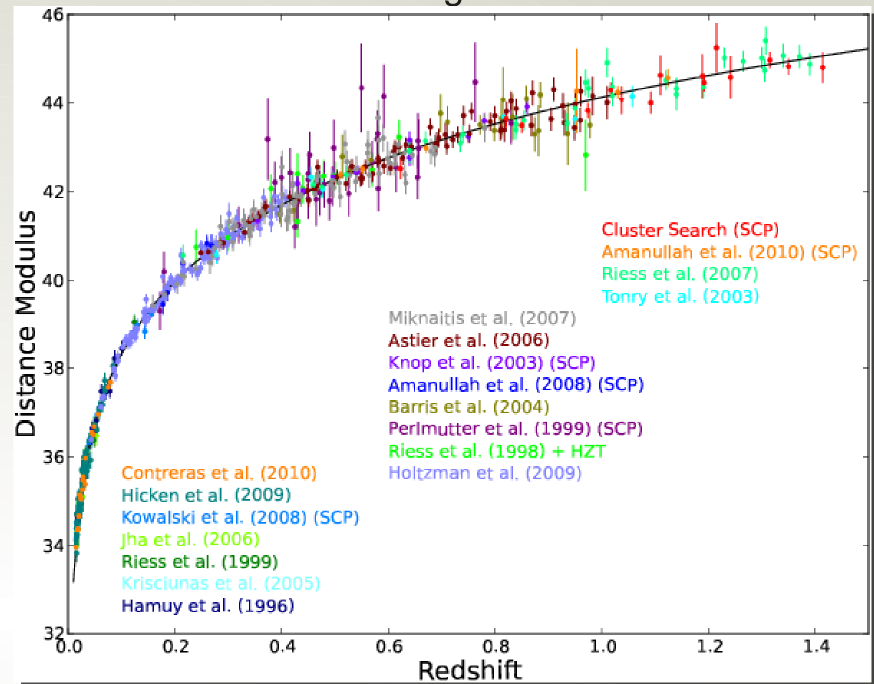
by S. Lilly / A. Refregier

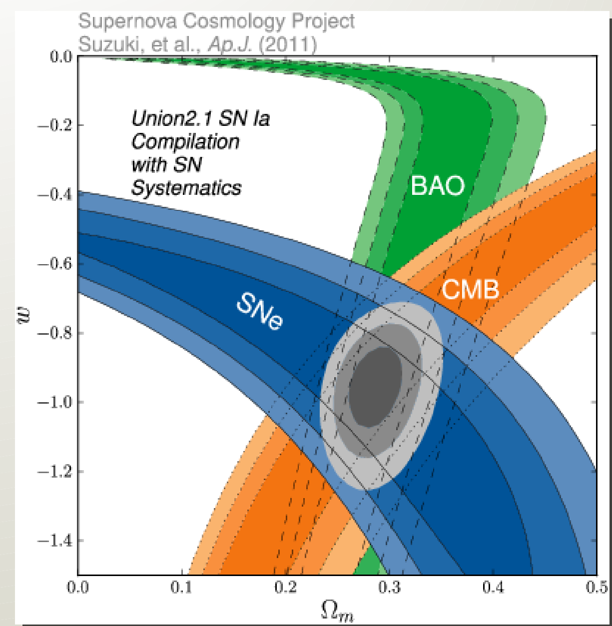


Supernovae Ia

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

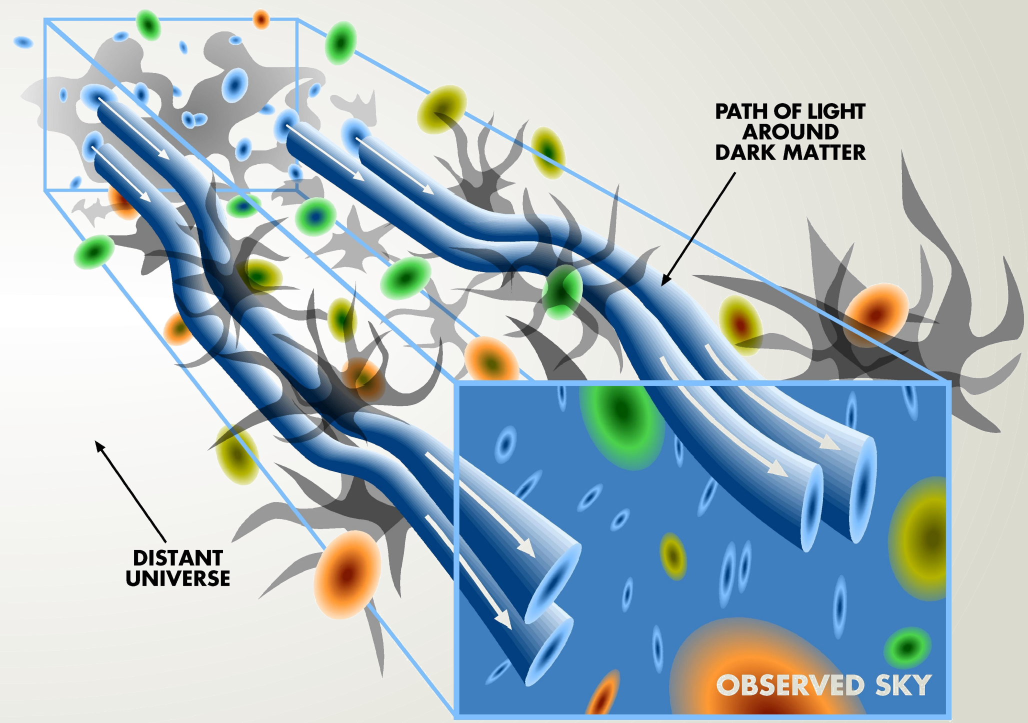
SCP Union2.1 Hubble diagram:





Weak Lensing, Cosmic Shear

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



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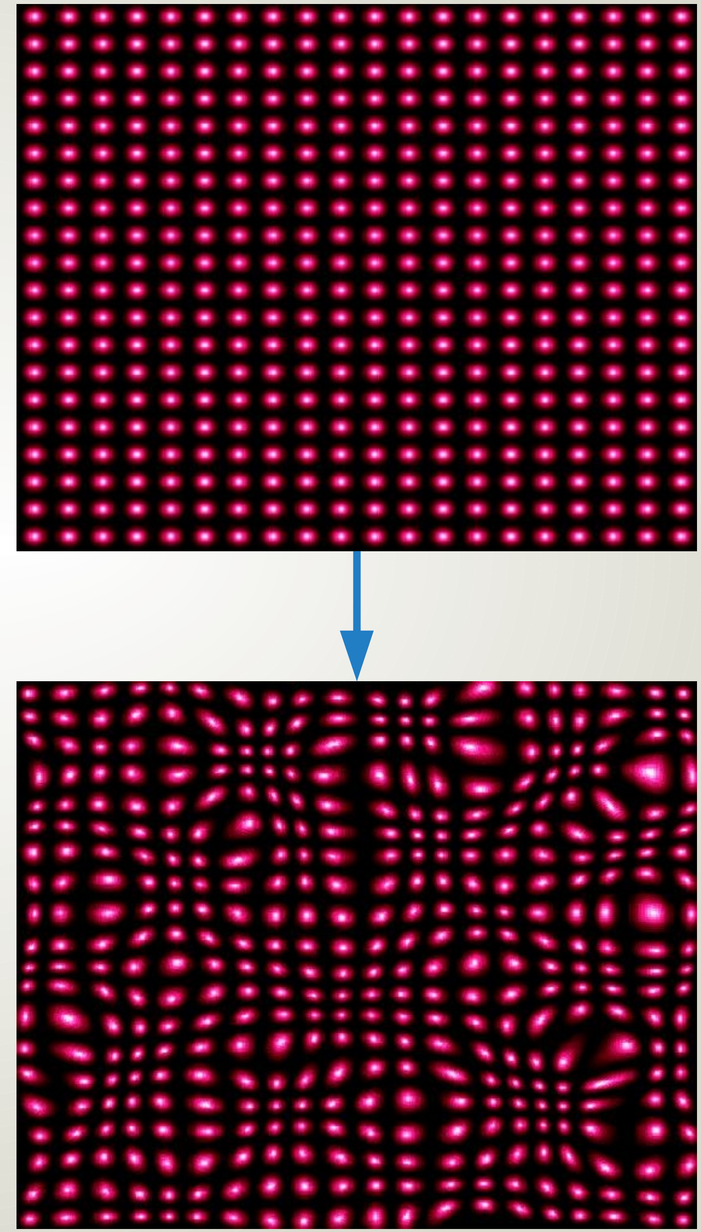

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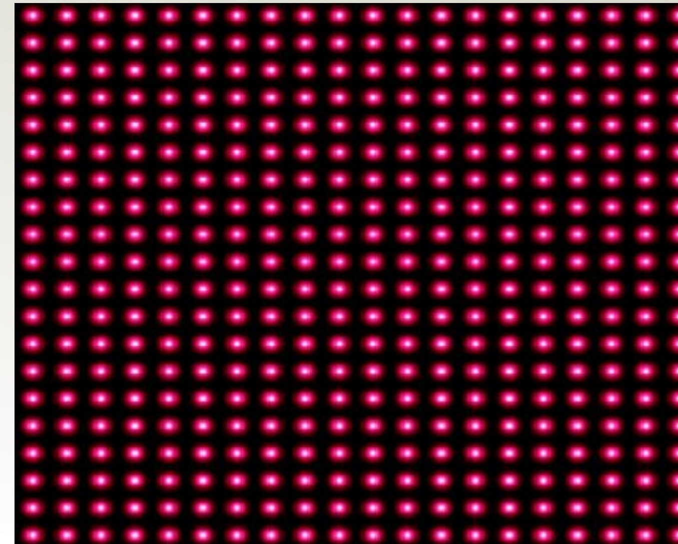

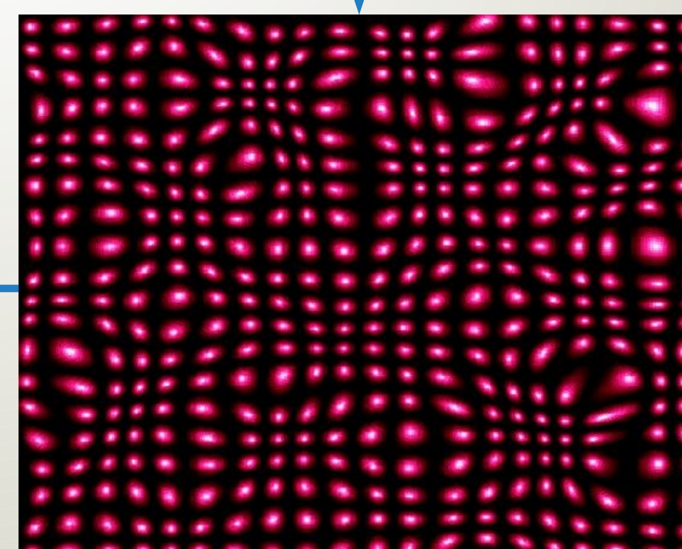

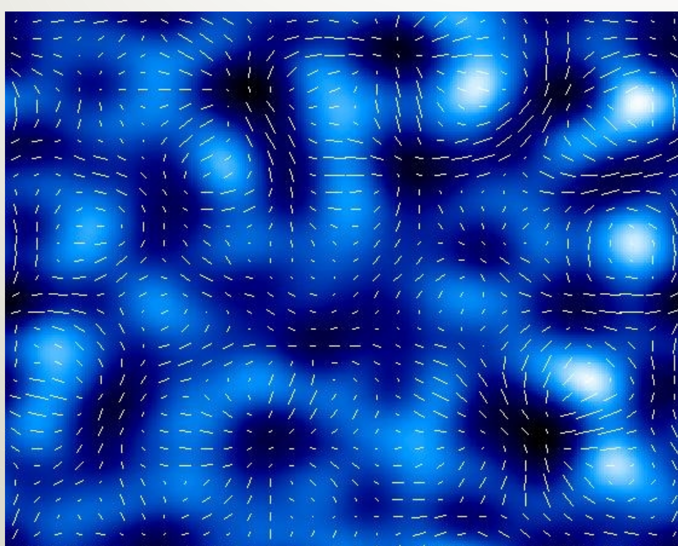

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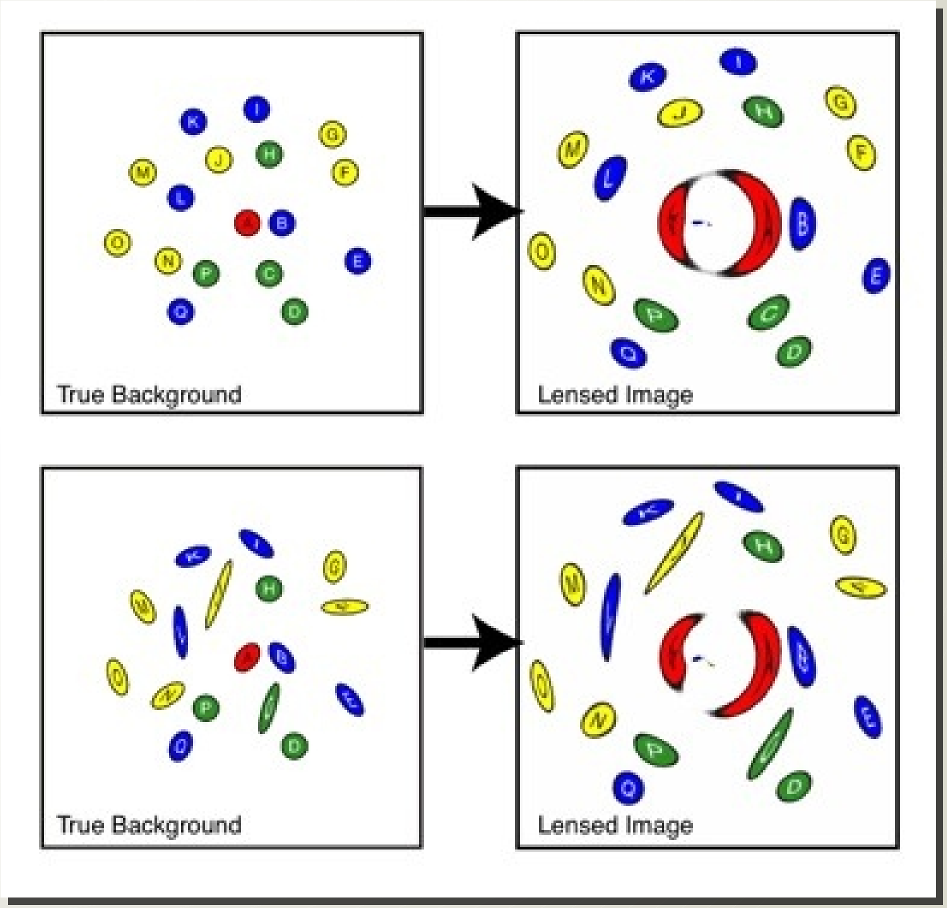

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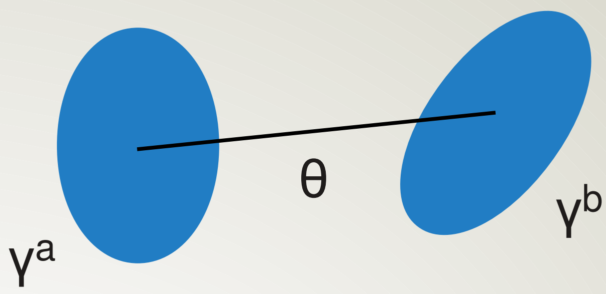
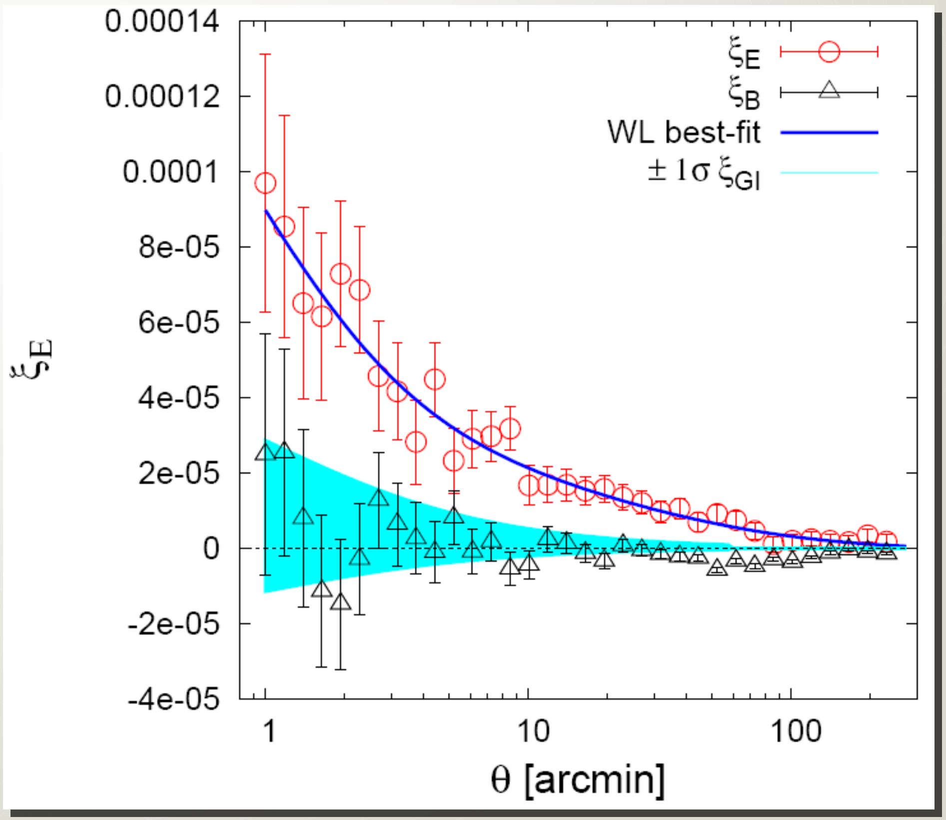
- Use ellipticities of large samples of galaxies to estimate shear correlation function (or power spectrum).



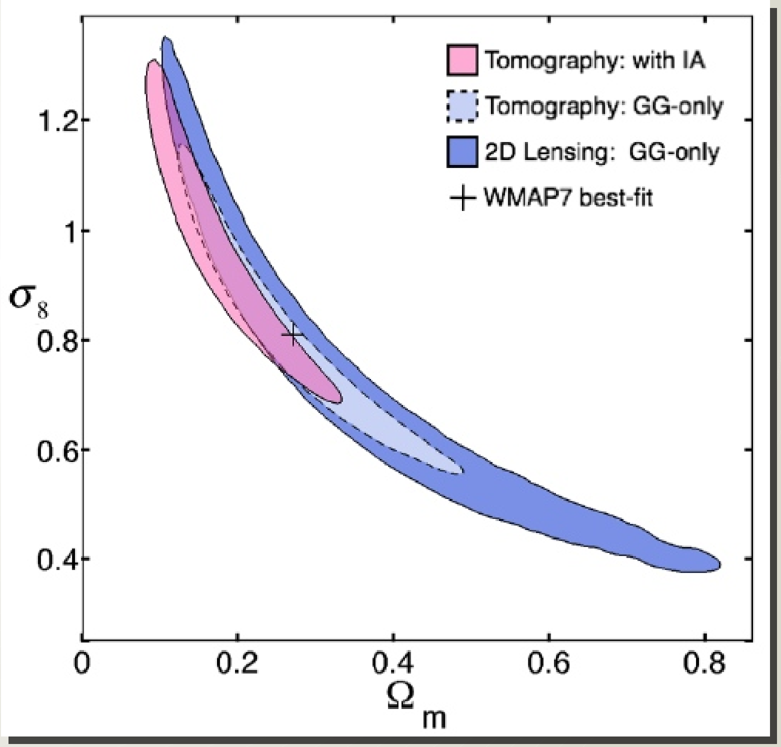


CFHTLS, Fu et al. (2008)

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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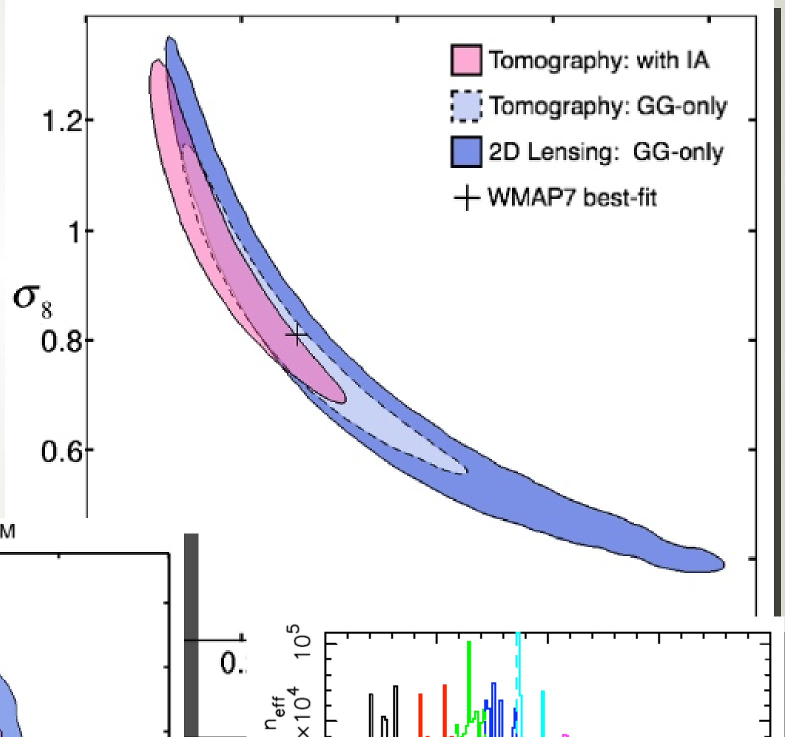

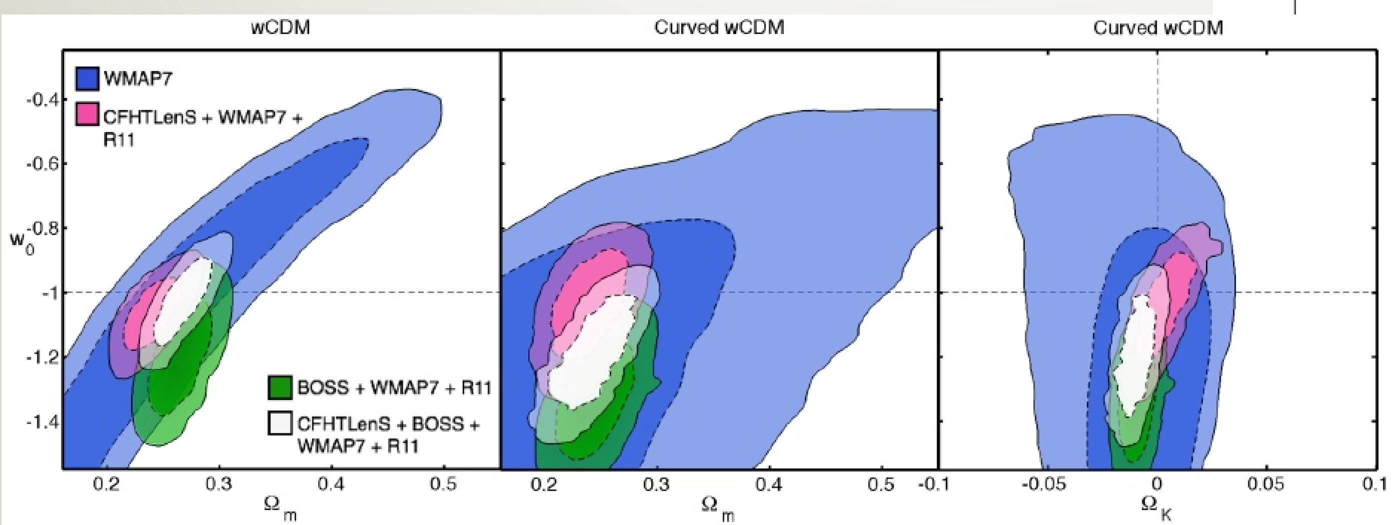

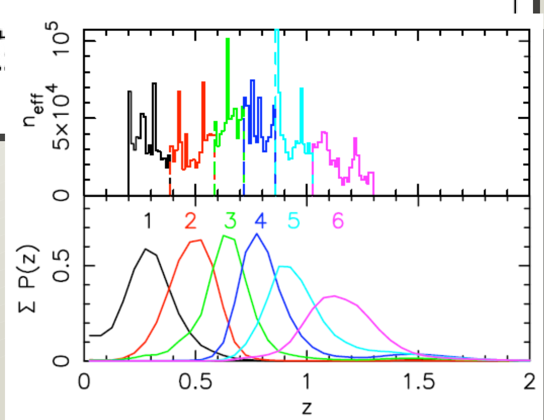

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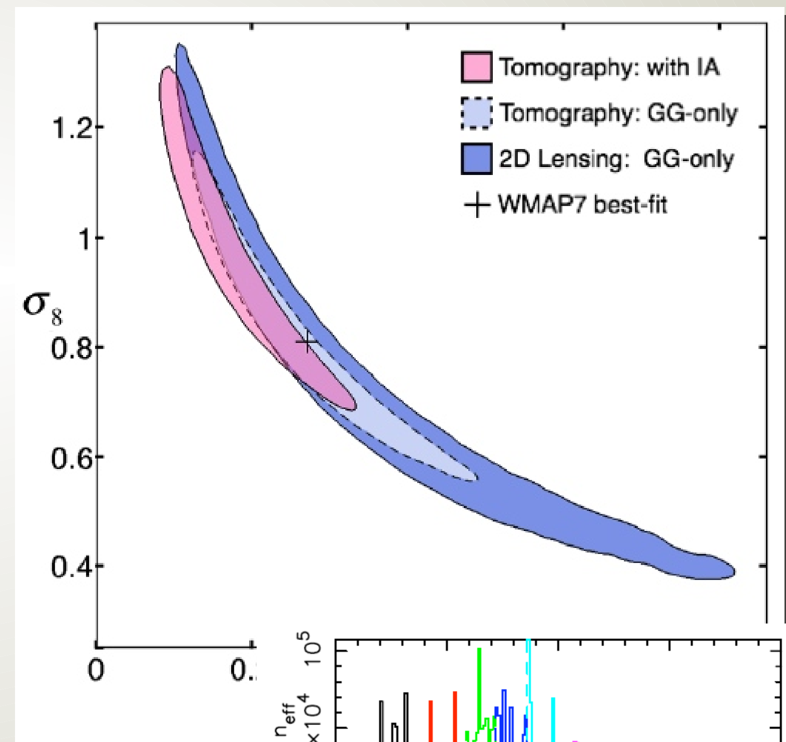
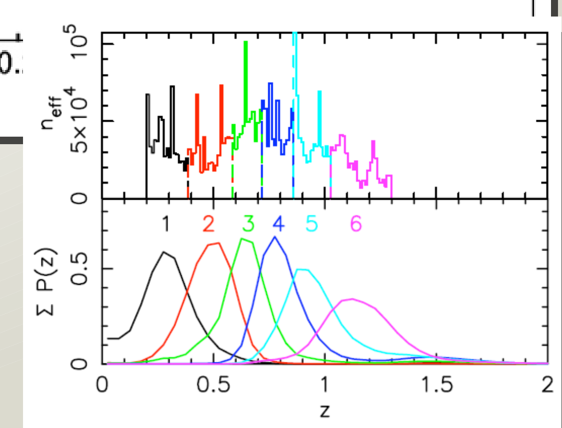
- This hard! Need:
  - huge imaging surveys
  - in multiple bands (for photo-z)
  - excellent control of PSF in at least one band
  - shape measurements
  - deal with intrinsic galaxy alignments

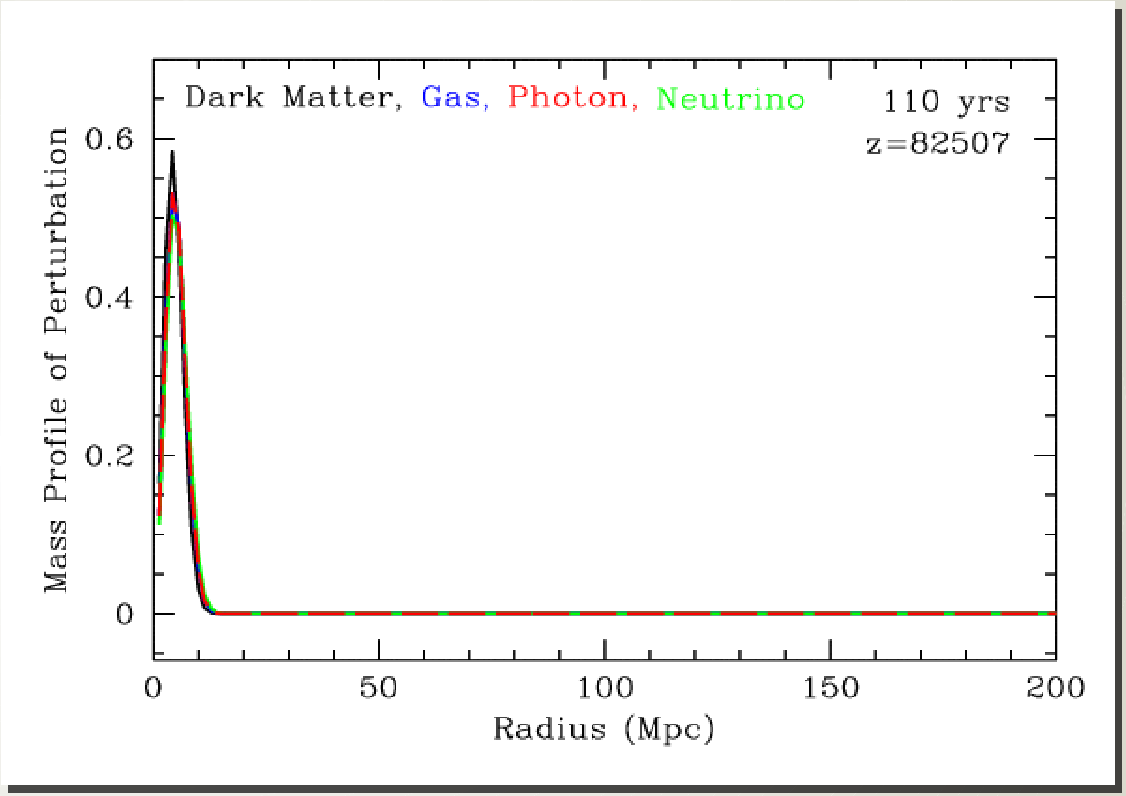




Baryon Acoustic Oscillations

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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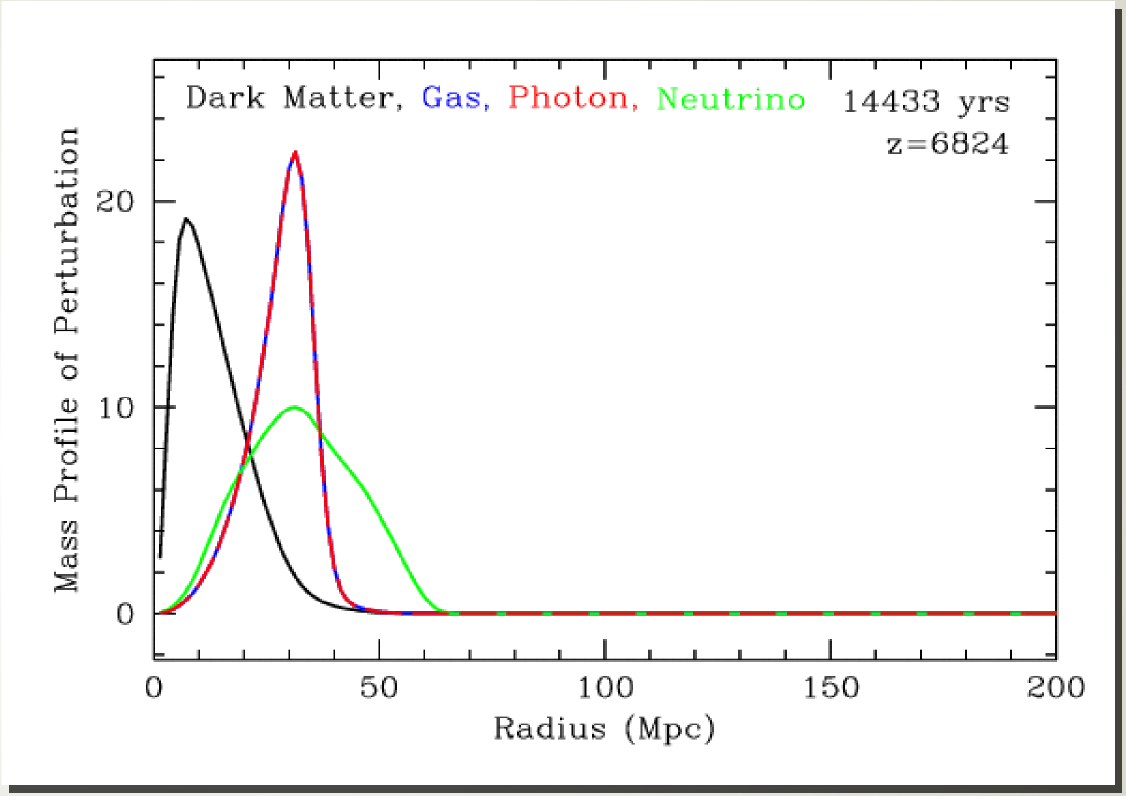

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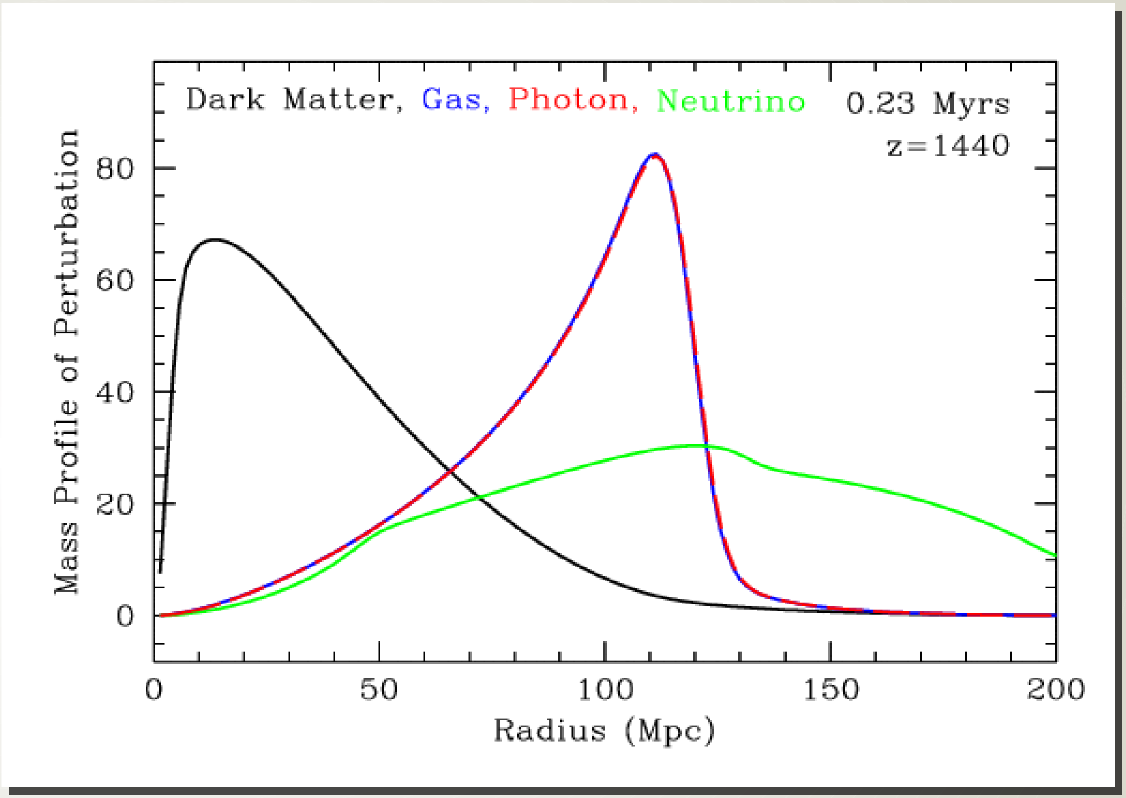

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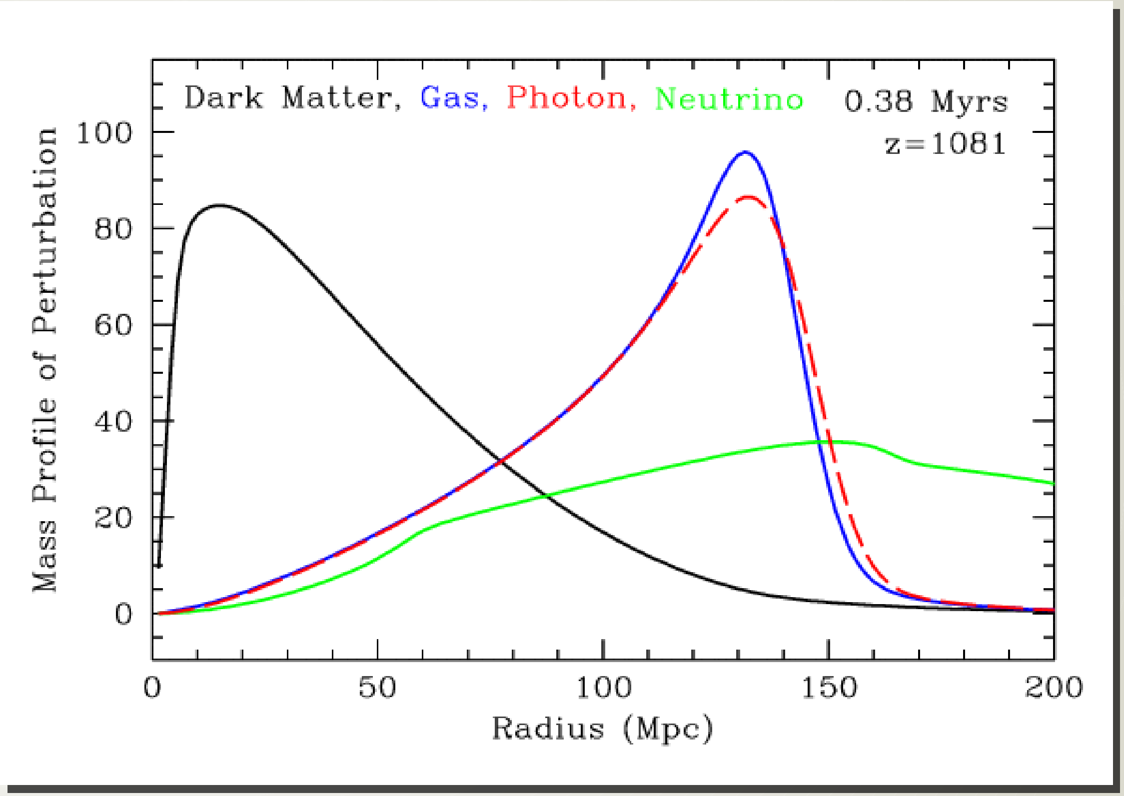

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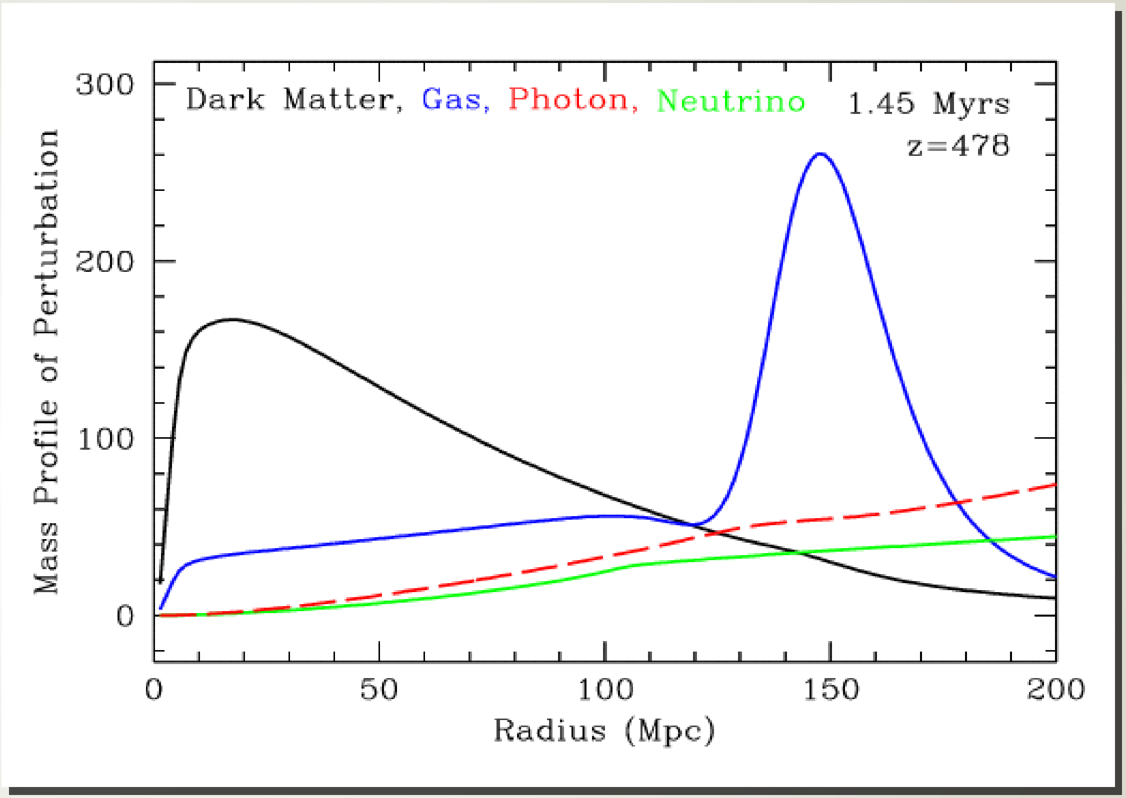

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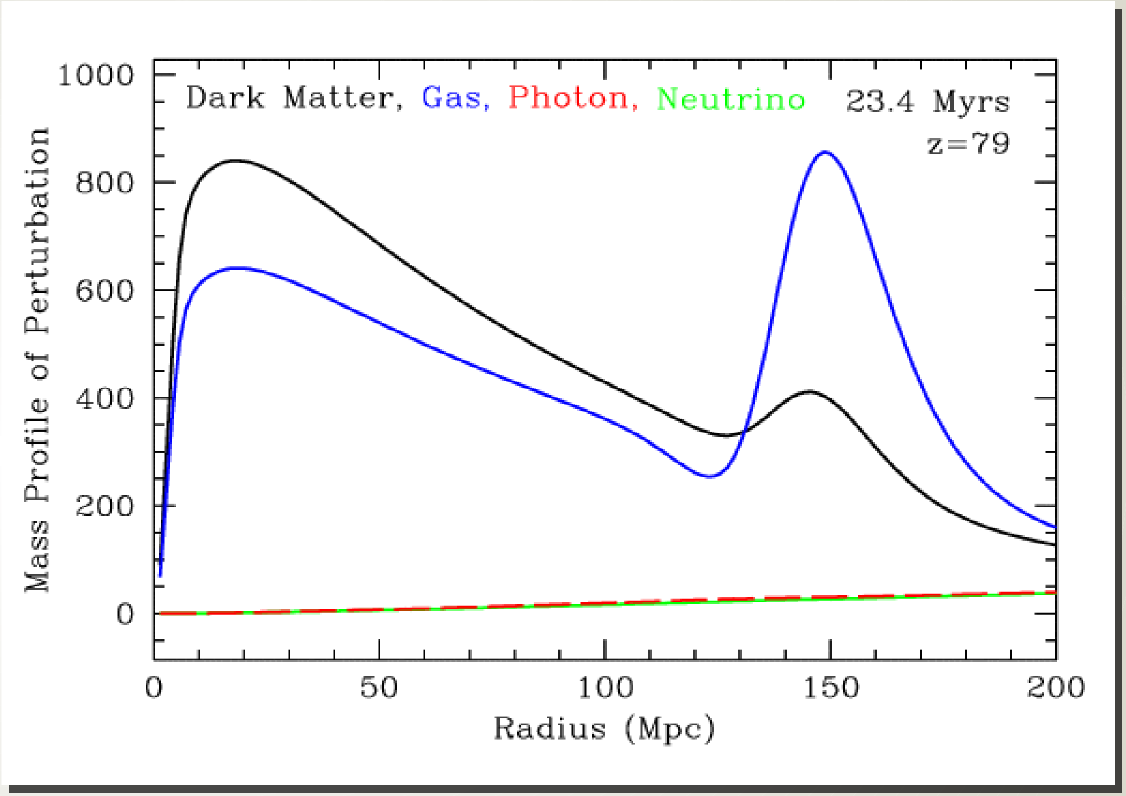

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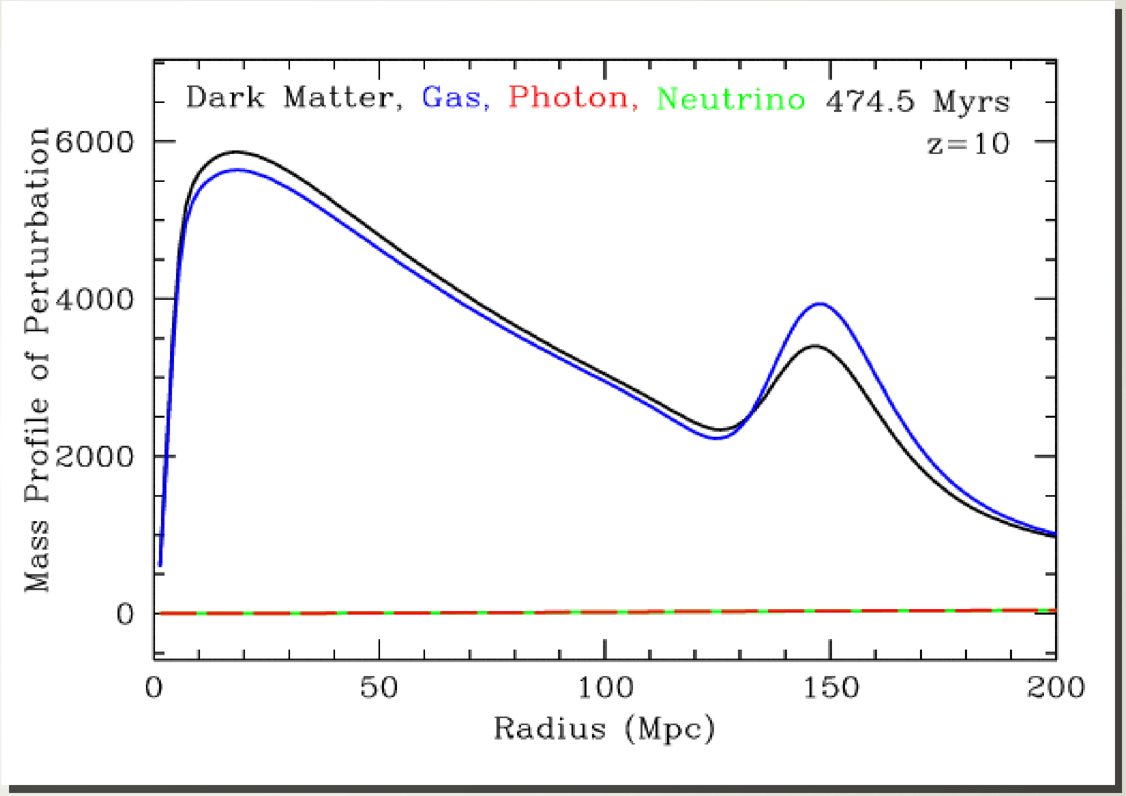

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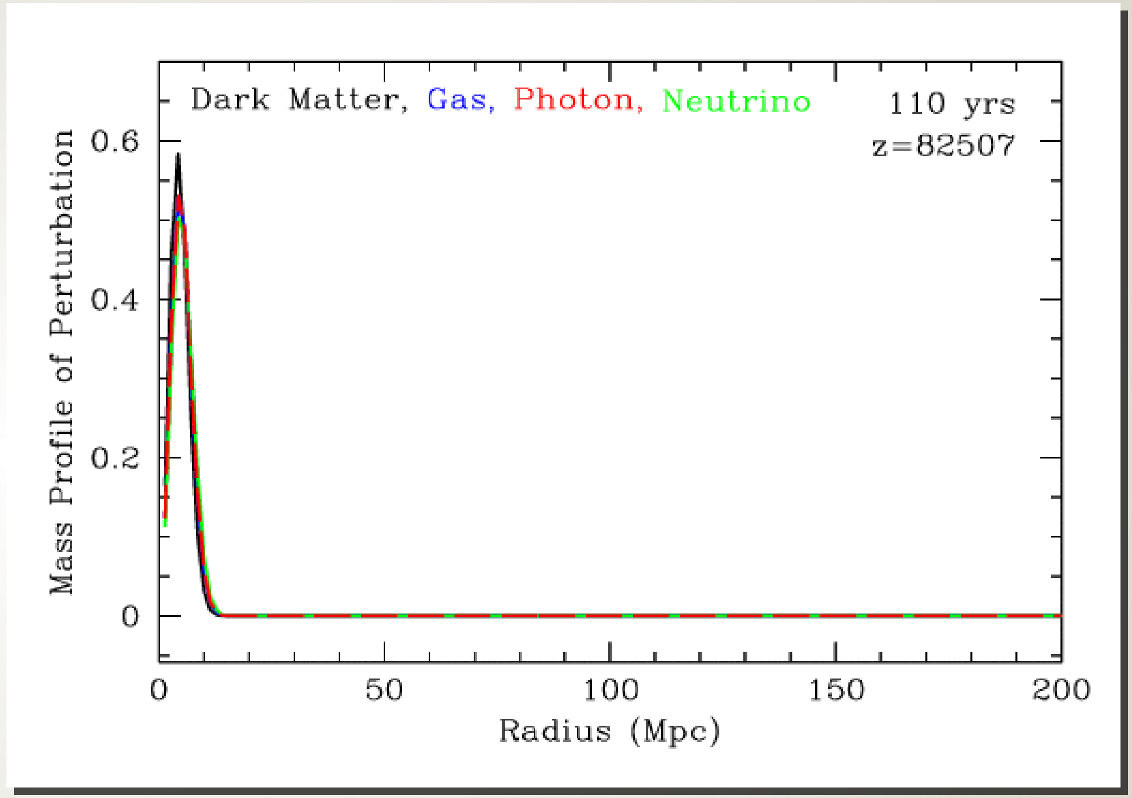

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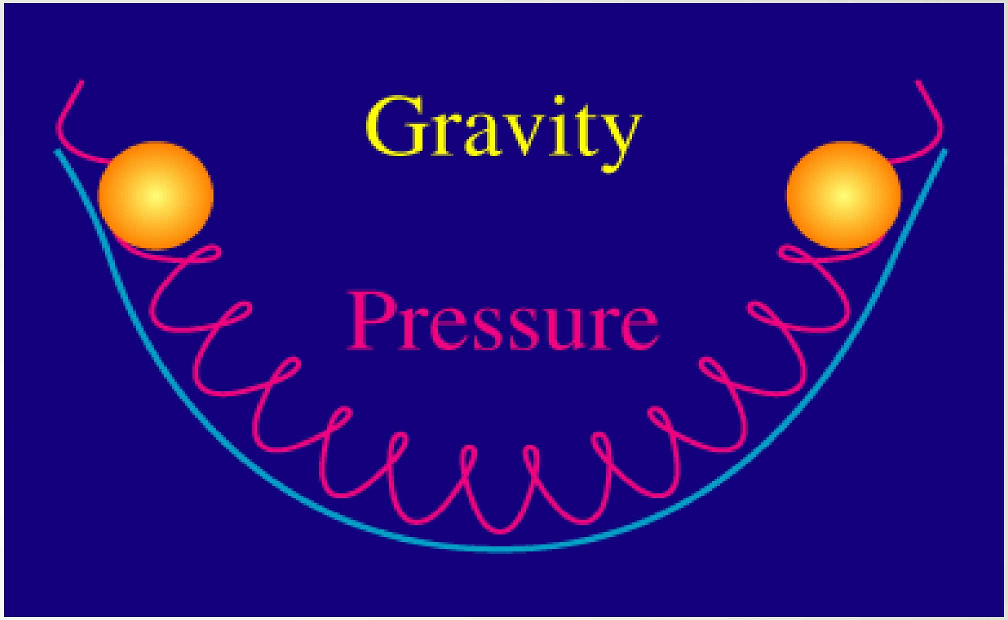

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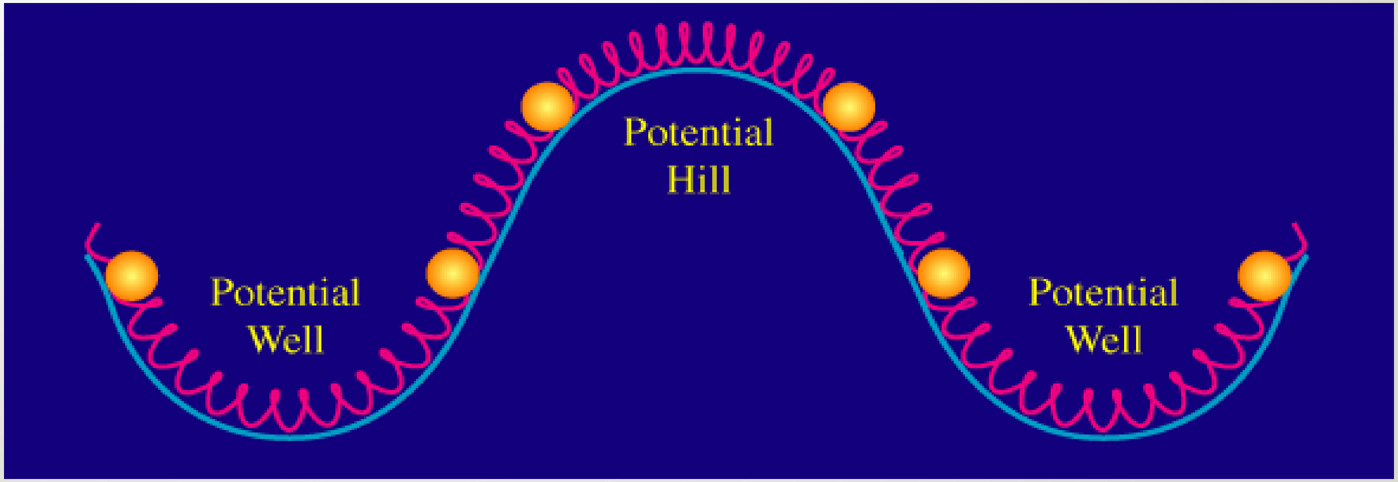

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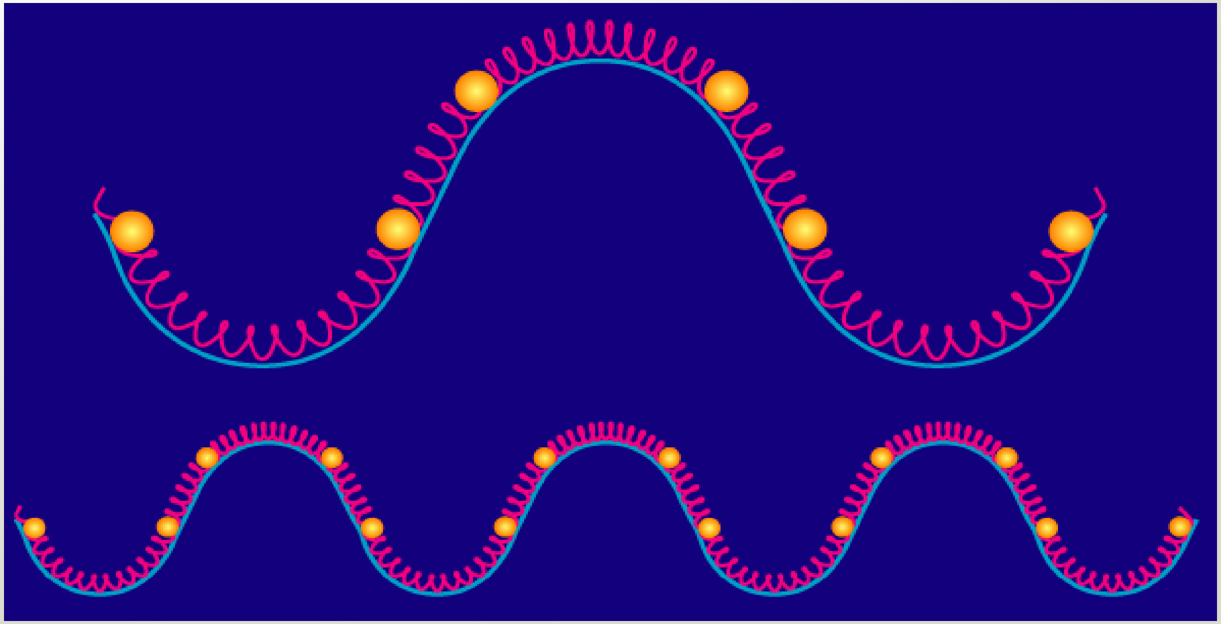

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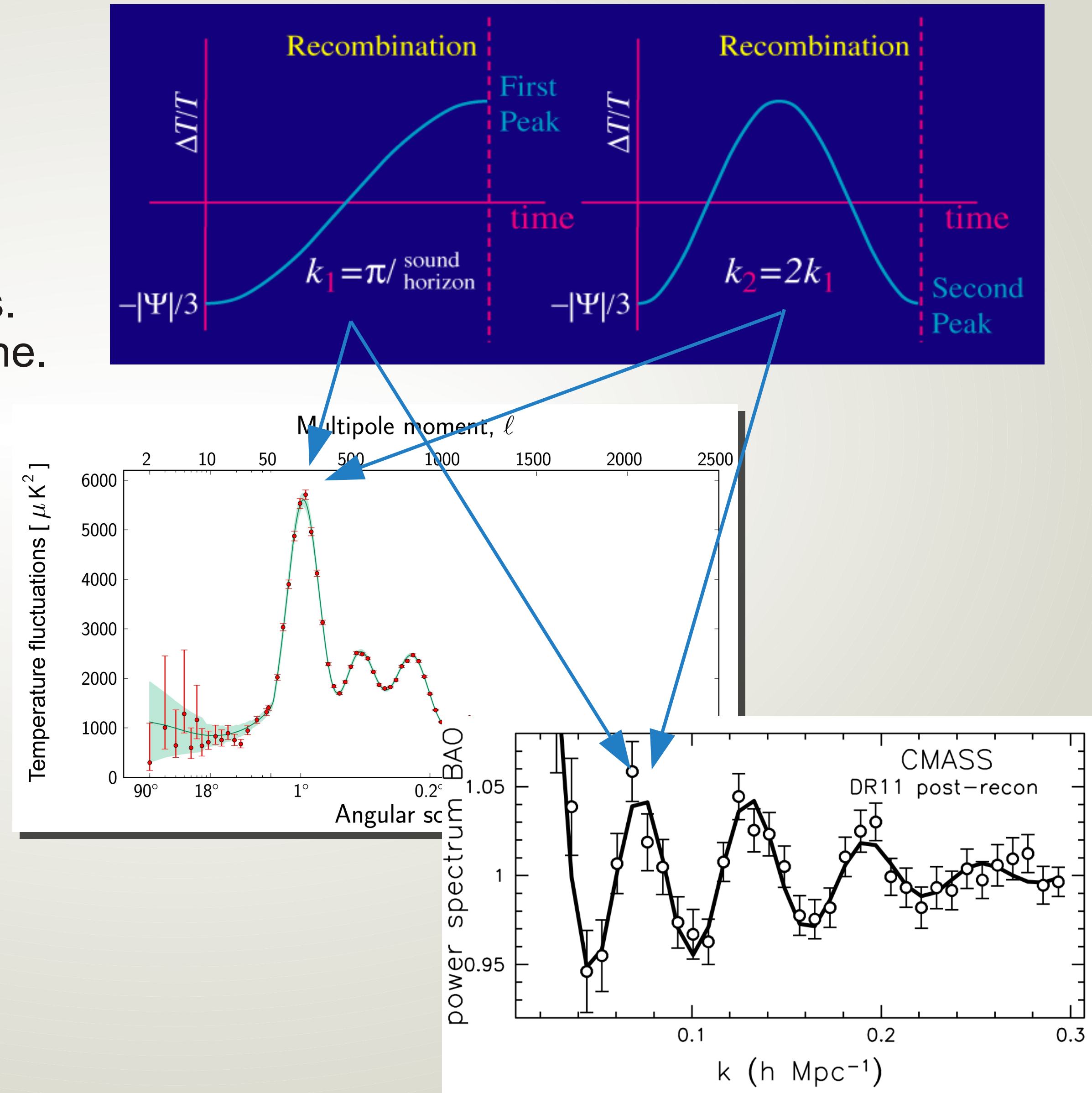
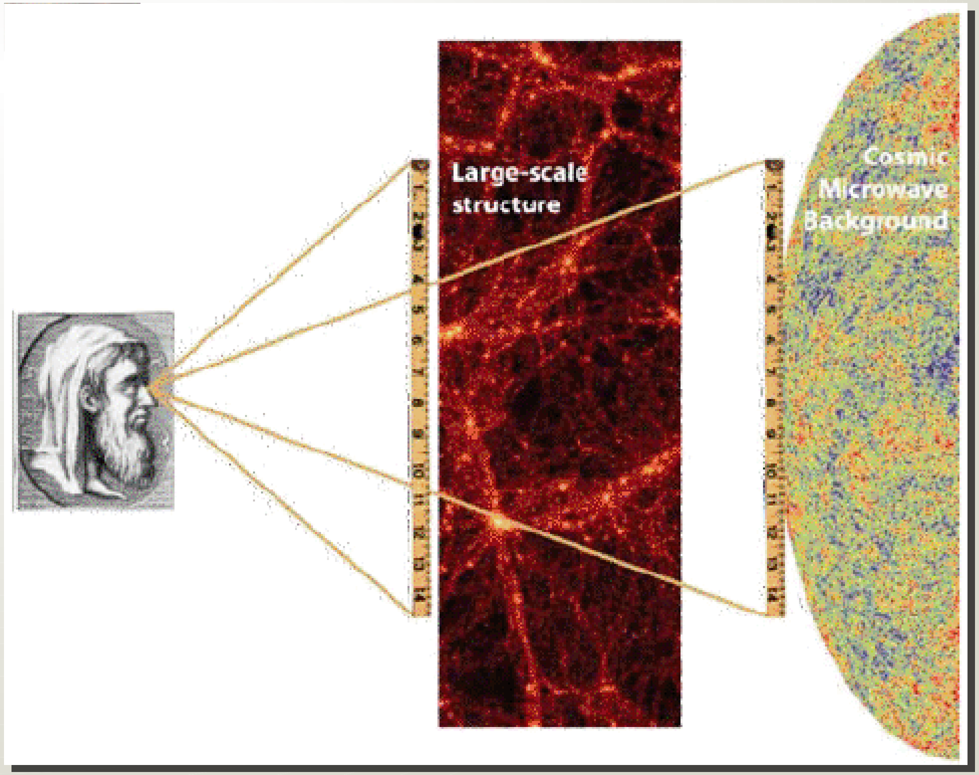
- All modes that are multiples of $c_s * t_{recomb}$ are enhanced.



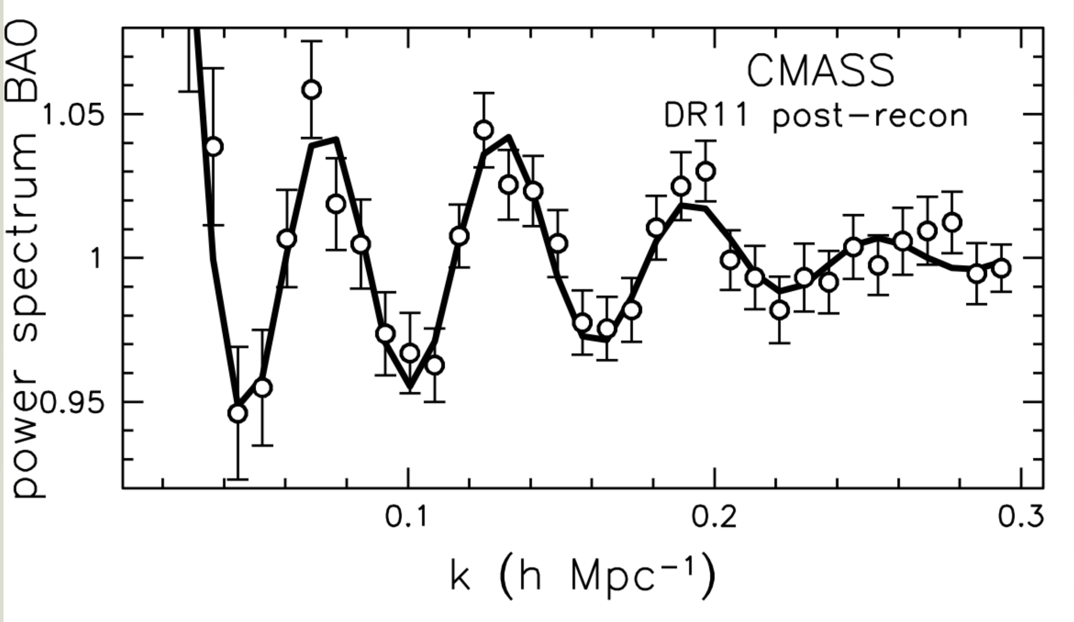
Baryon Acoustic Oscillations

- 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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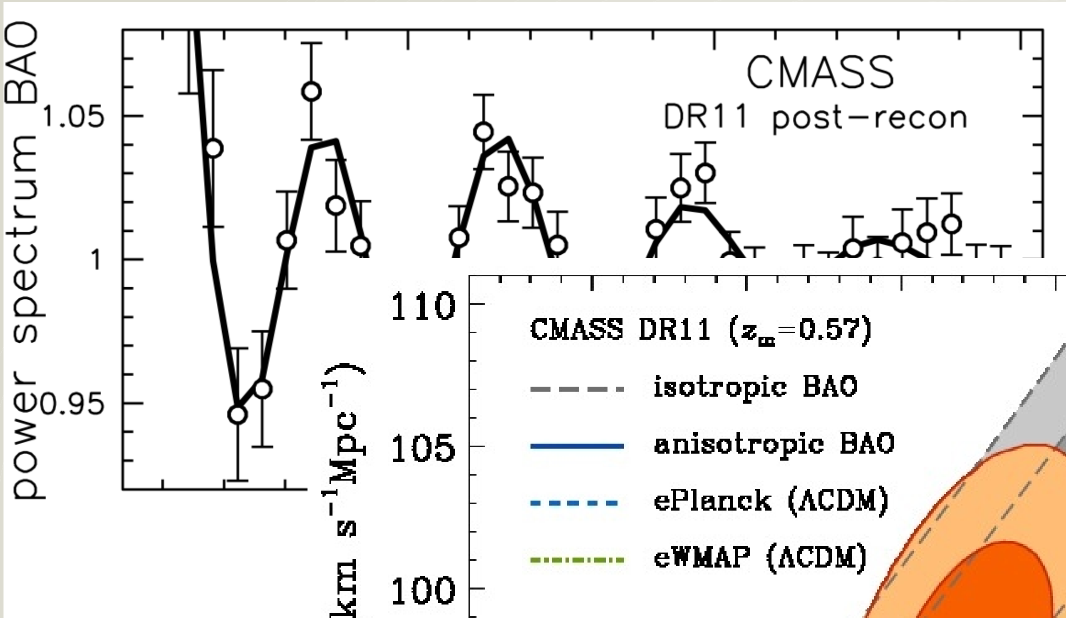

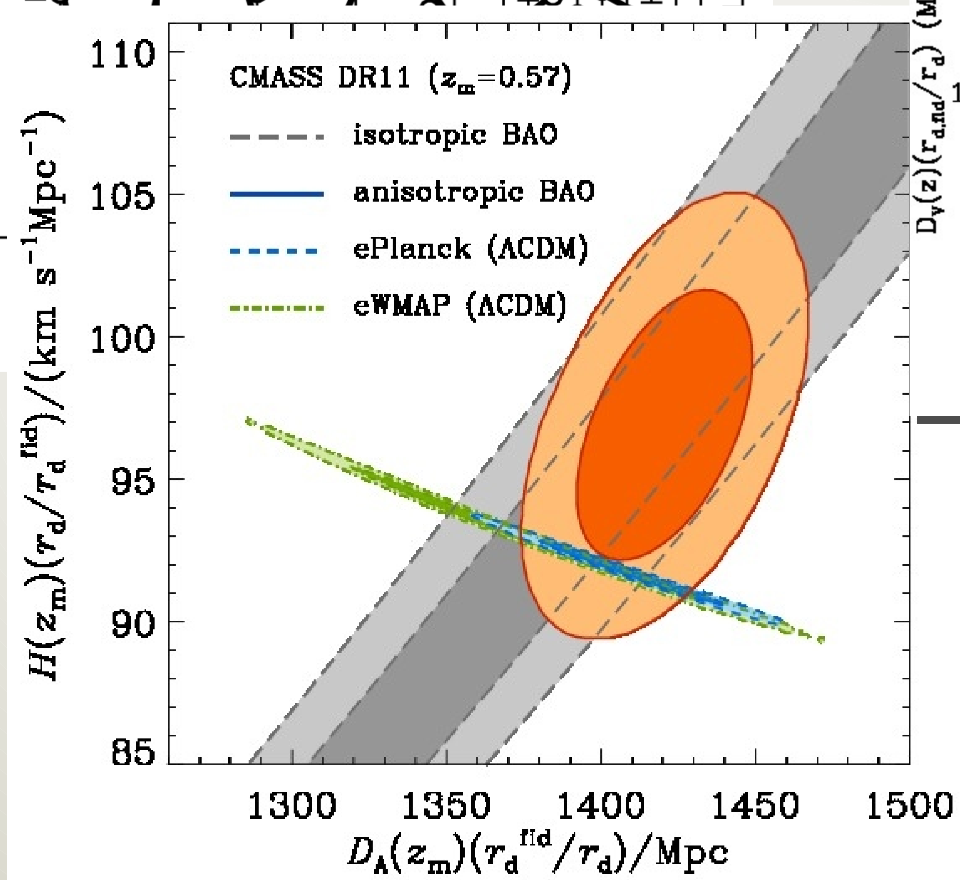

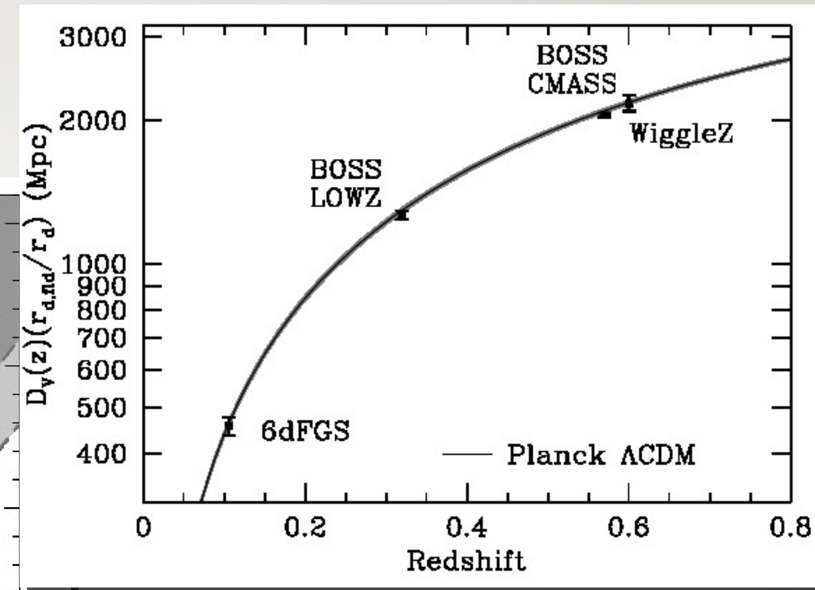

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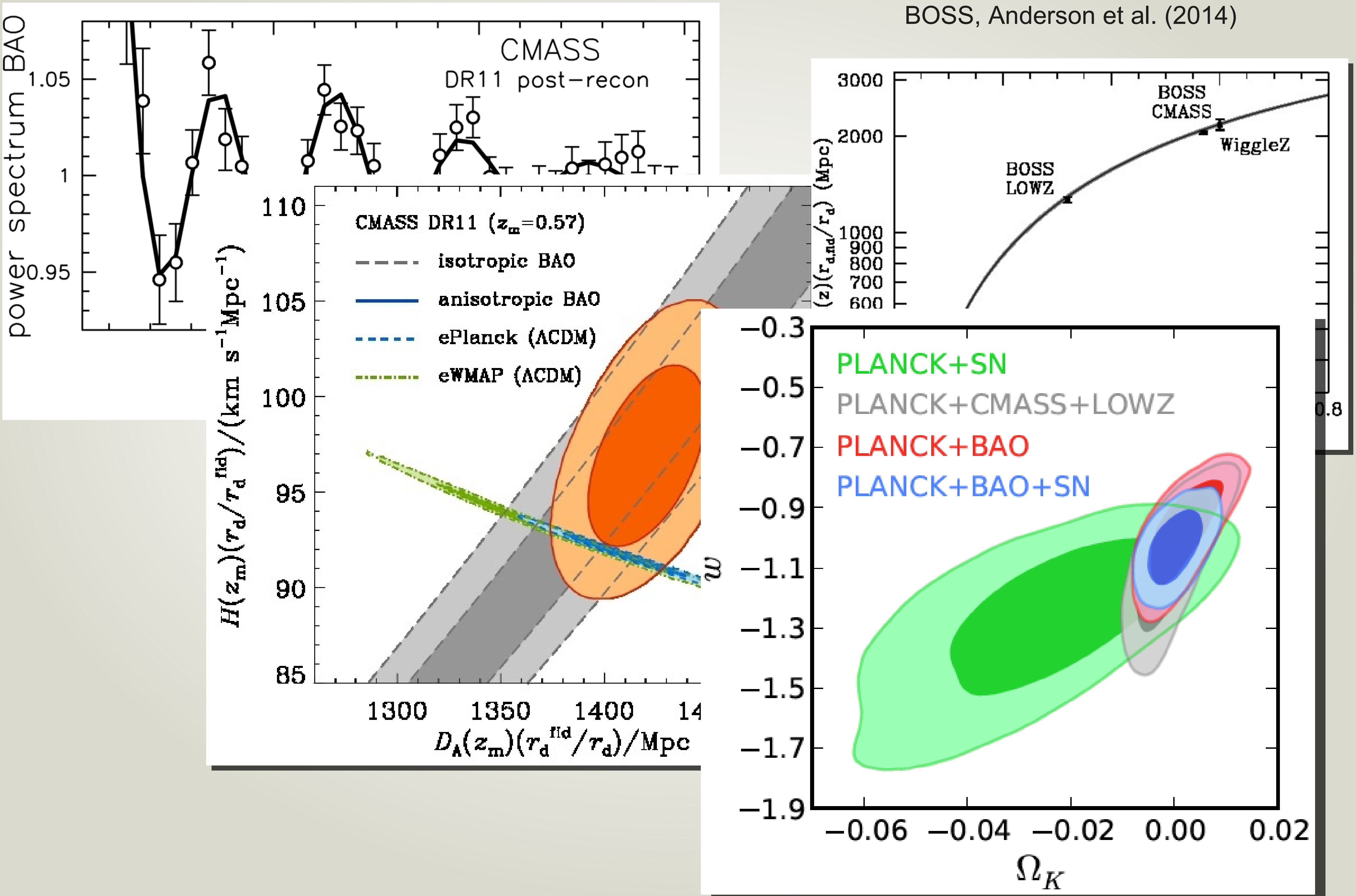
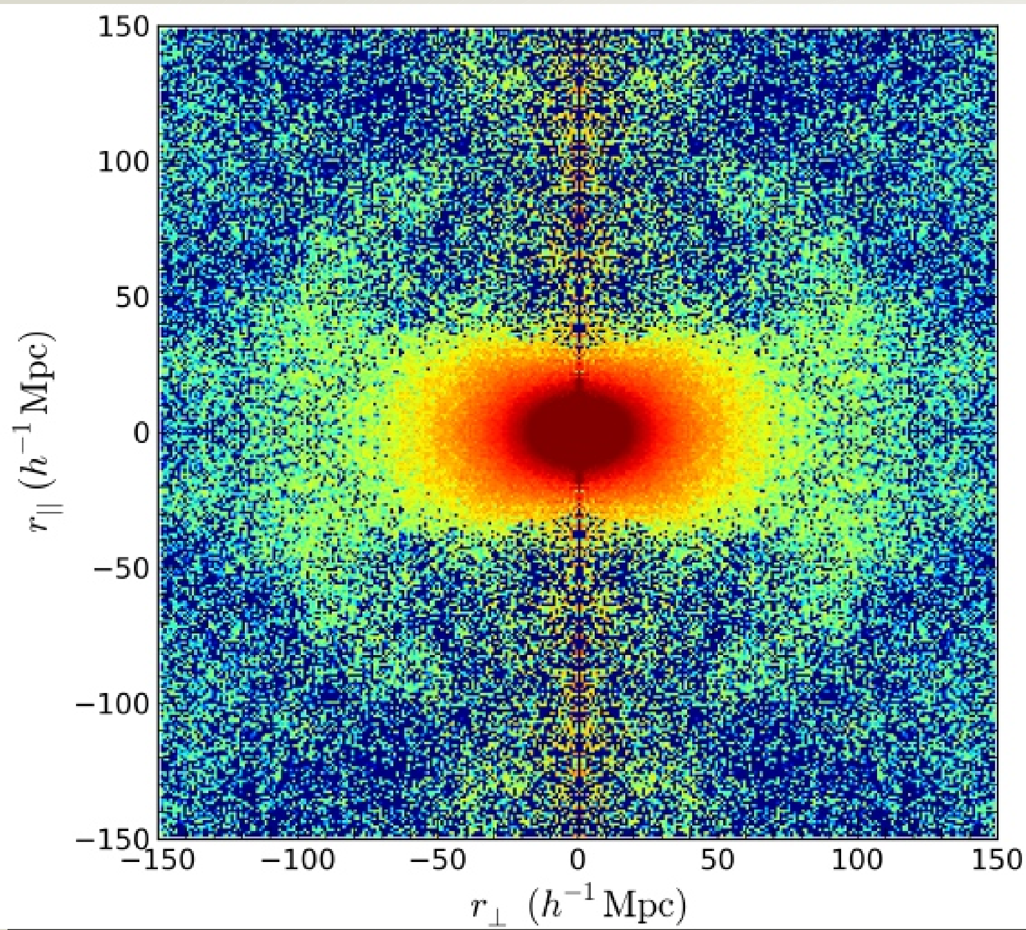


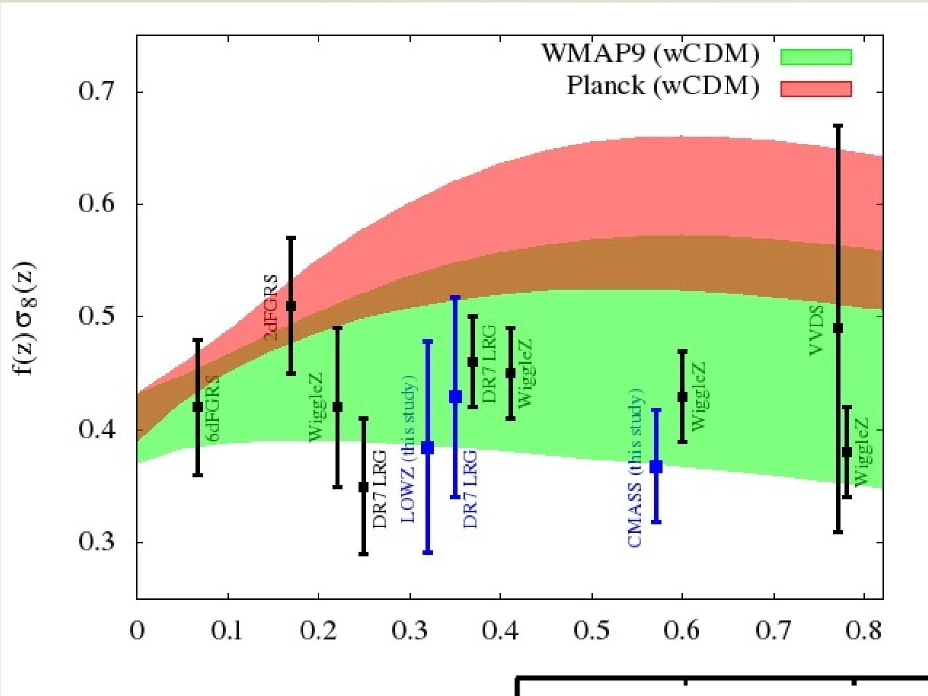
Redshift Space Distortions



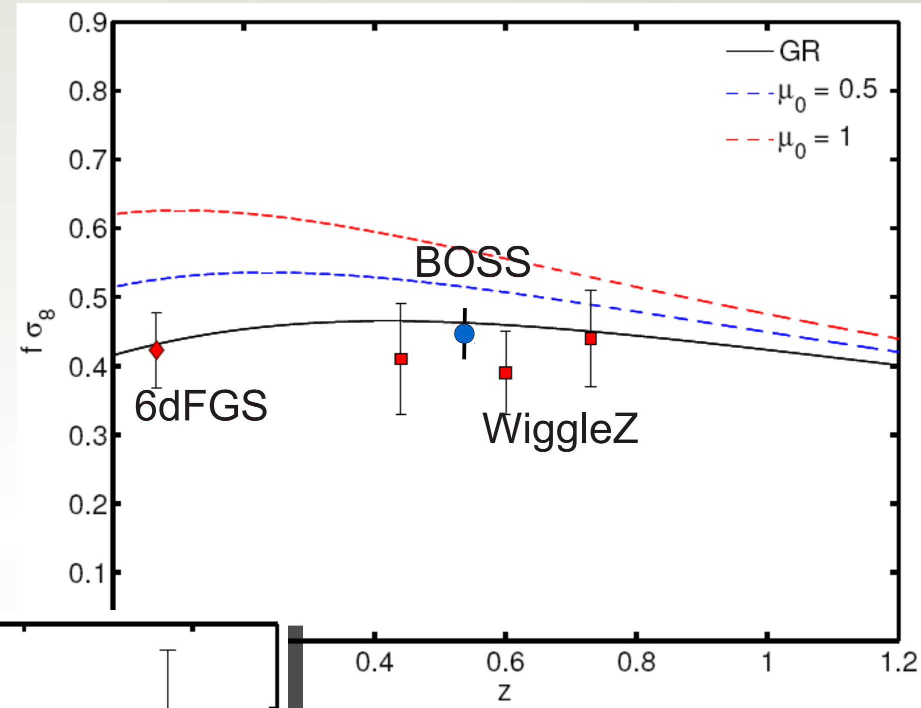
Samushia et al. (2013)

- 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)



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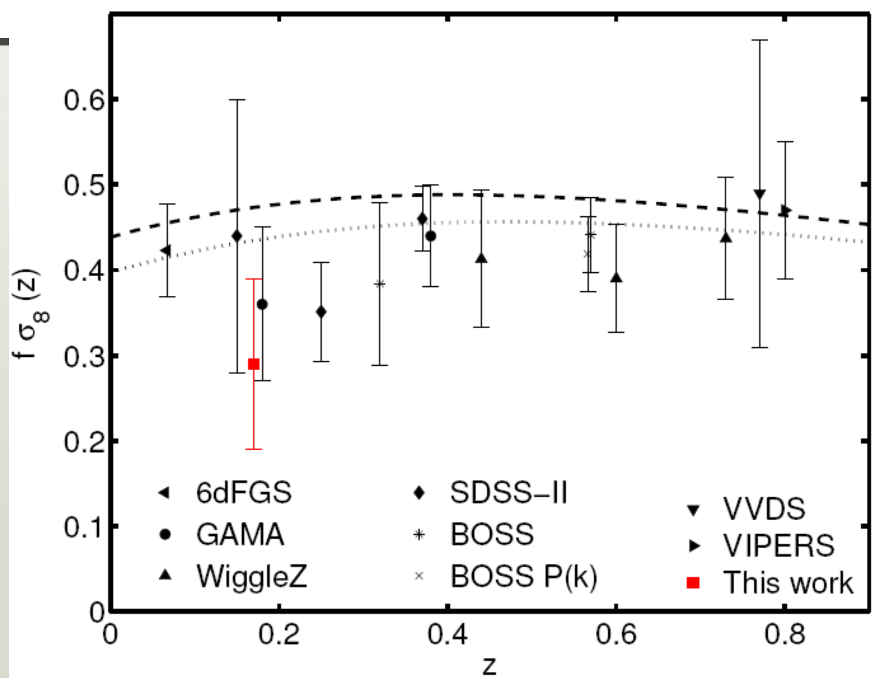

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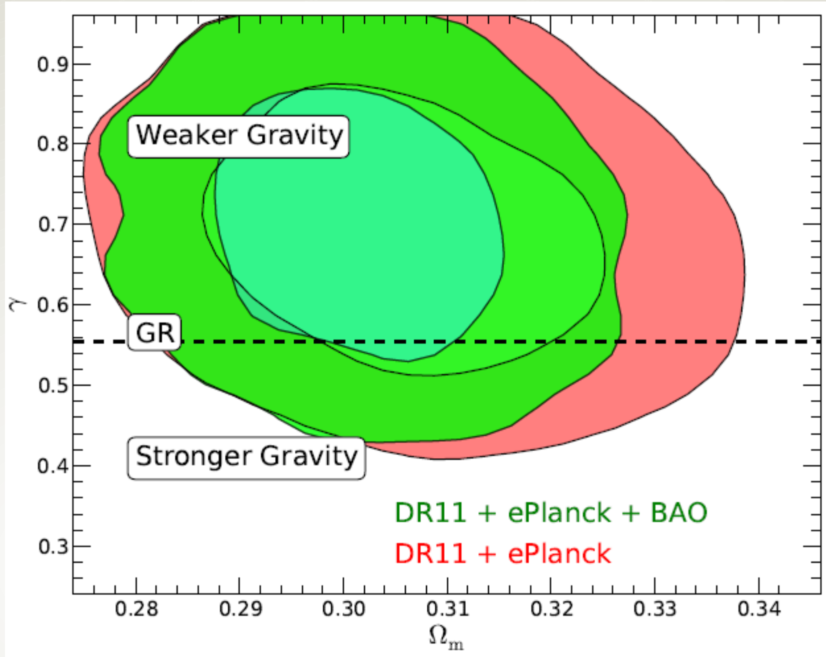

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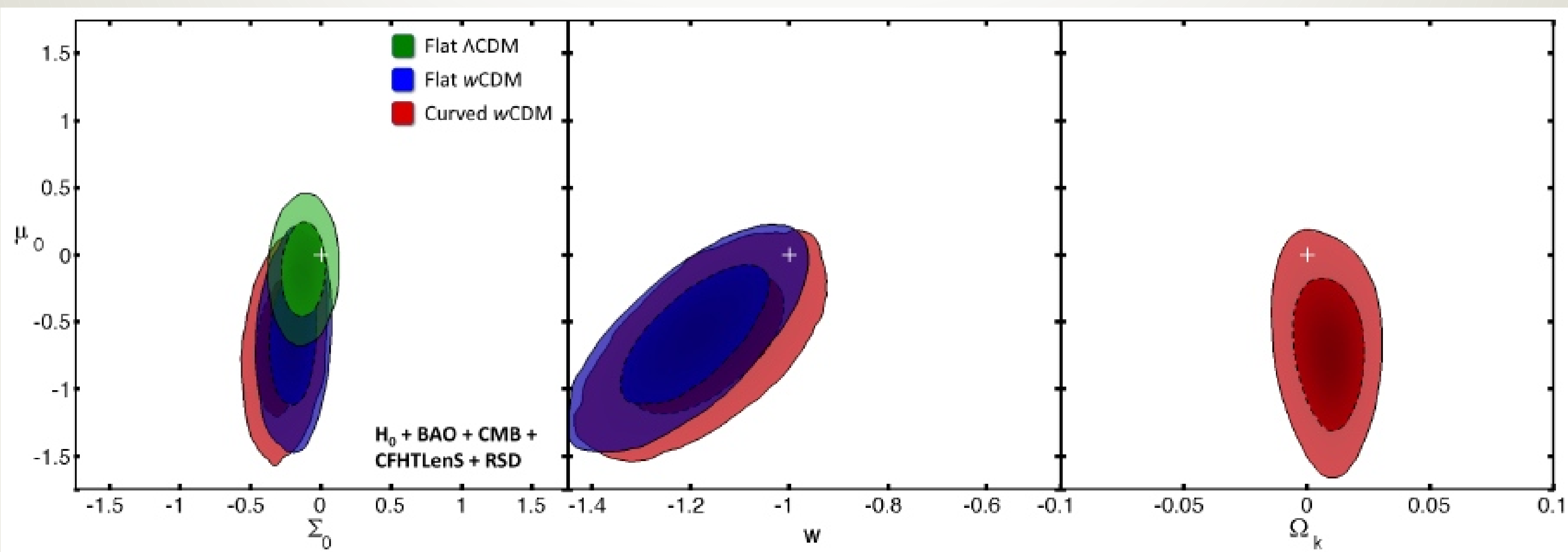

Simpson et al. (2013)

Accelerated Expansion

- Intense interest in the expansion history.
  Best current methods of measuring H(z):
  - SNIa
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- Many, many, many (really very many surveys) ongoing and planned surveys to probe any combination of the above (plus some more). These will constrain w and MG at the level of $\sigma_w \sim 0.01$ and $\sigma_\gamma \sim 0.01$.

DES eBOSS HETDEX 4MOST SKA

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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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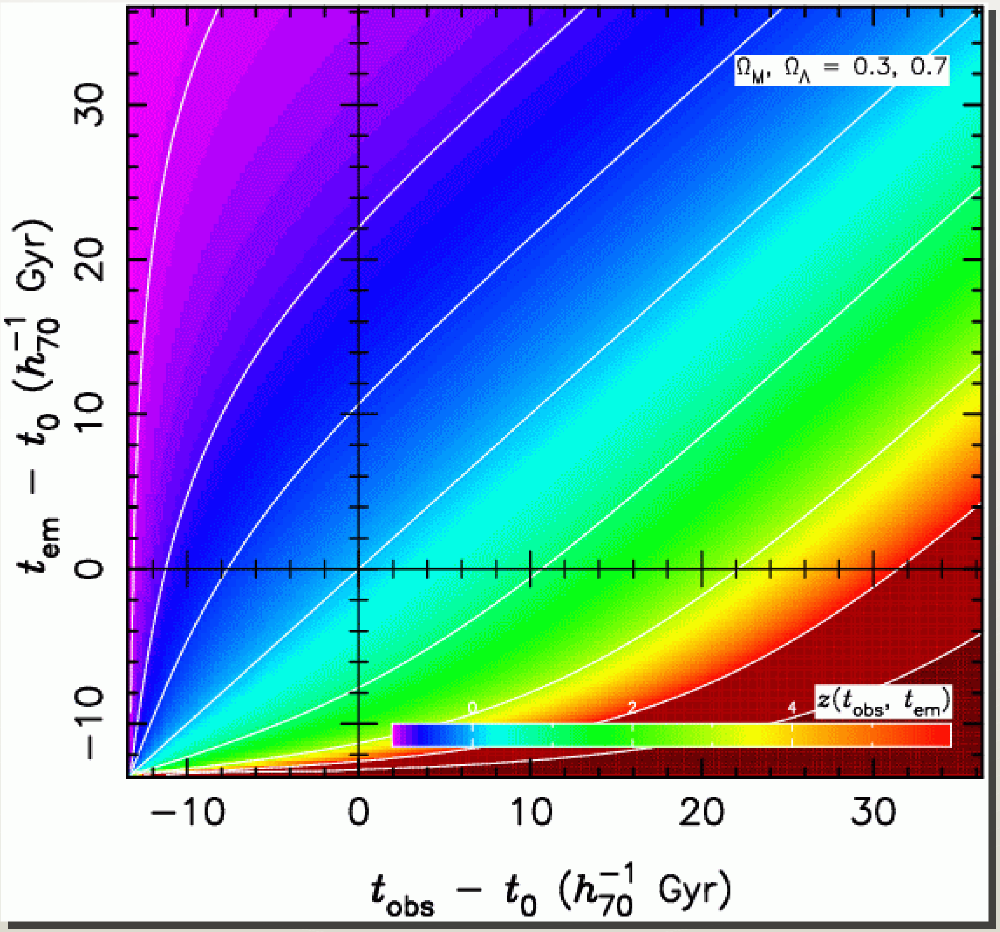

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Three ways to look at this equation:

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

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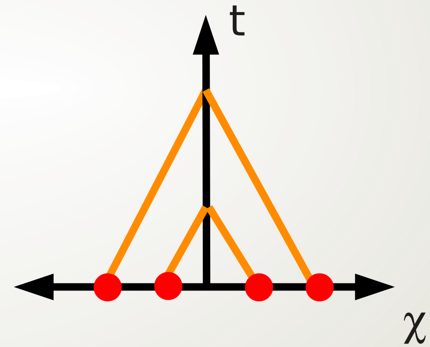

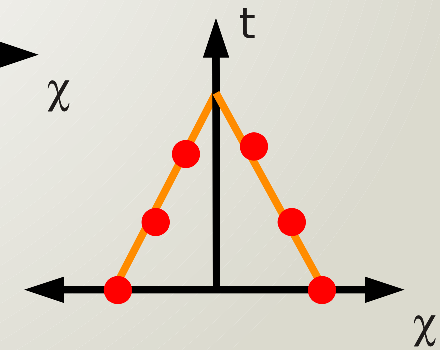

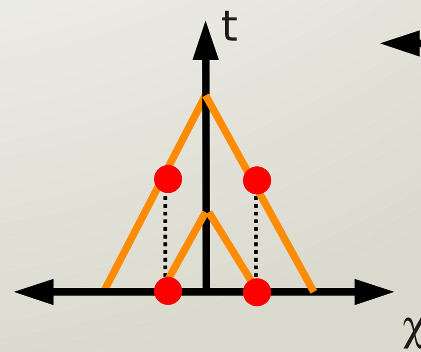

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Three ways to look at this equation:

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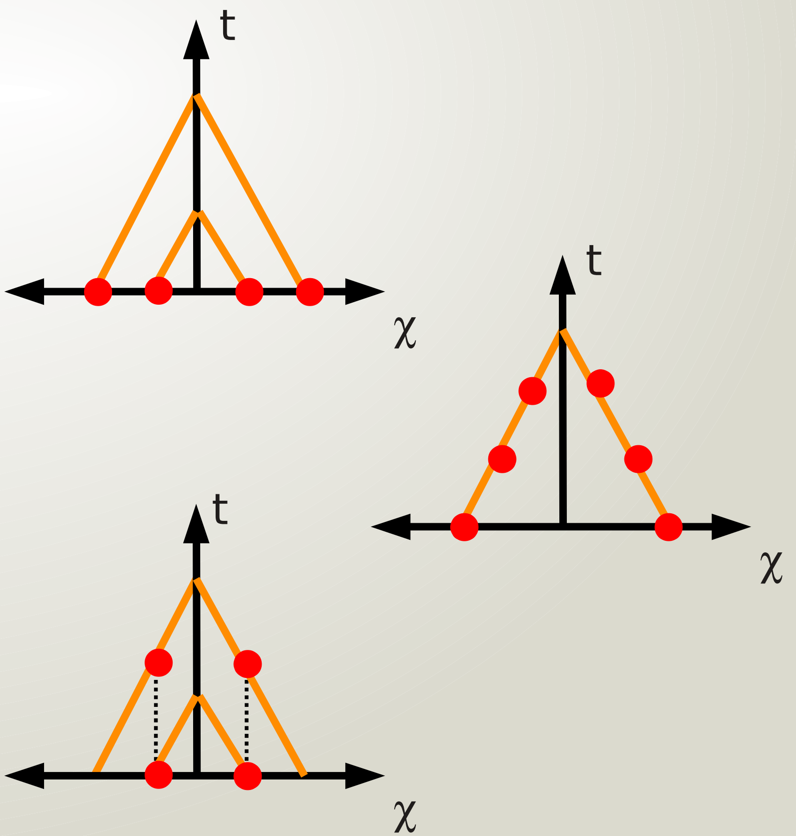
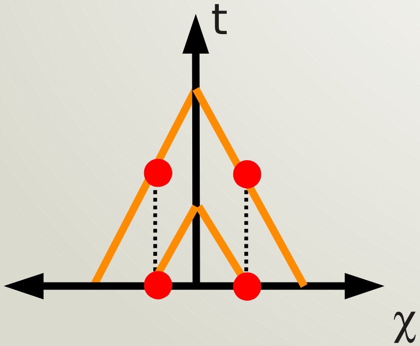
3. $$1+z(t_{obs}) = \frac{a(t_{obs})}{a(t_{em})}$$ χ const

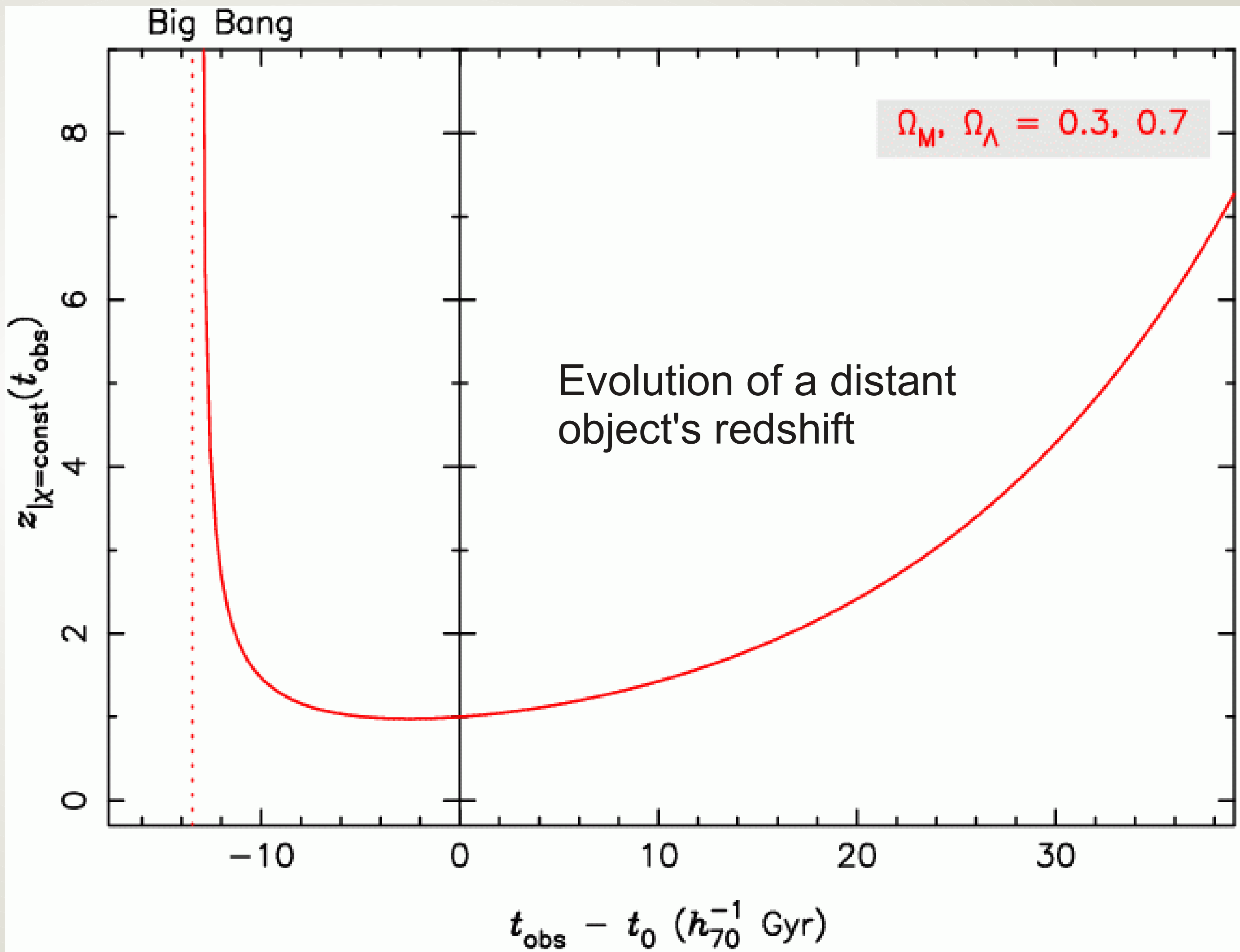


Evolving redshifts

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

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





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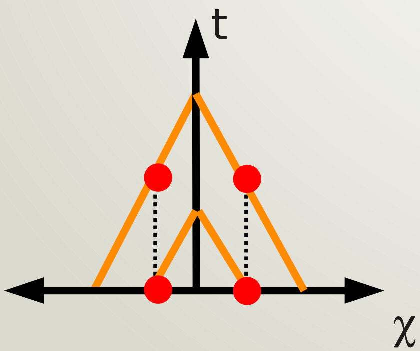

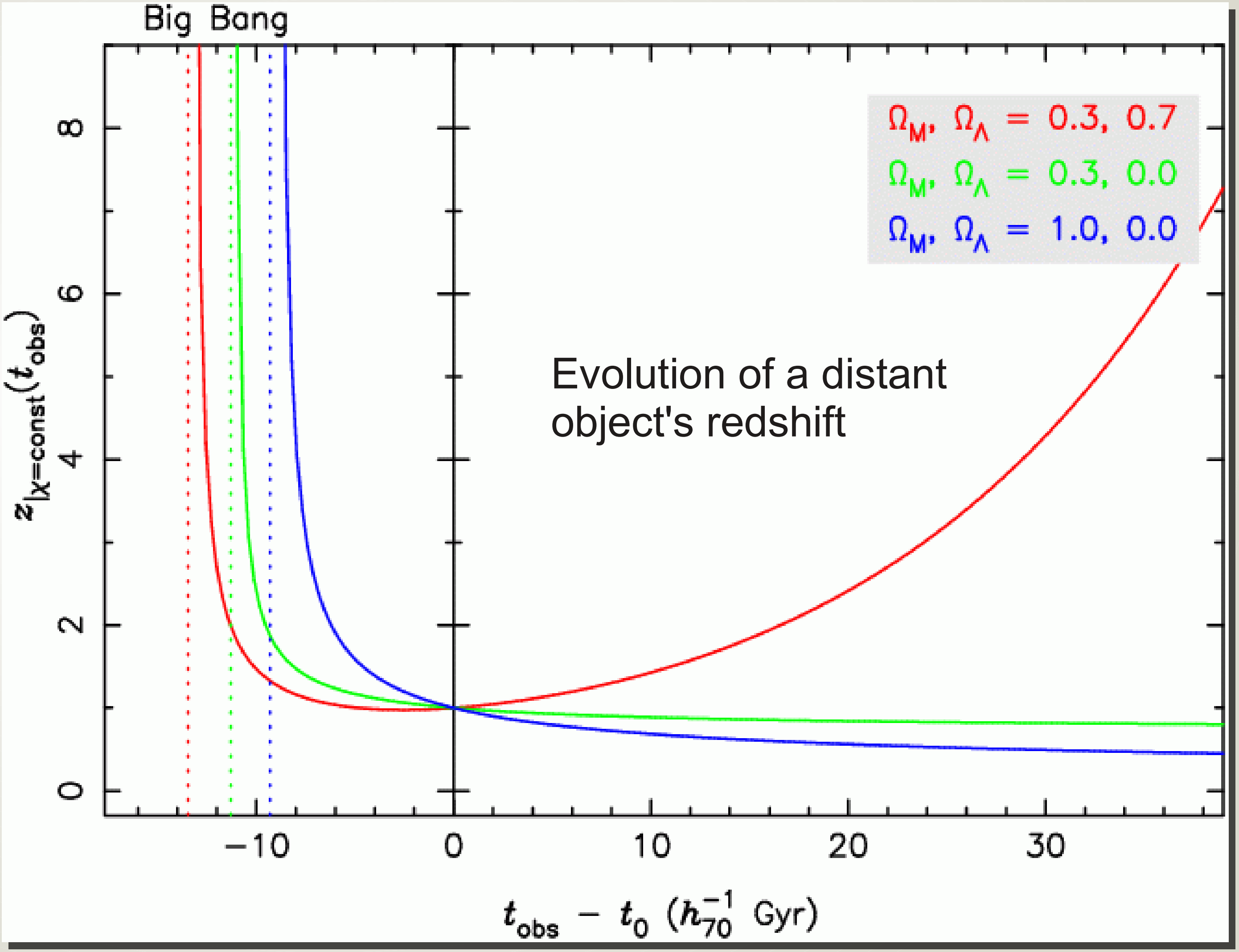

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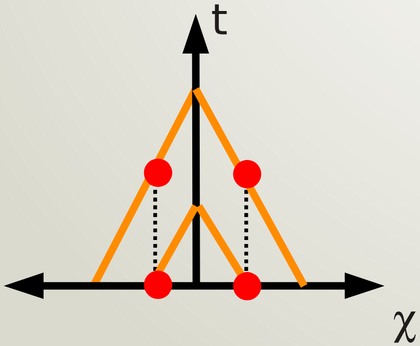
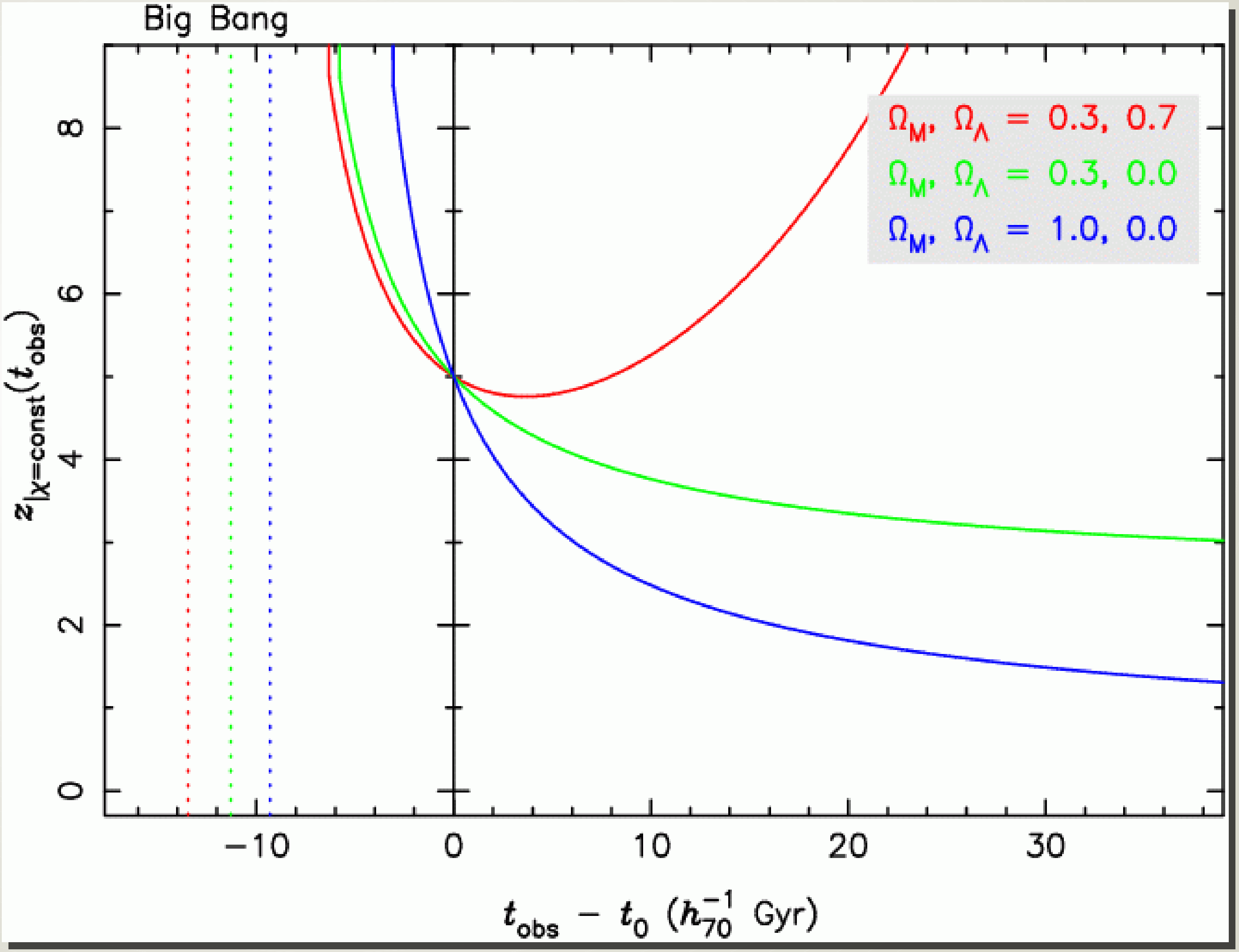


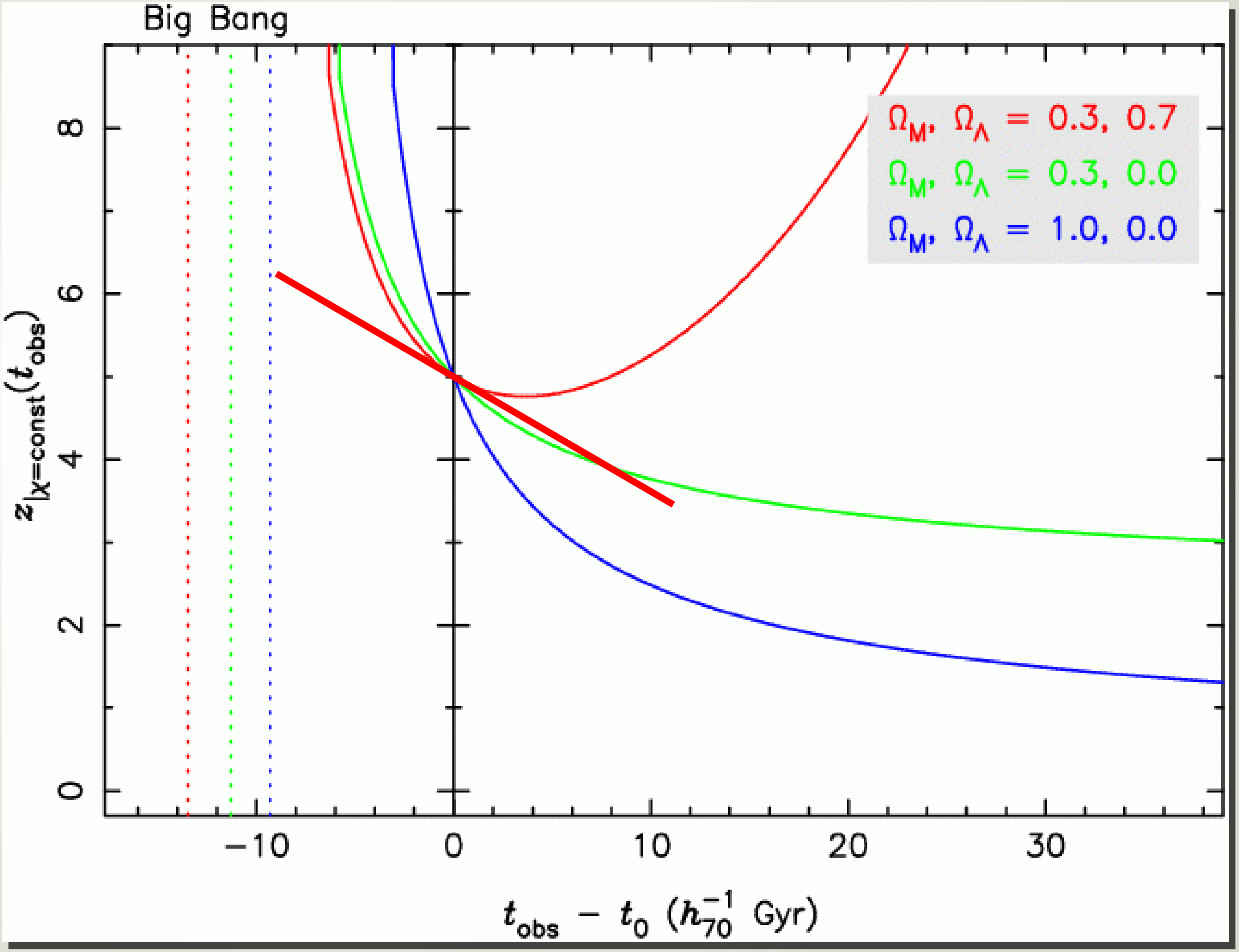


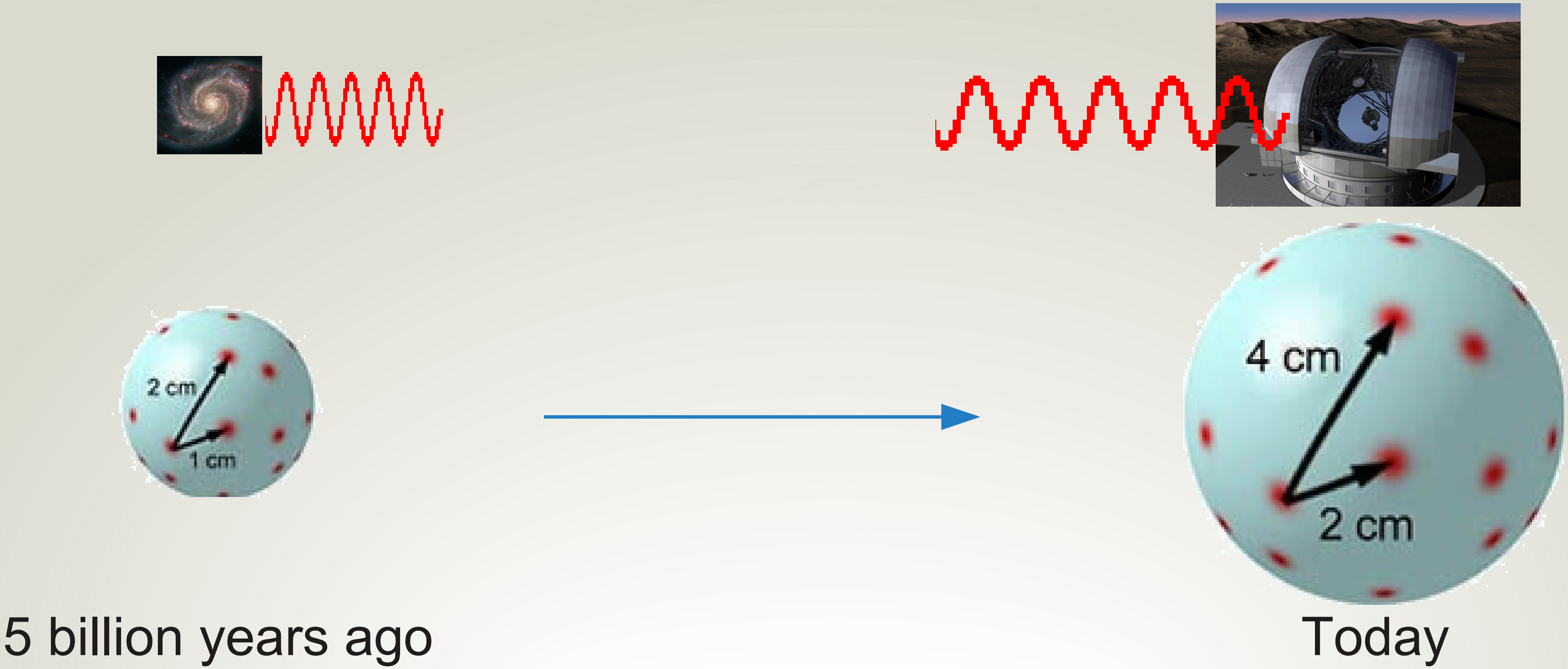
Evolving redshifts

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

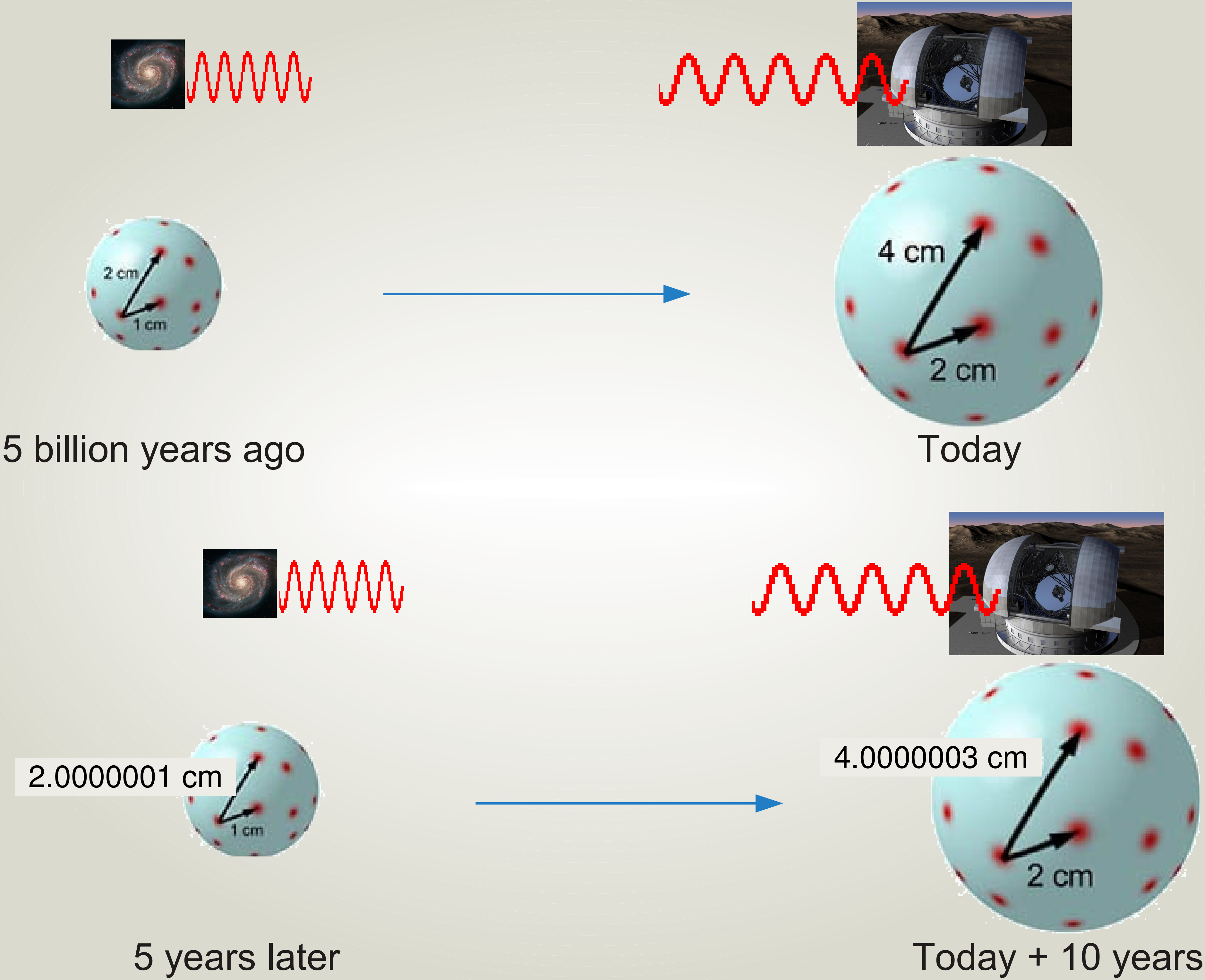
$$\frac{dz}{dt_{obs}}$$

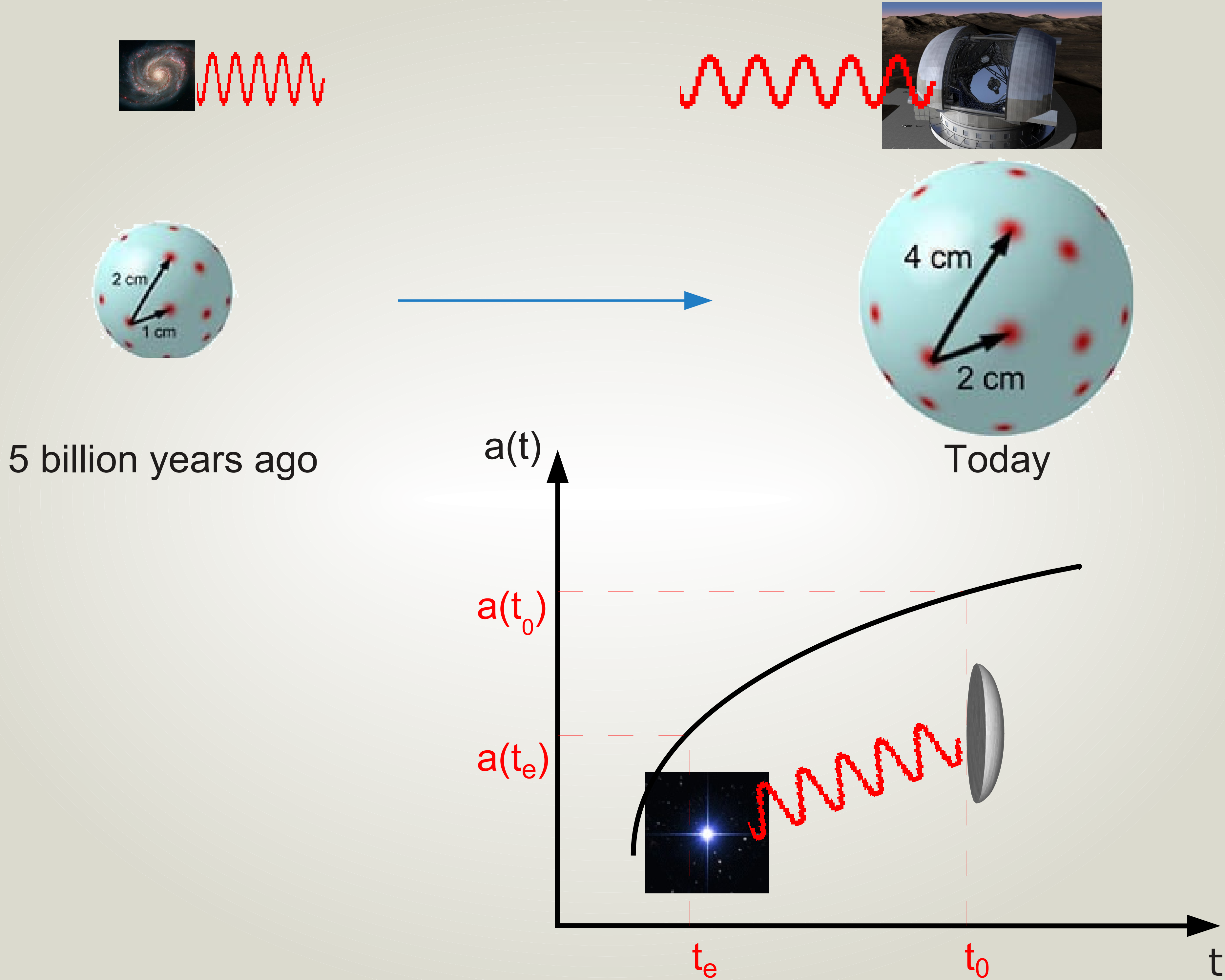
dz/dt = change of redshift as a fuction of time.

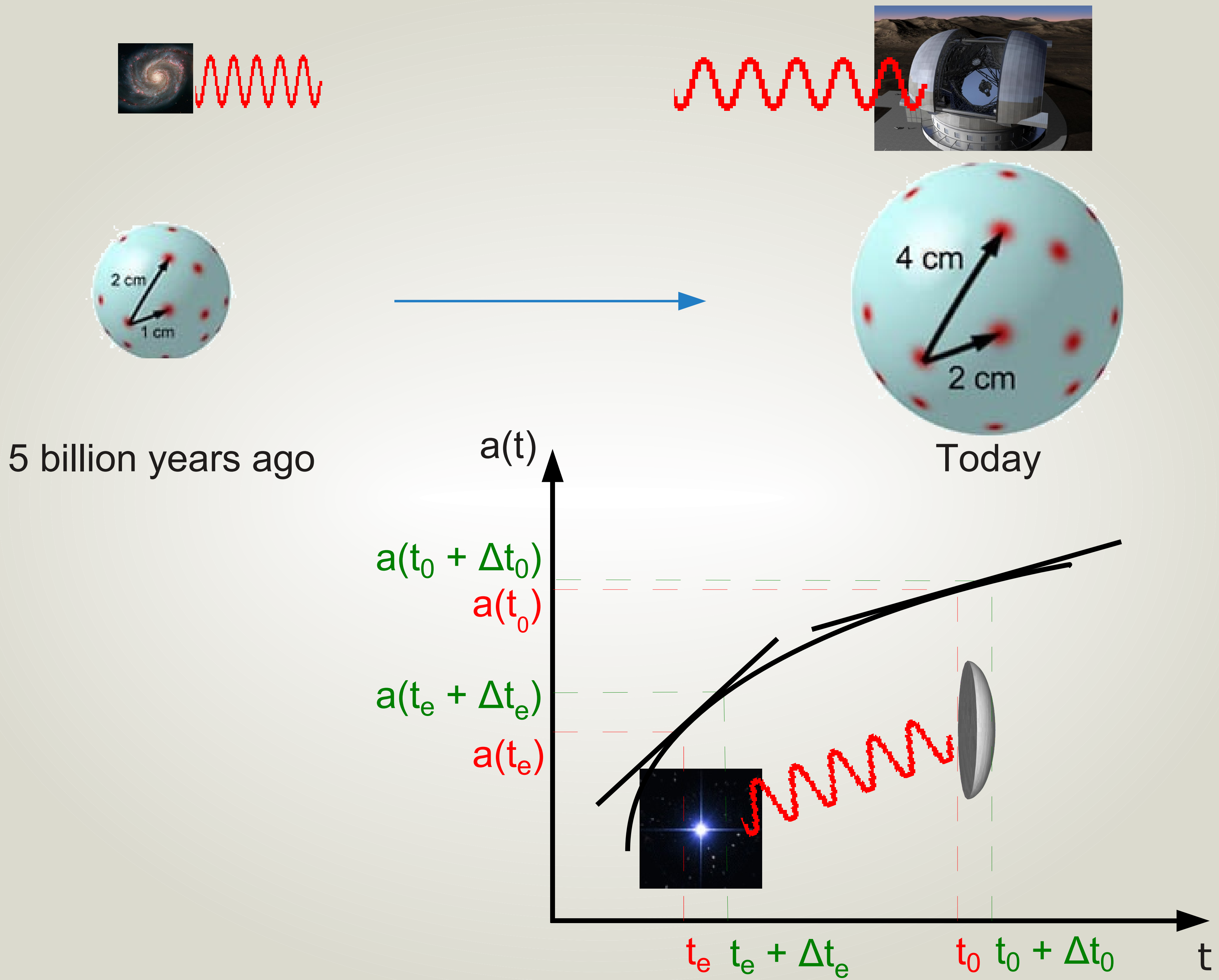




2 cm
1 cm
4 cm
2 cm
5 billion years ago
Today


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(t0)
a(te)
te
t0
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?

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

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

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

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

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

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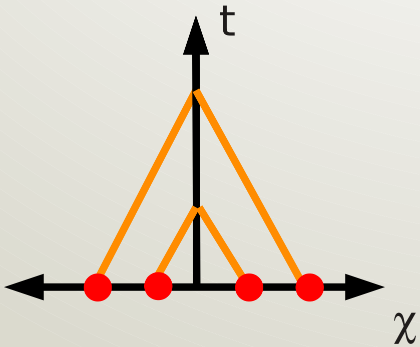

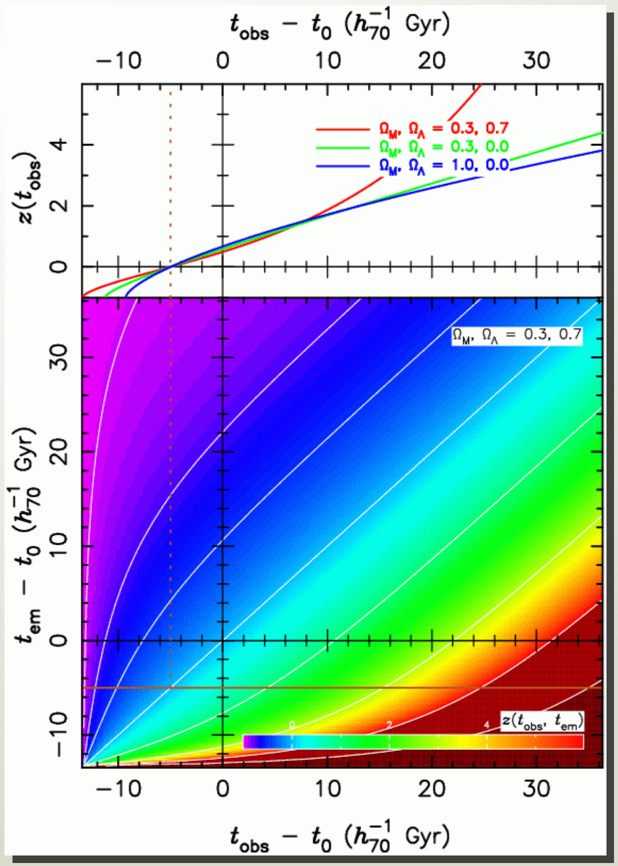

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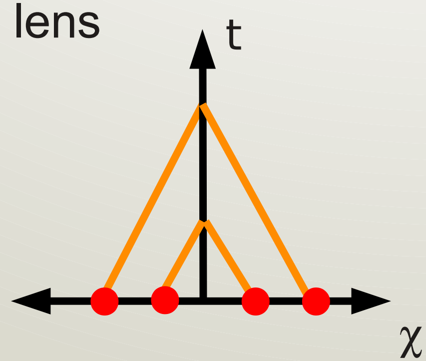
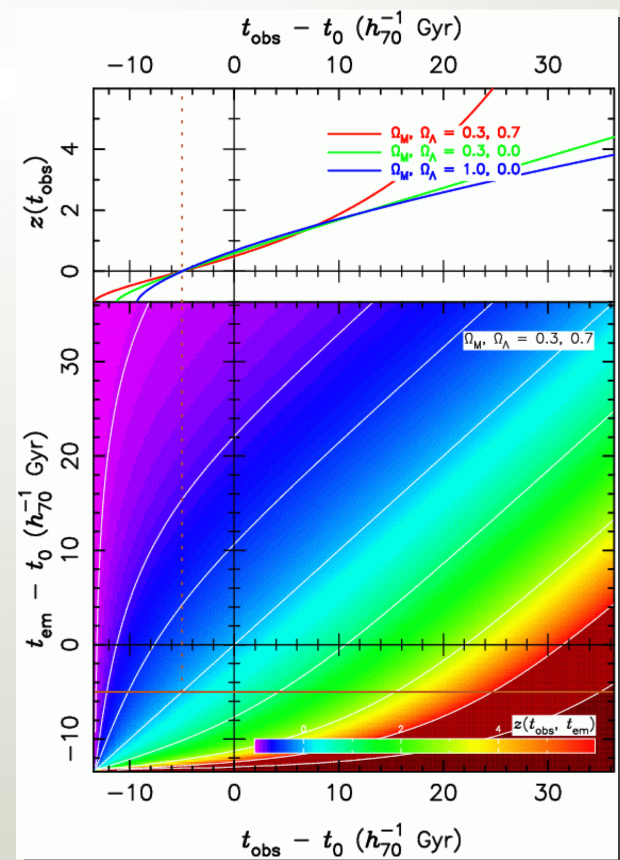
$$\left.\frac{dz}{dt_{obs}}\right|_{t_{em}=const} = (1+z)H_0$$

Need several events at t_{em}!

- CMB
- Gravitational lens





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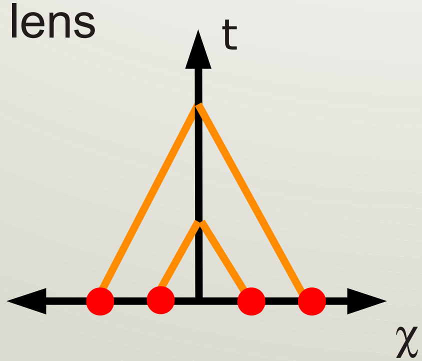

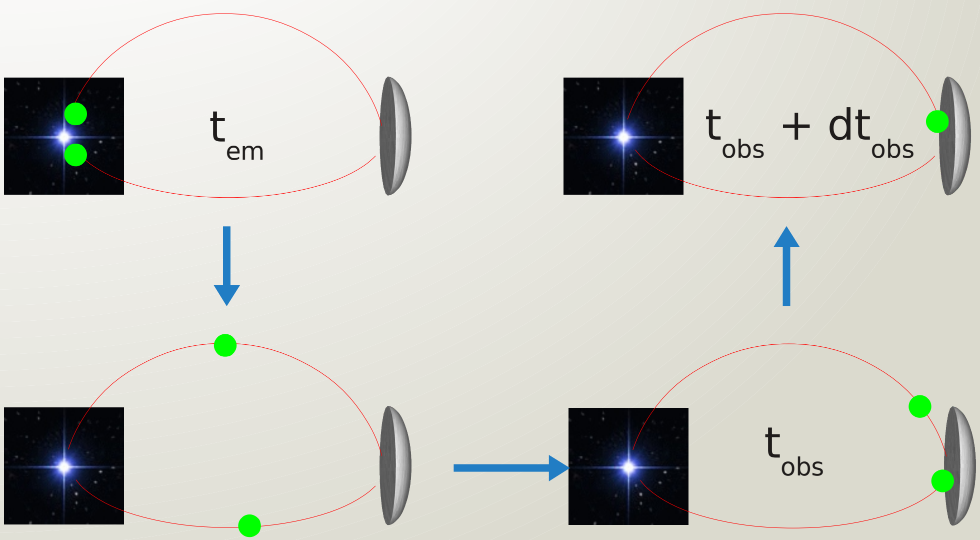

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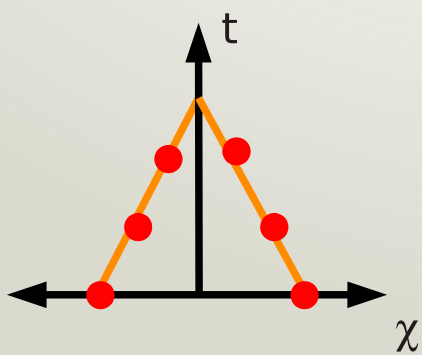

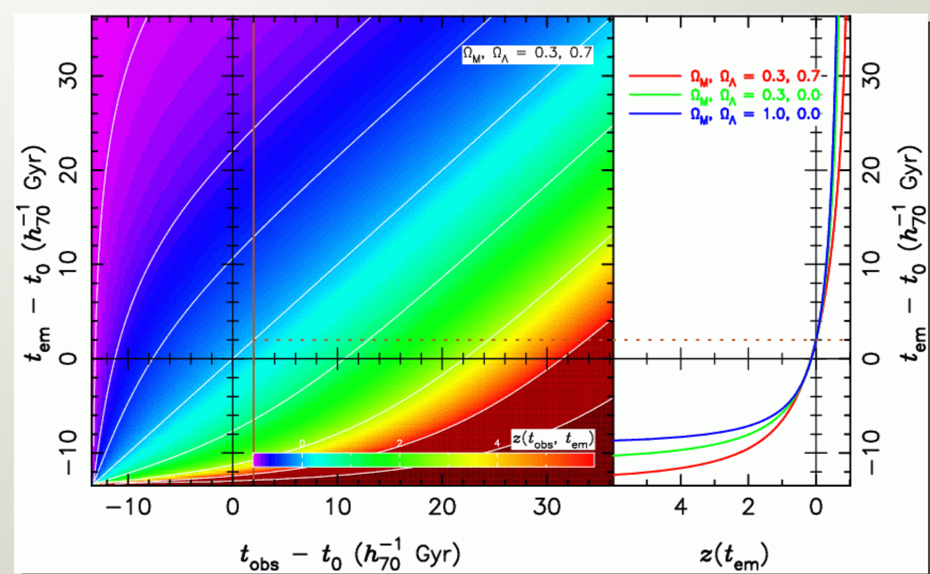

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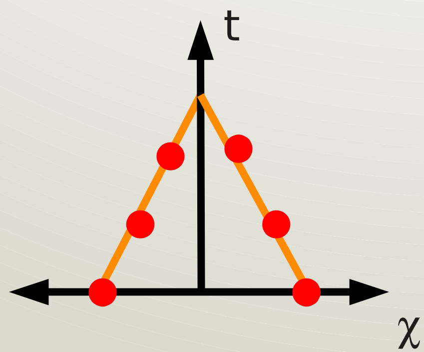
Three ways to look at this equation:

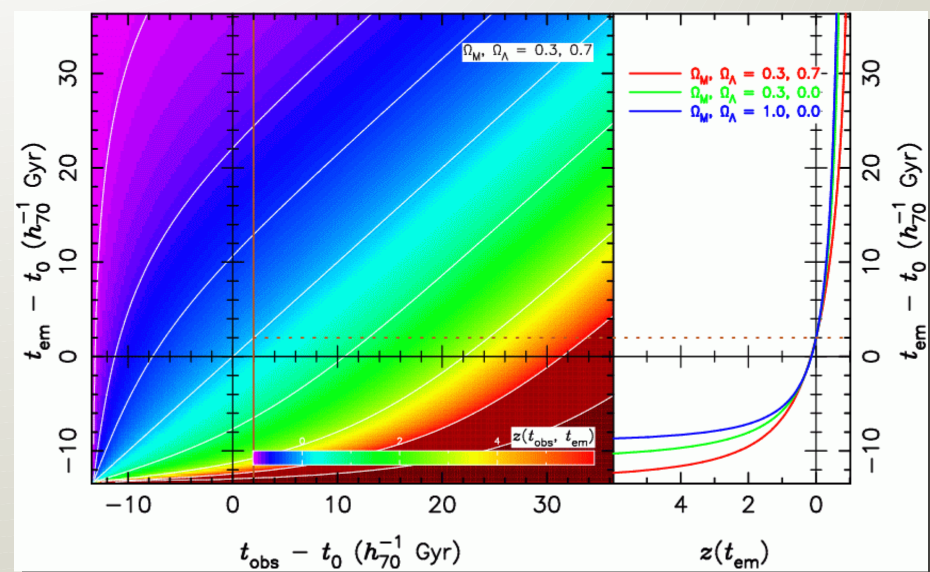
To use $z(t_{obs})$ to reconstruct a(t) we need to know t_{em}! Alternative: measure

$$\left.\frac{dz}{dt_{em}}\right|_{t_{obs}=const} = -(1+z)H(z)$$

Need to know dt_{em}!

- Gravitational lens





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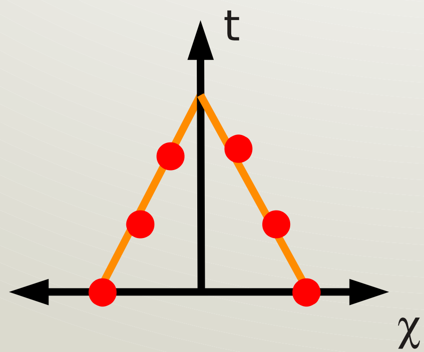
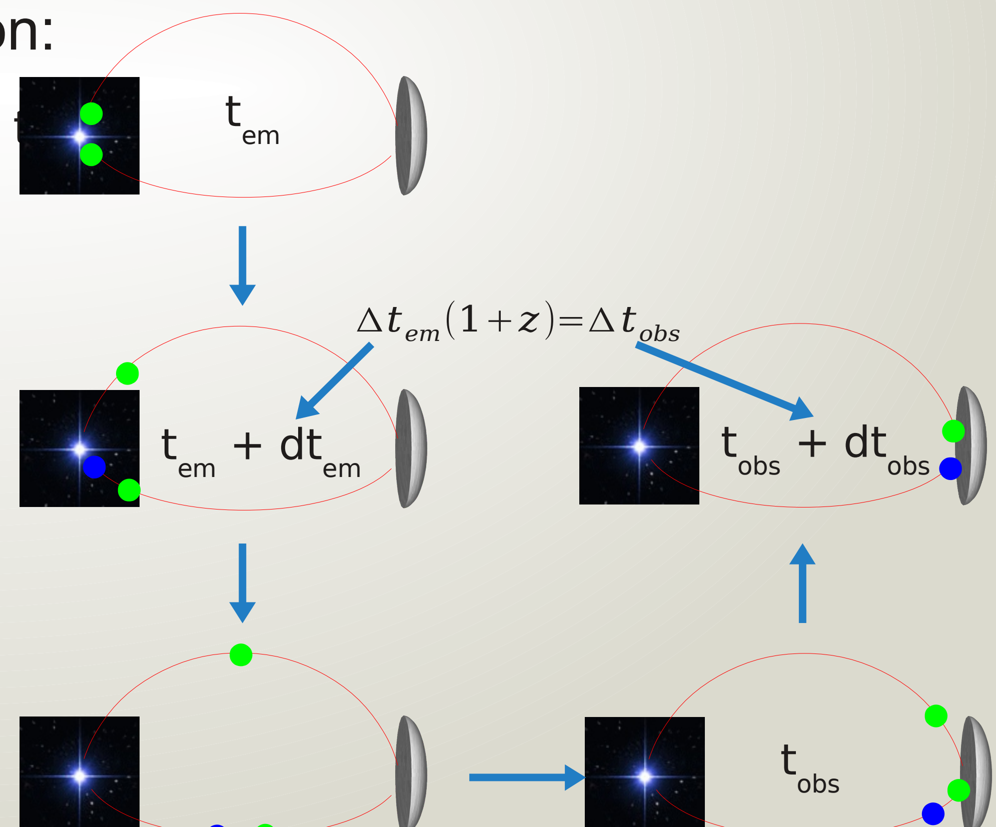




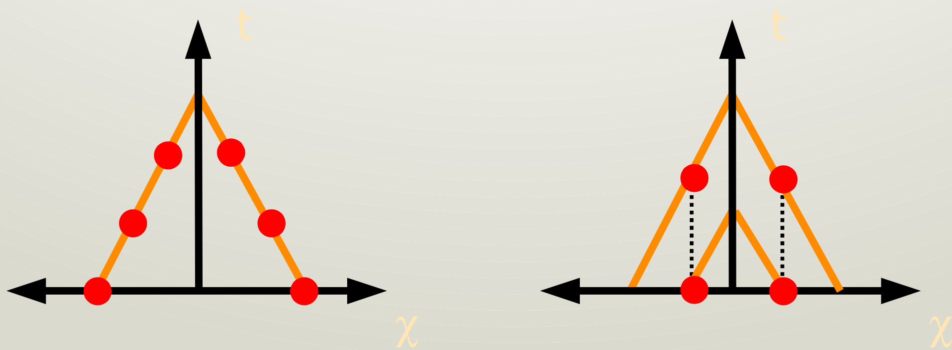
Cosmic Dynamics

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:

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

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.



Cosmic Dynamics

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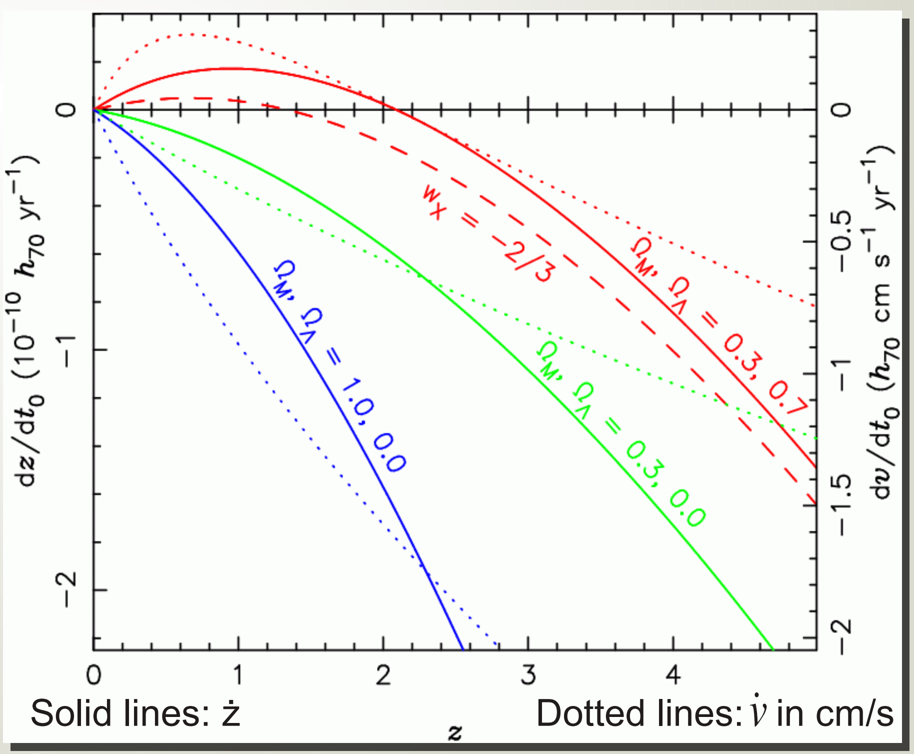
$$\dot{z} = (1+z)H_0 - H(z)$$

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

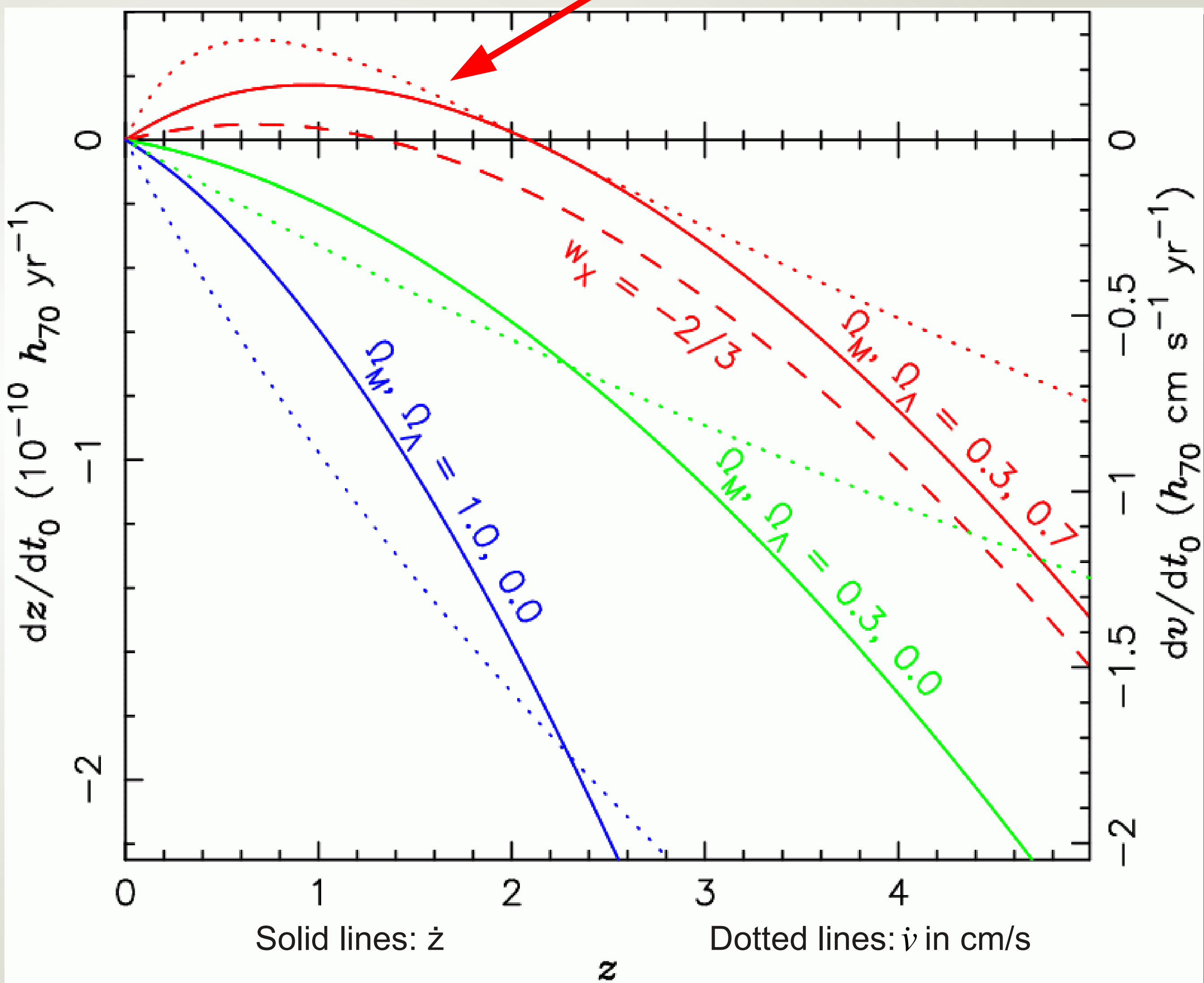
If Δt = 10 years then:

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



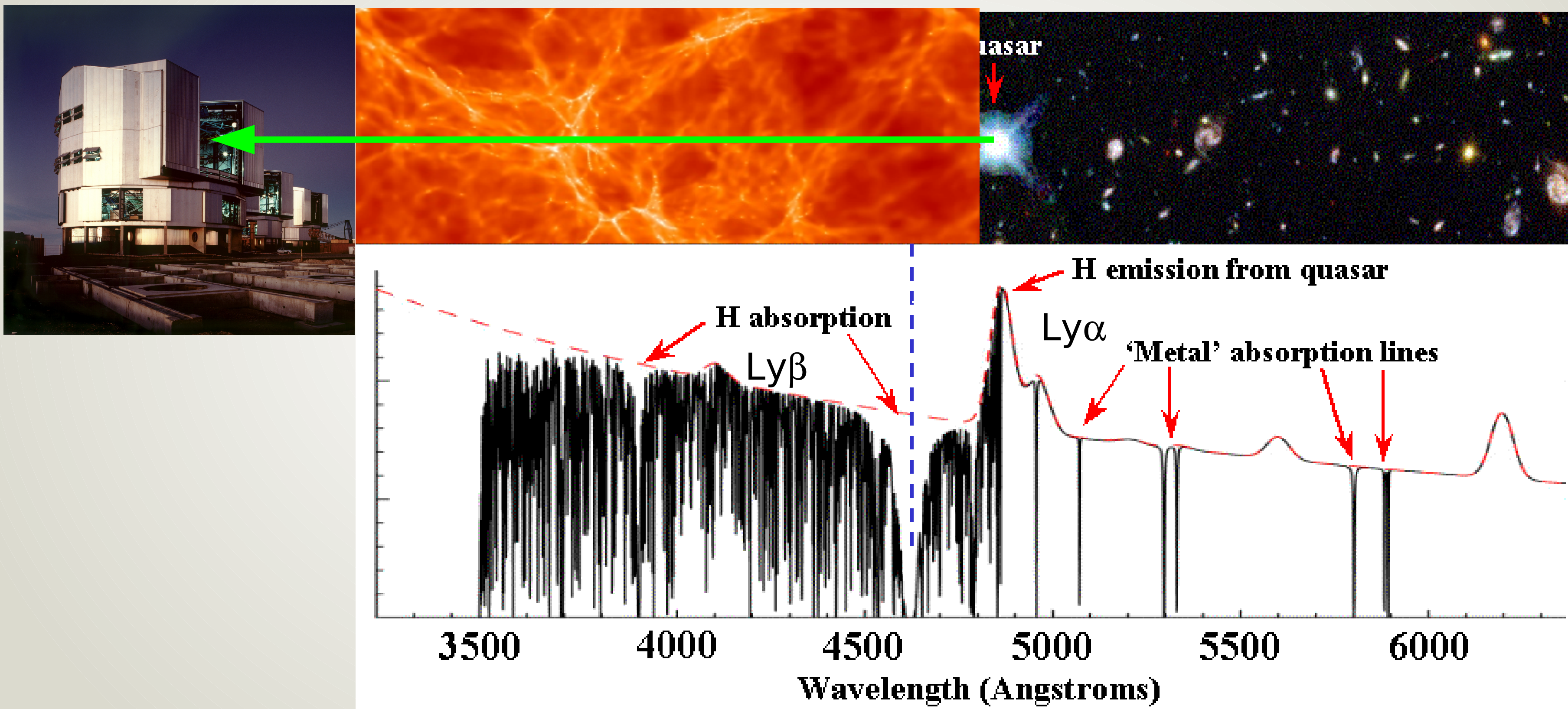
Solid lines: $\dot{z}$ Dotted lines: $\dot{v}$ in cm/s

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.

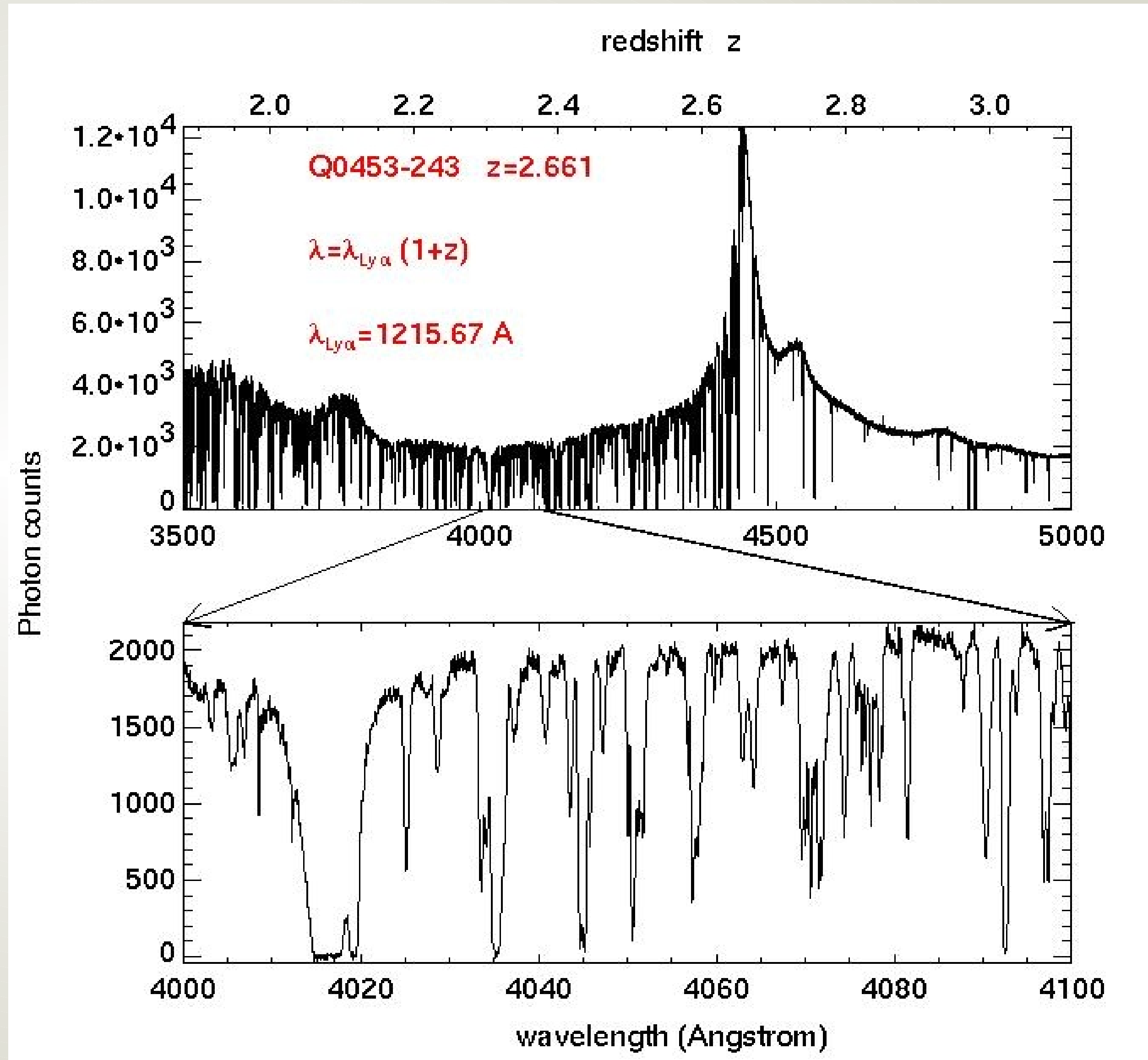
Measuring dz/dt in the IGM



by John Webb

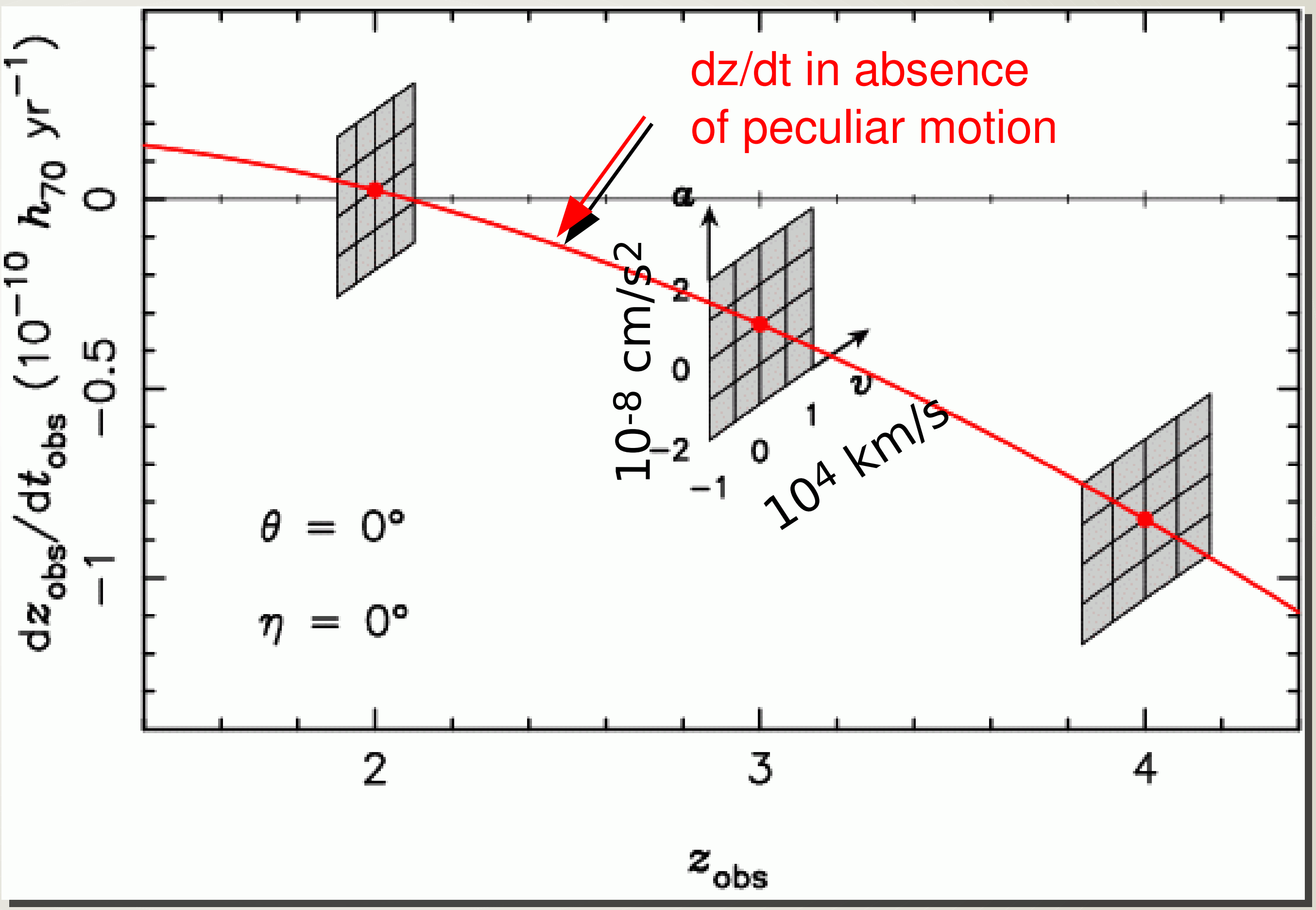
The Lyman α Forest

- ✔ 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.

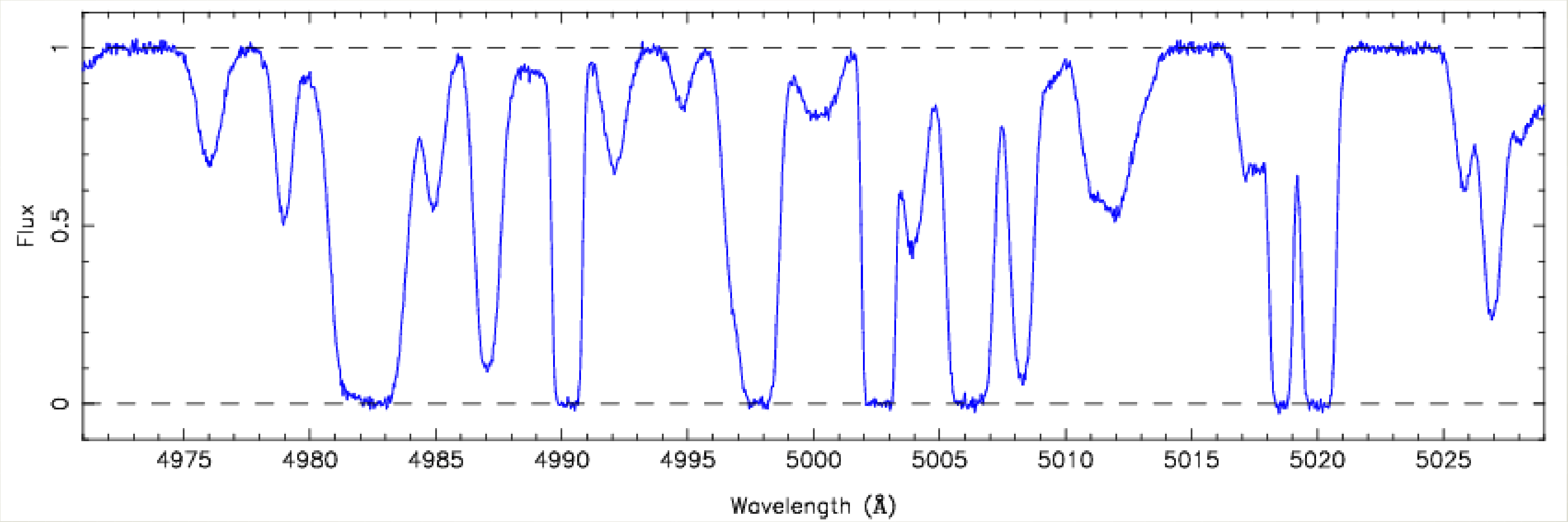


Liske et al. (2008)

→ 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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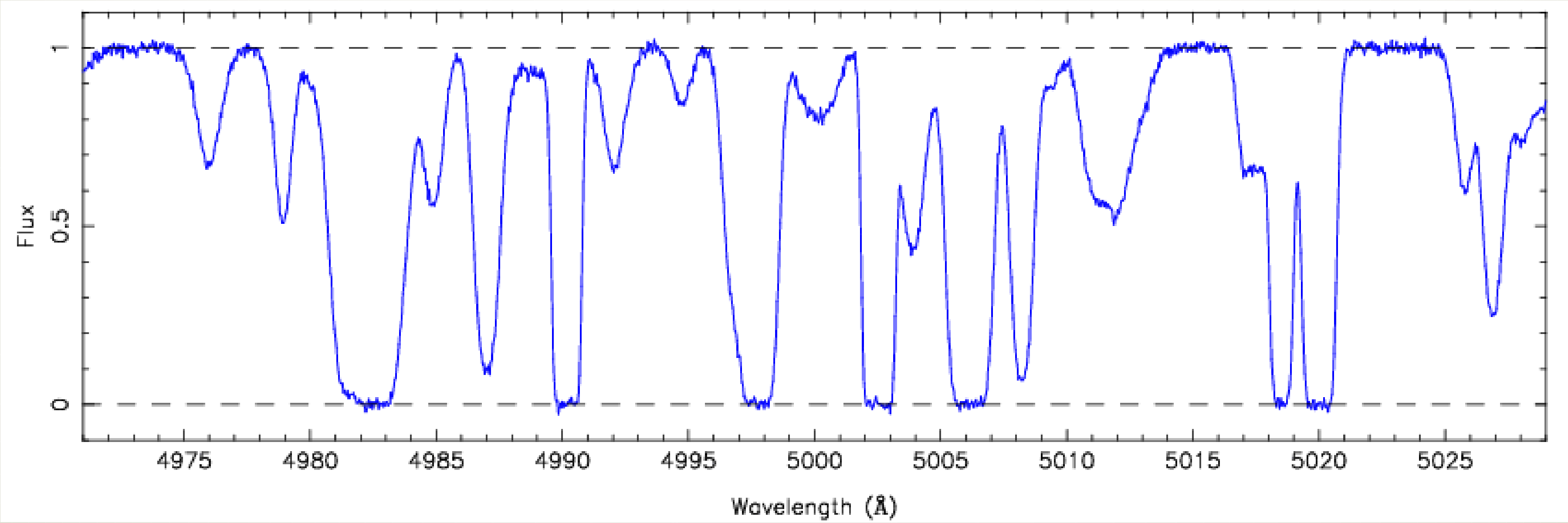

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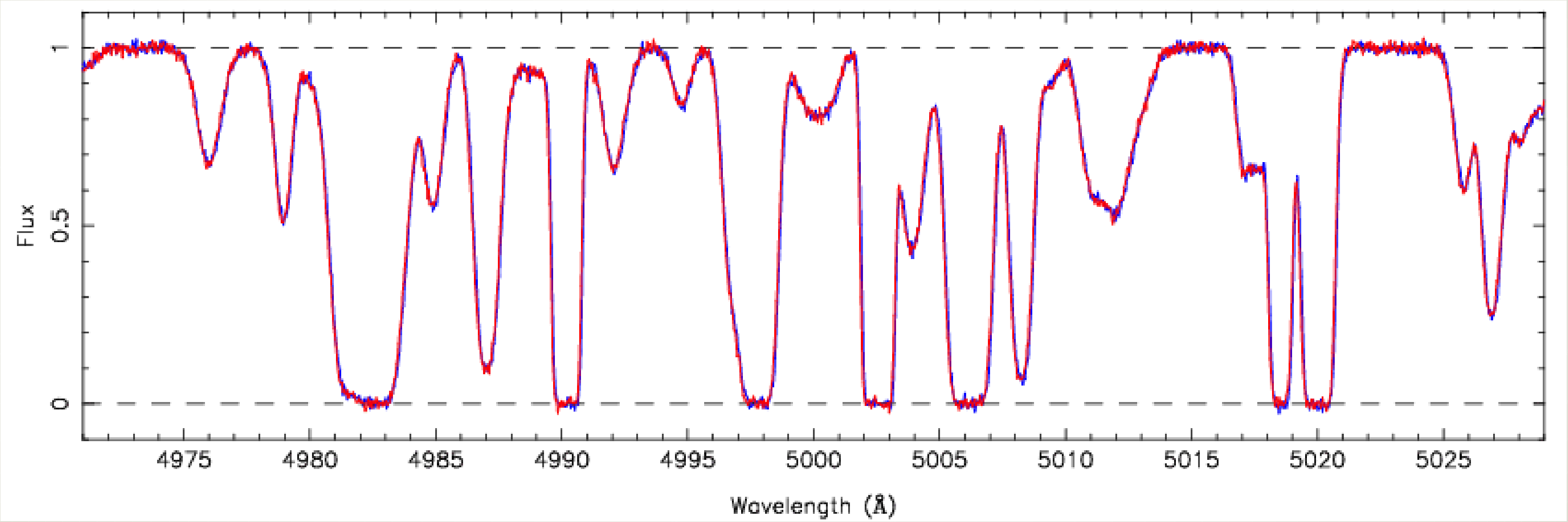

$\Delta t = 10^6$ years!

How can we measure the redshift drift?

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),
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Can we collect enough photons?

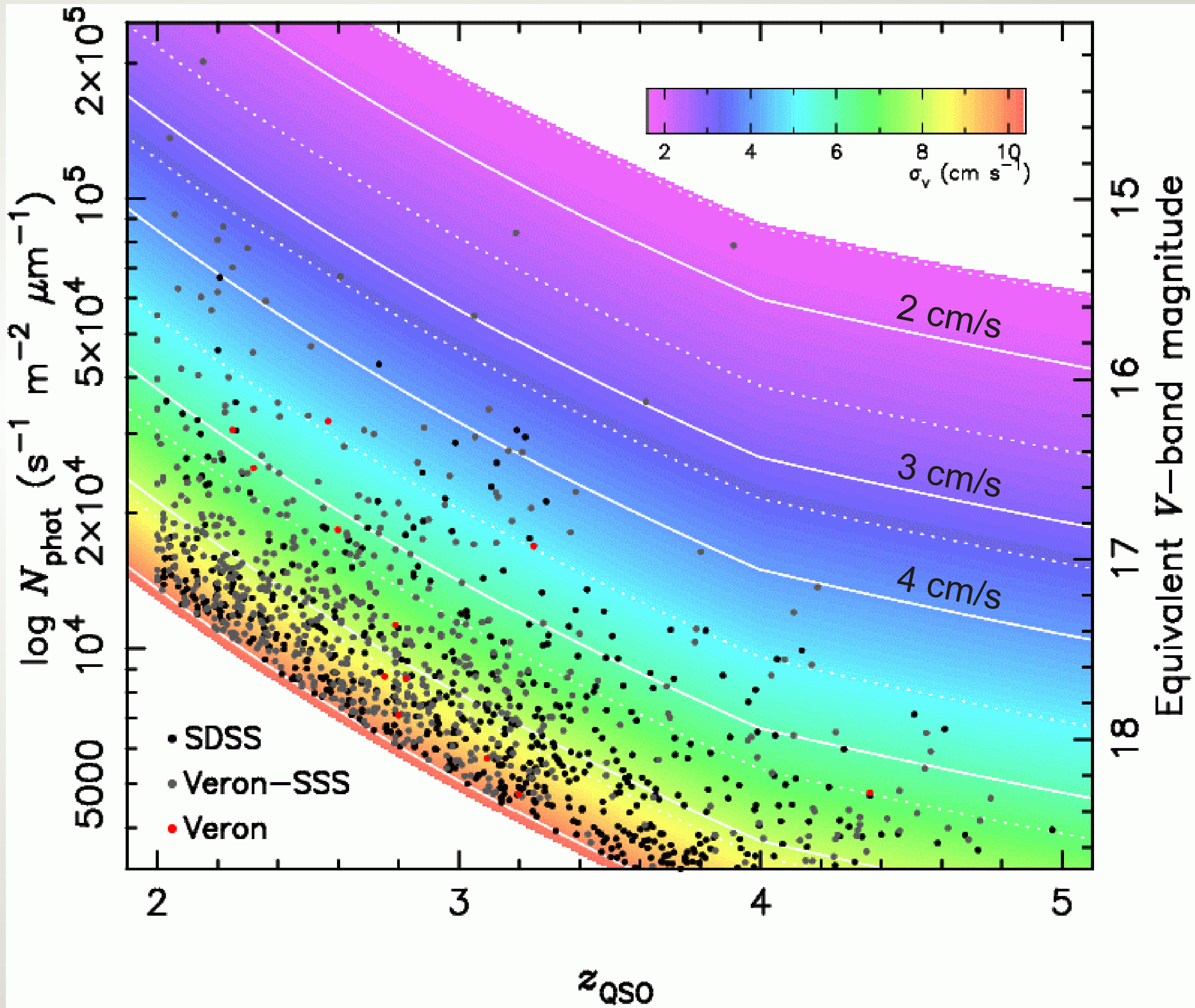
Can we collect enough photons to achieve the required radial velocity accuracy?

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.

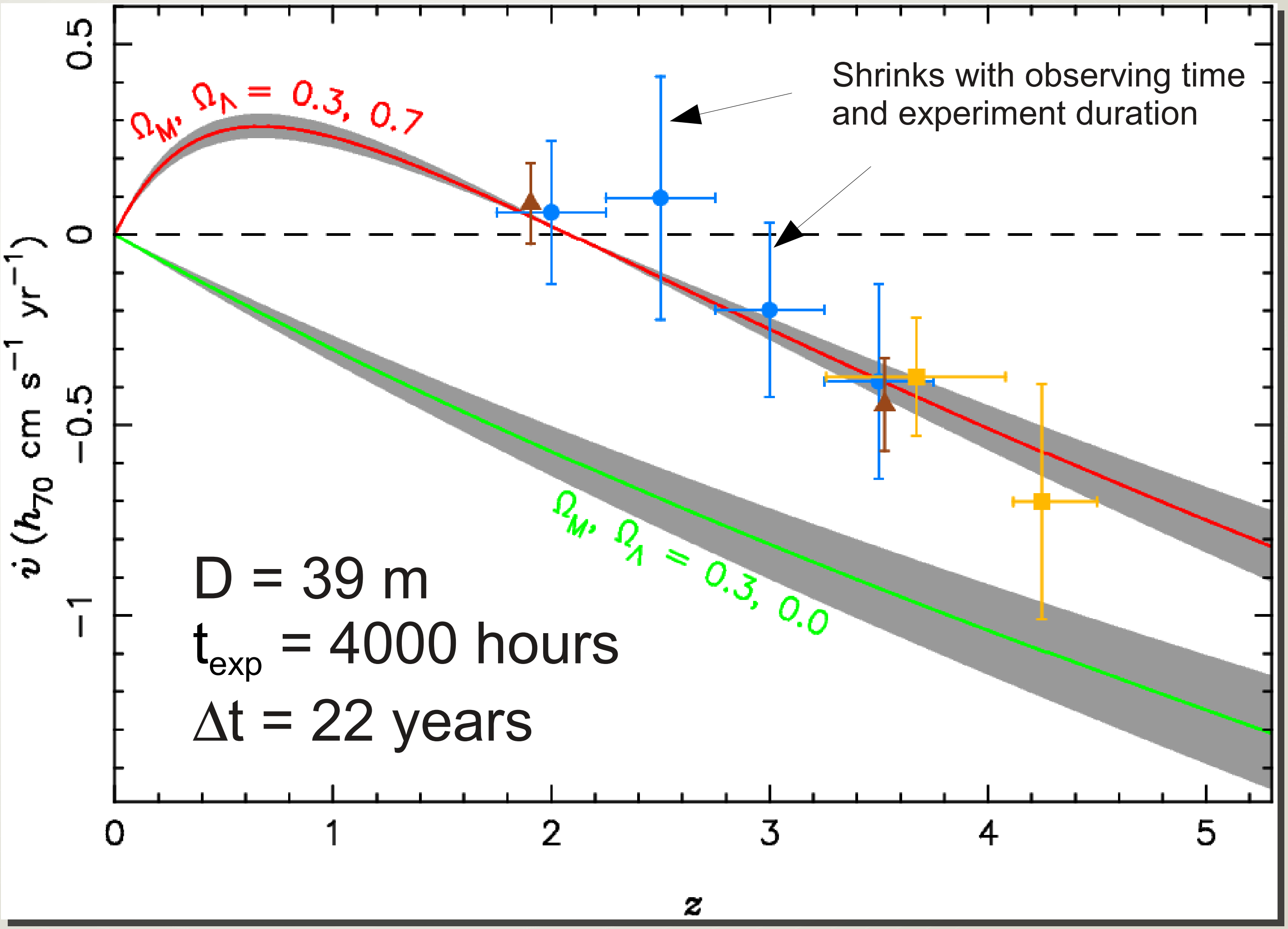


Liske et al. (2008)

Simulation Results

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

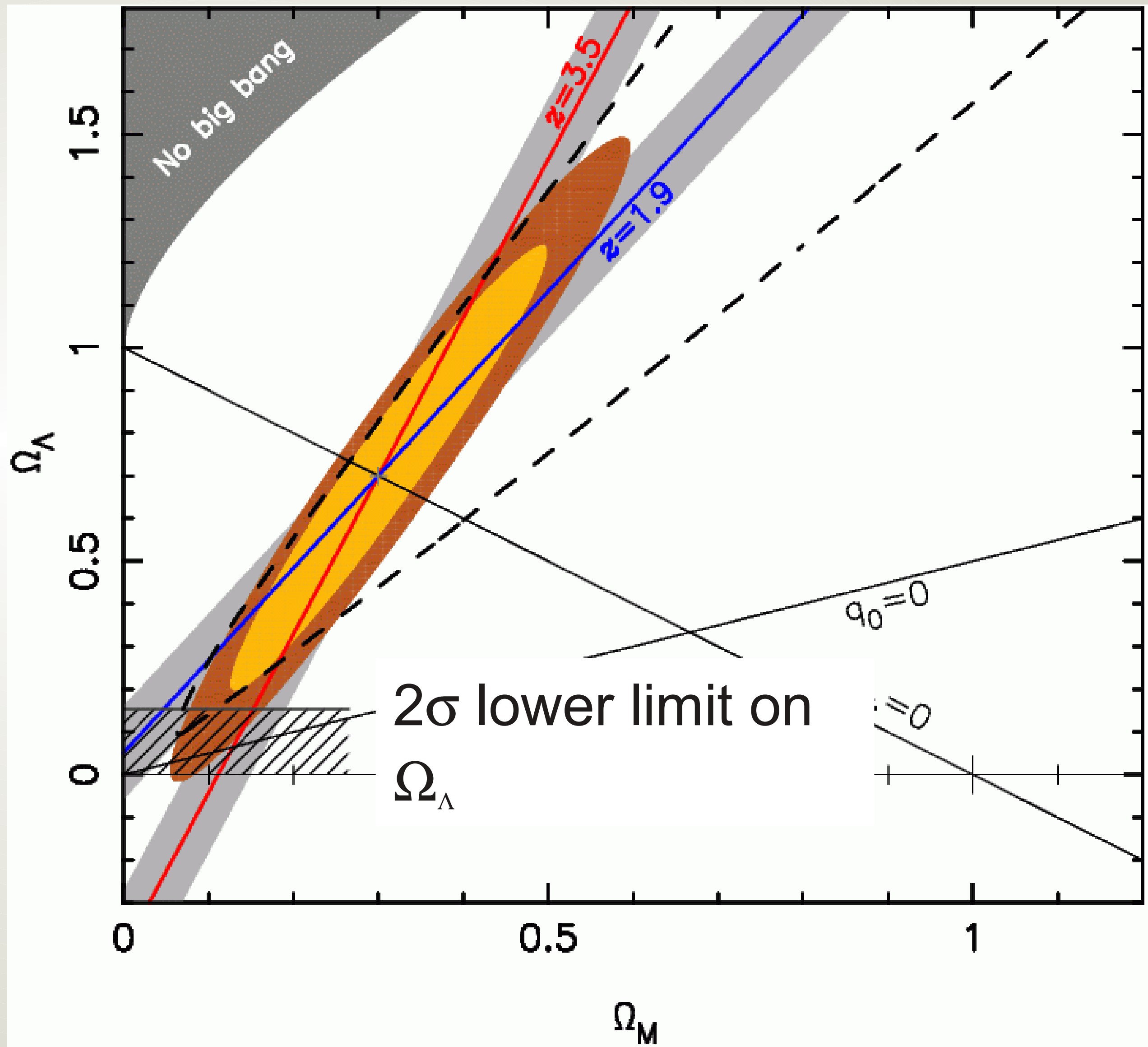
Different sets correspond to different target selection strategies.



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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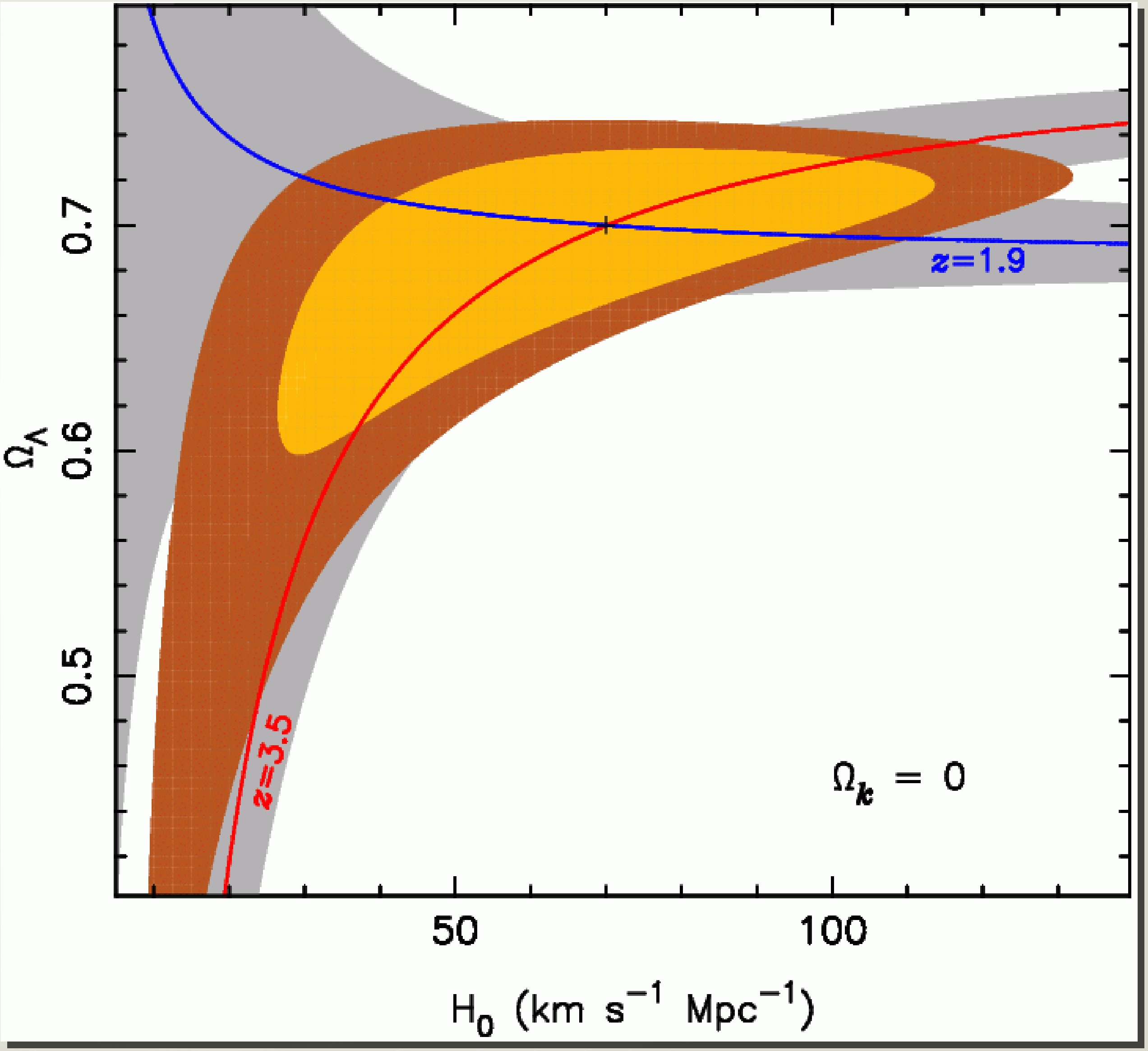

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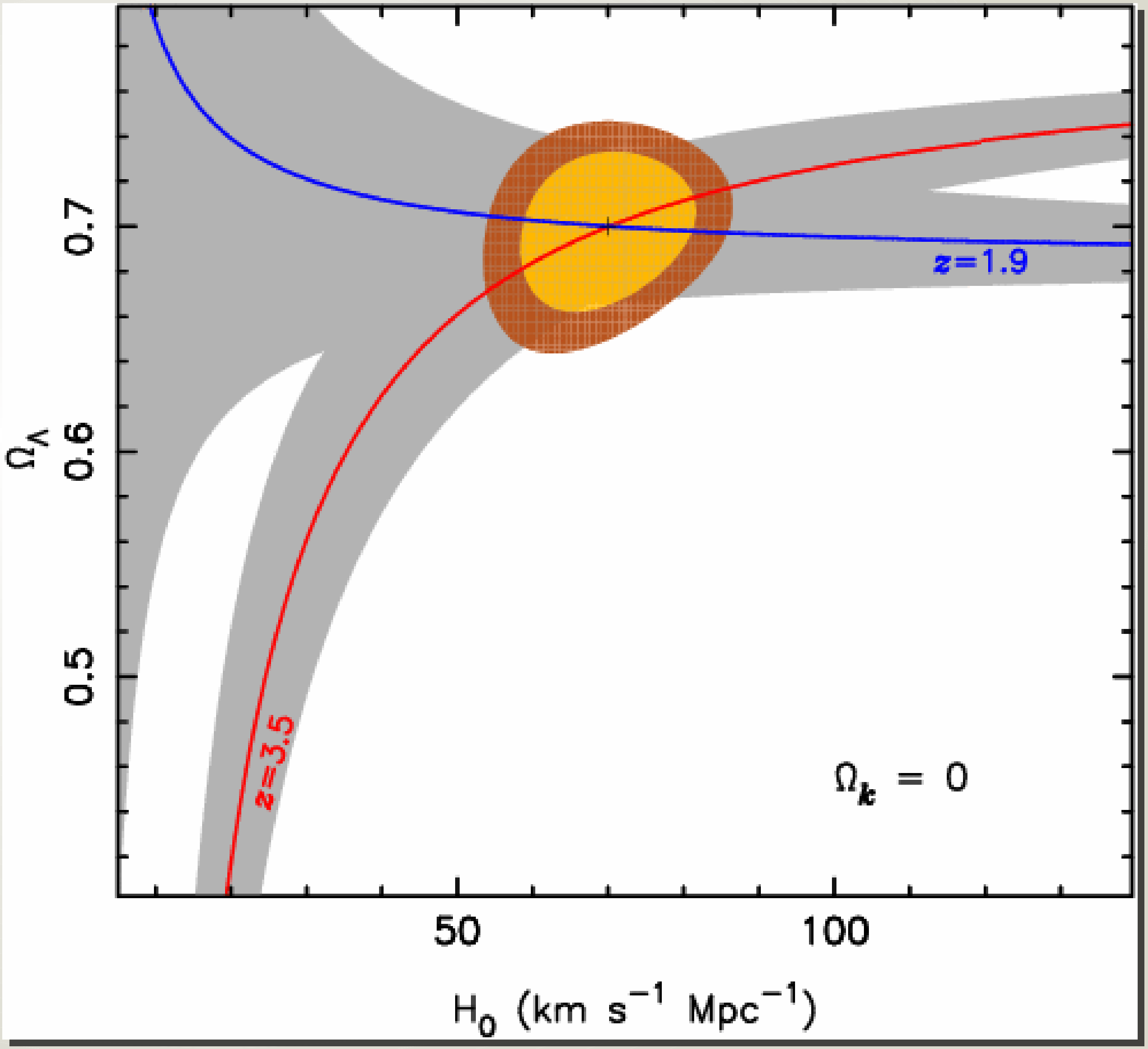
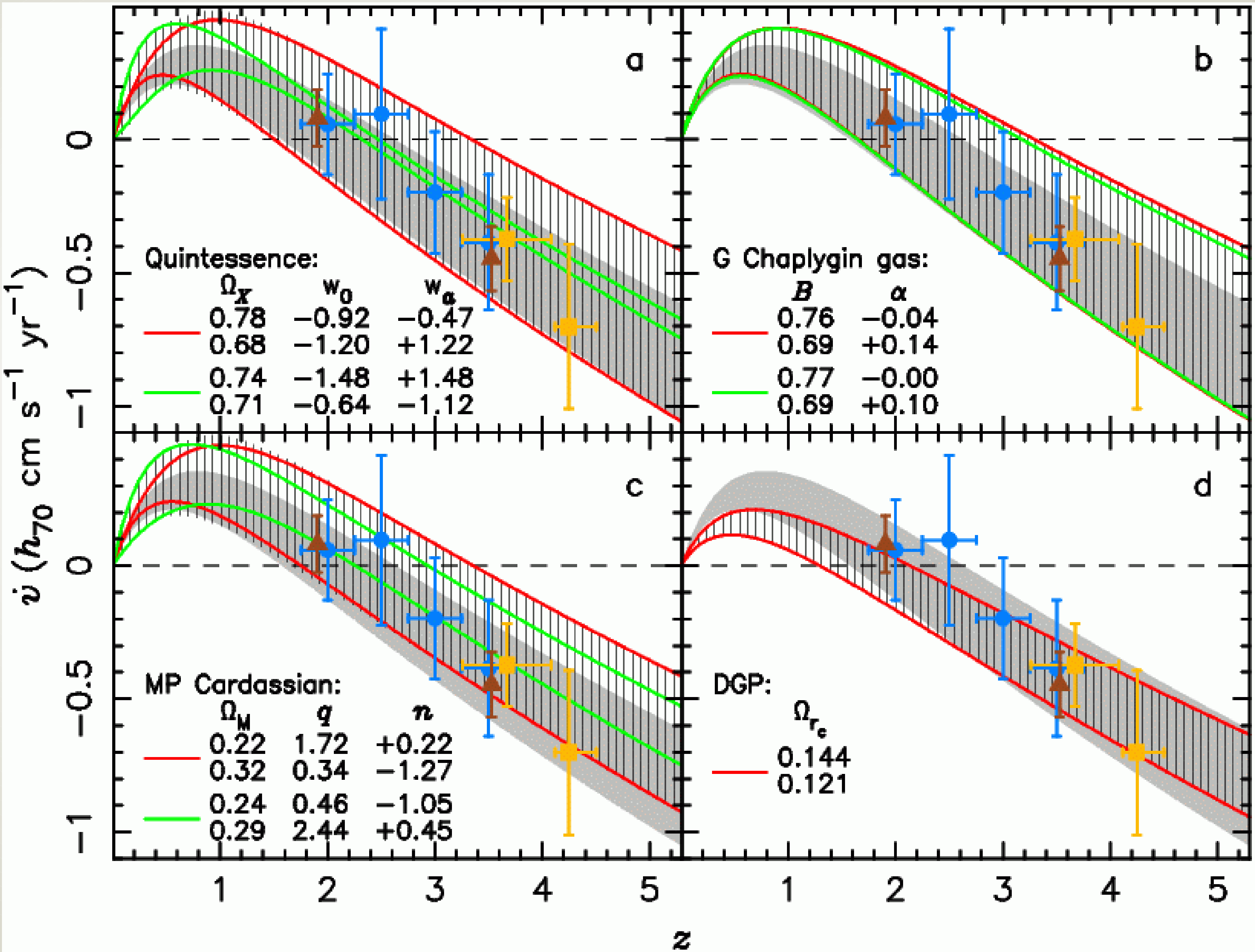


Liske et al. (2008)

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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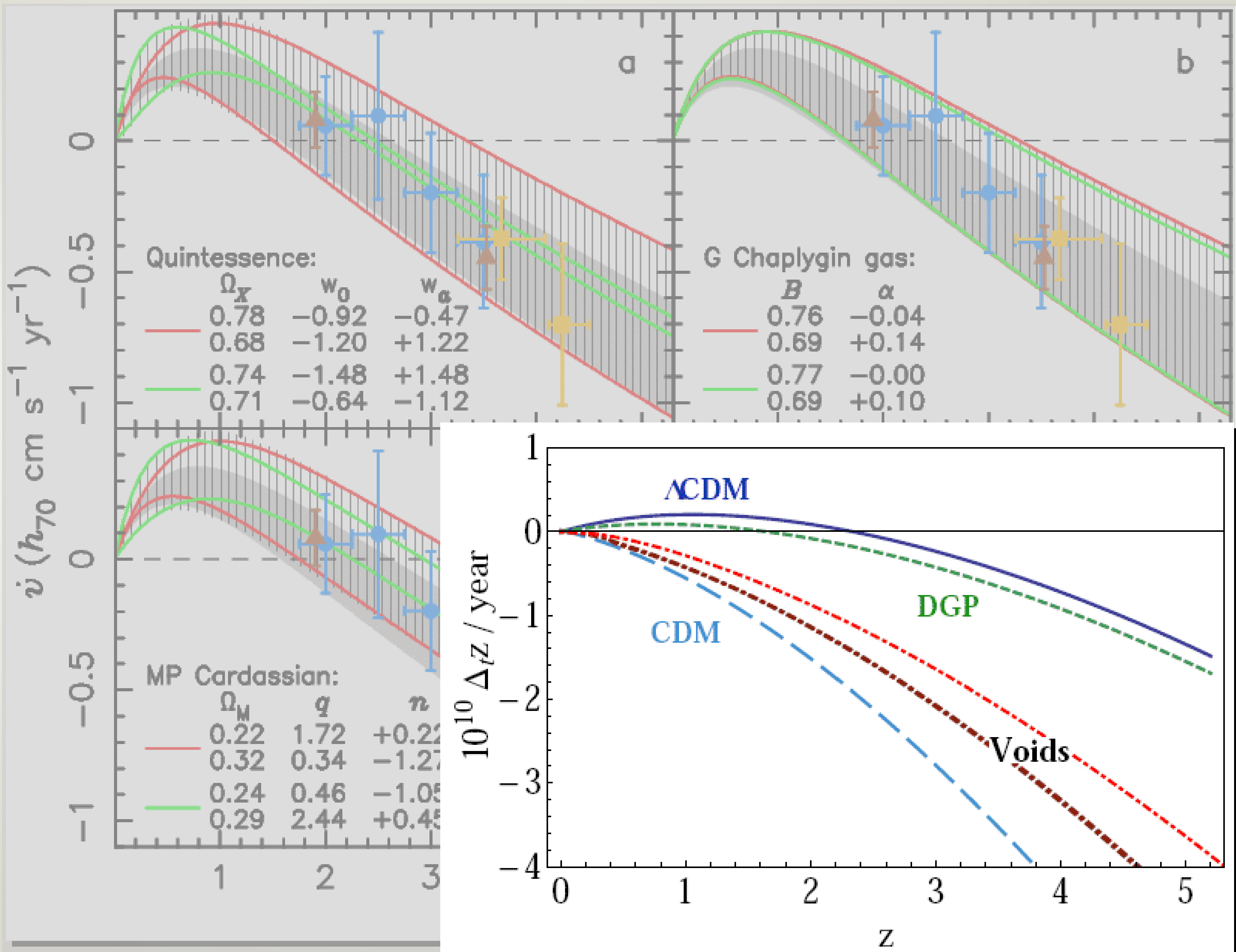
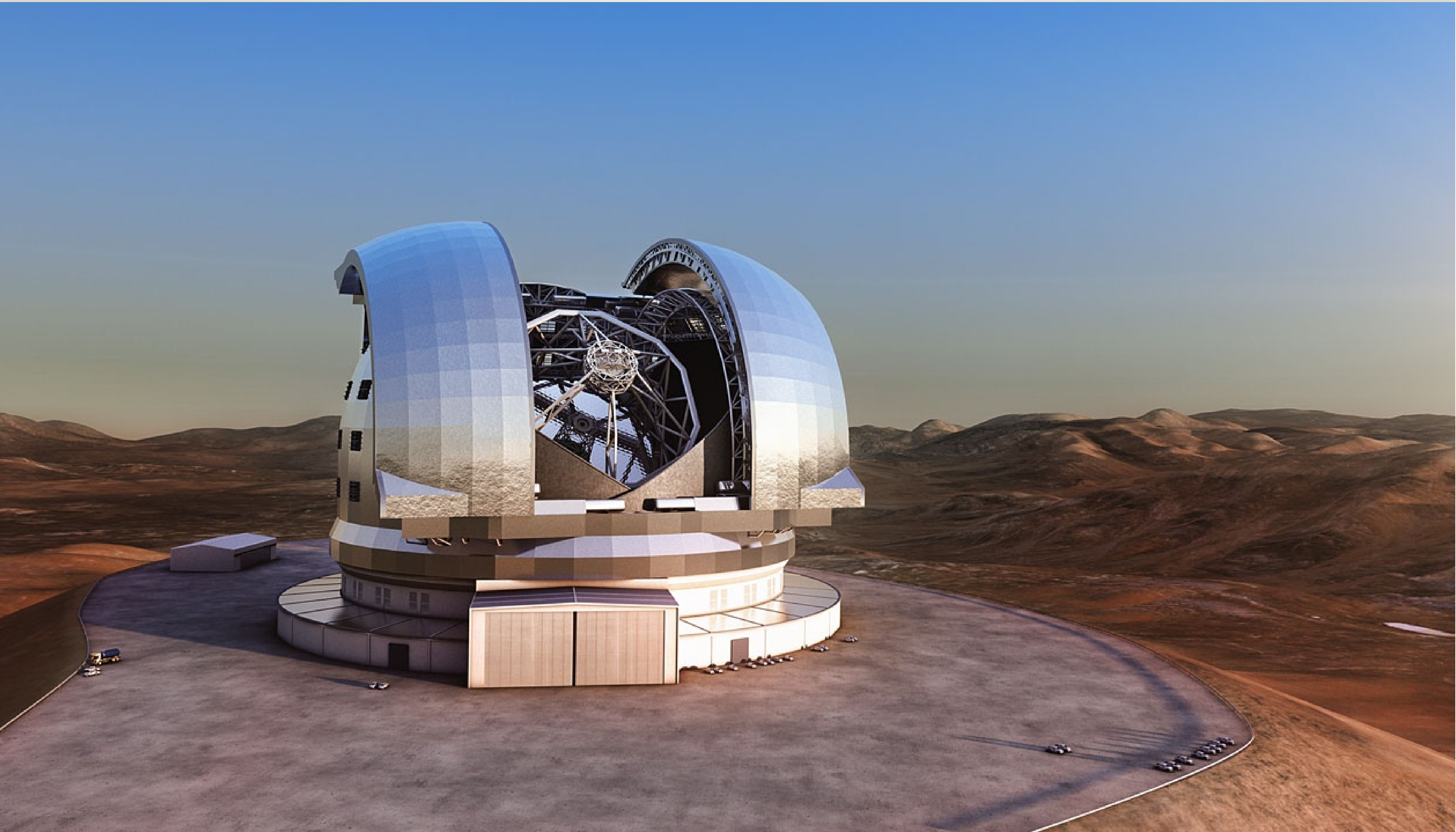


Quartin & Amendola (2009)

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

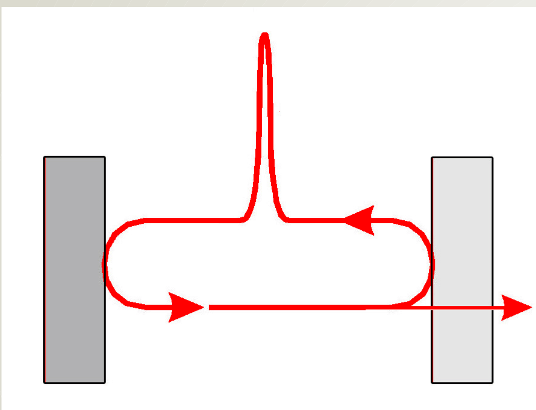
Wavelength Calibration

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)

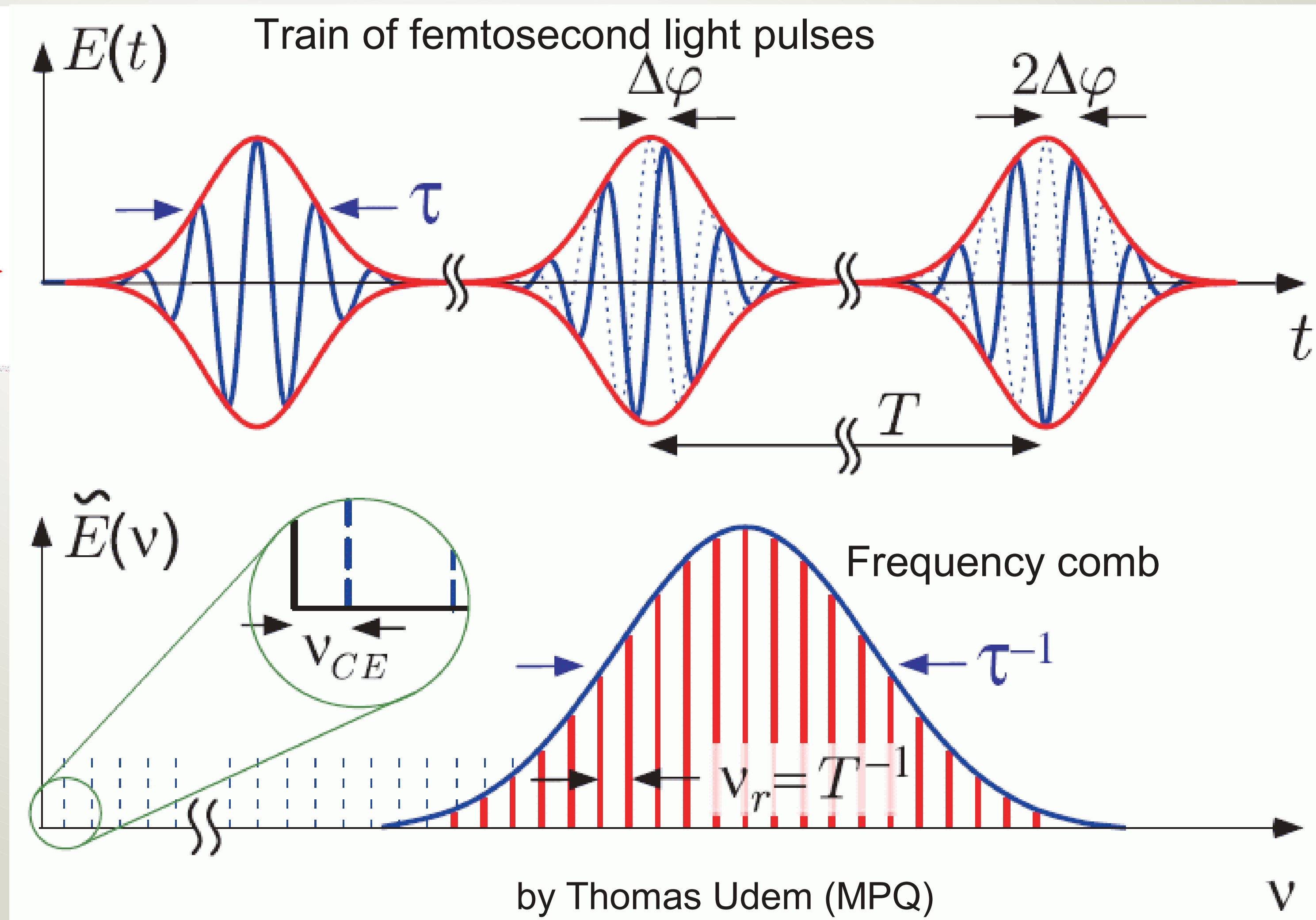
Laser Frequency Comb

- 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.

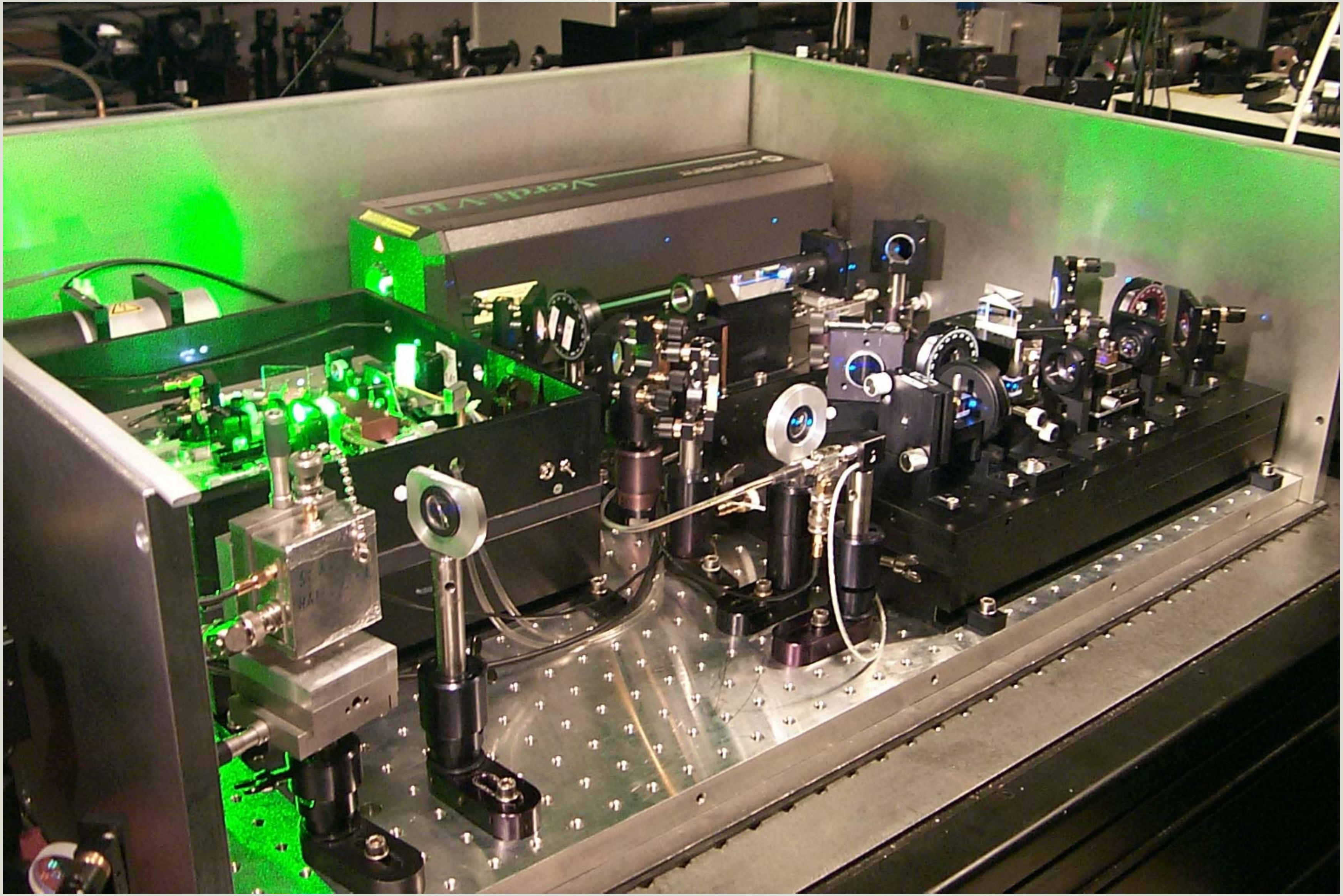


$$\nu_n = n\nu_r + \nu_{CE}$$

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



Laser Frequency Comb

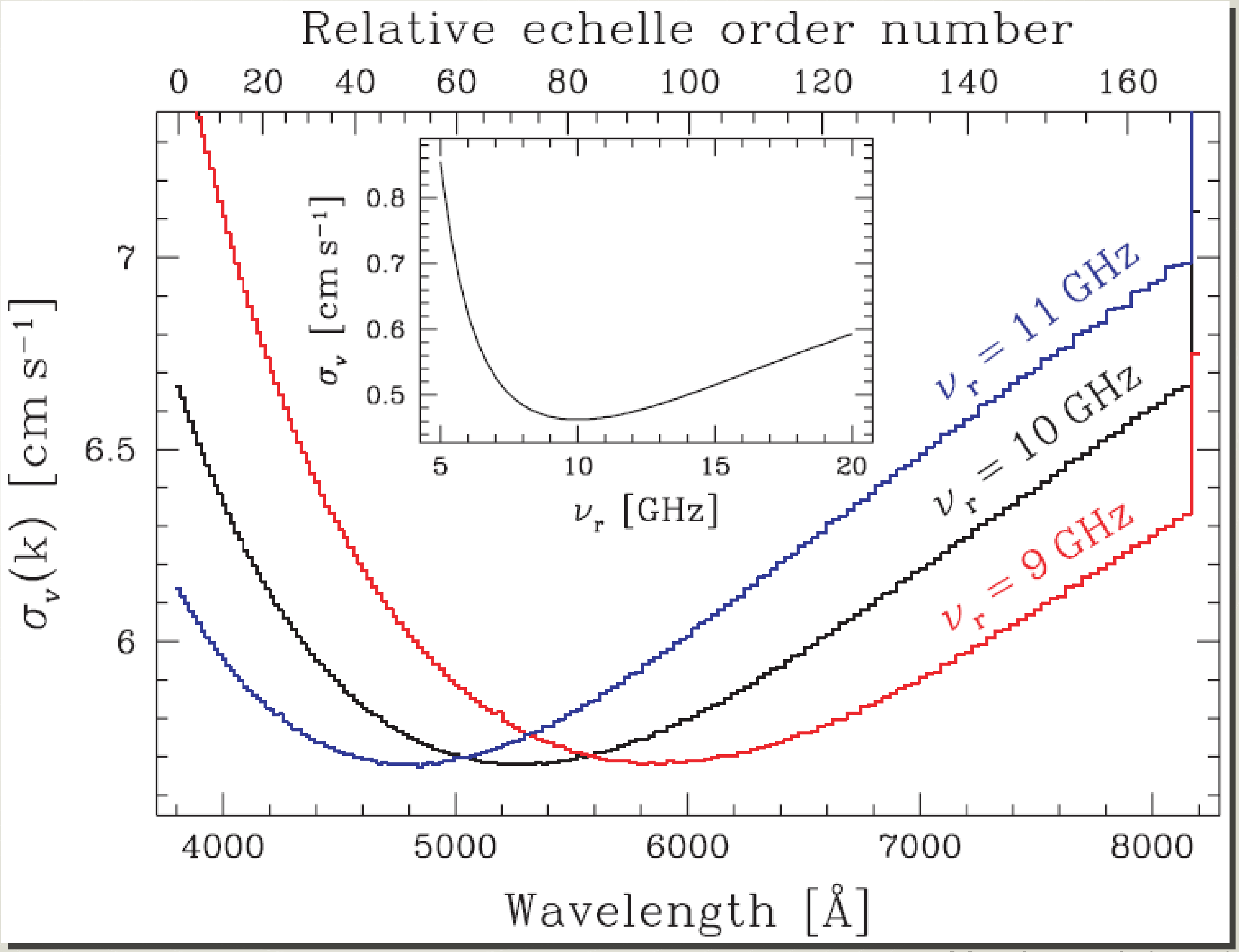


Thomas Udem (MPQ)

Simulation Results

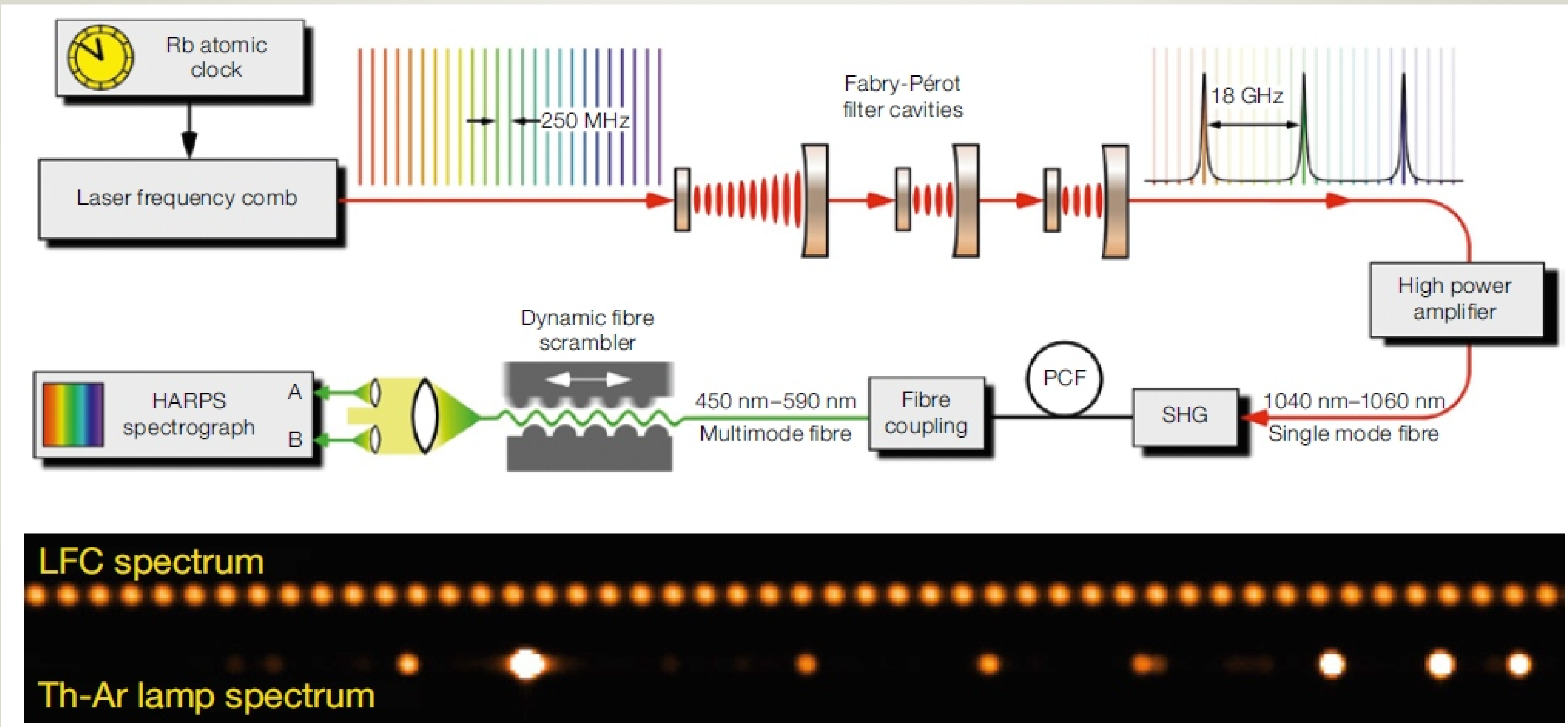
Photon-limited wavelength calibration precision is ~0.5 cm/s.

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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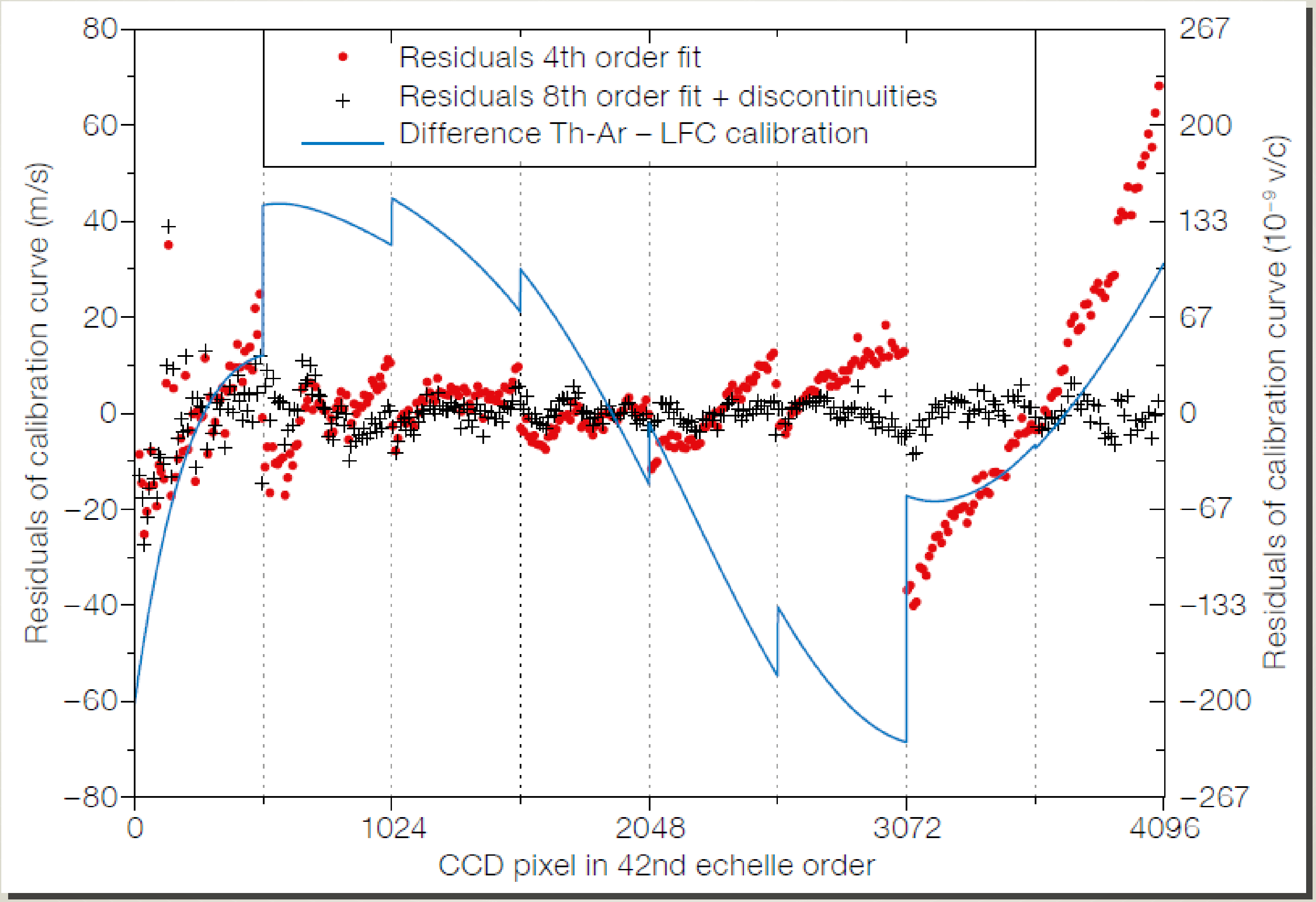
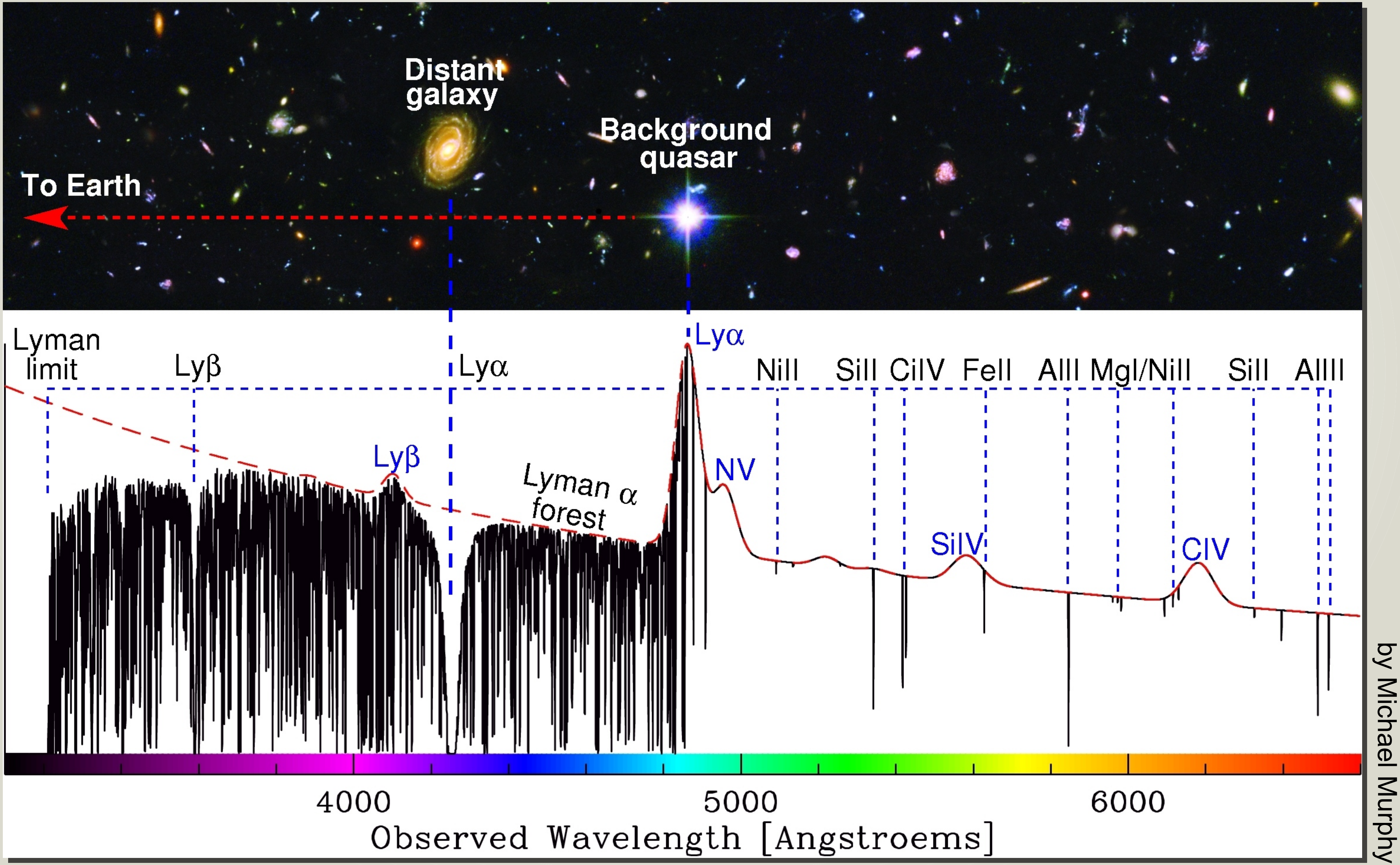


Lo Curto et al. (2012)

Fundamental Physics: Varying Constants?

- Constants like $\alpha = e^2/\hbar c$ and $\mu = m_p/m_e$ are parameters of the Standard Model and signify its incompleteness.
- Constancy based only on Earth-bound experiments on relatively short timescales. No theoretical reason at all.
- Unified theories (e.g. String/M theory):
  - Invoke extra spatial dimensions.
  - (3+1)-D constants are related to the size of the extra dimensions.
- Scalar fields:
  - Bekenstein's (1982) varying-e theory
  - Varying-c theories
  - Quintessence

Testing variability with QSO absorption lines



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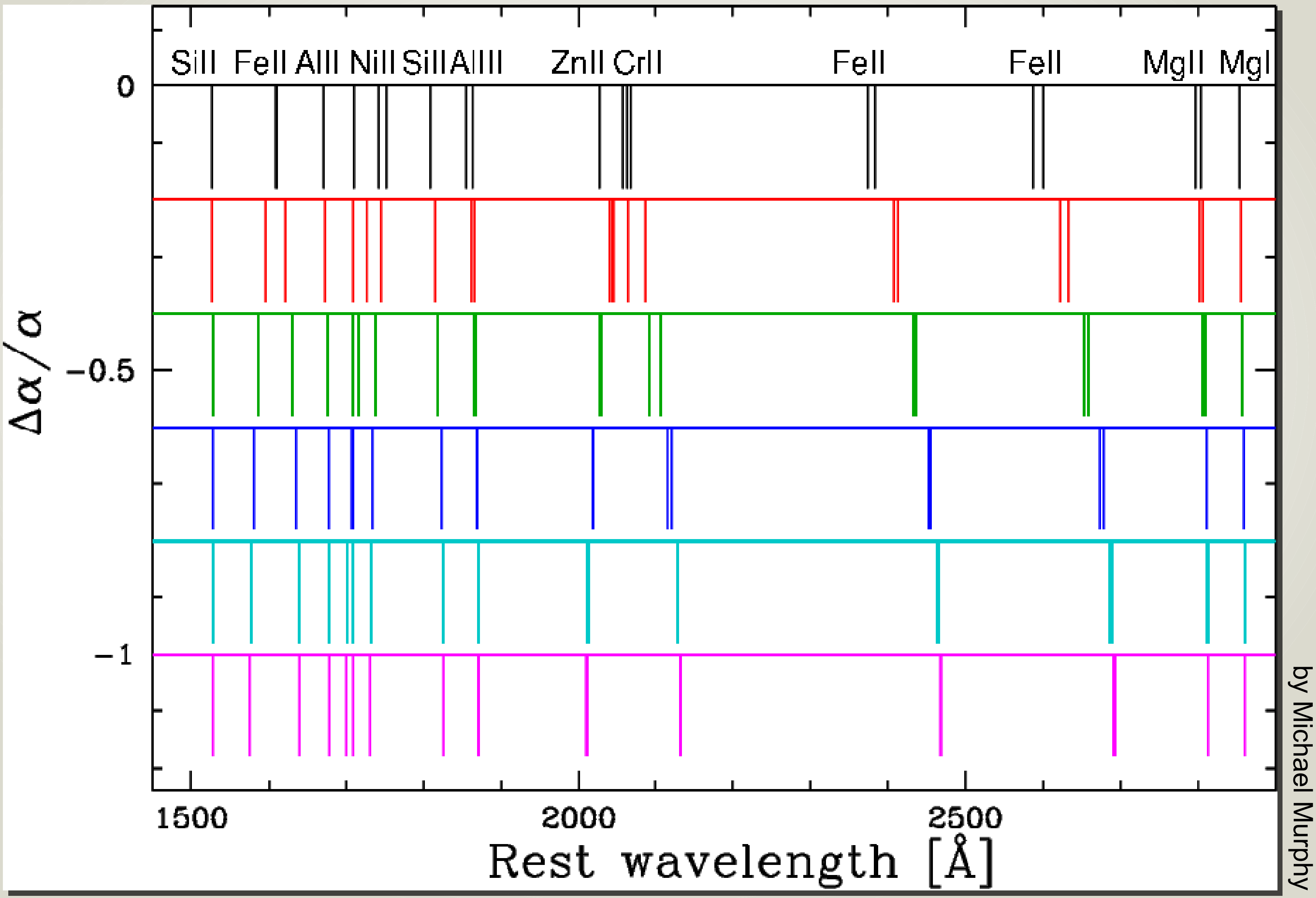

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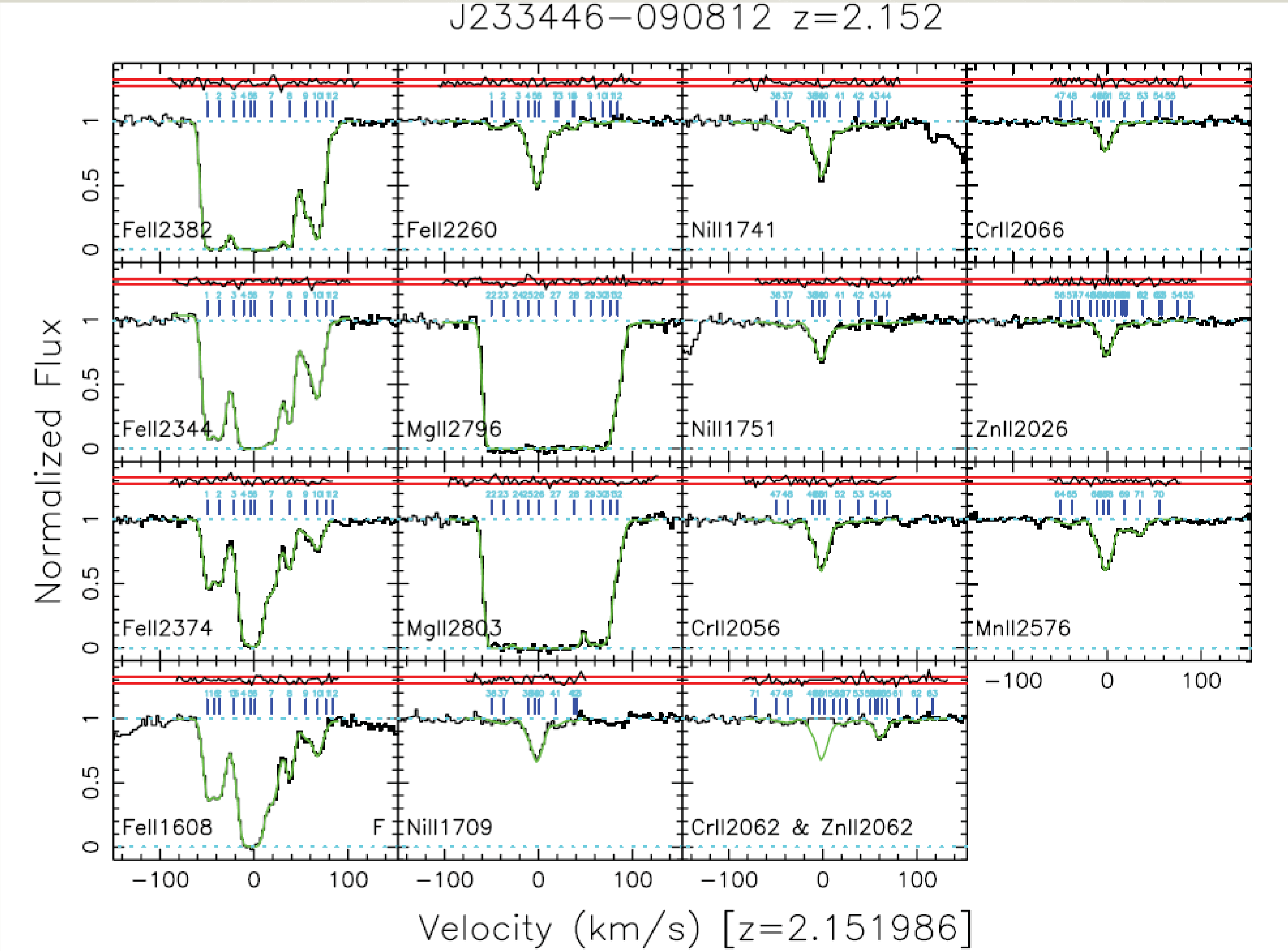
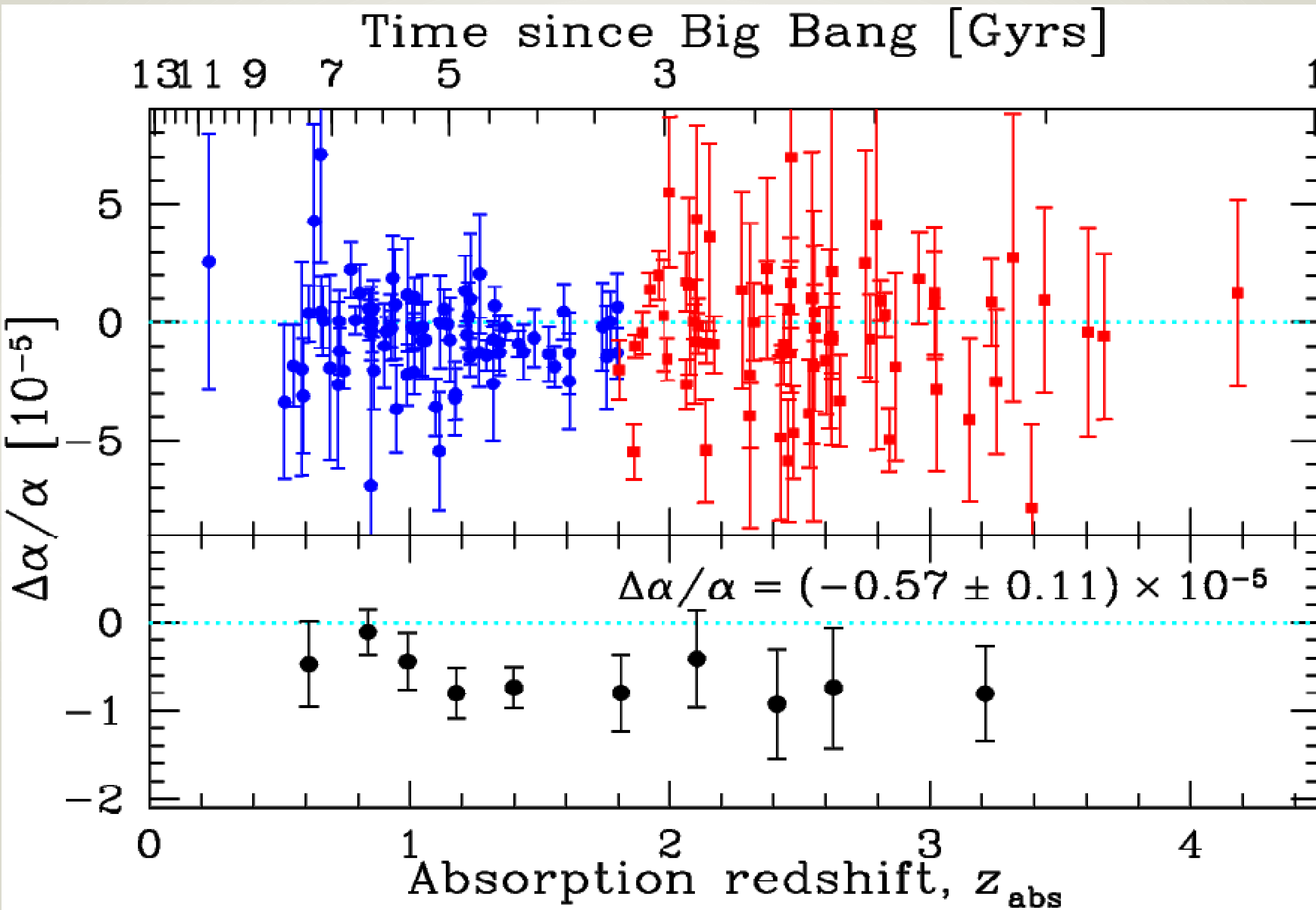


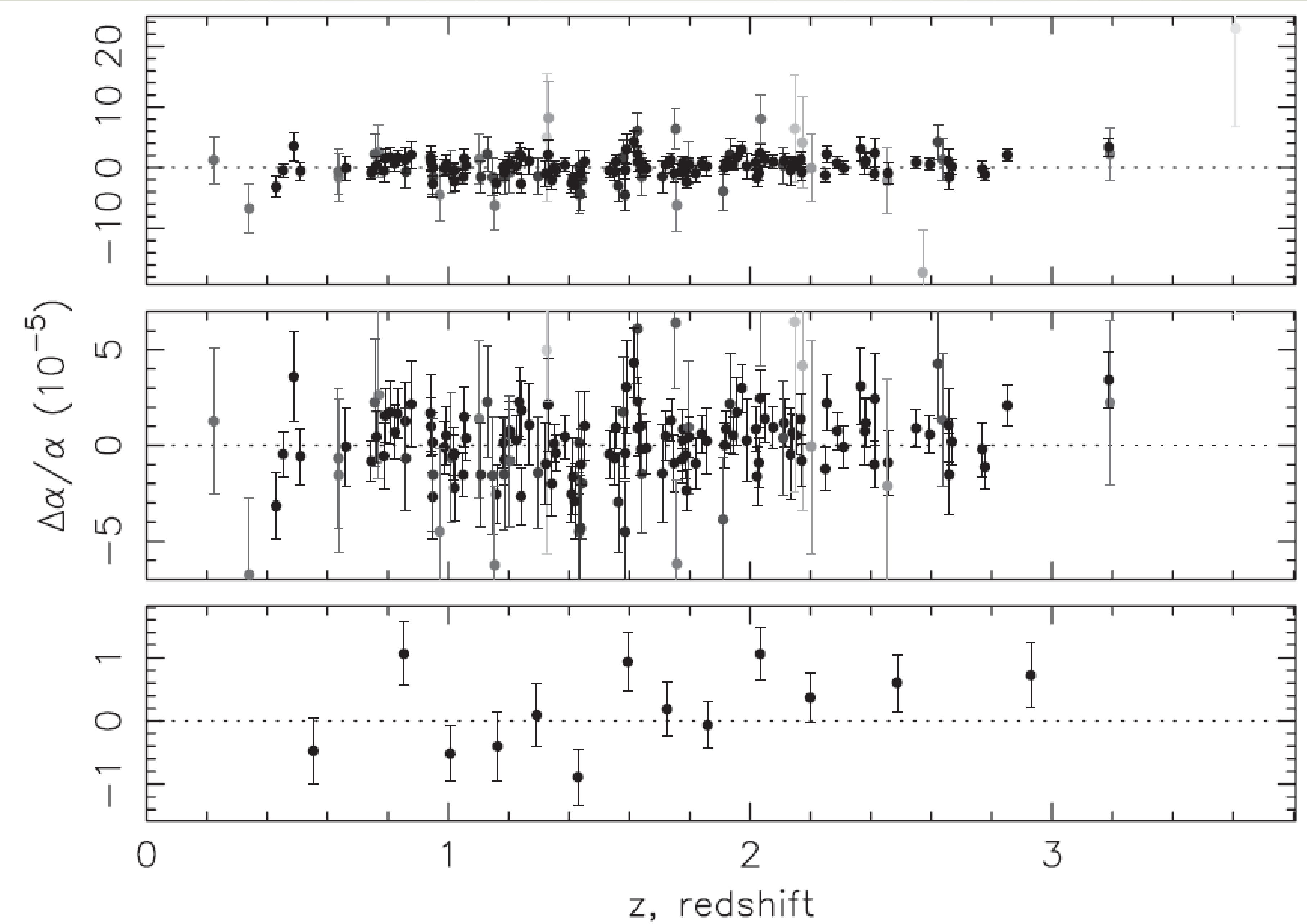
King et al. (2012)

Keck/HIRES constraints on α



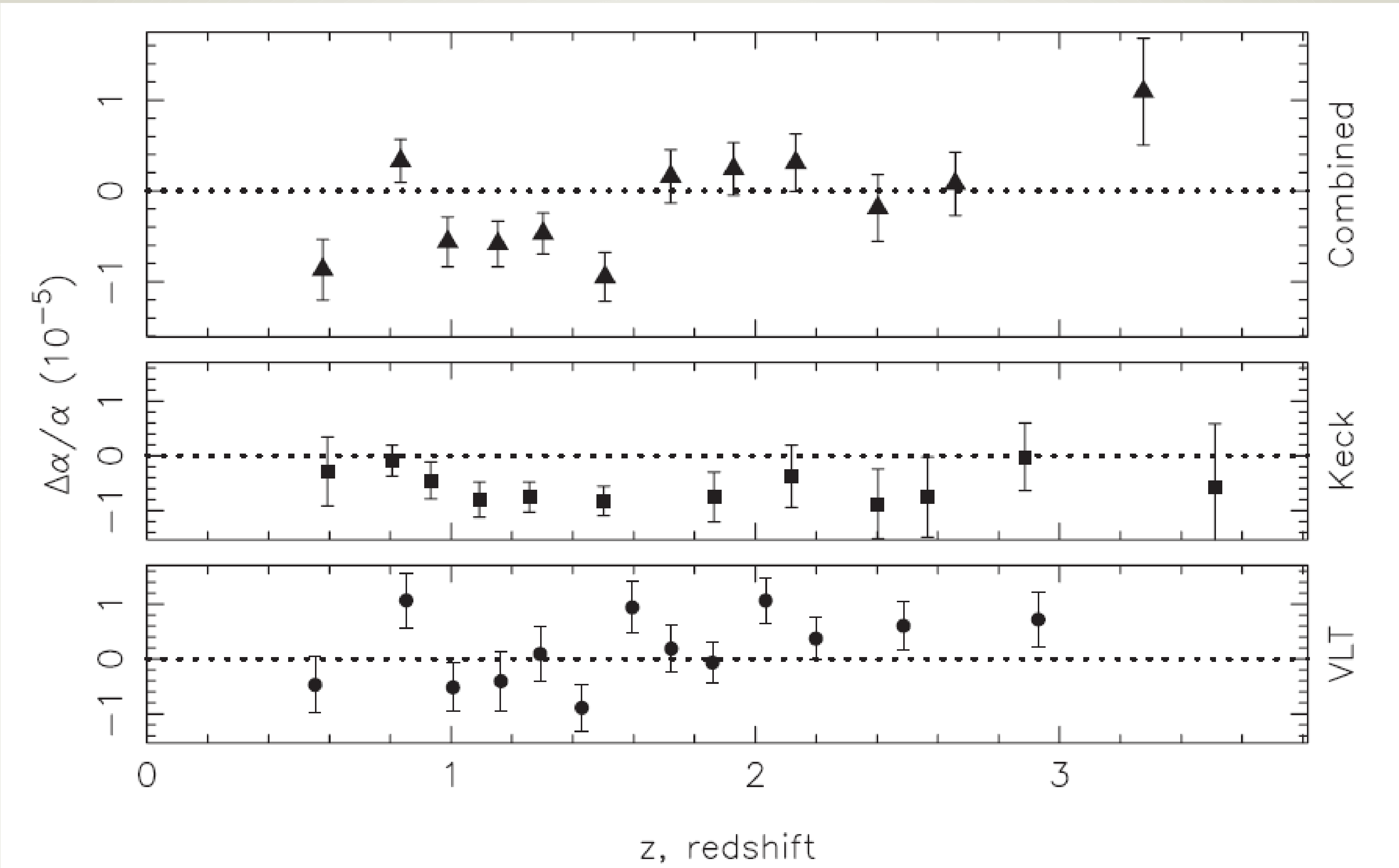
Murphy et al. (2004)

VLT/UVES constraints on α



King et al. (2012)

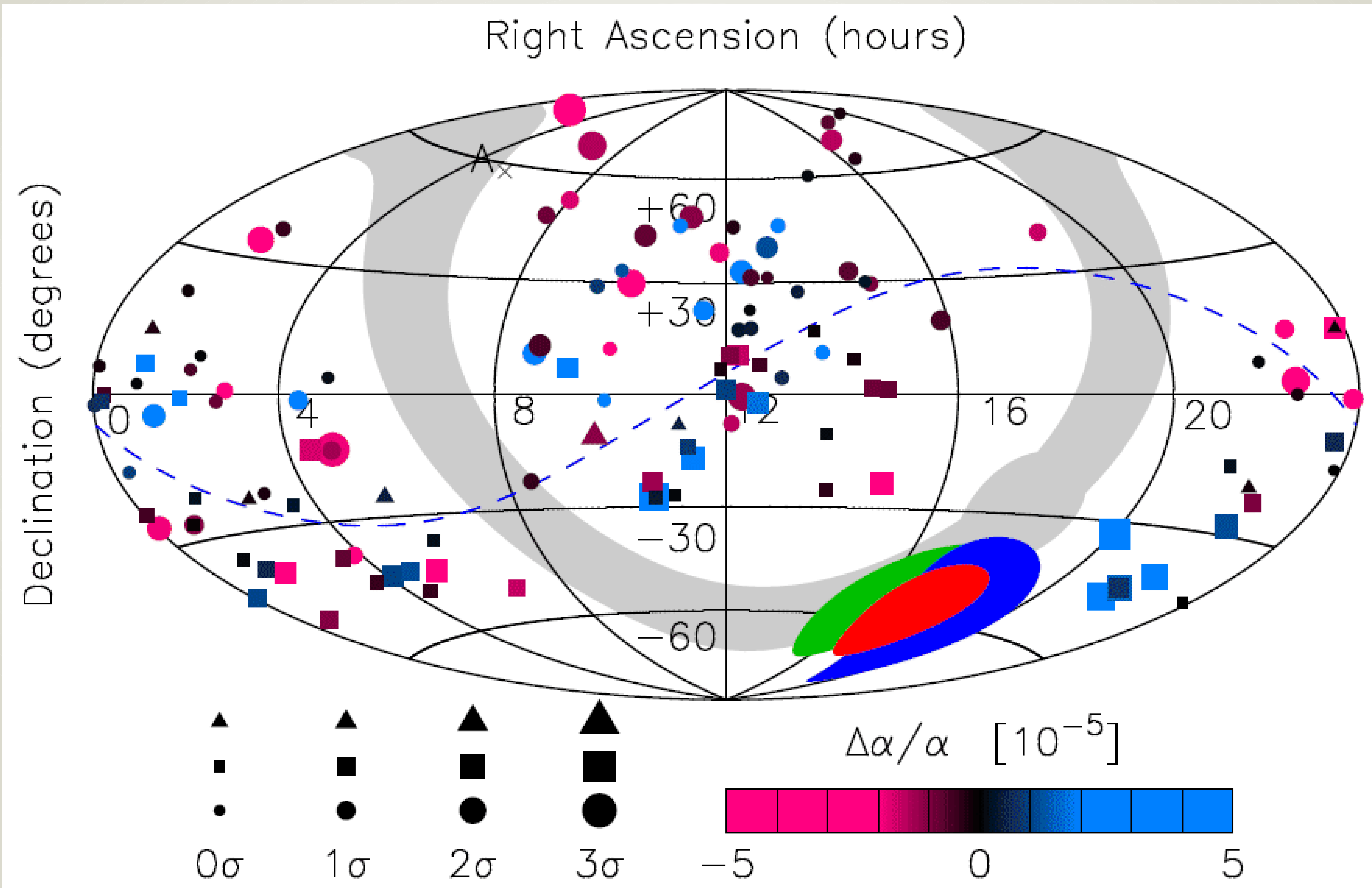
The Combined Sample



King et al. (2012)

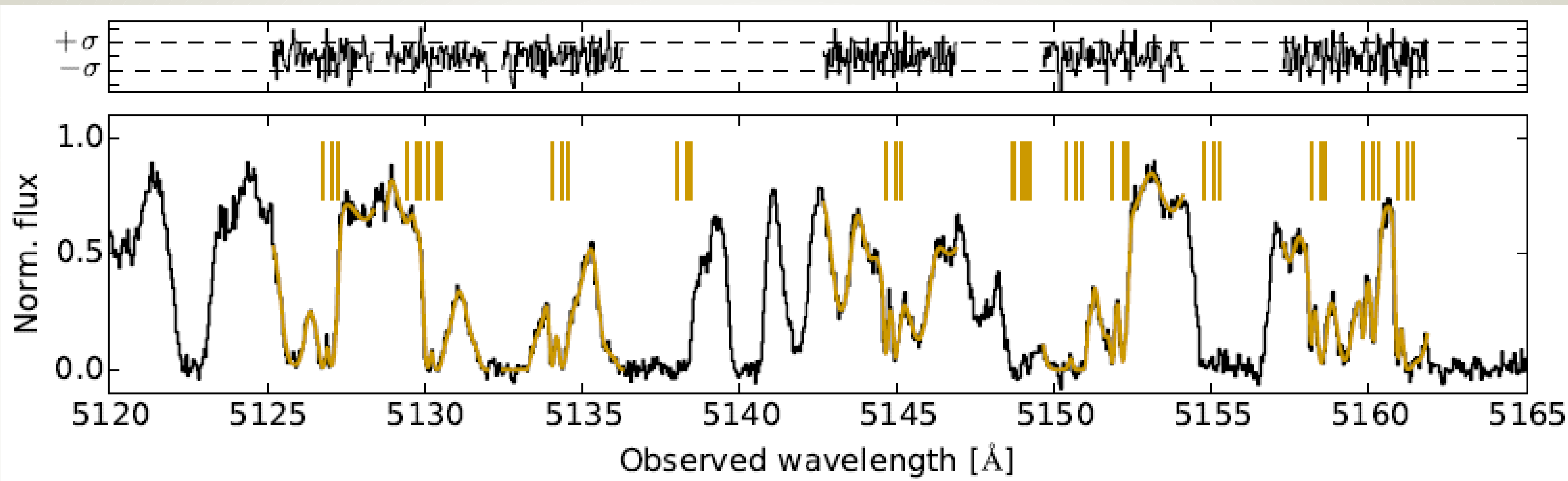
Combined constraints from Keck and VLT

Evidence for a dipole in $\Delta\alpha/\alpha$?



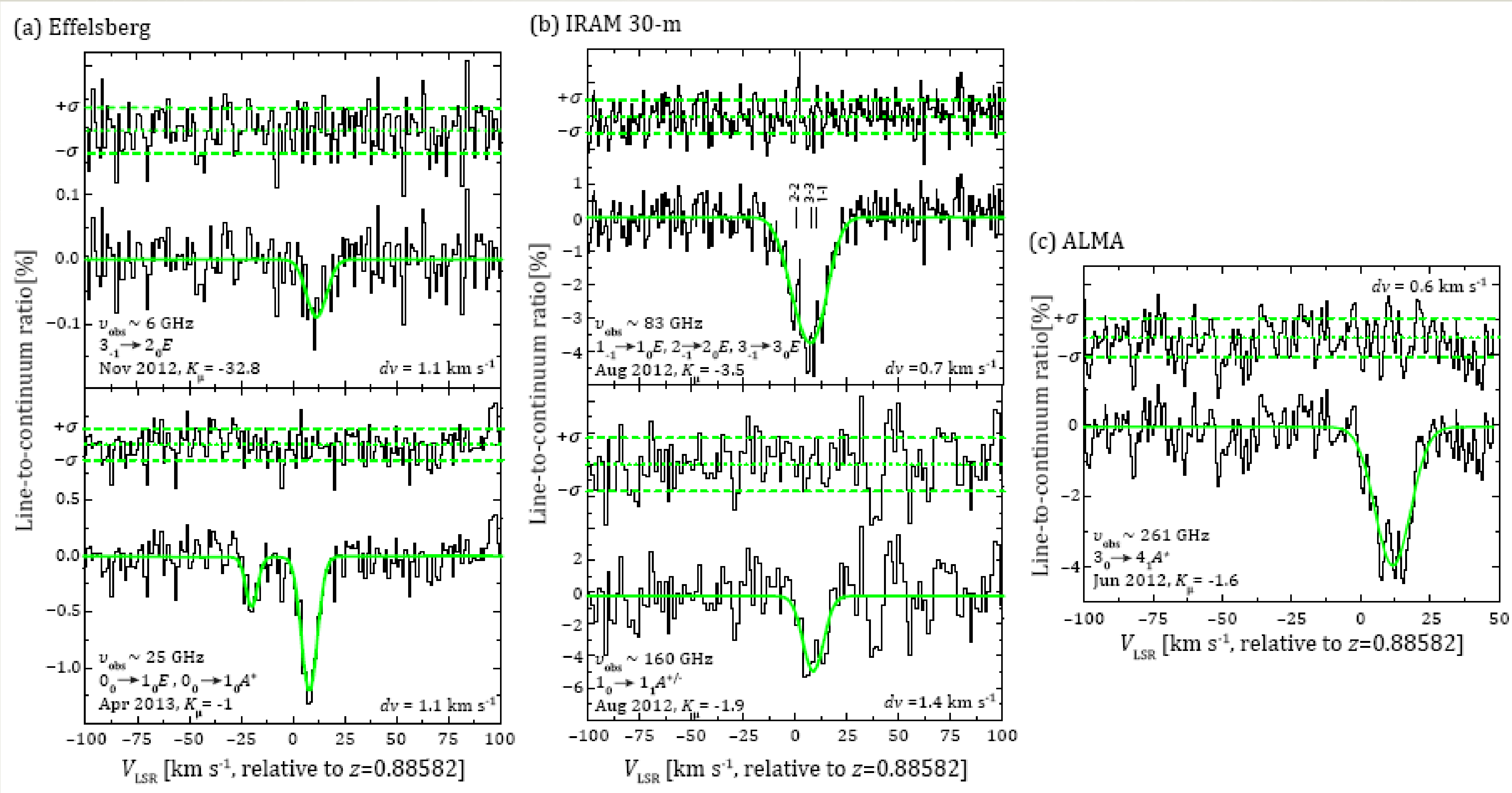
King et al. (2012)

VLT/UVES constraints on μ from H_2



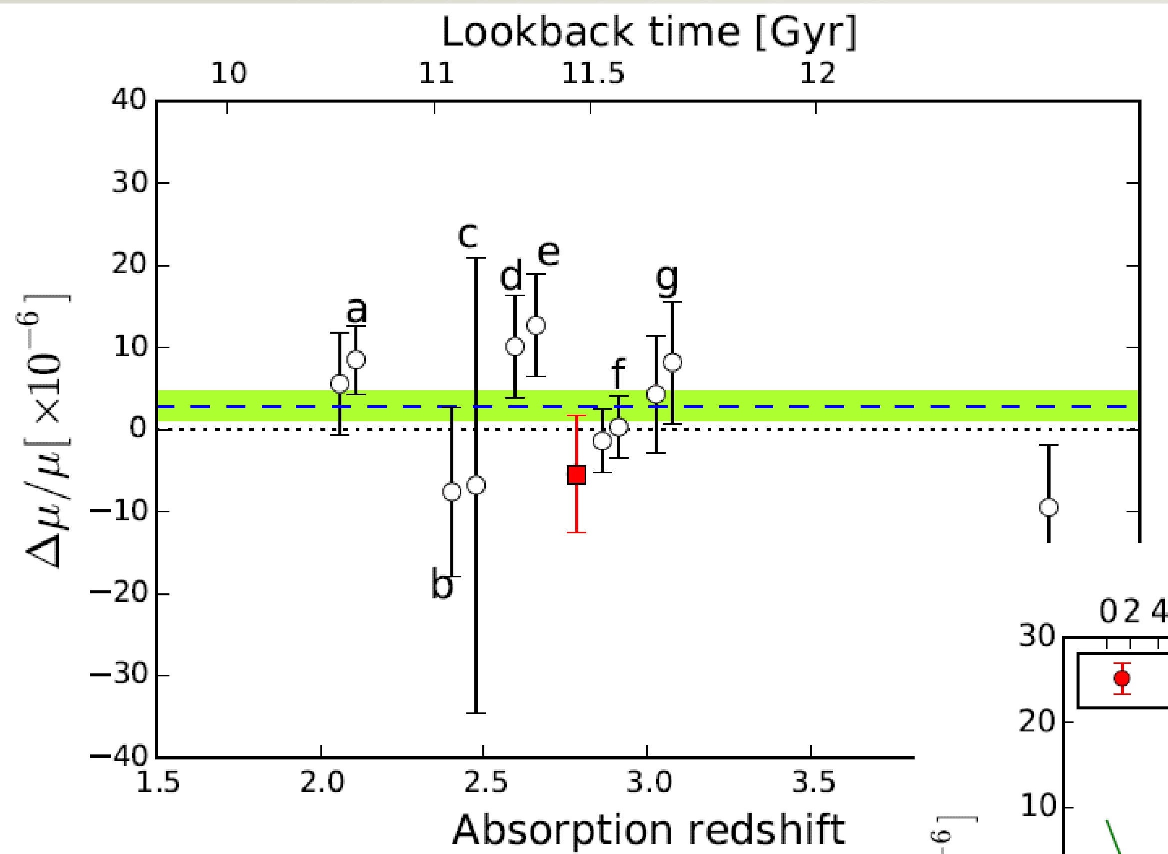
Bagdonaite et al. (2015)

Radio constraints on μ from CH_3OH



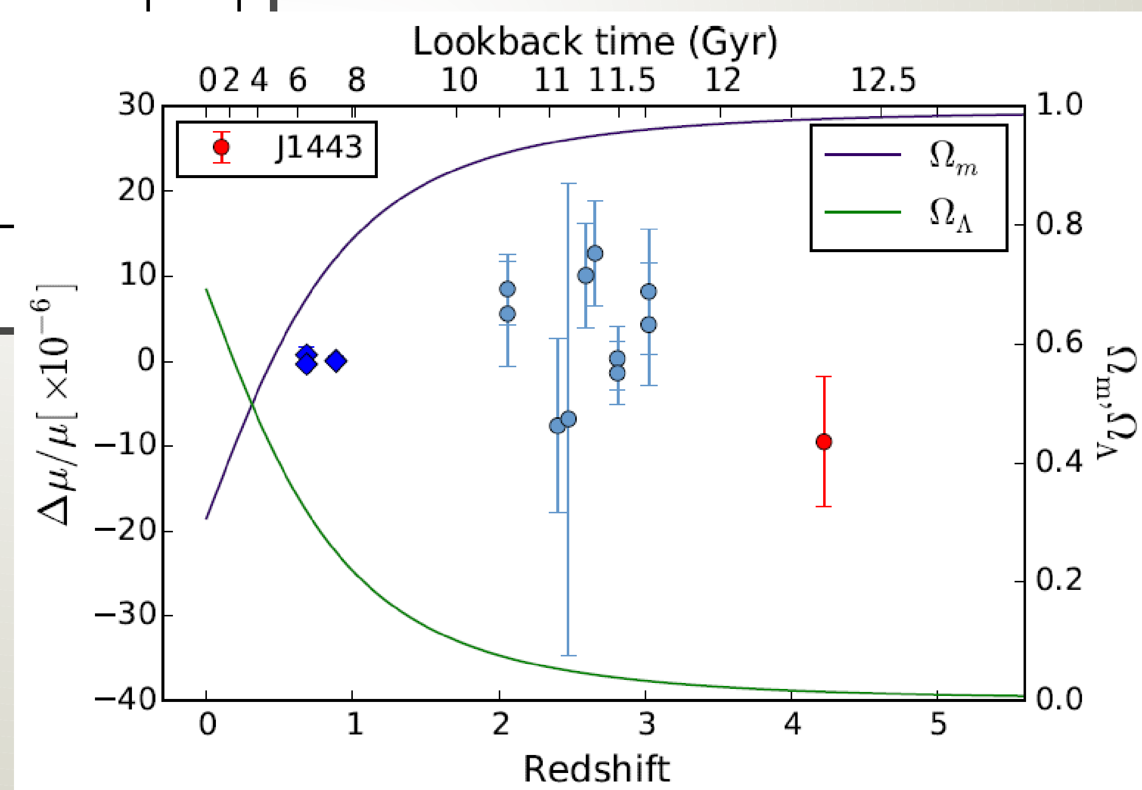
Bagdonaite et al. (2014)

Constraints on μ



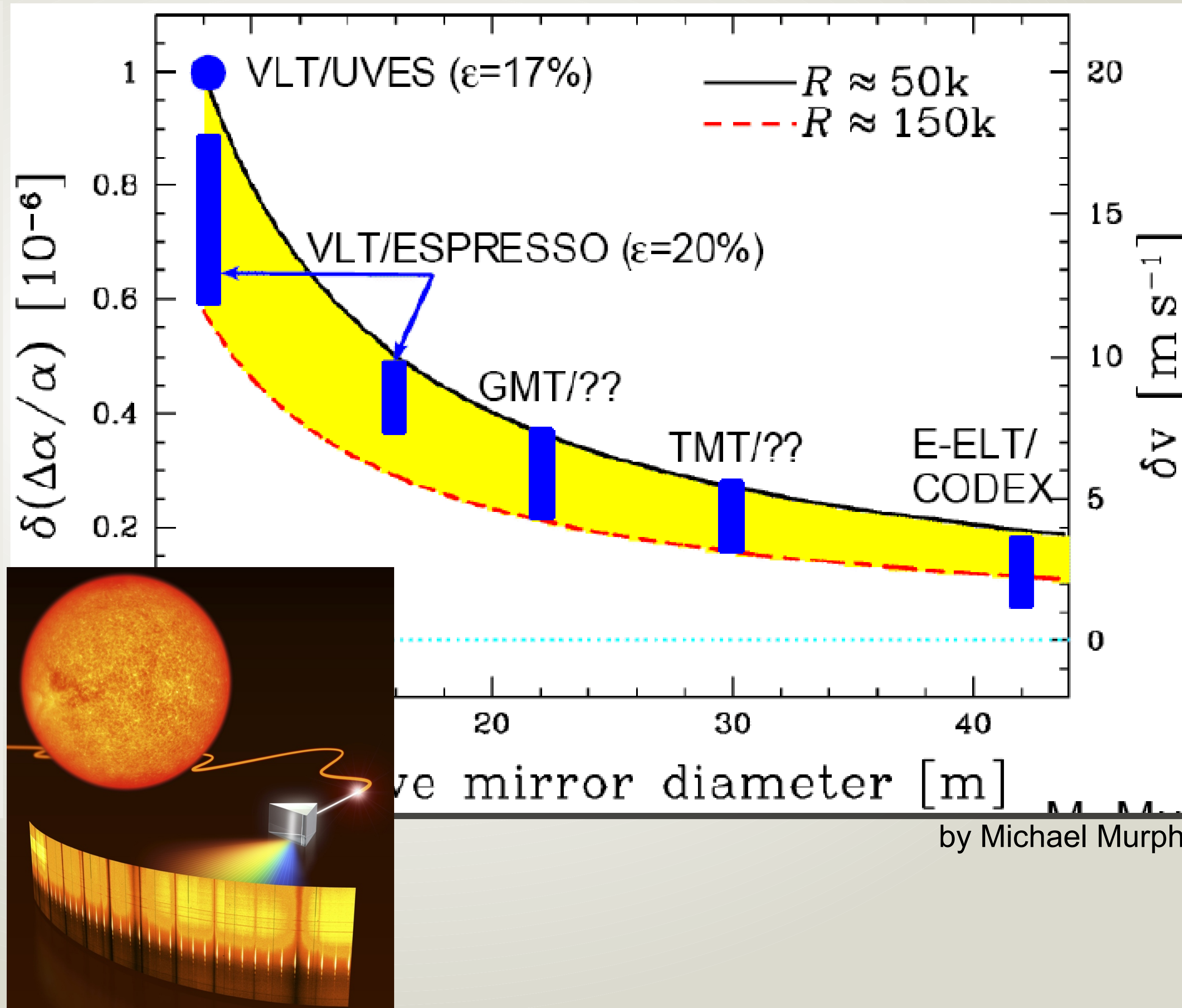
Dapra et al. (2015)

Bagdonaite et al. (2015)



What the E-ELT will bring

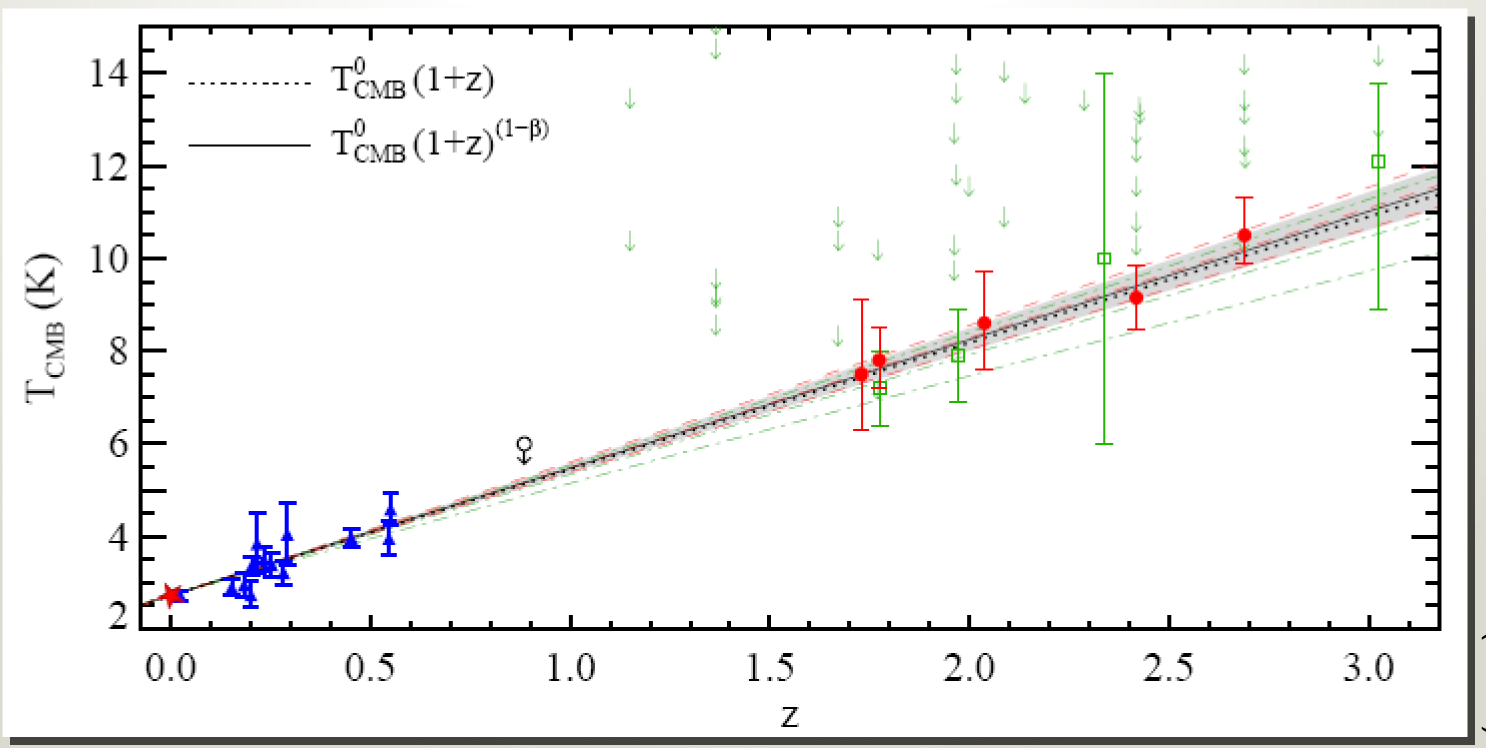
- Higher S/N and higher resolution to remove profile fitting uncertainties.
- Simultaneous calibration with frequency comb to remove calibration uncertainties.
- Order of magnitude increase in precision in $\Delta\alpha/\alpha$.



by Michael Murphy

T_{CMB}

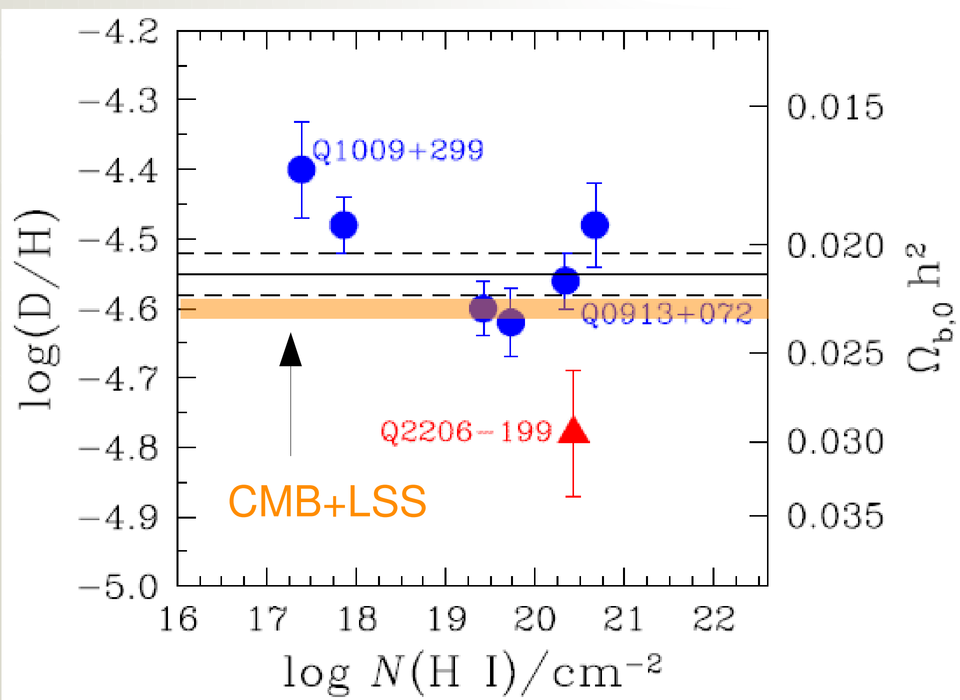
- In the present Universe we measure T_{CMB} = 2.7260 ± 0.0013 K
- Adiabatic expansion of the Universe: $T_{CMB} \propto 1 + z$
- If this relation does not hold then either the equivalence principle is violated or the number of CMB photons is not conserved.
- CMB populates rotational levels in molecules and fine-structure levels in atomic species such as CI.



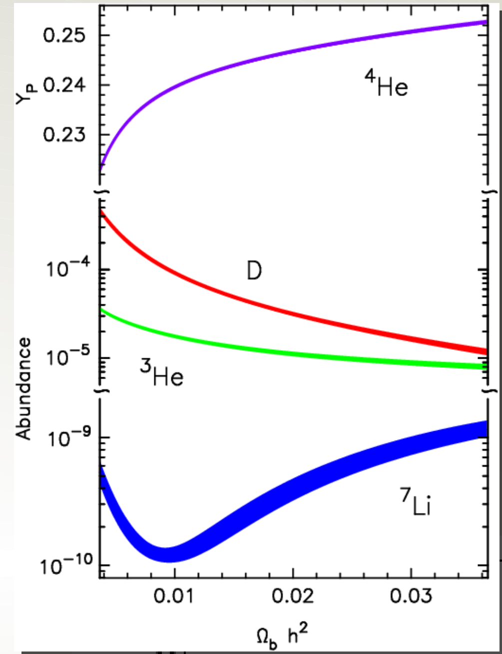
Noterdaeme et al. (2011)

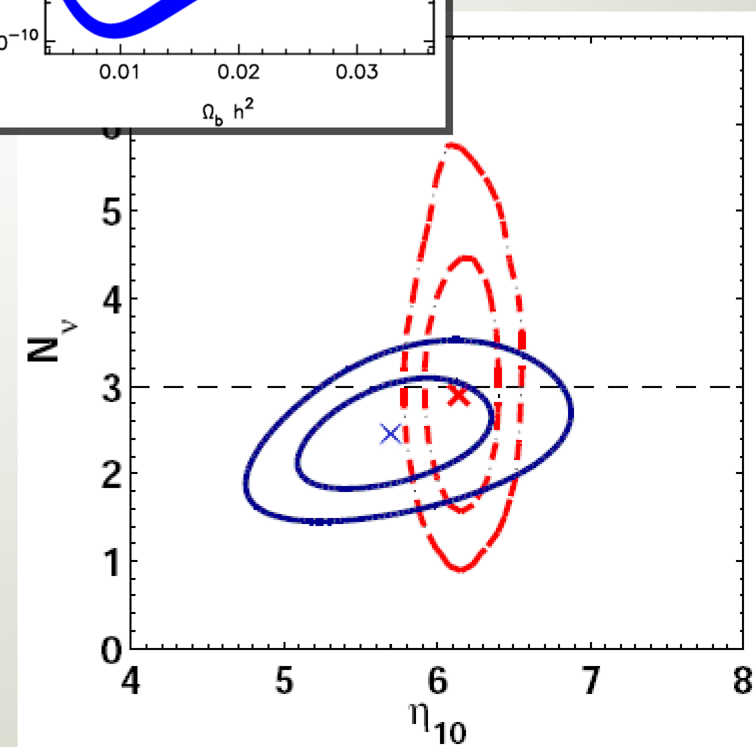
Big Bang Nucleosynthesis

- BBN and Ω_b
  - D/H in QSO absorbers
  - ^{7}Li and 'internal' consistency
  - Comparison with CMB and BAO
  - Non-standard BBN



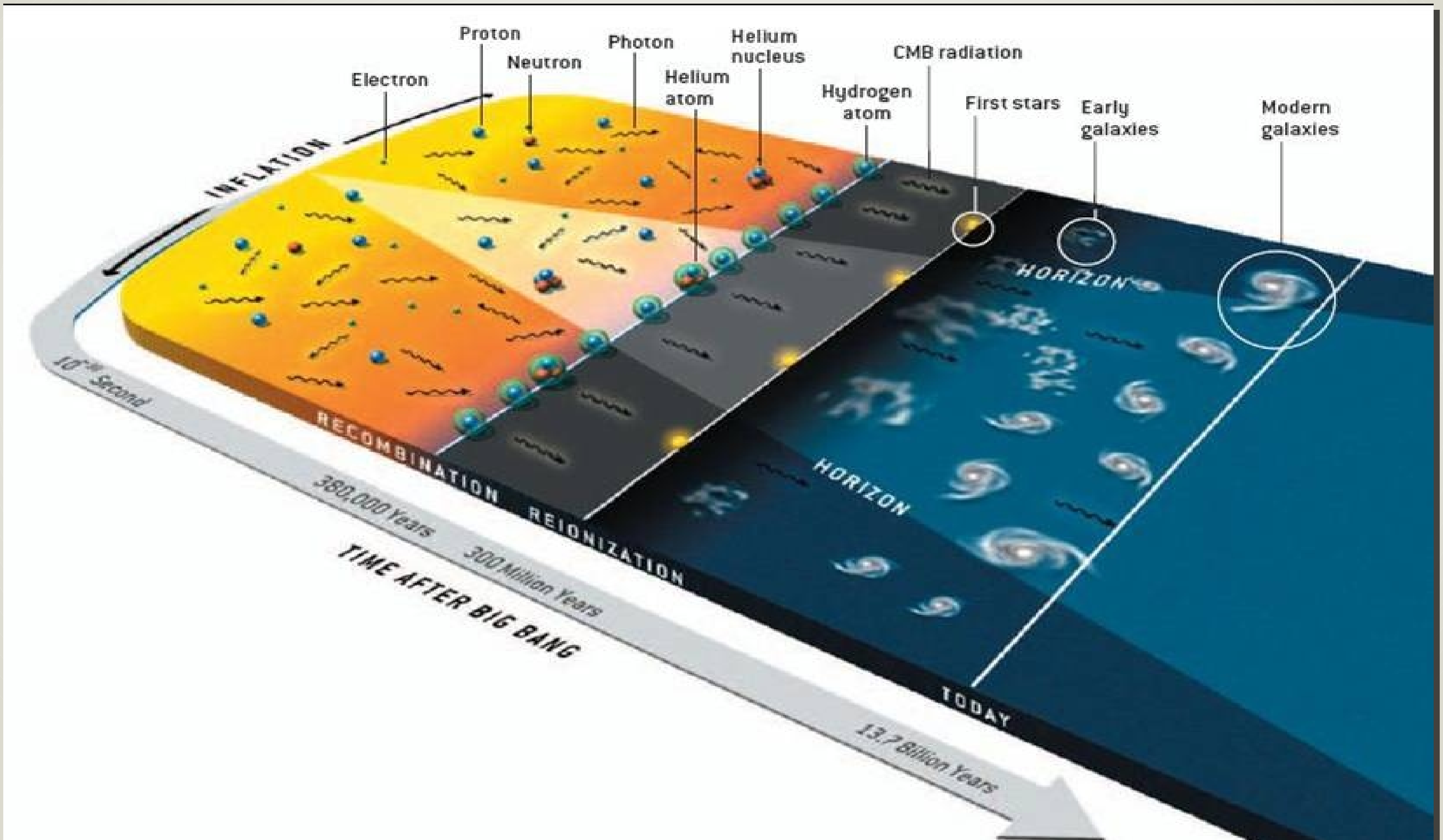
Pettini et al. (2008)





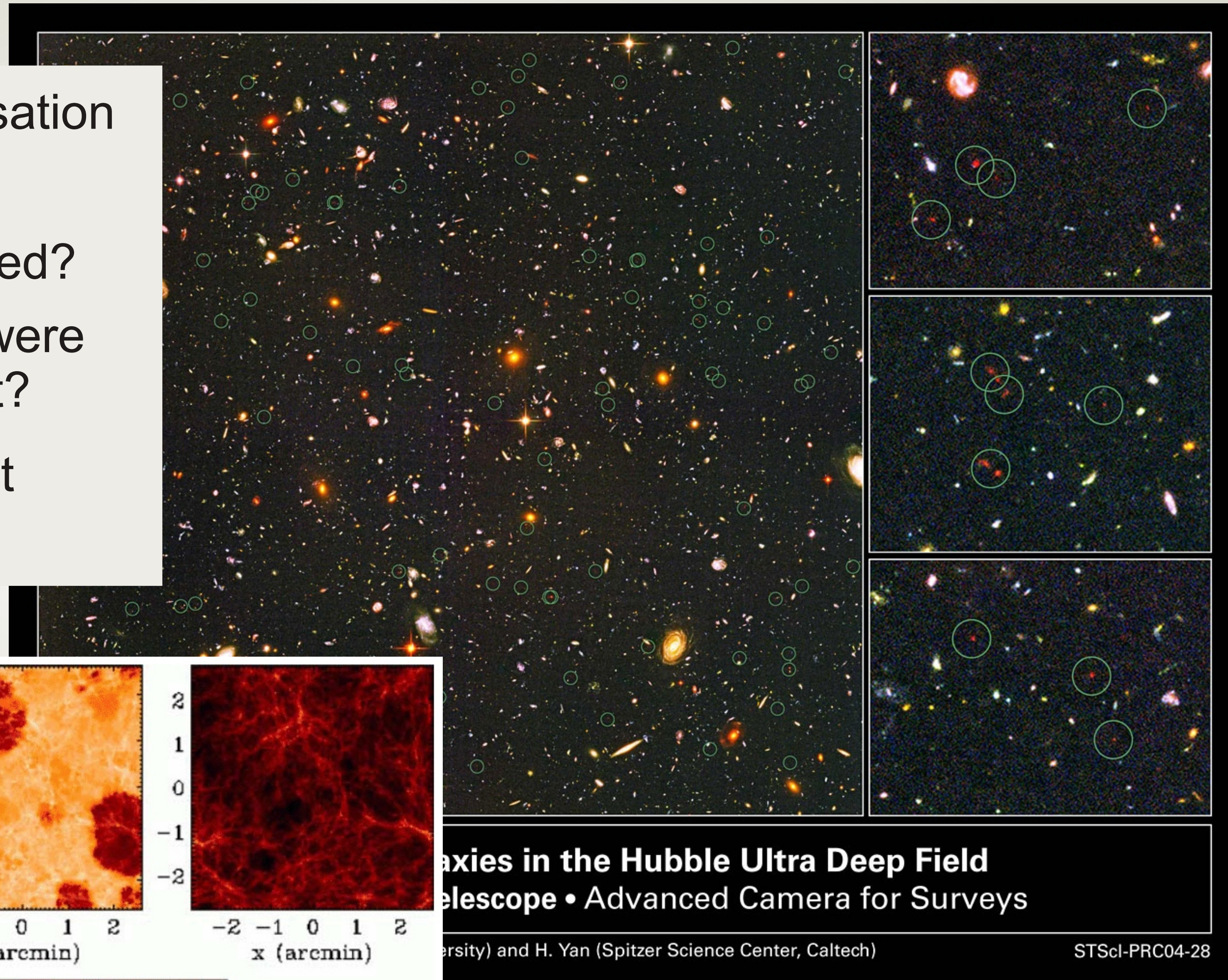
Simha & Steigman (2008)

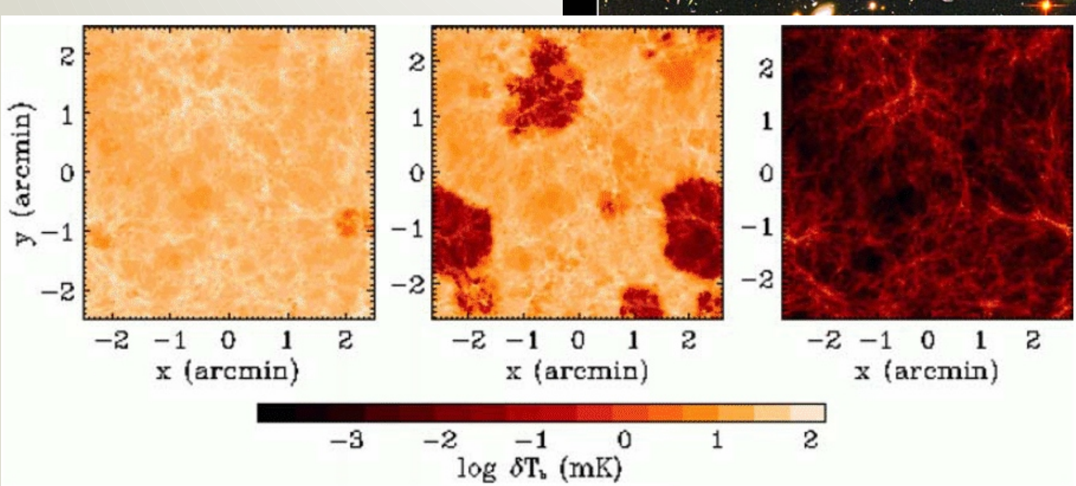
The End of the Dark Ages and the First Galaxies



The End of the Dark Ages and the First Galaxies

- When did reionisation happen?
- How did it proceed?
- Which sources were responsible for it?
- Properties of first galaxies?





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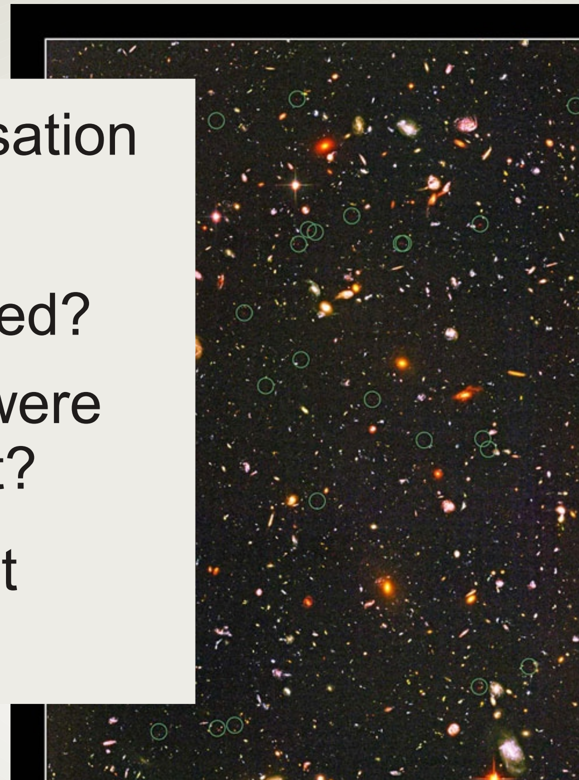
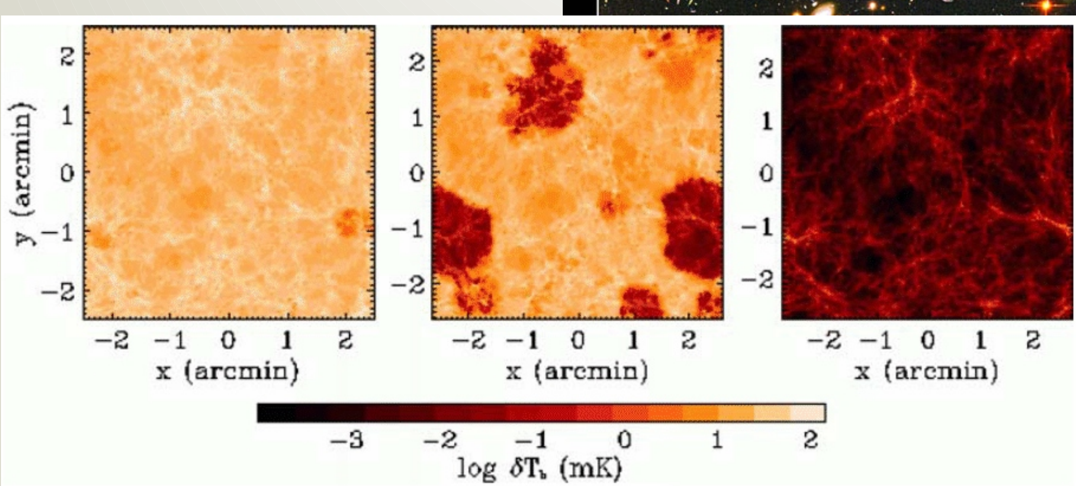
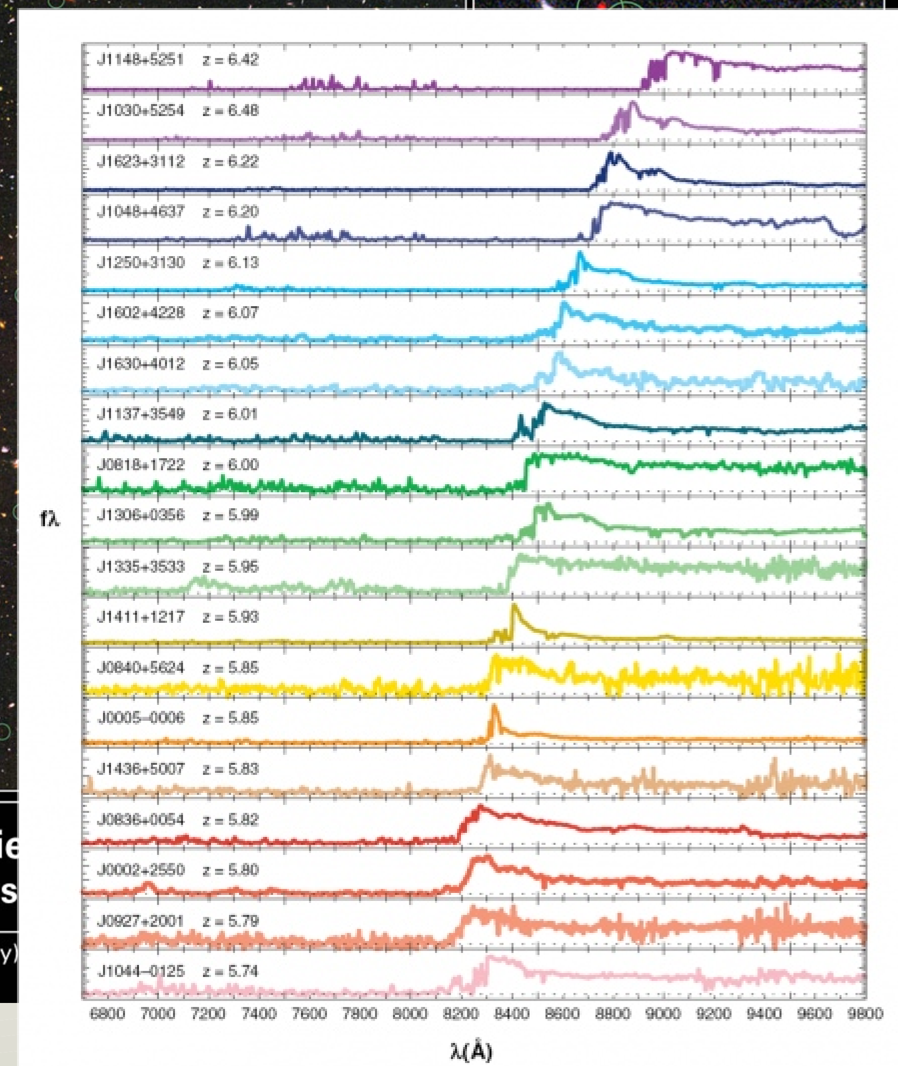
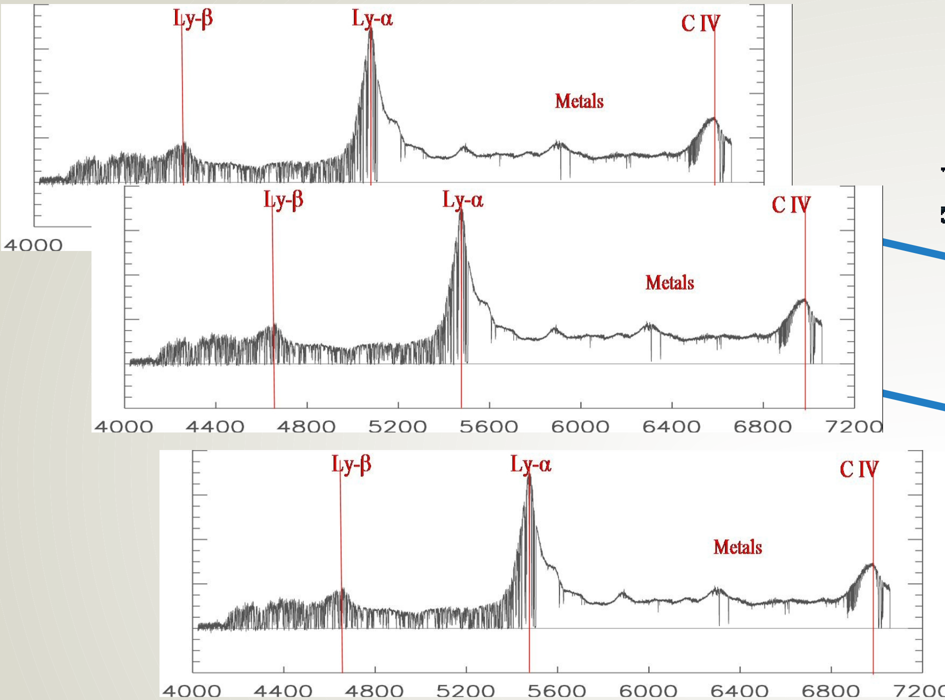
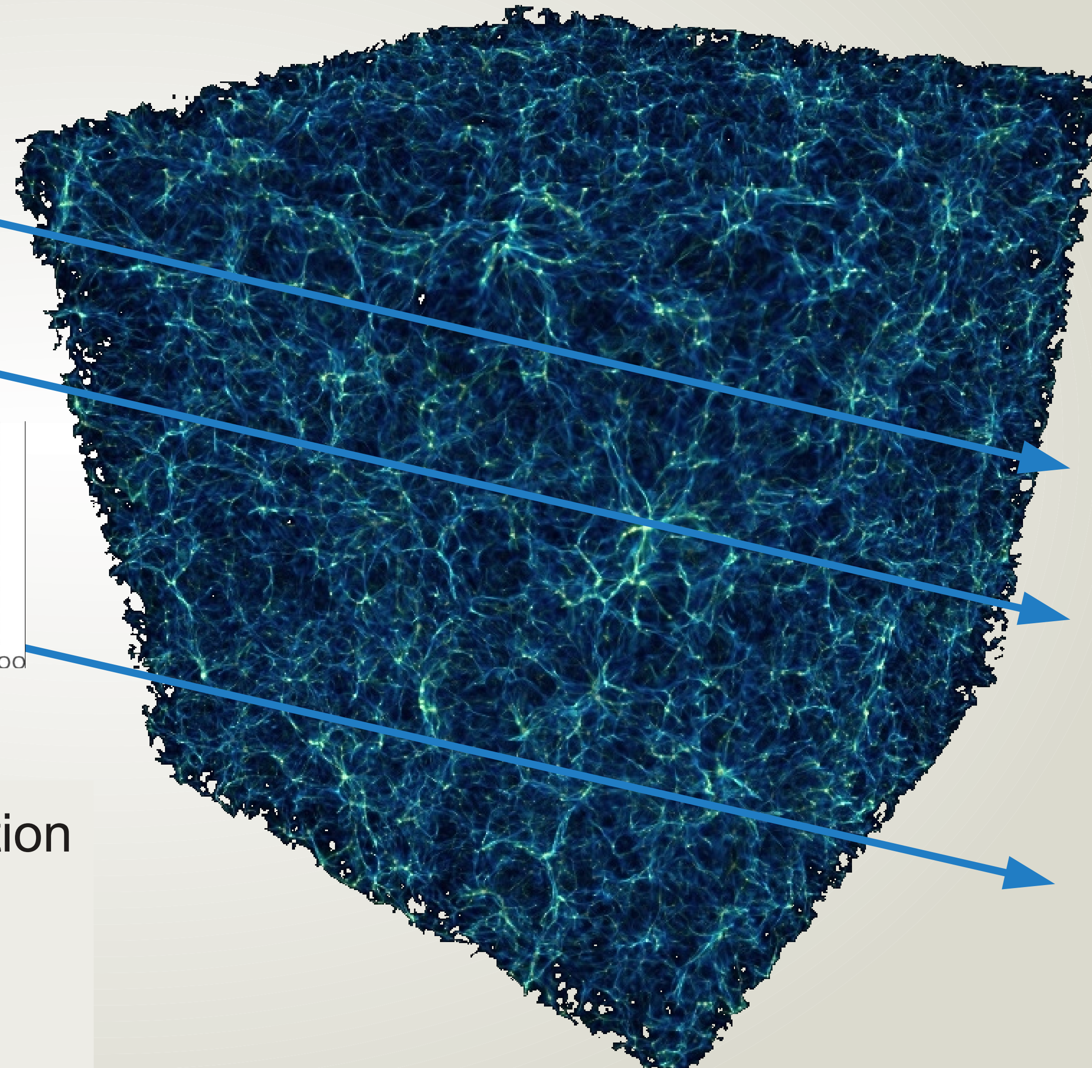






Intergalactic Medium

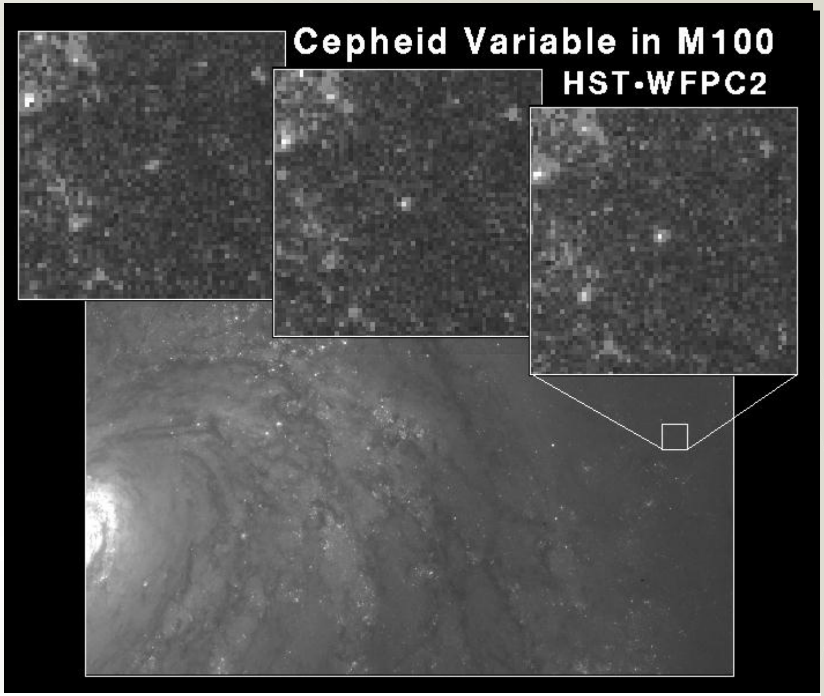


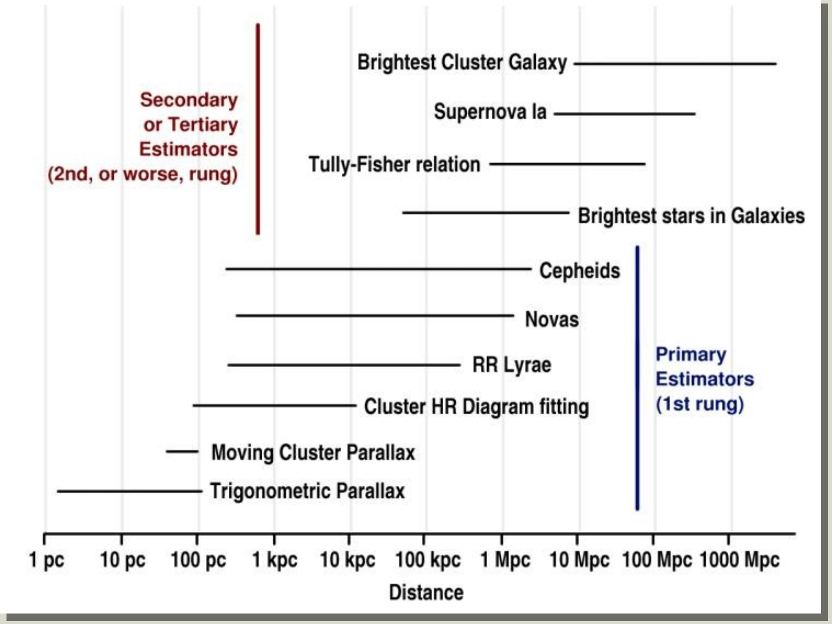


- Probing high-z galaxies in absorption
- Feedback
- IGM enrichment
- 3D tomography

Other distance / expansion indicators

- Extend HST's work: Cepheids, RR Lyrae, tip of the RGB in other galaxies.





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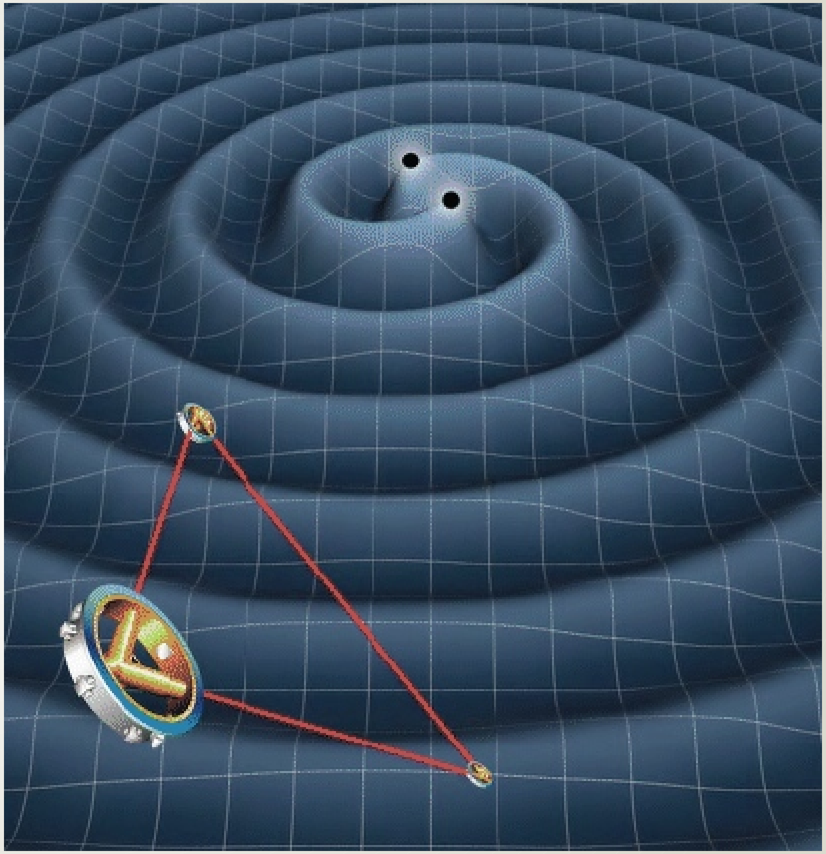
- E-ELT follow-up spectroscopy of SKA detections of massive binary black hole inspiral events: Given a redshift, measurements of the gravitational waveform provide D_L to 0.1-3% precision. Uncertainty: number and redshift distribution of useful events.



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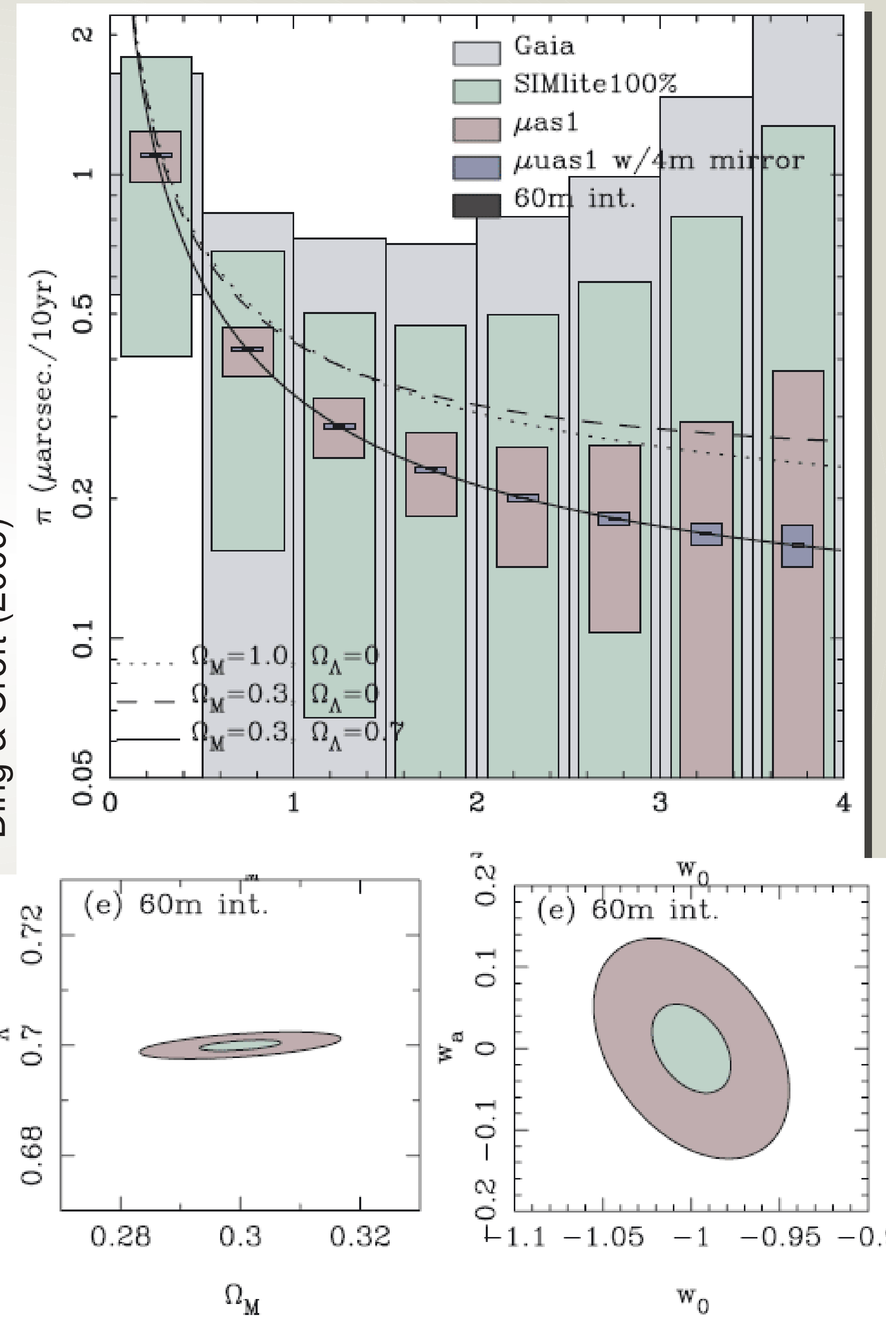
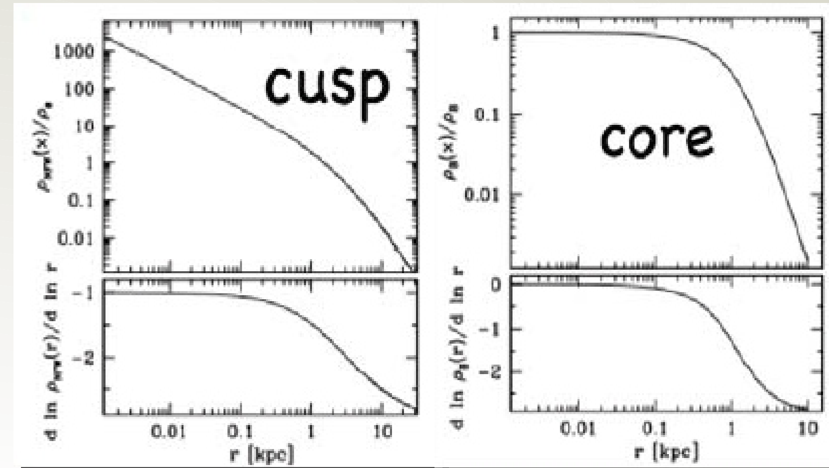
- Cosmological parallax? Over a decade the Earth's movement wrt the CMB produces a baseline of 3.8 mpc.

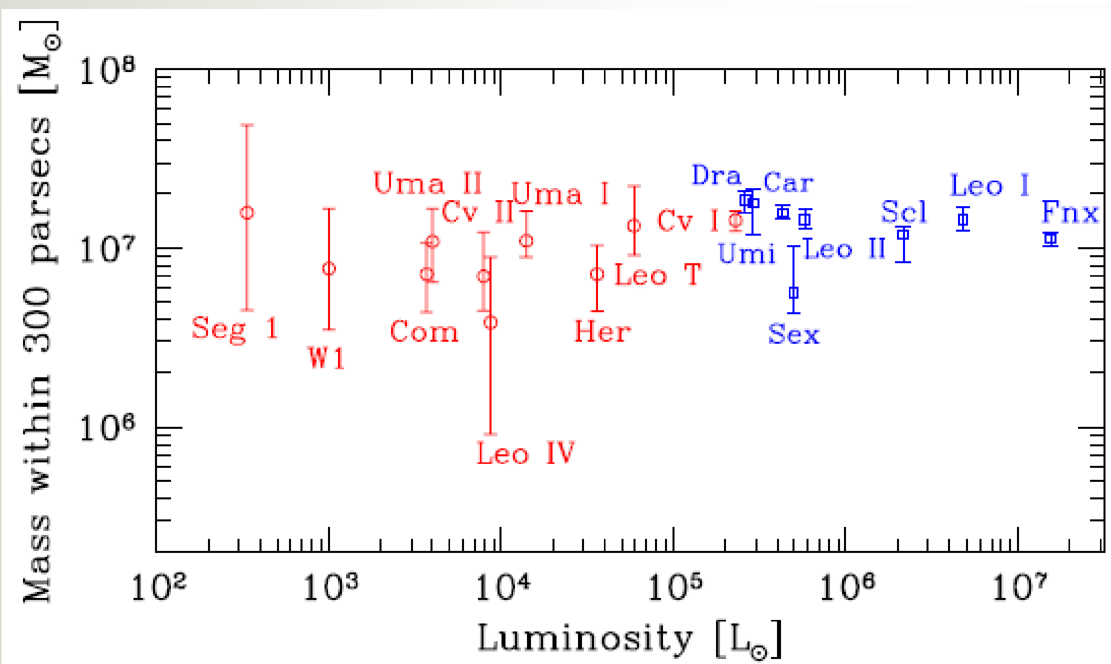


Ding & Croft (2009)

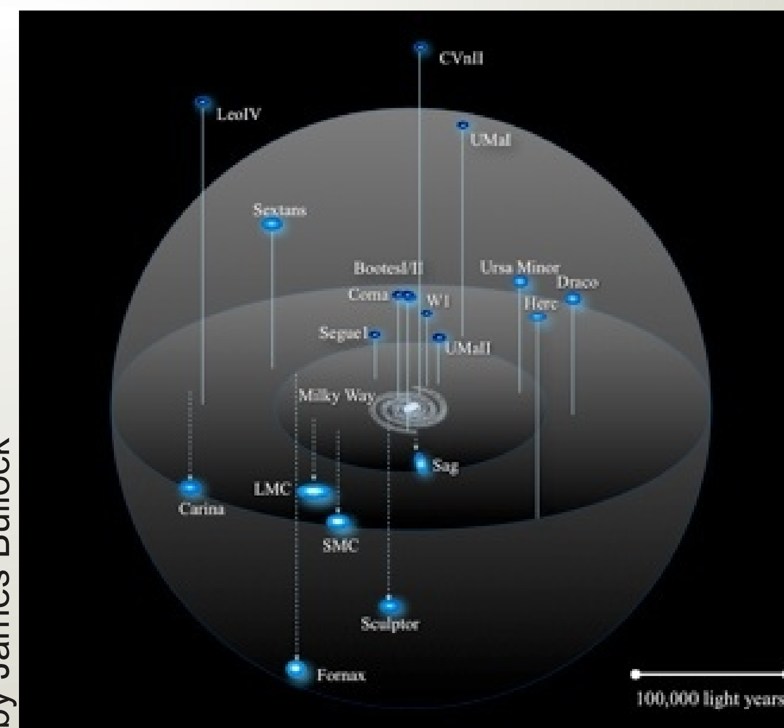
The Nature of Dark Matter

- dSph properties
  - Mass function
  - Halo density profiles





Strigari et al. (2008)



by James Bullock

The Nature of Dark Matter

- dSph properties
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The Nature of Dark Matter

- dSph properties
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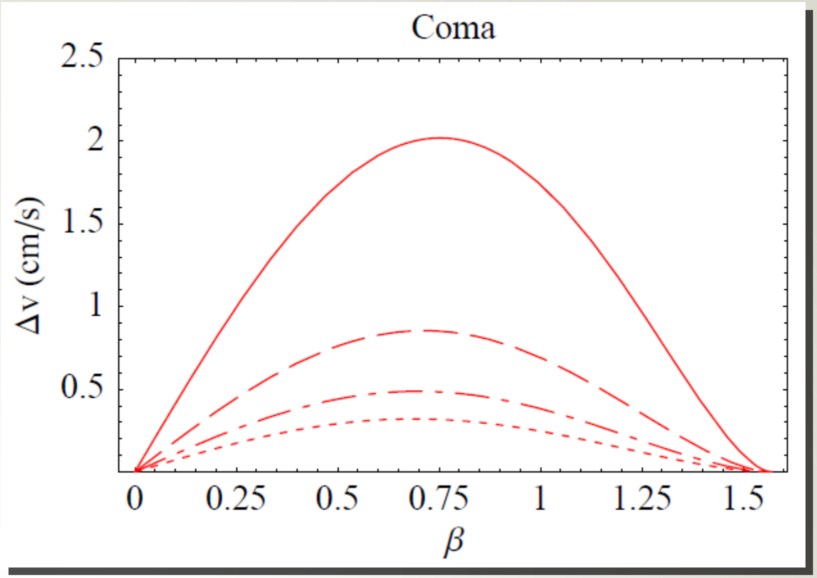
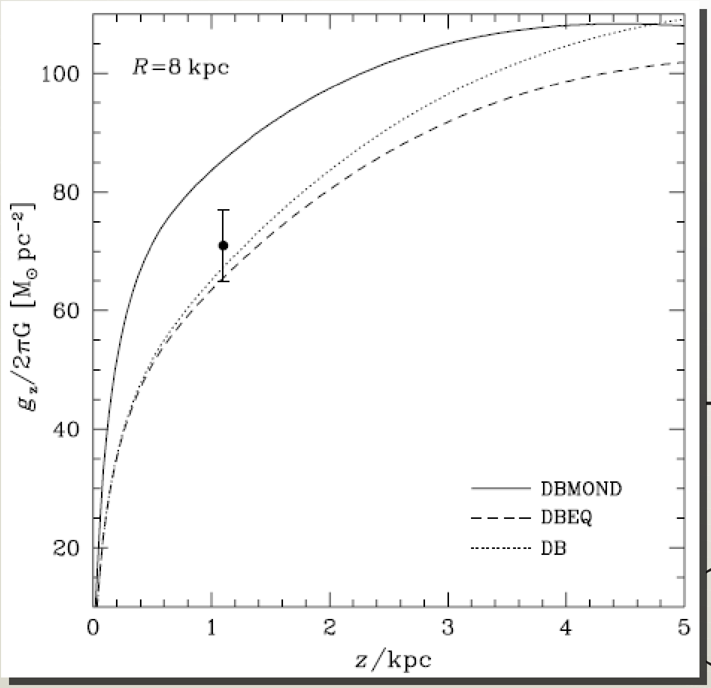
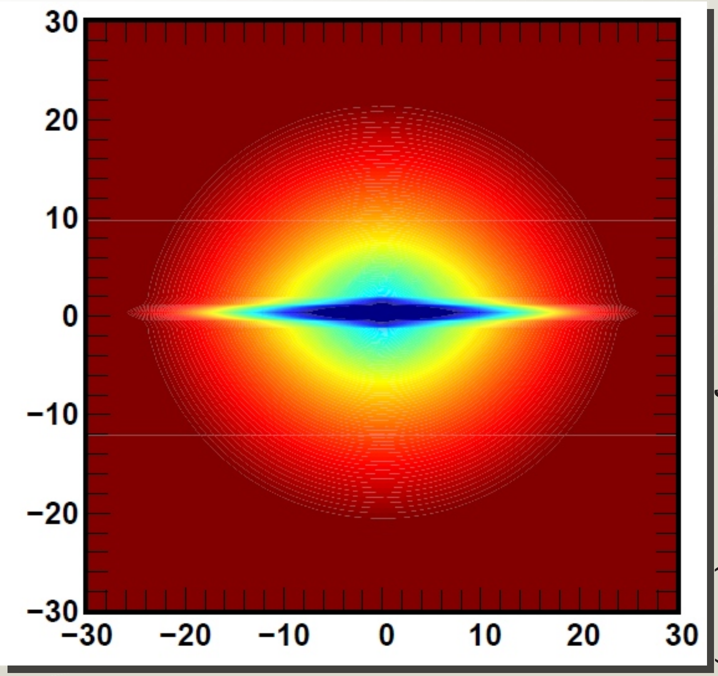
- Cluster dynamics
- Peculiar accelerations?



Amendola et al. (2008)



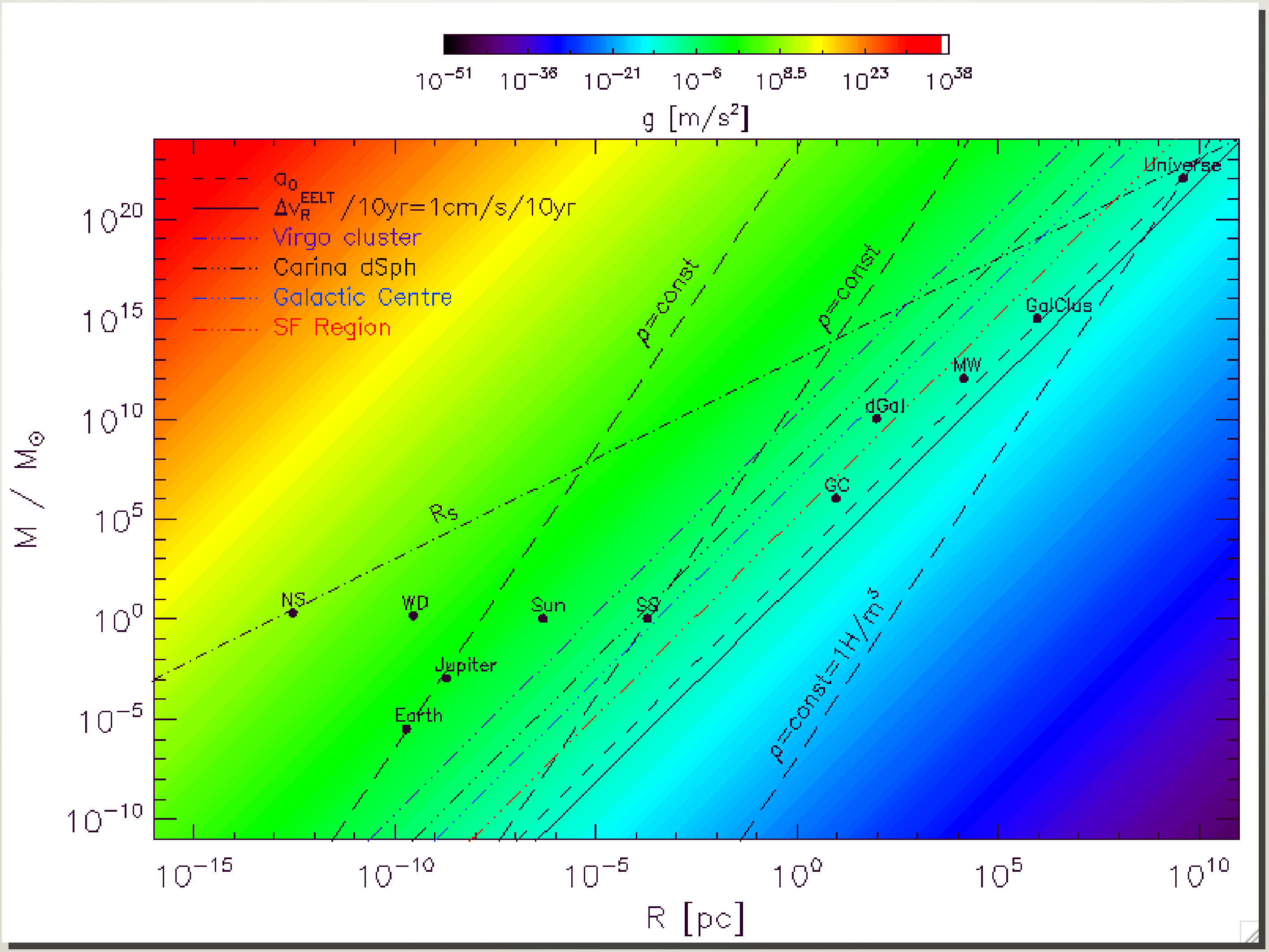
Nipoti et al. (2007)



Bienayme et al. (2009)

E-ELT = Gravity Machine?

- Astrometry at the level of 10s of μas → probe strong gravity at centre of MW
- Radial velocities at the level of a few cm/s → probe weak gravity in outskirts of MW?



Summary

- Much to look forward to!
- As the largest optical-IR telescope in the world for decades to come it the E-ELT will play a major role in advancing cosmology.
- PS: be sure to attend Carlos Martins' lectures!