Large-scale structure as a probe of dark energy

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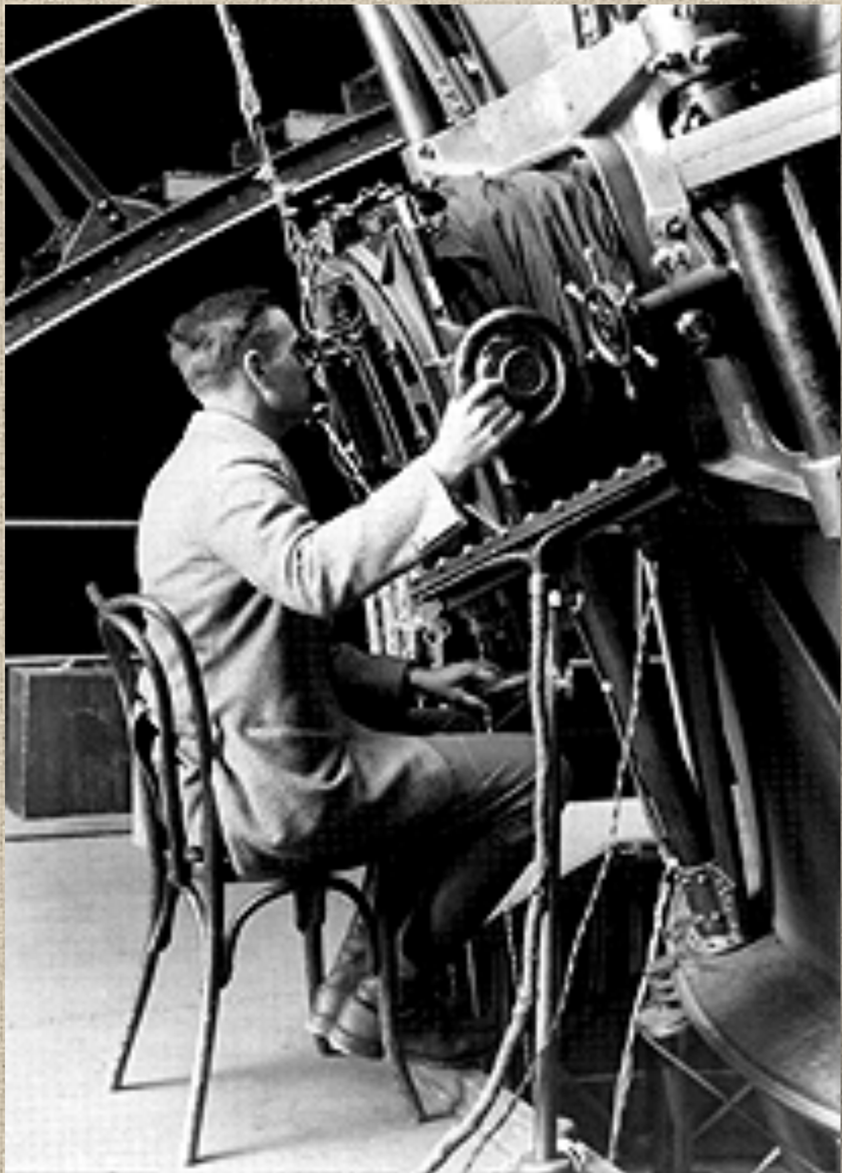
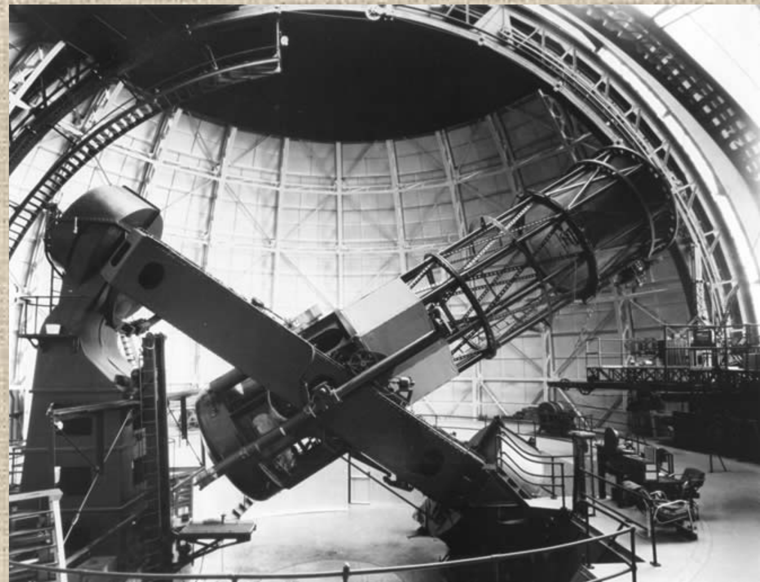
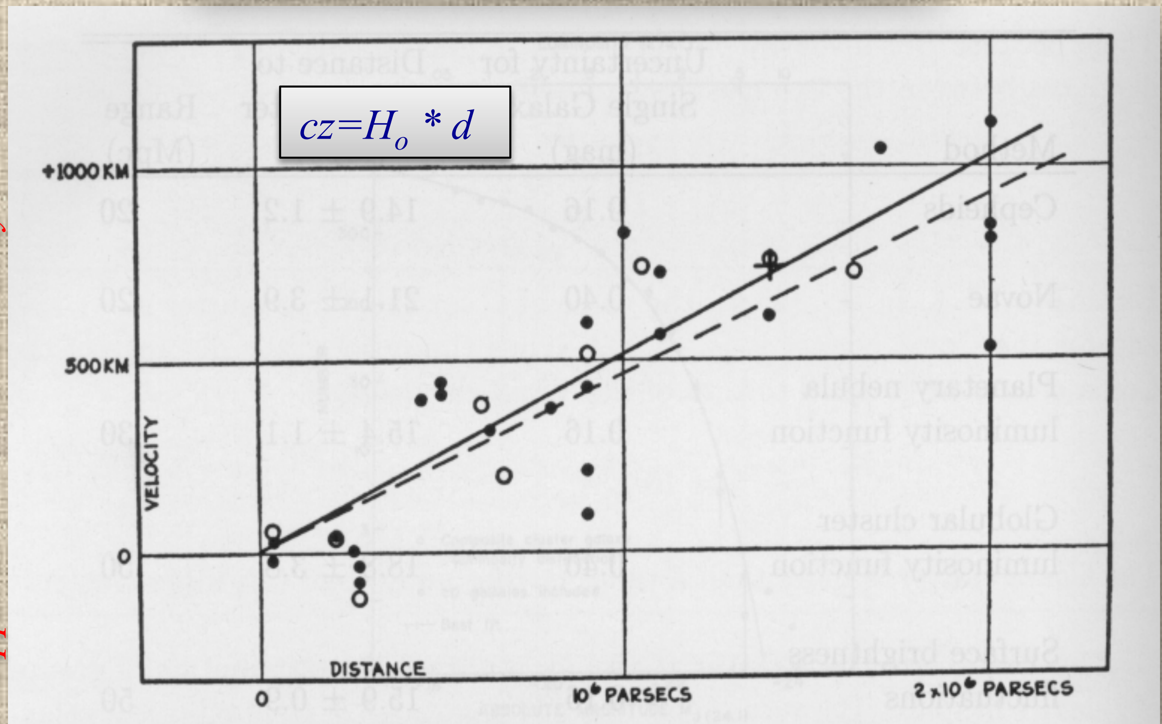
Outline

- Cosmic acceleration
- Statistical description of clustering
- LSS as a probe of expansion: Baryonic Acoustic Oscillations
- Is dark energy the only solution?
- LSS as a probe of the growth of structure: redshift-space distortions

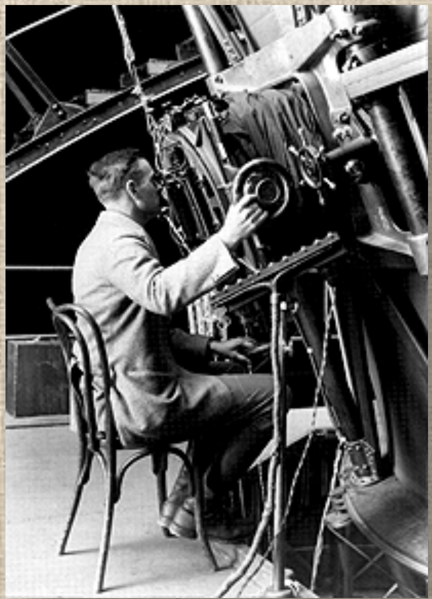
E. Hubble 1929

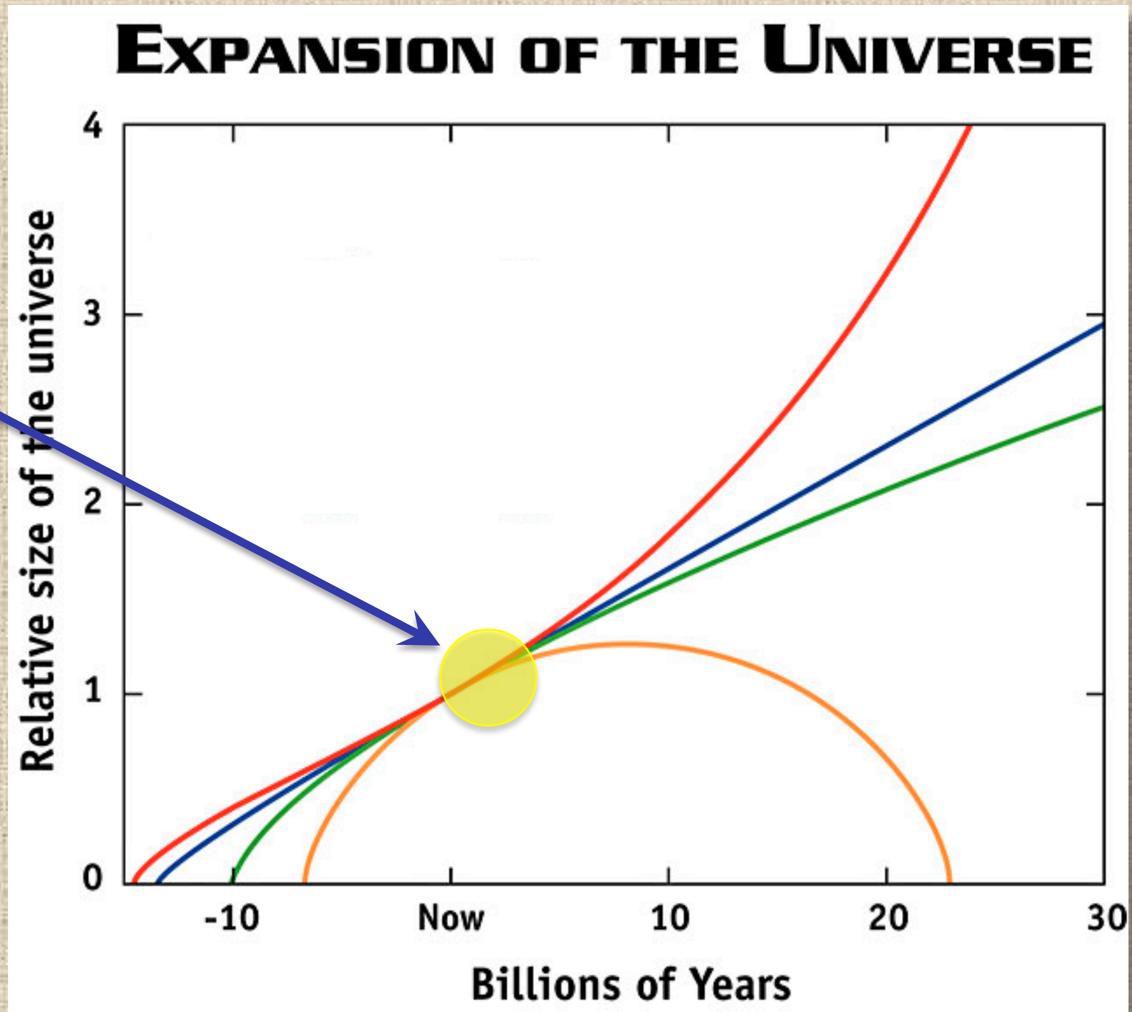




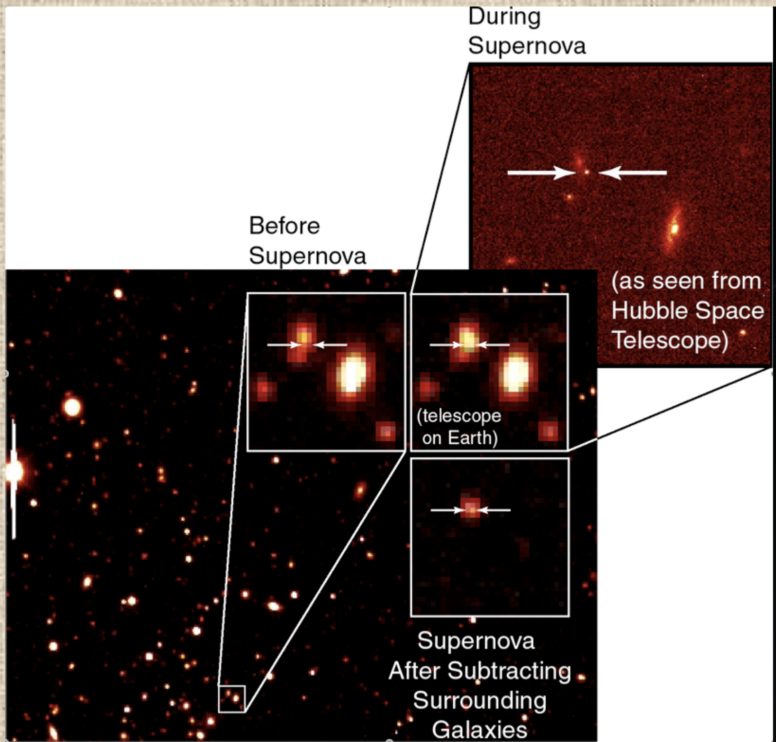


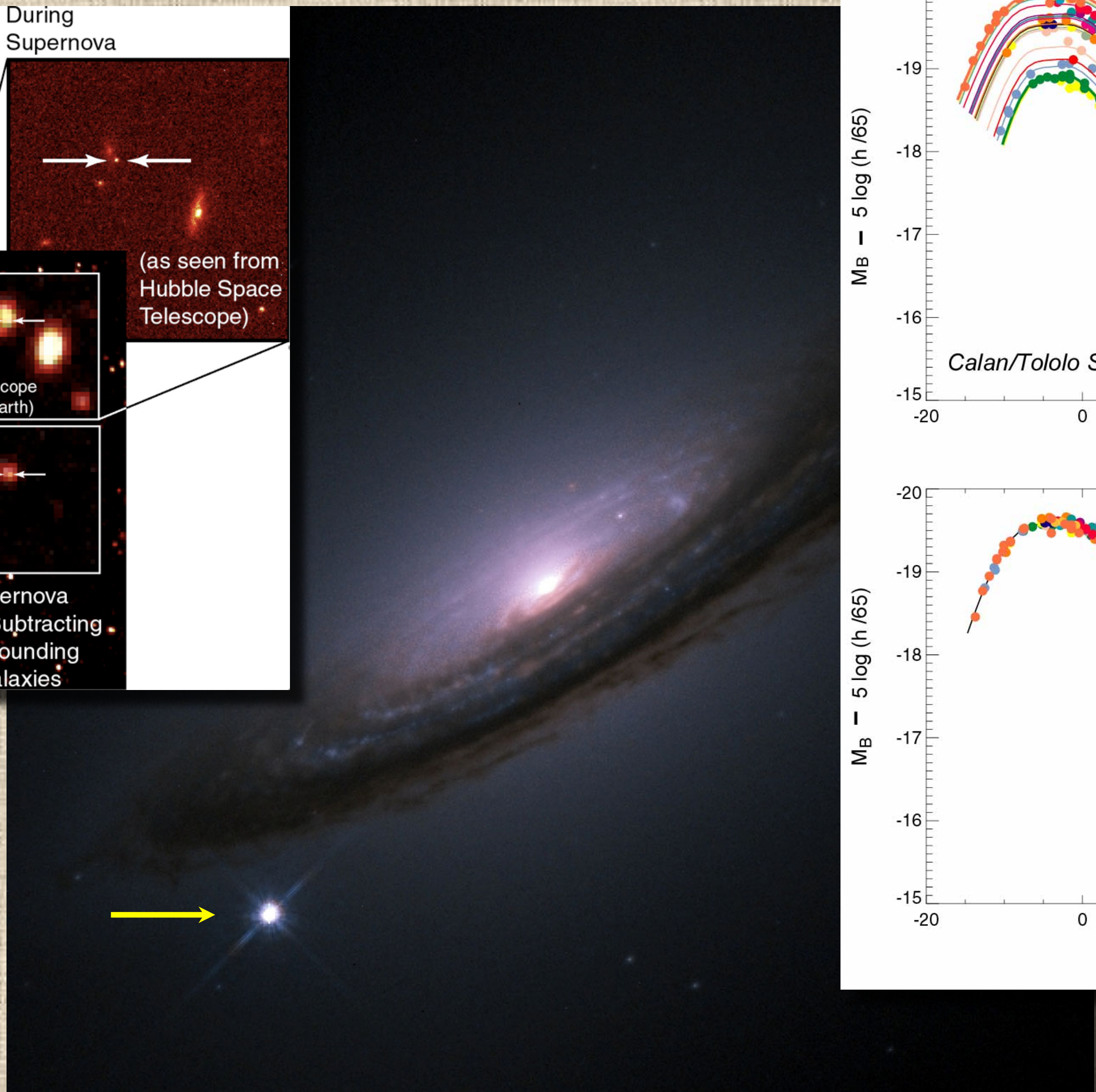
But, what is the past history of the expansion rate?

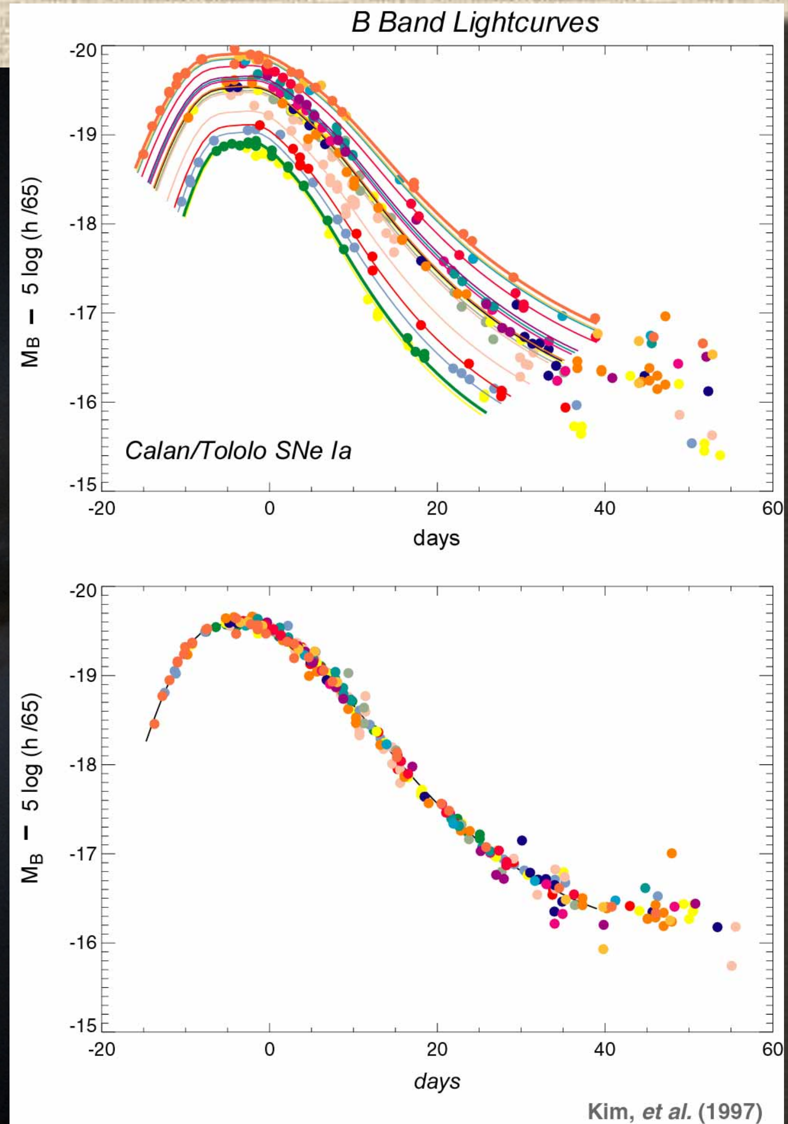




Beyond the Hubble law: Type-Ia supernovae as standard candles





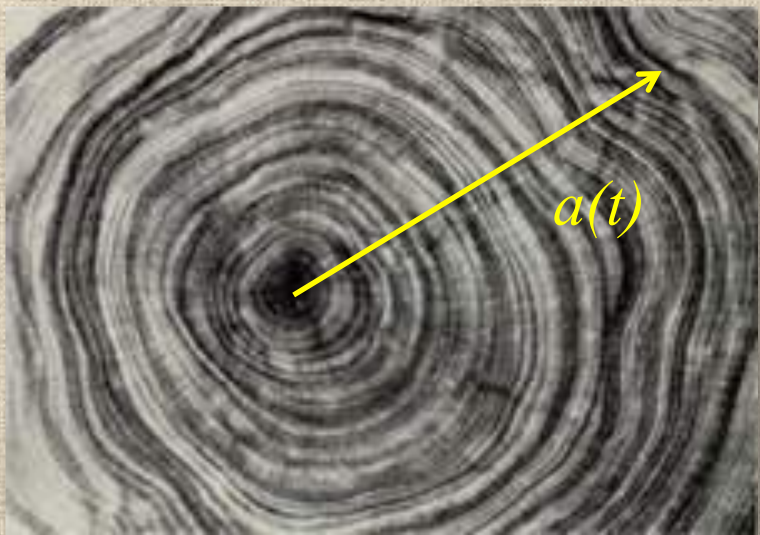


Perlmutter et al. 1999,
Riess et al. 1998

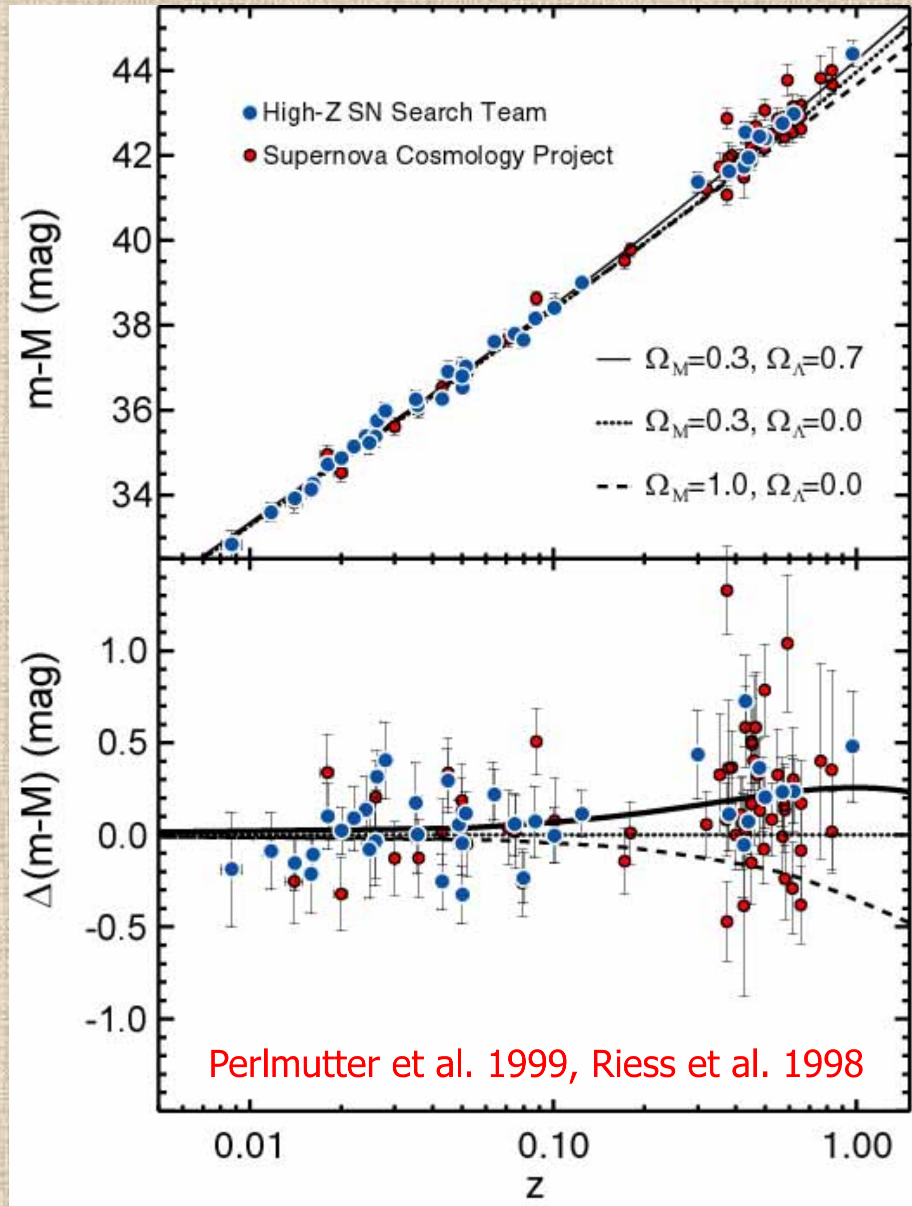
The "Hubble diagram" of Type Ia supernovae tells us that matter is not enough…

$$d_L = (1+z)\int_0^z \frac{c\,dz'}{H(z',\Omega_m,\Omega_\Lambda)}$$

$$H \equiv \frac{\dot{a}}{a}$$



$\log(Distance\ d_L)$



Redshift of spectral lines

… i.e. that the *expansion history* $H(z)$ given by the Friedmann equation:

$$H^2(z) = H_0^2\{\Omega_m(1+z)^3 + \Omega_k(1+z)^2 + \Omega_\gamma(1+z)^4 + \Omega_x(1+z)^{3(1+w_x)}\}$$

Matter | **Curvature** | **Radiation** | **Generic component**

$$\left(H \equiv \frac{\dot{a}}{a}; \quad w_x \equiv \frac{p_x}{\rho_x c^2}; \quad \Omega_i \equiv \frac{\rho_i}{\rho_c} \right)$$

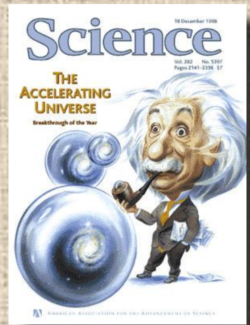
best matches observations when we add an extra component with *equation of state* $w_x = p/c^2\rho = -1$ corresponding to a cosmological constant Λ with energy density parameter today $\Omega_\Lambda \sim 3\Omega_m$

$$H^2(z) = H_0^2\{\Omega_m(1+z)^3 + \Omega_\Lambda\}$$

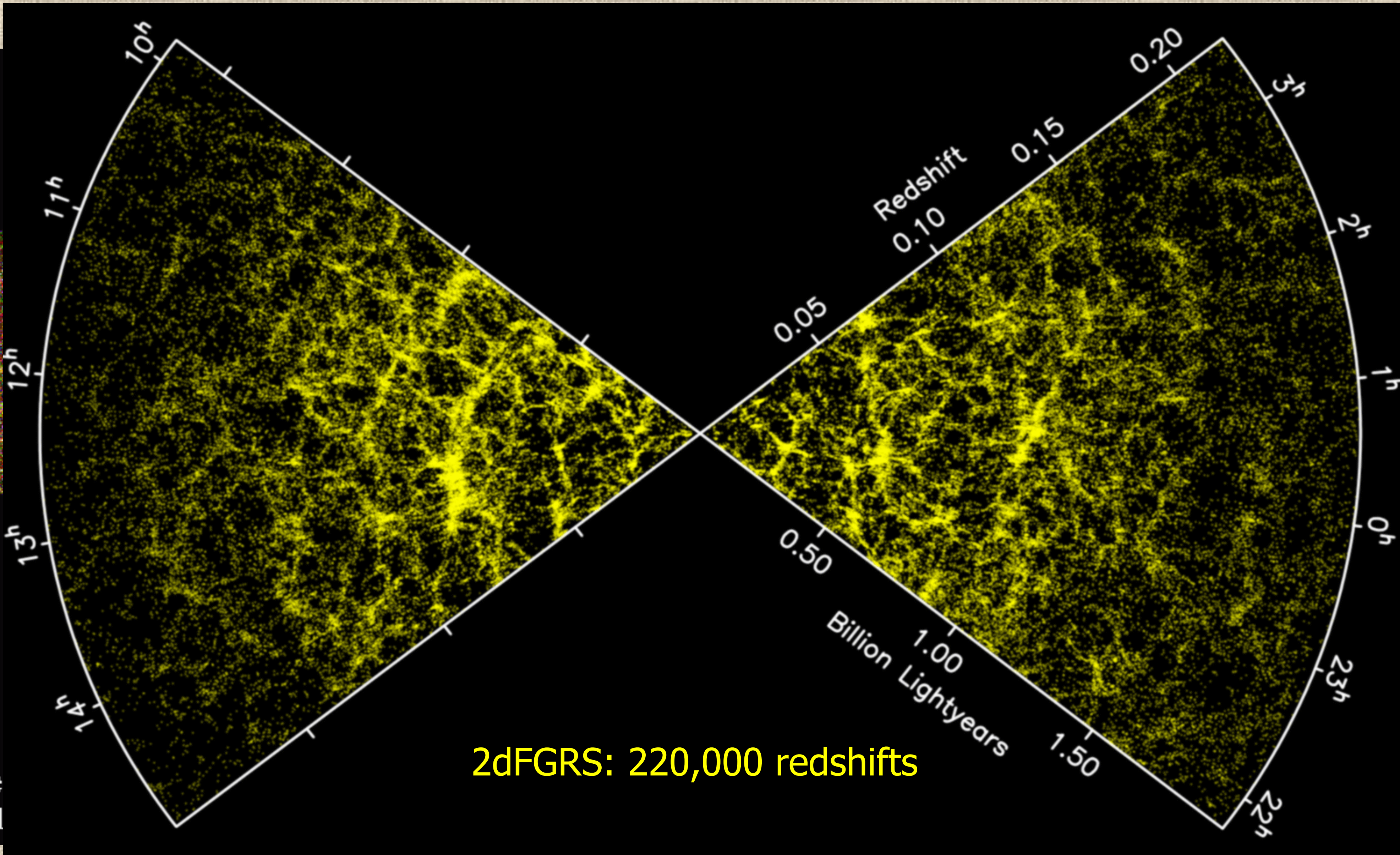
And thus the second equation

$$\frac{\ddot{a}}{a} = -\frac{H_0^2}{2}(\Omega_m - 2\Omega_\Lambda)$$

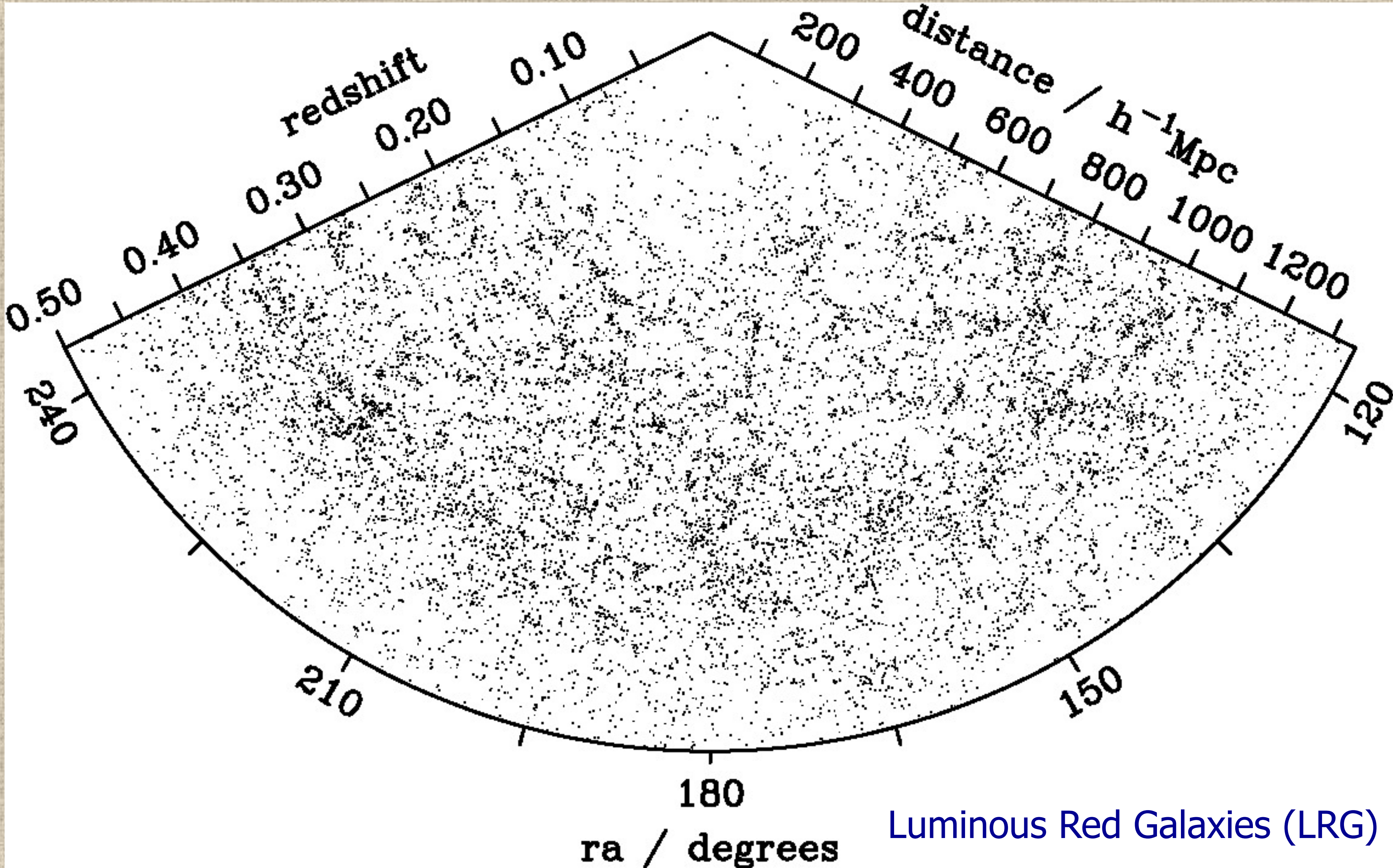
→ IMPLIES ACCELERATION OF THE EXPANSION (as soon as $\Omega_\Lambda > \Omega_m/2$)



Galaxy redshift surveys: reconstructing the 3D structure of the Universe



Sloan Digital Sky Survey



Luminous Red Galaxies (LRG)

Statistics of Fluctuations: two-point correlation function

overdensity field $\delta = \dfrac{\rho - \bar{\rho}}{\bar{\rho}}$

definition of correlation function

$$\begin{aligned} \xi(\mathbf{x}_1, \mathbf{x}_2) &\equiv \langle \delta(\mathbf{x}_1)\delta(\mathbf{x}_2) \rangle \\ &= \xi(\mathbf{x}_1 - \mathbf{x}_2) \\ &= \xi(|\mathbf{x}_1 - \mathbf{x}_2|) \end{aligned}$$

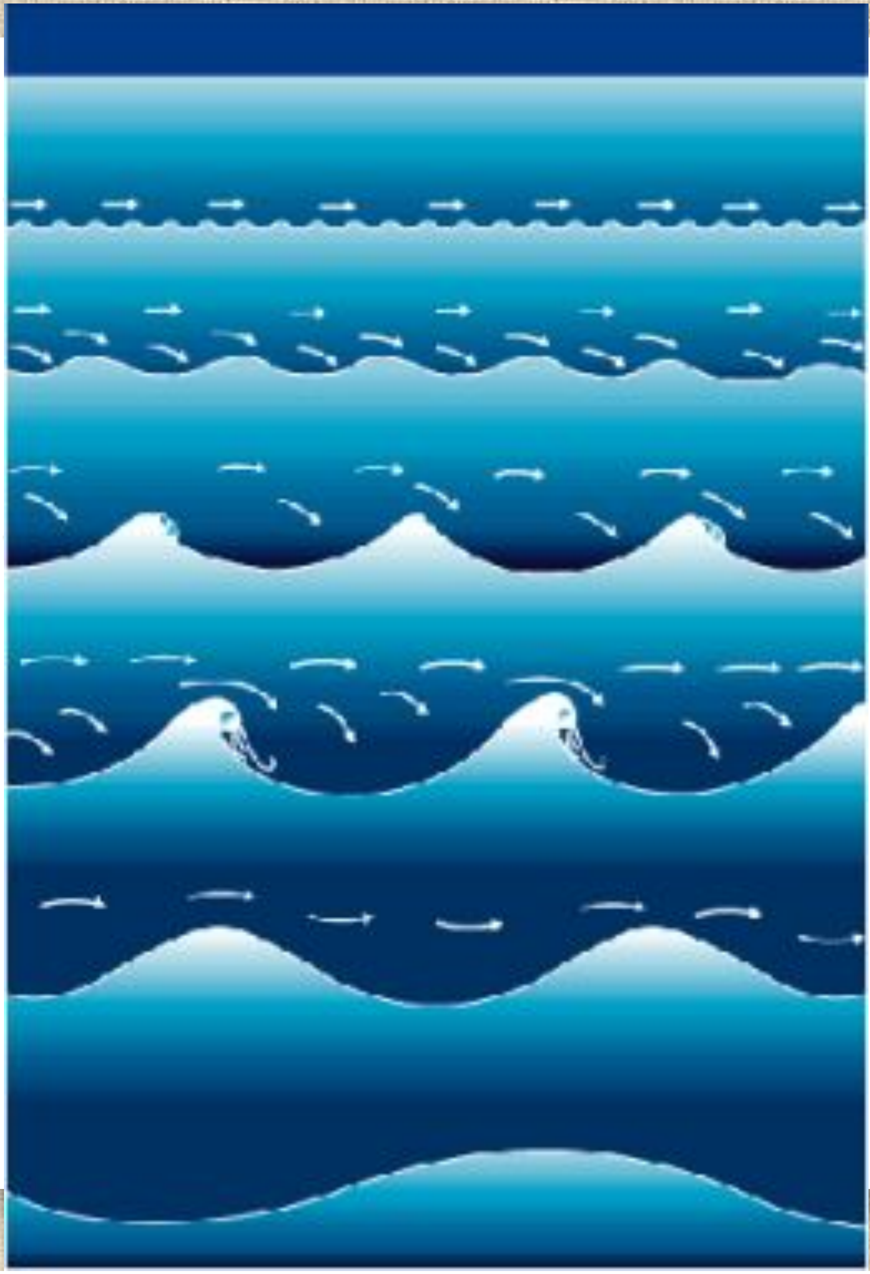
from statistical homogeneity

from statistical isotropy

can estimate correlation function using galaxy (DD) and random (RR) pair counts at separations ~r

$$1 + \xi(r) = \frac{\langle DD \rangle_r}{\langle RR \rangle_r}$$

Fluctuations statistics: Fourier decomposition



- The observed fluctuations can be decomposed into waves with different frequency (or wavelength)
- Standard Fourier decomposition is given by

$$\delta(\mathbf{k}) \equiv \int \delta(\mathbf{r}) e^{i\mathbf{k}.\mathbf{r}} d^3 r$$

$$\delta(\mathbf{r}) = \int \delta(\mathbf{k}) e^{-i\mathbf{k}.\mathbf{r}} \frac{d^3 k}{(2\pi)^3}$$

Fluctuations statistics: Power Spectrum

definition of
power spectrum

$$\langle \delta(\mathbf{k_1})\delta(\mathbf{k_2})\rangle = (2\pi)^3 \delta_D(\mathbf{k_1} - \mathbf{k_2}) P(k_1)$$

power spectrum is the Fourier
analogue of the correlation function

$$P(k) \equiv \int \xi(r) e^{i\mathbf{k}.\mathbf{r}} d^3 r$$

$$\xi(r) = \int P(k) e^{-i\mathbf{k}.\mathbf{r}} \frac{d^3 k}{(2\pi)^3}$$

sometimes written in
dimensionless form

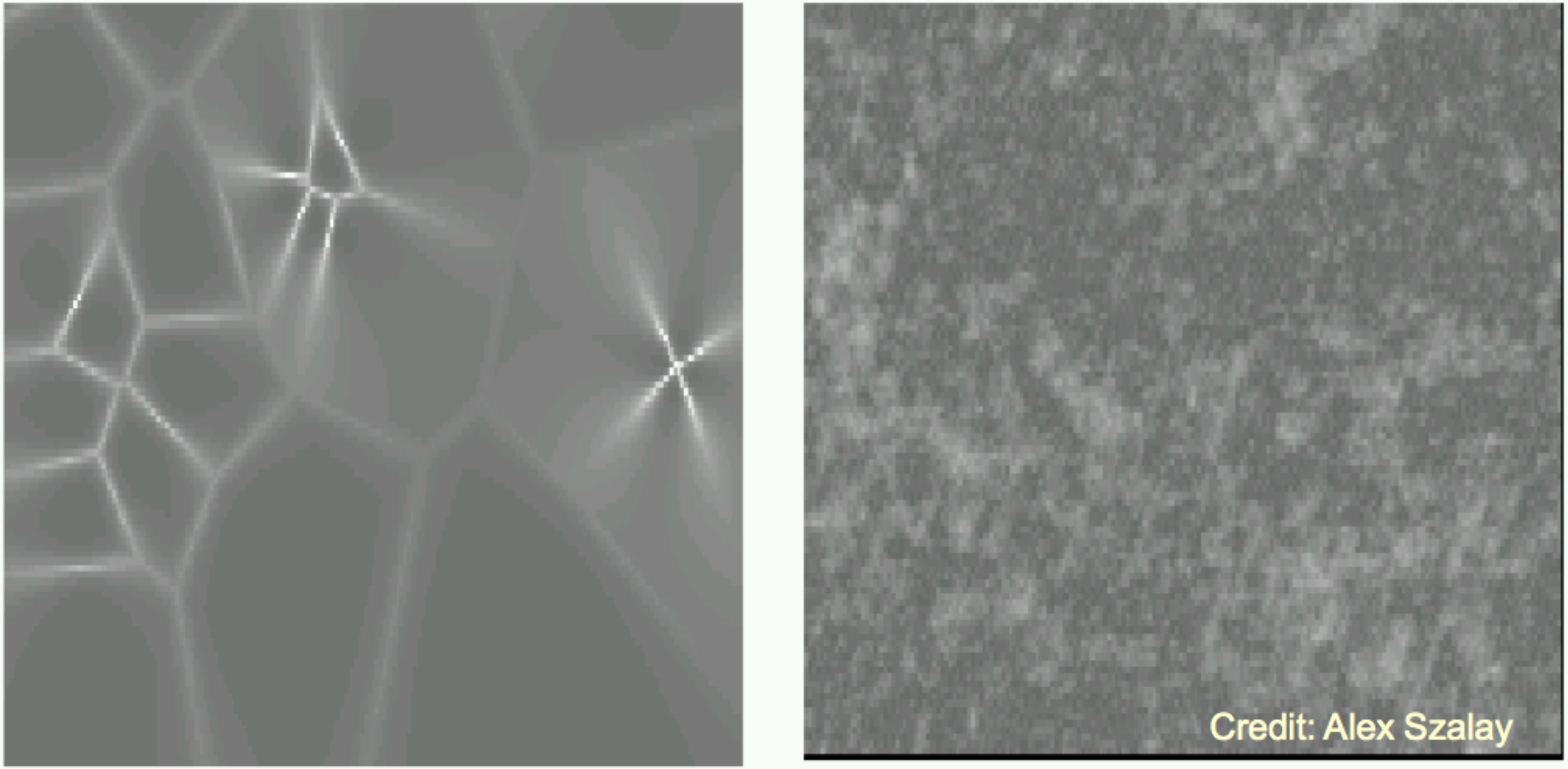
$$\Delta^2(k) = \frac{k^3}{2\pi^2} P(k)$$

Why two-point statistics so important?

- Because the central limit theorem implies that a density distribution is asymptotically Gaussian in the limit where the density results from the average of many independent processes;

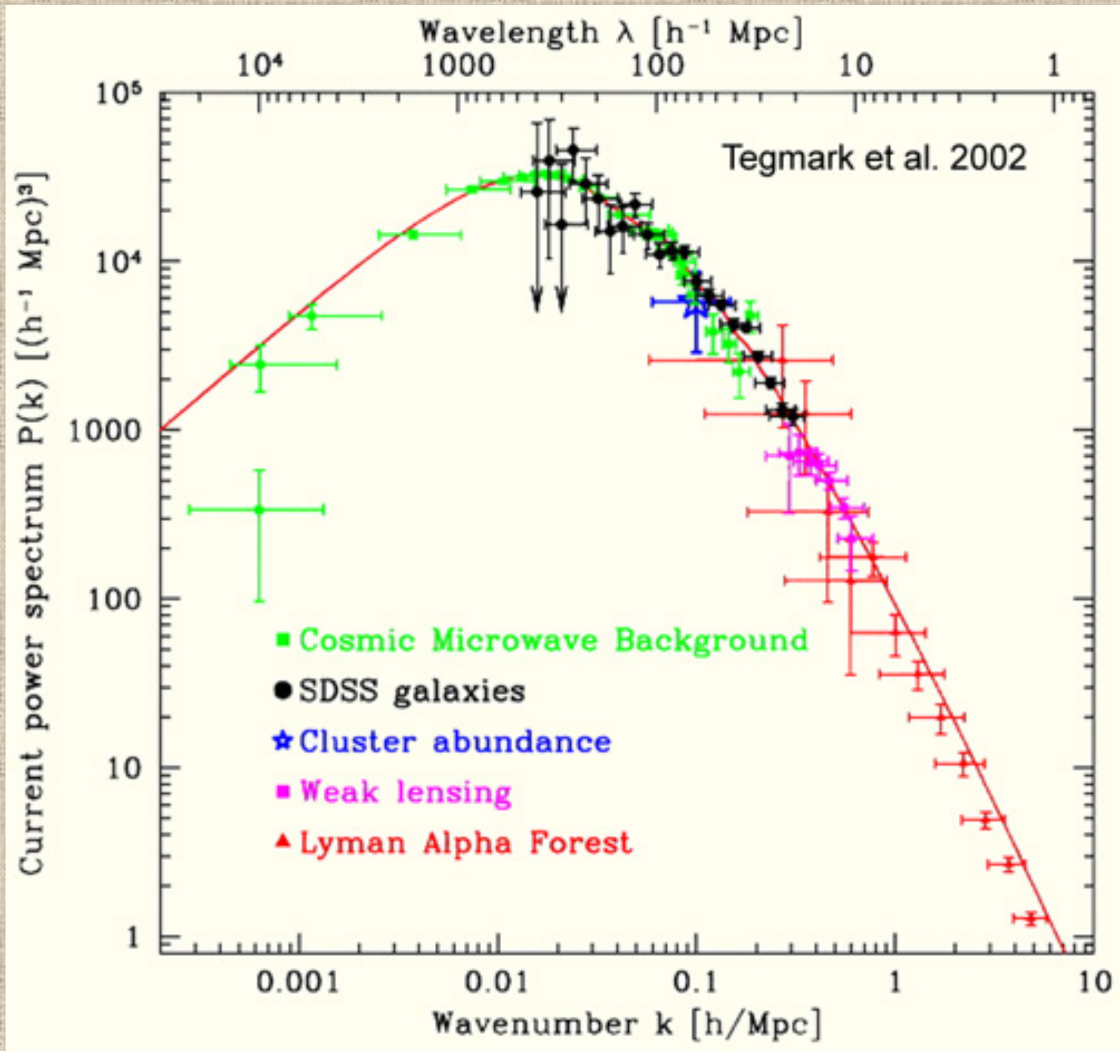
- and a Gaussian is completely characterised by its mean (overdensity=0) and variance (given by either the correlation function or the power spectrum)

But two-point statistics not necessarily enough

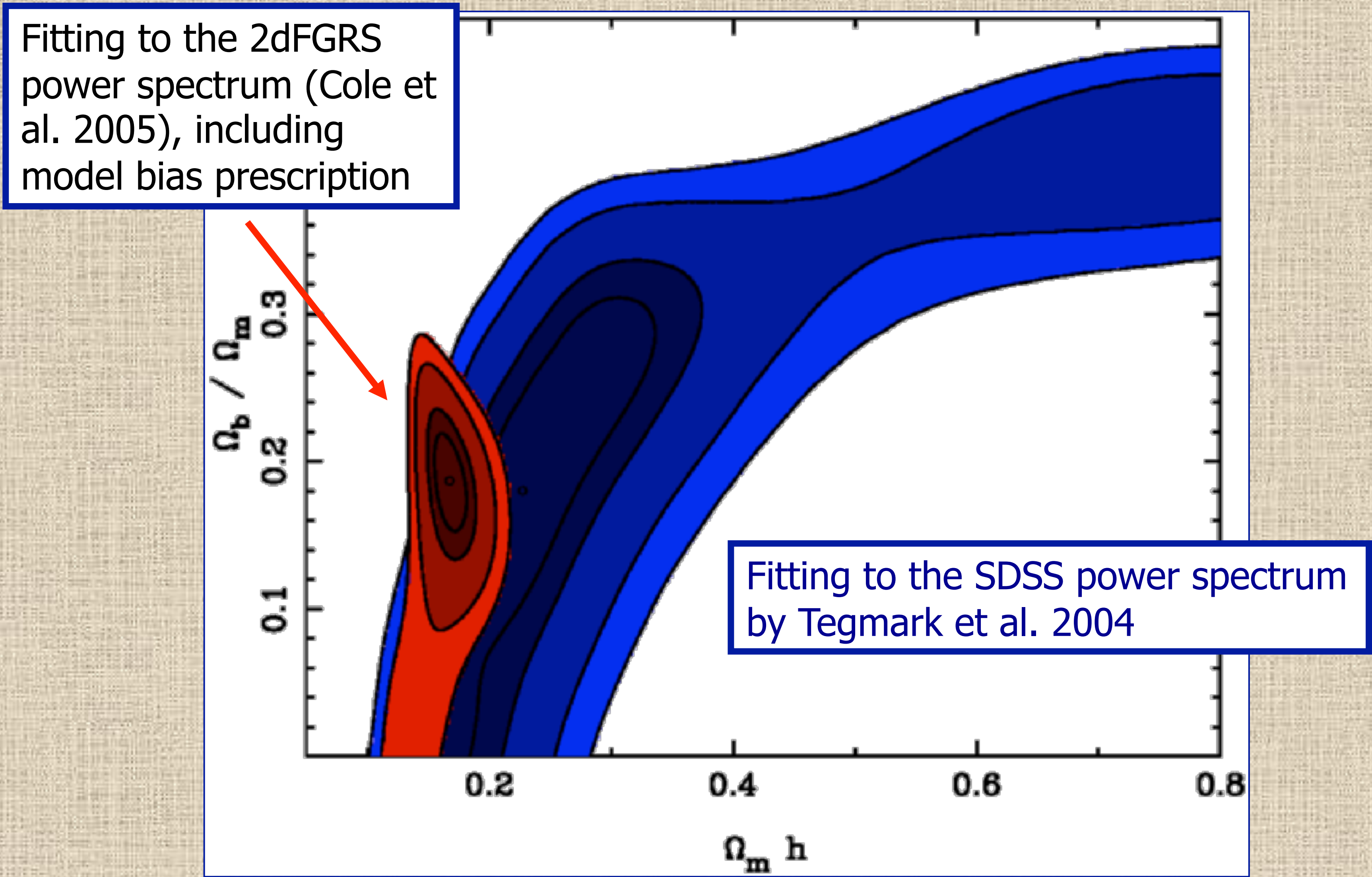


Same 2pt, different 3pt

The clustering power spectrum: scale-dependence of inhomogeneities

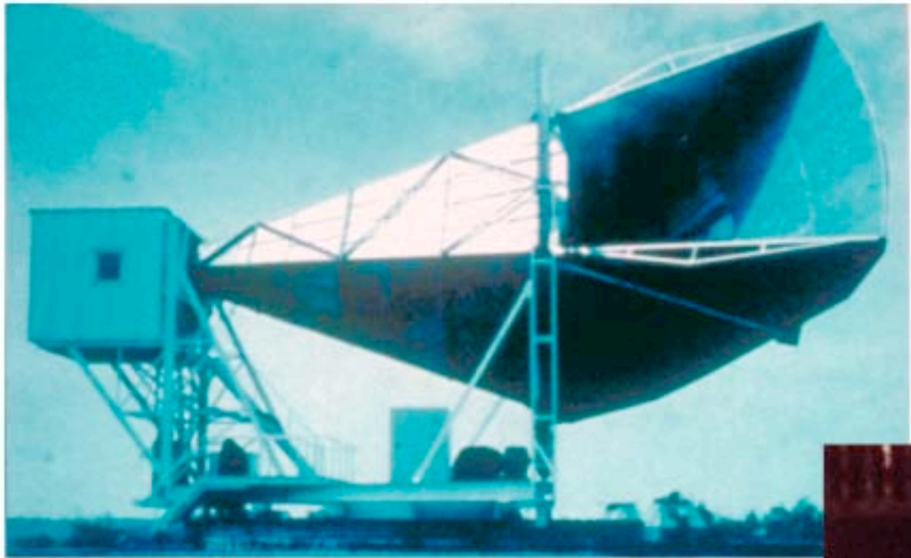


P(k) contains cosmological information: e.g. shape depends on Ω_m and Ω_b



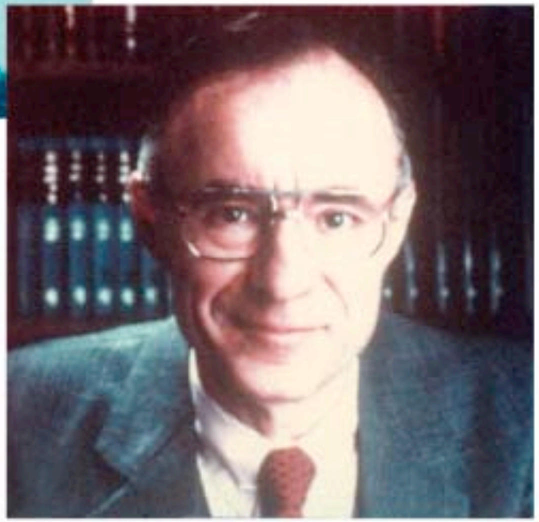
I. Baryonic acoustic oscillations

Discovery of Cosmic Background



Microwave Receiver

Robert Wilson

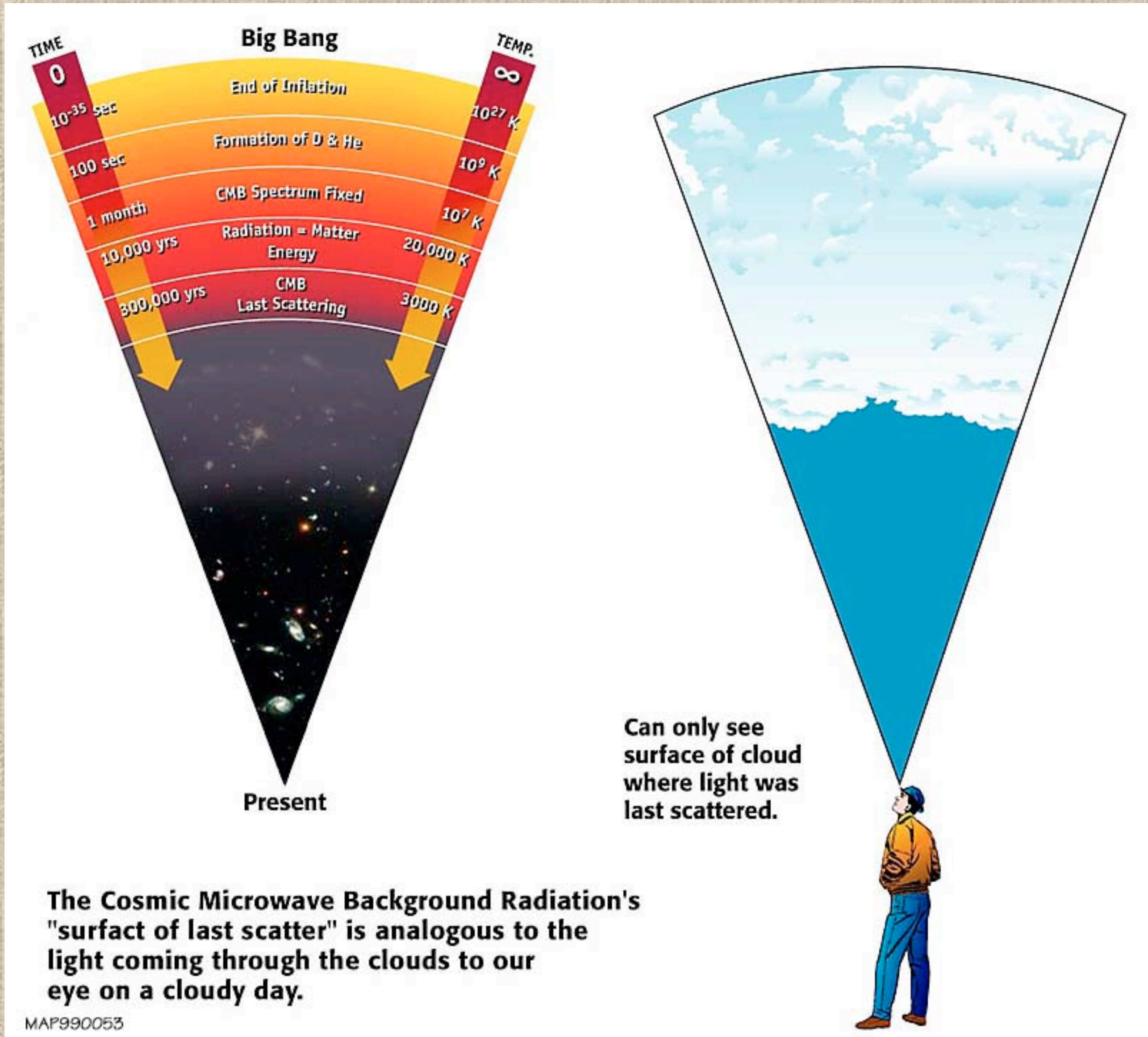


Arno Penzias

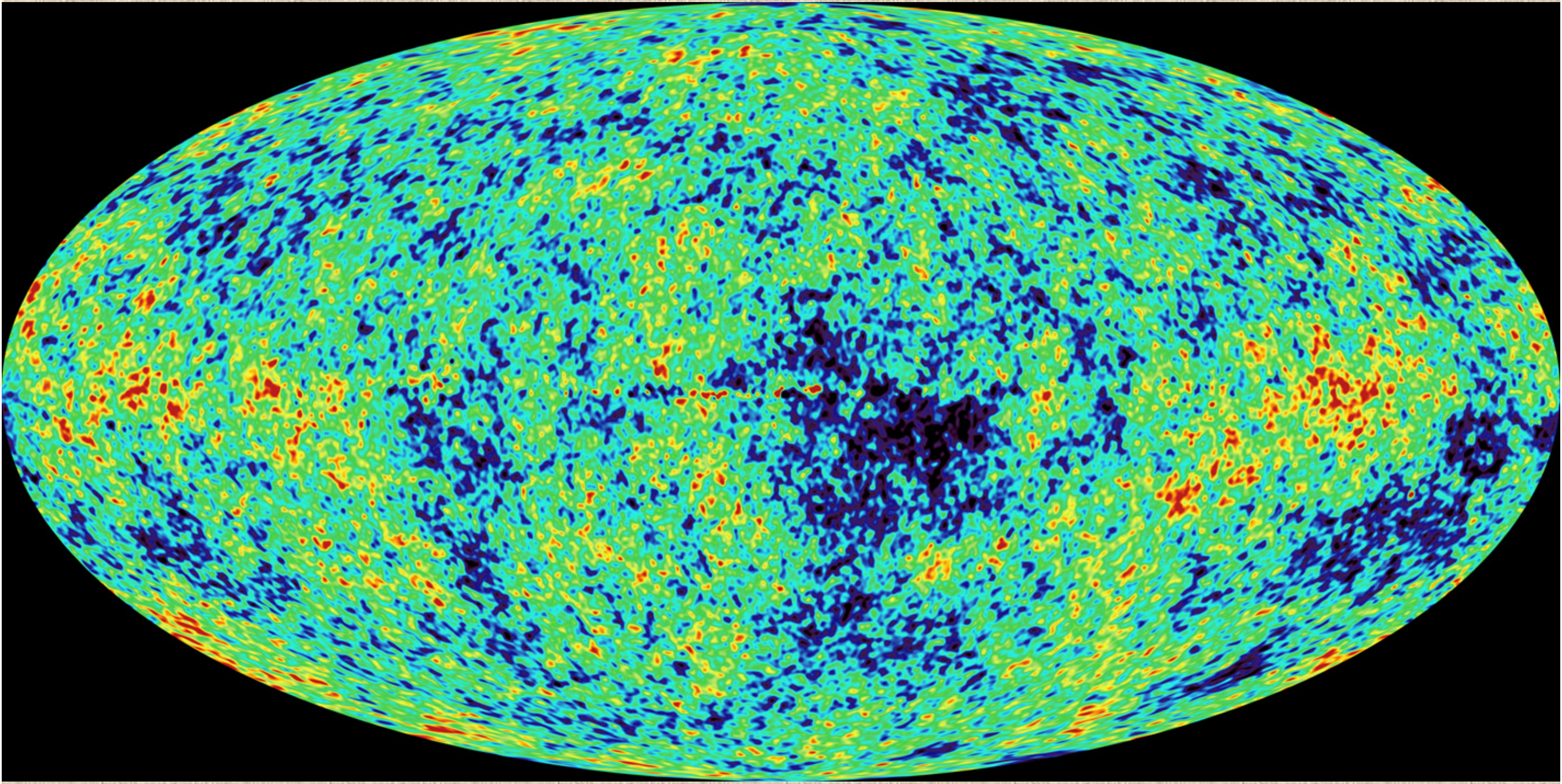
MAP990045

1964

Cosmic Microwave Background

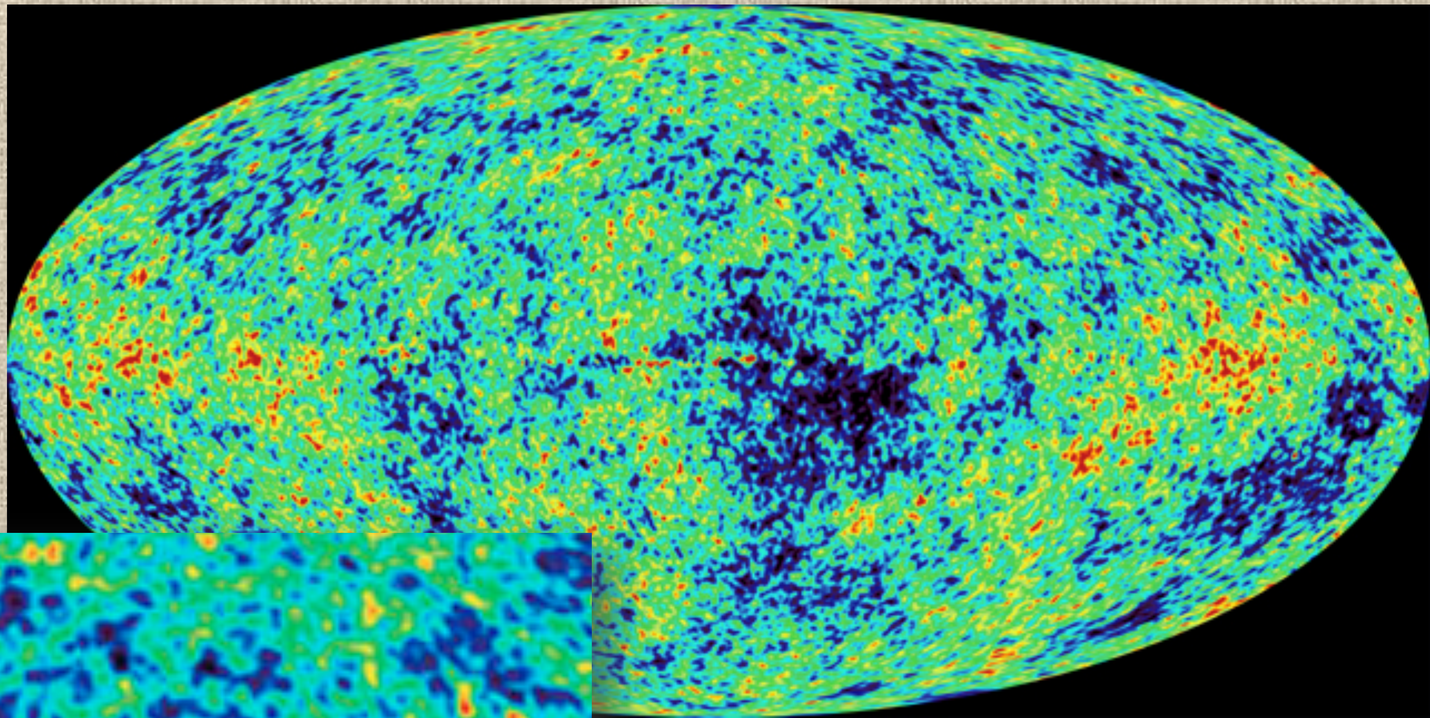


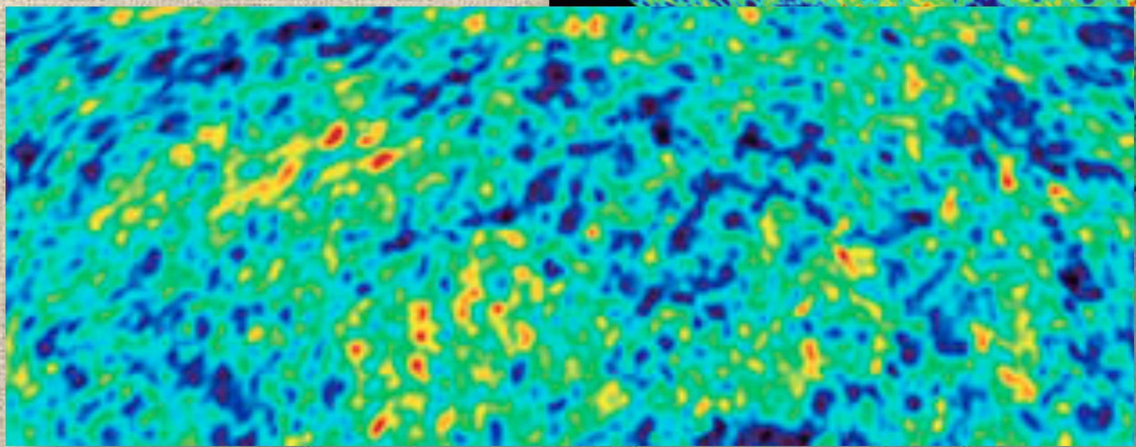
Cosmic Microwave Background



Inhomogeneities in the Cosmic Microwave Background

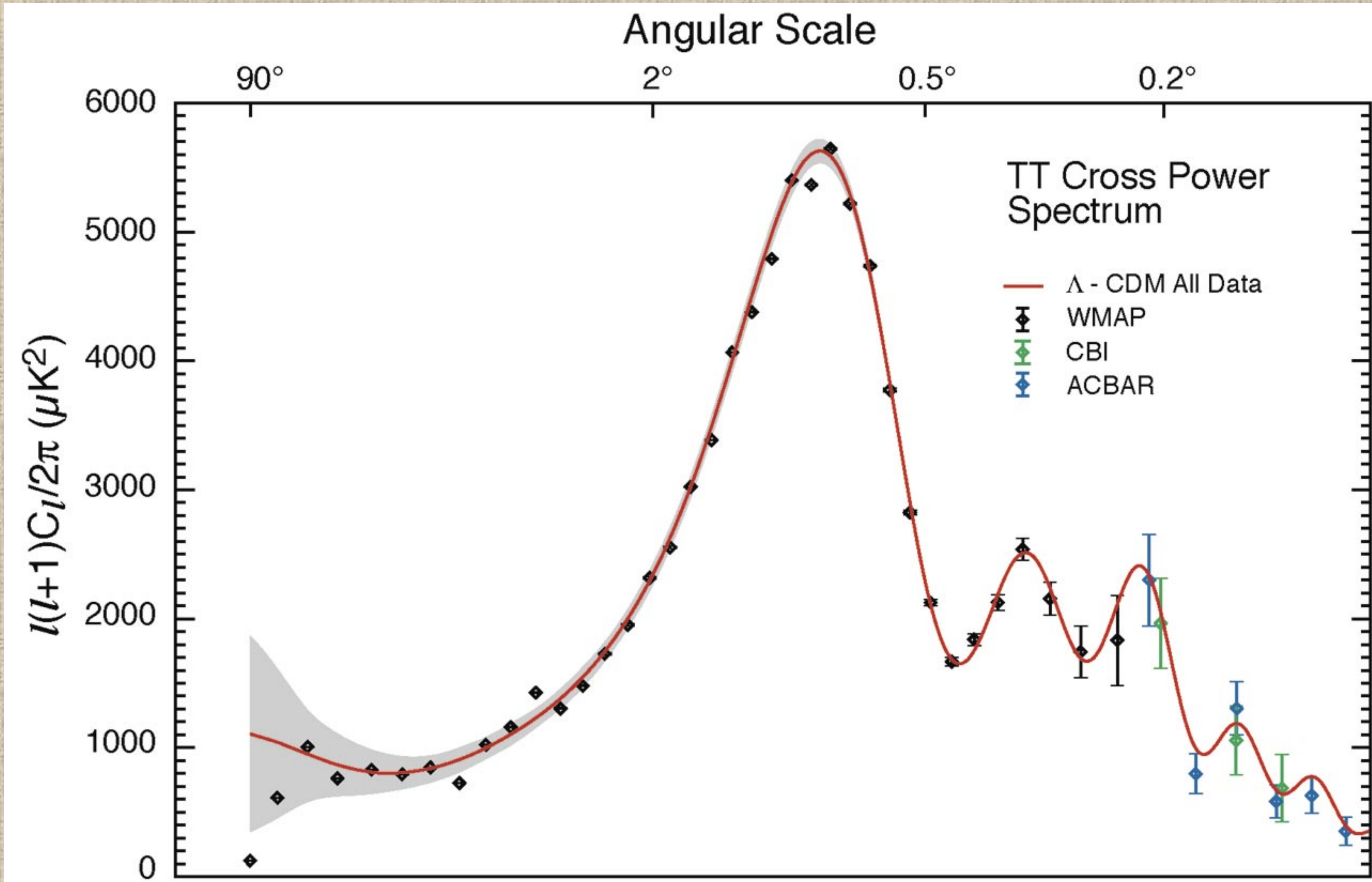
(WMAP, e.g. Bennett et al. 2003, Dunkley et al. 2009, Komatsu et al. 2009)





Fluctuations on all scales, however, one characteristic angular scale

Acoustic Oscillations in the CMB



e.g. Komatsu et al. 2009 WMAP. → First accurate observation by BOOMERANG balloon experiment (De Bernardis et al. 2000, Nature, 404, 955)

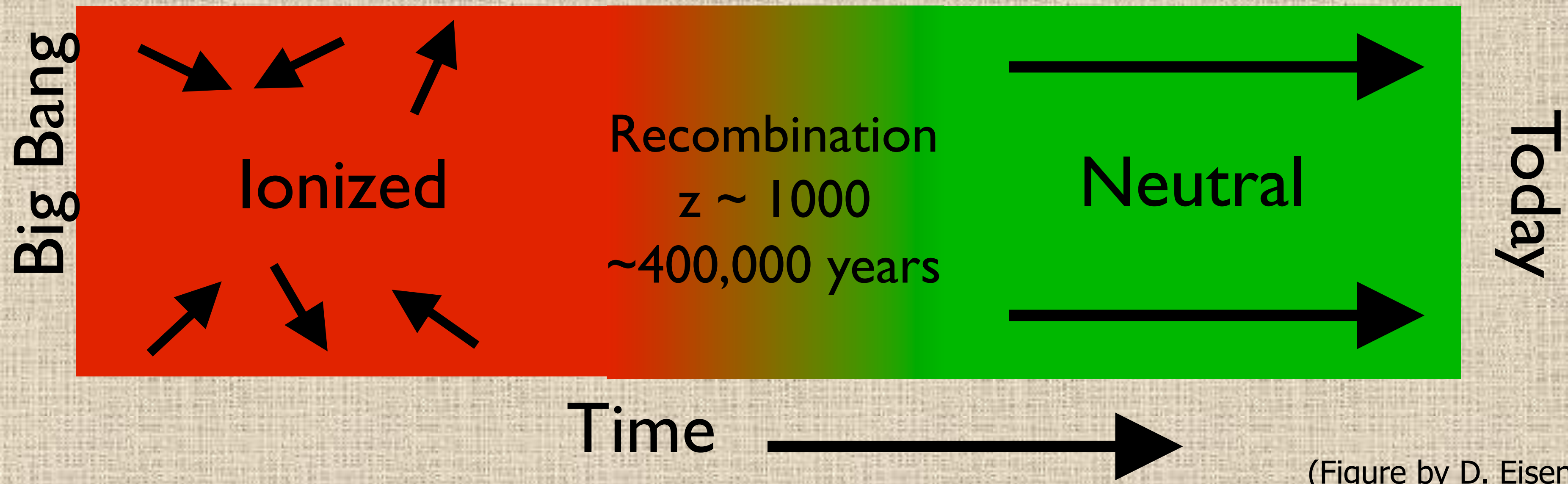
Density fluctuations in the baryon-radiation plasma

Before recombination:

- Universe is ionized
- Photons provide pressure counter-acting gravity
- As a consequence, perturbations oscillate as acoustic waves

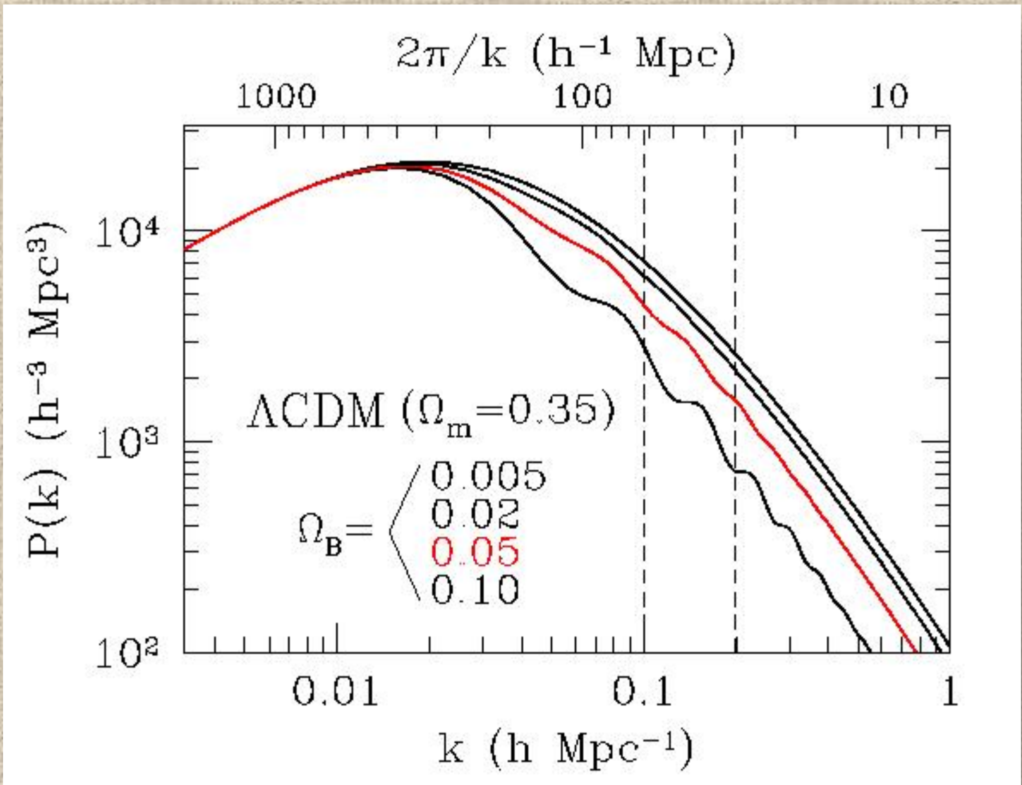
After recombination:

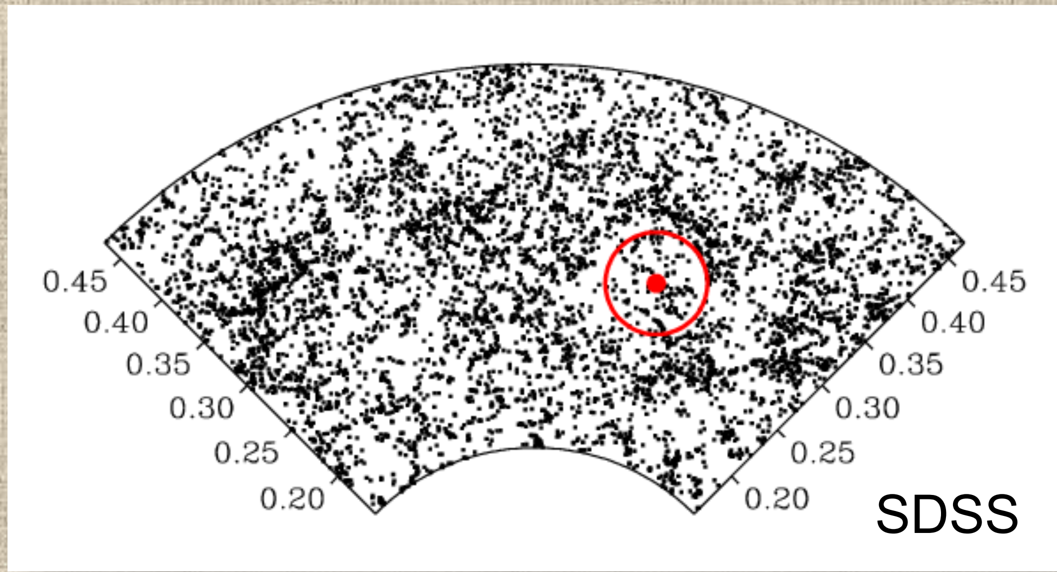
- Universe is neutral
- Photons can travel freely past the baryons
- The amplitude we see today depends on the phase of oscillation at t_{rec}



(Figure by D. Eisenstein)

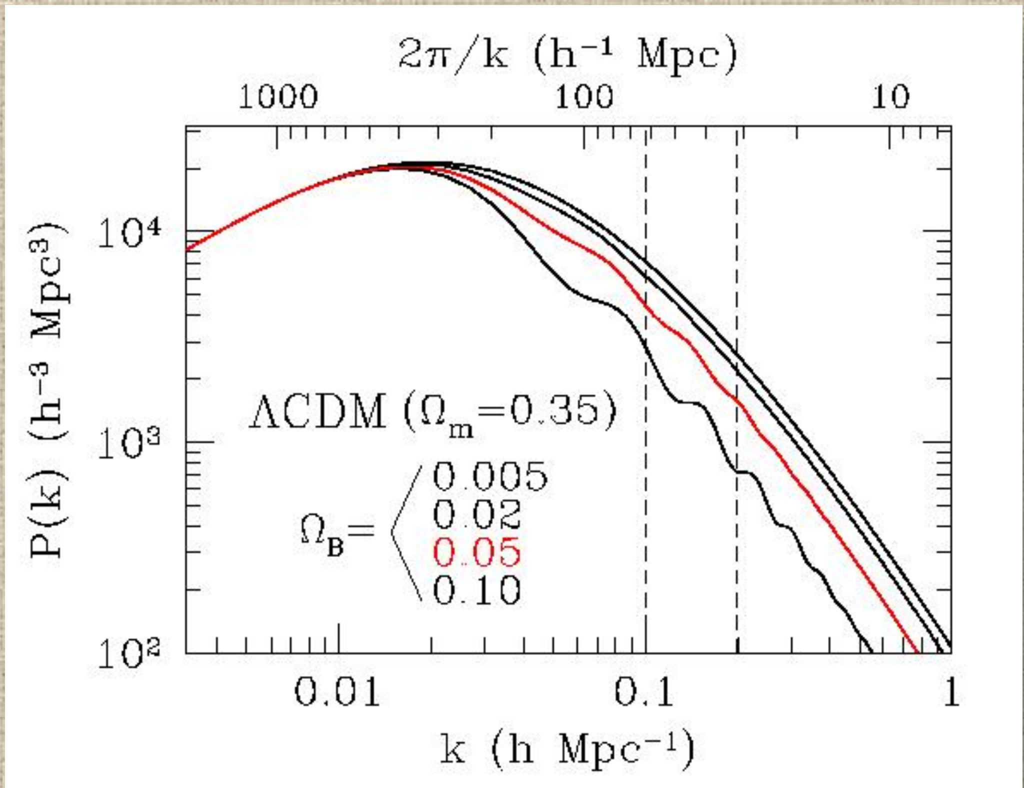
Baryonic Acoustic Oscillations imprint in the galaxy distribution





D. Eisenstein 2007

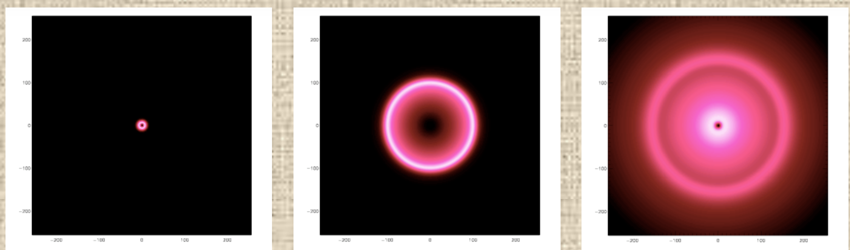
Baryonic Acoustic Oscillations



BAO "period" in k-space is essentially determined by the comoving sound horizon at recombination:

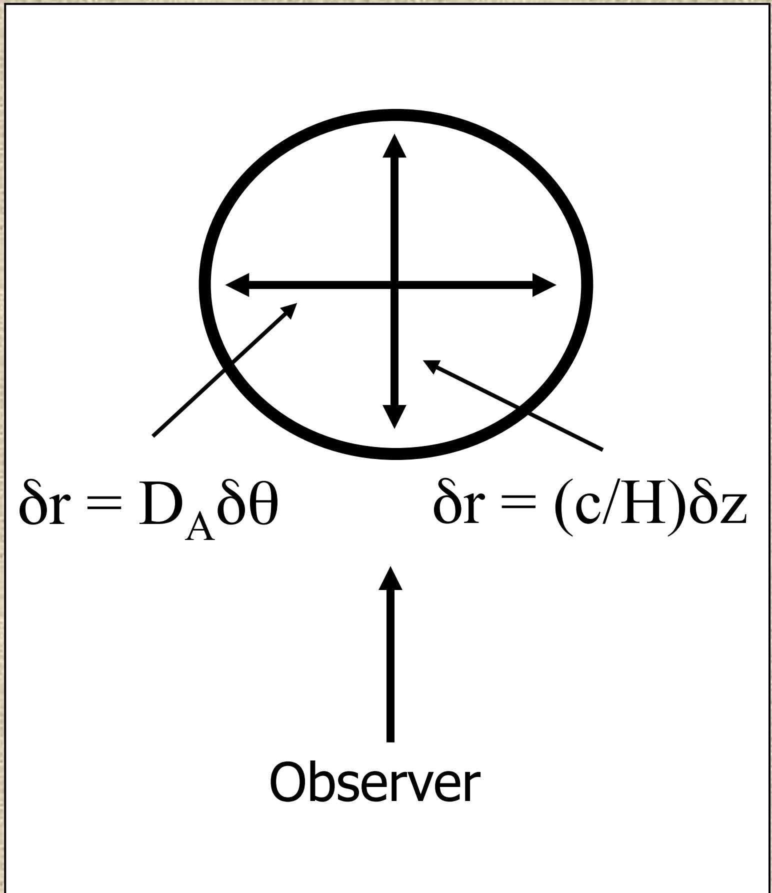
$$k_{\rm bao} = 2\pi/s$$

comoving sound horizon ~110h^{-1}Mpc,
BAO periodicity Δk = 0.06 h Mpc^{-1}



(See Martin White web site for useful tools)

BAO as a standard ruler



Observations linked to physical BAO scale δr in two ways:

1) Radial direction

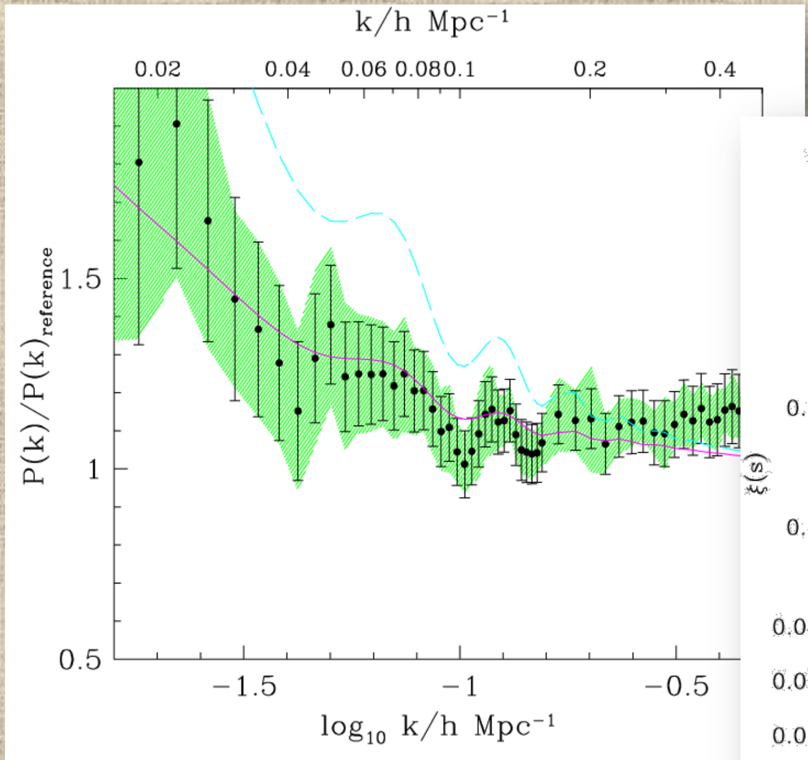
$$\delta r = (c/H)\delta z$$

2) Perpendicular direction

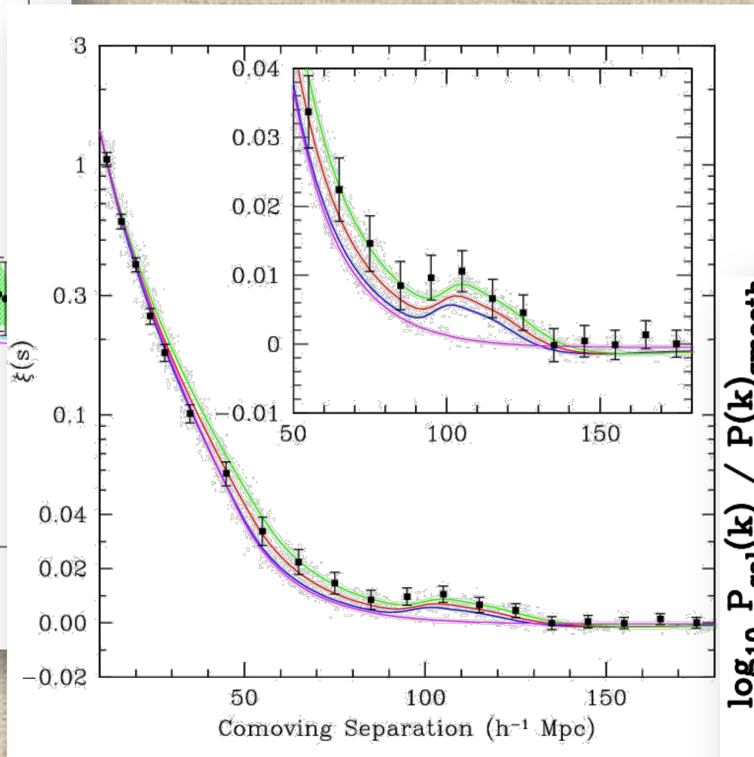
$$\delta r = D_A \delta\theta$$

D. Eisenstein 2007

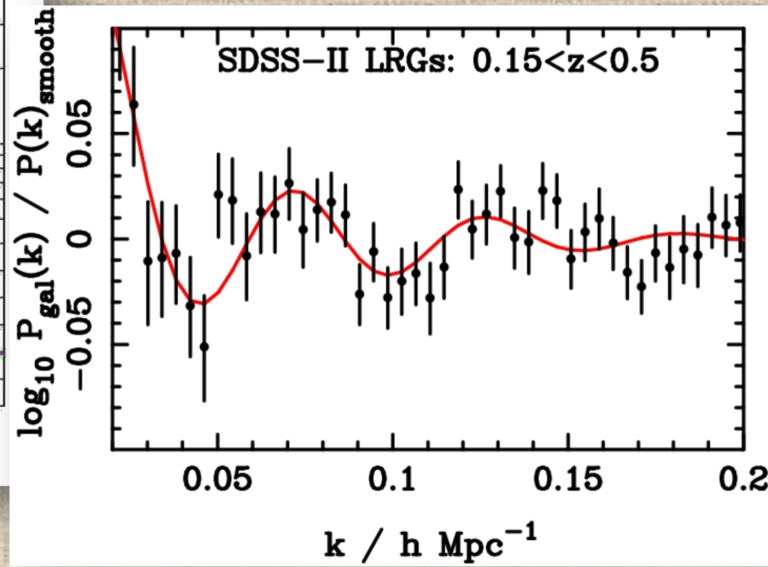
BAO detections from spectroscopic samples



2dFGRS: Cole et al 2005, MNRAS, 362, 505

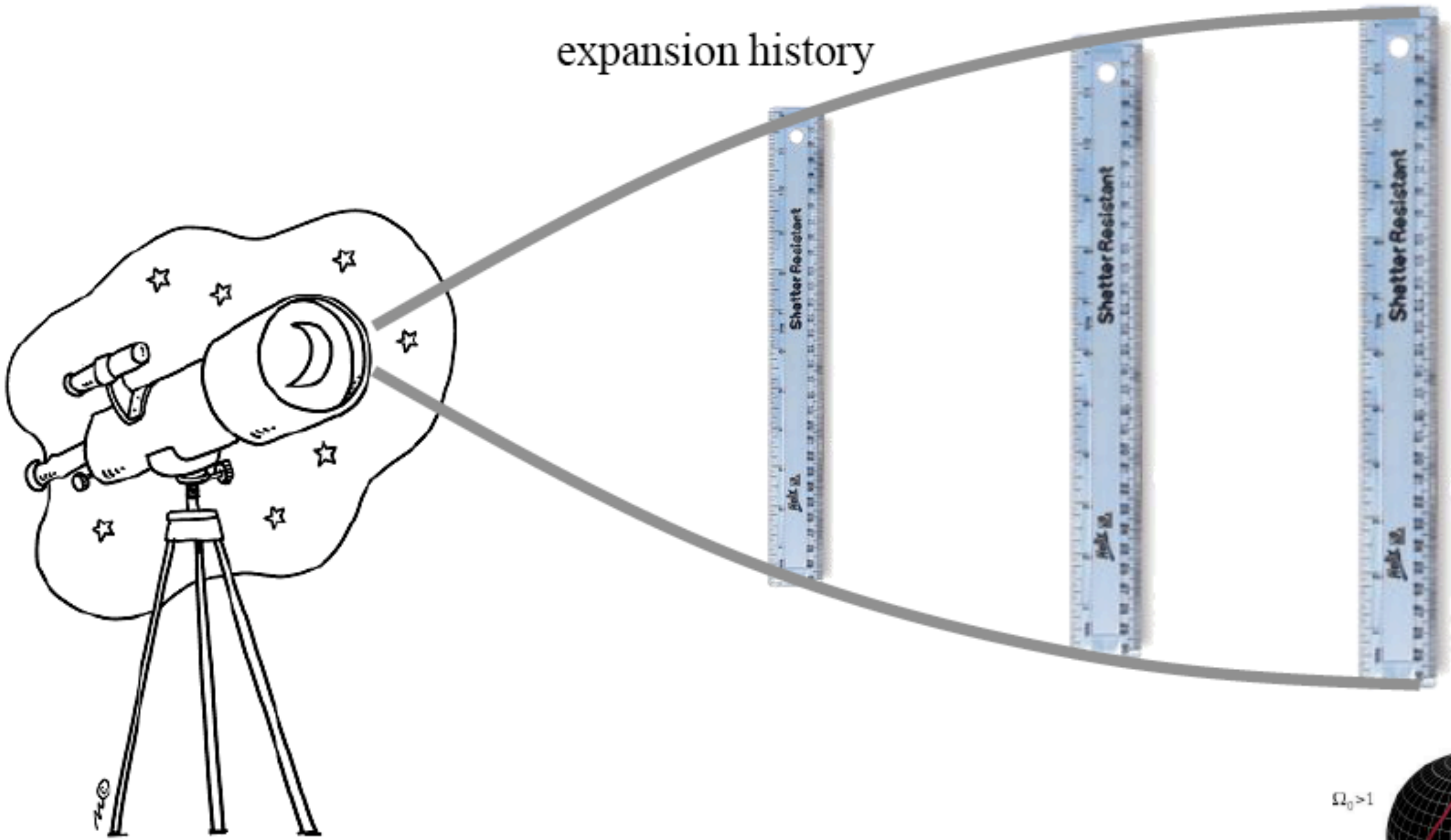


SDSS-LRG: Eisenstein et al 2005, ApJ, 633, 560

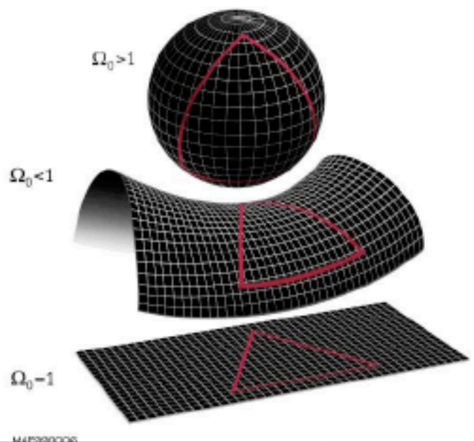


SDSS2-DR7: Percival et al 2010, MNRAS, 401, 2148

Baryonic Acoustic Oscillations: measure H(z) from redshift surveys



Give $D_A(z)$ and H(z): see Percival et al. 2010 for most recent application to SDSS and 2dFGRS

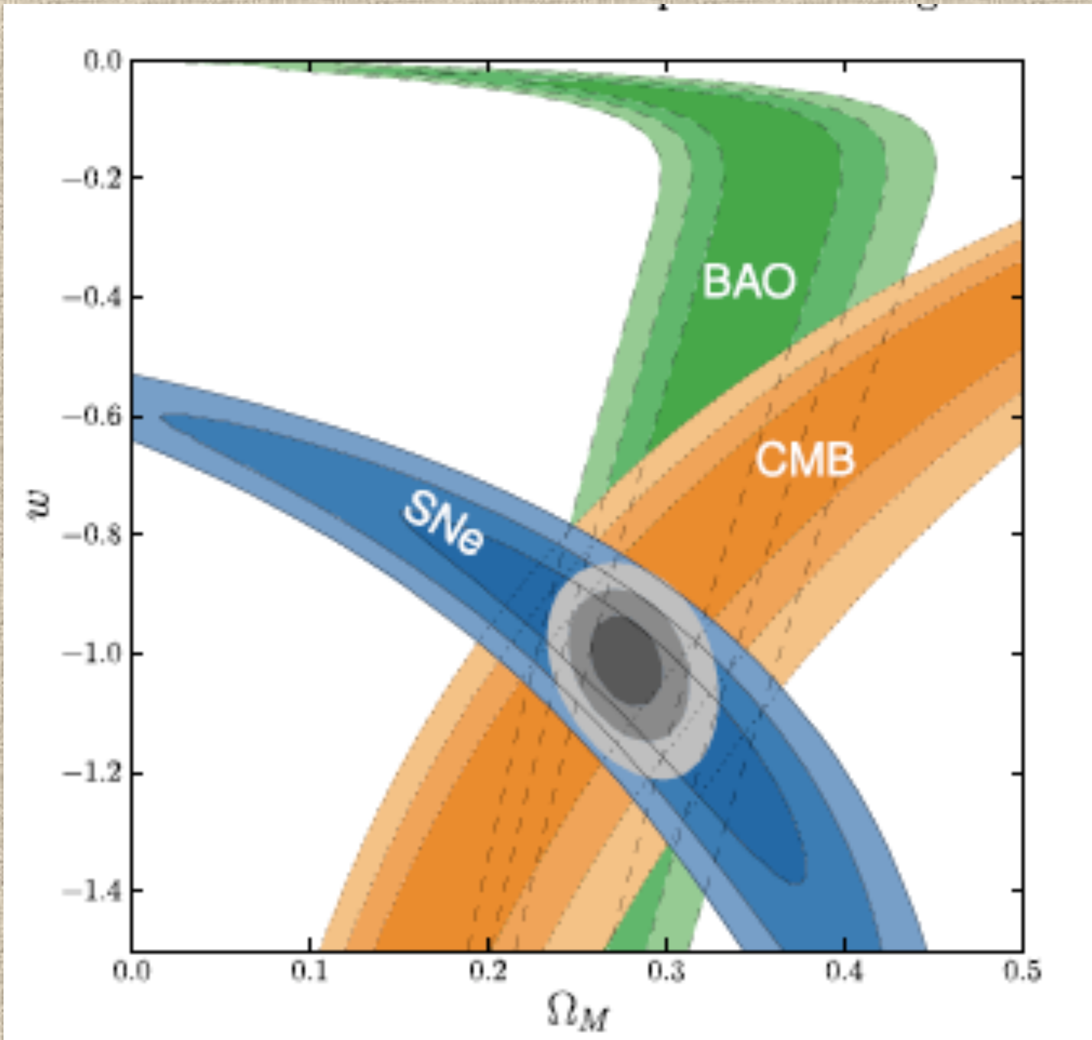


Virtues of BAO as standard ruler for cosmology

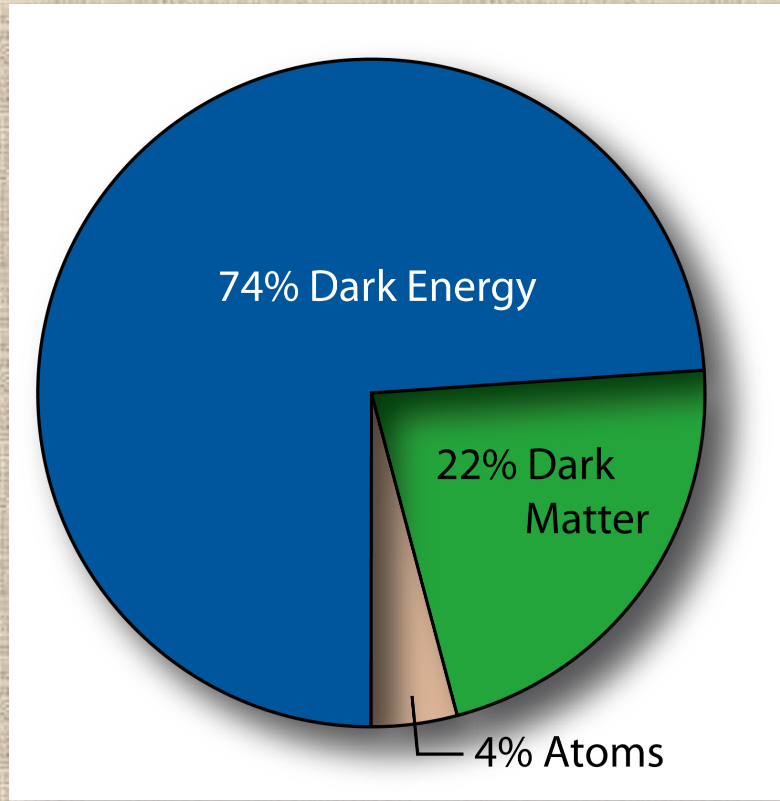
(according to D. Eisenstein)

- The acoustic signature is created by physics at z=1000 when the perturbations are 1 in 10^4. Linear perturbation theory is excellent.
- Measuring the acoustic peaks across redshift gives a geometrical measurement of cosmological distance.
- The acoustic peaks are a manifestation of a preferred scale. Still a very large scale today, so non-linear effects are mild and dominated by gravitational flows that we can simulate accurately.
  - No known way to create a sharp scale at 150 Mpc with low-redshift astrophysics.
- Measures absolute distance, including that to z=1000.
- Method has intrinsic cross-check between $H(z)$ & $D_A(z)$, since D_A is an integral of H.

Cosmic concordance: a w=-1 Universe?



Amanullah et al. 2010 (Union supernovae)



END of Lecture 1