The Great Galaxy Redshift Surveys

P J E Peebles

Einstein Professor of Science, Princeton 1984 ->

1965 prediction (with Robert Dicke) of 3K CMB; co-interpreter of the 3K radiation (Penzias and Wilson 1965)

Physical Cosmology (1971); The Large Scale Structure of the Universe (1980)

Big-bang nucleosynthesis, dark matter, dark energy, structure formation.....

Two- and n-point correlation functions, formalism, power-spectrum etc 1972 ->

Jim Peebles ~1995

What were we doing last lecture?

Hard to say. Several issues ....

1. A bit more on two-point correlation function and power spectrum.
2. The need to examine plots carefully to search for features of interest.
3. More pitfalls in power-law plots.
4. And while we're on plotting - what you missed in the signal-to-noise question (the sky!); how it relates to plotting technique.
5. The Principal Component Analysis question; model answers.
6. A note on the Runs Test.
7. The Anderson-Darling Test.
8. Final homework

The Galaxy Universe - What Happened in 1990?

(1) **The two-Point Angular Correlation Function** from the Automatic Plate Measuring galaxy survey (Maddox et al. 1990):

– there is no way that a CDM model with Ω_{matter} = 1.0000 can describe the large scale structure.

(2) The death of CDM models?

(3) Or $\Omega_{matter} = 0.3 + \Omega_{\Lambda} = 0.7$?

- the brilliant paper by Efstathiou, Sutherland and Maddox (Nature 1990)

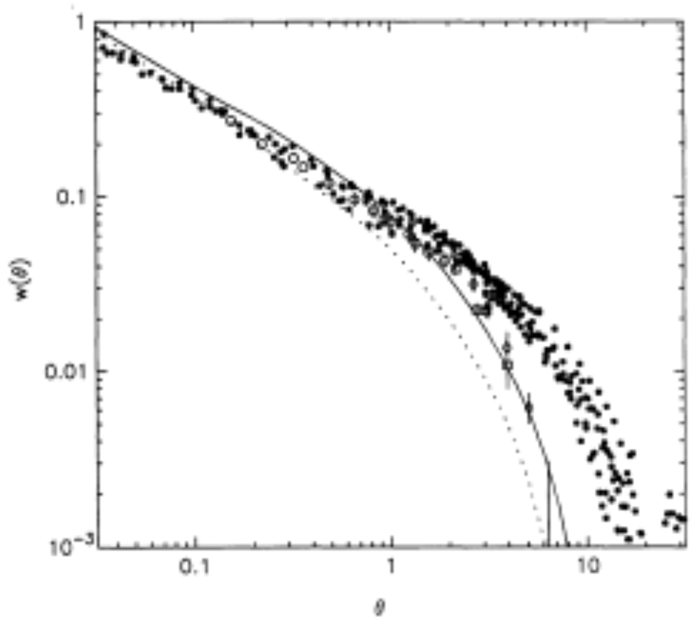


Figure 3. The filled circles show our estimates of $w(\theta)$ in six 0.5 mag slices (Fig. 2b) scaled to the Lick depth. The open symbols show $w(\theta)$ for the Lick catalogue from fig. 5 of Groth & Peebles (1977); the symbols have the same meaning as in their figure. The dotted and solid lines show computations of $w(\theta)$ based on the CDM model with $h = 0.5$ and $h = 0.4$, respectively, as discussed in the text.

What Happened in 1997 - 2002?

Our Universe changed direction!

(1) **The Hubble diagram for SN Ia** (Riess et al. 1998, Perlmutter et al. 1999):

- the modern-day Universe is accelerating =>

  Dark Energy, or a Cosmological Constant, $\Omega_\Lambda = 0.7$

(2) The first direct detections of CMB fluctuations via BOOMERanG (di Bernardis et al. 2000) and MAXIMA (Hananay et al. 2000)

- detection of the first acoustic peak =>

  Ω_{matter} **(0.3) +** Ω_Λ **(0.7) =** Ω_{total} **= 1.00000000...**

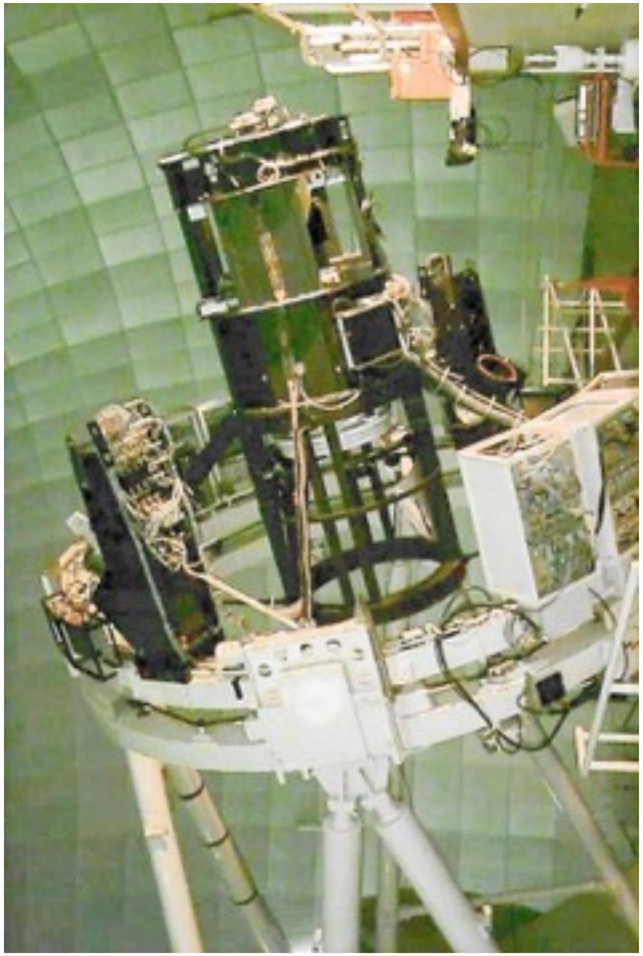
So, what could galaxy surveys add?

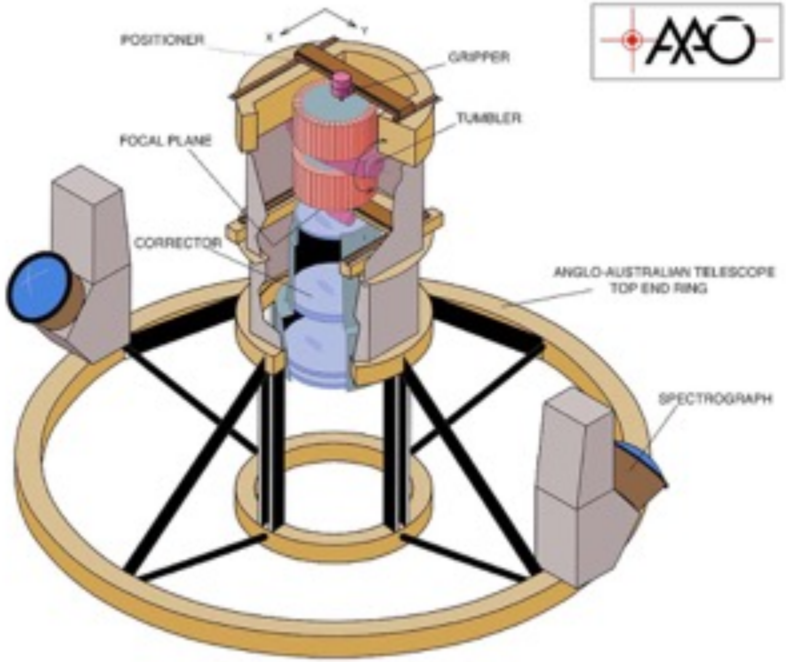
The 2dF Galaxy Redshift Survey (2dFGRS)

1997 - 2002

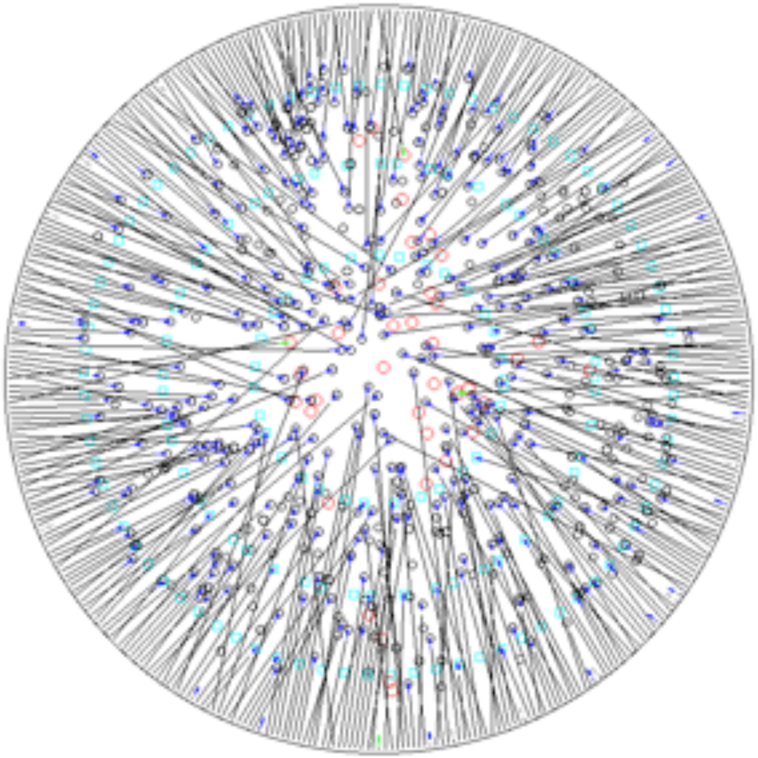
The Anglo-Australian Telescope: 3.9 m equatorial mount (the last!) at Siding Spring Observatory, Coonabarabran, NSW, Oz

2dF Top End Ring, AAT

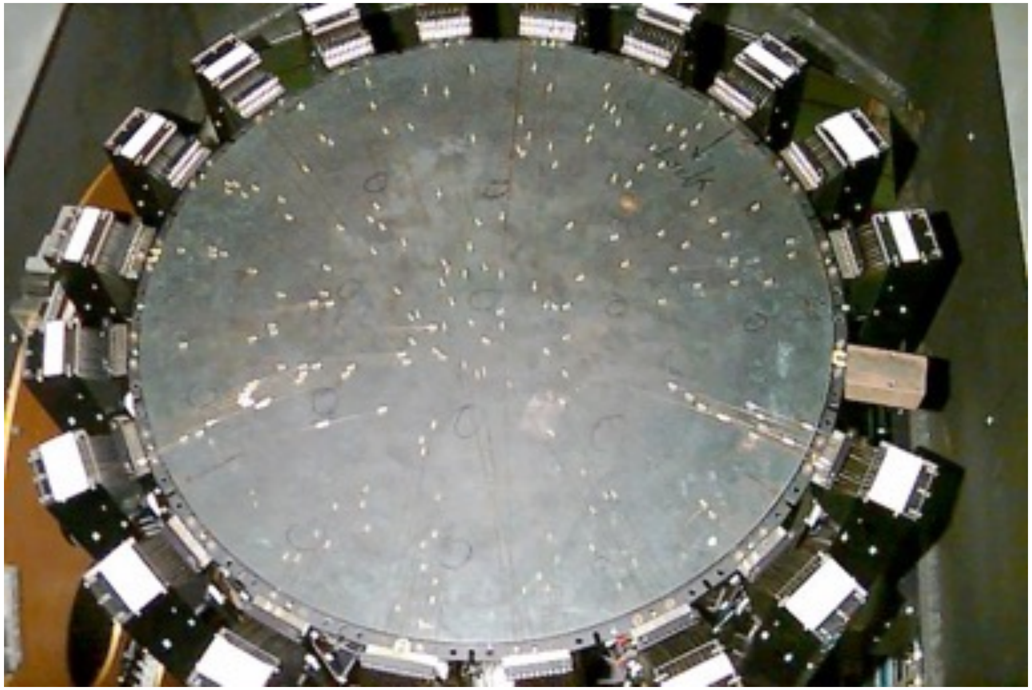




The AAT 2dF Prism-Fibre System

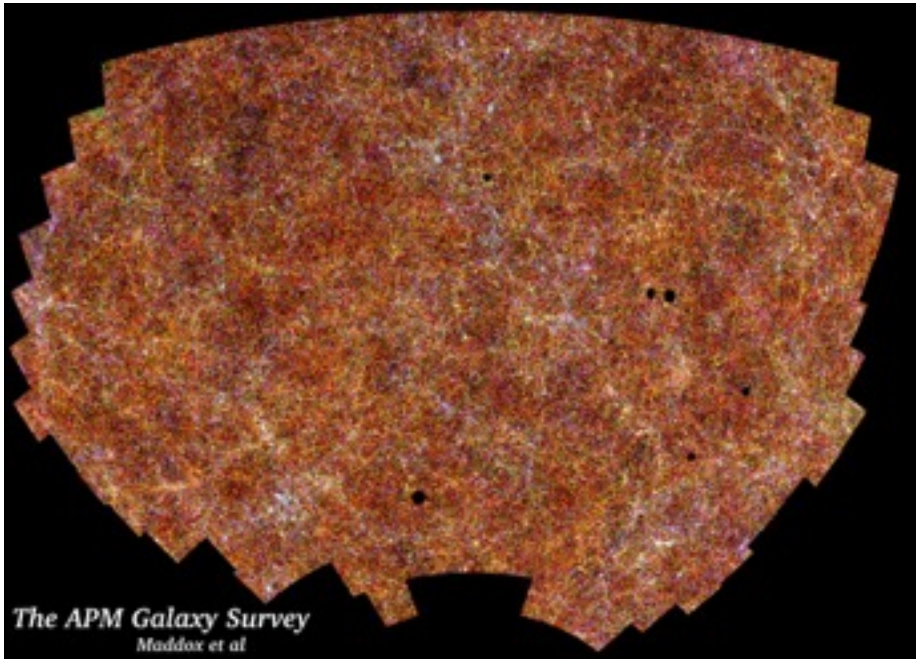


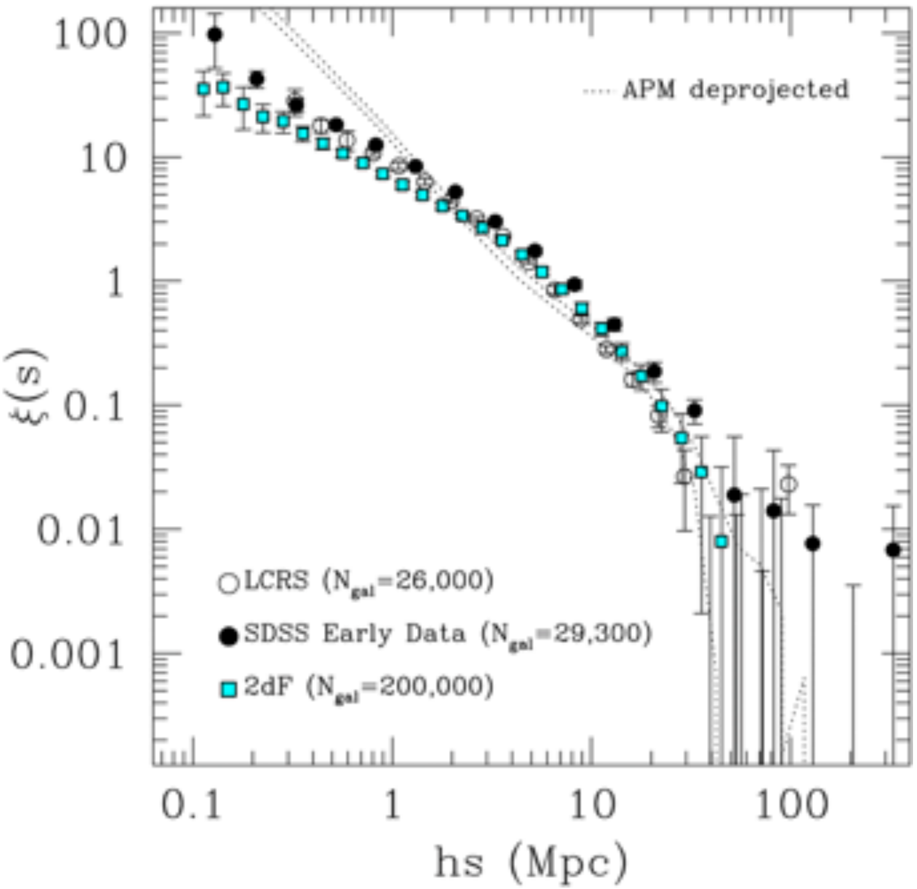
Schematic



The fibre-positioning magnetic plate

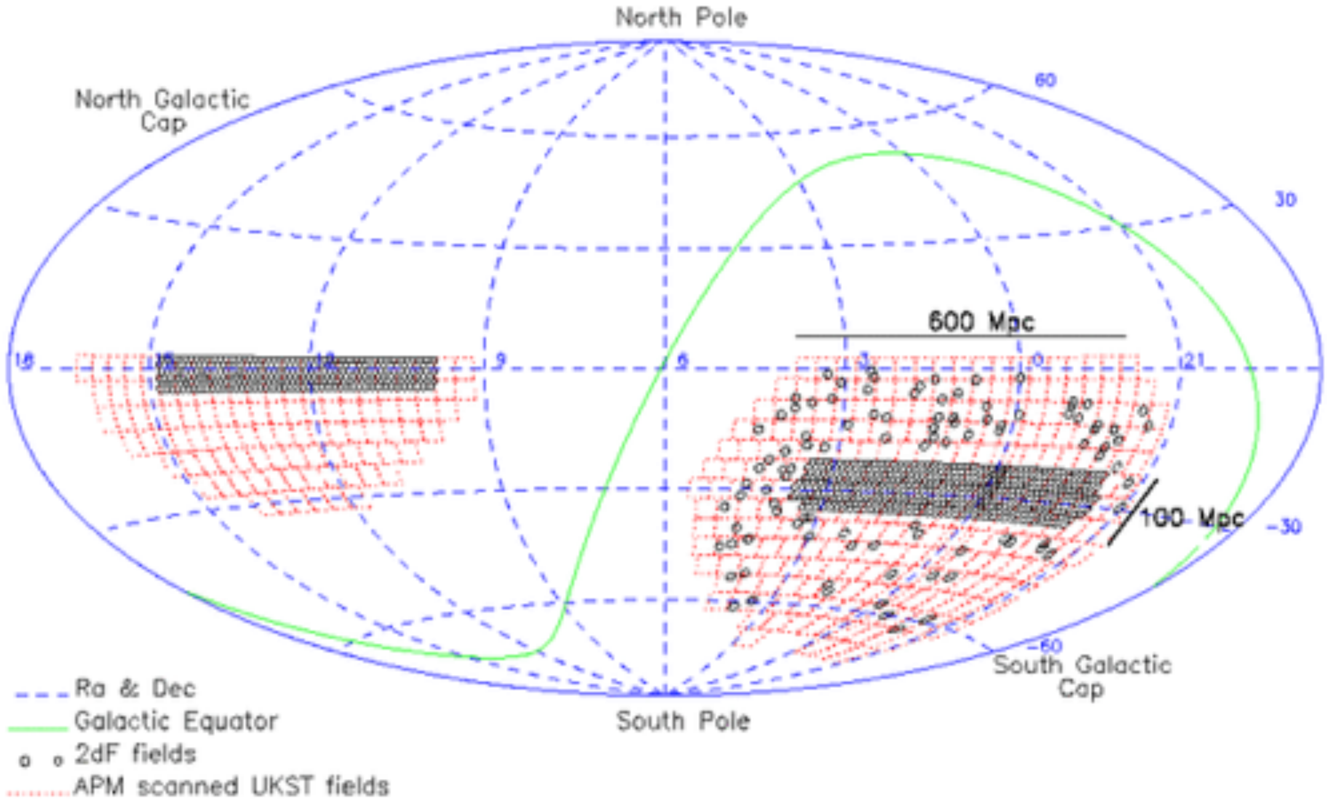
It started with the APM Galaxy Survey ....



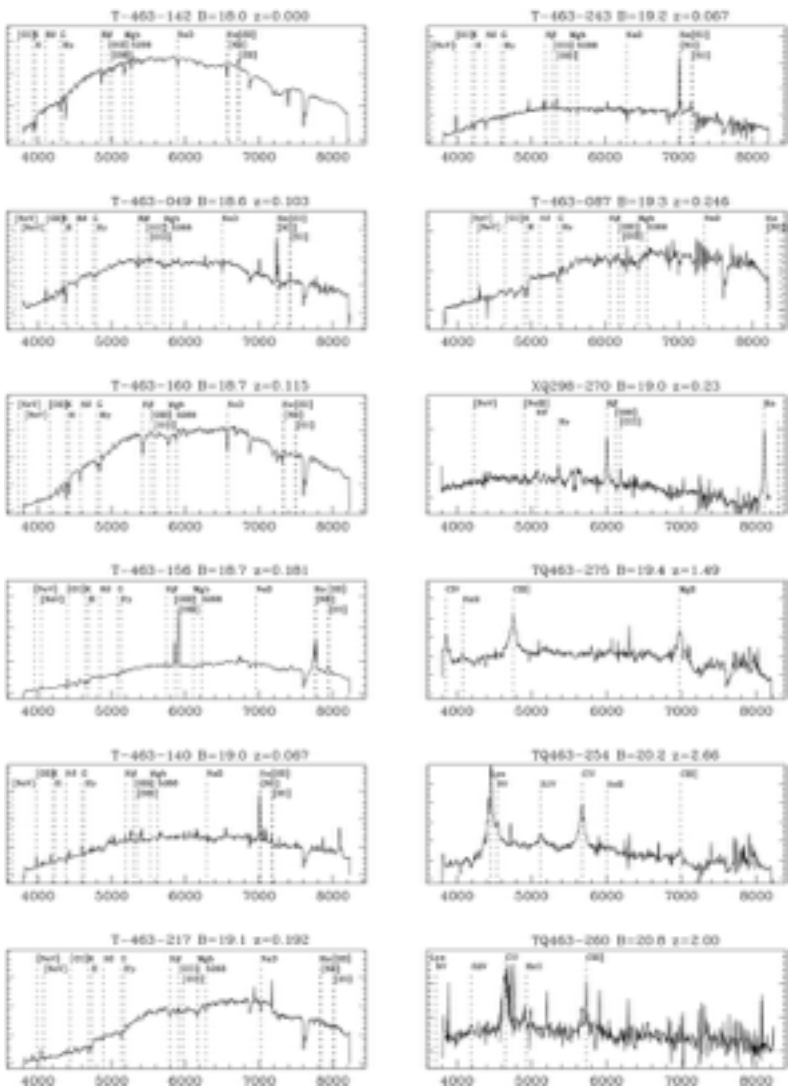


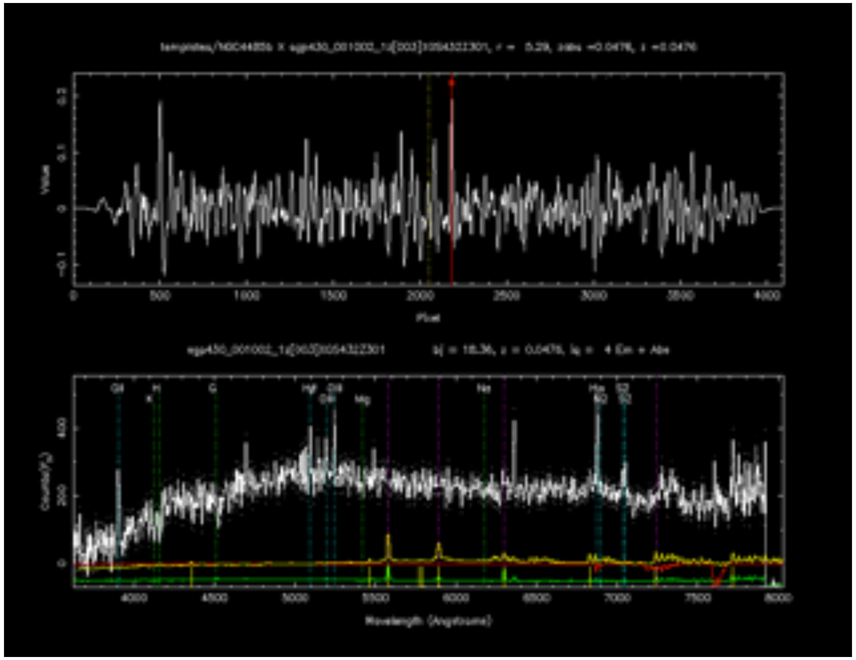
Left: UK Schmidt Telescope deep survey, 6.5x6.5° J (blue) plates, digitized with the Automatic Plate Measuring machine at Cambridge. Right: 2-point spatial correlation function, from the APM galaxy survey, followed by 2dF GRS and then SDSS.

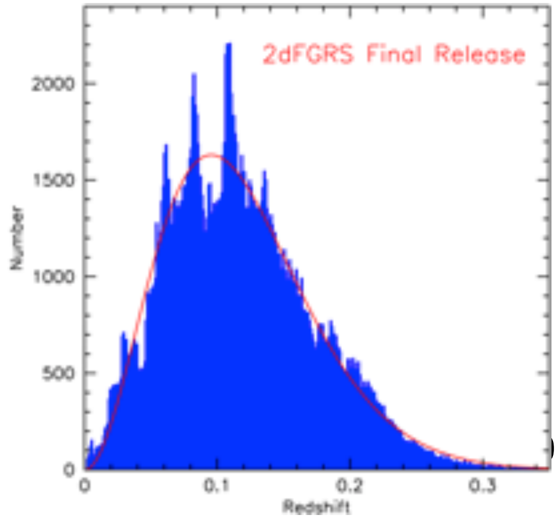
2dF GRS Sky Coverage



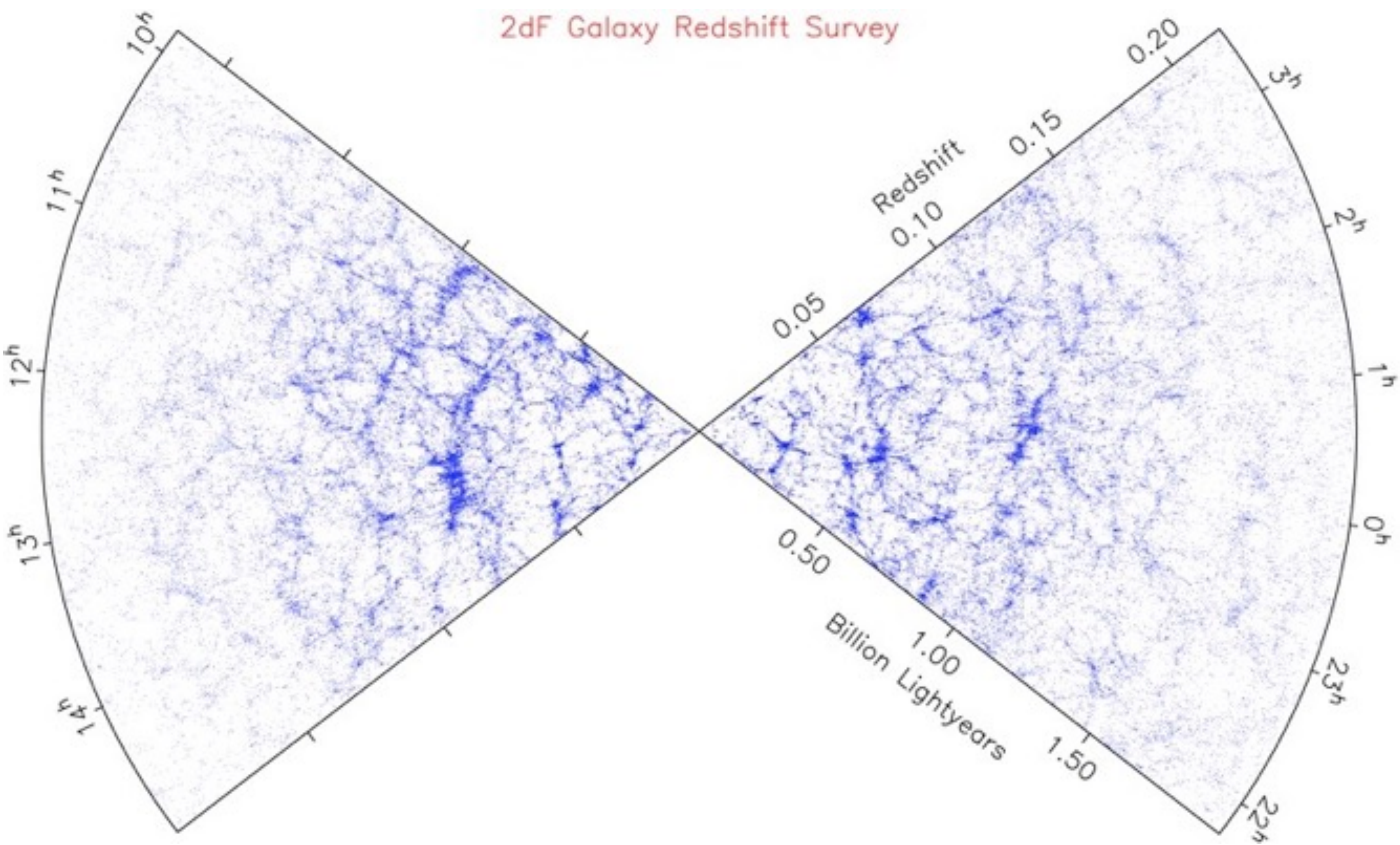
2dF GRS - data examples



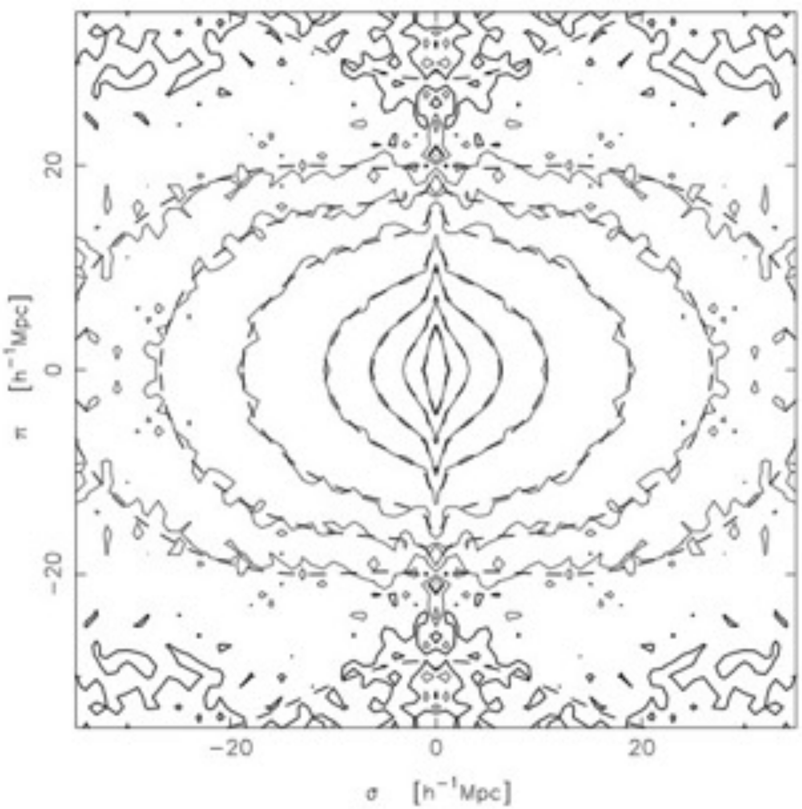




2dF GRS 'Cone' Diagram

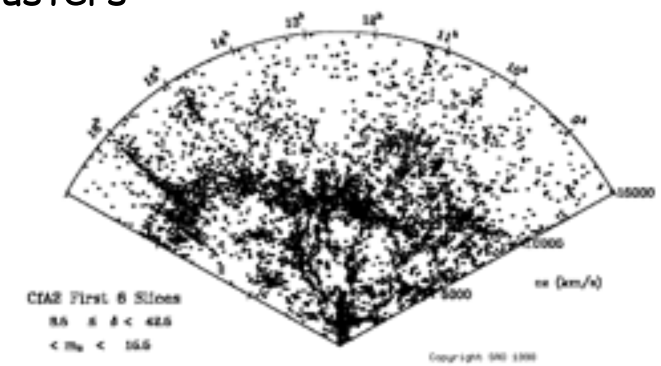


3-D Two-Point Correlation Function



$\xi(\sigma_t, \pi)$ – 2-pt correl fn with σ_t the transverse distance and π the 'redshift' distance (Hawkins et al 2003)

Effect 1: 'Fingers of God', due to the peculiar velocities of galaxies in clusters



Effect 2: the 'Kaiser effect' – the ellipticity describes the peculiar velocities of galaxies bound to a central mass as they undergo infall. The peculiar velocities are coherent, not random, towards the central mass

2dF and Cosmological Parameters

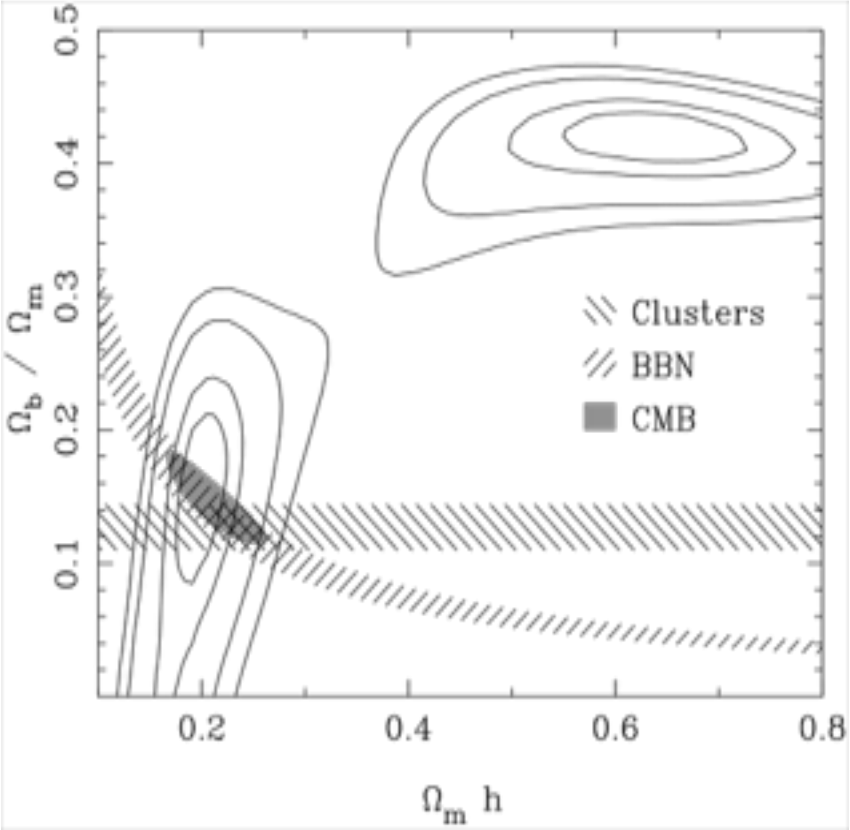
Flattening governed by $\Omega_m^{0.6}/b$, where **b is bias parameter**.

Need **Power Spectrum of 2dF GRS** to disentangle this (Percival et al 2001)

Shape of PS as expected for evolved linear density perturbations in a λCDM universe

Bayesian analysis of this shape **=>**

One further assumption: $n_s = 1$



2dF and Cosmological Parameters - Tools

Note the tools used:

Bayesian analysis

PS - Nyquist criterion for sampling

- window function

- correlation matrix

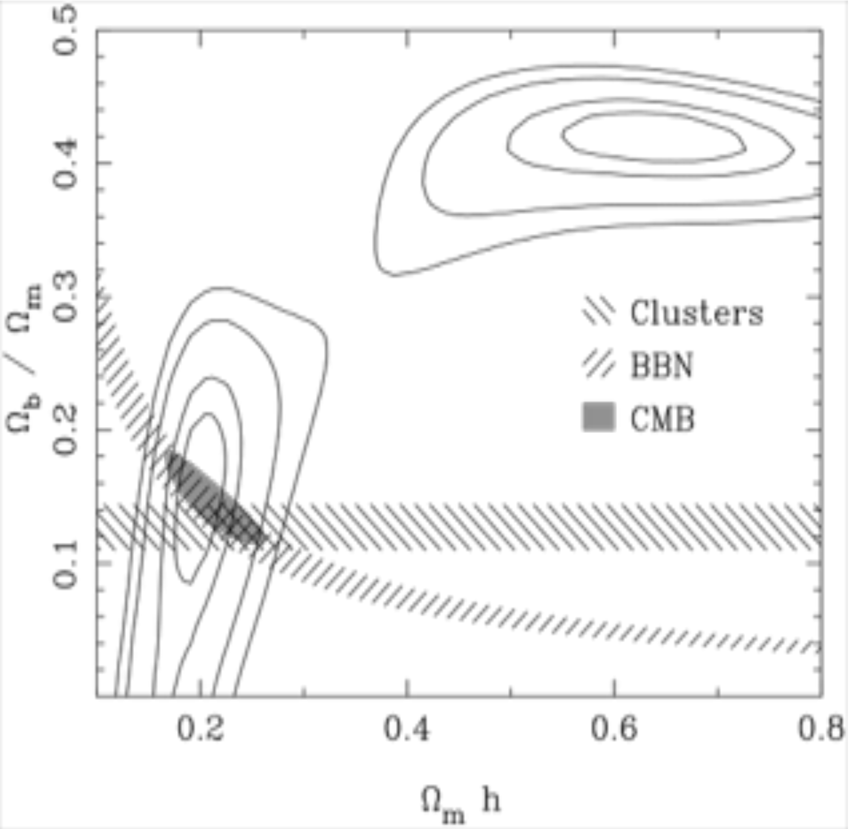
- priors (on h, and maybe Ω_m?)

Use of other data via likelihoods:

- most valuable if 'intersects'

- marginalization / contour form

Techniques: simulation, simulation, simulation....from APM sensitivity map, galaxy redshift distribution...



2dF GRS Achievements

240,000 new galaxy redshifts

Gravitational instability picture securely demonstrated

Mass Fraction determined

Baryon fraction determined

Bias parameter – and demo that it depends on galaxy luminosity

Derivation of luminosity functions for different galaxy types

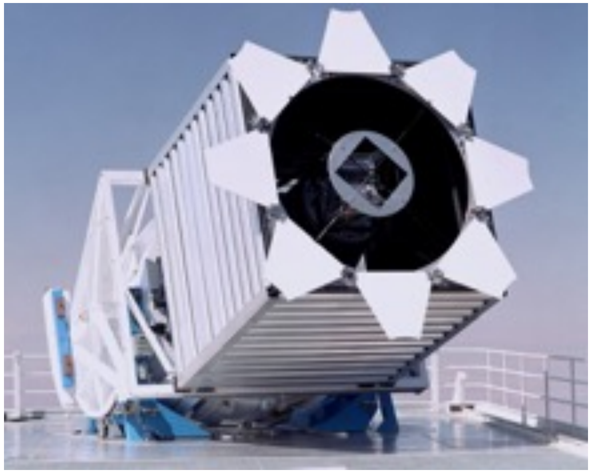
Cosmic evolution of these luminosity functions

Evolution of relatively low-power radio AGN

Upper limit on the neutrino mass fraction

(With early WMAP results) constraints on DE equation of state

2.5-m SDSS Telescope at Apache Point



2.5 m SDSS Telescope

6 columns of 5 - 2048x2048-pixel CCDs

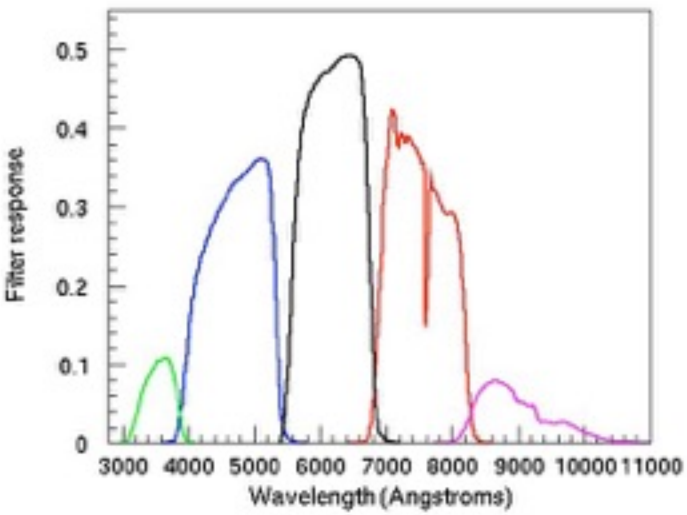
r, I, u, z, g filters cover each 5 CCDs in each column

Drift scan mode – CCD read out at same rate as telescope moves on great circle; images of objects move along CCD columns at the read rate.

Takes an object 54 sec to move across CCD => 54 sec exposure time

Spectra taken via plug plates, 3 deg across, taking up to 1000 fibres

Beamsplitter takes signal to red and blue end spectrographs



SDSS Luminous Red Galaxy Power Spectrum

LRGs – old red ellipticals with deep H&K breaks, excellent photo-z's

600,000 of these, out to redshifts of 0.6

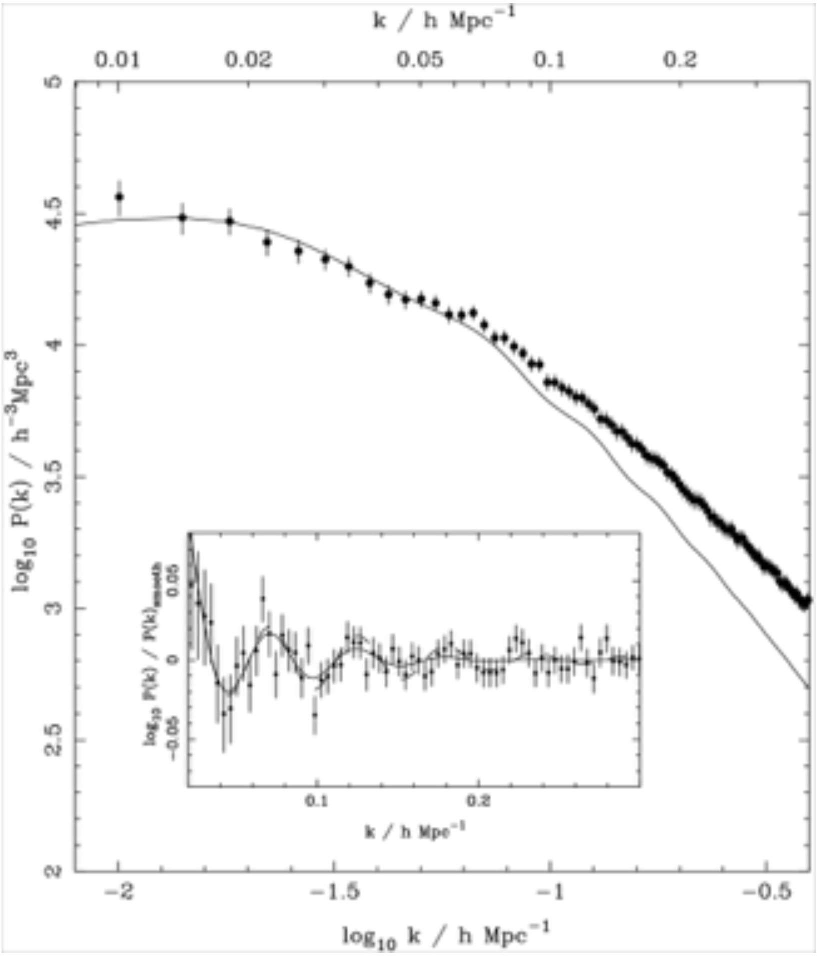
volume sampled 1.5**h**$^{-3}$ Gpc^3

Spatial frequencies 0.005 < k < 1**h** Mpc^{-1}

Advances in technique of PS measurement; e.g. Tegmark et al. (2006): PS estimators constructed to minimize error bars according to information theory,

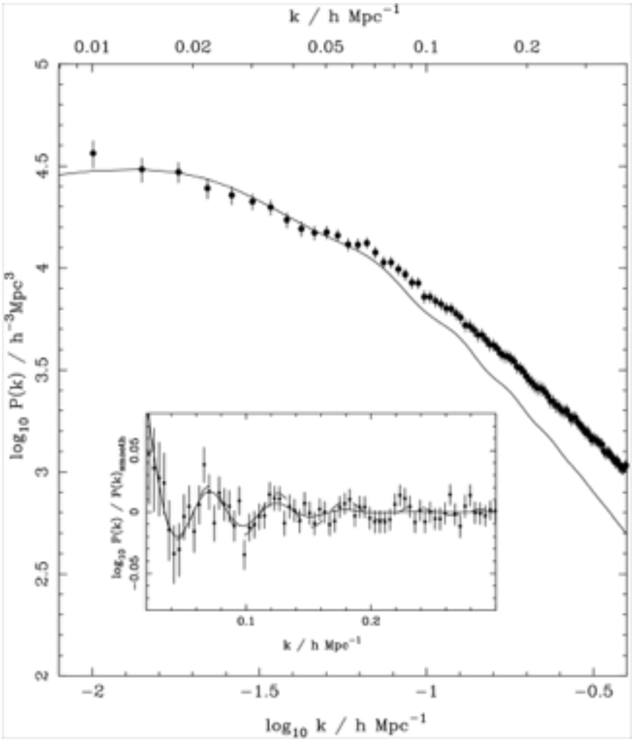
=> independent measurements along PS; but cpu time ~1 yr.

Curve shows different model obtained from WMAP cosmo parameters; discrepancy now resolved.

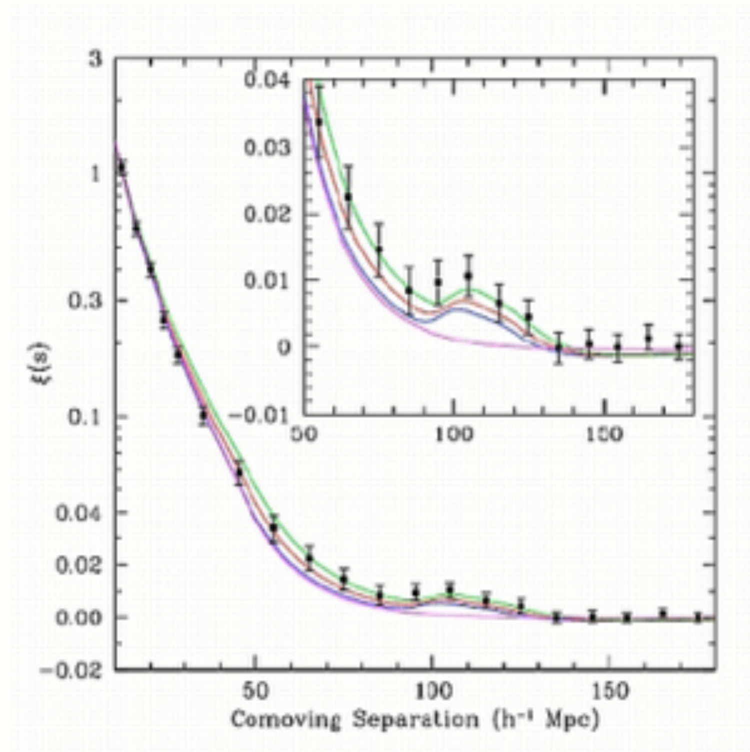


Percival et al. 2007

Baryon Acoustic Oscillations!



Percival et al. 2007



Eisenstein et al. 2005

BAO imprinted on matter-photon plasma at early epochs, but photon-frozen at epoch of recomb (z~1000). Then photons free-stream; but matter imprint remains.

Oscillations are seen in PS of the LRGs (Percival et al 2007), just.

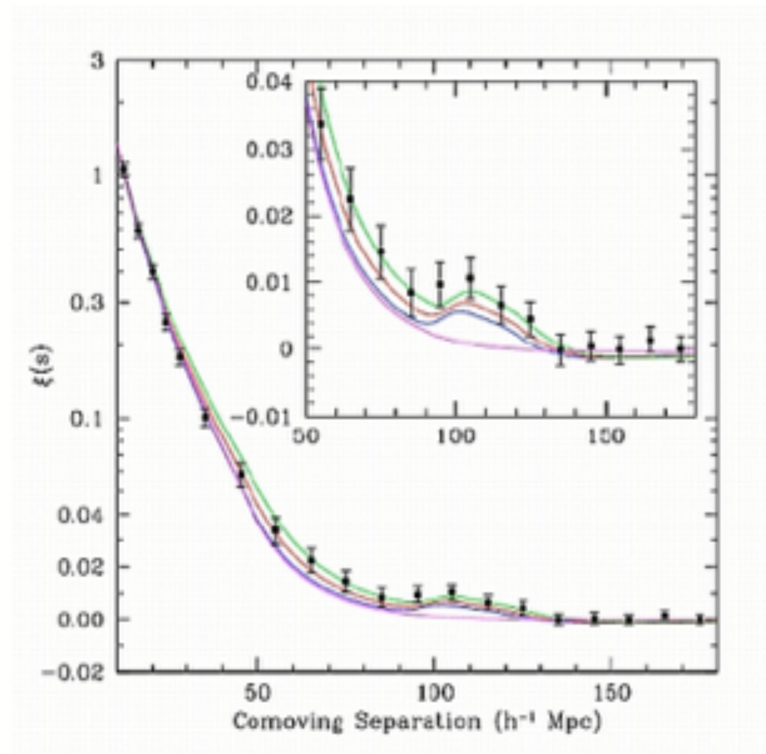
2-pt correlation function! This ~FT of the PS shows the single-peak feature at 3.4σ.

Baryon Acoustic Oscillations - Significance

1. Scale and amplitude agree with λCDM prediction from CMB power spectrum

2. The imprint at z~0.35 (mean z of LRGs) is fundamental – shows that (i) oscillations originally occur at z >1000, and (ii) that they survive to be detected at ~now.

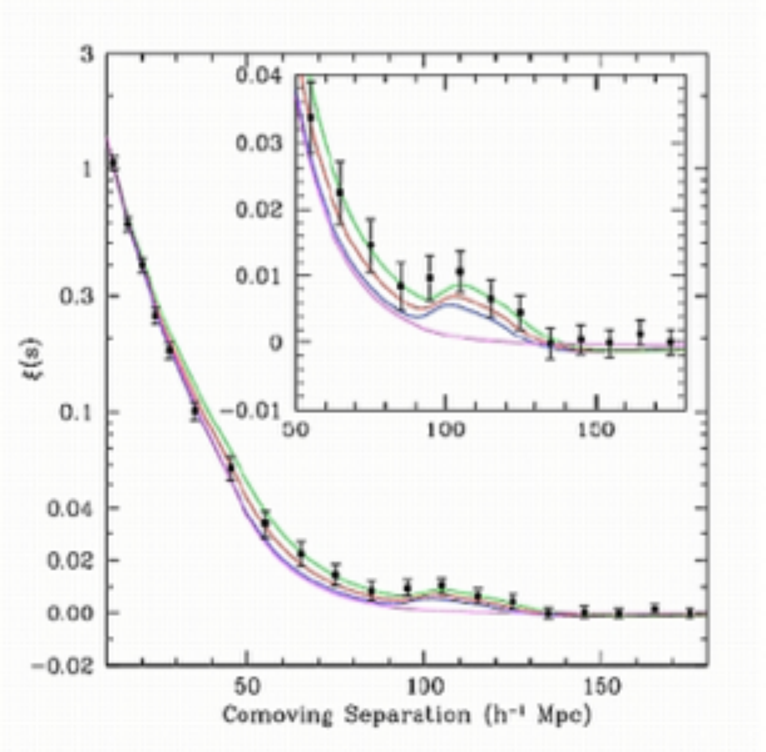
3. The small amplitude requires dilution of the photon-baryon fluid at z~1000 by matter not interacting with it, i.e. Dark Matter, direct proof.



Eisenstein et al. 2005

Baryon Acoustic Oscillations - Significance

4. This imprint in the late-time correl fn by baryonic physics at epoch of recomb is a brilliant cosmo ruler. It measures the acoustic scale at z~0.35 for the LRG sample.



This can be compared directly with the angular scale of the CMB anisotropies (z~1089) to determine a distance ratio, a ratio that relies only on well-understood linear perturbation theory of the recomb epoch.

=> spatial curvature Ω_K = -0.010±0.009 => flat universe => direct geometrical evidence for Dark Energy

SDSS Accomplishments

1. Detection of the baryon acoustic peak in the clustering of galaxies

2. Mapping of streams of stars left from galaxy mergers in the Milky Way, as well as the discovery of many new dwarf companion galaxies of the Milky Way

3. The most distant quasars known

4. Cool brown dwarfs, the largest sample of spectroscopically confirmed white dwarfs (by far), and many other classes of unusual stars