Large-scale structure as a probe of dark energy

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Question

Who was the greatest actor to portray James Bond in the 007 movies?

a) Sean Connery
b) George Lasenby
c) Anthony Lasenby
d) Roger Moore
e) Timothy Dalton
f) Pierce Brosnan
g) Daniel Craig

Dark Energy

Lots of well-defined questions:

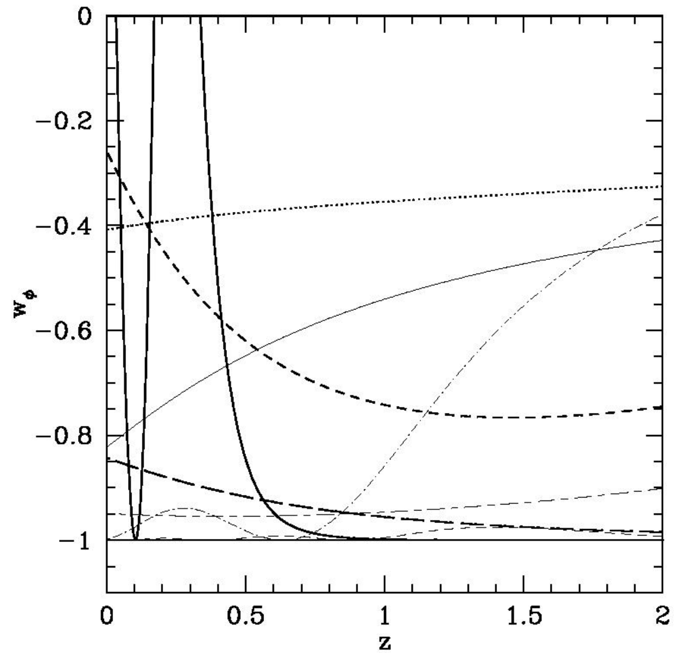
Is it a cosmological constant?

$$w = \frac{p_\Lambda}{\rho_\Lambda} = -1$$

Does w vary with time?

Does DE cluster?

Is it vacuum energy or modification of gravity?



Stress-Energy:

$G_{\mu\nu} = 8\pi G\,[T_{\mu\nu}(\text{matter}) + T_{\mu\nu}(\text{new})]$

Gravity:

$G_{\mu\nu} + f(g_{\mu\nu}) = 8\pi G\, T_{\mu\nu}(\text{matter})$

Albrecht & Weller 2002,
astro-ph/0106079

constraining dark energy

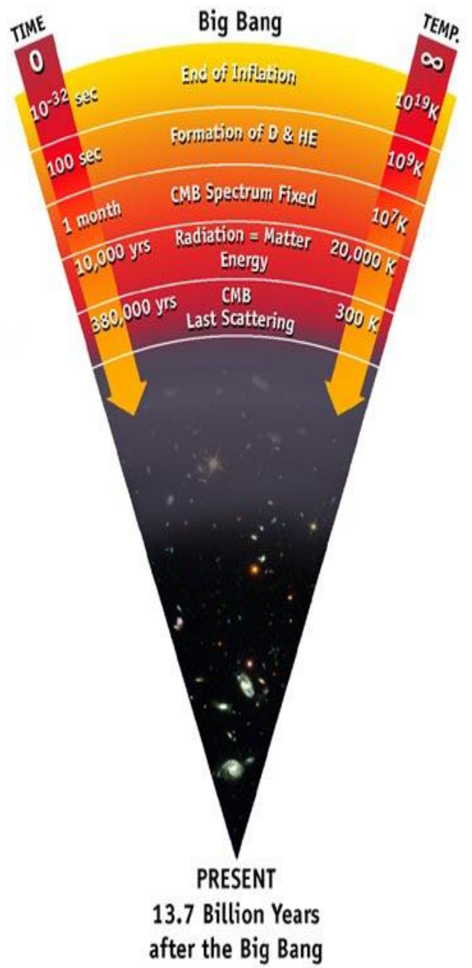
Two key ways of constraining dark energy:

1. build-up of structure (constrains DE form)
   - Mass function through cluster counts
   - Growth rate from weak lensing
   - Growth rate from merger rates/clustering amplitude
2. distance-redshift relation (constrains DE Equation of State *w*)
   - standard candles from SN-Ia
   - Standard rulers from Baryon Acoustic Oscillations (galaxy clustering)
   - Standard rulers from general clustering pattern (weak lensing)
3. Combined constraints
   - ISW effect (cross correlation of CMB & LSS)
   - Weak lensing constraints on structure
   - Strong lensing constraints on structure

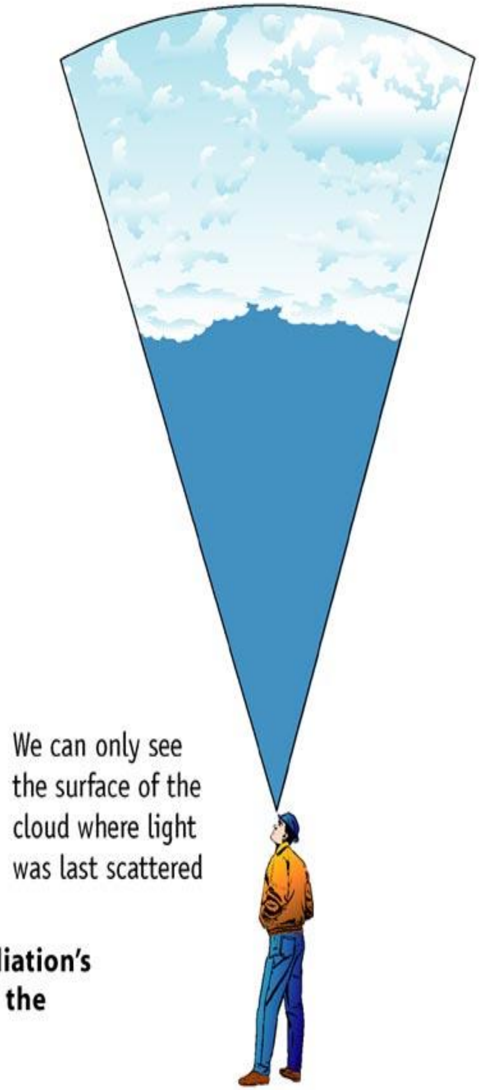
Focus on constraining cosmology using galaxy clustering

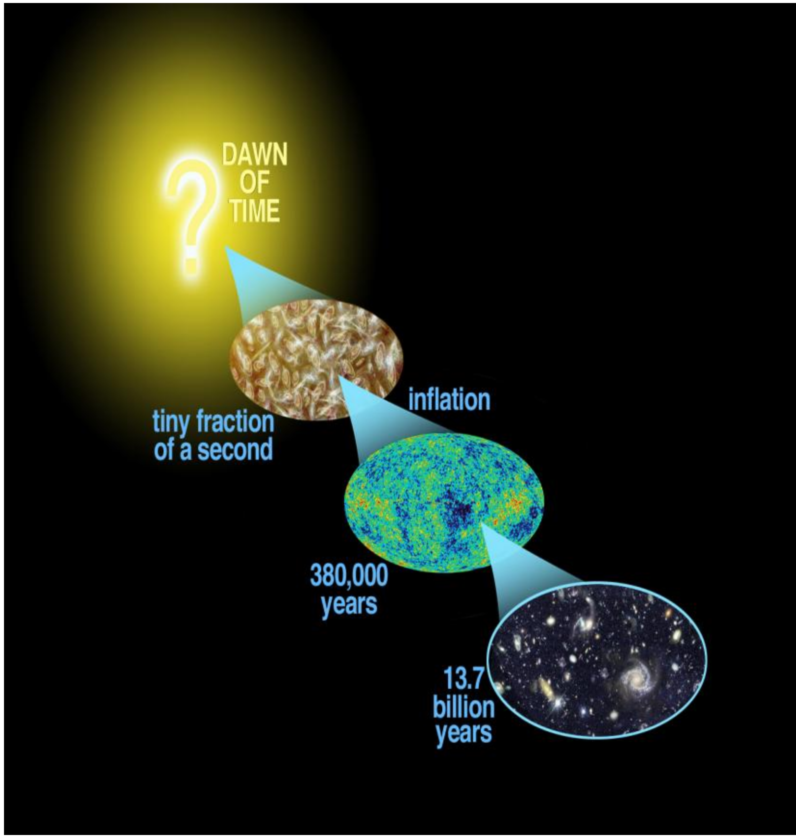
Cosmic Microwave Background

The cosmic microwave background

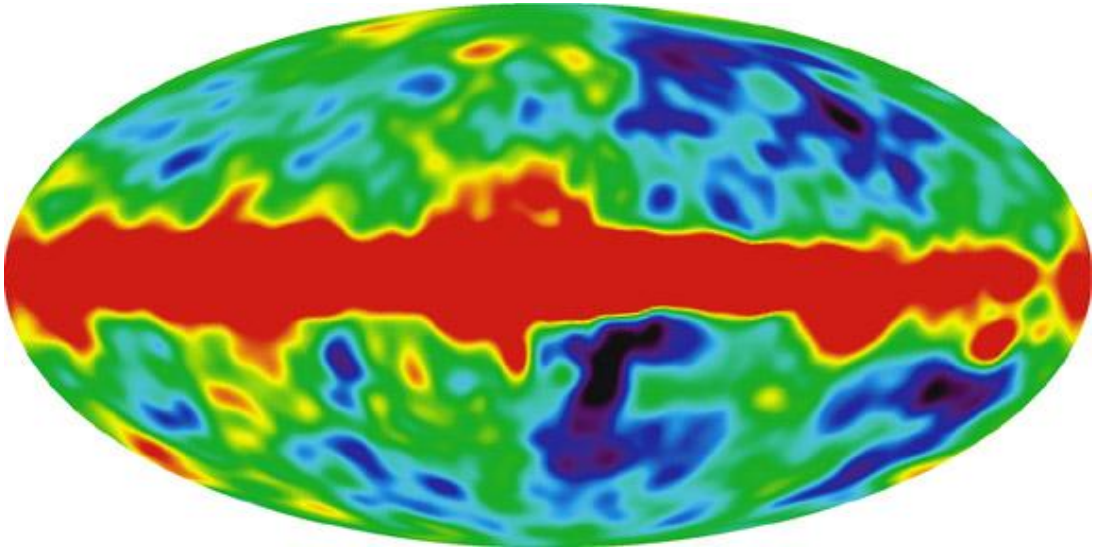


The cosmic microwave background Radiation's "surface of last scatter" is analogous to the light coming through the clouds to our eye on a cloudy day.



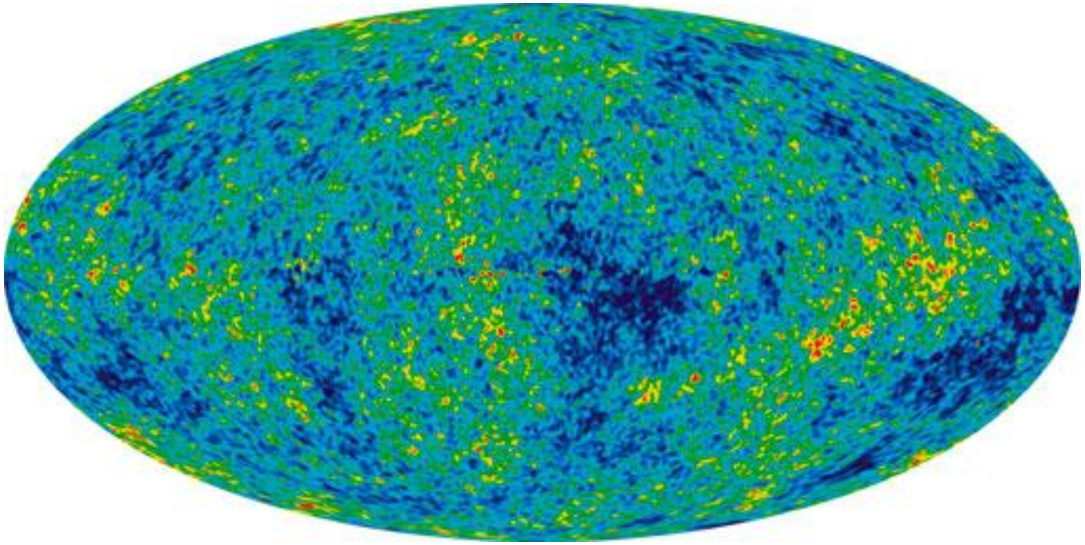


Change in CMB observations in the last 10 years

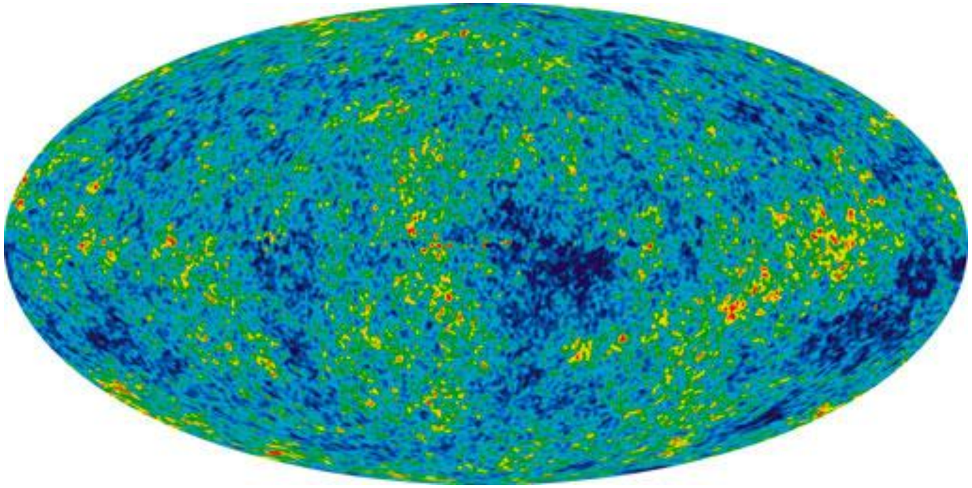


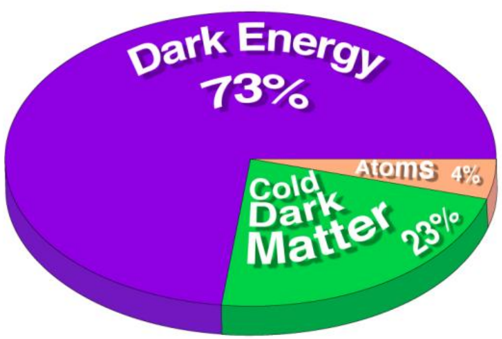
Fluctuations in the CMB: as measured by COBE satellite in 1992

Fluctuations in the CMB as measured by WMAP satellite in 2001

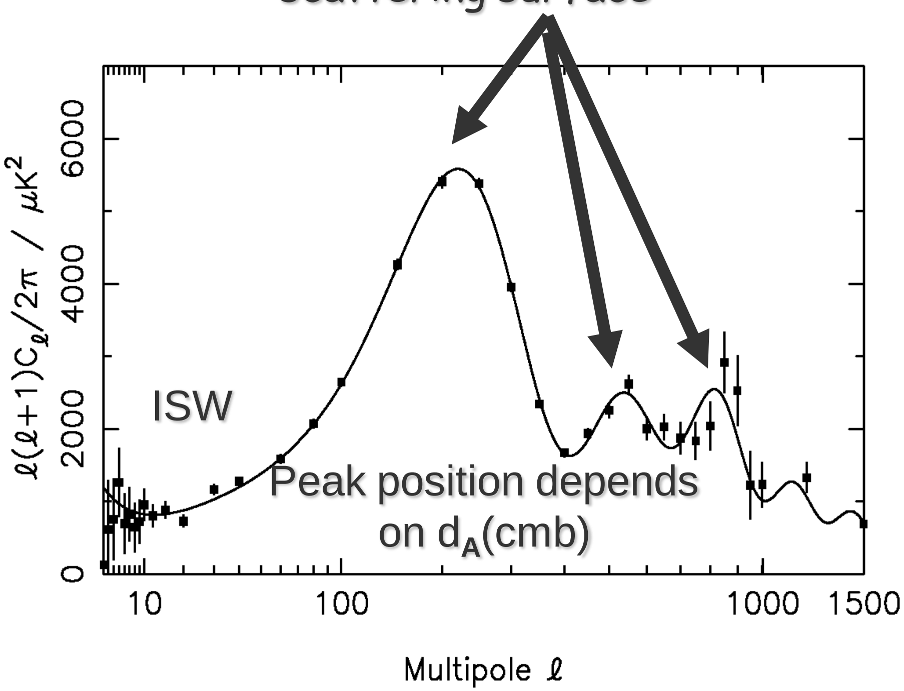


CMB only weakly dependent on dark energy



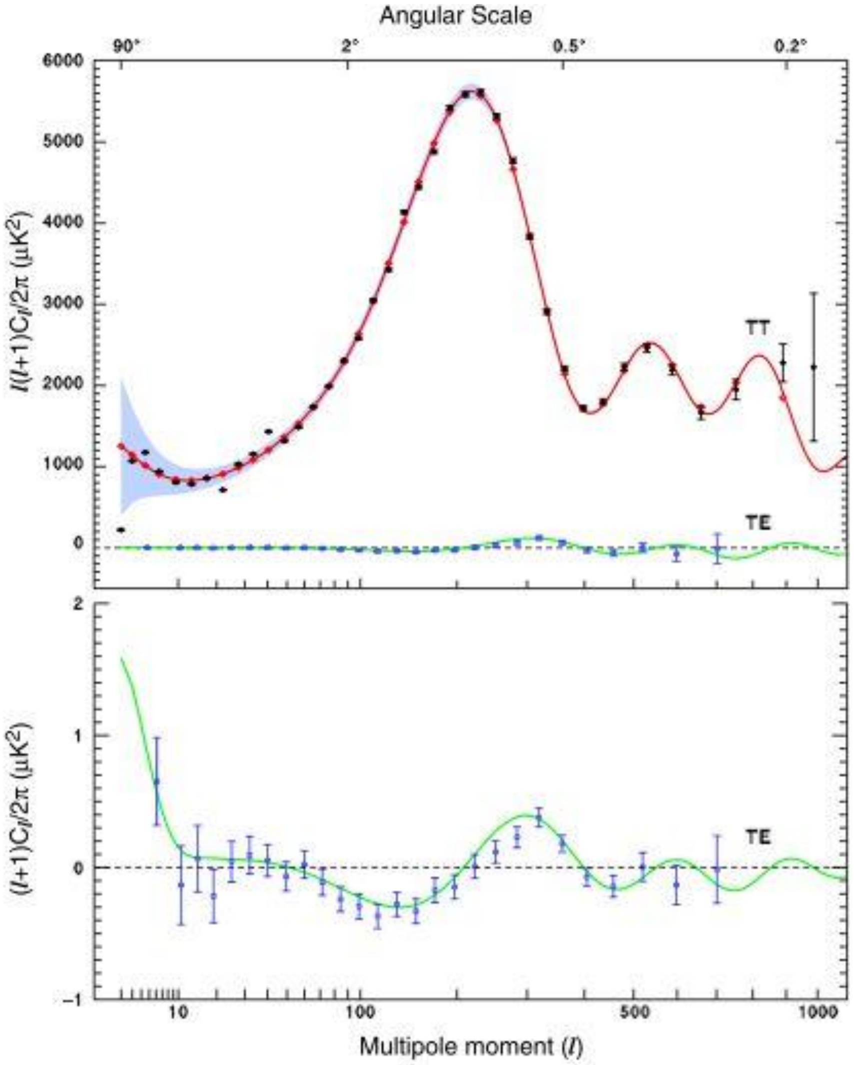


Baryon oscillations frozen into last scattering surface



CMB good measurement of Ω_m, Ω_k and H_0

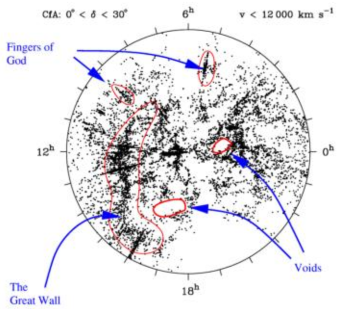
CMB Polarisation



- Polarisation measures bulk motions on last scattering surface
- Gives important information as to nature of perturbations (must be Adiabatic, not Isocurvature or Causal seeds)
- Models of dark energy with a sudden transition in w have an enhanced ISW effect, degenerate with τ, optical depth to reionisation (Corasaniti et al 2004)

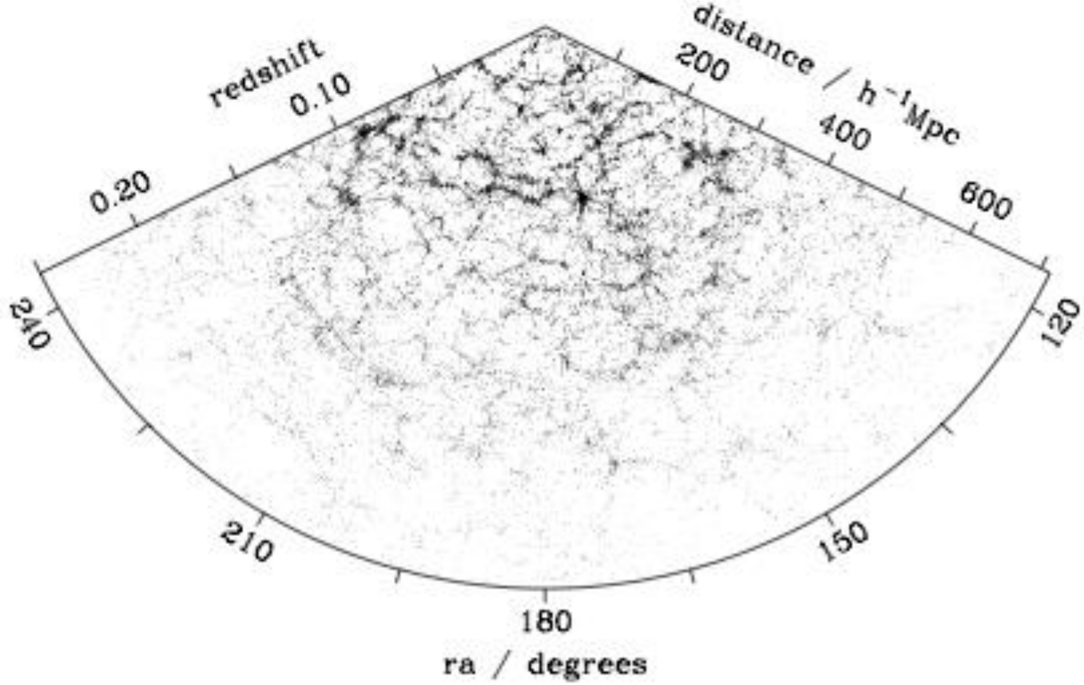
Galaxy redshift Surveys

Redshift survey progress



mid-1980s: few thousand

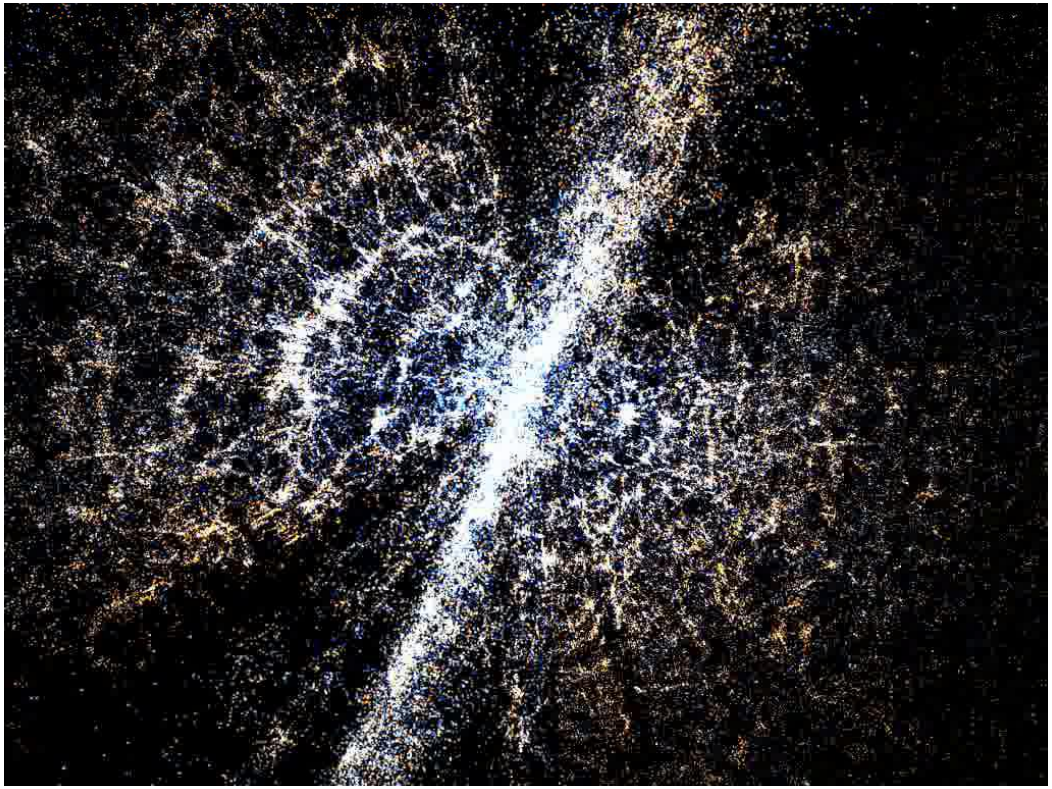
Now SDSS + 2dFGRS: soon 1 000 000



only ~2,000,000 z < 0.1: no more big local leaps

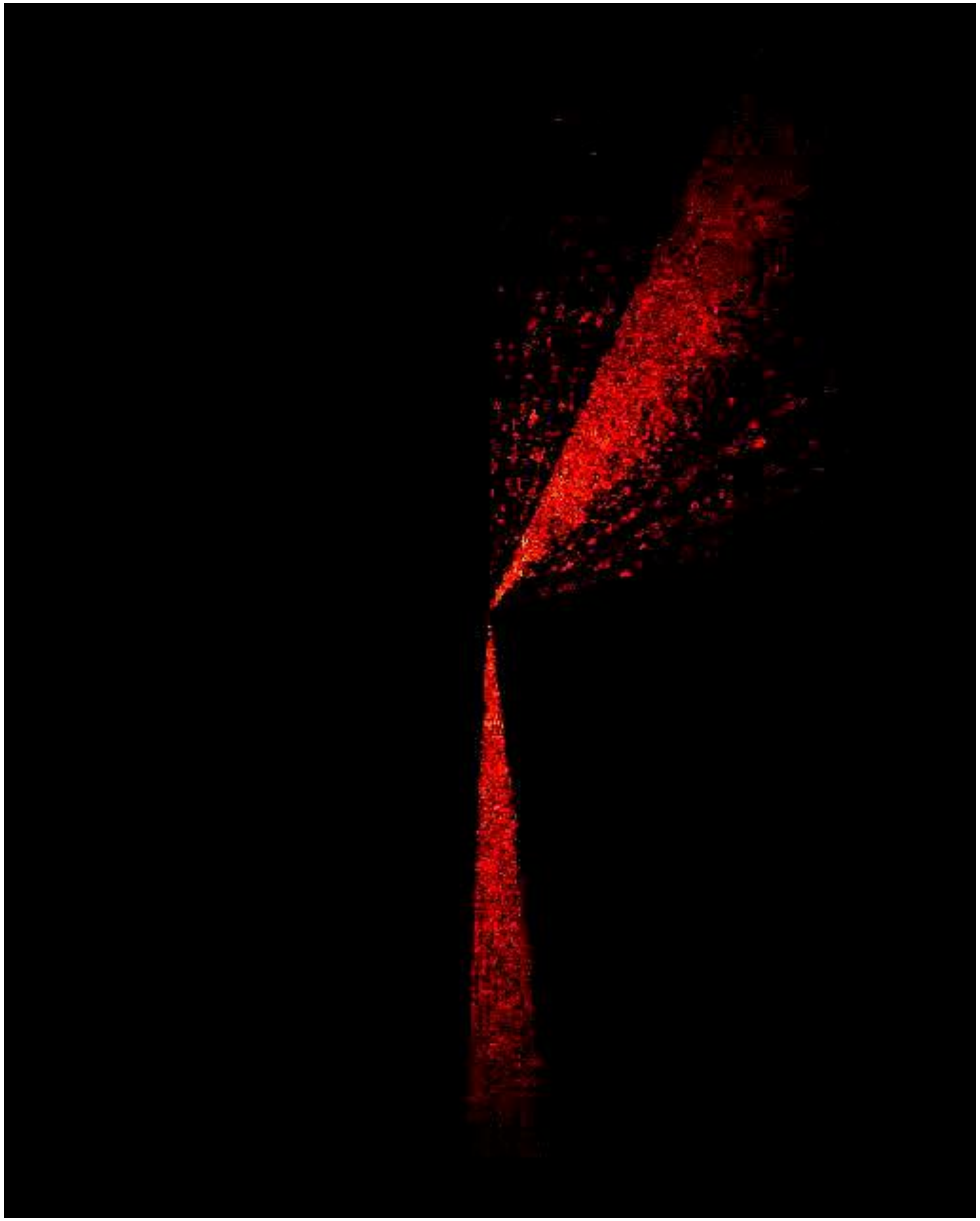
Sloan Digital Sky Survey (SDSS)

- collaboration of 200 scientists in 14 institutions
- ongoing survey will measure redshifts for 1000000 galaxies in the local Universe (r-band selection)
- also observed ~60000 luminous red galaxies out to higher redshift
- 4th data release (DR4) just made public with ~400000 redshifts



DR6 data now public: www.sdss.org

2dF Galaxy Redshift Survey (2dFGRS)

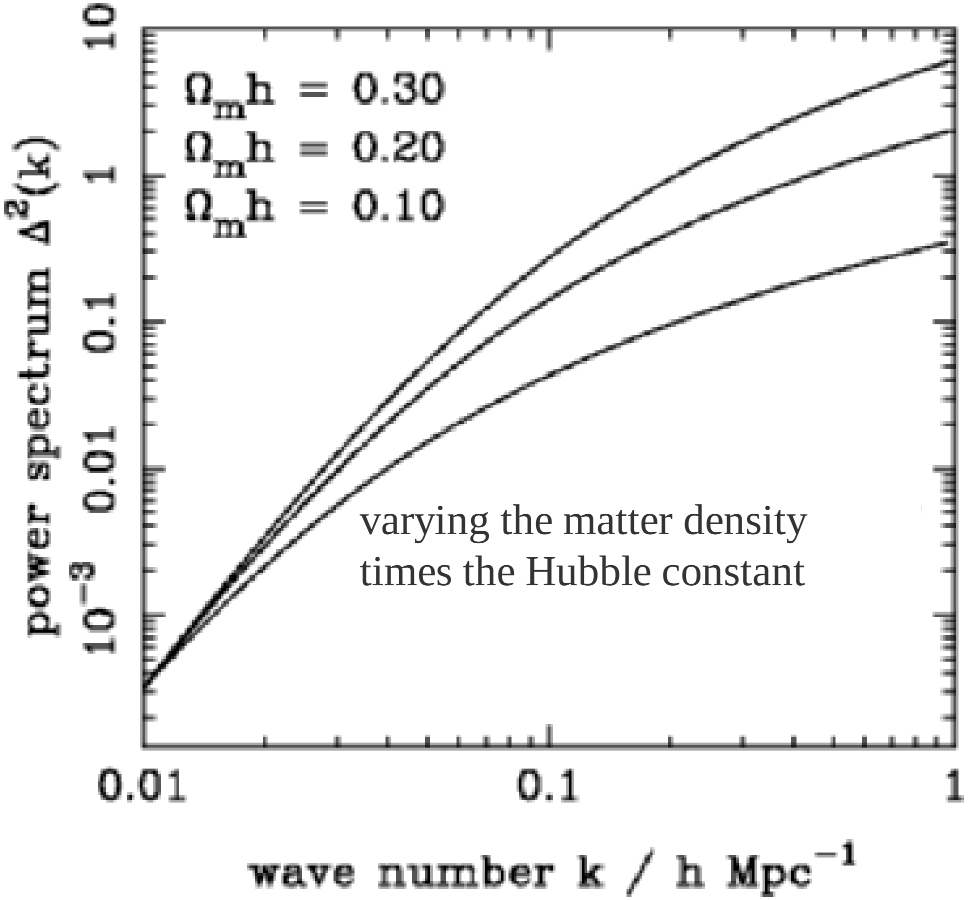


- collaboration of 30 astronomers split between Australia and the UK
- survey is now complete and has measured redshifts for 220000 galaxies in the local Universe (b-band selection)
- data has been released

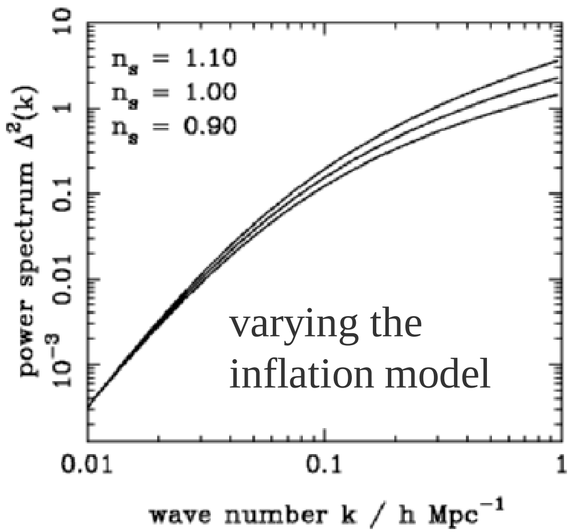
http://www.mso.anu.edu.au/2dFGRS/

The linear matter power spectrum

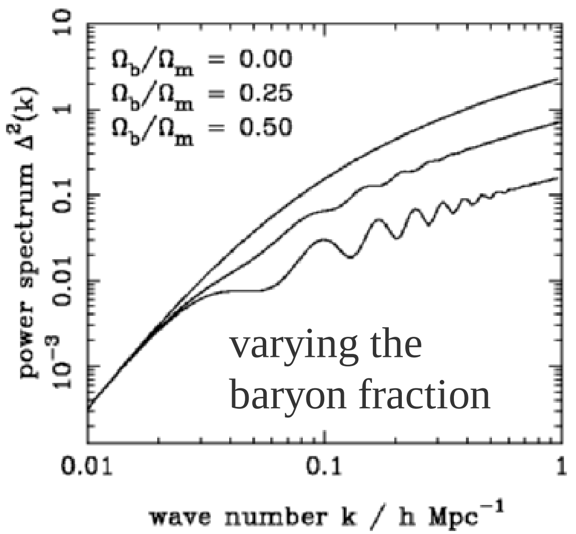
Can we use the power spectrum shape to tell us about evolution of scale?
Saw in last lecture that matter P(k) is fixed in the early universe, with simple evolution



varying the matter density times the Hubble constant

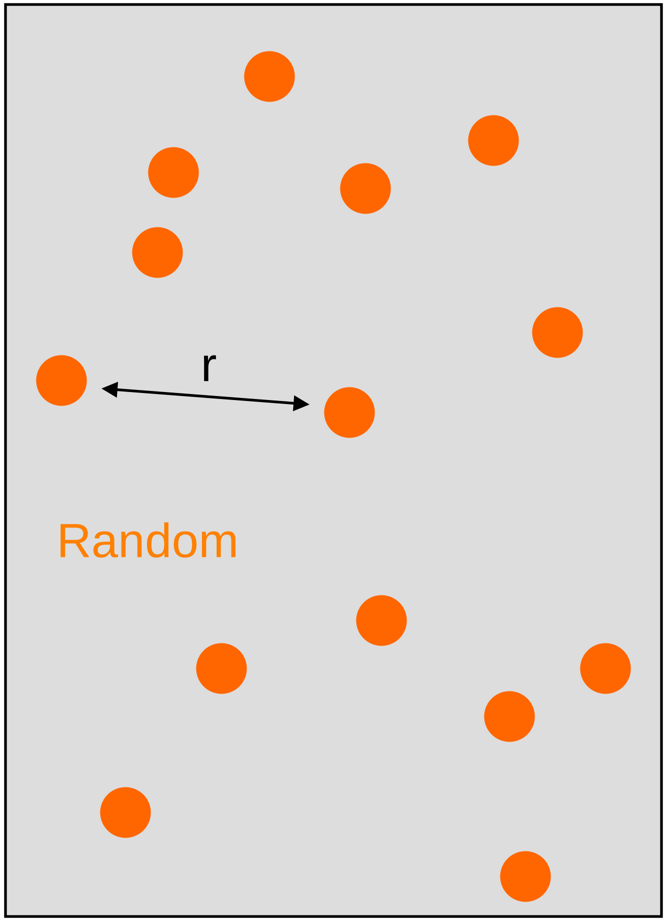


varying the inflation model



varying the baryon fraction

Measuring $\xi(r)$ and P(k)

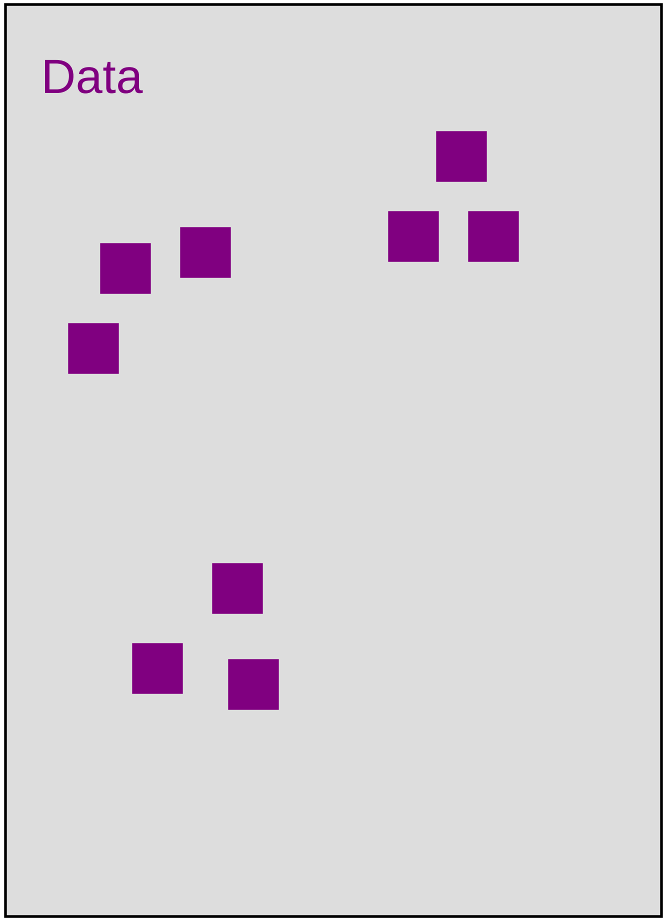


Simple estimator:
$\xi(r)$ = DD(r)/RR(r) - 1

Advanced estimator:
$\xi(r)$ = (DD-2DR+RR)/RR

The latter does a better job with edge effects, which cause a bias to the mean density of points.

Usually 10x as many random points over SAME area / volume



Same techniques for P(k) - take Fourier transform of density field relative to a random catalog over same volume. Several techniques for this - see Tegmark et al. and Pope et al. Also “weighted” and mark correlations

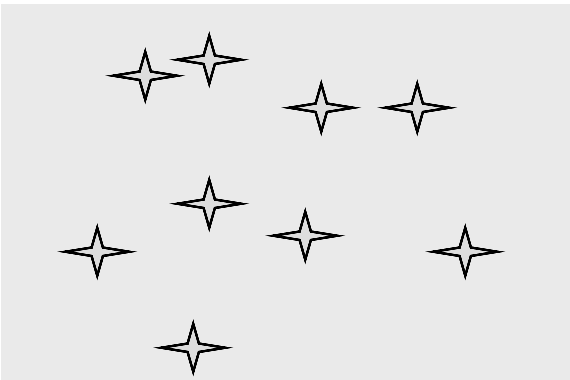
Errors on $\xi(r)$

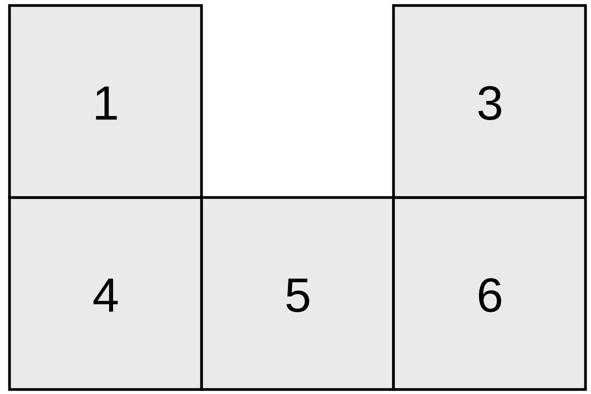
Hardest part of estimating these statistics

- On small scales, the errors are Poisson
- On large scales, errors correlated and typically larger than Poisson
- Use mocks catalogs
  - PROS: True measure of cosmic variance
  - CONS: Hard to include all observational effects and model clustering
- Use jack-knifes (JK)
  - PROS: Uses the data directly
  - CONS: Noisy and unstable matrices

Jack-knife errors

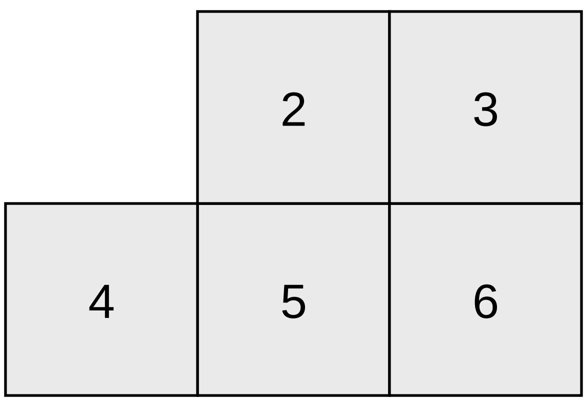
Real Data





N=6

- Split data into N equal subregions
- Remove each subregion in turn and compute $\xi(r)$
- Measure variance between regions as function of scale



$$\sigma^2 = \frac{(N-1)}{N}\sum_{i=1}^{N}(\xi_i - \bar{\xi})^2$$

Note the (N-1) factor because there or N-1 estimates of mean

Practicalities: measuring ξ(r) for discrete samples

- the 2-pt function of a discrete random sampling of a density field is related to the correlation function of the field by

$$\left\langle n_g(\mathbf{r}) n_g(\mathbf{r}') \right\rangle = \bar{n}(\mathbf{r})\bar{n}(\mathbf{r}')[1+\xi(\mathbf{r}-\mathbf{r}')]+\bar{n}(\mathbf{r})\delta_D(\mathbf{r}-\mathbf{r}')$$

shot noise term

where $n_g(\mathbf{r}) \equiv \sum_i \delta_D(\mathbf{r}-\mathbf{r_i})$

given a synthetic catalogue (containing α times as many galaxies) Poisson sampling the survey area $n_s(r)$, the correlation function can be estimated

$$1 + \langle \xi_{\mathsf{field}} \rangle = \left(1 + \alpha \frac{\langle DD \rangle}{\langle RR \rangle}\right)(1+\sigma^2)$$

ratio of pair counts of separation ~r in galaxy and synthetic catalogues

integral constraint (statistical bias as mean number of galaxies measured from survey itself)

Practicalities: measuring P(k) for discrete samples

as for the correlation function, given

$$F(\mathbf{r}) = n_g(\mathbf{r}) - n_s(\mathbf{r})/\alpha$$

the power spectrum can be written

$$\left\langle |F(\mathbf{k})|^2 \right\rangle = \int \frac{d^3k'}{(2\pi)^3}[P(\mathbf{k}') - P(0)\delta_D(\mathbf{k})]|G(\mathbf{k}-\mathbf{k}')|^2$$

$$+(1+\frac{1}{\alpha})\int d^3r\bar{n}(\mathbf{r})$$

shot noise term (not as easily corrected as for the correlation function)

correction for the fact that not knowing true mean galaxy density

convolution with window function

Practicalities: weighting galaxies by number density

If:

1. The wavelength $2\pi/k$ is small compared with the survey scale
2. fluctuations are Gaussian

then the optimal weight for each galaxy is

$$w_i = \frac{1}{1 + \bar{n}(\mathbf{r_i})\widehat{P}(k)}$$

Depends on P(k) prior

low densities – weights by galaxy
high densities – weights by volume

change over scale dependent on P(k)

Practicalities: weighting galaxies by bias

- galaxies do not form a Poisson sampling of the matter distribution
- they are biased with respect to the distribution of mass

  $P_{gal}(k) = b^2(\text{galaxy})\, P_{mass}(k)$
- bias changes with galaxy colour and luminosity

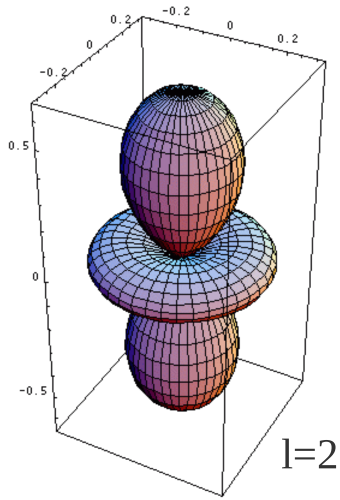
Given a sample of galaxies, each with linear bias b_j, the optimal weight is

$$w_i = \frac{b_i^2}{1 + \sum_j \bar{n}(\mathbf{r_i}, L_j) b_j^2 \widehat{P}(k)}$$

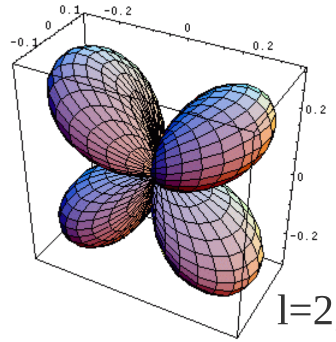
up-weights very biased galaxies, containing the most signal

normalisation changes to match

Practicalities: weighting galaxies by bias



l=2,m=0

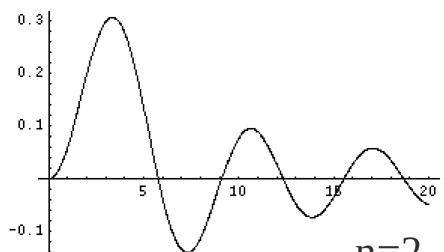


l=2,m=1

Spherical
Harmonics
(❏📪♐)

+

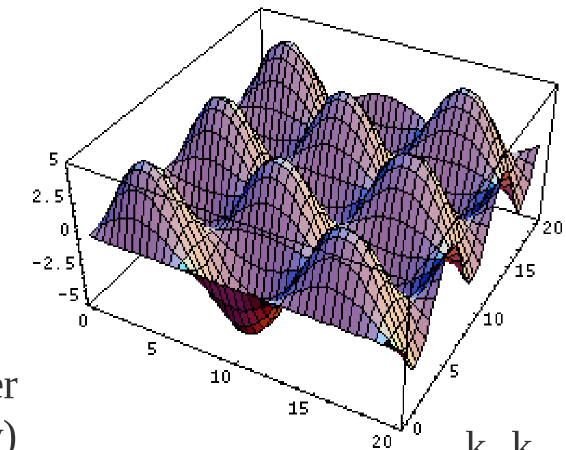
Spherical Bessel
function (r)



r

n=2

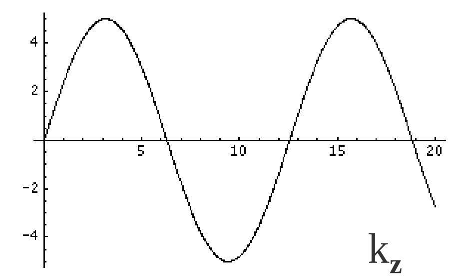
2d Fourier
basis (x,y)



k_x,k_y

+

1d Fourier
basis (z)



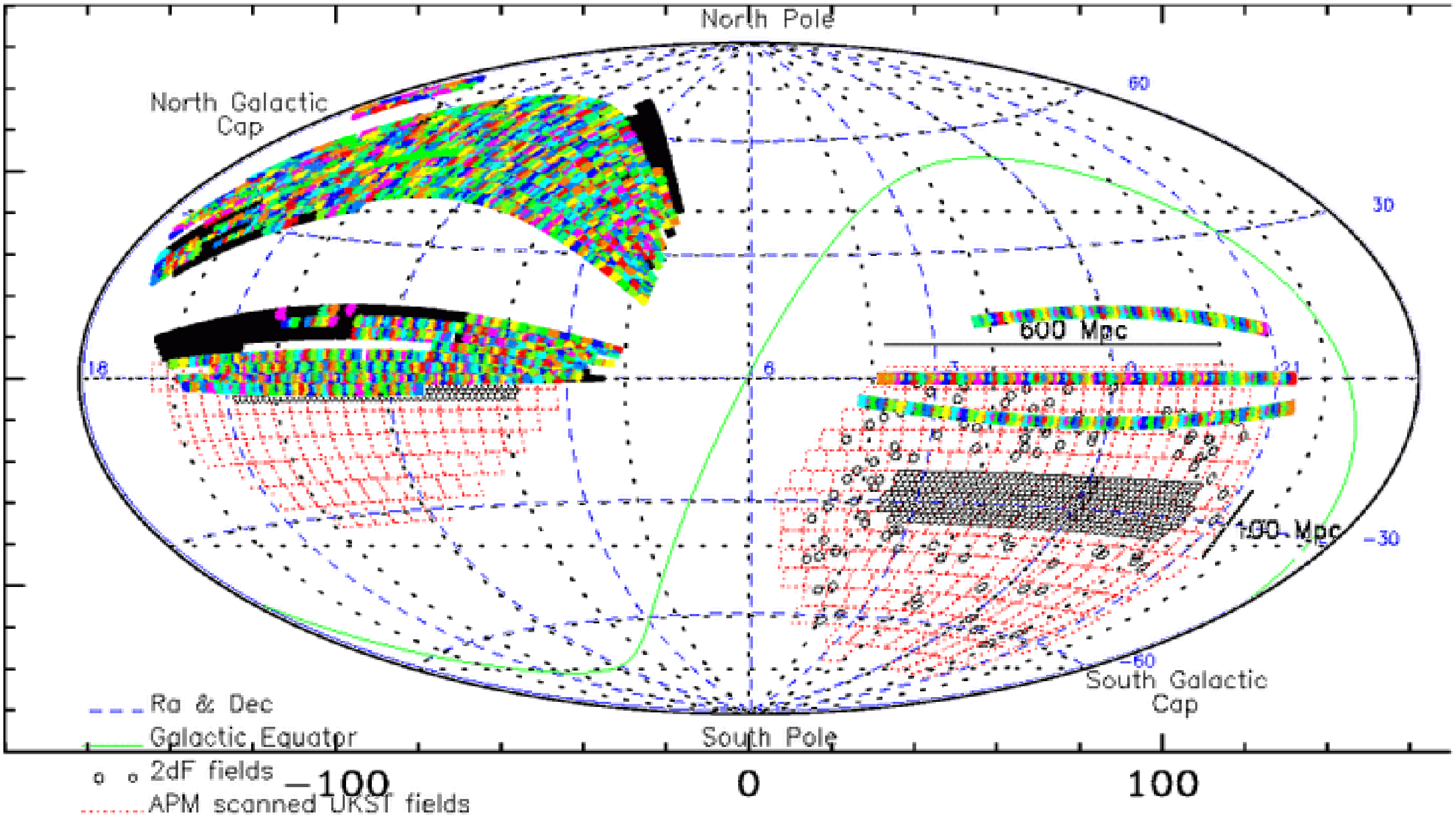
z

k_z

advantage: radial/angular split – more matched to survey geometry, easily
model redshift space distortions

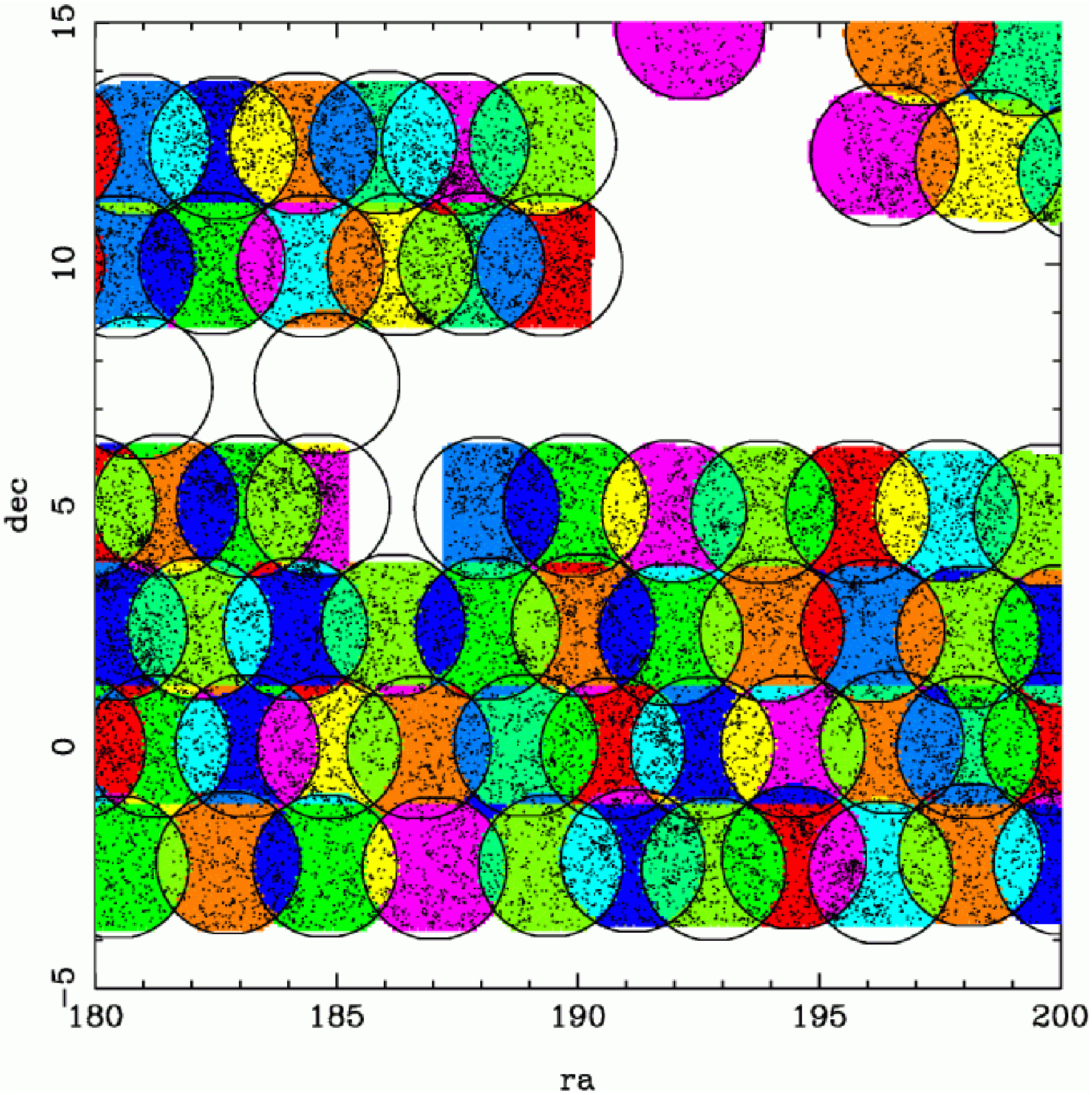
advantage: simplicity, speed

SDSS DR4 survey geometry



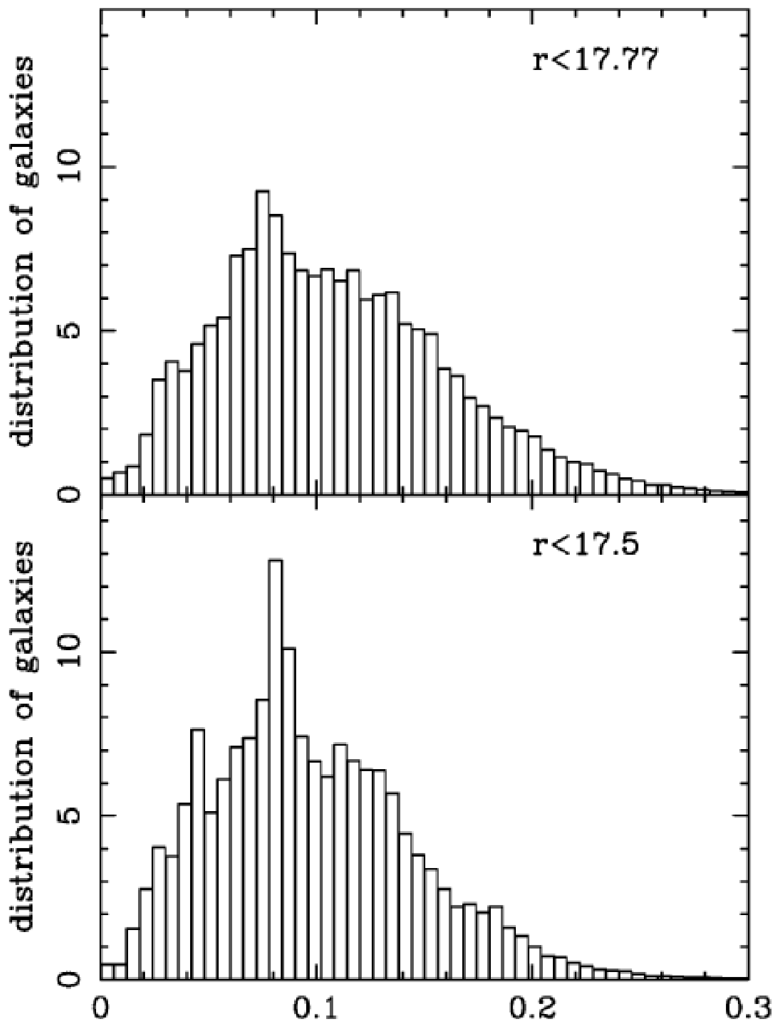
DR6 data now public: www.sdss.org

Need to determine the angular mask



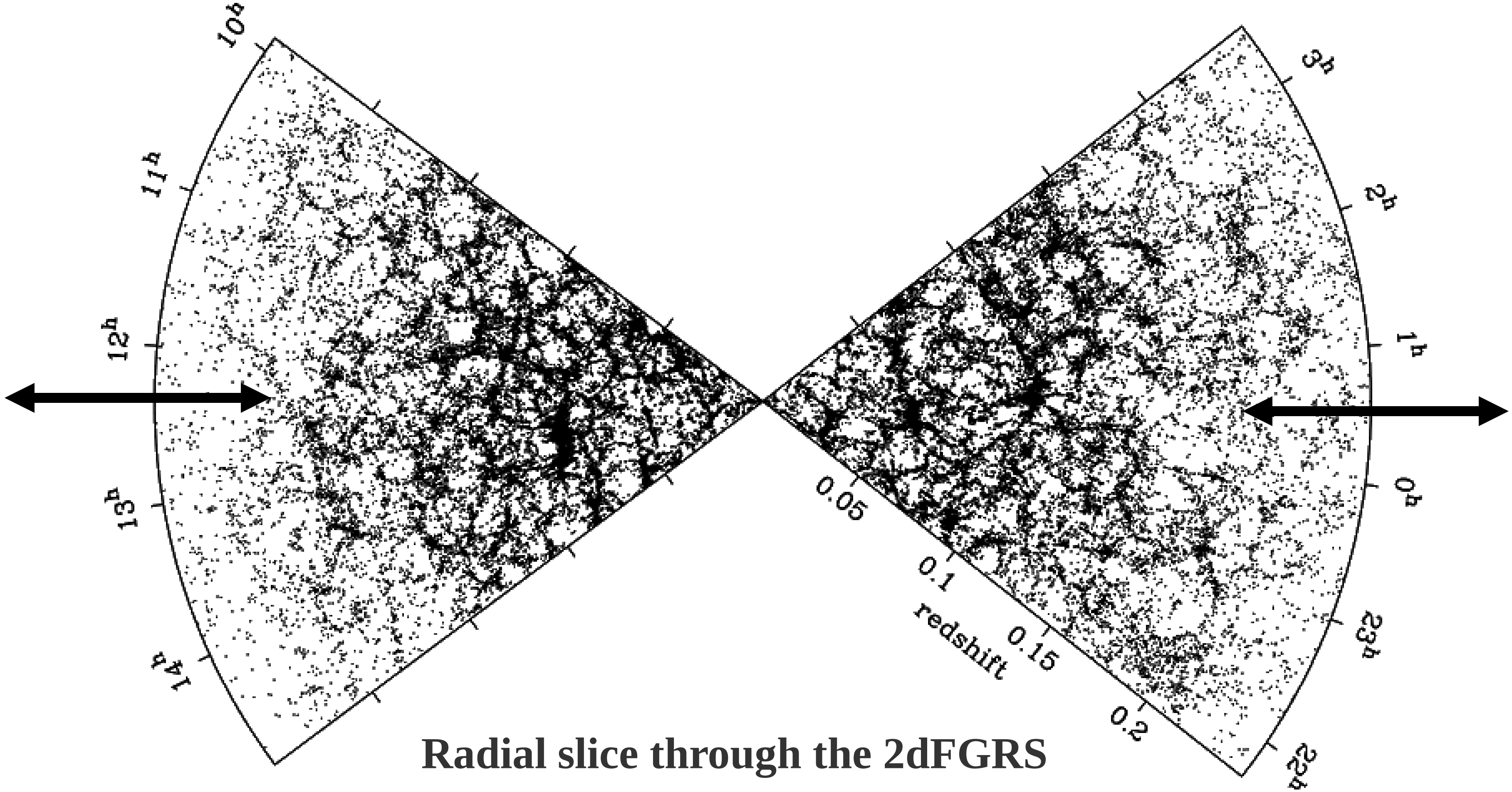
- both SDSS and 2dFGRS use an adaptive tiling strategy
- completeness varies between plate overlap regions
- also need to consider region covered by parent catalogue

Need to determine the radial galaxy distribution



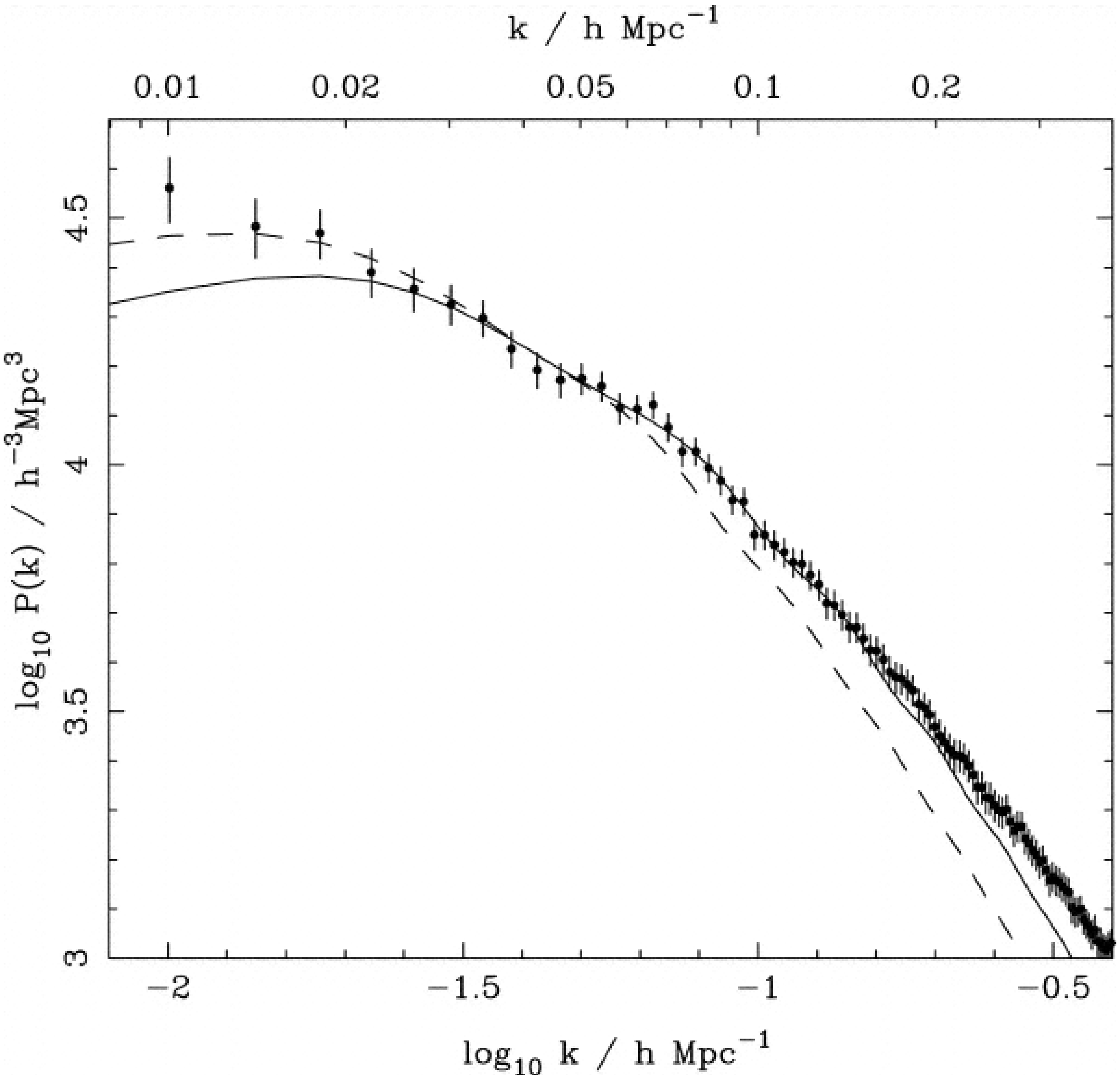
- for both the 2dFGRS and SDSS the magnitude limit changes with angular position
- Best approach – fit absolute magnitude function (allowing for K+E corrections)
- possible to also just fit to redshift distribution

Galaxy surveys probe DE through geometry & structure growth

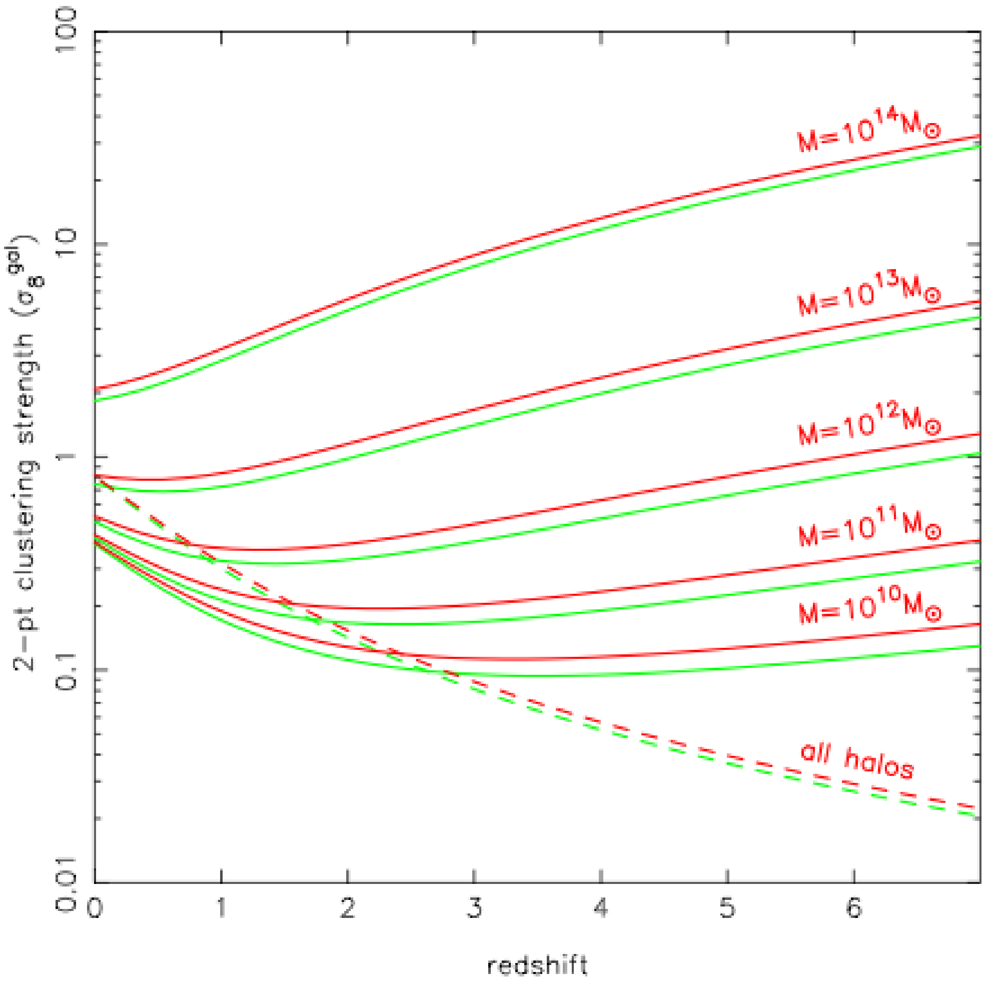


Radial slice through the 2dFGRS

Latest power spectrum from SDSS



Amplitude of clustering on large scales



$\Omega_m = 0.25, \Omega_\Lambda = 0.75$

$\Omega_m = 0.3, \Omega_\Lambda = 0.7$

Need to accurately know galaxy bias before we can get cosmological constraints - need to understand astrophysics of galaxy formation

Main practical problem: galaxies do NOT sample the mass

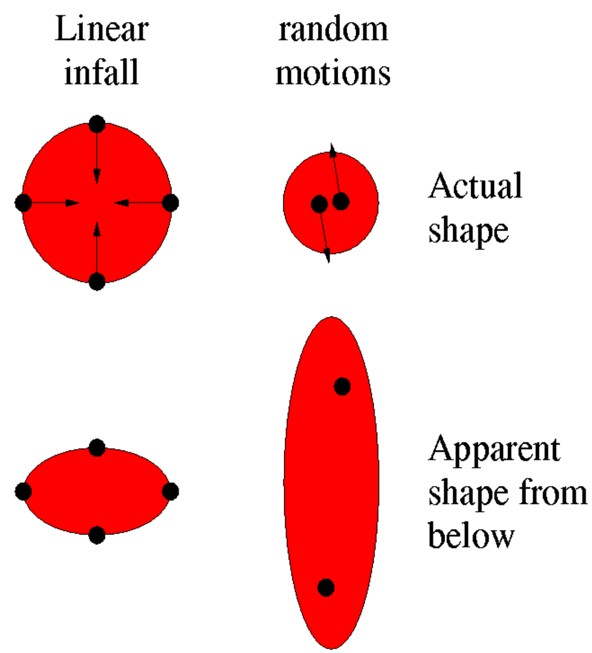
observed redshift-space
galaxy clustering power

galaxies might not trace
the mass:
scale dependent bias?

$$\frac{P^s_{\rm gal}}{P_{\rm mass}} = \frac{P^s_{\rm gal}}{P^r_{\rm gal}} \times \frac{P^r_{\rm gal}}{P_{\rm mass}}$$

linear matter
power spectrum

redshift-space
distortions



At large distances, redshift-space distortions
affect the power spectrum through:

$$P_s = P_r(1 + \beta\mu^2)^2(1 + k^2\mu^2\sigma_p^2/2)^{-1}$$

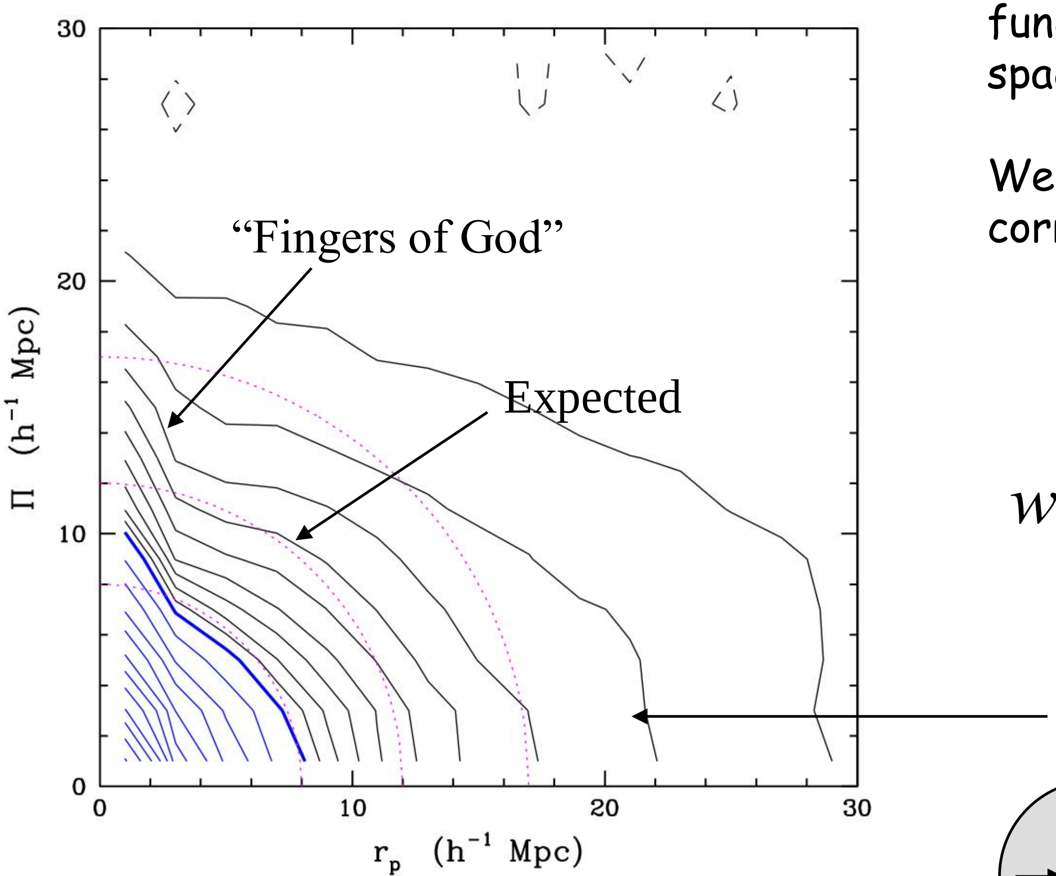
Redshift-space distortions

We only measure redshifts not distances

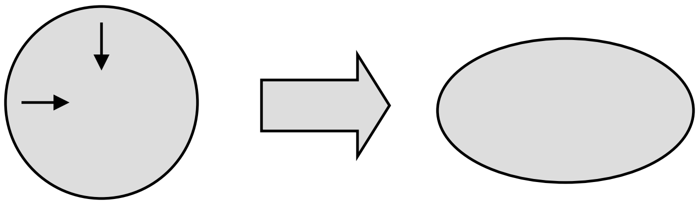
Therefore we usually quote $\xi(s)$ as the "redshift-space" correlation function, and $\xi(r)$ as the "real-space" correlation function.

We can compute the 2D correlation function $\xi(\pi, r_p)$, then

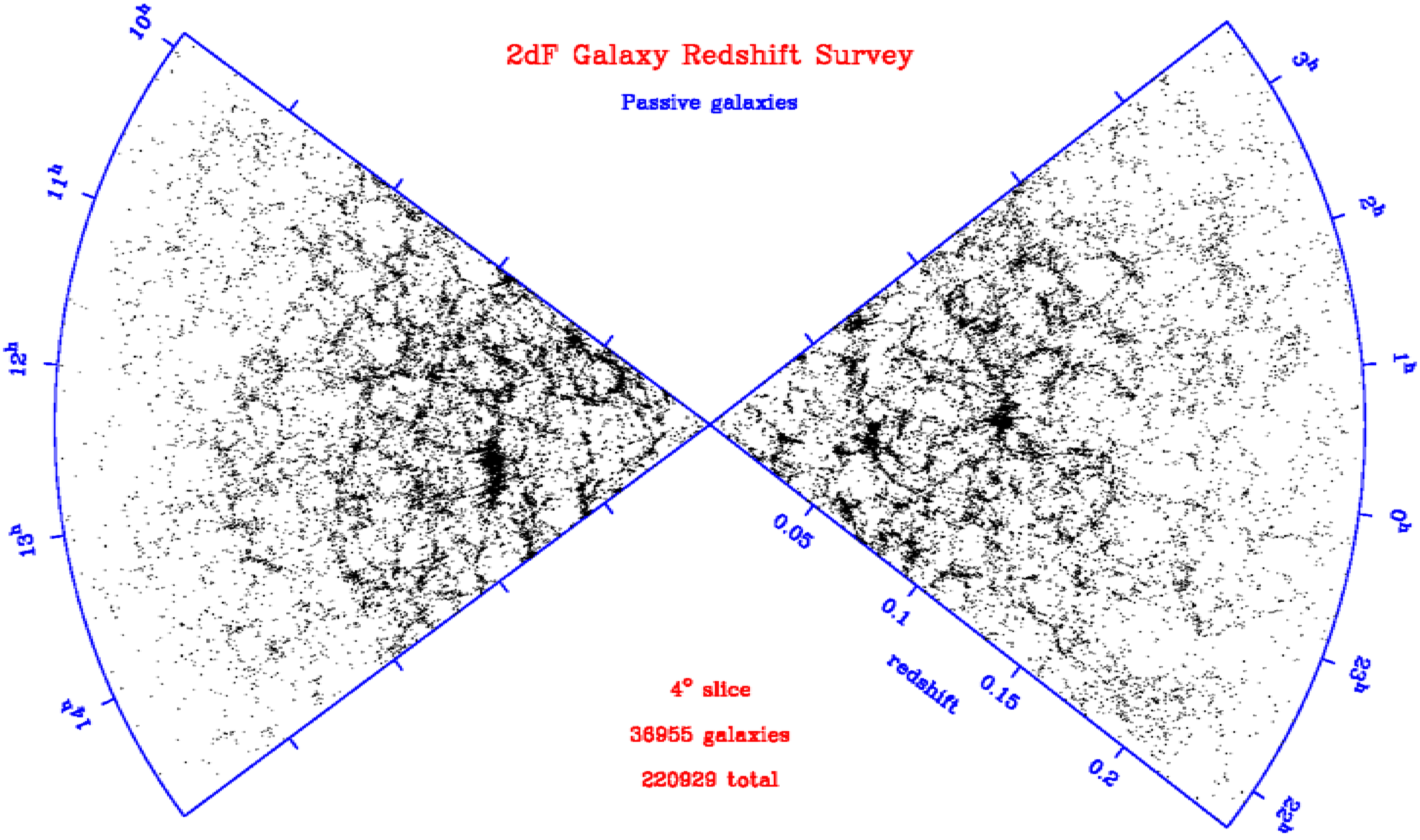
$$w(r_p) = 2\int_0^{\pi_{\max}} \xi(r_p, \pi)\, d\pi$$



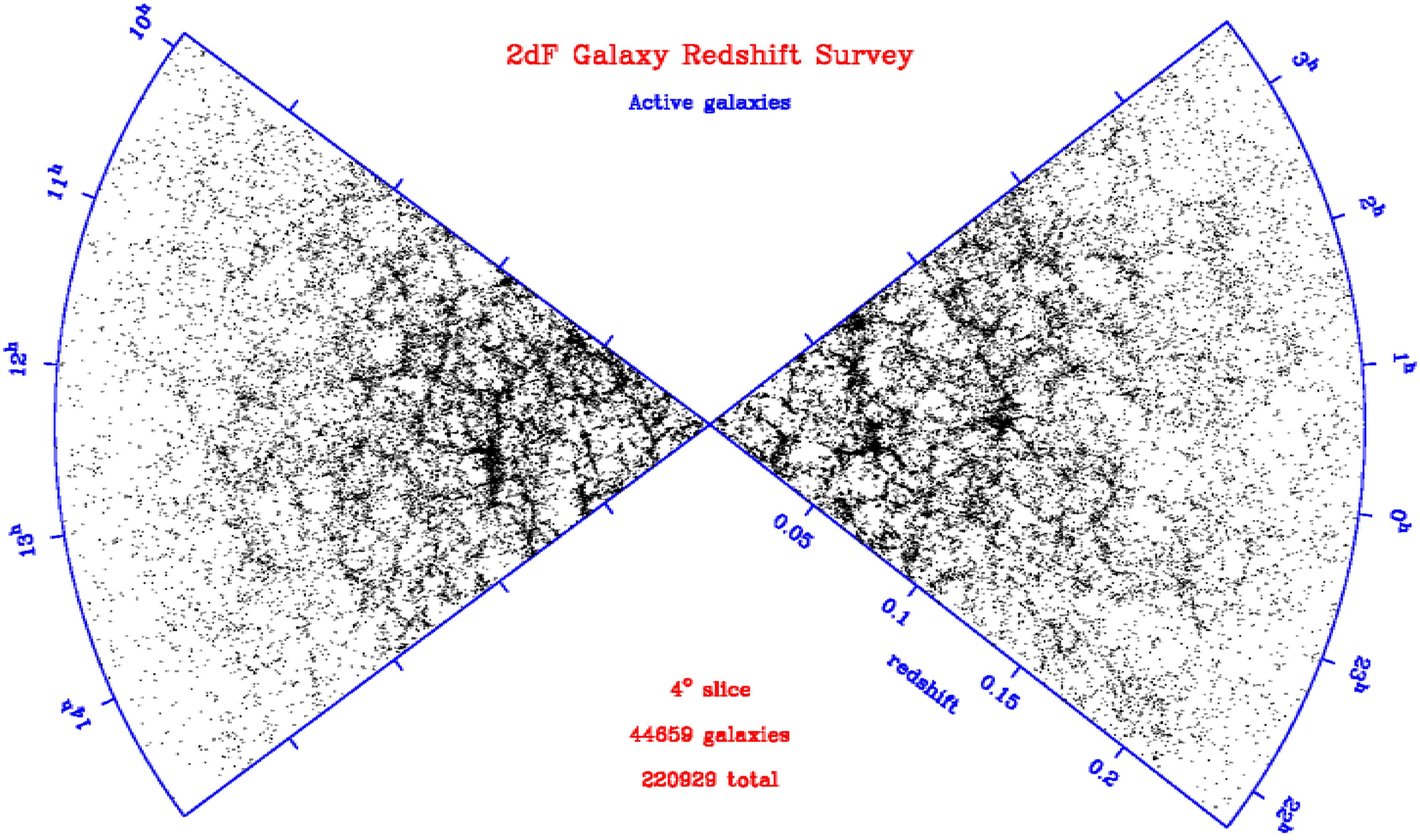
Infall around clusters



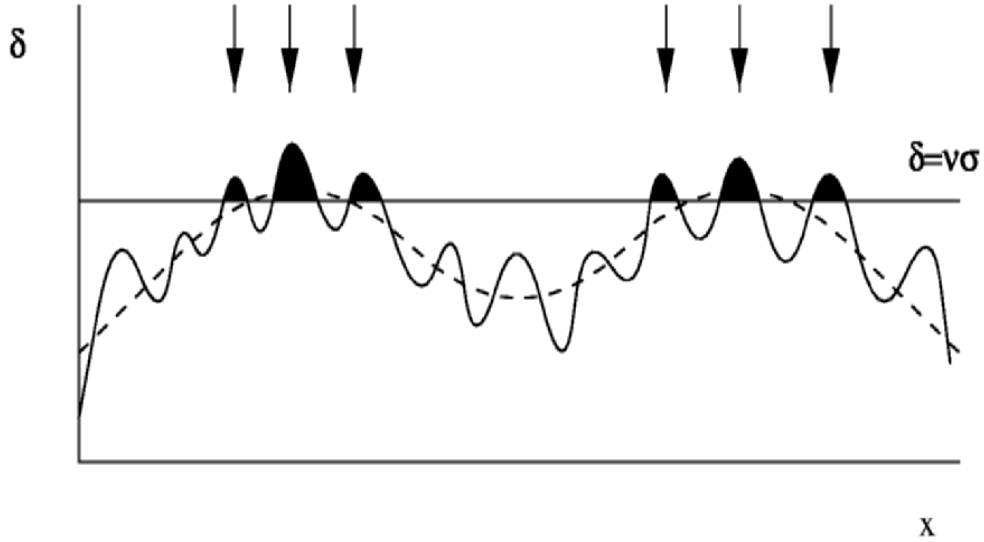
Galaxy bias : Red galaxies



Galaxy bias : Blue galaxies



Large-scale bias is inevitable for rare systems



Cole-Kaiser-Mo-White:

$$b(M) = 1 + (\nu^2 - 1)/\delta_c$$

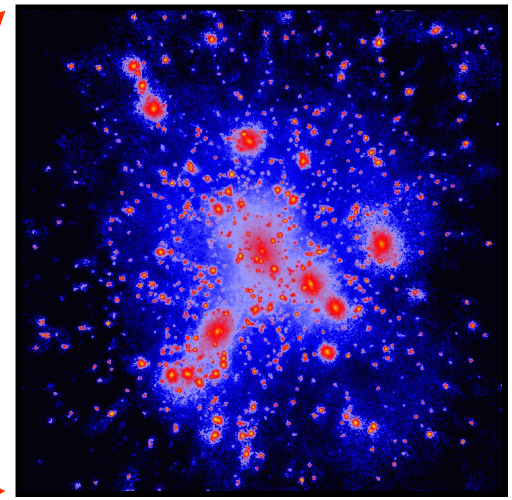
$$\nu \equiv \delta_c/\sigma(M)$$

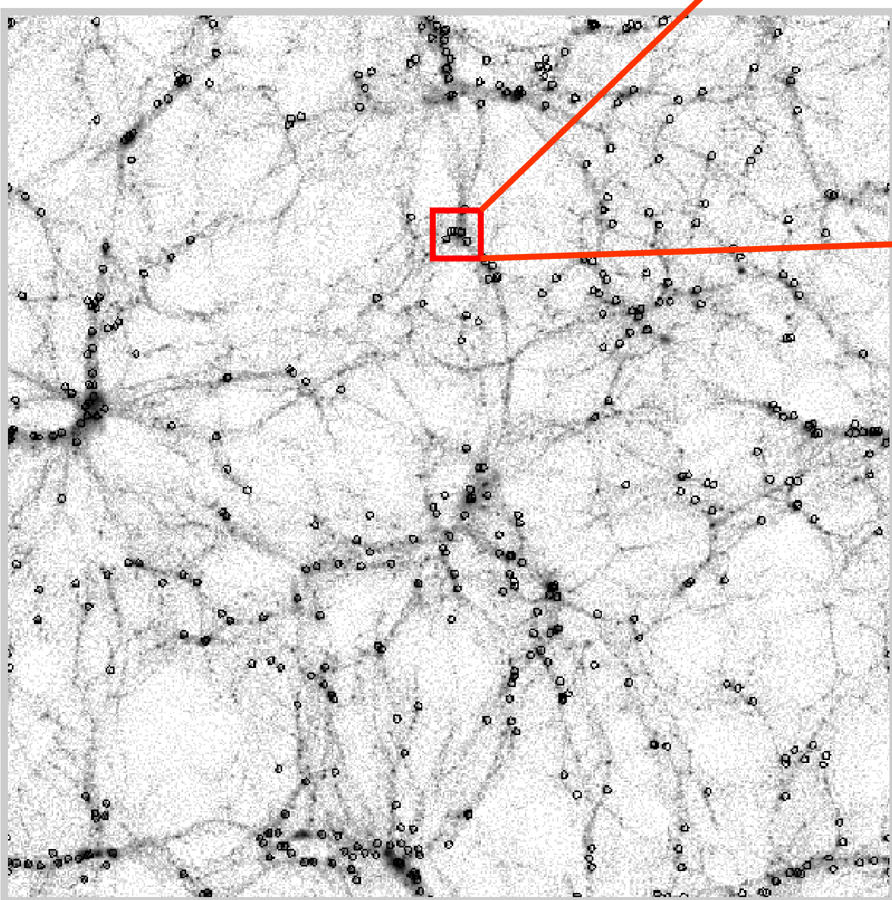
Peak-background split: $\delta_c \rightarrow \delta_c$ - ε;

n(m) $\rightarrow$ n(m) + (dn/dn)(dn/dε) ε = n(m) [1+bε]

bias: $\xi \rightarrow b^2\xi$ depends on halo mass

Small-scale bias is inevitable from halo profiles





N-body *gives* halo profile:

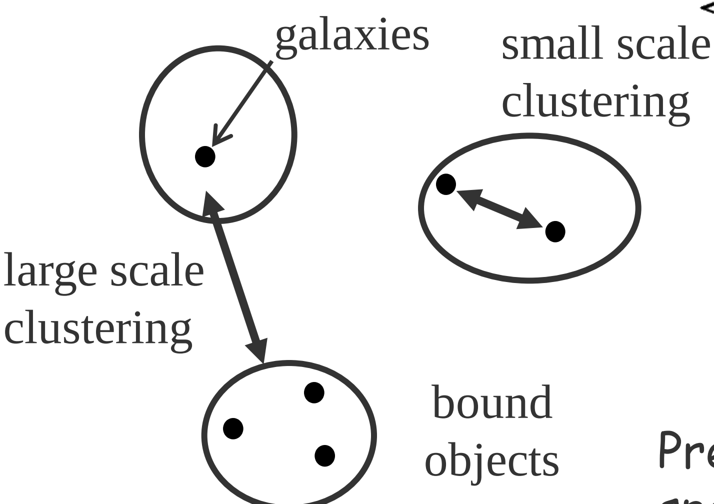
$r = [\ y(1+y)^2\ ]^{-1}$; $y = r/r_c$ (NFW)

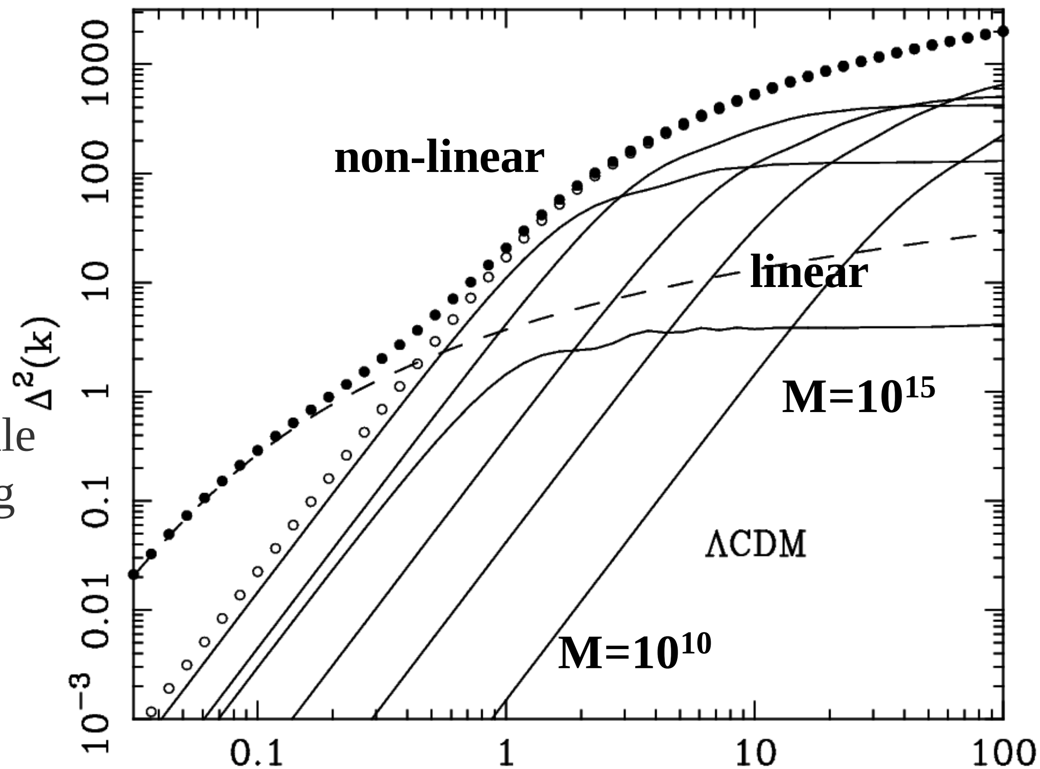
$r = [\ y^{3/2}(1+y^{3/2})\ ]^{-1}$; $y = r/r_c$ (Moore)

(cf. Isothermal sphere $r = 1/y^2$)

The halo model

- Simple model which splits galaxy clustering into 2 components
  - Small scale clustering of galaxies within a single halo
  - Large scale clustering between halos



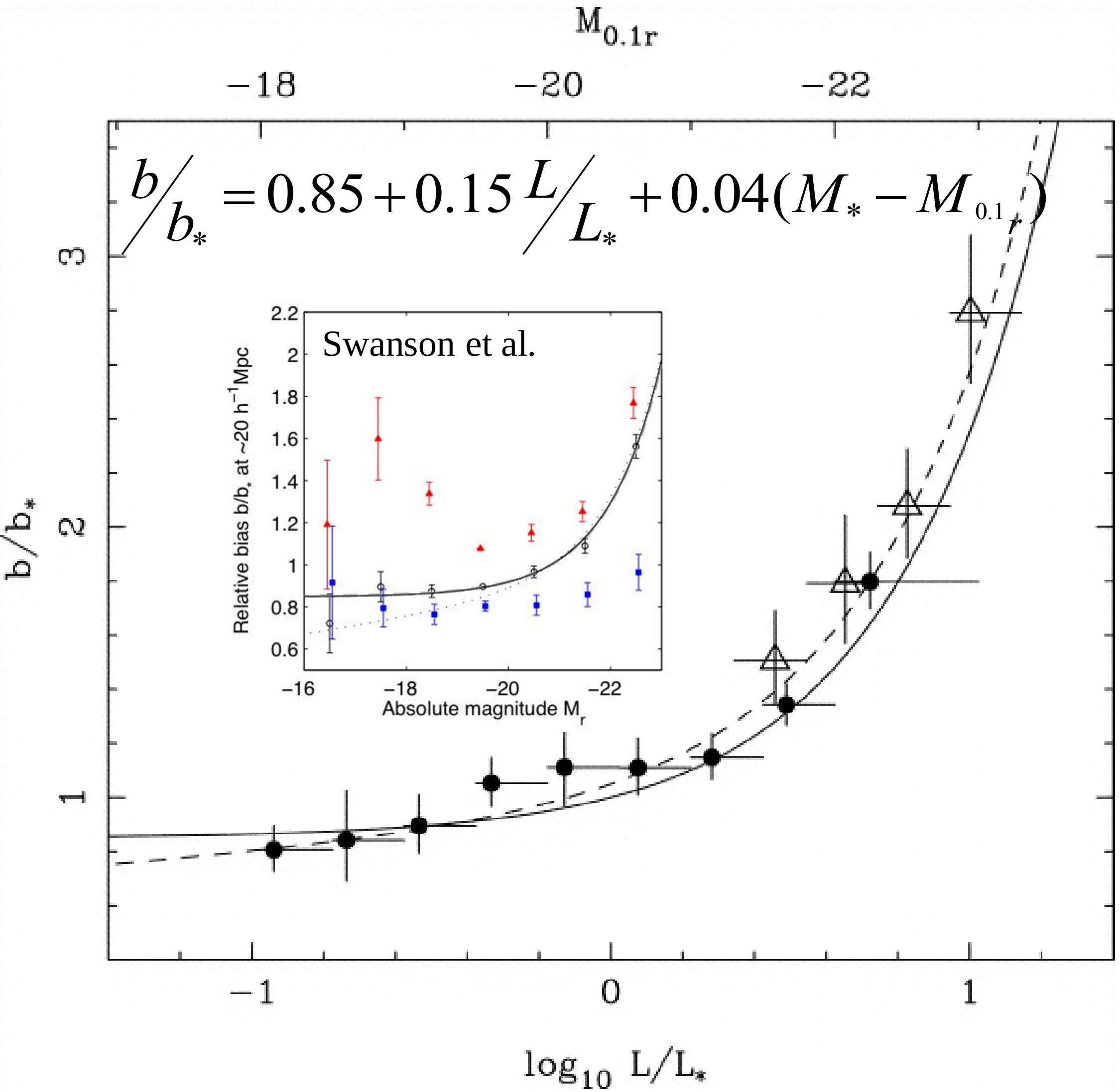


Predicts power spectrum of the form

$$P(k)_{\rm obs} = b^2(k)P(k)_{\rm lin} + P(k)_{\rm extra}$$

Observed amplitude of galaxy biasing

We see galaxies not dark matter



Maximal ignorance

$$\delta_{gal} = b\delta_{dm}$$

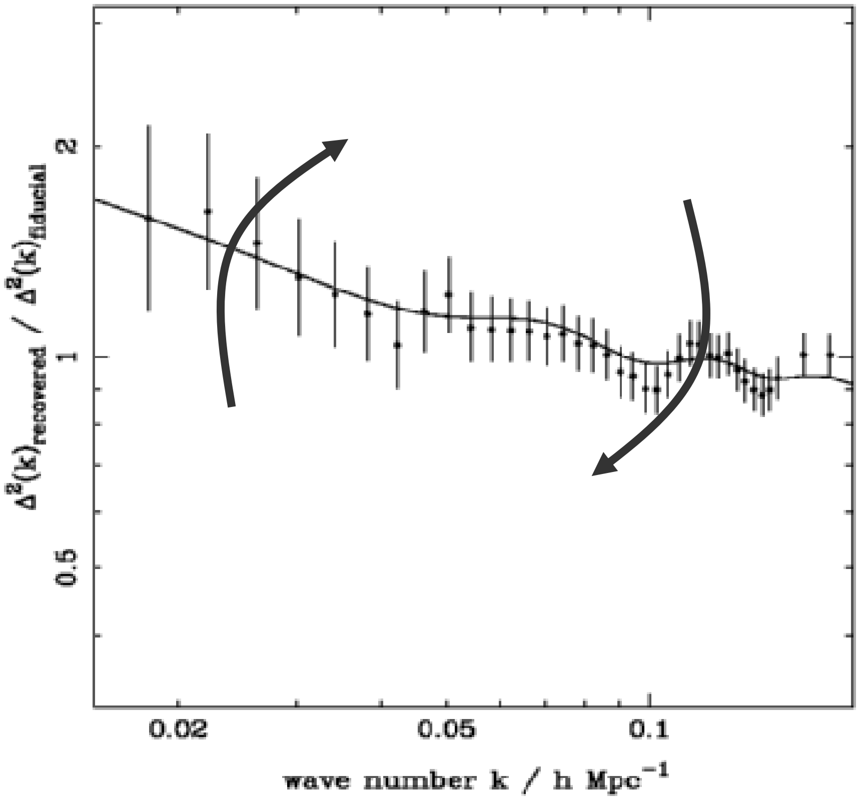
$$P(k)_{gal} = b^2 P(k)_{dm}$$

However, we know it depends on colour & L

Is there also a scale dependence?

The problem with not correcting for bias

- assume that galaxies have luminosity-dependent bias on the large-scales of interest, with $\langle b/b_* \rangle = 0.85 + 0.15(L/L_*)$ (Norberg et al. 2001)
- survey geometry means that larger scales are traced by more luminous galaxies
- leads to a potential tilt in the power
- can be corrected given model of bias



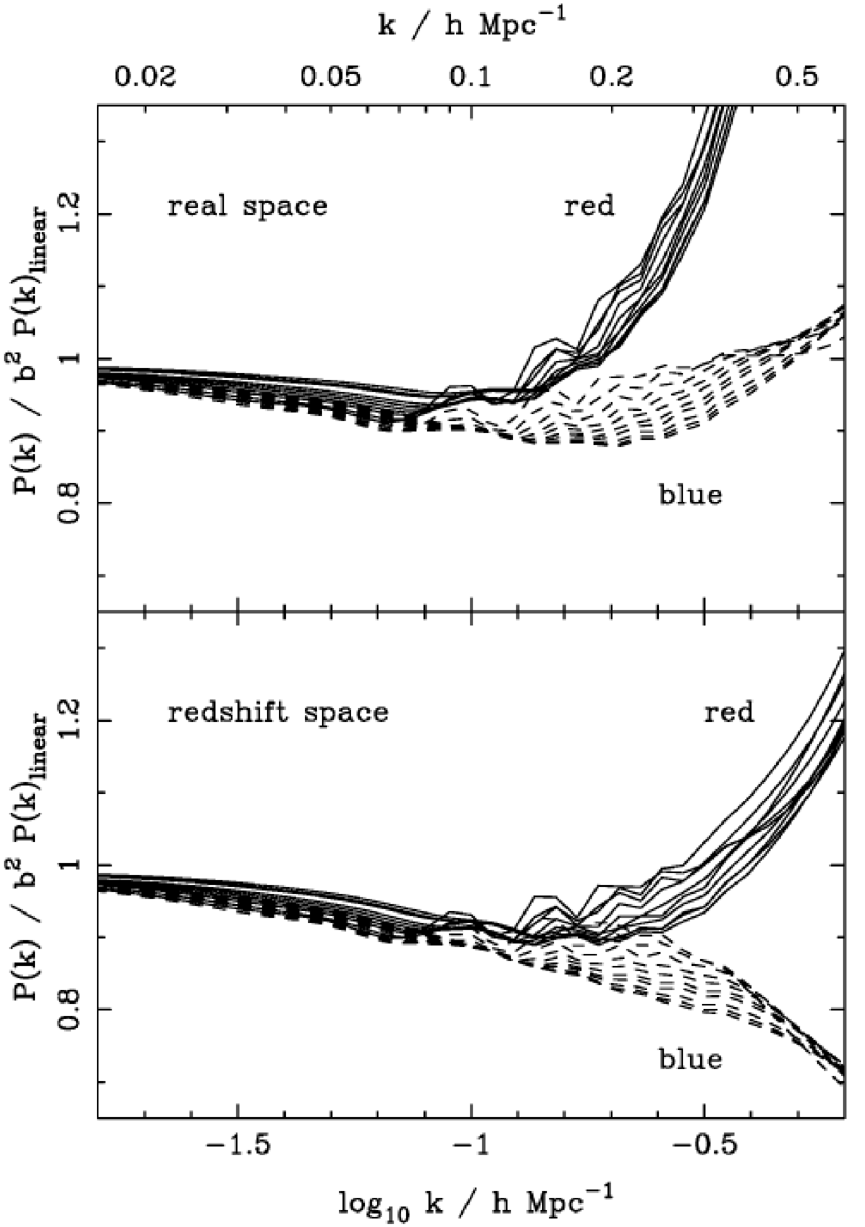
from Percival, Verde & Peacock, 2004, MNRAS, 347, 645

Scale-dependent bias (from the halo model)

- cosmological dependence of bias is weak, so can adopt a fitting formula for all (reasonable) power spectra

$$P^{r}_{\mathrm{gal}} = \frac{1+Qk^2}{1+Ak}\, P_{\mathrm{lin}}$$

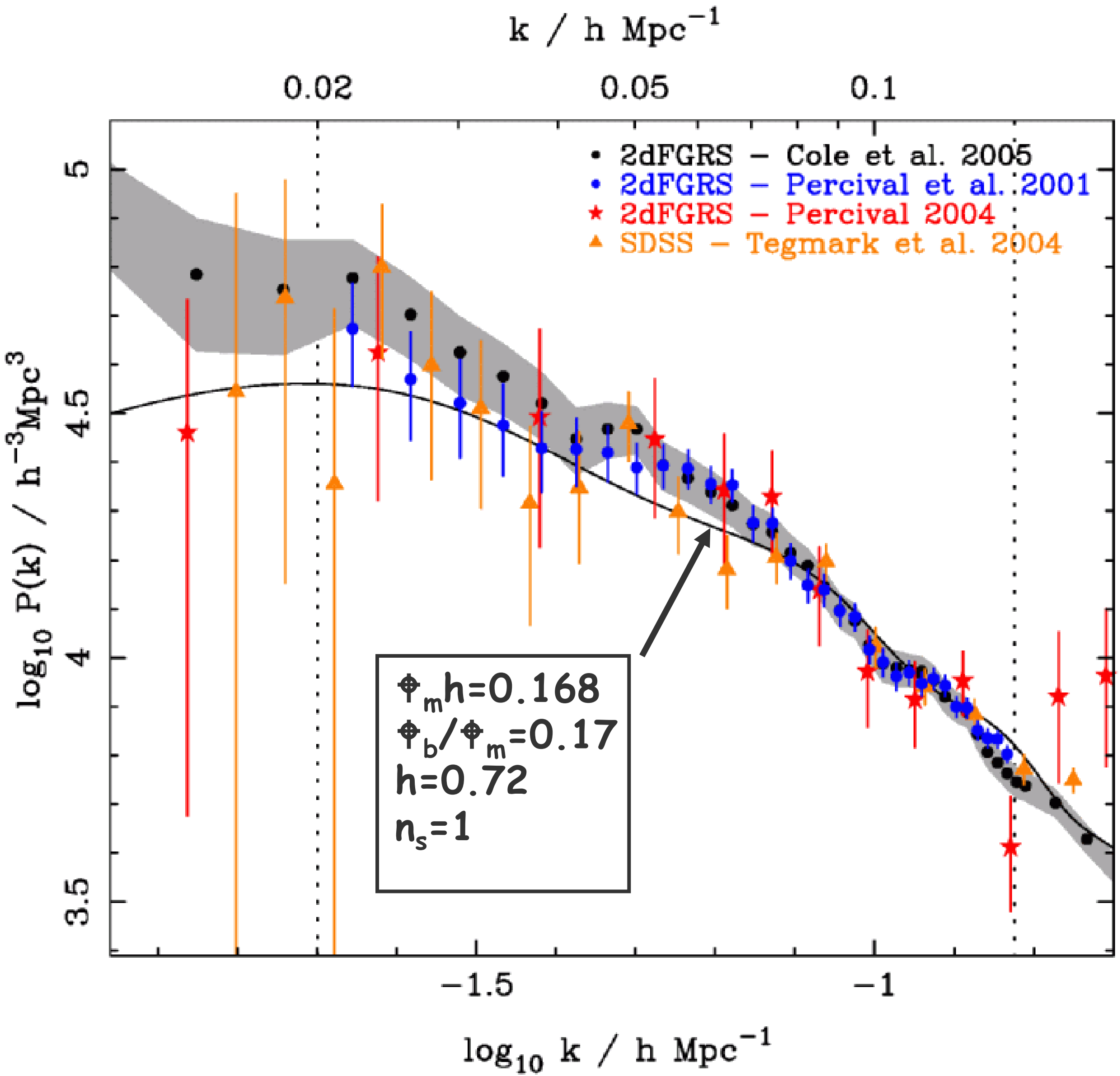
- A=1.4 from halo model. Q is allowed to vary to cover lack of knowledge of small-scale effects.



from Cole et al. (2005) astro-ph/0501174

Cosmology

Pre-2006 power spectra from SDSS and 2dFGRS



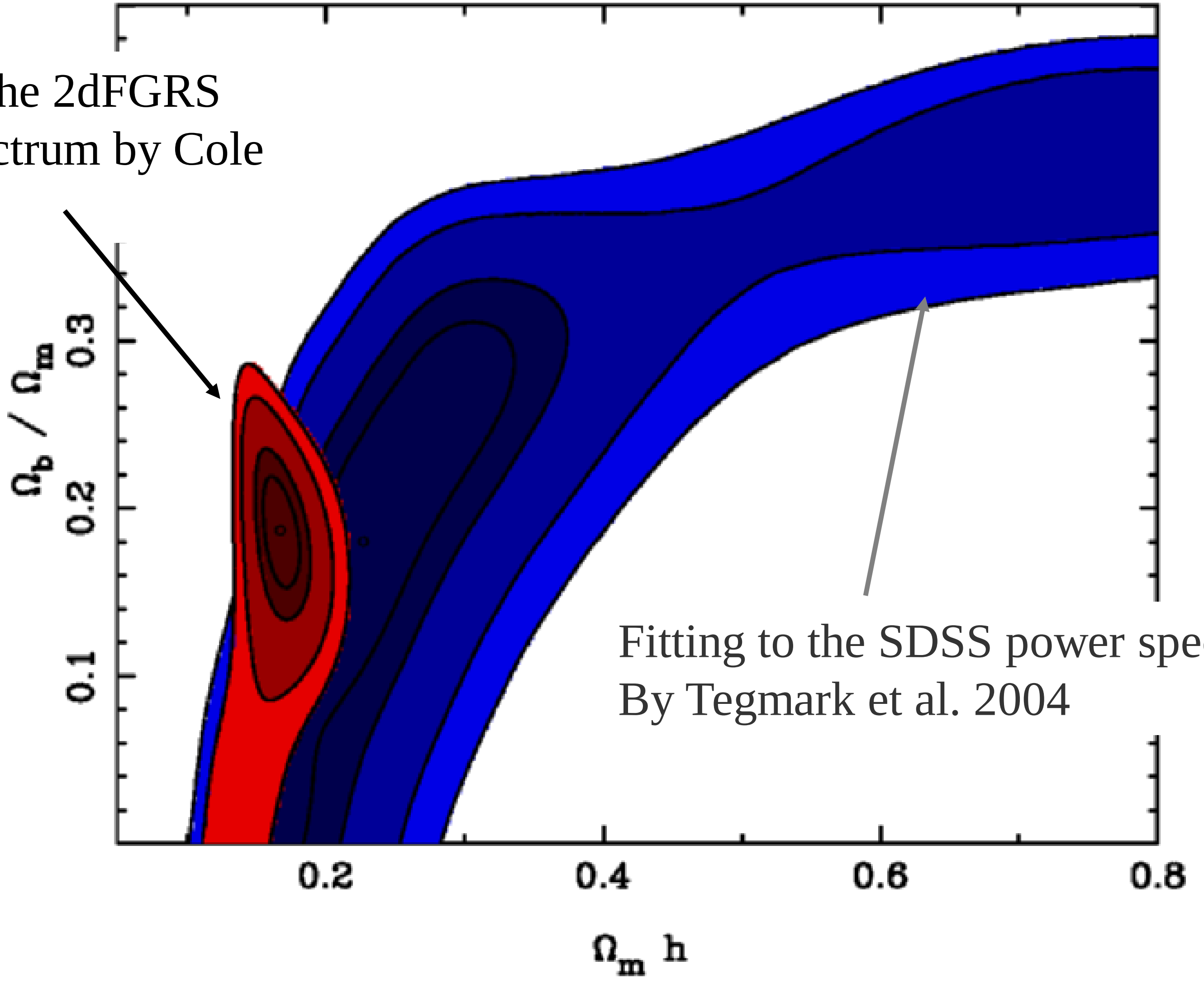
Pre-2006 constraints from P(k)

SURVEY	publication	redshifts	method	$\Omega_m h$	f_b	$\Omega_m h$ f_b=0.17
2dFGRS	Percival et al. 2001	166,490	Fourier analysis	0.20 ± 0.03	0.15 ± 0.07	0.206 ± 0.023
2dFGRS	Percival et al. 2004	142,756	Spherical Harmonics			0.215 ± 0.035
2dFGRS	Cole et al. 2005	221,414	Fourier analysis	0.168 ± 0.016	0.185 ± 0.046	0.172 ± 0.014
SDSS	Pope et al. 2004	205,484	KL analysis	0.264 ± 0.043	0.286 ± 0.065	0.207 ± 0.030
SDSS	Tegmark et al. 2004	205,443	Spherical Harmonics			0.225 ± 0.040
SDSS LRGs	Eisenstein et al 2005	46,748	correlation function			0.185 ± 0.015*

*uses $\Omega_b h^2$=0.024, rather than f_b=0.17

2dFGRS vs SDSS likelihood contours

Fitting to the 2dFGRS power spectrum by Cole et al. 2005



Fitting to the SDSS power spectrum By Tegmark et al. 2004

WMAP 3-year analysis found a discrepancy

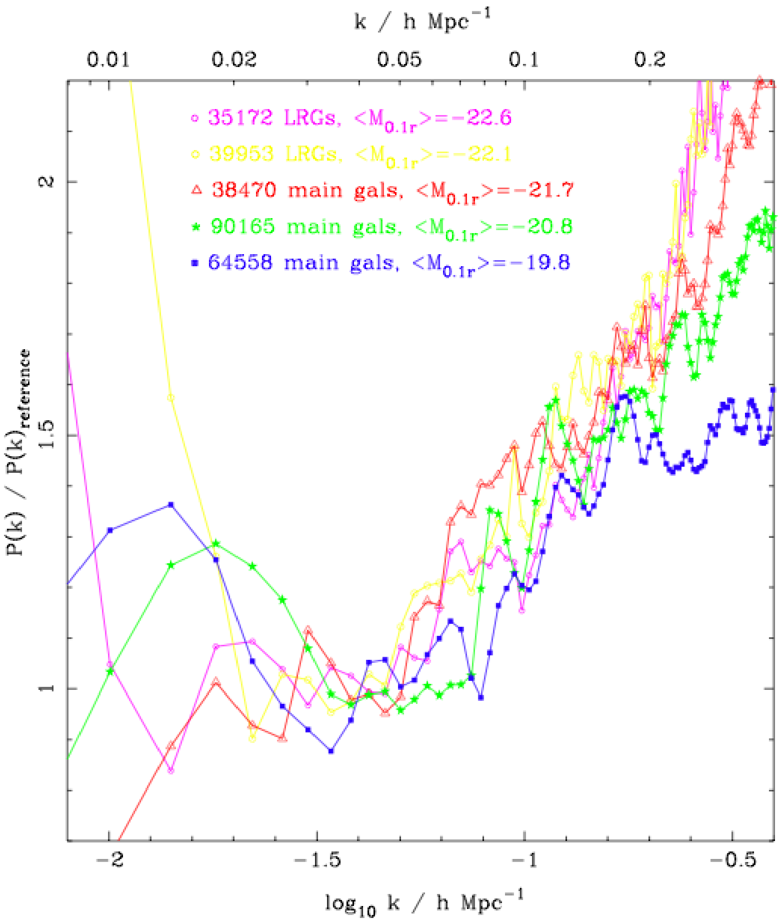
Parameter	WMAP Only	WMAP +CBI+VSA	WMAP+ACBAR +BOOMERanG	WMAP + 2dFGRS
$100\Omega_b h^2$	$2.233^{+0.072}_{-0.091}$	$2.203^{+0.072}_{-0.090}$	$2.228^{+0.066}_{-0.082}$	$2.223^{+0.066}_{-0.083}$
$\Omega_m h^2$	$0.1268^{+0.0073}_{-0.0128}$	$0.1238^{+0.0066}_{-0.0118}$	$0.1271^{+0.0070}_{-0.0128}$	$0.1262^{+0.0050}_{-0.0103}$
h	$0.734^{+0.028}_{-0.038}$	$0.738^{+0.028}_{-0.037}$	$0.733^{+0.030}_{-0.038}$	$0.732^{+0.018}_{-0.025}$
A	$0.801^{+0.043}_{-0.054}$	$0.798^{+0.047}_{-0.057}$	$0.801^{+0.048}_{-0.056}$	$0.799^{+0.042}_{-0.051}$
τ	$0.088^{+0.028}_{-0.034}$	$0.084^{+0.031}_{-0.038}$	$0.084^{+0.027}_{-0.034}$	$0.083^{+0.027}_{-0.031}$
n_s	$0.951^{+0.015}_{-0.019}$	$0.945^{+0.015}_{-0.019}$	$0.949^{+0.015}_{-0.019}$	$0.948^{+0.014}_{-0.018}$
σ_8	$0.744^{+0.050}_{-0.060}$	$0.722^{+0.044}_{-0.056}$	$0.742^{+0.045}_{-0.057}$	$0.737^{+0.033}_{-0.045}$
Ω_m	$0.238^{+0.027}_{-0.045}$	$0.229^{+0.026}_{-0.042}$	$0.239^{+0.025}_{-0.046}$	$0.236^{+0.016}_{-0.029}$

Parameter	WMAP+ SDSS	WMAP+ LRG	WMAP+ SNLS	WMAP + SN Gold	WMAP+ CFHTLS
$100\Omega_b h^2$	$2.233^{+0.062}_{-0.086}$	$2.242^{+0.062}_{-0.084}$	$2.233^{+0.069}_{-0.088}$	$2.227^{+0.065}_{-0.082}$	$2.247^{+0.064}_{-0.082}$
$\Omega_m h^2$	$0.1329^{+0.0057}_{-0.0109}$	$0.1337^{+0.0047}_{-0.0098}$	$0.1295^{+0.0055}_{-0.0106}$	$0.1349^{+0.0054}_{-0.0106}$	$0.1410^{+0.0042}_{-0.0094}$
h	$0.709^{+0.024}_{-0.032}$	$0.709^{+0.016}_{-0.023}$	$0.723^{+0.021}_{-0.030}$	$0.701^{+0.020}_{-0.026}$	$0.686^{+0.017}_{-0.024}$
A	$0.813^{+0.042}_{-0.052}$	$0.816^{+0.042}_{-0.049}$	$0.808^{+0.044}_{-0.051}$	$0.827^{+0.045}_{-0.053}$	$0.852^{+0.036}_{-0.047}$
τ	$0.079^{+0.029}_{-0.032}$	$0.082^{+0.028}_{-0.033}$	$0.085^{+0.028}_{-0.032}$	$0.079^{+0.028}_{-0.034}$	$0.088^{+0.021}_{-0.031}$
n_s	$0.948^{+0.015}_{-0.018}$	$0.951^{+0.014}_{-0.018}$	$0.950^{+0.015}_{-0.019}$	$0.946^{+0.015}_{-0.019}$	$0.950^{+0.015}_{-0.019}$
σ_8	$0.772^{+0.036}_{-0.048}$	$0.781^{+0.032}_{-0.045}$	$0.758^{+0.038}_{-0.052}$	$0.784^{+0.035}_{-0.049}$	$0.826^{+0.023}_{-0.035}$
Ω_m	$0.266^{+0.025}_{-0.040}$	$0.267^{+0.017}_{-0.029}$	$0.249^{+0.023}_{-0.034}$	$0.276^{+0.022}_{-0.036}$	$0.301^{+0.018}_{-0.031}$

Spergel et al. 2006, astro-ph/0603449

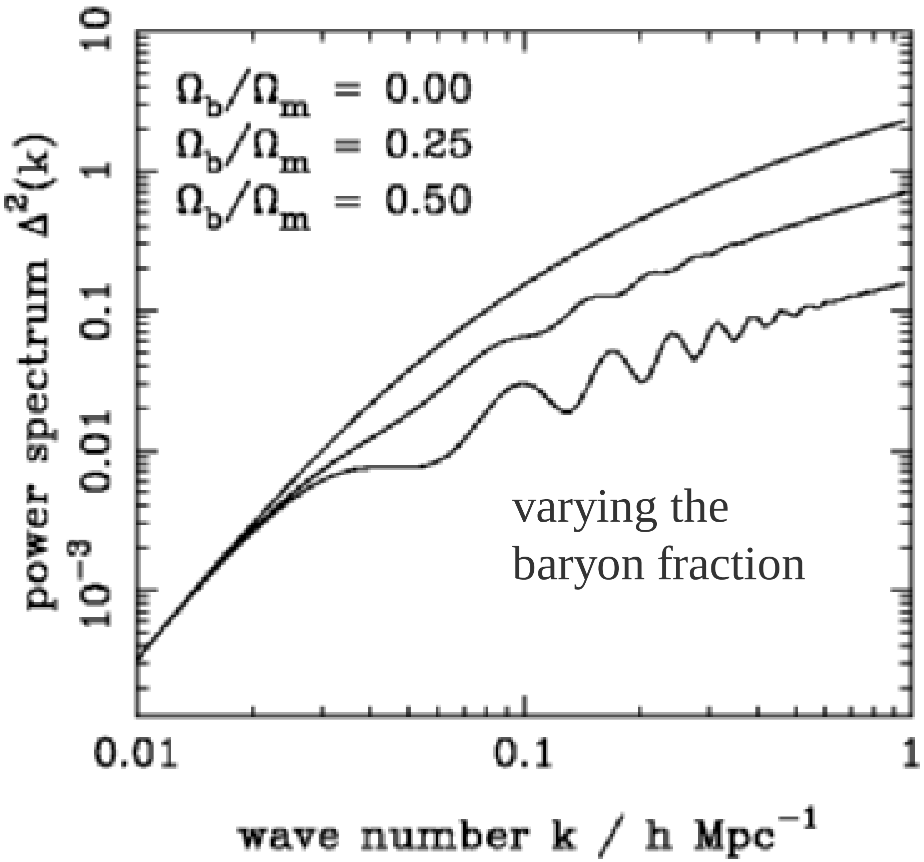
Is there large-scale scale dependent bias?

- SDSS data show a shape change caused by scale dependent bias dependent on r-band luminosity
- Obvious change on scales k>0.2hMpc-1
- Inconclusive on large scales, but there may be something there
- This effect is far less significant than change in overall bias amplitude (curves corrected in plot) with luminosity



Percival et al. 2007, ApJ, 657, 645

Baryon oscillations in the large-scale matter power spectrum



varying the baryon fraction

“Wavelength” of baryonic acoustic oscillations is determined by the comoving sound horizon at recombination

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

At early times can ignore dark energy, so comoving sound horizon is given by

$$s = \frac{1}{H_0 \Omega_m^{1/2}} \int_0^{a_*} da \frac{c_s}{(a + a_{\rm eq})^{1/2}}$$

Sound speed c_s

Gives the comoving sound horizon ~110h^{-1}Mpc, and BAO wavelength 0.06hMpc^{-1}

BAO in the galaxy power spectrum

Linear baryon acoustic oscillations are ratio of linear matter power spectrum to a smooth fit

$$B_{\rm lin} = \frac{P(k)_{\rm lin}}{\bar{P}(k)_{\rm lin}}$$

Suppose that we measure an observed power that is related to the linear power by (halo model)

$$P_{\rm obs}(k) = b^2(k)P(k)_{\rm lin} + P(k)_{\rm extra}$$

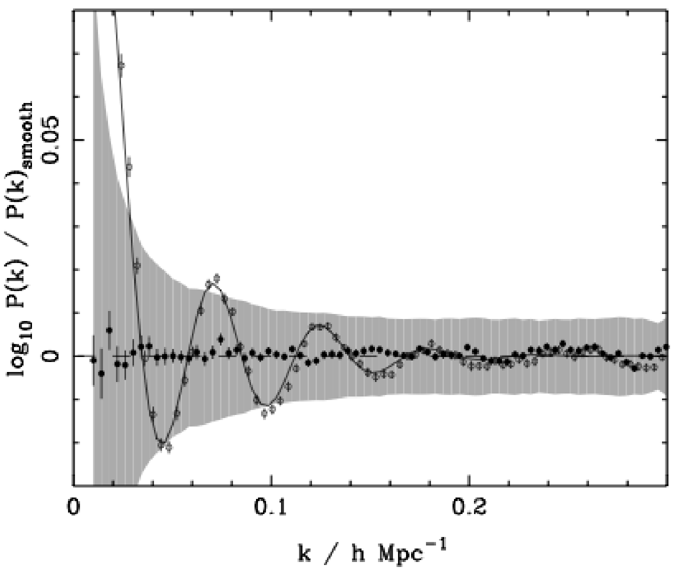
Then observed oscillations are related to linear BAO by

$$B_{\rm obs} = \frac{P(k)_{\rm obs}}{\bar{P}(k)_{\rm obs}} = g(k)B_{\rm lin} + [1 - g(k)]$$

No change in position of oscillations, just a damping term. Eisenstein, Seo & White (2006) argued that this was well fitted by a Gaussian.

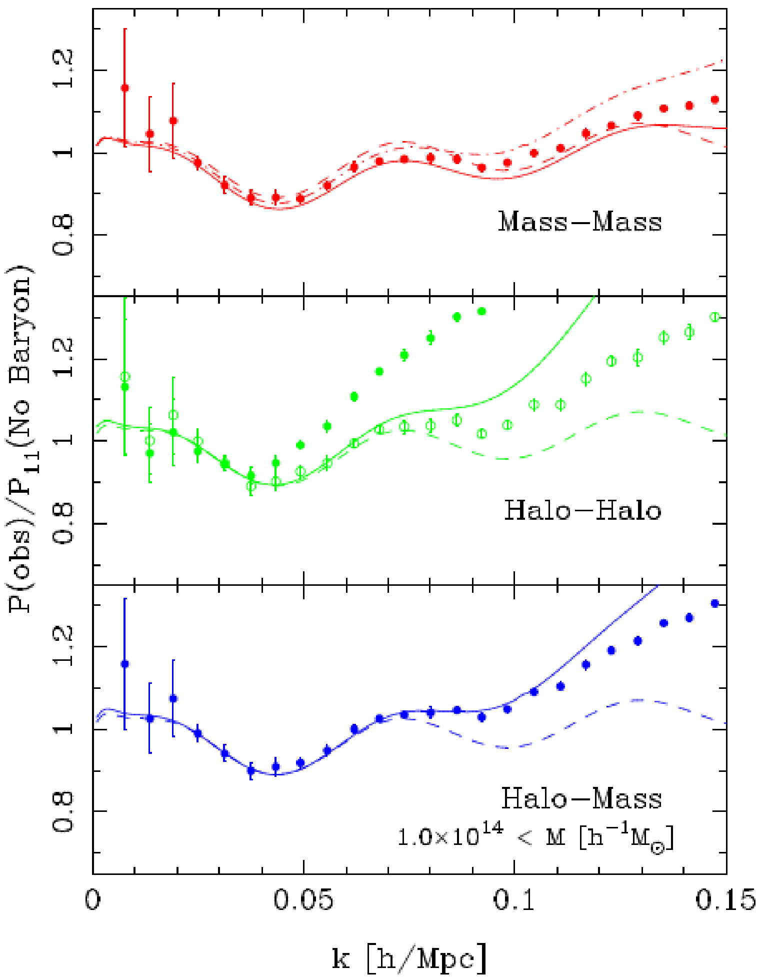
$$g(k) = \frac{b^2(k)\bar{P}(k)_{\rm lin}}{\bar{P}(k)_{\rm obs}}$$

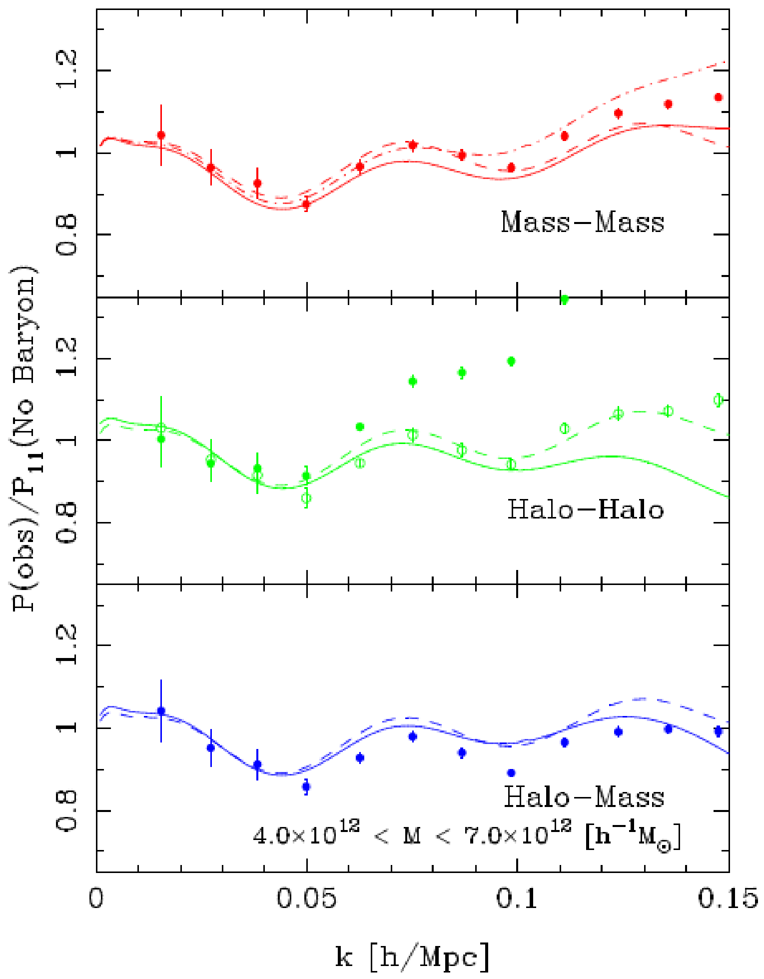
To change the observed positions of BAO, we need sharp features in the observed power?



fit data with a 2-component model comprising a smooth spline (node separation 0.05hMpc^{-1}), and the sinosoidal (in the transfer function) multiplicative BAO component usually applied to a CDM model. The ability of this model to fit linear CDM power spectra is good.

“systematic errors” in BAO measurements

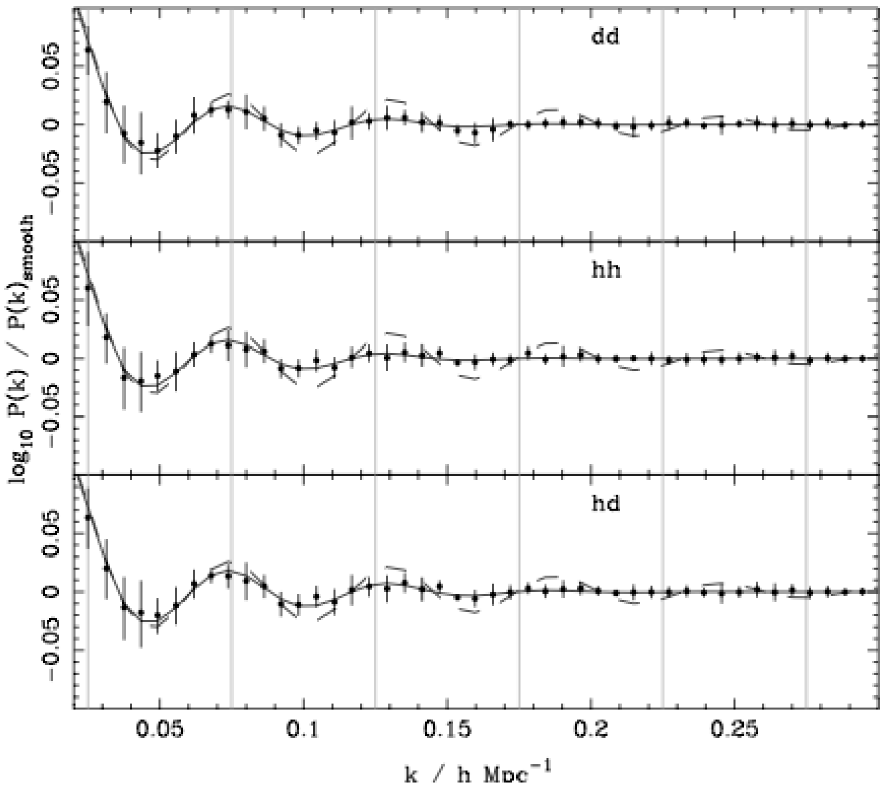


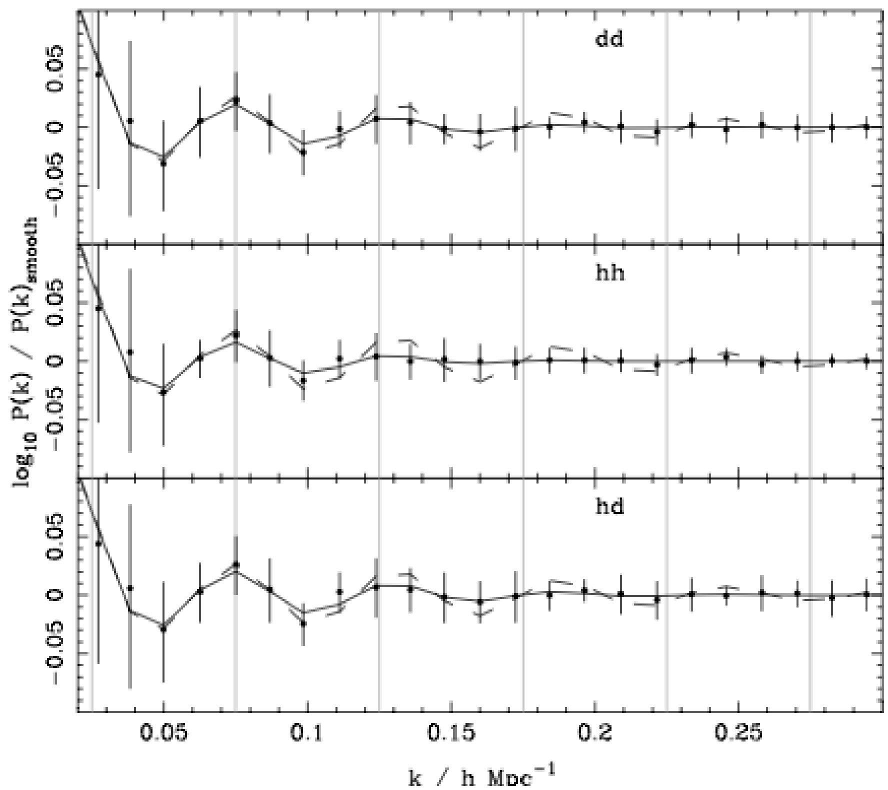


Plots from
Smith, Scoccimarro & Sheth 2006, astro-ph/0609547

Errors in distance scale of up to 5% claimed

BAO in simulations





High mass
halos

low mass halos

Data from simulations of
Smith, Scoccimarro & Sheth 2006, astro-ph/0609547

Fit with spline × BAO model: no evidence
for distance scale errors

Summary

- The matter power spectrum generated from galaxy redshift surveys is a useful probe of the cosmological parameters, including those relevant to the dark energy
- However, there are many systematic sources of error that have to be carefully treated, including:
  - convolution with the window function
  - correct treatment of the bias
  - redshift space distortions, etc
- In the future, Baryon Acoustic Oscillations may work very well as a systematic free measurement of the angular diameter distance

Answer

- The answer to my question is (a) Sean Connery
- Although I will also accept (g) Daniel Craig