Constraining cosmological models using LSS & BAO Observations

Will Percival

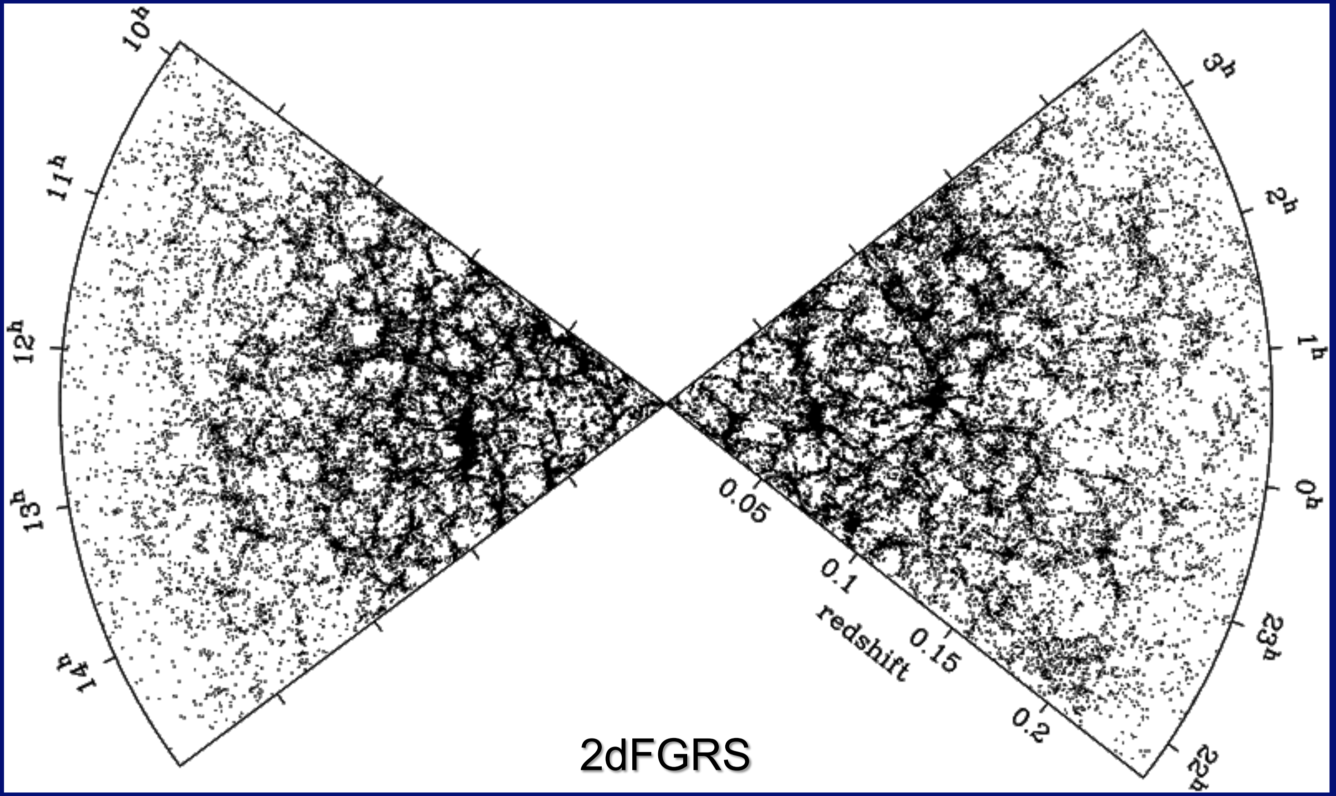
University of Portsmouth

UC Berkeley seminar, May 20th 2008

outline

- Introduction to large-scale structure analyses
- Measure $\Omega_M h$ from relative clustering strength on large and small scales
  - problems with galaxy bias
  - possible resolution?
- Baryon Acoustic Oscillations
  - why these are more robust to galaxy bias
  - background
  - a recent study of the SDSS galaxies
- Future surveys

Galaxy clustering

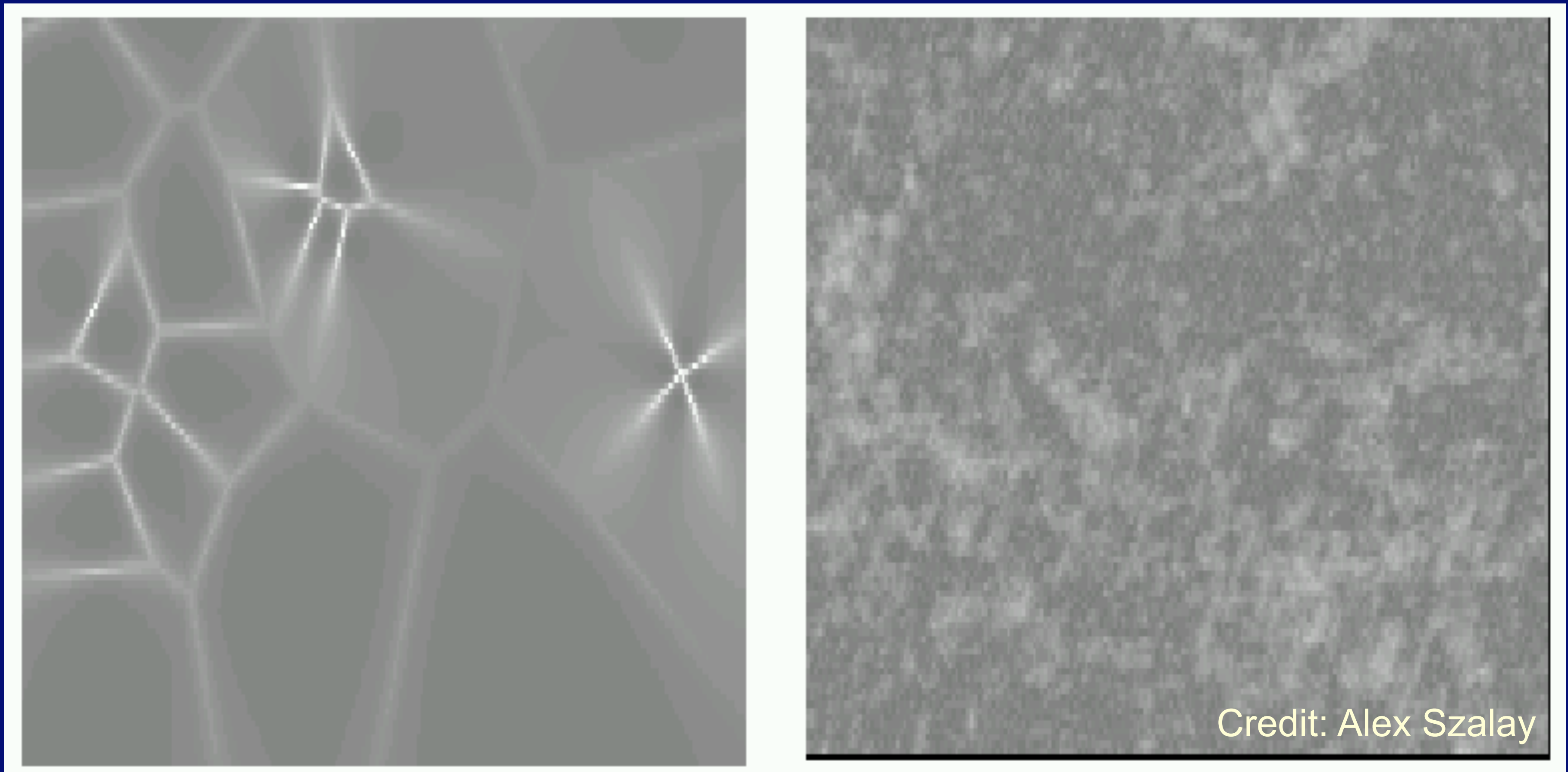


overdensity field $\delta \equiv \frac{\rho - \bar{\rho}}{\bar{\rho}}$

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

Beyond 2-pt statistics

2-pt statistics complete for Gaussian random field, but no phase information



Same 2pt, different 3pt

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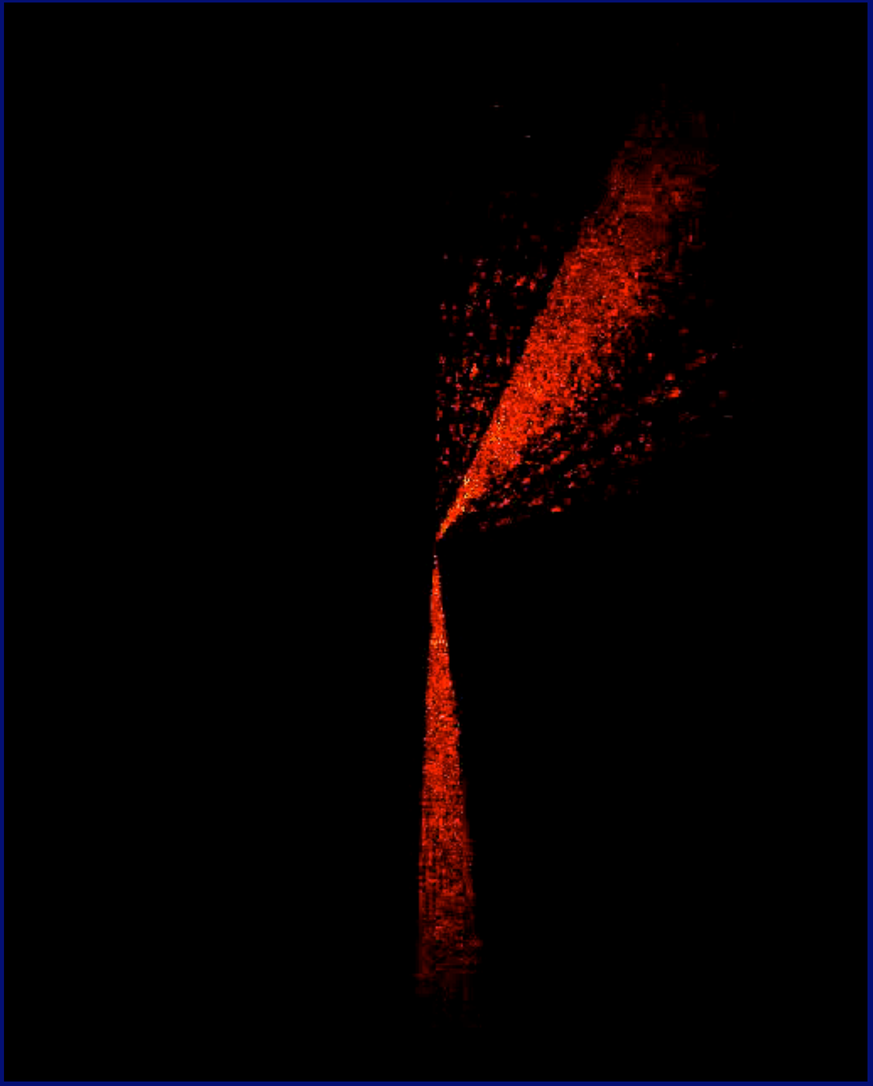
The 2dF Galaxy Redshift Survey

- 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)

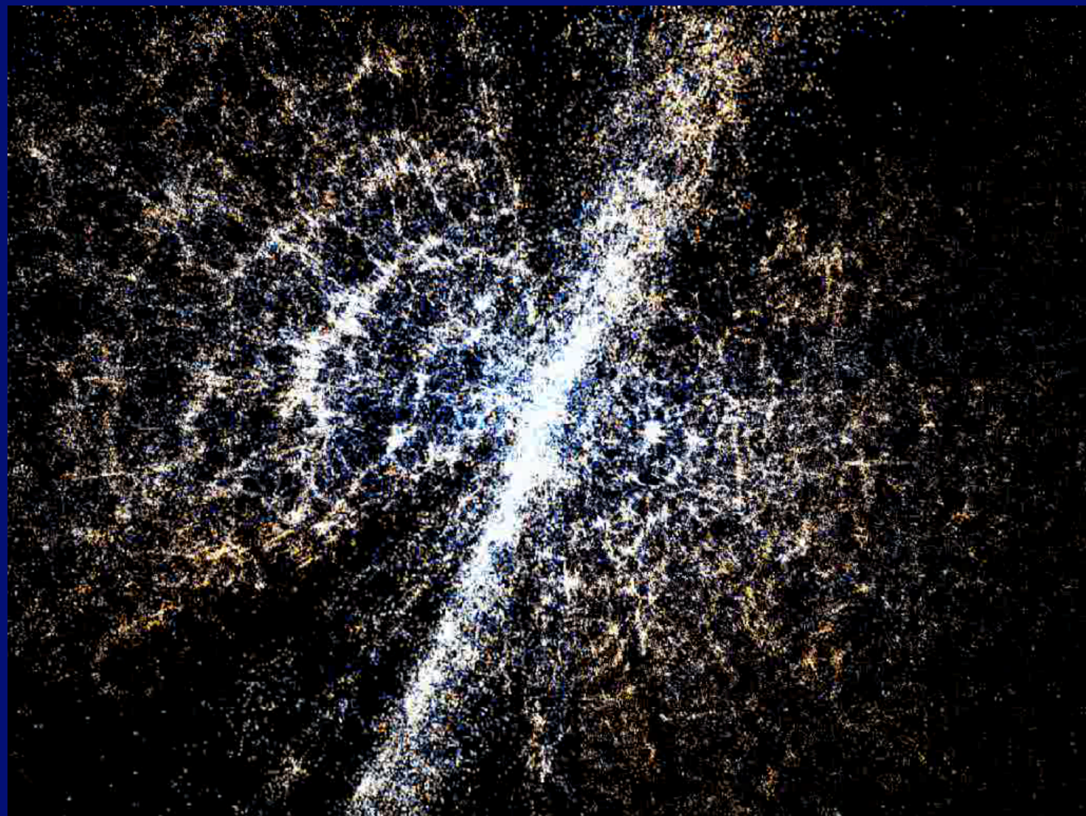
- data has been released (team disbanded 2005)

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



The Sloan Digital Sky Survey

- collaboration of over 200 scientists in 14 institutions
- survey will measure redshifts for 1000000 galaxies in the local Universe (r-band selection)
- also observed ~60000 luminous red galaxies out to higher redshift
- all data now taken. Currently waiting for final data release (October 2008)



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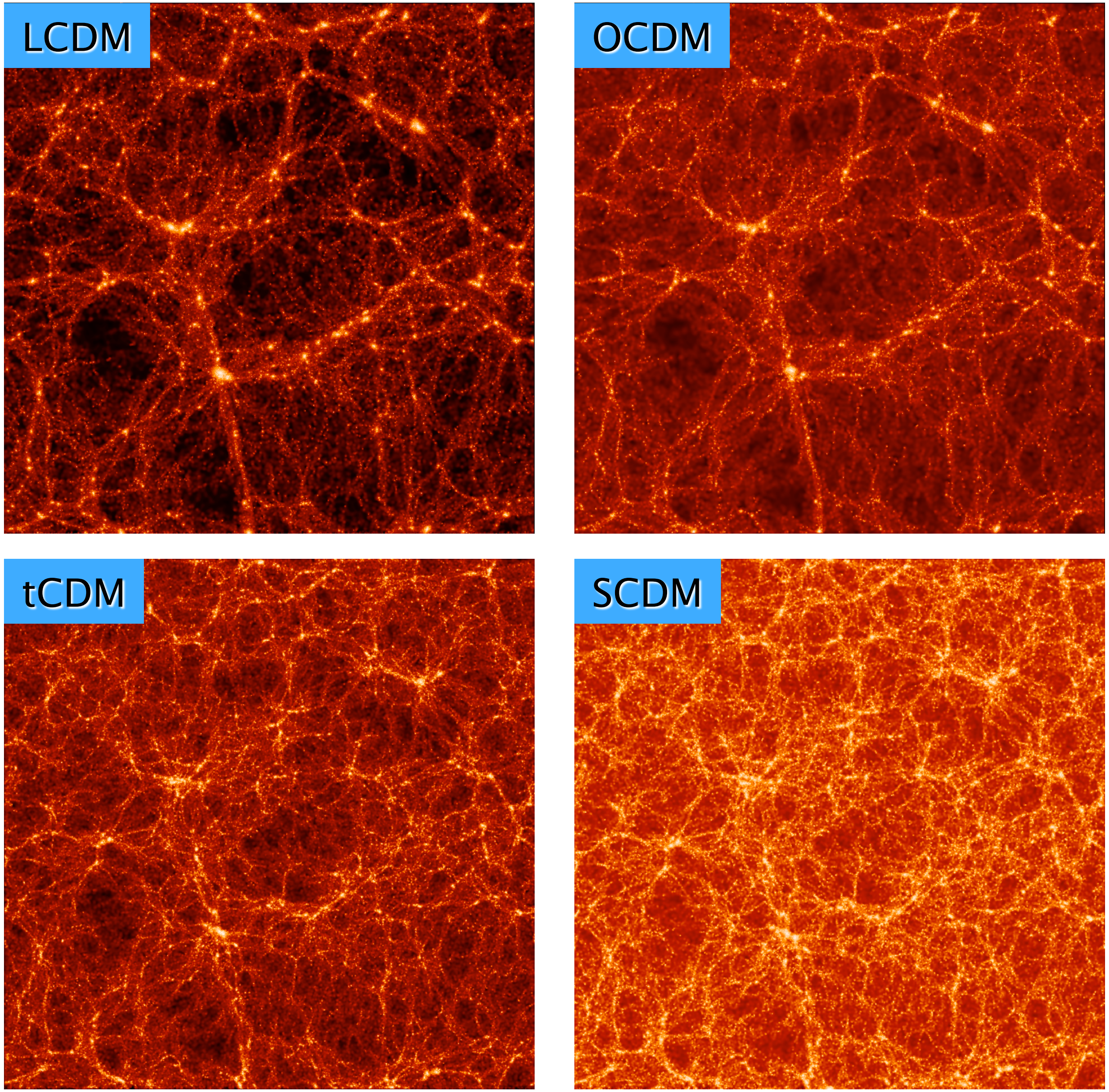
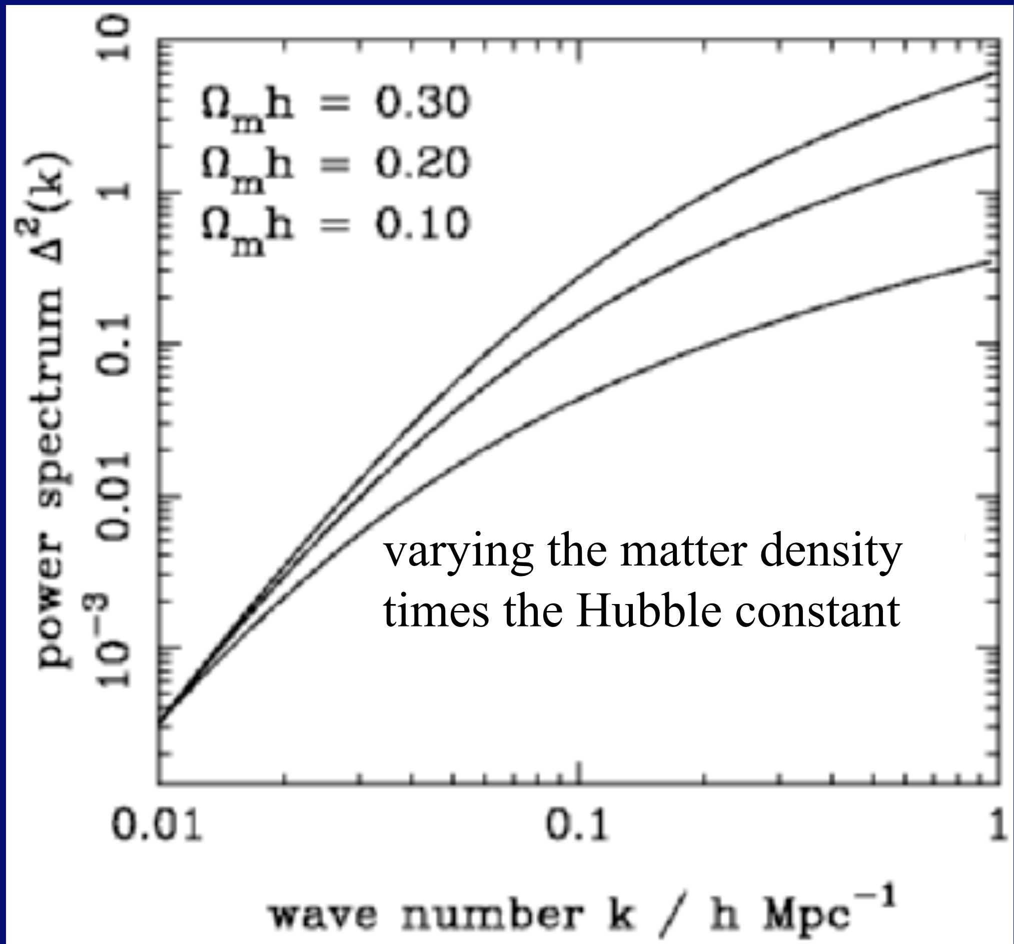
Measuring $\Omega_m h$ from the power spectrum shape

The shape of the power spectrum



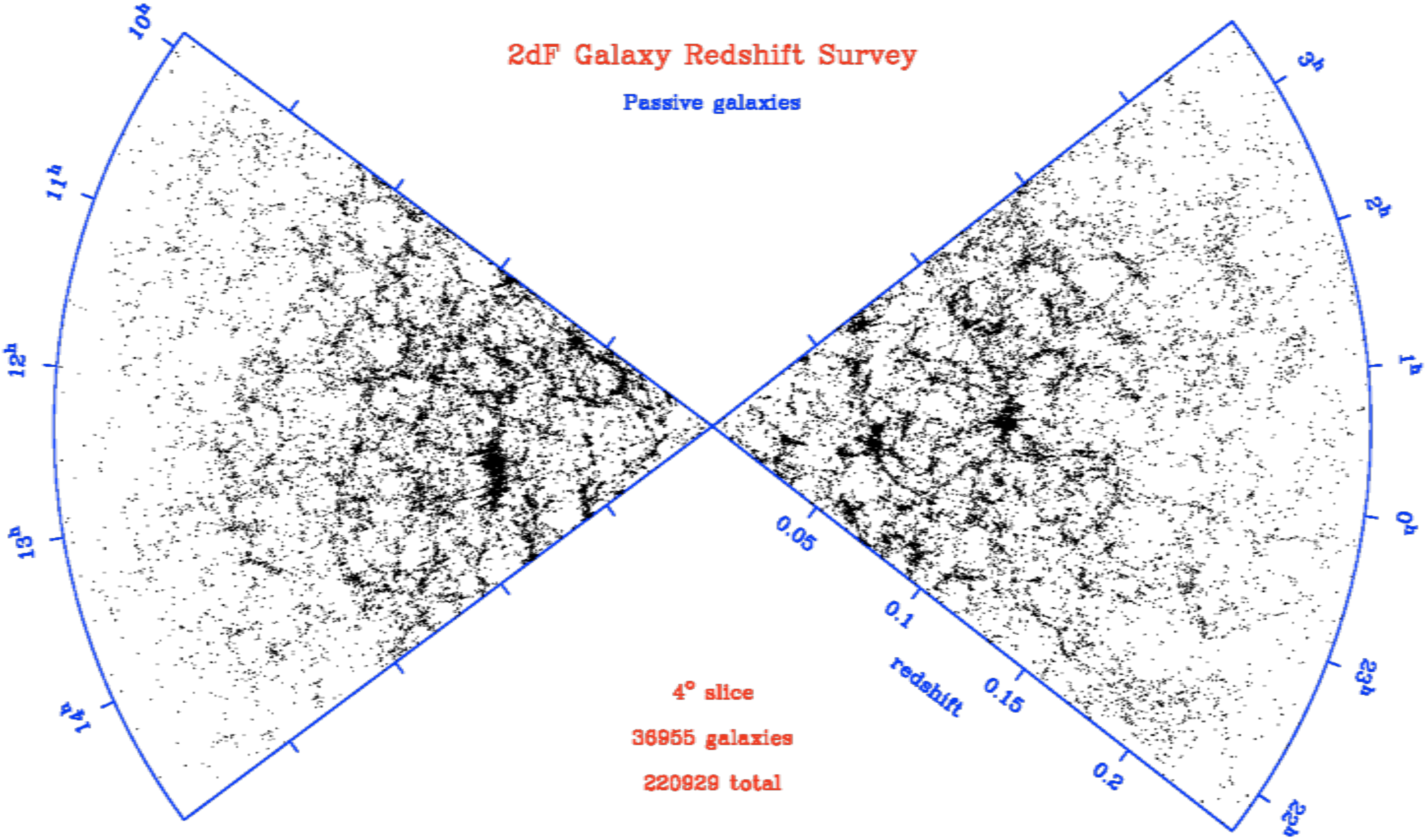
The power spectrum turn-over



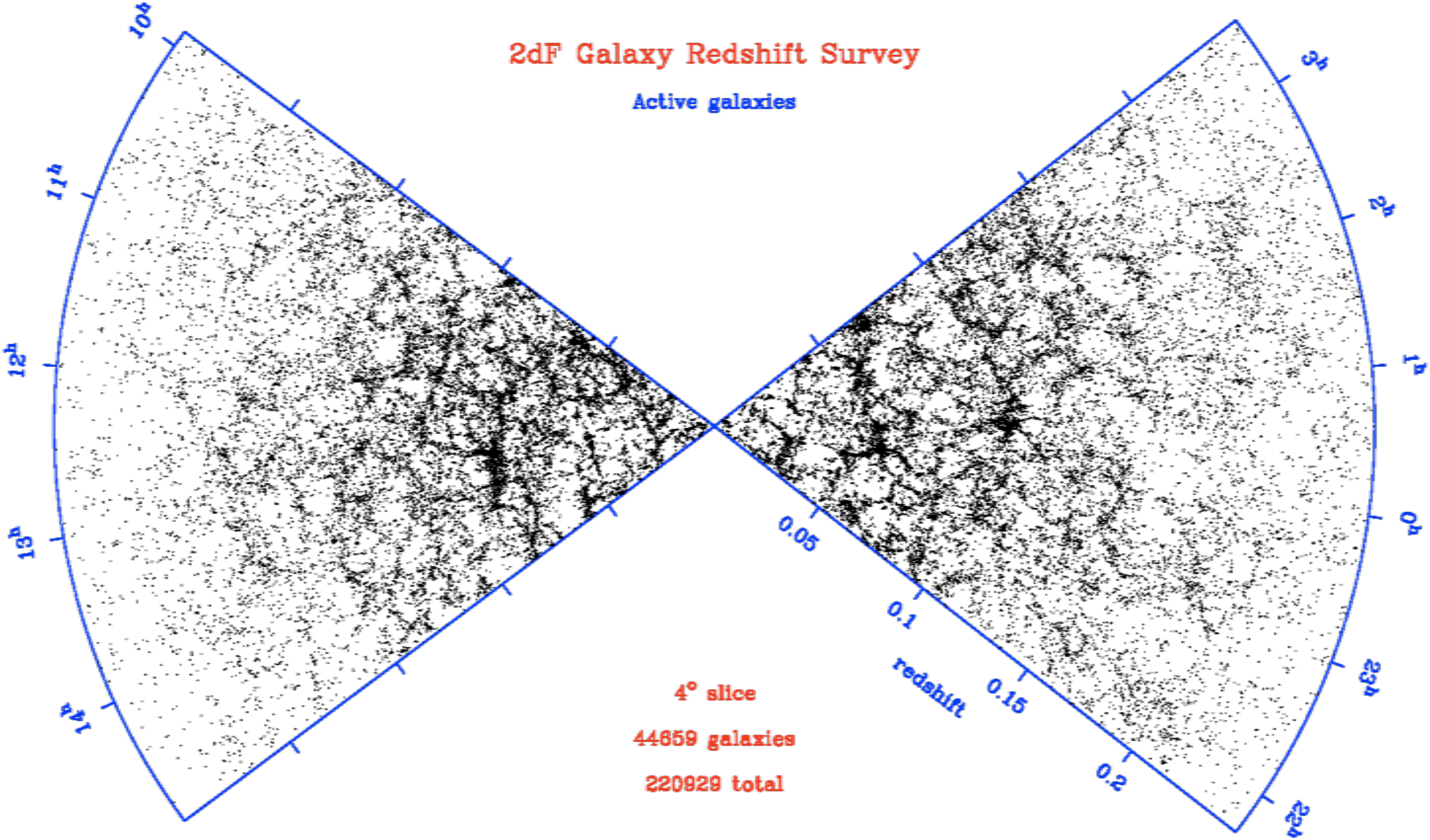
During radiation domination, pressure support means that small perturbations cannot collapse.

➔ Can measure $\Omega_M h$ from shape of power spectrum

Galaxy bias : red galaxies

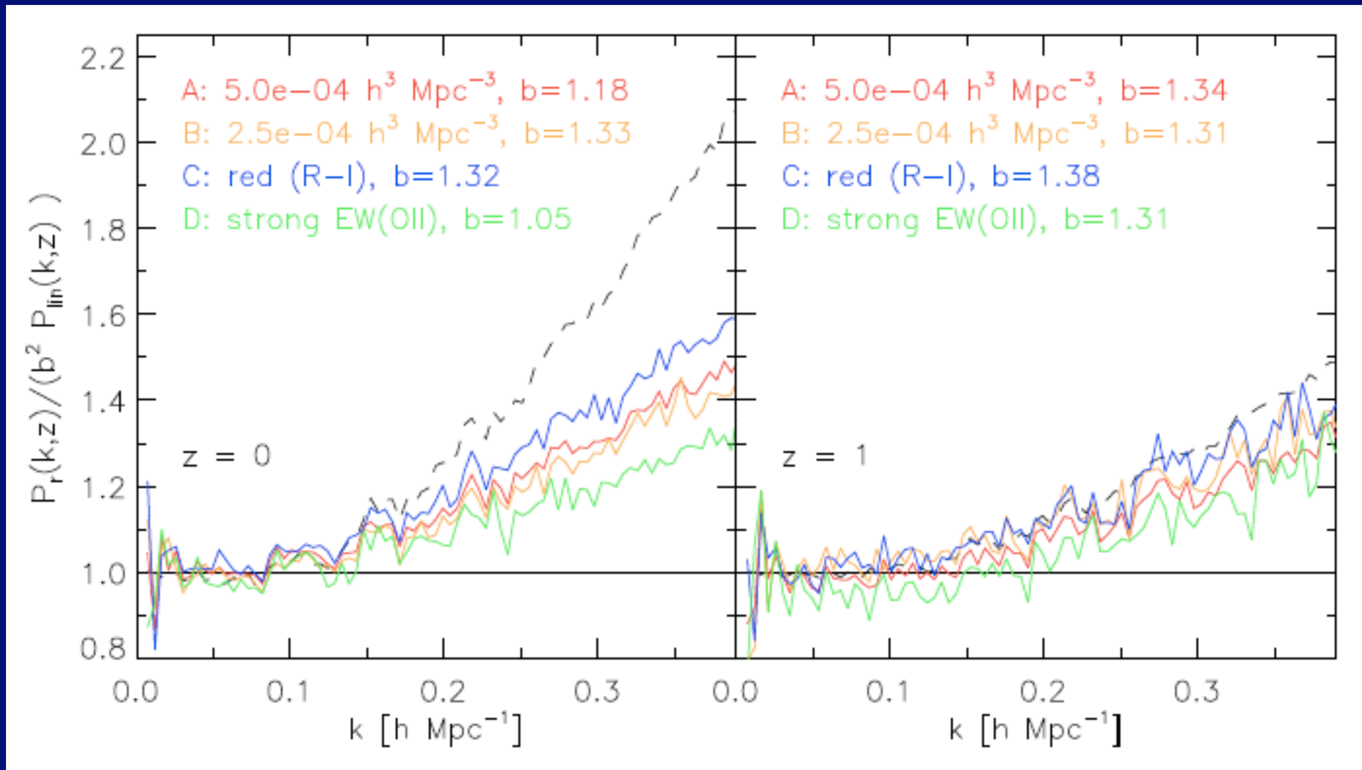


Galaxy bias: blue galaxies



Problem: galaxy bias

Galaxies not expected to form a Poisson sampling of the matter field



Angulo et al., 2007, MNRAS, astro-ph/0702543

modelling galaxy bias

Bias in this context means relation between $P(k)_{\mathbf{lin}}$ & $P(k)_{\mathbf{obs}}$

shot noise change (Seljak 2001)

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

Quadratic (Seo & Eisenstein 2005)

$$P(k)_{\rm obs} = b^2 P(k)_{\rm lin} + A_0 + A_1 k + A_2 k^2$$

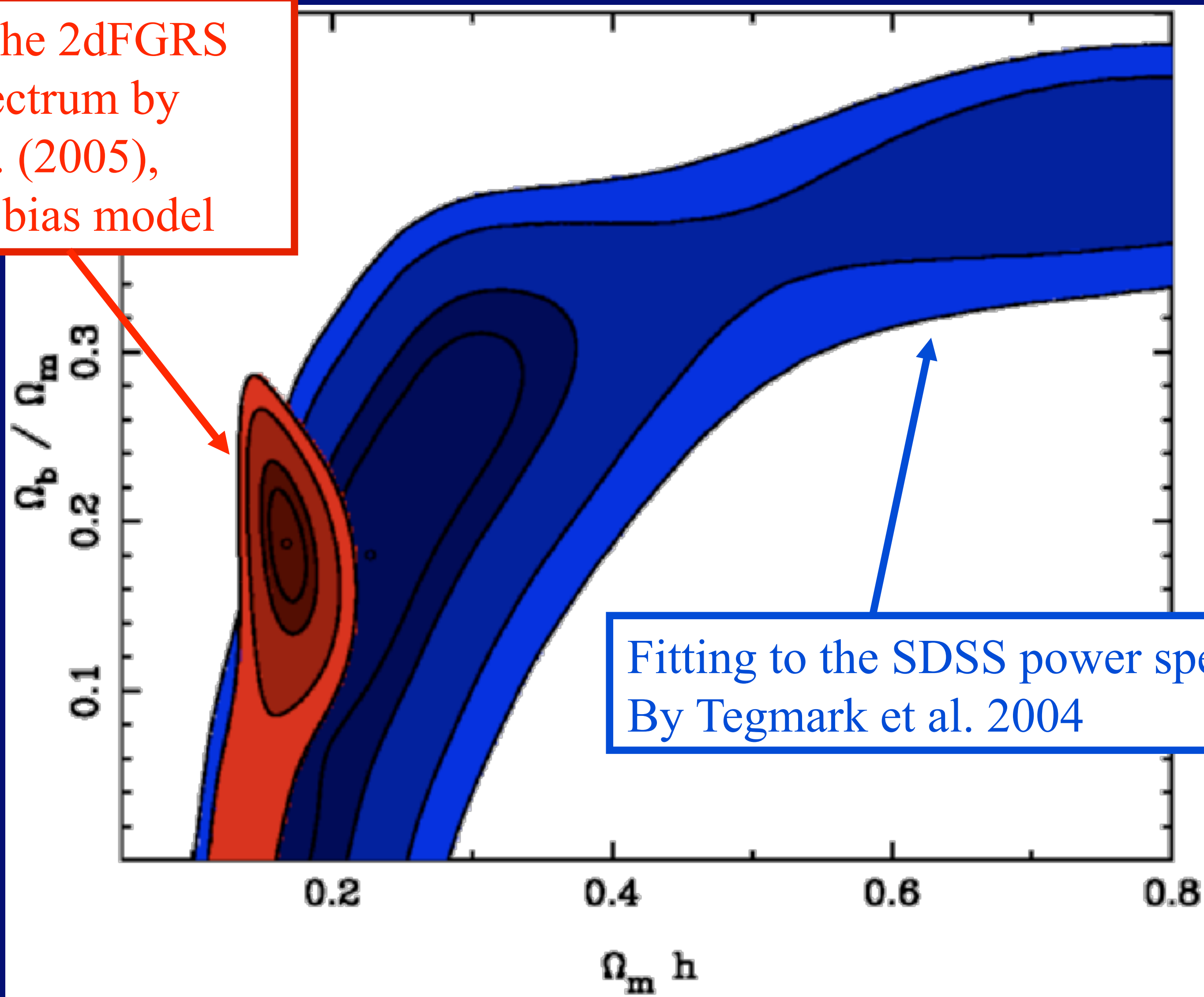
Q model (Cole 2005)

$$P(k)_{\rm obs} = b^2 P(k)_{\rm lin} \frac{1 + Qk^2}{1 + Ak}$$

We really want a full model for galaxy formation

see review by Smith et al. 2007, astro-ph/0609547

power spectrum shape constraints

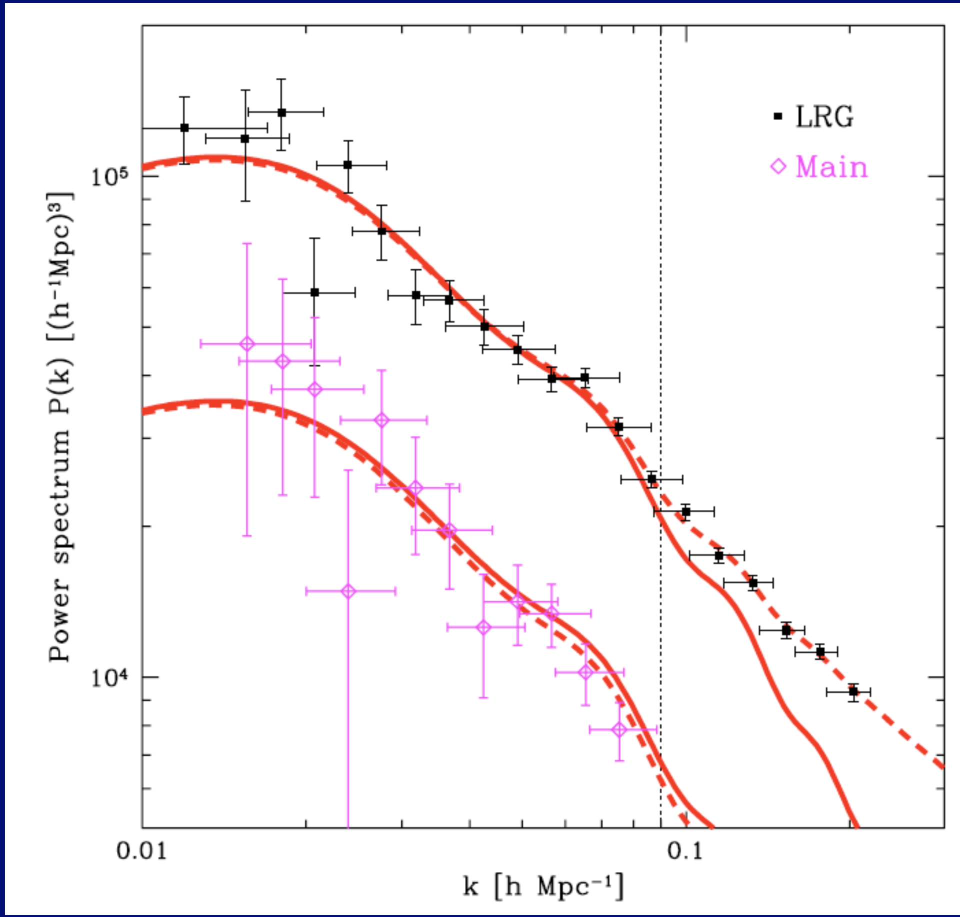


Fitting to the 2dFGRS power spectrum by Cole et al. (2005), including bias model

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

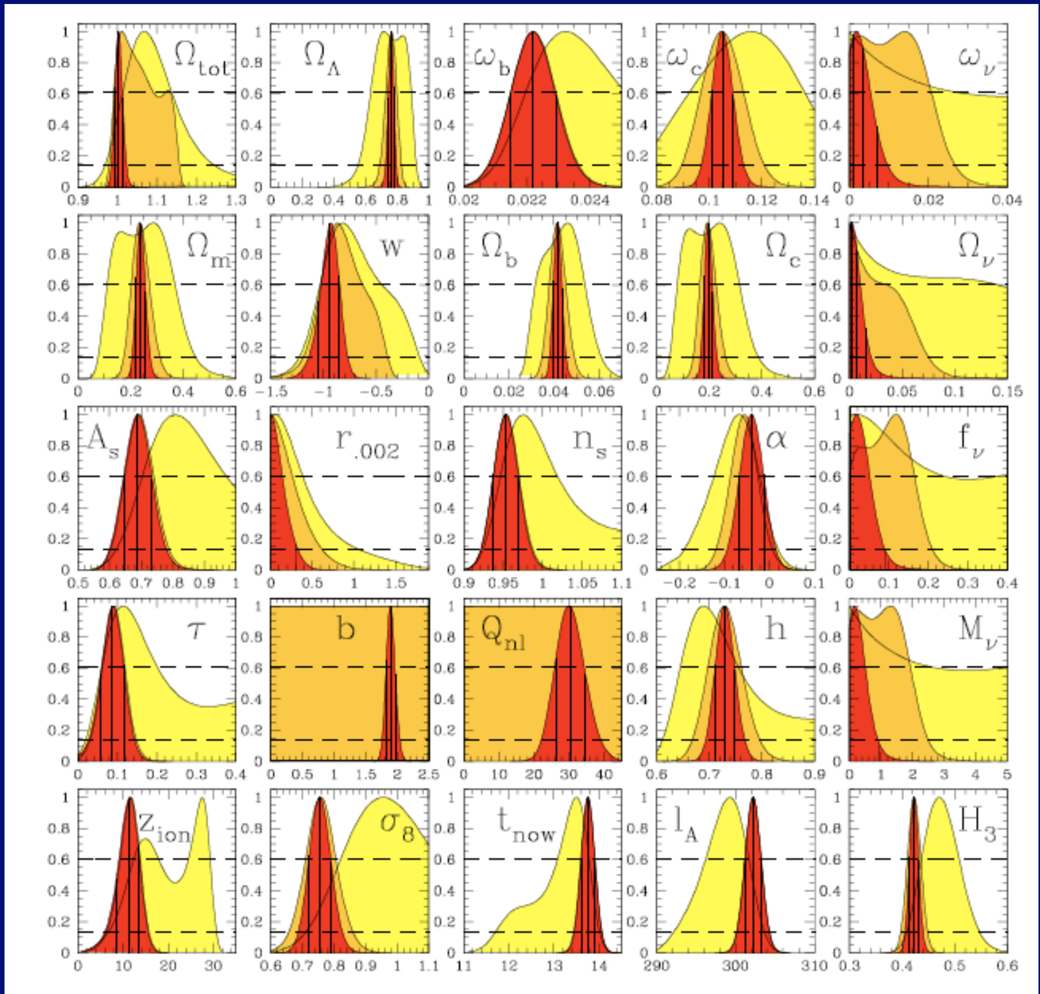
latest SDSS results from the shape of P(k)

- Quadratic estimator
- Used Q model for galaxy bias
- Fingers-of-God compression using assumed halo size
- Primary signal from shape of power spectrum (weak signal form baryons)



Tegmark et al. 2006, astro-ph/0608632

SDSS results from the shape of P(k)



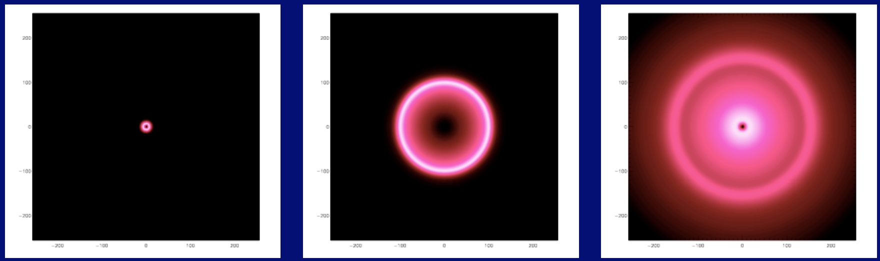
- Possible 2nd order effects associated with this sort of analysis
  - Fingers-of-God compression
  - Bias model

Tegmark et al. 2006, astro-ph/0608632

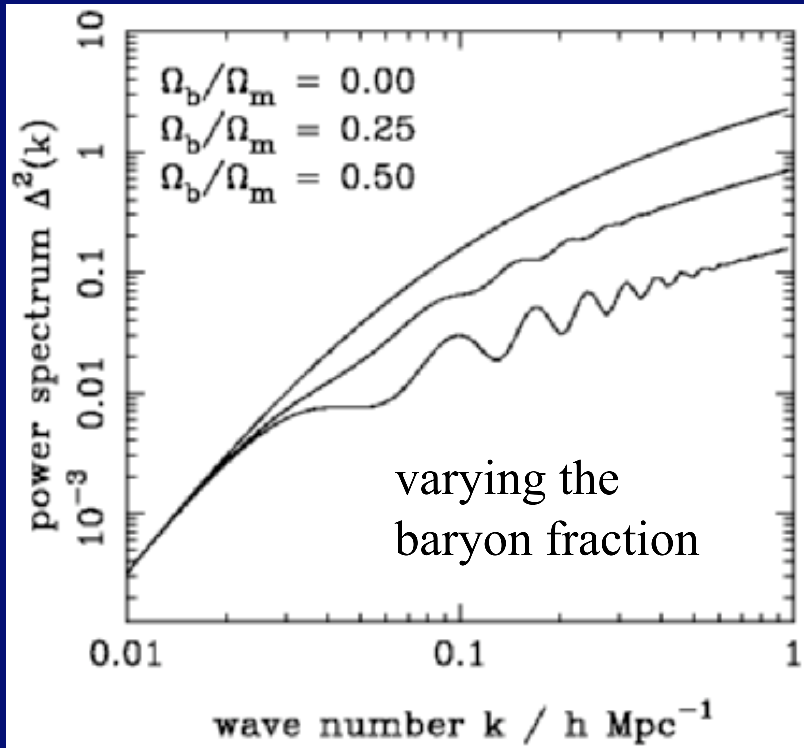
Constraining dark energy using

Baryon Acoustic Oscillations

Baryon Acoustic Oscillations (BAO)



(images from Martin White)



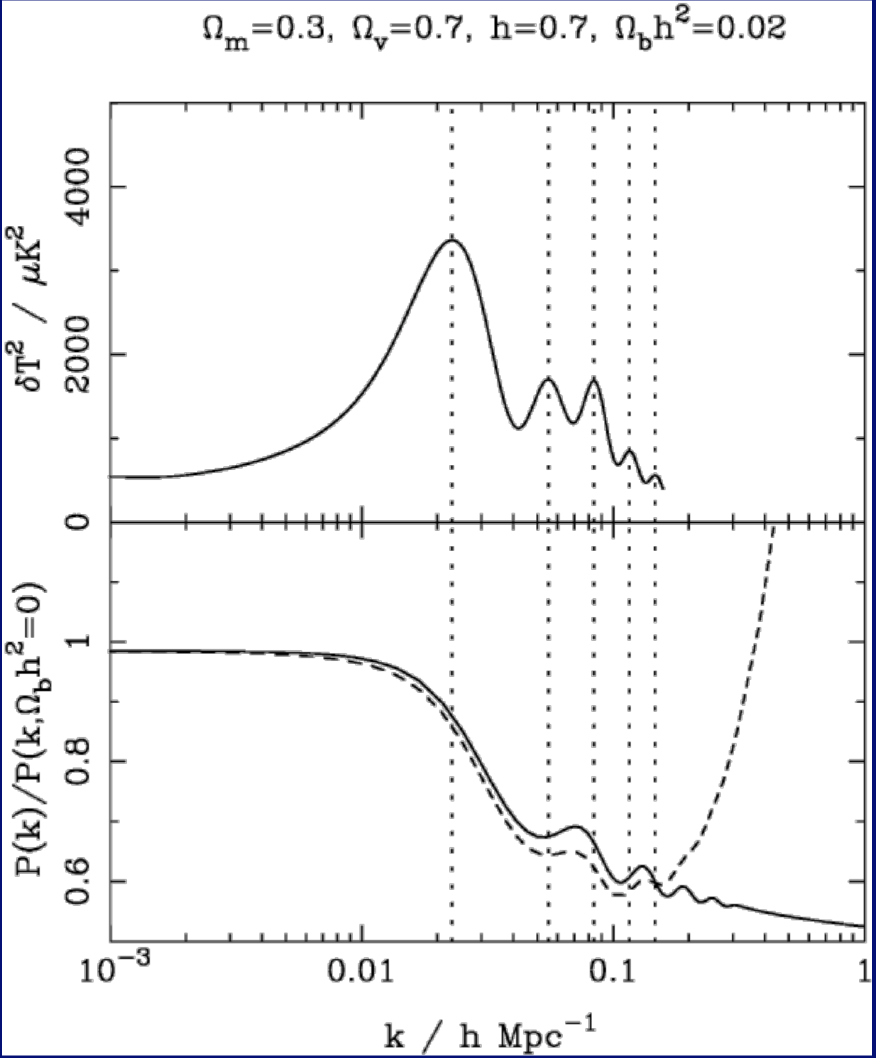
To first approximation, BAO wavelength is determined by the comoving sound horizon at recombination

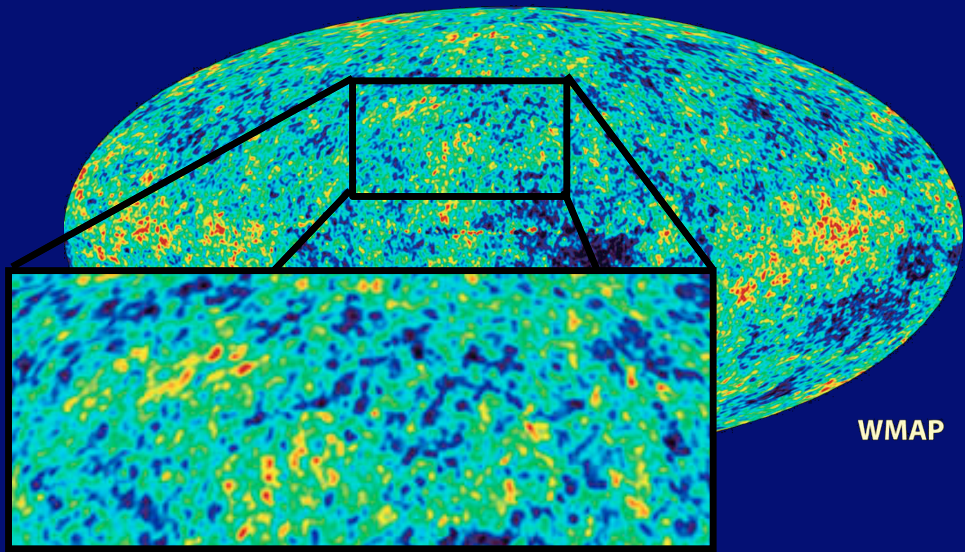
$$k_{\mathrm{bao}} = 2\pi/s$$

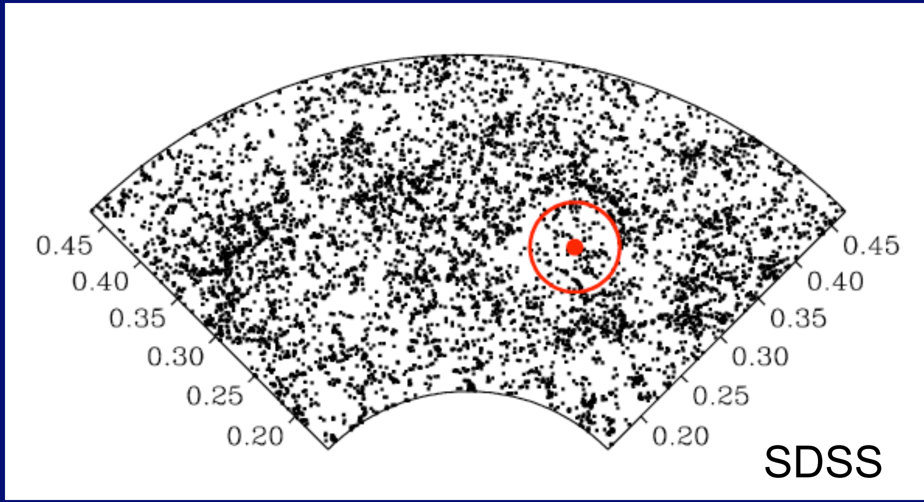
$$s = \frac{1}{H_0\Omega_m^{1/2}} \int_0^{a_*} da \frac{c_s}{(a + a_{\mathrm{eq}})^{1/2}}$$

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

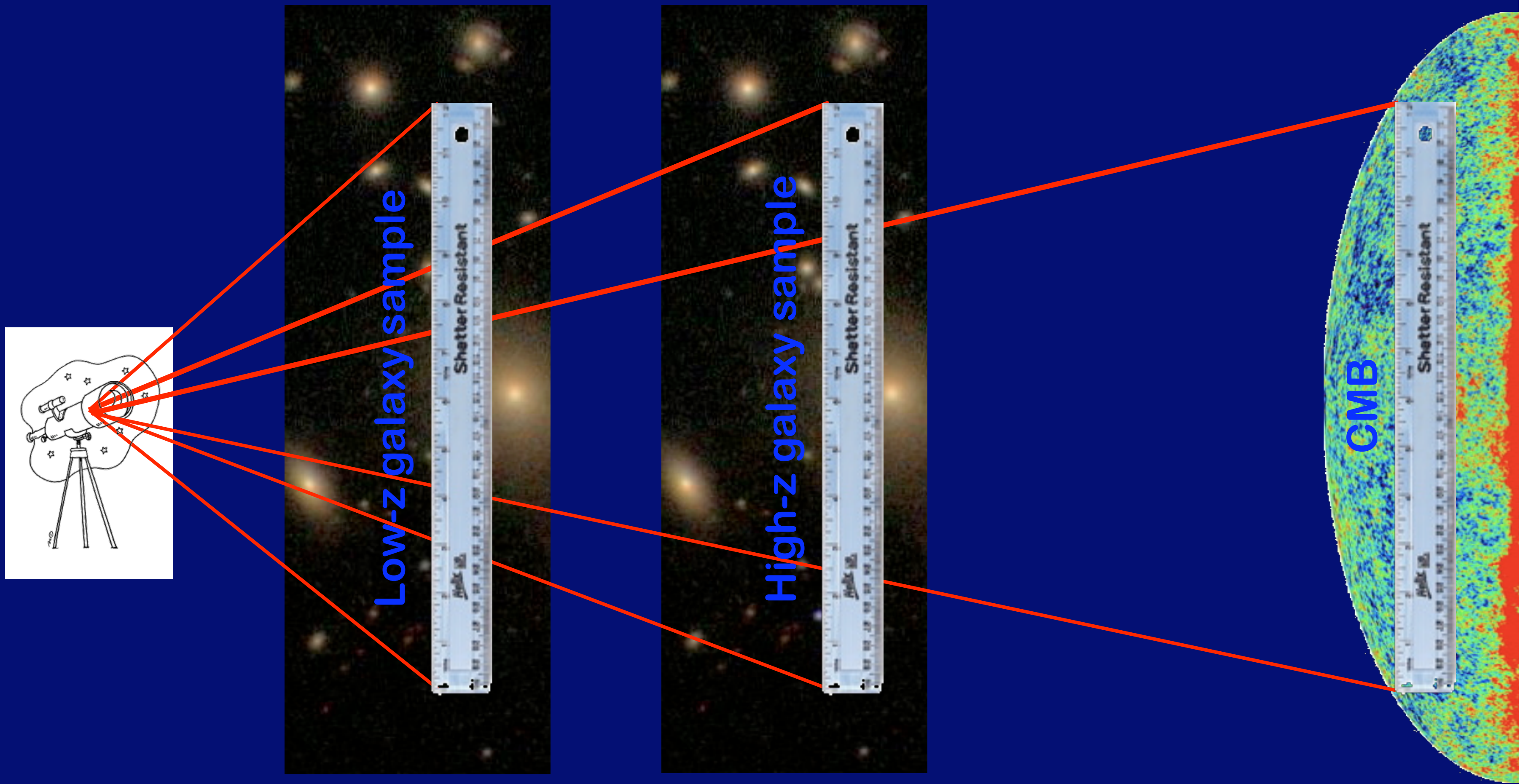
Relationship between CMB and LSS power spectra







Using BAO to measure cosmic acceleration



Idea described in:
Blake & Glazebrook 2003, ApJ, 594, 665
Seo & Eisenstein 2003, ApJ 598, 720

Why BAO are a good ruler

Linear BAO

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

Observed power

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

Observed BAO

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

(no change in position)

Damping factor

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

Need sharp features in P(k) or correlations to change BAO position

Eisenstein, Seo & White 2006, astro-ph/0604361
Percival et al. 2007, astro-ph/0705.3323

BAO as a standard ruler

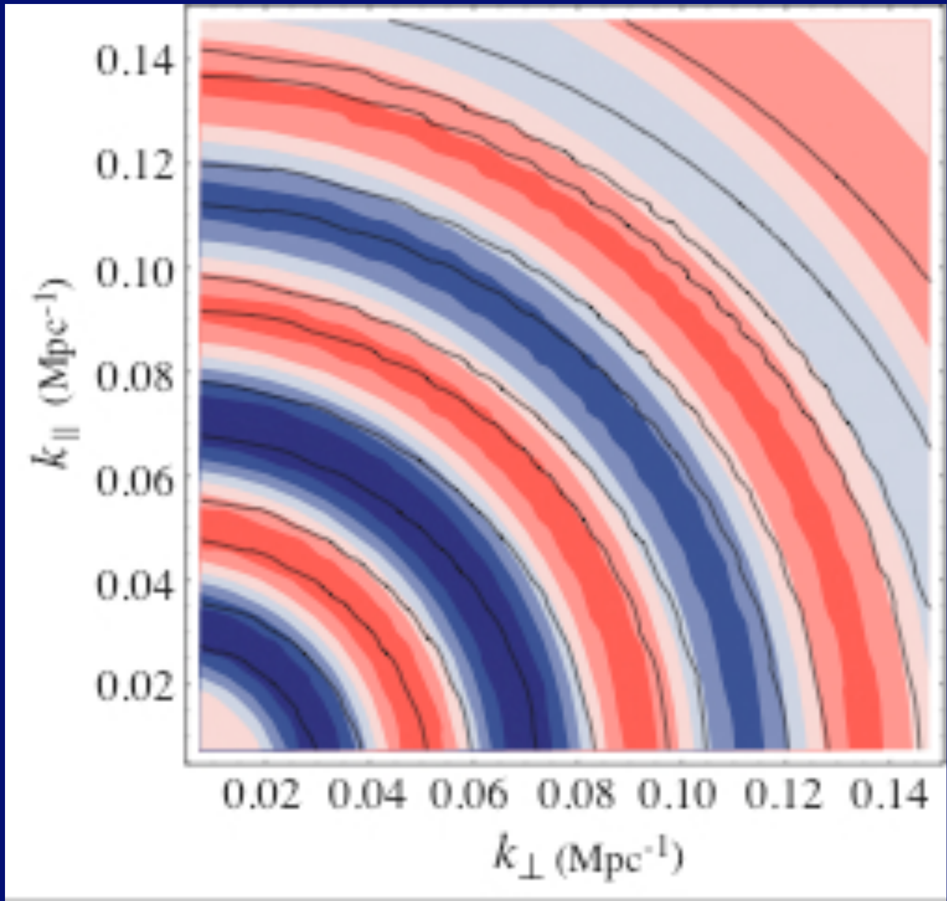
BAO measurements linked to physical BAO scale through:

Radial direction

$$\frac{c}{H(z)}\Delta z$$

Angular direction

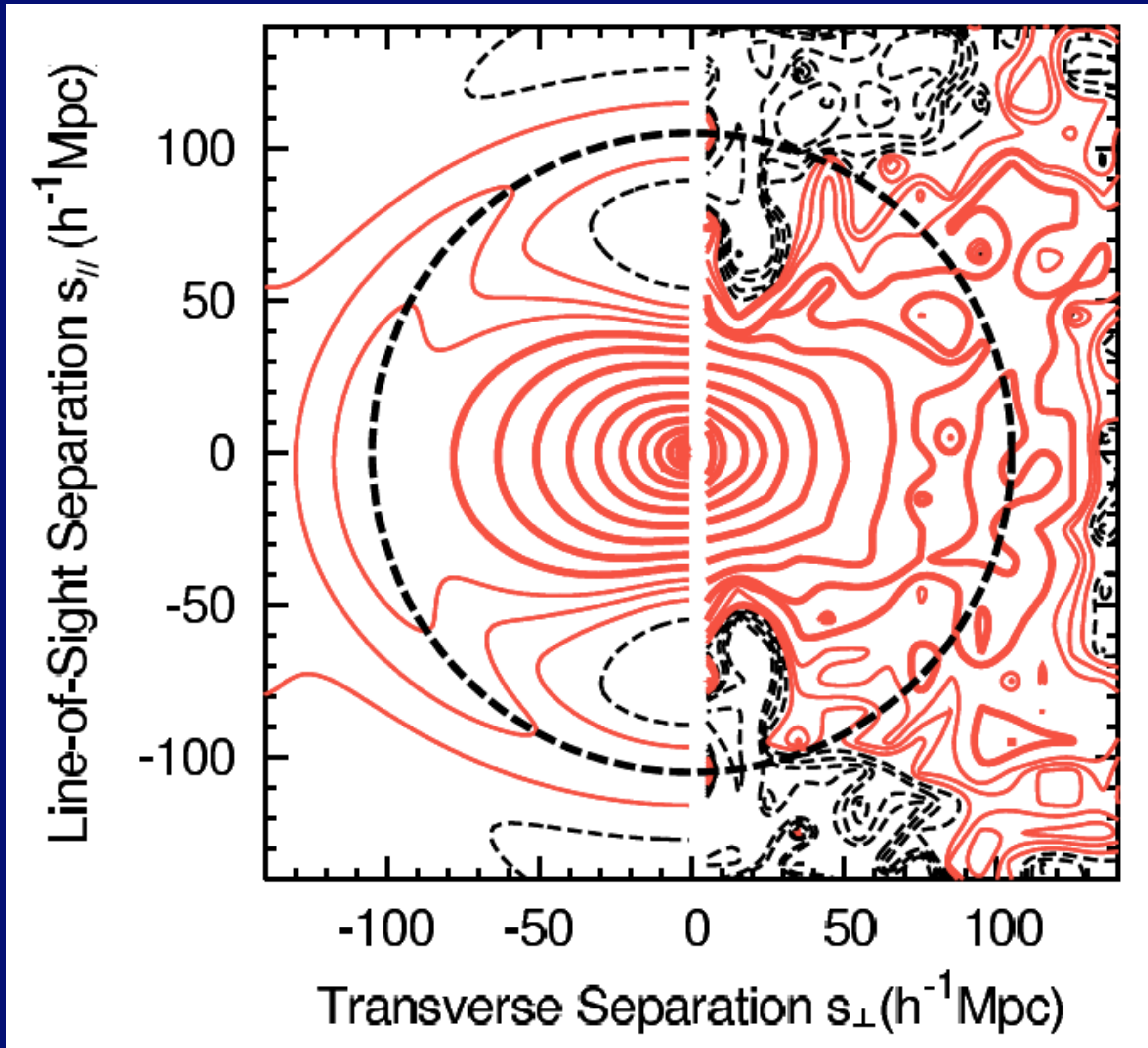
$$(1+z)D_A\Delta\theta$$



Hu & Haiman 2003, PRD, 68, 3004

BAO as a function of angle

Linear theory prediction



Contours of SDSS LRG correlation function ~DR3 sample

Okumura et al (2007), astro-ph/0711.3640

Averaging over all pairs

BAO measurements linked to physical BAO scale through:

Radial direction

$$\frac{c}{H(z)}\Delta z$$

Angular direction

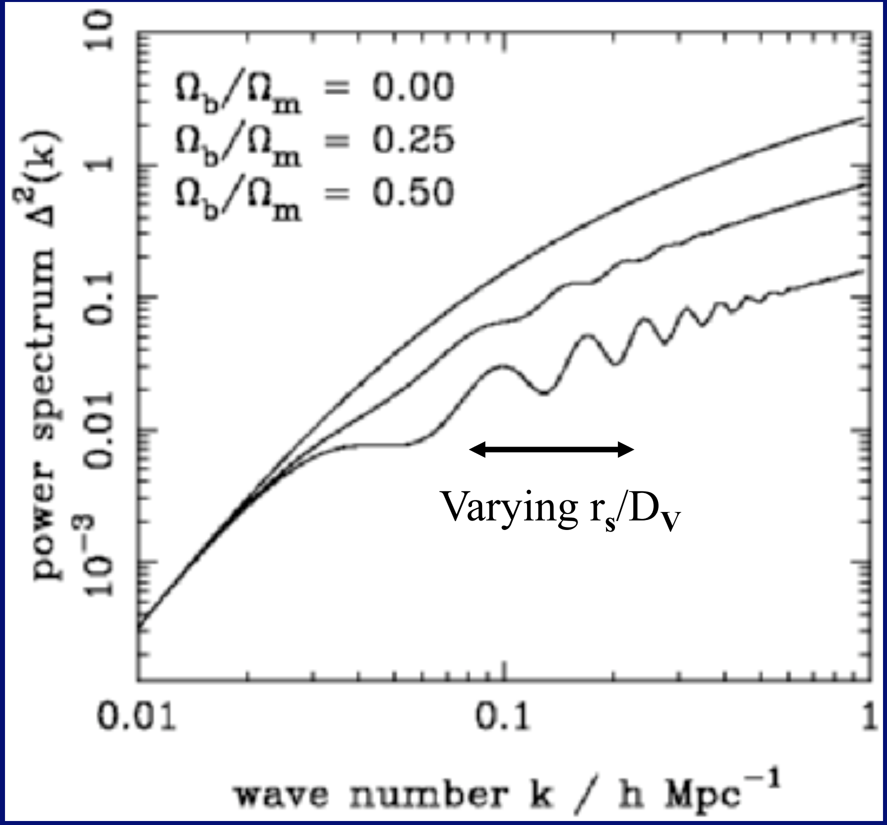
$$(1+z)D_A\Delta\theta$$

To first order, random pairs depend on

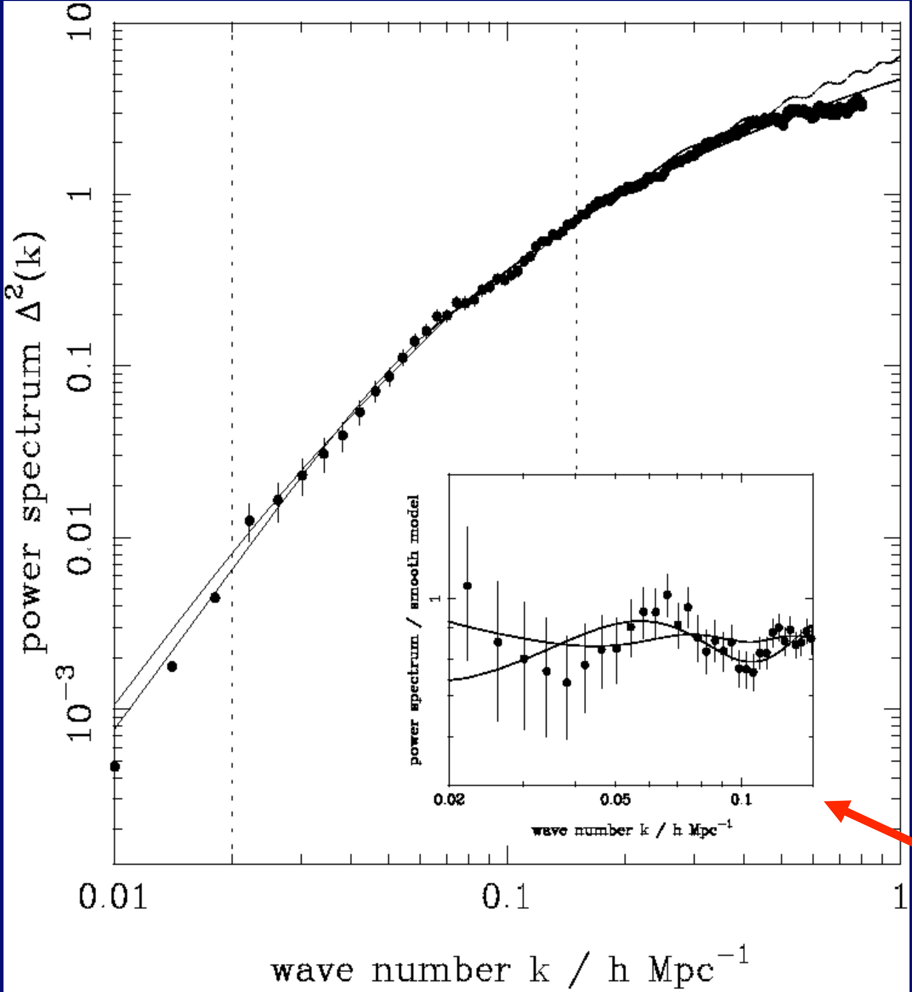
$$D_V = \left[(1+z)^2 D_A^2(z)\frac{cz}{H(z)}\right]^{1/3}$$

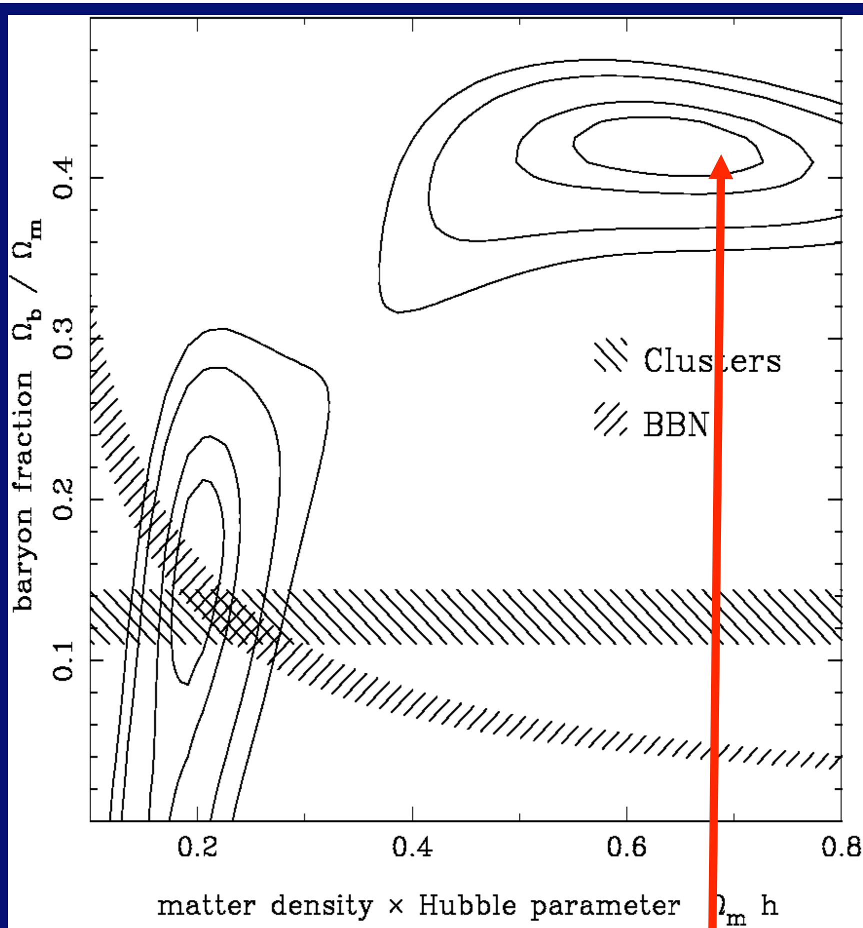
Observed BAO position therefore constrains some multiple of

$$\frac{r_s}{D_V}$$



2dFGRS: the wiggles that weren't

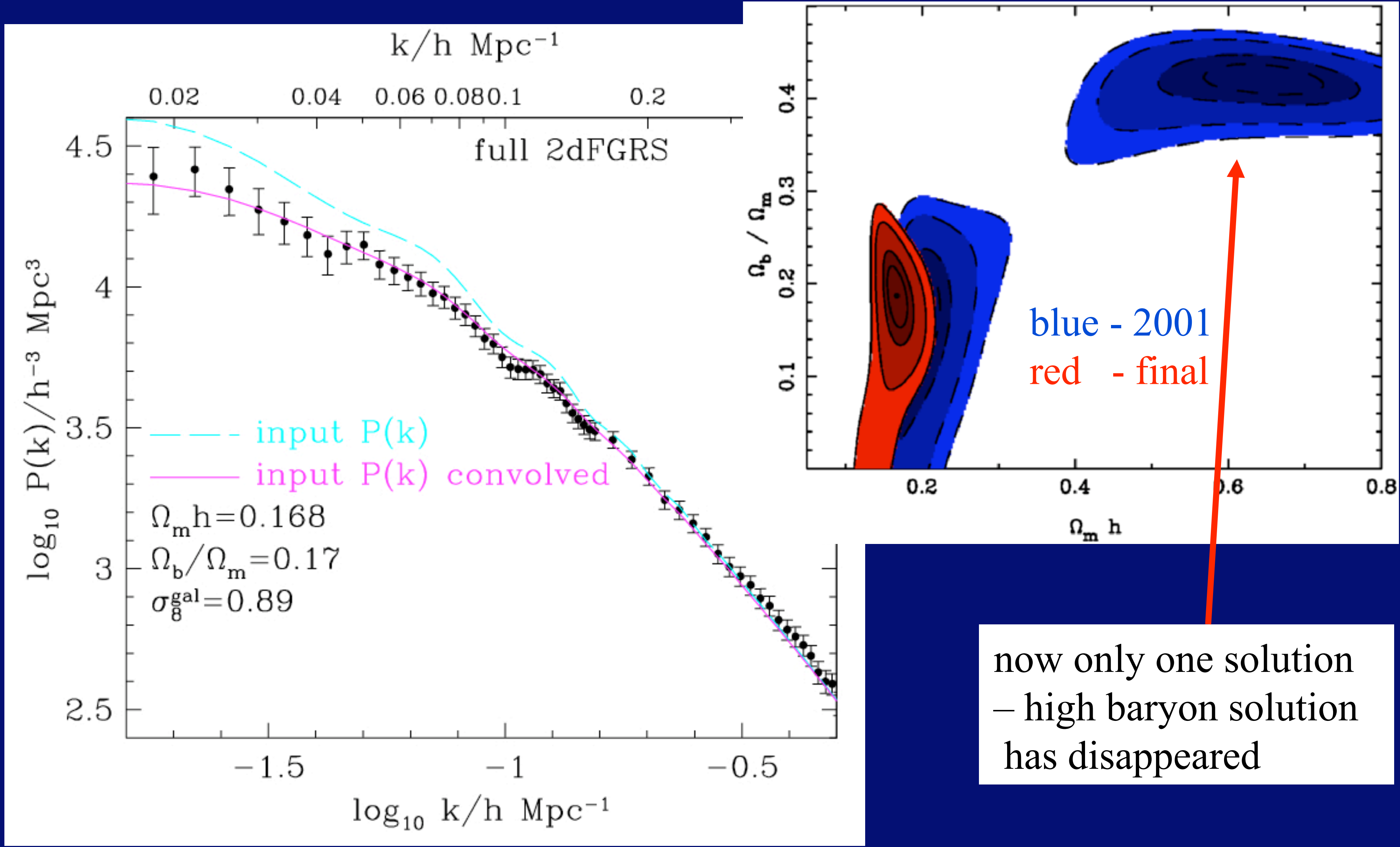




cosmological interpretation of wiggles requires high baryon fraction

Percival et al. 2001, MNRAS, 327, 1297

2dFGRS: the wiggles that were



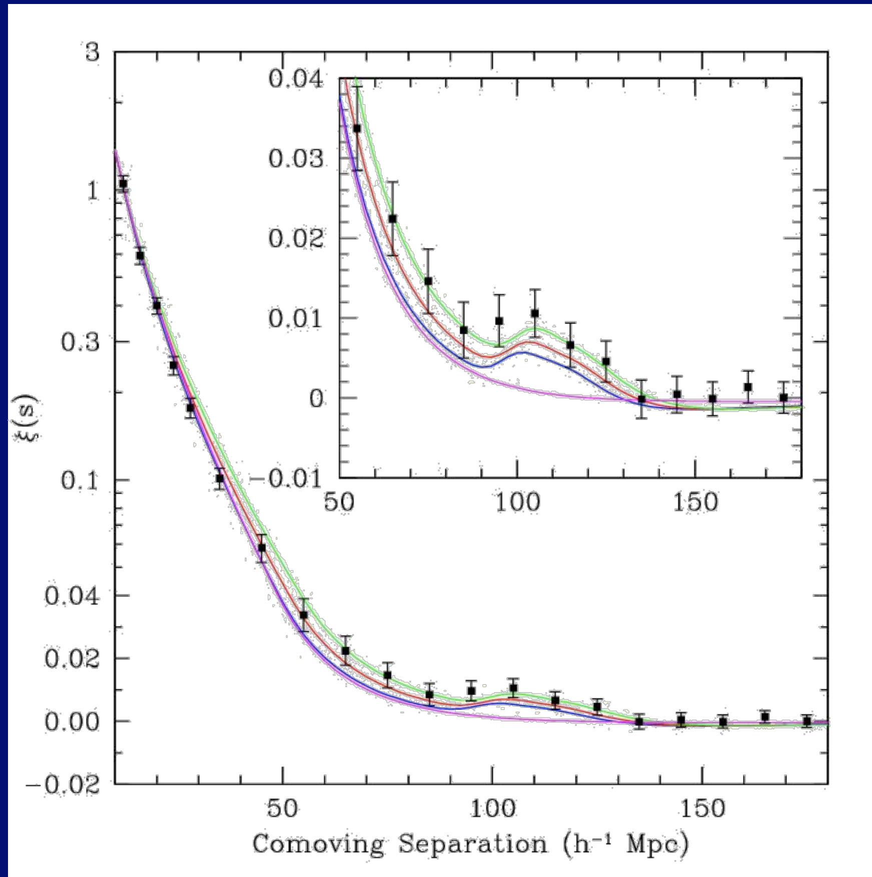
now only one solution
– high baryon solution
has disappeared

Cole, Percival et al. 2005, MNRAS, 362, 505

SDSS LRG Correlation Function analysis

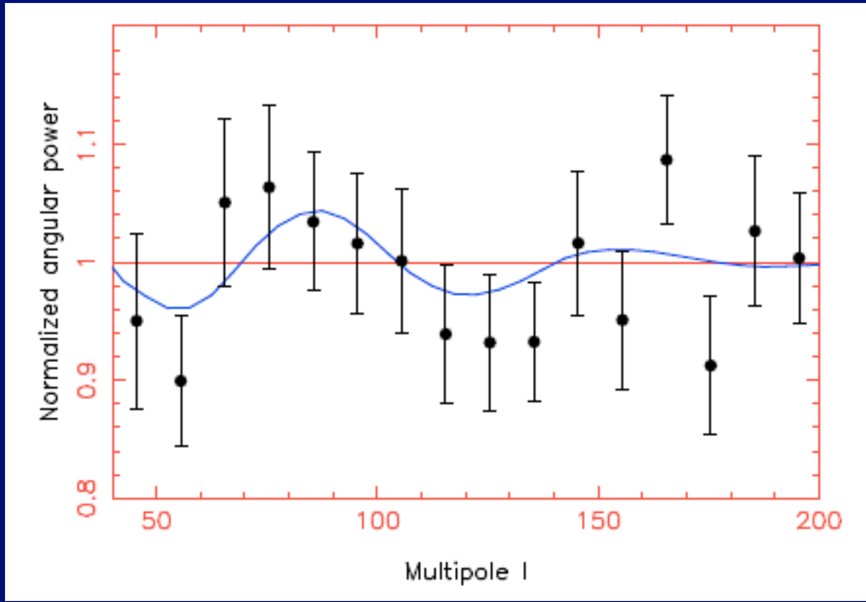
Again, CDM models fit the correlation function adequately well (although peak height is slightly too large) with (assuming n_s=1, h=0.72)

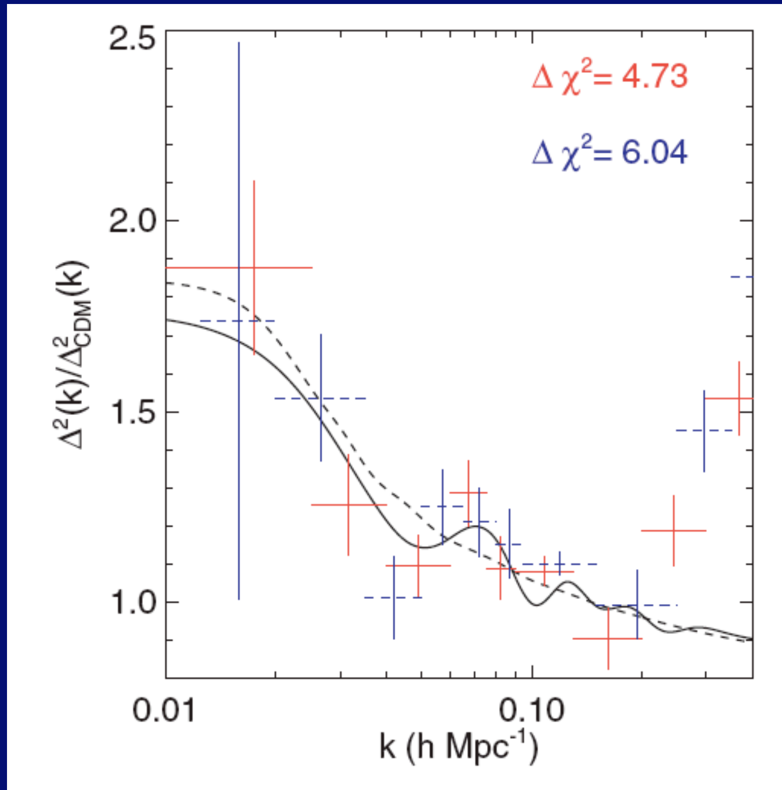
assuming $W_b h^2$ =0.024,
$W_m h^2$ =0.133±0.011,
Giving W_b/W_m= 0.18



Eisenstein et al., 2005, ApJ, 633, 560

BAO from SDSS LRG with photo-z

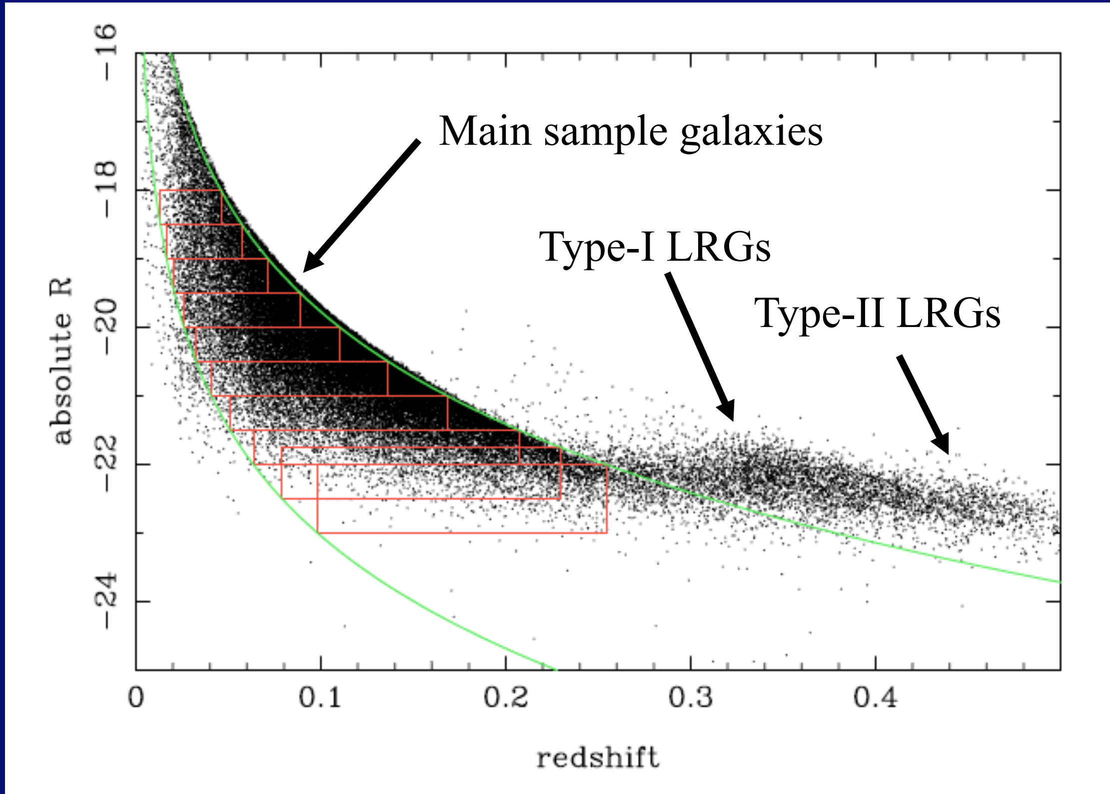




SDSS photometric LRG sample:
Blake et al 2007, MNRAS, 374, 1527

SDSS photometric LRG sample:
Padmanabhan et al 2007, MNRAS, 378, 852

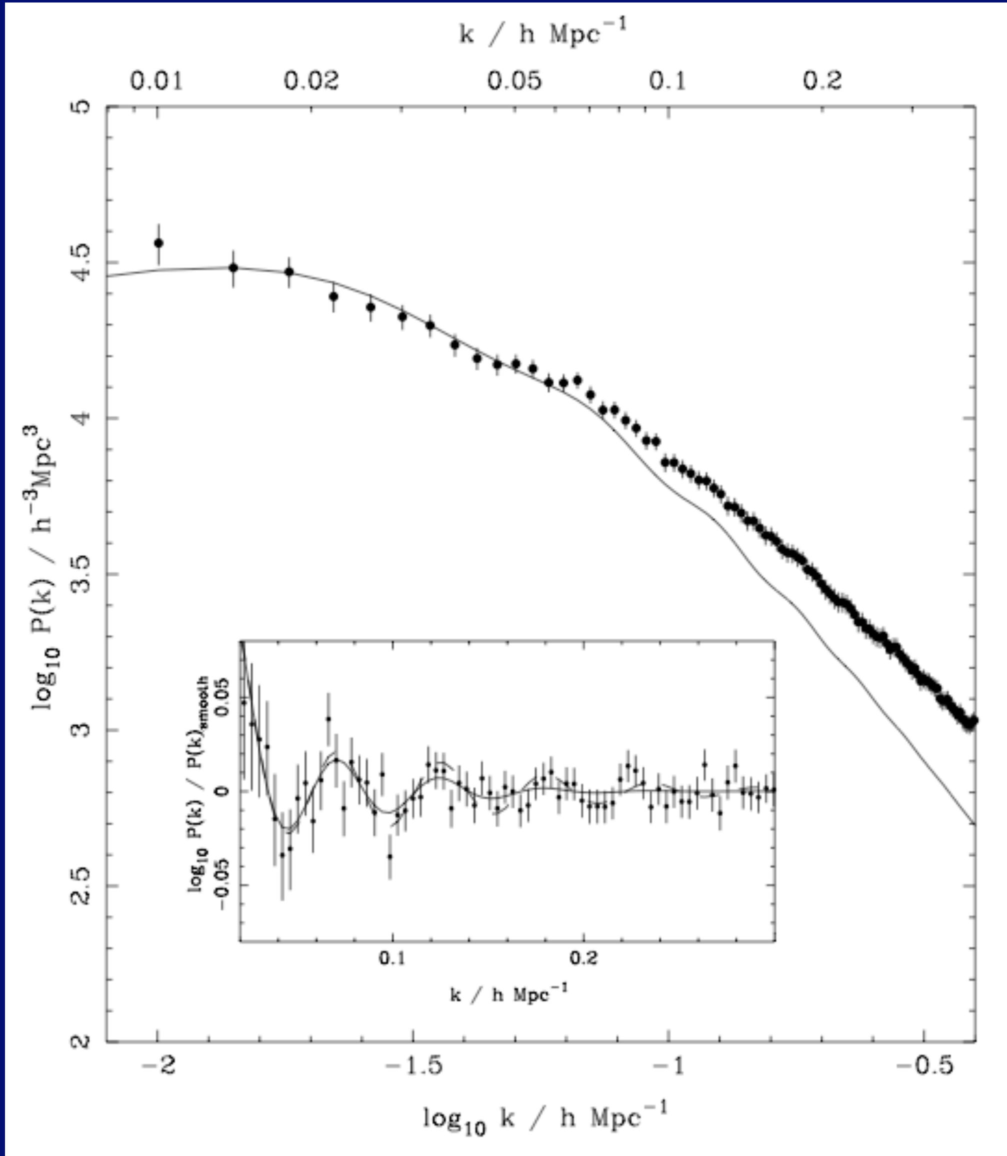
The SDSS DR5 sample



After various selection cuts, the DR5 sample gives 51251 LRGs and 462791 main galaxies

SDSS and 2dFGRS work undertaken with key members of both teams

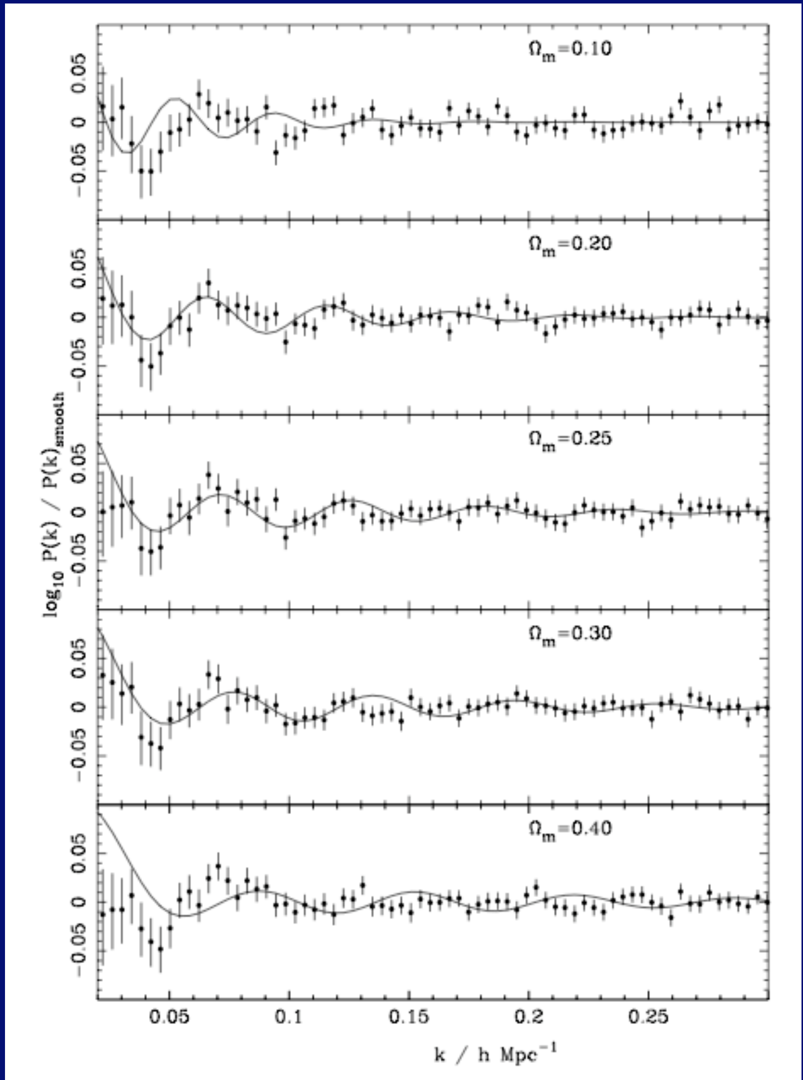
The SDSS DR5 power spectrum

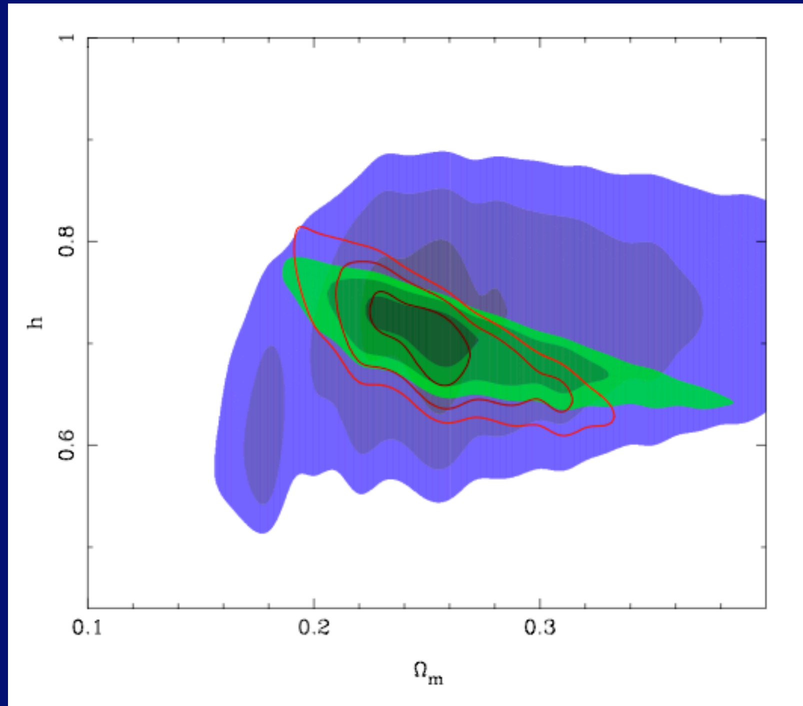


Data from SDSS main galaxies + LRGs

WMAP (3-year) best fit linear CDM cosmological model.

Matter density from SDSS BAO



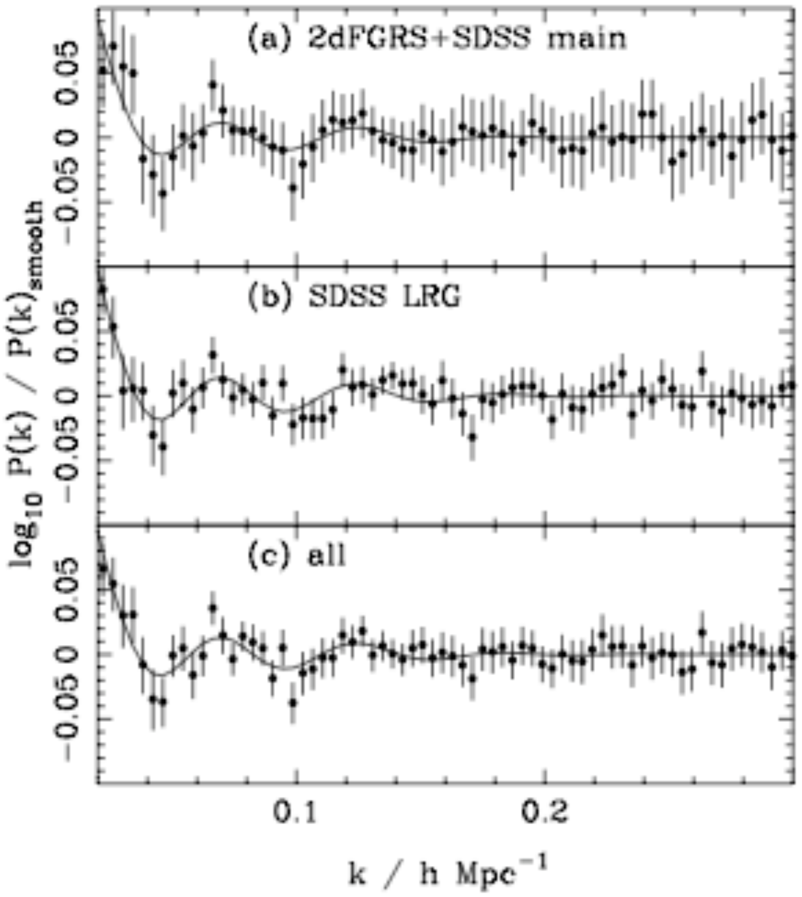


Data from SDSS main galaxies + LRGs consistent with ΛCDM, giving

$$\Omega_M = 0.257^{+0.029}_{-0.024}$$

Percival et al., 2007, ApJ, 657, 51

BAO from the 2dFGRS + SDSS



BAO detected at z~0.2

BAO detected at z~0.35

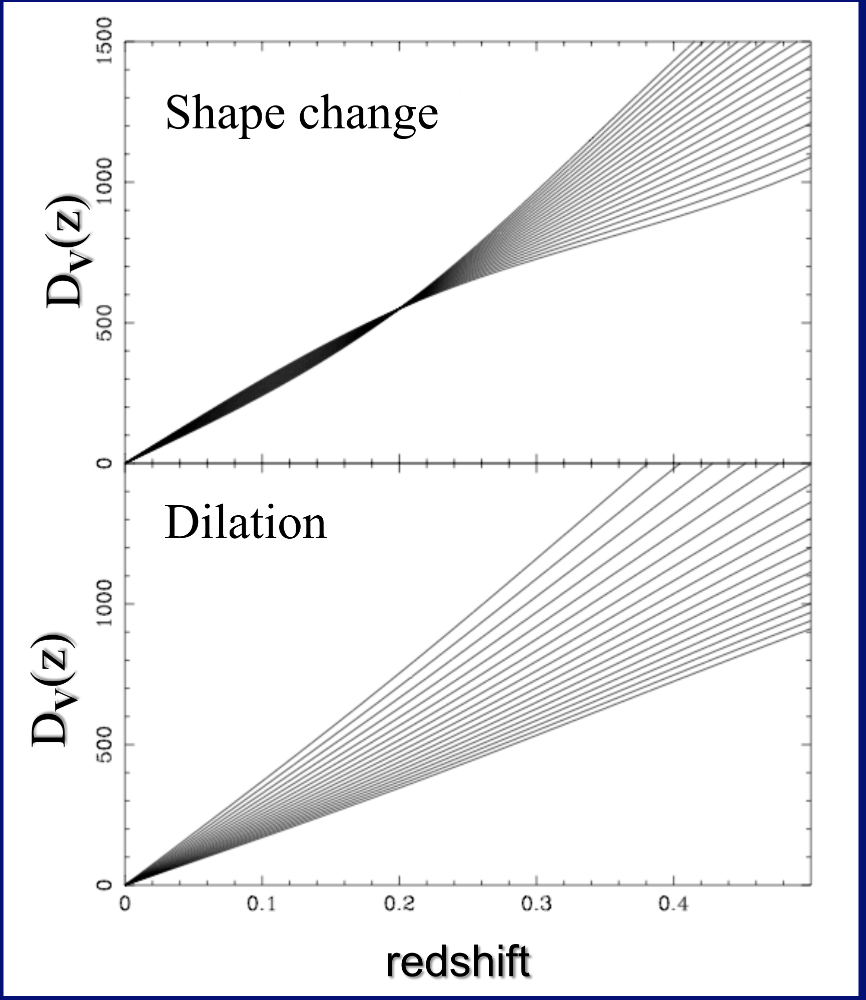
BAO from combined sample

Percival et al., 2007, MNRAS, astro-ph/0705.3323

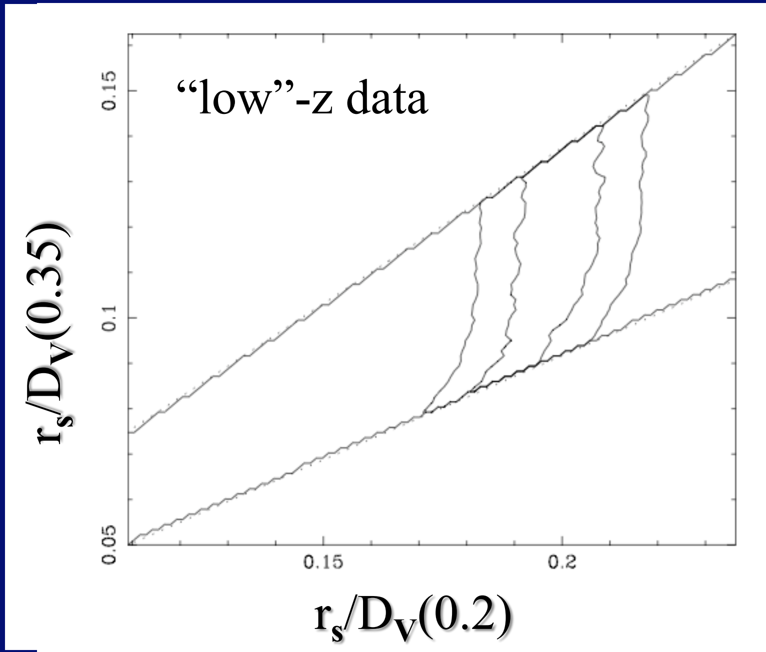
Fitting the distance-redshift relation

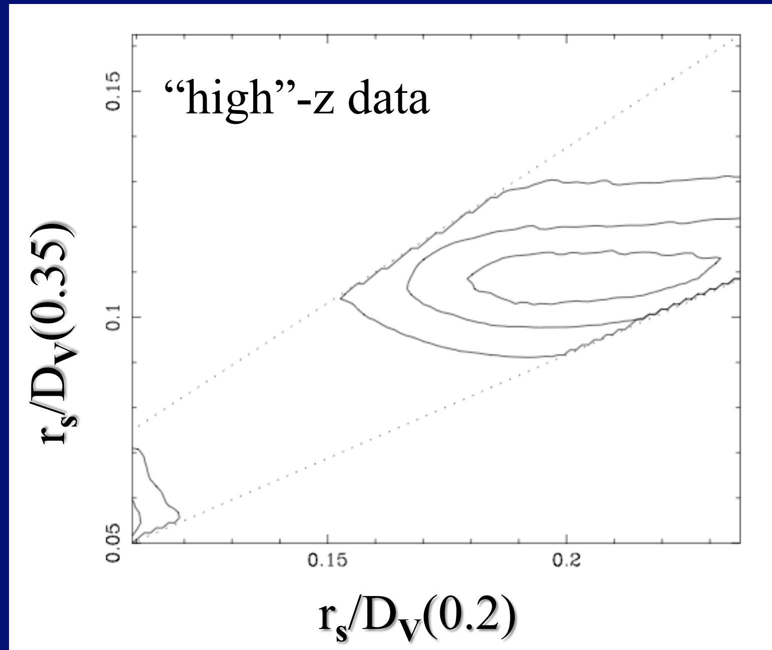
Parameterize $D_V(z)$ by spline fit with nodes at $z=0.2$ and $z=0.35$

distance-redshift model applied individually to all galaxies



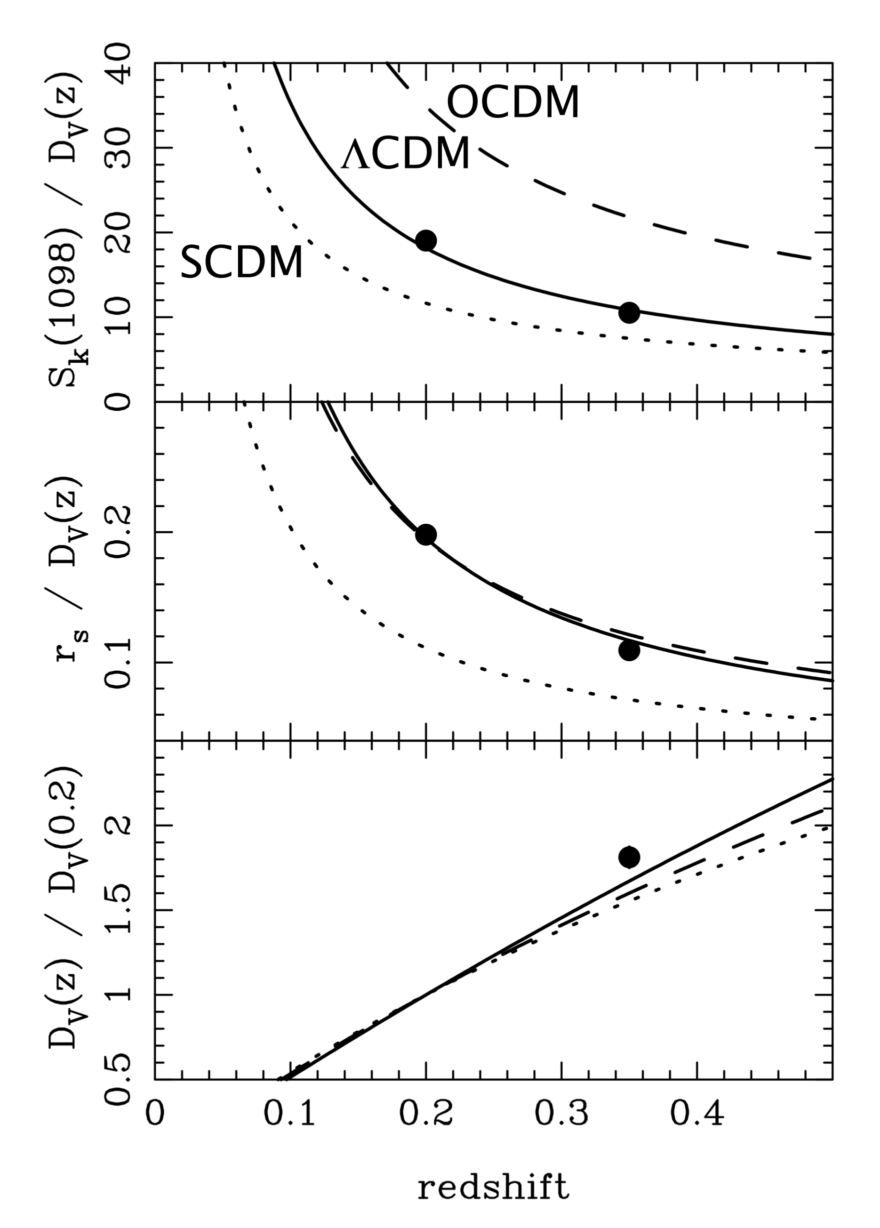
Distance-scale constraints





$$r_s/D_V(0.2) = 0.1978 \pm 0.0069$$
$$r_s/D_V(0.35) = 0.1095 \pm 0.0040$$
$$\text{corrrelation coefficient} = 0.50$$

BAO distance scale measurements



including $r_s/d_A(\text{cmb})=0.0104$,

$D_V(0.2)/d_A(\text{cmb}) = 0.0525\pm0.0016$
$D_V(0.35)/d_A(\text{cmb}) = 0.0951\pm0.0029$

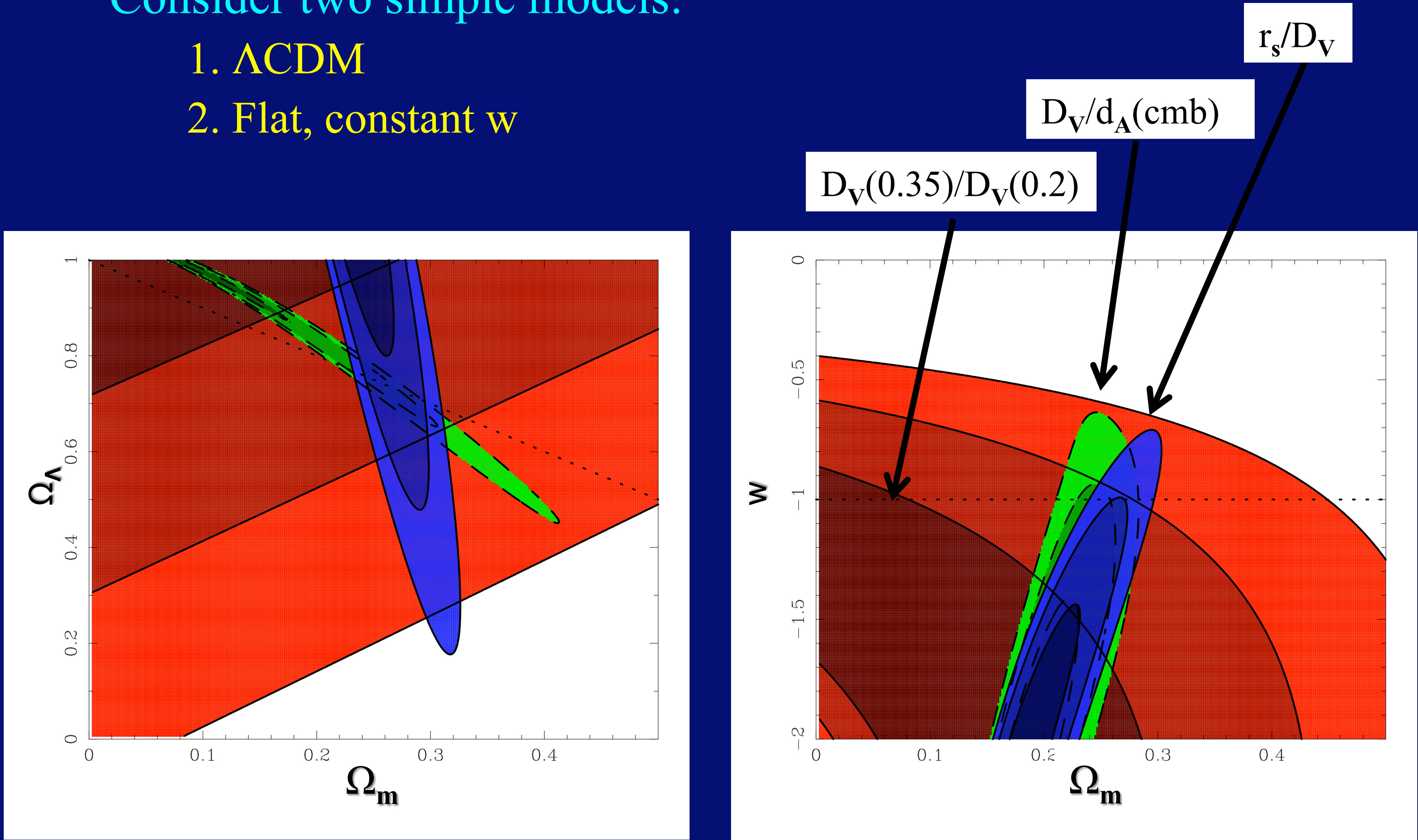
$r_s/D_V(0.2) = 0.1980 \pm 0.0060$
$r_s/D_V(0.35) = 0.1094 \pm 0.0033$

$D_V(0.35)/D_V(0.2) = 1.812 \pm 0.060$

Cosmological constraints

Consider two simple models:

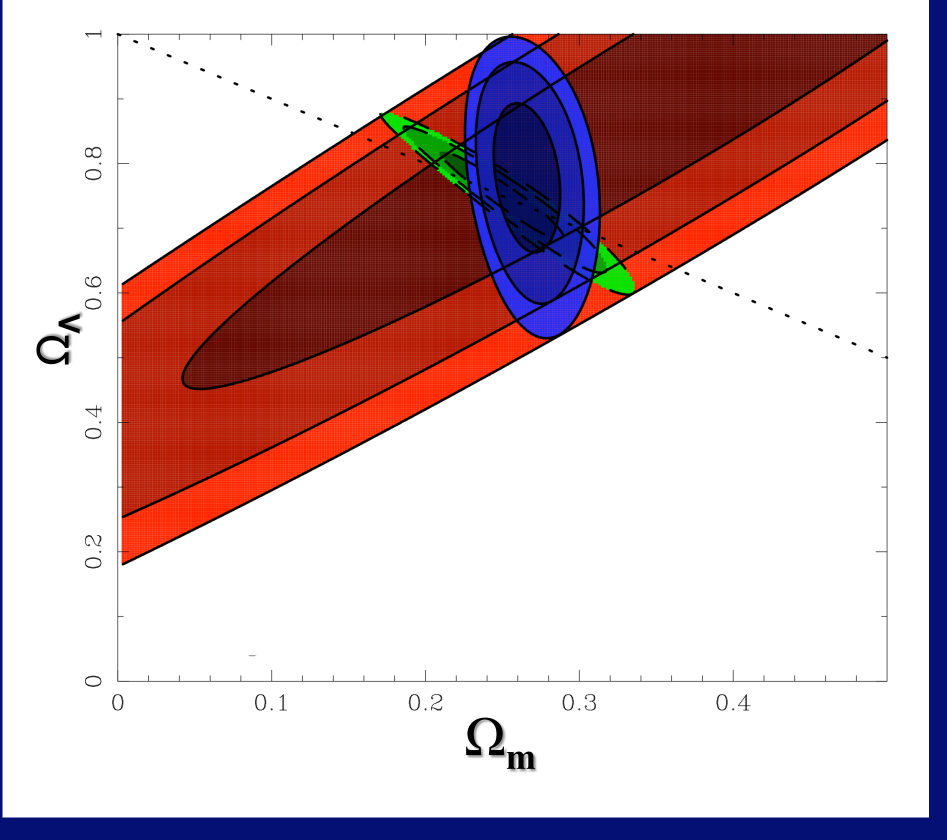
1. ΛCDM
2. Flat, constant w

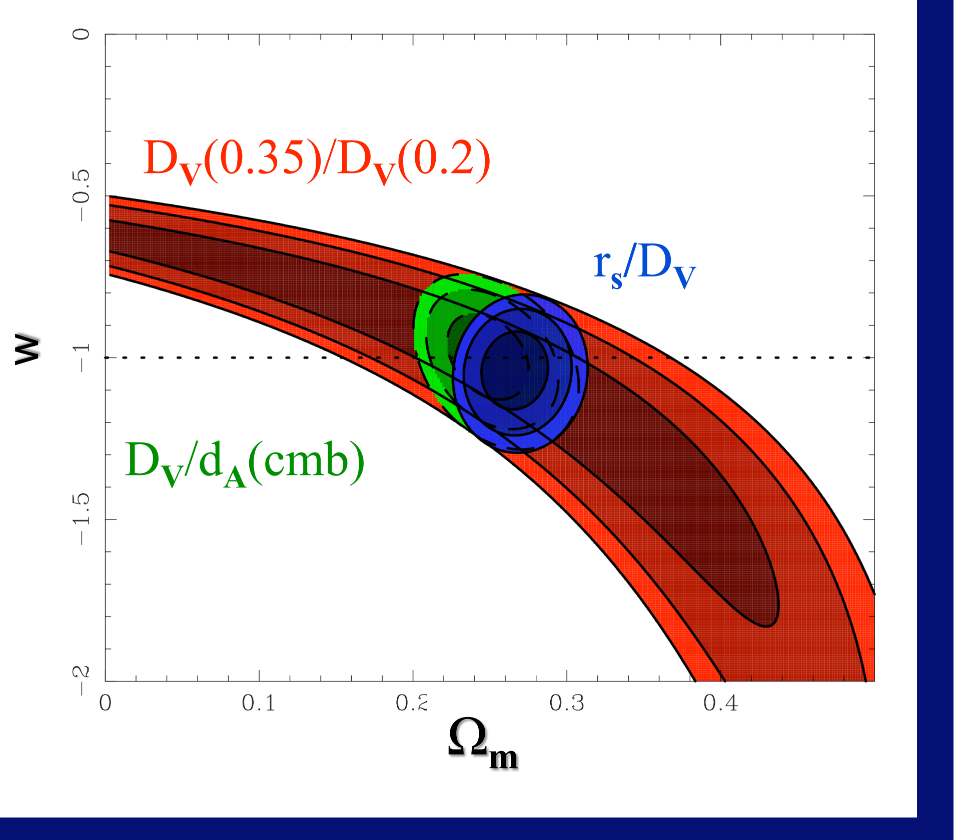


Cosmological constraints with SNLS data

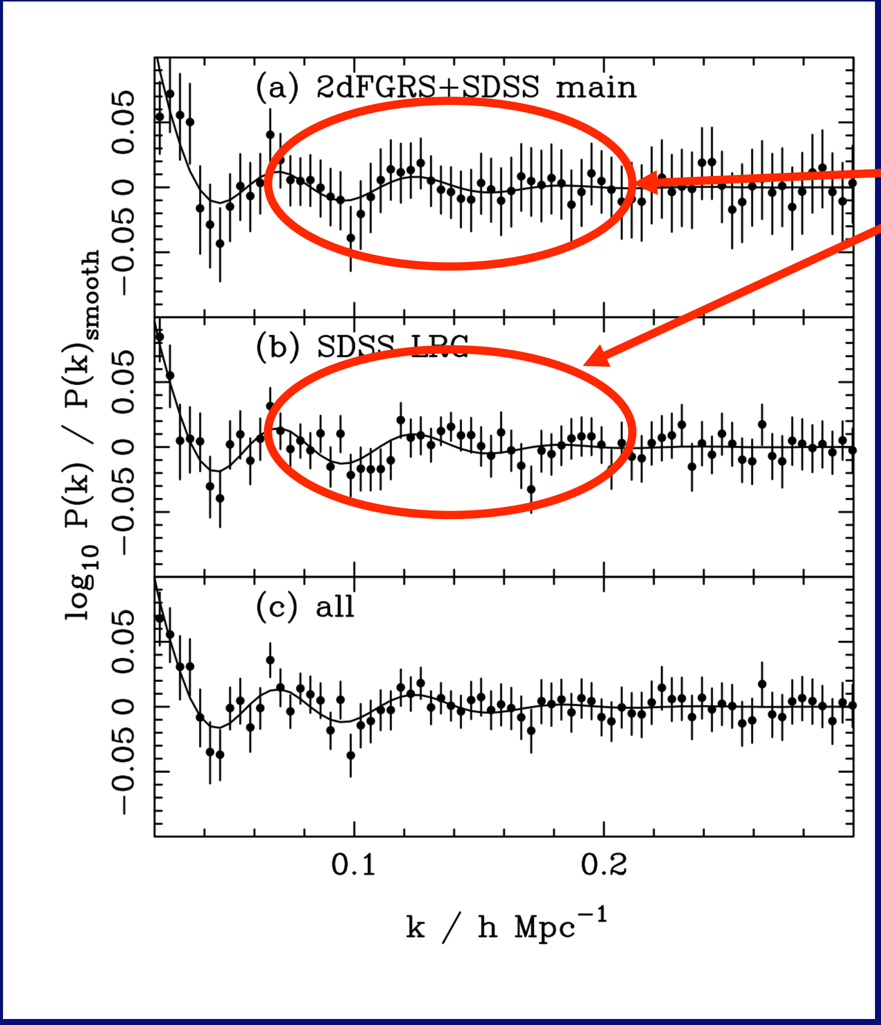
- Consider two simple models:
  - –Lambda-CDM
  - –Flat, constant w

$$\Omega_m = 0.249 \pm 0.018$$
$$w = -1.004 \pm 0.089$$





Discrepancy with ΛCDM?



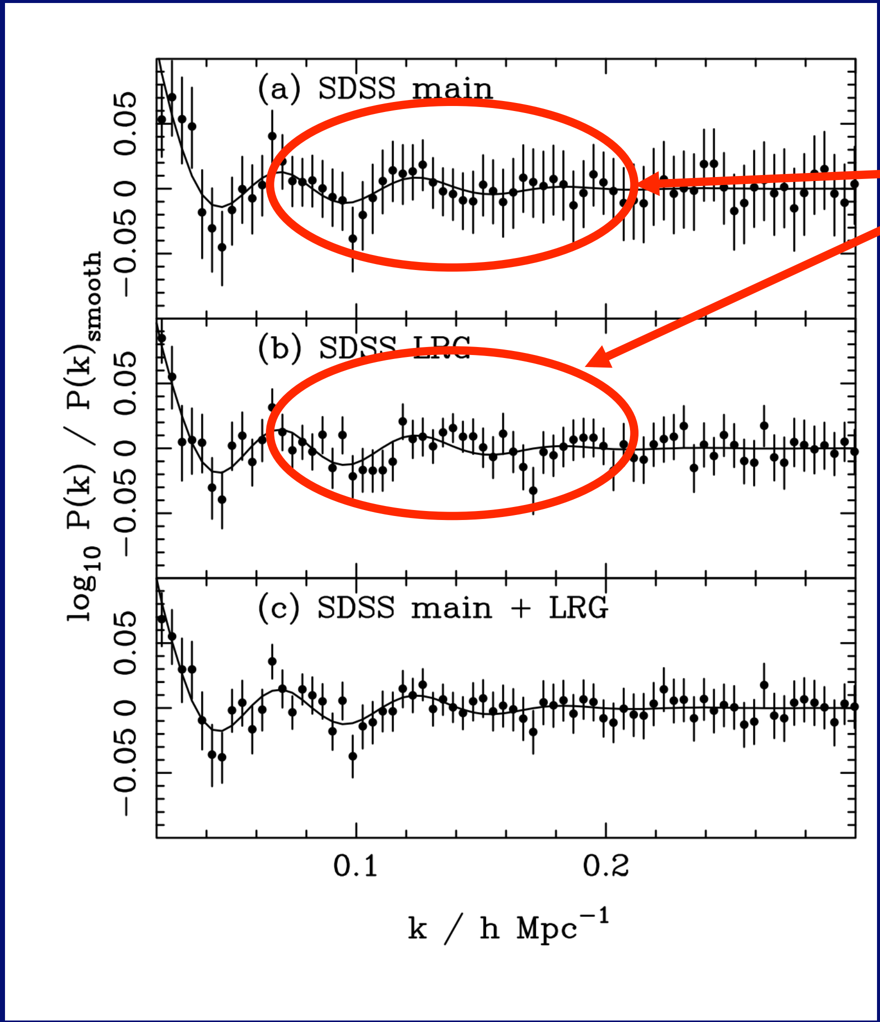
LRG BAO on too small scales: further away than expected, so more acceleration between z=0.2 and 0.35

Distance ratio found is
$D_V(0.35)/D_V(0.2) = 1.812 \pm 0.060$

CDM expects
$D_V(0.35)/D_V(0.2) = 1.67$

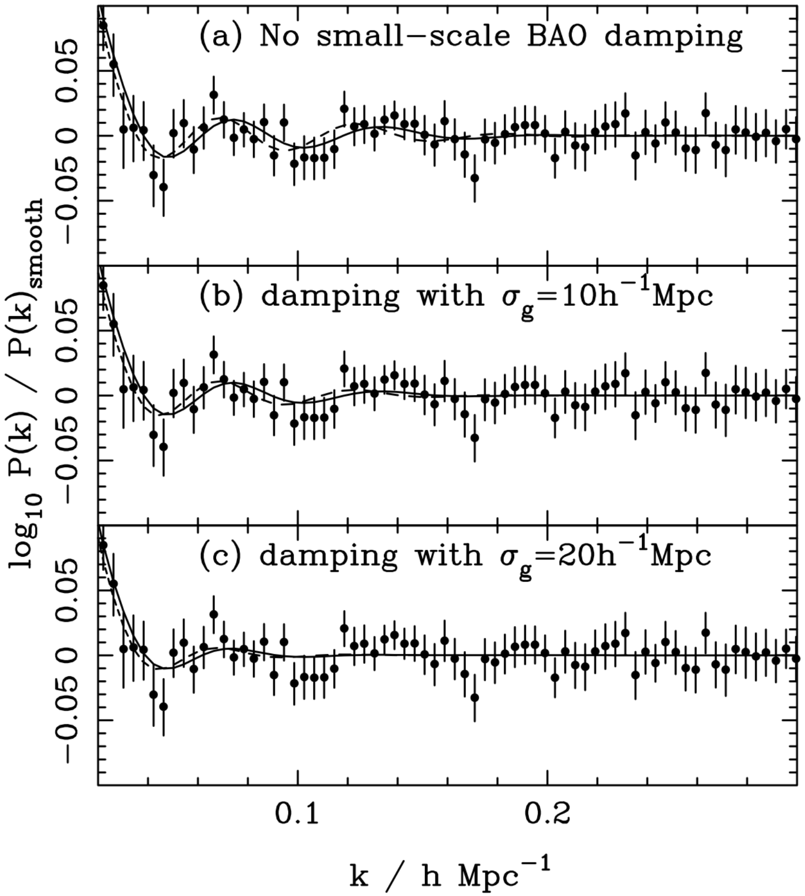
Discrepancy is 2.4σ

not 2dFGRS vs SDSS issue



Same discrepancy seen in just the SDSS data

not simple damping of the BAO



Observed BAO

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

Damping factor

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

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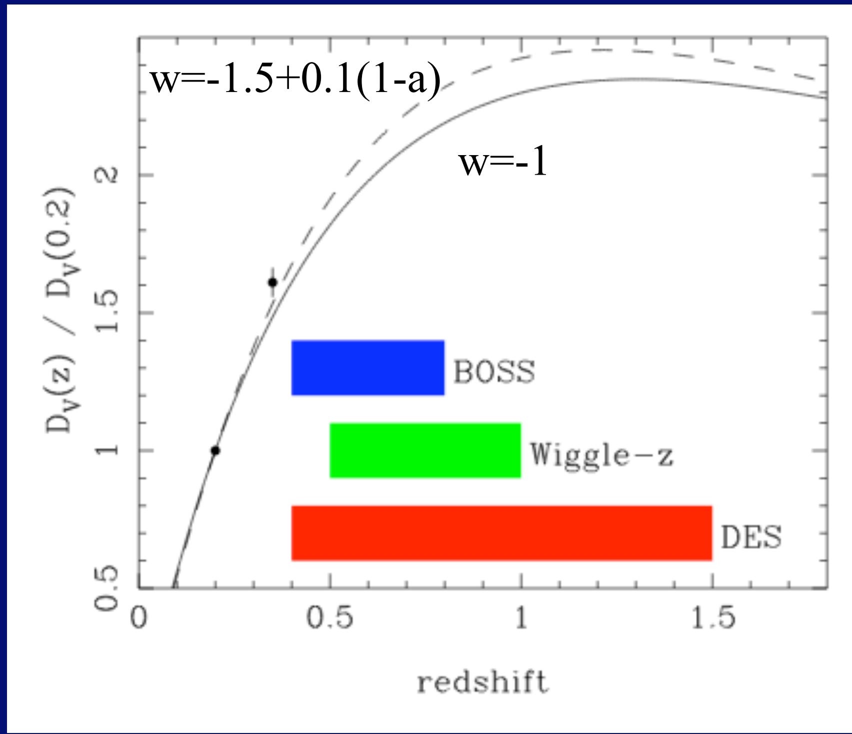
possible resolution

- extreme bad luck (at 2.4σ, 2% level)
  - errors are underestimated?
- damping model for BAO is not sophisticated enough
  - correlations between scales?
  - shift in scale (but simulations show <1% in distance)?
- BAO/power spectrum modeling biased
- data/analysis flawed in a way that evades tests done to date (unknown unknown?)
- simple ΛCDM model is wrong
- some combination of the above

Present/Future BAO Surveys

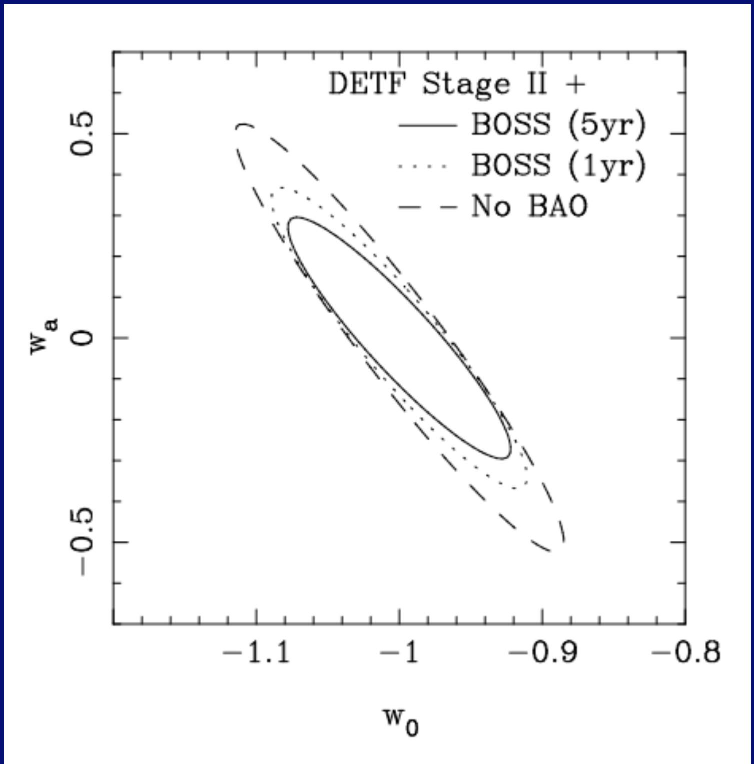
- SDSS-II (present - 2008)
  - 800,000 $z<0.5$ spectra over 9000deg^2
- Wiggle-Z (present - 2010)
  - 400,000 $z\sim0.75$ spectra over 1000deg^2
- Baryon Oscillation Spectroscopic Survey (BOSS: 2009-2014)
  - 1,500,000 $z\sim0.6$ spectra over 10,000deg^2 +QSOs
- Dark Energy Survey (DES: 2010-2015)
  - 5000deg^2 multi-colour imaging survey on Blanco 4m + VISTA
  - photo-z for 300,000,000 galaxies
- Plus: VST-Atlas, WFMOS, SKA, ADEPT, HETDEX, LAMOST, LSST, Pan-STARRS, PAU, SPACE/DUNE, + other MOS plans?



Predicted Dark Energy Constraints

DETF Figure-of-merit is area of 1σ confidence region for 2-parameter DE model, with equation of state:

$$\begin{aligned} w(z) &= w_0 + (1-a)w_a \\ &= w_p + w_a(a_p - a) \end{aligned}$$



Survey	DETF figure of merit
Current + Planck	53.7
+ BOSS (1 year)	79.7
+ BOSS (5 year)	109.9
+ DES (BAO only)	75.1
+ Wiggle-Z	71.5

conclusions

- Geometric nature of BAO test is appealing
- Complementary to SN1a
- Detections
  - from spectroscopic samples (2dFGRS & SDSS)
  - from photometric samples (SDSS)
  - as a function of angular position (SDSS)
  - at different redshifts (SDSS)
- Data require acceleration, and are approximately consistent with ΛCDM
- However, there is an (as yet) unexplained 2.4σ offset from ΛCDM (with Sn1a constraints) when comparing BAO at $z=0.2$ and $z=0.35$
- future surveys will give % level distance constraints at many redshifts