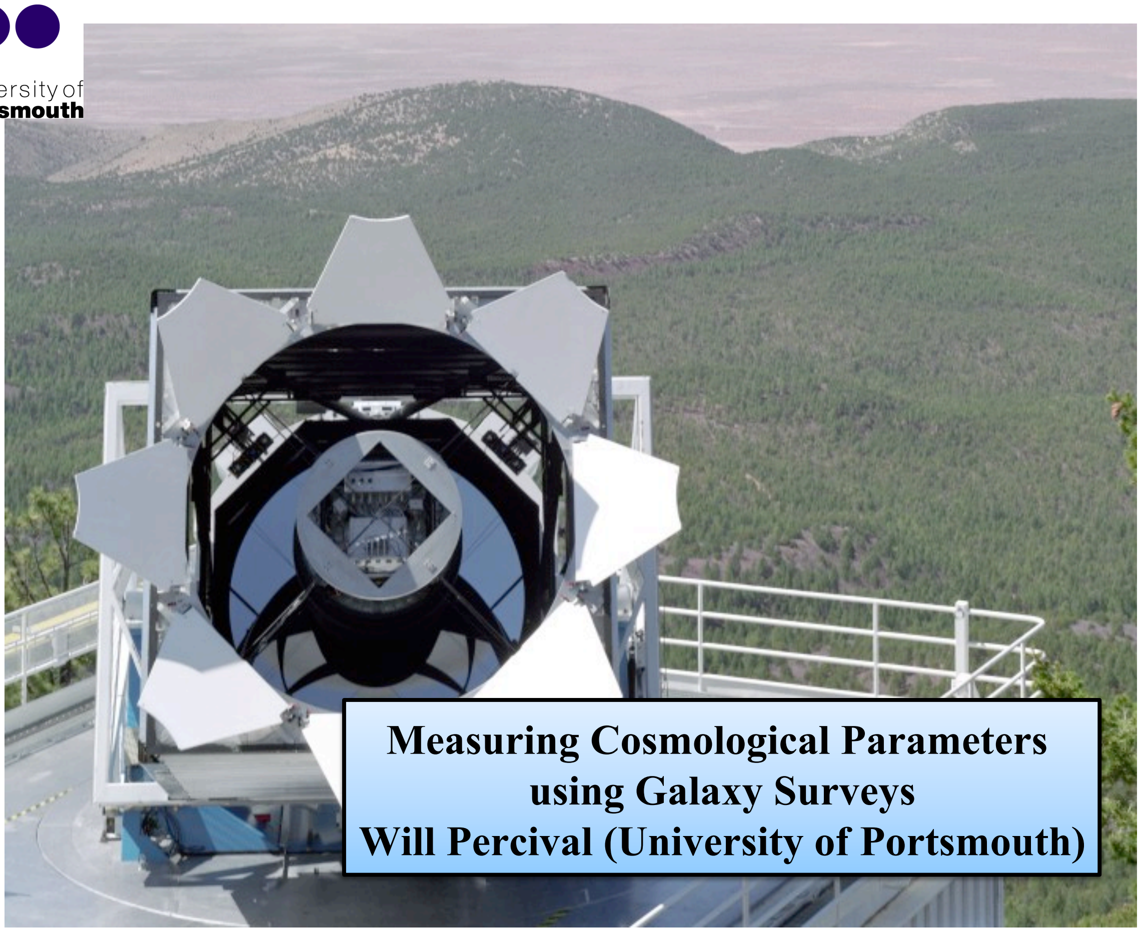
University of Portsmouth



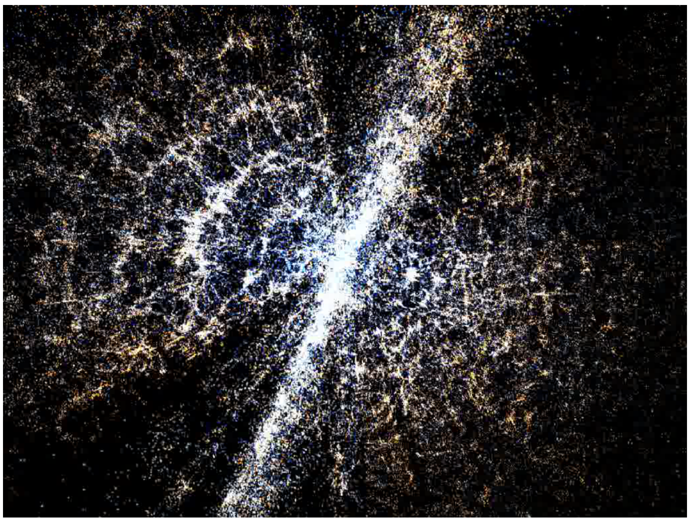
Measuring Cosmological Parameters using Galaxy Surveys

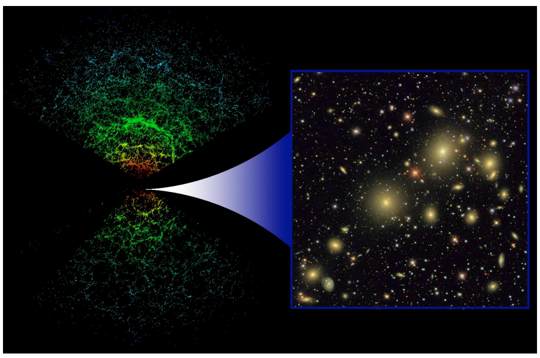
Will Percival (University of Portsmouth)

University of Portsmouth

Sloan Digital Sky Survey (SDSS)

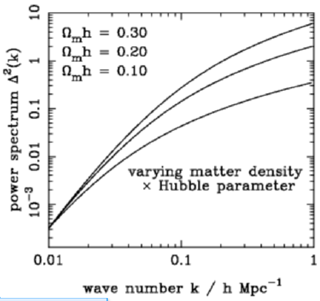
- (SDSS-II) collaboration of over 200 scientists in 14 institutions
- survey measured redshifts for 800,000 galaxies in the local Universe (r-band selection)
- also observed ~100,000 luminous red galaxies out to higher redshift
- all data now taken and publically released: DR7 now available



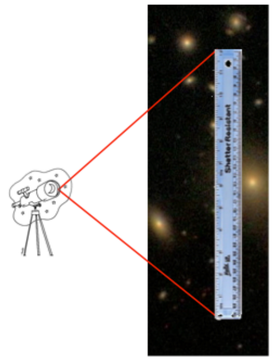


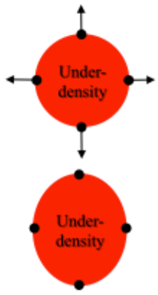
Talk outline: Cosmological Physics from 2-pt statistics

Comoving power spectrum or correlation function
- Matter, baryon densities
- Neutrino mass
- Inflation fluctuation spectrum
- f_{NL}



Information from geometry: we measure angles, redshifts
- Galaxy clustering as a standard ruler
- Baryon Acoustic Oscillations
- Alcock-Paczynski effect





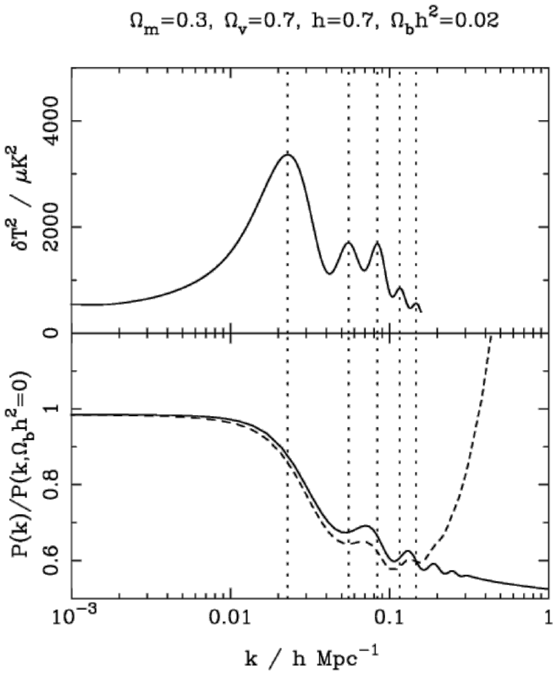
Information from structure growth
- redshift-space distortions
- amplitude of power spectrum

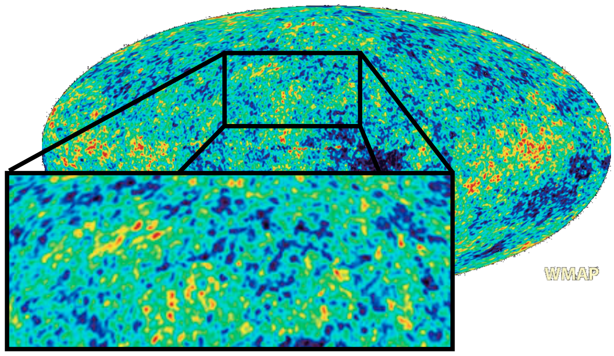
Selected future surveys

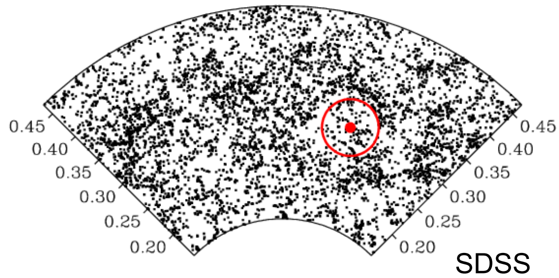
Information from the comoving power spectrum

University of Portsmouth

Relationship between CMB and LSS clustering



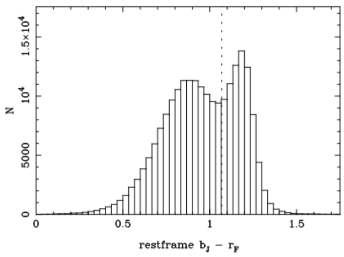




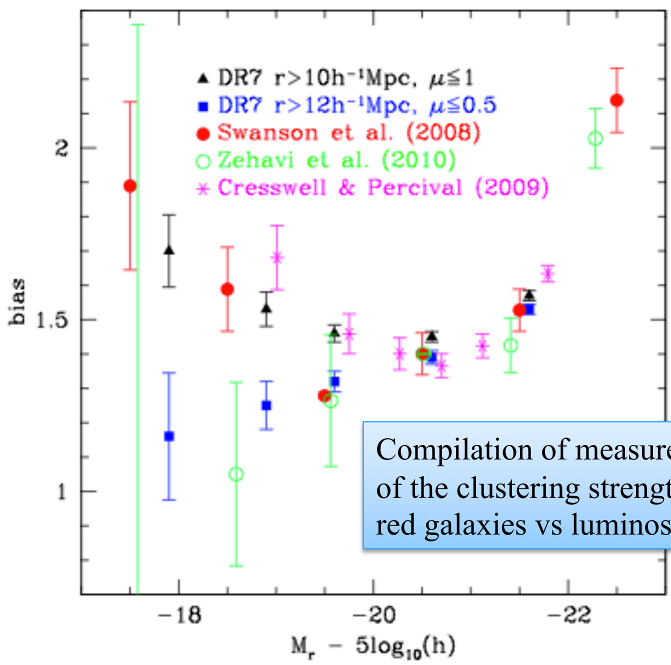
SDSS

University of Portsmouth

Problem: we do not observe the mass



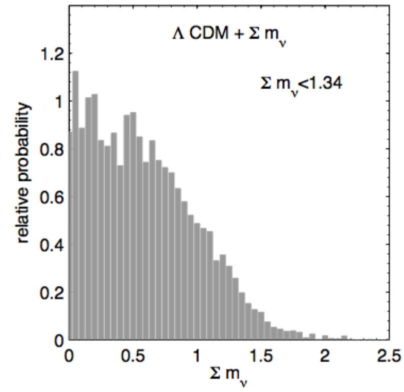
Colour bimodality of galaxies, as demonstrated by the 2dFGRS (Cole, Percival, et al. 2005)



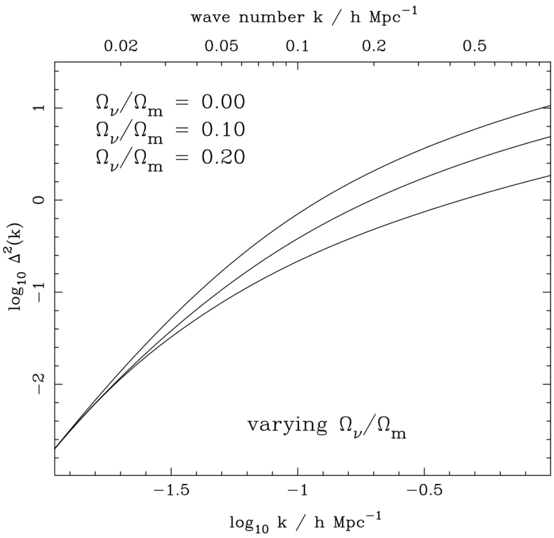
Compilation of measurements of the clustering strength of red galaxies vs luminosity

Ross, Tojeiro & Percival (in prep)

neutrino mass

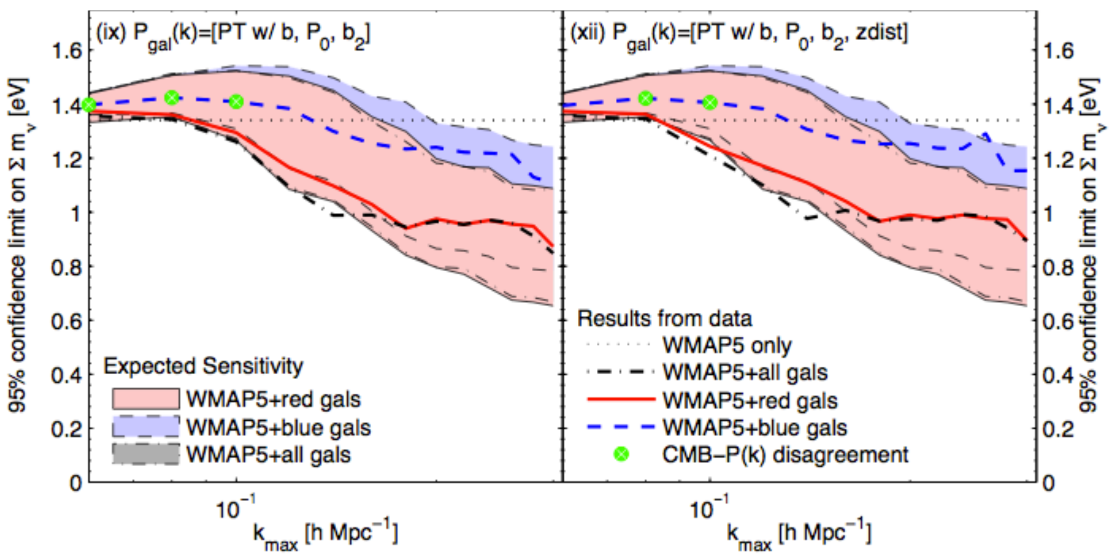


WMAP 7 year data:
Dunkley et al. (2009: ApJS,180, 306)



LSS can help through comoving shape and breaking CMB projection degeneracies

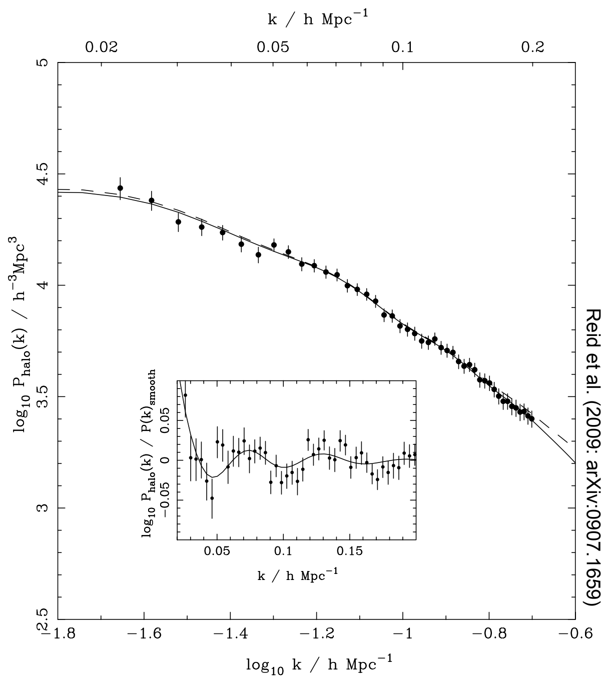
neutrino mass



For current SDSS data: red and blue galaxies give constraints that are ~1 σ apart, using shape of P(k)

Swanson, Percival & Lahav (2010, arXiv:1006.2825)

P(k) fit for SDSS DR7 LRGs



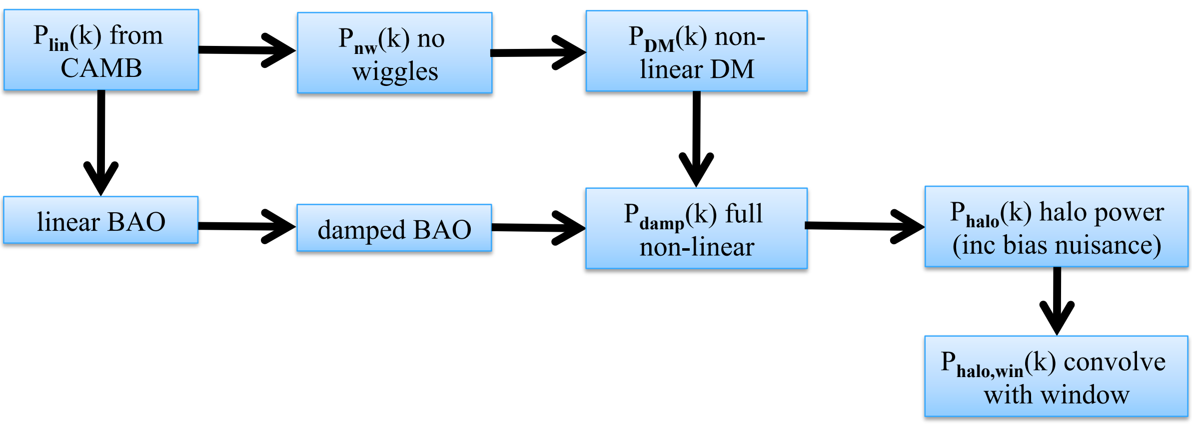
Use luminous red galaxies (LRGs) to extract the halo power spectrum and use the shape to constrain cosmological models

Include information from both shape of P(k) and geometry

Reid, Percival, Eisenstein, et al. (2009, arXiv:0907.1659)

Have to carefully model non-linearities, bias

$P(k)$	Definition	Reference
$\hat{P}_{LRG}(k)$	measured angle averaged redshift-space power spectrum of the LRGs	-
$\hat{P}_{halo}(k)$	measured power spectrum of reconstructed halo density field	-
$P_{lin}(k)$	linear power spectrum computed by CAMB	Lewis et al. (2000)
$P_{DM}(k)$	theoretical real-space non-linear power spectrum of dark matter	-
$P_{nw}(k)$	theoretical linear power spectrum without BAO ("no wiggles")	Eisenstein & Hu (1998)
$P_{damp}(k)$	theoretical linear power spectrum with damped BAO (Eqn. 10)	Eisenstein et al. (2007b)
$P_{halo}(k, \mathbf{p})$	model for the reconstructed halo power spectrum for cosmological parameters $\mathbf{p}$	Reid et al. (2008)
$P_{halo,win}(k, \mathbf{p})$	$P_{halo}(k, \mathbf{p})$ convolved with survey window function (Eqn. 5) and directly compared with $\hat{P}_{halo}(k)$ in the likelihood calculation (Eqn. 6)	Percival et al. (2007)



Reid, Percival, Eisenstein, et al. (2009, arXiv:0907.1659)

P(k) fit for SDSS DR7 LRGs

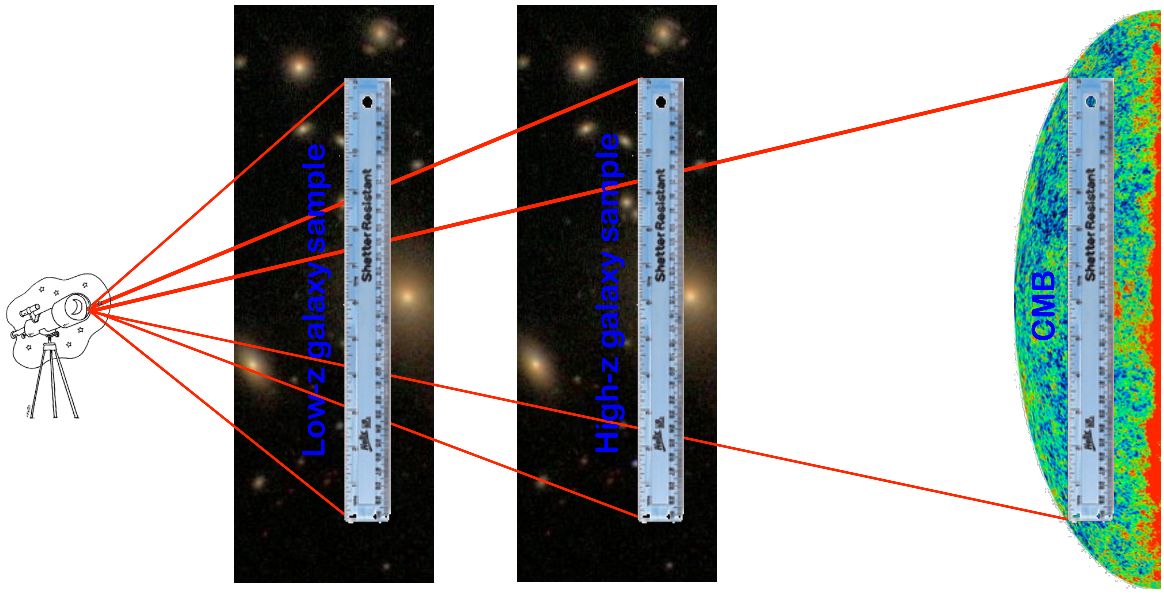
parameter	ΛCDM	oΛCDM	wCDM	owCDM	owCDM+SN
Ω_m	0.289 ± 0.019	0.309 ± 0.025	0.328 ± 0.037	0.306 ± 0.050	0.312 ± 0.022
H_0	69.4 ± 1.6	66.0 ± 2.7	64.3 ± 4.1	$66.7^{+5.9}_{-5.6}$	65.6 ± 2.5
$D_V(0.35)$	1349 ± 23	1415 ± 49	1398 ± 45	1424 ± 49	1418 ± 49
$r_s/D_V(0.35)$	0.1125 ± 0.0023	0.1084 ± 0.0034	0.1094 ± 0.0032	$0.1078^{+0.0033}_{-0.0034}$	0.1081 ± 0.0034
Ω_k	-	$-0.0114^{+0.0076}_{-0.0077}$	-	-0.009 ± 0.012	-0.0109 ± 0.0088
w	-	-	-0.79 ± 0.15	-1.06 ± 0.38	-0.99 ± 0.11
Ω_Λ	0.711 ± 0.019	0.703 ± 0.021	0.672 ± 0.037	$0.703^{+0.057}_{-0.058}$	0.699 ± 0.020
Age (Gyr)	13.73 ± 0.13	14.25 ± 0.37	13.87 ± 0.17	14.27 ± 0.52	14.24 ± 0.40
Ω_{tot}	-	$1.0114^{+0.0077}_{-0.0076}$	-	1.009 ± 0.012	1.0109 ± 0.0088
$100\Omega_b h^2$	2.272 ± 0.058	2.274 ± 0.059	$2.293^{+0.062}_{-0.063}$	$2.279^{+0.066}_{-0.065}$	$2.276^{+0.060}_{-0.059}$
$\Omega_c h^2$	$0.1161^{+0.0039}_{-0.0038}$	0.1110 ± 0.0052	$0.1112^{+0.0056}_{-0.0057}$	$0.1103^{+0.0055}_{-0.0054}$	$0.1110^{+0.0051}_{-0.0052}$
τ	0.084 ± 0.016	0.089 ± 0.017	0.088 ± 0.017	0.088 ± 0.017	0.088 ± 0.017
n_s	0.961 ± 0.013	0.962 ± 0.014	0.969 ± 0.015	0.965 ± 0.016	0.964 ± 0.014
$\ln(10^{10} A_{05})$	$3.080^{+0.036}_{-0.037}$	3.068 ± 0.040	$3.071^{+0.040}_{-0.039}$	3.064 ± 0.041	3.068 ± 0.039
σ_8	0.824 ± 0.025	0.796 ± 0.032	0.735 ± 0.073	0.79 ± 0.11	$0.790^{+0.045}_{-0.046}$

Table 3. Marginalized one-dimensional constraints (68%) for WMAP5+LRG for flat ΛCDM, ΛCDM with curvature (oΛCDM), flat wCDM (wCDM), wCDM with curvature (owCDM), and wCDM with curvature and including constraints from the Union Supernova sample. Here τ is the optical depth to reionization, n_s is the scalar spectral index, and A_{05} is the amplitude of curvature perturbations at $k = 0.05/\mathrm{Mpc}$; these parameters are constrained directly by the CMB only.

Reid, Percival, Eisenstein, et al. (2009, arXiv:0907.1659)

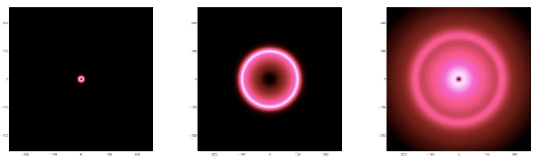
Cosmology from geometry

Using clustering to measure geometry

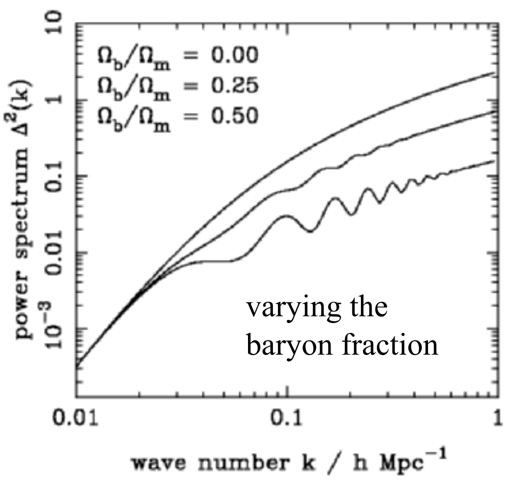


Sunyaev & Zel'dovich (1970); Peebles & Yu (1970); Doroshkevitch, Sunyaev & Zel'dovich (1978); …
Cooray, Hu, Huterer & Joffre (2001); Eisenstein (2003); Seo & Eisenstein (2003);
Blake & Glazebrook (2003); Hu & Haiman (2003); …

Baryon Acoustic Oscillations (BAO)



(images from Martin White)



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

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

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

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

BAO measurements

BAO measurements linked to physical BAO scale through:

Radial direction

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

Angular direction

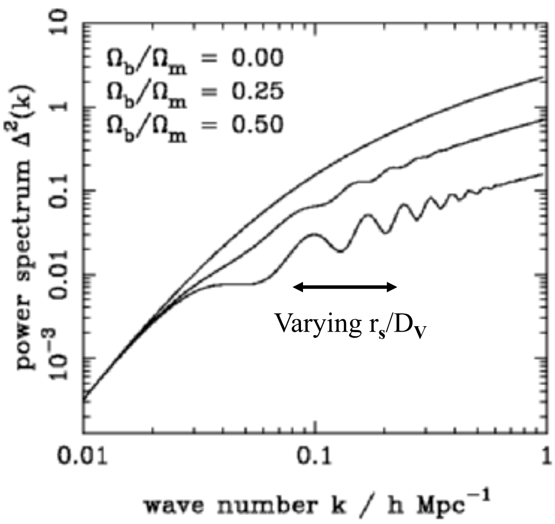
$$(1+z)D_A\Delta\theta$$

To first order, random pairs depend on

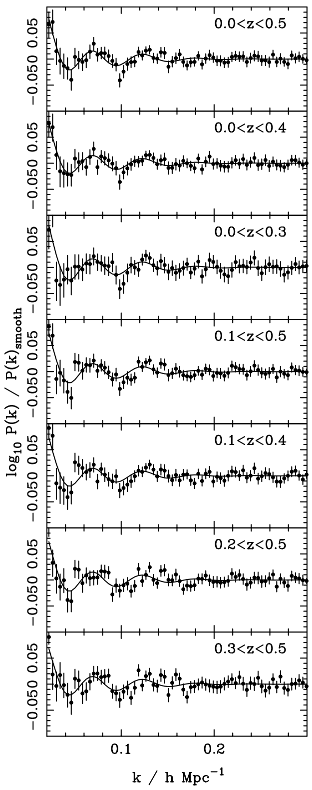
$$D_V(z) = \left[(1+z)^2 D_A^2(z)\frac{cz}{H(z)}\right]^{1/3}$$

Observed BAO position therefore constrains some multiple of

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



BAO in SDSS DR7 + 2dFGRS power spectra



Percival et al. (2009; arXiv:0907.1660)

- Combine 2dFGRS, SDSS DR7 LRG and SDSS Main Galaxy samples
- split into redshift slices and fit P(k) with model comprising smooth fit × BAO
- results can be written as independent constraints on a distance measure to z=0.275 and a tilt around this

$$r_s(z_d)/D_V(0.275) = 0.1390 \pm 0.0037 \ (2.7\%)$$
$$D_V(0.35)/D_V(0.2) = 1.736 \pm 0.065$$

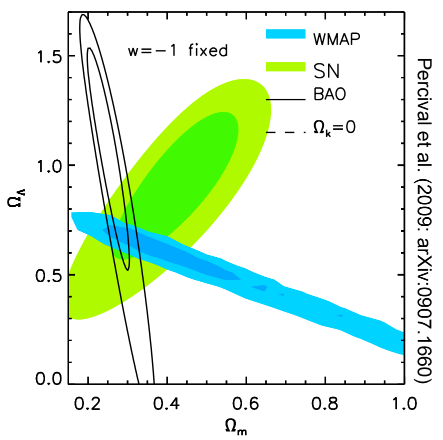
- consistent with ΛCDM models at 1.1σ when combined with WMAP5

Percival, Reid, Eisenstein et al. (2009, arXiv:0907.1660)

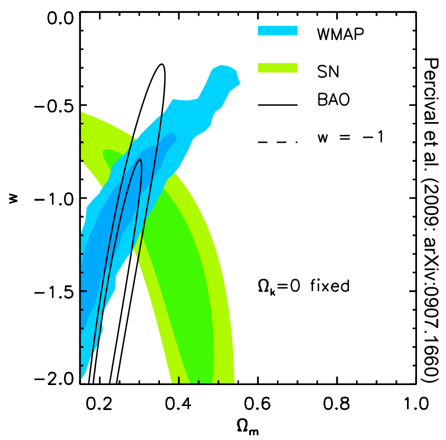
Comparing BAO constraints vs other data

University of Portsmouth

ΛCDM models with curvature



flat wCDM models



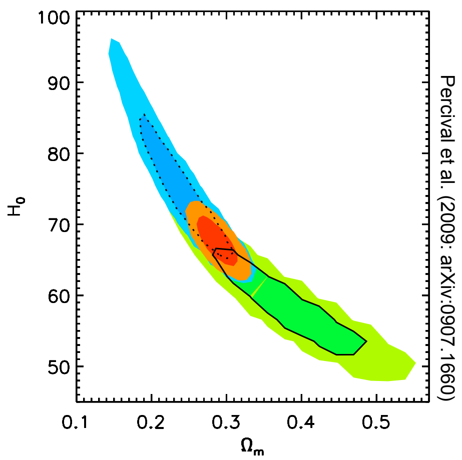
- Union supernovae
- WMAP 5year
- SDSS BAO Constraint on $r_s(z_d)/D_V(0.2)$ & $r_s(z_d)/D_V(0.35)$

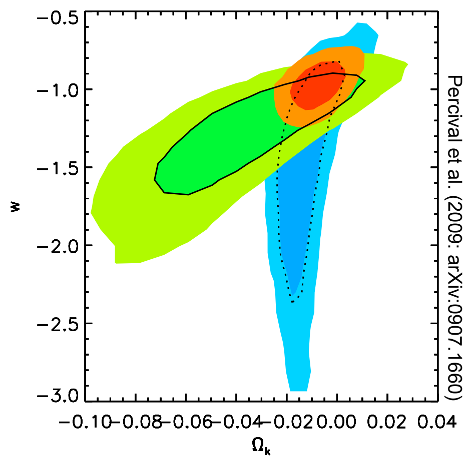
Percival, Reid, Eisenstein et al. (2009, arXiv:0907.1660)

BAO + CMB + SN model constraints

University of Portsmouth

w-CDM models with curvature



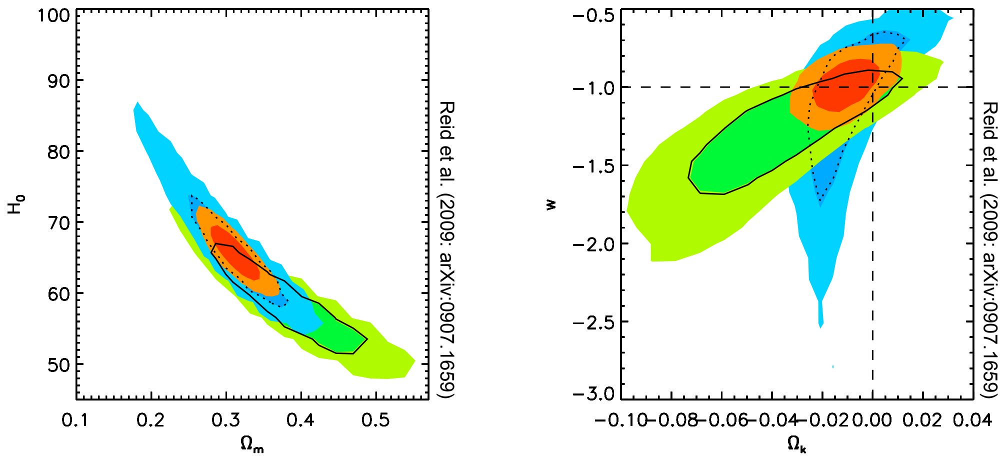


- SDSS + WMAP5
- Union supernovae + WMAP5
- SDSS + Union supernovae + WMAP5

Percival, Reid, Eisenstein et al. (2009, arXiv:0907.1660)

LRG halo P(k) + CMB + SN model constraints

w-CDM models with curvature



SDSS + WMAP5

Union supernovae + WMAP5

SDSS + Union supernovae + WMAP5

Reid, Percival, Eisenstein, et al. (2009, arXiv:0907.1659)

Cosmology from redshift-space distortions

redshift-space distortions

When we measure the position of a galaxy, we measure its position in redshift-space; this differs from the real-space because of its peculiar velocity:

$$s(r) = r - v_r(r)\hat{r}$$

Where s and r are positions in redshift- and real-space and v_r is the peculiar velocity in the radial direction

RSD on small scales

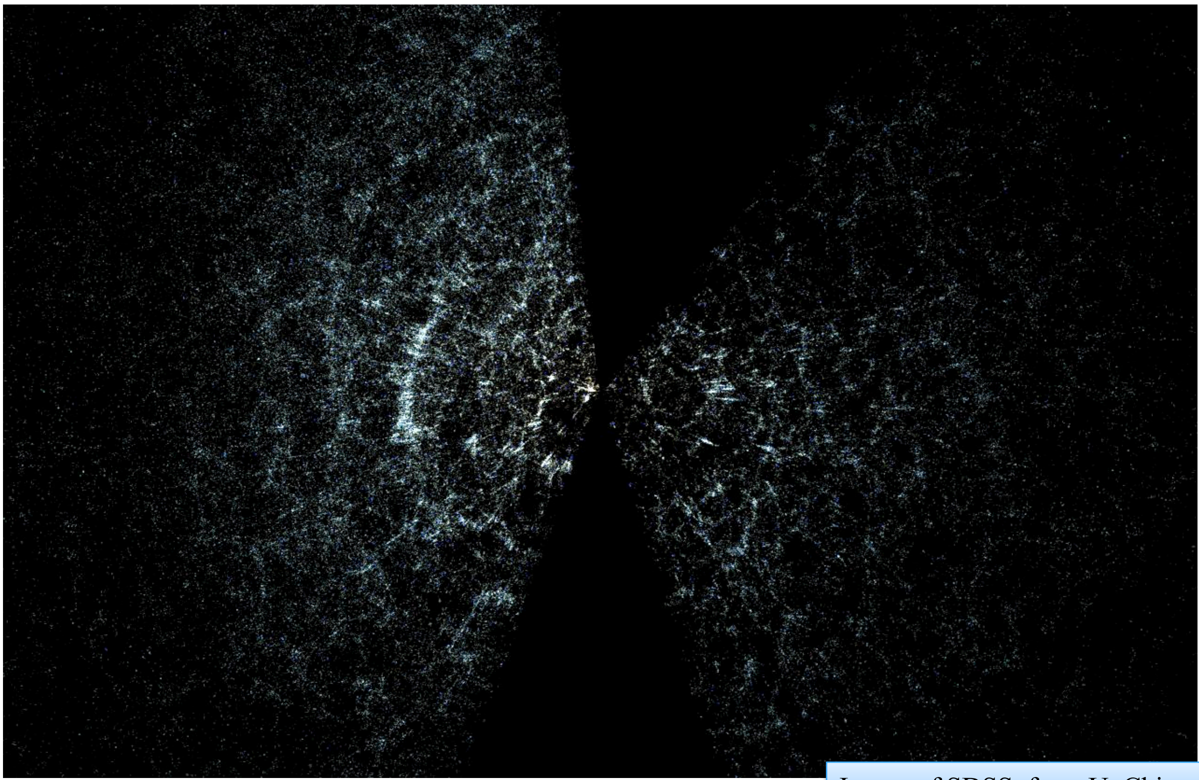
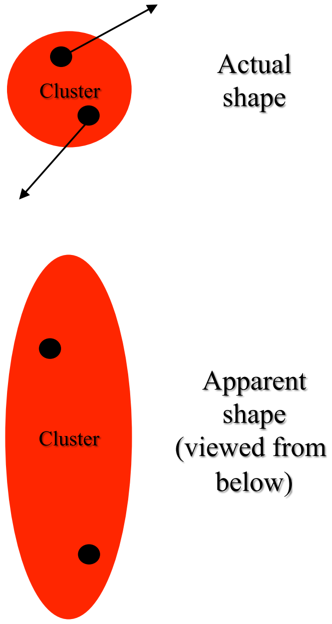


Image of SDSS, from U. Chicago

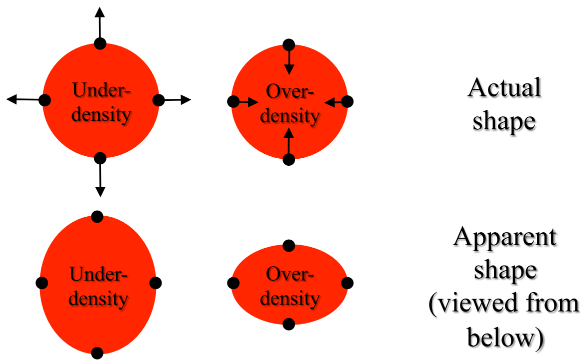
RSD on small scales

- Virial motions of galaxies in collapsed objects misinterpreted as Hubble flow
- Leads to apparent elongation of clusters along line-of-sight
- non-linear physics, so hard to extract cosmological information



RSD on large scales

- Structure growth is
  - driven by the motion of matter
  - inhibited by the cosmological expansion
- Motion of galaxies carries an imprint of the rate of growth of large-scale structure.
- On large scales, galaxies move coherently towards the overdensities and away from underdensities

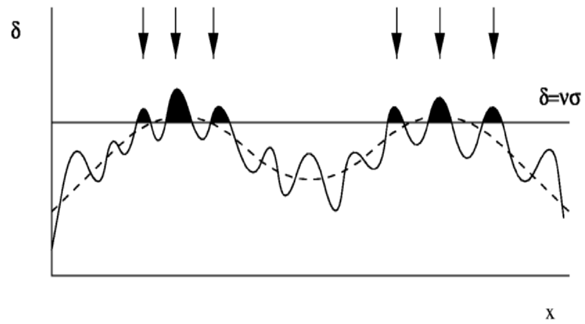


Kaiser (1987: MNRAS 227, 1)

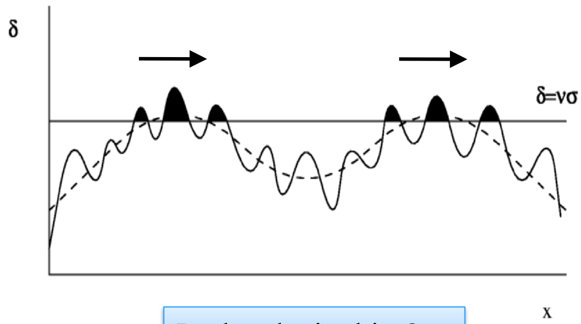
Galaxies act as test particles

Galaxies act as test particles with the flow of matter

On large-scales, the distribution of galaxy velocities is unbiased provided that the positions of galaxies fully sample the velocity field



Peak overdensity bias



Peak velocity bias?

If fact, we can expect a small peak velocity-bias due to motion in Gaussian random fields

Percival & Schafer, 2008, MNRAS 385, L78

What parameter do RSD measure?

Two ways of writing the over-density in linear limit

$$\delta_{\rm gal}(k,\mu) = b\delta_{\rm mass}(1+\mu^2\beta)$$
$$\delta_{\rm gal}(k,\mu) = b\delta_{\rm mass}+\mu^2 b_v f\delta_{\rm mass}$$

Two ways of writing the power spectrum

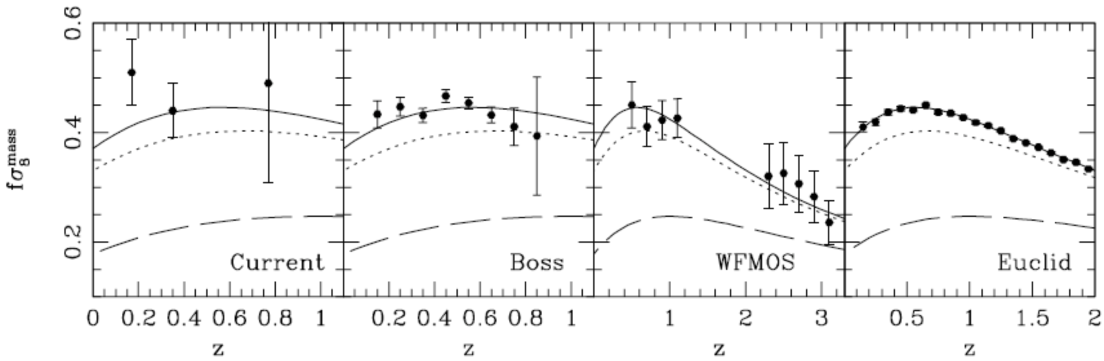
$$P_{\rm gal}(k,\mu) = b^2 P_{\rm mass}(1+\beta\mu^2)^2$$
$$P_{\rm gal}(k,\mu) = P_{\rm mass}(b^2+2\mu^2 b b_v f+\mu^4 b_v^2 f^2)$$

We measure the normalizations of the galaxy over-density field ($b_\delta\sigma_8$), and the galaxy velocity field ($fb_v\sigma_8$, with b_v=1). You can obviously measure any combinations of these (e.g. β), or other combinations.

Do we need to know galaxy bias?

Assuming we know b_v RSD constrain $f\sigma_8$, the amplitude of the matter **velocity** power spectrum, which can be as good a test of GR as f.

$$f \equiv \frac{d\log D}{d\log a} \qquad f\sigma_8 \propto \frac{dD}{d\log a}$$



Song, Percival, 2008, astro-ph/0807.0810

Direct estimator for the velocity power spectrum

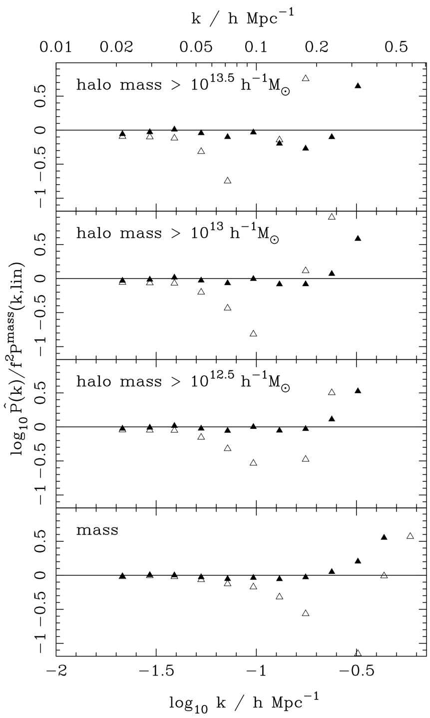
Can construct an estimator for the linear **mass velocity** power spectrum (mass power spectrum multiplied by f^2)

$$\hat{P}(k) = \frac{7}{48}\left[5(7P_0 + P_2) - \sqrt{35}(35P_0^2 + 10P_0P_2 - 7P_2^2)^{1/2}\right]$$

Where P_0 and P_2 are the standard expansions of the power in Legendre polynomials

On large-scales, the primary systematic is a possible velocity-bias.

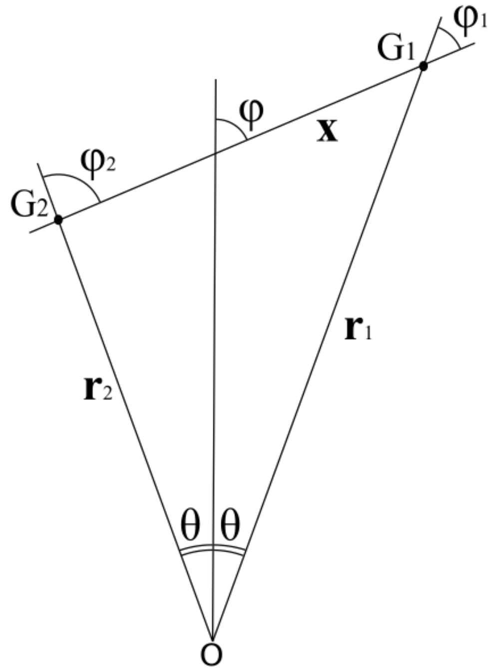
This estimator follows the plane-parallel, distant observer limit



Percival, White, 2008, astro-ph/0808.0003

Wide-angle RSD

- Geometry is actually a different triangle for each pair of galaxies
- In plane-parallel limit,
  - $\theta=0$
  - $\phi_1=\phi_2=\phi_3$
  - $r_1=r_2$



Raccanelli, Samushai & Percival 2010, arXiv:1006:1652

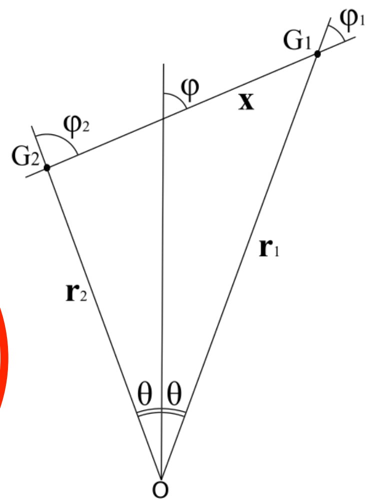
The full power spectrum

Following Papai & Szapudi (2008) we can write the full power spectrum

$$\langle \delta^s(\mathbf{r}_1)\delta^{s*}(\mathbf{r}_2)\rangle = \int \frac{d^3k}{(2\pi)^3} P(k) e^{ik(r_1-r_2)}$$
$$\left[1+\frac{f}{3}+\frac{2f}{3}L_2(\mu_1)-\frac{i\alpha f}{r_1 k}L_1(\mu_1)\right]$$
$$\left[1+\frac{f}{3}+\frac{2f}{3}L_2(\mu_2)-\frac{i\alpha f}{r_2 k}L_1(\mu_2)\right]$$

where

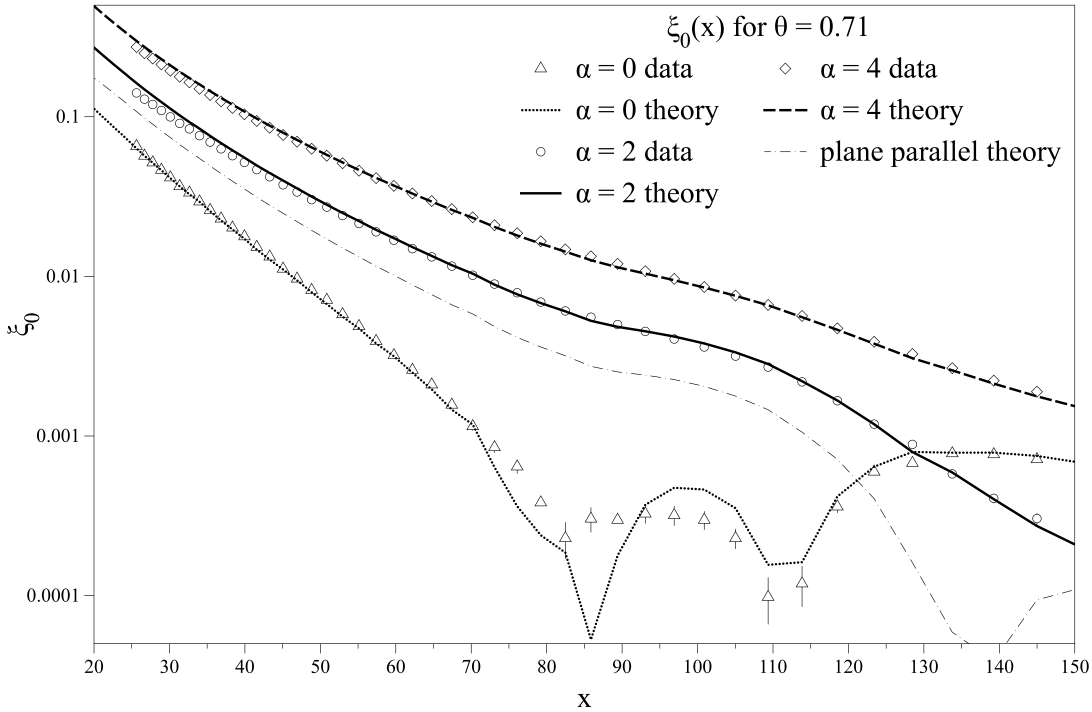
$$\mu_1=\cos(\phi_1), \quad \mu_2=\cos(\phi_2)$$



Wide-angle RSD terms

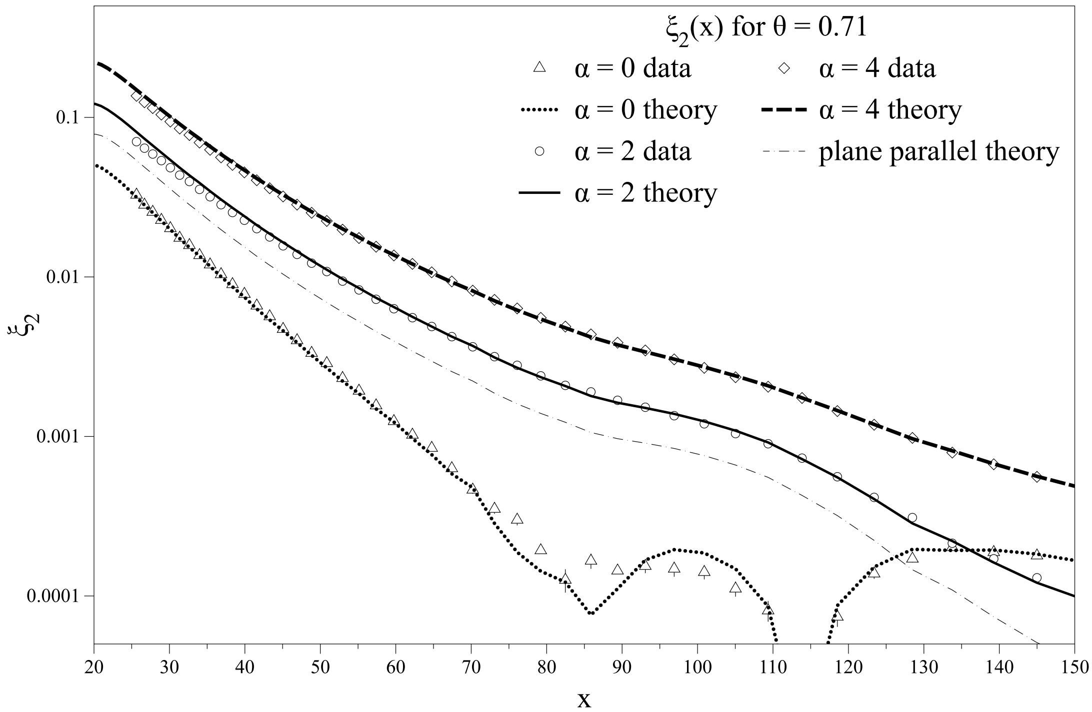
Mode-coupling RSD terms

Testing wide angle RSD: results



Raccanelli, Samushai & Percival 2010, arXiv:1006:1652

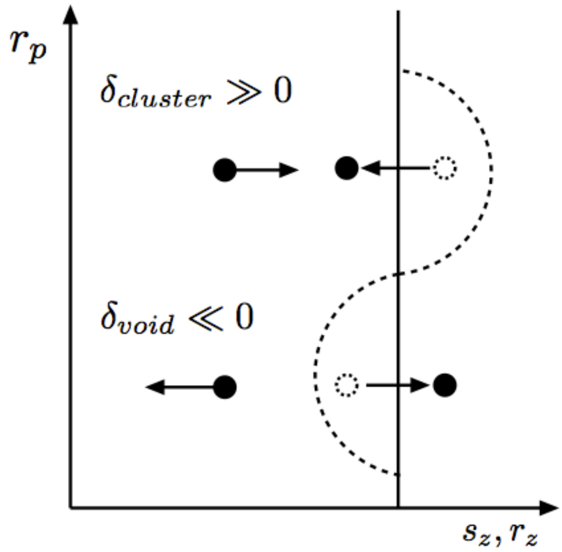
Testing wide angle RSD: results



Raccanelli, Samushai & Percival 2010, arXiv:1006:1652

Projected clustering measurements

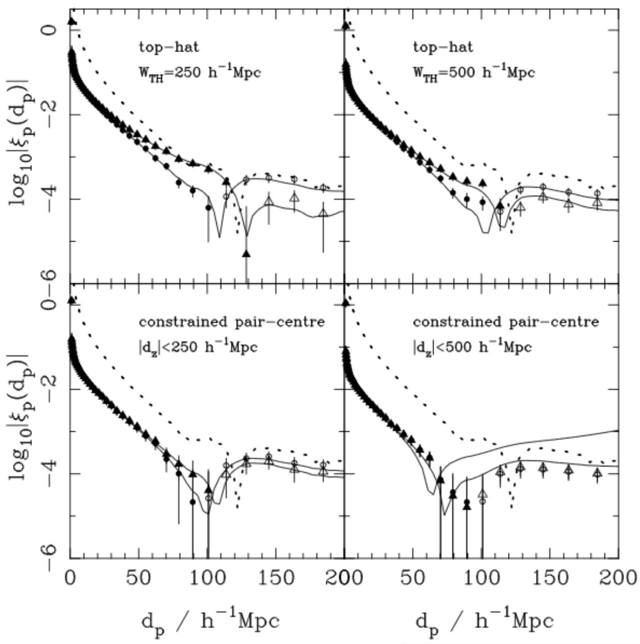
We even have to include RSD when modeling projected measurements (even though RSD do not change angular positions)



Nock, Percival & Ross 2010, arXiv:1003.0896

Projected clustering measurements

Although there are ways to mitigate RSD effects – for example by binning based on pair centers, rather than galaxy redshifts

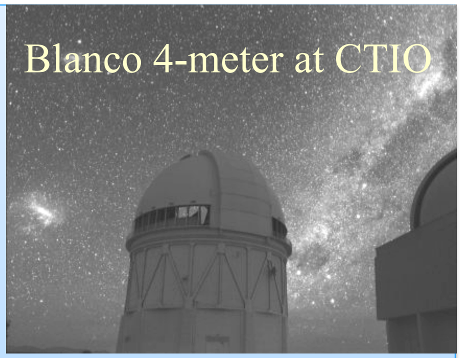


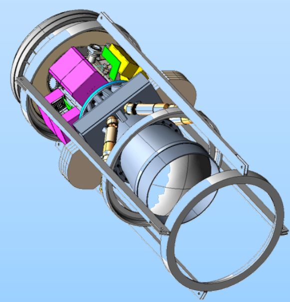
Nock, Percival & Ross 2010, arXiv:1003.0896

Selected future surveys

DES: summary

- Survey due to start autumn 2011
- 5000deg^2 multi-colour imaging
- Will include IR data from VISTA hemisphere survey
- photo-z for 300,000,000 galaxies
- Will be used to constrain dark energy using 4 probes
  - LSS/BAO
  - weak lensing
  - supernovae
  - cluster number density
- Radial information from photometric redshifts
  - no redshift-space distortions
  - weaker constraints
- See also: Pan-STARRS, VST-VISTA, SkyMapper





University of Portsmouth

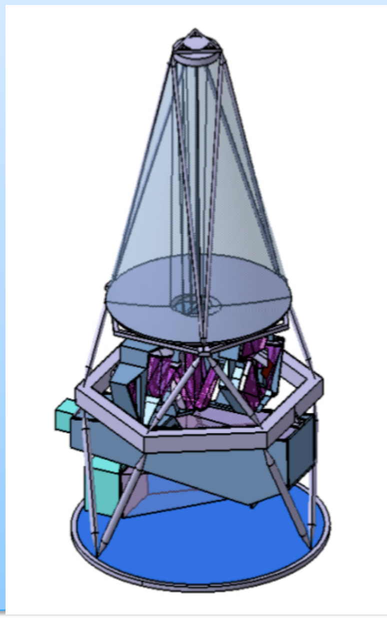
BOSS: summary

- Ω = 10,000deg²
- Selected from 11,000deg² of imaging
  - 8,500deg² in North
  - 2,500deg² in South (fill in SDSS-II Southern stripes)
- LRGs : 150/deg², z ~ 0.1 – 0.7 (direct BAO)
- 1% d_A, 1.8% H at z ~ 0.35, 0.6
- QSOs : 20/deg², z ~ 2.1 – 3.0 (BAO from Ly-α forest)
- 1.5% d_A, 1.2% H at z ~ 2.5
- Cosmic variance limited to z ~ 0.6 : as good as LSS mapping will get with a single ground based telescope
- Leverage existing SDSS hardware & software where possible
- Sufficient funding is in place and project is underway
- www.sdss3.org/boss
- See also: WiggleZ, VIPERS

University of Portsmouth

Euclid: summary

- ESA Cosmic Vision proposal (600M€, M-class mission)
- Now entering definition phase
- 5 year mission, L2 orbit, 1.2m primary mirror
- nominal 2016 launch date
- 20,000deg² imaging and spectroscopic survey
- weak lensing (WL) from imaging survey
- BAO and P(k) from spectroscopic survey
- combination of probes (BAO, WL, z-space distortions) allows tests of
  - geometry
  - structure formation
- allows fundamental tests of GR
- See also: LSST, BigBOSS



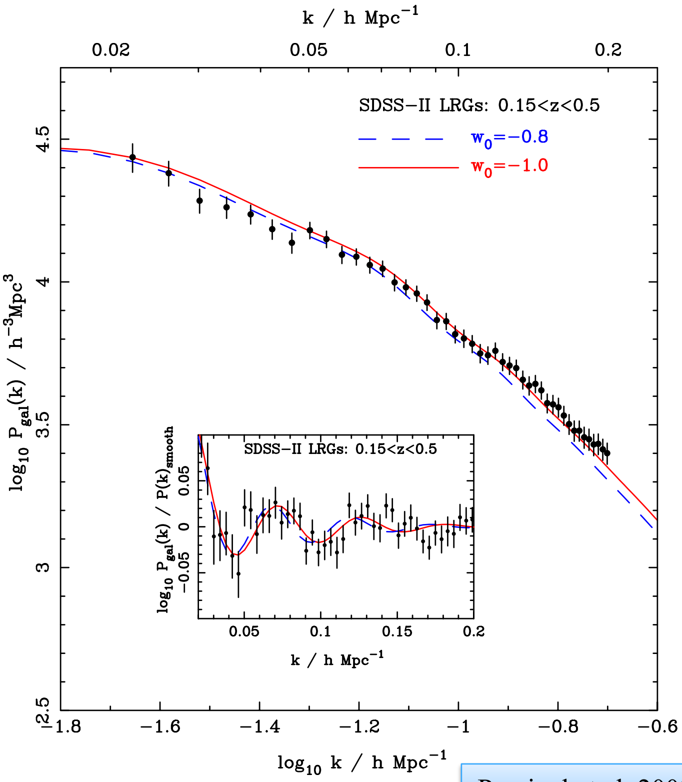
Current large-scale galaxy clustering measurements

SDSS LRGs at z~0.35

The largest volume of the Universe currently mapped

Total effective volume
V_{eff} = 0.26 Gpc^3h^{-3}

Power spectrum gives amplitude of Fourier modes, quantifying clustering strength on different scales

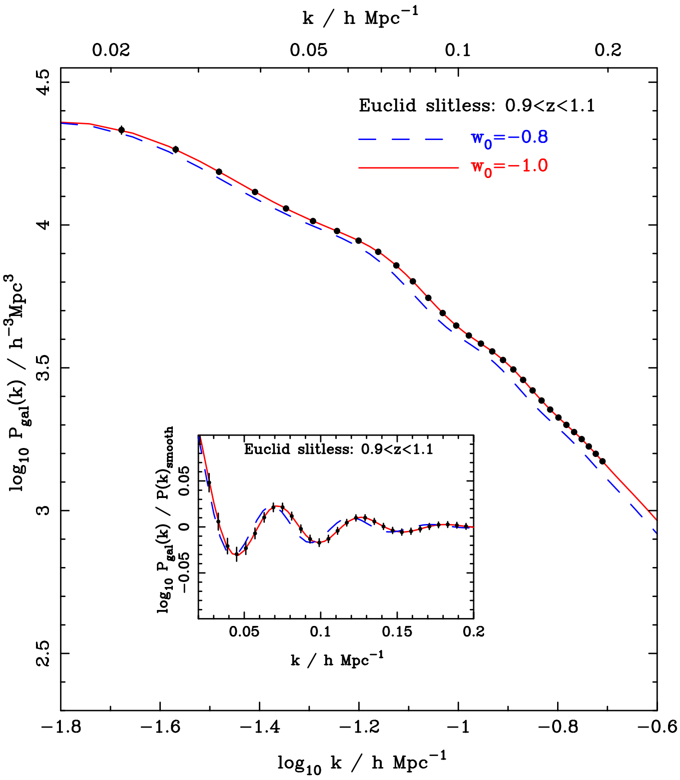


Percival et al. 2009; arXiv:0907.1660

Predicted galaxy clustering measurements by Euclid

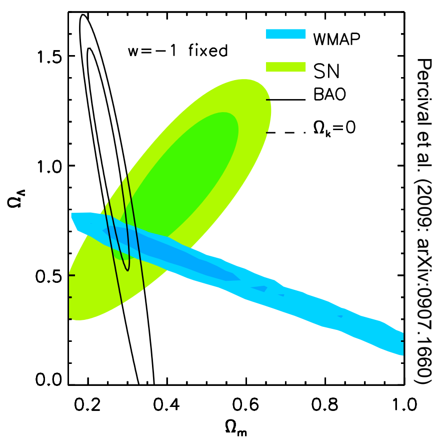
20% of the Euclid data, assuming the slitless baseline at z~1

Total effective volume (of Euclid)
V_{eff} = 19.7 Gpc^3h^{-3}

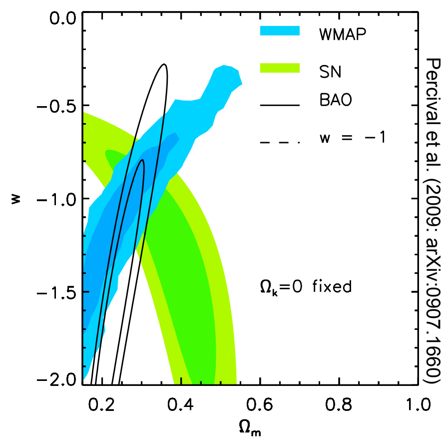


Current BAO constraints vs other data

ΛCDM models with curvature



flat wCDM models

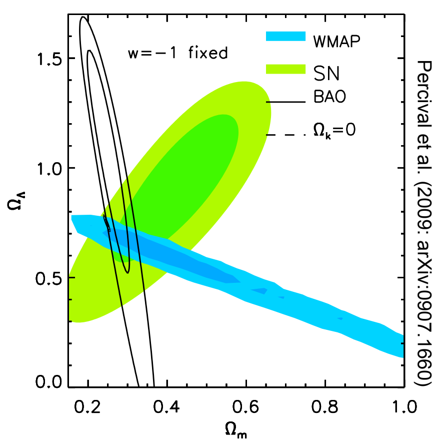


Union supernovae
WMAP 5year
SDSS-II BAO Constraint on $r_s(z_d)/D_V(0.2)$ & $r_s(z_d)/D_V(0.35)$

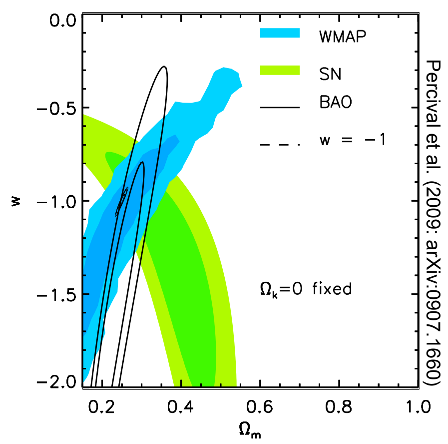
Percival et al. 2009; arXiv:0907.1660

How does Euclid BAO compare?

ΛCDM models with curvature



flat wCDM models



Union supernovae
WMAP 5year
SDSS-II BAO Constraint on $r_s(z_d)/D_V(0.2)$ & $r_s(z_d)/D_V(0.35)$

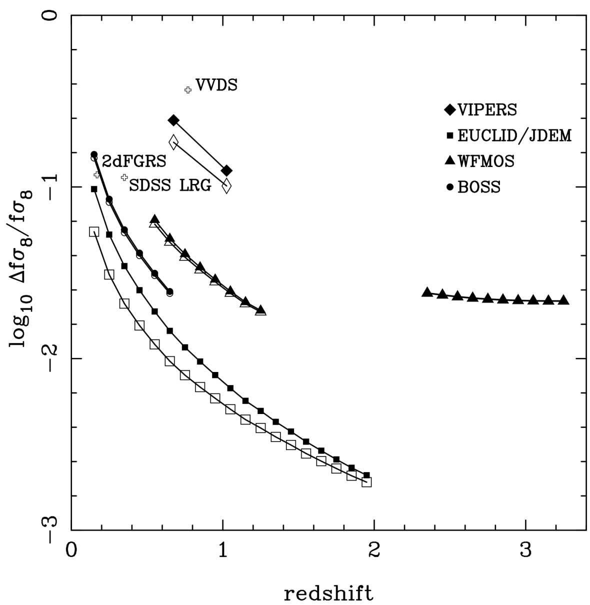
Fisher matrix prescription

Fisher matrix is statistical tool to translate from errors on parameters that you think you know (e.g. P(k)) to errors on parameters that you want to know (e.g. $f\sigma_8$, Ω_m, Ω_b, h, etc)

For overdensities, can base method on δ or P(k) as the "observed" quantity: give the same result

Code to estimate errors on $f\sigma_8$ is available from:

http://mwhite.berkeley.edu/Redshift



White, Song & Percival, astro-ph/0808.1518

Summary

- Galaxy clustering in surveys allows us to test cosmological models in many ways
- Smooth shape of the power spectrum?
  – degenerate with galaxy bias
  – bias measurements can tell us about galaxy formation
  – SDSS data shows that galaxy bias is a strong function of luminosity and color
- Baryon acoustic oscillations
  – avoids (almost all of) galaxy bias
  –Already sets interesting constraints on geometry using SDSS
- Redshift-space distortions
  – avoids density bias completely
  – get "for free" for spectroscopic BAO surveys (eg. BOSS)
  – structure formation test so complementary to geometrical tests
  – techniques are currently being advanced
  – similar to weak lensing but tests only temporal metric fluctuations
- Future surveys
  – next generation underway giving an order of magnitude better constraints
  – plans for the next generation of surveys such as Euclid will provide the next leap forwards