Answering Cosmological Questions with Galaxy Surveys

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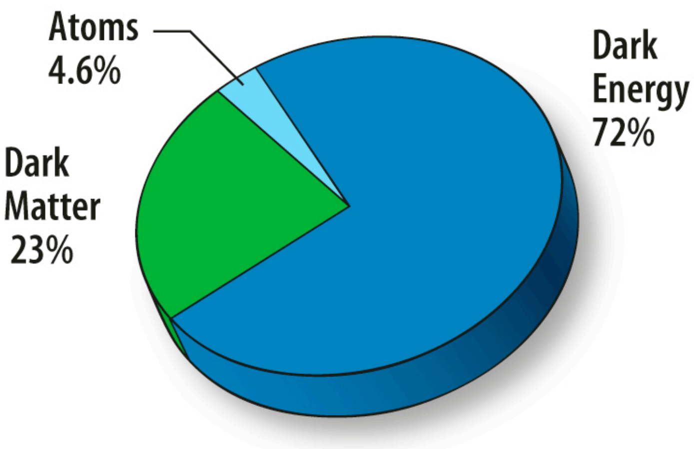
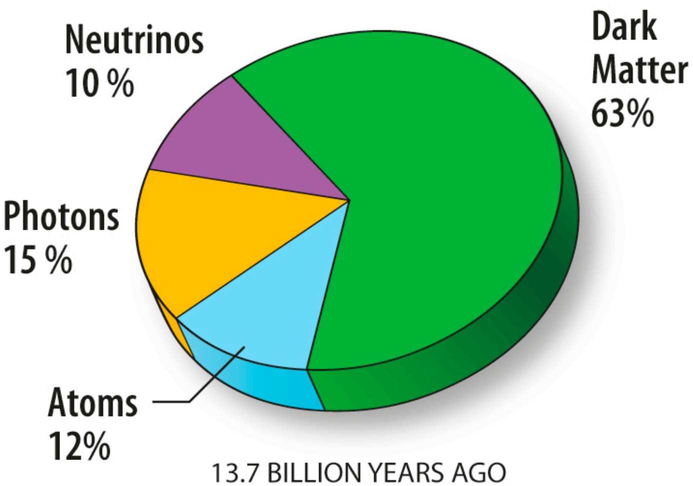
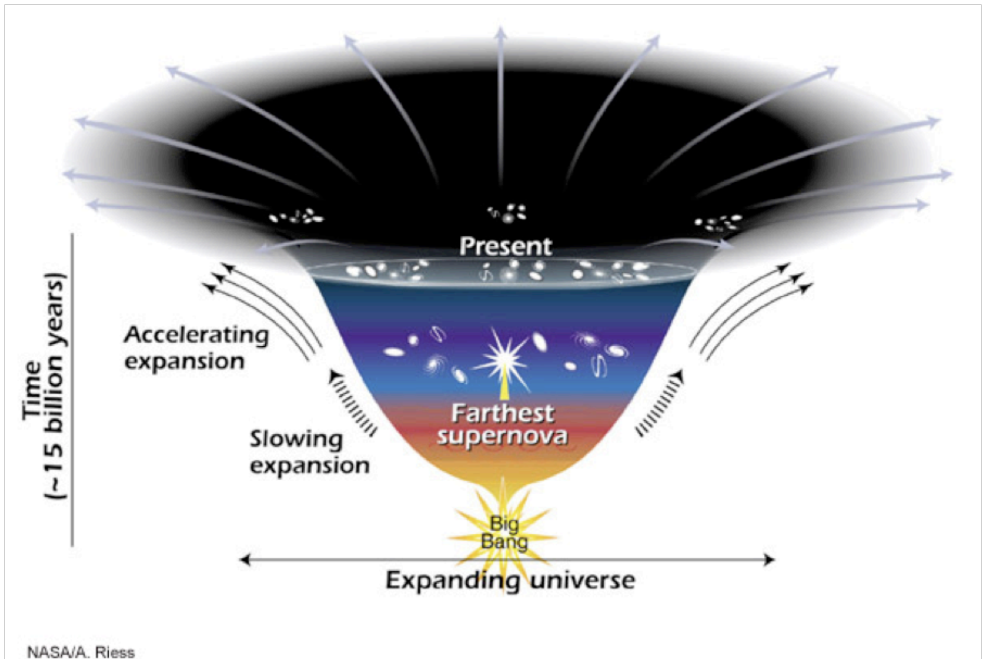
The standard “model” for cosmology



TODAY



13.7 BILLION YEARS AGO
(Universe 380,000 years old)



Remaining questions

- What are the constituents of matter?
  - undiscovered particles
  - neutrino masses
- Why do we see an accelerating Universe?
  - vacuum energy density (Einstein's cosmological constant)
  - new scalar field / other phenomenon
- How does structure form within this background?
  - large-scale General Relativity deviations?
- Why is the Universe homogeneous on large scales?
  - inflation or other model?
  - inflation parameters
- How do galaxies form and evolve?

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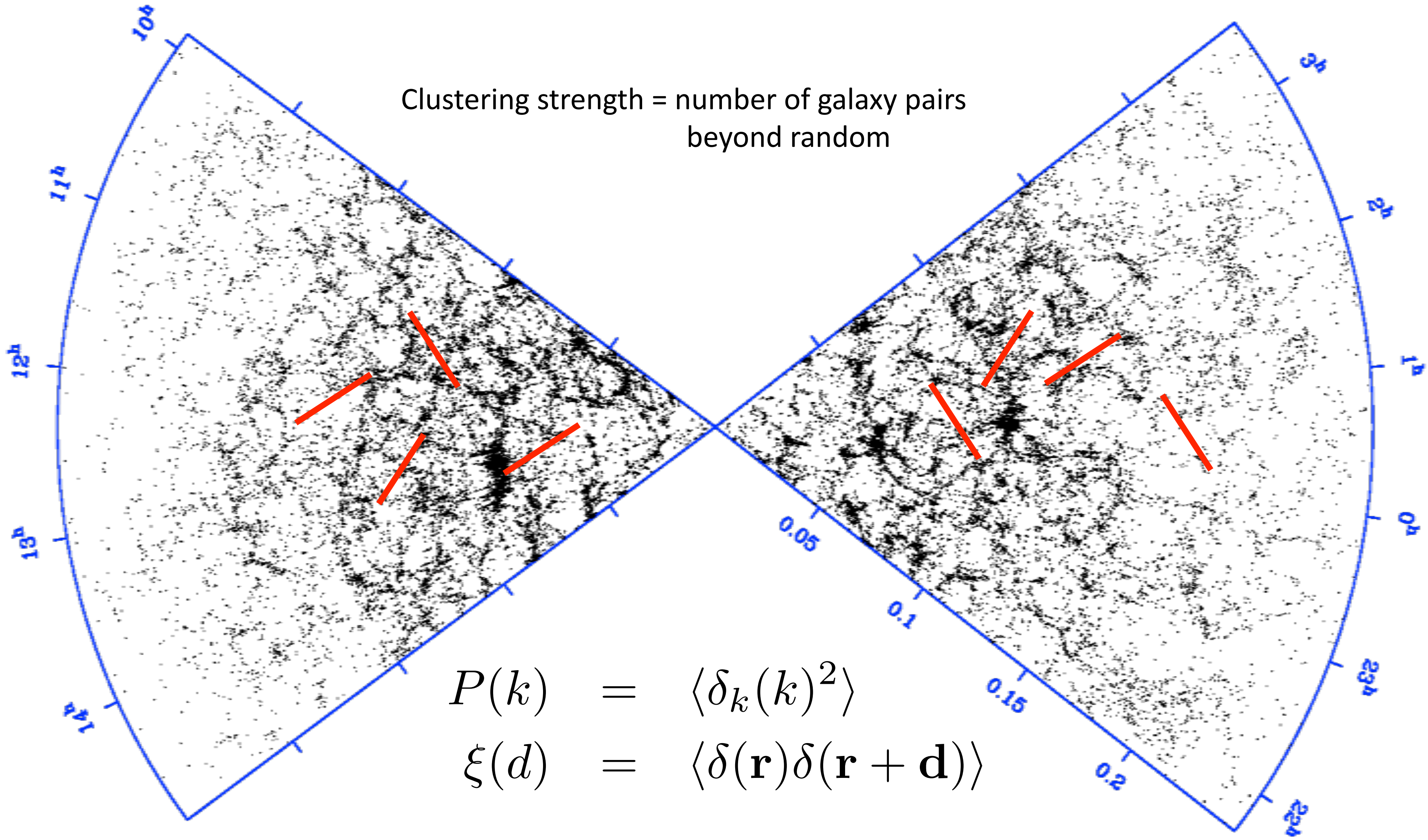
Using galaxy clustering to answer these questions

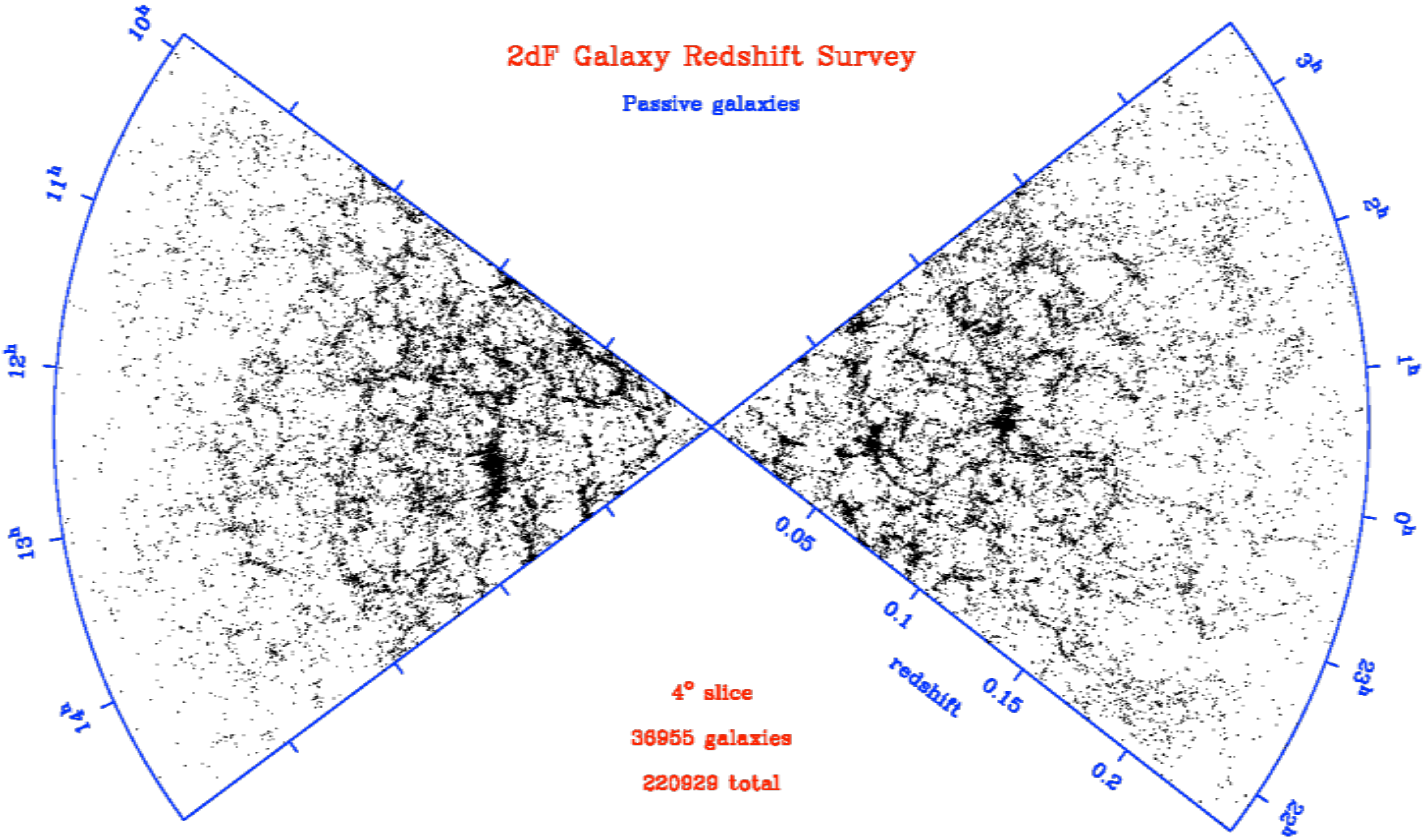


Clustering strength = number of galaxy pairs beyond random

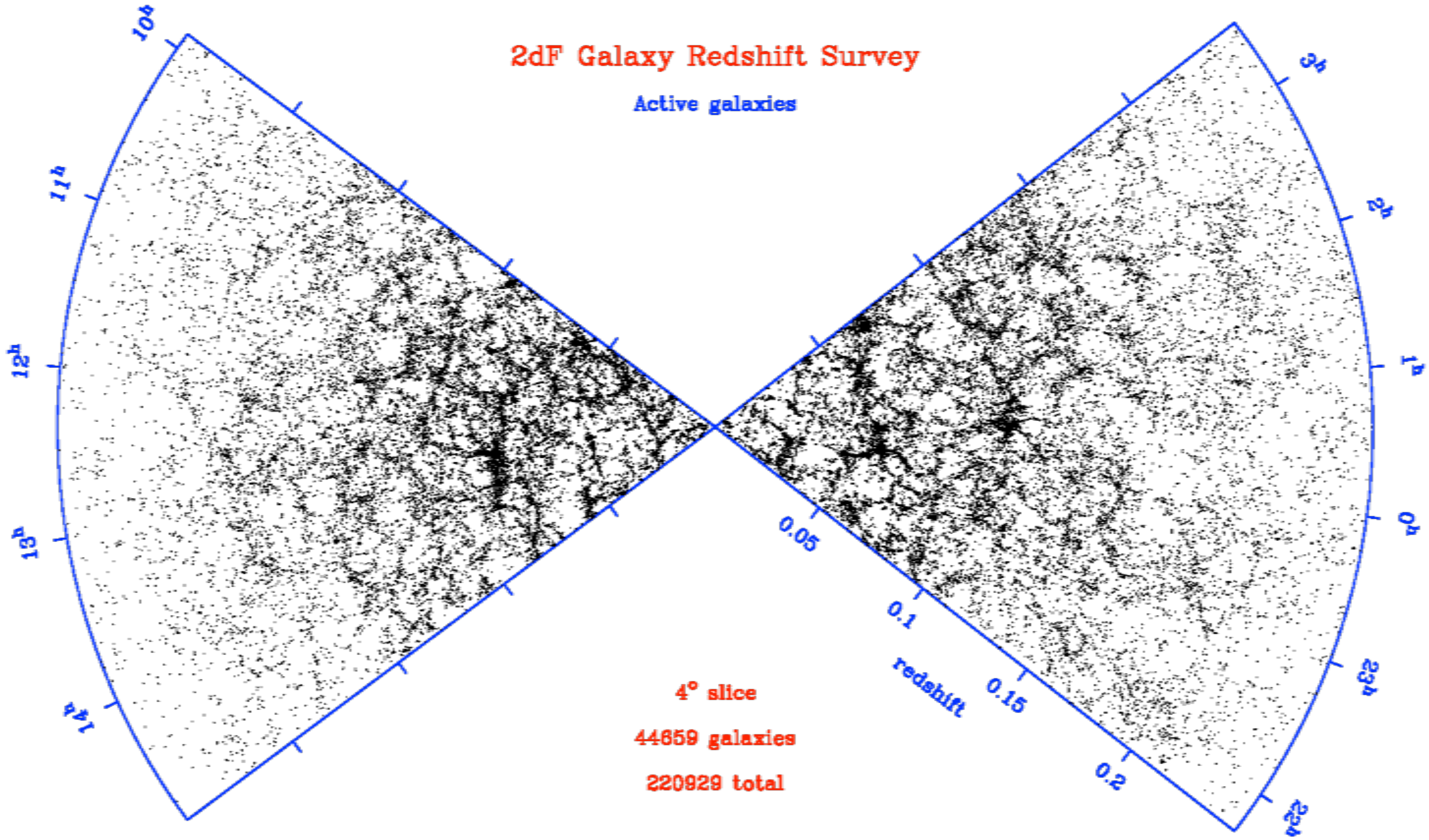
$$P(k) = \langle \delta_k(k)^2 \rangle$$
$$\xi(d) = \langle \delta(\mathbf{r})\delta(\mathbf{r}+\mathbf{d}) \rangle$$

How do galaxies form and evolve?

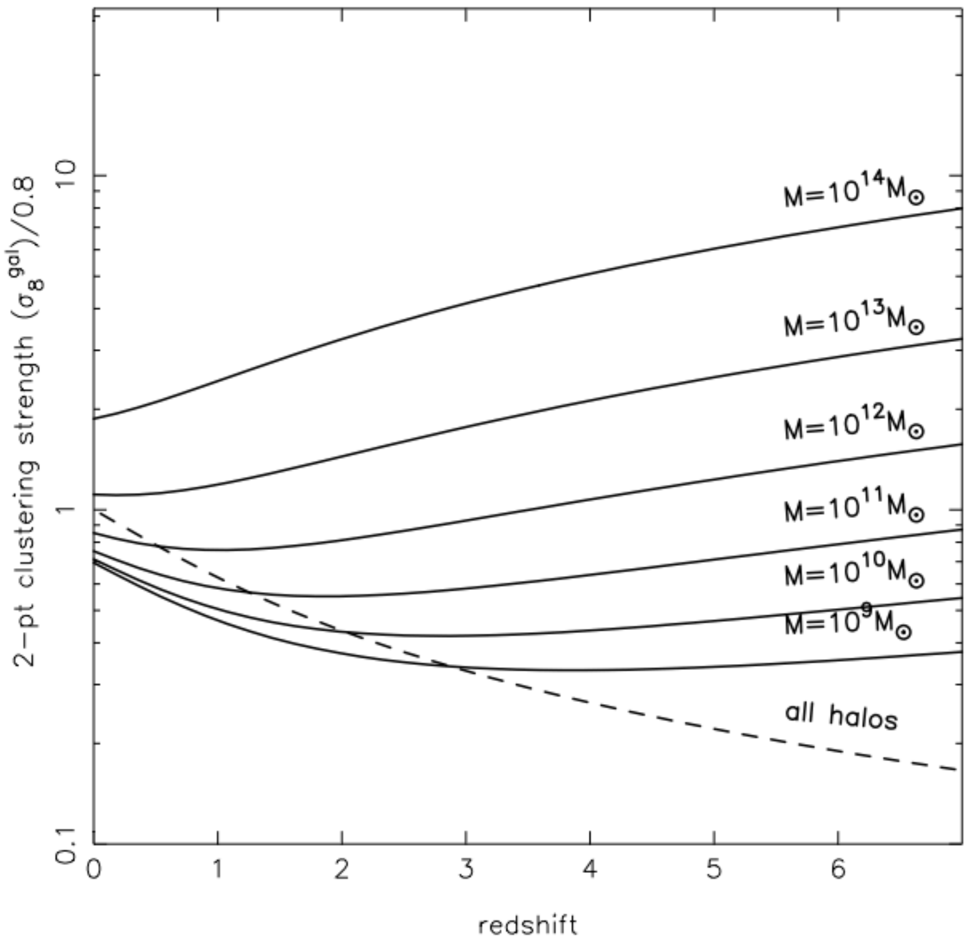
Galaxy bias : red galaxies

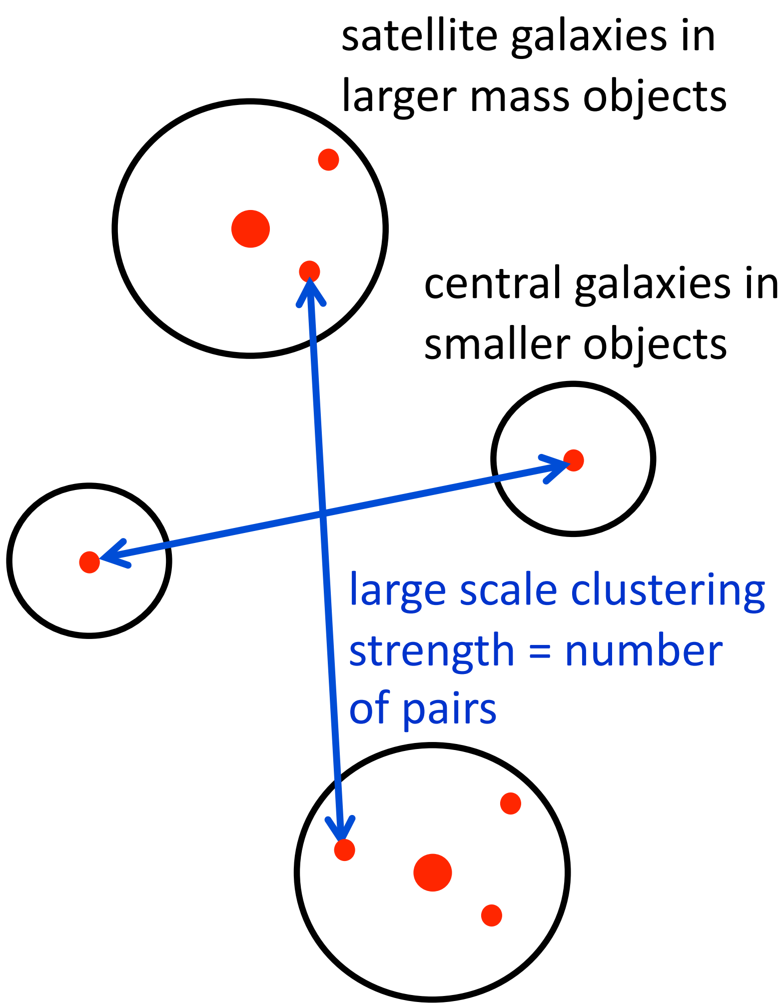


Galaxy bias: blue galaxies



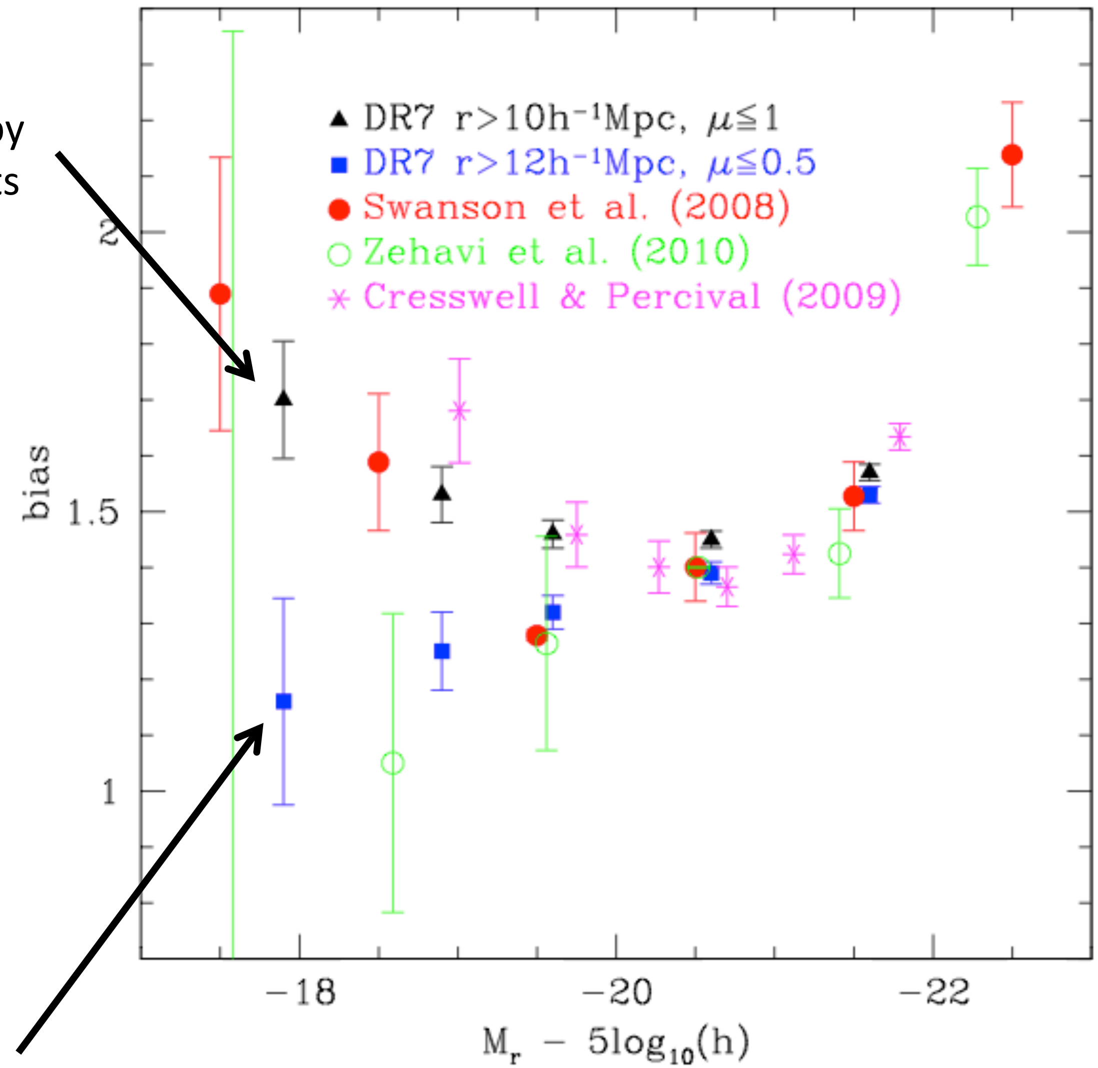
information from the large-scale galaxy clustering





making robust measurements

Contamination by non-linear effects



Robust measurements show faint red galaxies are predominantly in lower mass haloes

Ross, Tojeiro & Percival (2010, arXiv:1010.1403)

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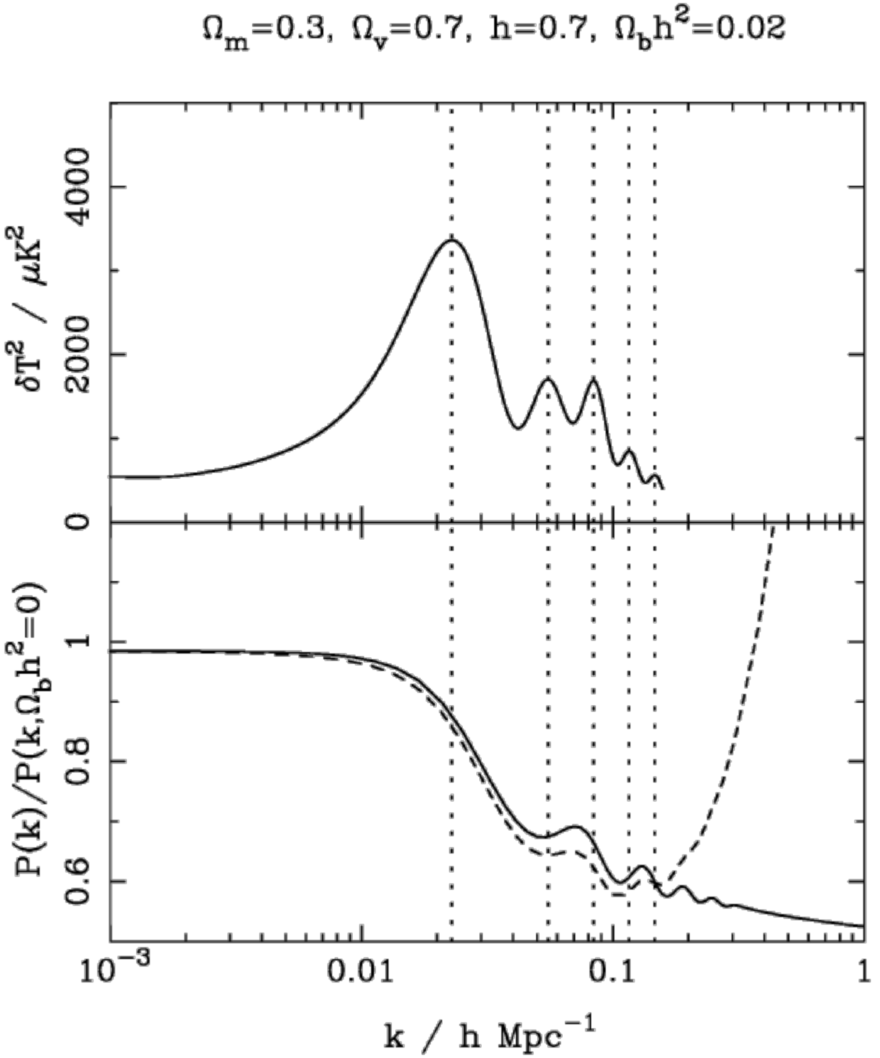
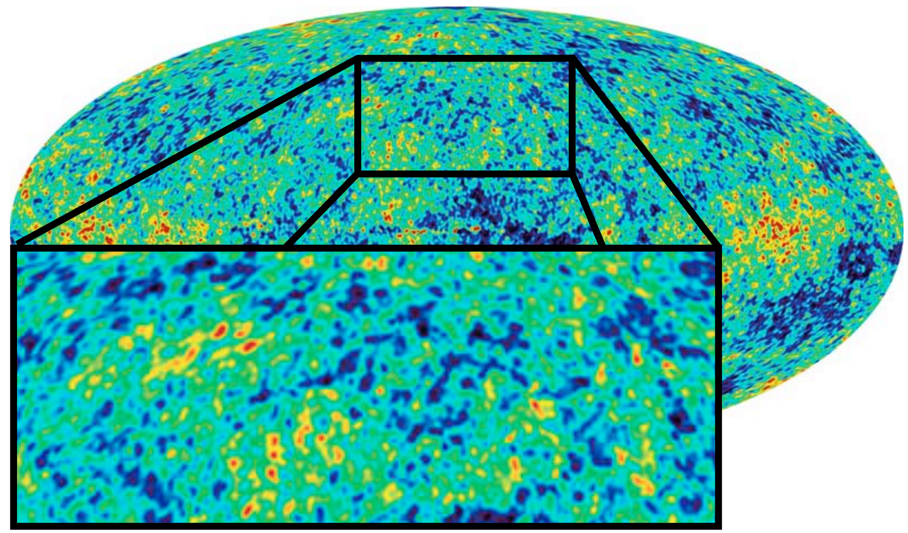
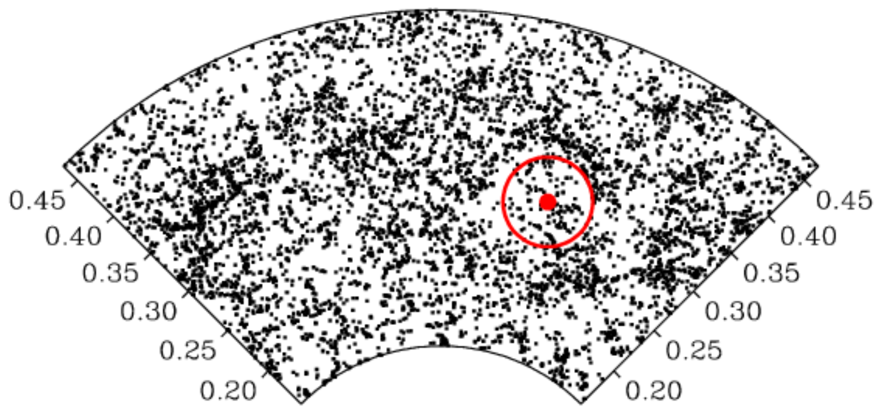
What are the constituents of matter?

Why is the Universe homogeneous on large scales?

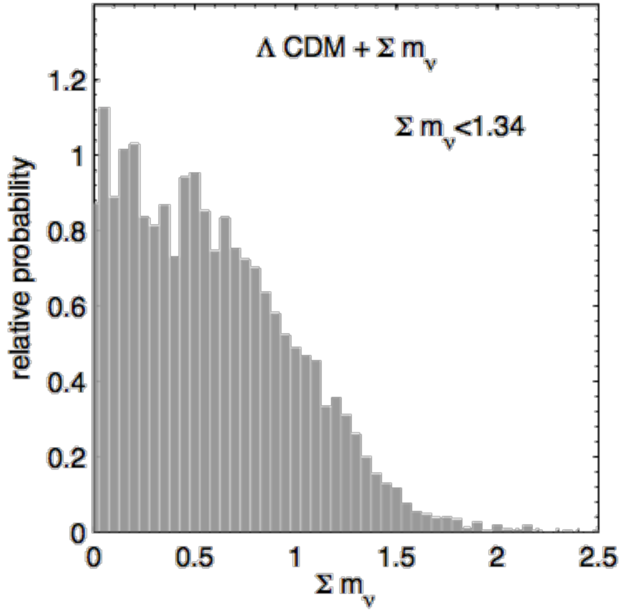
Relationship between CMB and LSS clustering



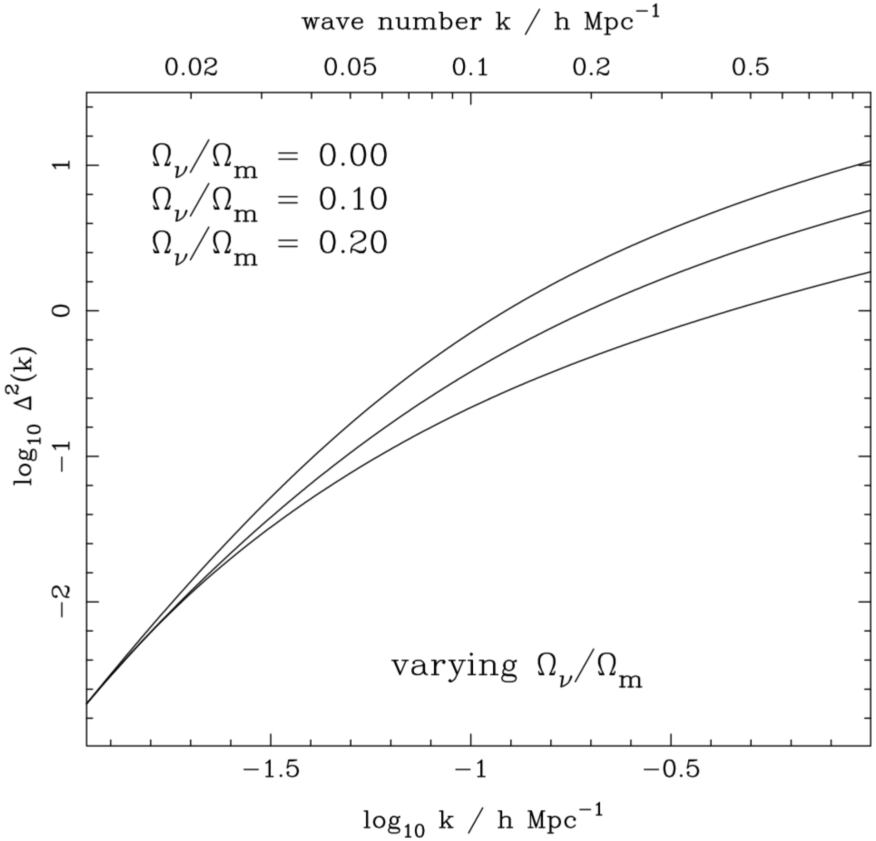




neutrino mass from comoving clustering

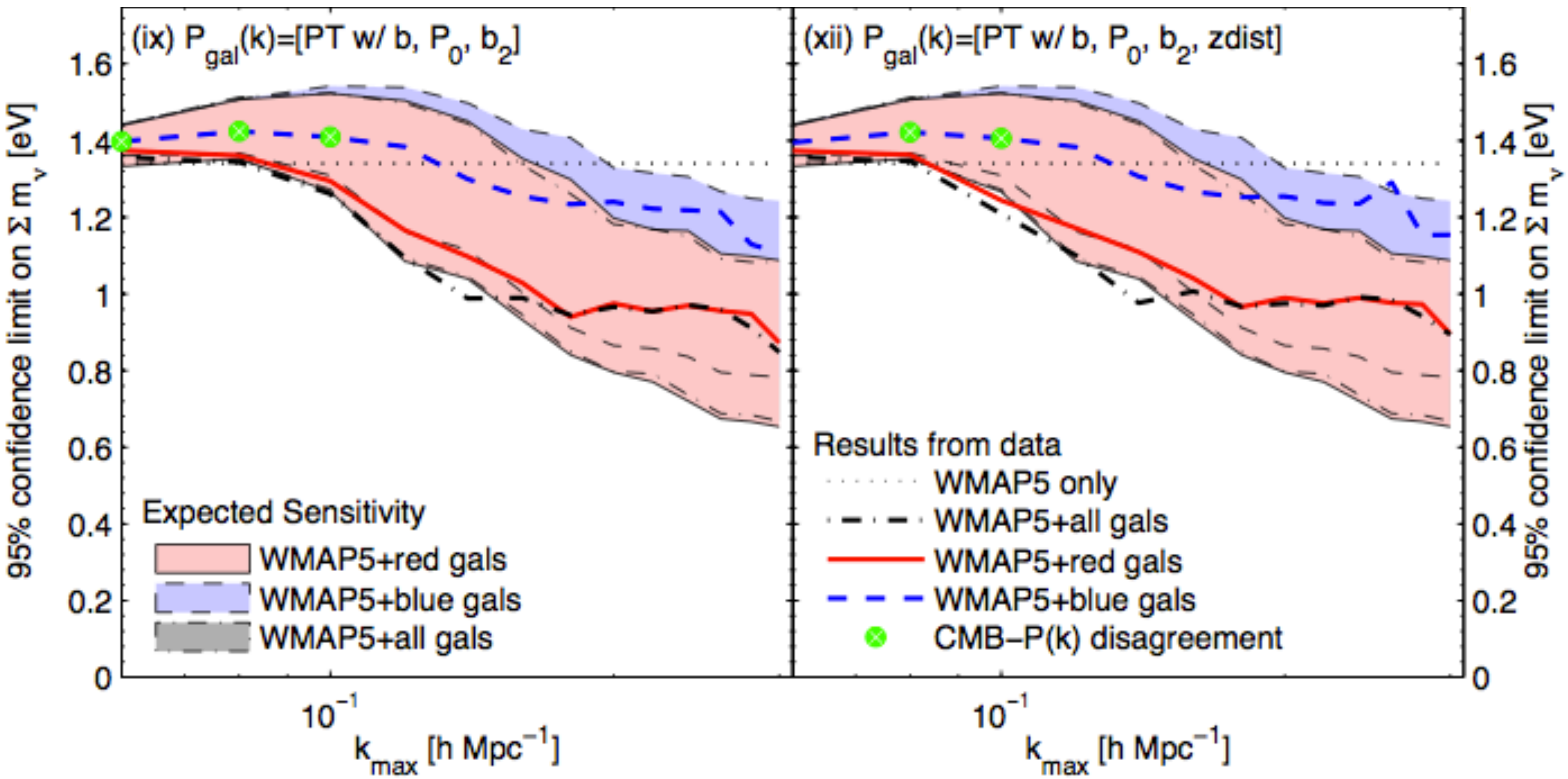


WMAP 7 year data:
Dunkley et al. (2009: ApJS,180, 306)



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 ~1σ apart, using shape of P(k)

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

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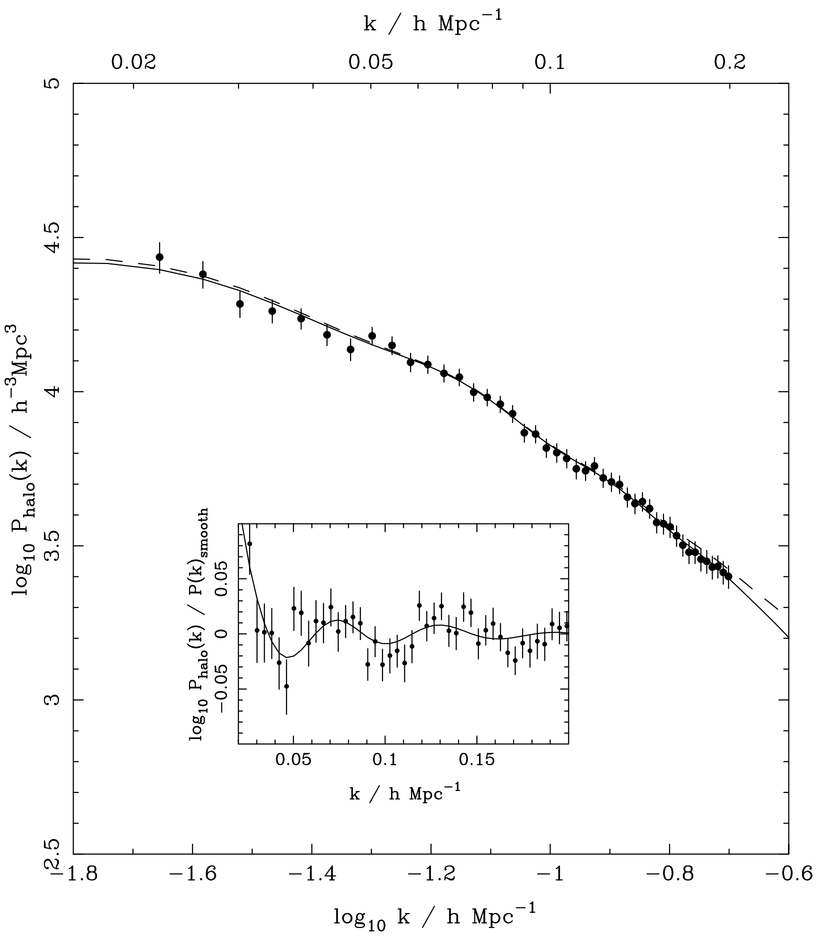
Full fit giving parameters of inflation



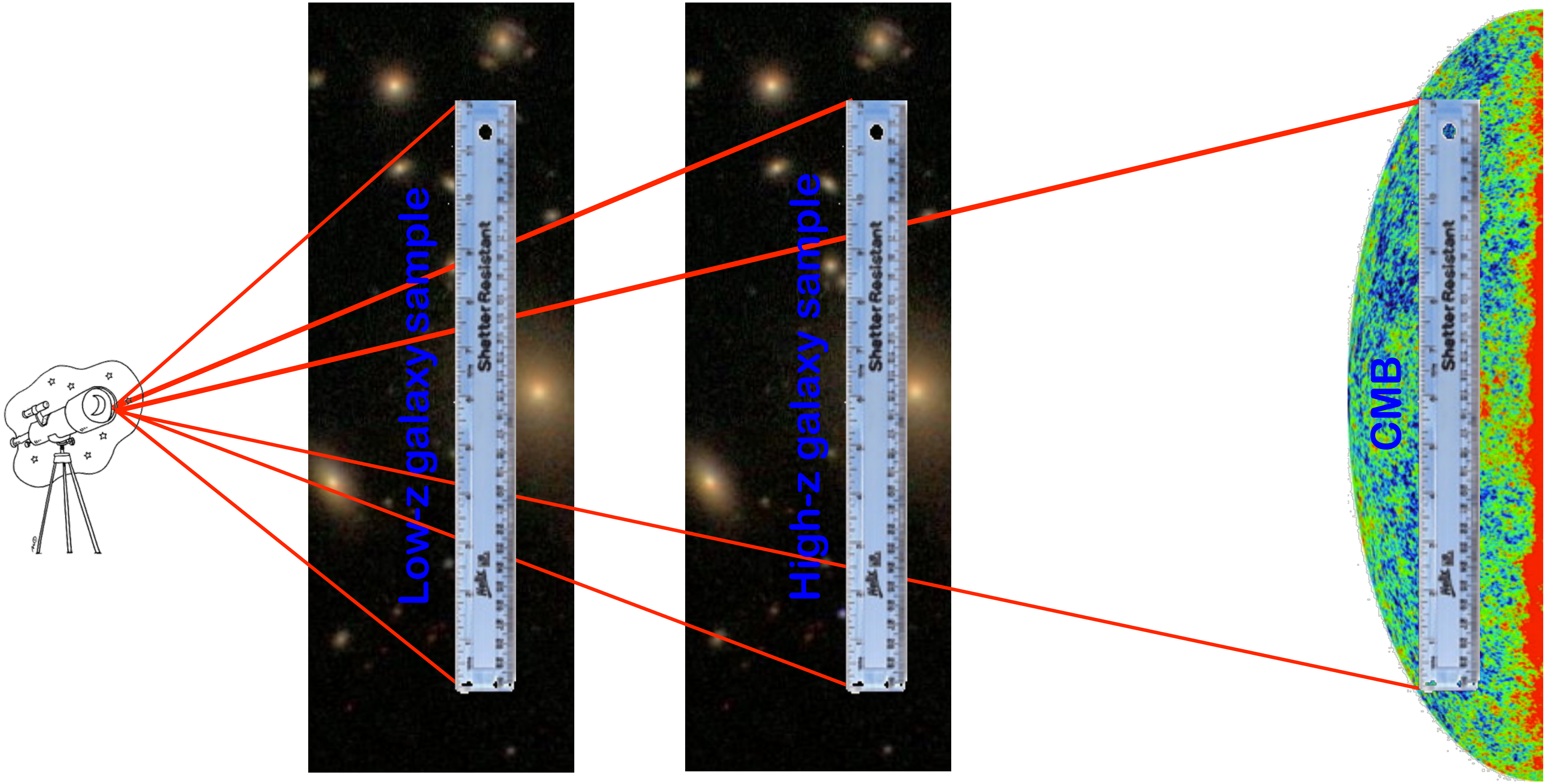
Use luminous red galaxies (LRGs) to extract the halo power spectrum and model the shape to constrain cosmological models

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

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

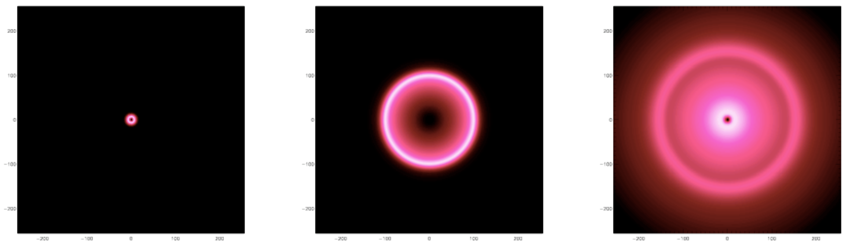
Why do we see an accelerating Universe?

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)

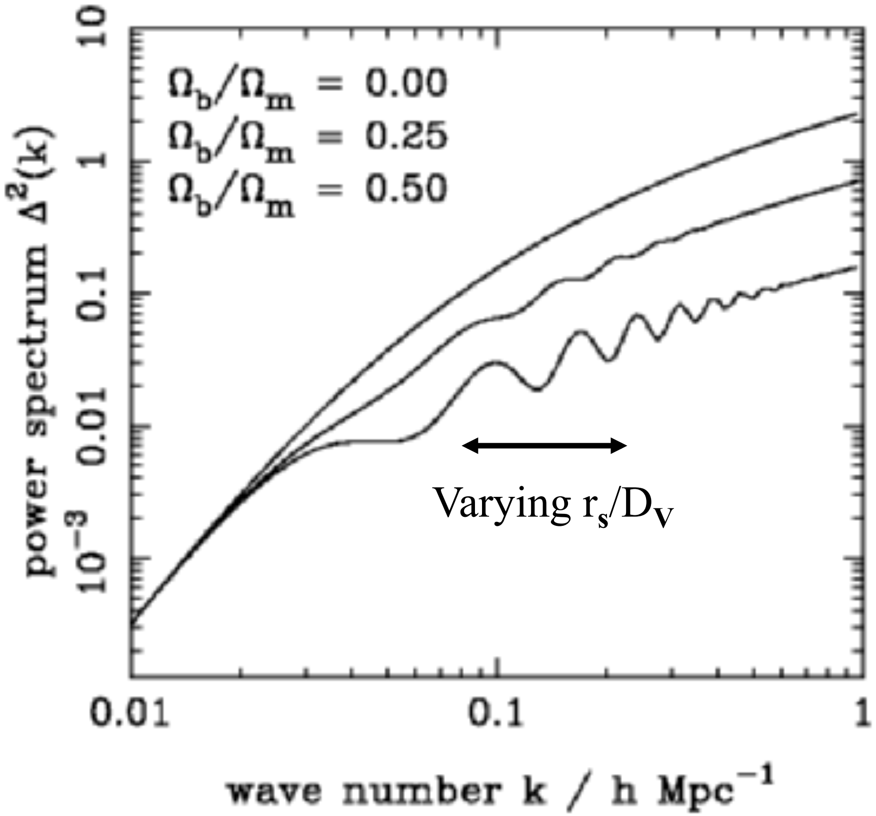


(images from Martin White)

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

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

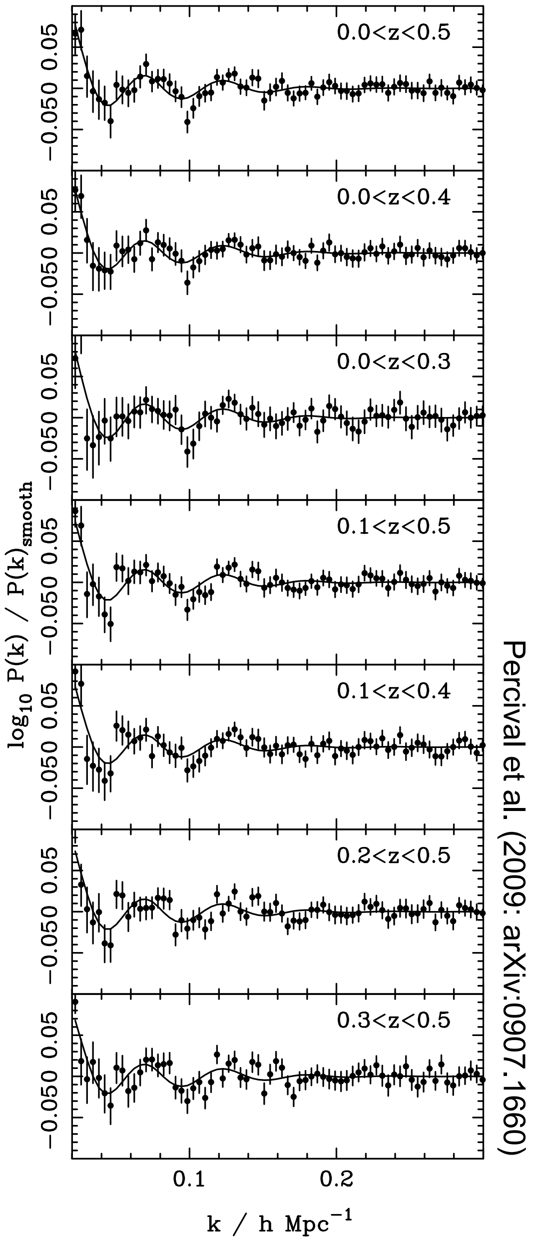
comoving sound horizon ~110h^{-1}Mpc, BAO wavelength 0.06hMpc^{-1}



projection onto the observed galaxy distribution depends on

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

BAO in SDSS DR7 + 2dFGRS power spectra



- 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

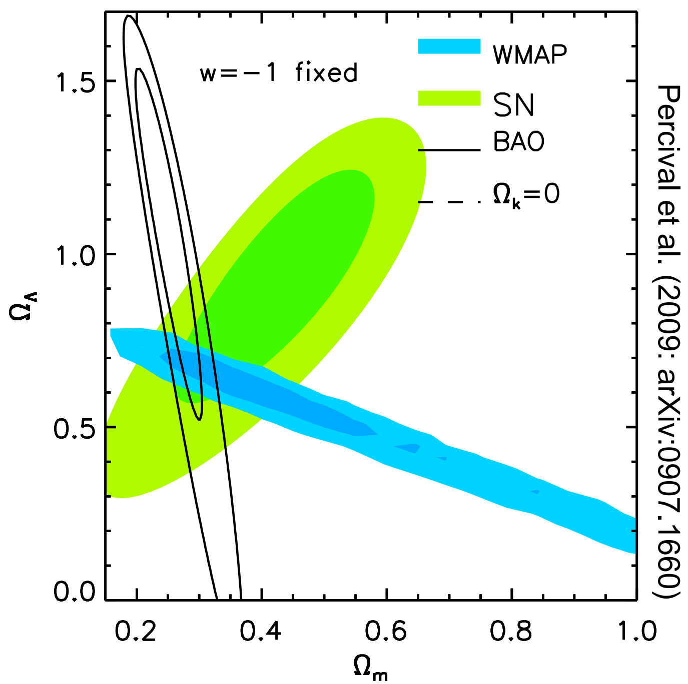
$$r_s(z_d)/D_V(0.275) = 0.1390 \pm 0.0037 \quad (2.7\%)$$
$$D_V(0.35)/D_V(0.2) = 1.736 \pm 0.065$$

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

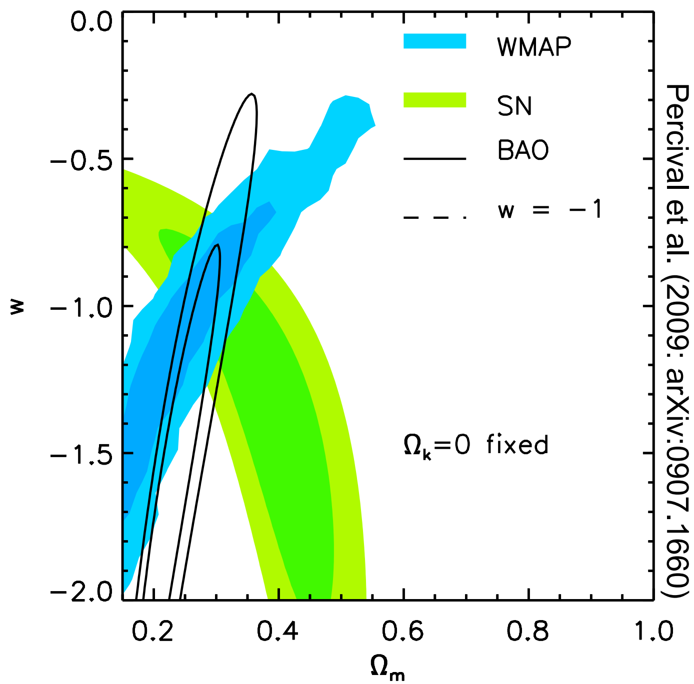
Percival, Reid, Eisenstein et al. (2009, arXiv:0907.1660)

Comparing BAO constraints vs other data

ΛCDM models with curvature



flat wCDM models



Union supernovae

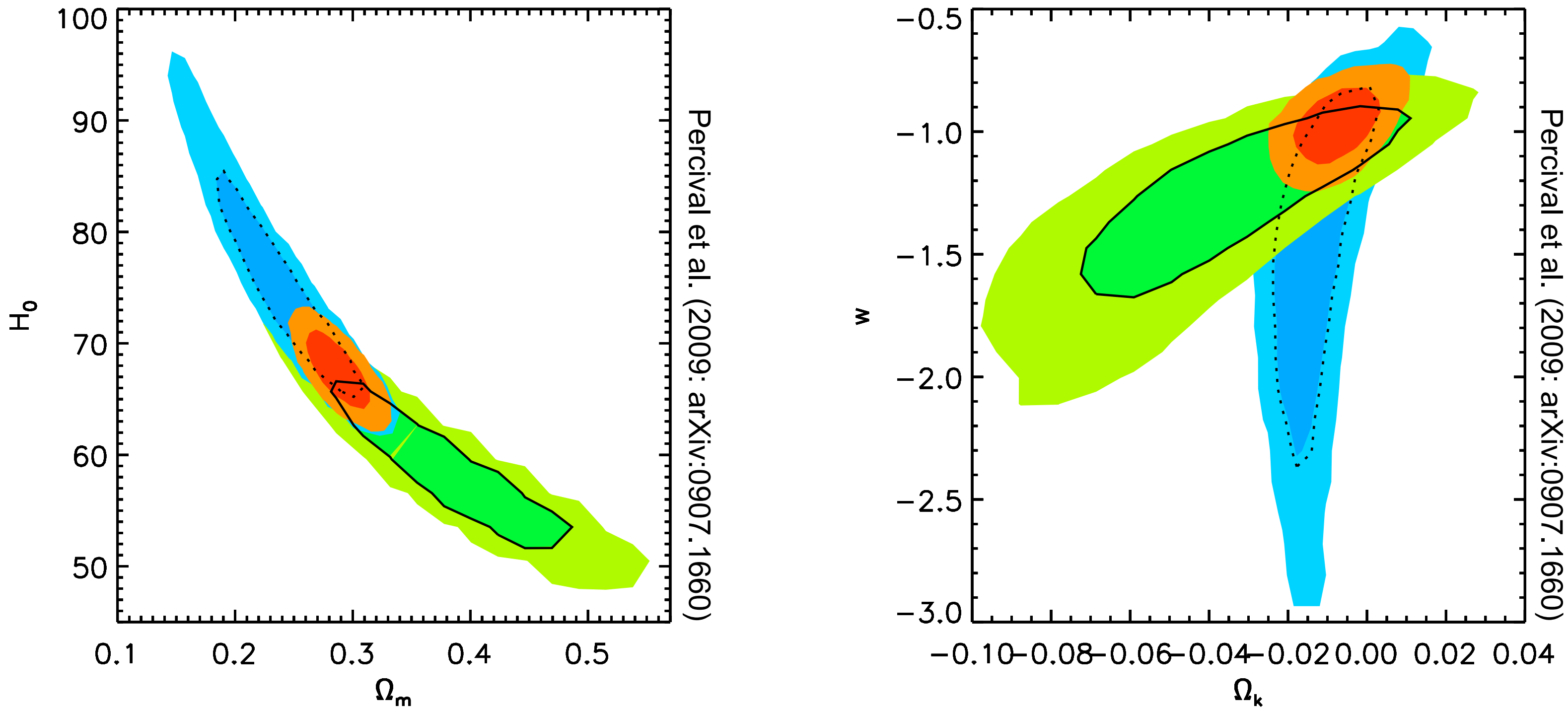
WMAP 5year

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

w-CDM models with curvature



SDSS + WMAP5

Union supernovae + WMAP5

SDSS + Union supernovae + WMAP5

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

How does structure form within this background?

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

Redshift-Space Distortions

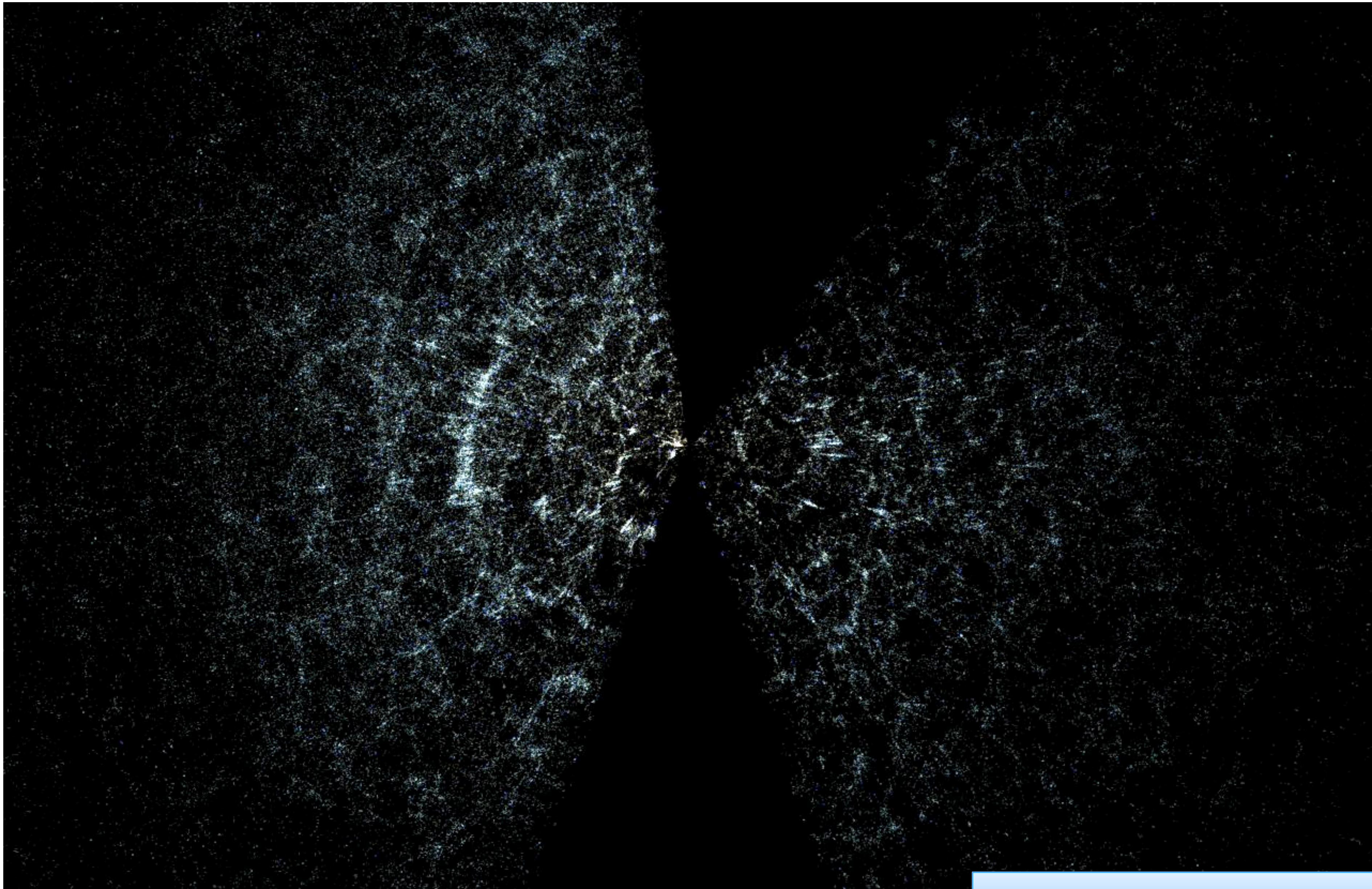
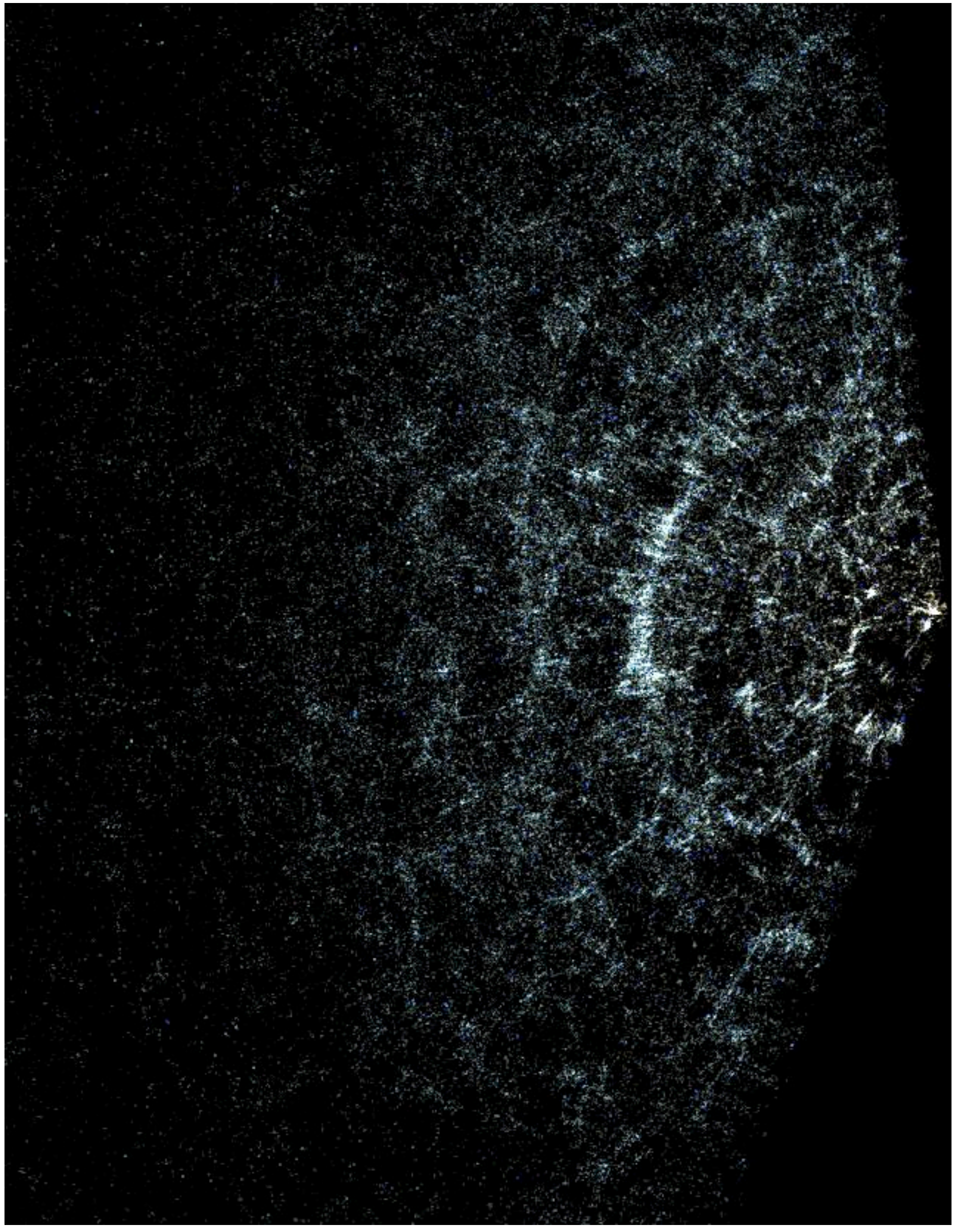
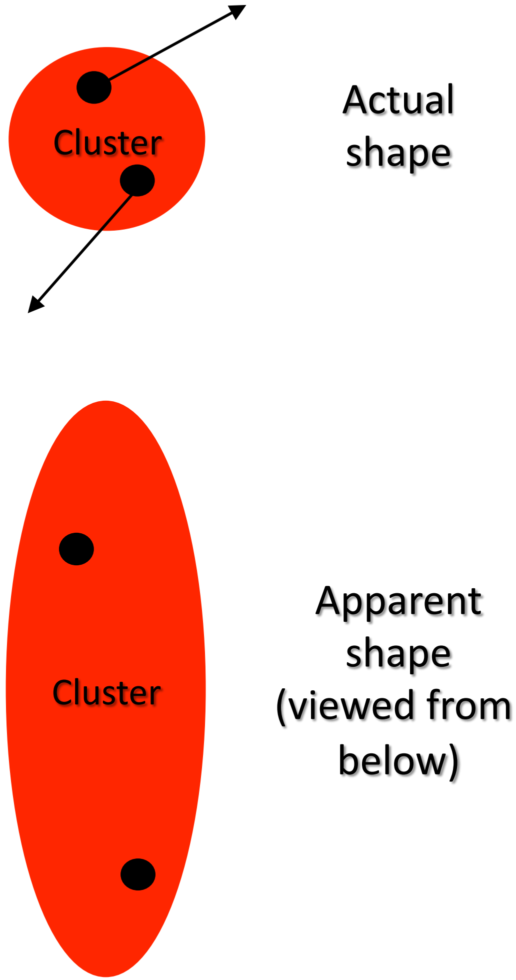


Image of SDSS, from U. Chicago

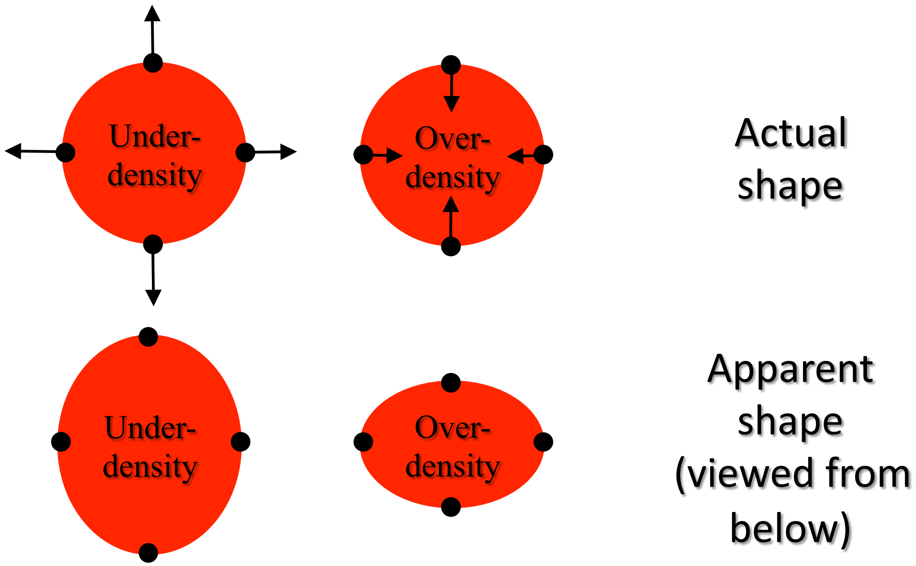
Redshift-Space Distortions



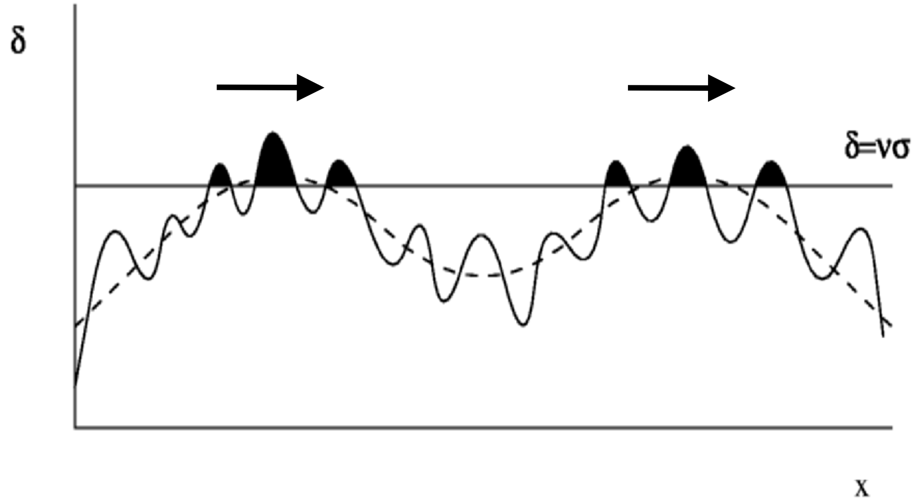


Galaxies act as test particles

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



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

Percival & Schafer, 2008, MNRAS 385, L78

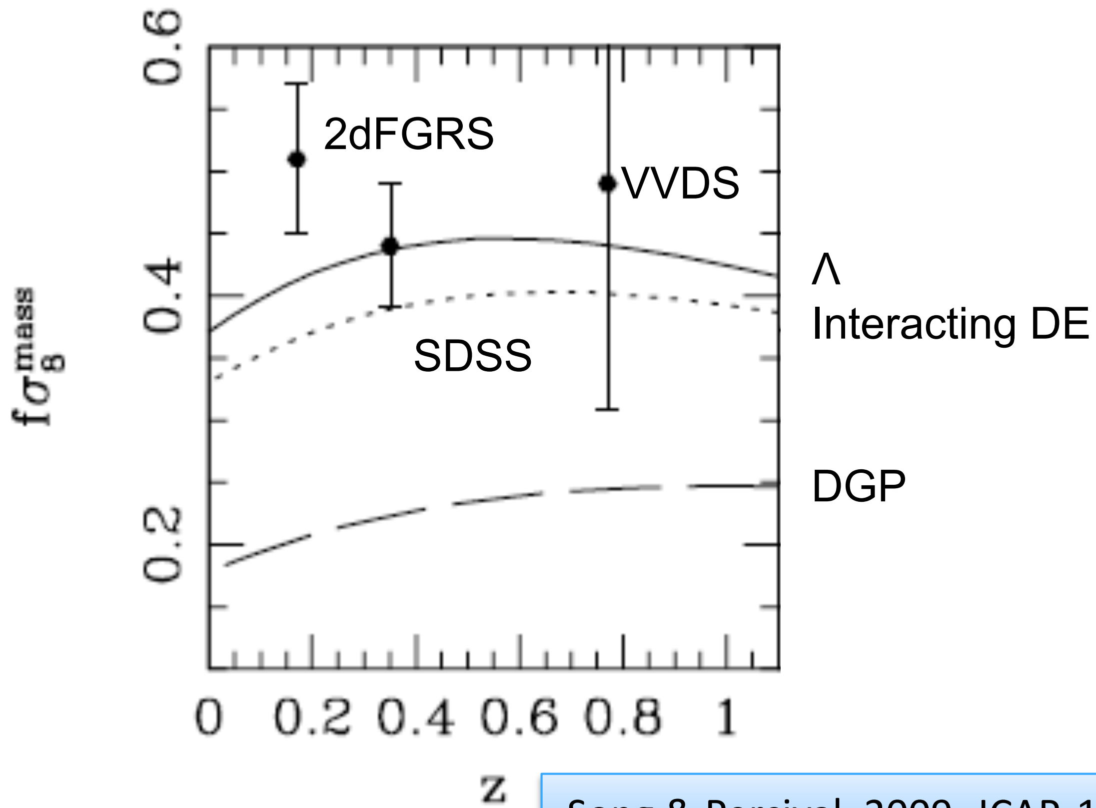
Measurements provide good test of models

Assuming small velocity bias, RSD constrain $f\sigma_8$, the amplitude of the **velocity** power spectrum

$$\begin{aligned} \delta_{\rm gal}(k,\mu) &= b\delta_{\rm mass} + \mu^2 b_v f \delta_{\rm mass} \\ P_{\rm gal}(k,\mu) &= P_{\rm mass}(b^2 + 2\mu^2 b b_v f + \mu^4 b_v^2 f^2) \end{aligned}$$

$$f \equiv \frac{d\log D}{d\log a}$$

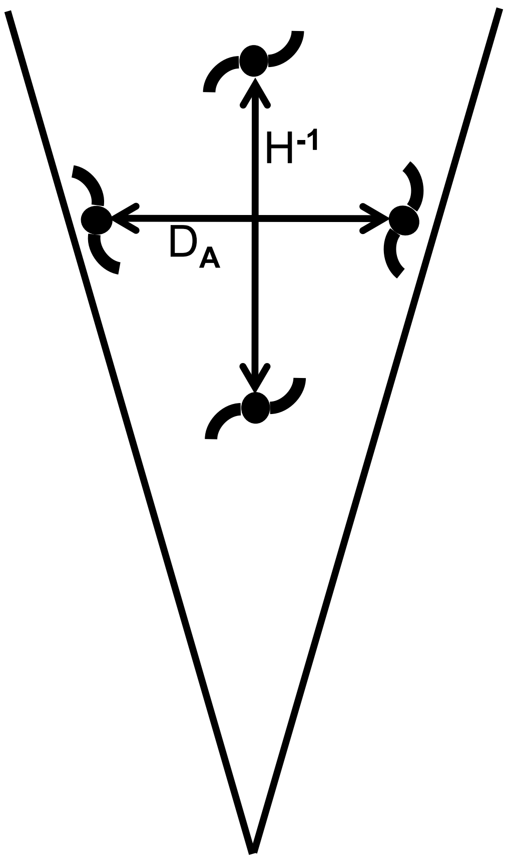
$$f\sigma_8 \propto \frac{dD}{d\log a}$$

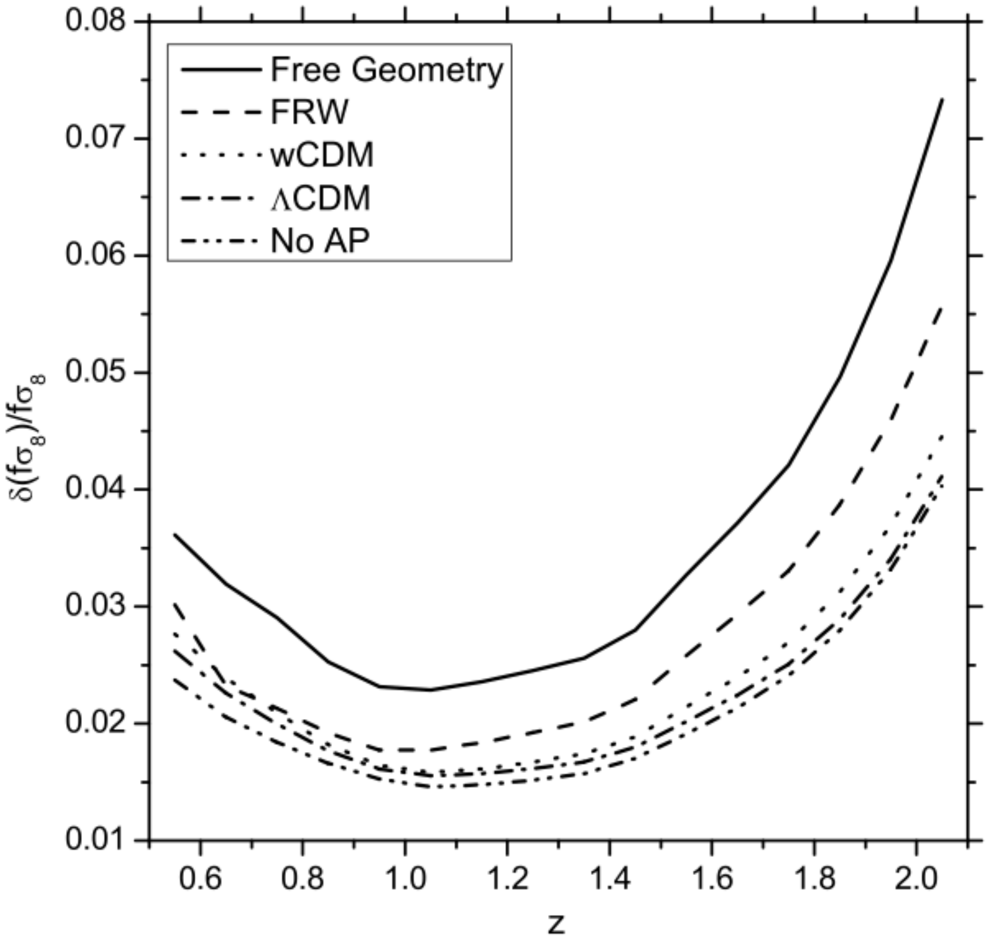


Song & Percival, 2009: JCAP, 10, 4

Degeneracies – RSD vs Alcock-Palczynski

RSD distortion resembles distortion obtained by applying wrong distance-redshift relation through $D_A H$ (Alcock-Palczynski effect)





Samushia et al 2010, arXiv:1006.0609

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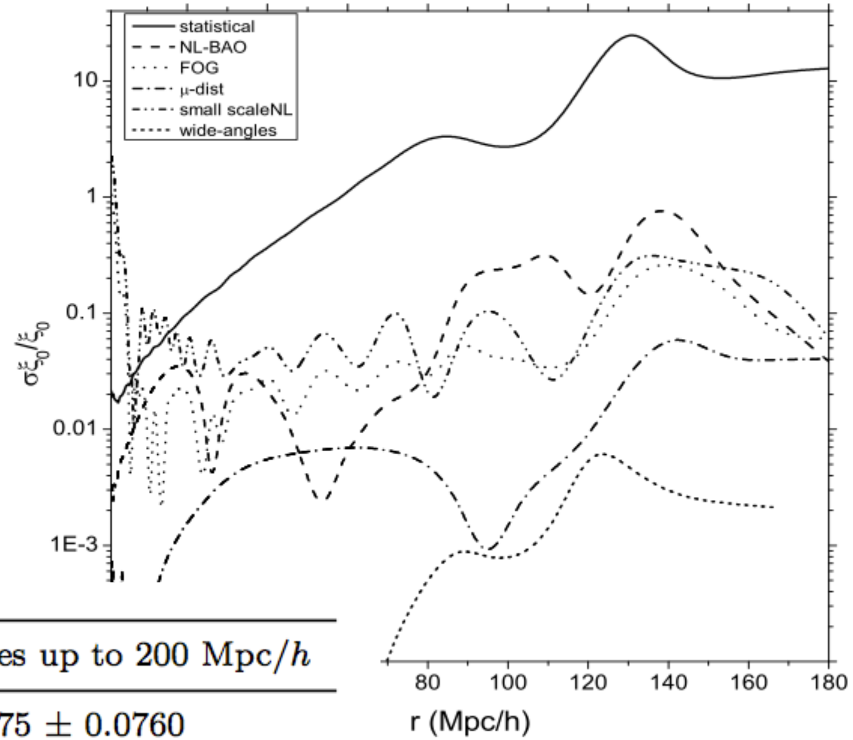
Modeling Redshift-Space Distortions

- Direct estimator for velocity power spectrum
  - Constructed from Legendre moments of anisotropic power
  - shown to work against numerical simulations
  - Percival, White, 2009, MNRAS, 393, 297
- Simulating correct survey geometry
  - Geometry is actually a different triangle for each pair of galaxies
  - Isolated extra effects in simulations and tested models for the first time
  - Raccanelli, Samushai & Percival 2010, arXiv:1006:1652
- Redshift-Space Distortions for projected clustering
  - Angles do not change, but selection function does
  - Can be mitigated by sample selection using pair-centre binning
  - Nock, Percival & Ross 2010, arXiv:1003.0896

Undertaking a robust analysis

- Consider:
  - Wide-angle effects
  - Non-linear growth of structure
  - Fingers-of-God
  - Non-Gaussian Likelihood

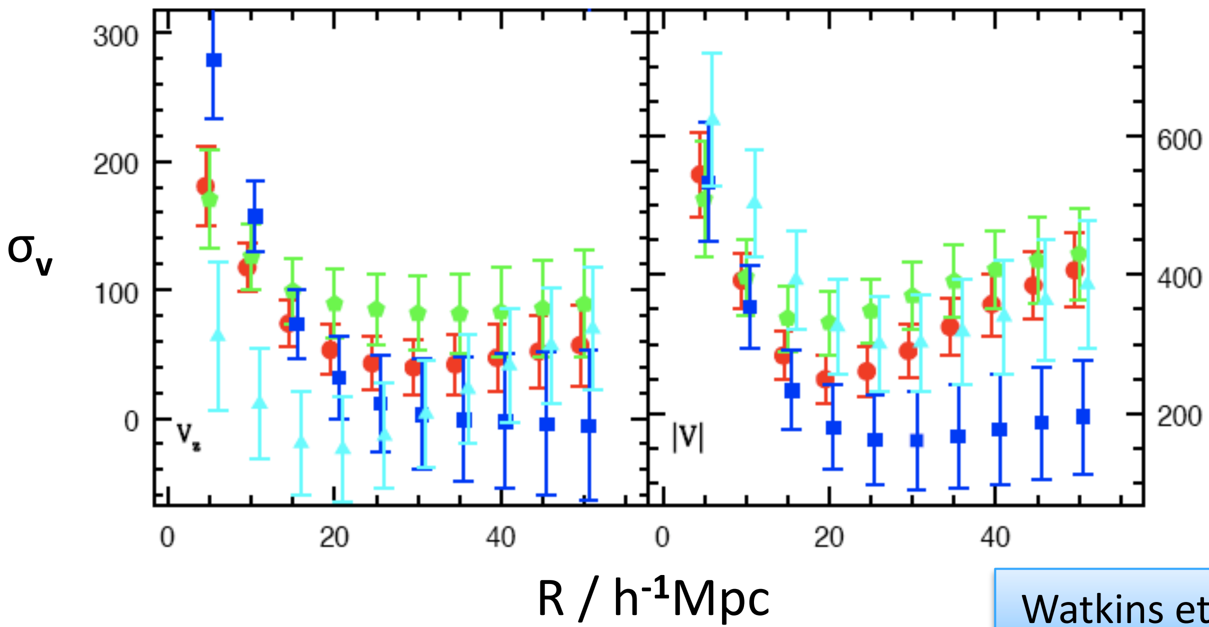


Model	Variable	Scales less than 60 Mpc/h	Scales up to 200 Mpc/h
wCDM	$b(z_1)\sigma_8(z_1)$	1.4949 ± 0.0772	1.5175 ± 0.0760
	$b(z_2)\sigma_8(z_2)$	1.5316 ± 0.0717	1.57435 ± 0.0672
γ	$b(z_1)\sigma_8(z_1)$	1.5462 ± 0.0911	1.6098 ± 0.0840
	$b(z_2)\sigma_8(z_2)$	1.5522 ± 0.0916	1.5882 ± 0.0727
	γ	0.6545 ± 0.1100	0.6007 ± 0.1206
Free growth	$b(z_1)\sigma_8(z_1)$	1.4733 ± 0.0640	1.4388 ± 0.0619
	$b(z_2)\sigma_8(z_2)$	1.4557 ± 0.0496	1.5038 ± 0.0436
	$f(z_1)\sigma_8(z_1)$	0.3930 ± 0.0457	0.3481 ± 0.0594
	$f(z_2)\sigma_8(z_2)$	0.4328 ± 0.0370	0.4522 ± 0.0418

Samushia et al 2011, in prep

Comparison with bulk velocity results

- Some recent measurements of nearby bulk velocities claim discordance with ΛCDM
- RSD and bulk flow observations try to measure the same thing
  - The amplitude of the linear velocity power spectrum
  - σ_v, $f\sigma_8$ are both ways of normalizing the fluctuations
- Measurements are made on fundamentally different scales

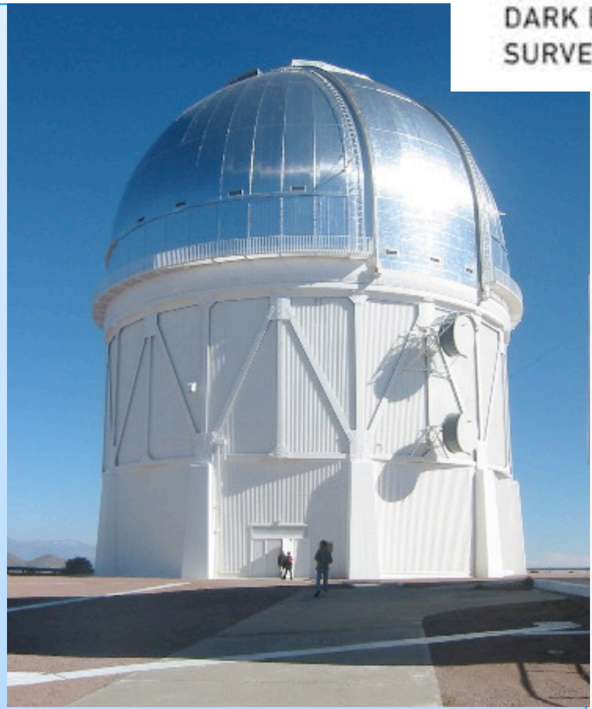


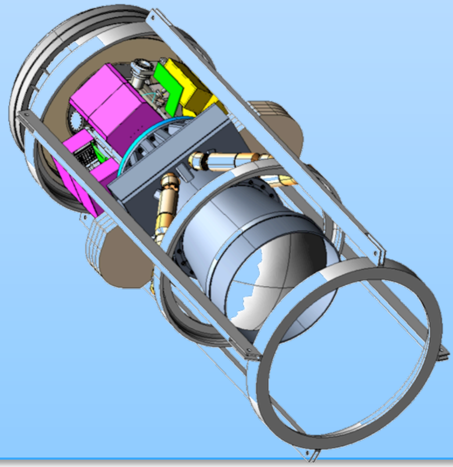
Watkins et al. 2008; arXiv:0809.4041

Future surveys

Dark Energy Survey (DES)

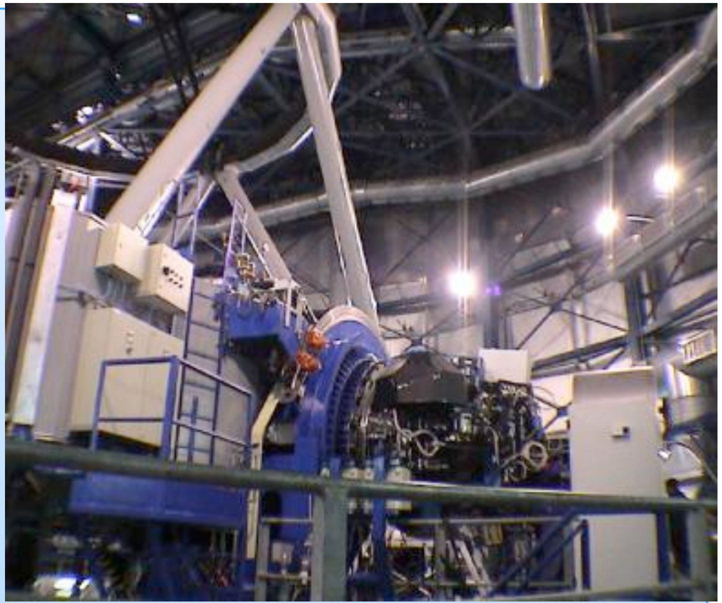
- New wide-field camera for the 4m Blanco telescope
- Currently being moved from Fermilab to site,
  Survey due to start autumn 2011
- Ω = 5,000deg2
- multi-colour optical imaging (g,r,i,z) with link to IR data from VISTA hemisphere survey
- 300,000,000 galaxies
- Aim is to constrain dark energy using 4 probes
  LSS/BAO, weak lensing, supernovae
  cluster number density
- Redshifts based on photometry
  weak radial measurements
  weak redshift-space distortions
- See also: Pan-STARRS, VST-VISTA, SkyMapper

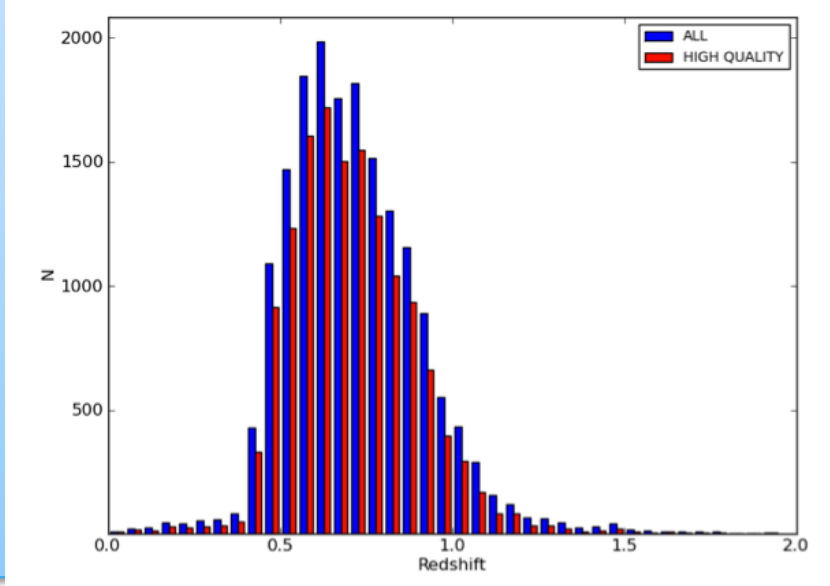




VIMOS Public Extragalactic Redshift Survey (VIPERS)

- Uses upgraded VIMOS on VLT
- $\Omega = 24\text{deg}^2$
- 100,000 galaxies
- emission line galaxies: $0.5<z<1.0$
- insufficient volume for BAO measurement
- Unique redshift-space distortion science
- 18,500 redshifts from pre-upgrade data
- expect ~10,000 redshifts this season
- see also: FMOS surveys





Baryon Oscillation Spectroscopic Survey (BOSS)

- New fibre-fed spectroscope now on the 2.5m SDSS telescope
- $\Omega = 10{,}000\text{deg}^2$
- 1,500,000 galaxies
- 150,000 quasars
- LRGs : z ~ 0.1 – 0.7 (direct BAO)
- QSOs : z ~ 2.1 – 3.0 (BAO from Ly-α forest)

  $0.1<z<0.3$: 1% d_A, 1.8% H

  $0.4<z<0.7$: 1% d_A, 1.8% H

  $z \sim 2.5$: 1.5% d_A, 1.2% H
- 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: part of SDSS-III
- Sufficient funding is in place and project is 1 year into 5 year duration
- All imaging data now public (DR8 12/01/11)
- See also: WiggleZ

BigBOSS

- New fibre-fed spectroscope proposed for 4m Mayall telescope
- NOAO endorsement following proposal evaluation
- Ω = 14,000deg^2 – 25,000deg^2
- 20,000,000 galaxies (direct BAO)
- 600,000 quasars (BAO from Ly-α forest)
- LRGs : z ~ 0.1 – 1.0
- ELGs: z~0.5-1.7
- QSOs : 40/deg^2, z ~ 2.1 – 3.0

  z<0.5: 0.9% d_A, 1.5% H

  0.5<z<1: 0.4% d_A, 0.6% H

  z>1: 0.6% d_A, 0.8% H
- Cosmic variance limited to z ~ 1.4
- See also: DESpec, WEAVE, other instruments on 4m-class telescopes?

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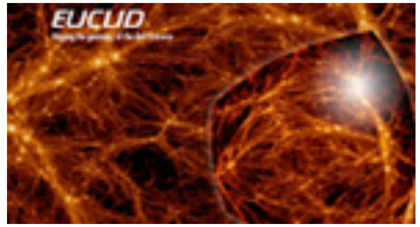
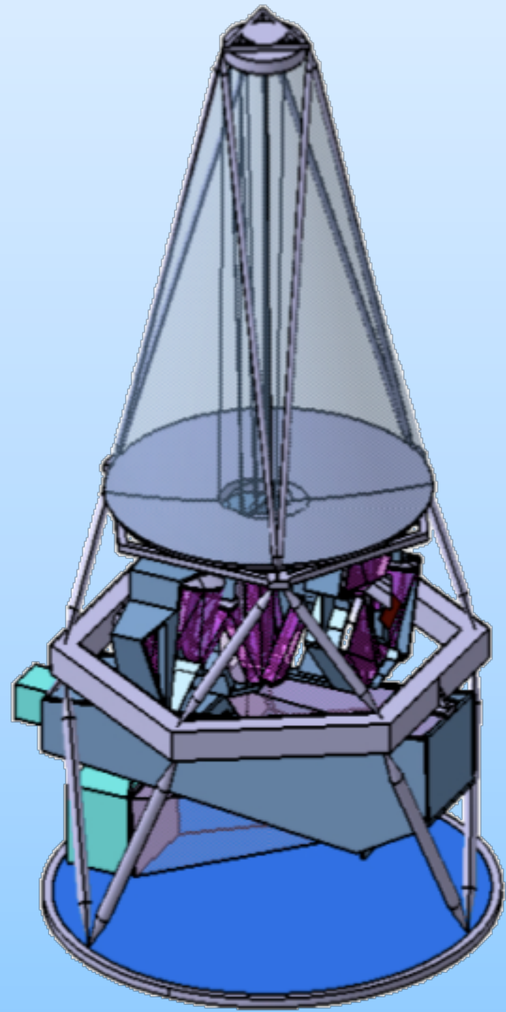


Euclid

- ESA Cosmic Vision satellite proposal (600M€, M-class mission)
- 5 year mission, L2 orbit
- 1.2m primary mirror, 0.5 sq. deg FOV
- $\Omega = 20{,}000\mathrm{deg}^2$ imaging and spectroscopy
- slitless spectroscopy:
  - 100,000,000 galaxies (direct BAO)
  - ELGs (H-alpha emitters): z~0.5-2.1
- imaging:
  - deep broad-band optical + 3 NIR images
  - 2,900,000,000 galaxies (for WL analysis)
  - photometric redshifts
- Space-base gives robustness to systematics
- Final down-selection due mid 2011
- nominal 2017 launch date
- See also: LSST, WFIRST



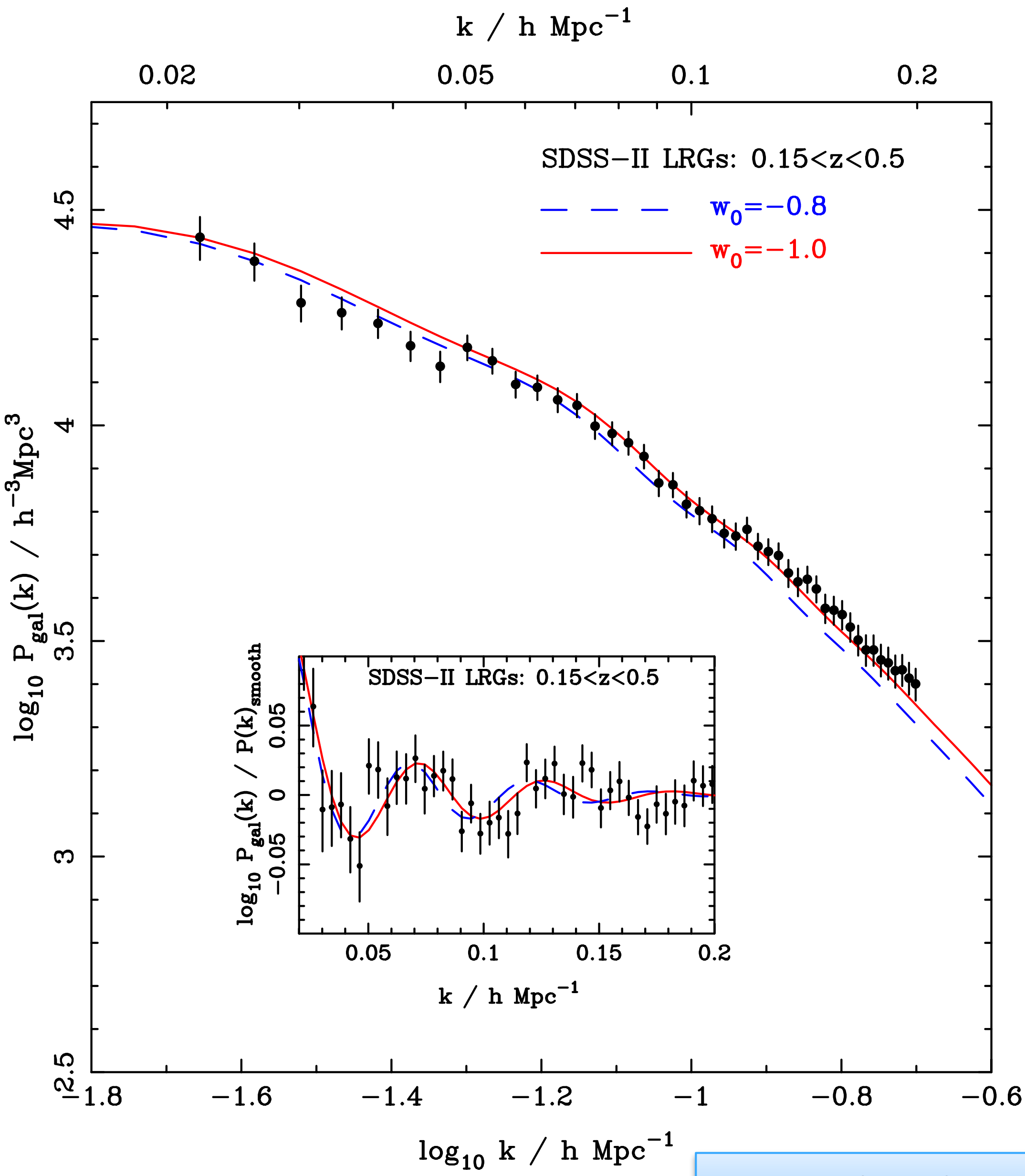
Current large-scale galaxy clustering measurements

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

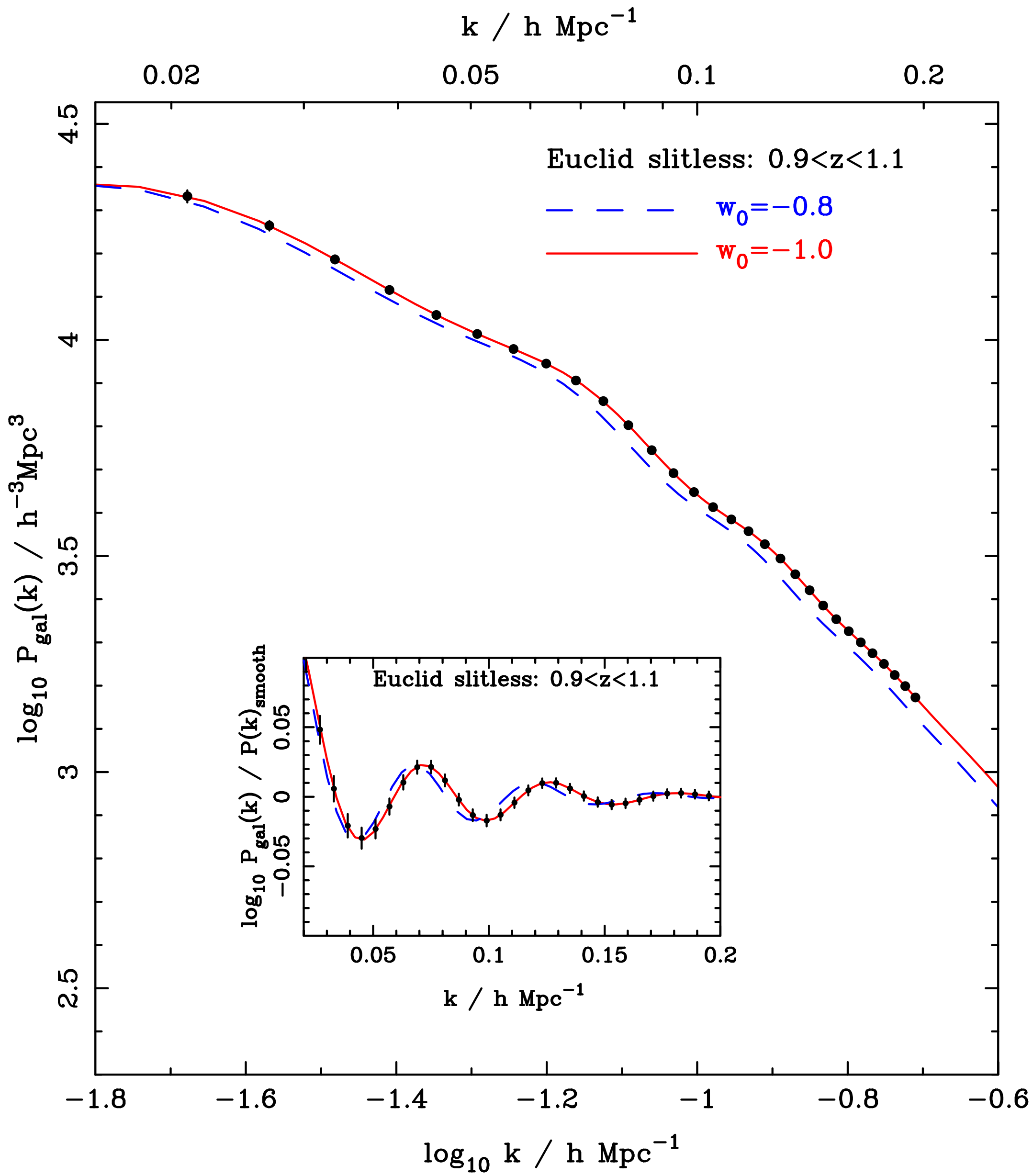


Percival et al. 2009; arXiv:0907.1660

Predicted galaxy clustering measurements by Euclid

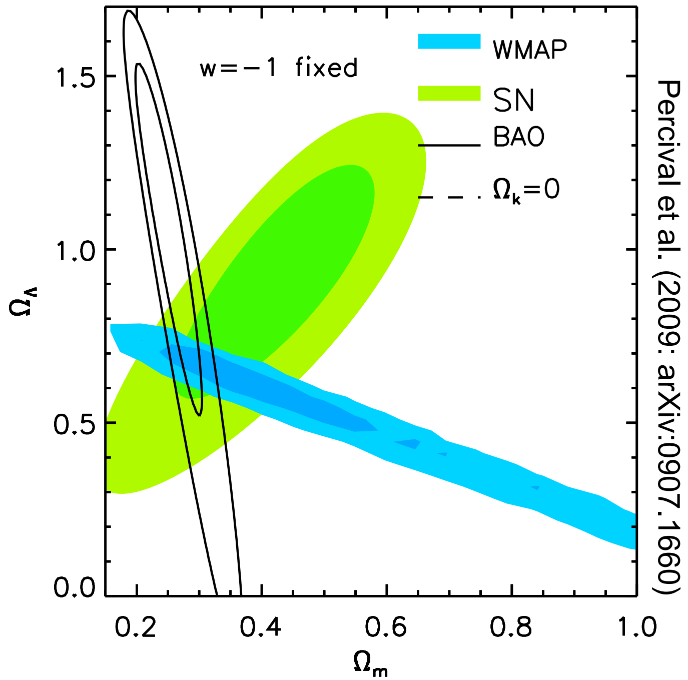
20% of the Euclid data, assuming the slitless baseline at z~1

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

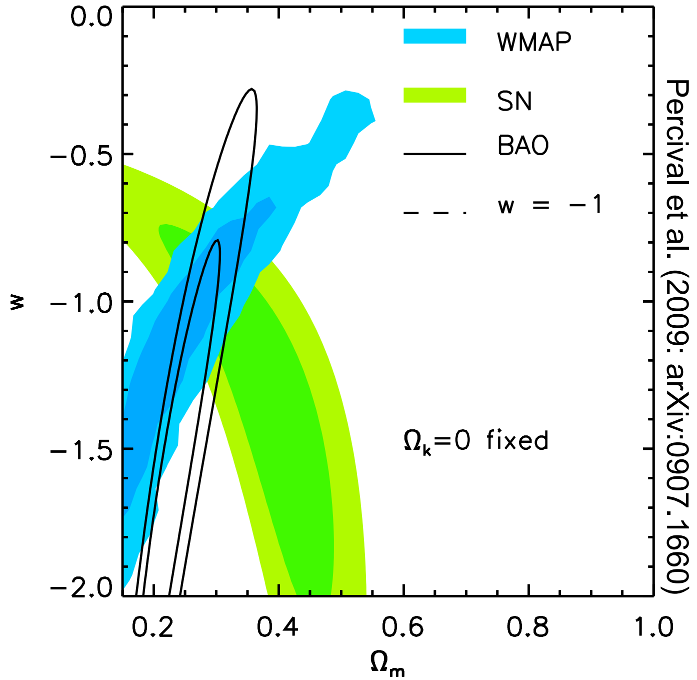


Current BAO constraints vs other data

ΛCDM models with curvature



flat wCDM models



Union supernovae

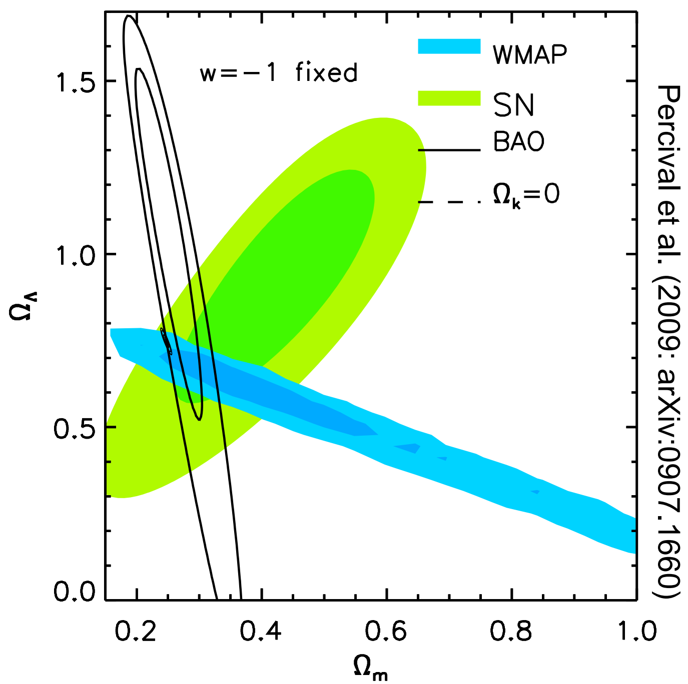
WMAP 5year

SDSS-II BAO Constraint on $r_s(z_d)/D_V(0.2)$ & $r_s(z_d)/D_V(0.35)$

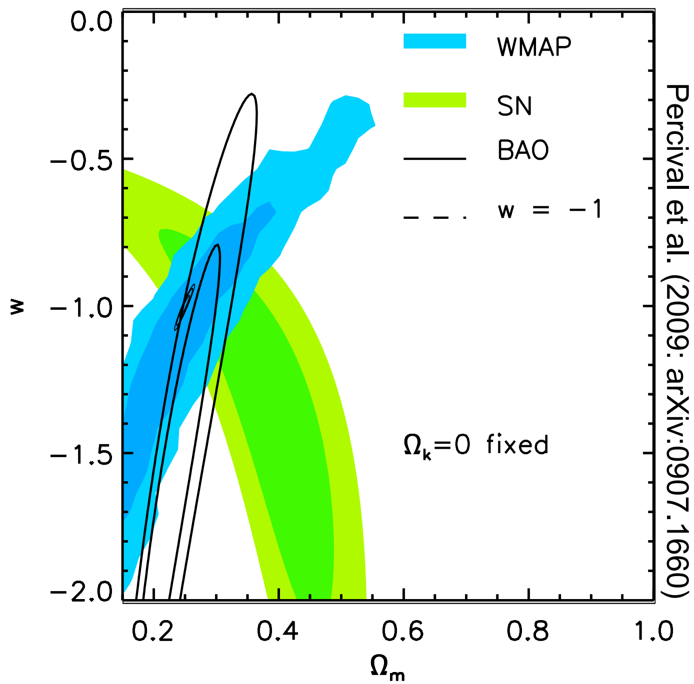
Percival et al. 2009; arXiv:0907.1660

How does Euclid BAO compare?

ΛCDM models with curvature



flat wCDM models



Union supernovae

WMAP 5year

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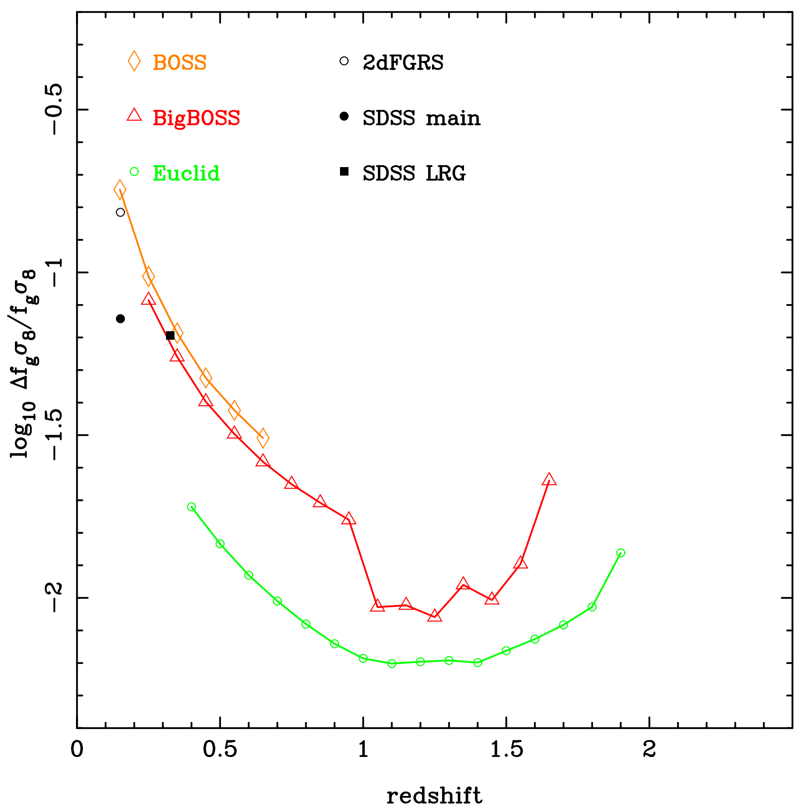
Expected errors: RSD

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) in an optimal way

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

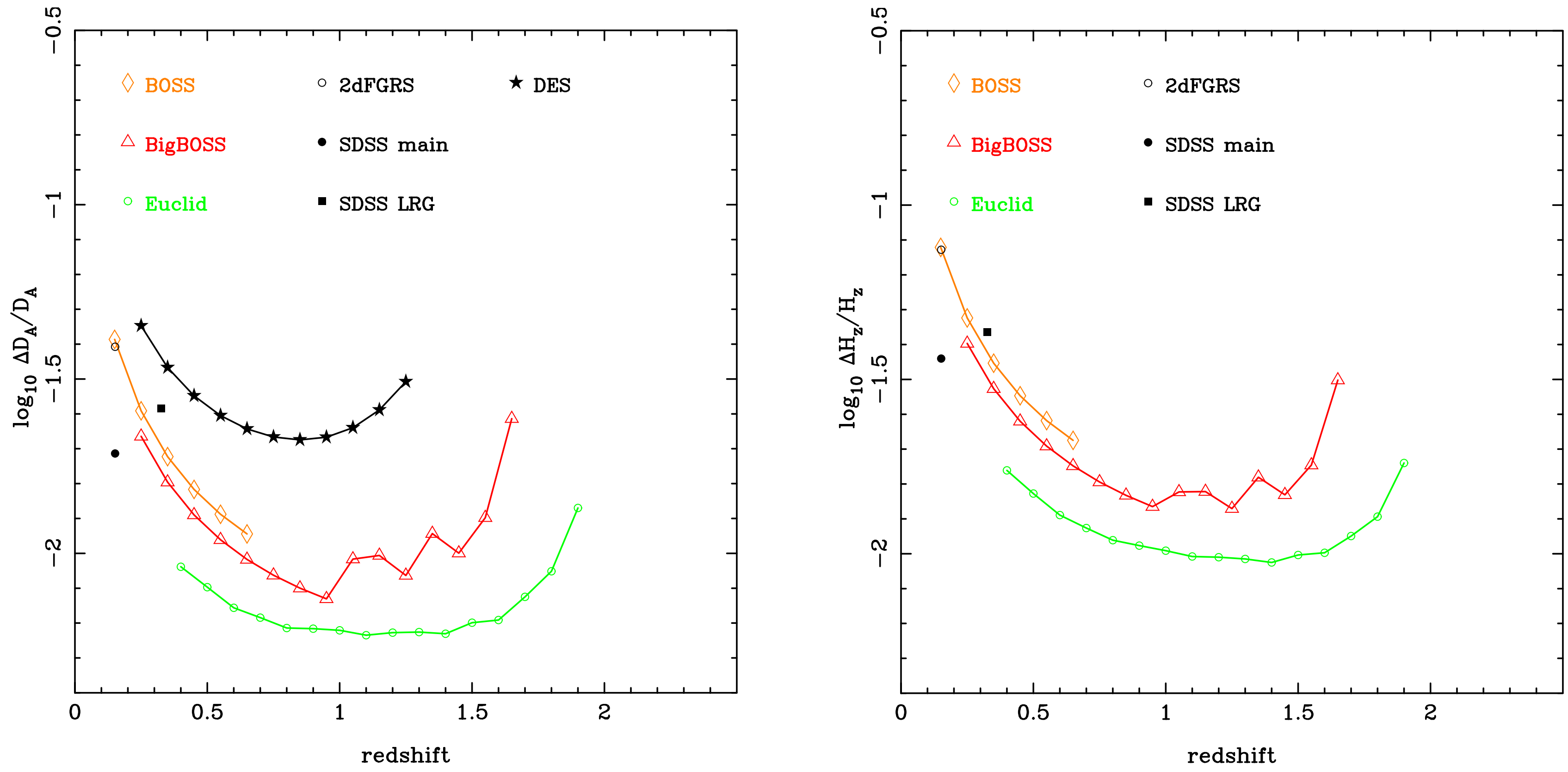
Code to estimate errors on $f\sigma_8$ is available from:

http://mwhite.berkeley.edu/Redshift



White, Song & Percival, 2008, MNRAS, 397, 1348

Expected errors: BAO



Code to estimate these errors from BAO observations is available from:

http://cmb.as.arizona.edu/~eisenste/acousticpeak/bao_forecast.html

Seo & Eisenstein 2007: ApJ, 665, 14

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Summary

- Galaxy clustering will help to answer remaining questions for astrophysical and cosmological models
- Shape of the power spectrum
  - measures galaxy properties (e.g. faint red galaxies)
  - neutrino masses (current systematic limit)
  - models of inflation
- Baryon acoustic oscillations
  - sets geometrical constraints on evolution
- Redshift-space distortions
  - avoids density bias – galaxies act as test particles
  - structure formation test so complementary to geometrical tests
  - similar to weak lensing but tests only temporal metric fluctuations
- Future surveys
  - next generation underway giving an order of magnitude better constraints
  - many different avenues being explored for future projects
  - exciting developments over the next 10—20 years

Summary: Cosmological Physics from 2-pt statistics

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

Primordial power spectrum
- Matter density
- Baryon density
- Neutrino mass
- Inflation fluctuation spectrum
- f_{NL}

$$P_{\rm gal}(k,\mu,a) = k^n T^2(k) D^2(a)[b(a) + f(a)\mu^2]^2$$

k = comoving wavenumber
μ = cos(angle to line-of-sight)
a = cosmological scale factor
b = galaxy bias factor
D = linear growth rate
f = dlnD/dlna

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