Answering Cosmological Questions with Galaxy Surveys

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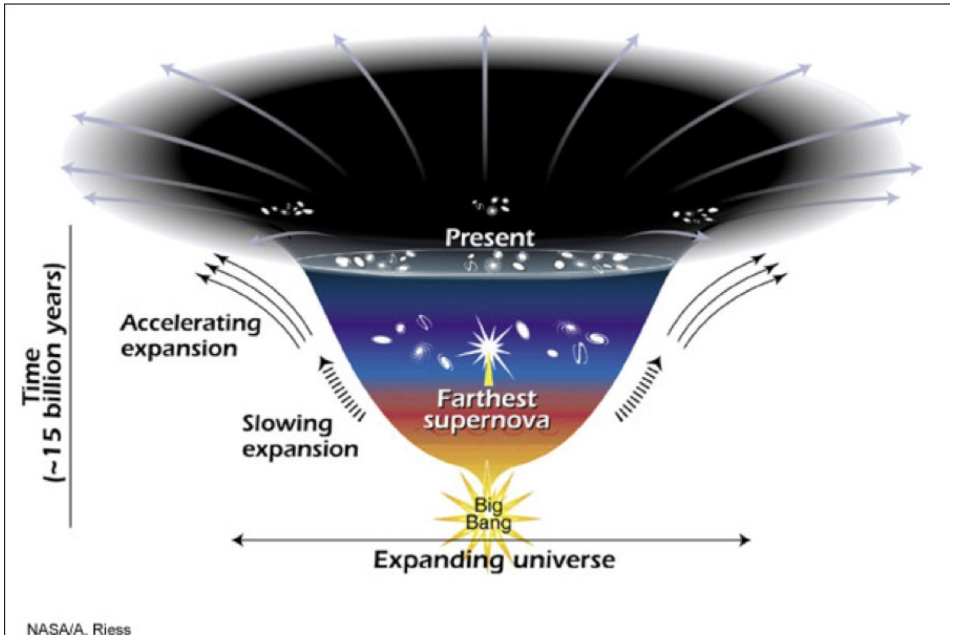
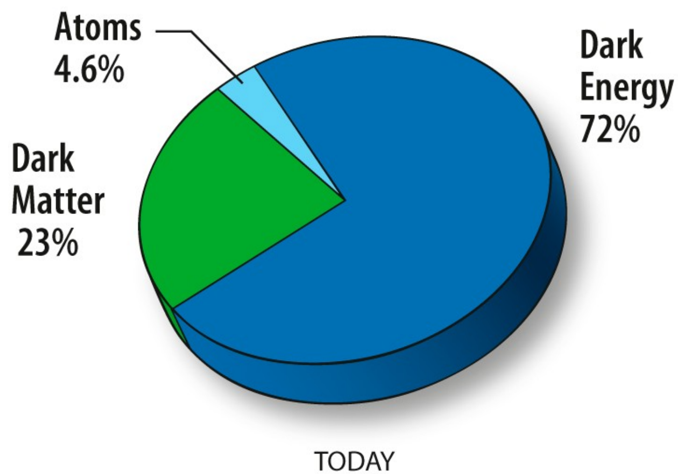
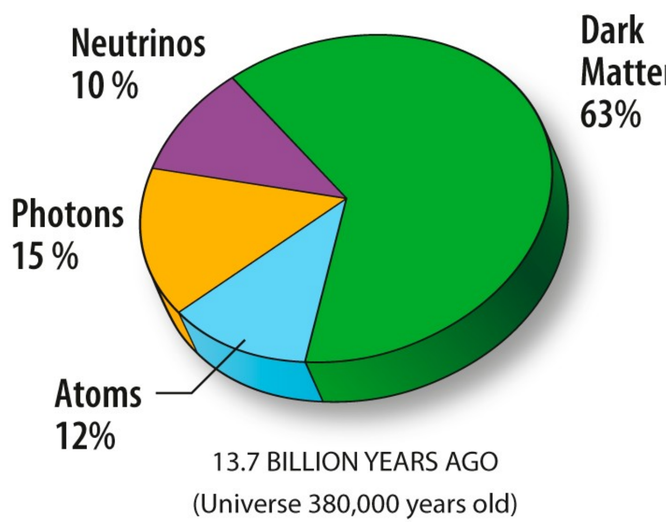
The standard "model" for cosmology based on energy







$$\frac{H^2}{H_0^2} = \Omega_R a^{-4} + \Omega_M a^{-3} + \Omega_k a^{-2} + \Omega_\Lambda$$

An alternative model based on gravity

- Can acceleration be driven by GR modifications rather than a new component of stress-energy?
- Changes to the laws of gravitation affect the relationship between the geometry (metric) and density (matter) fields
- assume scalar degrees of freedom in the gravitational field
- two physically relevant scalar functions (or potentials)

$$ds^2 = a^2 \left[-(1+2\psi)d\tau^2 + (1-2\phi)d\bar{x}^2\right]$$

  – conformal Newtonian gauge
  – time-time (time-like) metric potential Ψ
  – space-space (space-like) metric potential Φ
  – scale factor a
  – conformal time τ
  – spatial coordinate x

Modified Gravity Models

- assume dominant stress-energy component can be modeled as a non-relativistic perfect fluid
  - no pressure or anisotropic stress terms
- assume conservation of stress-energy
  - continuity equation
  - Euler equation
- left with two gravitational field equations to close the system
  - no consensus in field on how to parameterize!

$$
\begin{aligned}
-k^2 \frac{A\phi + B\psi}{A+B} &= 4\pi G \mu(k,a) \bar{\rho}_m \Delta_m \\
\phi &= \eta(k,a)\psi
\end{aligned}
$$

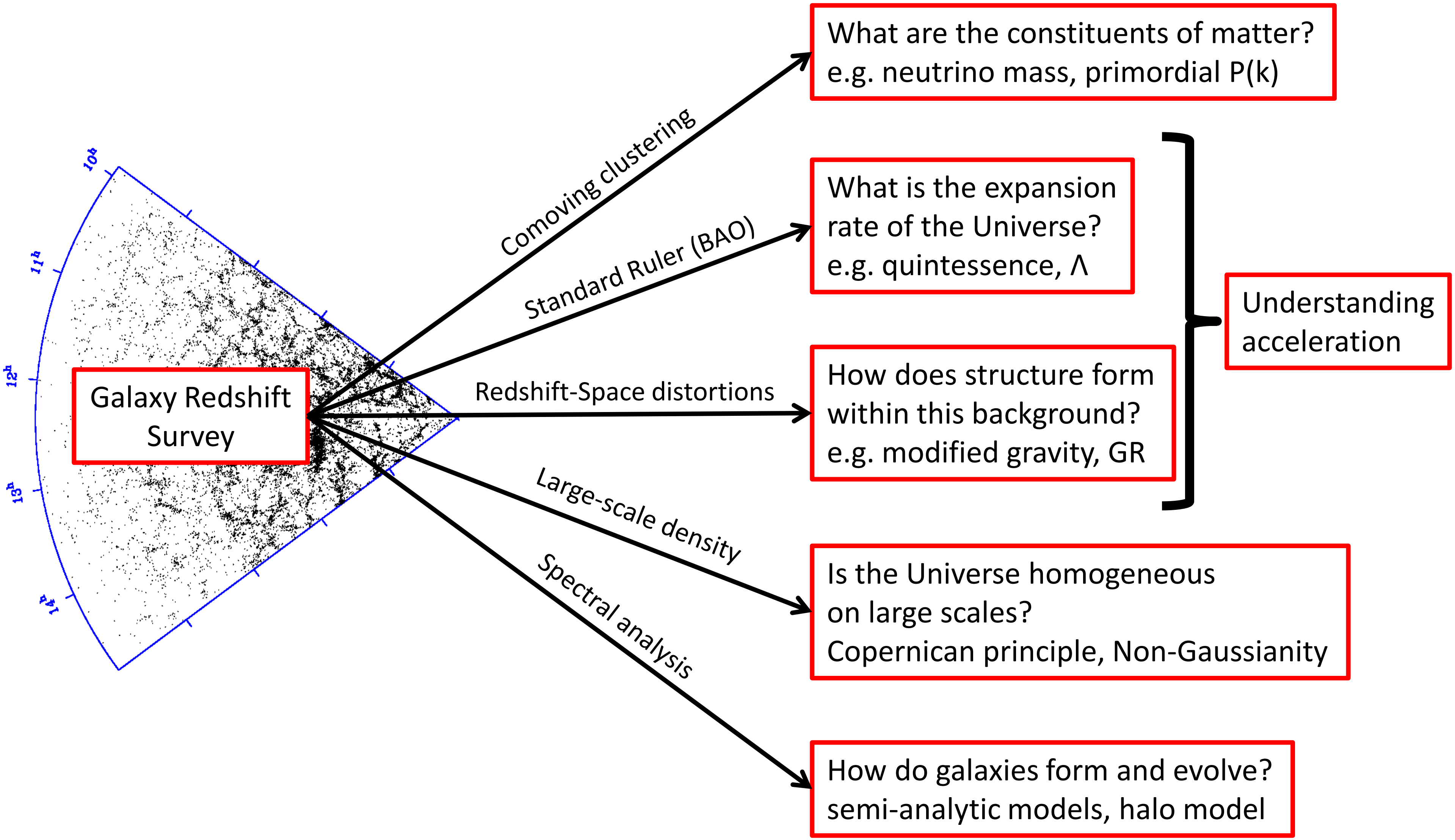
(e.g. Daniel et al. 2010; 1002.1962)

$$
\begin{aligned}
-k^2(\phi + \psi) &= 8\pi G_N a^2 \bar{\rho}_m \Delta_m \times \mathcal{G}(k,a) \\
-k^2 \psi &= 4\pi G_N a^2 \bar{\rho}_m \Delta_m \times \mathcal{V}(k,a)
\end{aligned}
$$

(e.g. Linder 2011; arXiv:1103.0282)

- need two functions: expansion and growth rates

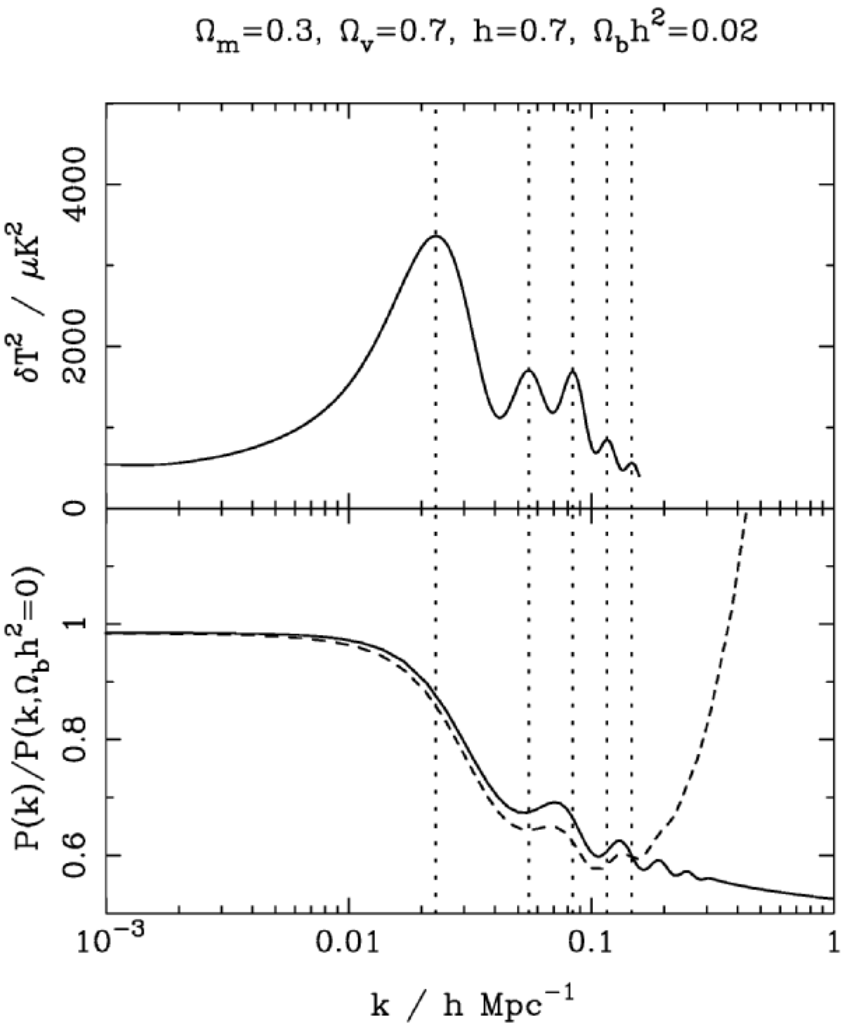
Galaxy Surveys can constrain model choices

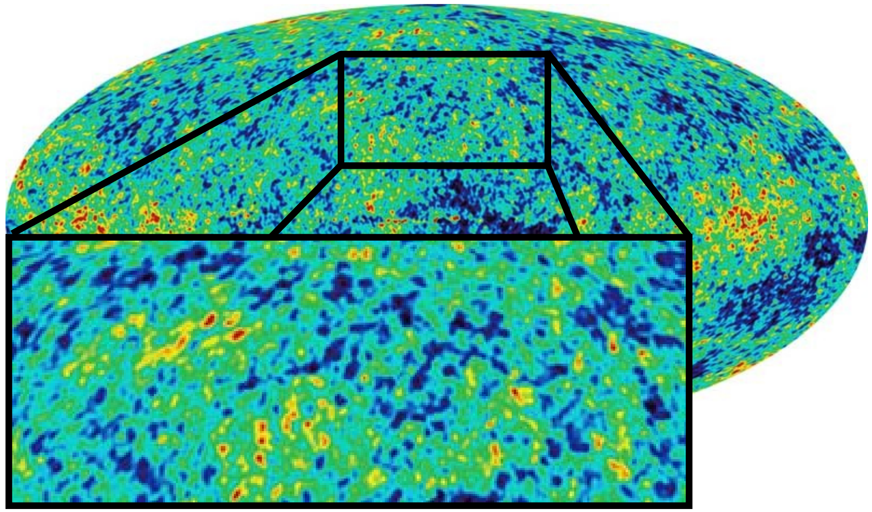


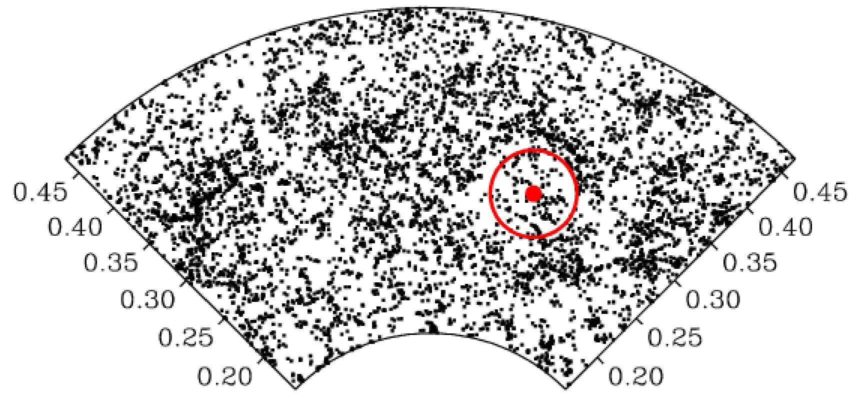
What are the constituents of matter?

Why is the Universe homogeneous on large scales?

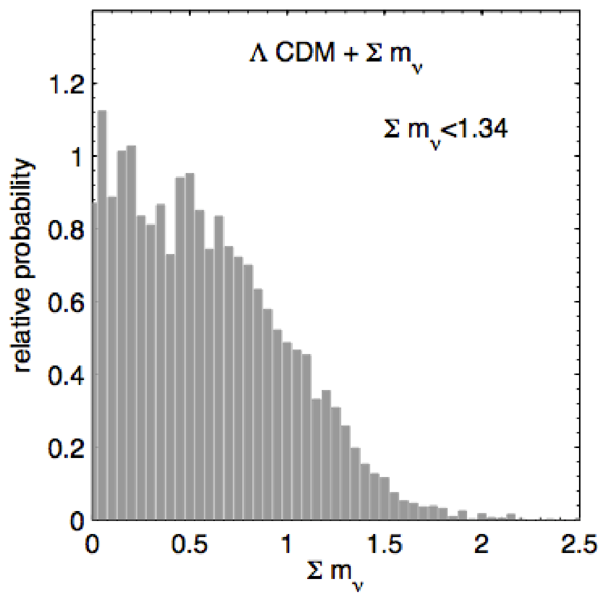
Relationship between CMB and LSS clustering



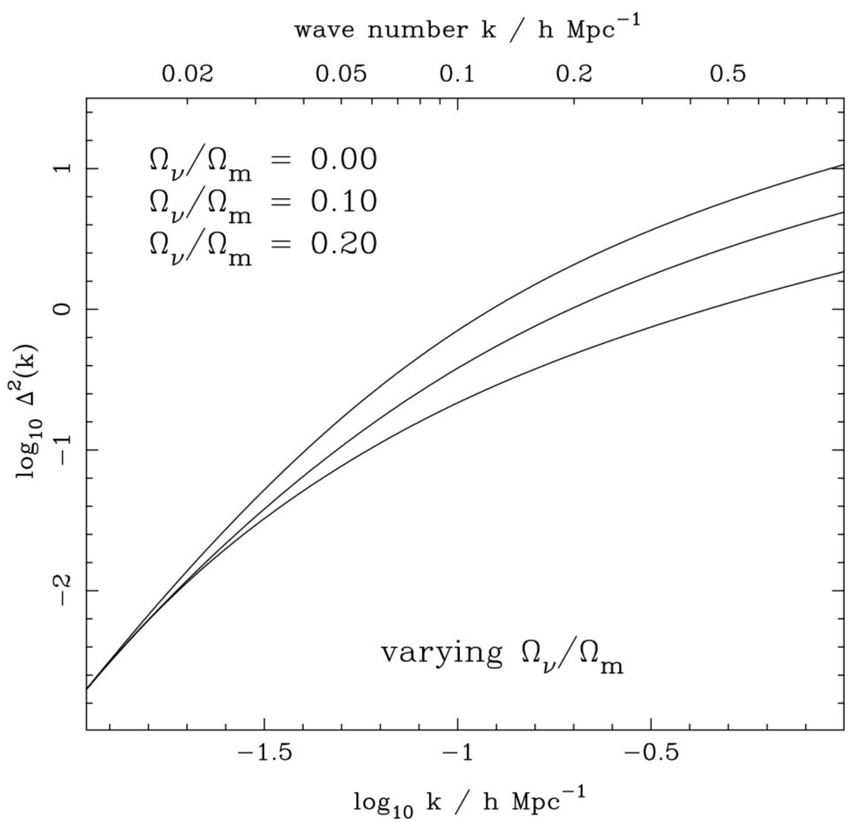




neutrino mass from comoving clustering

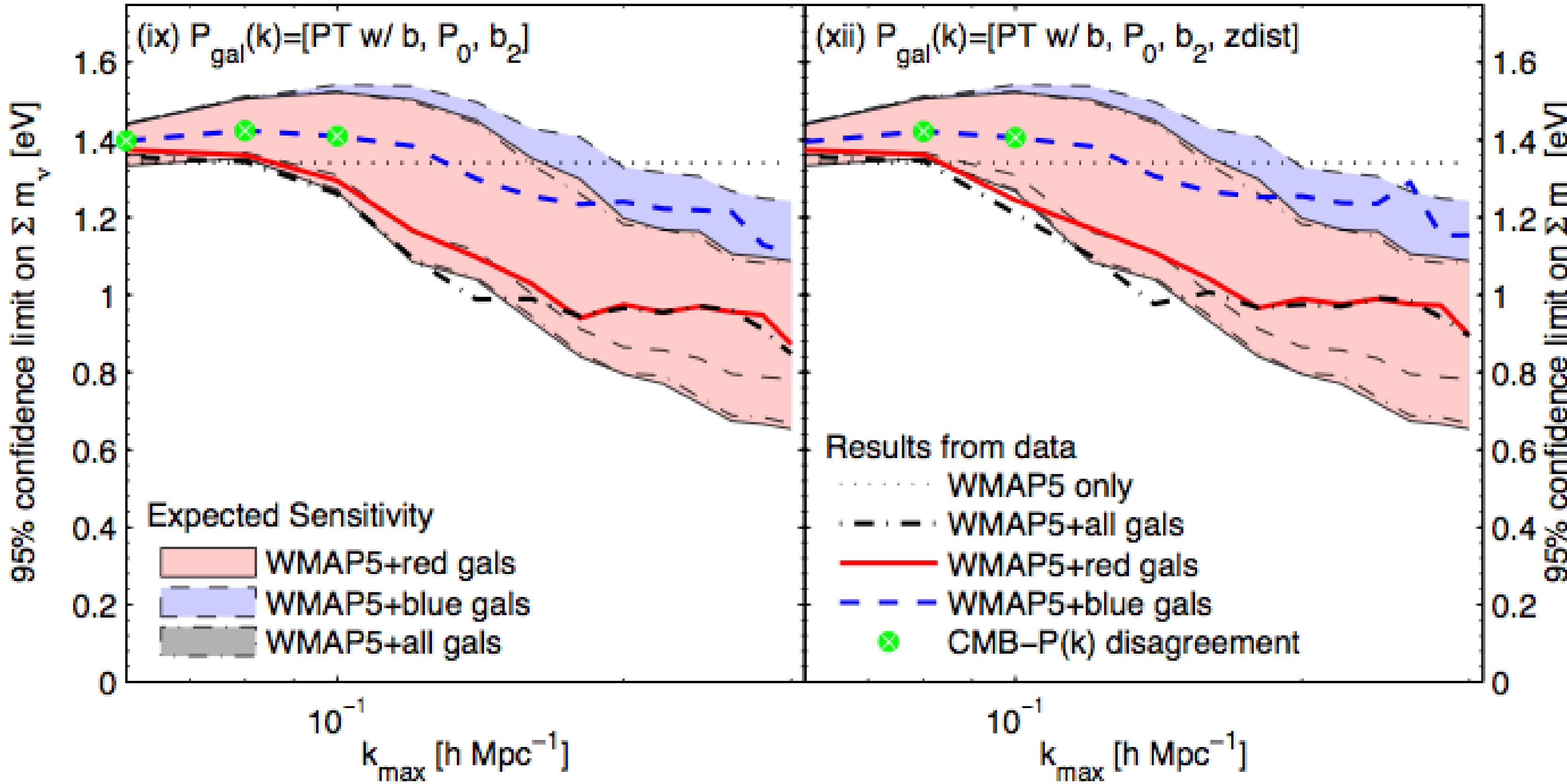


WMAP 7 year data:
Dunkley et al. (2009: ApJS,180, 306)



LSS can help through comoving shape
and breaking CMB projection degeneracies

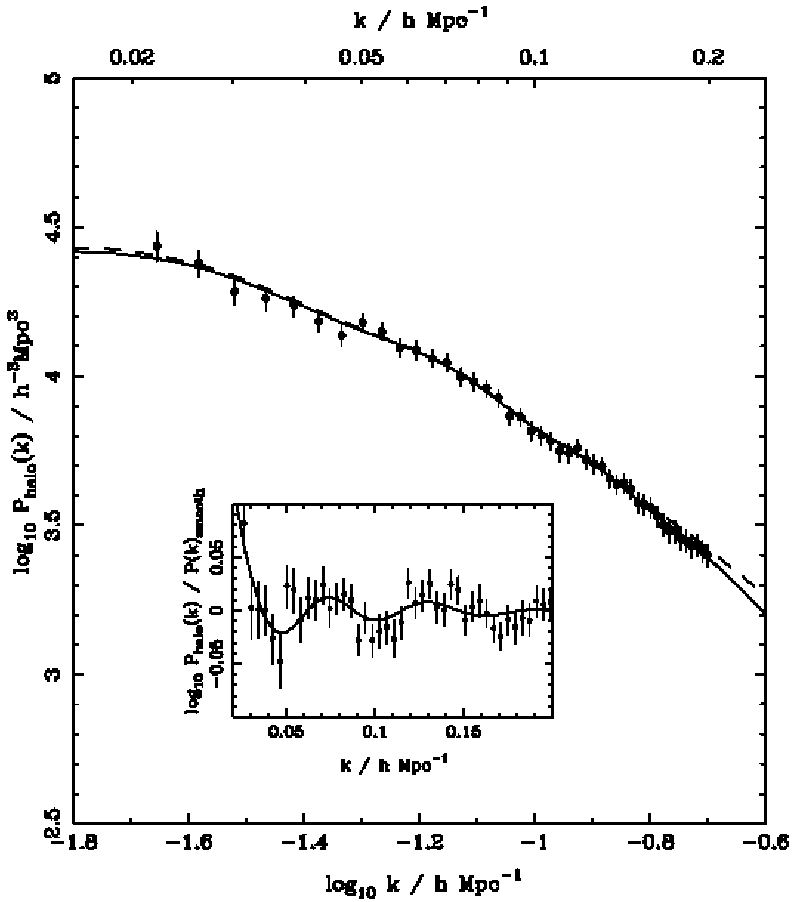
neutrino mass



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)

Full fit giving parameters of inflation



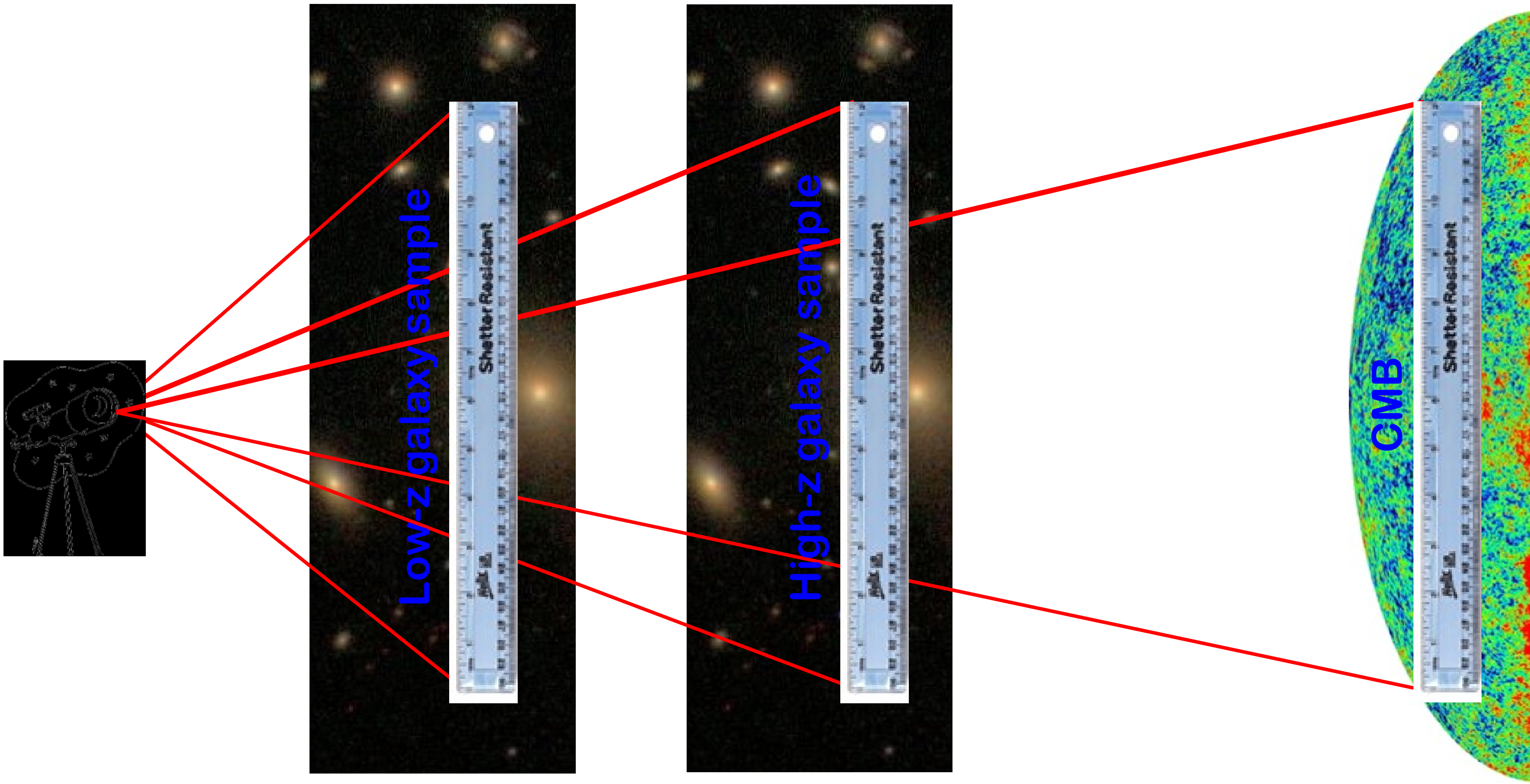
Use luminous red galaxies (LRGs) to extract the halo power spectrum and model the shape to constrain cosmological models

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)

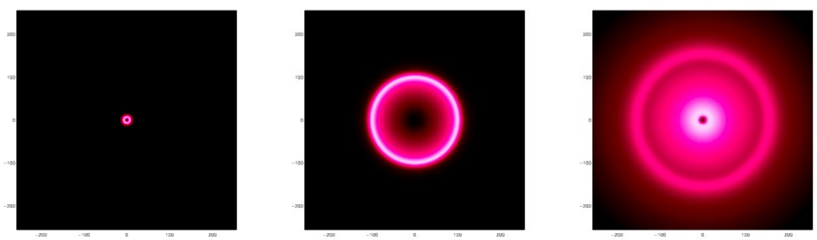
Why do we see an accelerating Universe?

Using clustering to measure geometry

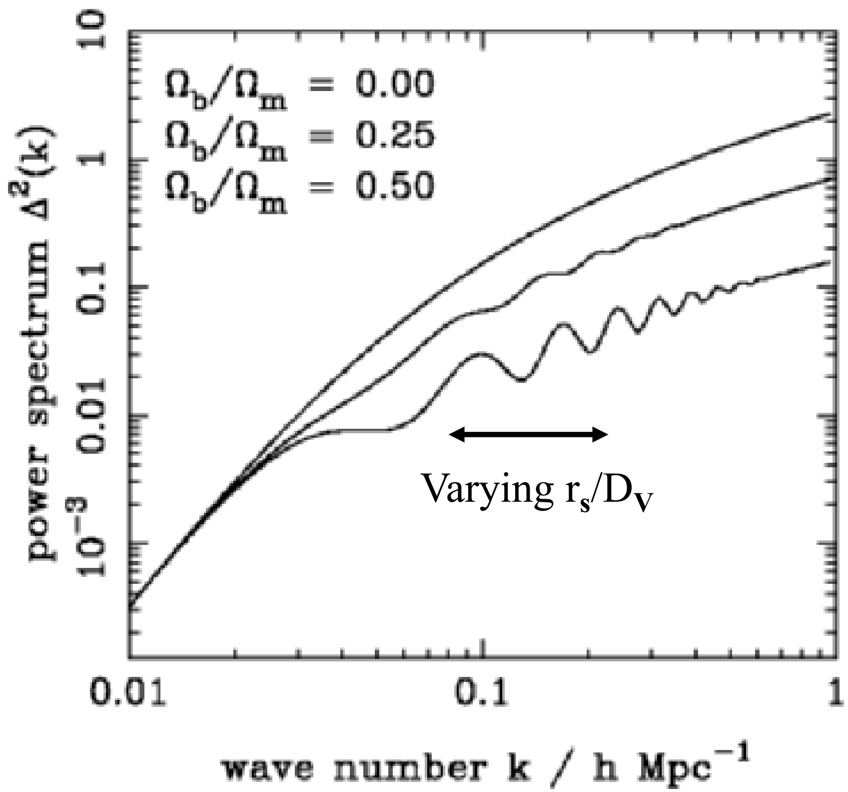


Sunyaev & Zel'dovich (1970); Peebles & Yu (1970); Doroshkevitch, Sunyaev & Zel'dovich (1978); Cooray, Hu, Huterer & Joffre (2001); Eisenstein (2003); Seo & Eisenstein (2003); Blake & Glazebrook (2003); Hu & Haiman (2003); …

Baryon Acoustic Oscillations (BAO)



(images from Martin White)



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

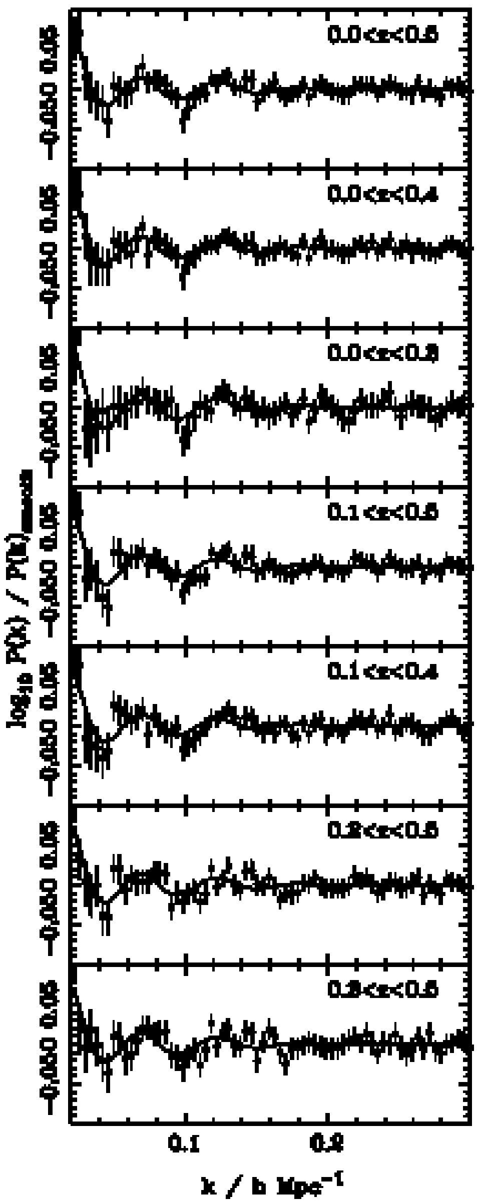
$$r_s = \frac{1}{H_0 \Omega_m^{1/2}} \int_0^{a_*} da \frac{c_s}{(a + a_{eq})^{1/2}}$$

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



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

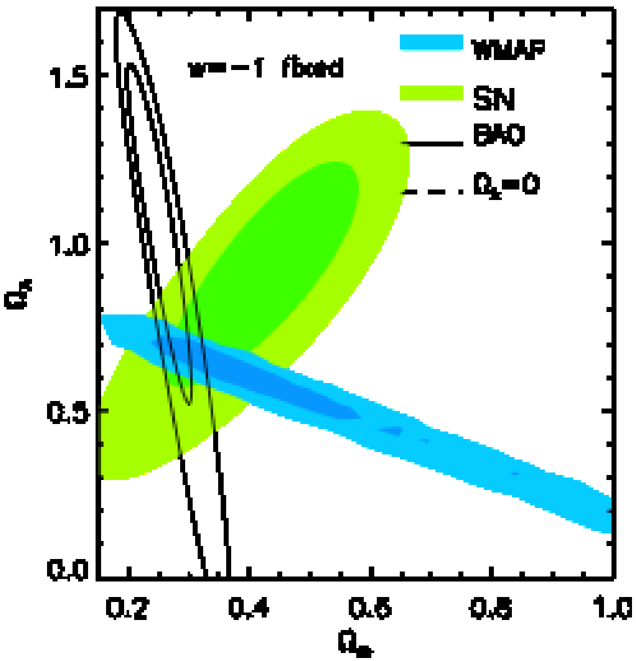
$$r_s(z_d)/D_V(0.275) = 0.1390 \pm 0.0037 \quad (2.7\%)$$
$$D_V(0.35)/D_V(0.2) = 1.736 \pm 0.065$$

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

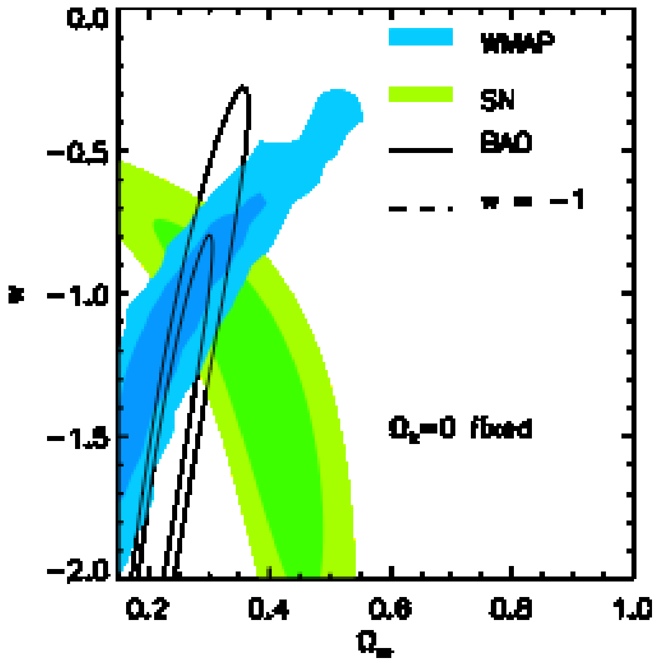
Percival, Reid, Eisenstein et al. (2009, arXiv:0907.1660)

Comparing BAO constraints vs other data

ΛCDM models with curvature



flat wCDM models



Union supernovae

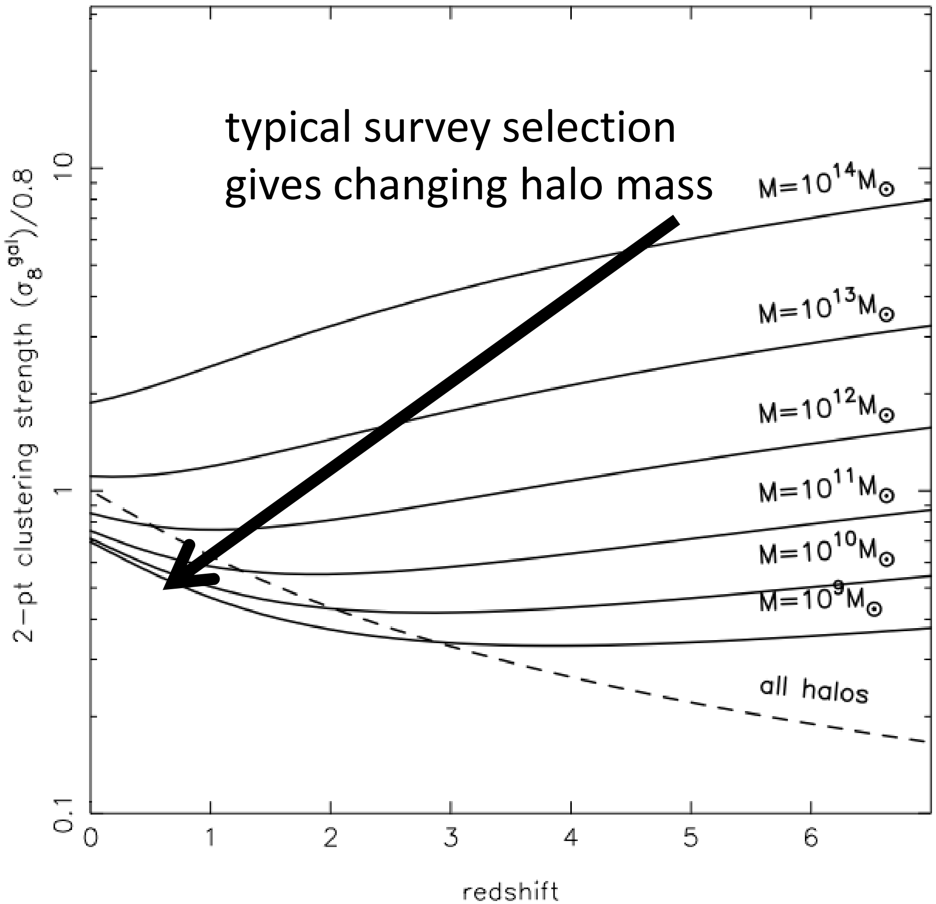
WMAP 5year

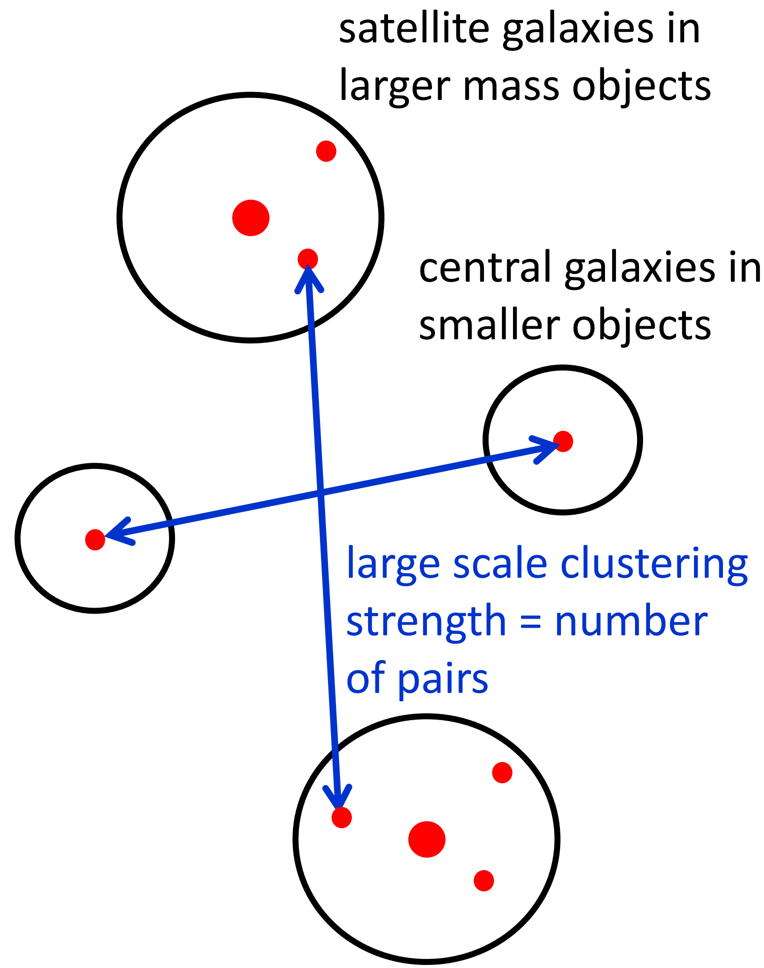
SDSS BAO Constraint on $r_s(z_d)/D_V(0.2)$ & $r_s(z_d)/D_V(0.35)$

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

How does structure form within this background?

We cannot see growth of structure directly from galaxies





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

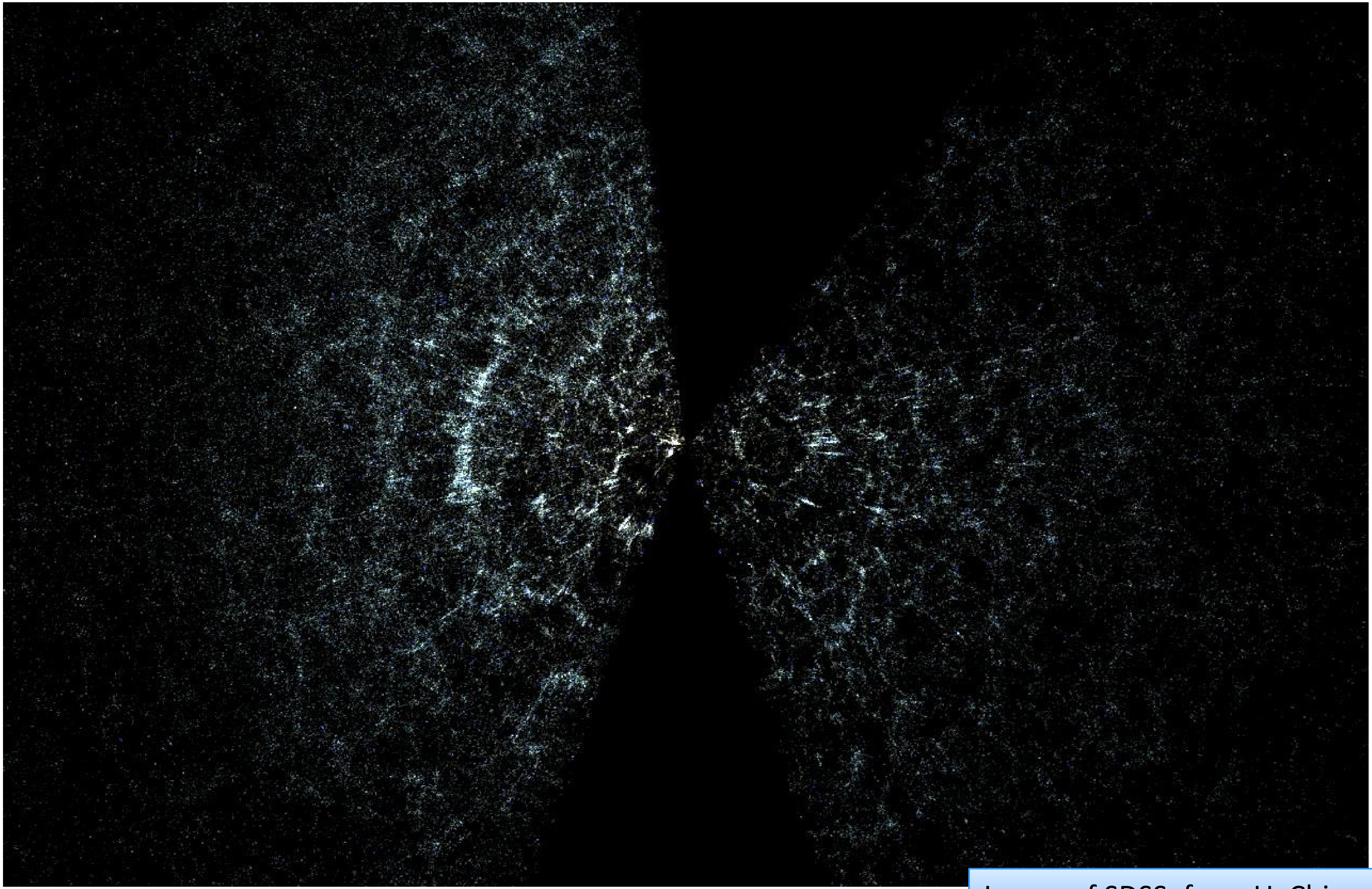
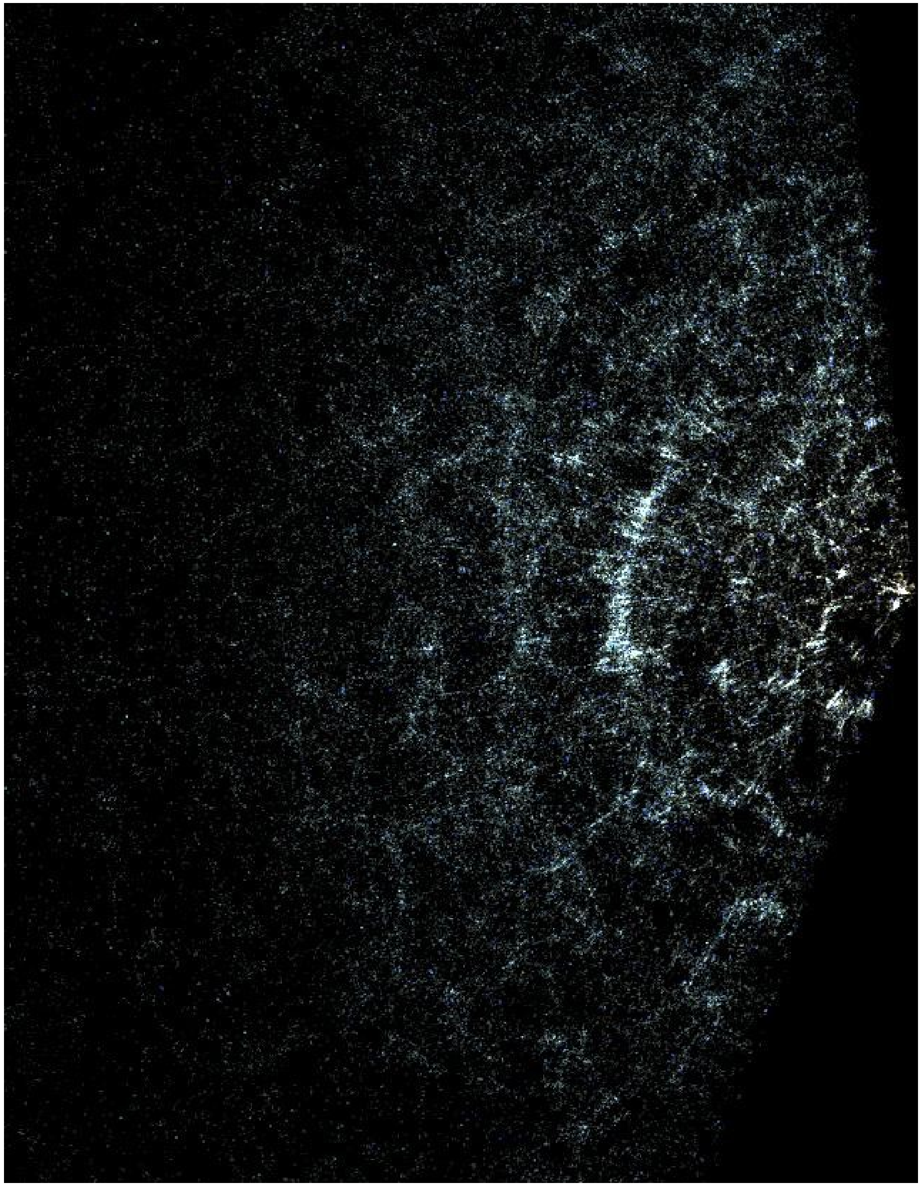
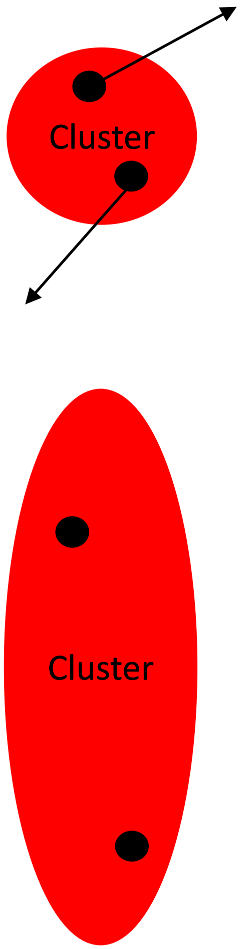


Image of SDSS, from U. Chicago

Redshift-Space Distortions





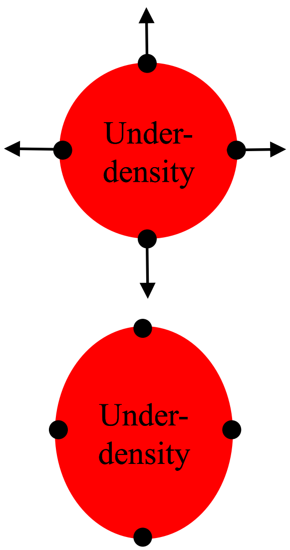
Actual shape

Apparent shape (viewed from below)

Galaxies act as test particles

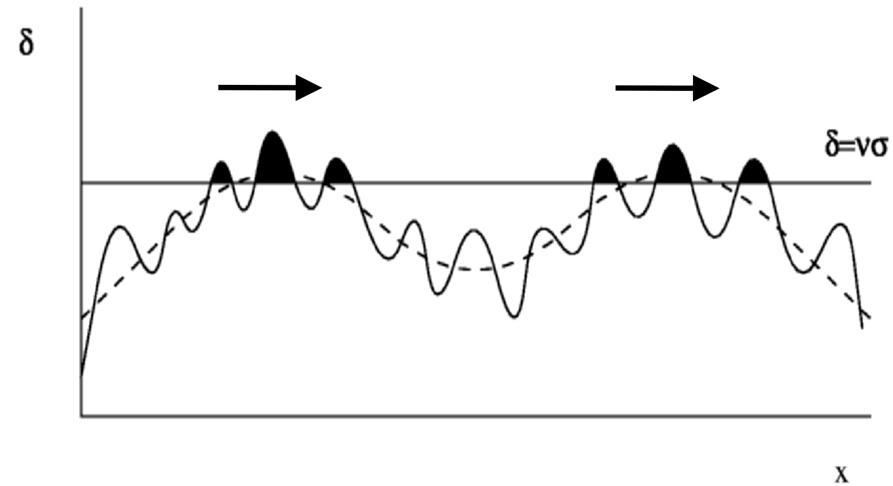
Galaxies act as test particles with the flow of matter

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



Actual shape

Apparent shape (viewed from below)



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

Standard measurements provide good test of models

assume: irrotational velocity field due to structure growth, plane-parallel approximation, linear deterministic density & velocity bias, first order in δ, θ

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

Normalise RSD to σ_v

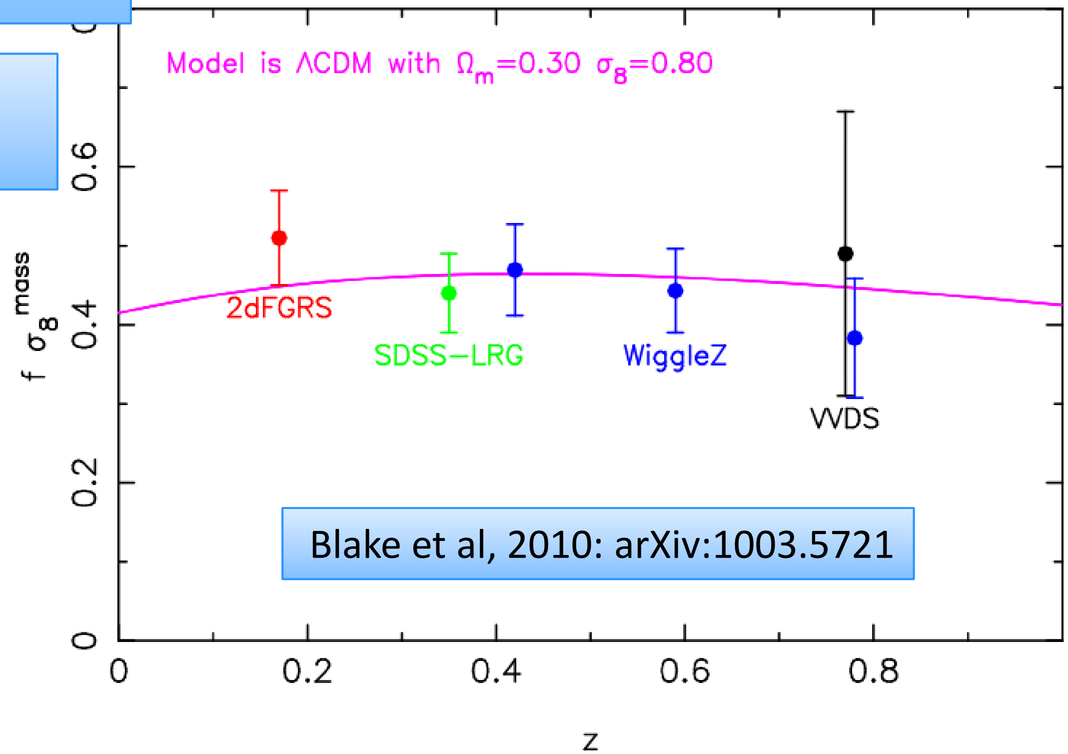
Normalise RSD to $\beta=f/b$

Normalise RSD to $f\sigma_8$

} assume continuity, scale-independent growth

Standard assumption: $b_v=1$ (current simulations limit this to a 10% effect).

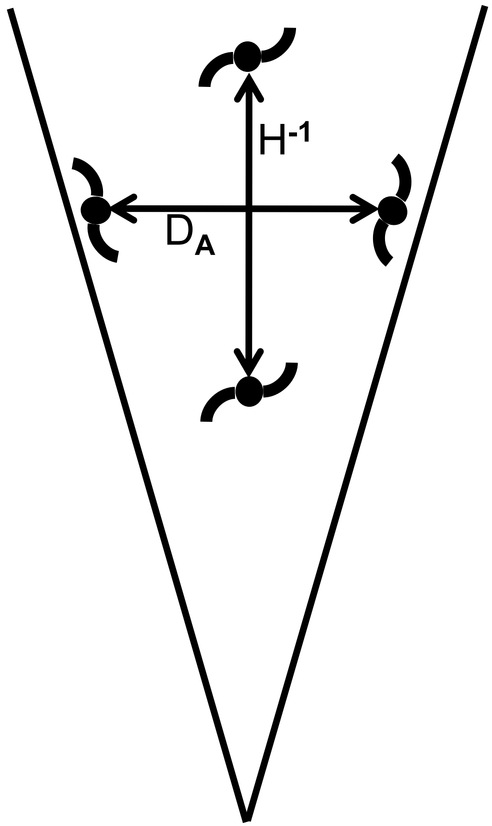
$$f \equiv \frac{d\log G}{d\log a}$$
$$f\sigma_8 \propto \frac{dG}{d\log a}$$
$$G = \frac{\delta(z,\text{mass})}{\delta(0,\text{mass})}$$

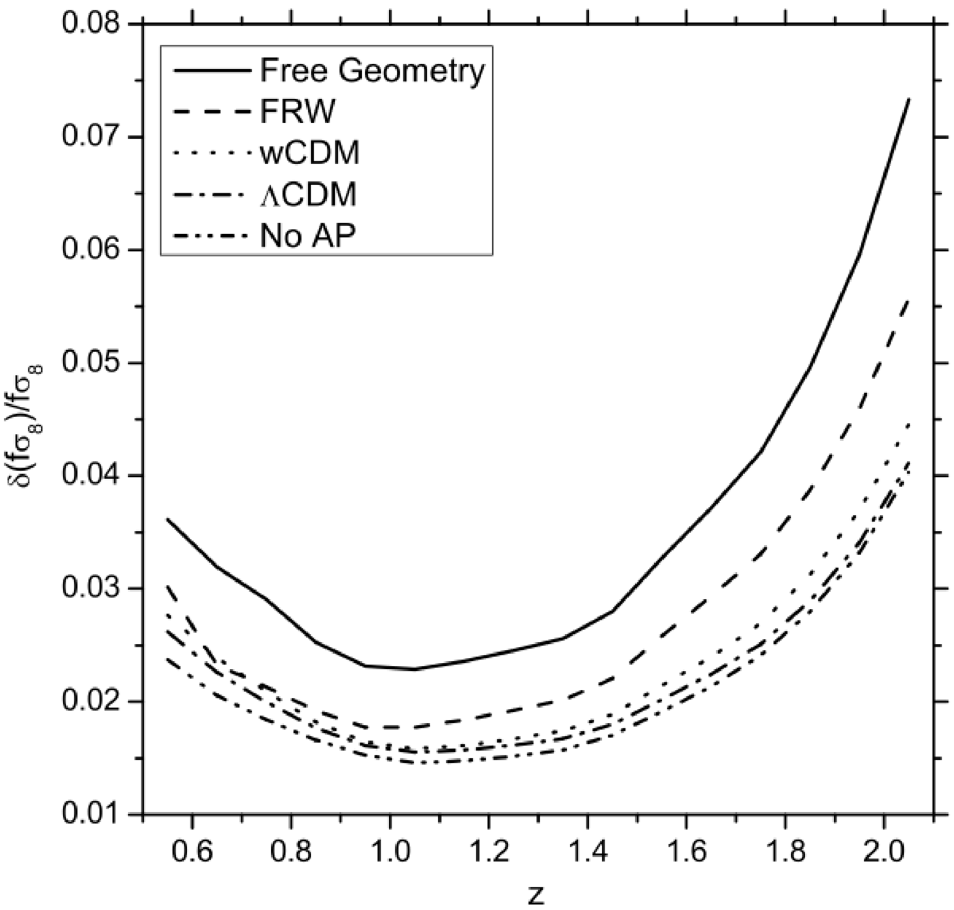


Blake et al, 2010: arXiv:1003.5721

Degeneracies – RSD vs Alcock-Palczynski

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

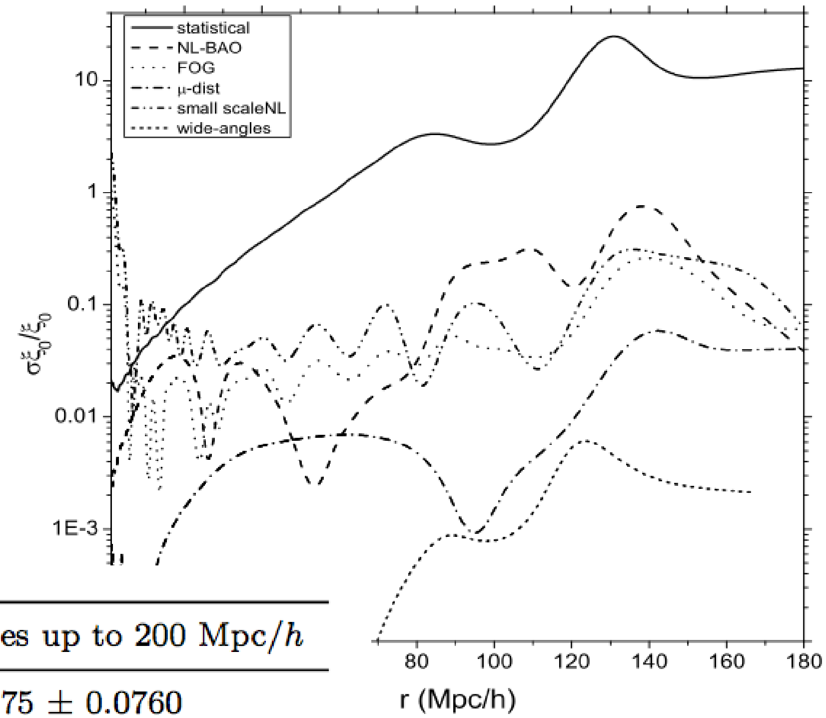




Samushia et al 2010, arXiv:1006.0609

Undertaking a robust analysis

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



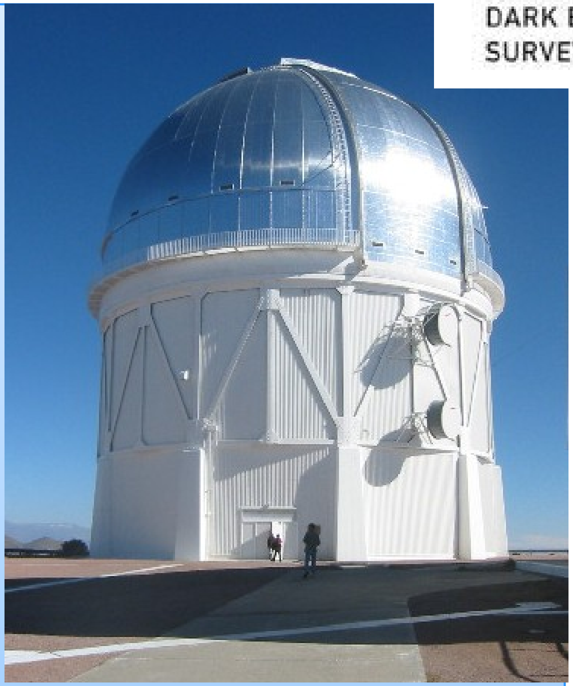
Model	Variable	Scales less than 60 Mpc/h	Scales up to 200 Mpc/h
wCDM	$b(z_1)\sigma_8(z_1)$	1.4949 ± 0.0772	1.5175 ± 0.0760
	$b(z_2)\sigma_8(z_2)$	1.5316 ± 0.0717	1.57435 ± 0.0672
γ	$b(z_1)\sigma_8(z_1)$	1.5462 ± 0.0911	1.6098 ± 0.0840
	$b(z_2)\sigma_8(z_2)$	1.5522 ± 0.0916	1.5882 ± 0.0727
	γ	0.6545 ± 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

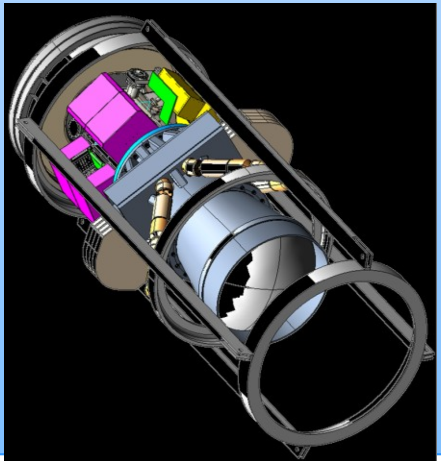
Samushia et al 2011: arXiv:1102.1014

Future surveys

Dark Energy Survey (DES)

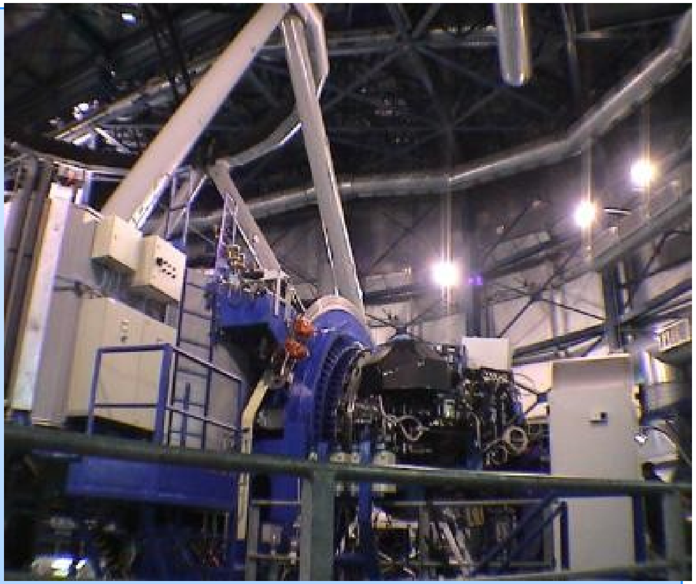
- New wide-field camera for the 4m Blanco telescope
- Currently being moved from Fermilab to site, Survey due to start autumn 2011
- Ω = 5,000deg2
- multi-colour optical imaging (g,r,i,z) with link to IR data from VISTA hemisphere survey
- 300,000,000 galaxies
- Aim is to constrain dark energy using 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

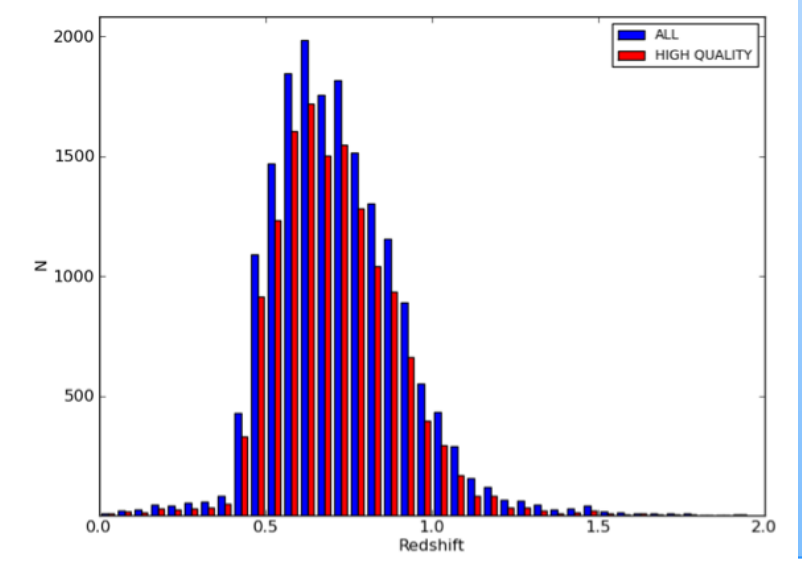




VIMOS Public Extragalactic Redshift Survey (VIPERS)

- 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)

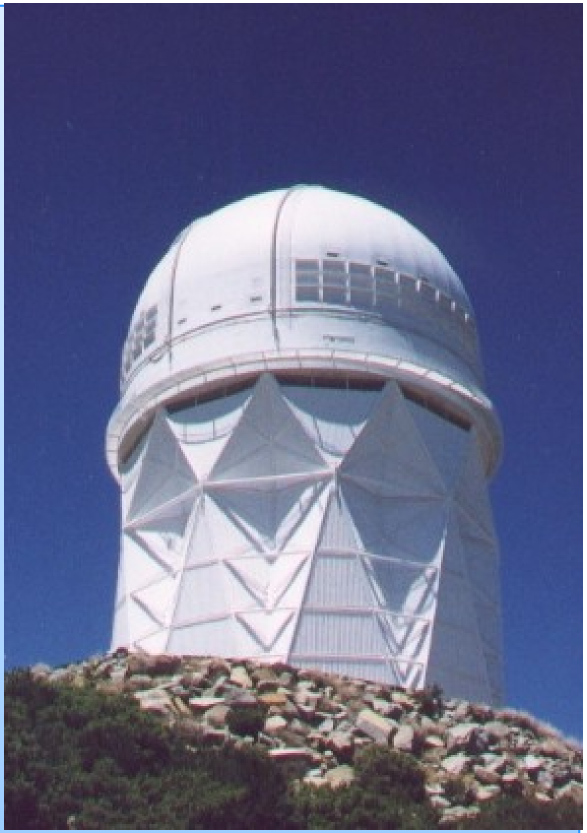
- New fibre-fed spectroscope now on the 2.5m SDSS telescope
- Ω = 10,000deg^2
- 1,500,000 galaxies
- 150,000 quasars
- LRGs : z ~ 0.1 – 0.7 (direct BAO)
- QSOs : z ~ 2.1 – 3.0 (BAO from Ly-α forest)

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

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

  $z\sim2.5$: 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

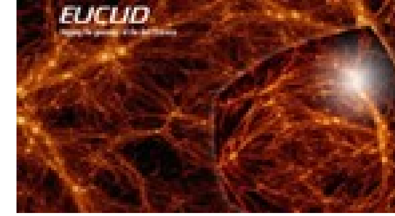


- New fibre-fed spectroscope proposed for 4m Mayall telescope
- NOAO endorsement following proposal evaluation
- $\Omega = 14{,}000\,\mathrm{deg}^2$
- 20,000,000 galaxies (direct BAO)
- 600,000 quasars (BAO from Ly-α forest)
- LRGs : z ~ 0.1 – 1.0
- ELGs: z~0.5-1.7
- QSOs : $40/\mathrm{deg}^2$, z ~ 2.1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

  $z<0.5$: 0.9% d_A, 1.5% H

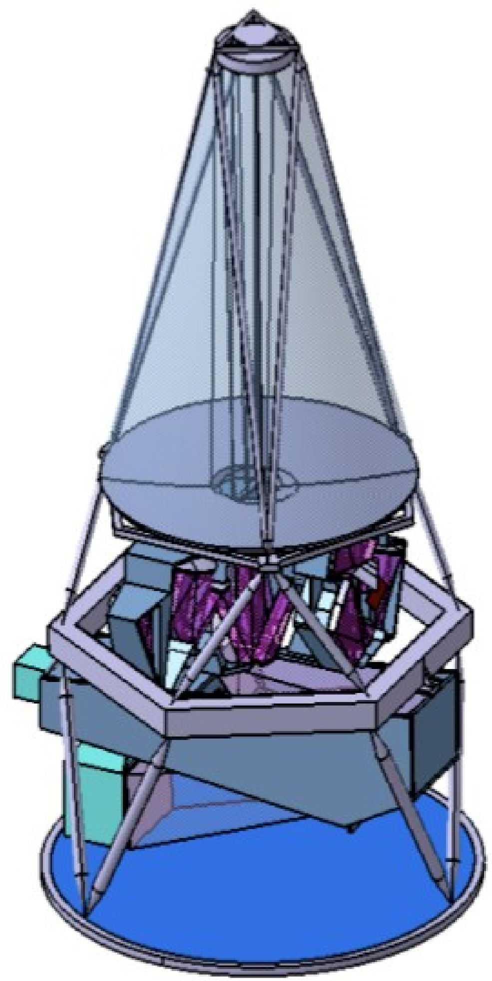
  $0.5<z<1$: 0.4% d_A, 0.6% H

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



Euclid

- ESA Cosmic Vision satellite proposal (600M€, M-class mission)
- 5 year mission, L2 orbit
- 1.2m primary mirror, 0.5 sq. deg FOV
- Ω = 20,000deg^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, SKA

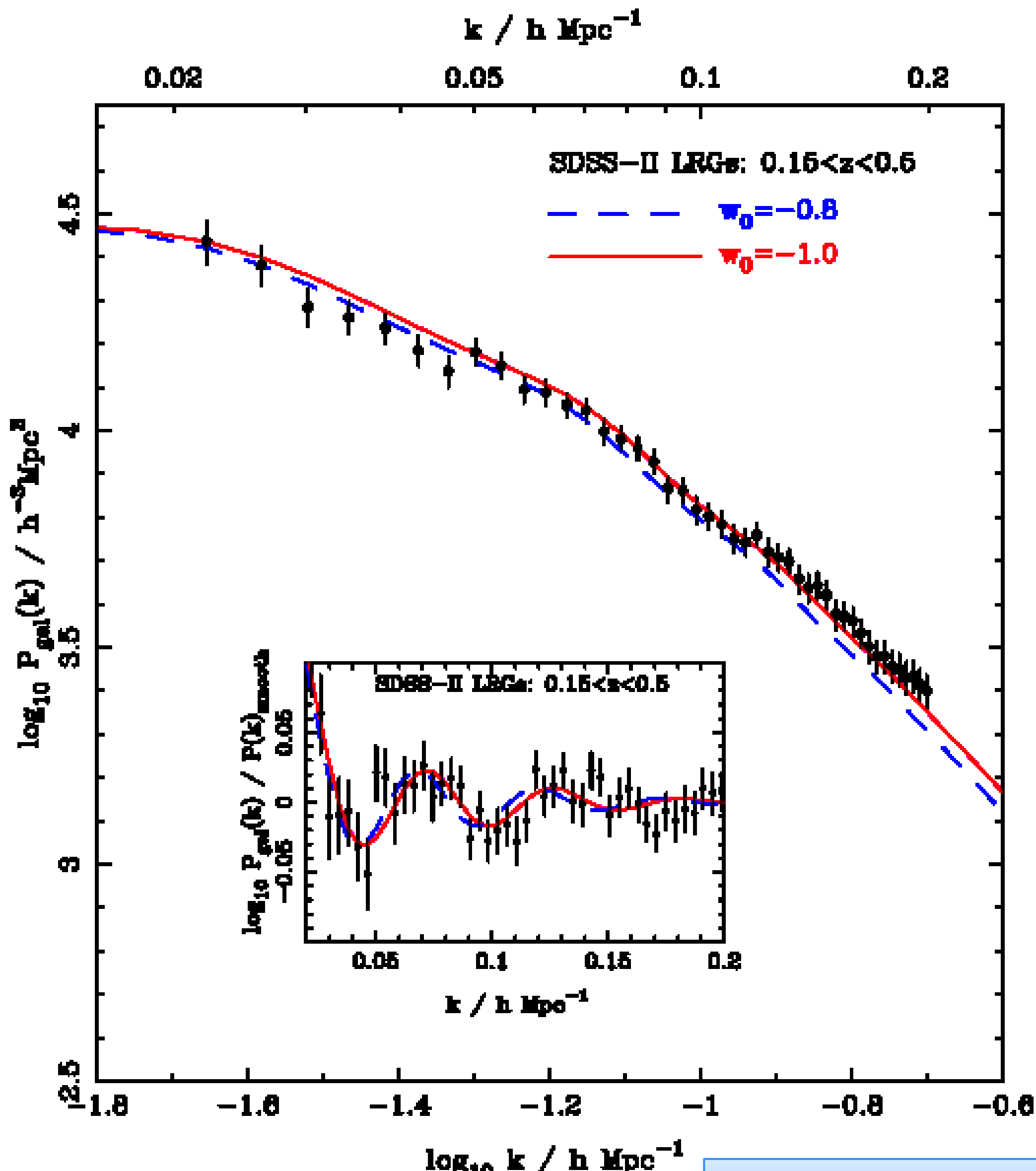


Current large-scale galaxy clustering measurements

SDSS LRGs at z~0.35

The largest volume of the Universe currently mapped

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



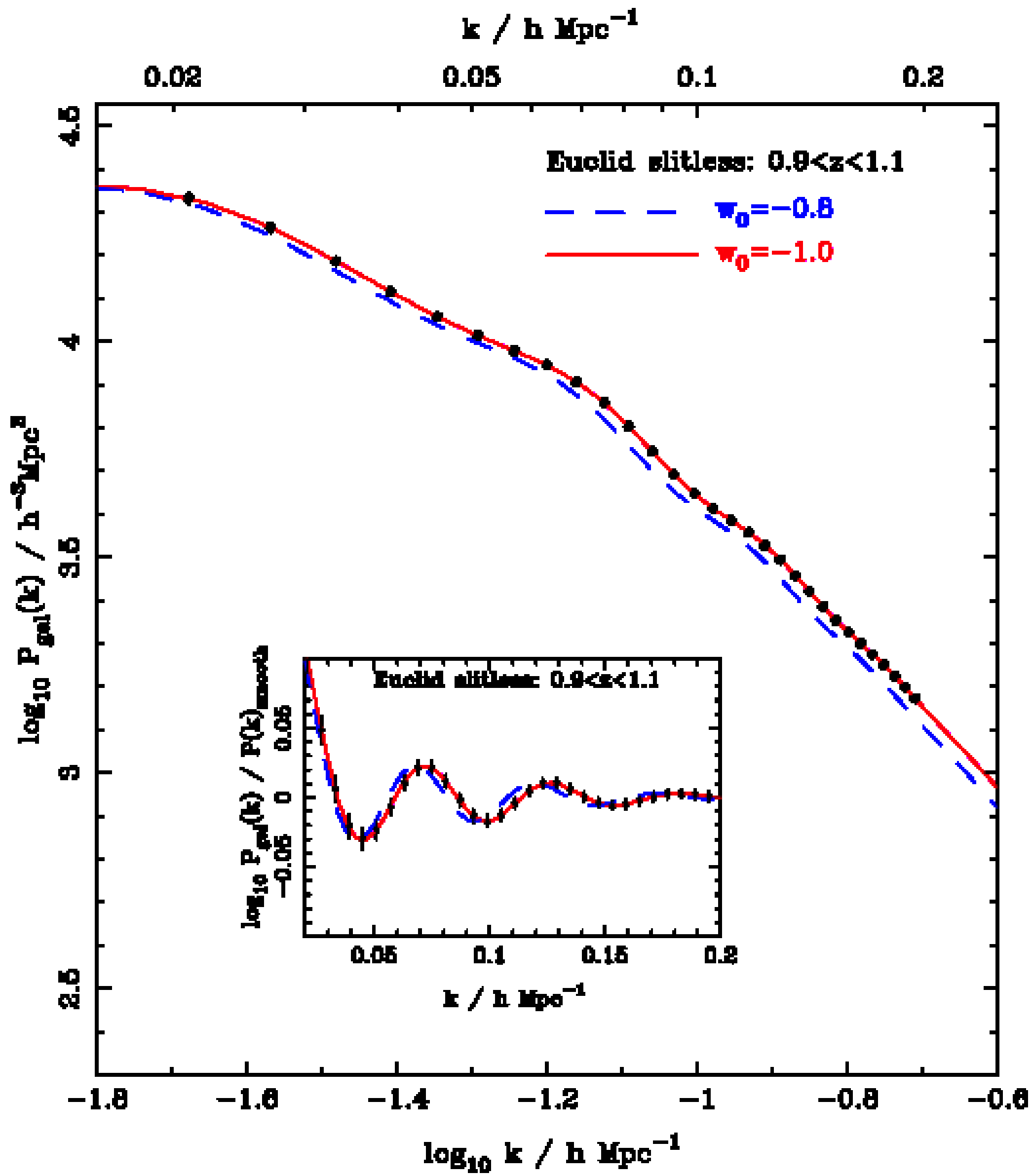
Power spectrum gives amplitude of Fourier modes, quantifying clustering strength on different scales

Percival et al. 2009; arXiv:0907.1660

Predicted galaxy clustering measurements by Euclid

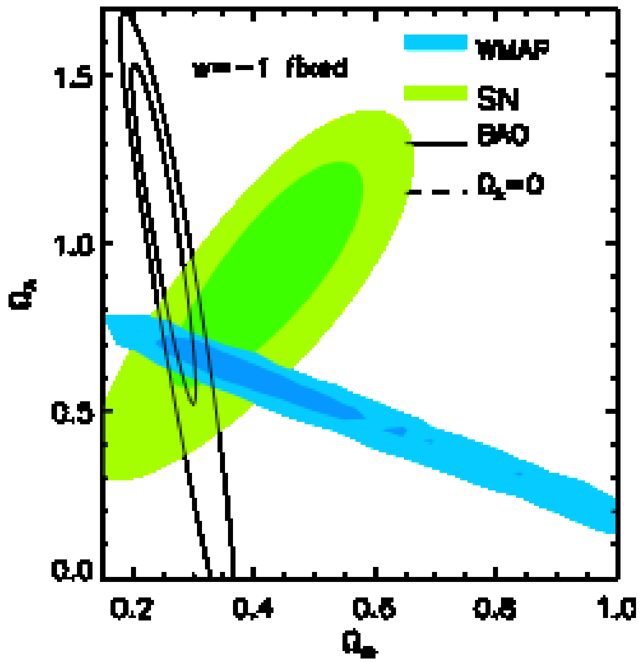
20% of the Euclid data, assuming the slitless baseline at z~1

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

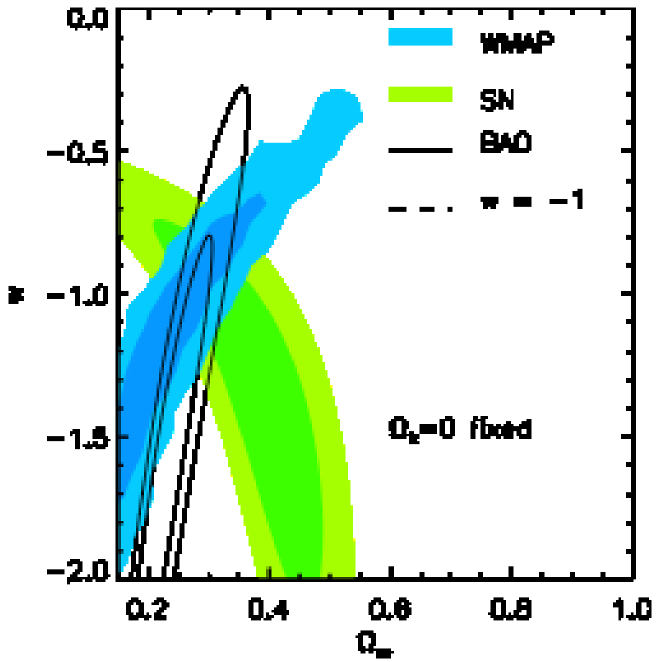


Current BAO constraints vs other data

ΛCDM models with curvature



flat wCDM models



Union supernovae

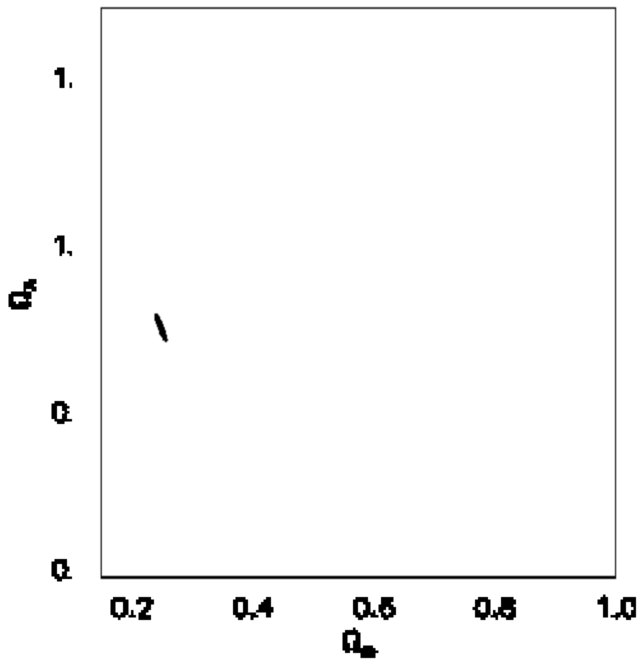
WMAP 5year

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

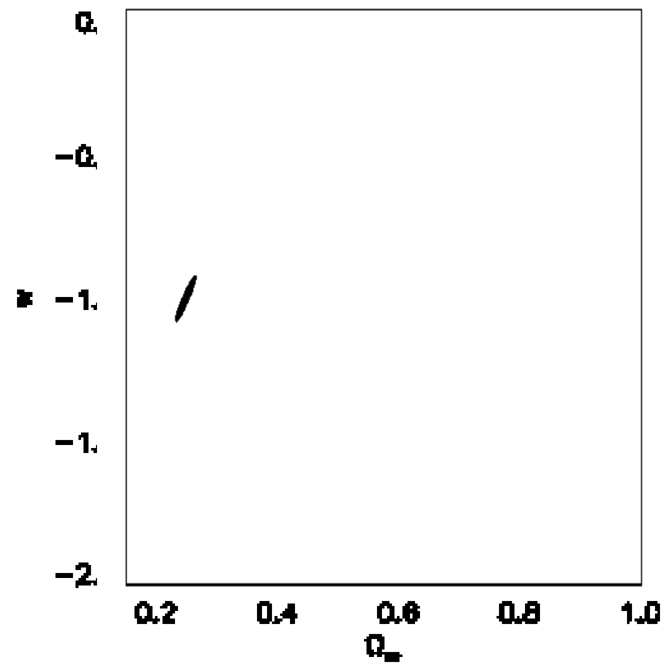
Percival et al. 2009; arXiv:0907.1660

How does Euclid BAO compare?

ΛCDM models with curvature



flat wCDM models

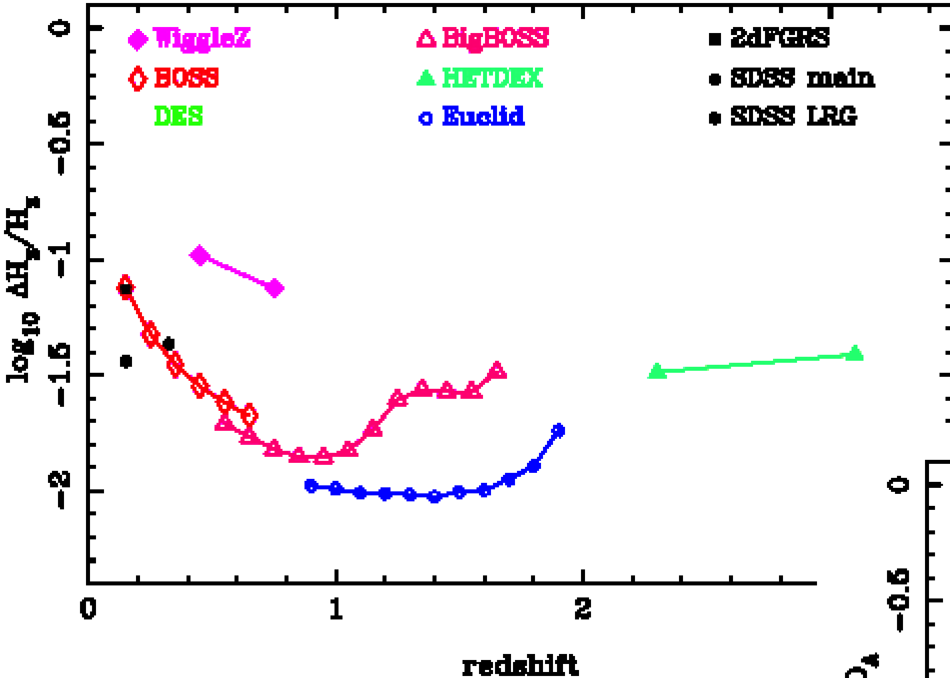


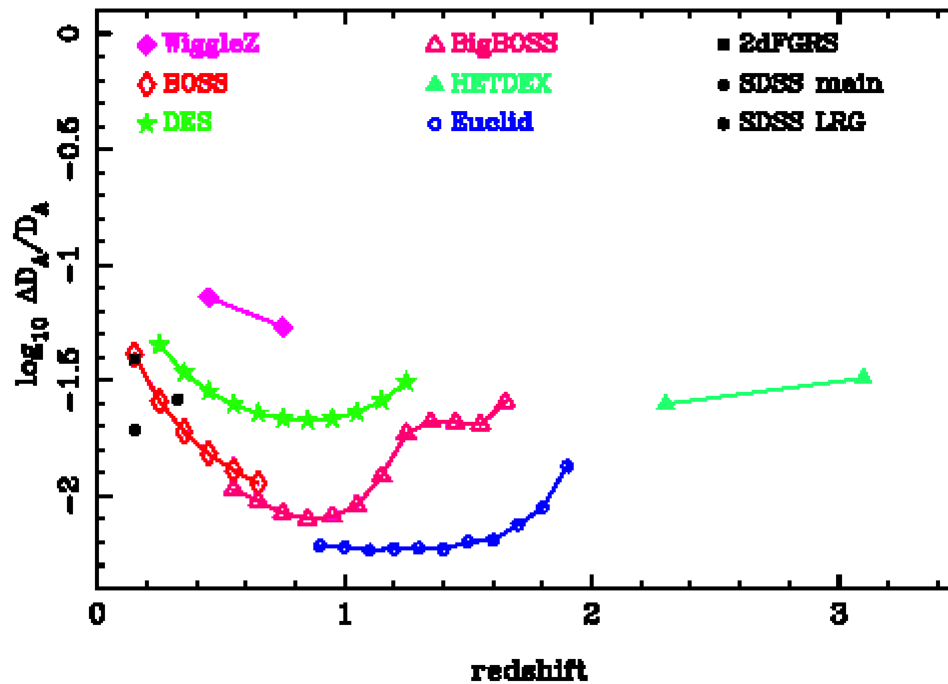
Union supernovae

WMAP 5year

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

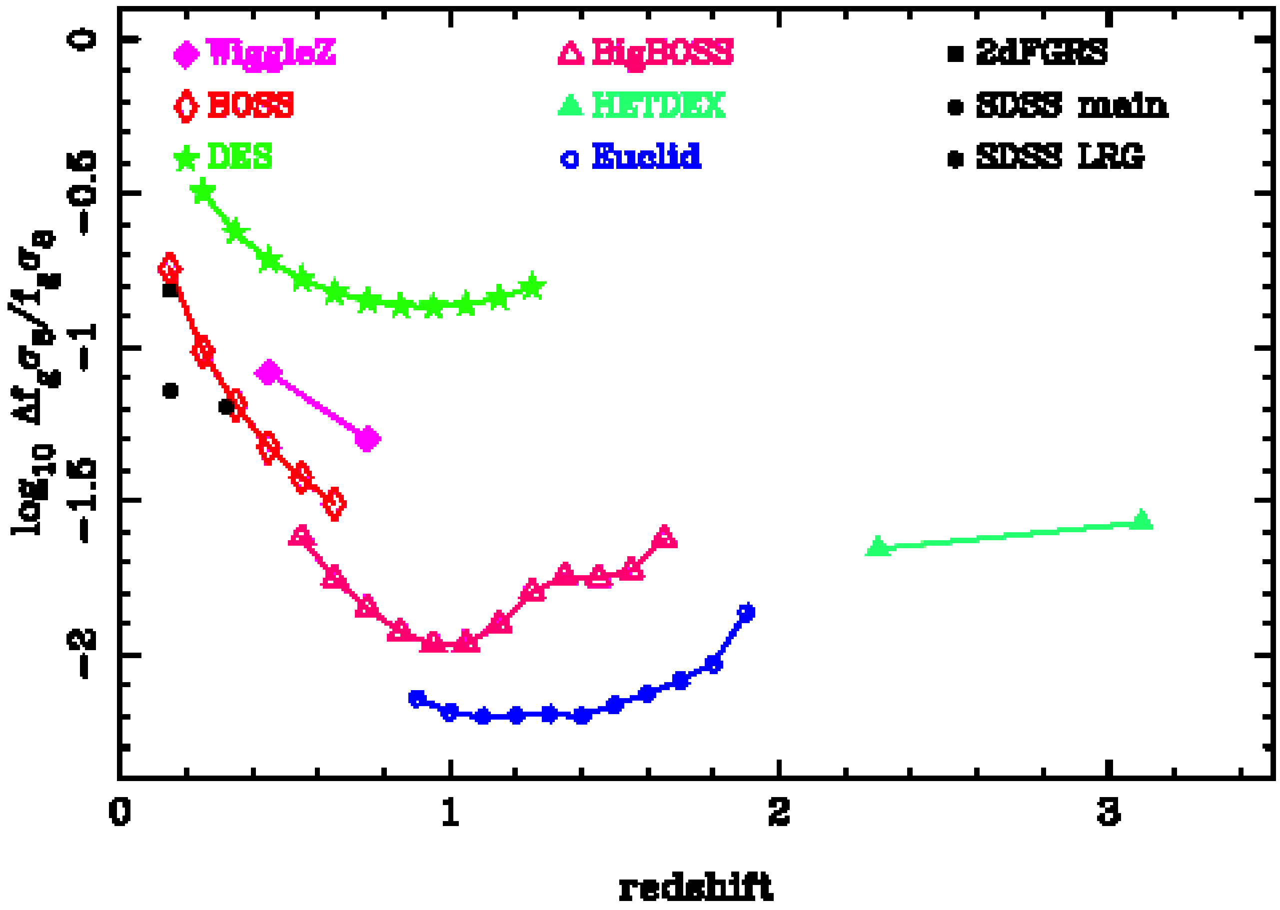
Predicted BAO constraints





Uses public code to estimate errors from BAO measurements from Seo & Eisenstein (2007: astro-ph/0701079)

Predicted RSD Constraints



Code to estimate errors on $f\sigma_8$ is available from: http://mwhite.berkeley.edu/Redshift

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

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