Observational cosmology

Galaxy Clustering

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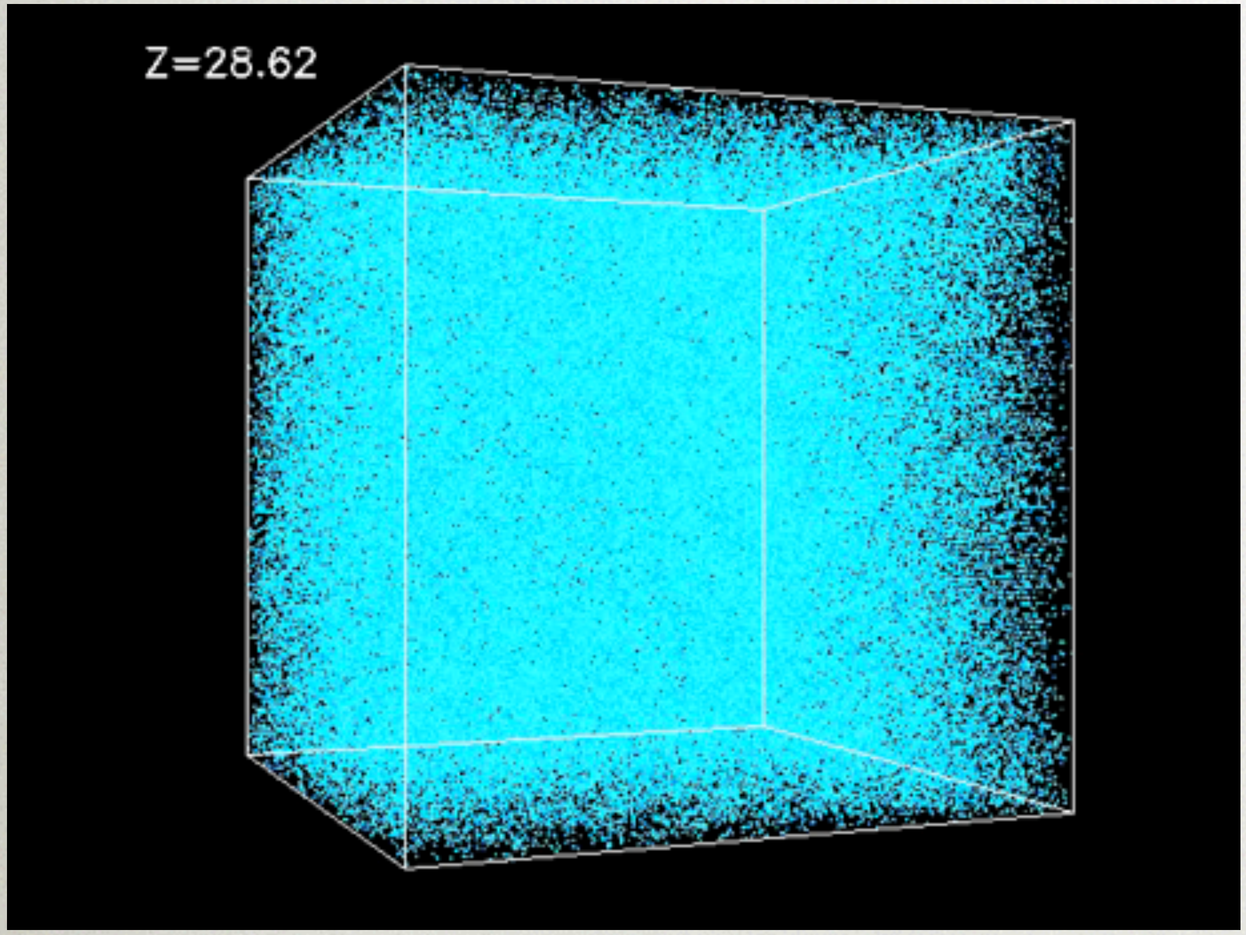
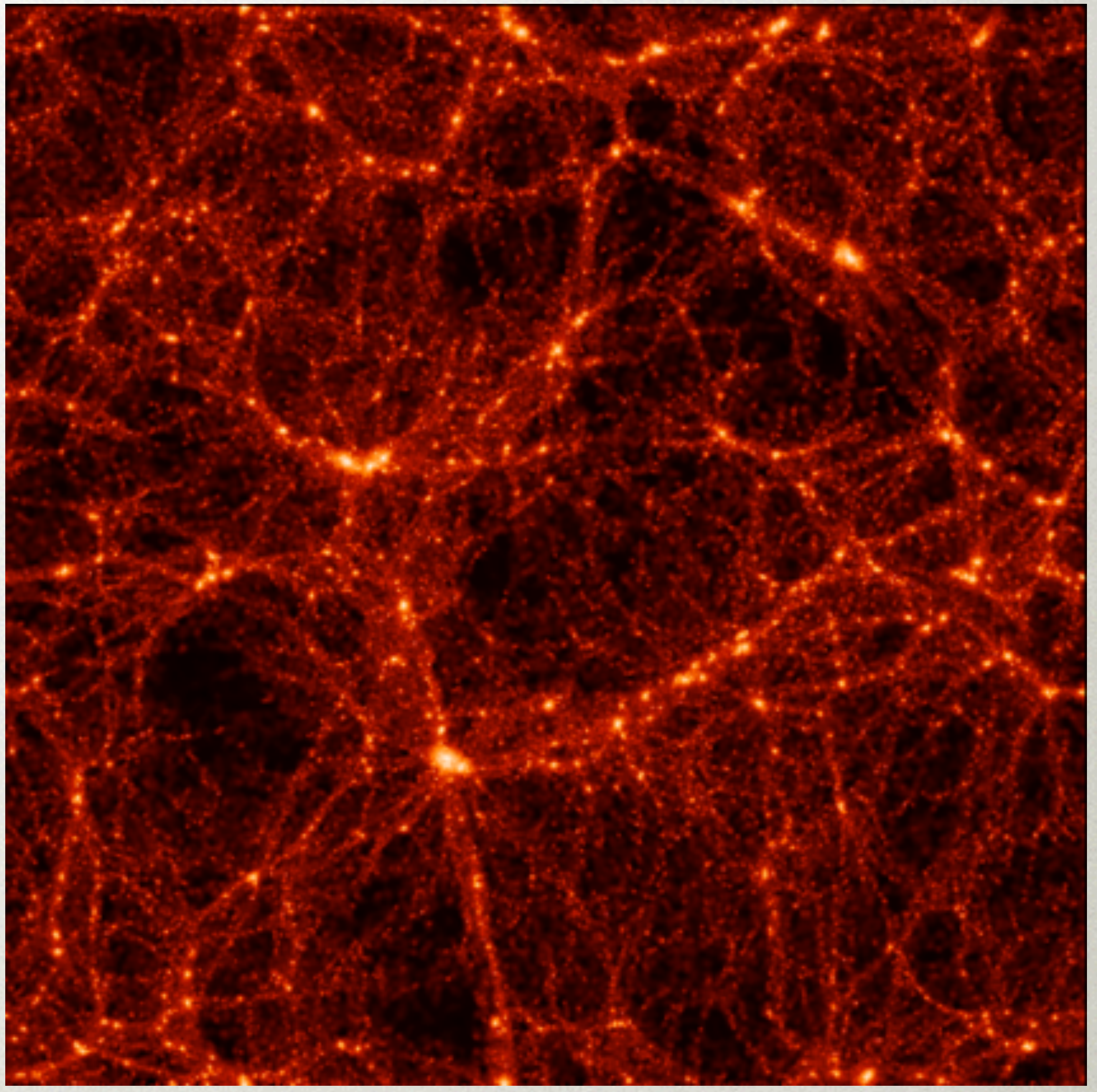
N-Body Simulations



A, Babul

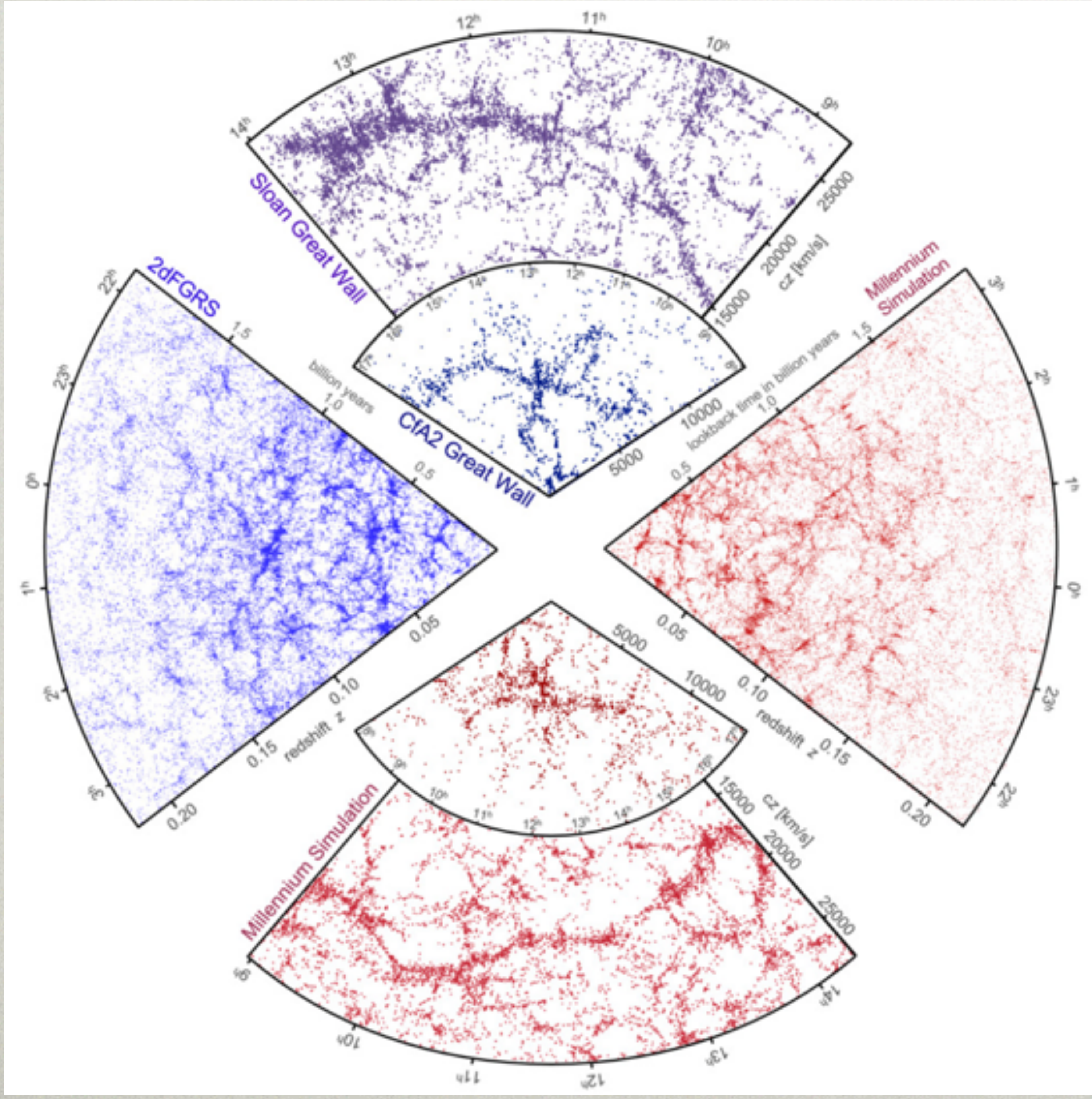
The statistics of the density field can be compared with galaxy clustering.

LCDM



VIRGO consortium

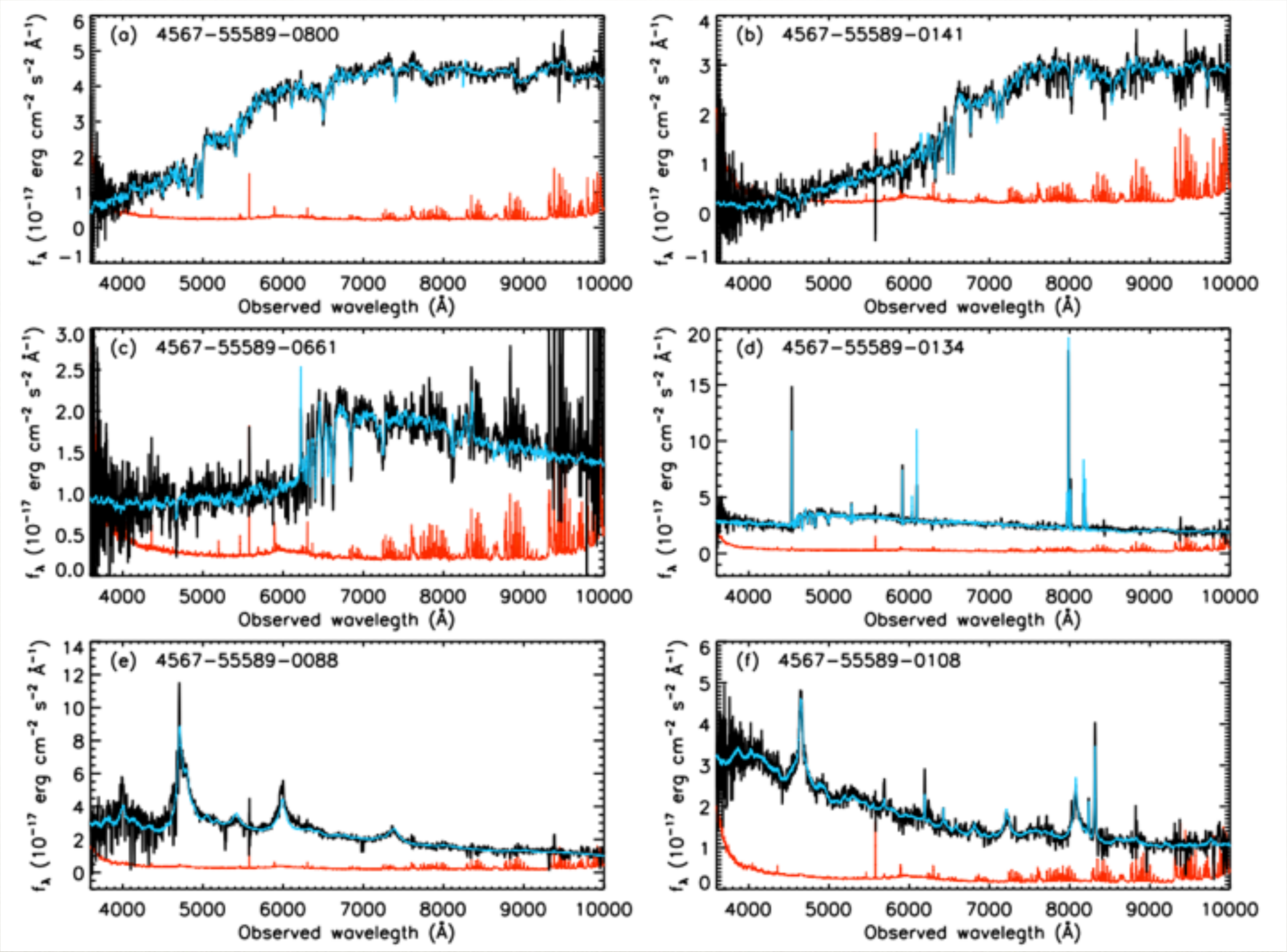
N-Body Simulations



How do we compare theory and data?

VIRGO consortium

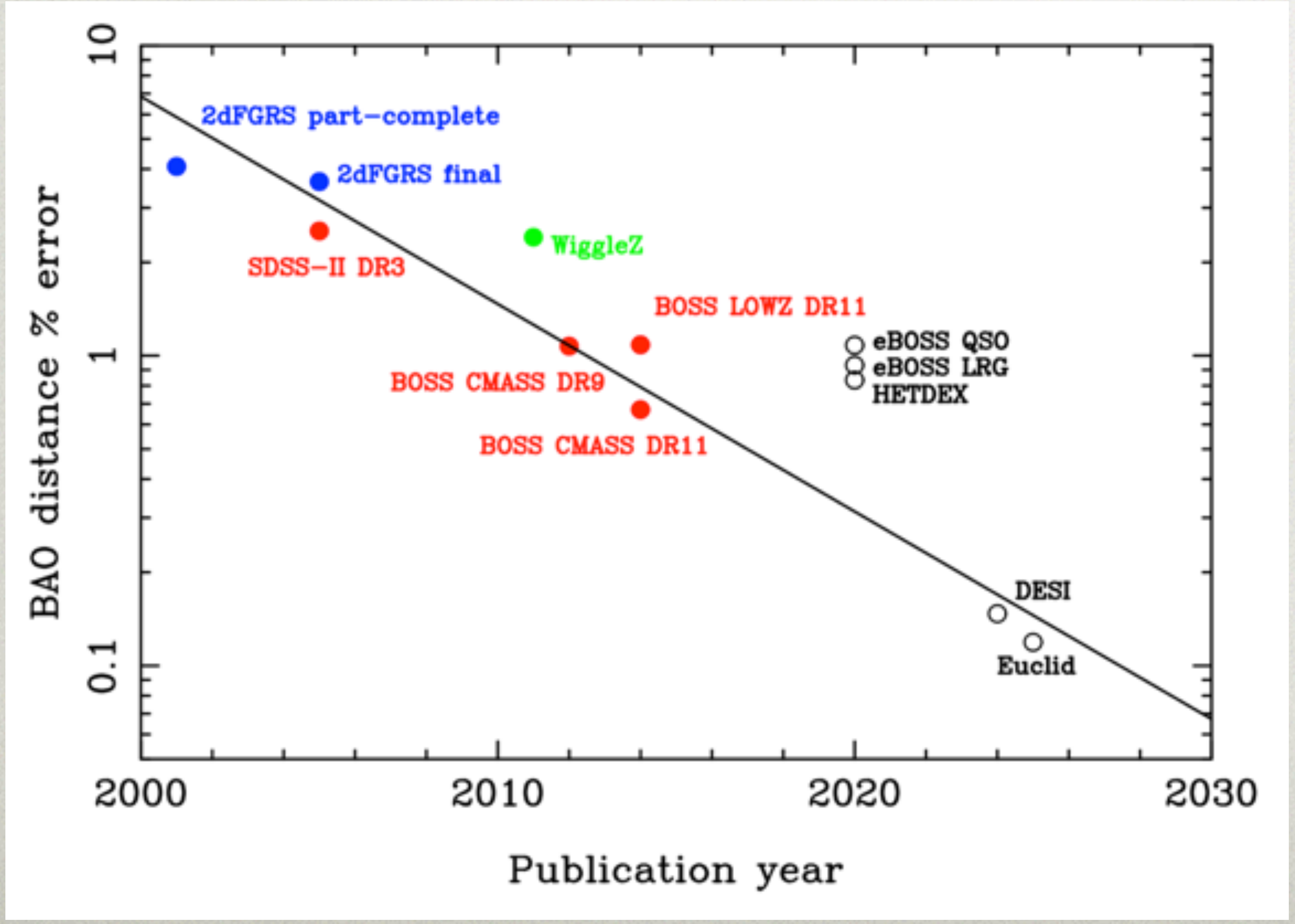
Measure redshifts and angular positions of galaxies



Bolton et al 2012

Galaxy redshift survey history

- 1986 CfA 3500
- 1996 LCRS 23000
- 2003 2dFGRS 250000
- 2005 SDSS-I/II 800000
- 2012 SDSS-III 1500000

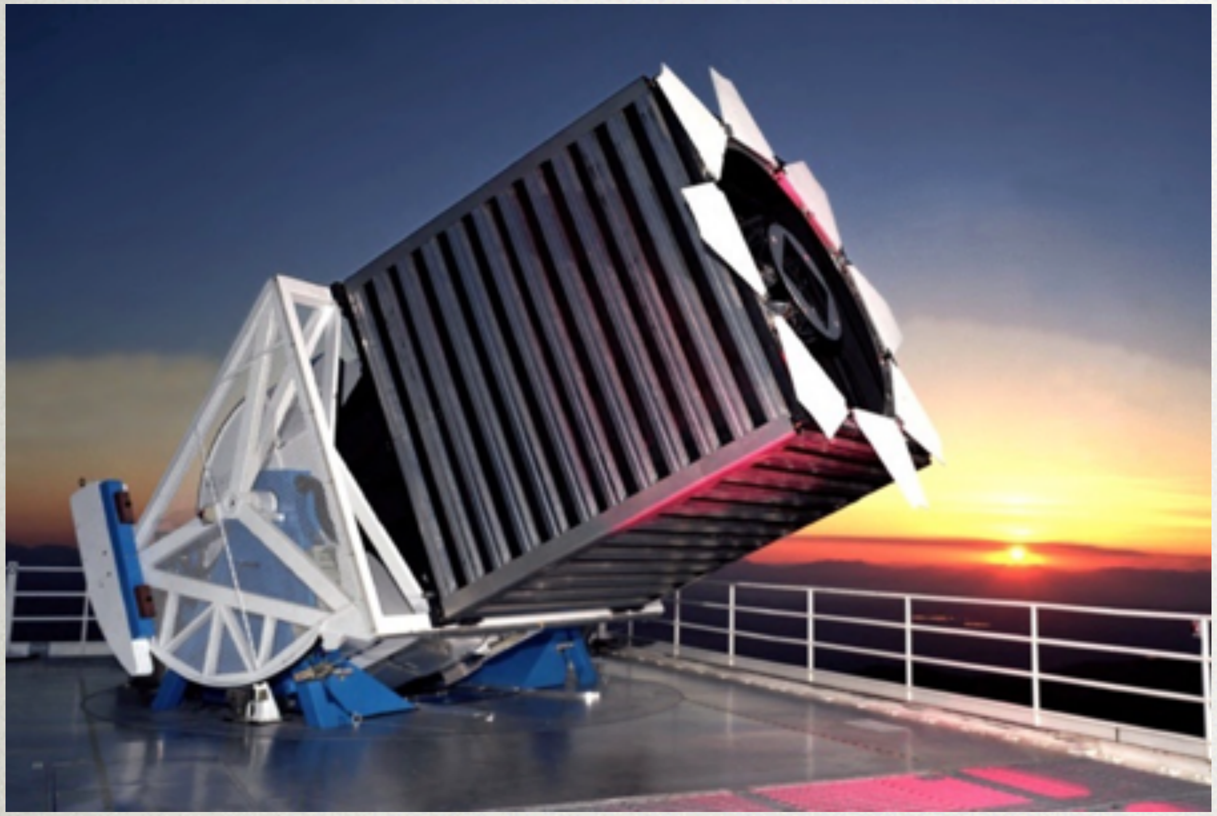


Fractional error in the amplitude of the fluctuation spectrum

1970	x100
1990	x2
1995	±0.4
1998	±0.2
1999	±0.1
2002	±0.05
2003	±0.03
2009	±0.01
2012	±0.002

Driven by the development of instrumentation

SDSS-III BOSS



Sloan telescope (2.5m) at
Apache Point, New Mexico
2009-2014
SDSS *ugriz* imaging to select:
- 1.5 million galaxies
- 1.5×10^5 quasars

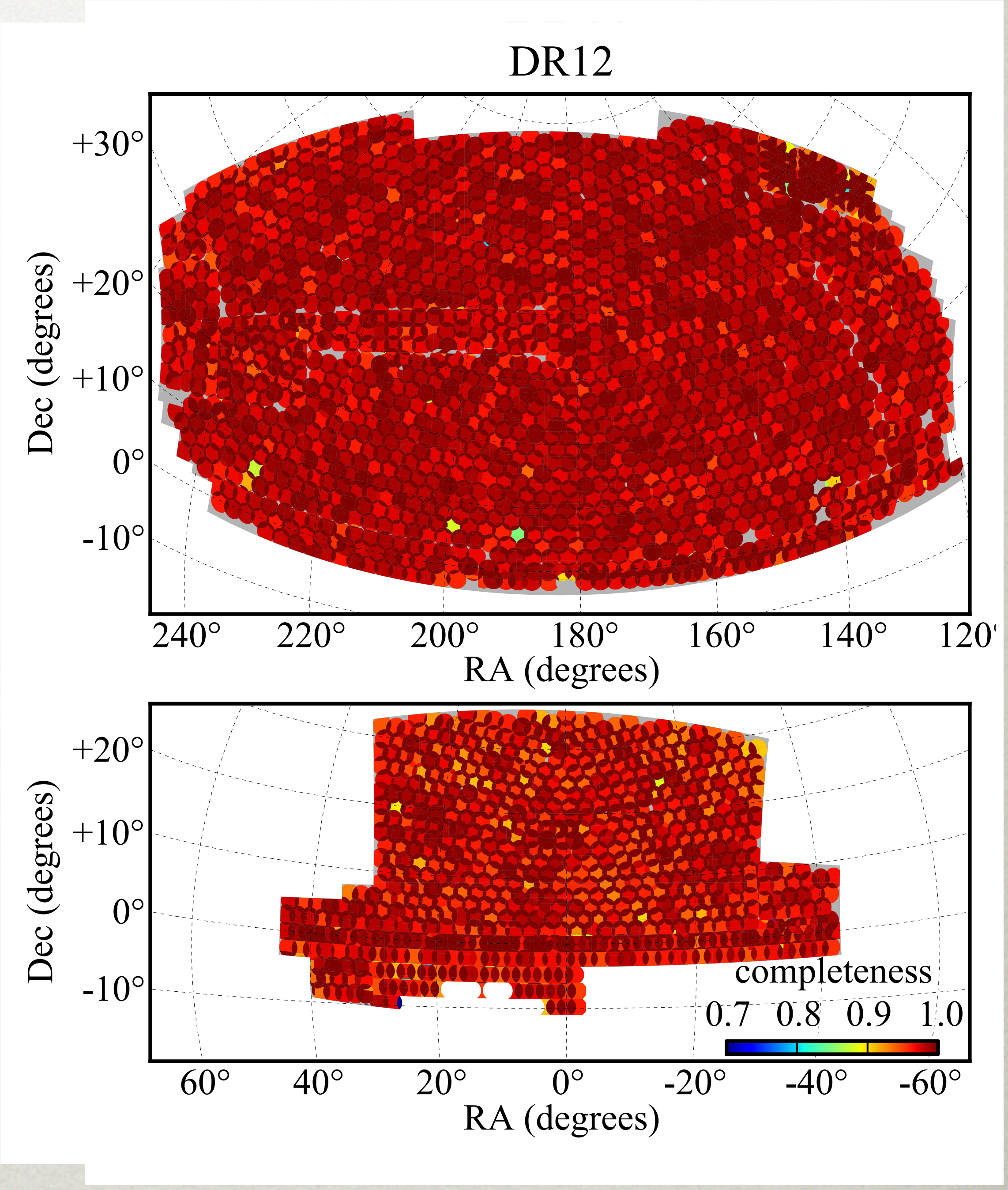
BOSS spectrograph:
- $3600Å < \lambda < 10{,}000Å$
- $R = \lambda/\Delta\lambda = 1300 - 3000$
- 1000 spectra at a time

BOSS FOOTPRINT

Total footprint >10,000 deg^2
DR11 8500 deg^2 (published results)
DR12 10000 deg^2 - raw data public, results coming

931517 CMASS redshifts
368335 $0.15<z<0.43$ ("LOWZ")

Volume of 6Gpc^3



BOSS Samples

'CMASS':

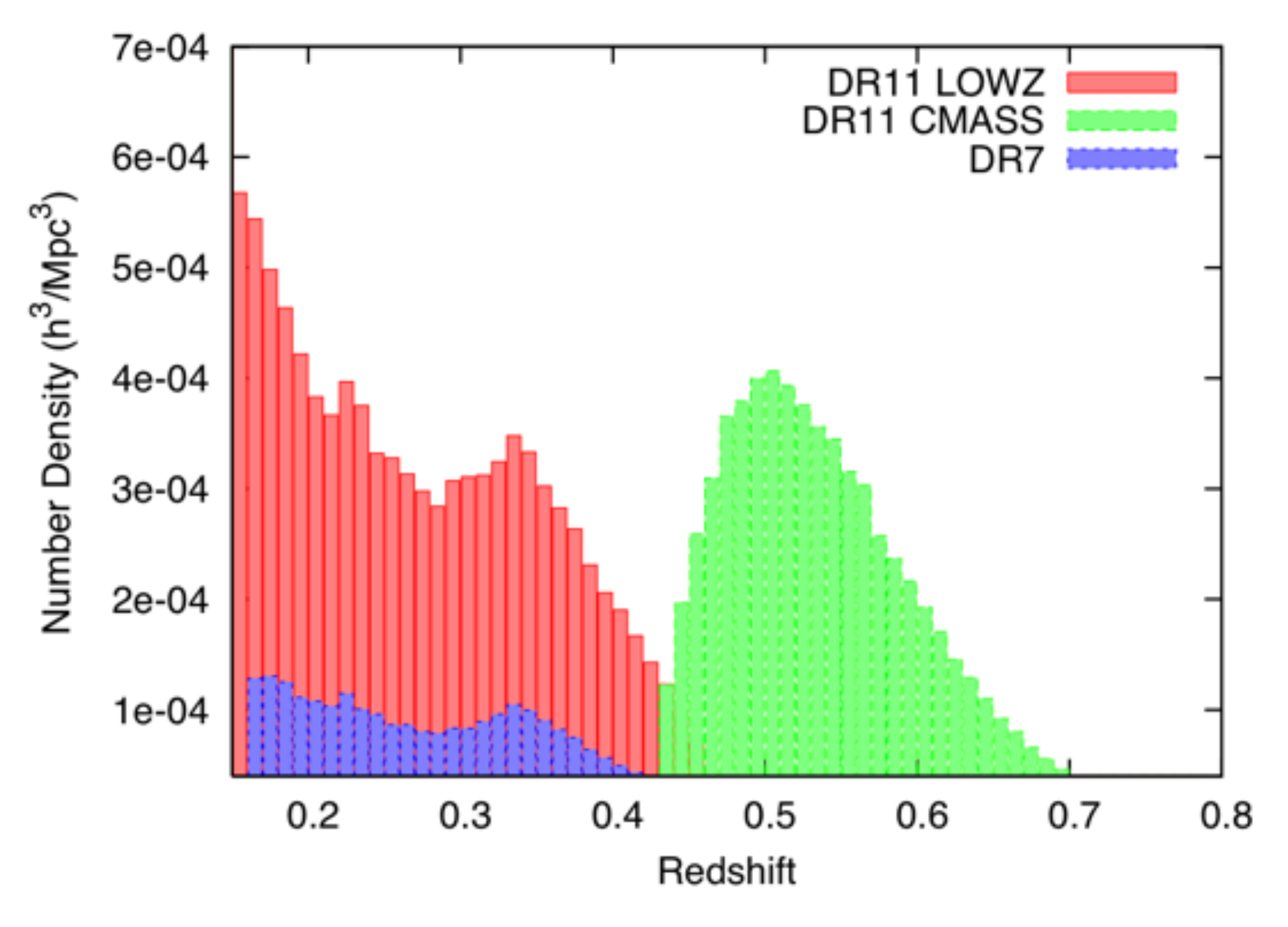
i < 19.9 + color cuts

redshifts 0.43<z<0.7

'LOWZ':

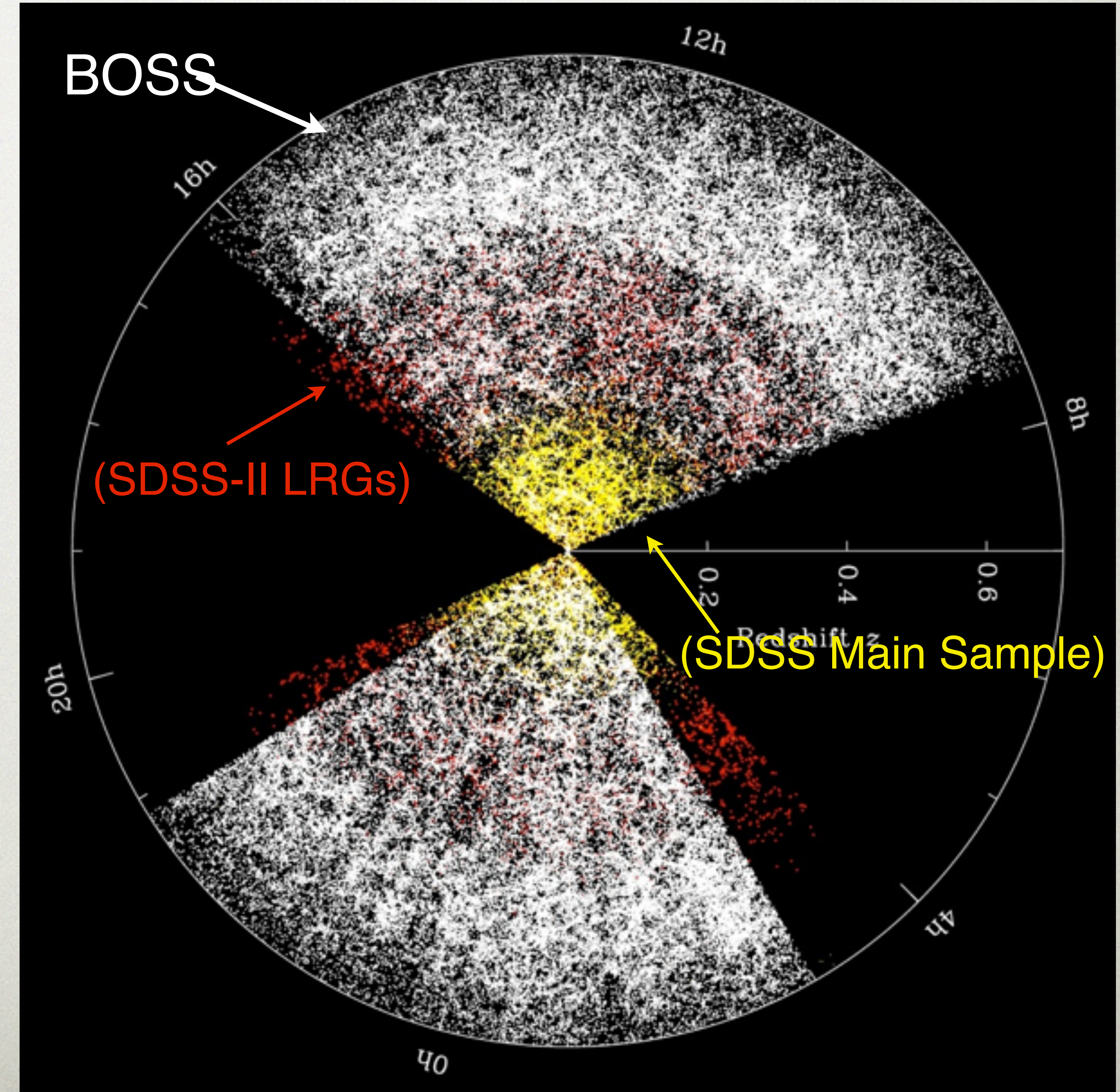
r < 19.5 + color cuts

0.15<z<0.43



3D Map

This is in z, angle



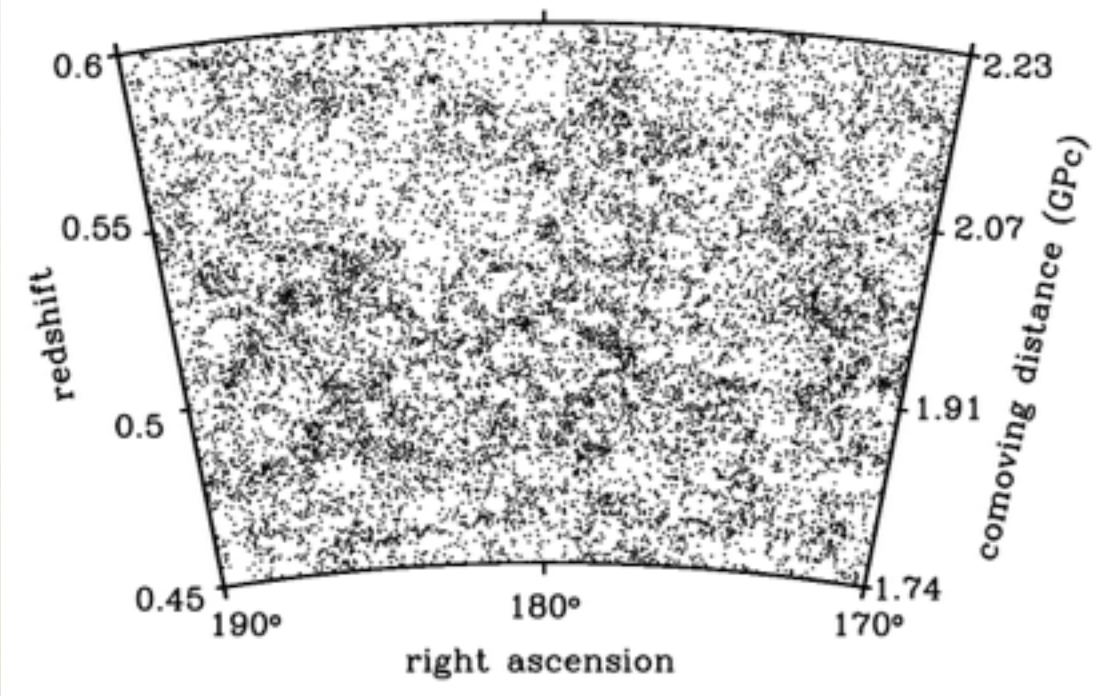
Can move to comoving coordinates

Find comoving distances from angles and redshifts.

$$a = \frac{1}{1+z}$$

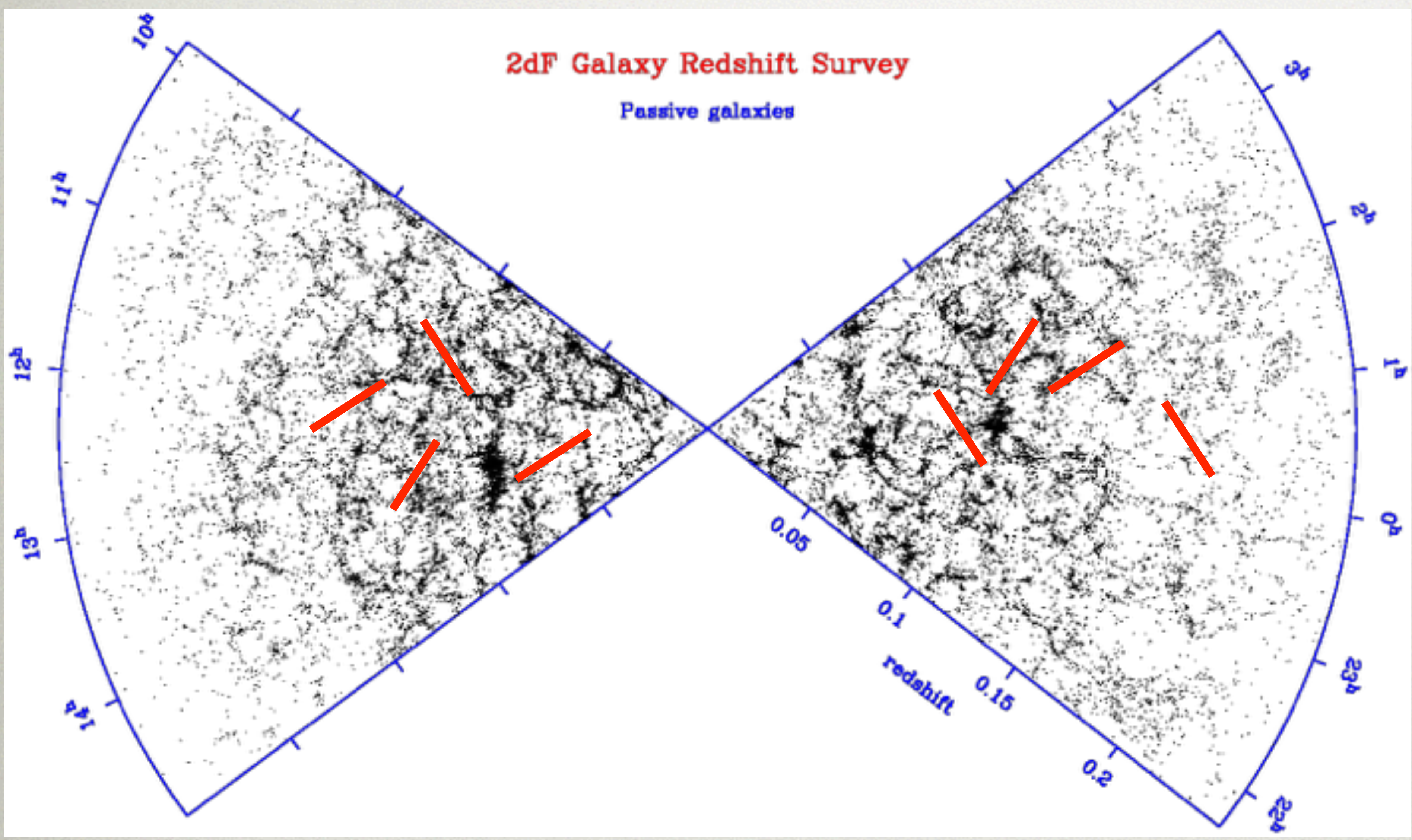
$$c\,dt = -a\,dr \rightarrow dr = \frac{c\,dz}{H(z)}$$

$$r = \int_0^z \frac{c dz}{H(z)}$$



Transversely use $D_A\theta/a$

Measuring clustering



Degree to which number of pairs is in excess of that expected by laying objects down at random

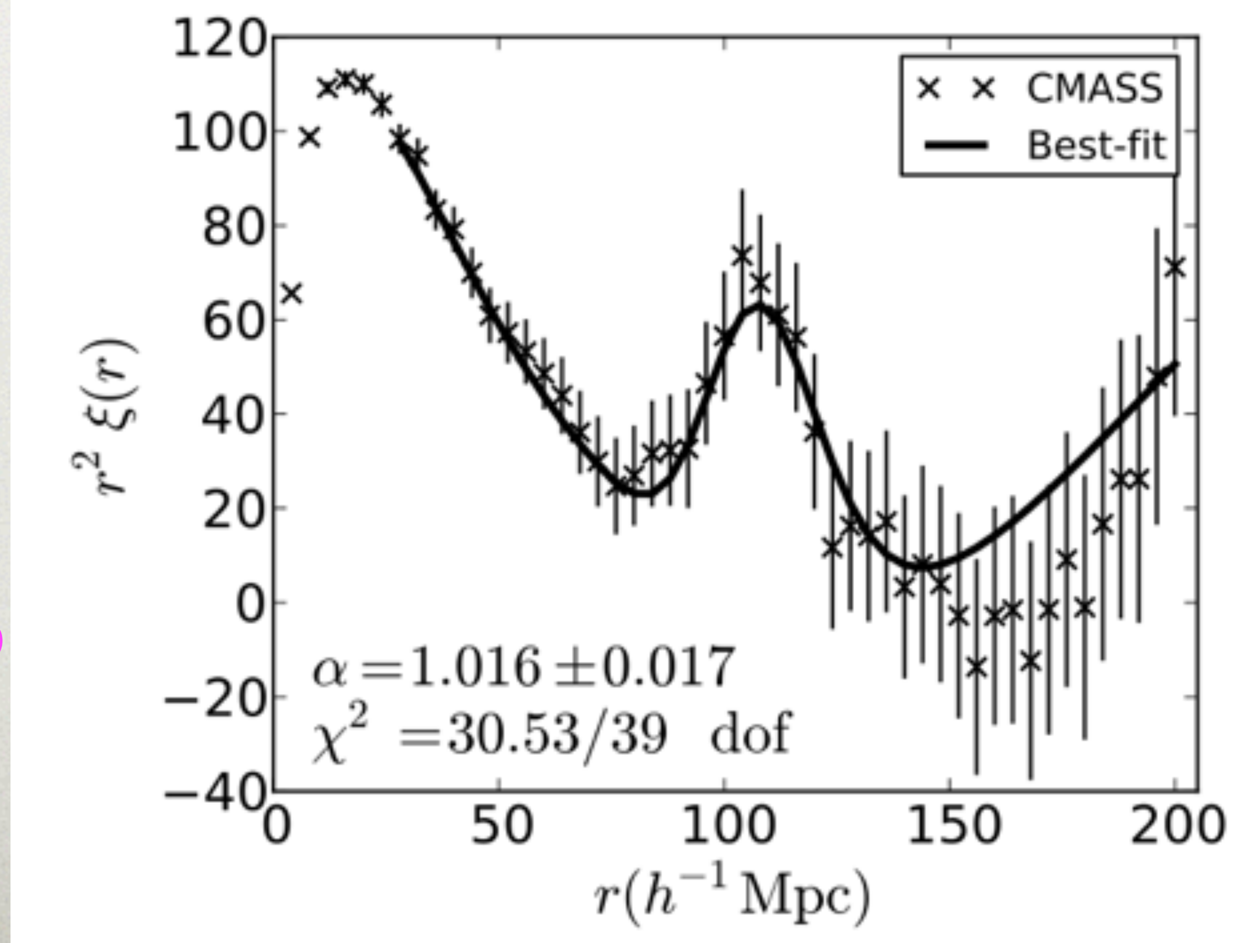
$$dP = \rho_0^2 \left[1 + \xi(r)\right] dV_1 dV_2$$

Correlation Function

We examine the overdensity, $\delta = \dfrac{\rho - \rho_0}{\rho_0}$

The correlation function is
$$\begin{aligned} \xi(\mathbf{x_1}, \mathbf{x_2}) &= \langle \delta(\mathbf{x_1}) \delta(\mathbf{x_2}) \rangle \\ &= \xi(\mathbf{x_1} - \mathbf{x_2}) \\ \text{Isotropy} \rightarrow \quad &= \xi(|\mathbf{x_1} - \mathbf{x_2}|) \end{aligned}$$

So consider $\xi(r) = \langle \delta(\mathbf{x}) \delta(\mathbf{x} + \mathbf{r}) \rangle$

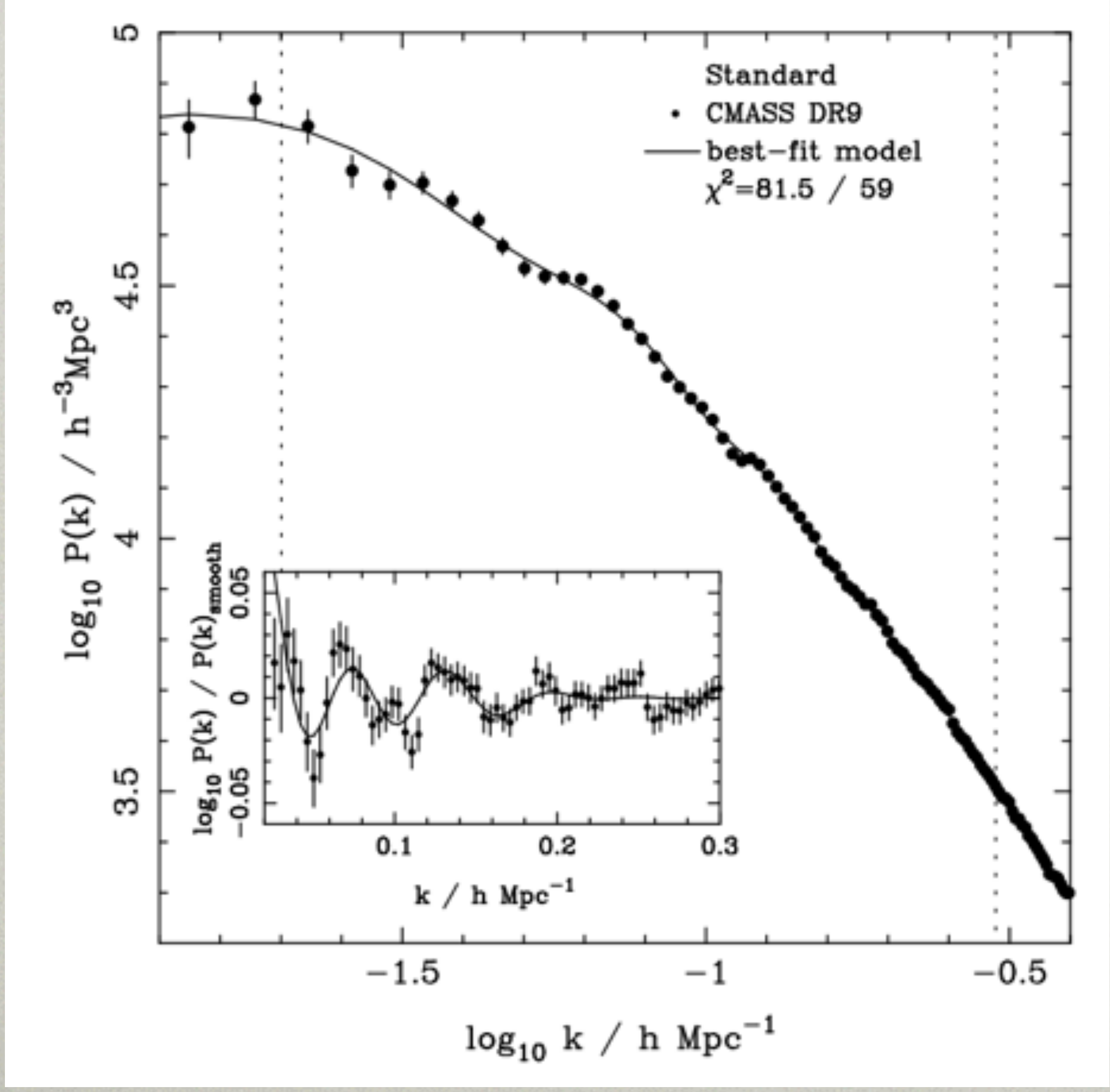


Neighbouring objects are likely to cluster.

Power spectrum

The equivalent in Fourier space:

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



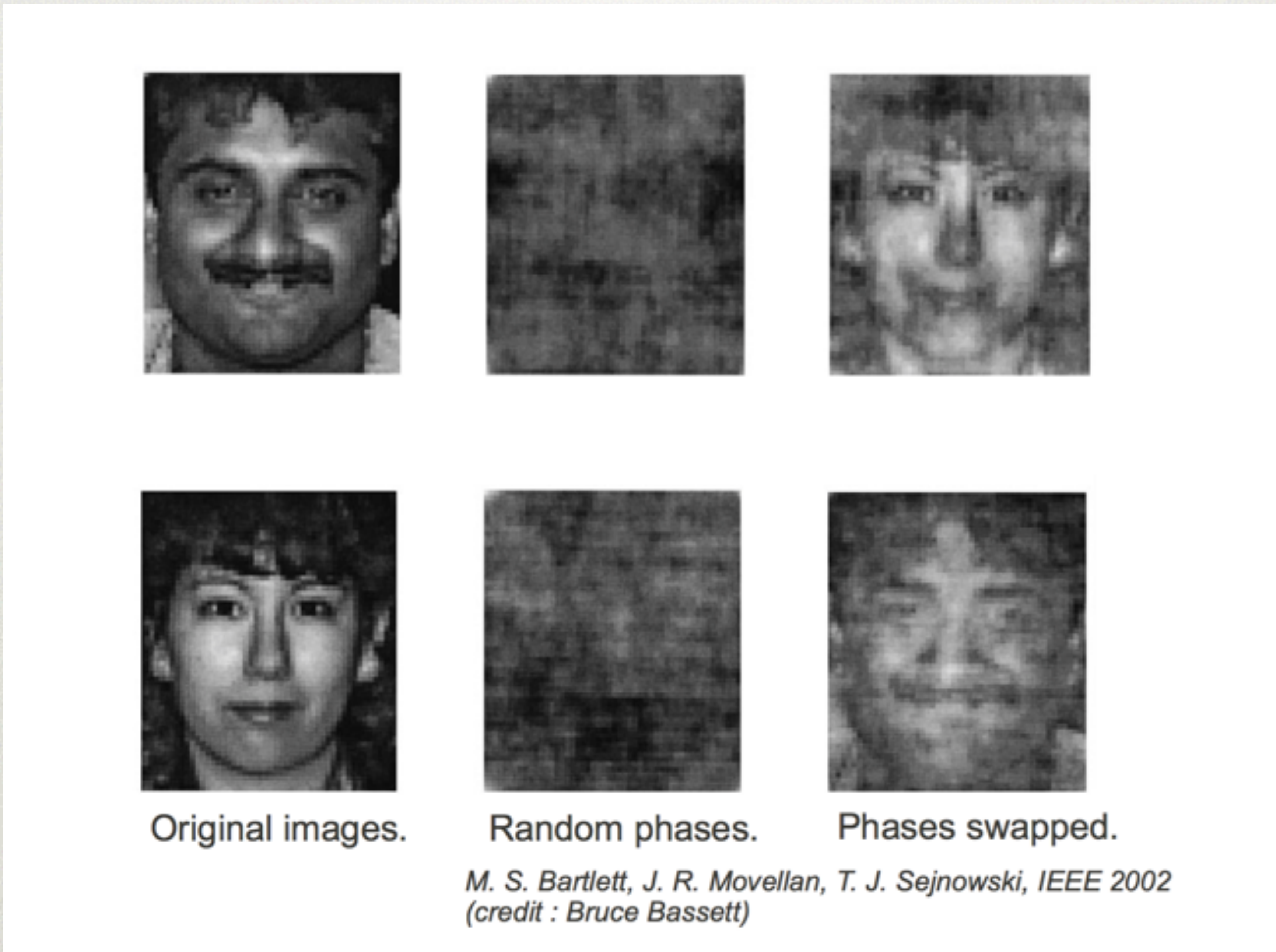
This is the typical amplitude squared of modes of wavenumber k.

Often written:

$$\Delta^2(k) = \frac{k^3 P(k)}{2\pi^2}$$

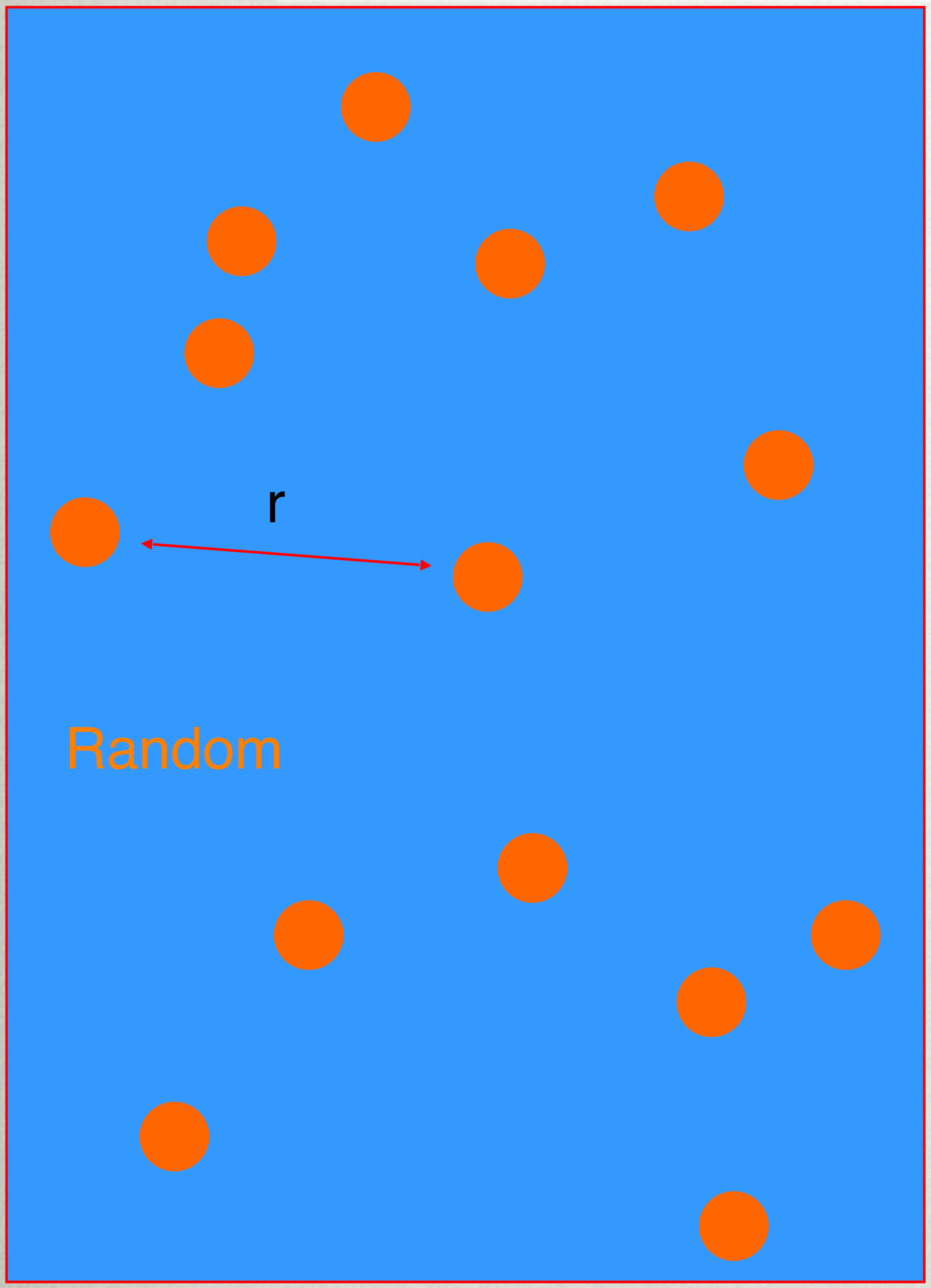
which is dimensionless.

There is more to cosmology...



If the field isn't Gaussian, there is more information in higher order statistics, phase correlations

MEASURING ξ(R)

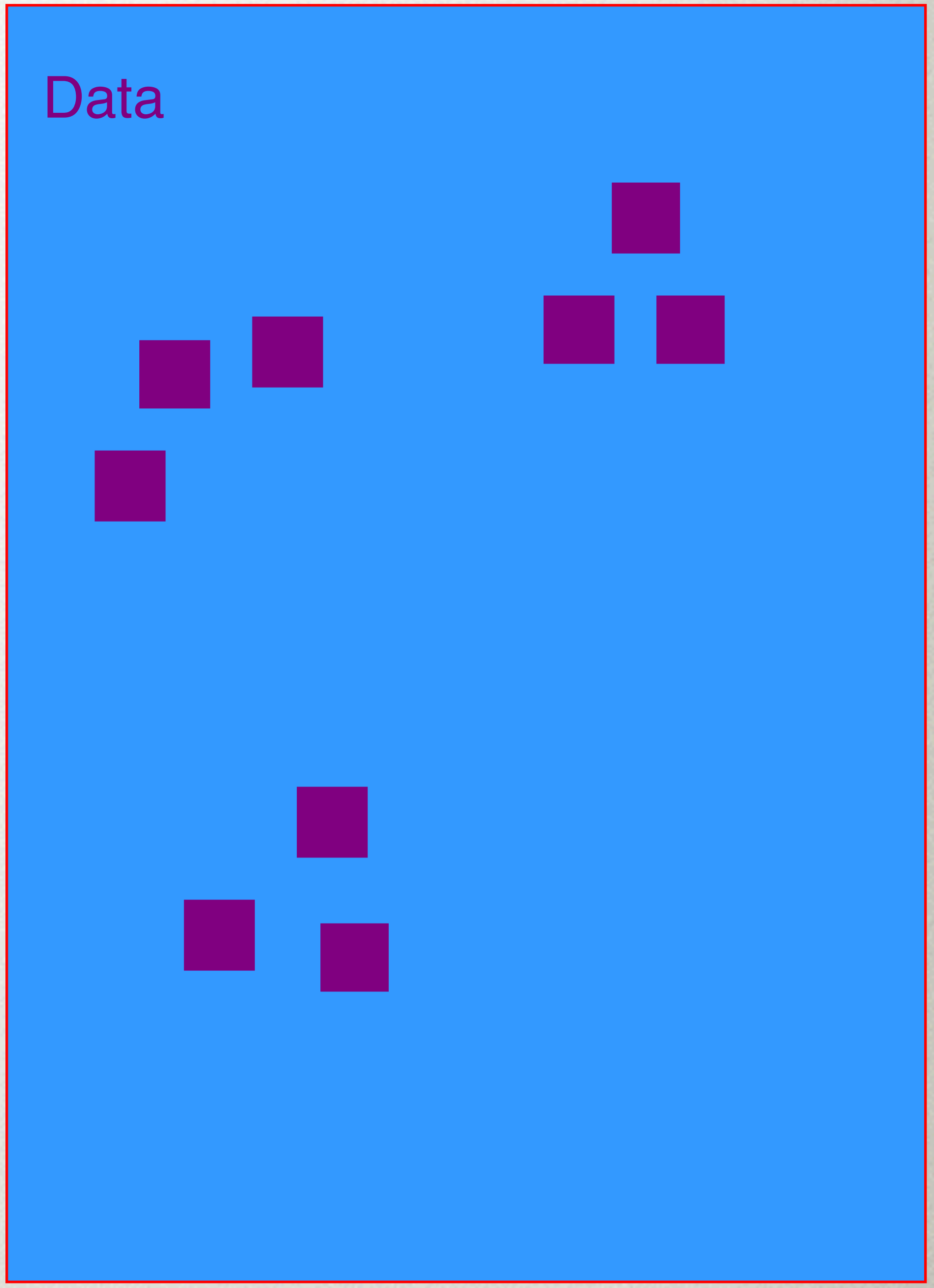


Simple estimator:
$\xi(r) = DD(r)/RR(r) - 1$

Better estimator (Landy & Szalay 93):
$\xi(r) = (DD-2DR+RR)/RR$

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

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



Errors on ξ

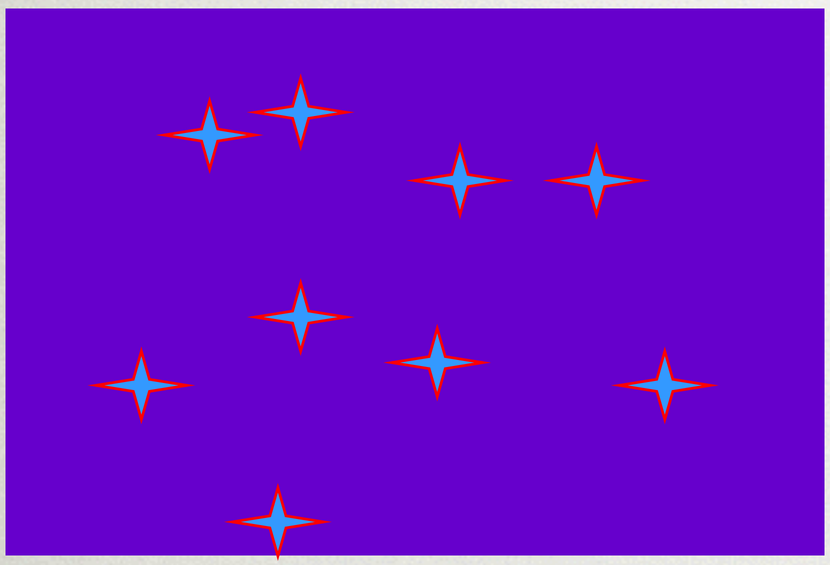
On small scales, the errors are Poisson

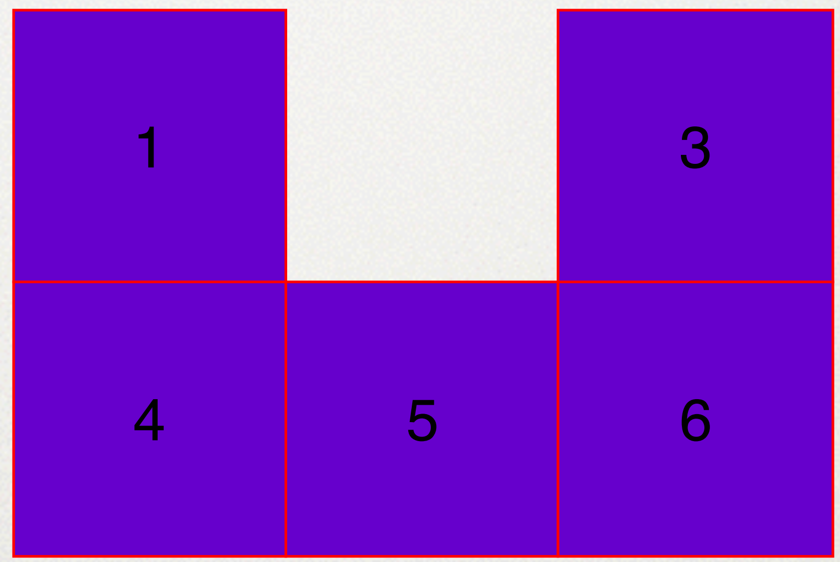
On large scales, errors are correlated and typically larger than Poisson

- *Use mock catalogs*
  - PROS: True measure of cosmic variance
  - CONS: Hard to include all observational effects
- *Use jack-knifes (JK)*
  - PROS: Uses the data directly
  - CONS: Noisy and unstable matrices

Jack-knife Errors

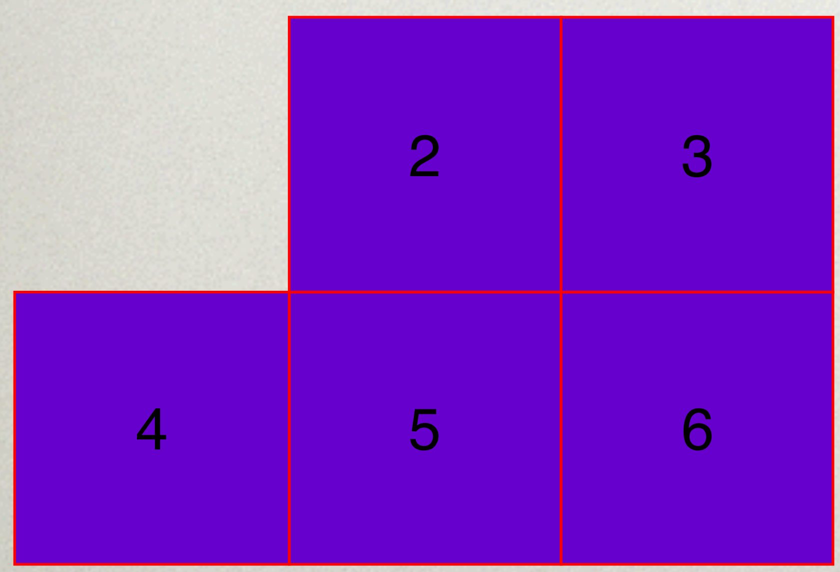
Real Data





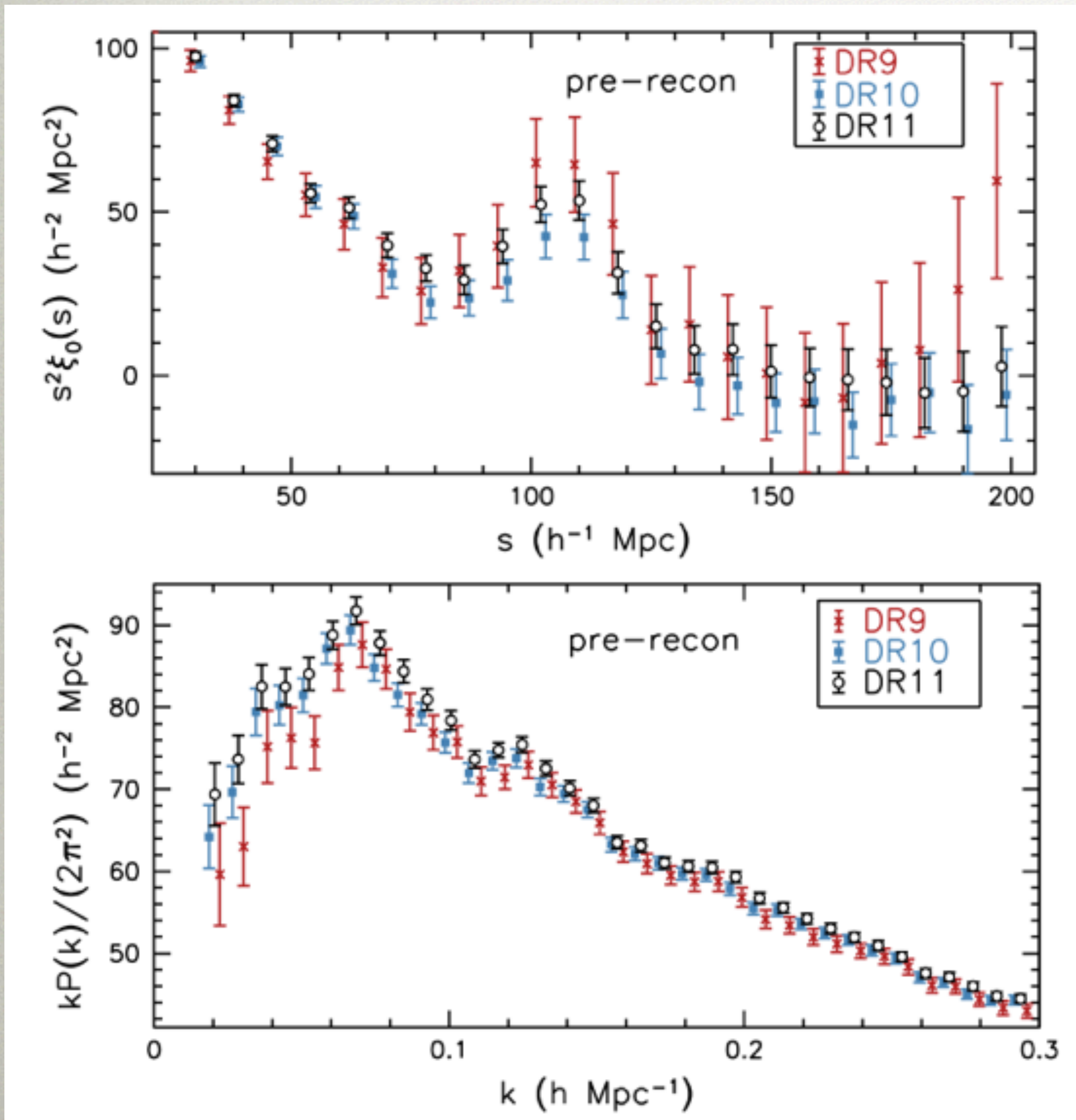
N=6

- Split data into N equal subregions
- Remove each subregion in turn and compute $\xi(r)$
- Measure covariance between regions



$$\mathrm{Covar}(\xi_i, \xi_j) = \frac{N-1}{N} \sum_{l=1}^{N} ({\xi_i}^l - \bar{\xi}_i)({\xi_j}^l - \bar{\xi}_j)$$

Measured 2-point functions



NB Correlated data points

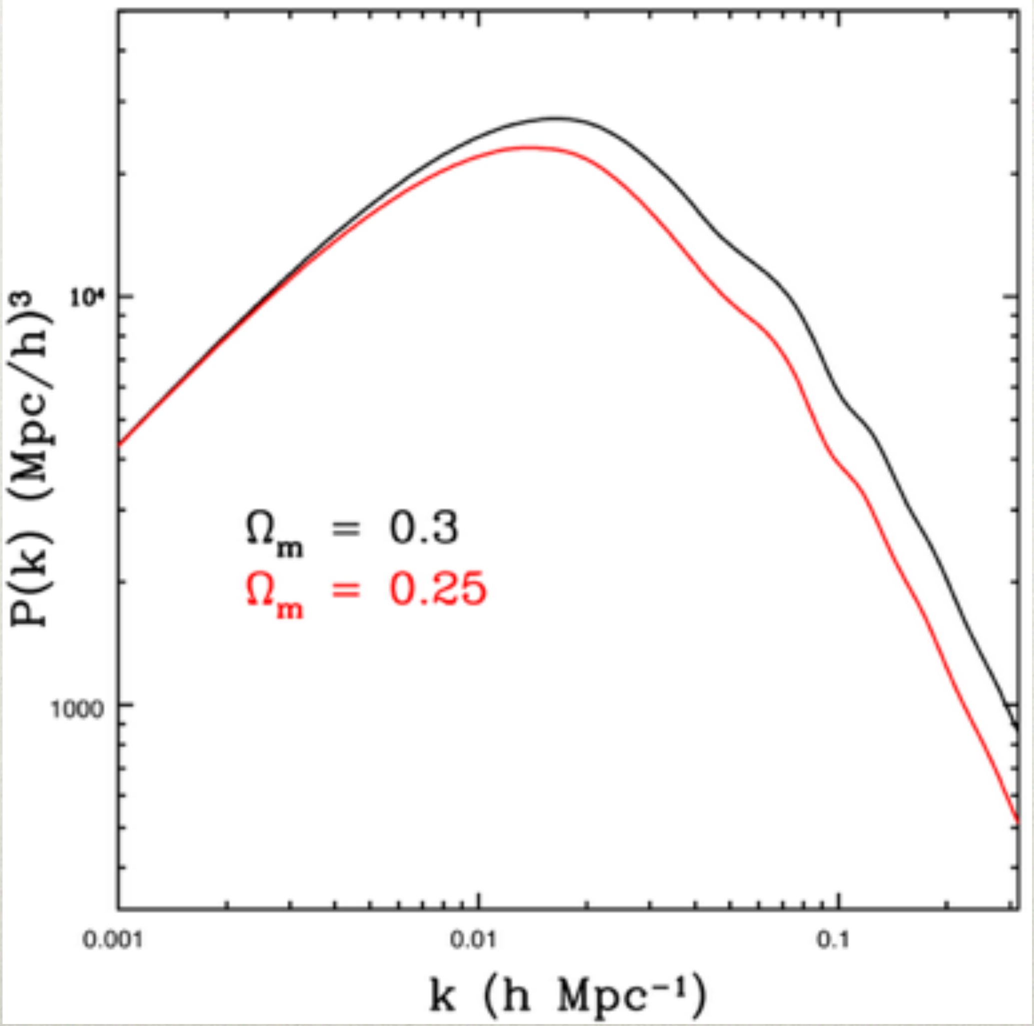
Baryon acoustic oscillations

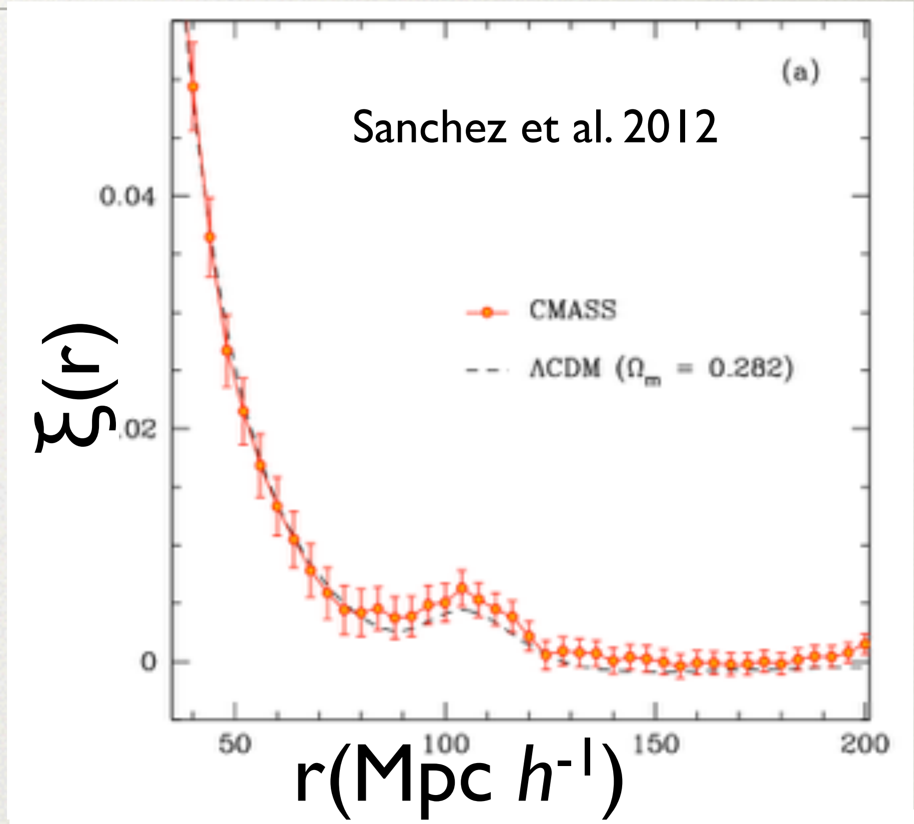
Anderson et al. 2013

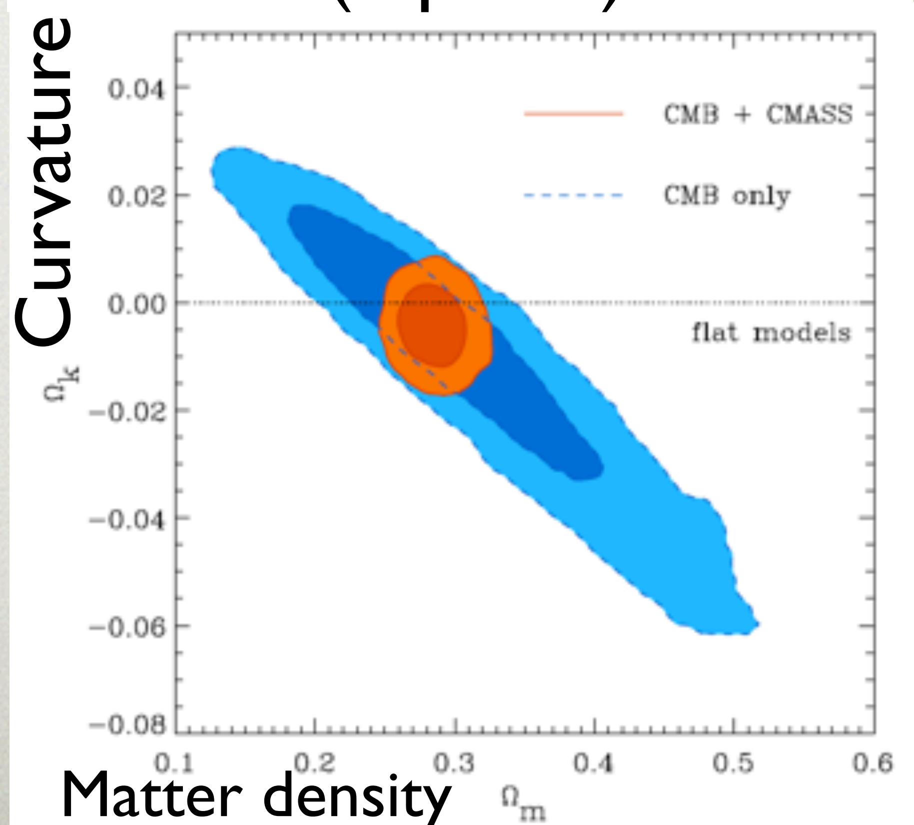
Using the entire Power Spectrum

The power spectrum depends on density and clumpiness of matter.

Turnover corresponds to when modes can collapse (Meszaros); depends on time of matter-rad equality, hence matter density







Observational Systematics

All sorts of issues can enter to upset the number of galaxies counted:

Sky background varies

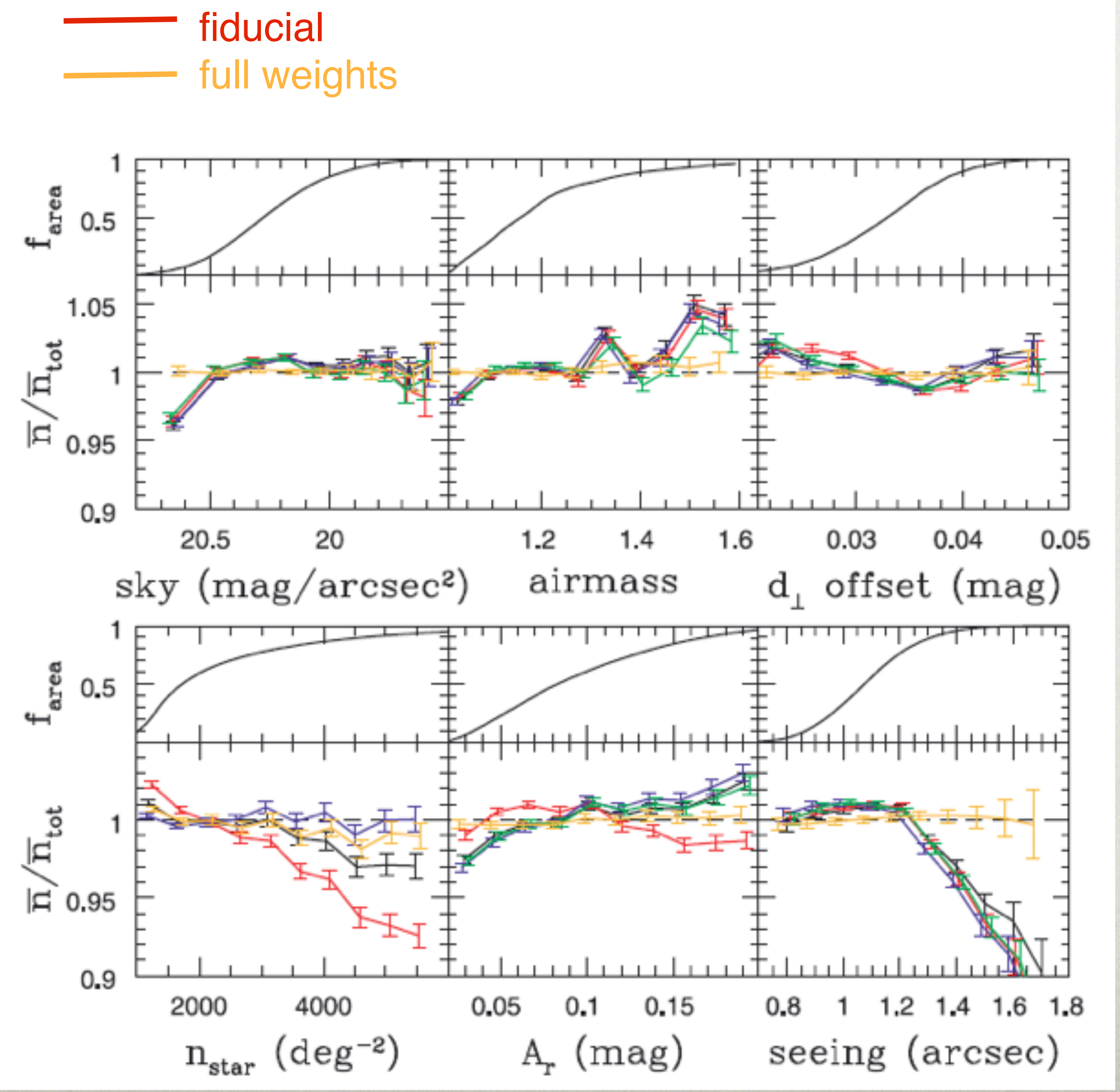
Look through more/less atmosphere (airmass)

Atmospheric conditions - seeing

Number of stars

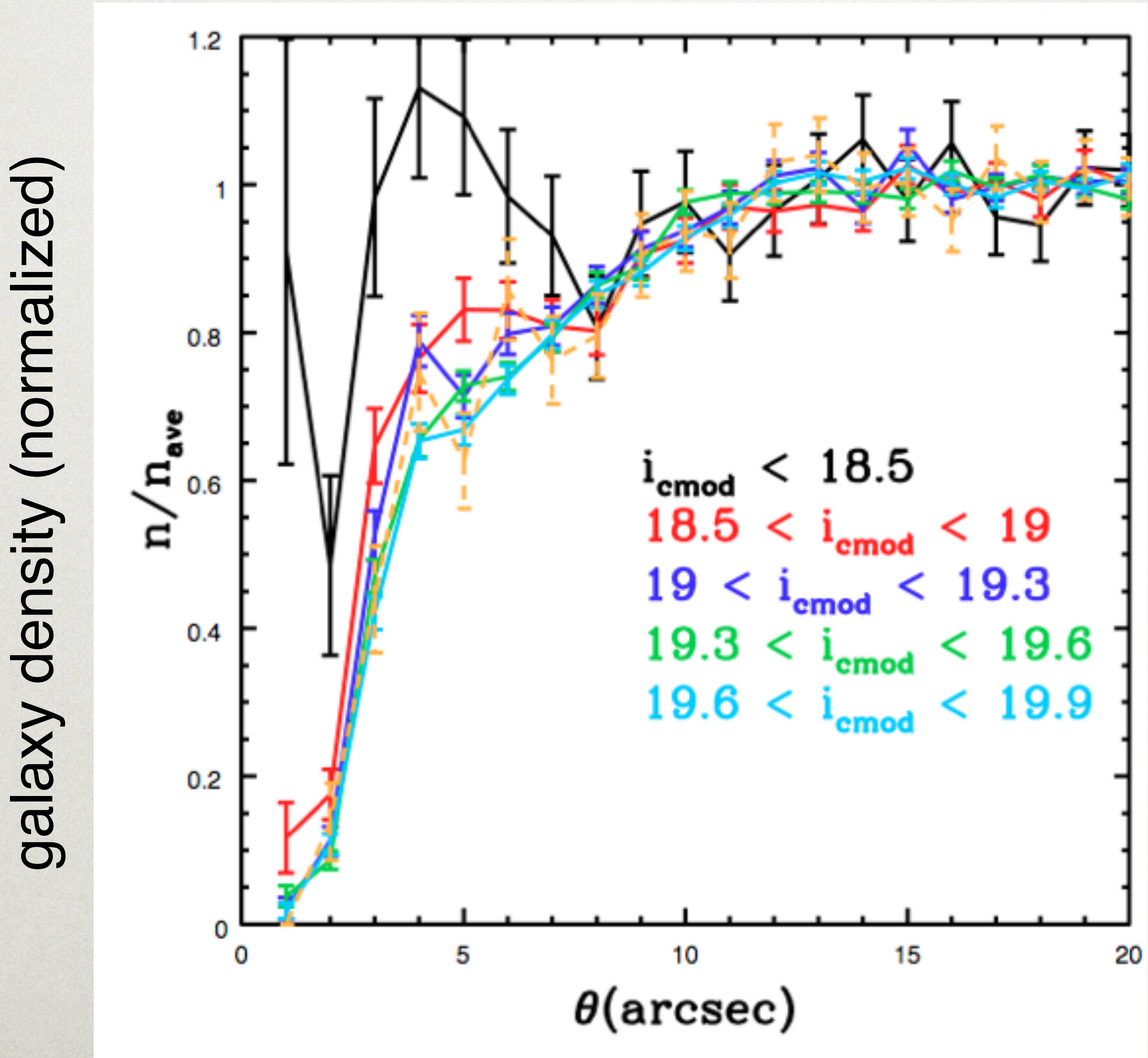
Galactic dust

IMAGING SYSTEMATICS



Ross et al. 2011

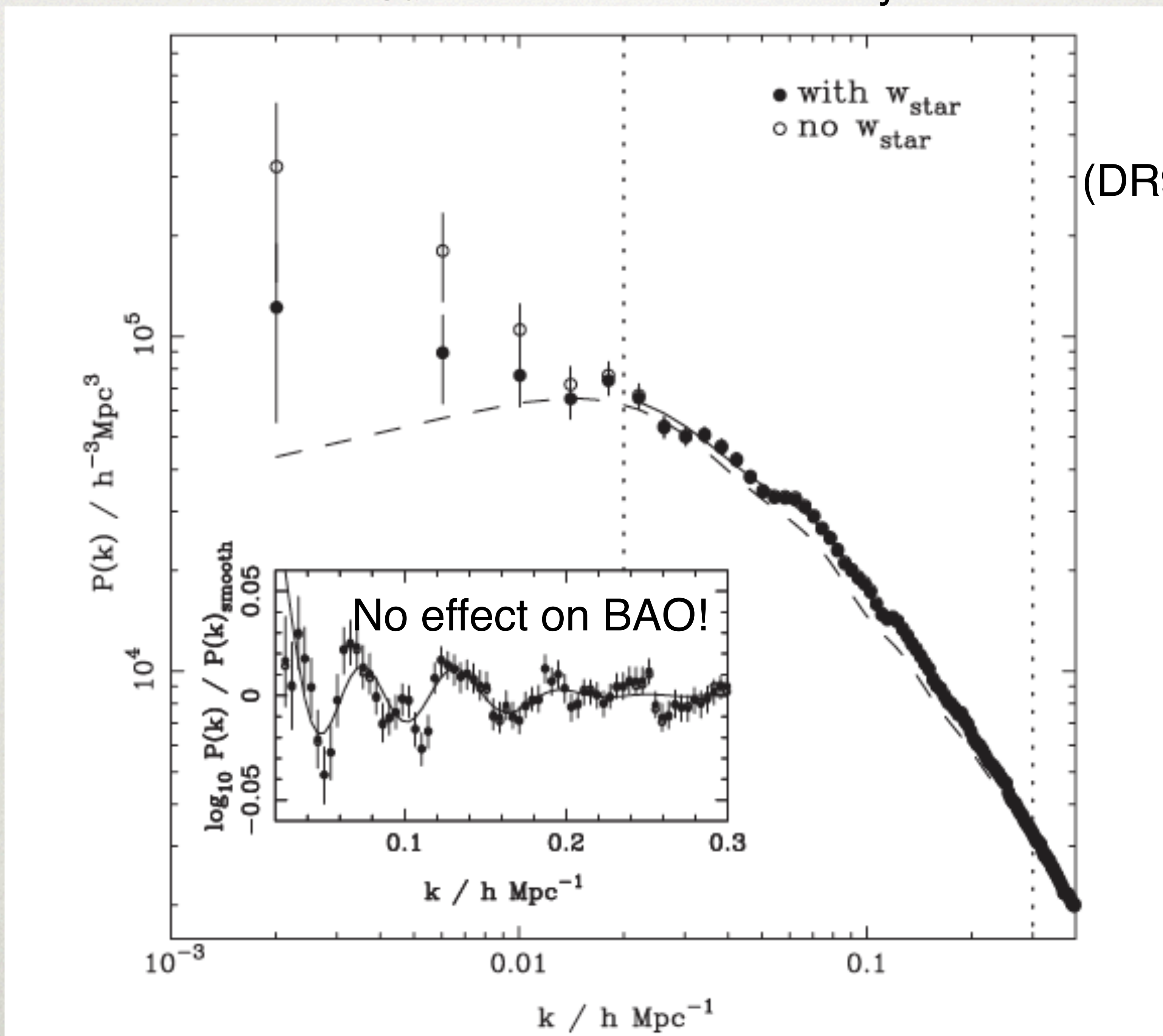
Effect of stars



Ross et al. 2011

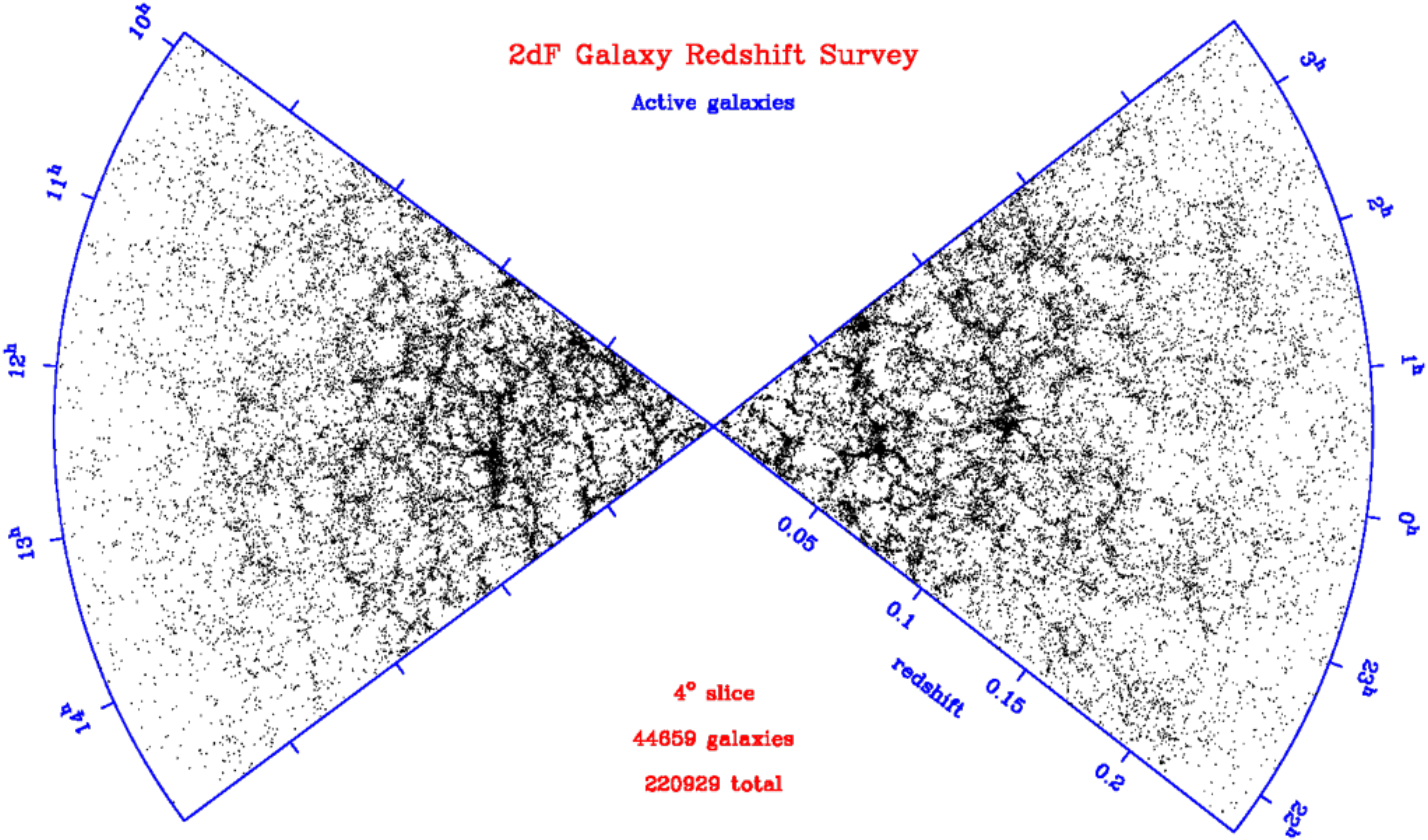
Effect on clustering

w_{star}: correction for stellar systematic

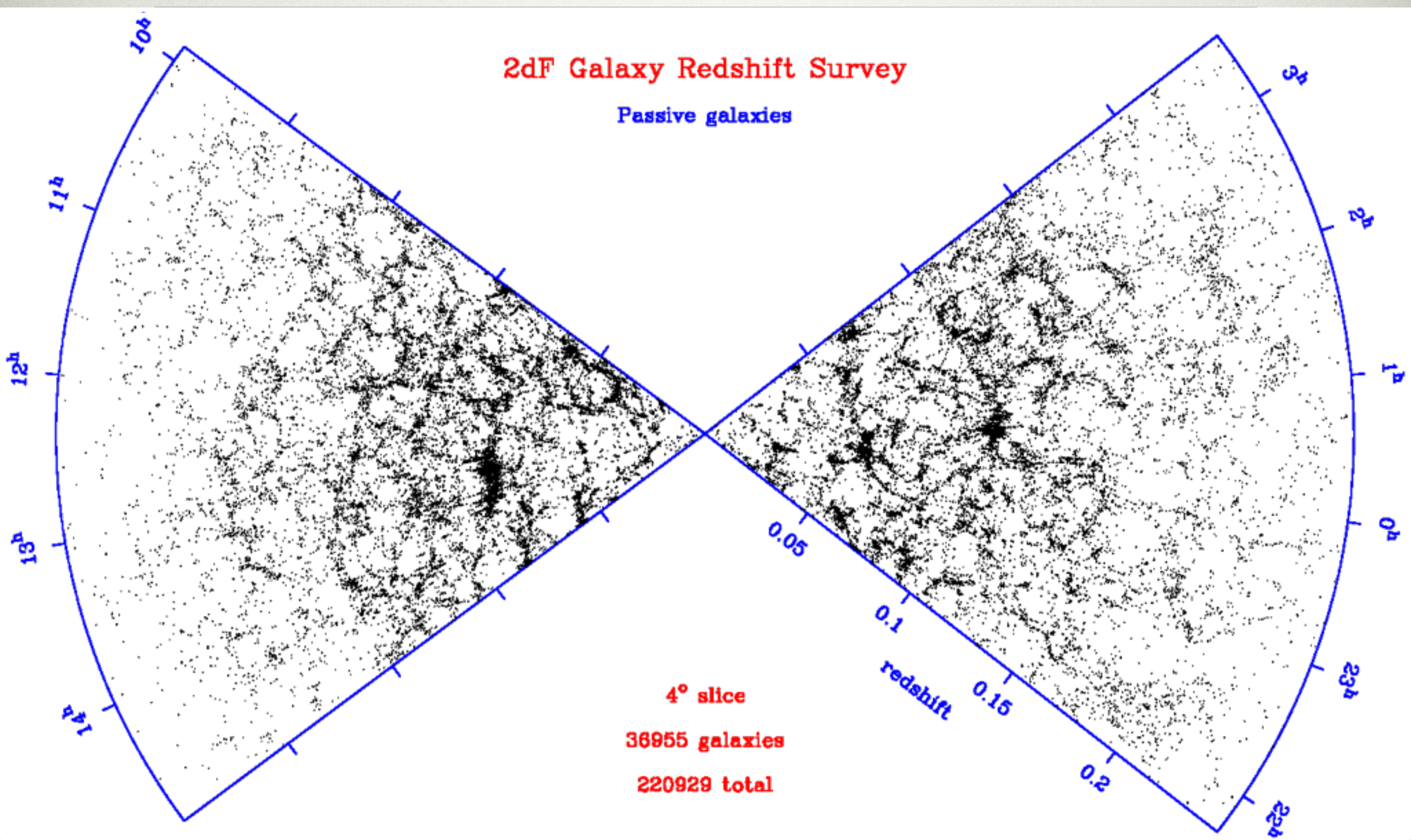


Ross et al. 2012

Galaxies are Biased



Galaxies are Biased



Galaxy are Biased

$$\delta_g = b\delta$$

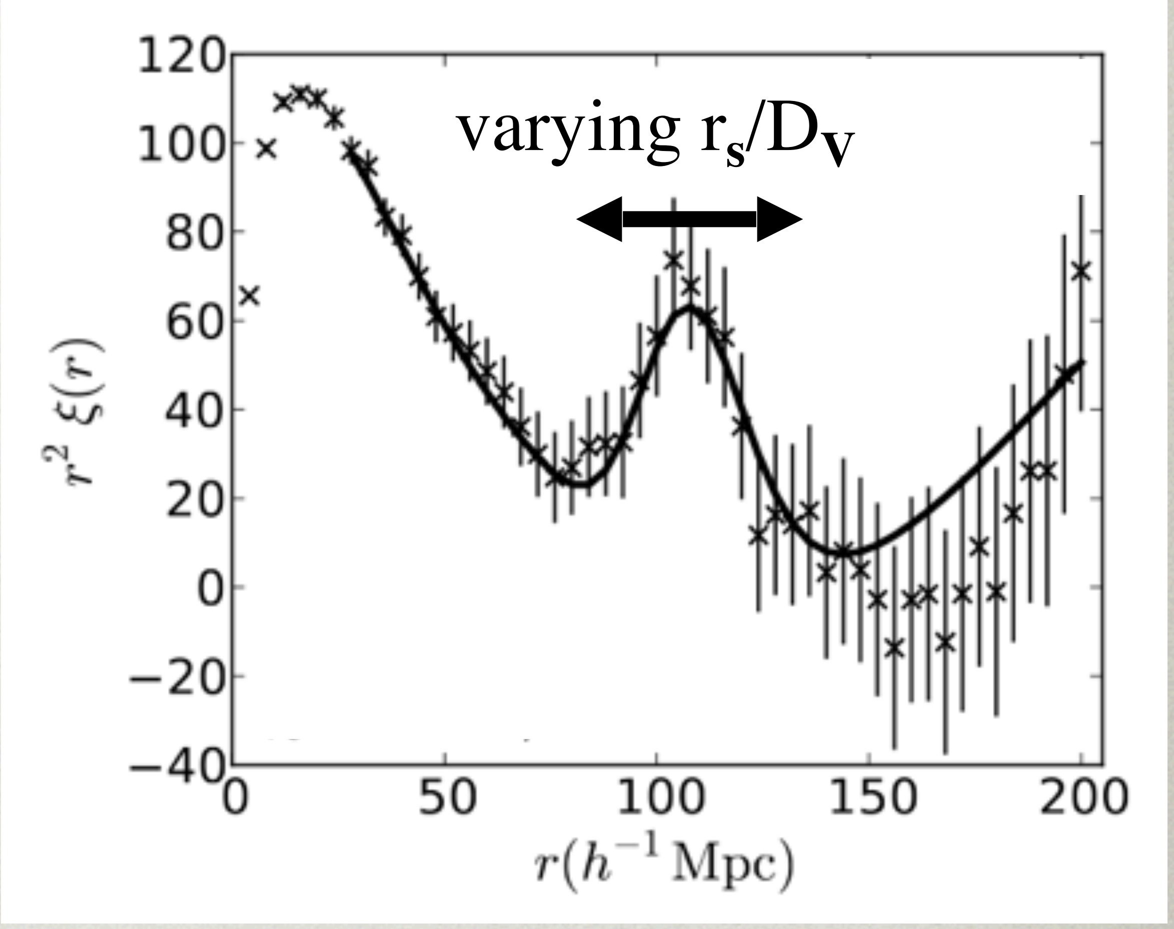
Baryon acoustic oscillations: Standard Ruler

Using all pairs in a thick redshift slice, we have pairs orientated radially and transversely and everything in between.

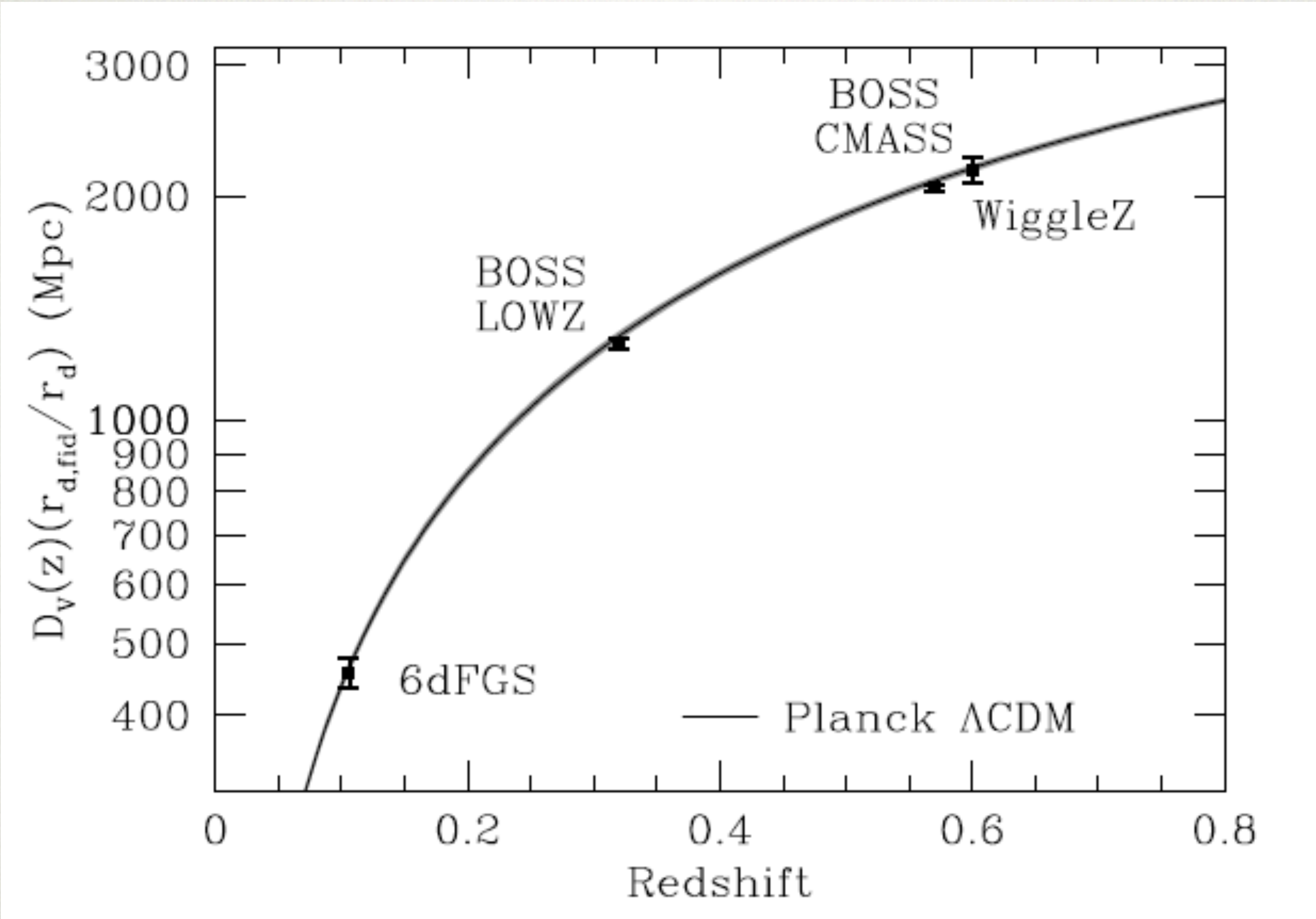
We can try to constrain an averaged distance measure,

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

Transverse Radial

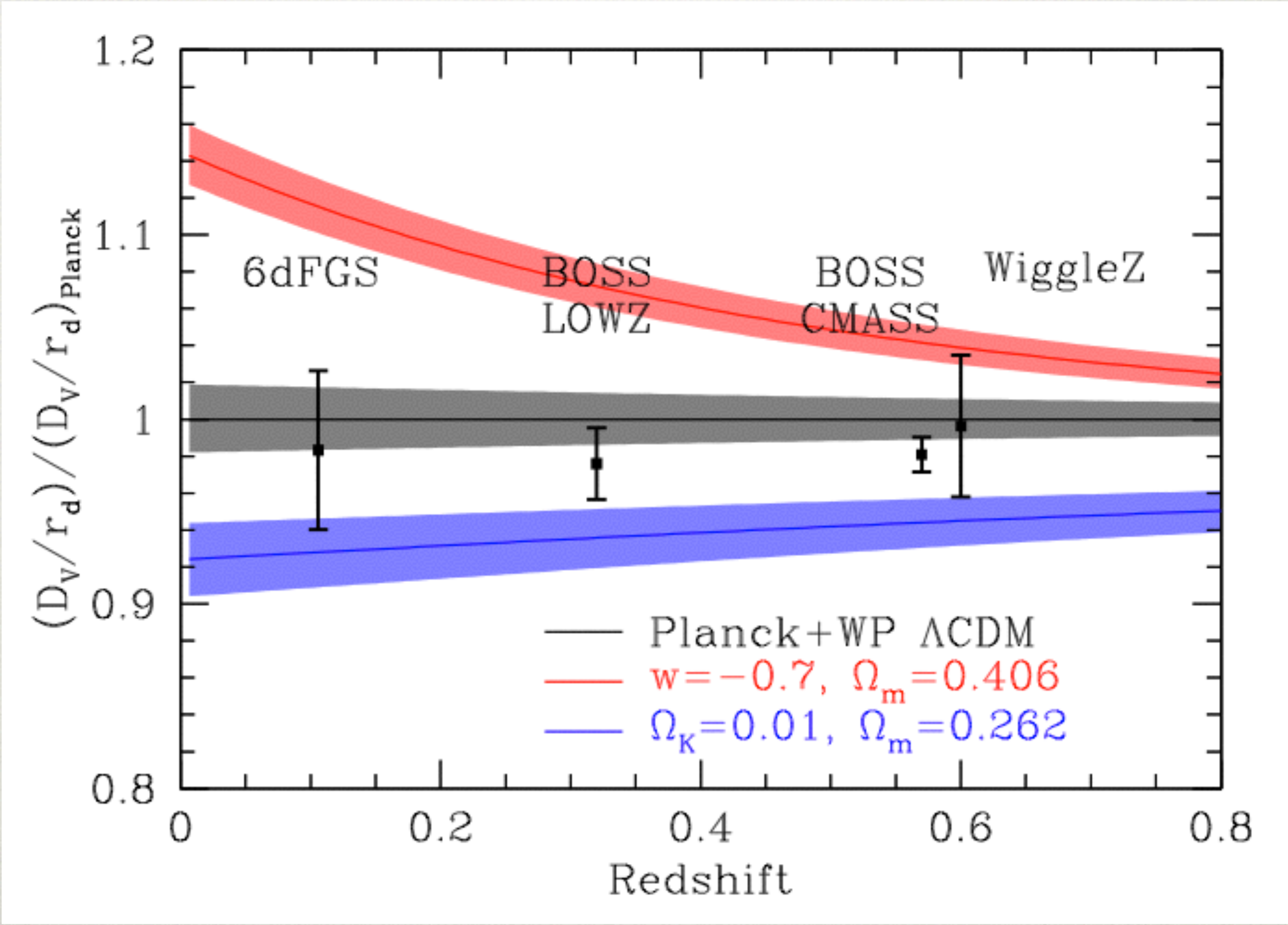


Expansion History



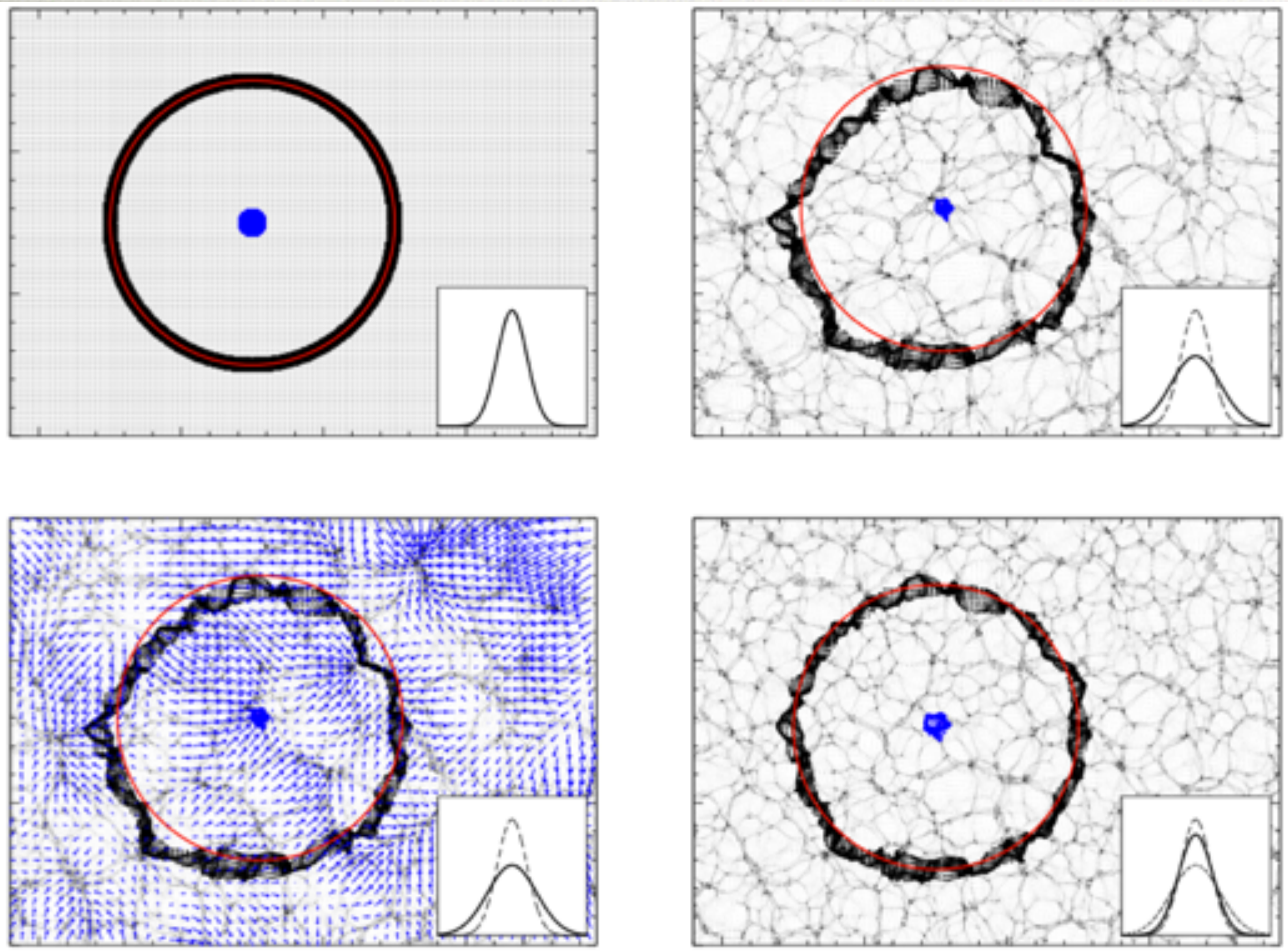
Anderson et al. (2014)

Expansion History

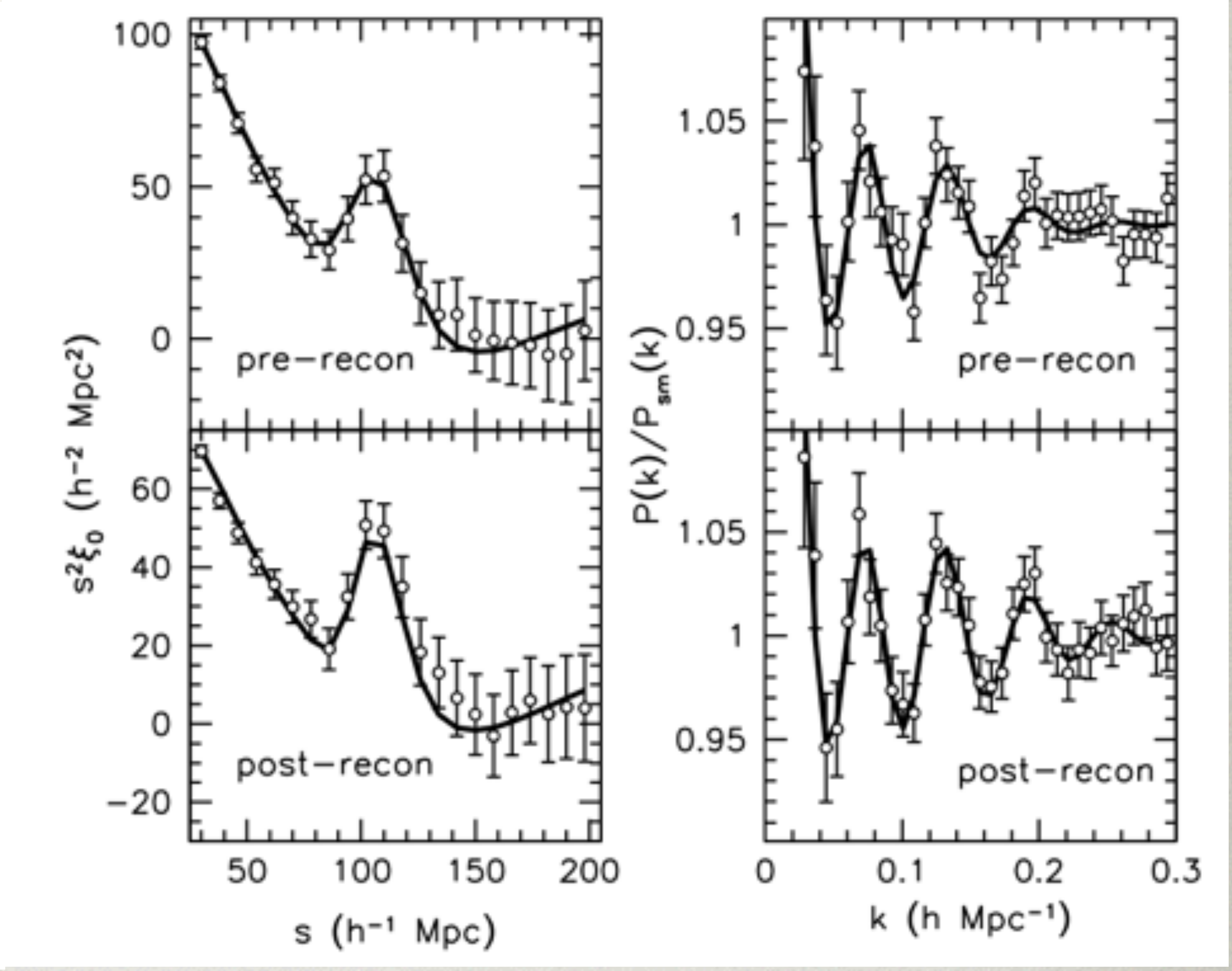


Anderson et al 2013

Velocities blur BAO



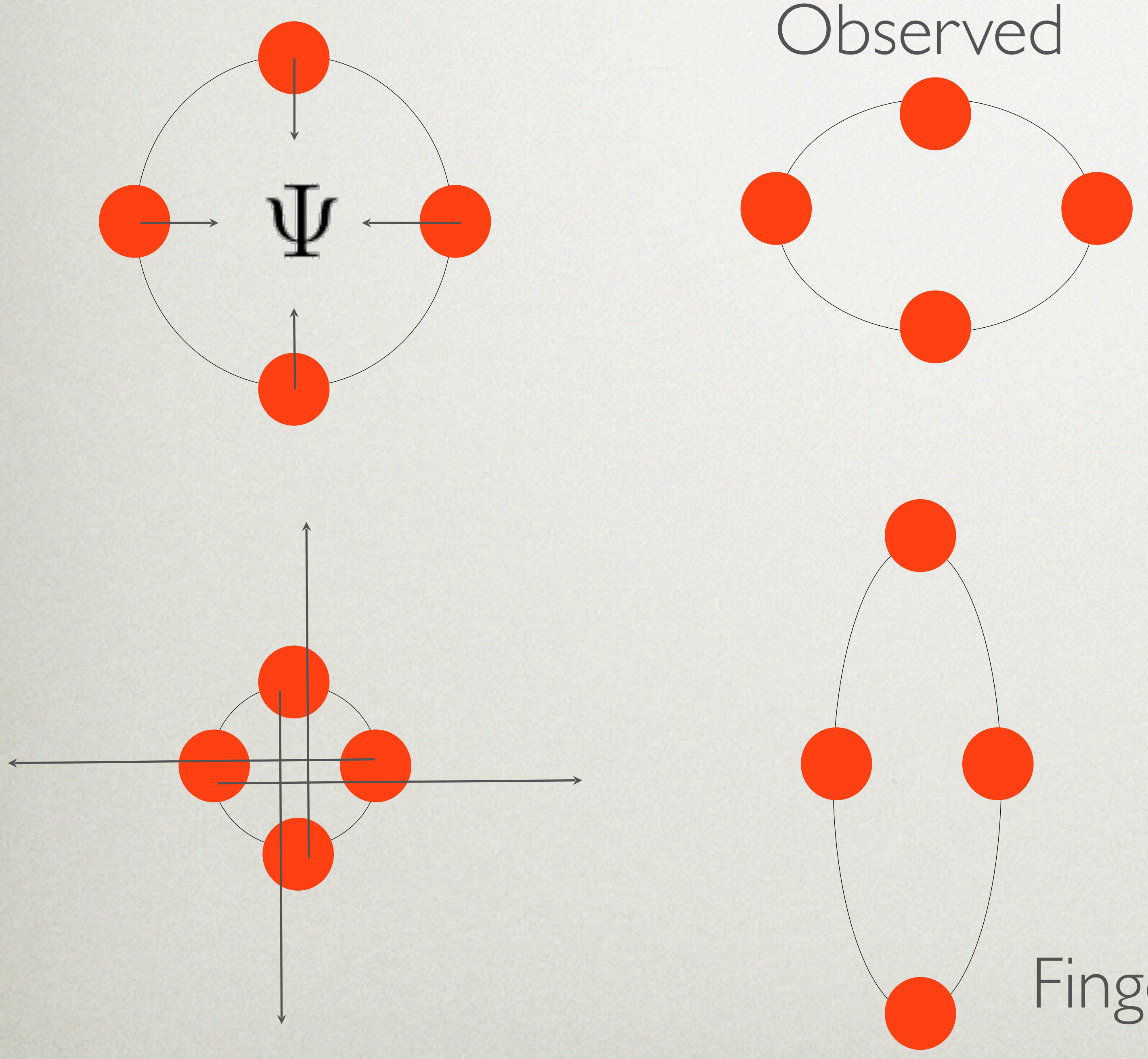
Padmanabhan et al 2012

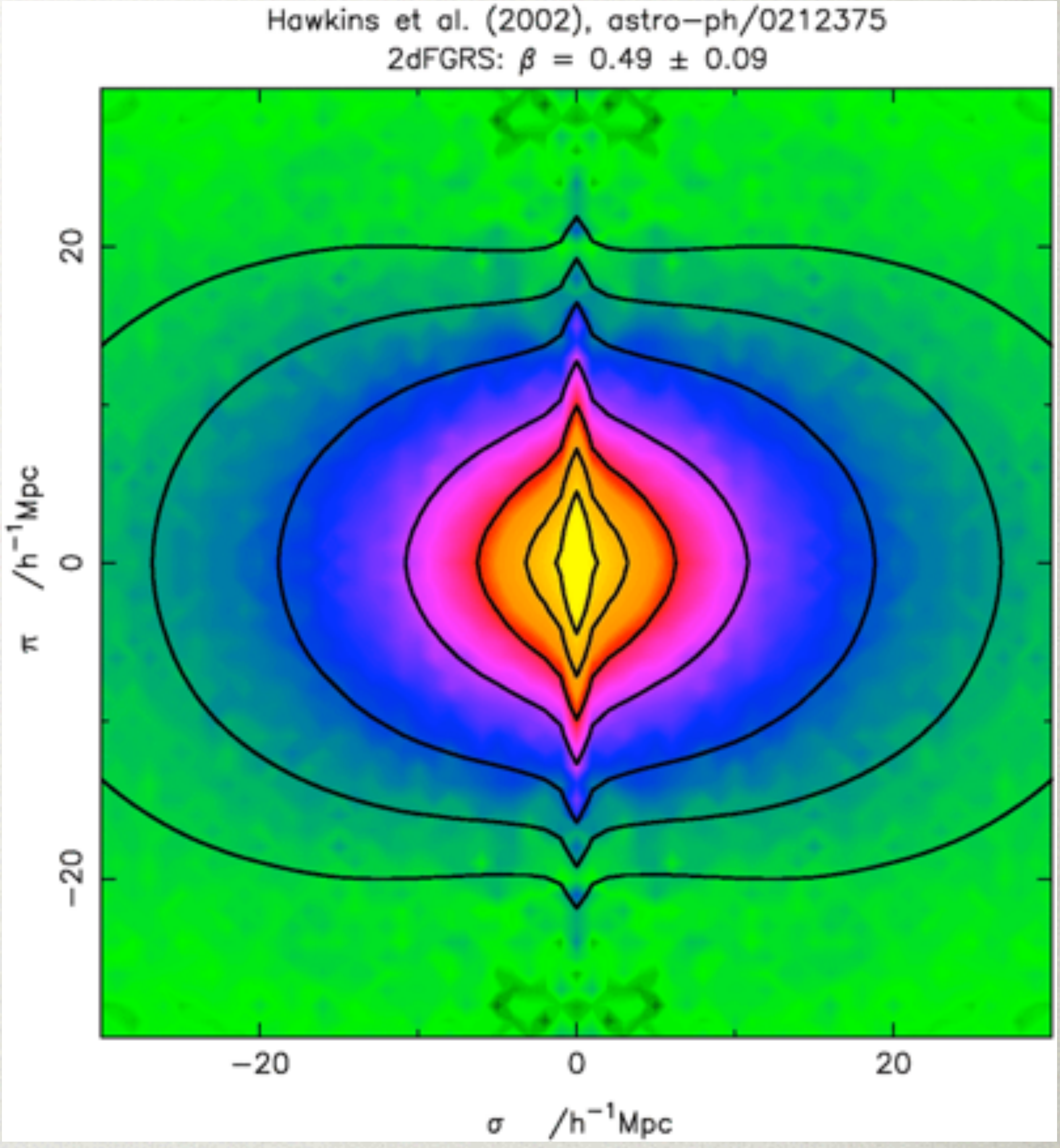


Anderson et al 2013

Peculiar Velocities

Redshift space distortions:





How do velocities act?

Redshift space $\mathbf{s} = \mathbf{x} + v_z(\mathbf{x})\widehat{\mathbf{z}}$

Continuity

Euler

Poisson

$$\delta \propto D(a)$$

$$\frac{d \ln D}{d \ln a}$$

Velocities flow towards mass concentrations

$$\nabla \cdot \mathbf{v} = -f\delta$$

How do velocities act?

Leads in Fourier domain to

$$v_z = -\frac{k_z}{k^2} f\delta$$

$$\theta \equiv \nabla \cdot \mathbf{v} = -f\delta$$

For galaxies including bias,

$$v_z = -\frac{k_z}{k^2}\frac{f}{b}\delta_{\mathrm{gal}} = -\frac{k_z}{k^2}\beta\delta_{\mathrm{gal}}$$

How do velocities act?

Mapping densities from physical to redshift space gives

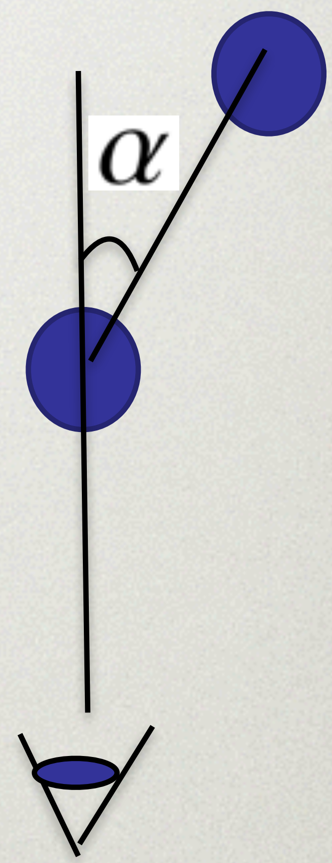
$$\delta^s_{\mathrm{gal}} = \delta^r_{\mathrm{gal}} - \frac{\partial v_z}{\partial r_z}$$

In Fourier space this gives

$$\delta^s_{\mathrm{gal}} = \delta^r_{\mathrm{gal}} - \frac{k_z^2}{k^2}\theta$$

Now

$$\frac{k_z}{k} = \mu = \cos(\alpha)$$

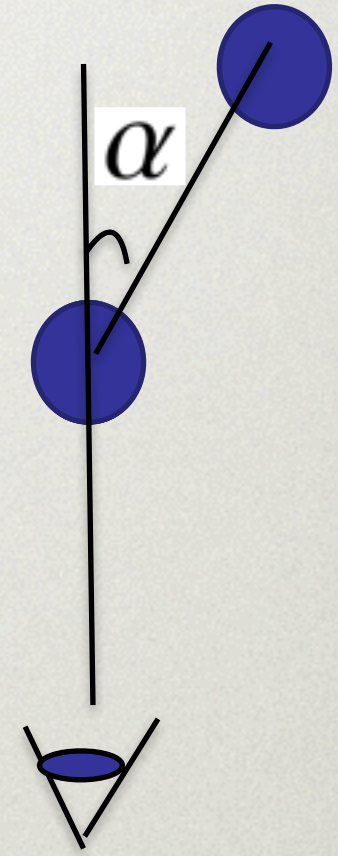


How do velocities act?

So finally $$\delta^s_{\rm gal} = \delta^r_{\rm gal} - \mu^2\theta$$

Then $$P^s_{gg} = P^r_{gg} - 2\mu^2 P^r_{g\theta} + \mu^4 P^r_{\theta\theta}$$

or $$P^s_{gg} = (b + \mu^2 f)^2 P^r_{\delta\delta}$$

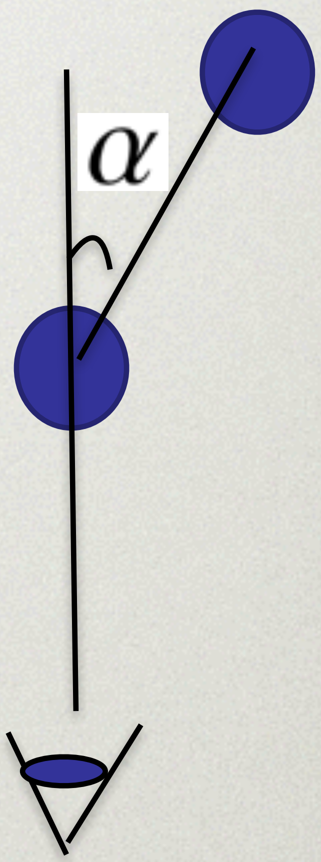


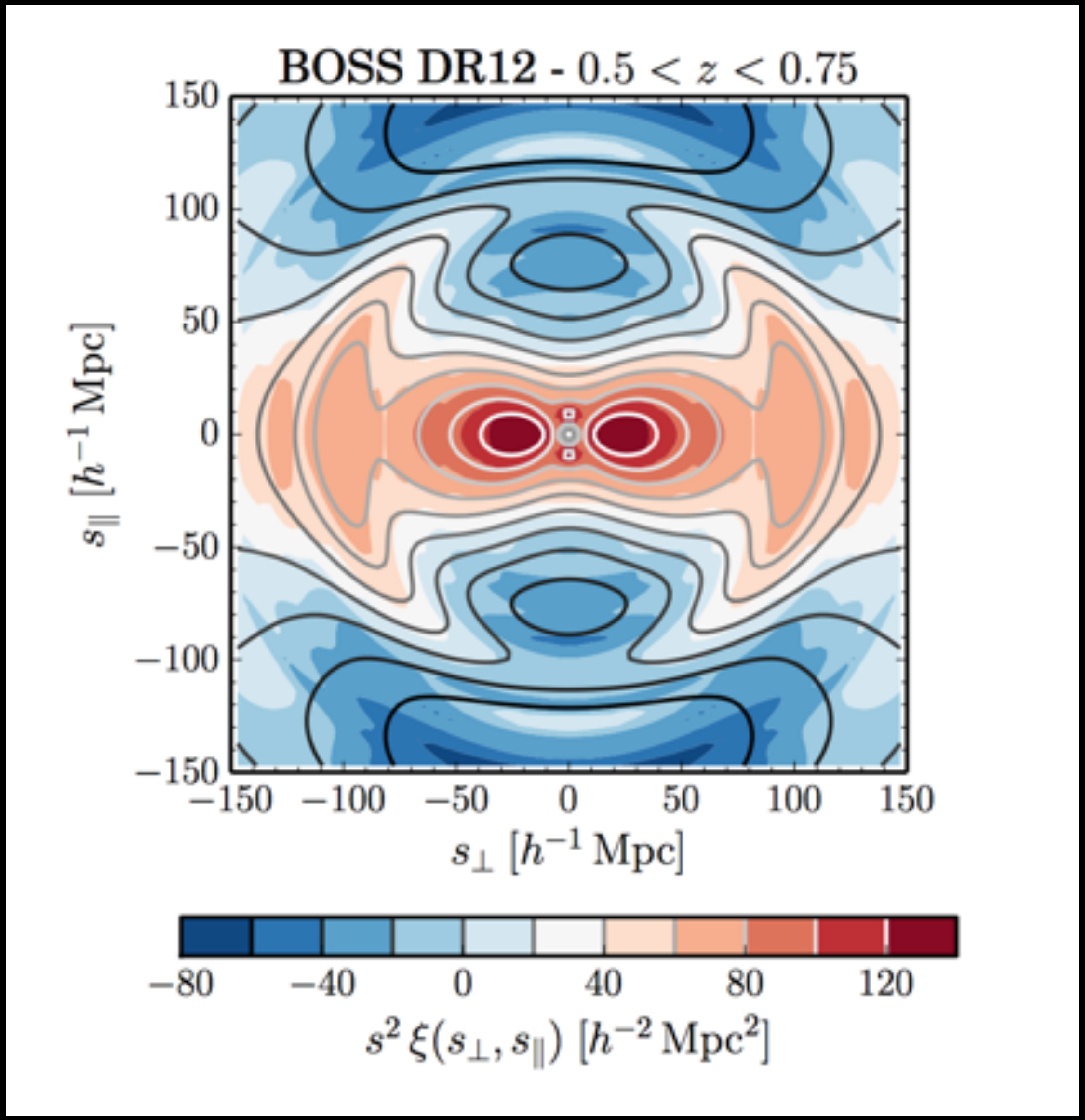
How do velocities act?

$$P^s_{gg} = (b + \mu^2 f)^2 P^r_{\delta\delta}$$

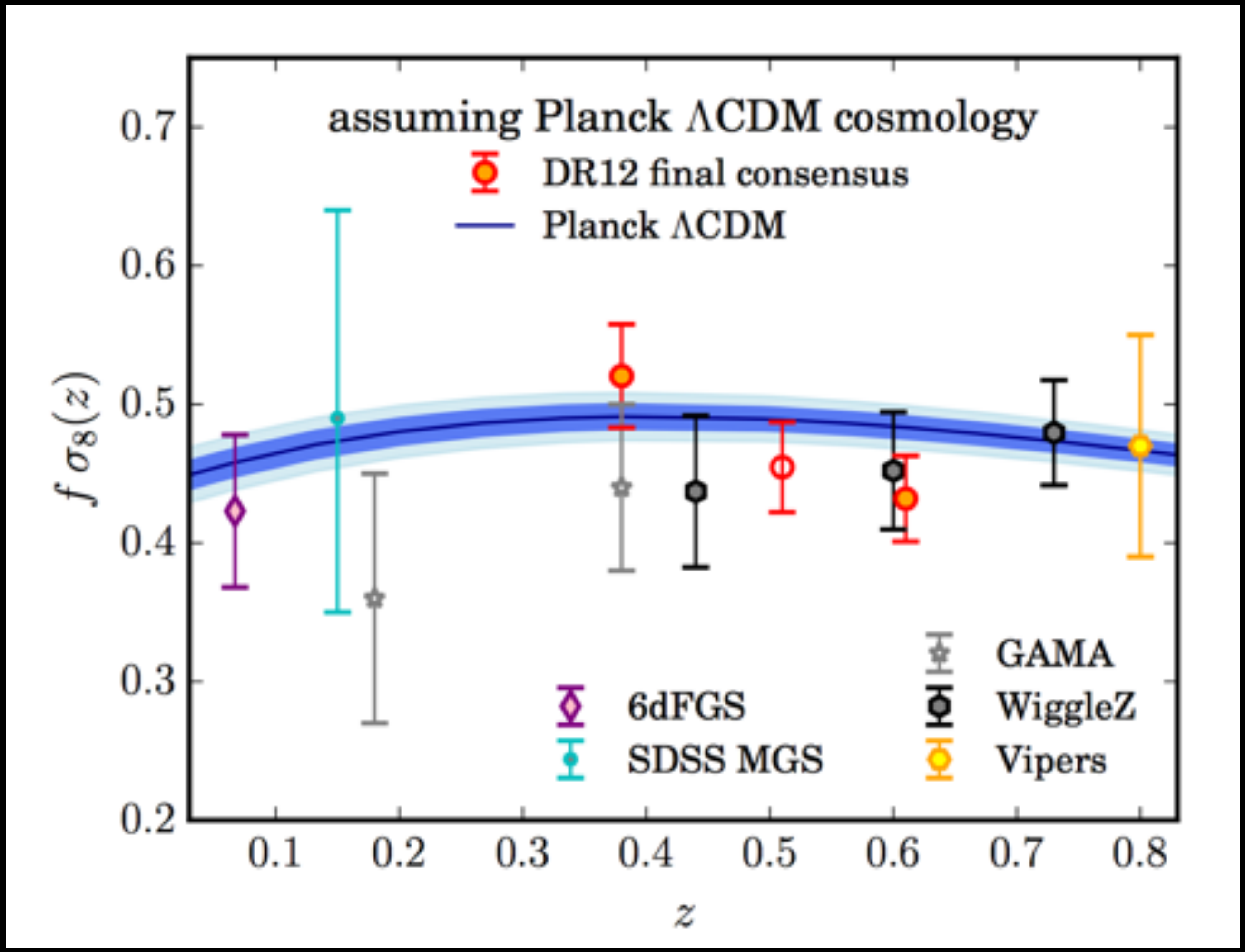
So anisotropic clustering amplitude constrains

$$(b + \mu^2 f)\sigma_8$$





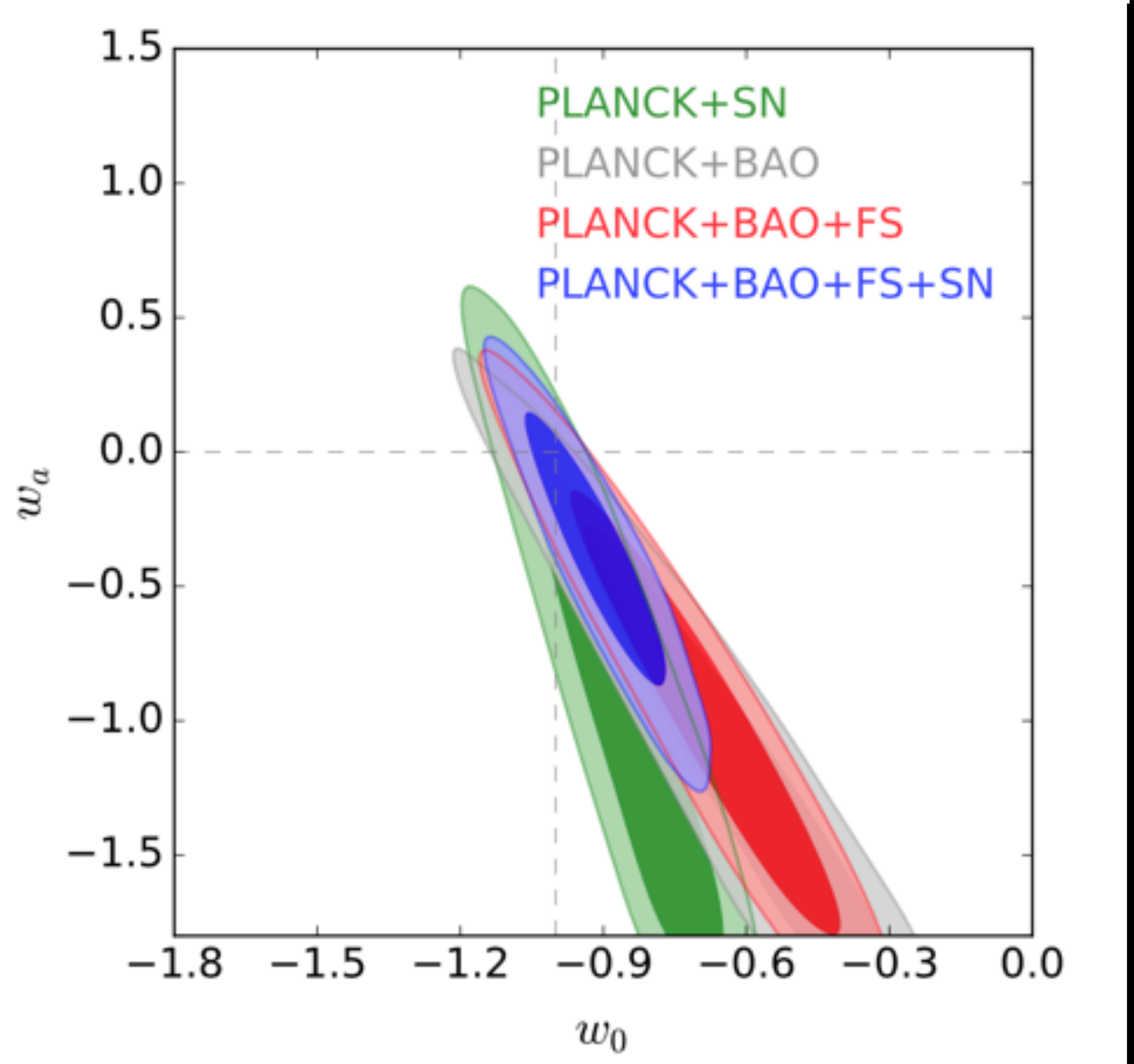
BOSS DR12



Alam et al 16

DARK ENERGY PHYSICS

$$w(a) = w_0 + (1 - a)w_a$$



Alam et al 16

Summary

We can use the clustering of galaxies to learn about cosmological quantities.

The full power spectrum constrains e.g. matter density.

Observational and cosmological systematics need careful control.

The baryon acoustic oscillations can precisely constrain distances in the Universe and hence properties of dark energy.

Redshift space distortions inform us about growth of structure.