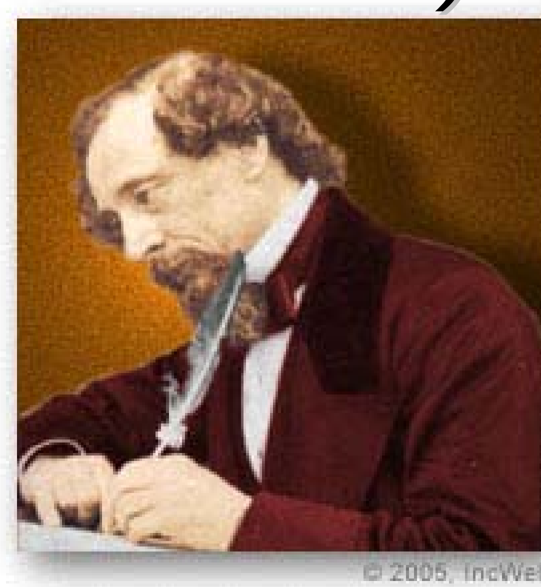
Large Scale Structure (Galaxy Correlations)

Bob Nichol (ICG,Portsmouth)

QuickTime™ and a
TIFF (Uncompressed) decompressor
are needed to see this picture.

“majority of its surface area is only about 10 feet above sea level”



Overview

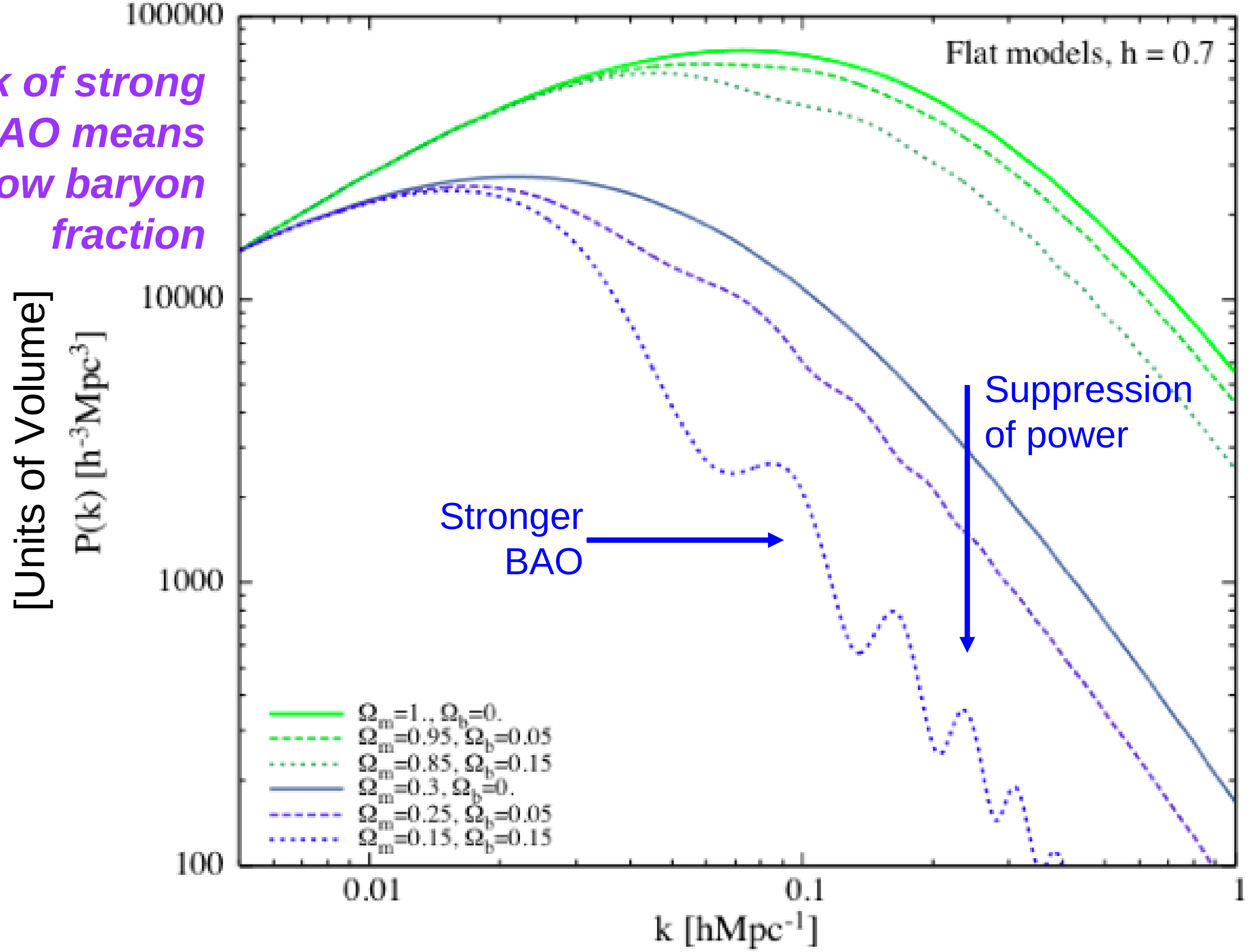
- **Redshift Surveys**
- **Theoretical expectations**
- **Statistical measurements of LSS**
- **Observations of galaxy clustering**
- **Baryon Acoustic Oscillations (BAO)**
- **ISW effect**

I will borrow heavily from two recent reviews:

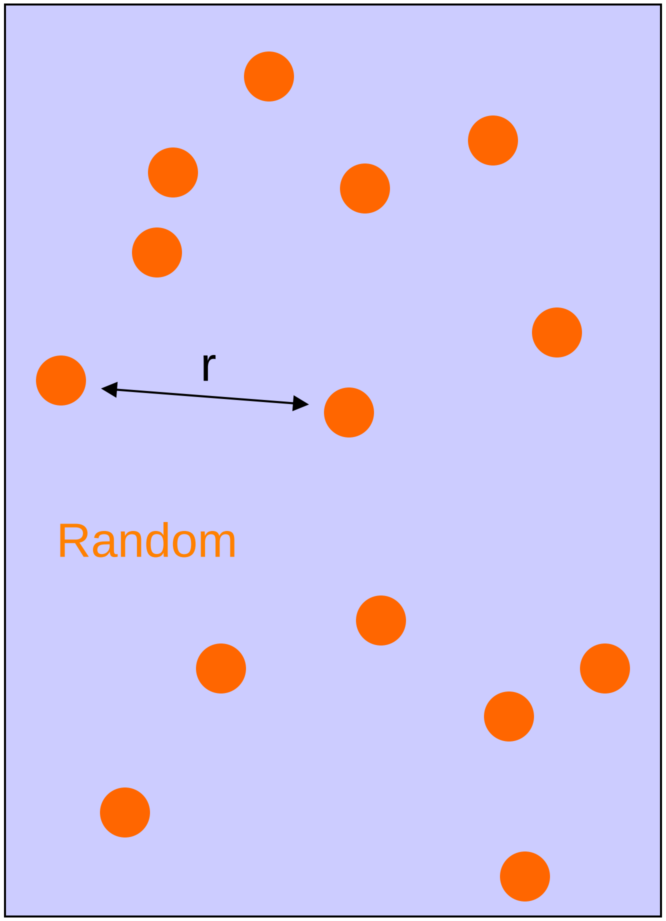
1. Percival et al. 2006, astro-ph/0601538
2. Nichol et al. 2007 (see my webpage)

P(k) models II

Lack of strong BAO means low baryon fraction



Measuring $\xi(r)$ or P(k)

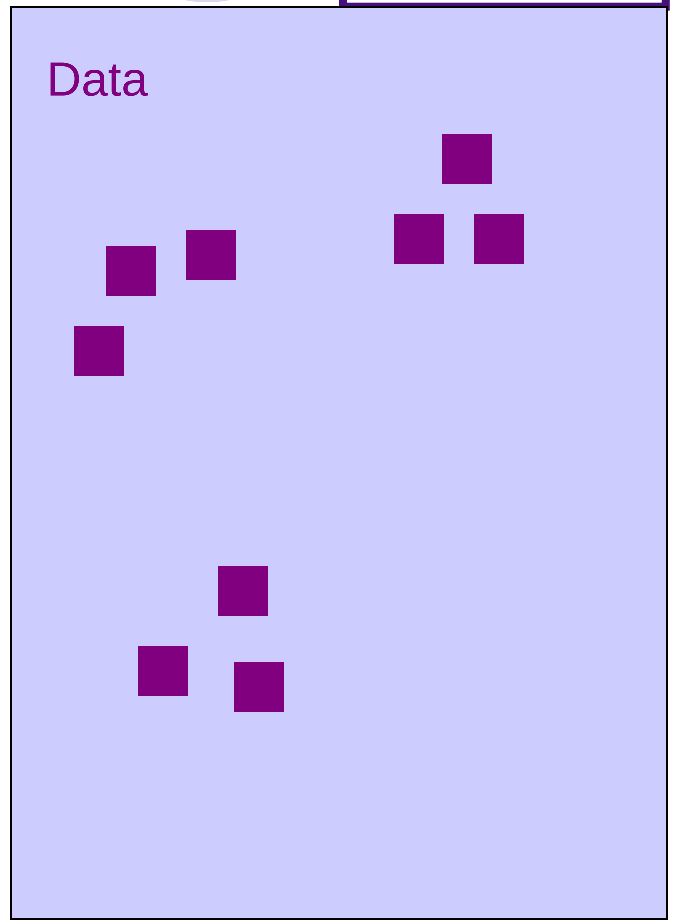


Simple estimator:
$\xi(r)$ = DD(r)/RR(r) - 1

Advanced estimator:
$\xi(r)$ = (DD-2DR+RR)/RR

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

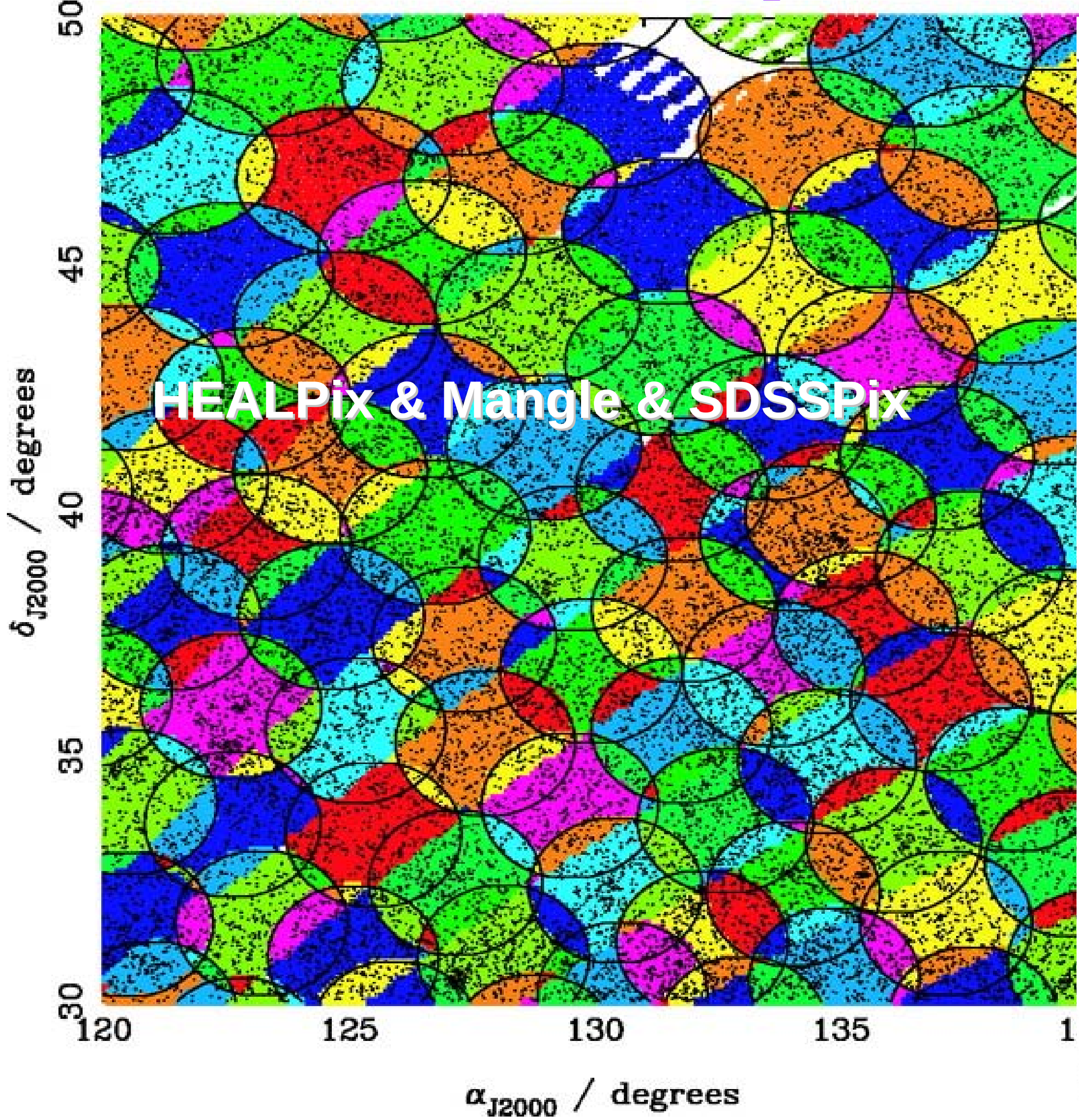
Usually 10x as many random points over SAME area / volume

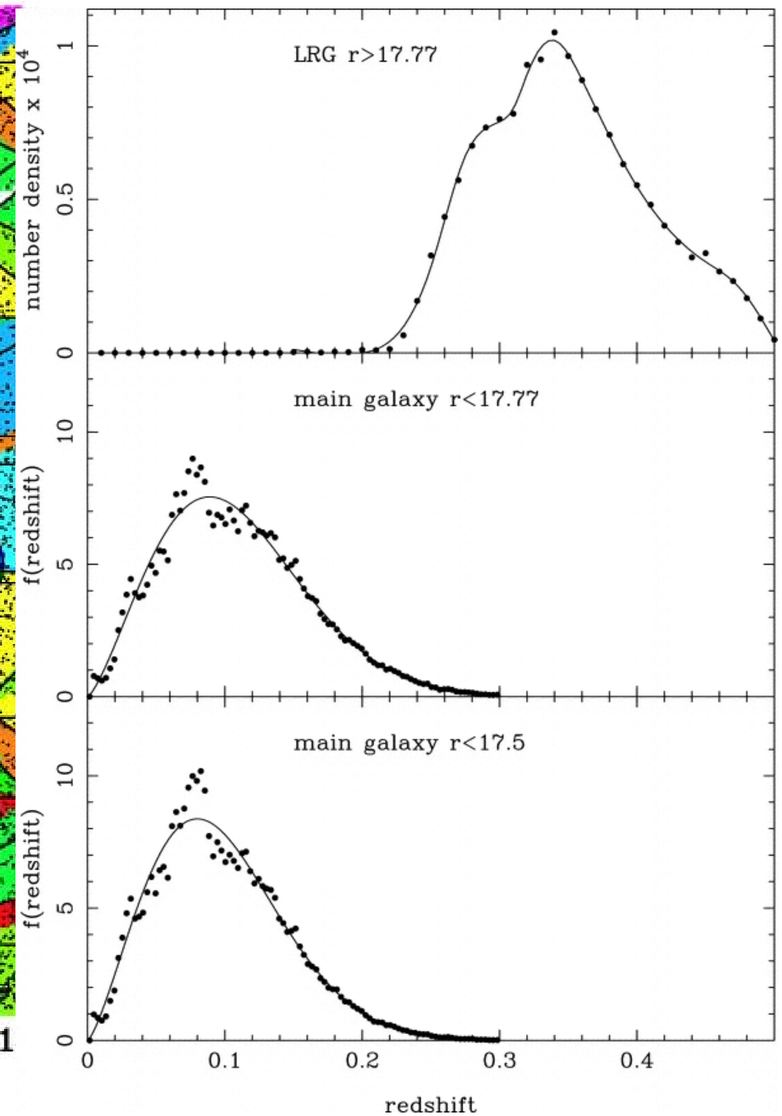


Same techniques for P(k) - take Fourier transform of density field relative to a random catalog over same volume. Several techniques for this - see Tegmark et al. and Pope et al. Also "weighted" and mark correlations

Measuring ξ(r) II

Essential the random catalog looks like the real data!





ξ(r) for LRGs

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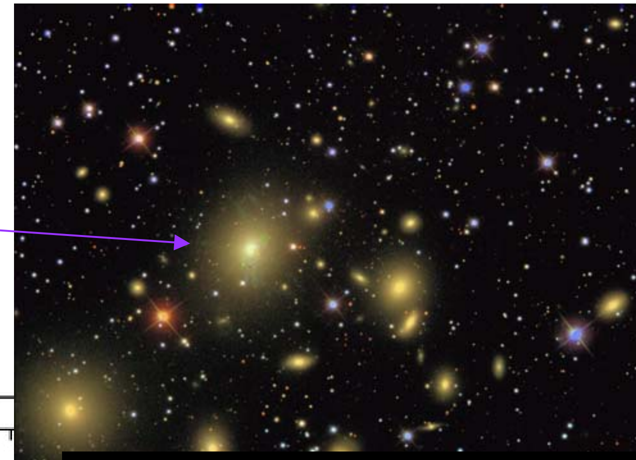
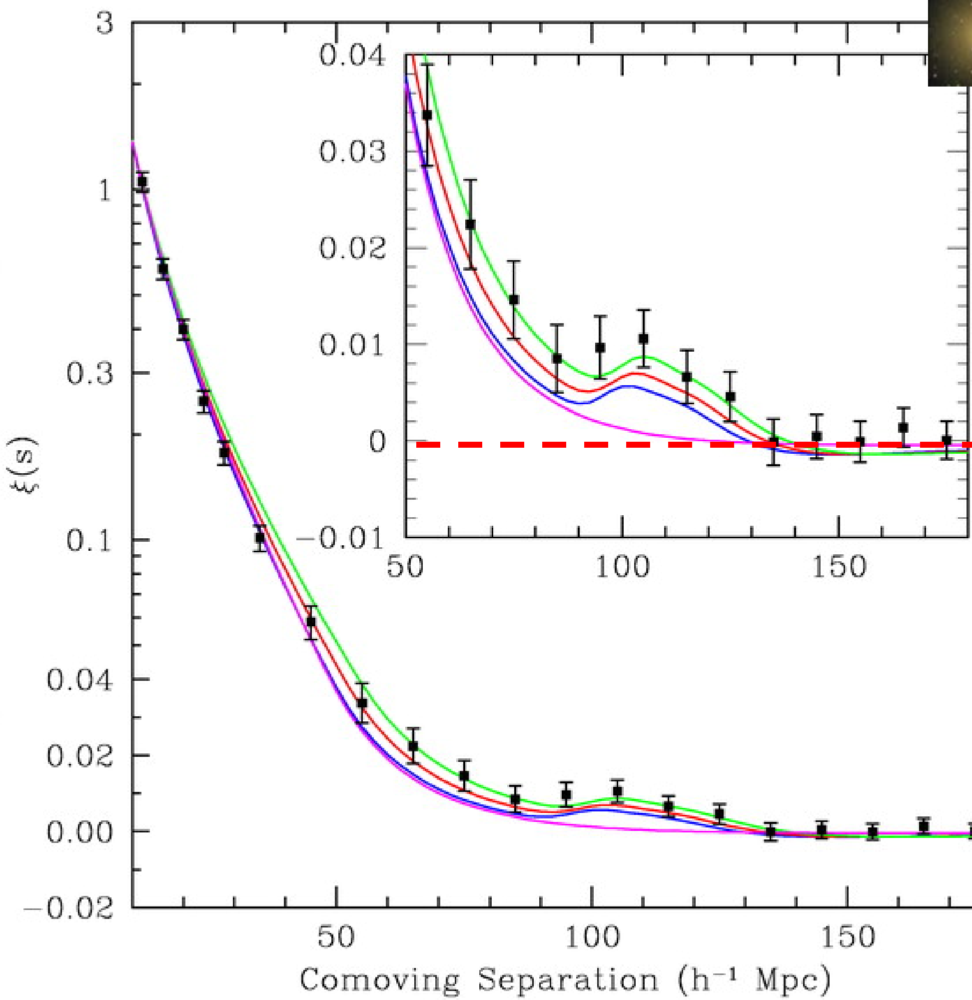
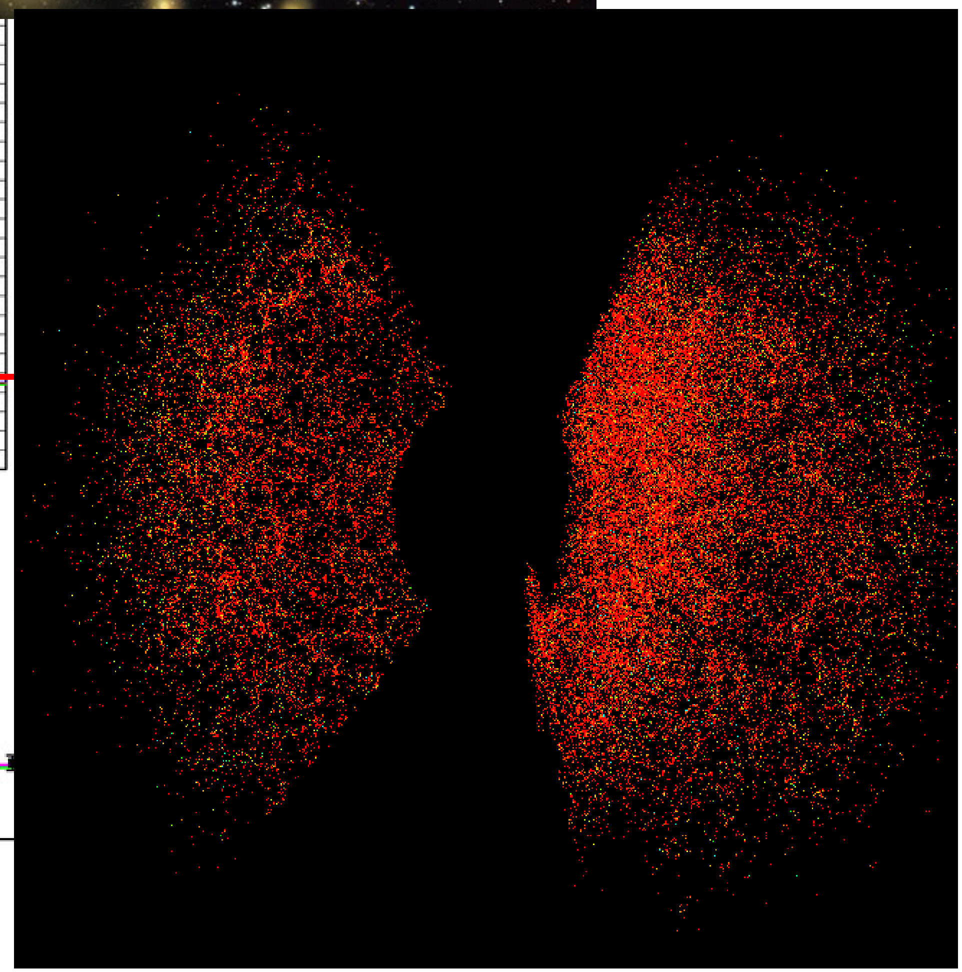






Errors on $\xi(r)$

Hardest part of estimating these statistics

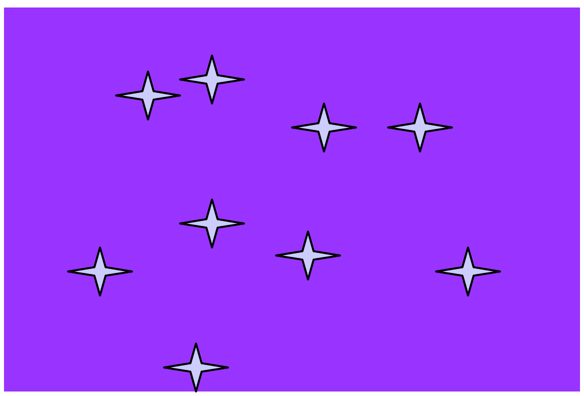
On small scales, the errors are Poisson

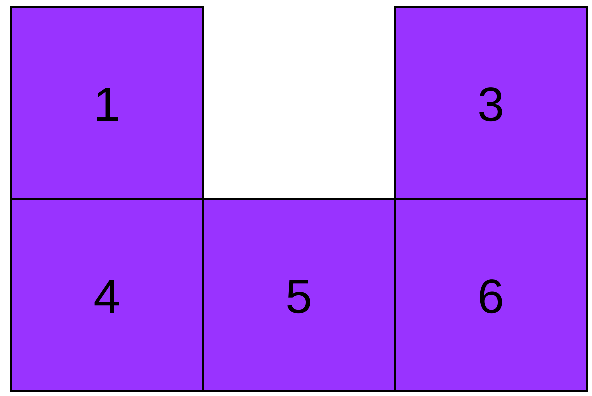
On large scales, errors correlated and typically larger than Poisson

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

Jack-knife Errors

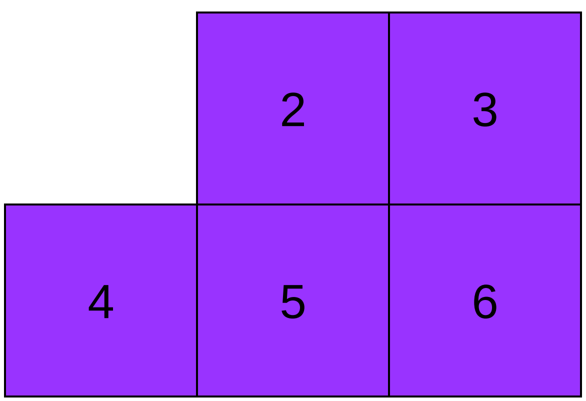
Real Data





N=6

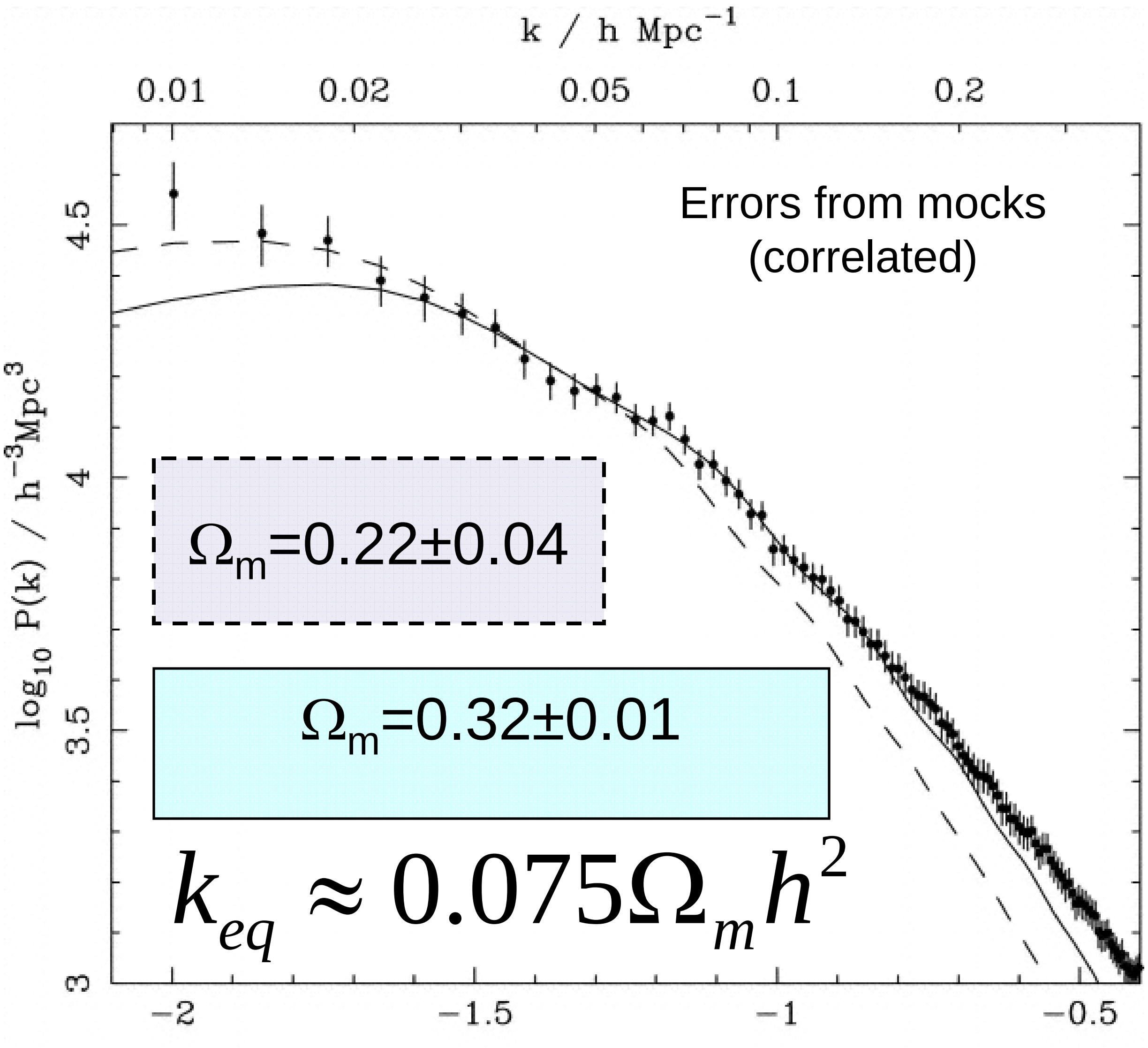
- Split data into N equal subregions
- Remove each subregion in turn and compute ξ(r)
- Measure variance between regions as function of scale



$$\sigma^2 = \frac{(N-1)}{N}\sum_{i=1}^{N}(\xi_i - \bar{\xi})^2$$

Note the (N-1) factor because there or N-1 estimates of mean

Latest P(k) from SDSS



No turn-over yet seen in data!

2σ difference

Depart from "linear" predictions at much lower k than expected

Strongest evidence yet for Ω_m << 1 and therefore, DE

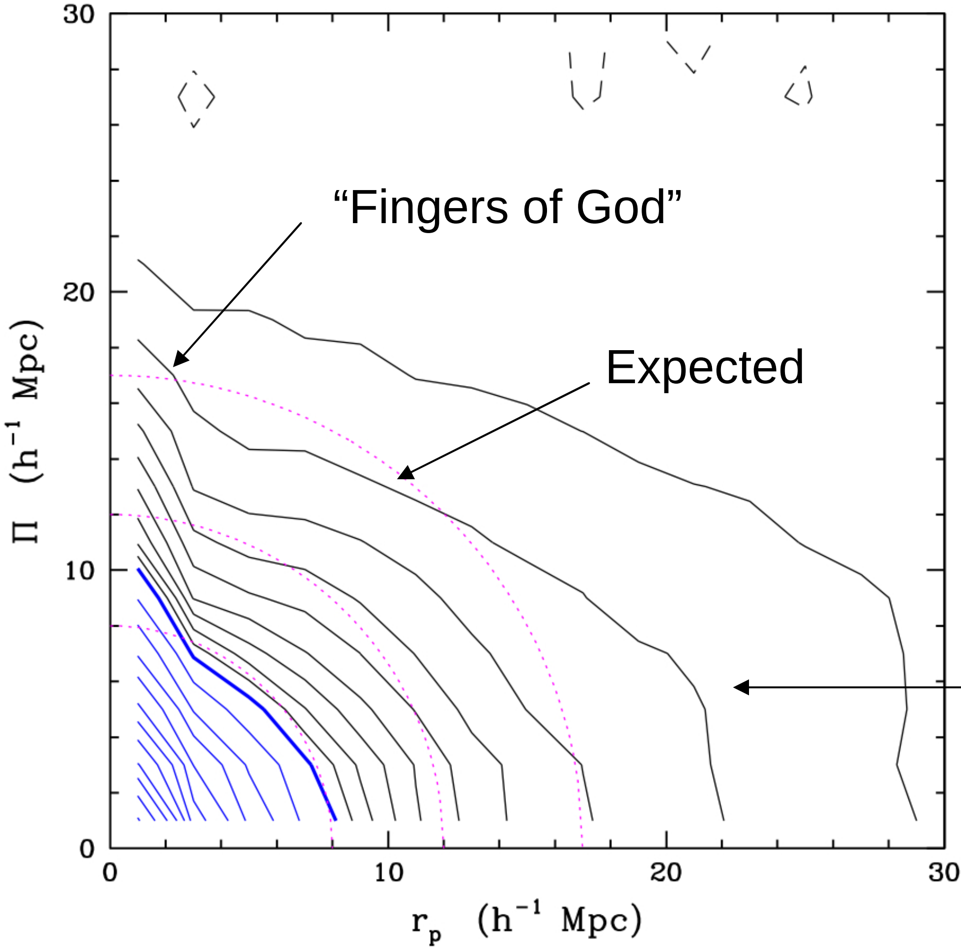
Hindrances

There are two “hindrances” to the full interpretation of the P(k) or $\xi(r)$

- *Redshift distortions: Helped using modeling & simulations*
- *Galaxy biasing: Helped through higher order correlations*

Redshift distortions

We only measure redshifts not distances

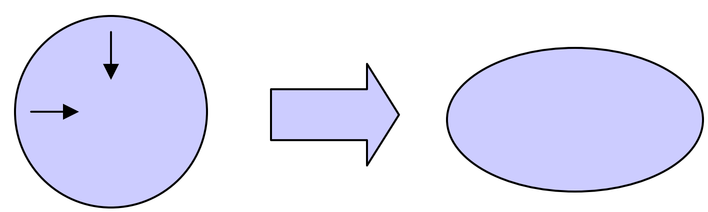


Therefore we usually quote ξ(s) as the “redshift-space” correlation function, and ξ(r) as the “real-space” correlation function.

We can compute the 2D correlation function $\xi(\pi, r_p)$, then

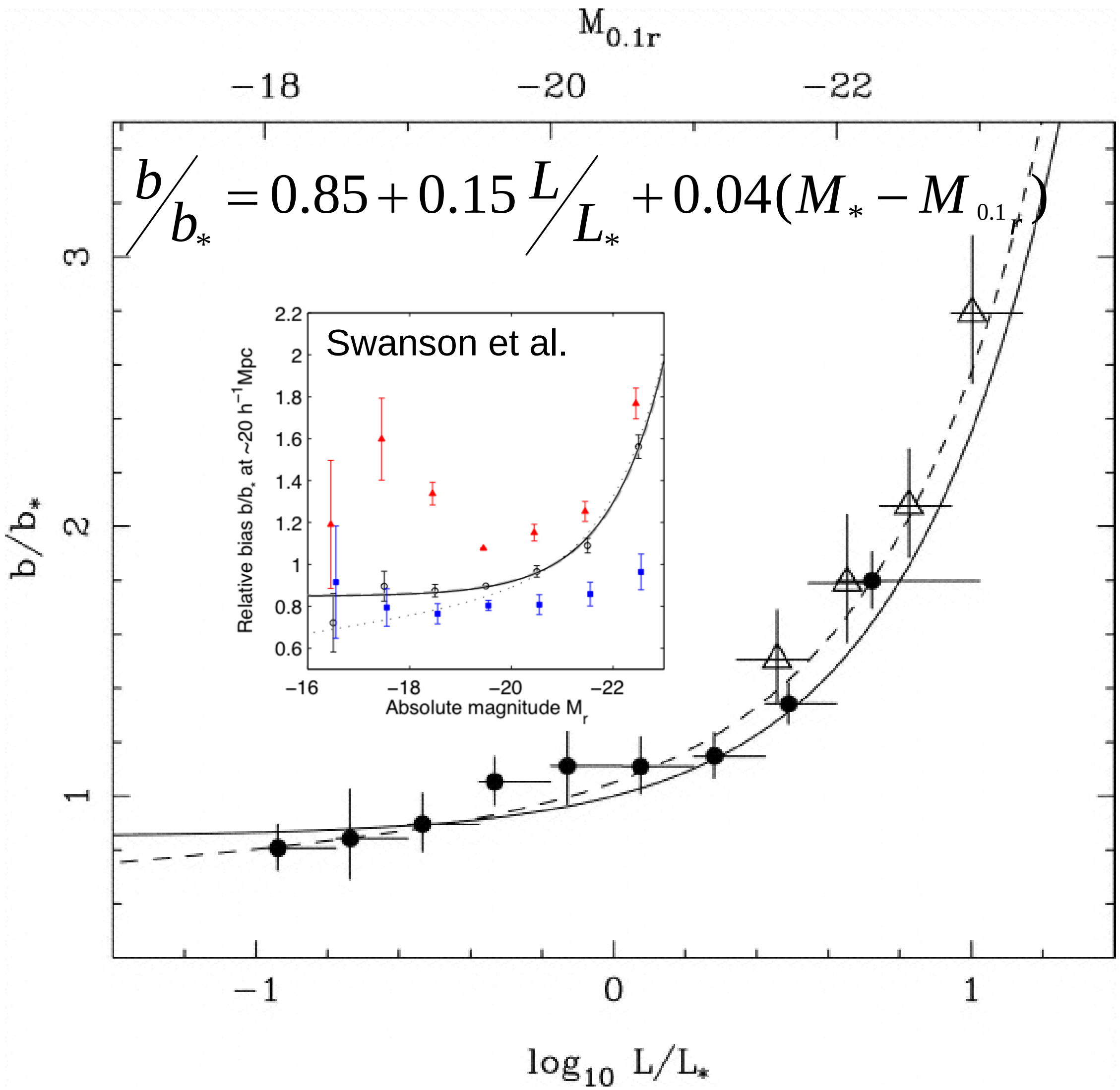
$$w(r_p) = 2\int_0^{\pi_{\max}} \xi(r_p, \pi)\, d\pi$$

Infall around clusters



Biasing

We see galaxies not dark matter



Maximal ignorance

$$\delta_{gal} = b\,\delta_{dm}$$

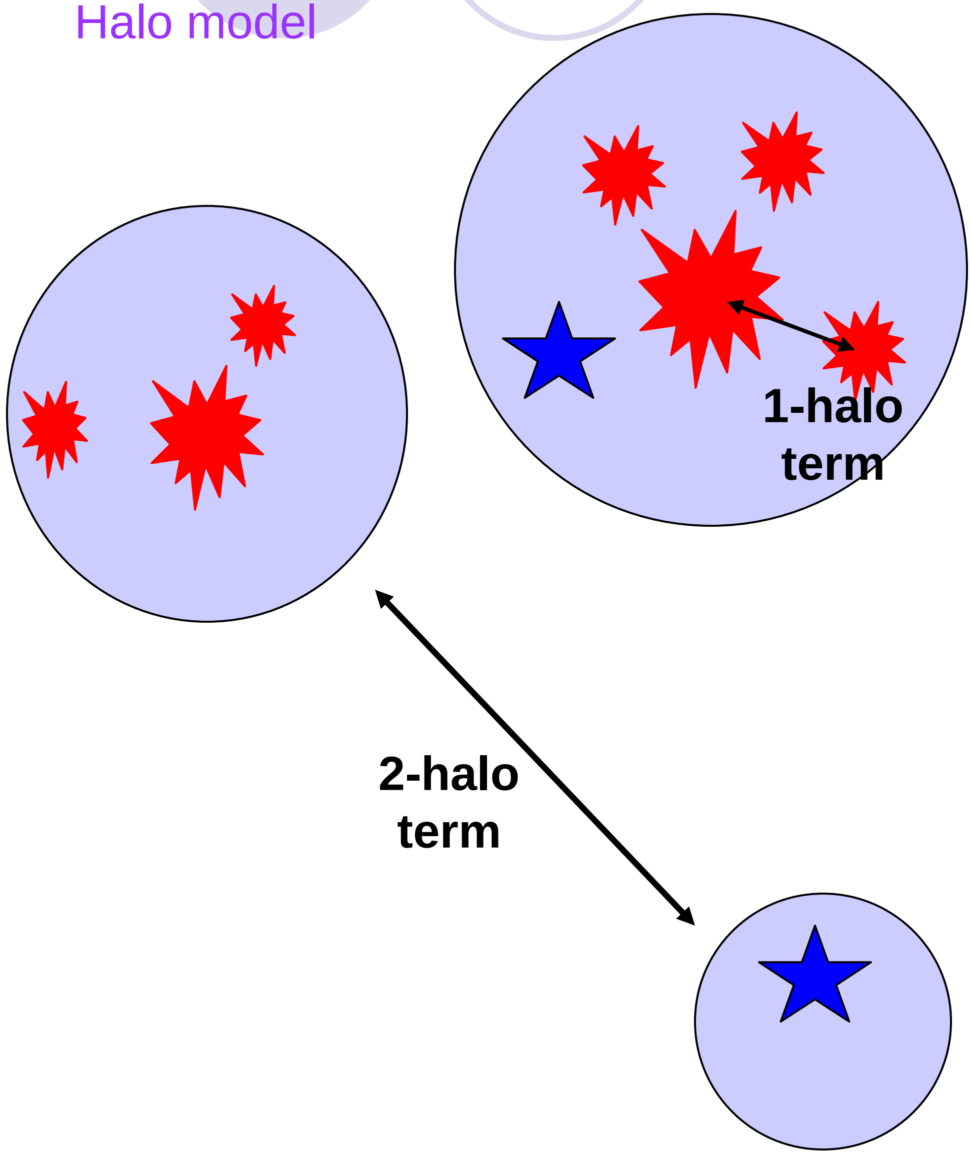
$$P(k)_{gal} = b^2 P(k)_{dm}$$

However, we know it depends on color & L

Is there also a scale dependence?

Biasing II

Halo model

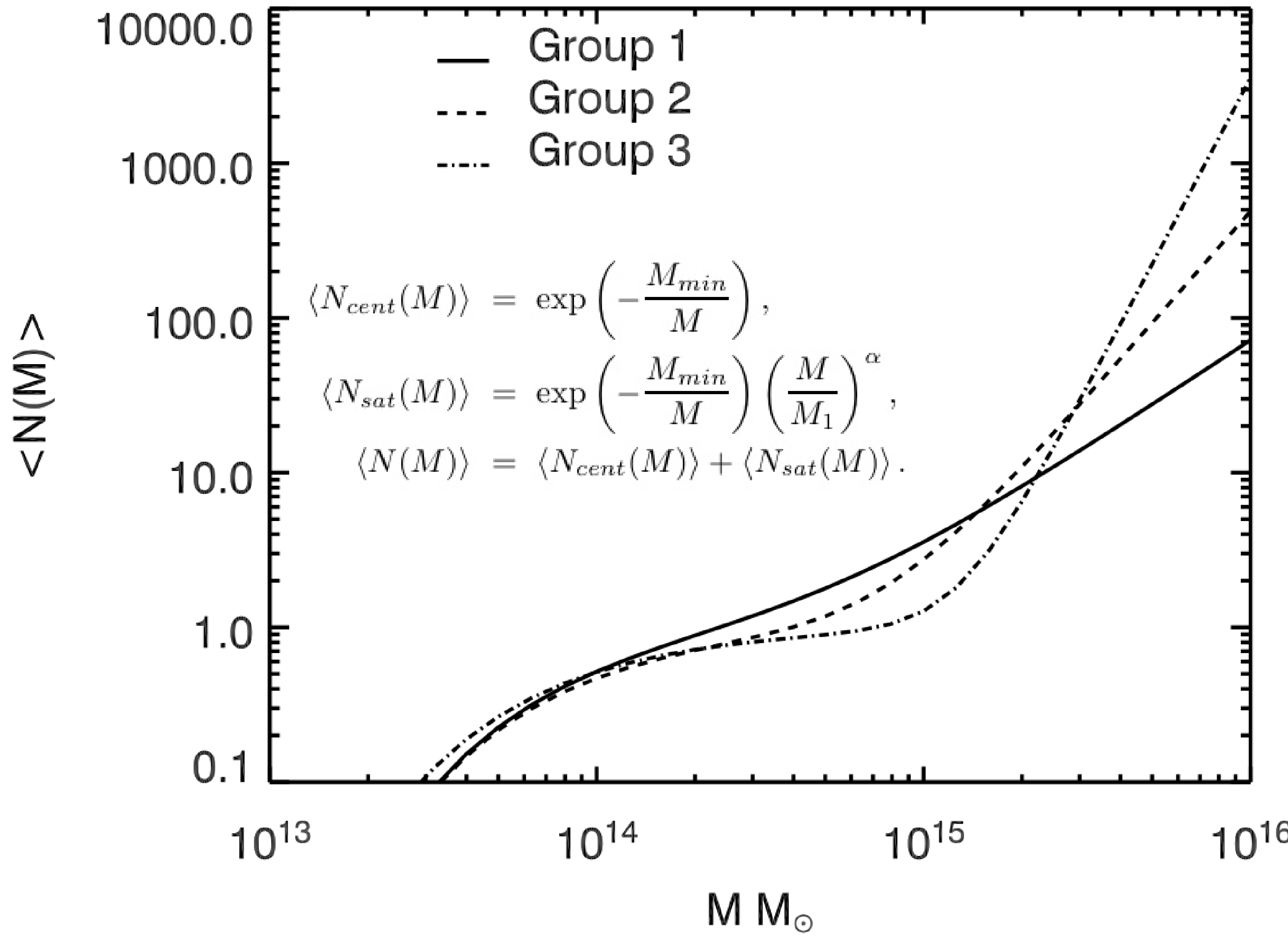


All galaxies reside in a DM halo

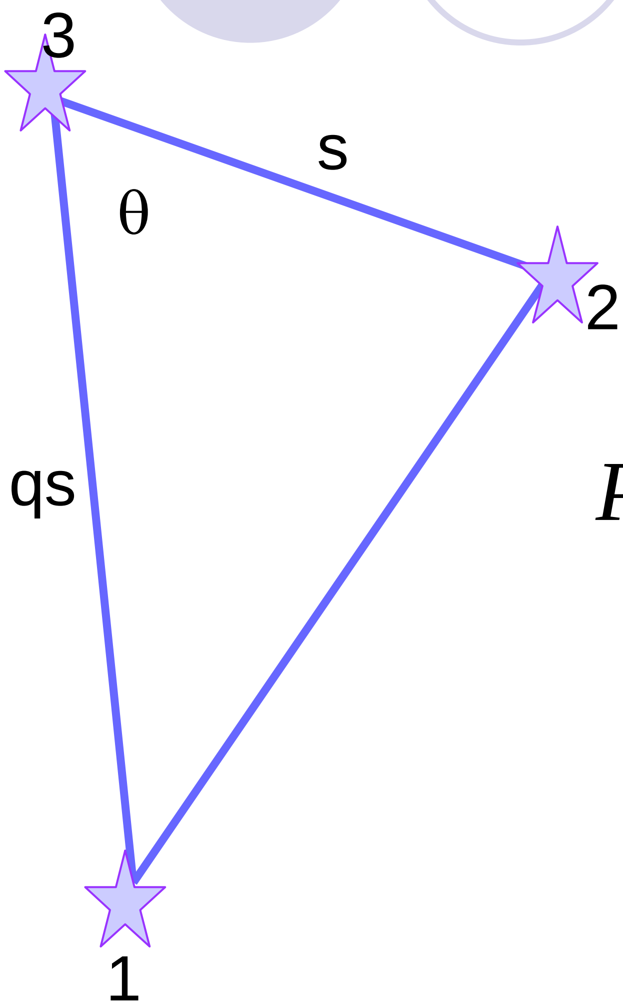
Elegant model to decompose intra-halo physics (biasing) from inter-halo physics (DM clustering)

$$P(k) = P_{1-halo} + P_{2-halo}$$

Biasing III


Group 1
Group 2
Group 3
$\langle N_{cent}(M)\rangle = \exp\left(-\frac{M_{min}}{M}\right),$
$\langle N_{sat}(M)\rangle = \exp\left(-\frac{M_{min}}{M}\right)\left(\frac{M}{M_1}\right)^{\alpha},$
$\langle N(M)\rangle = \langle N_{cent}(M)\rangle + \langle N_{sat}(M)\rangle.$
10000.0
1000.0
100.0
10.0
1.0
0.1
<N(M)>
10^{13}
10^{14}
10^{15}
10^{16}
M $M_{\odot}$

Higher order correlations



Biasing could be helped through use of higher order correlations e.g. 3-point correlation function (bispectrum)

$$P_{123} = n^3 (1 + \xi_{23} + \xi_{13} + \xi_{12} + \xi_{123}) dV^3$$

Peebles "Hierarchical Ansatz"

$$Q(s,q,\theta) = \frac{\xi_{123}}{\xi_{23}\xi_{13} + \xi_{12}\xi_{13} + \xi_{12}\xi_{23}}$$

Higher order correlations II

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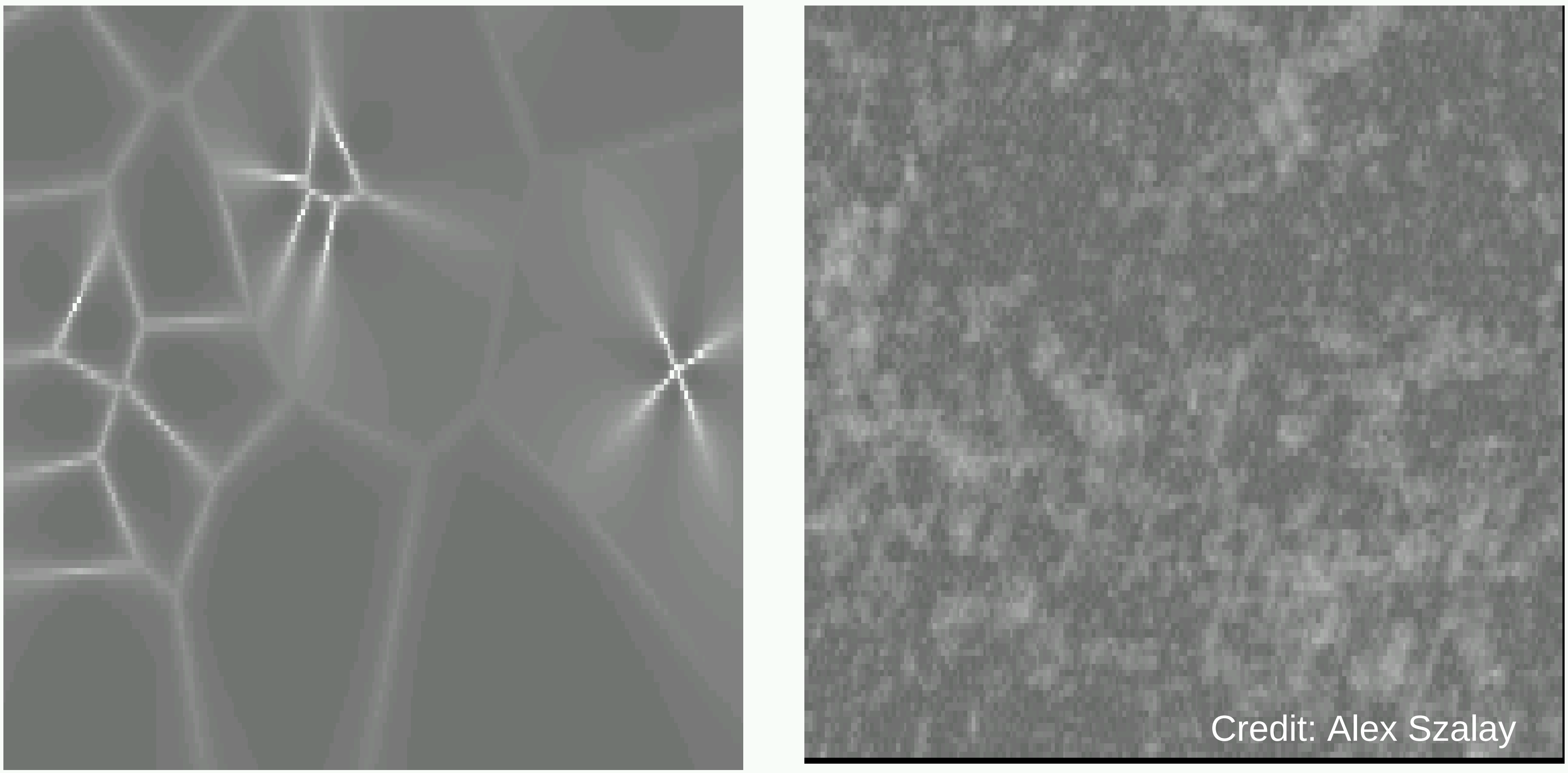
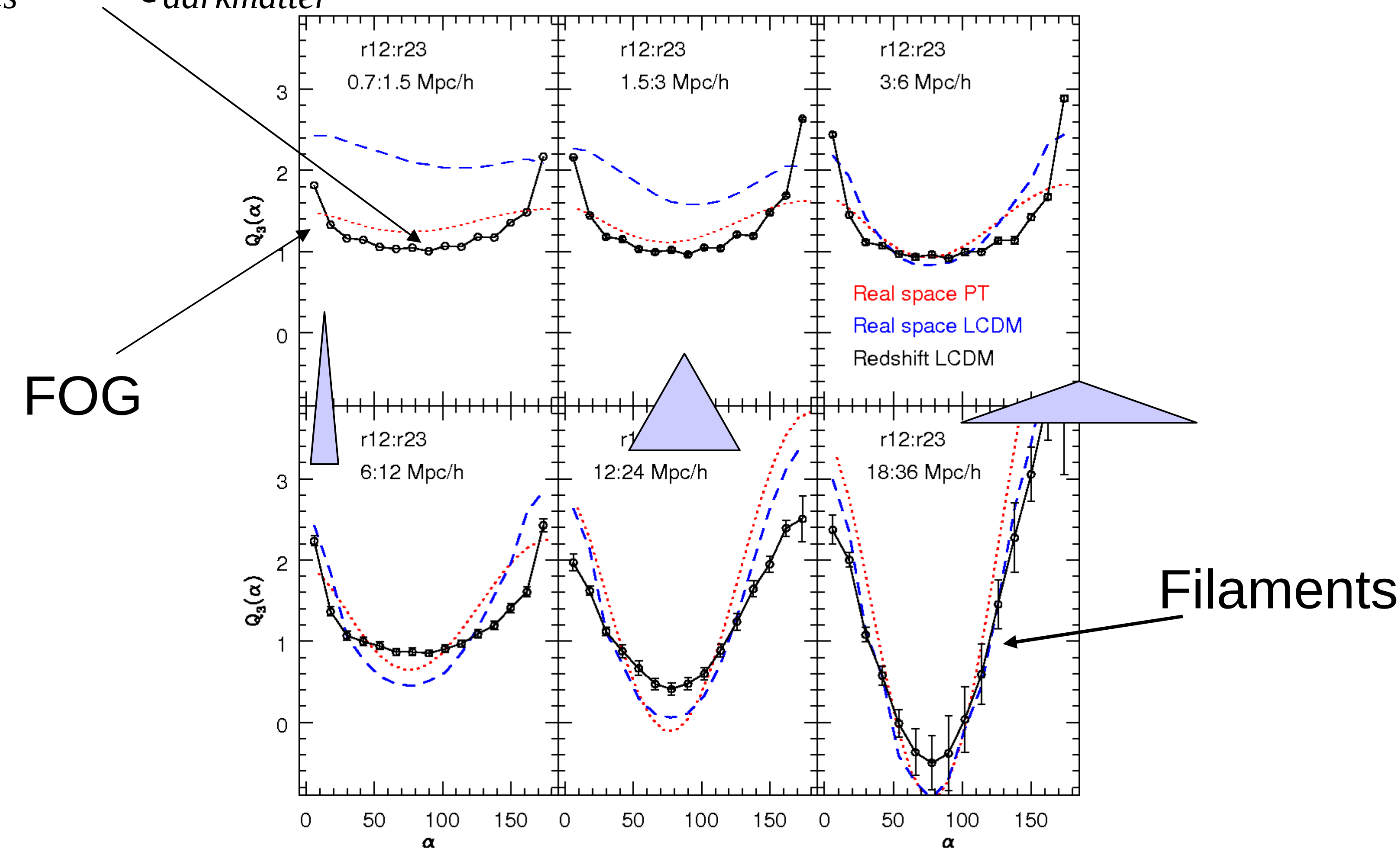


Same 2pt, different 3pt

Higher order correlations III

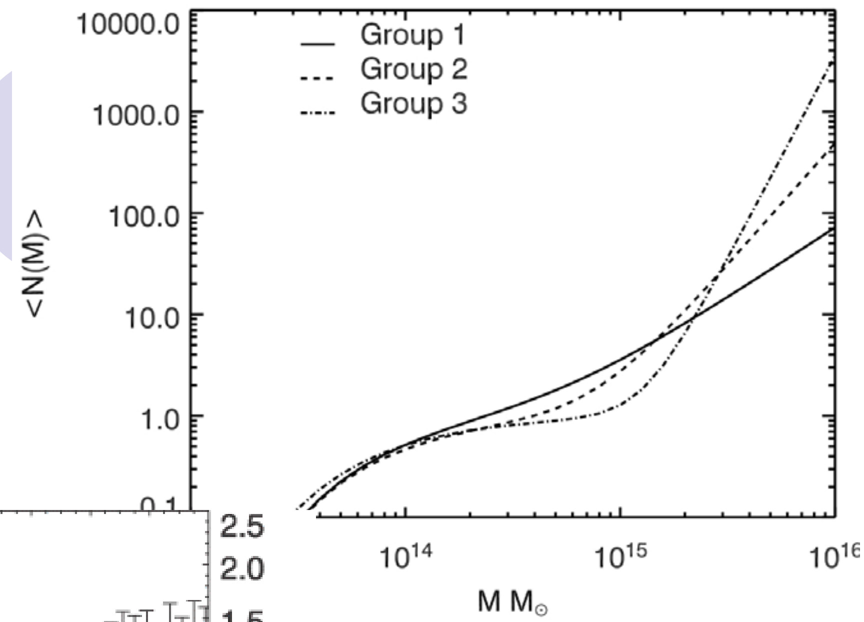
Gaztanaga & Scoccimarro 2005

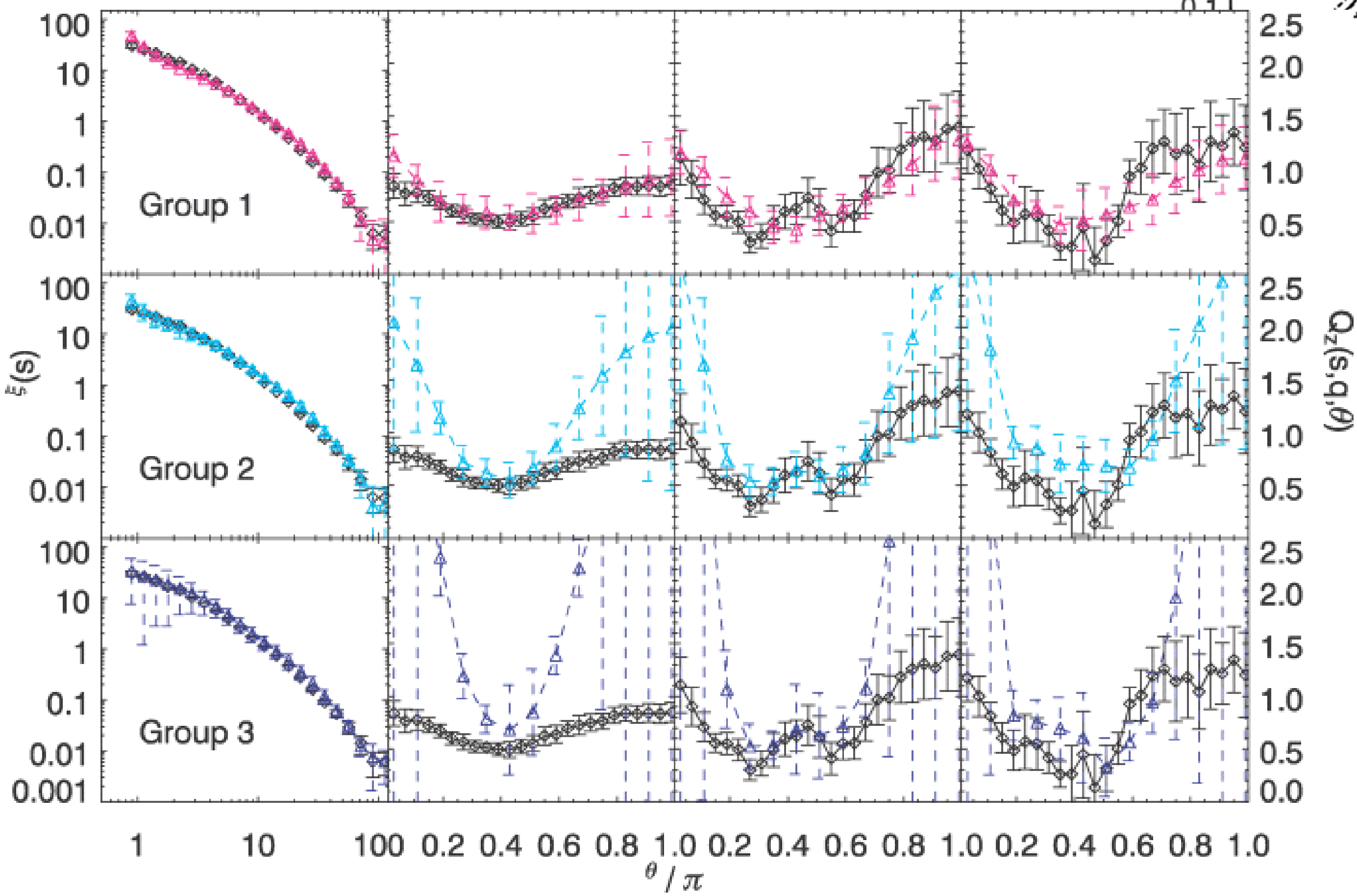
$$Q_{galaxies} = bQ_{darkmatter}$$



Halo Model

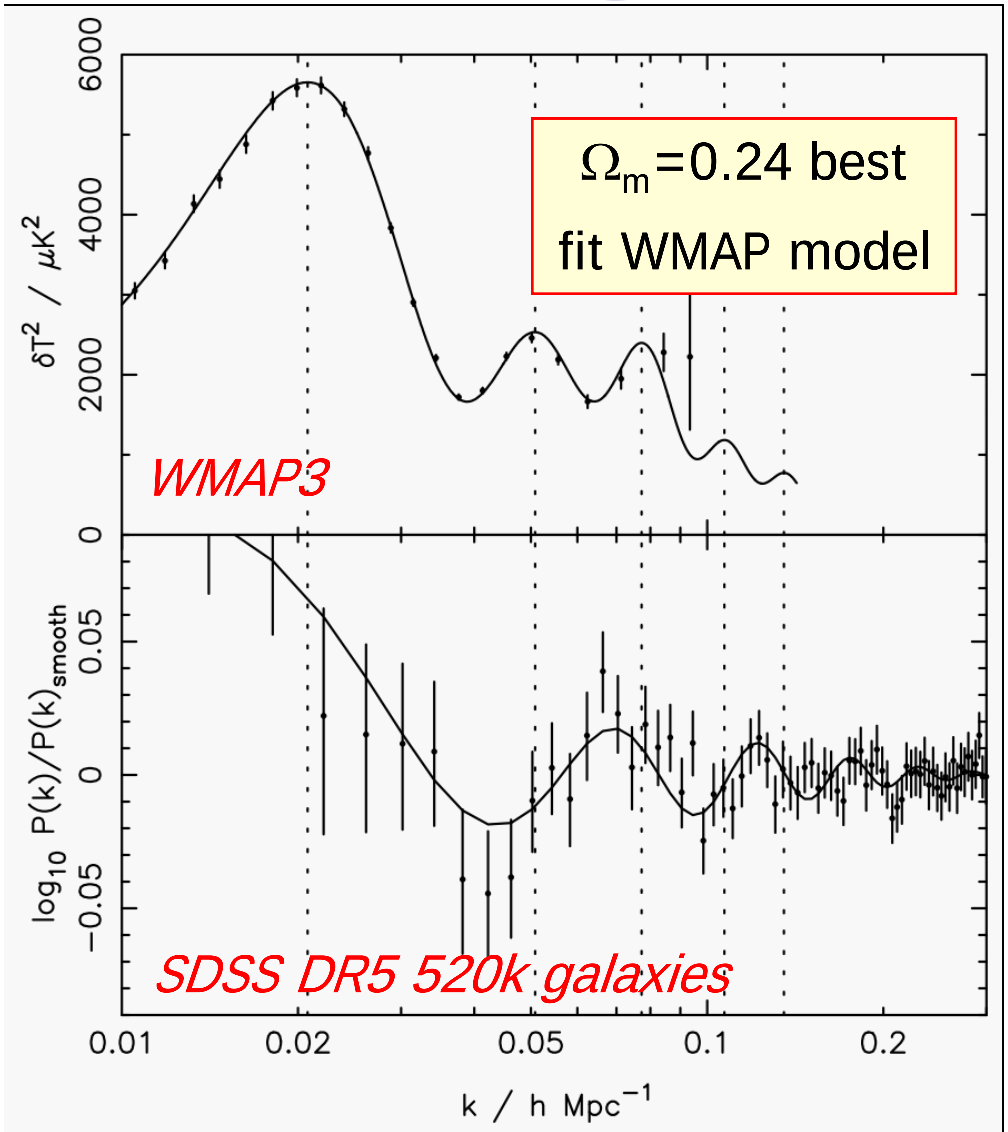
Kulkarni et al. 2007



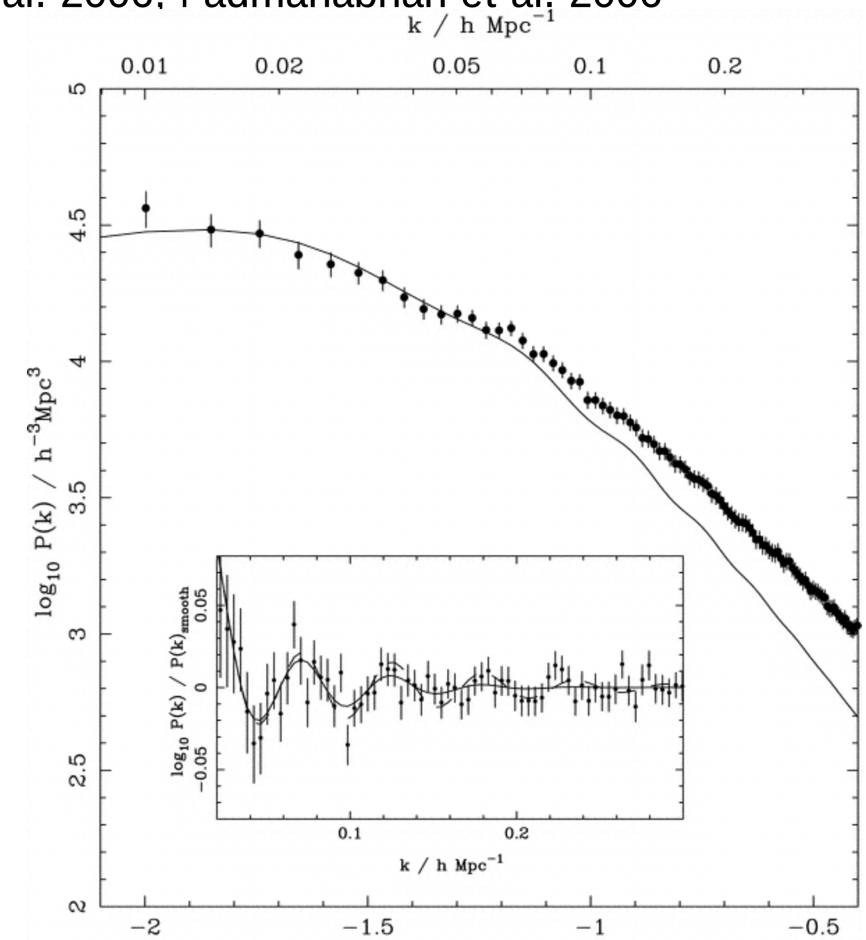


BAO Measurements

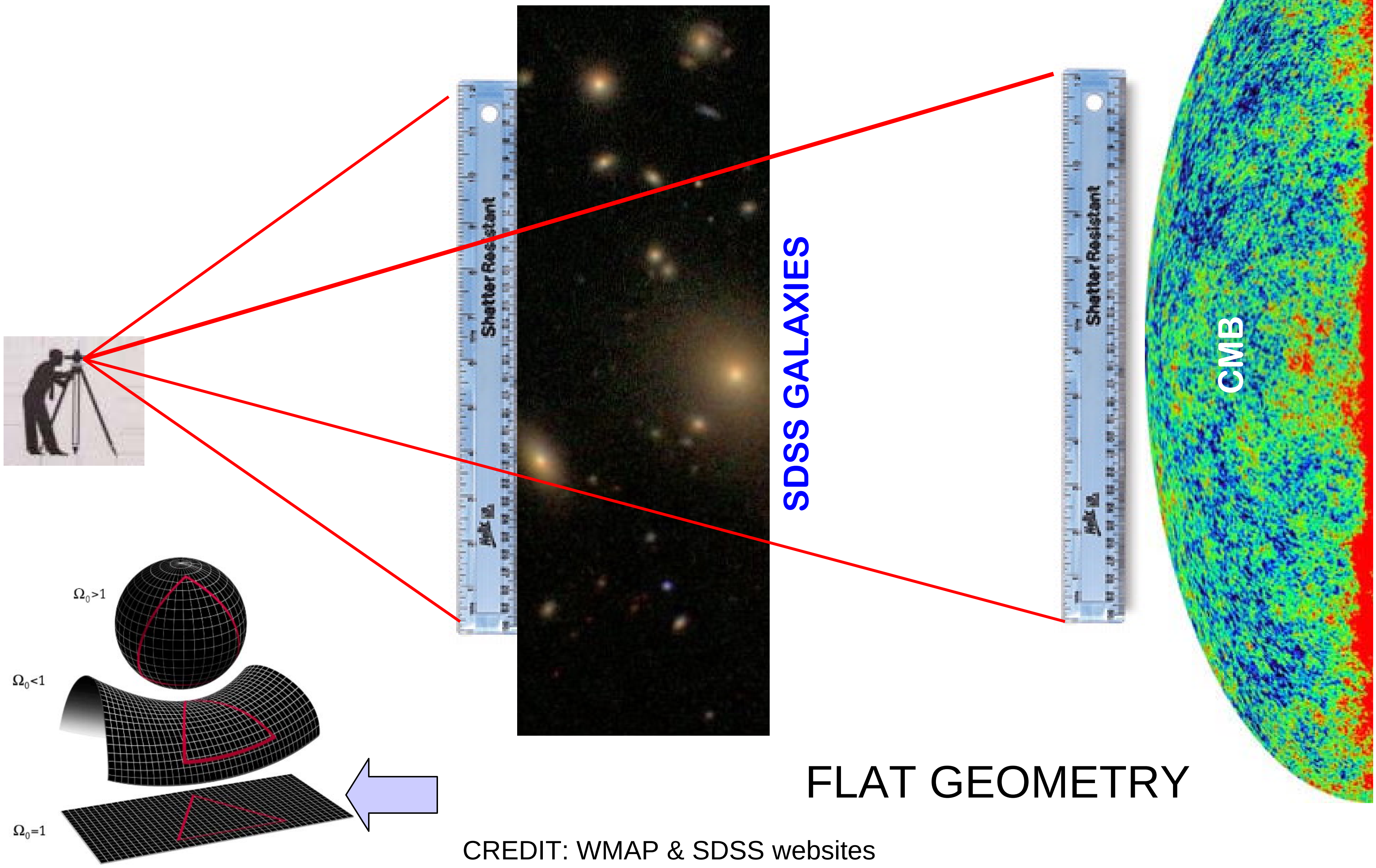
Percival et al. 2006



Miller et al. 2001, Percival et al. 2001, Tegmark et al. 2006, Cole et al. 2005, Eisenstein et al. 2005, Hutsi 2006, Blake et al. 2006, Padmanabhan et al. 2006

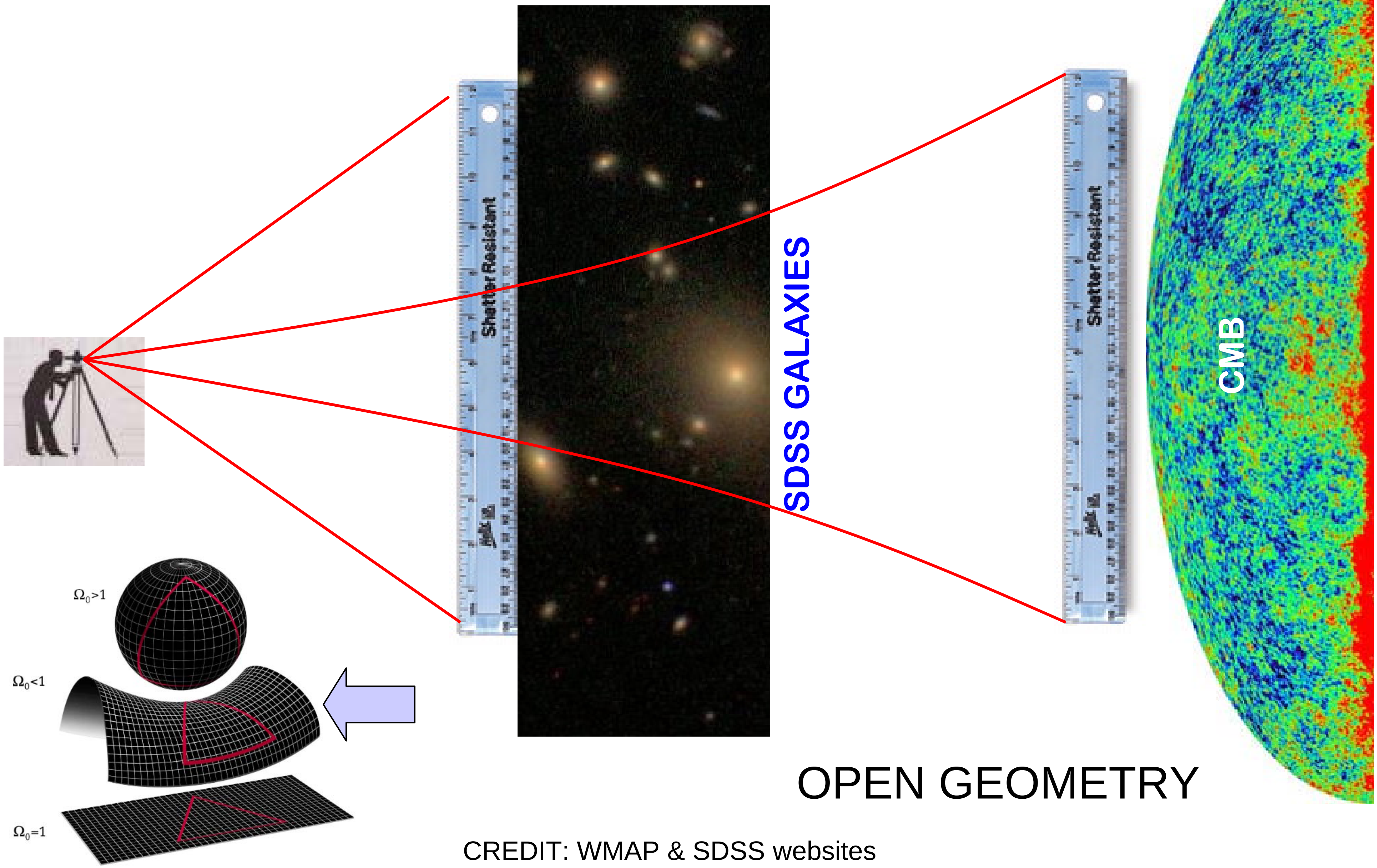


Looking back in time in the Universe



CREDIT: WMAP & SDSS websites

Looking back in time in the Universe



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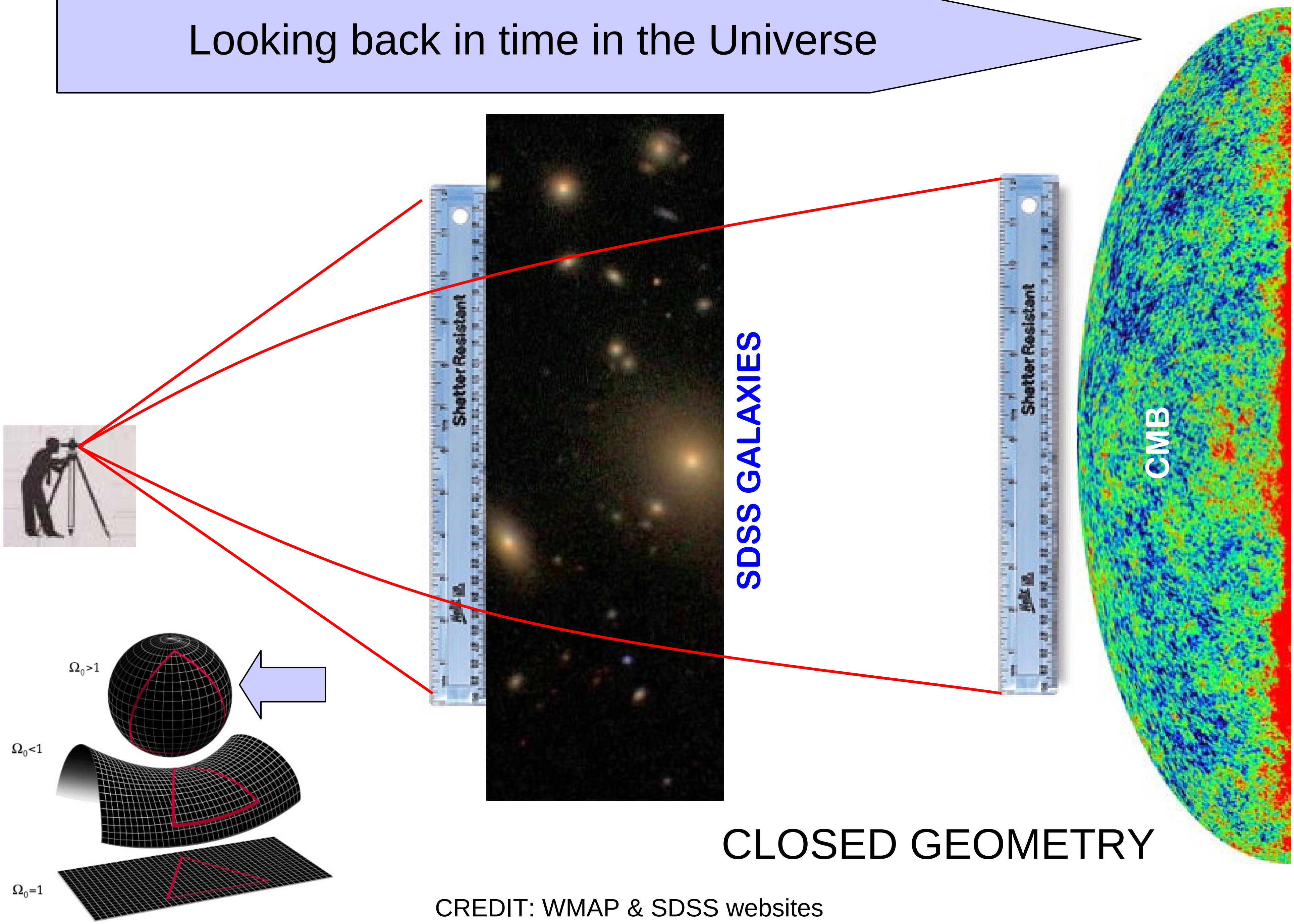
Looking back in time in the Universe

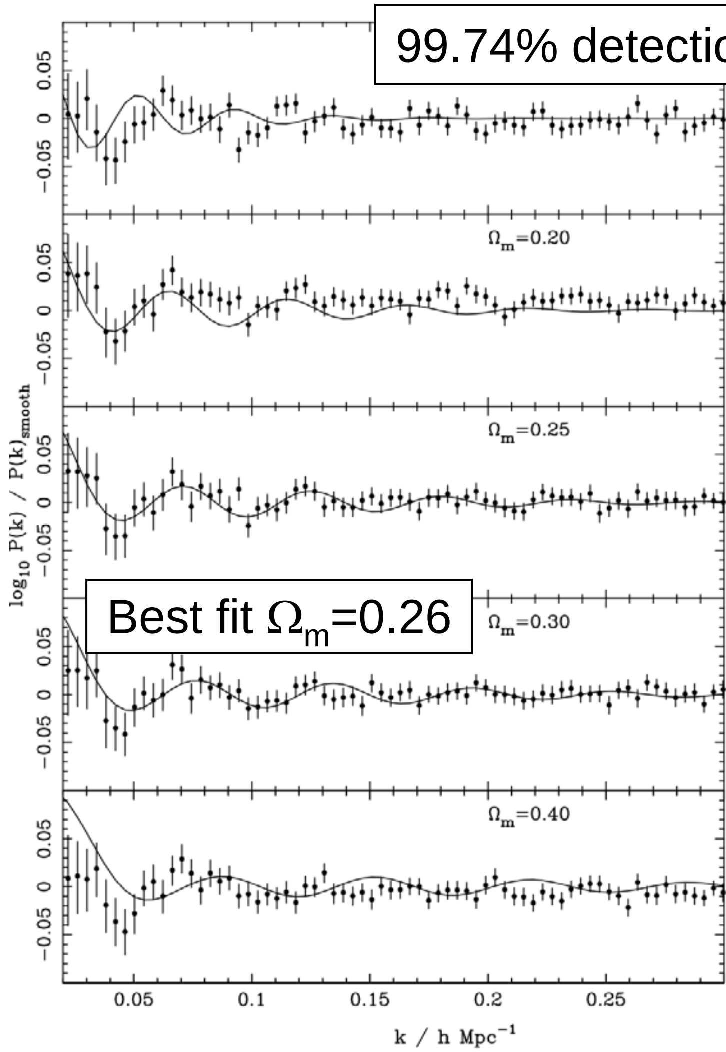


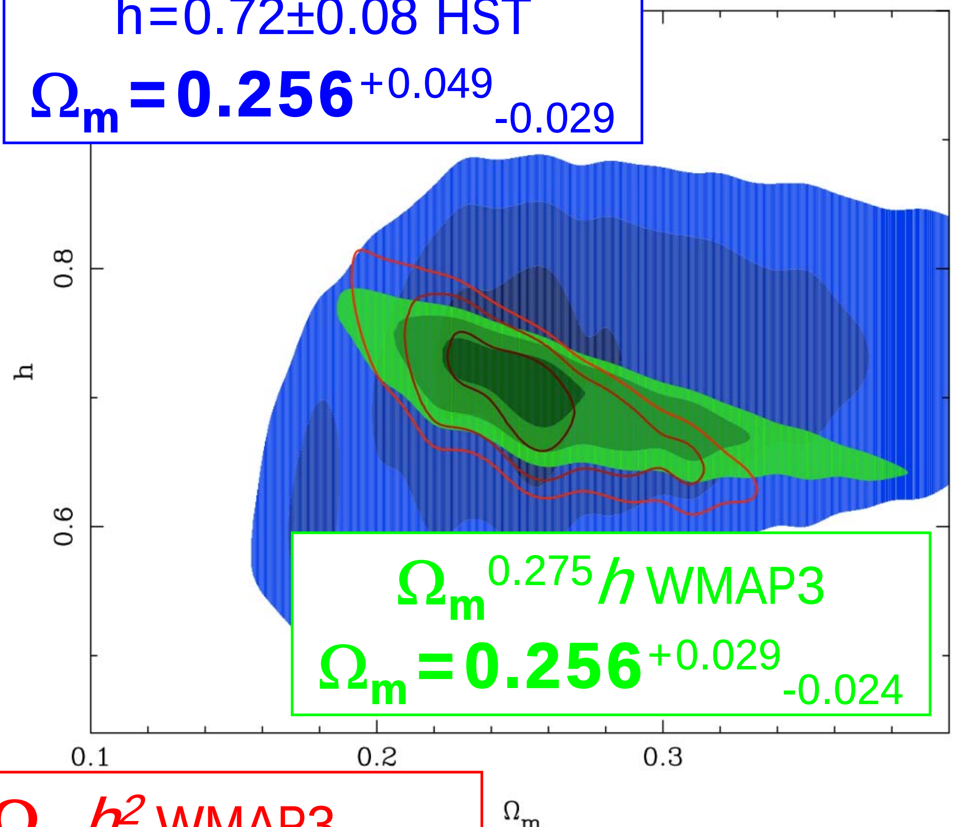
CREDIT: WMAP & SDSS websites

Cosmological Constraints

Standard ruler (flat, h=0.73, Ω_b=0.17)

Percival et al. (2006)





h=0.72±0.08 HST

$\Omega_m = \mathbf{0.256}^{+0.049}_{-0.029}$

$\Omega_m^{0.275} h$ WMAP3

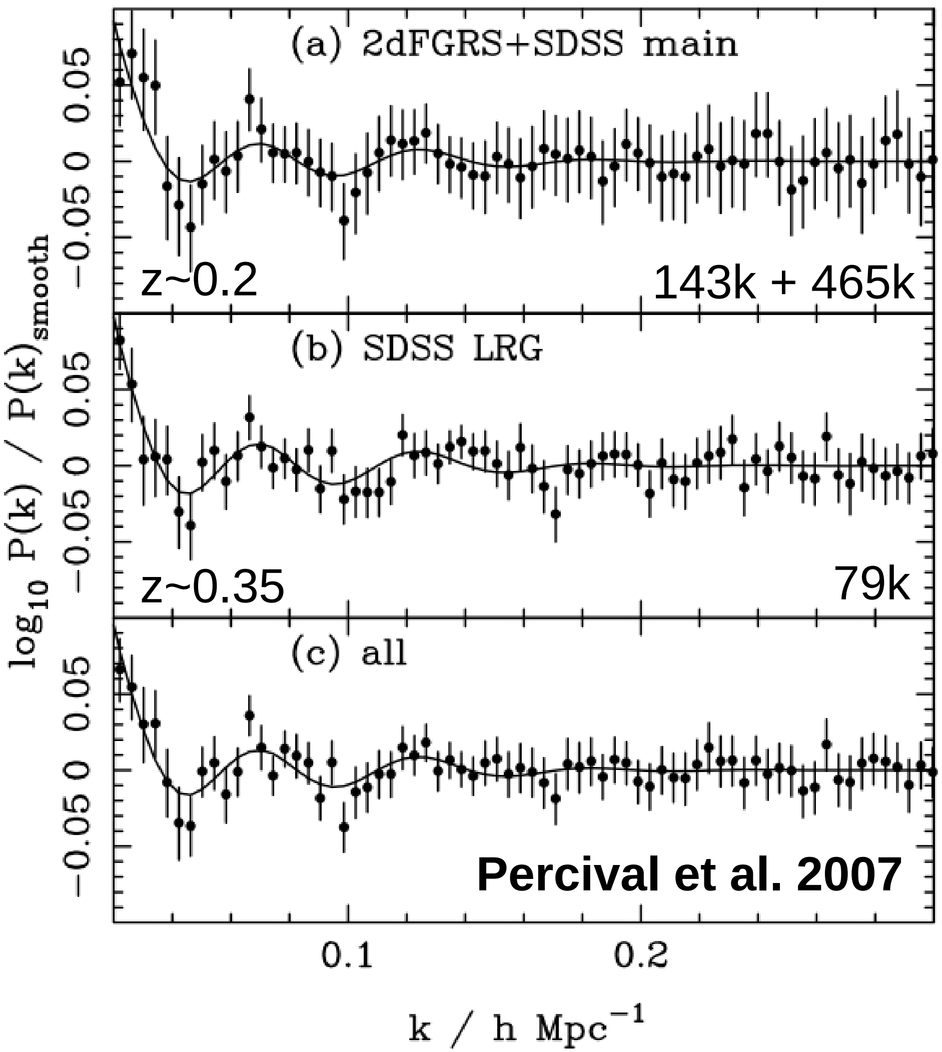
$\Omega_m = \mathbf{0.256}^{+0.029}_{-0.024}$

$\Omega_m h^2$ WMAP3

$\Omega_m = \mathbf{0.256}^{+0.019}_{-0.023}$

BAO with Redshift

>3σ detection (Hutsi et al., Percival et al)



Measure ratio of volume averaged distance

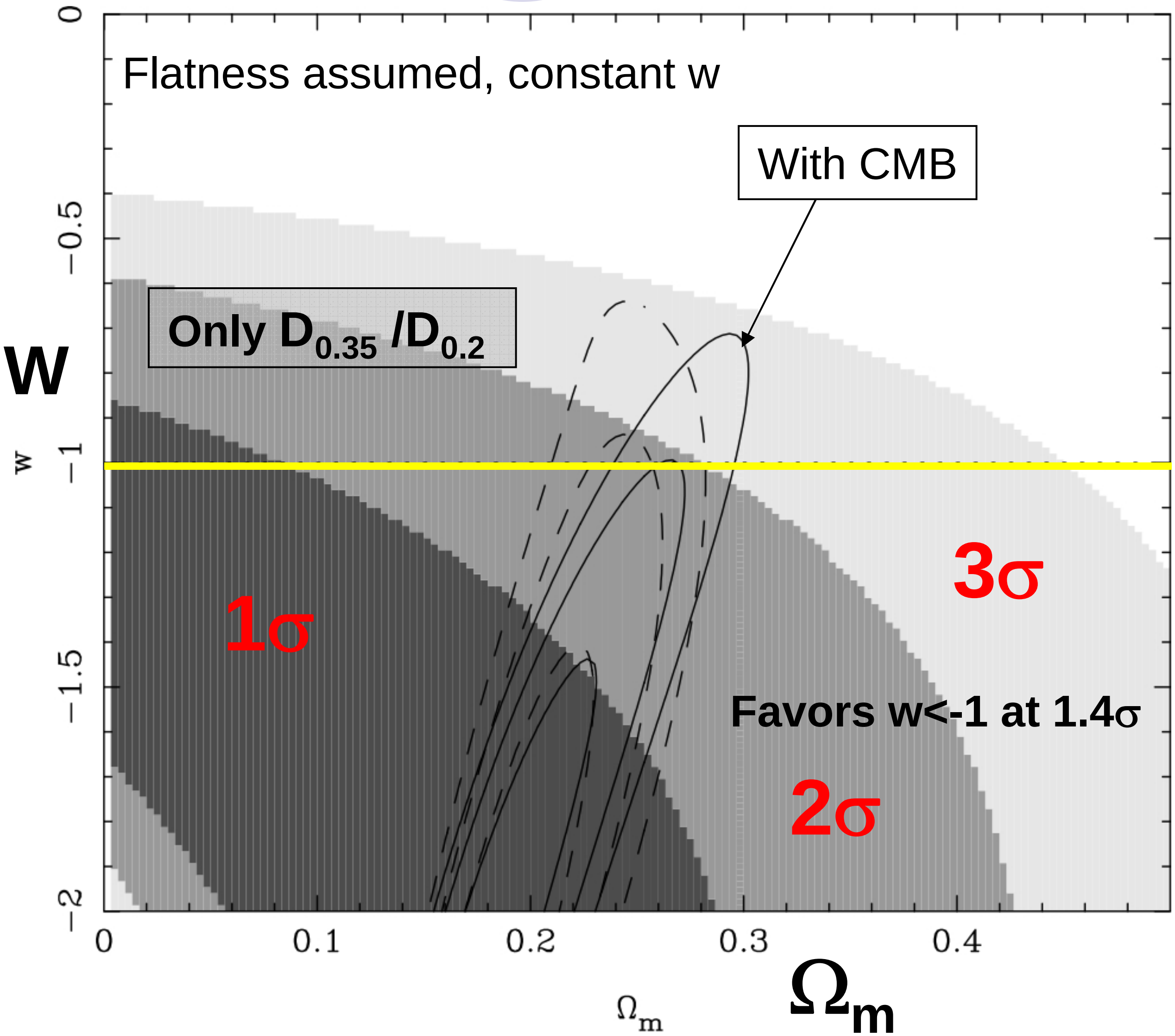
$$D_v(z) = \left[\frac{(1+z)^2 cz D_A(z)^2}{H(z)} \right]^{\frac{1}{3}}$$

$D_{0.35} / D_{0.2} = 1.812 \pm 0.060$

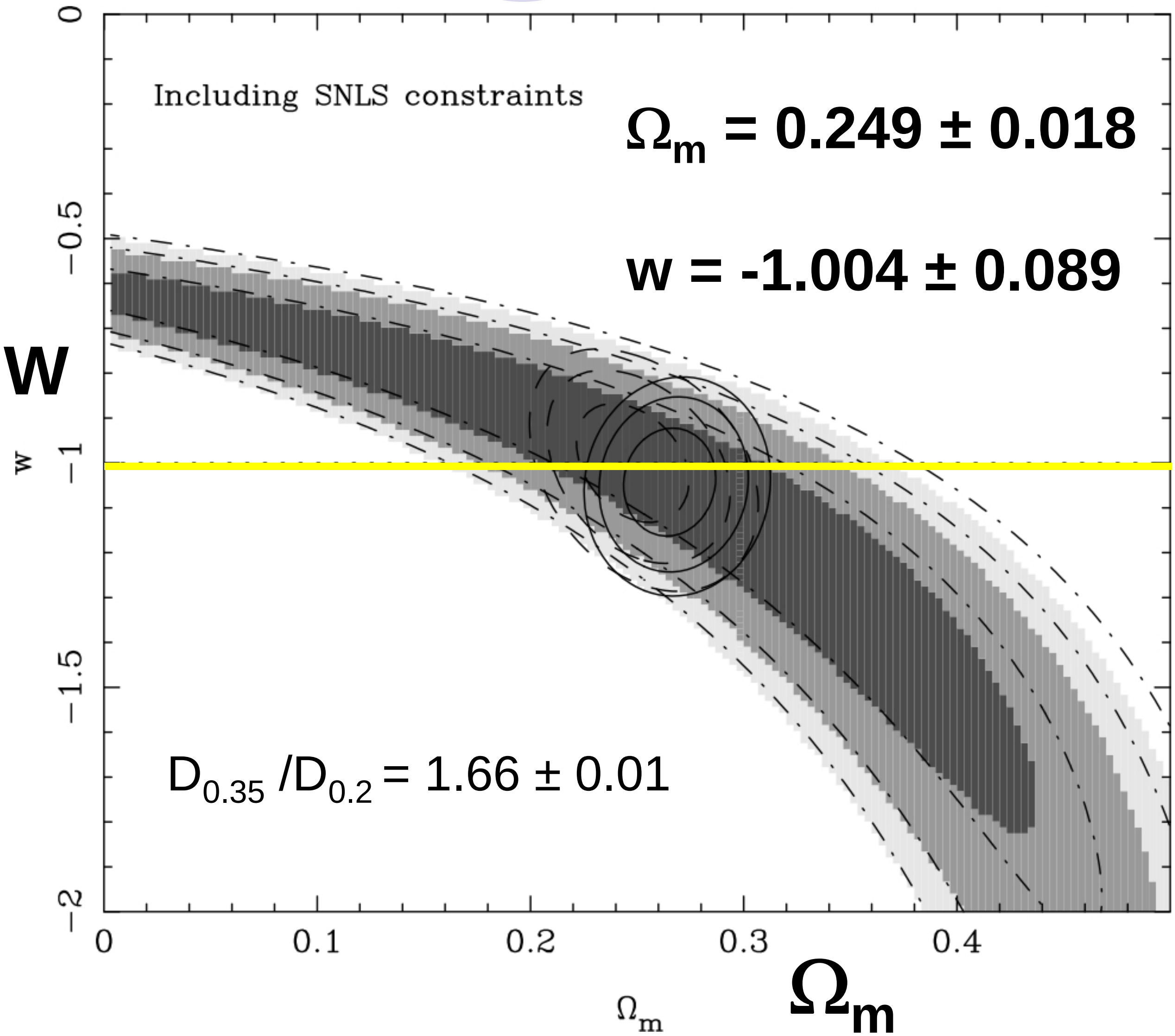
Flat ΛCDM = 1.67

Systematics (damping, BAO fitting) also ~1σ. Next set of measurements will need to worry about this

Cosmological Constraints



Cosmological Constraints



Discrepancy!
What Discrepancy?

- 2.4σ difference between SN & BAO. The BAO want more acceleration at $z<0.3$ than predicted by $z>0.3$ SNe (revisit with SDSS SNe)

- ~1σ possible from details of BAO damping - more complex then we thought

- Assumption of flatness and constant w needs to be revisited

Integrated Sachs-Wolfe Effect

Dark Energy effects the rate of growth of structure in Universe

- Poisson equation with dark energy:

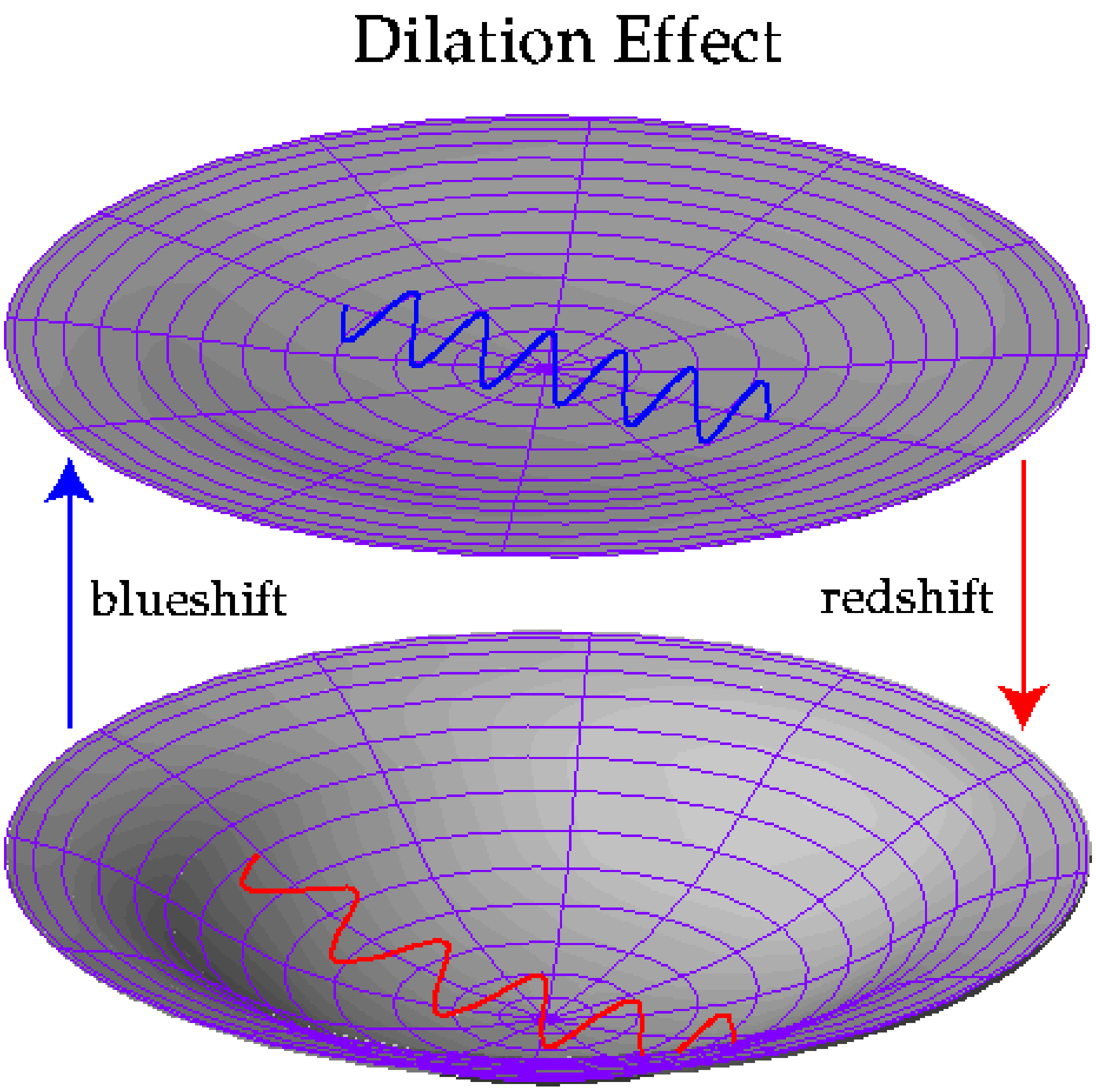
$$k^2\Phi' = -4\pi G \frac{d}{d\eta}\left[a^{-1}(\delta\rho_m + \delta\rho_{DE})\right]$$

- In a flat, matter-dominated universe (CMB tells us this), then density fluctuations grow as:

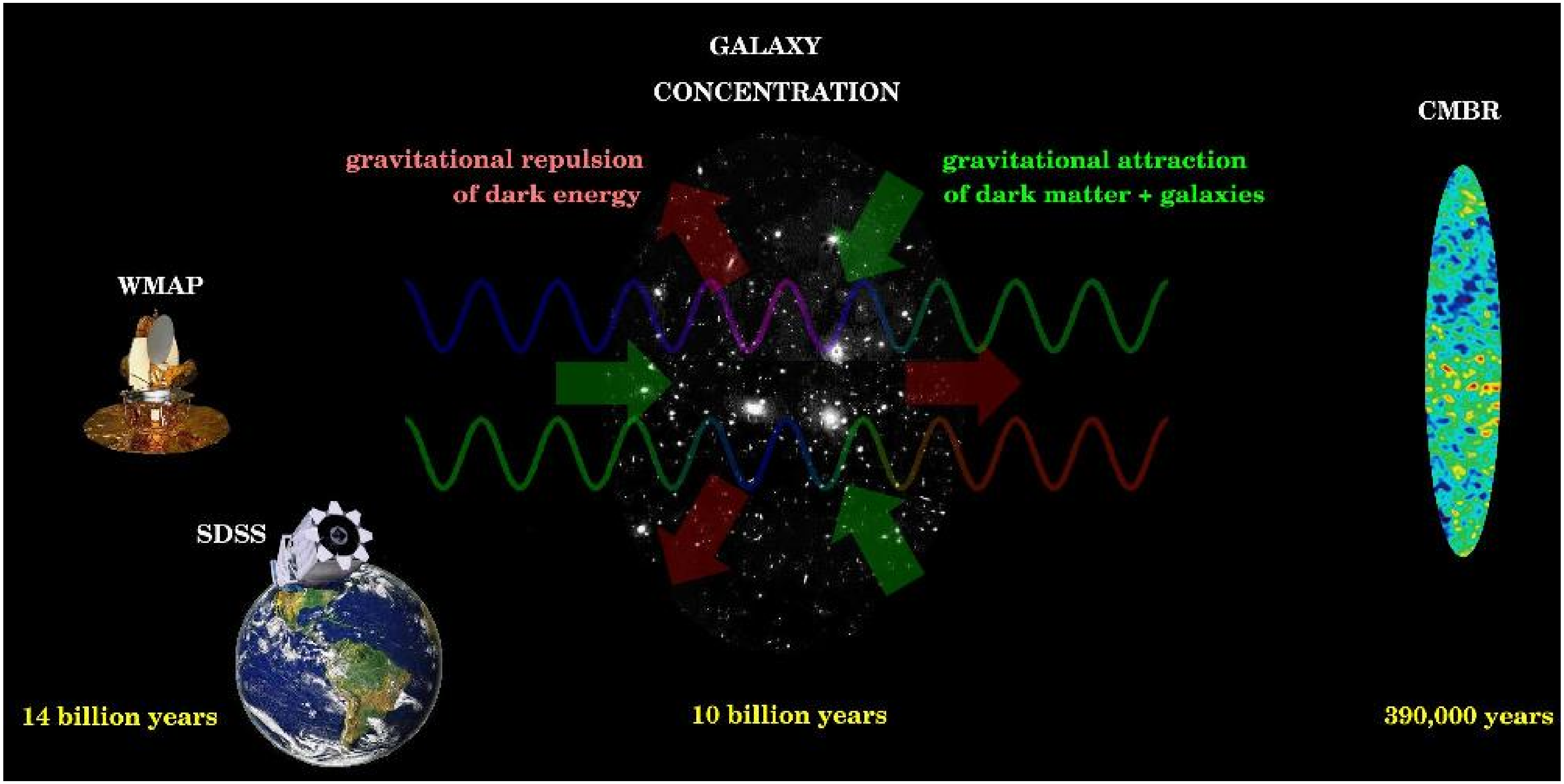
$$\delta\rho_m \propto a \Rightarrow d\Phi / d\eta = 0$$

- Therefore, curvature or DE gives a change in the gravitational potential

ISW II



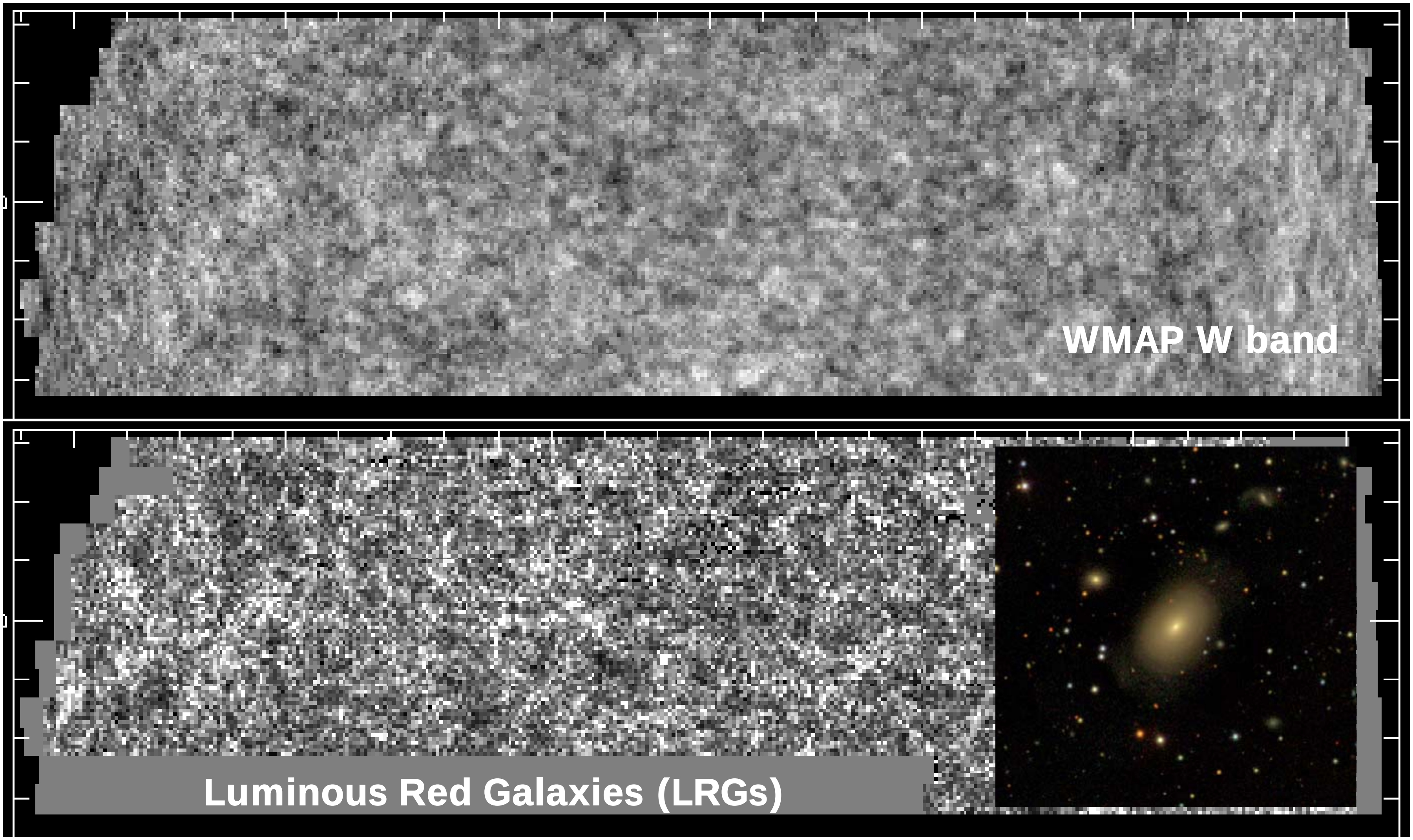
Experimental Set-up



Nolta et al, Boughn & Crittenden, Myers et al, Afshordi et al, Fosalba et al., Gaztanaga et al., Rassat et al.

WMAP-SDSS Correlation

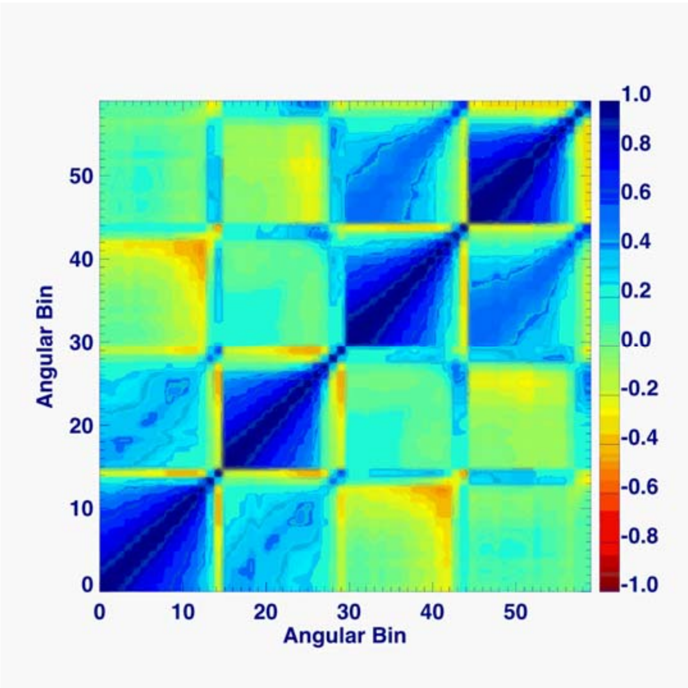
No signal in a flat, matter-dominated Universe

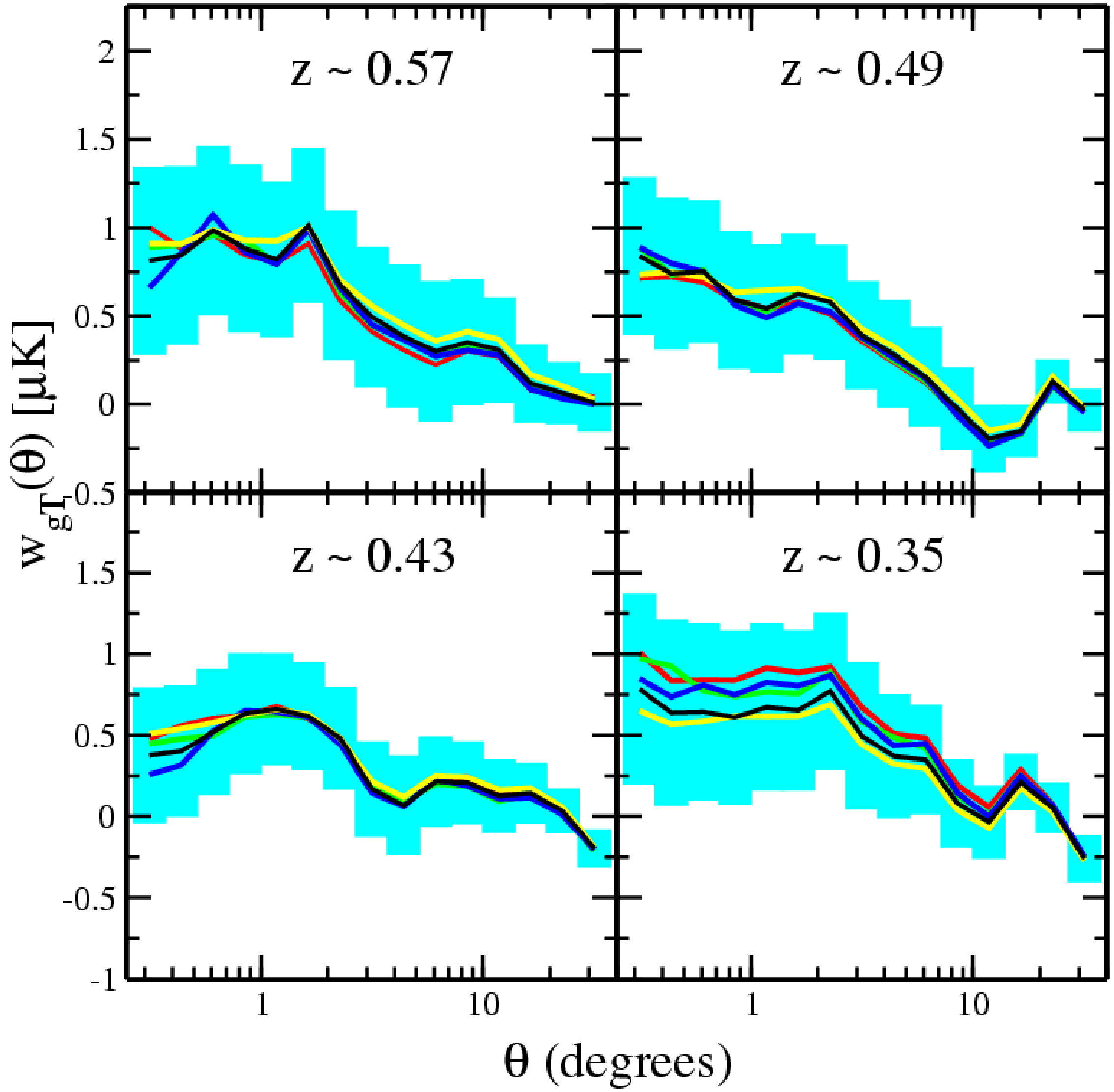


ISW Detected

Update of the Scranton et al. (2003) paper

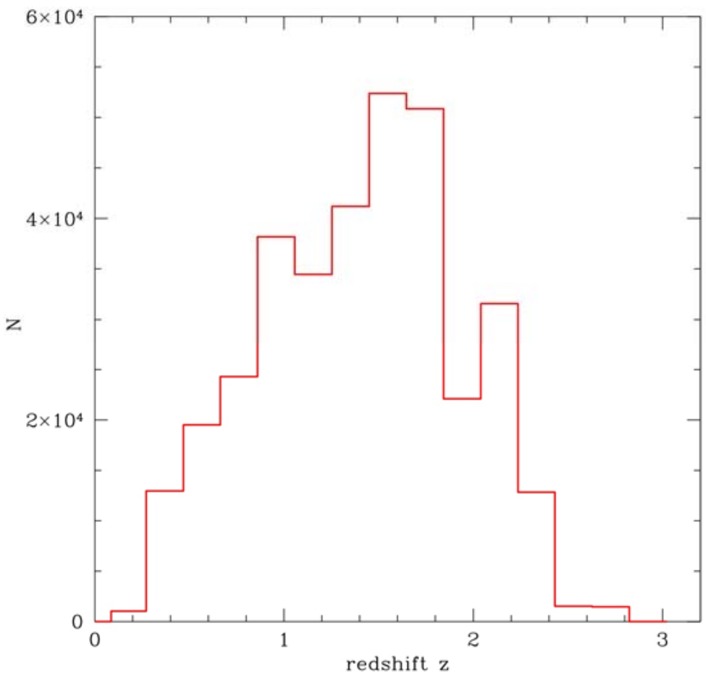
- 6300 sq degrees
- Achromatic
- 3σ detection

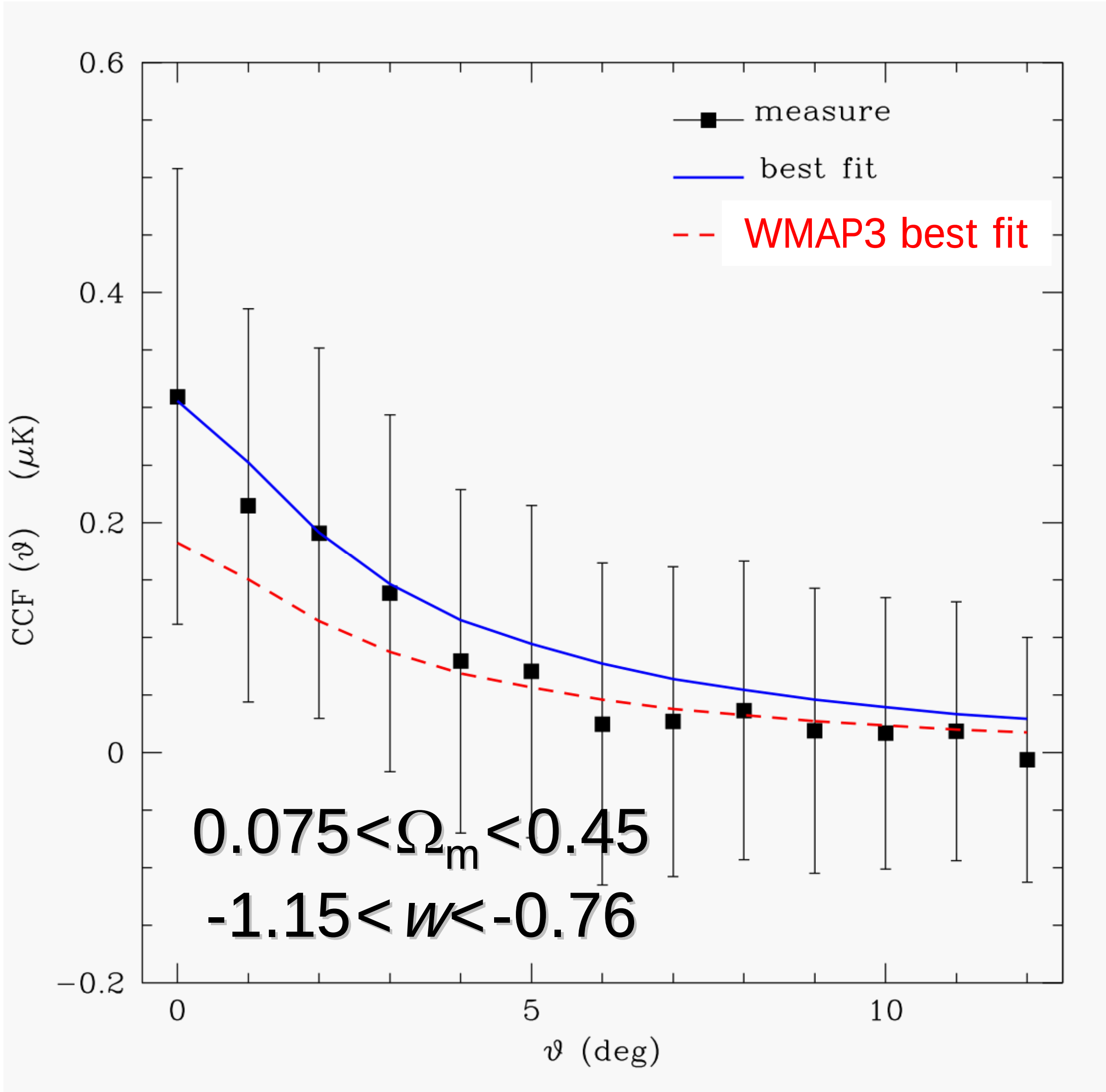




Giannantonio et al. (2006)

Cross-correlation of WMAP3 and SDSS quasars



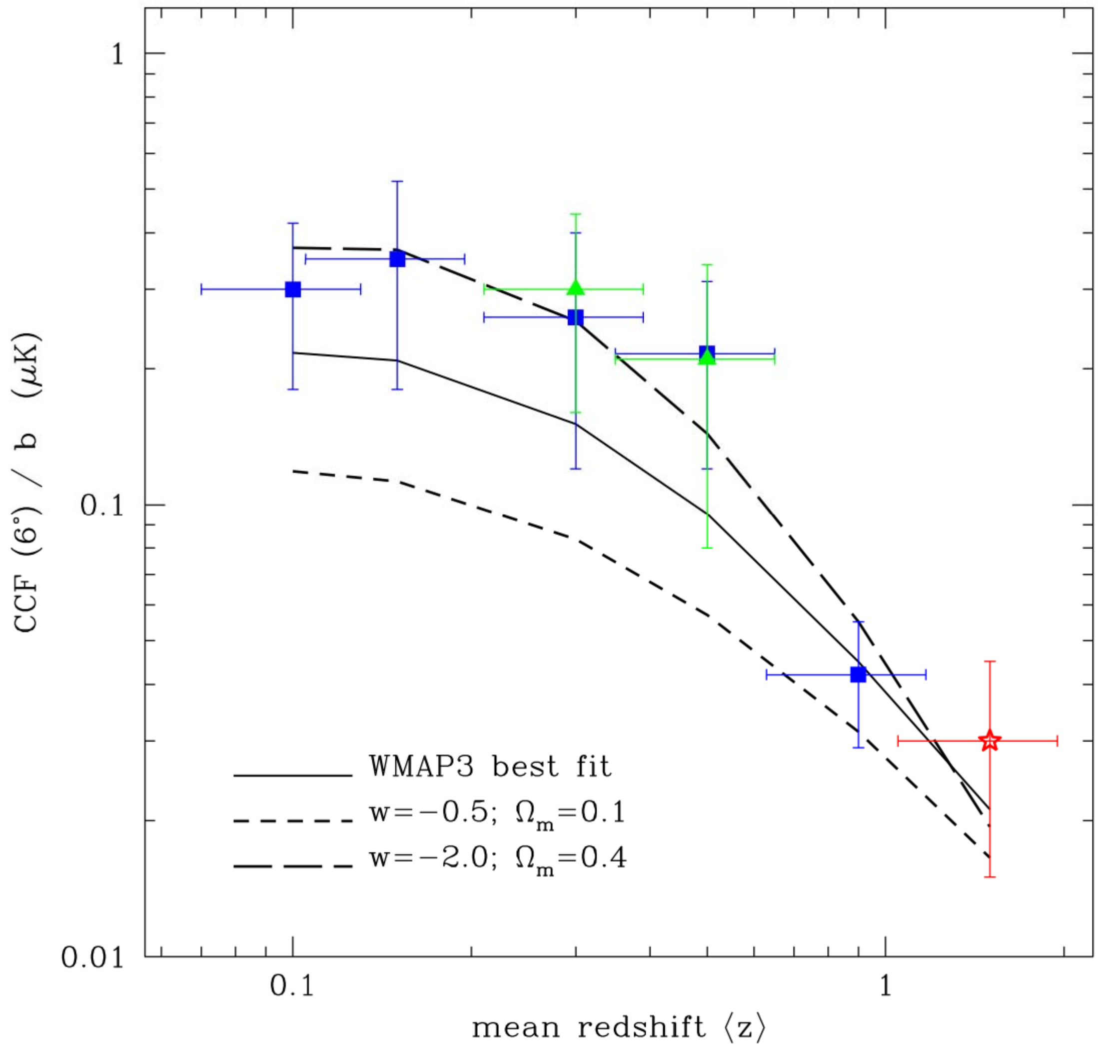


$0.075 < \Omega_m < 0.45$

$-1.15 < w < -0.76$

Detection of DE at z>1

Evolution of DE

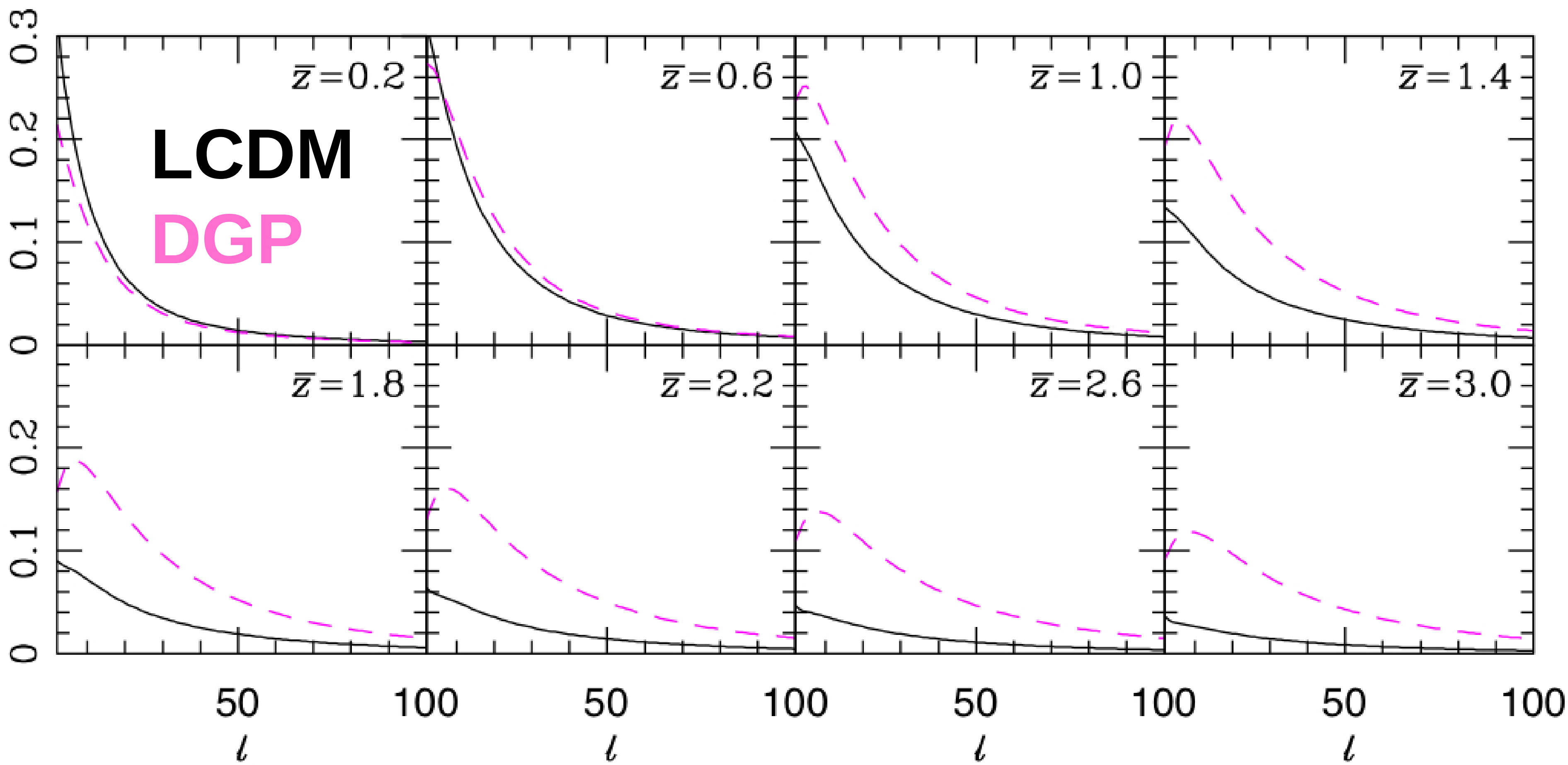


Consistent with w=-1

Rules out models Ω_D (z=1.5) > 0.5

Modified Gravity

Song et al. (2006)



Future Dark Energy Survey

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DETF Terminology

- **Stage II are experiments going on now (most are still limited by statistics and systematics)**
- **Stage III are next generation (before end of decade). Investigate systematics and gain factor of >3**
- **Stage IV are next decade and gain factor of 10**

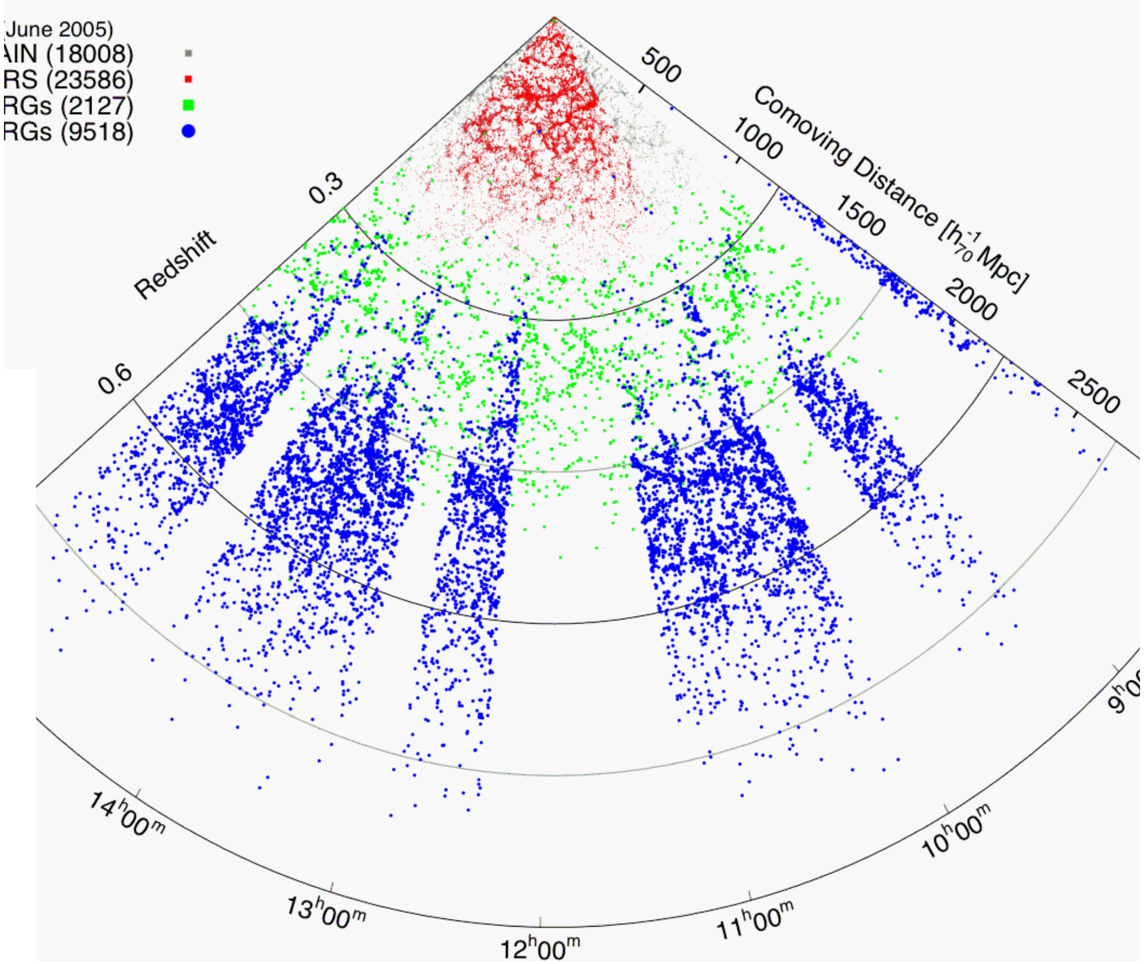
Trotta & Bower PPARC Report / Peacock et al. report from ESA/ESO WG

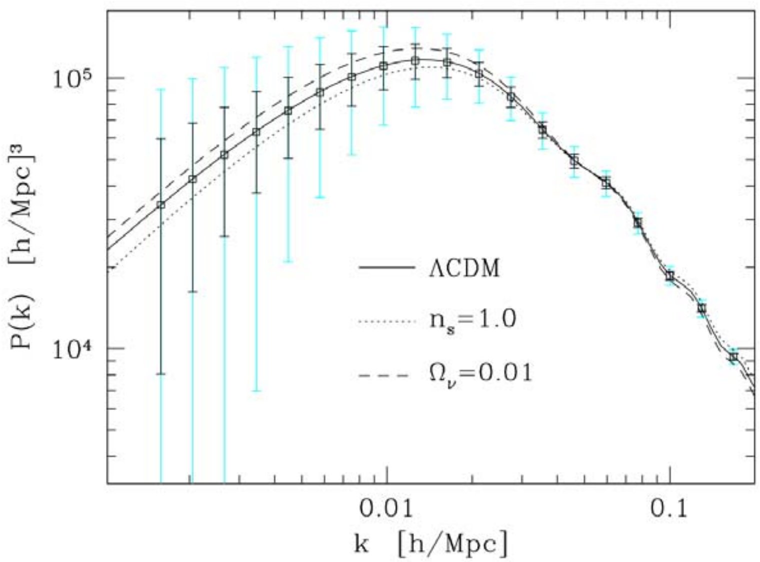
After SDSSII (AS2)

Baryon Oscillation Spectroscopic Survey (BOSS)

- Measure distance to ~1% at z=0.35 and z=0.6
- 10000 deg^2 with 1.5m LRGs to 0.2<z<0.8
- 160k quasars at 2.3<z<2.8
- Starting 2009
- h to 1% with SDSS SNe

2SLAQ (www.2slaq.info)





Dark Energy Survey (DES)

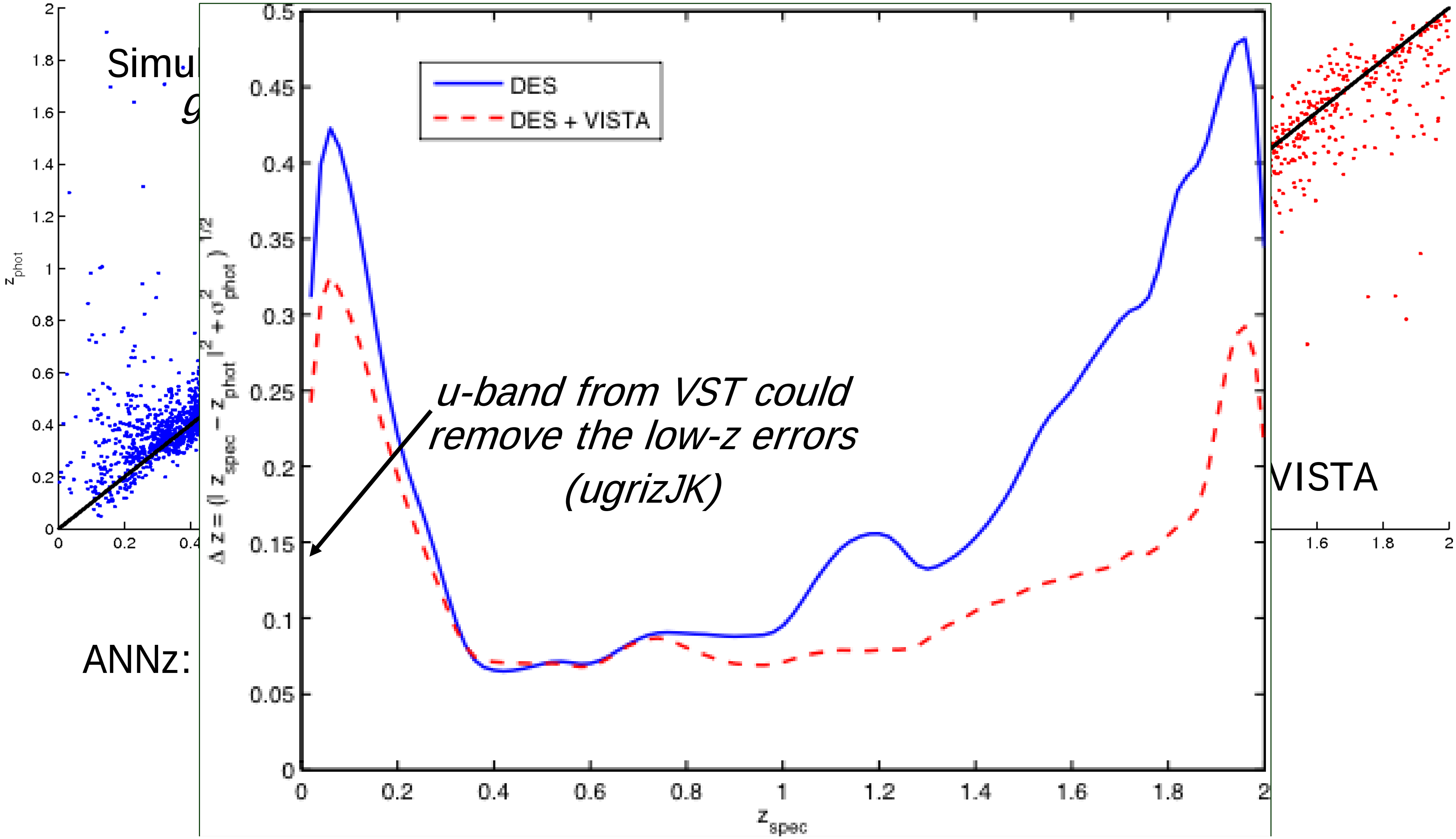
- 5000 sq deg multiband (g,r,i,z) survey of SGP using CTIO Blanco with a new wide-field camera
- 9 sq deg time domain search for SNe

Method	$\sigma(\Omega_{DE})$	$\sigma(w_0)$	$\sigma(w_a)$	z_p	$\sigma(w_p)$	$[\sigma(w_a)\sigma(w_p)]^{-1}$
BAO	0.010	0.097	0.408	0.29	0.034	72.8
Clusters	0.006	0.083	0.287	0.38	0.023	152.4
Weak Lensing	0.007	0.077	0.252	0.40	0.025	155.8
Supernovae	0.008	0.094	0.401	0.29	0.023	107.5
Combined DES	0.004	0.061	0.217	0.37	0.018	263.7
DETF Stage II Combined	0.012	0.112	0.498	0.27	0.035	57.9

Table 1: 68% CL marginalized forecast errorbars for the 4 DES probes on the dark energy density and equation of state parameters, in each case including Planck priors *and* the DETF Stage II constraints. The last column is the DETF FoM; z_p is the pivot redshift. Stage II constraints used here agree with those in the DETF report to better than 10%.

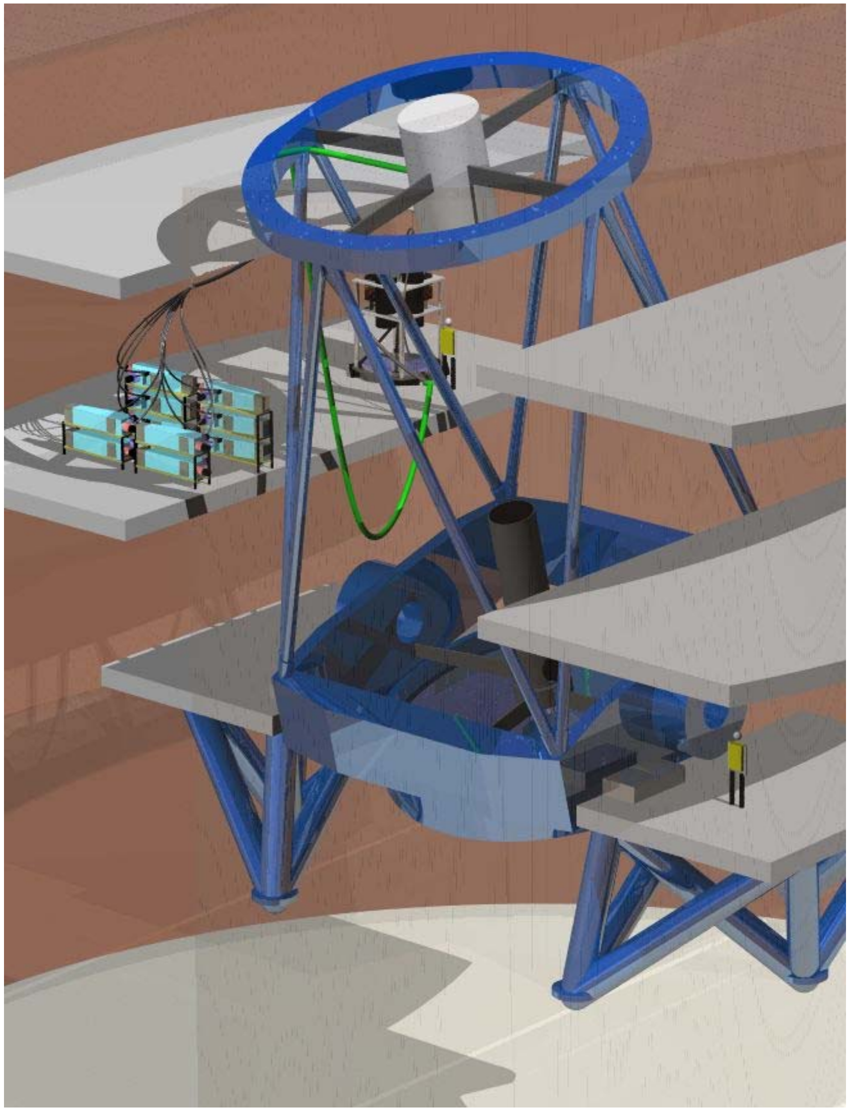
DES Photo-z's

DES science relies on good photometric estimates of the 300 million expected galaxies



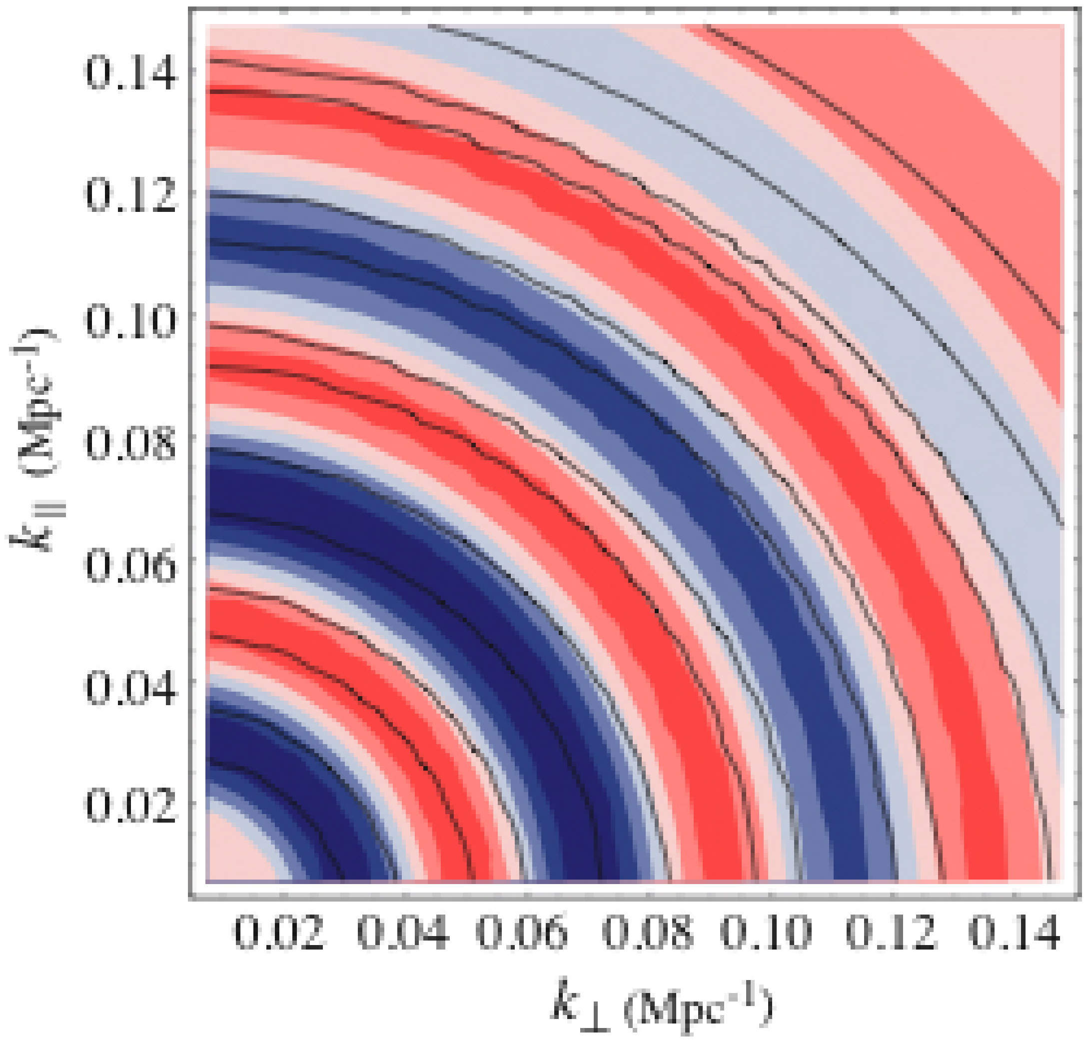
WFMOS

- Proposed MOS on Subaru via an international collaboration of Gemini and Japanese astronomers
- 1.5deg FOV with 4500 fibres feeding 10 low-res spectrographs and 1 high-res spectrograph
- ~20000 spectra a night *(2dfGRS at z~1 in 10 nights)*
- DE science, Galactic archeology, galaxy formation studies and lots of ancillary science from database
- Design studies underway; on-sky by 2013
- Next Generation VLT instruments; meetings in Garching
- Combine with an imager and do "SDSS at z=1"



DE Science

Measure BAO at z~1 and z~3 to determine w(z)



WFMOS Legacy

Facility instrument

z range	R limit (AB)	Volume (h^{-1} Gpc)	Area (sq degs)	Number	Nights
0.5 - 1.3	***22.7***	***4***	***2000***	***2000000***	***100***
2.3 - 3.3	***24.5***	***1***	***300***	***600000***	***100***
Galaxy Archeology				***400000***	***400***

(Glazebrook et al. 2005)

- *Galaxy Evolution:* Every galaxy in Coma (M_r < -11)
- *IGM and Quasars:* Simultaneously observing QSOs and galaxies in the same fields
- *Calibrate photo-z's:* LSST and DES require > a few 10^5 unbiased redshifts (Abdalla et al. 2007)