Latest results from BOSS
(and as they're delayed a look at future surveys)

Will Percival

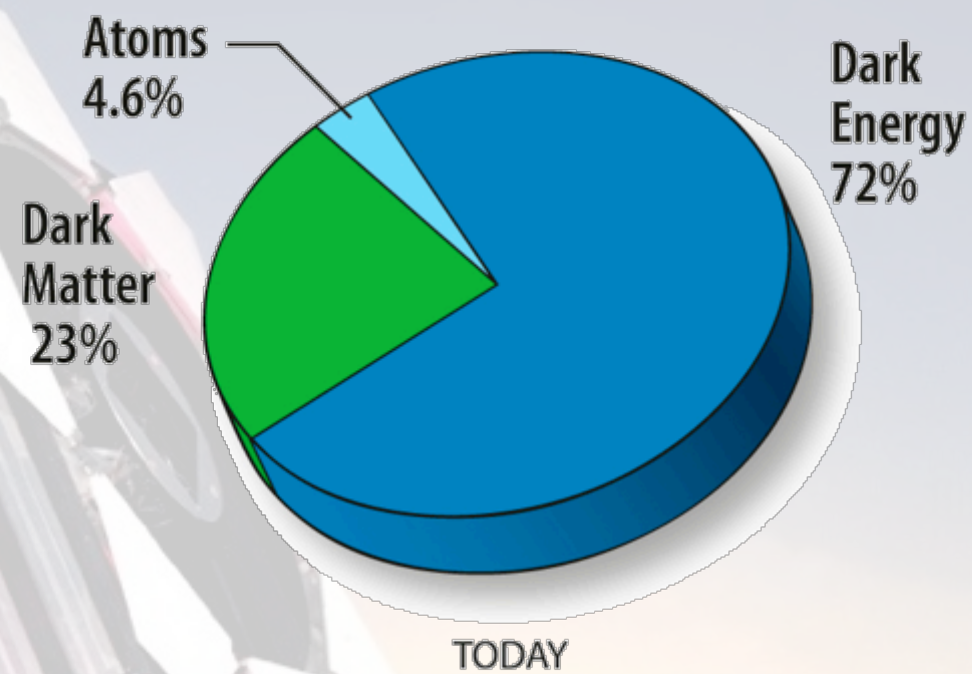
including work by the BOSS galaxy clustering working group

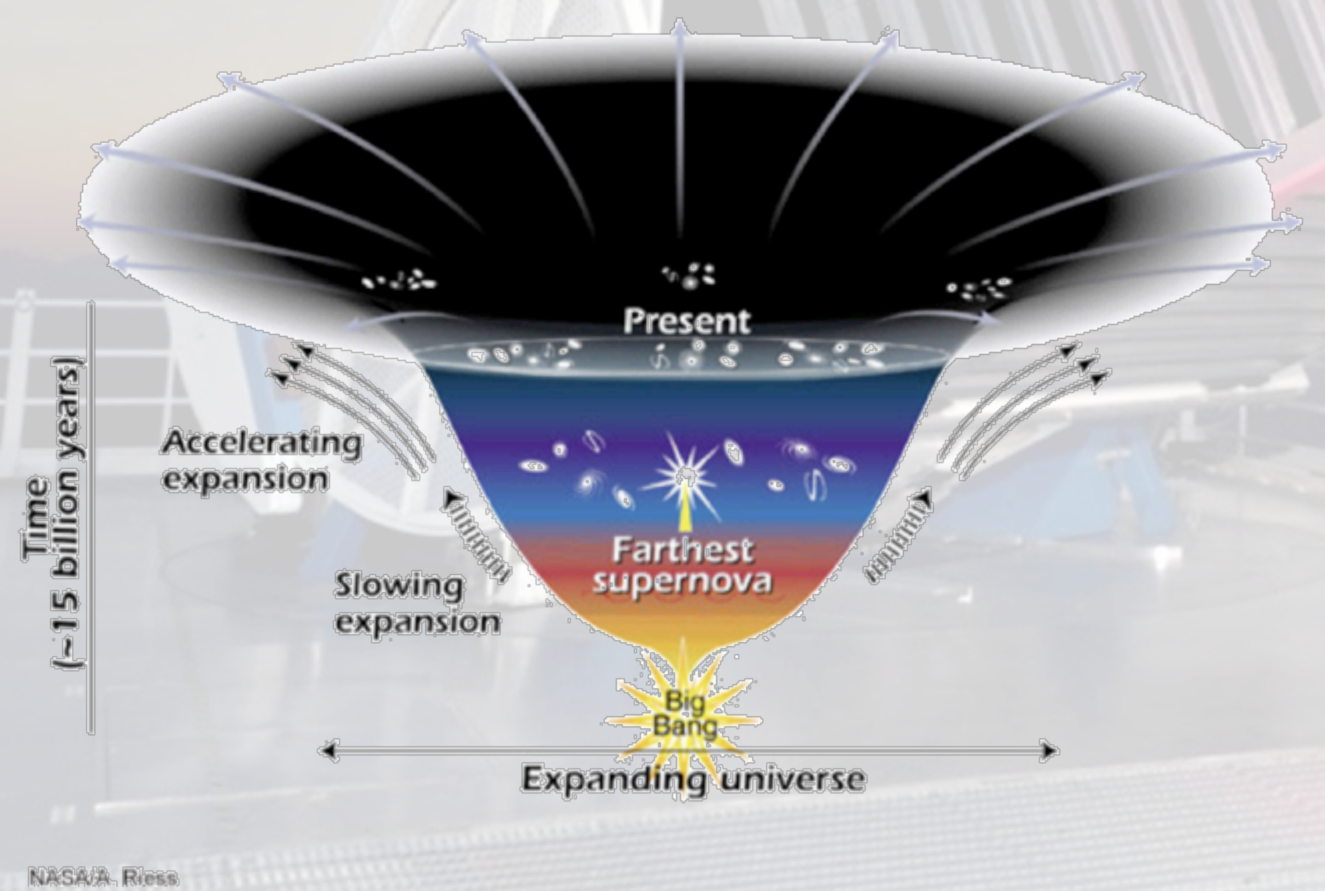
The standard “model” for cosmology

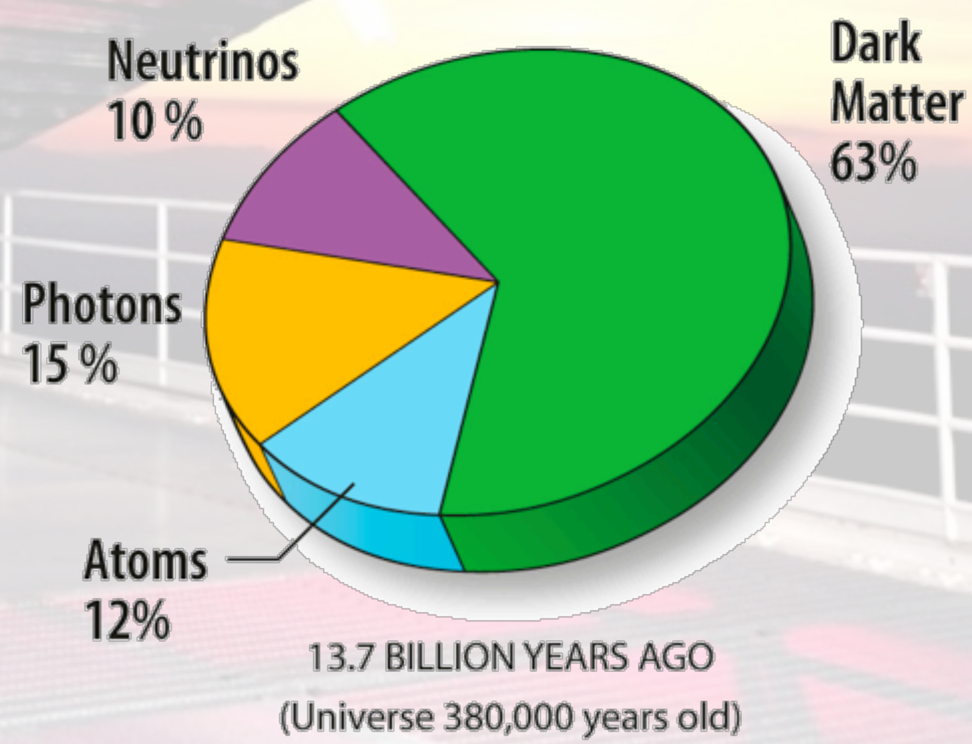
$$\frac{H^2}{H_0^2} = \Omega_R a^{-4} + \Omega_M a^{-3} + \Omega_k a^{-2} + \Omega_\Lambda$$

$$\frac{H^2}{H_0^2} = \Omega_M a^{-3} + \underbrace{(1 - \Omega_M)}_{}$$

The last 17 years has seen
the introduction of this term

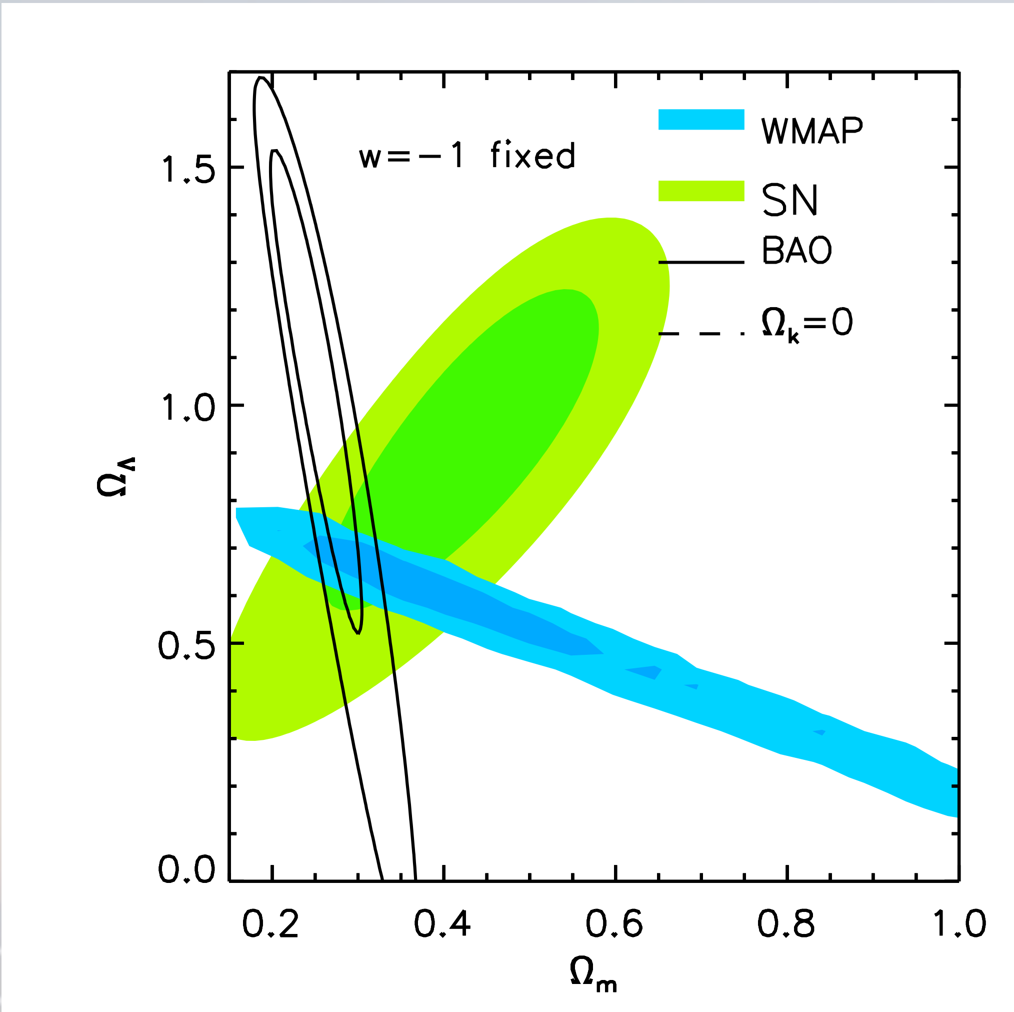




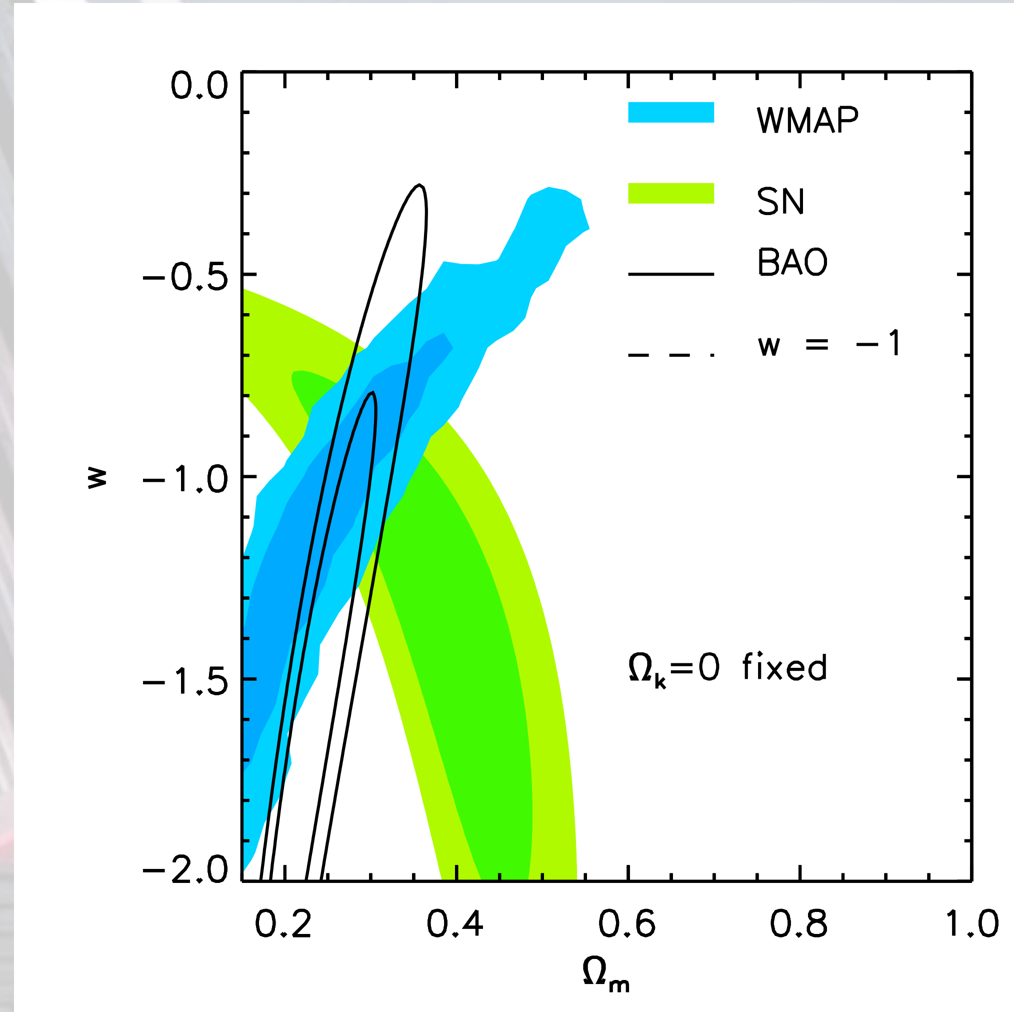


Concordance cosmology

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

The problem of Λ

ΛCDM fits all (believable?) current data well
It's the simplest (mathematical) model available
But … we cannot explain Λ with physics

- why so small?

$$\rho_\Lambda|_{\rm obs} = \frac{\Lambda}{8\pi G} \sim (10^{-3}\,{\rm eV})^4$$

$$\rho_\Lambda|_{\rm theory} \sim (M_{\rm new\ physics})^4 \sim (1\,{\rm TeV})^4 >> \rho_\Lambda|_{\rm obs}$$

- why so fine tuned?

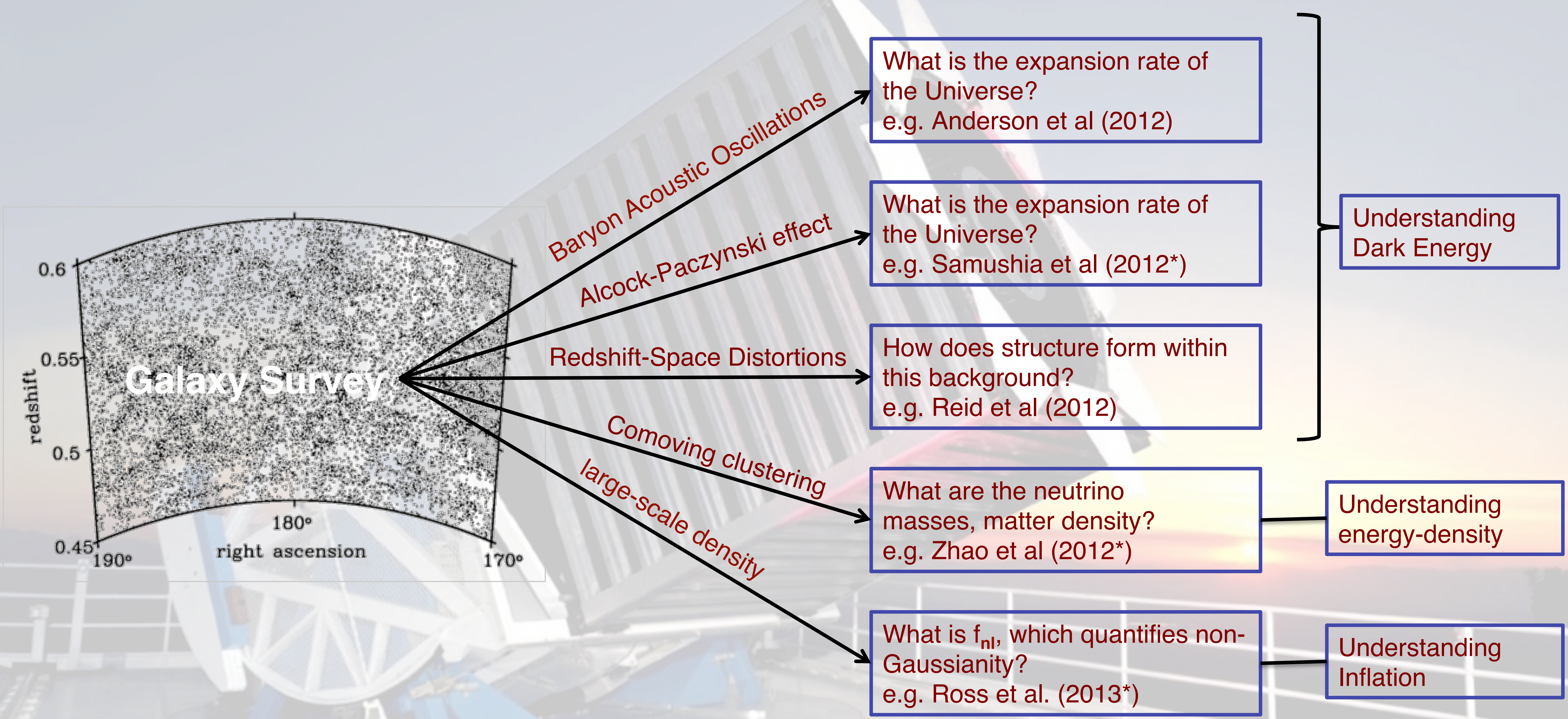
$$\rho_\Lambda \lesssim \rho_m \ : \ \text{crucial for structure formation}$$

$$\text{but } \rho_\Lambda \propto a^0 \text{ while } \rho_m \propto a^{-3}$$

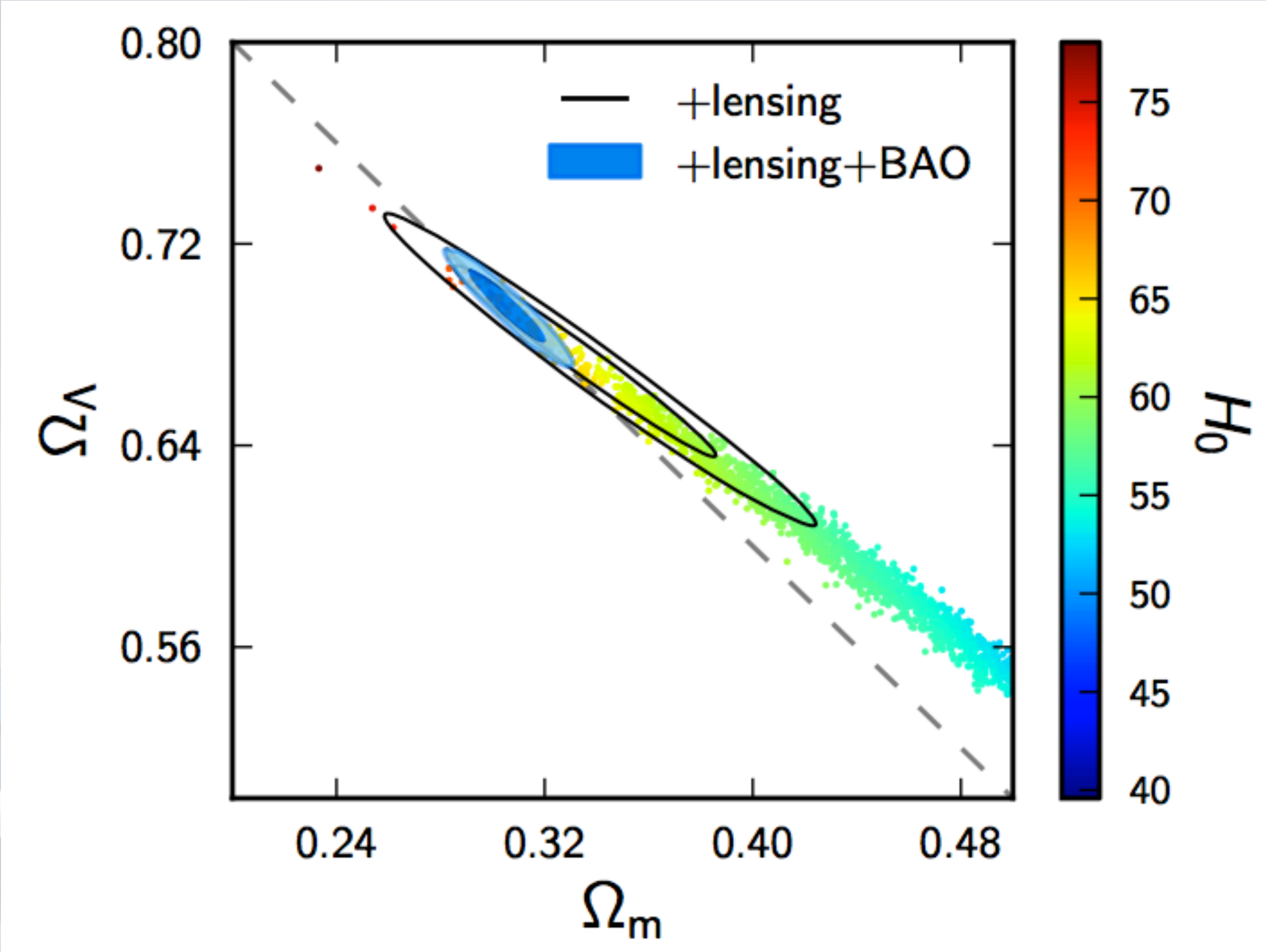
Many alternative explanations

- modify gravity on large-scales or at low densities?
- more general scalar field model?
- link with Dark Matter?
- back-reaction from structure growth?

Cosmology from galaxy surveys

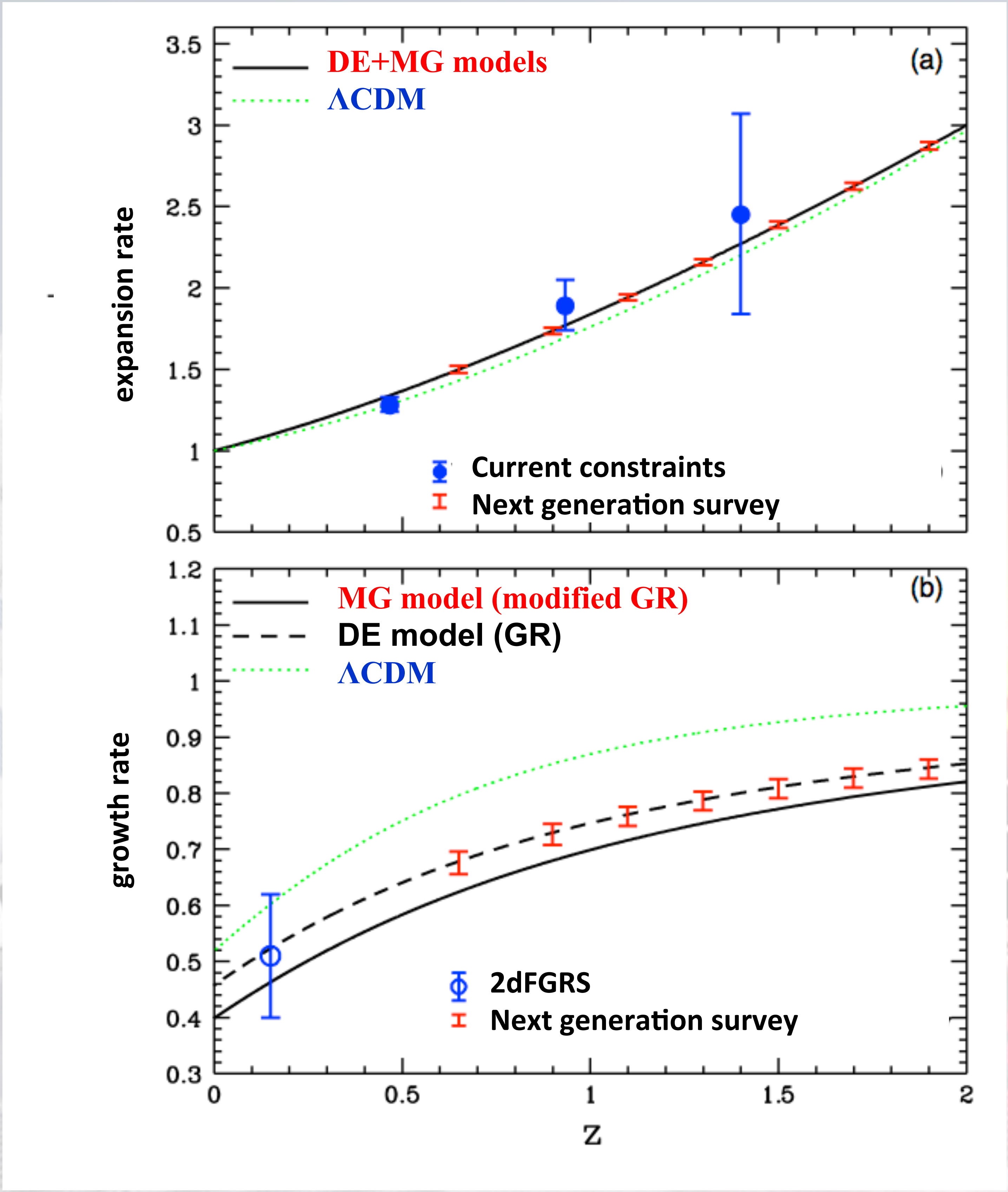


Why BAO measurements are needed



Planck collaboration 2013; arXiv:1303.5076

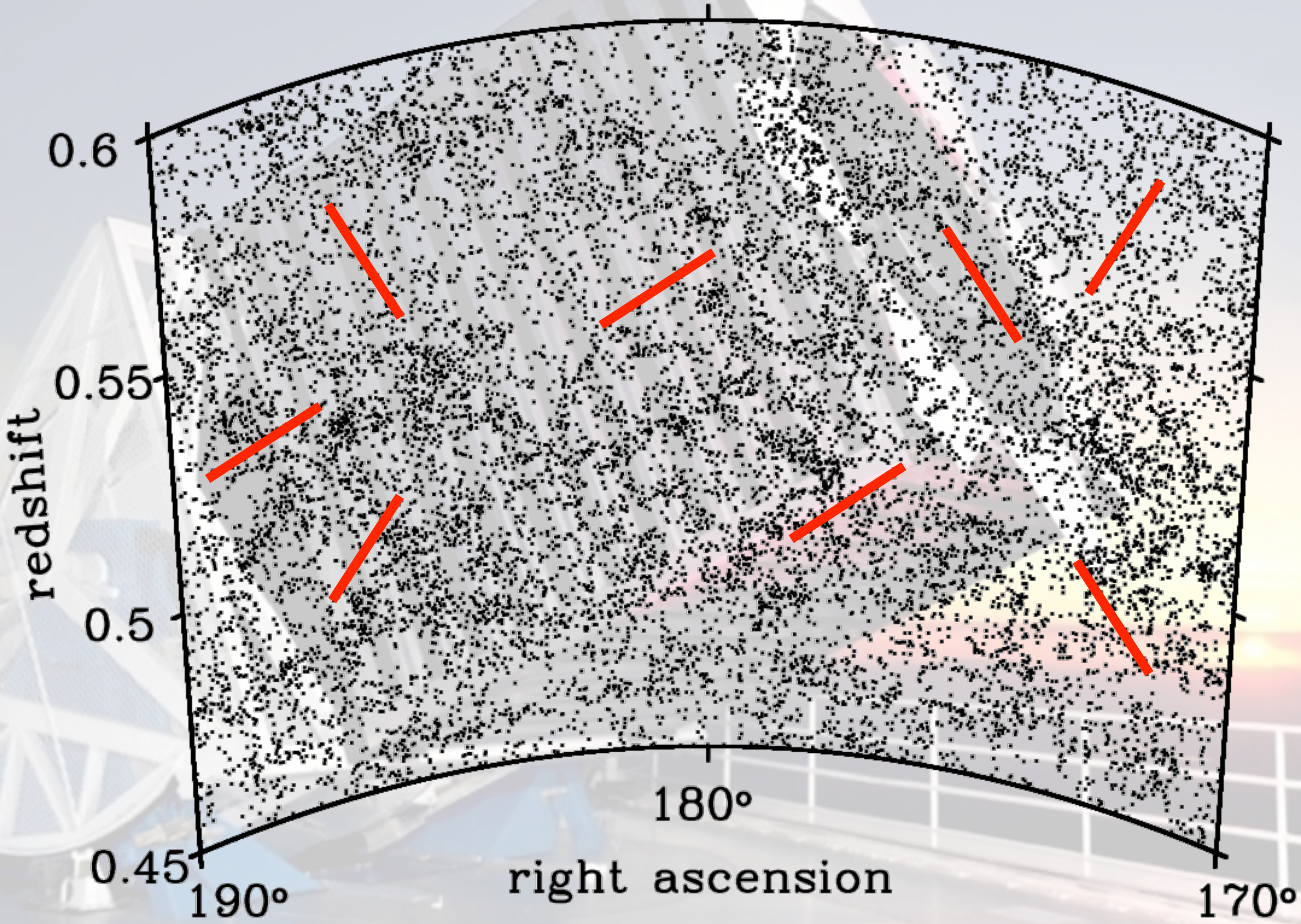
Why RSD measurements are needed



Wang 2008: JCAP, 05, 21

What does “galaxy clustering” mean?

Clustering strength = number of galaxy pairs beyond random



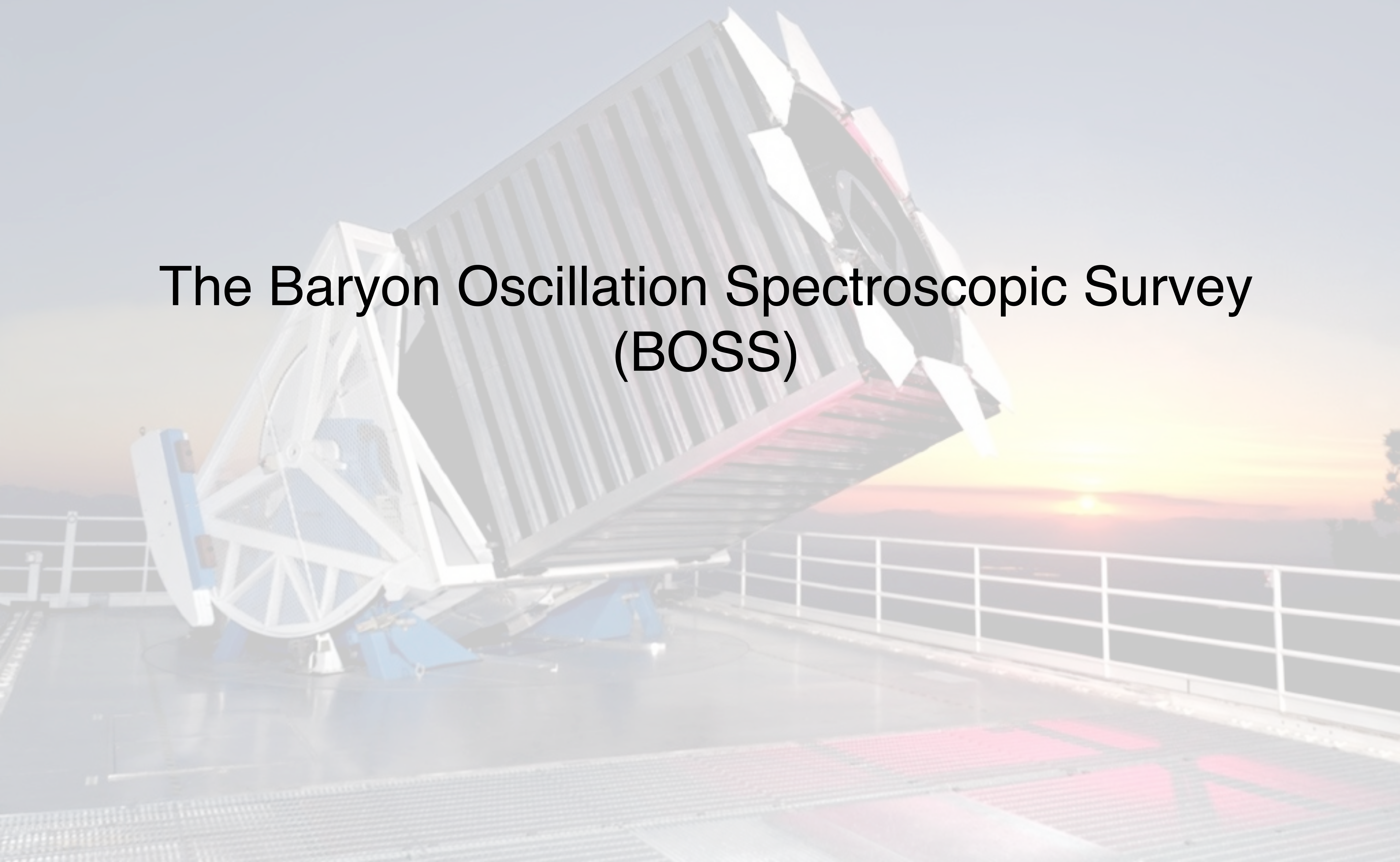
$$\delta = \frac{\rho - \rho_0}{\rho_0}$$

$$P(k) = \langle \delta_k(k)^2 \rangle$$

$$\xi(d) = \langle \delta(\mathbf{r})\delta(\mathbf{r}+\mathbf{d}) \rangle$$

SDSS

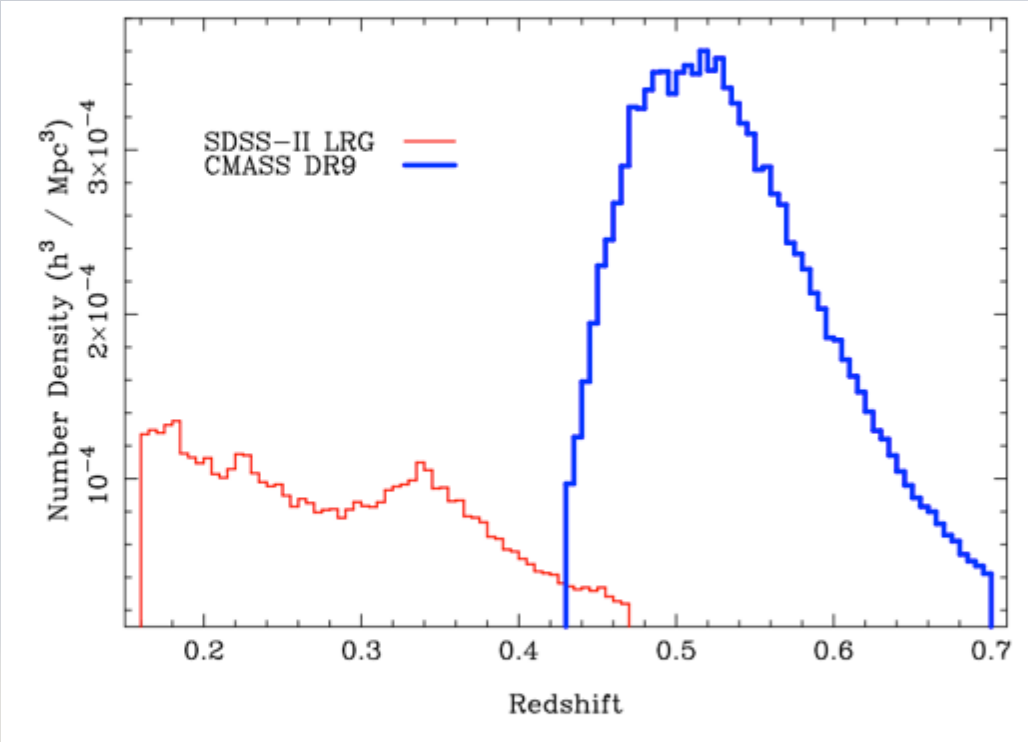
The Baryon Oscillation Spectroscopic Survey (BOSS)

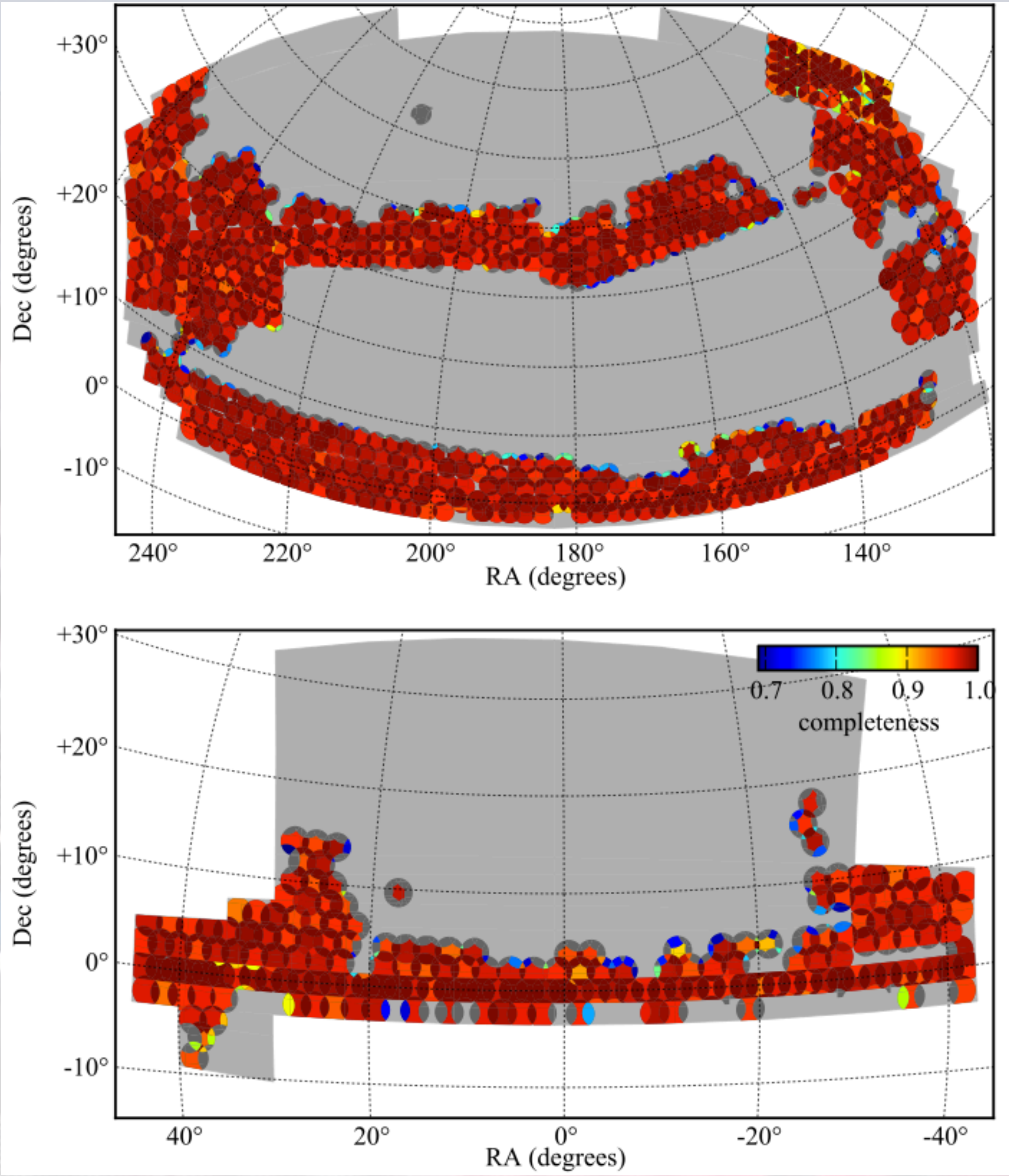


Baryon Oscillation Spectroscopic Survey

- Duration: Fall 2009 - Summer 2014, dark time
- Telescope: 2.5m Sloan
- Upgrade to SDSS-II spectrograph
  - 1000 smaller fibers
  - higher throughput
- Spectra:
  - $3600\,\mathring{A} < \lambda < 10,000\,\mathring{A}$ New spectrograph
  - $R = \lambda/\Delta\lambda = 1300 - 3000$
  - (S/N) at mag. limit
    - 22 per pix. (averaged over 7000-8500Å)
    - 10 per pix. (averaged over 4000-5500Å)
- Area: 10,000 deg2
- Targets:
  - **1.5×10^6 massive galaxies, $z < 0.7$, $i < 19.9$**
  - $1.5{\times}10^5$ quasars, $z>2.2$, $g<22.0$ selected from 4×10^5 candidates
  - 75,000 ancillary science targets, many categories
- **Measurements from Galaxies:**
  - **$d_A(z)$ to 1.2% at $z = 0.35$ and 1.2% $z = 0.6$**
  - **$H(z)$ to 2.2% at $z = 0.35$ and 2.0% at $z = 0.6$**
- Measurements from Lyα Forest:
  - $d_A(z)$ to 4.5% at $z = 2.5$ $H(z)$ to 2.6% at $z = 2.5$

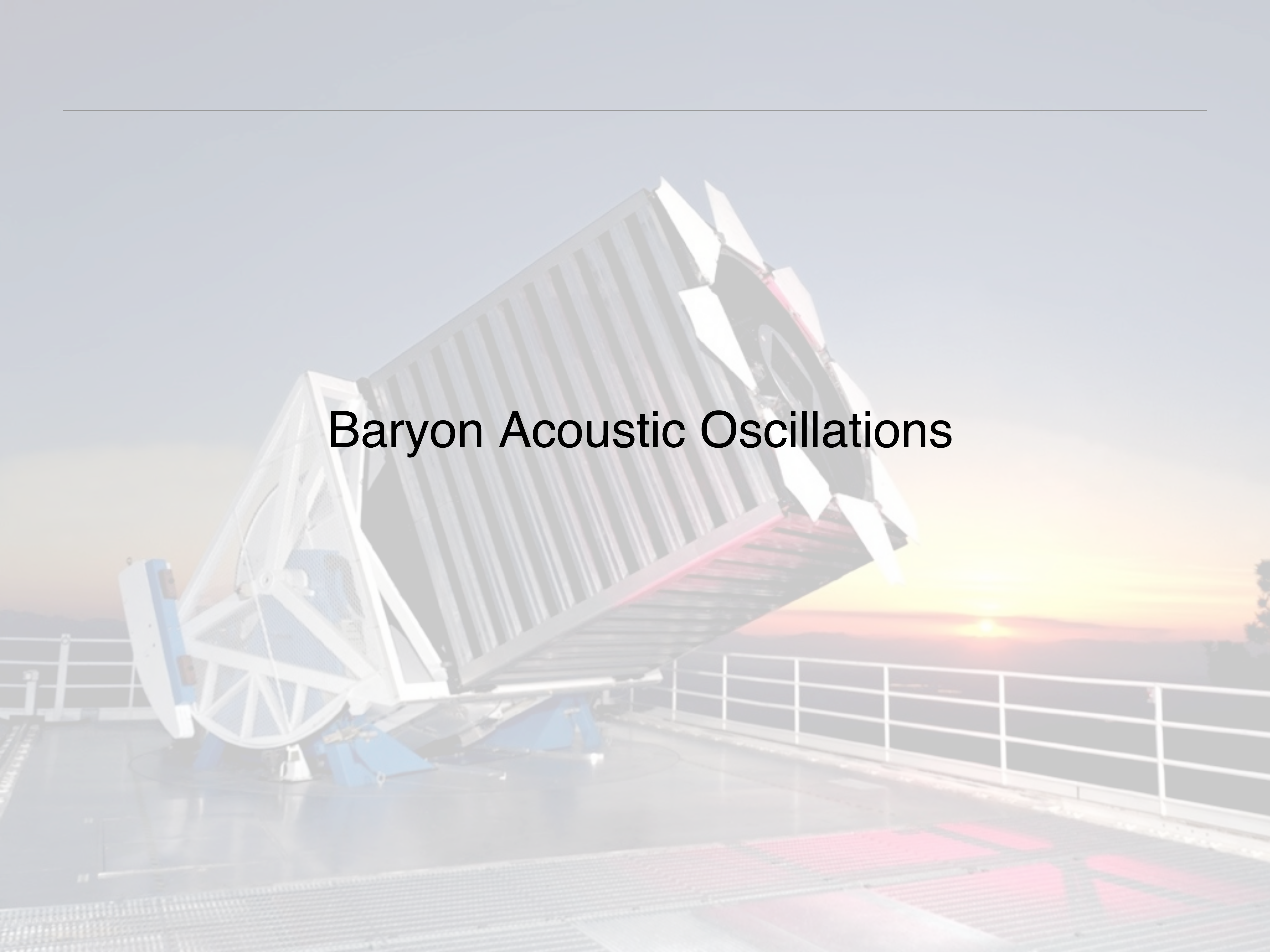
Data Release 9 (DR9)



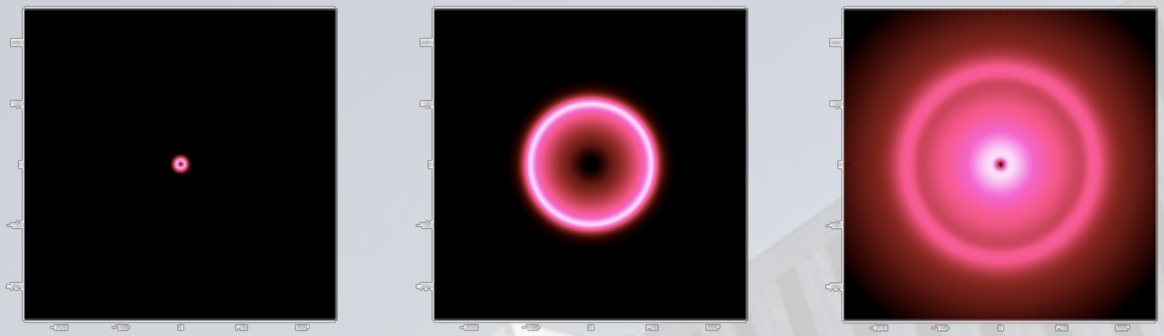


- 264 283 massive galaxies
- 3275 deg²
- effective redshift $z = 0.57$ and redshift range $0.43 < z < 0.7$
- effective volume of 2.2 Gpc³ (Assuming ΛCDM)
- largest sample of the Universe ever surveyed at this density, $n \approx 3 \times 10^{-4} h^{-3} \mathrm{Mpc}^3$

Baryon Acoustic Oscillations



Baryon Acoustic Oscillations (BAO)

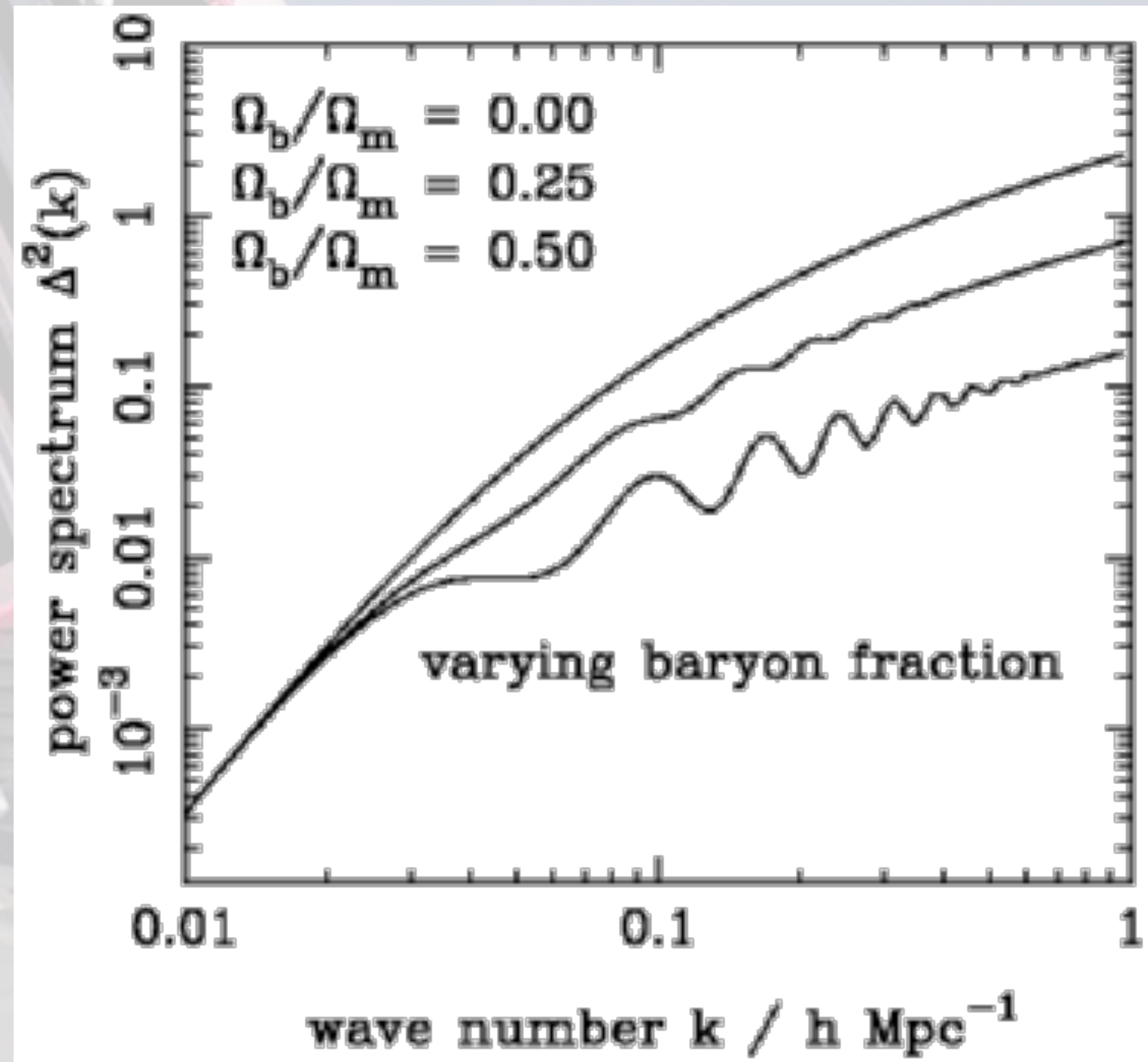


(images from Martin White)

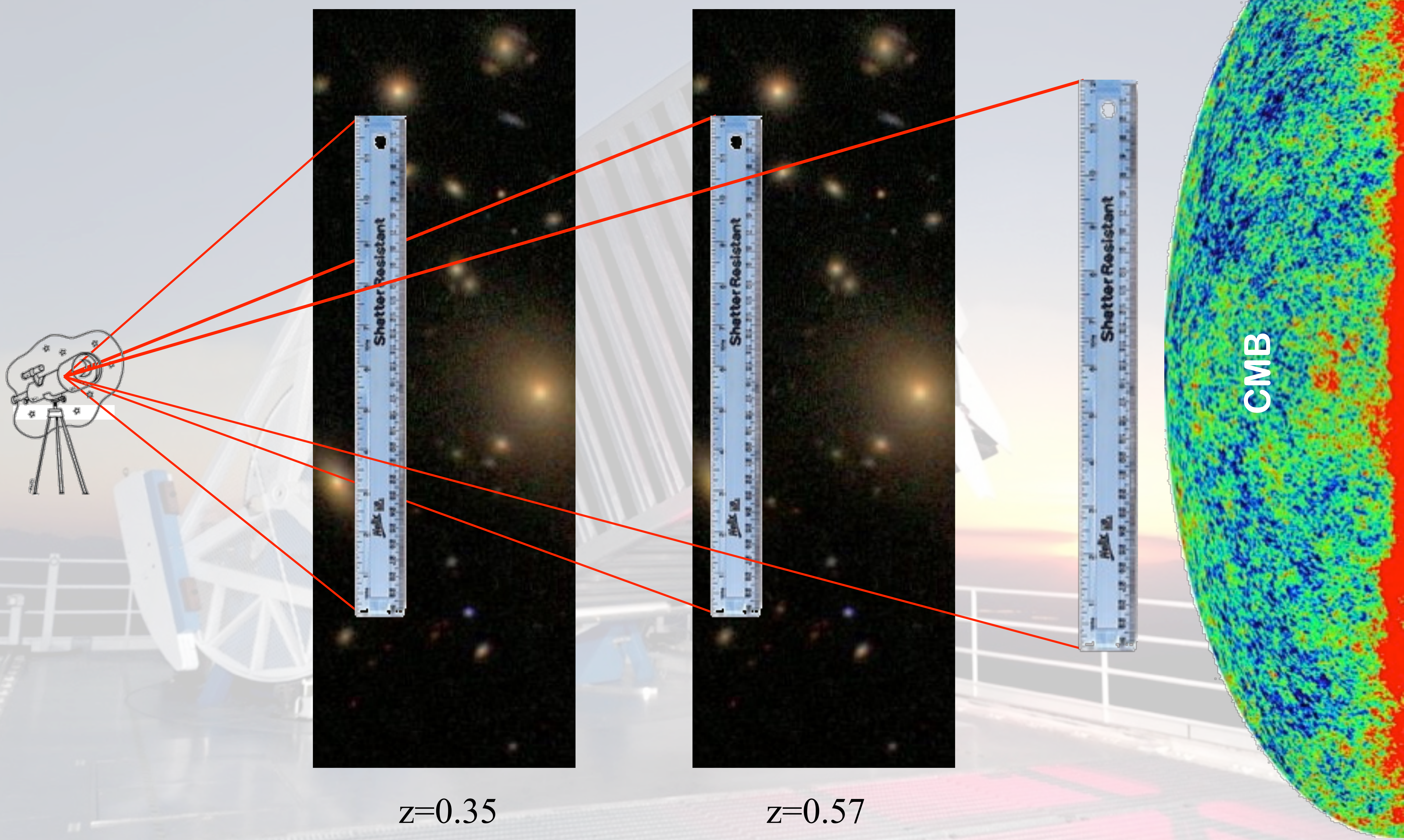
To first approximation, comoving BAO wavelength is determined by the comoving sound horizon at recombination

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

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

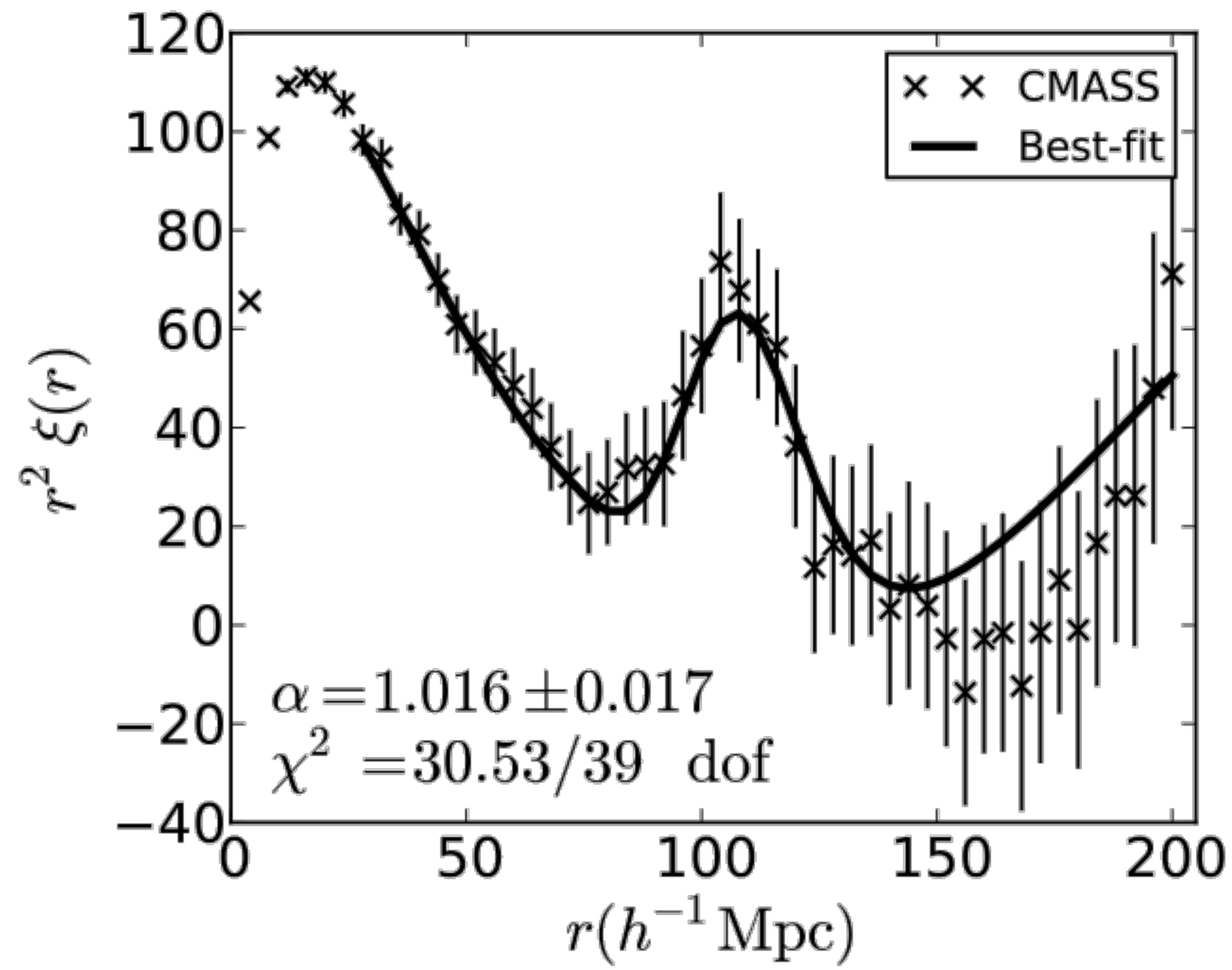


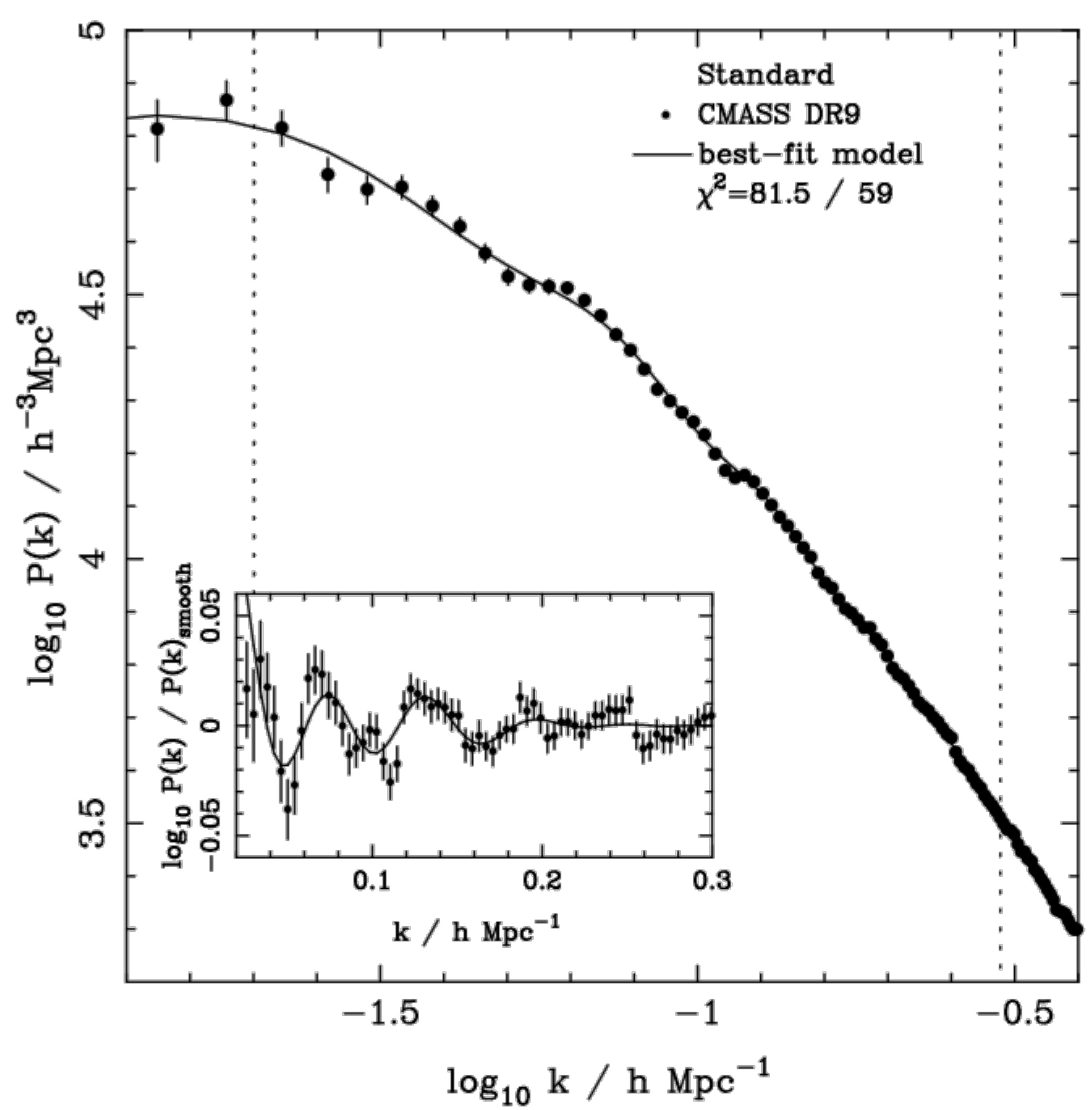
BAO as a standard ruler



CREDIT: WMAP & SDSS websites

BOSS DR9 CMASS isotropic clustering





Anderson et al. 2012

Measuring a distance

Fit the observed acoustic feature using some way to parameterize over nuisance broad-band features (different approaches for P(k) and ξ(r))

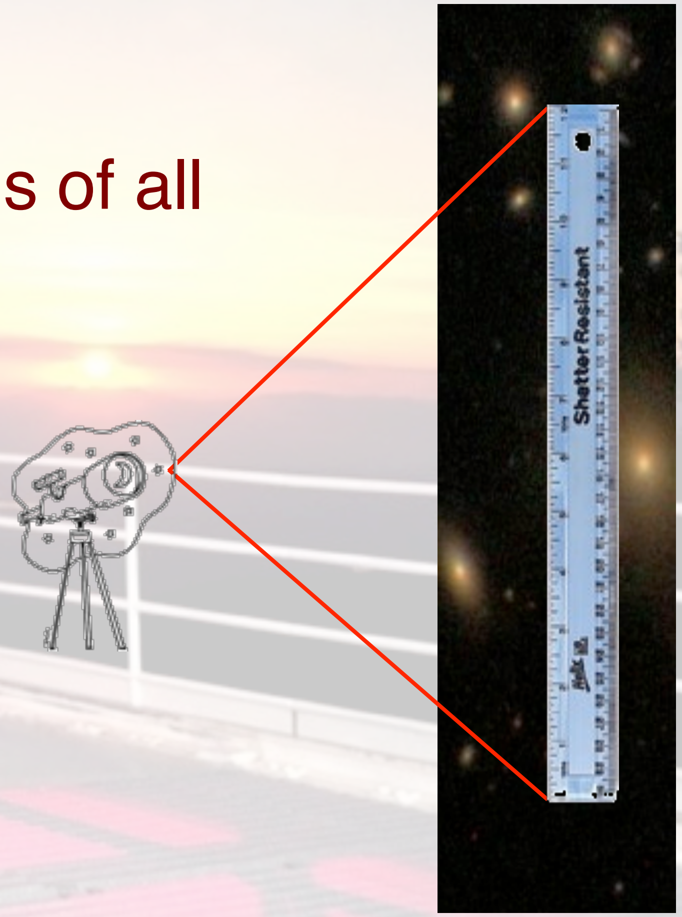
Use a fiducial model to compare against observed features in spherically averaged statistics. Departures quantified by dilation scale α:

$$P(k/\alpha) \quad \xi(\alpha r)$$

The dilation scale α depends on cosmology (for an analysis of all galaxies over all directions) through:

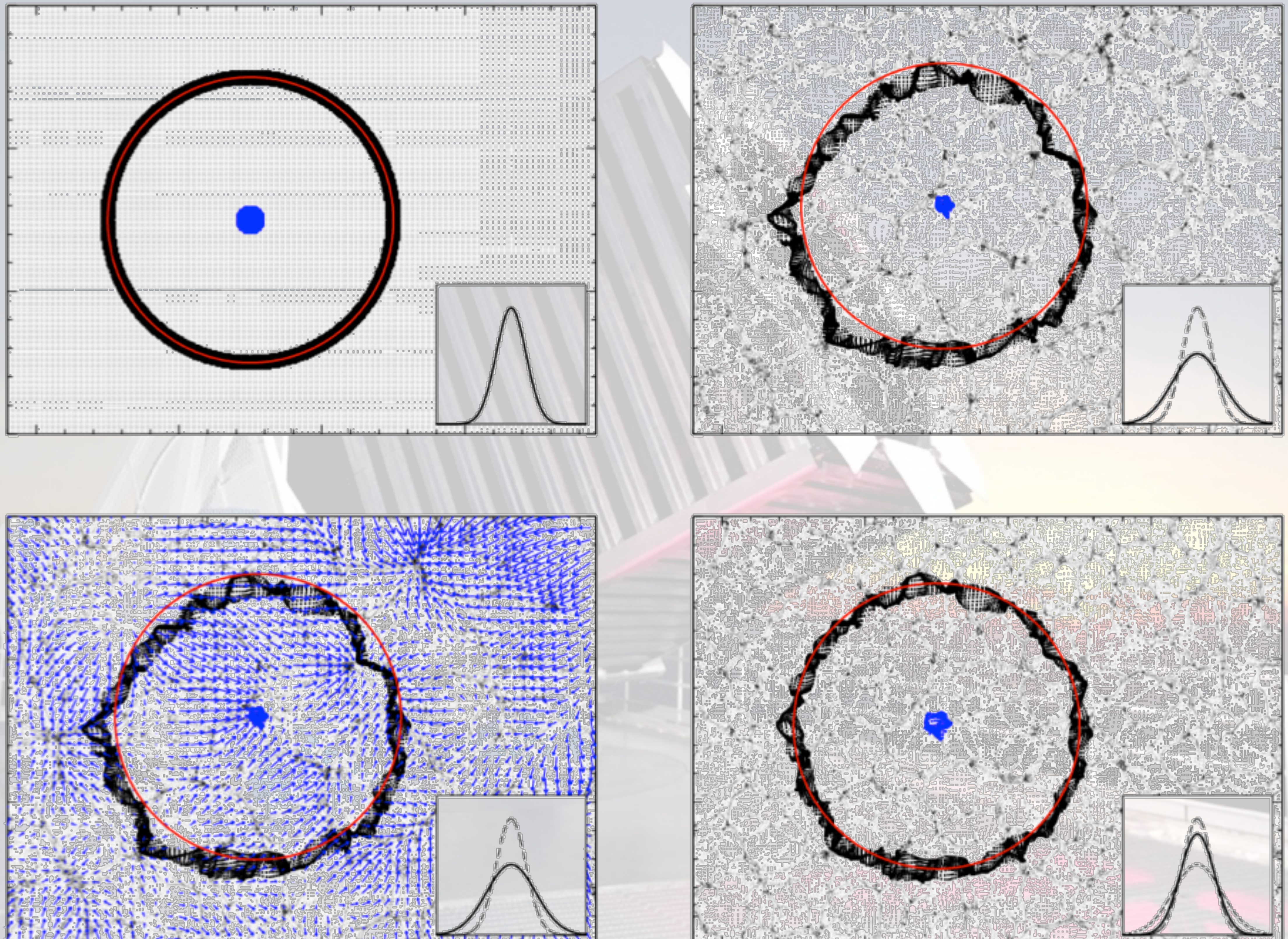
$$D_V / r_s = \alpha (D_V / r_s)_{fid}$$

$$D_V = [cz(1 + z)^2 d_A^2 H^{-1}]^{1/3}$$



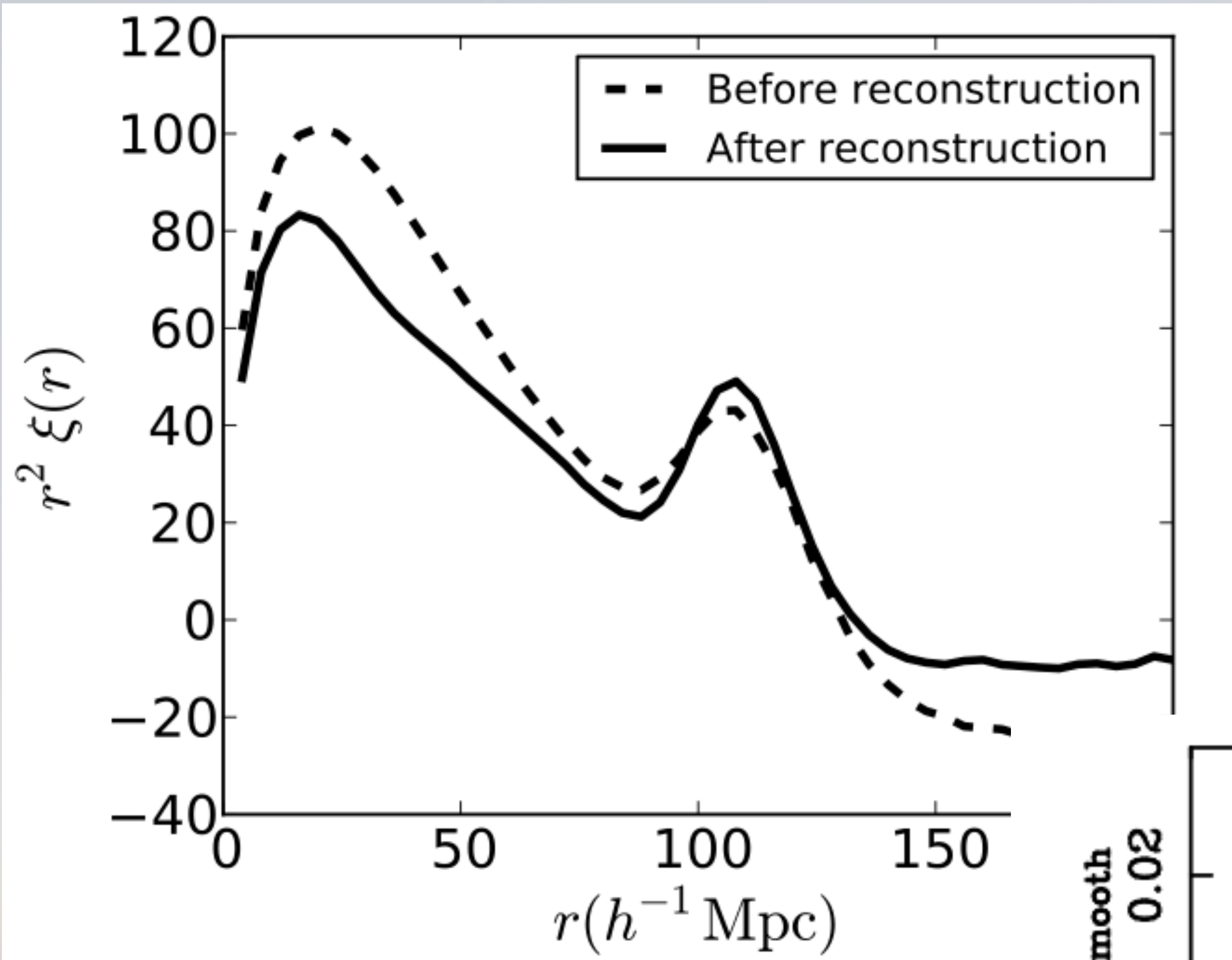
Anderson et al. 2012

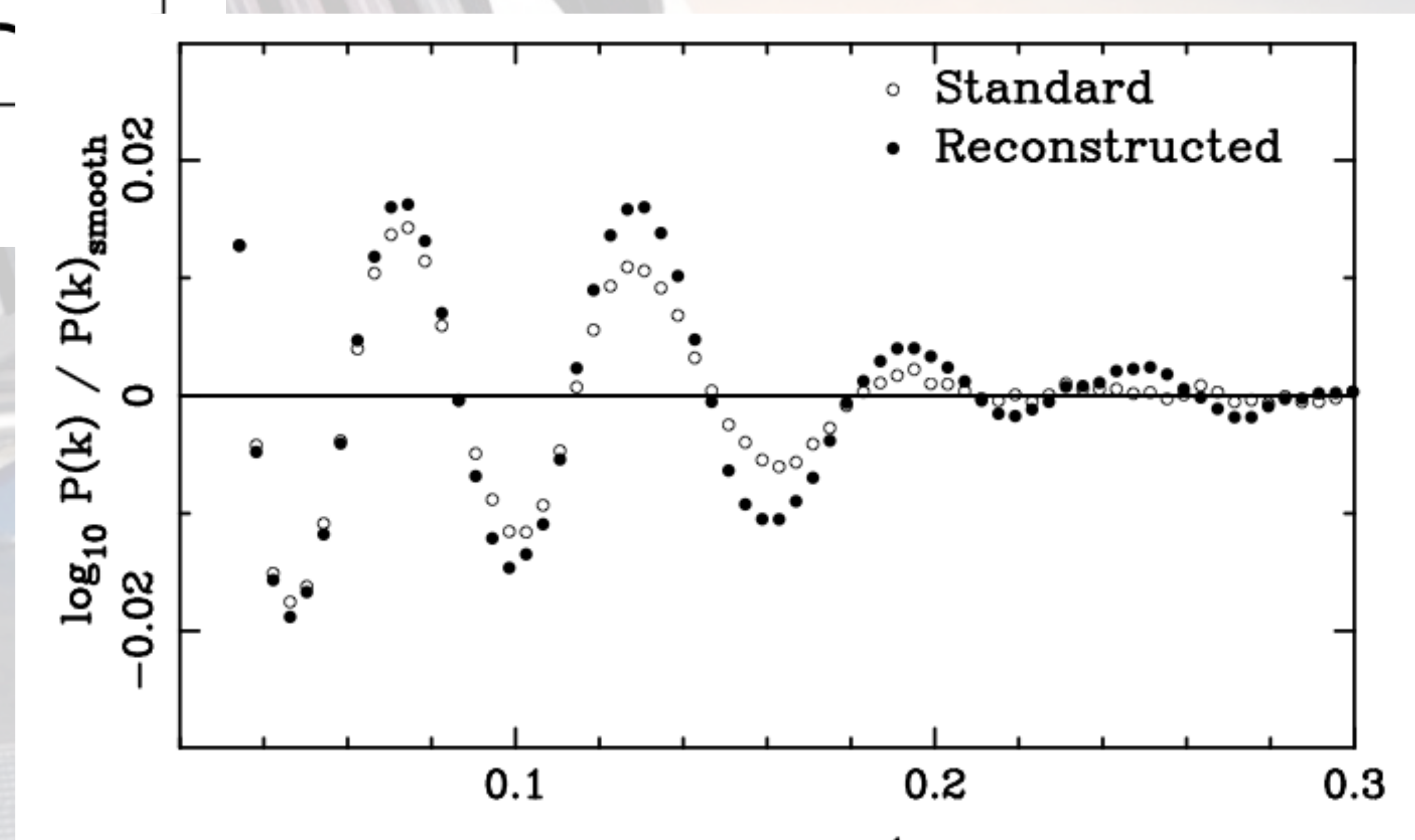
Reconstruction of linear positions



Padmanabhan et al. 2012; arXiv:1202.0090

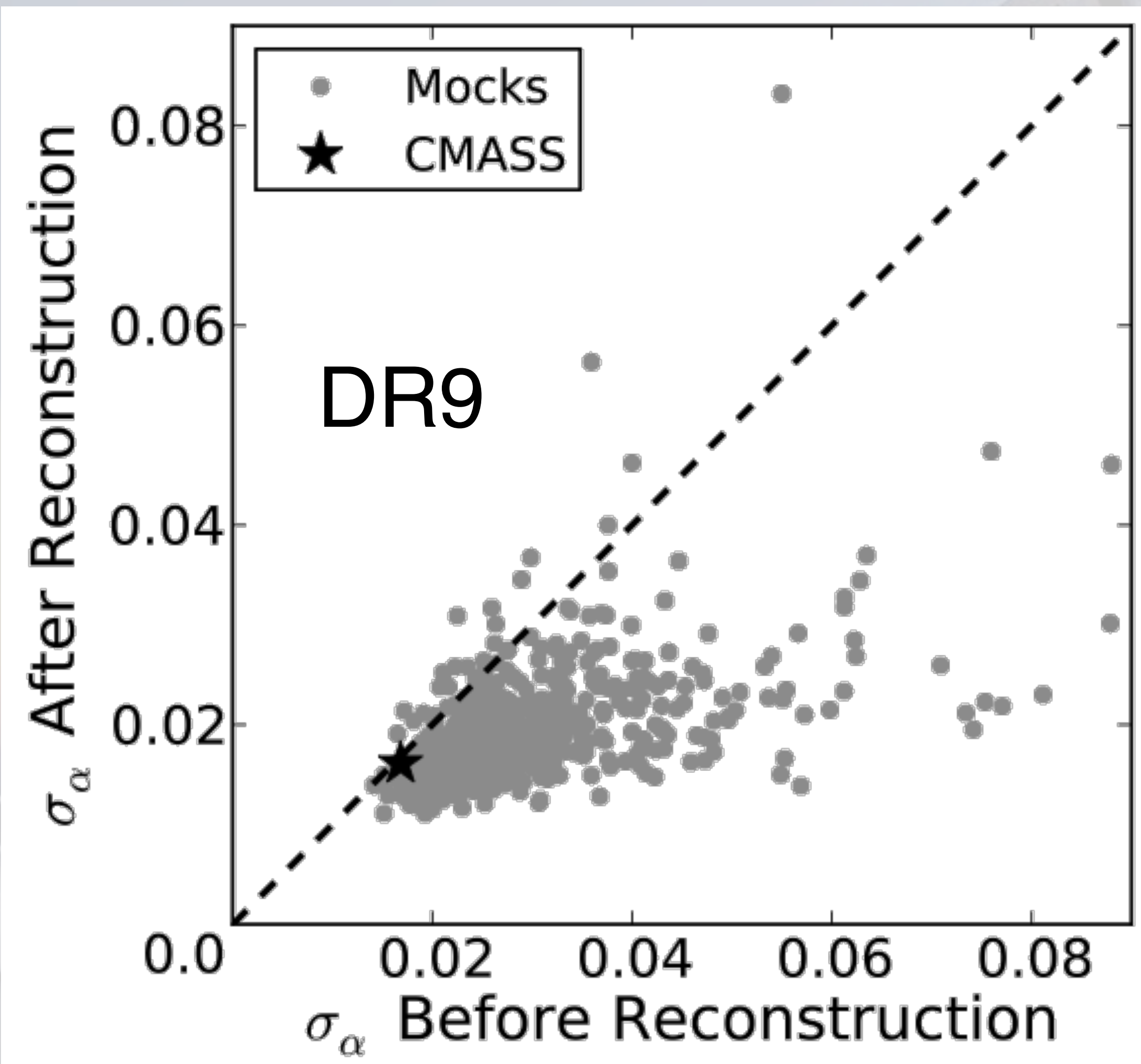
Reconstruction on DR9 CMASS mocks



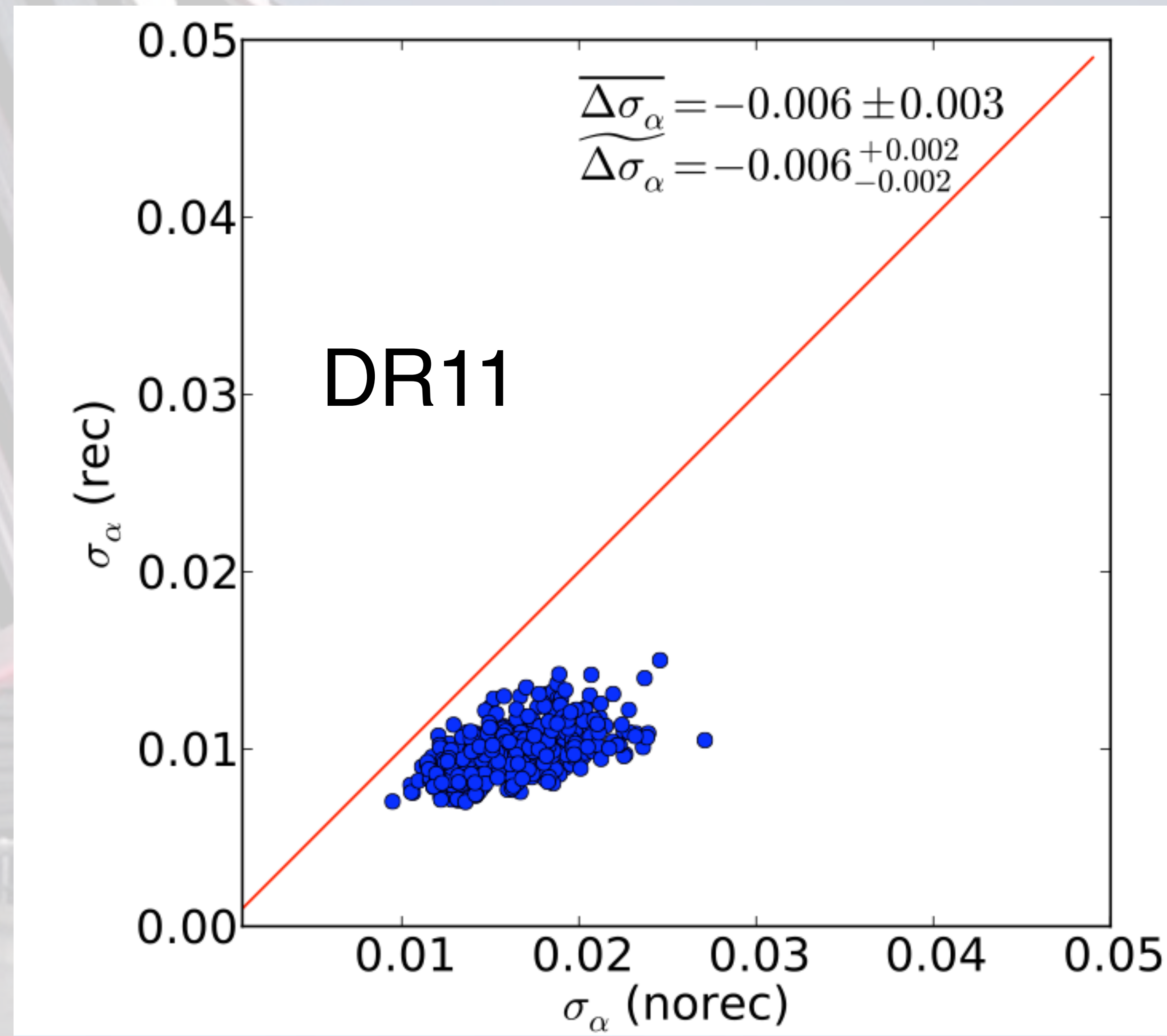


Anderson et al. 2012

Reconstruction: error on α



Anderson et al. 2012



SDSS collaboration, in prep

Isotropic DR9 BAO measurements

	α	χ^2/dof	$D_V/r_s(z=0.57)$
		Before Reconstruction	
$\xi(r)$	1.016 ± 0.017	$30.53/39$	13.44 ± 0.22
$P(k)$	1.022 ± 0.017	$81.5/59$	13.52 ± 0.22
		After Reconstruction	
$\xi(r)$	1.024 ± 0.016	$34.53/39$	13.55 ± 0.21
$P(k)$	1.042 ± 0.016	$61.1/59$	13.78 ± 0.21
Consensus	1.033 ± 0.017	$--$	13.67 ± 0.22

- ξ(r) and P(k) based estimations are **appropriate** and **unbiased,** but they include the noise from small scales and shot noise differently
- We **average** the two results, and compute the error bar using the **observed scatter** of the average value in the mocks. This shows no significant departure from a Gaussian distribution

Anderson et al. 2012

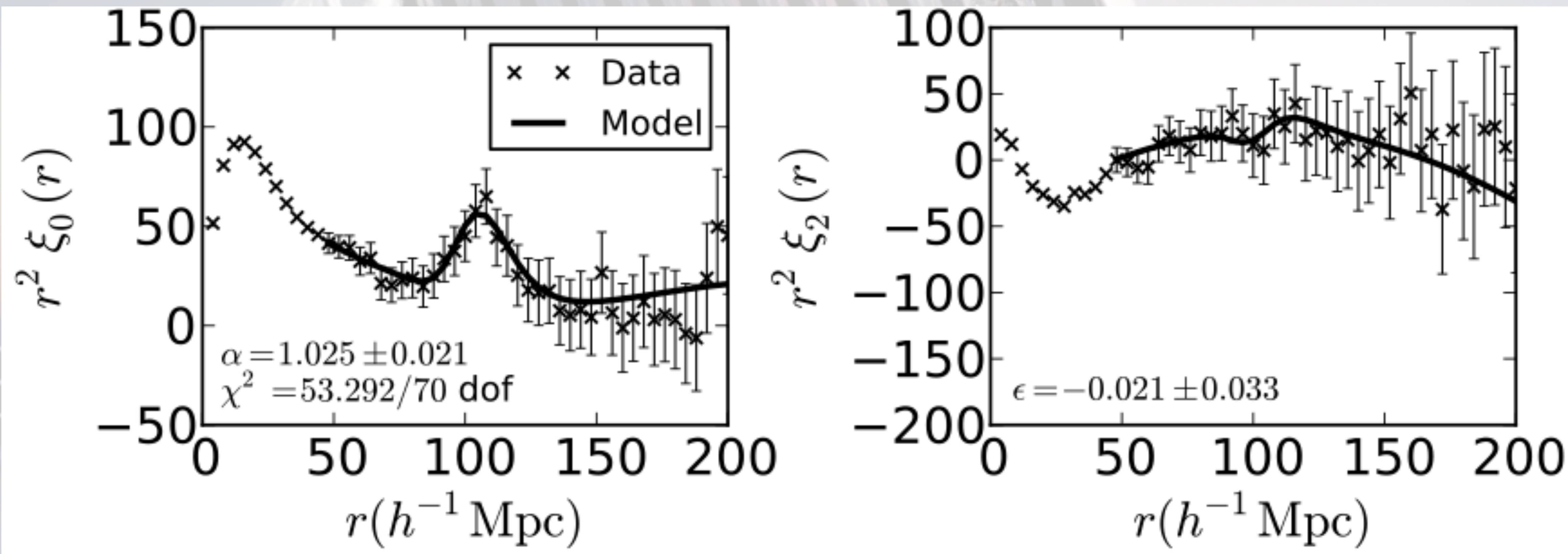
Anisotropic fits …

monopole

$$\xi_2^s(r) = \frac{3}{2}\int_{-1}^{+1} d\mu\ \xi^s(r,\mu)$$

quadrupole

$$\xi_2^s(r) = \frac{5}{2}\int_{-1}^{+1} d\mu\ \xi^s(r,\mu)\frac{3\mu^2-1}{2}$$



Anderson et al. 2013

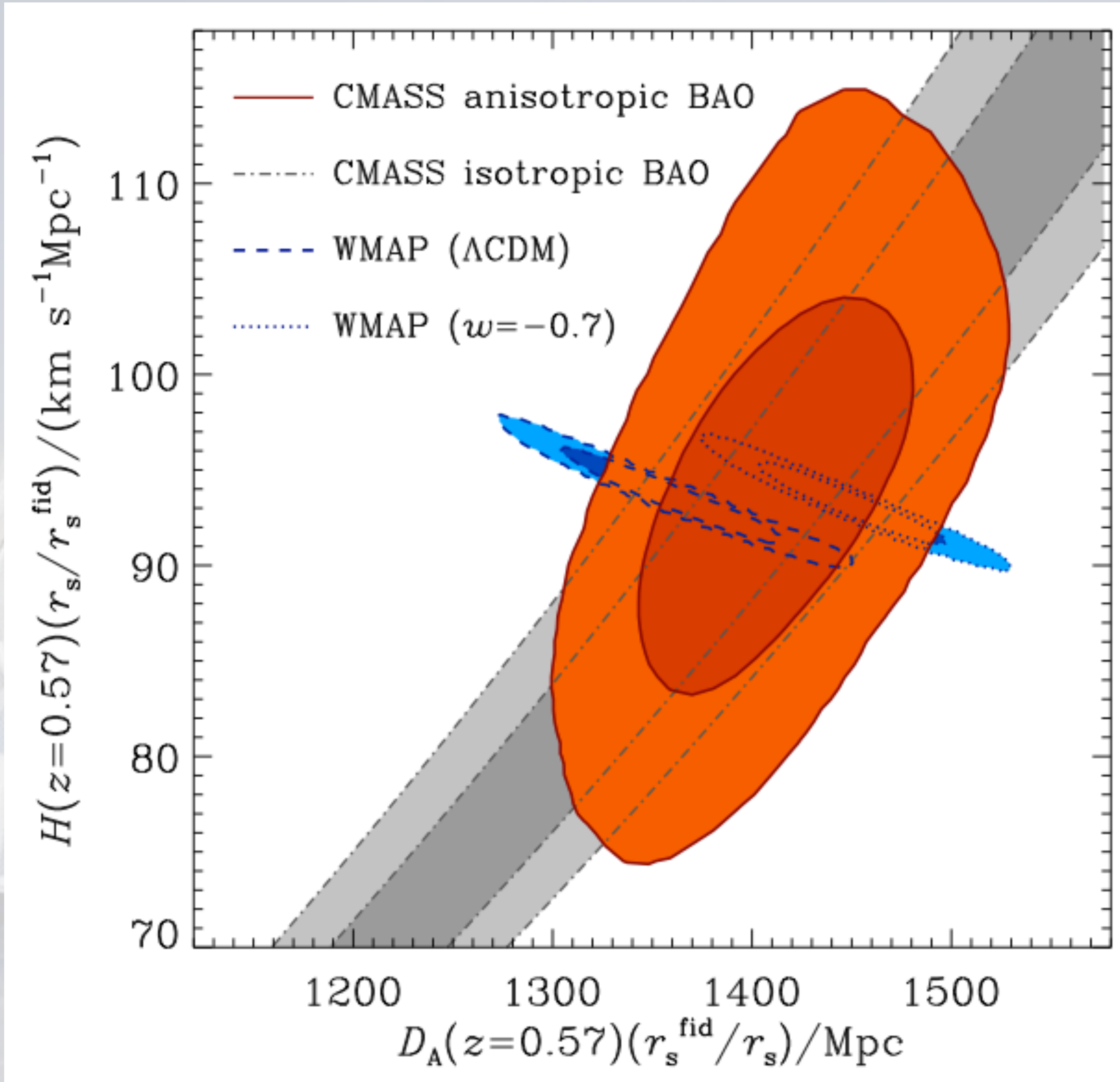
Anisotropic fits …

	$D_A(z)(r_s^{\rm fid}/r_s)$	$H(z)(r_s/r_s^{\rm fid})$	$\rho_{D_A H}$
	Before Reconstruction		
$(\xi_0(s), \xi_2(s))$	1367 ± 44	86.6 ± 6.2	0.65
$(\xi_\perp(s), \xi_\parallel(s))$	1379 ± 42	88.3 ± 5.1	0.52
	After Reconstruction		
$(\xi_0(s), \xi_2(s))$	1424 ± 43	95.4 ± 7.5	0.63
$(\xi_\perp(s), \xi_\parallel(s))$	1386 ± 36	90.6 ± 6.7	0.50
Consensus	1408 ± 45	92.9 ± 7.8	0.55

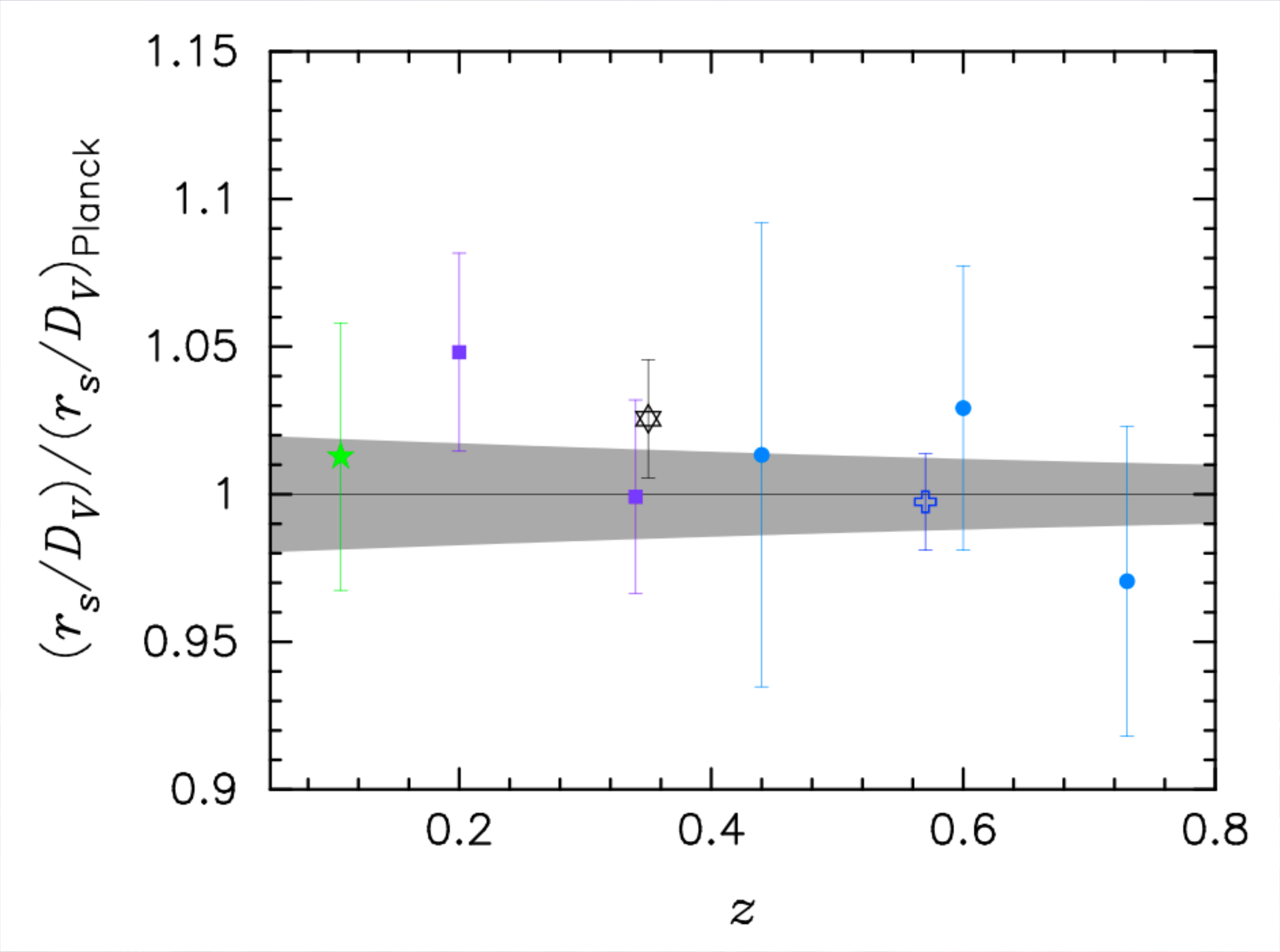
- correlation function is easier to split into line-of-sight and transverse directions
- can decompose into multipoles or other bases (e.g. wedges – see Kazin et al. 2013)
- Results are consistent and a concordance value is given

Anderson et al. 2013

DR9 Measurements vs WMAP



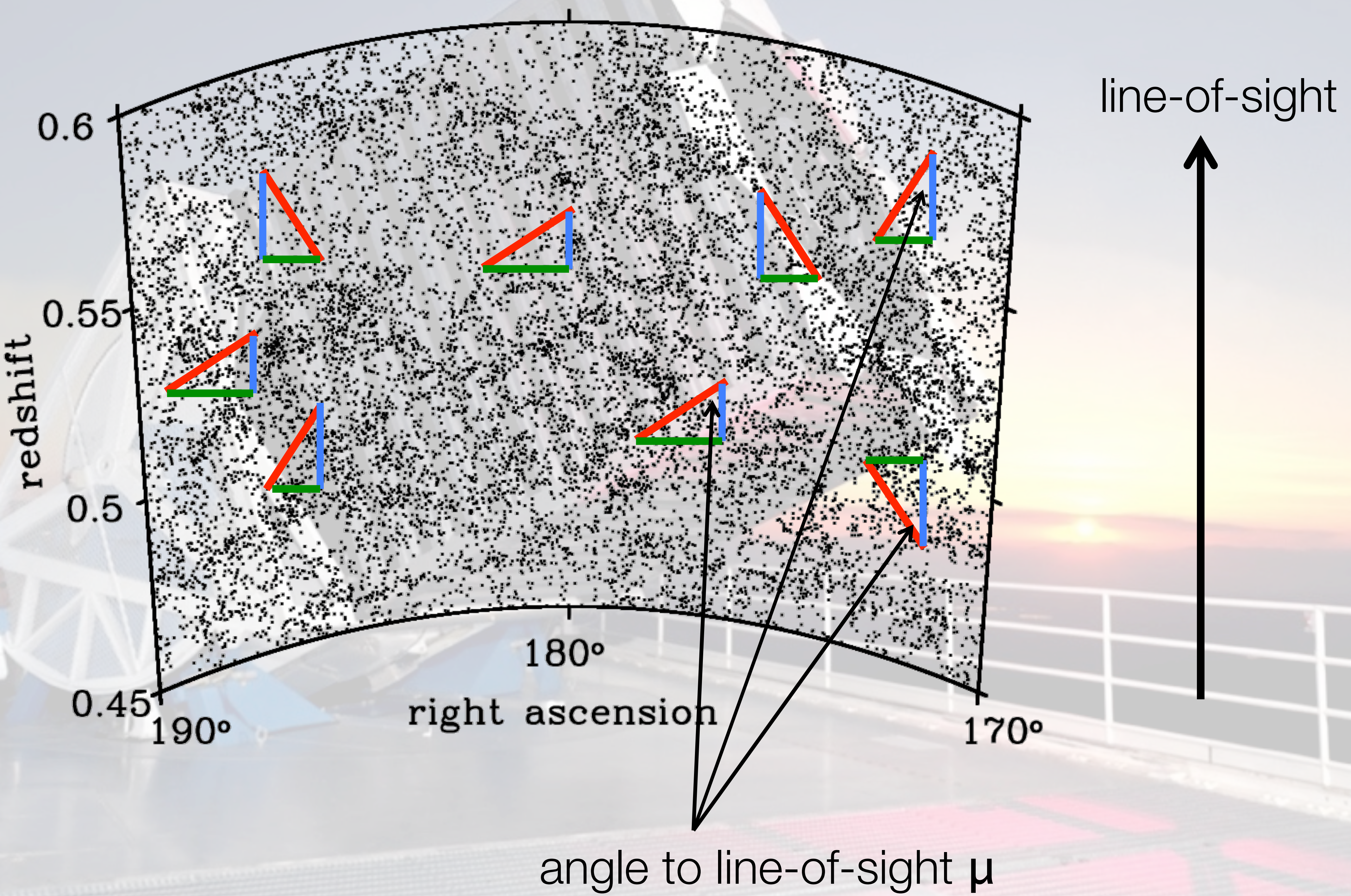
Planck BAO "predictions"



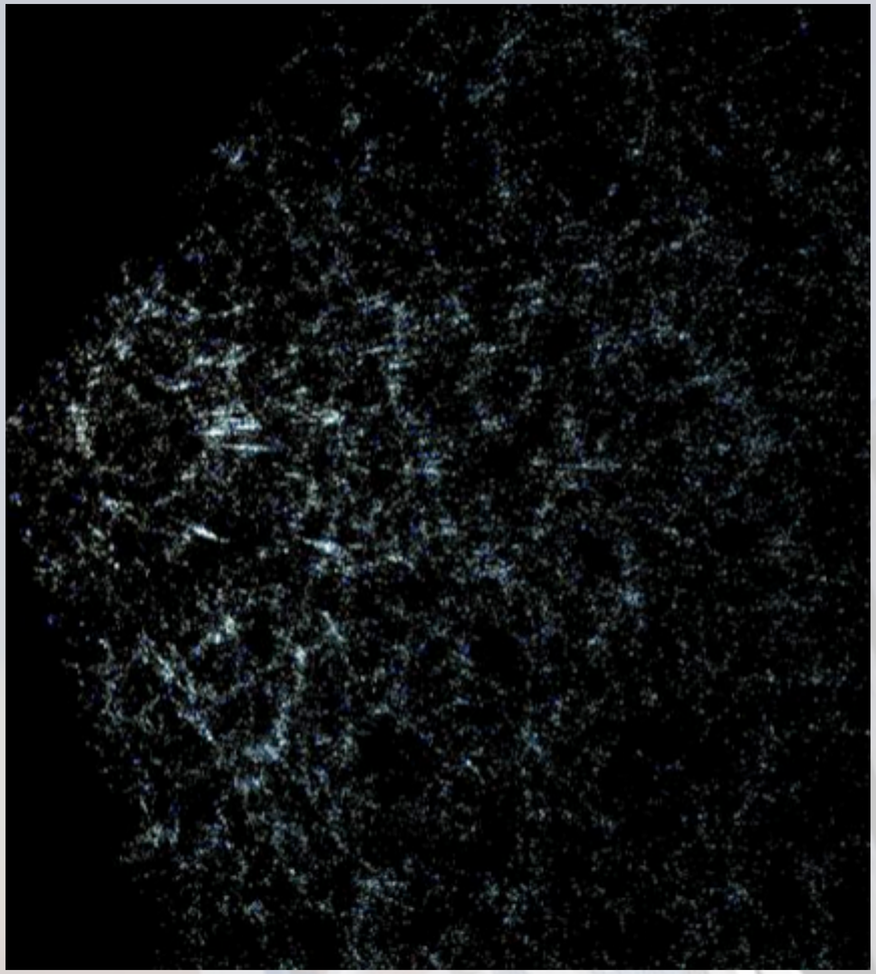
Planck collaboration, 2013

Full fits to anisotropic clustering

Clustering as a function of direction



Redshift-Space Distortions



Observed redshift depends on both Hubble expansion and additional "peculiar velocity"

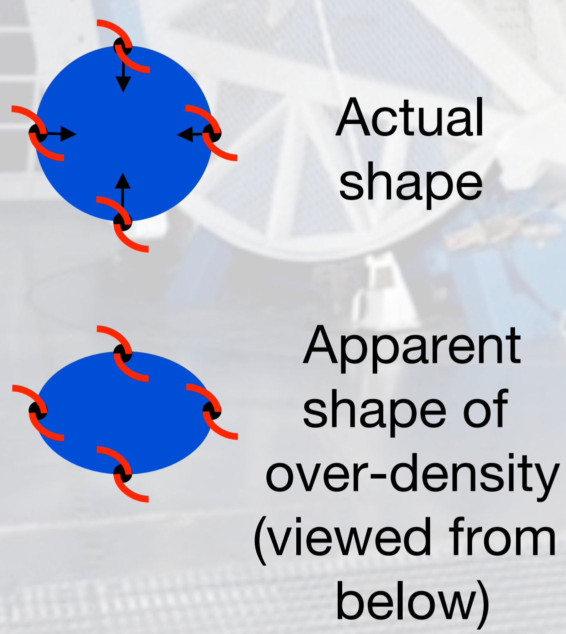
Galaxies move because cosmological structure is growing

Resulting change in redshift is coherent with structure

extra component depends on amplitudes of peculiar velocities

$$f(z)\sigma_8(z) \propto \frac{dG}{d\log a}$$

where G is the linear growth rate



The Alcock-Paczynski Effect

If the Universe is isotropic, clustering is same radial & tangential

Stretching at a single redshift slice (for galaxies expanding with Universe) depends on

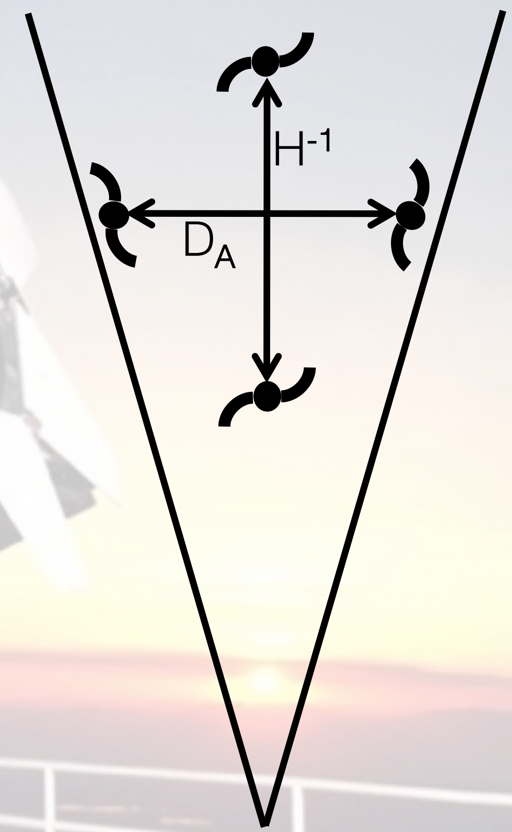
$H^{-1}(z)$ (radial)

$D_A(z)$ (angular)

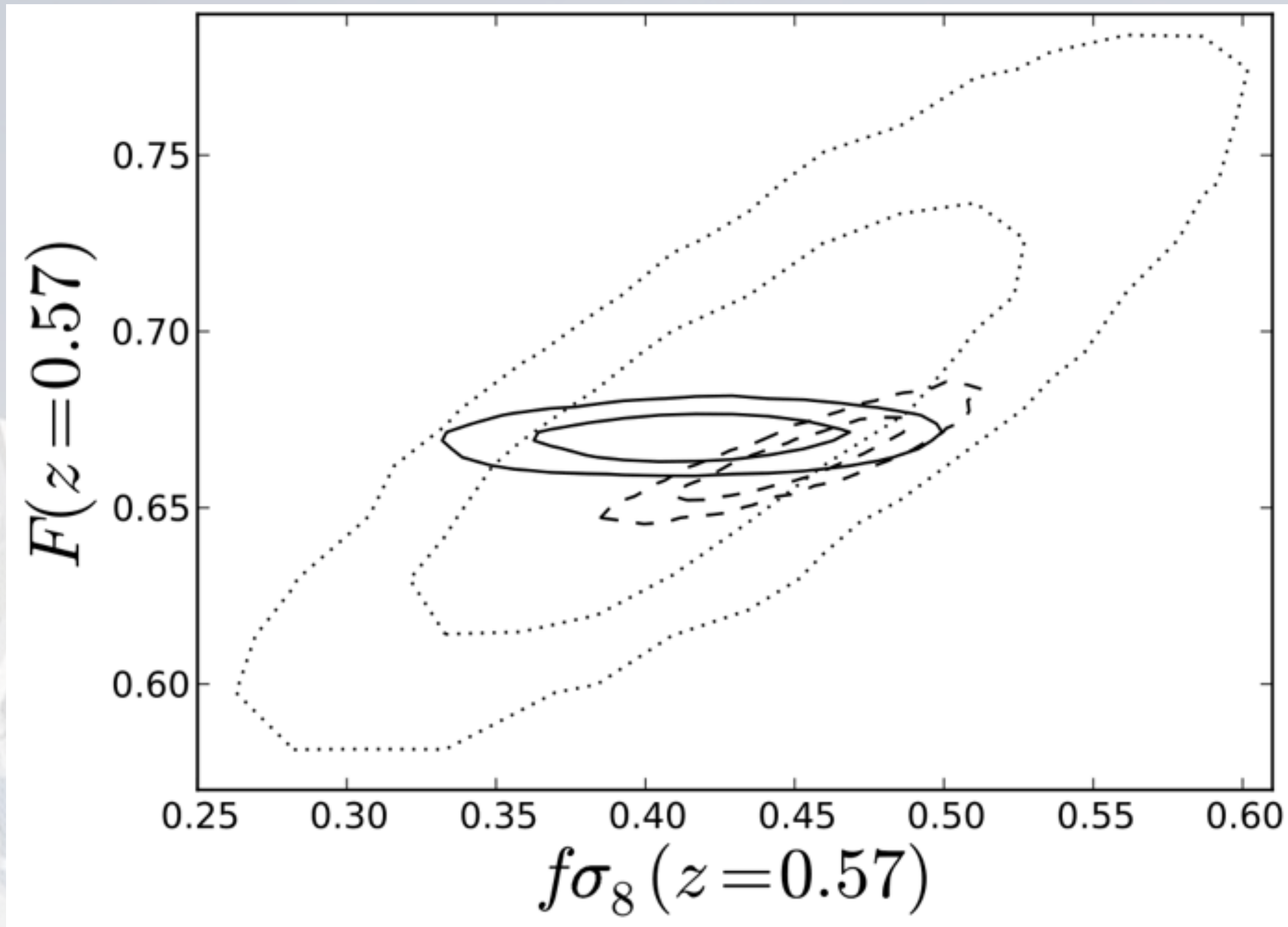
Analyze with wrong model -> see anisotropy

AP effect measures $D_A(z)H(z)$

RSD limits test (on amplitude) to scales where can be modeled



Degeneracy between AP & RSD



Dotted: free growth, geometry, ΛCDM prior on large-scale linear P(k) shape at z=0.57

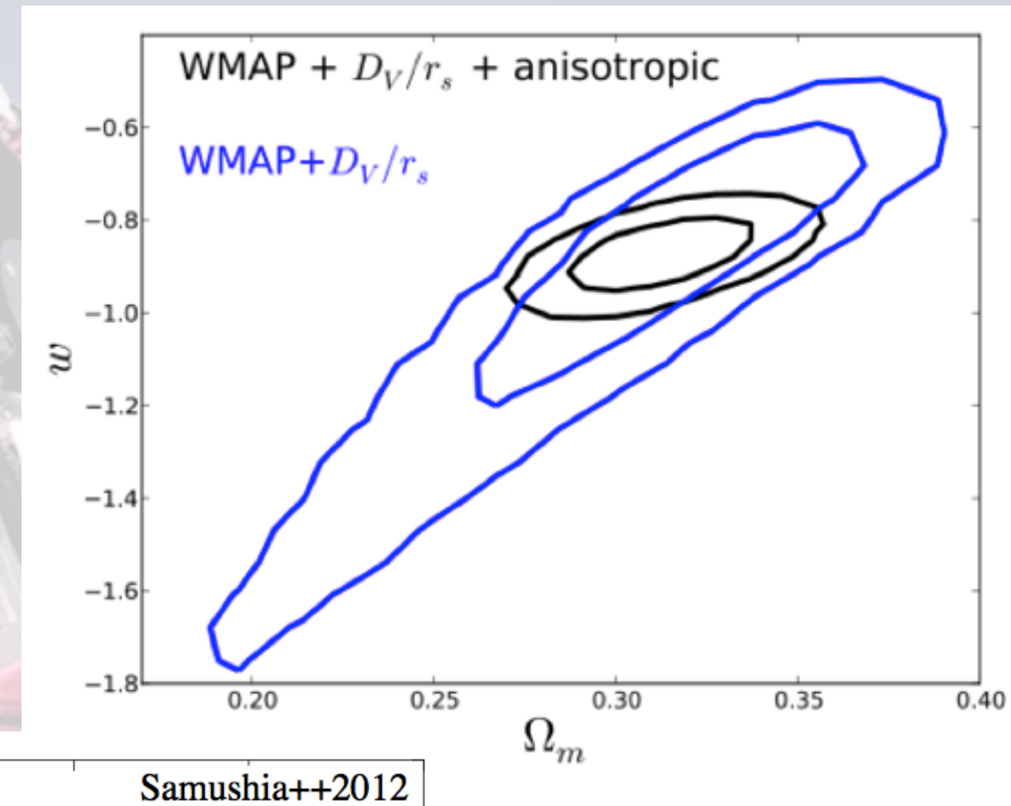
Solid: F forced to match ΛCDM model

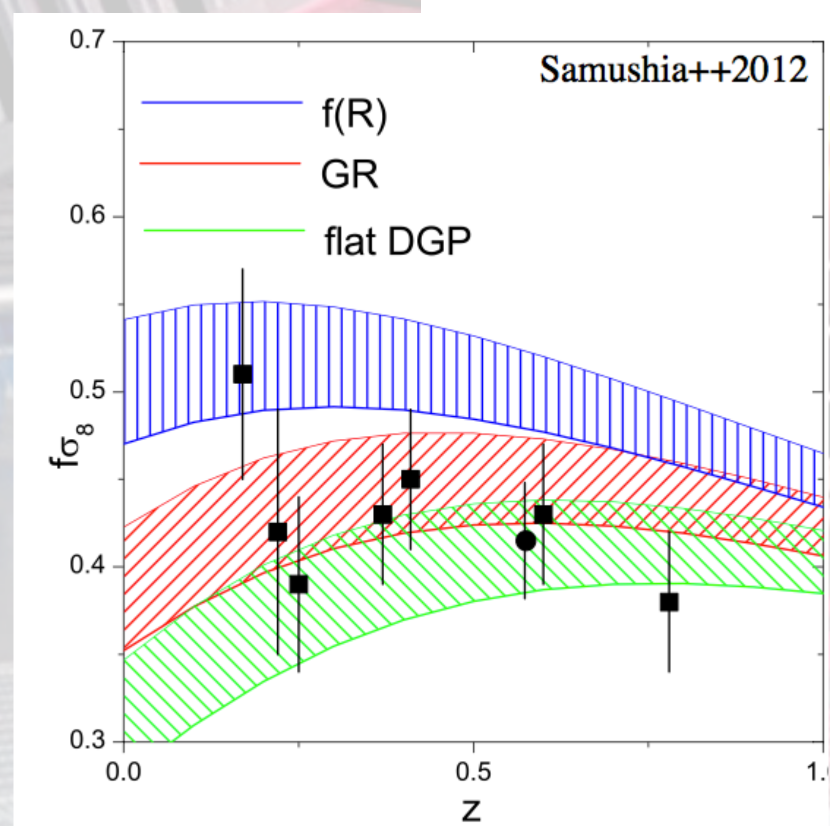
Dashed: WMAP ΛCDM+GR prediction

Reid et al.

Cosmology improved with RSD

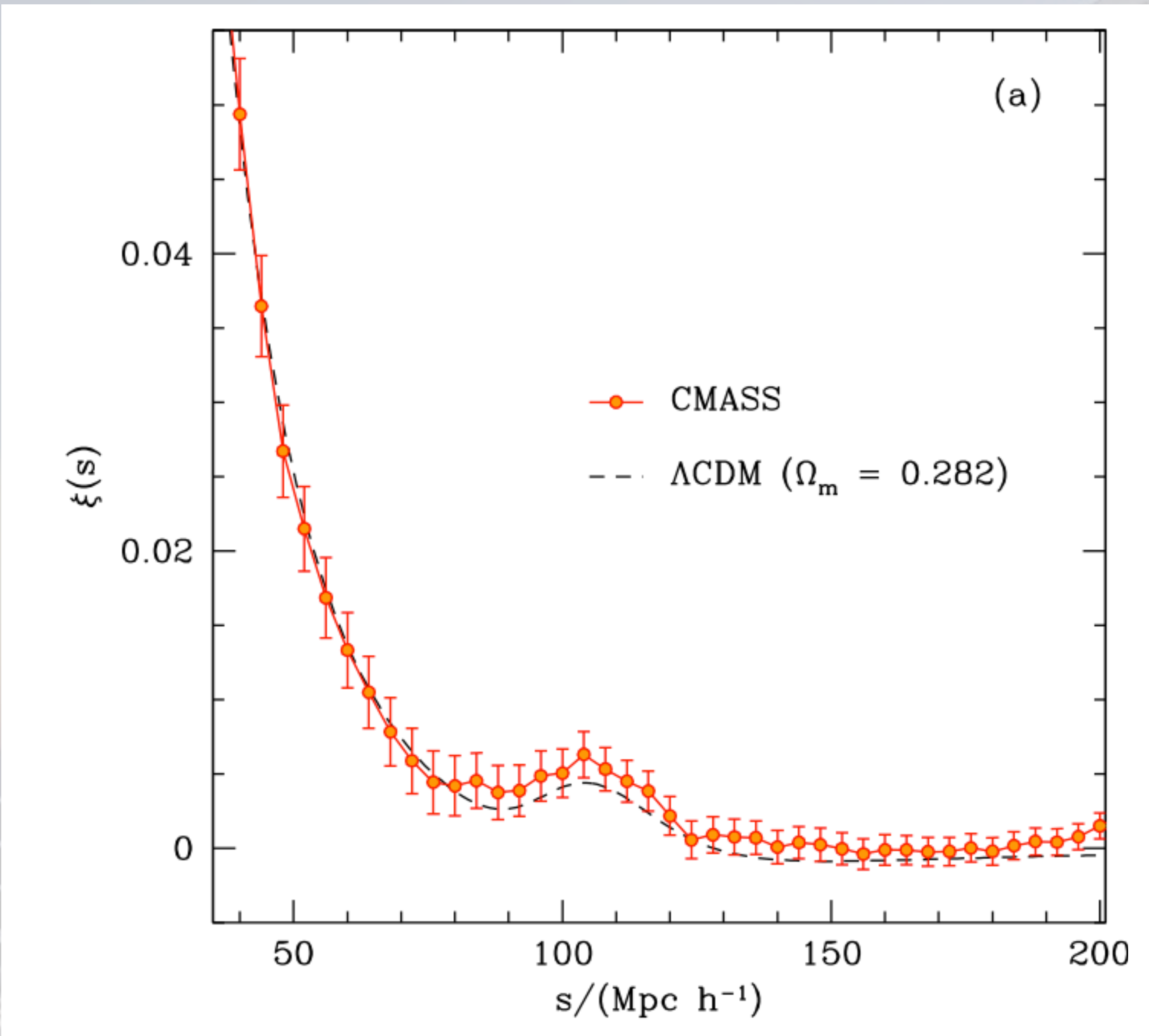
- Anisotropic clustering allows huge improvement on w!
- w = -0.95 ± 0.25 (WMAP + $D_V(0.57)/r_s$)
- w = -0.88 ± 0.055 (WMAP + anisotropic)
- Provided a number of GR tests

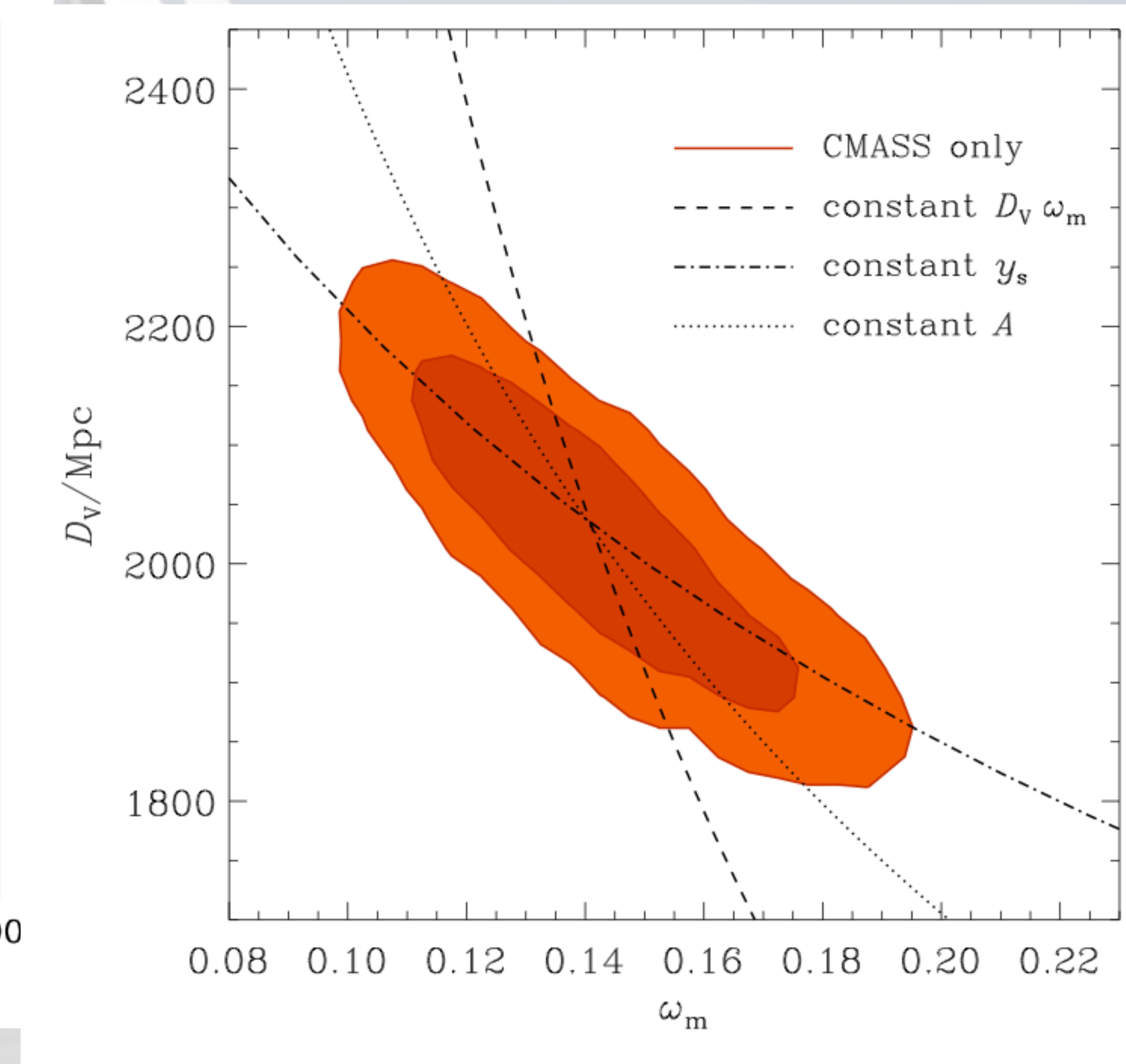




Samushia et al.

Matter density measurement from shape

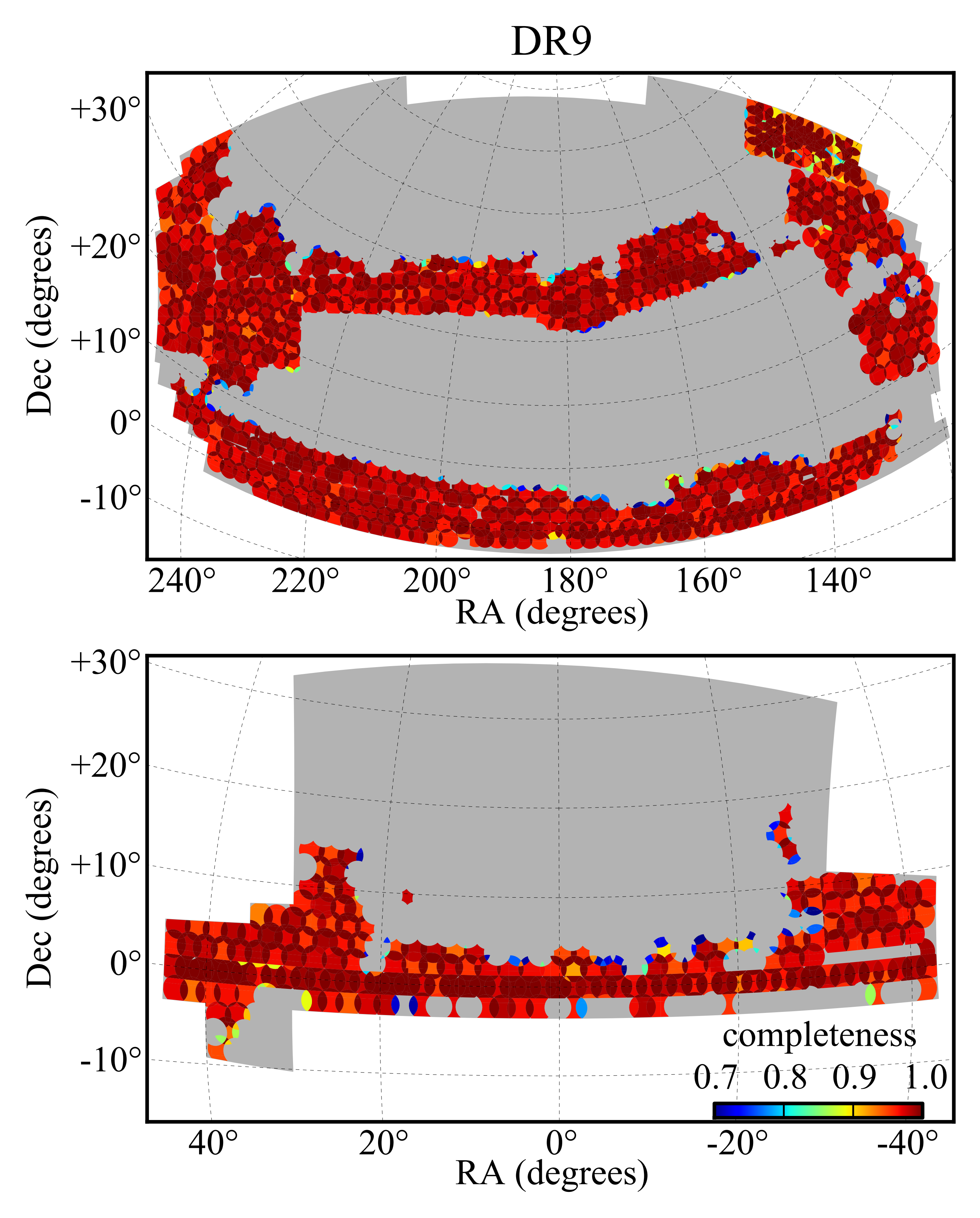




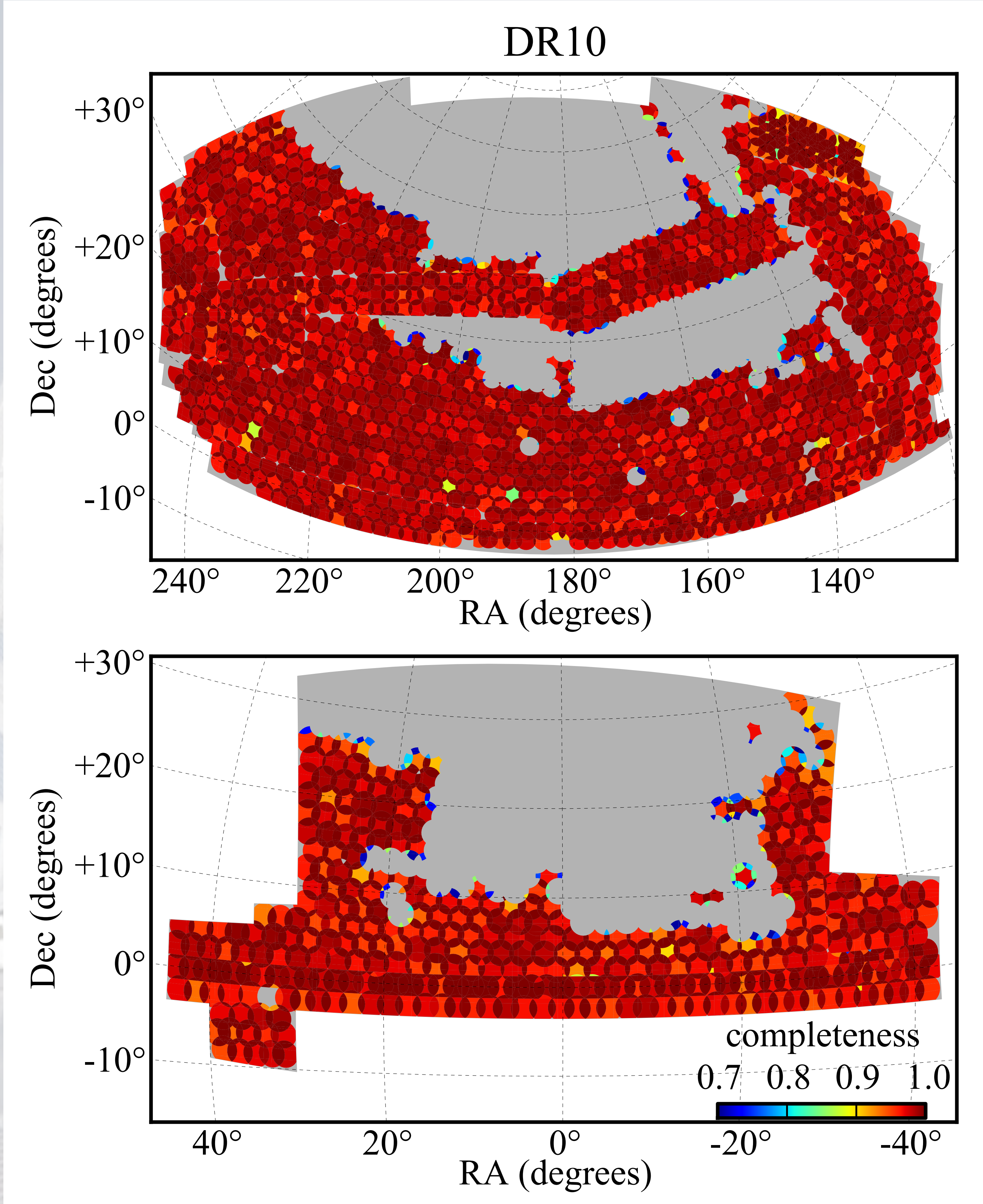
Sanchez et al.

next 18 months

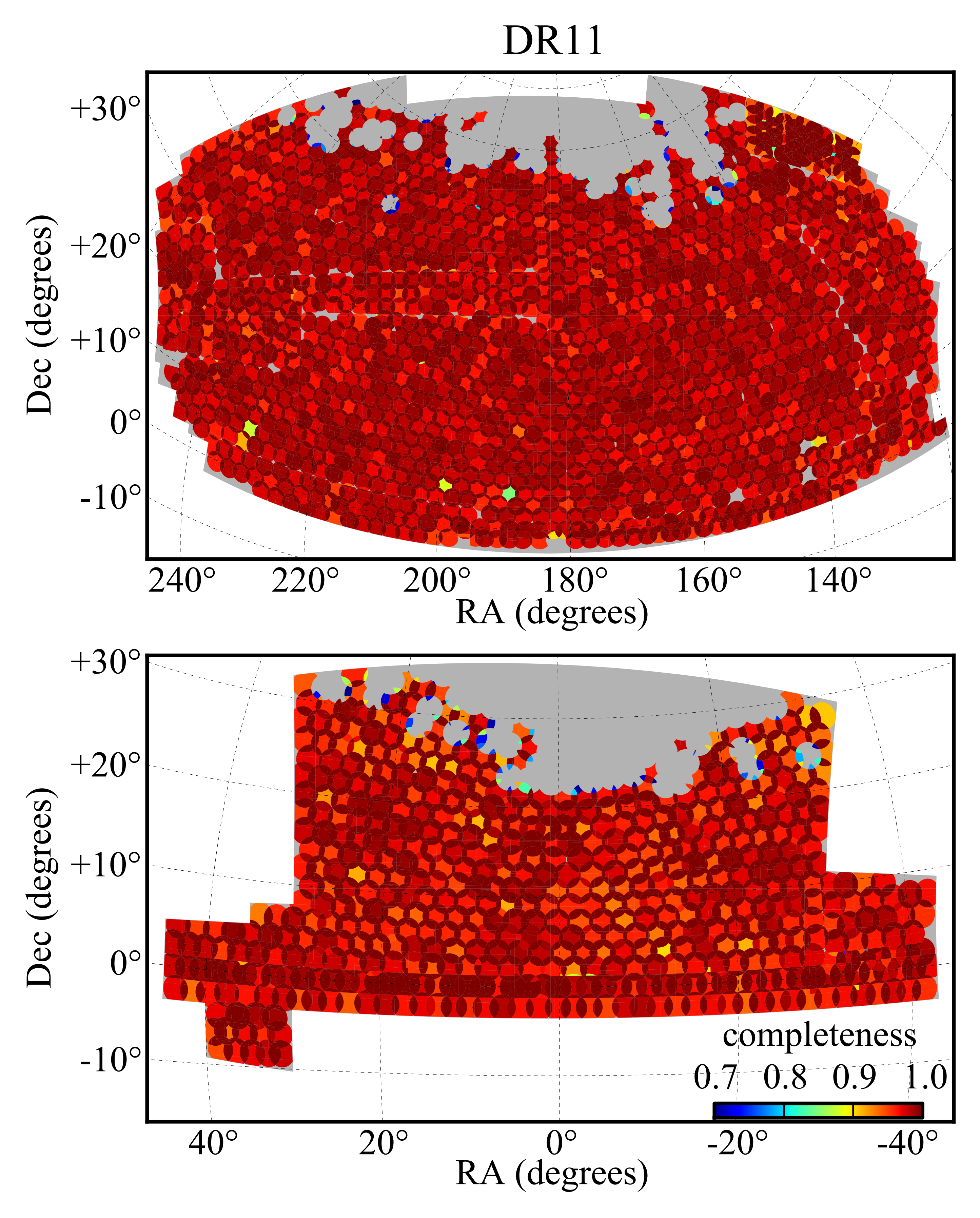
BOSS DR9 galaxies



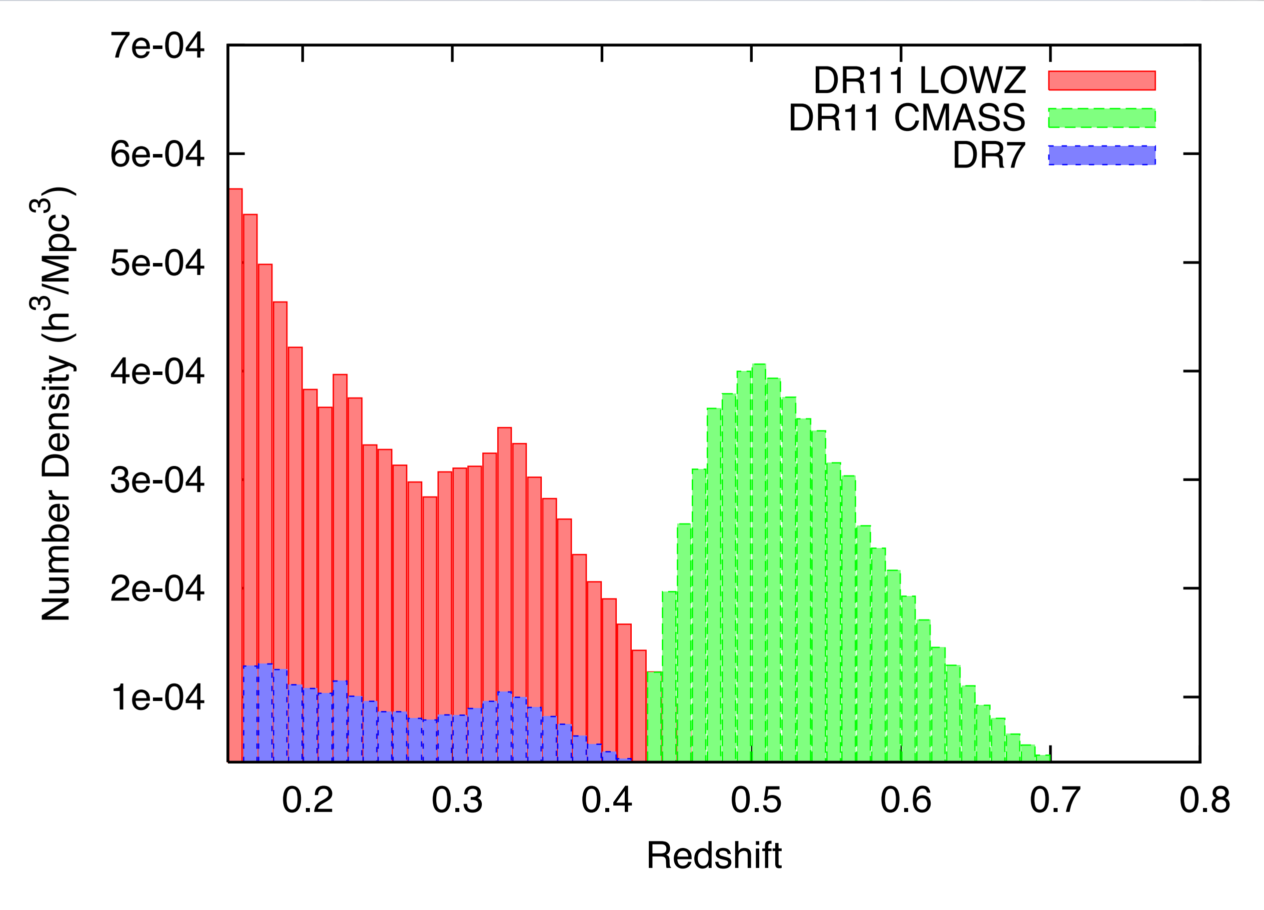
BOSS DR10 galaxies

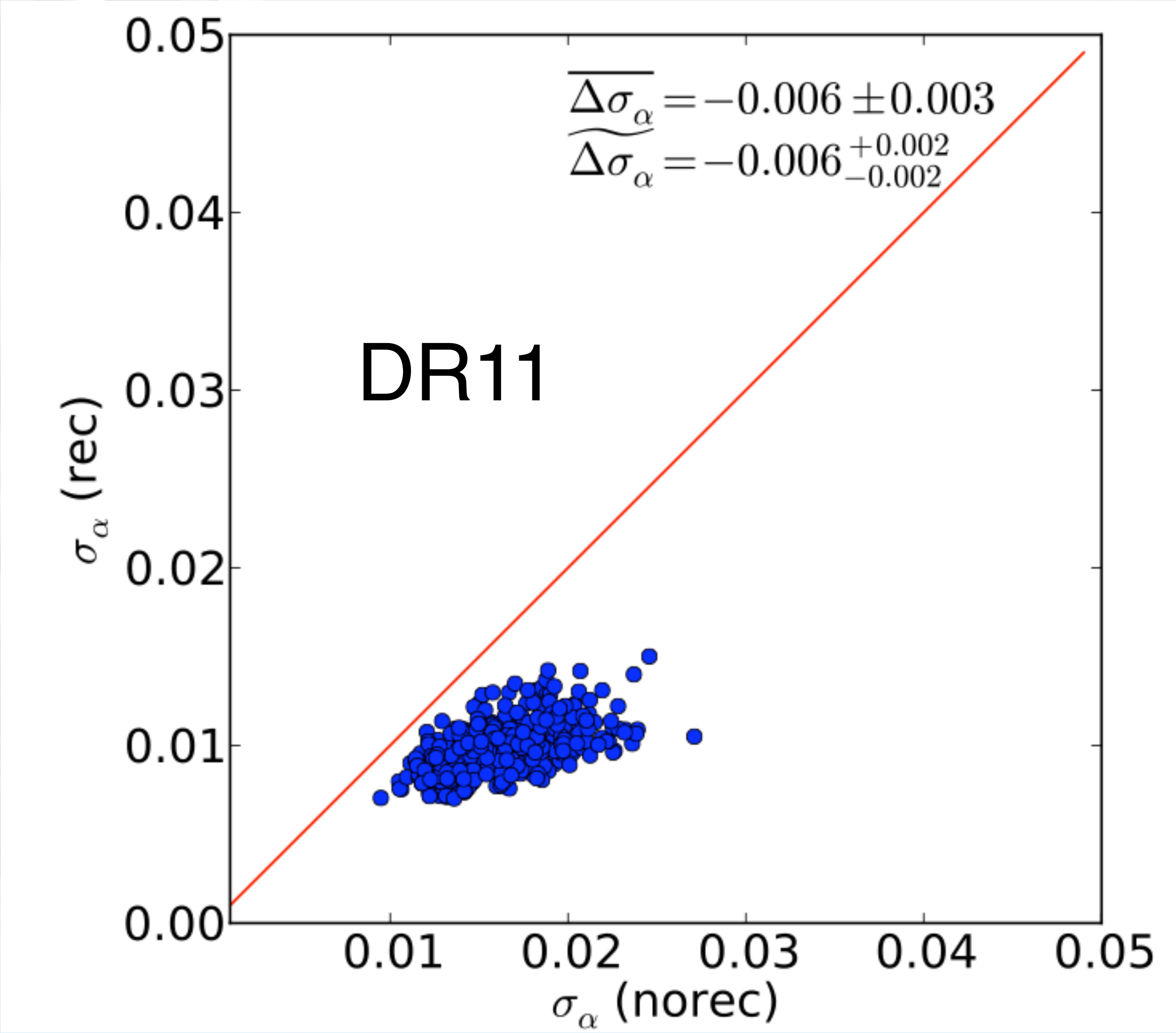


BOSS DR11 galaxies



What to expect for DR11?

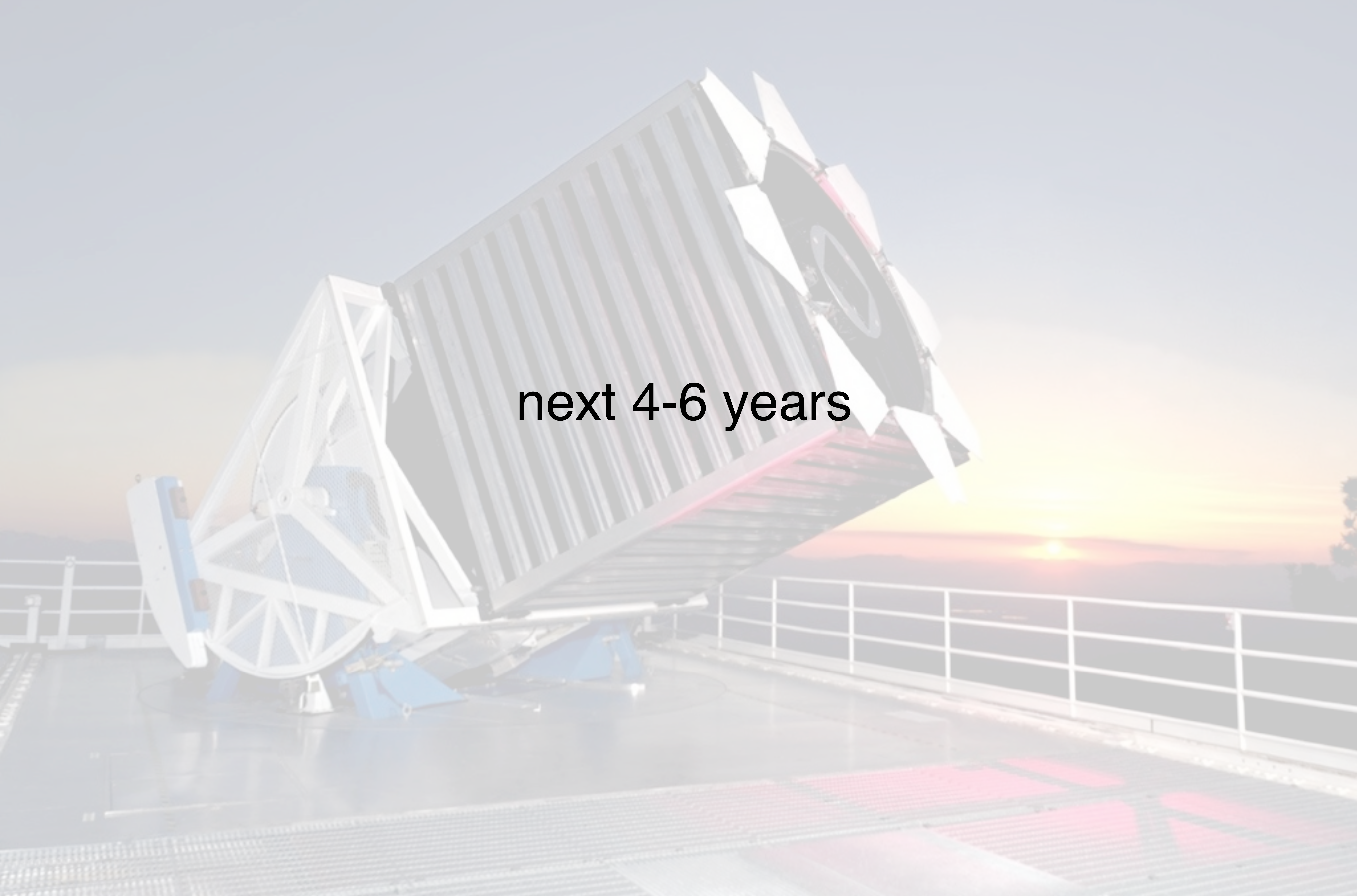




DR9 2.2 Gpc³

DR11 8.4 Gpc³

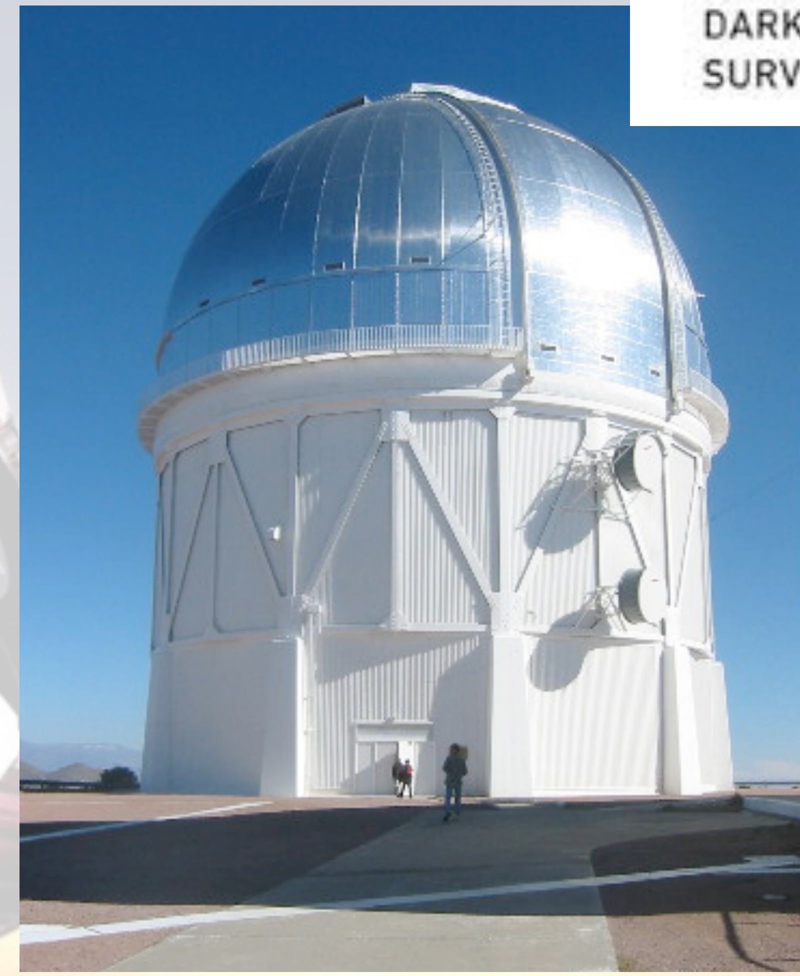
SDSS collaboration, in prep

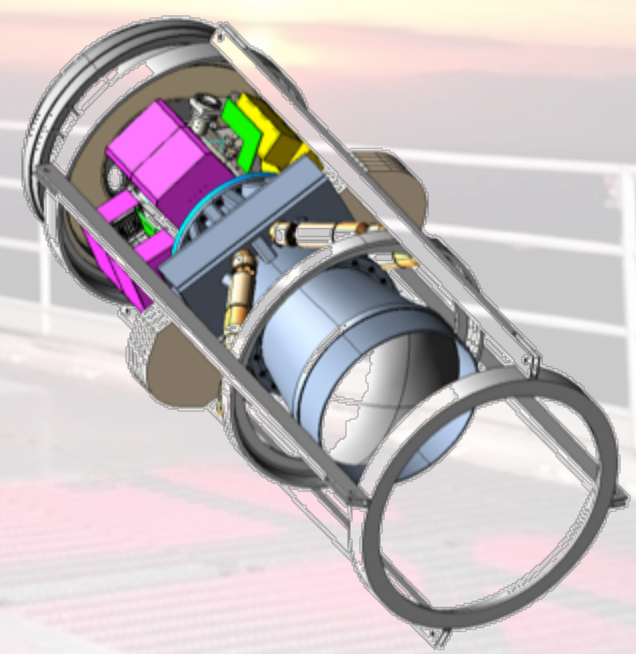


next 4-6 years

Dark Energy Survey (DES)

- New wide-field camera for the 4m Blanco telescope
- Commissioning currently finishing, Survey due to start September 2013
- $\Omega = 5{,}000\text{deg}^2$
- 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



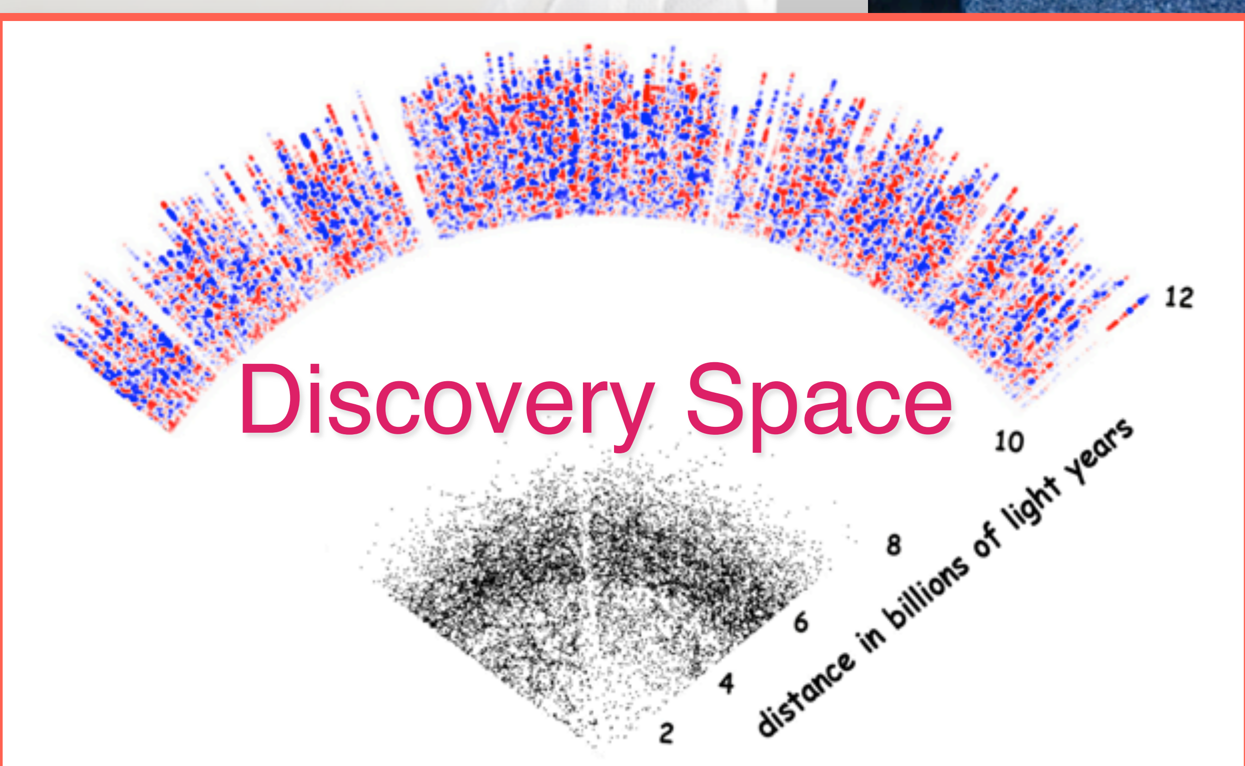


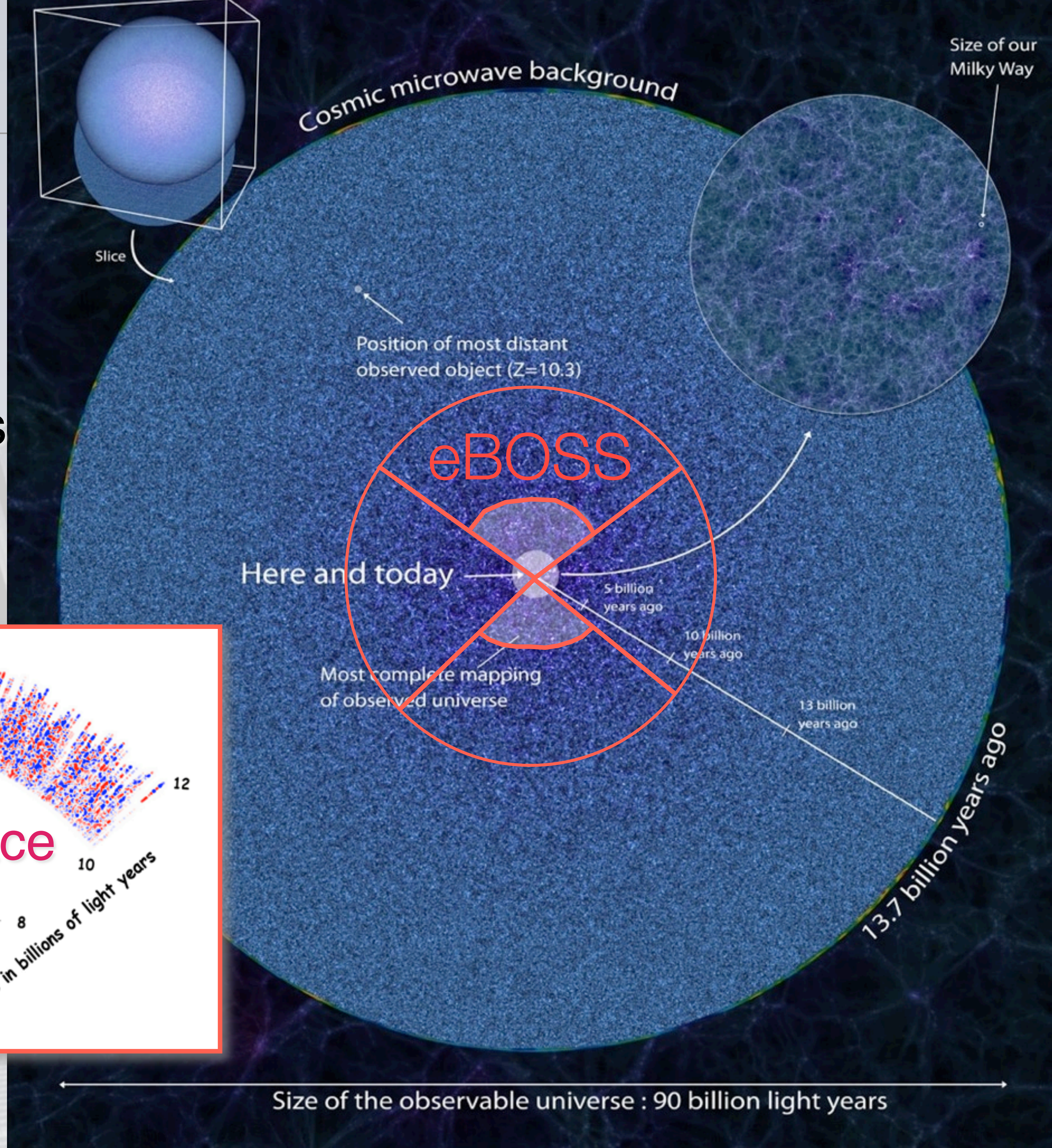
eBOSS / SDSS-IV

- The new cosmology project with SDSS
- Use the Sloan telescope and MOS to observe to higher redshift
- Basic parameters
  - Ω = 1,500deg^2 – 7,500deg^2
  - ~ 1,000,000 galaxies (direct BAO)
  - ~ 60,000 quasars (BAO from Ly-α forest)
- Distance measurements
  - 0.9% at z=0.8 (LRGs)
  - 1.8% at z=0.9 (ELGs)
  - 2.0% at z=1.5 (QSOs)
  - 1.1% at z=2.5 (Ly-α forest, inc. BOSS)
- Survey will start 2014, lasting 6 years
- Received $10M from Sloan foundation
  and significant funding from partners

eBOSS:

Measuring the Expansion History of the Universe between 7 and 11 billions of light years with Galaxies & Quasars





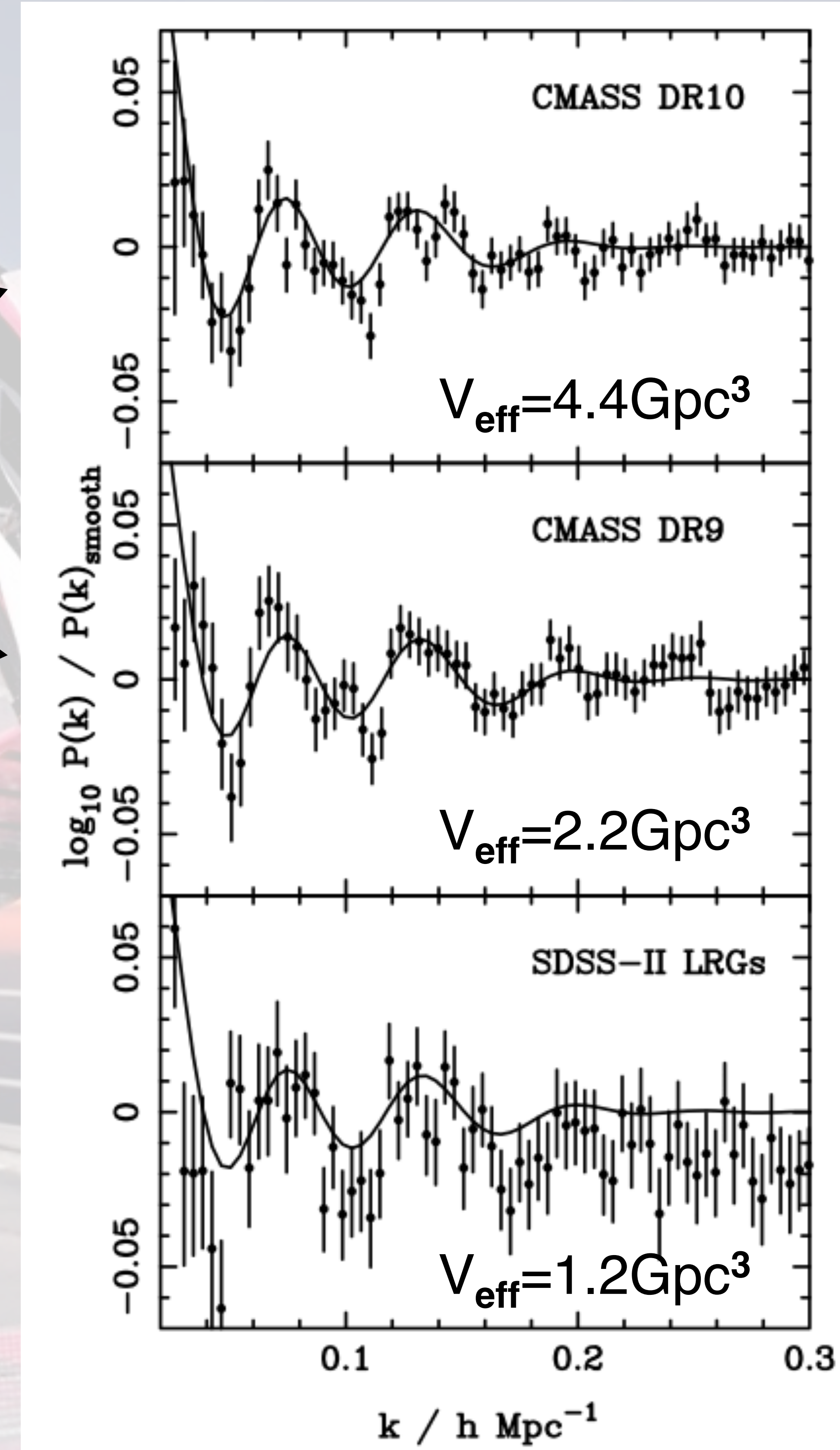
eBOSS targets

- LRGs – WISE+SDSS selected aiming for z~0.8 galaxies
- ELGs – SCUSS (u-band)+SDSS, South only (+DES over some area)
- QSOs – WISE+SDSS selected

Galaxies	Redshifts	Target sky density	Total area	Target success	Number of good redshifts	Distance precision	Effective volume
LRG	$0.7<z<0.9$	60deg^{-2}	7500deg^{2}	95%	430k	0.8%	4.7 Gpc^{3}
ELG	$0.6<z<1.0$	180deg^{-2}	1500deg^{2}	80%	216k	2.0%	2.3 Gpc^{3}
QSO	$0.9<z<2.3$ all	105deg^{-2}	7500deg^{2}	70% 90%	525k 700k	1.5%	6.6 Gpc^{3}
Lya QSO	$z>2.15$	5+22deg^{-2}	5000deg^{2}	30%	64k (+revisit)	-	-

eBOSS BAO measurements

Galaxies	Effective volume
LRG	4.7 Gpc^3
ELG	2.3 Gpc^3
QSO	6.6 Gpc^3
Lya QSO	-

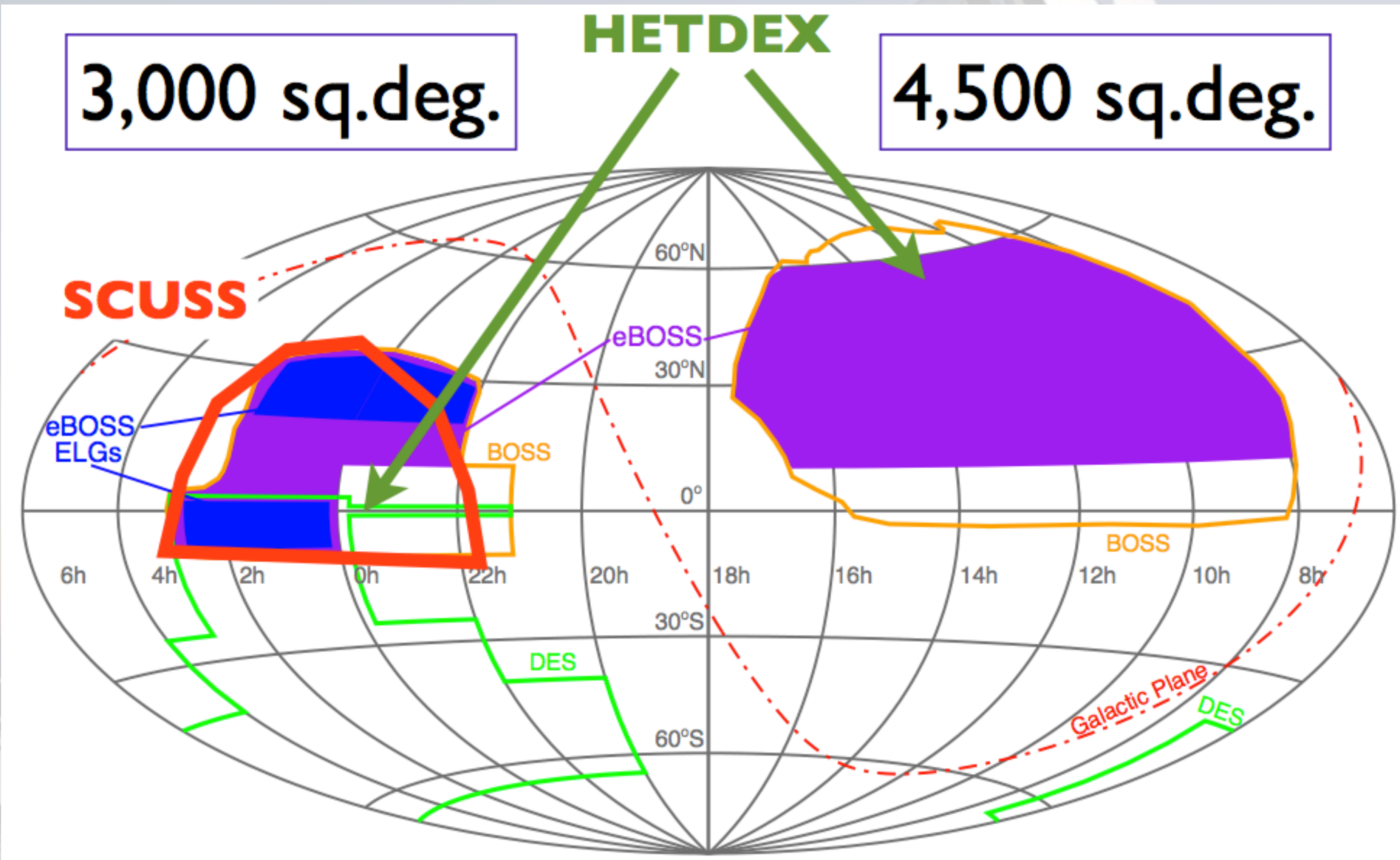


eBOSS further science

- DES – eBOSS overlap
  - ~500 deg^2 overlap with eBOSS in Southern sky
  - Synergy by “Cross-Correlation” of imaging and spectroscopic surveys for cosmological constraints (BAO+RSD+WL)
  - eBOSS will play a critical role allowing high-precision calibration of photo-z through cross-correlation

- eBOSS science will include many other cross-correlation opportunities
  - internally in eBOSS (LRG-ELG, LRG-QSO, ELG-QSO, CMASS-QSO, QSO absorbers-Galaxies ...)
  - U-band, WISE, Planck temperature, Planck lensing, eROSITA, DES, HSC, HETDEX ...

eBOSS strategy / timeline

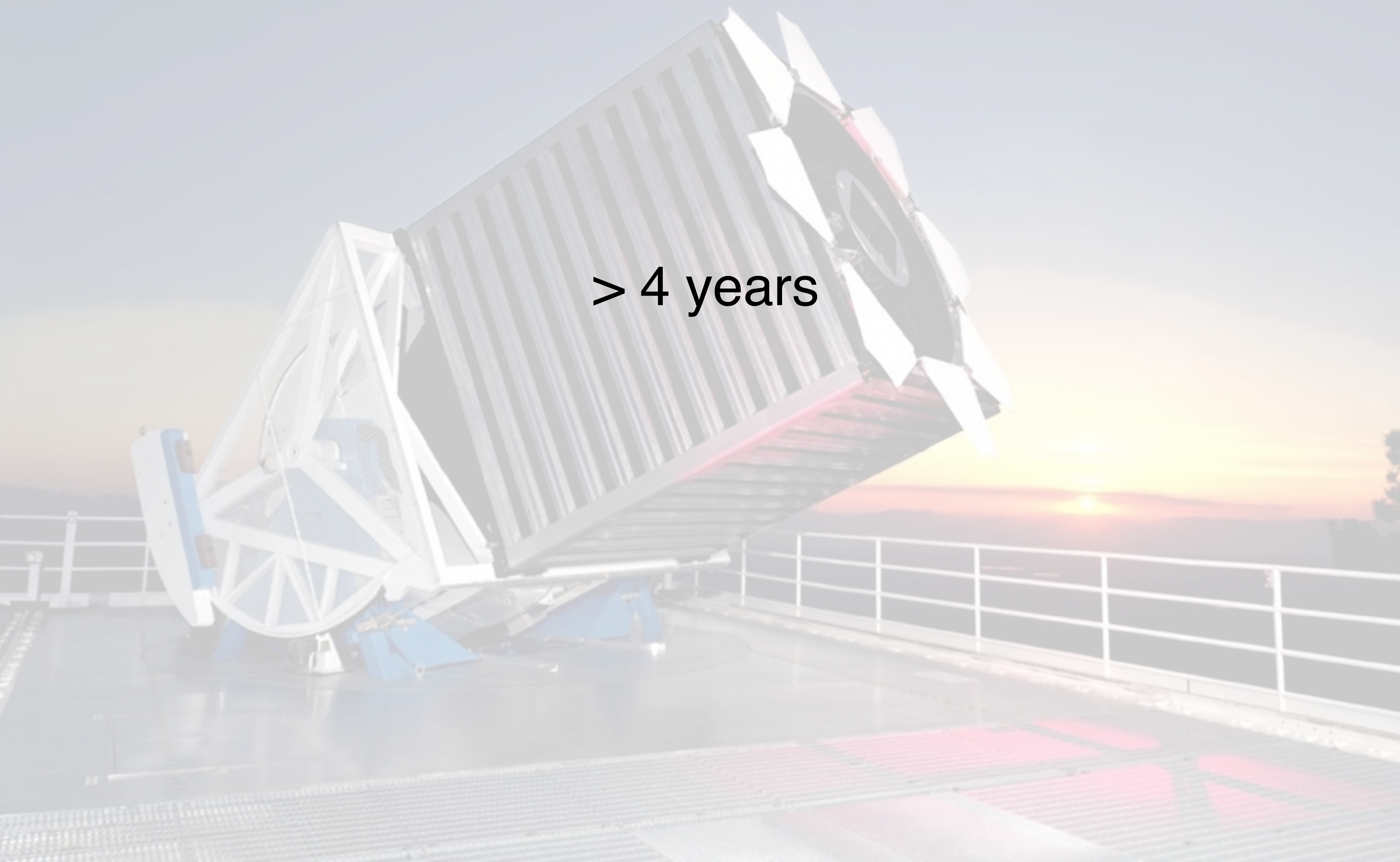


Footprint depends on:

- SDSS-IV timeshare between projects
- DES coverage (500deg² overlap)
- SCUSS u-band survey on SGC (using Bok at Kitt-Peak)
- eROSITA (German sky) for additional follow-up program

Start date: summer 2014, but could be earlier!

Duration: 6 years



> 4 years

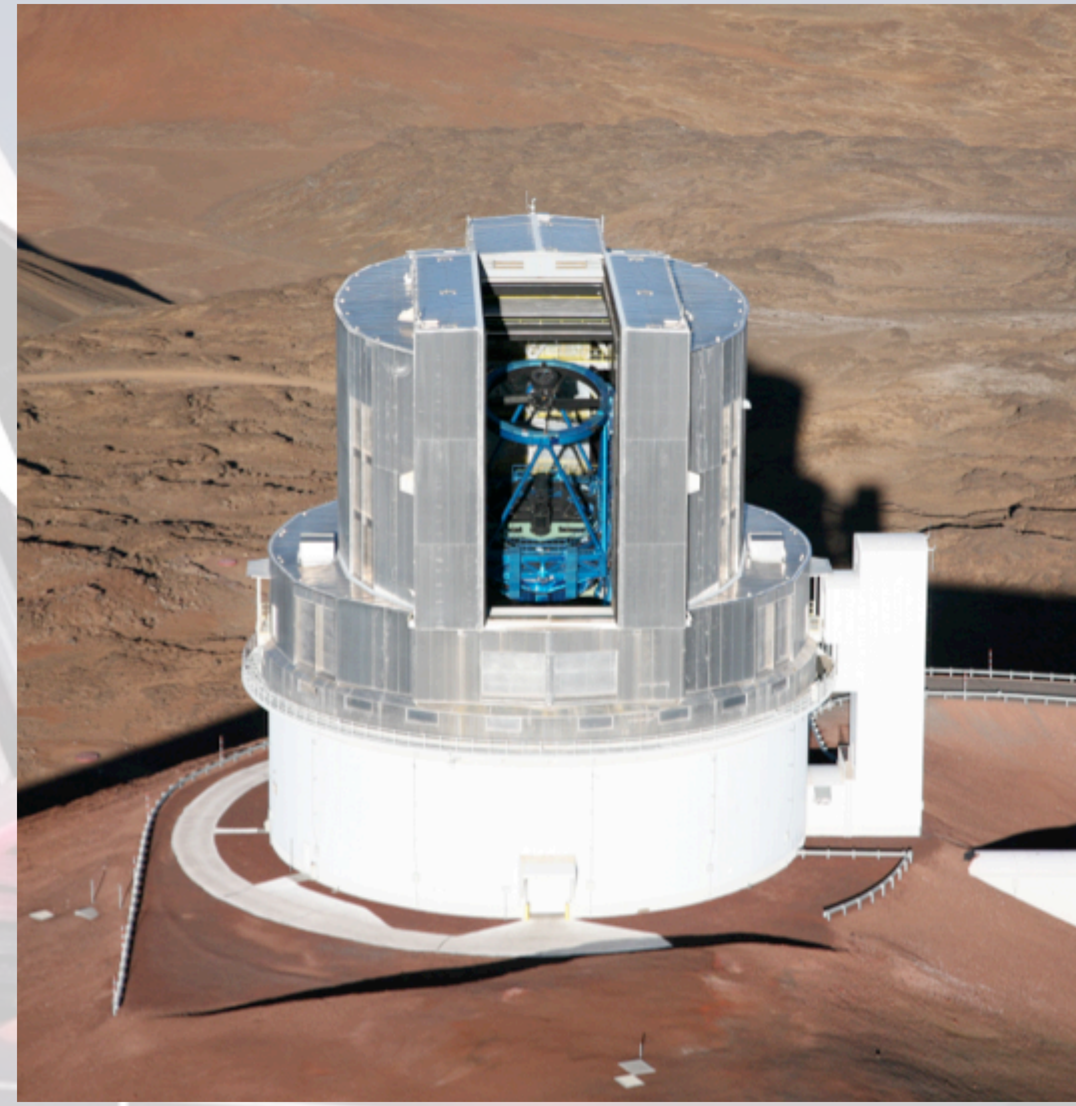
MOS on 4m-telescope

- New fibre-fed spectroscopes proposed for 4m telescopes
  - Mayall (BigBOSS)
  - Blanco (DESpec)

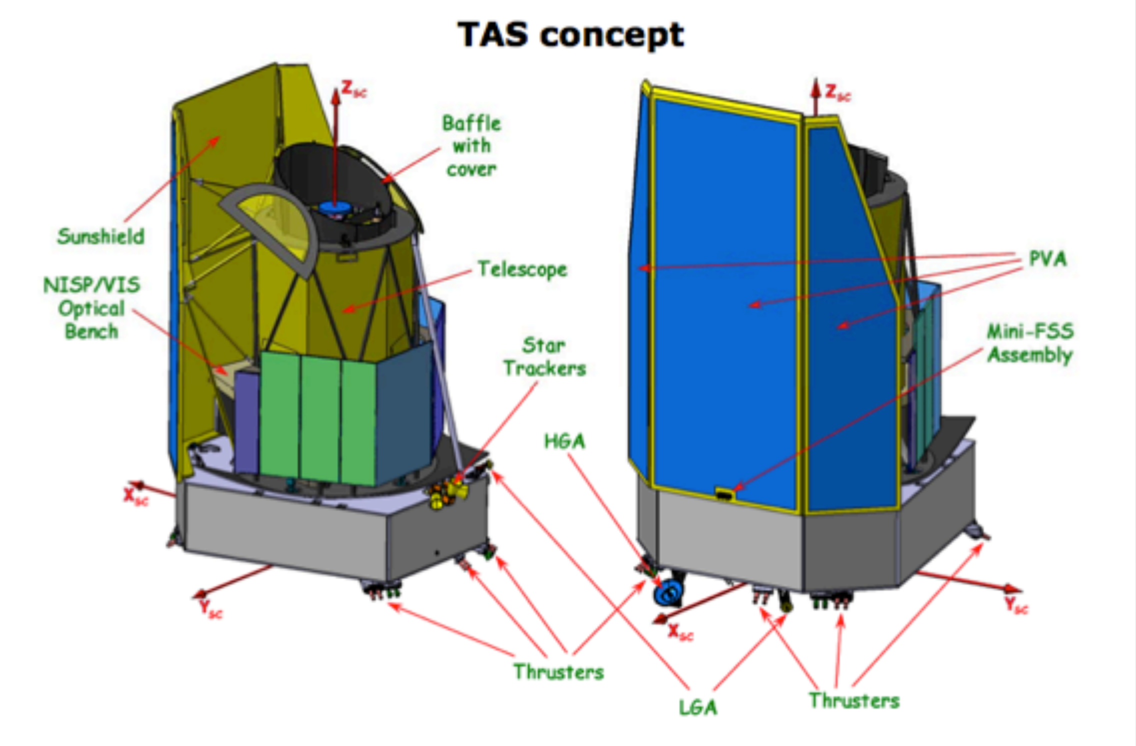
    DESi
  - WHT (WEAVE)
  - VISTA (4MOST)
- Various stages of planning & funding
  - DESi now funded
  - 4MOST chosen by ESO, 1-year delay
  - WEAVE waiting for UK/Spain/Holland/France
- All capable of observing
  - Ω =5--14,000deg^2
  - 2--20,000,000 galaxies (direct BAO)
  - 1--600,000 quasars (BAO from Ly-α forest)
  - Cosmic variance limited to z ~ 1.4

MOS on 10m-telescope

- New fibre-fed spectroscopes proposed for 10m telescopes
  - Hobby-Eberly (HETDEX)
  - Subaru (PFS)
- Different baseline strategies
- HETDEX
  - 420deg^2 Ly-alpha emitters
  - 800,000 galaxies $1.9<z<3.5$
  - Greig, Komatsu & Wyithe, 2012, arXiv:12120977
- PFS
  - 1400deg^2 ELGs
  - 3,000,000 galaxies $0.6<z<2.4$
  - Ellis et al., 2012, arXiv:1206.0737

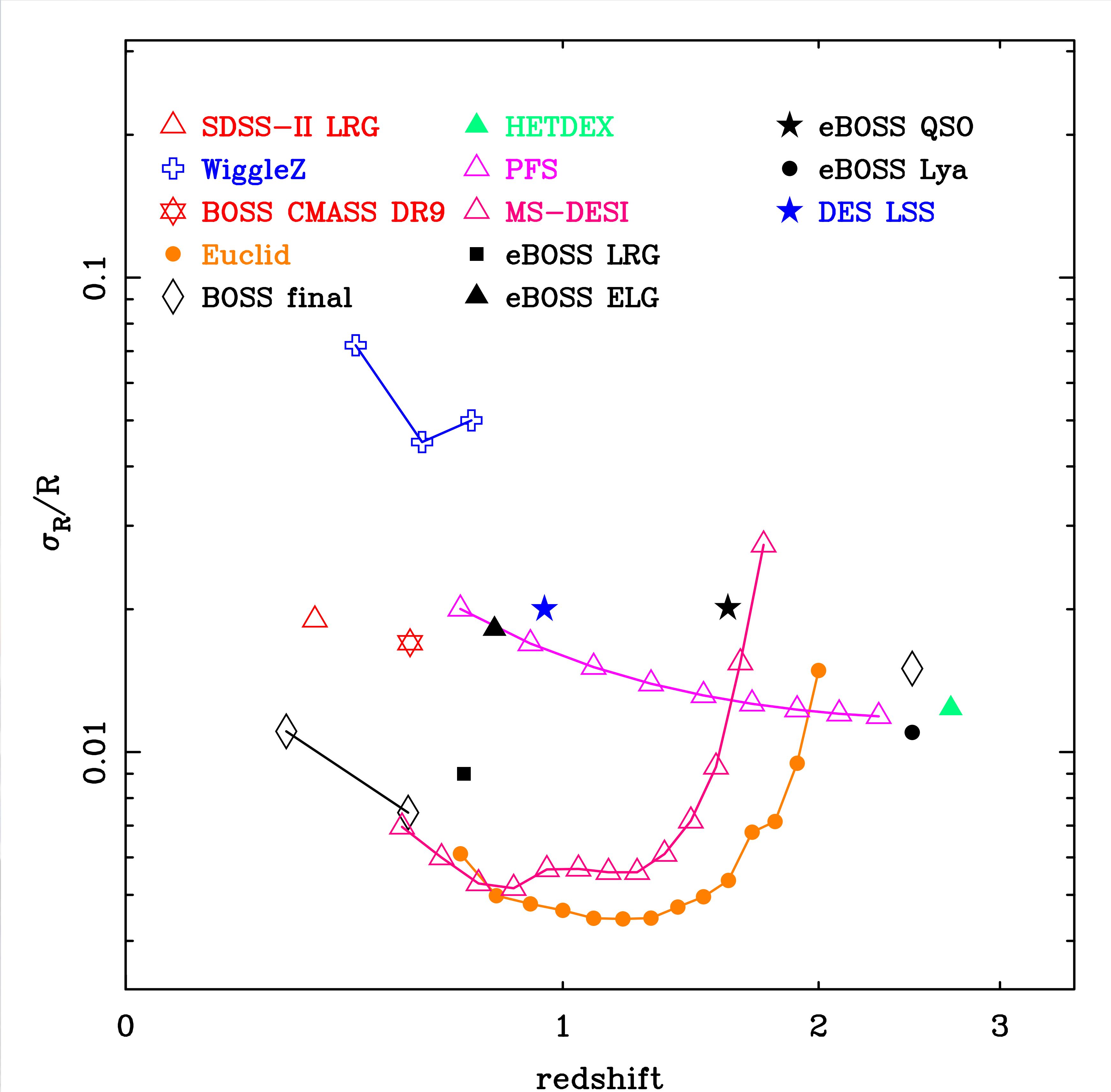


The Euclid spectroscopic survey



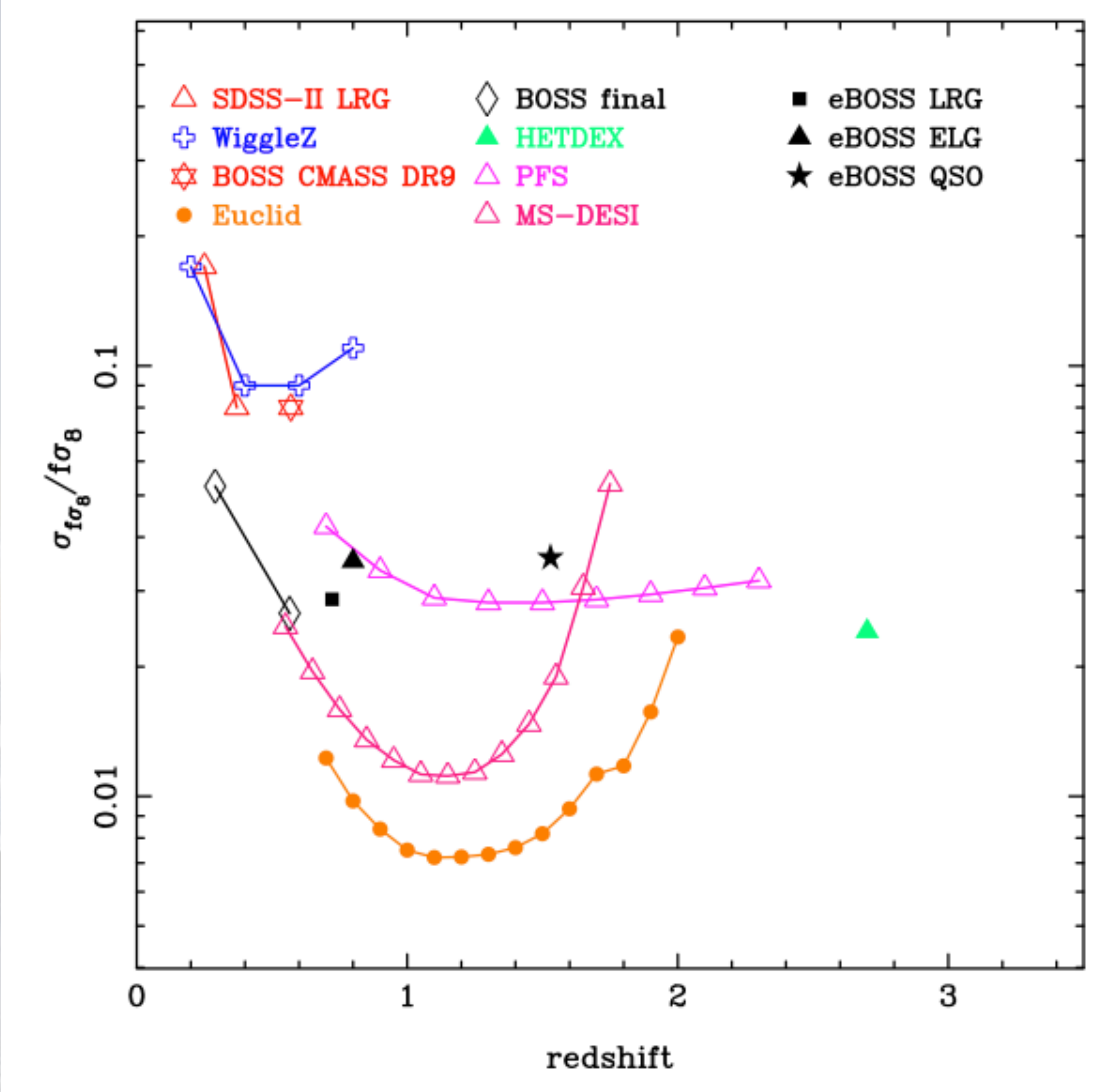
- Wide survey
  - 15,000deg^2
  - 4 dithers
  - NIR Photometry
    - Y, J, H
    - 24mag, 5σ point source
  - NIR slitless spectroscopy
    - 1100-2000nm
    - 3×10^{-16}ergcm^{-2}s^{-1} 3.5σ line flux
    - 2 dispersion directions, 2 wavebands
    - 65M galaxies
- Deep survey
  - 40deg^2
  - 48 dithers
  - 12 passes, as for wide survey
  - dispersion directions for 12 passes >10deg apart

Distance measurements for future surveys



using the code of Seo & Eisenstein 2007, arXiv:0701079

RSD measurements for future surveys

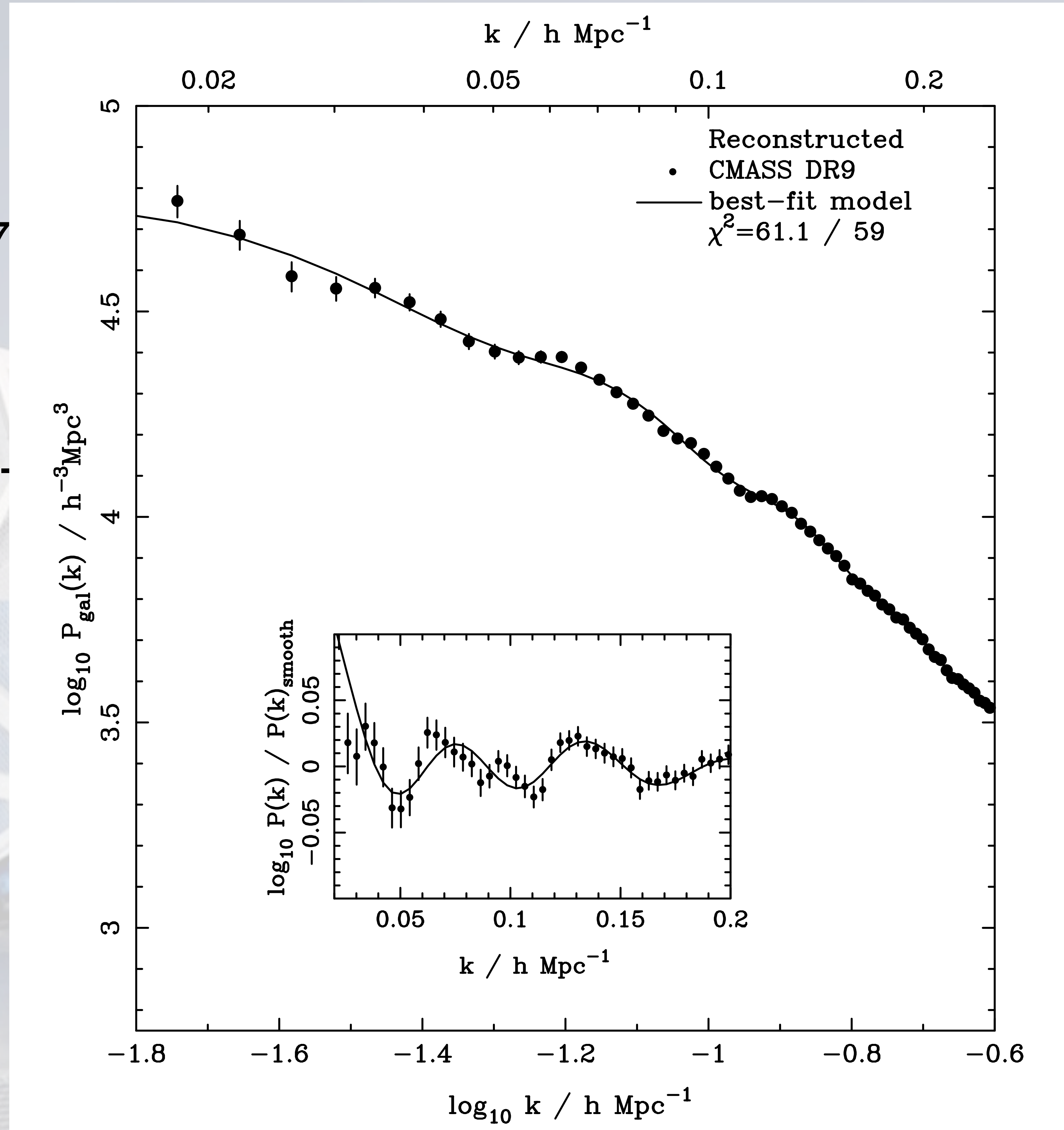


using the code of White et al. 2008, arXiv:0810.1518

BOSS CMASS DR9 galaxy clustering

BOSS CMASS galaxies at z~0.57

Total effective volume
V_{eff} = 0.77 Gpc^3h^{-3}

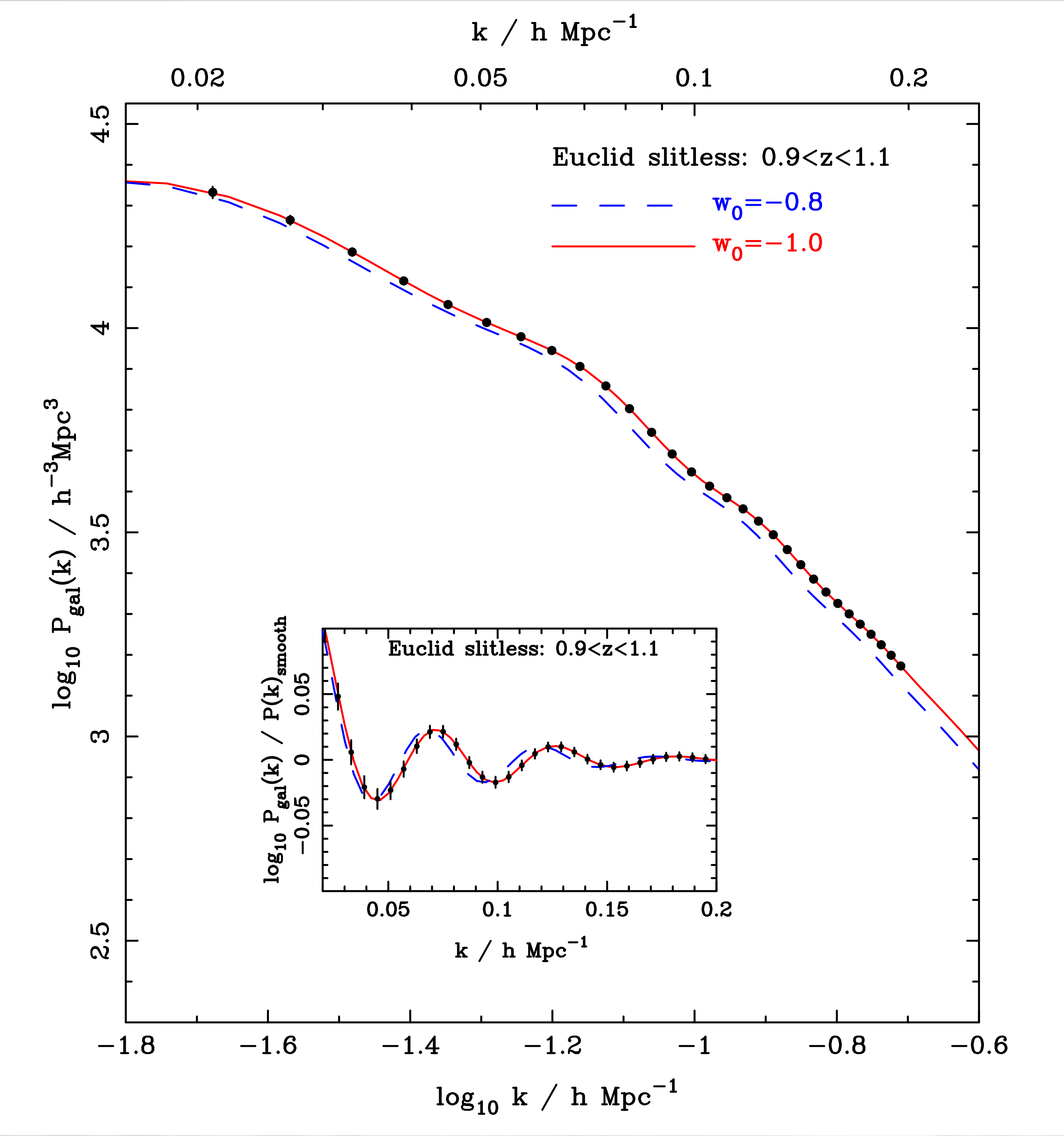


Anderson et al. 2012; arXiv:1203.6565

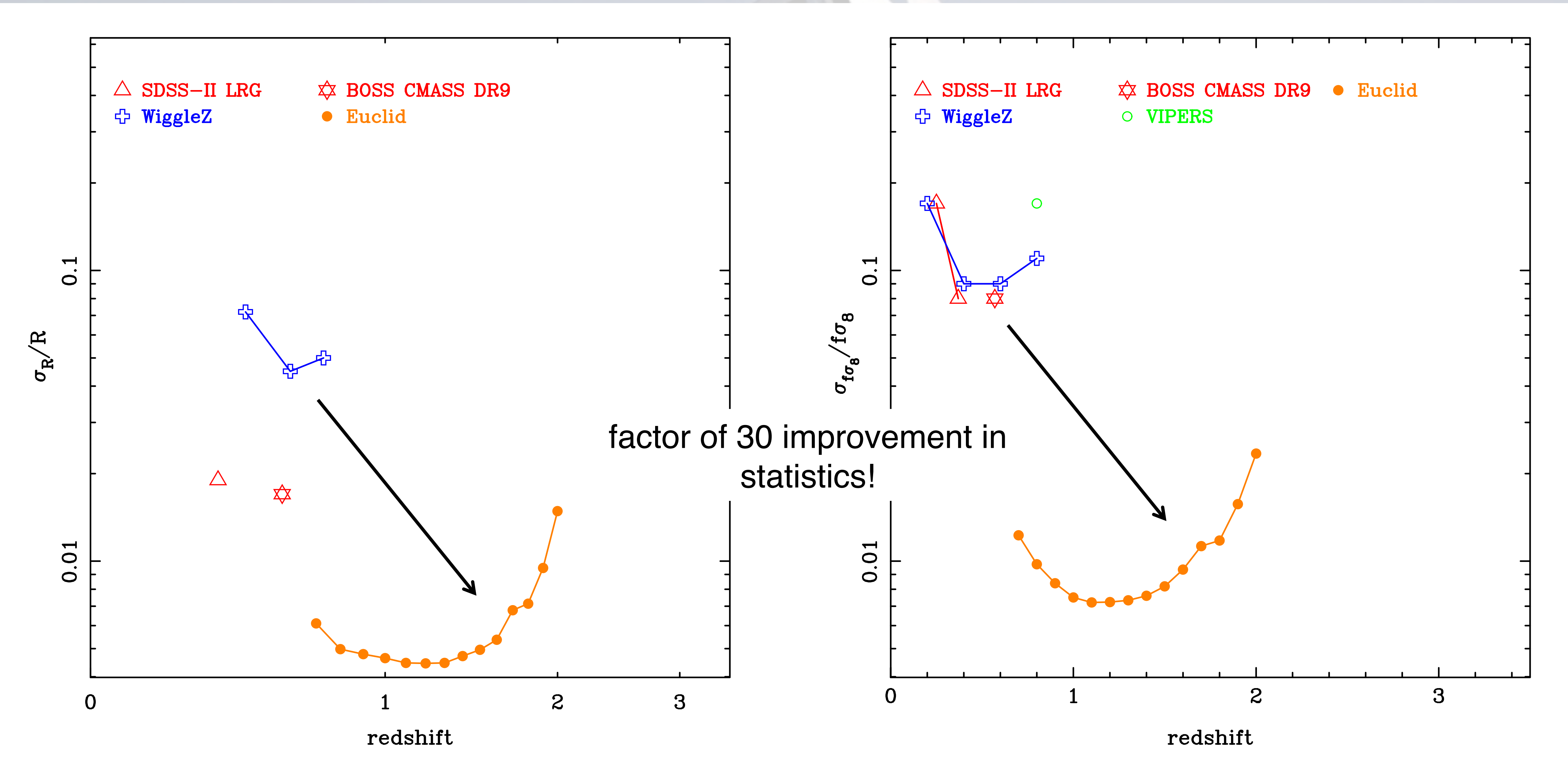
Predicted Euclid galaxy clustering

Redshift slice
$0.9 < z < 1.1$

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

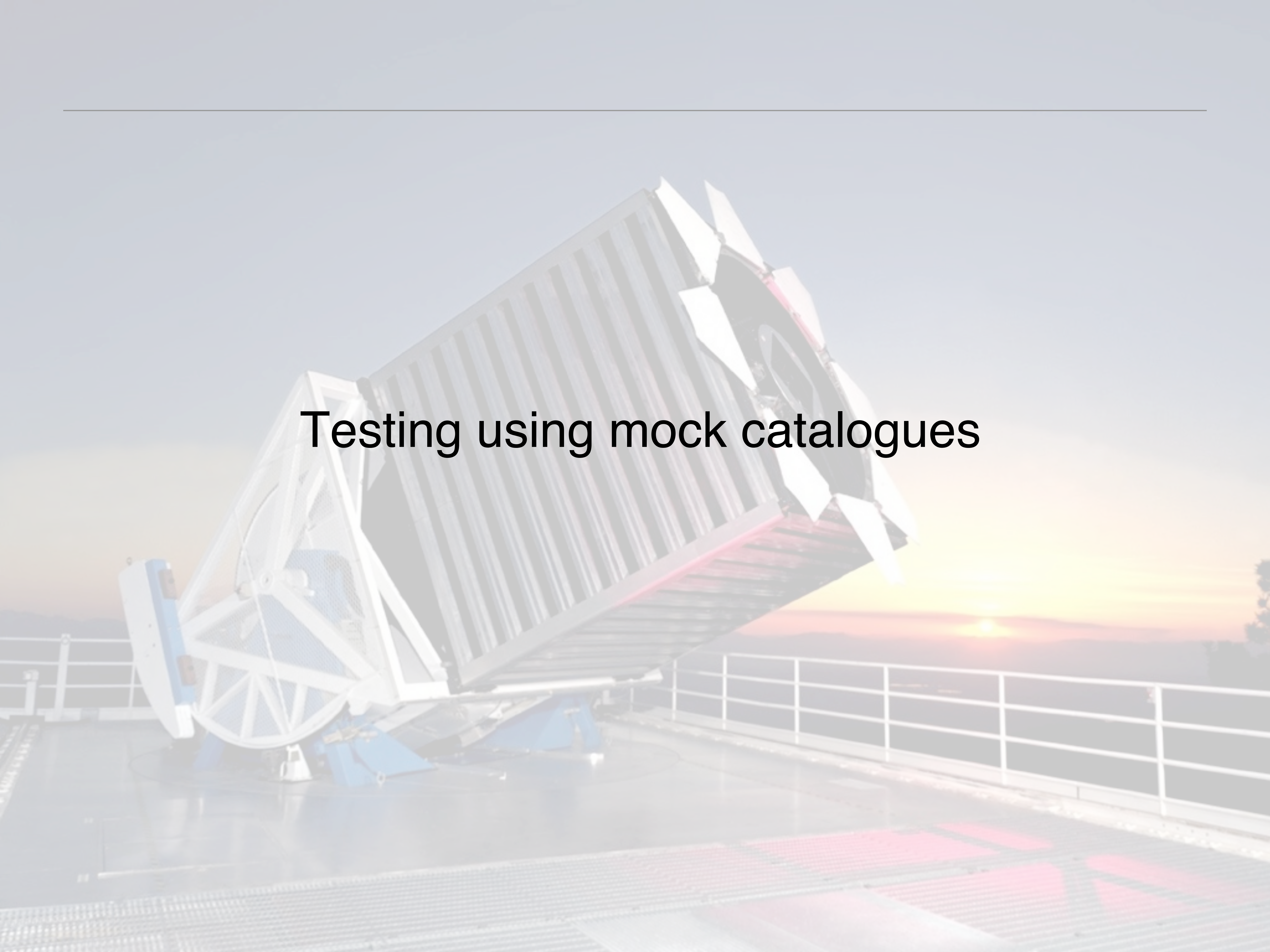


Improvement in precision



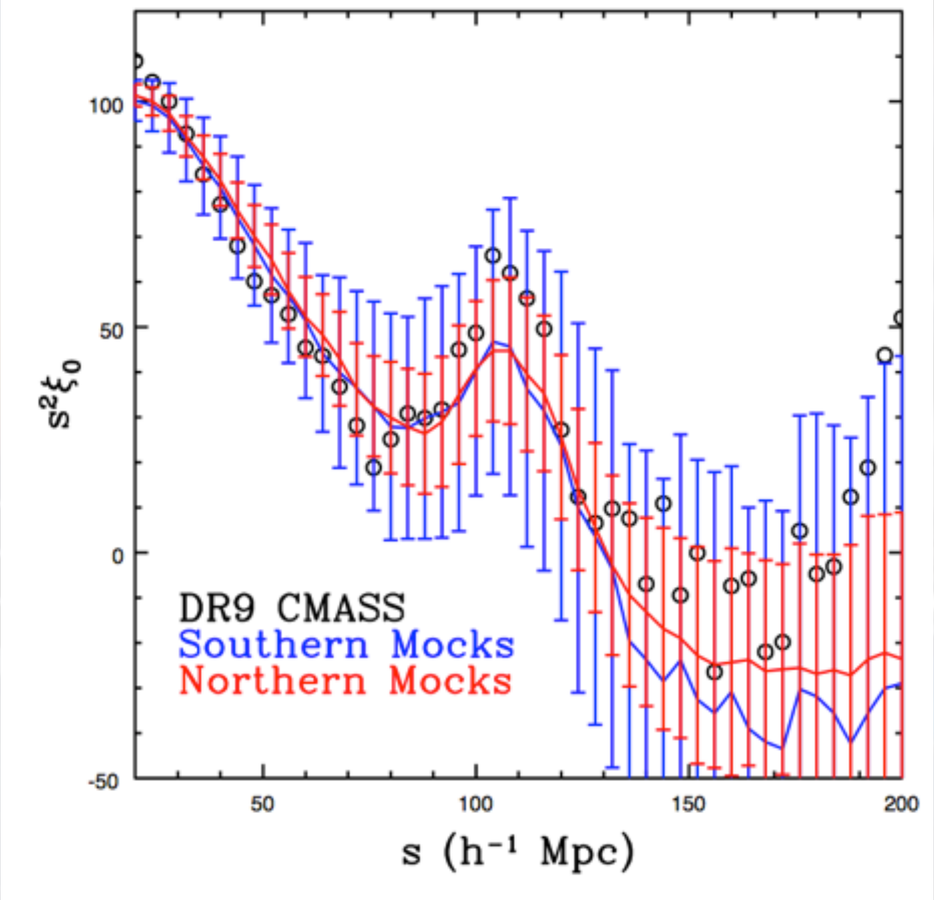
… but what about systematics? …

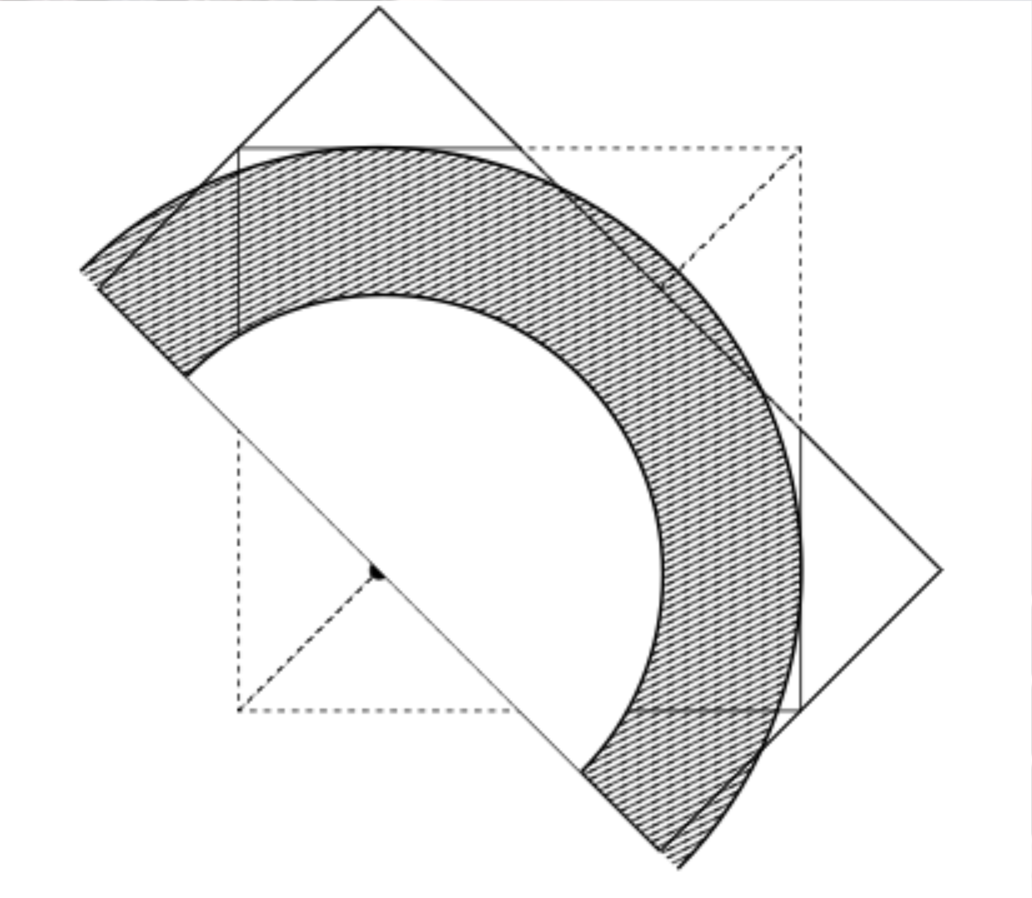
Testing using mock catalogues



Mock catalogues

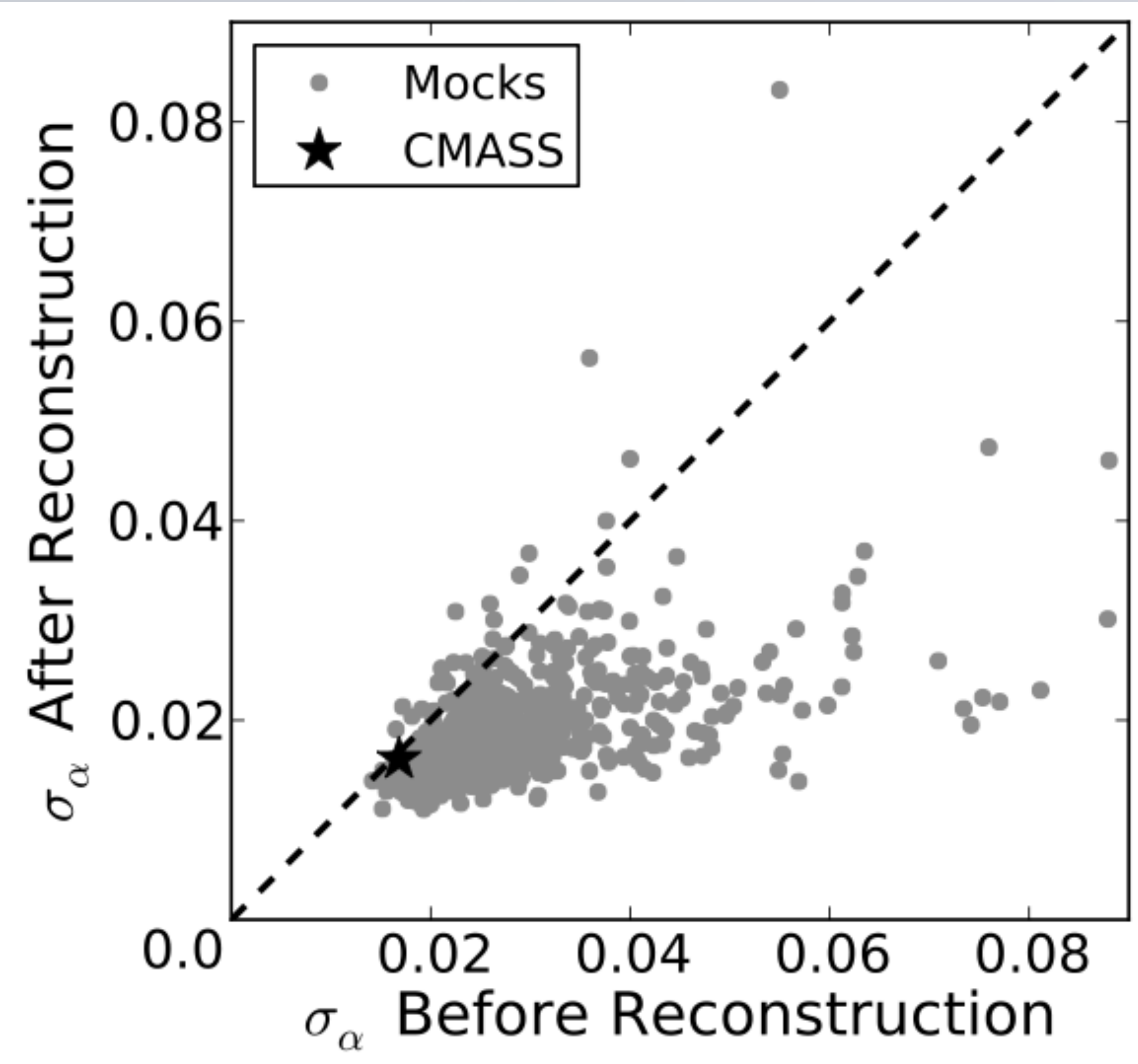
- 600 mocks created by populating 2LPT field using the CMASS HOD
- Redshift-space effects added based on 2LPT velocities
- Matches simulation large-scale clustering at 10% level
- Used to test method and estimate covariances





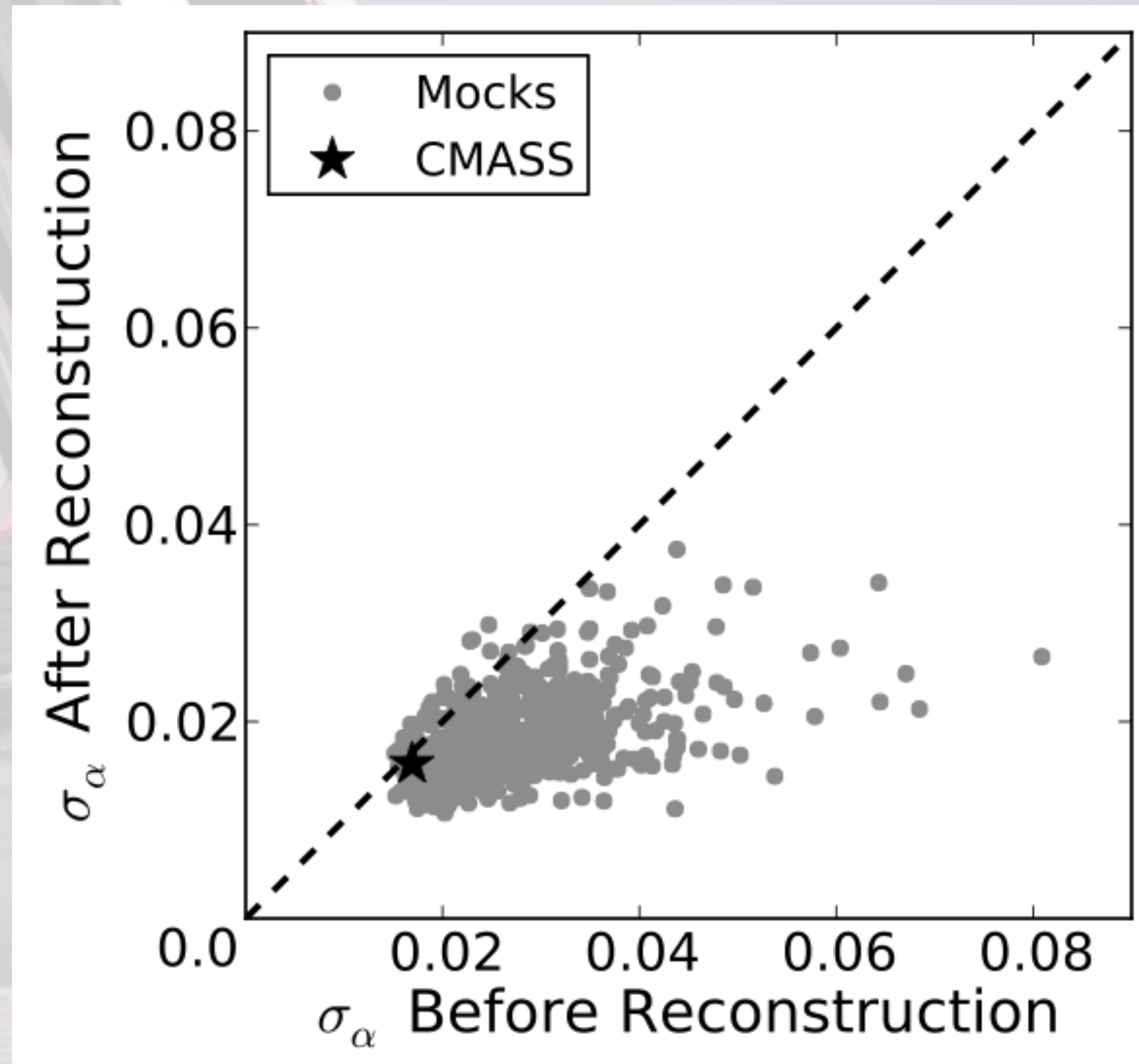
Manera et al. 2012; 1203.6609

Reconstruction: error on α



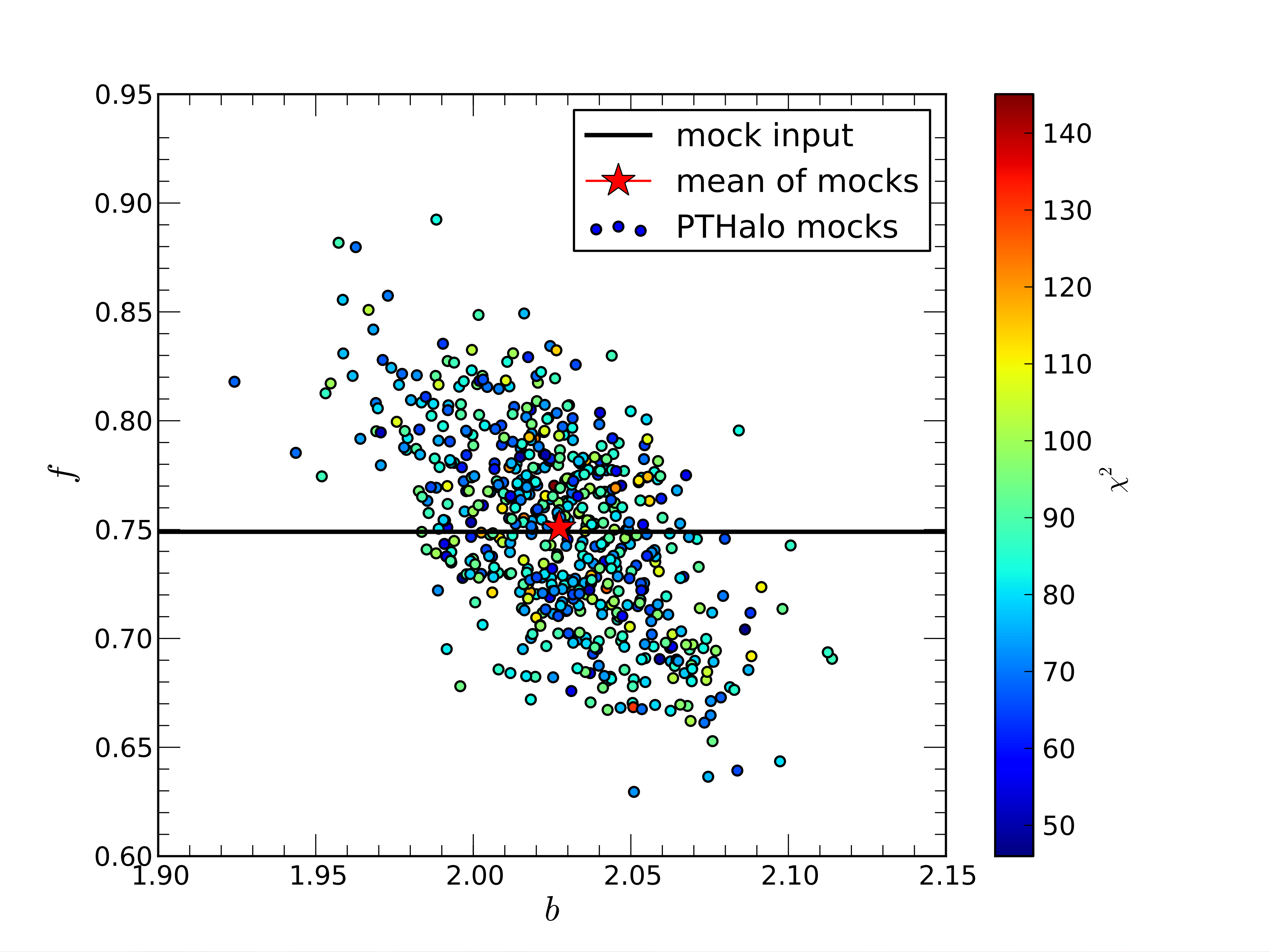
Correlation function

Power spectrum



Anderson et al. 2012; arXiv:1203.6565

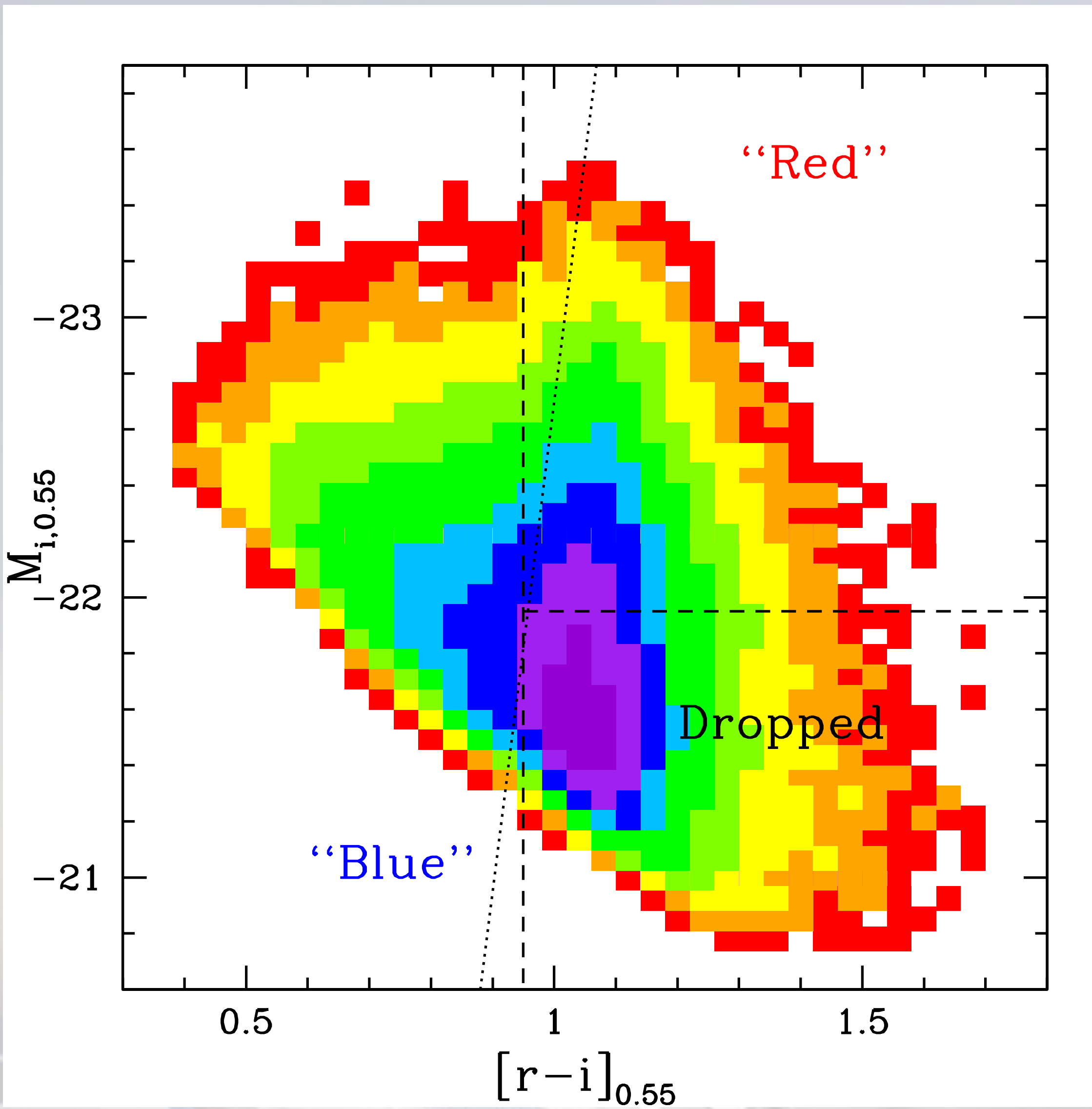
Using mocks to test DR11 RSD measurements

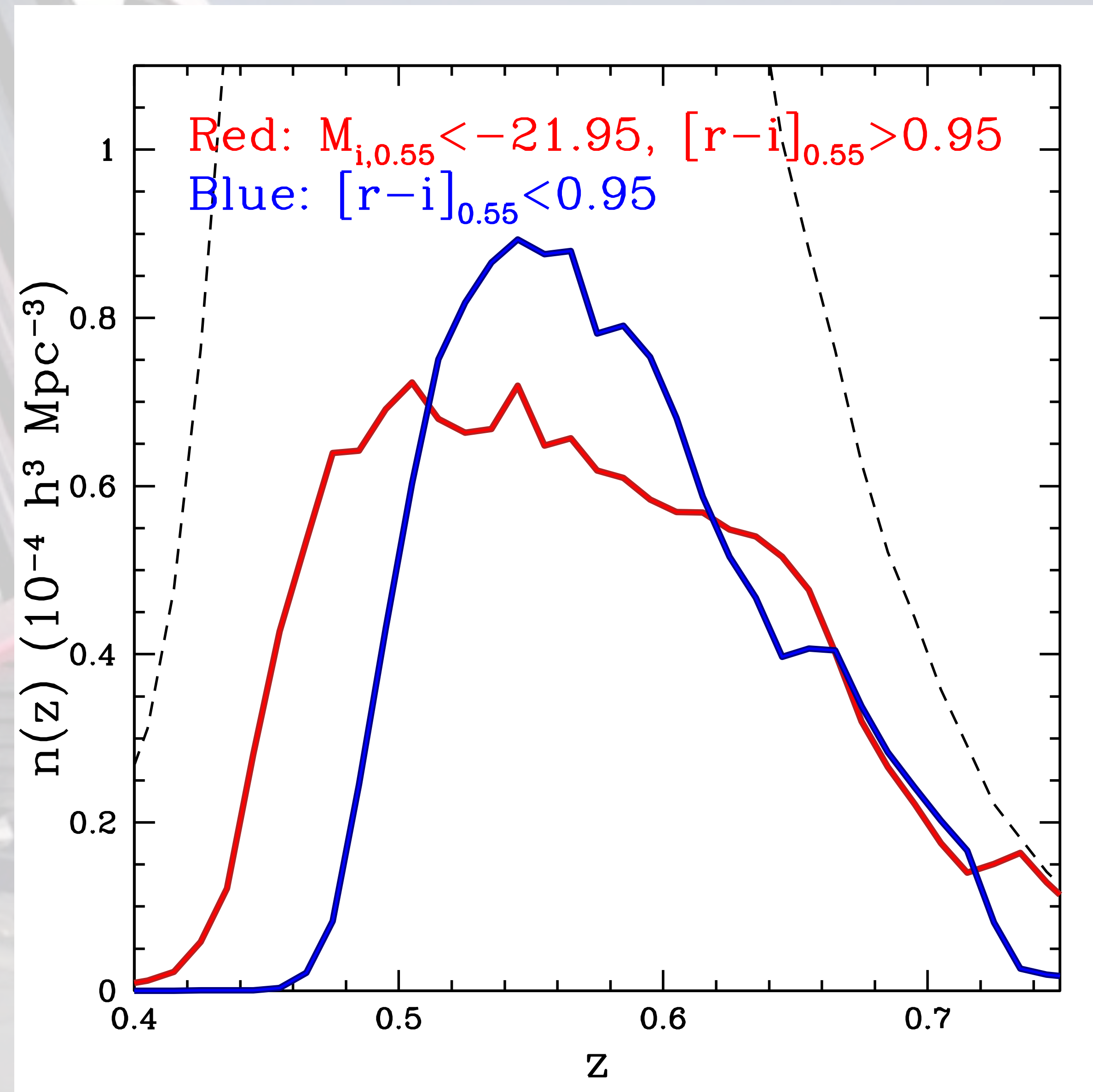


Samushia et al. 2012; in prep

Testing with subsamples

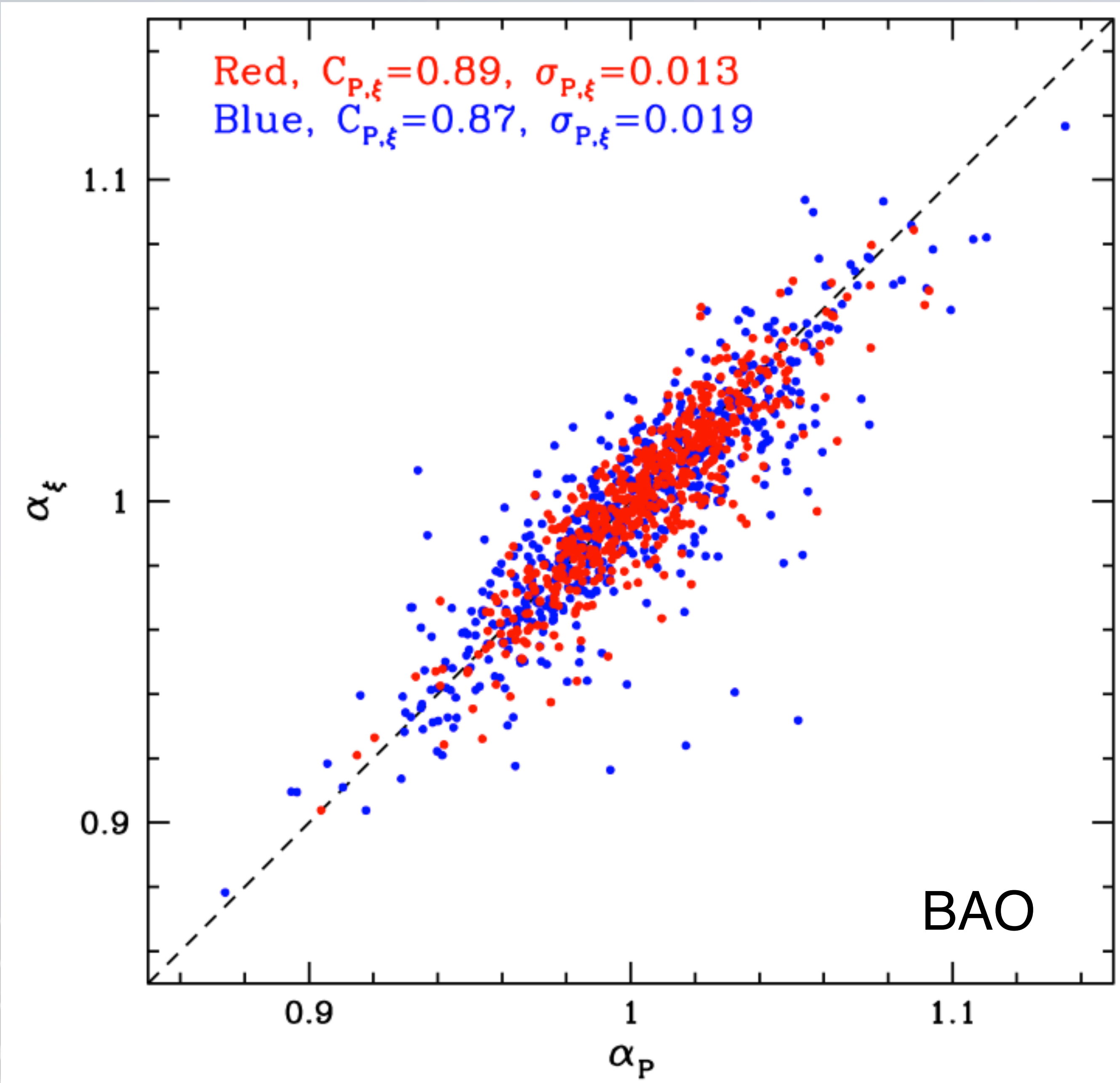
Testing with blue / red subsamples

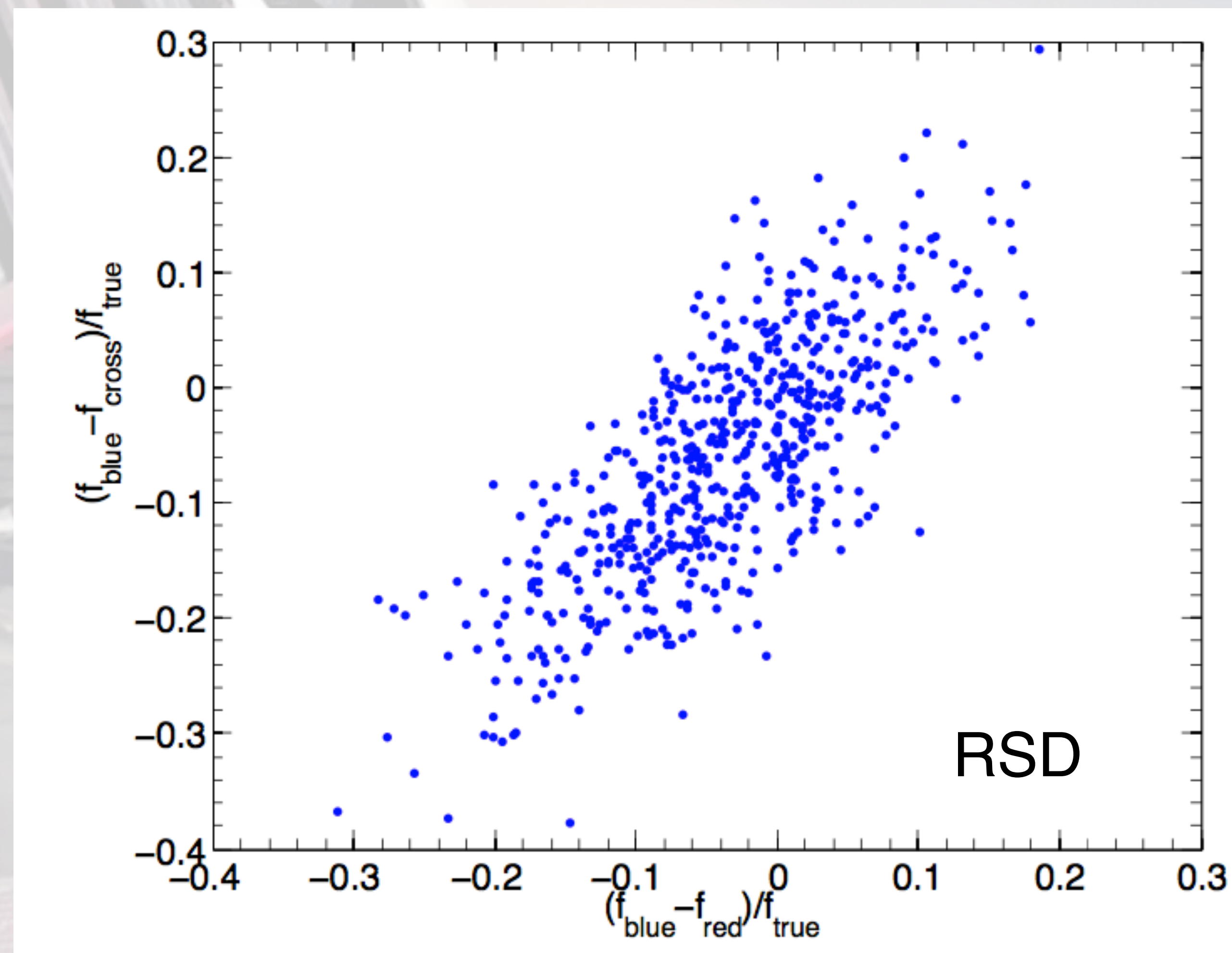




Ross et al. 2013, in prep

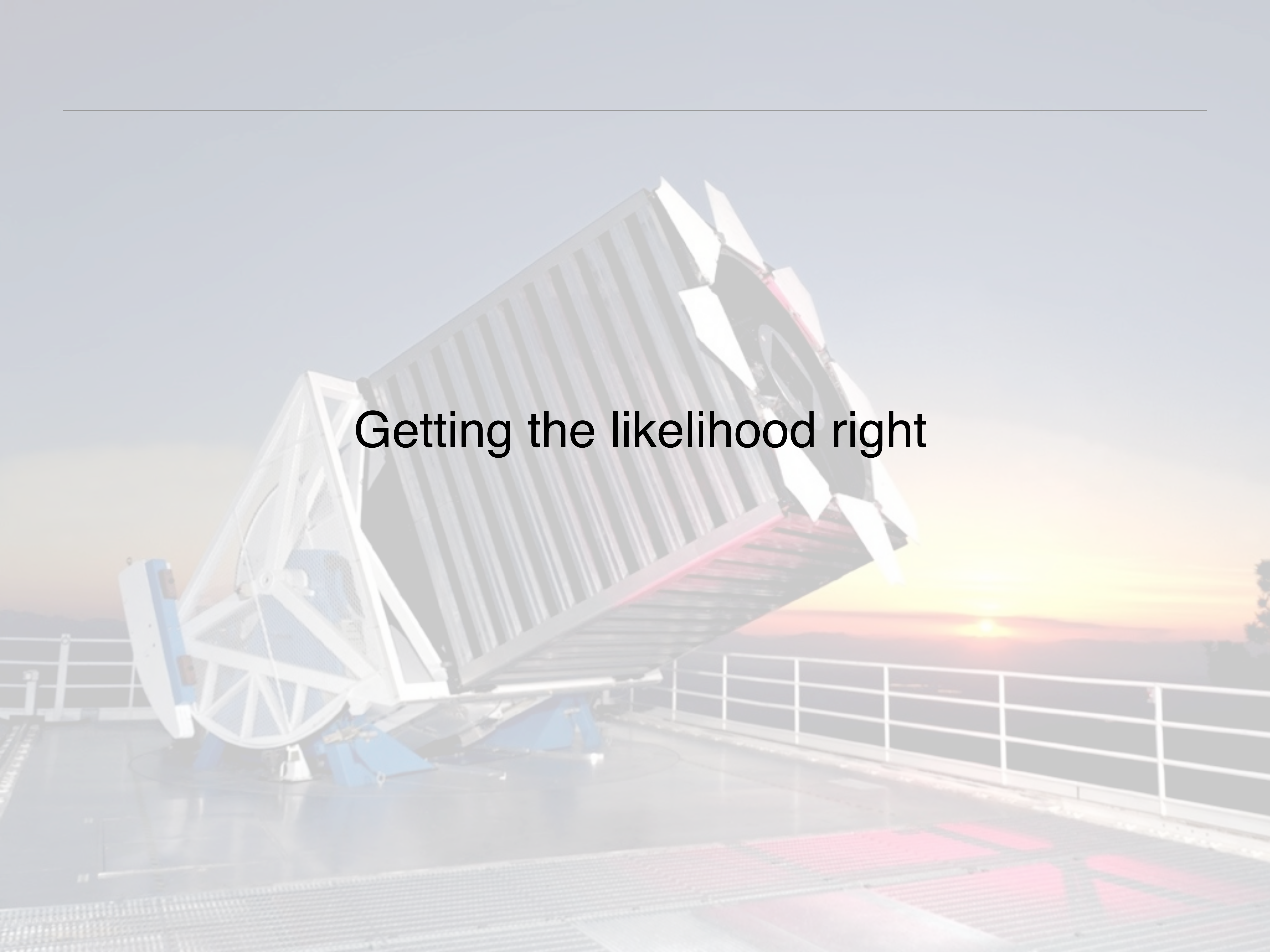
Testing with blue / red subsamples





The data also show no statistically significant change between red 7 blue samples

Ross et al. 2013, in prep



Getting the likelihood right

Getting the likelihood calculation 100% correct

The Likelihood under the standard assumption of a set of data drawn from a multi-variate Gaussian distribution is given by

$$\mathcal{L}(\mathbf{x}|\mathbf{p}, \Psi^t) = \frac{|\Psi^t|}{\sqrt{2\pi}} \exp\left[-\frac{1}{2}\chi^2(\mathbf{x}, \mathbf{p}, \Psi^t)\right],$$

where $$\chi^2(\mathbf{x}, \mathbf{p}, \Psi^t) \equiv \sum_{ij} \left[x_i^d - x_i(\mathbf{p})\right] \Psi_{ij}^t \left[x_j^d - x_j(\mathbf{p})\right].$$

now suppose that the covariance matrix (size n_b x n_b) has been calculated from n_s simulations

$$\mu_i = \frac{1}{n_s}\sum_s x_i^s \qquad C_{ij} = \frac{1}{n_s - 1}\sum_s (x_i^s - \mu_i)(x_j^s - \mu_j)$$

then an unbiased estimator of the inverse covariance matrix is

$$\Psi = \frac{n_s - n_b - 2}{n_s - 1} C^{-1}$$

Hartlap J., Simon P., Schneider P., 2007, A&A, 464, 399

Errors in the covariance matrix

Simply providing an unbiased estimator of the inverse covariance matrix is not enough

The inverse covariance matrix also has its own error

$$\langle \Delta\Psi_{ij}\Delta\Psi_{i'j'}\rangle = A\Psi_{ij}\Psi_{i'j'} + B(\Psi_{ii'}\Psi_{jj'} + \Psi_{ij'}\Psi_{ji'}),$$

$$A = \frac{2}{(n_s - n_b - 1)(n_s - n_b - 4)}$$

$$B = \frac{(n_s - n_b - 2)}{(n_s - n_b - 1)(n_s - n_b - 4)}$$

Strictly, we should form a joint likelihood

$$\mathcal{L}(\mathbf{x}, \Psi|\mathbf{p}, \Psi^t) = \mathcal{L}(\mathbf{x}|\mathbf{p}, \Psi)\mathcal{L}(\Psi|\Psi^t),$$

If we don't, this leads to an additional error on the $n_\mathbf{p}$ parameters being fitted

$$\langle p_\alpha p_\beta\rangle|_{s.o.} = B(n_b - n_p)F^{-1}_{\alpha\beta},$$

Taylor et al., 2012, arXiv:1212.4359; Dodelson & Schneider 2007, arXiv:1212.4359

Errors in likelihood calculations

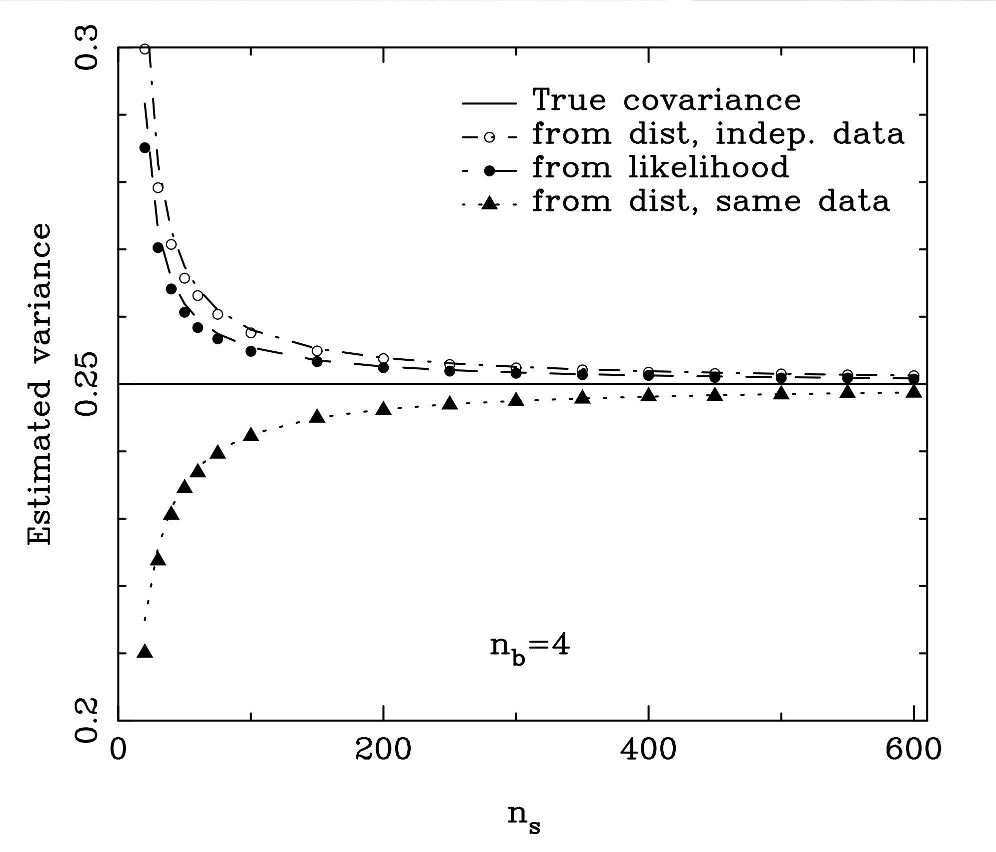
Given a set of mocks, we can form two possible estimates of the errors:

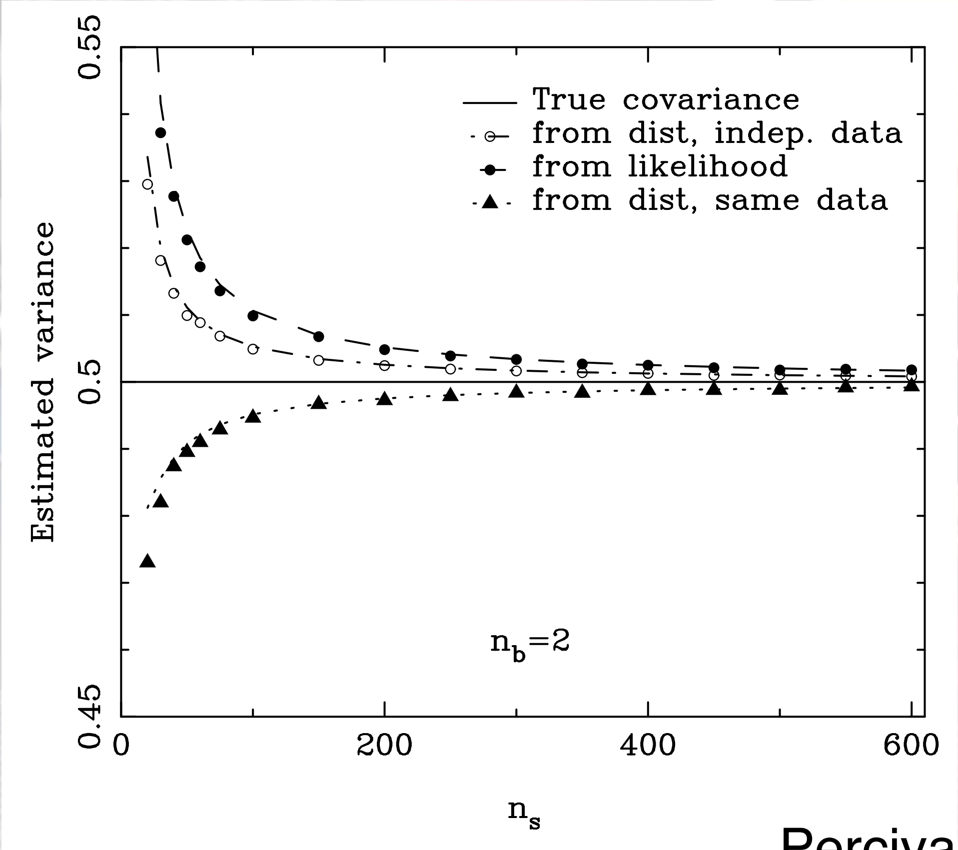
1. From the individual likelihood surface from each mock

2. From the distribution of recovered measurements from the set of mocks

These should agree!

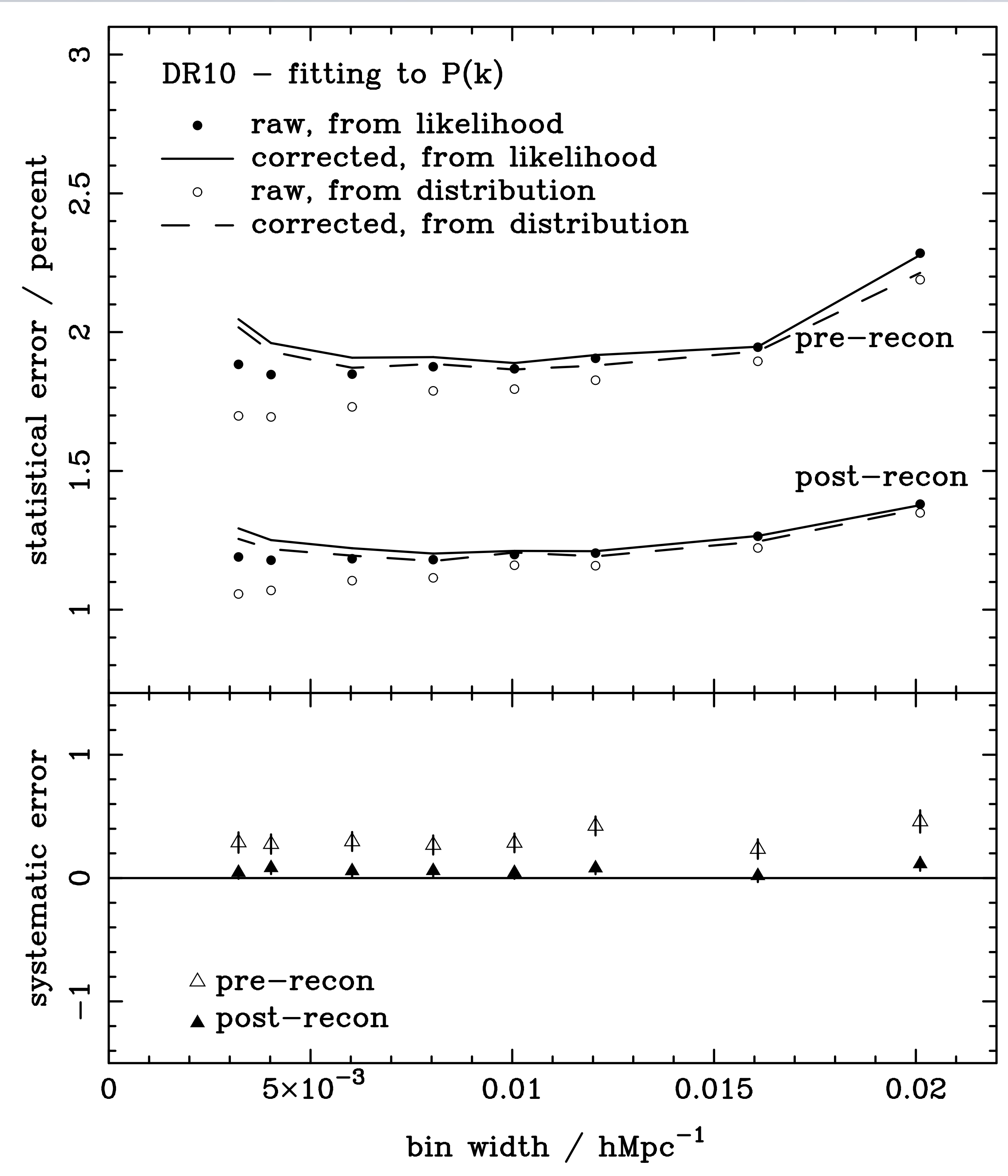
The estimates from each are biased in subtly different ways gives errors in the covariance matrix

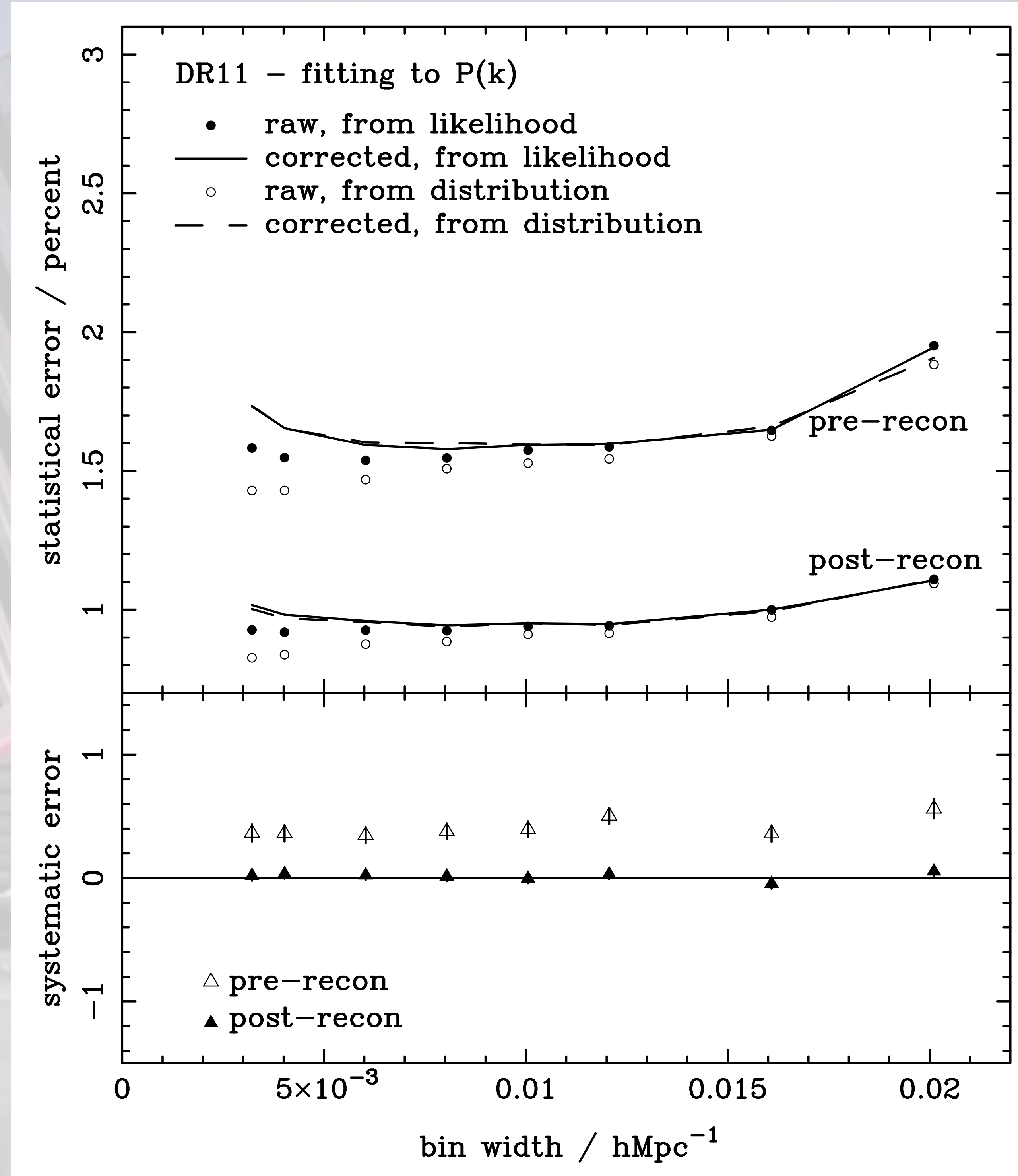




Percival et al., MNRAS submitted

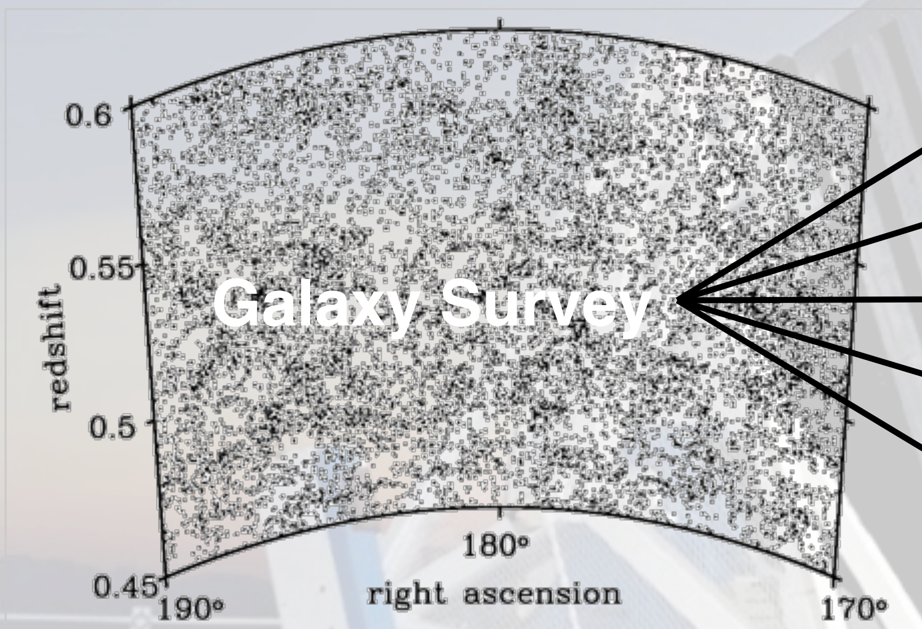
Application to BOSS





Percival et al., MNRAS submitted

Cosmology from galaxy surveys



Baryon Acoustic Oscillations → What is the expansion rate of the Universe? e.g. Anderson et al (2012)

Alcock-Paczynski effect → What is the expansion rate of the Universe? e.g. Samushia et al (2012*)

Redshift-Space Distortions → How does structure form within this background? e.g. Reid et al (2012)

Understanding Dark Energy

Comoving clustering → What are the neutrino masses, matter density? e.g. Zhao et al (2012*) — Understanding energy-density

large-scale density → What is f_{nl}, which quantifies non-Gaussianity? e.g. Ross et al. (2013*) — Understanding Inflation

Forthcoming surveys extremely exciting, but will require methodology development to reach statistical limit