Cosmological results from the SDSS -III and (IV) (extended) Baryon Oscillation Spectroscopic Survey

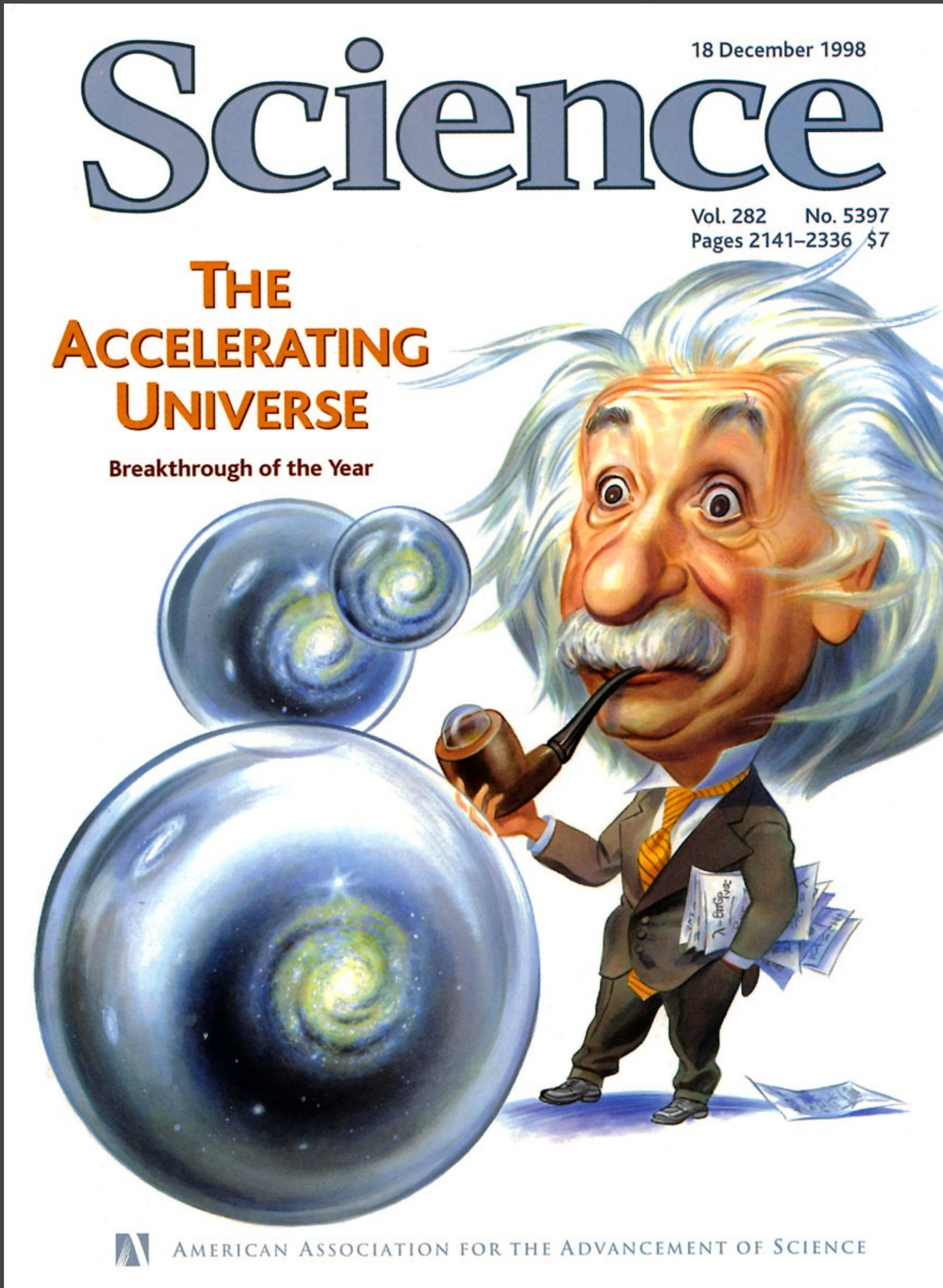
The Ohio State University

CCAPP

Ashley J. Ross + BOSS and eBOSS collaborations

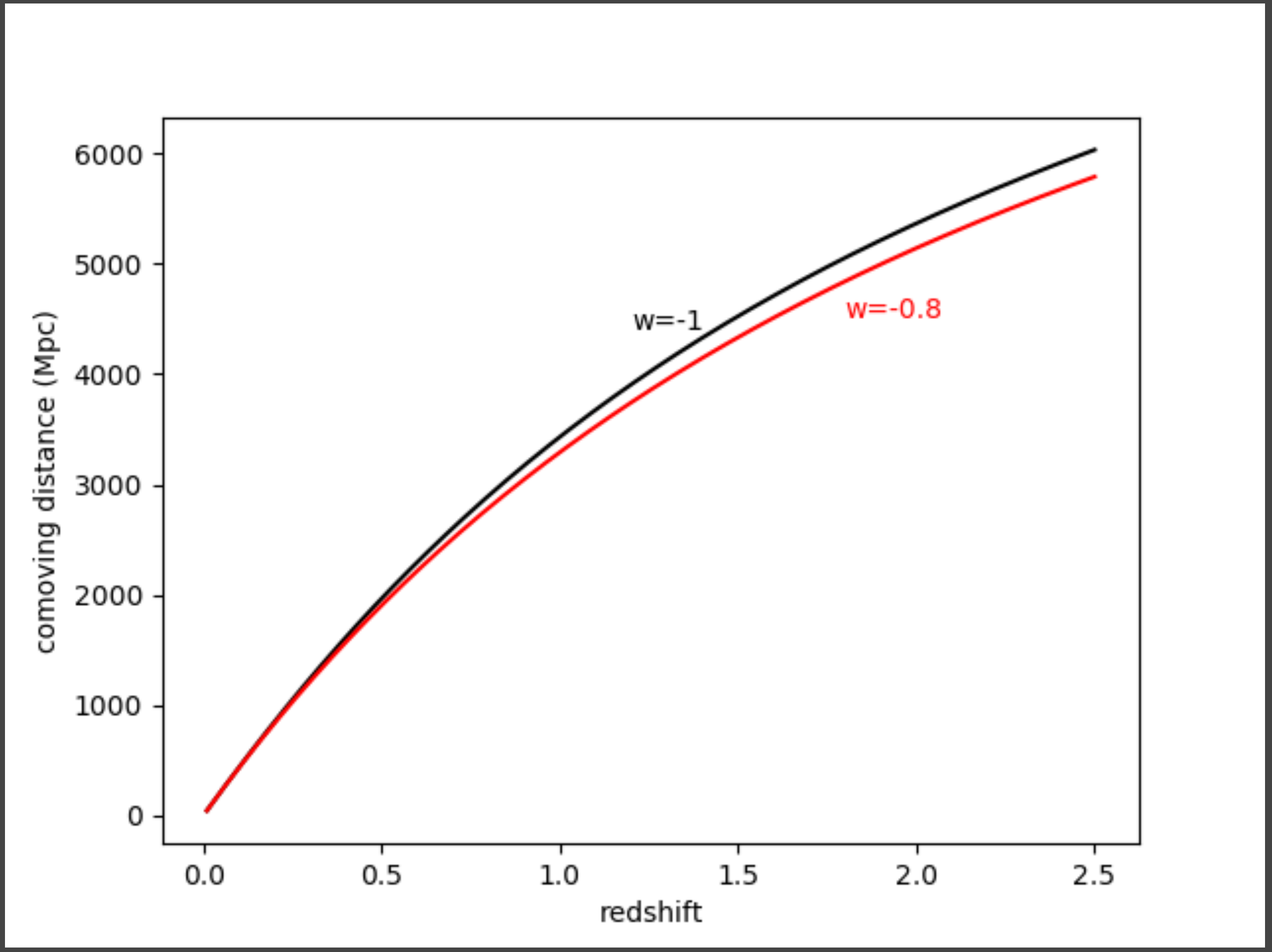
Dark Energy

- Expansion of Universe is accelerating!
- Dominant component of Universe today (~70%)
- Consistent with "cosmological constant" Λ
- something like 10^{100} off (smaller) from vacuum energy estimate
- ???



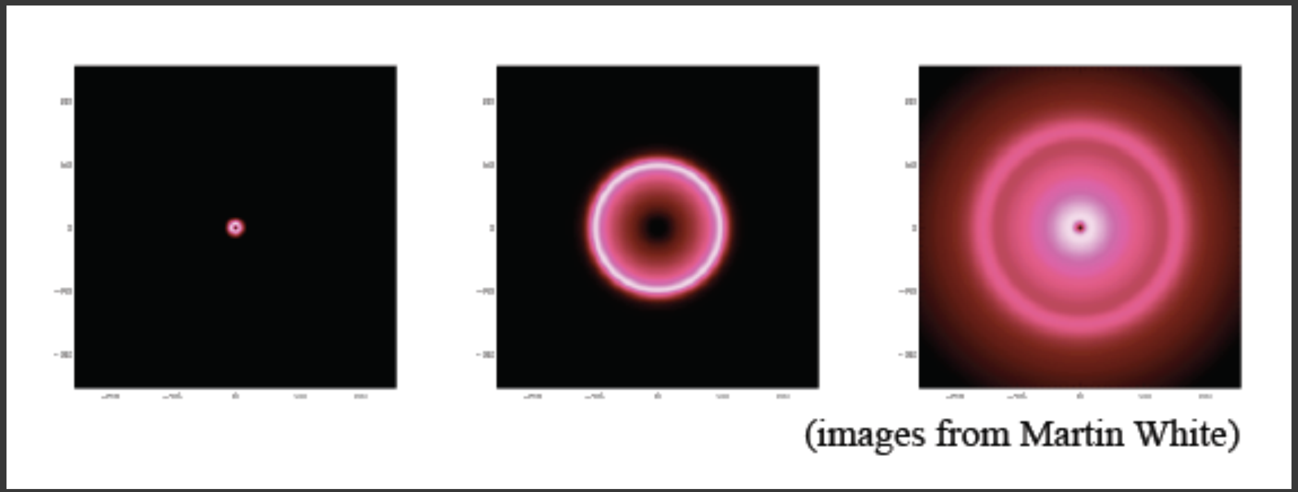
Measuring Dark Energy

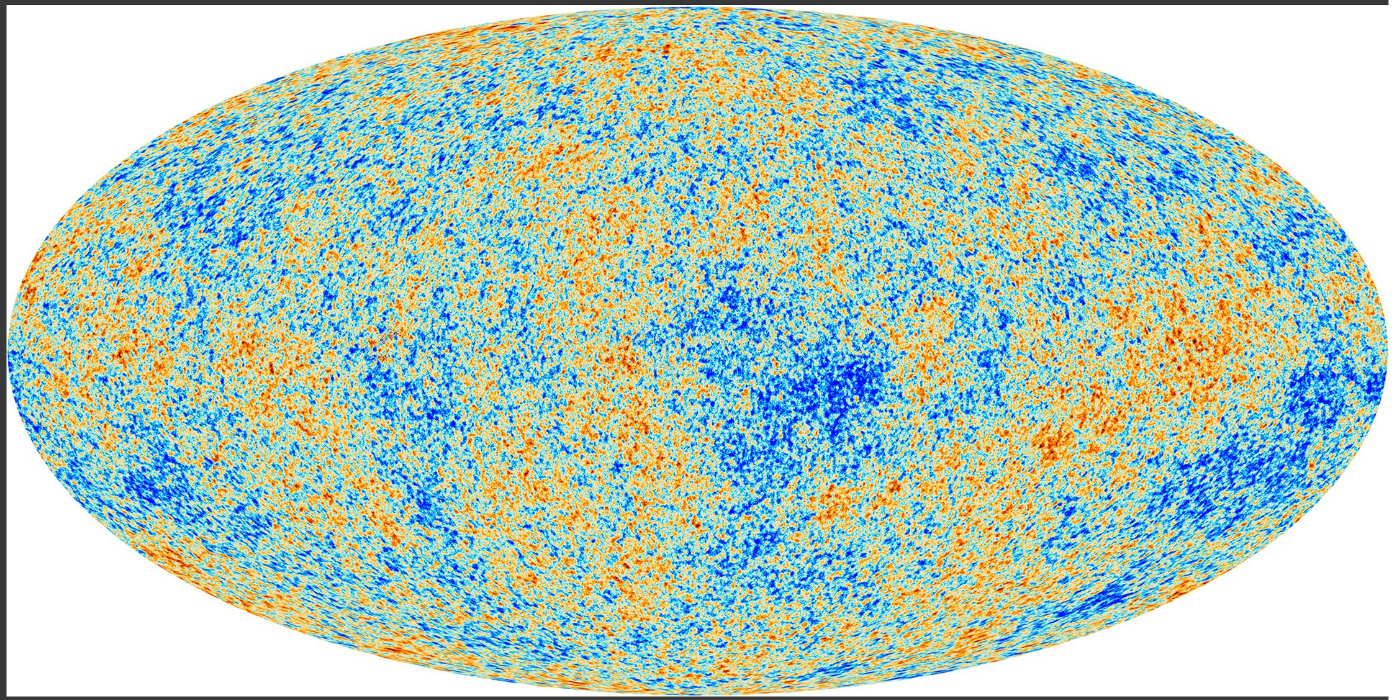
- Equation of state $w = p/\rho$
- Cosmological constant, Λ, $w=-1$
- common parameterization is $w(a) = w_0+(1-a)w_a$
- scale factor, $a = 1/(1+z)$

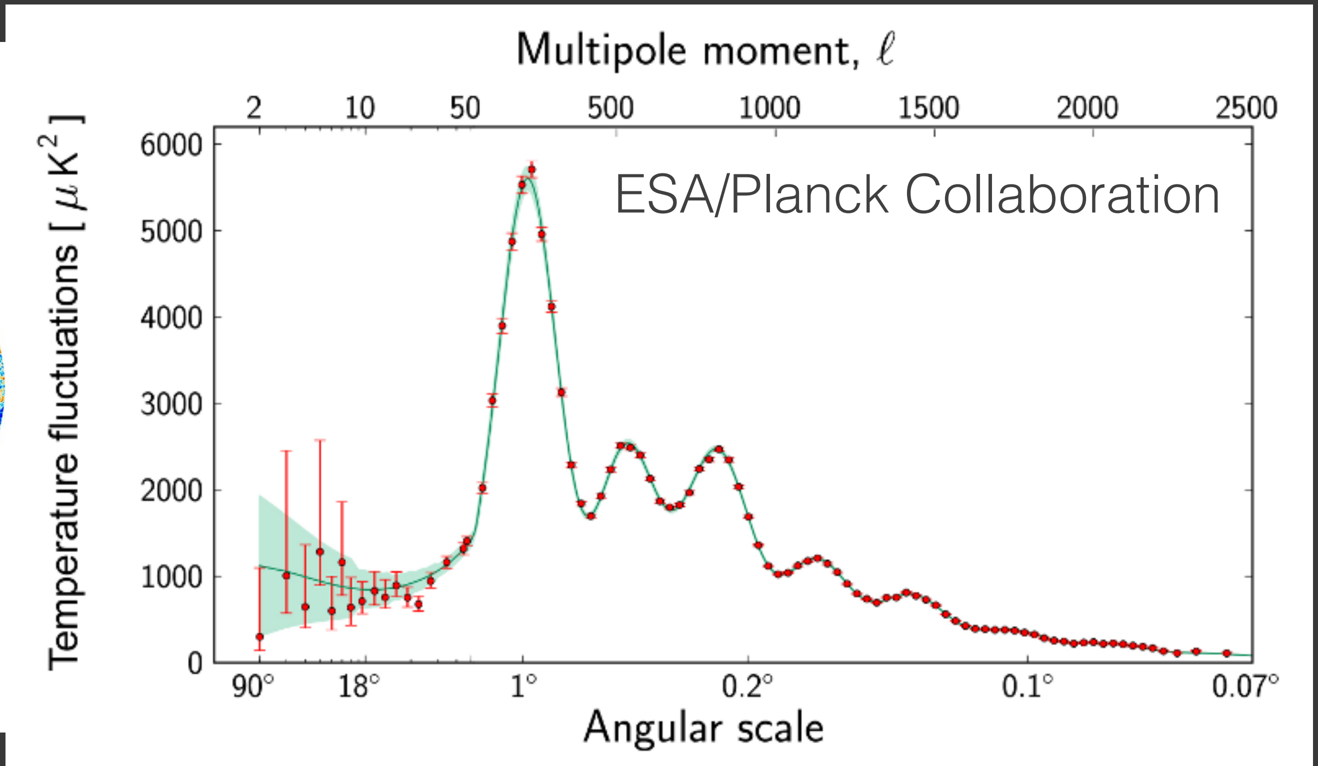


Baryon Acoustic Oscillations

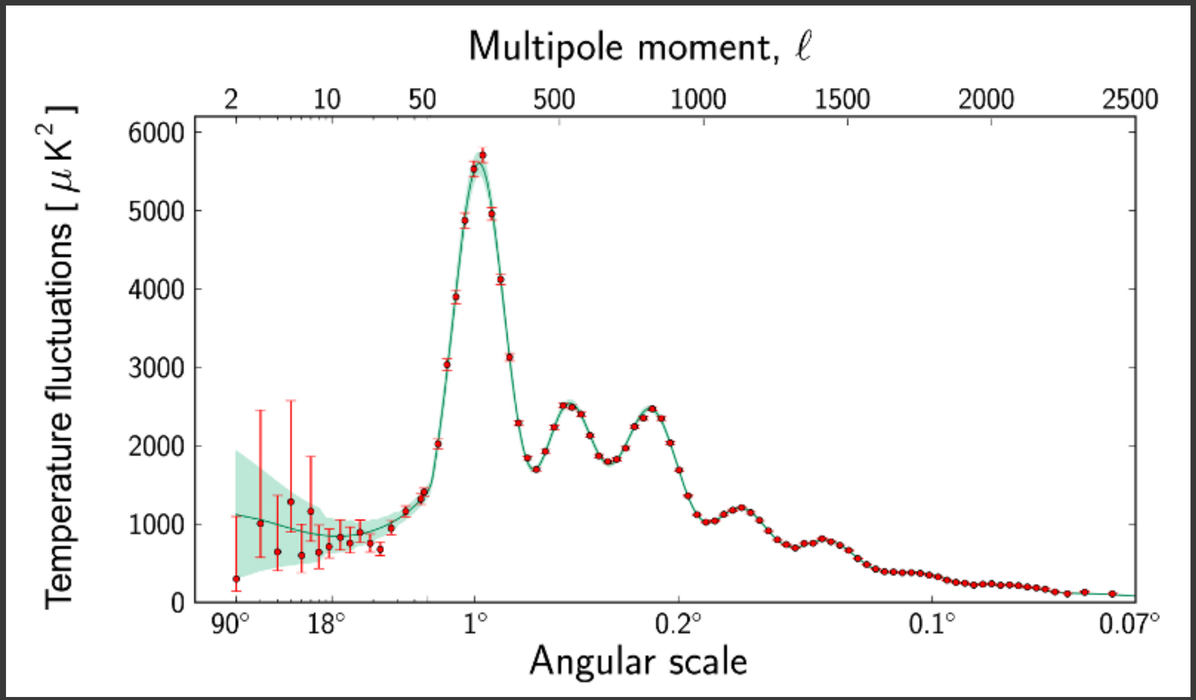
- early Universe radiation pressure/ matter density -> standing wave in baryon density



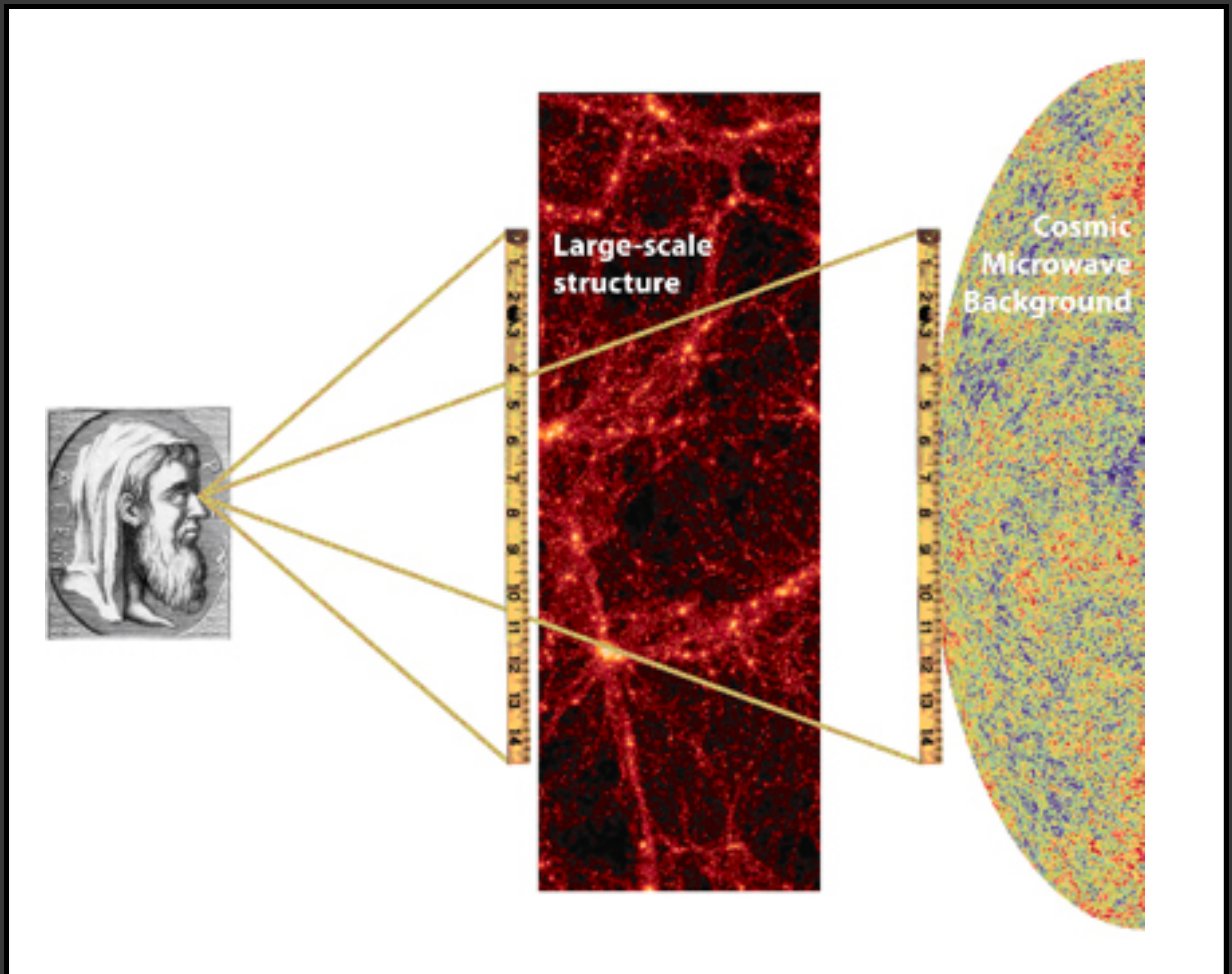


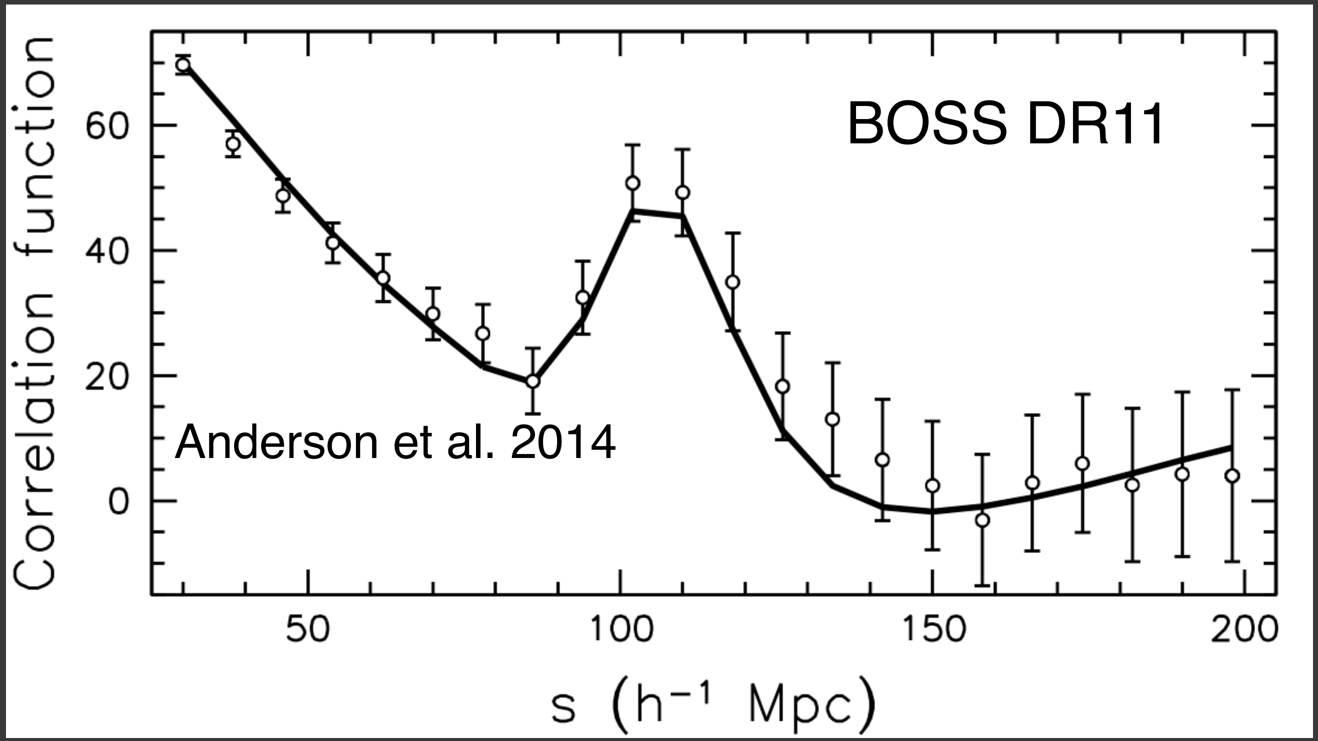


Baryon Acoustic Oscillations



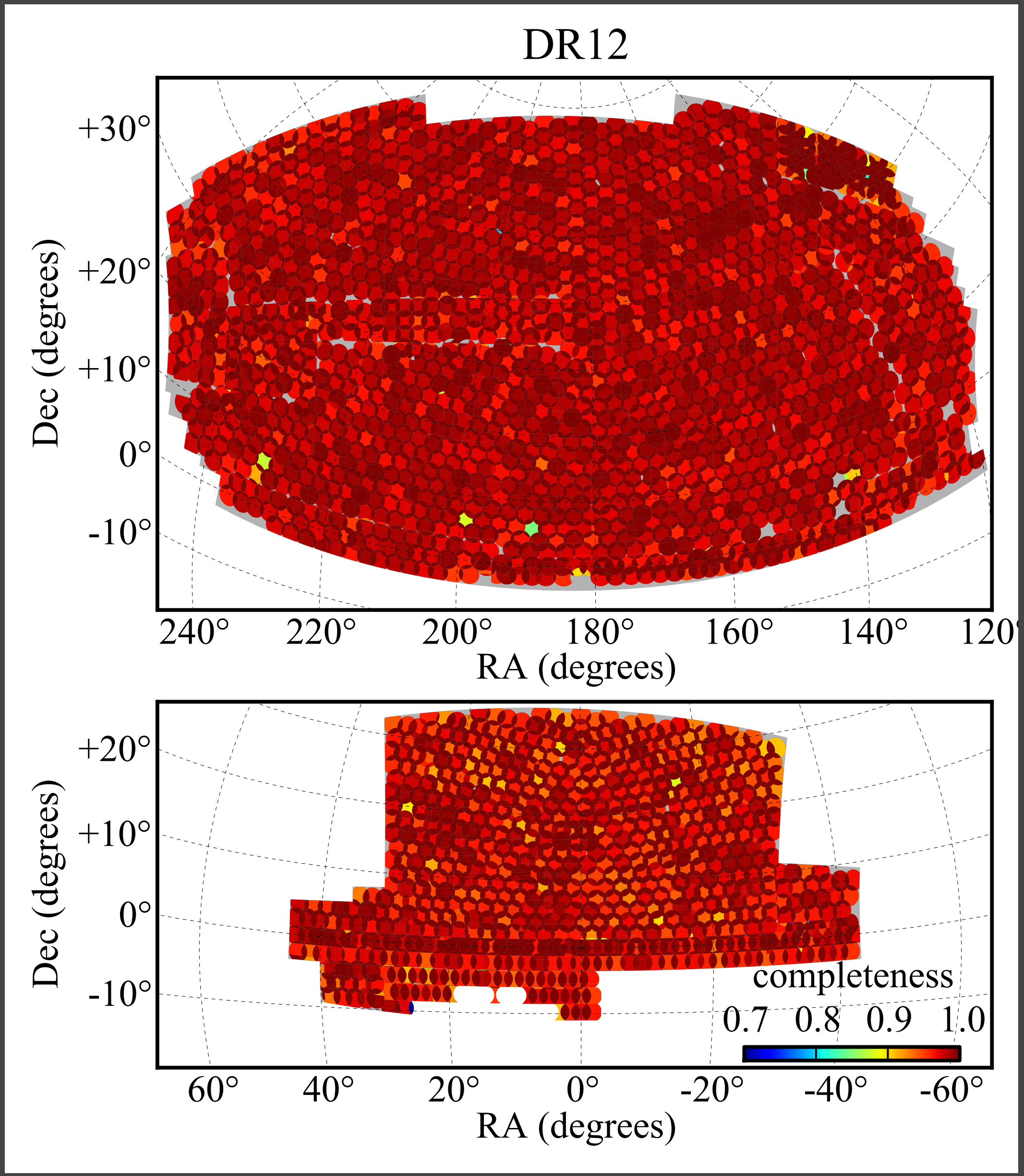
- CMB measurement gives calibrated "standard ruler" for feature found in galaxies

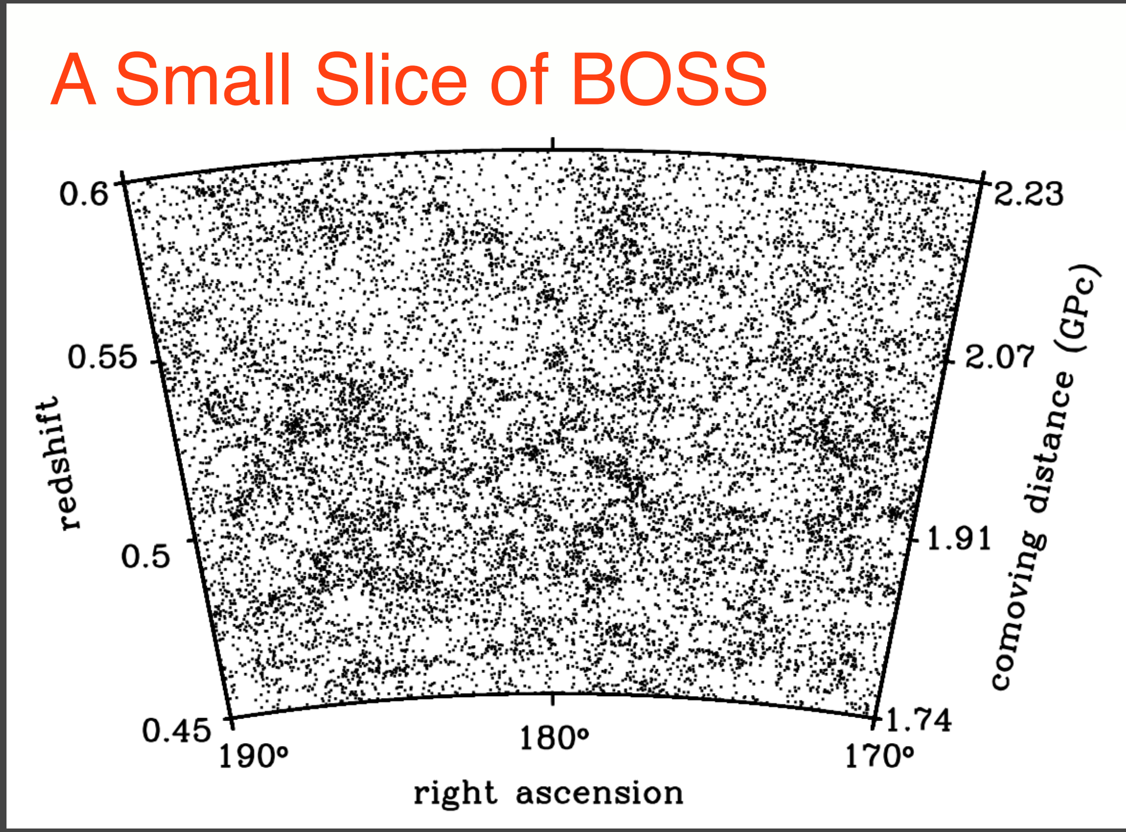




Finding BAO

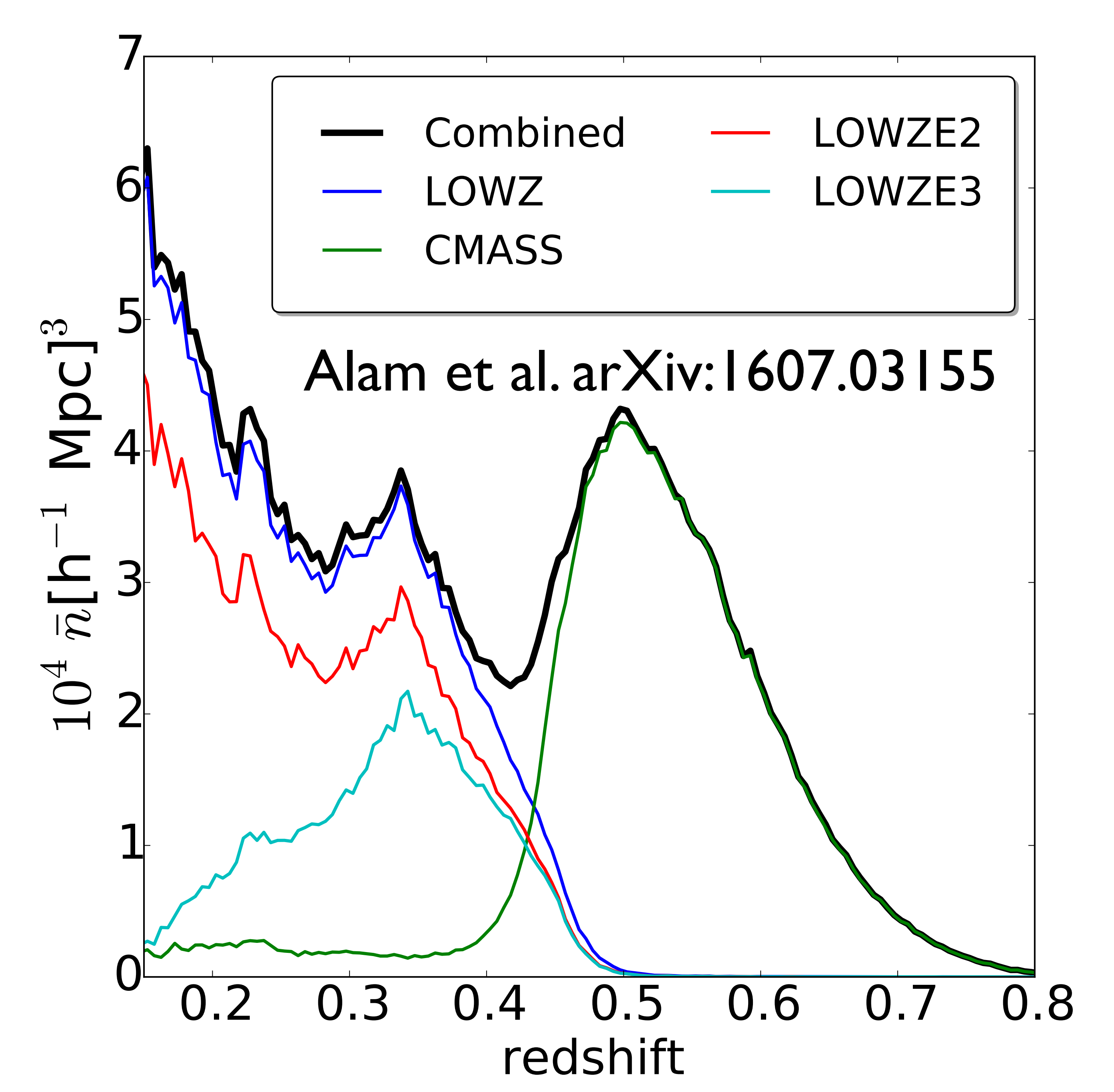
- Need to construct large, 3D maps
- (Imaging + spectroscopy)
- SDSS III Baryon Oscillation Spectroscopic Survey (BOSS):
  1.2 million galaxy redshifts, 9300 $\deg^2$, $0.2 < z < 0.75$





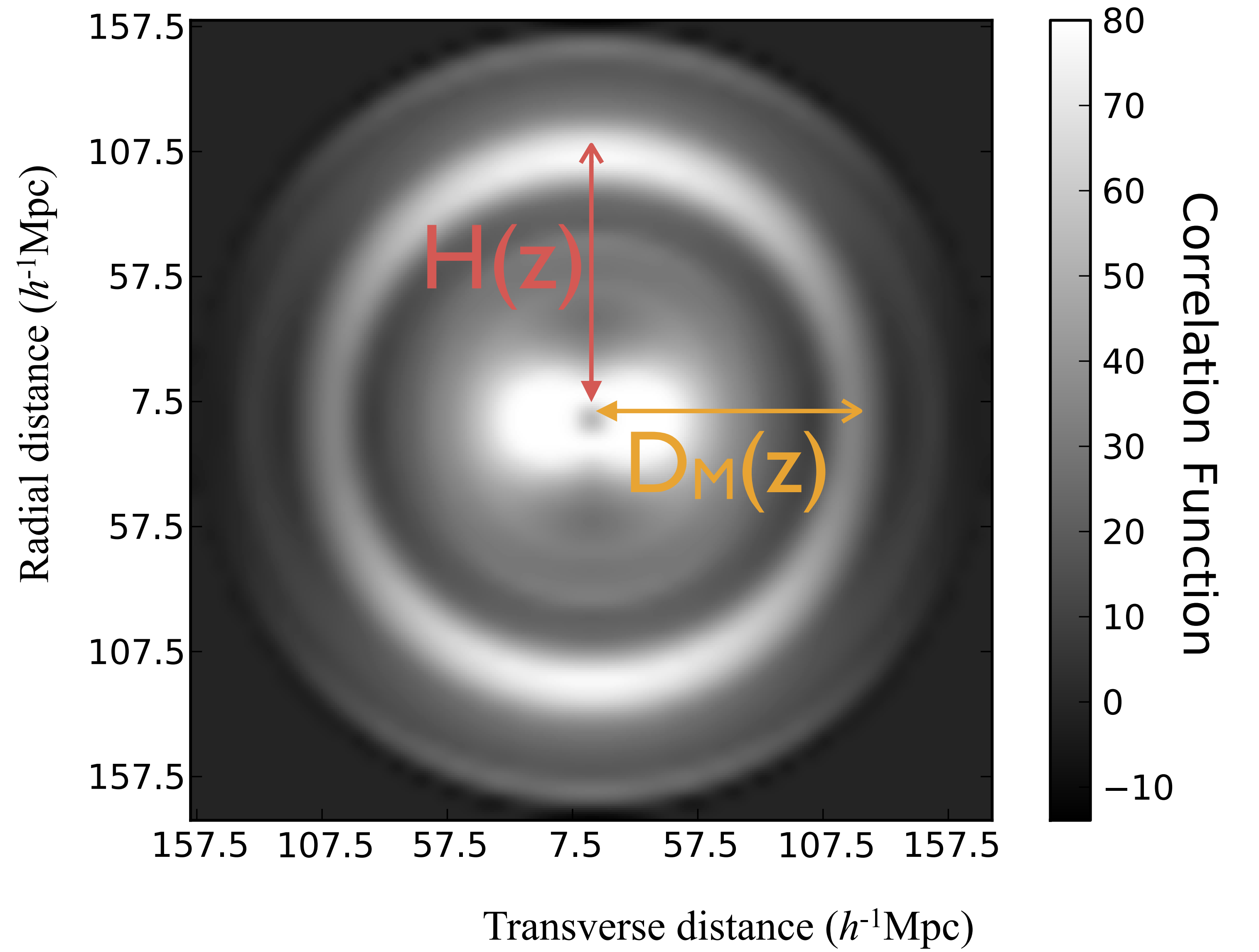
BOSS Galaxies

- 1.2 million galaxy redshifts, 9300 deg^2, $0.2 < z < 0.75$



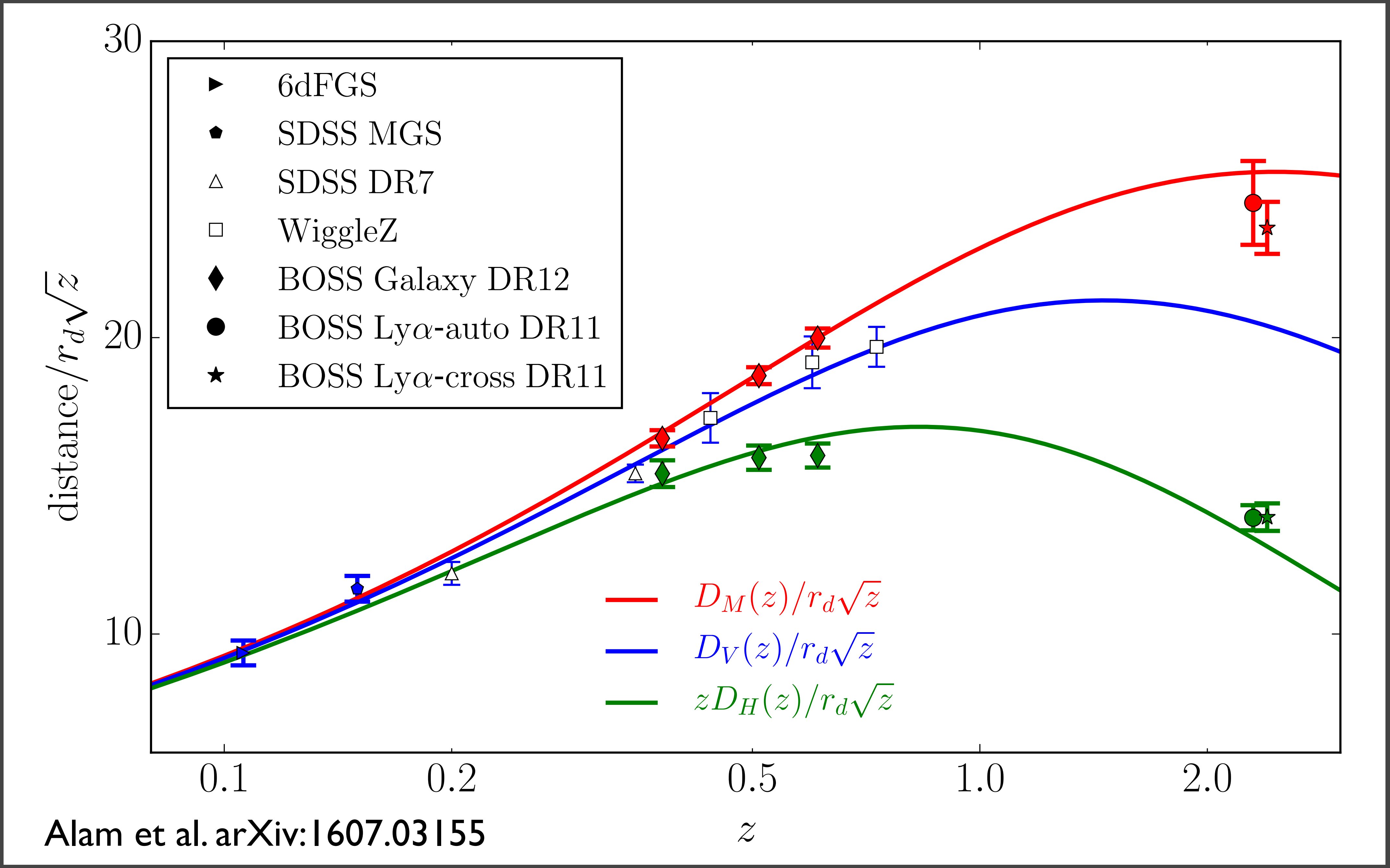
What BAO measures

- Radial clustering measures H(z)
- Transverse clustering measures $D_M(z)=(1+z)D_A(z)$
- $D_V(z) \equiv [czH^{-1}(z)D_M^2(z)]^{1/3}$; (spherical average)



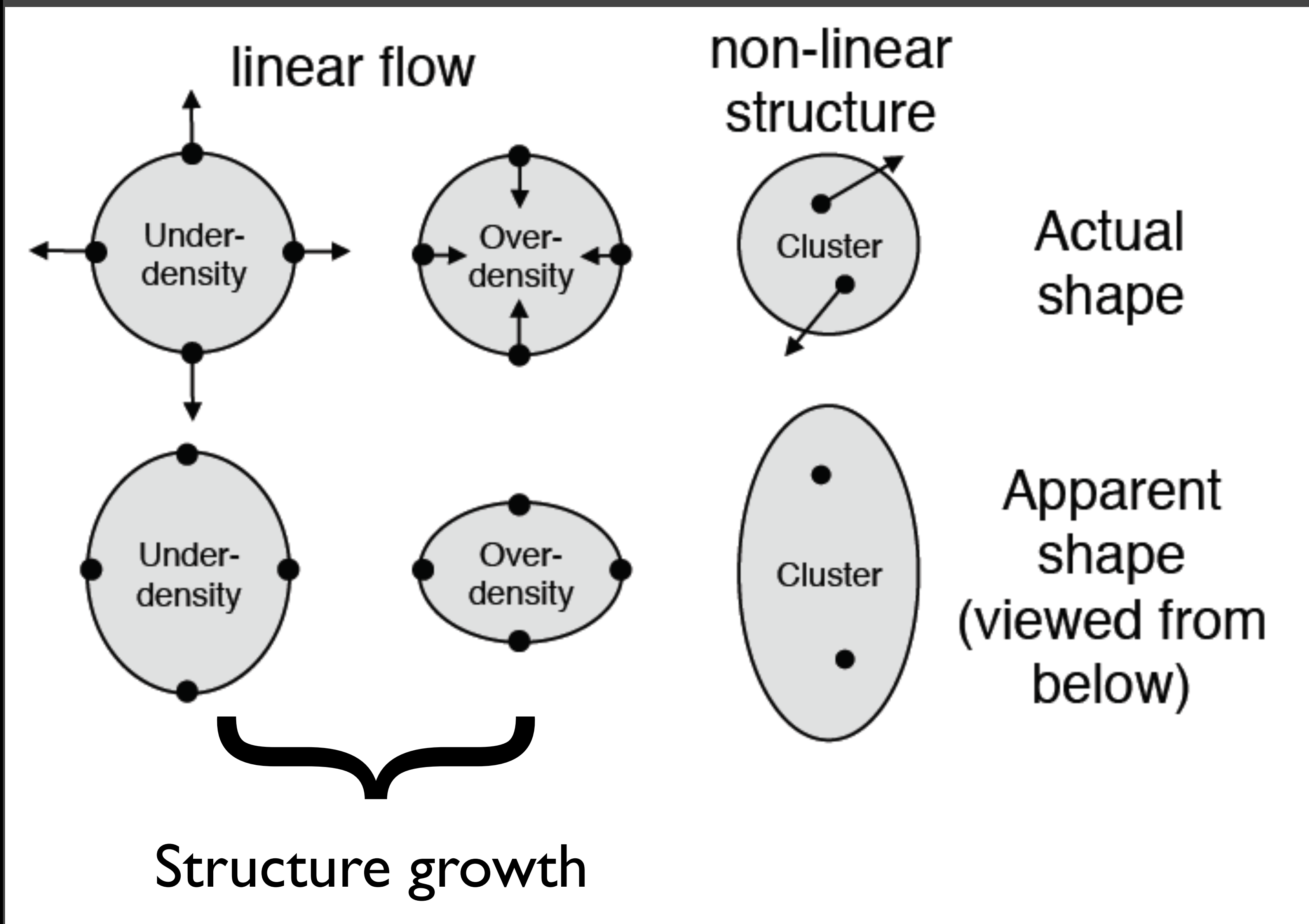
Alam et al. arXiv:1607.03155

BAO Distance Ladder

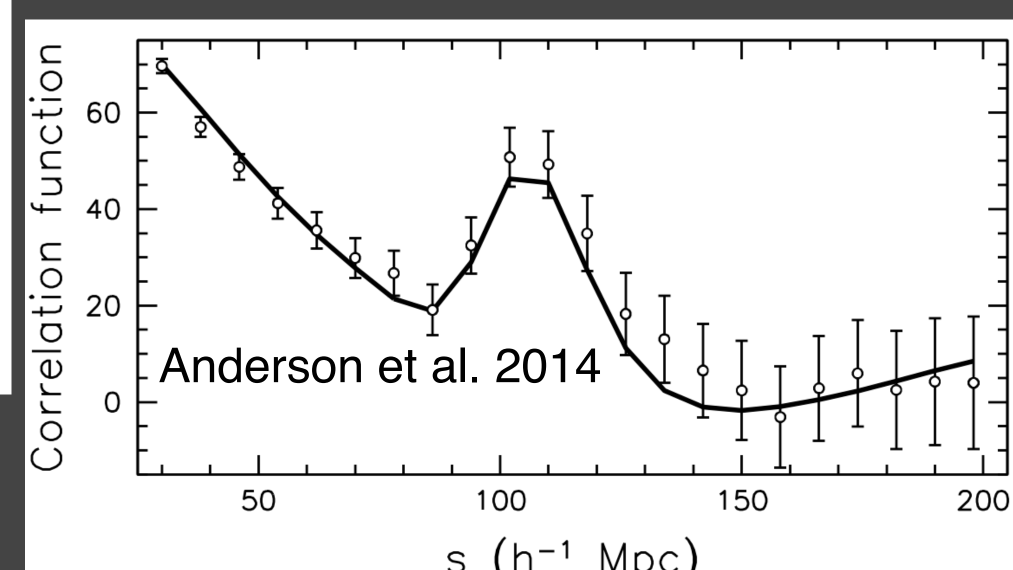


Extra Information from full shape (FS)

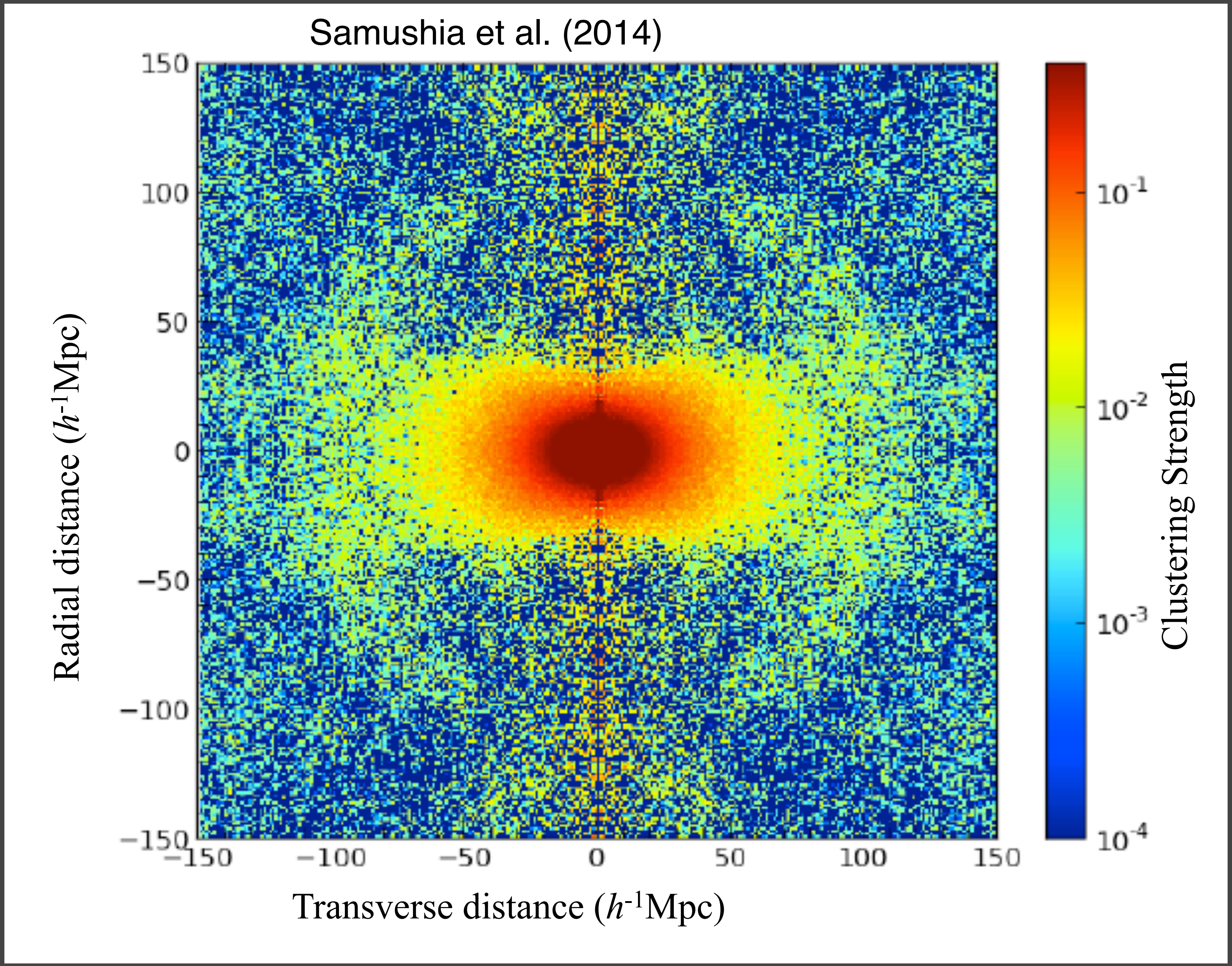
Redshift Space Distortions (RSD)



- Measuring anisotropic clustering over all scales
- +modeling RSD
- -> structure growth measurement, better measurement of warping (AP effect)

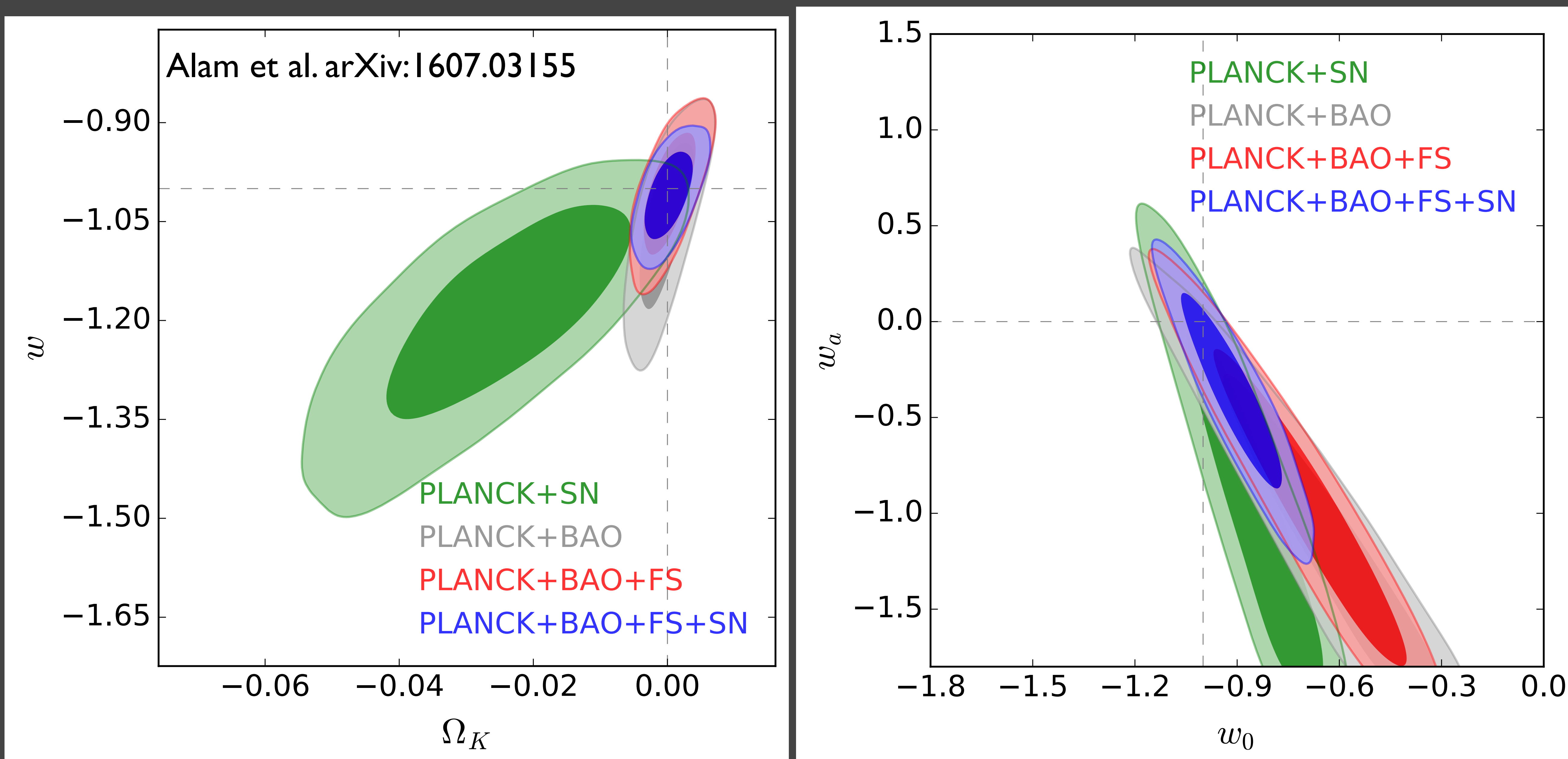


BOSS Anisotropic Clustering for FS



- Degree of anisotropy depends on rate of structure growth, *f*
  - f(a)≡dln(D)/dln(a); (a = 1/[1+z]); f is determined given GR, Ω_m(z)

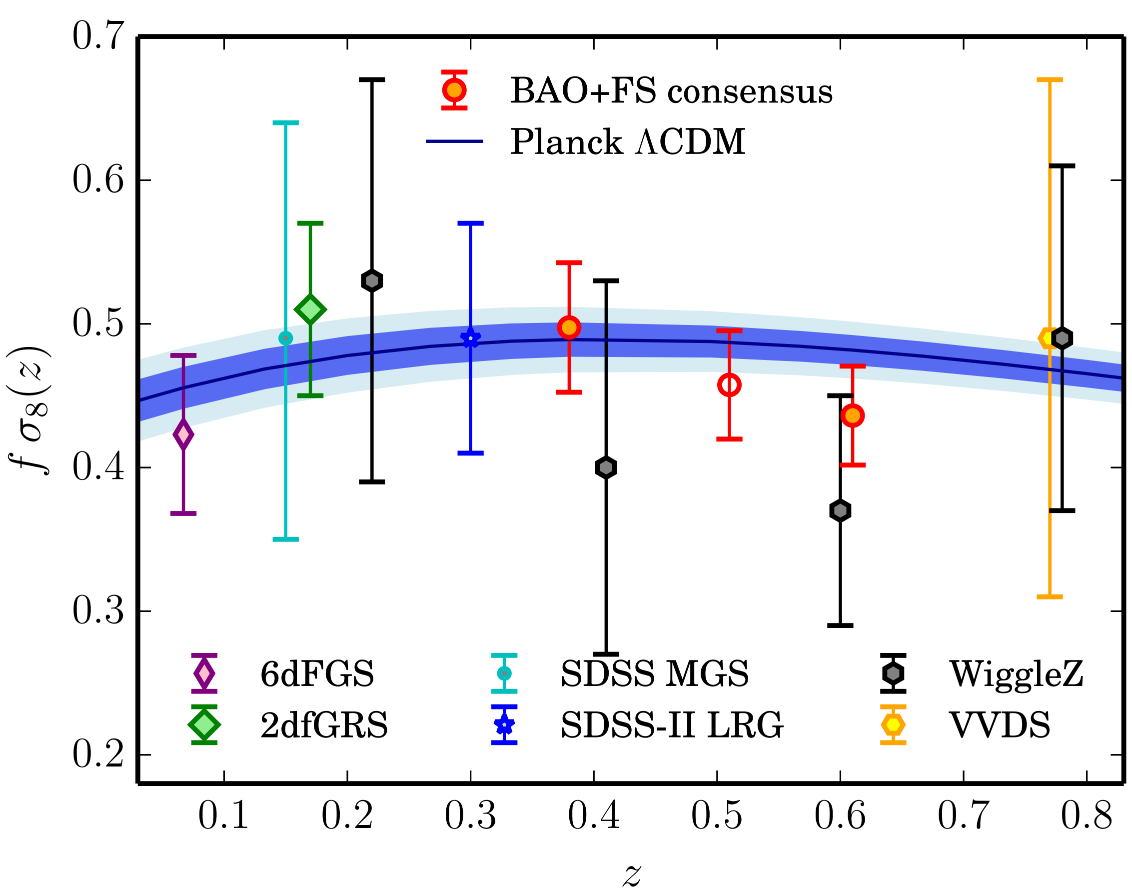
Testing Dark Energy



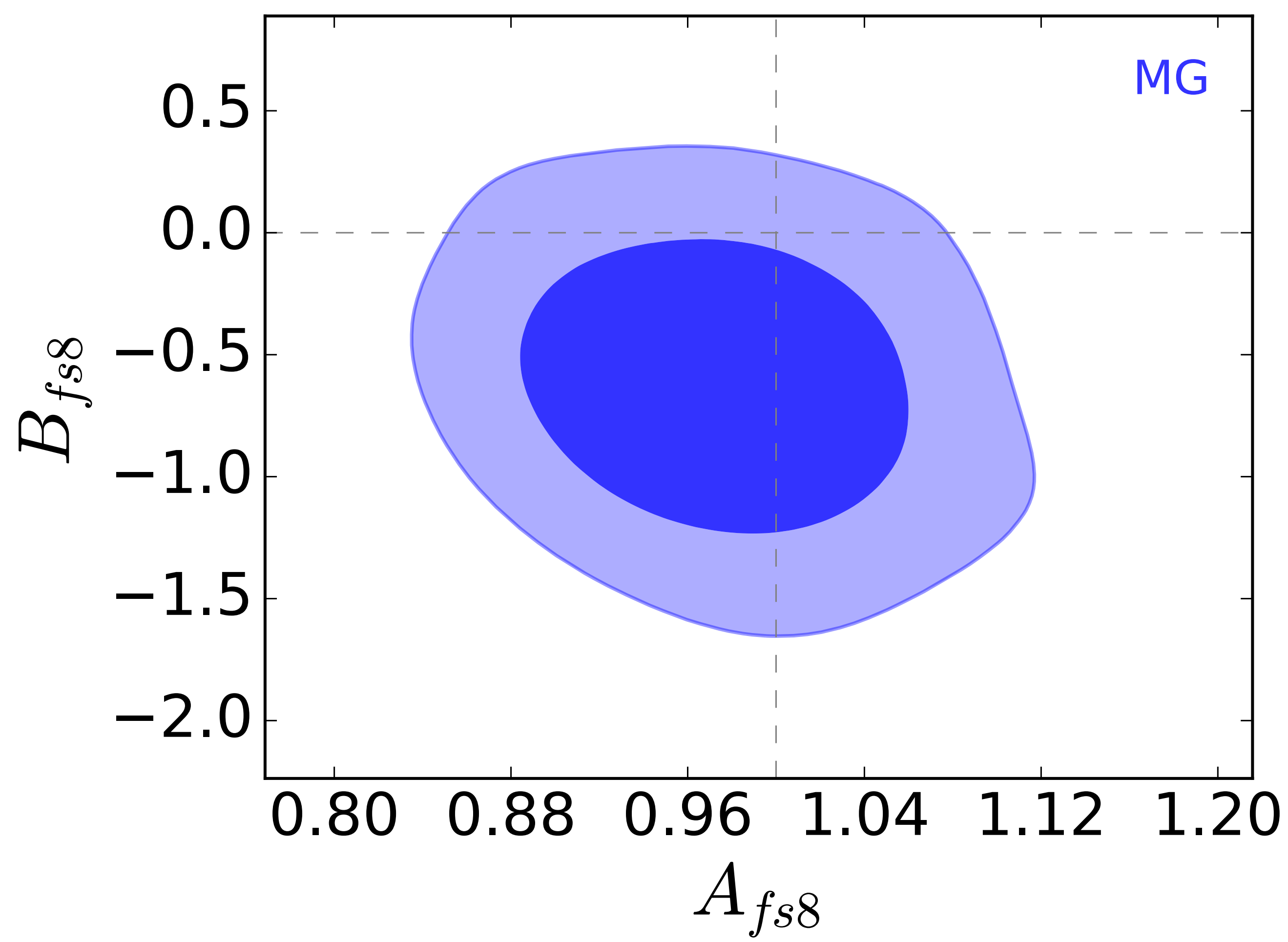
Testing General Relativity

- FS measures $f\sigma_8$, in GR $f \equiv \Omega_m^{0.557}$

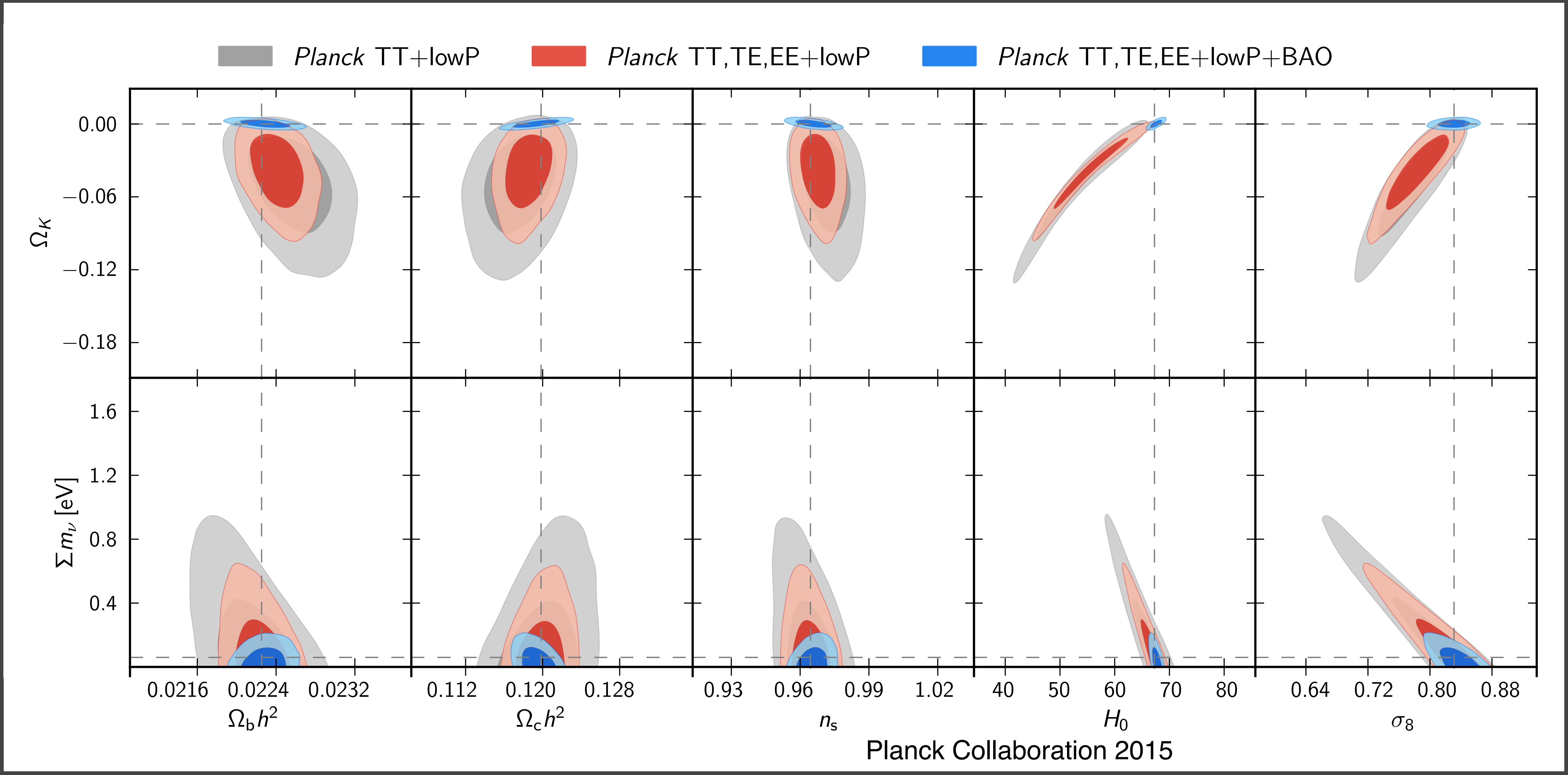
Alam et al. arXiv:1607.03155



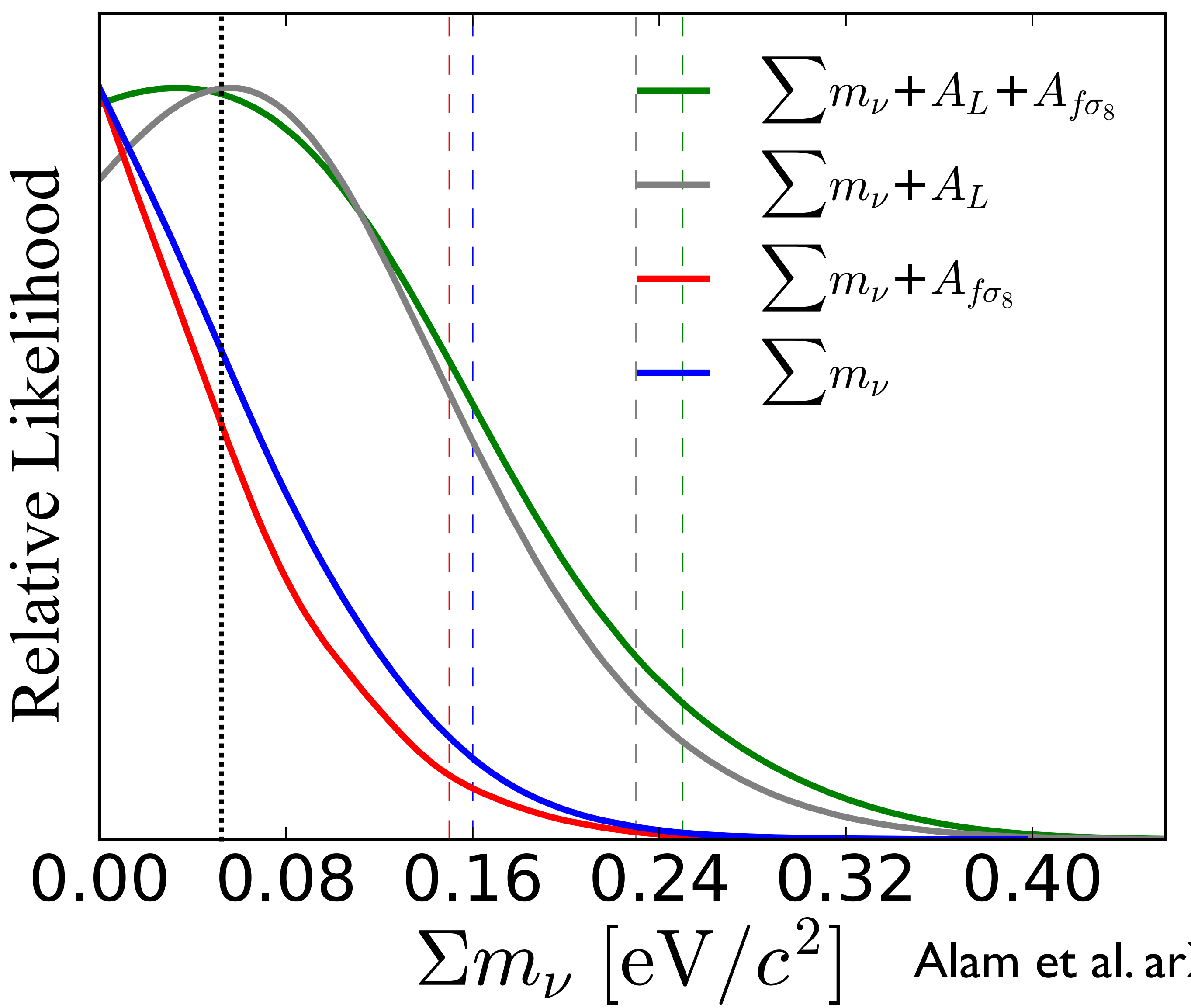
$f\sigma_8 \to f\sigma_8\,(A_{f\sigma_8} + B_{f\sigma_8}(z - z_p))$



Neutrino mass constraints: CMB+BAO



Neutrino mass constraints: CMB+BAO, BOSS DR12

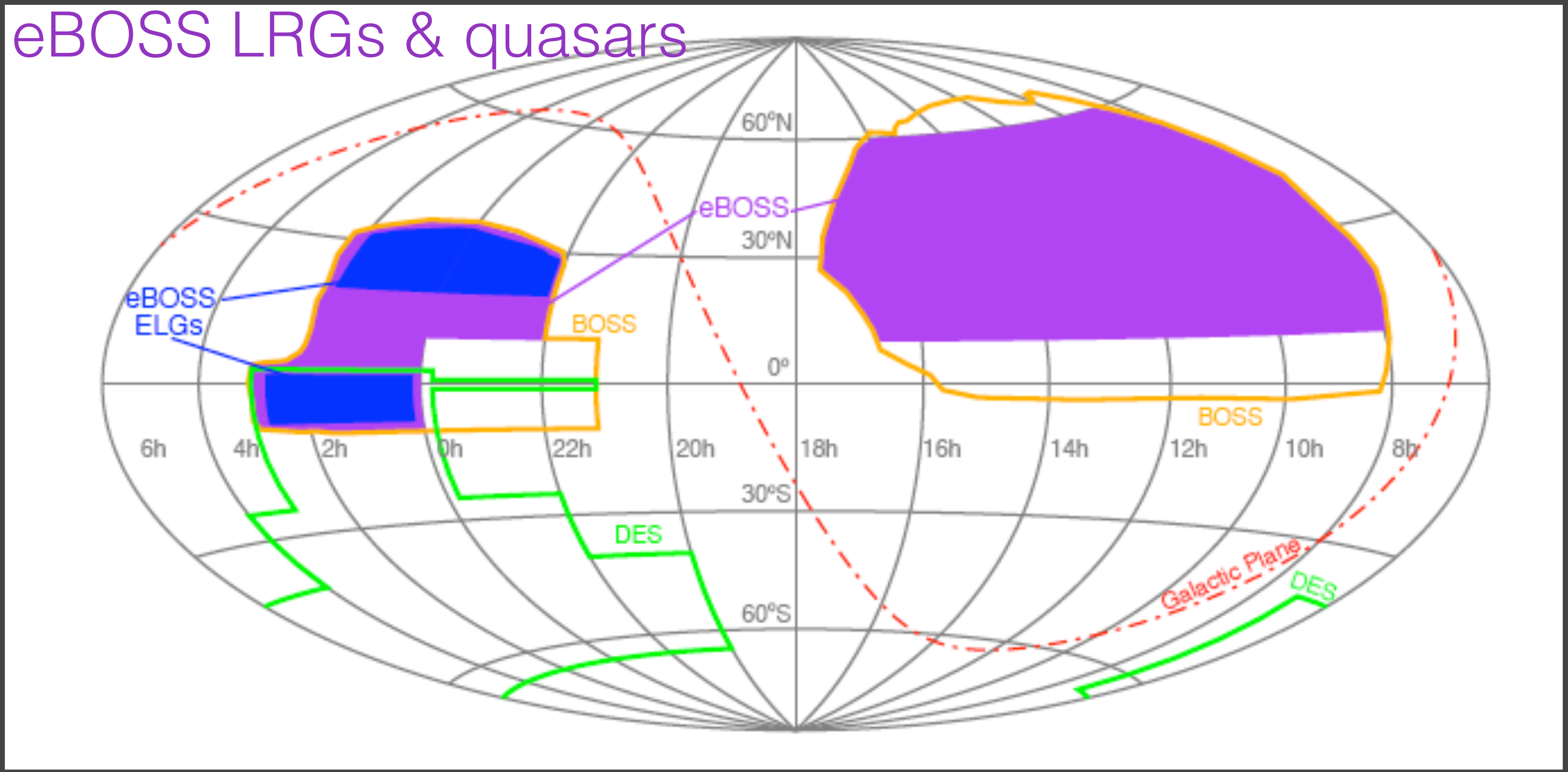


Alam et al. arXiv:1607.03155

'+' denotes parameter added to marginalize information

eBOSS

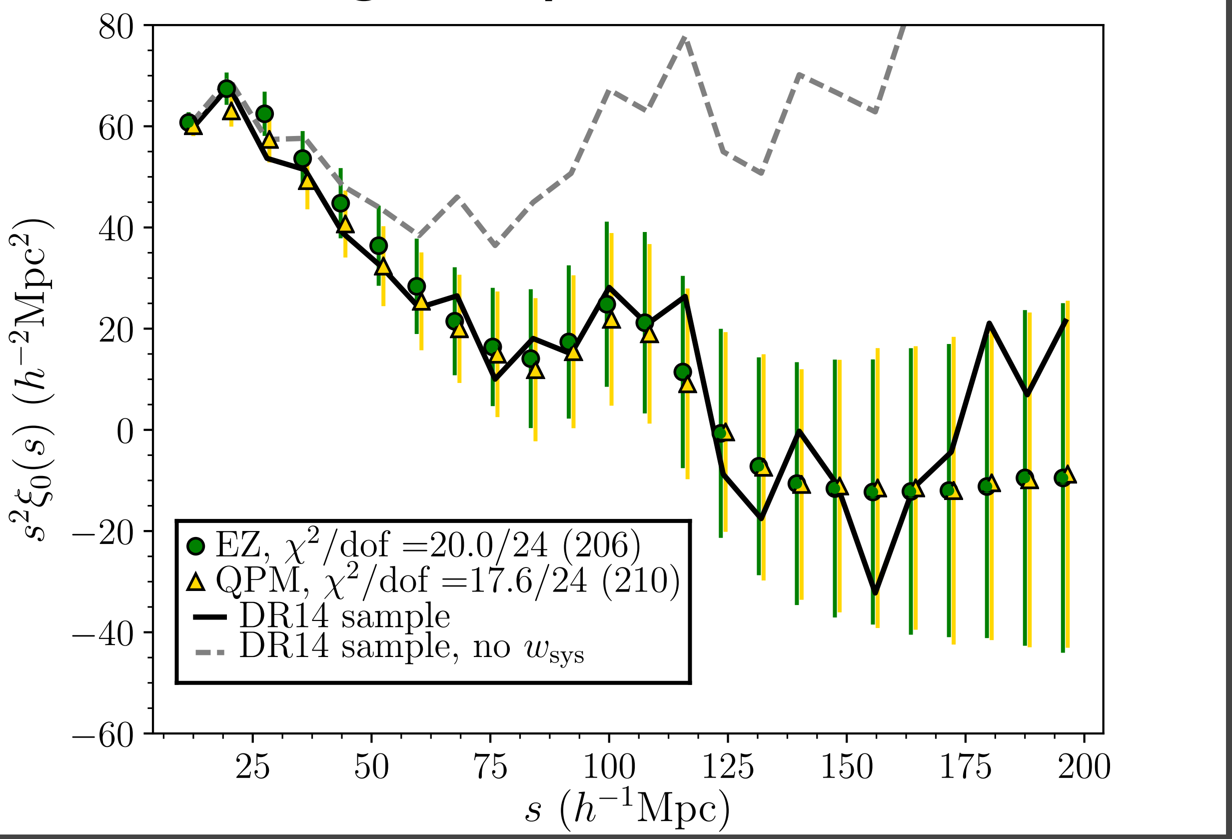
- Use SDSS telescope/spectrograph to extend BAO to $z > 0.6$
- 7500 deg^2 in SDSS imaging footprint
- Supplement SDSS with infrared data from WISE
- 3×10^5 LRGs $0.6 < z < 1.0$
- 2×10^5 ELGs $0.7 < z < 1.1$
- 6×10^5 quasars $0.8 < z < 2.2$



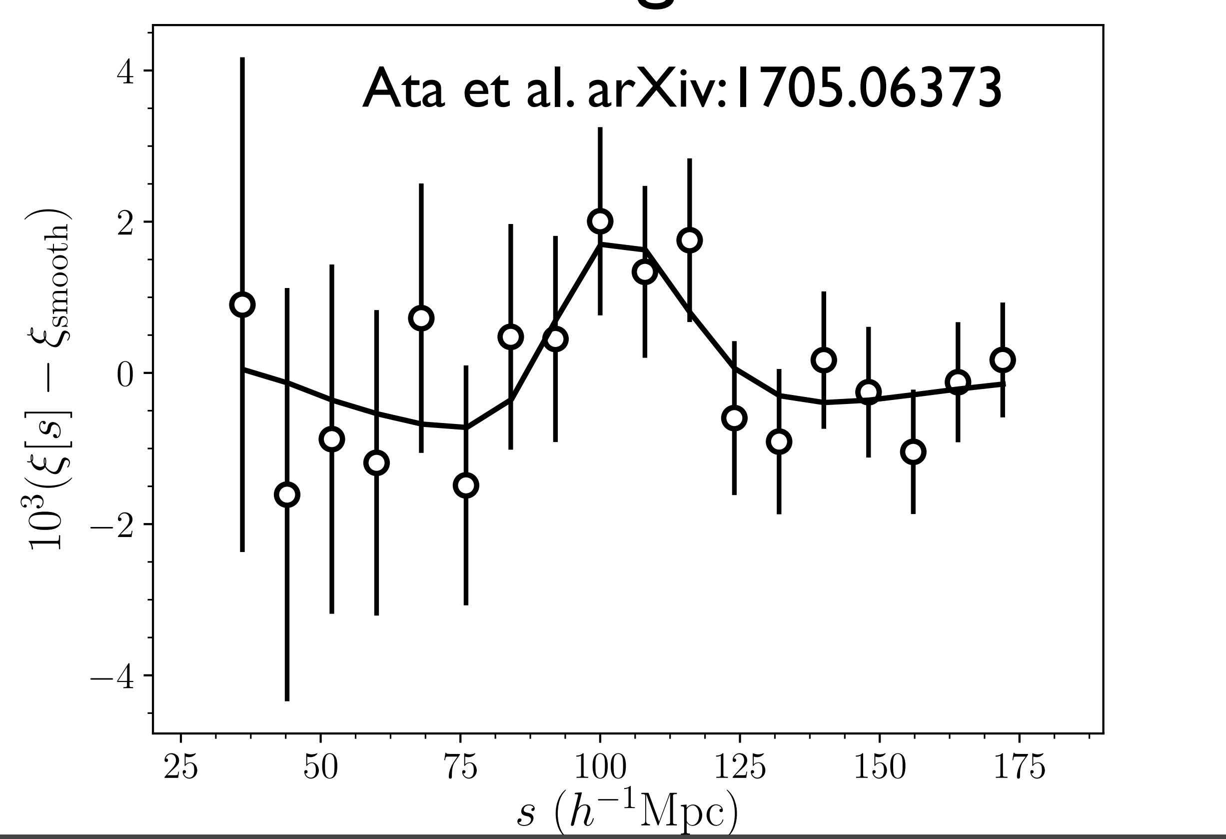
First eBOSS BAO measurement

- SDSS IV extended BOSS (eBOSS) DR14 quasar sample
- 150,000 quasars with 0.8 < z < 2.2
- 4.4% distance measurement to z=1.5

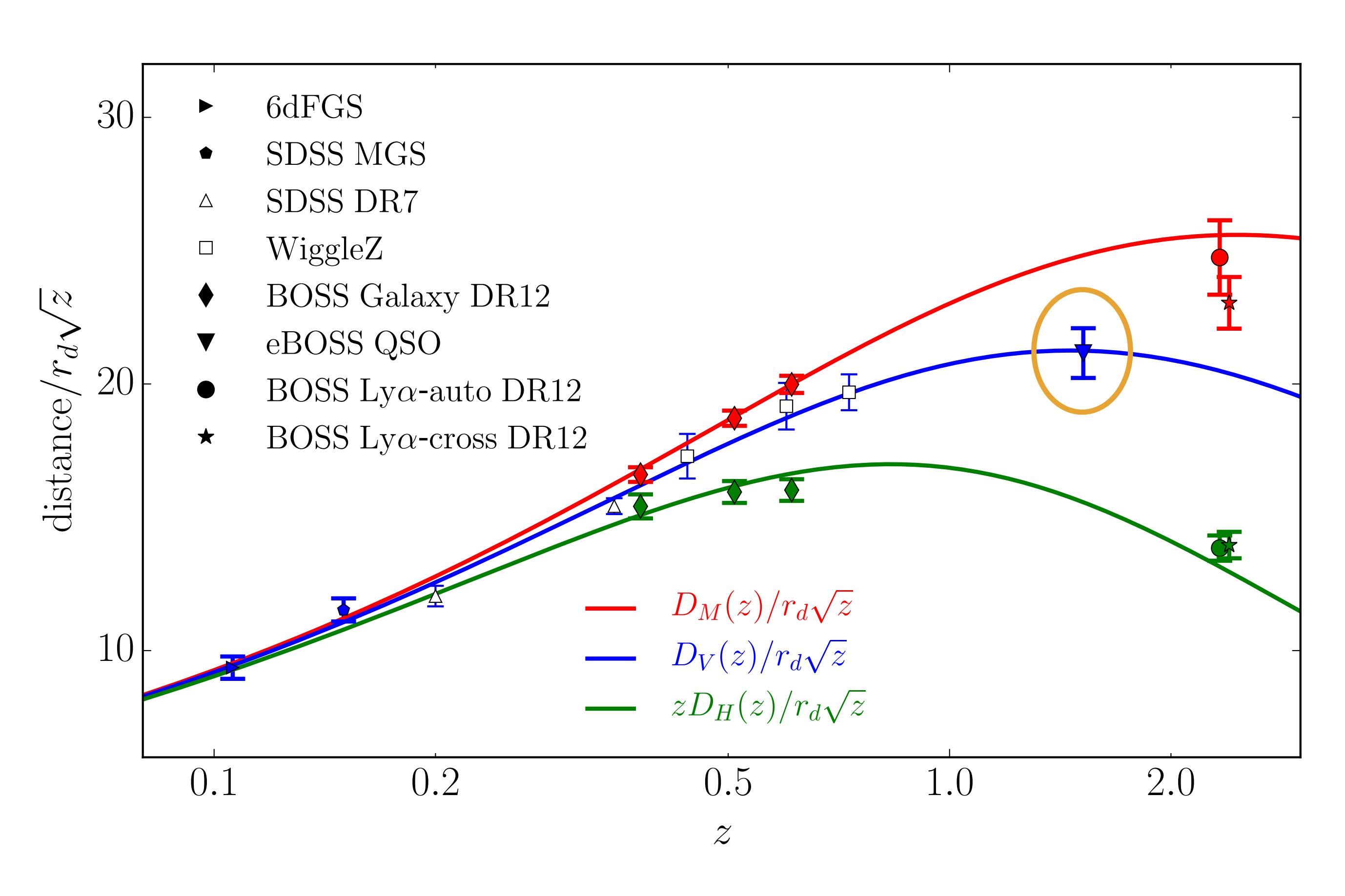
Clustering, compared to simulations

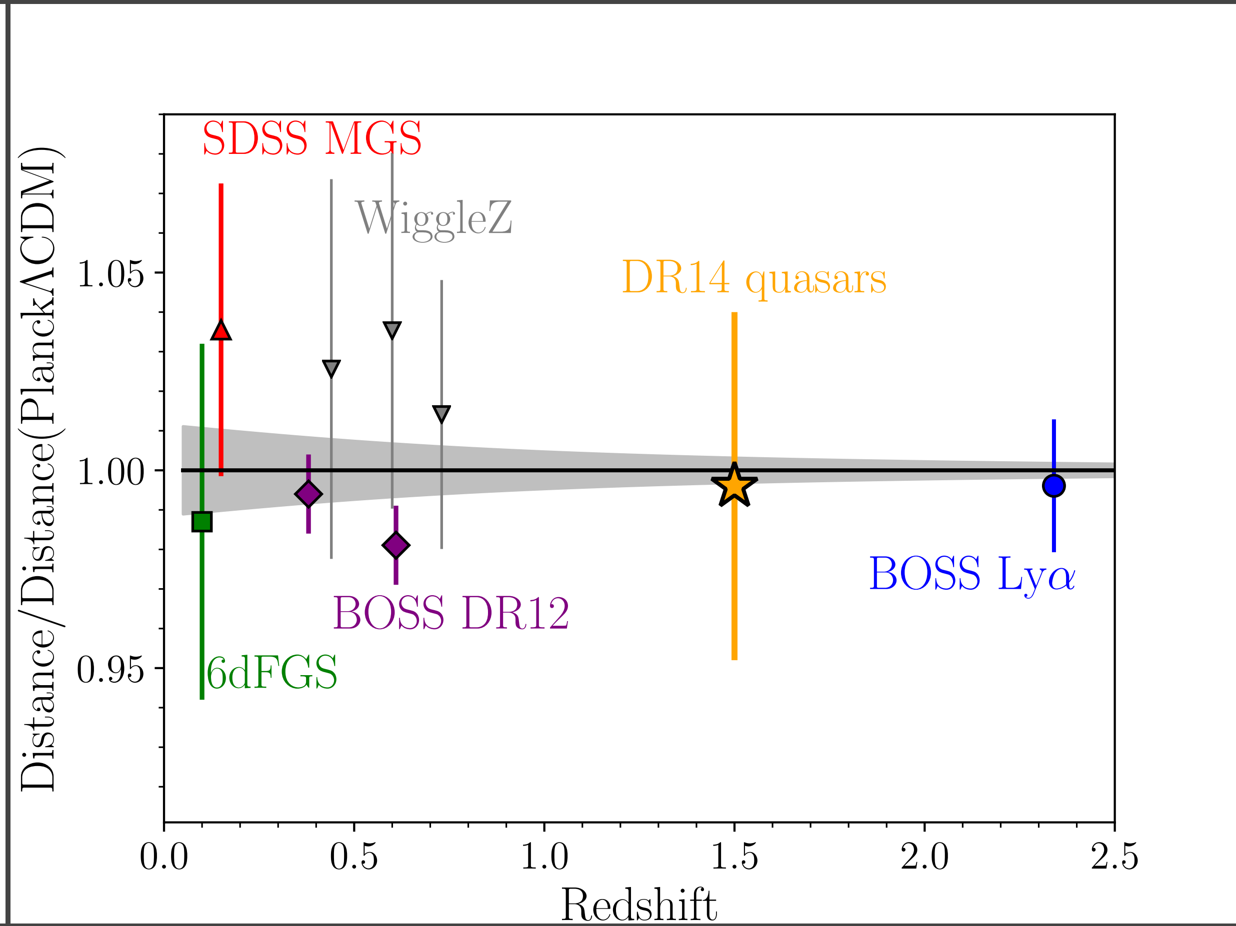


Isolating BAO



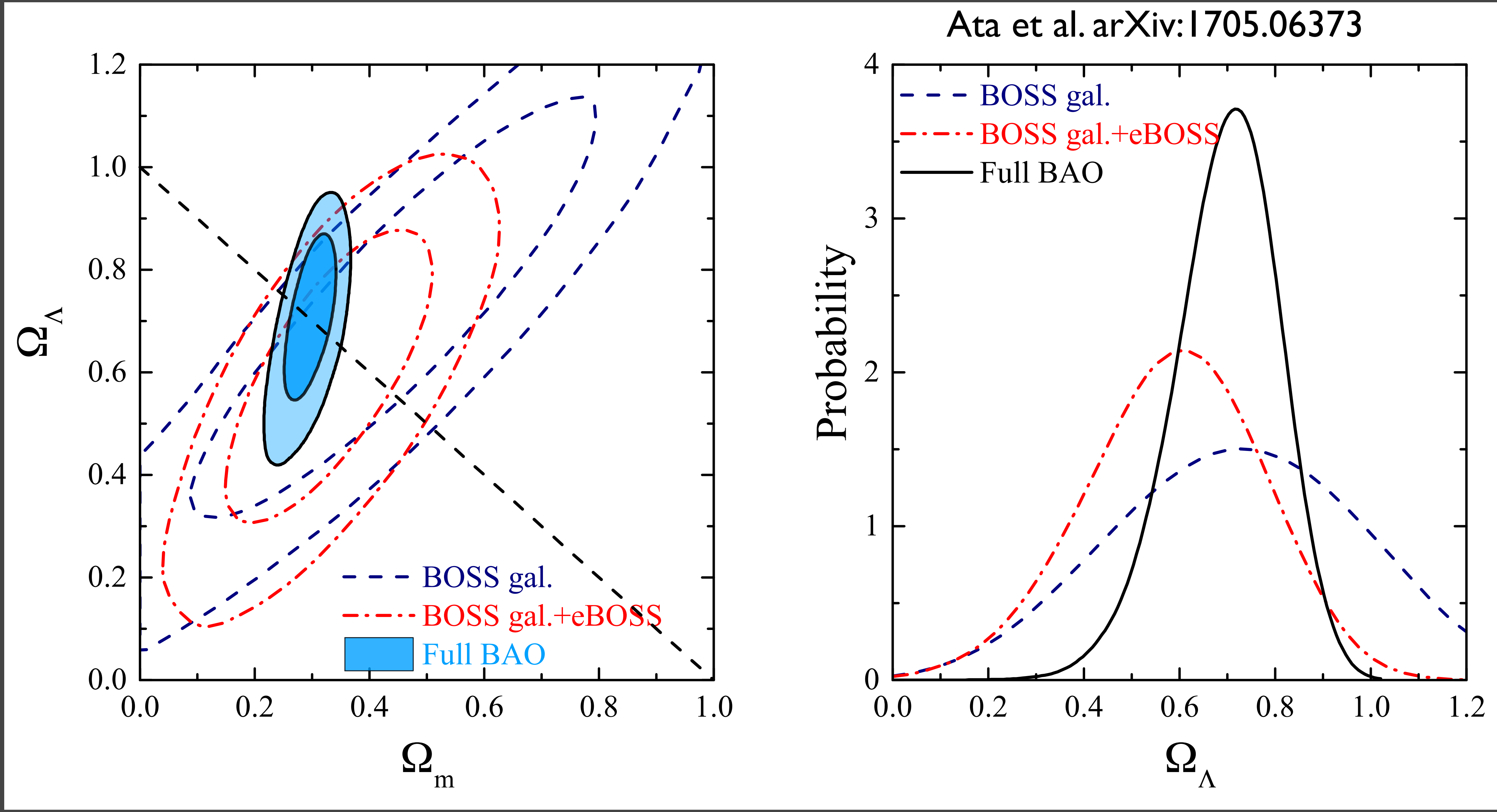
Updated BAO Distance Ladder





Testing Dark Energy with only BAO

- Treat BAO as *uncalibrated* standard ruler
- BOSS galaxies + eBOSS quasars > 3σ detection of DE
- All BAO, 6.5σ detection!

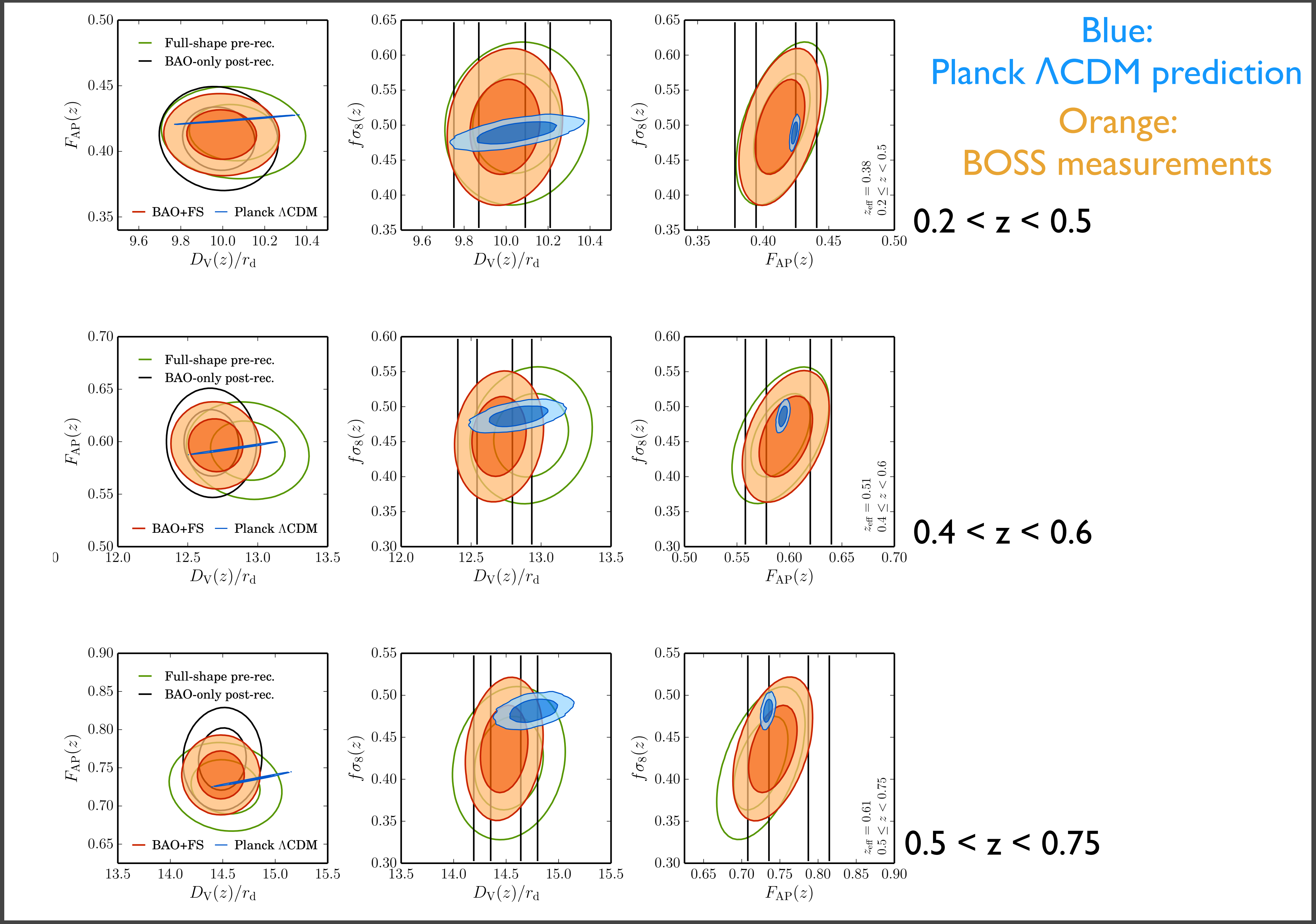


Conclusions

- BOSS + eBOSS provide powerful tests of dark energy
  - Consistent with ΛCDM
- Look for more eBOSS results coming soon
- Sets stage for DESI, should shrink contours by ~factor of 10

What BOSS measures: Combined

- Three BAO analyses and four full-shape analyses have been combined
- 9x9 likelihood: 3 redshift bins/3 parameters

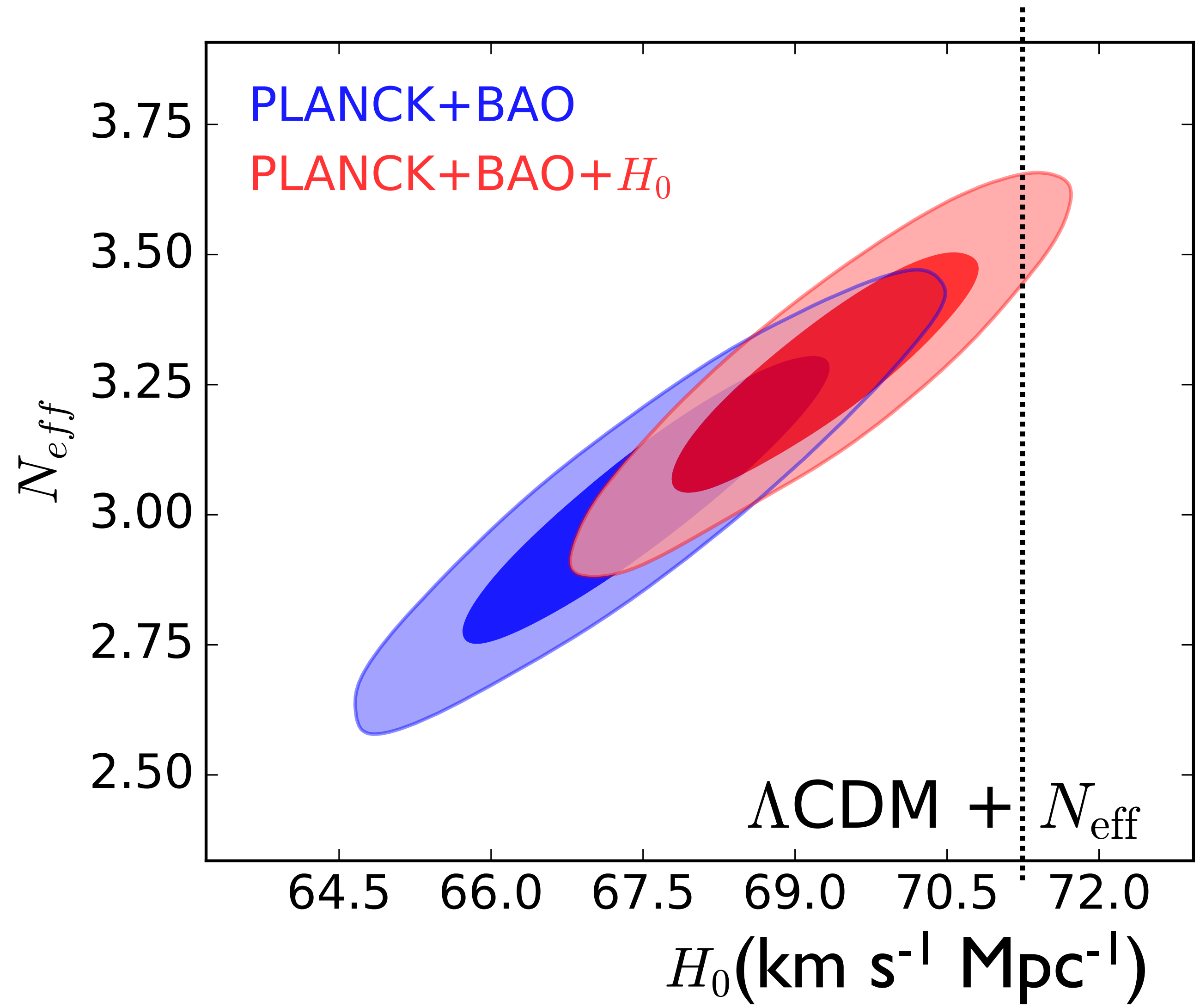


Tension with direct H_0 measurements

Planck+BOSS ΛCDM:
H_0 =67.6±0.4 km s^{-1} Mpc^{-1}

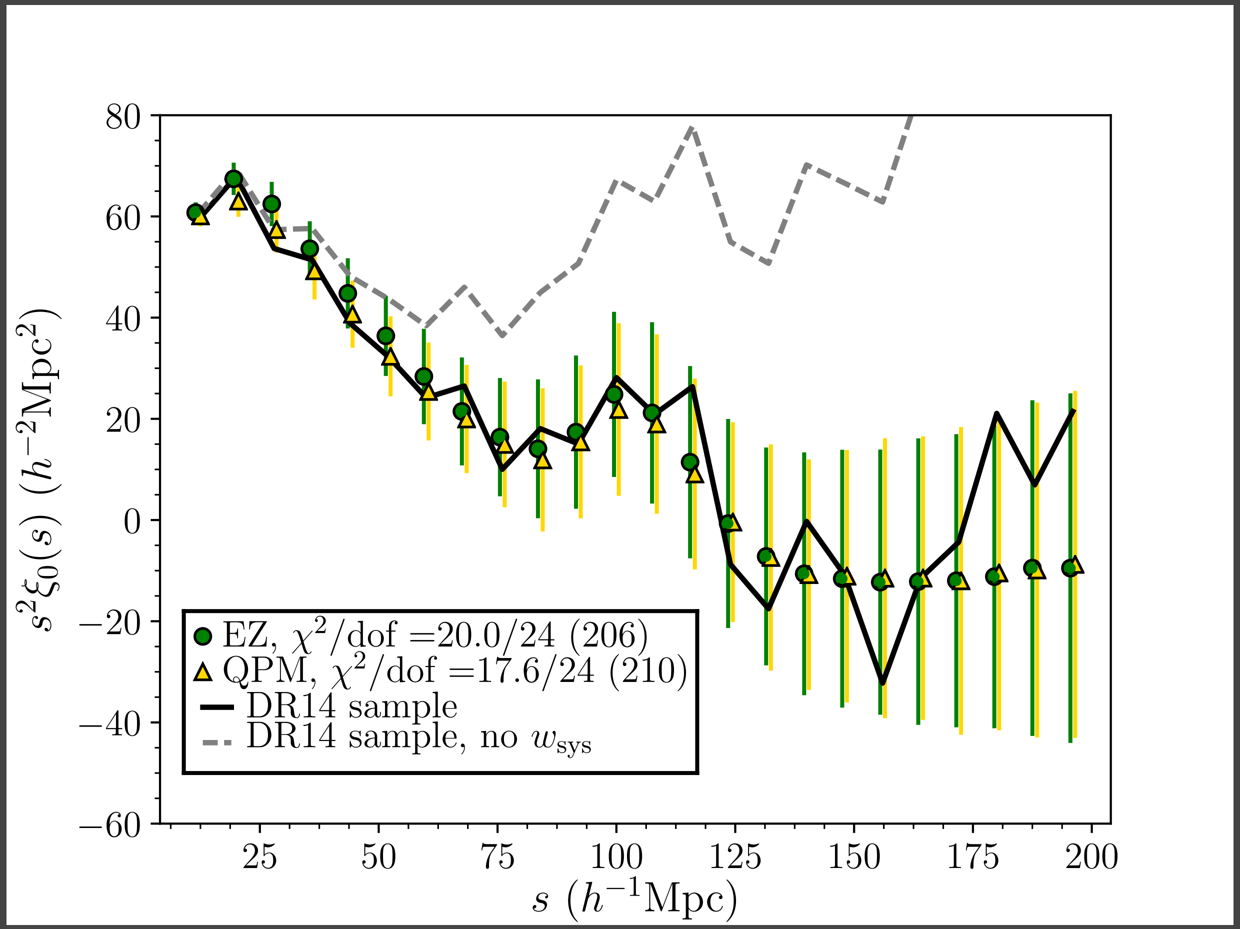
Riess et al. (2016):
H_0 =73.0±1.8 km s^{-1} Mpc^{-1}

2.9σ tension!

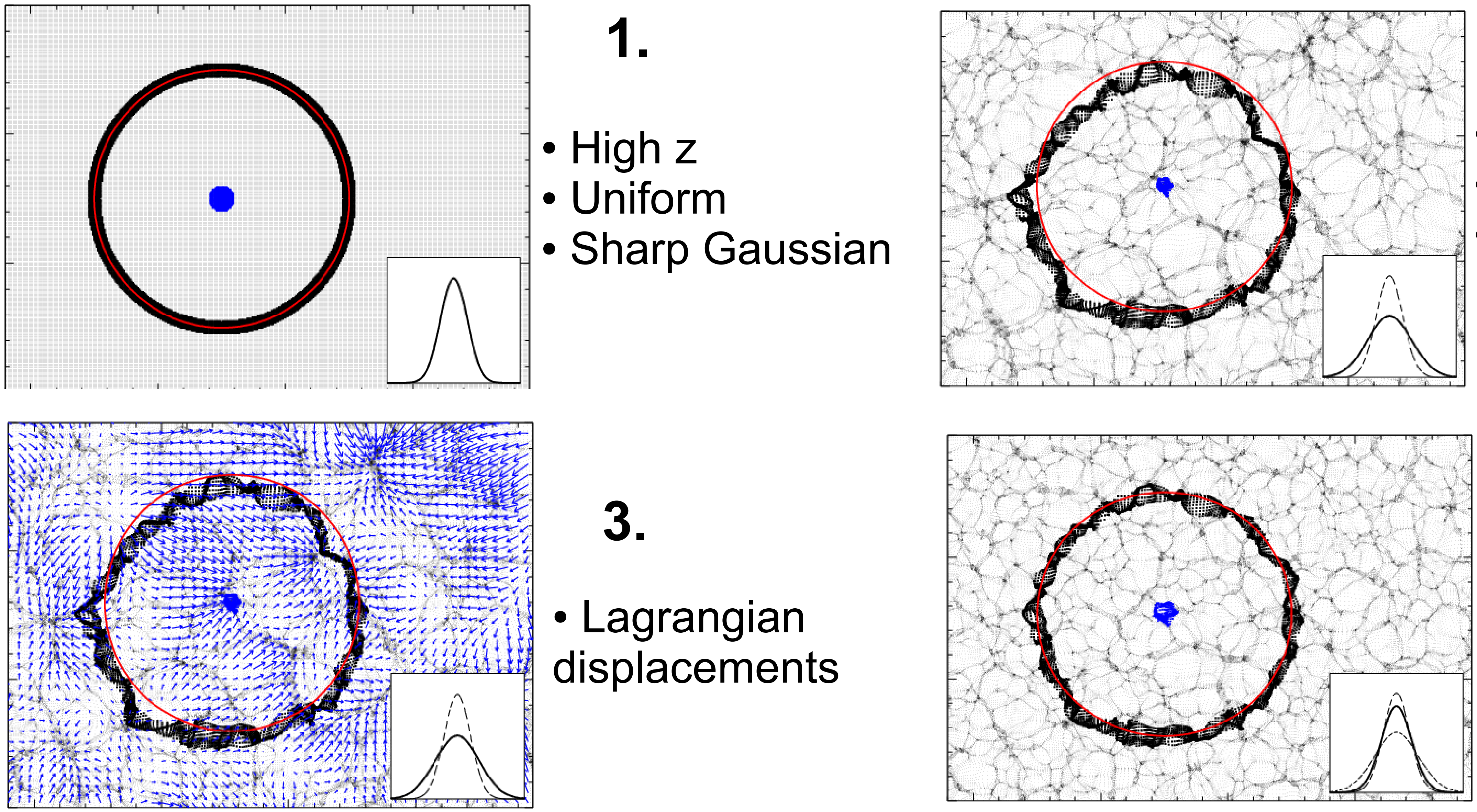


BAO is Robust!

- Observational systematics have 13σ effect on clustering
- No effect on BAO!
- Similar results found for BOSS (Ross et al. 2012, 2017)
- Theoretical systematics (e.g., galaxy bias) < 0.5%



Reconstruction



1.

- High z
- Uniform
- Sharp Gaussian

2.

- Evolved to z=0
- Ring distorted
- Gaussian wider

3.

- Lagrangian displacements

4.

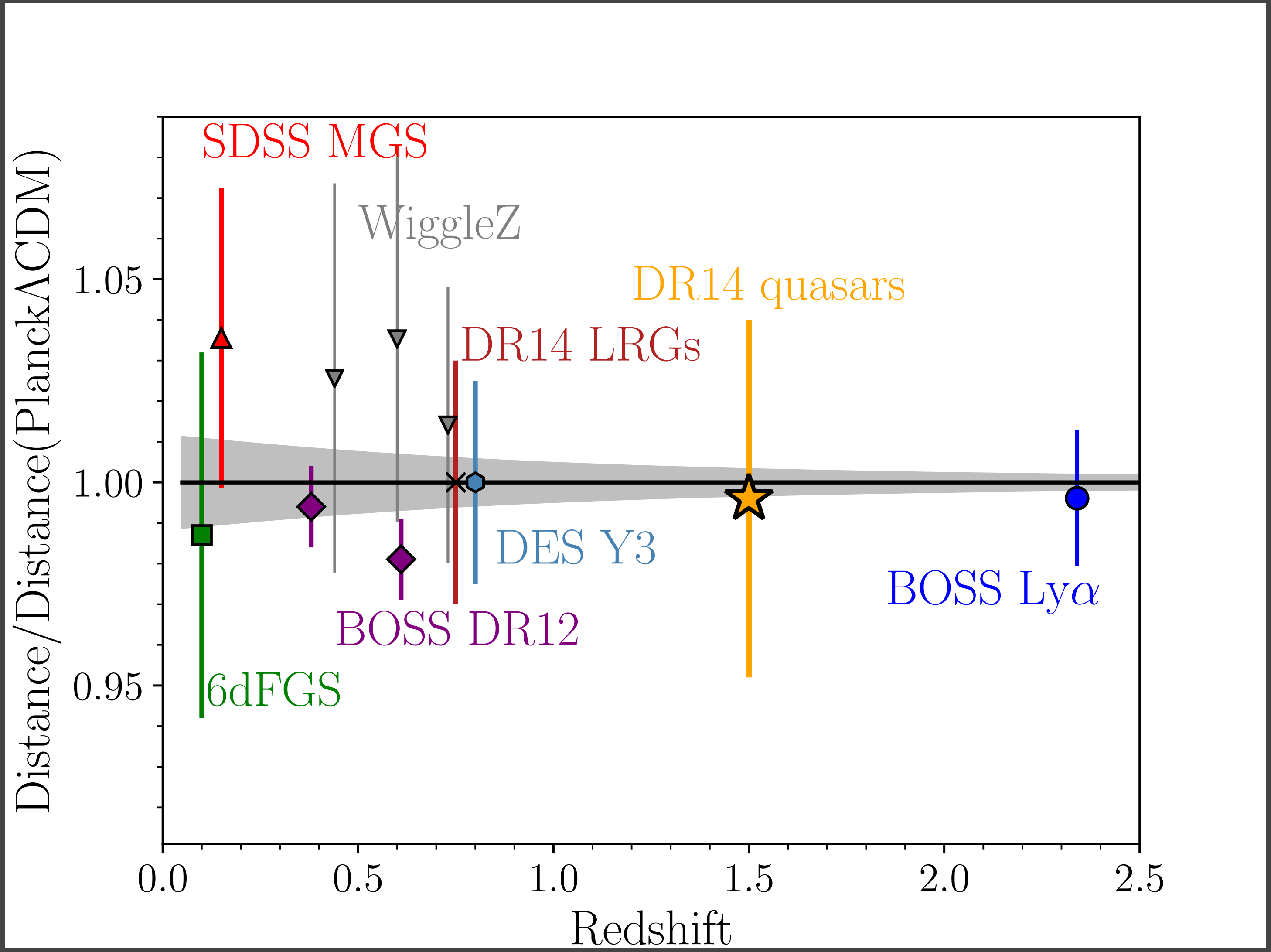
- Particles moved back.
- Gaussian peak sharper

Figures from Padmanabhan et al. 2012

Removes RSD effects

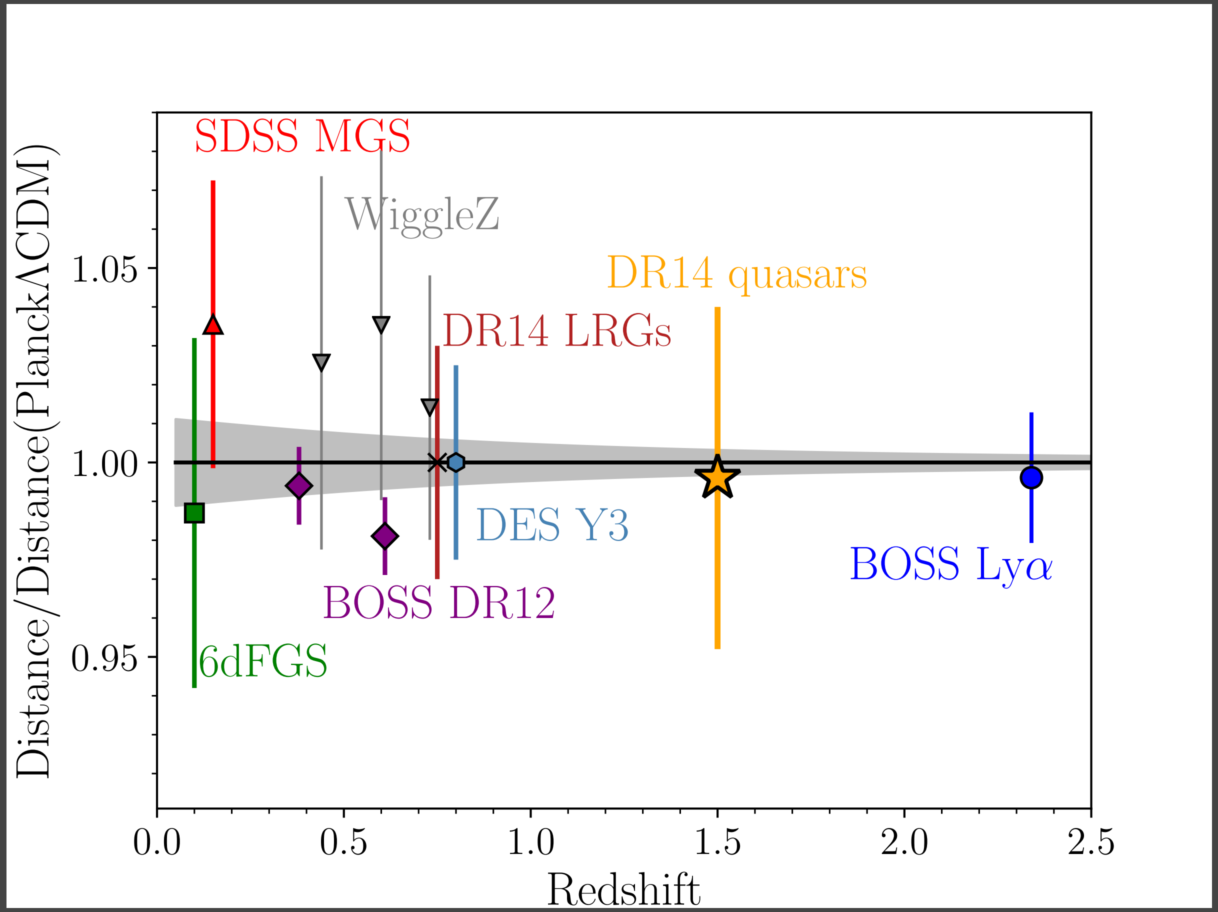
Coming Soon

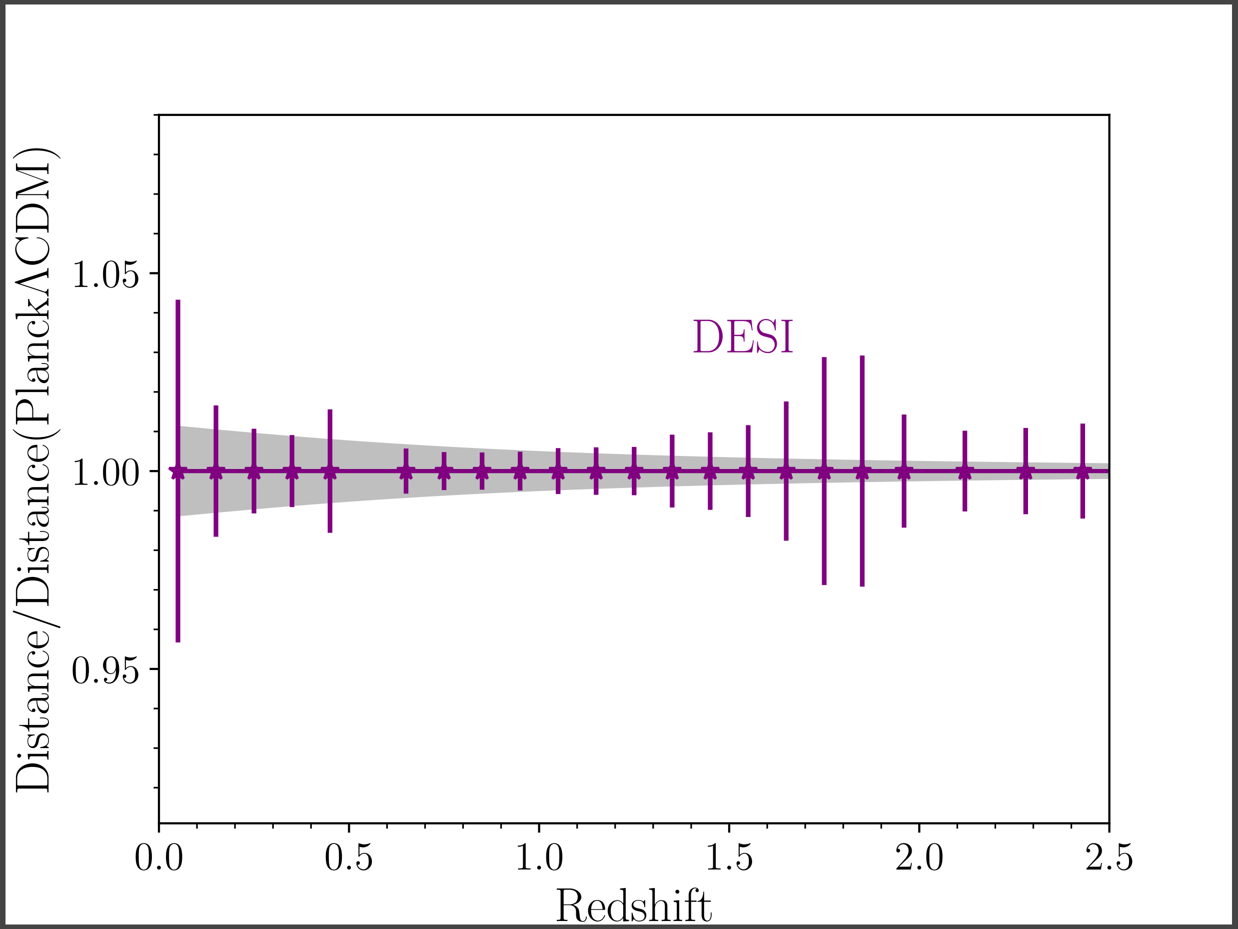
- DR14 LRG data and DES Y3 data already observed



DESI

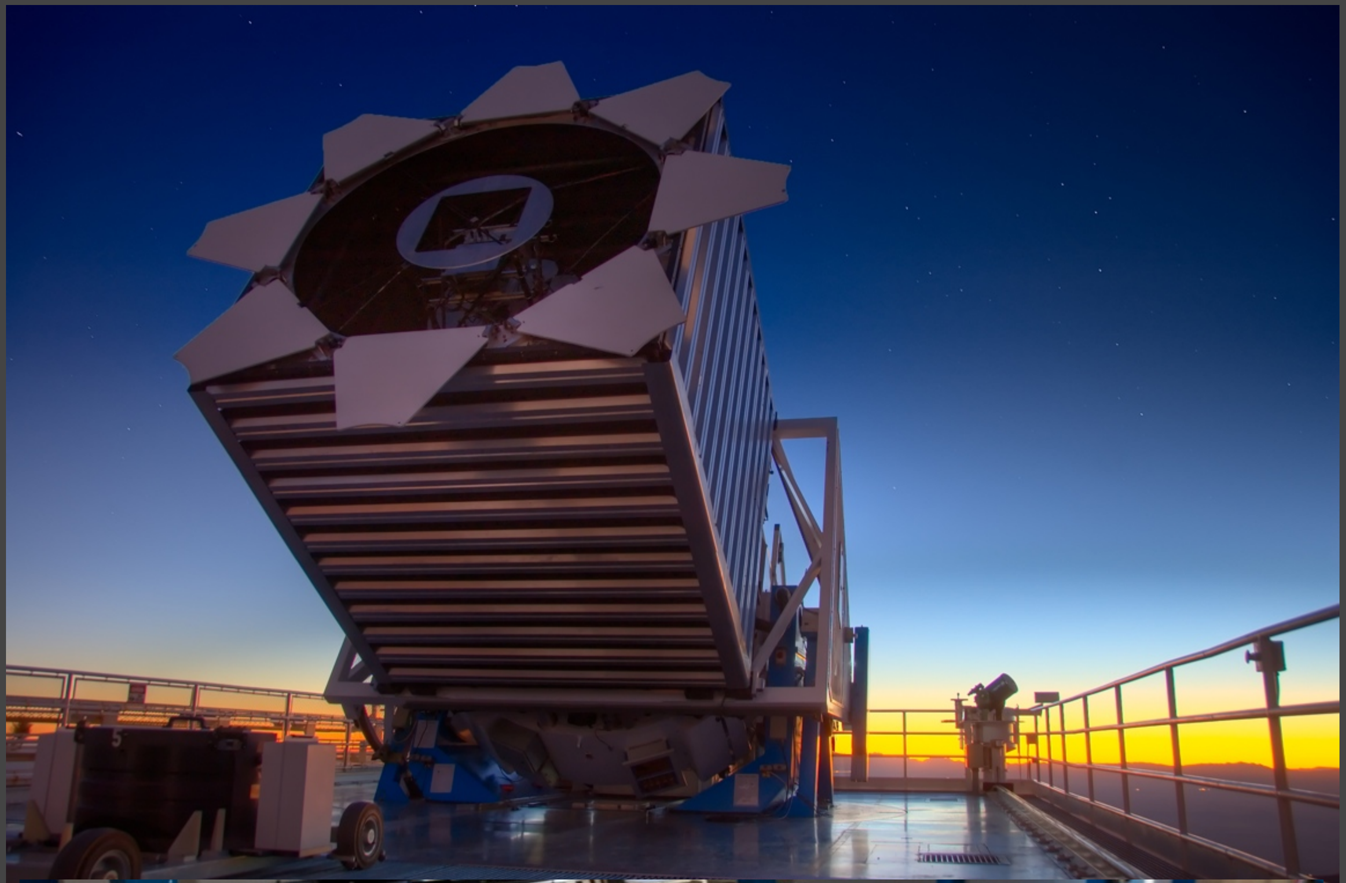
- Dark Energy Spectroscopic Instrument being built
- Goes on 4 meter Mayall telescope in 2019
- Basically, an order of magnitude improvement in BAO constraining power





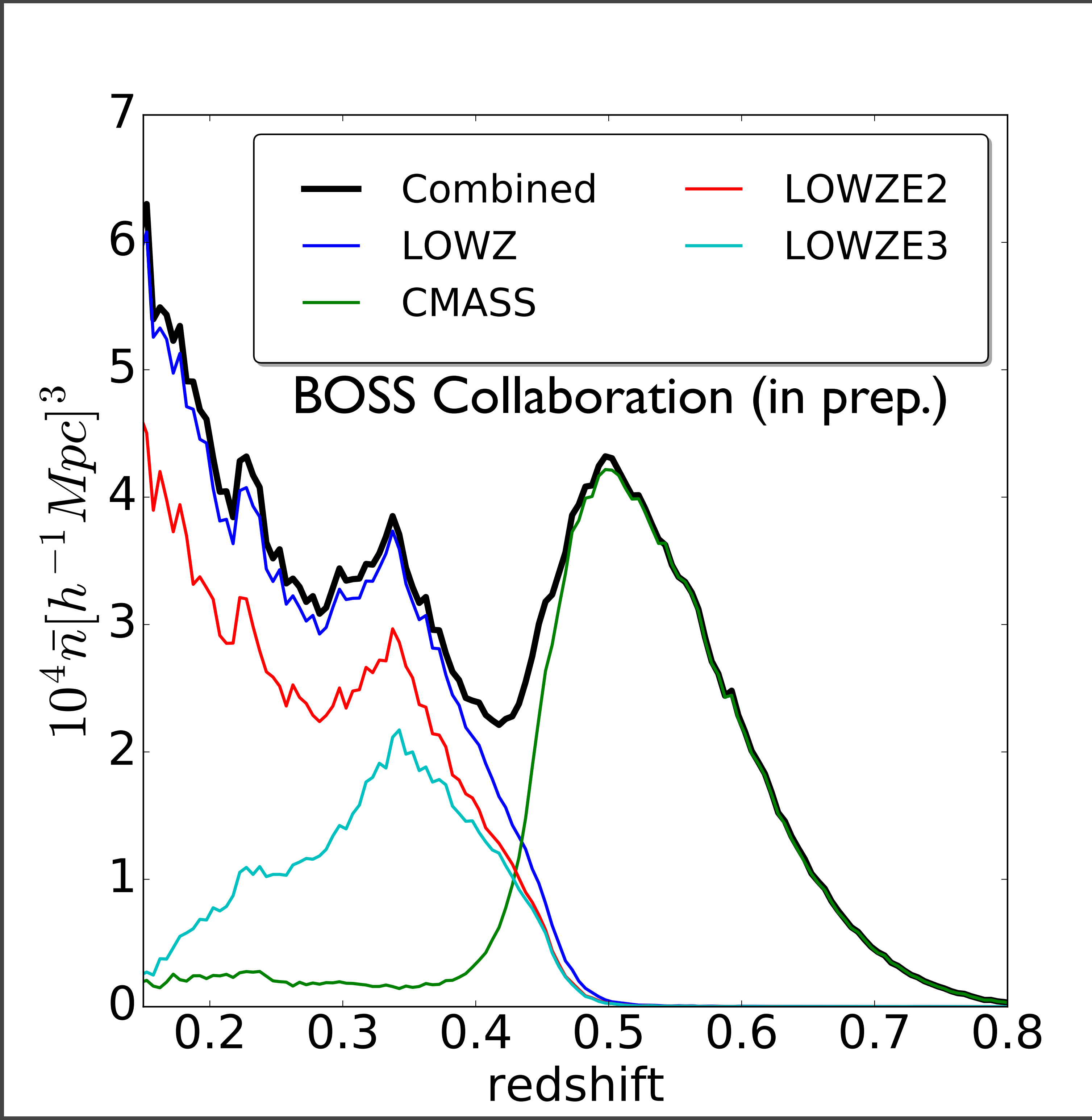
SDSS-III BOSS

- Sloan Digital Sky Survey
- Uses Sloan telescope at Apache Point NM
- BOSS uses:
- SDSS *ugriz* imaging to select:
  - 1.5 million galaxies
  - $1.5\text{x}10^5$ quasars
  - (out of $3.6\text{x}10^8$ sources)
- BOSS spectrograph
  - $3600\text{Å} < \lambda < 10{,}000\text{Å}$
  - $R = \lambda/\Delta\lambda = 1300 - 3000$
  - 1000 spectra at a time



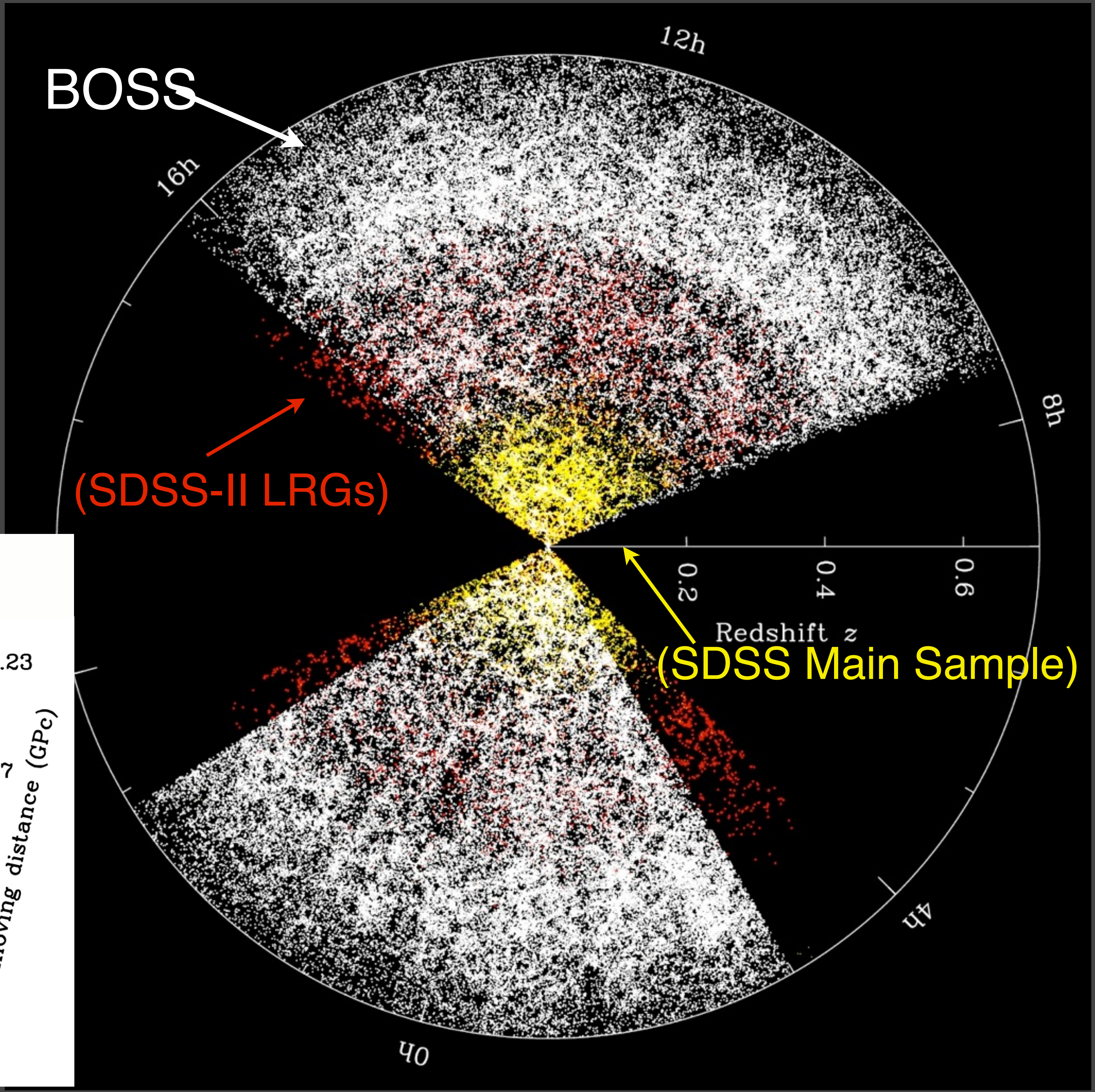
BOSS Galaxies

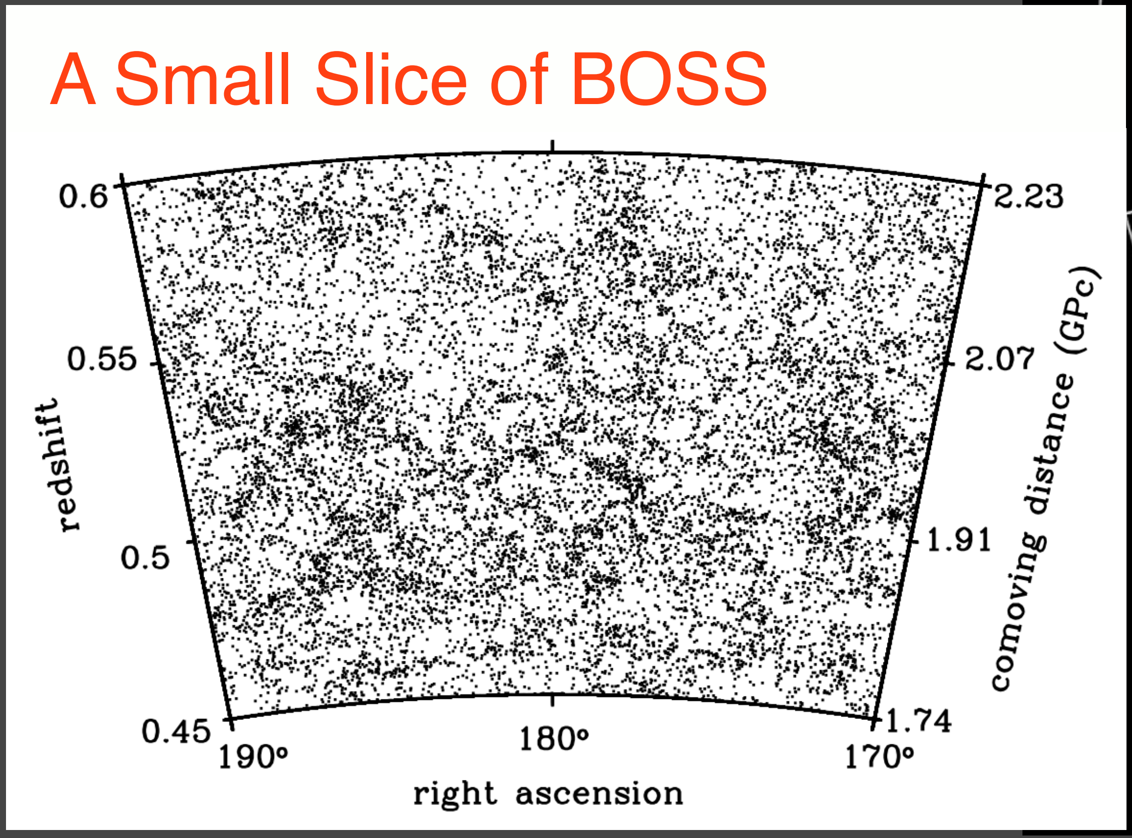
- 1.2 million galaxy redshifts, 9400 deg^2, $0.2 < z < 0.75$



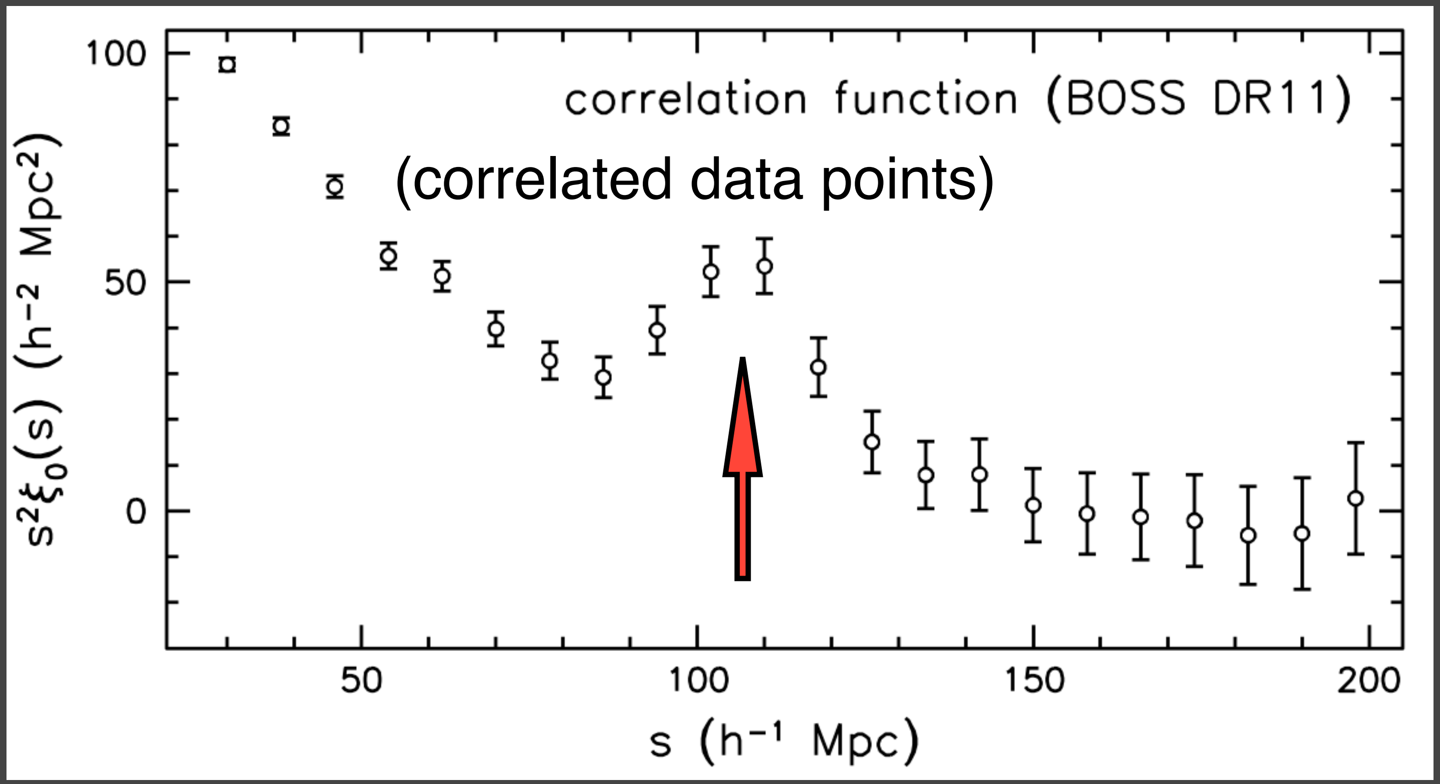
BOSS Galaxies

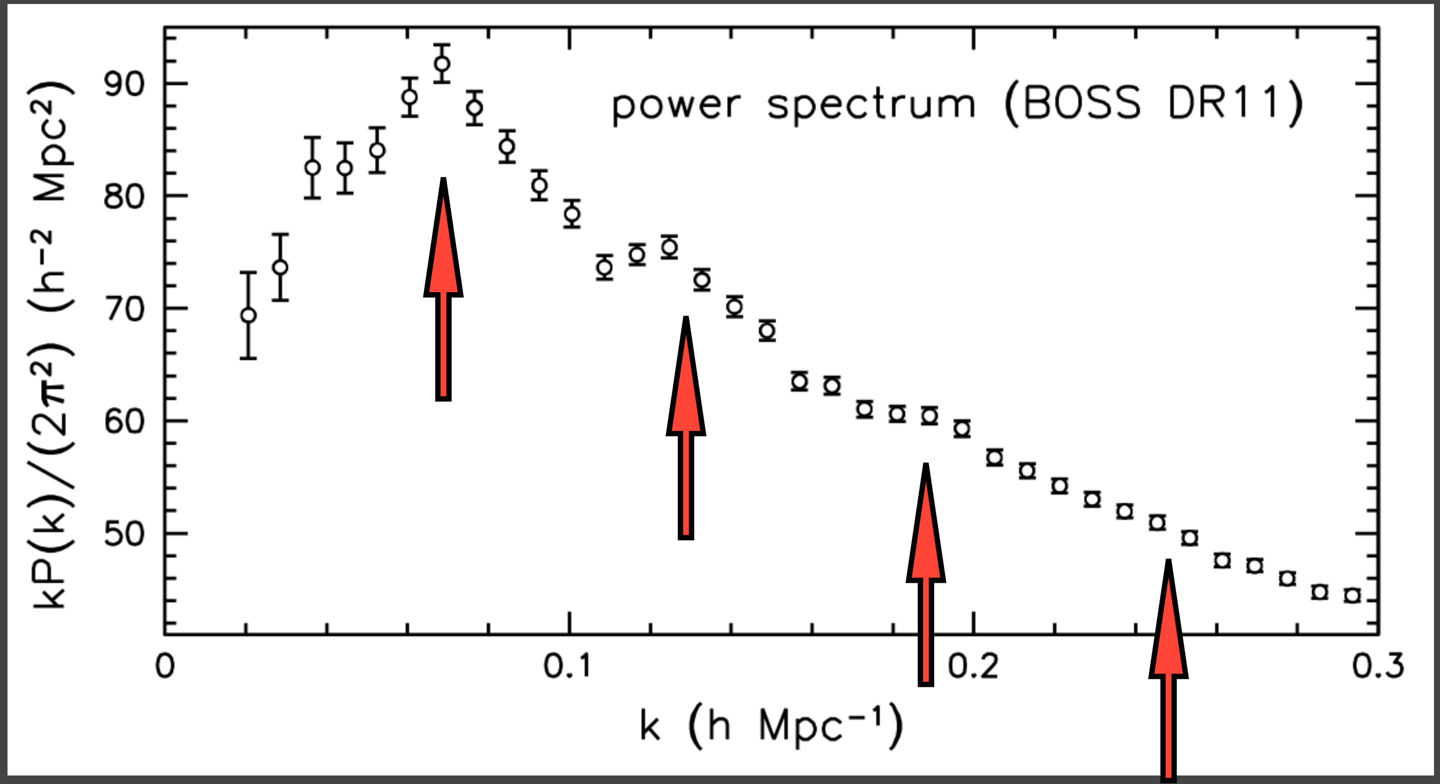
- Largest 3D map of galaxies





Galaxy Clustering





- Power spectrum $P(k) = \langle \delta_k(k)^2 \rangle$
- Correlation function $\xi(r) = \langle \delta(x)\delta(x+r) \rangle$

- k~2π/r
- r and s interchangeable

Theoretical details

theoretical clustering of matter

observed clustering of galaxies

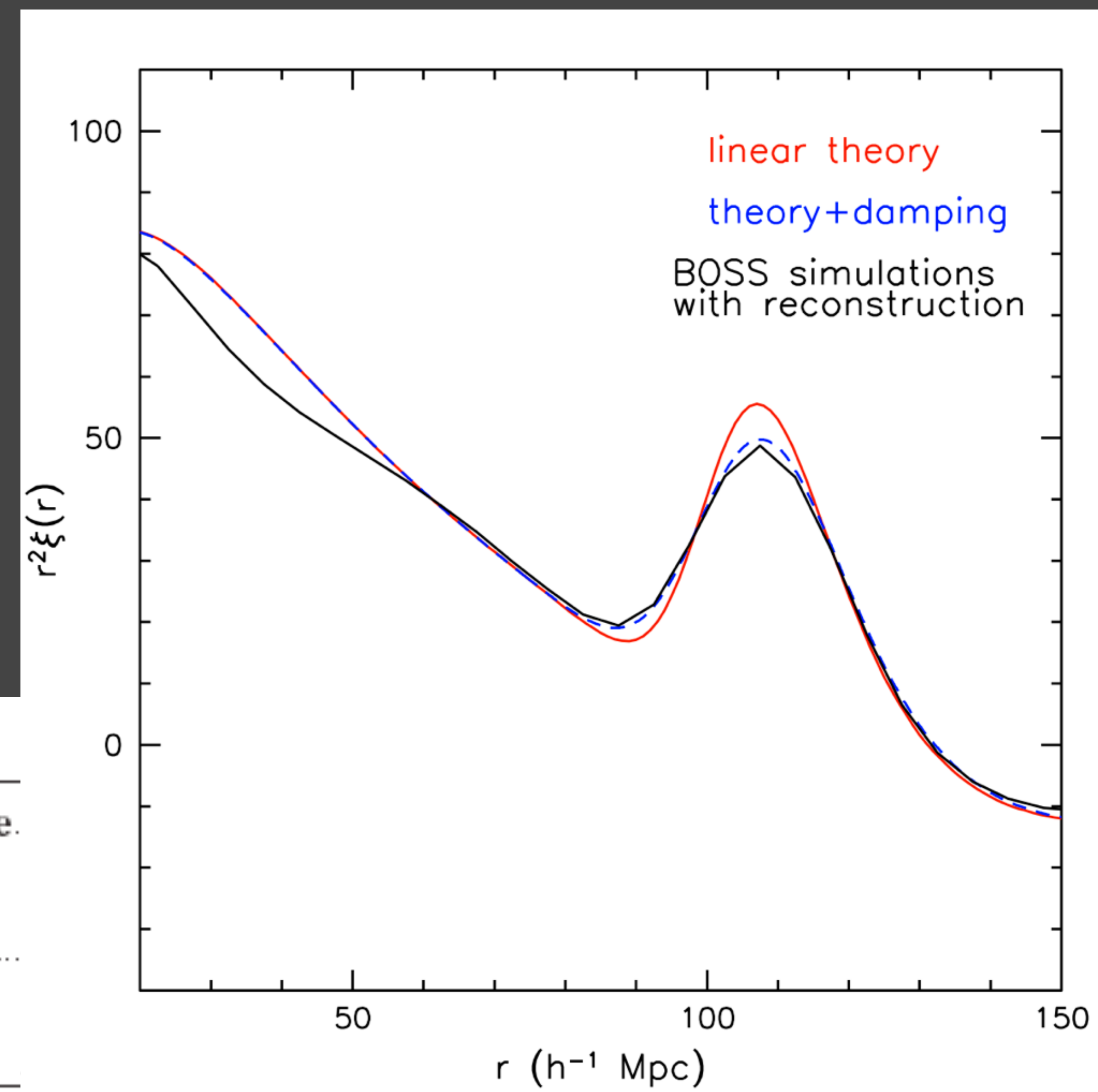
Galaxy bias: light ≠ mass

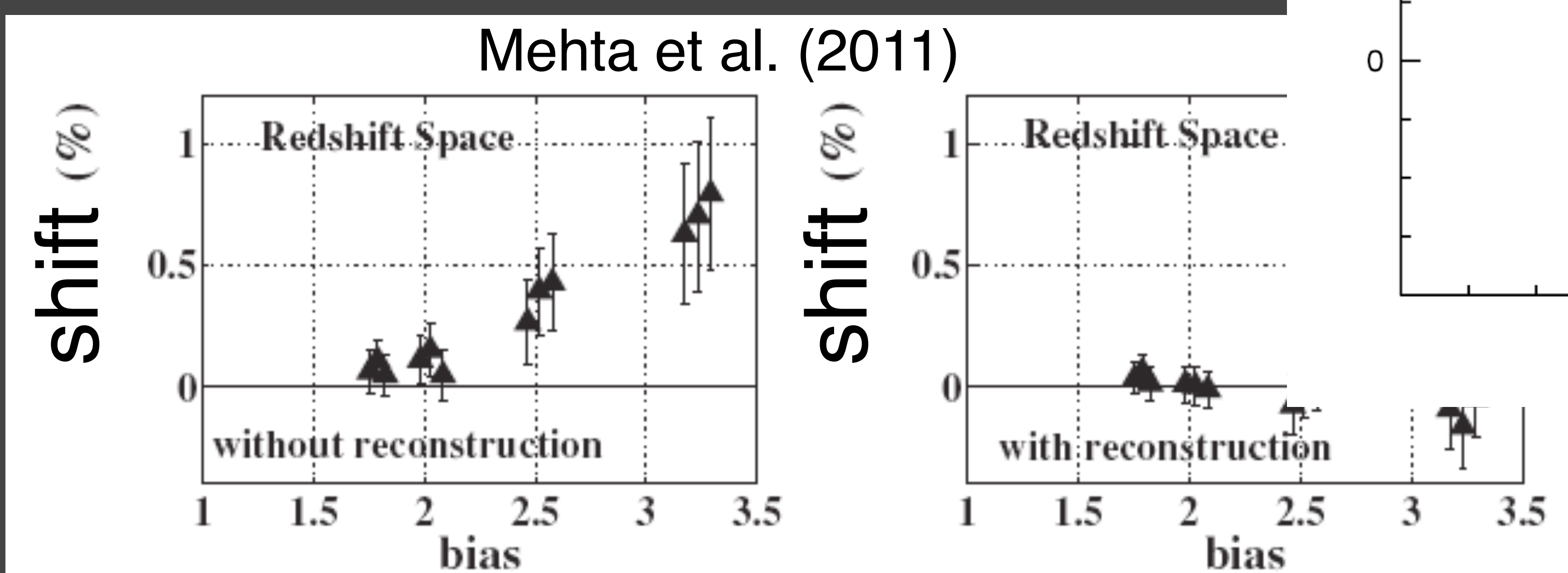
Impact on BAO

Theoretical results + simulations show:

• non-linearities smear BAO scale

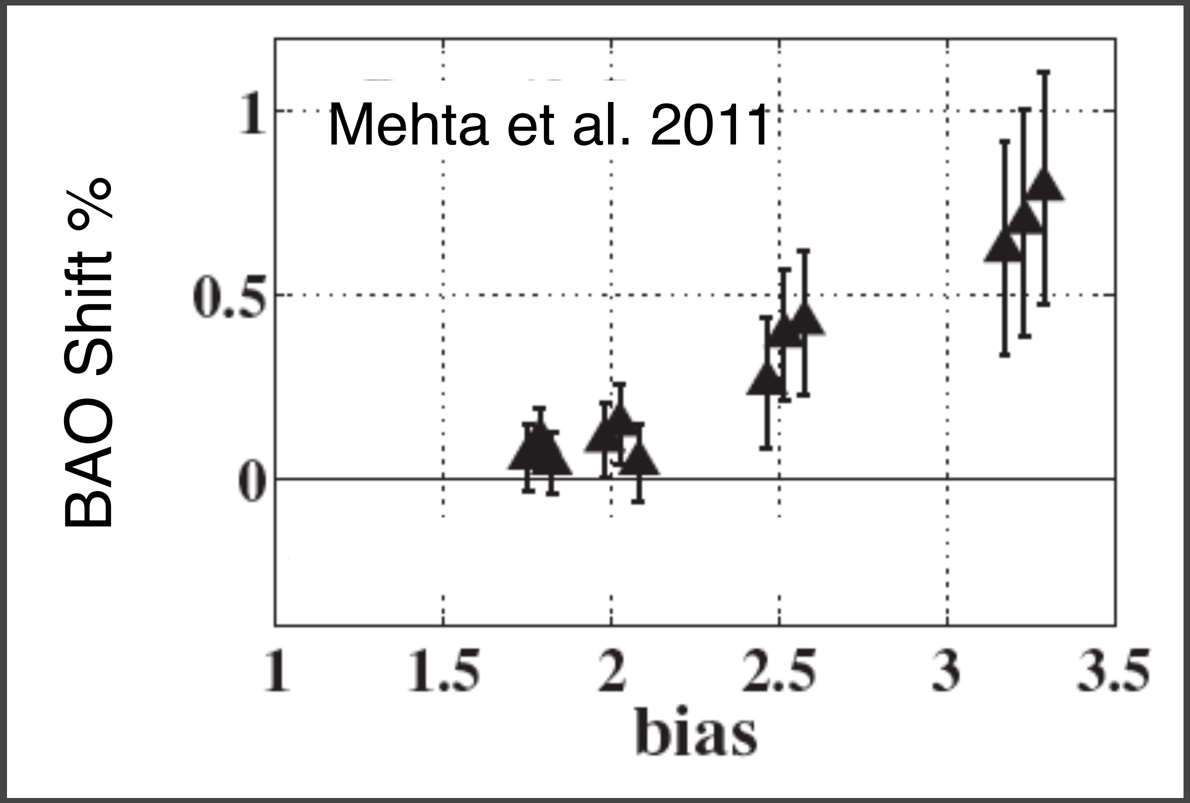
•(small) bias (halo mass) dependent shift

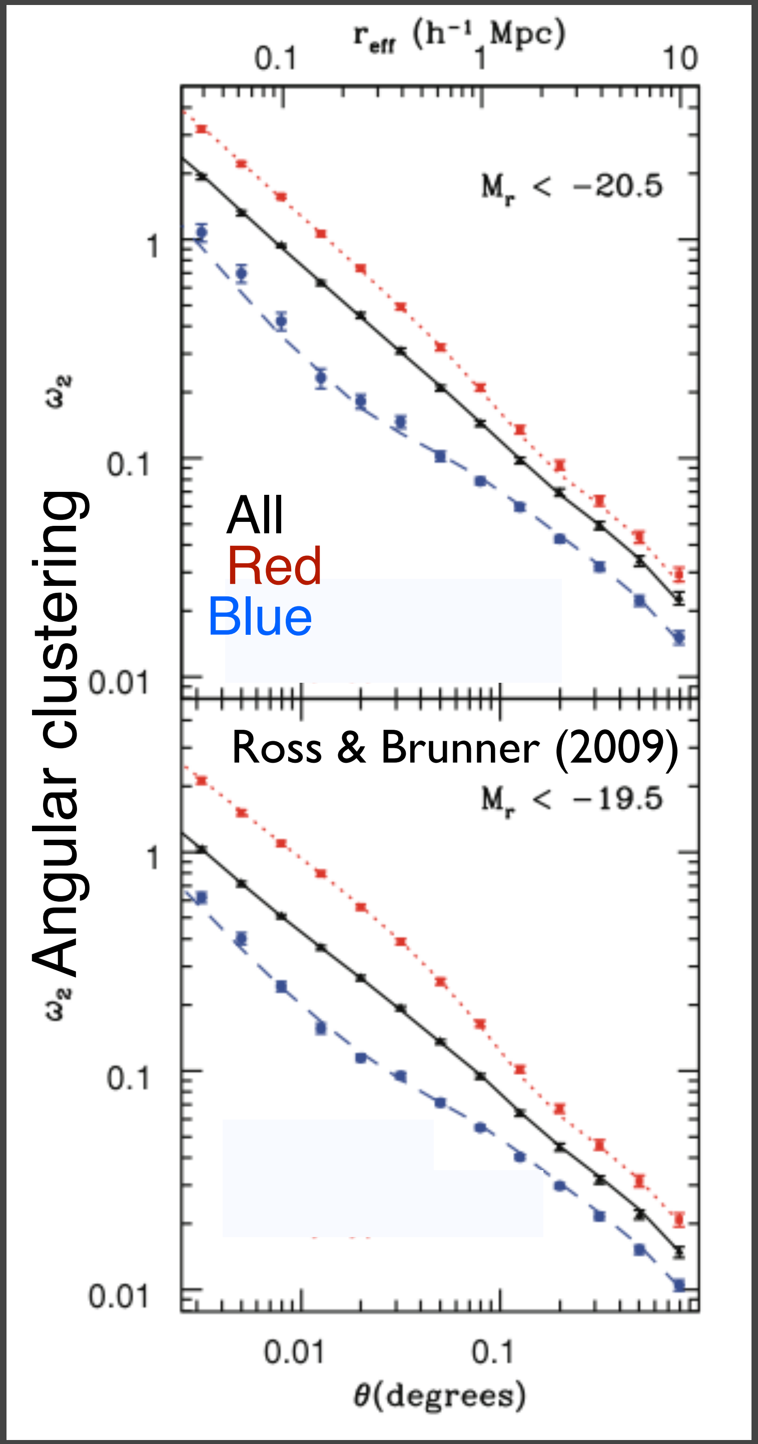




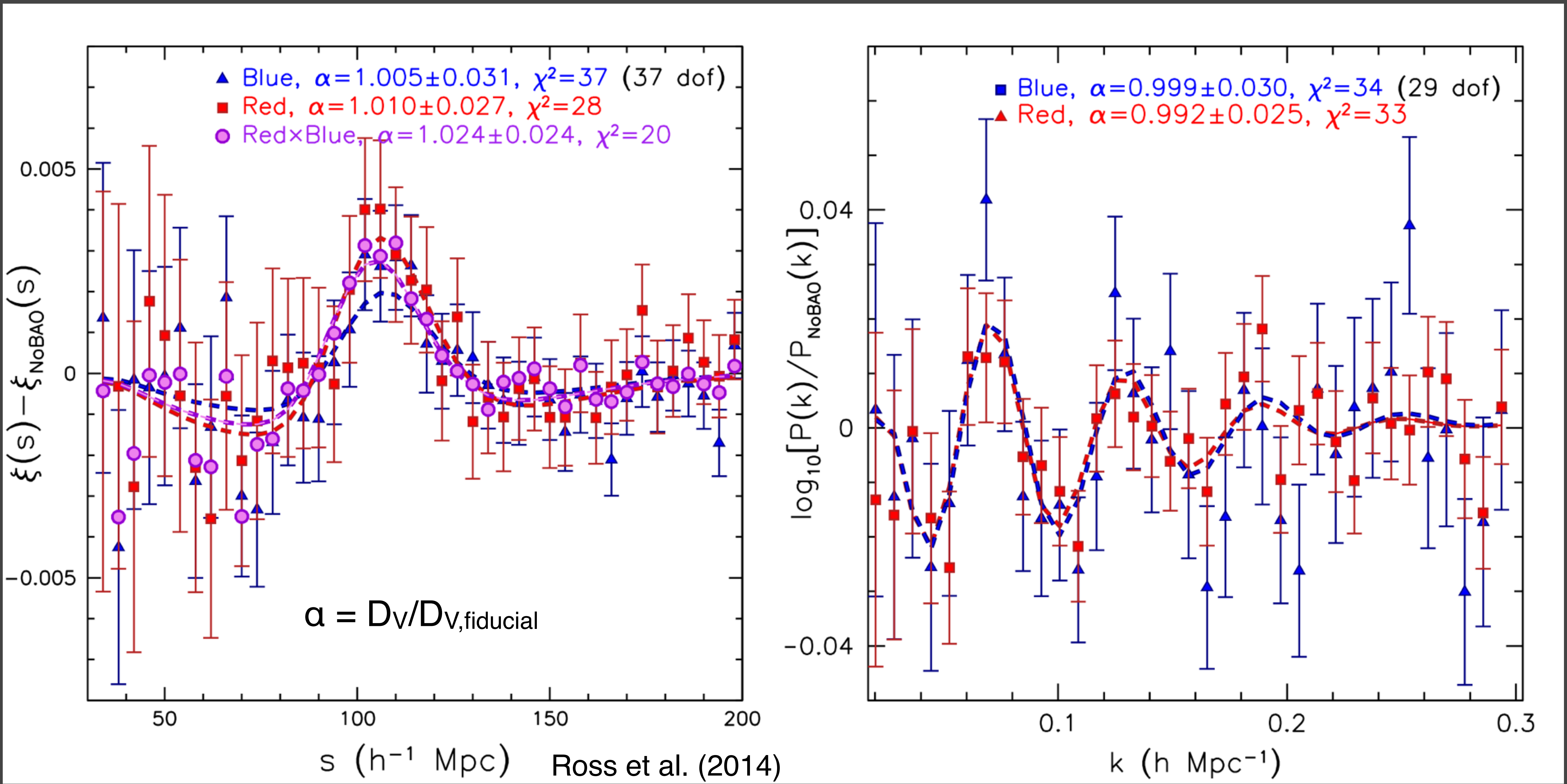
Red and Blue Galaxies

- Galaxy population bi-modal red/ blue
- ideal for testing systematic effect from galaxy evolution



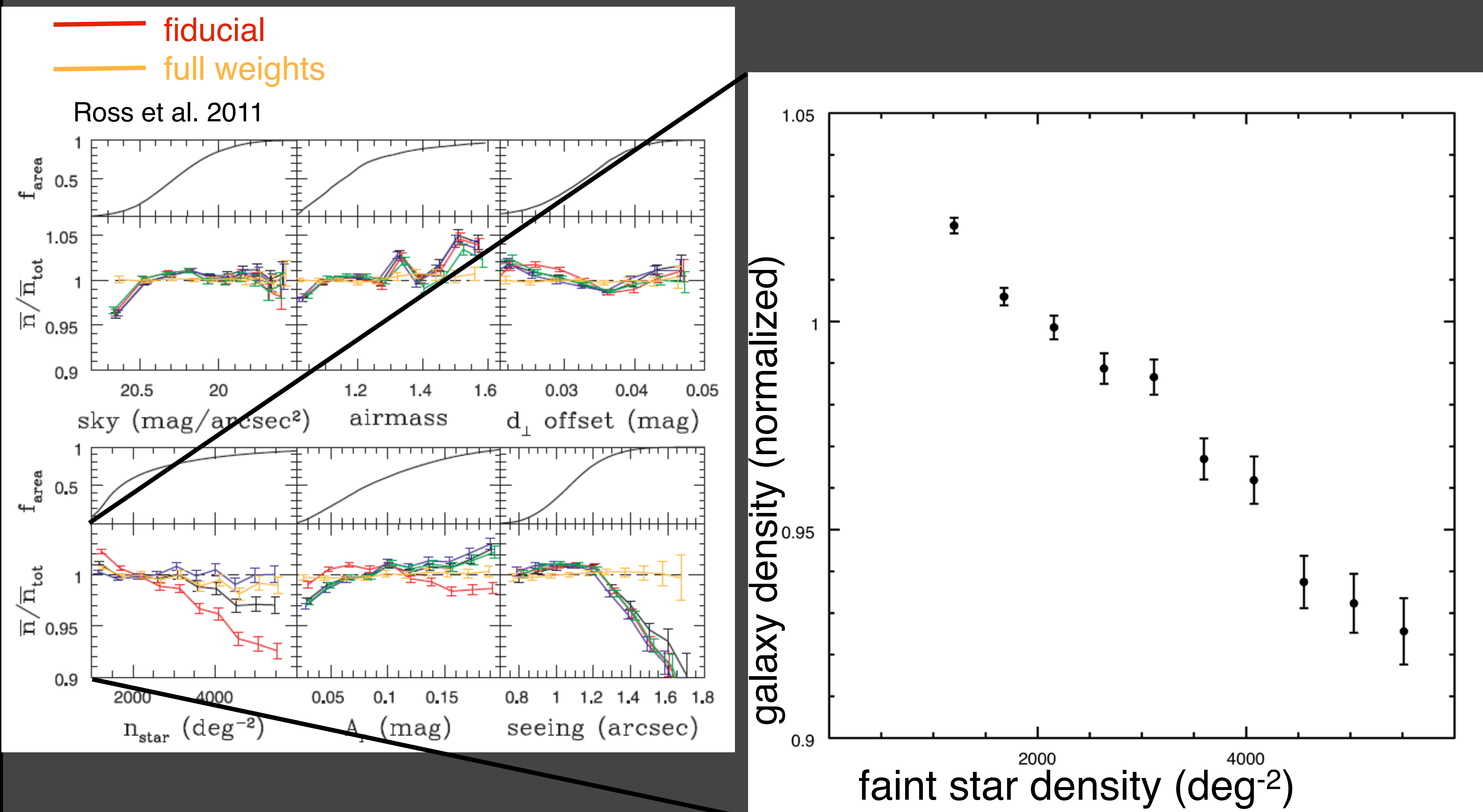


Red/Blue BOSS BAO

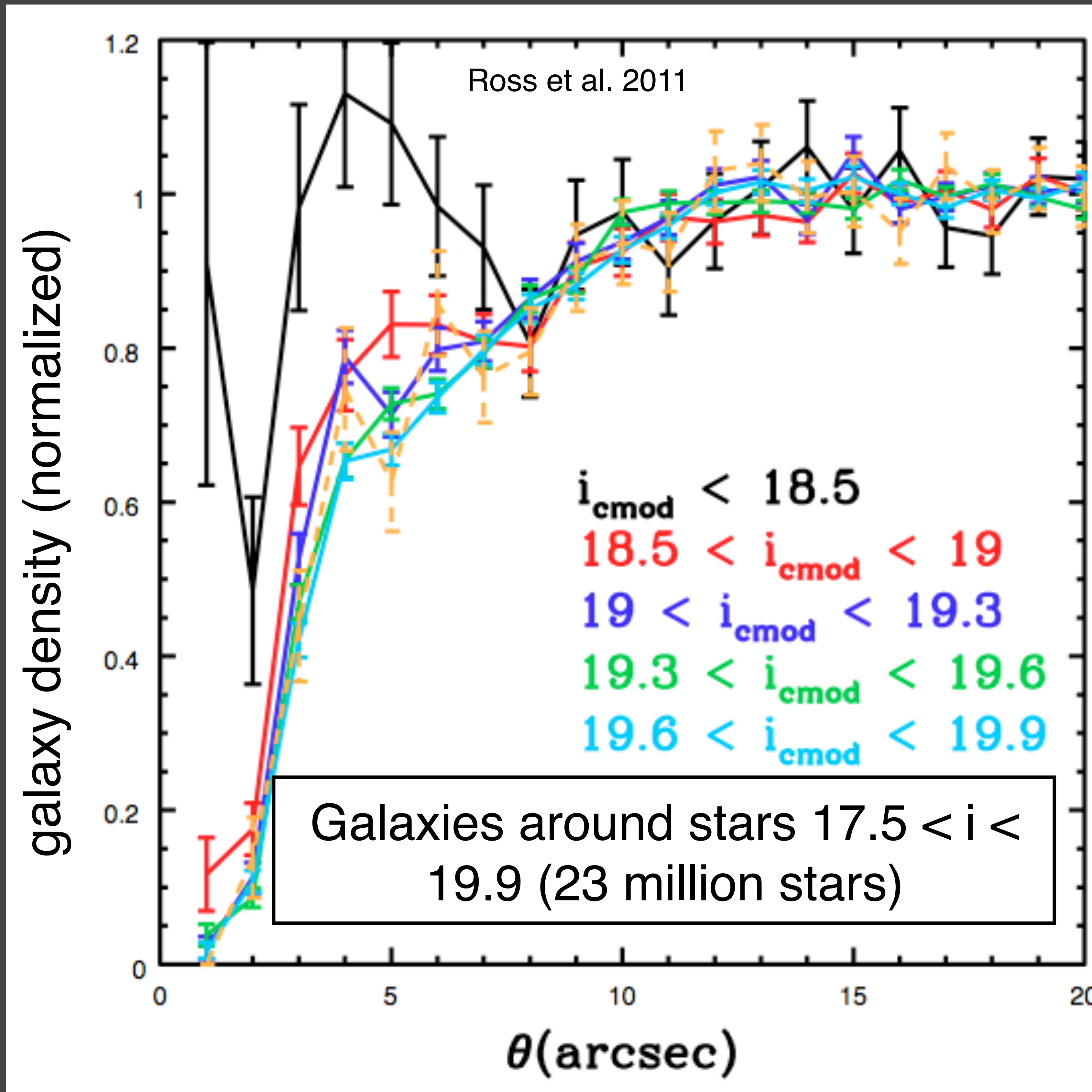


Ross et al. (2014)

BOSS imaging systematics

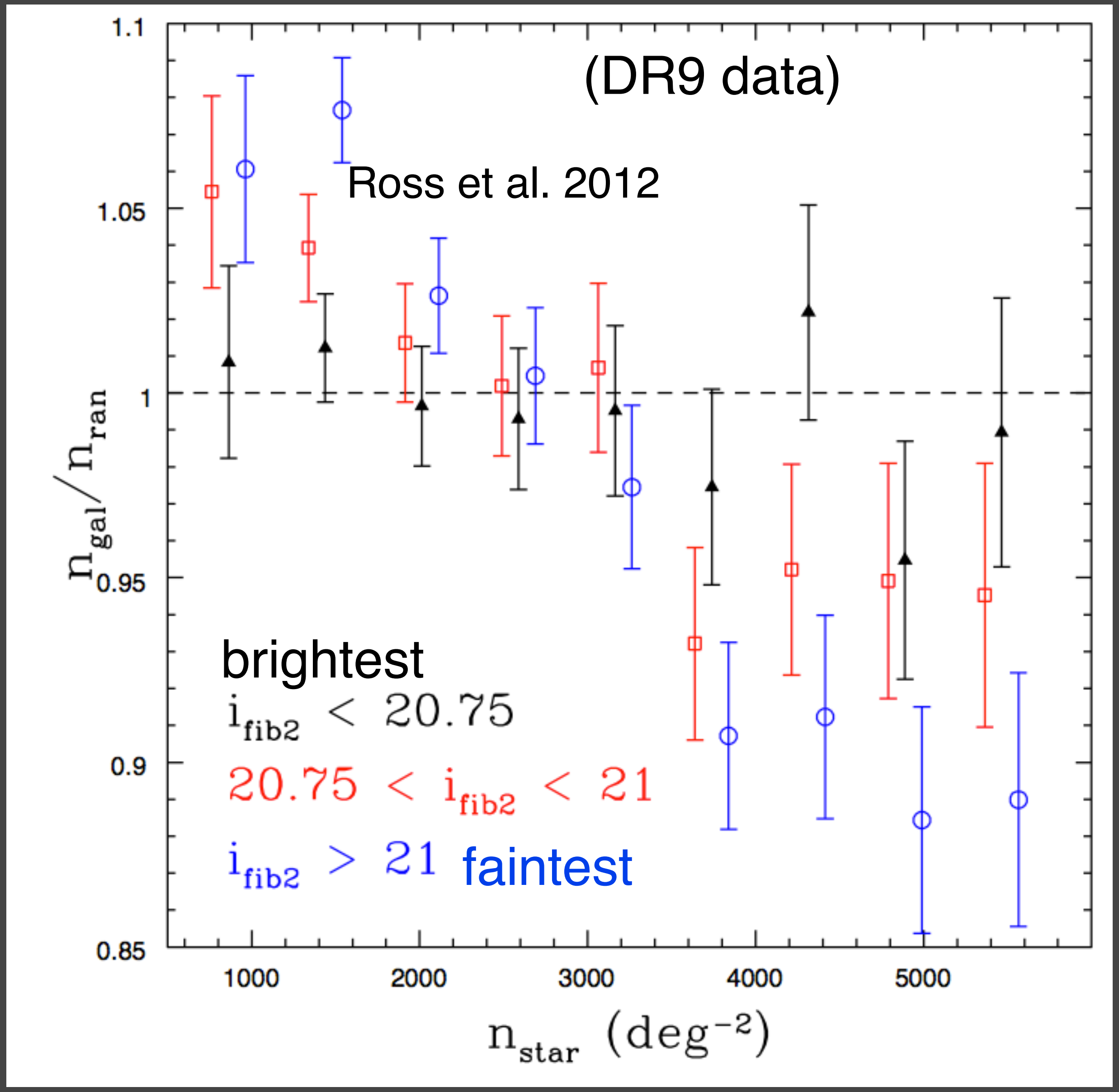


Stars Occult Area

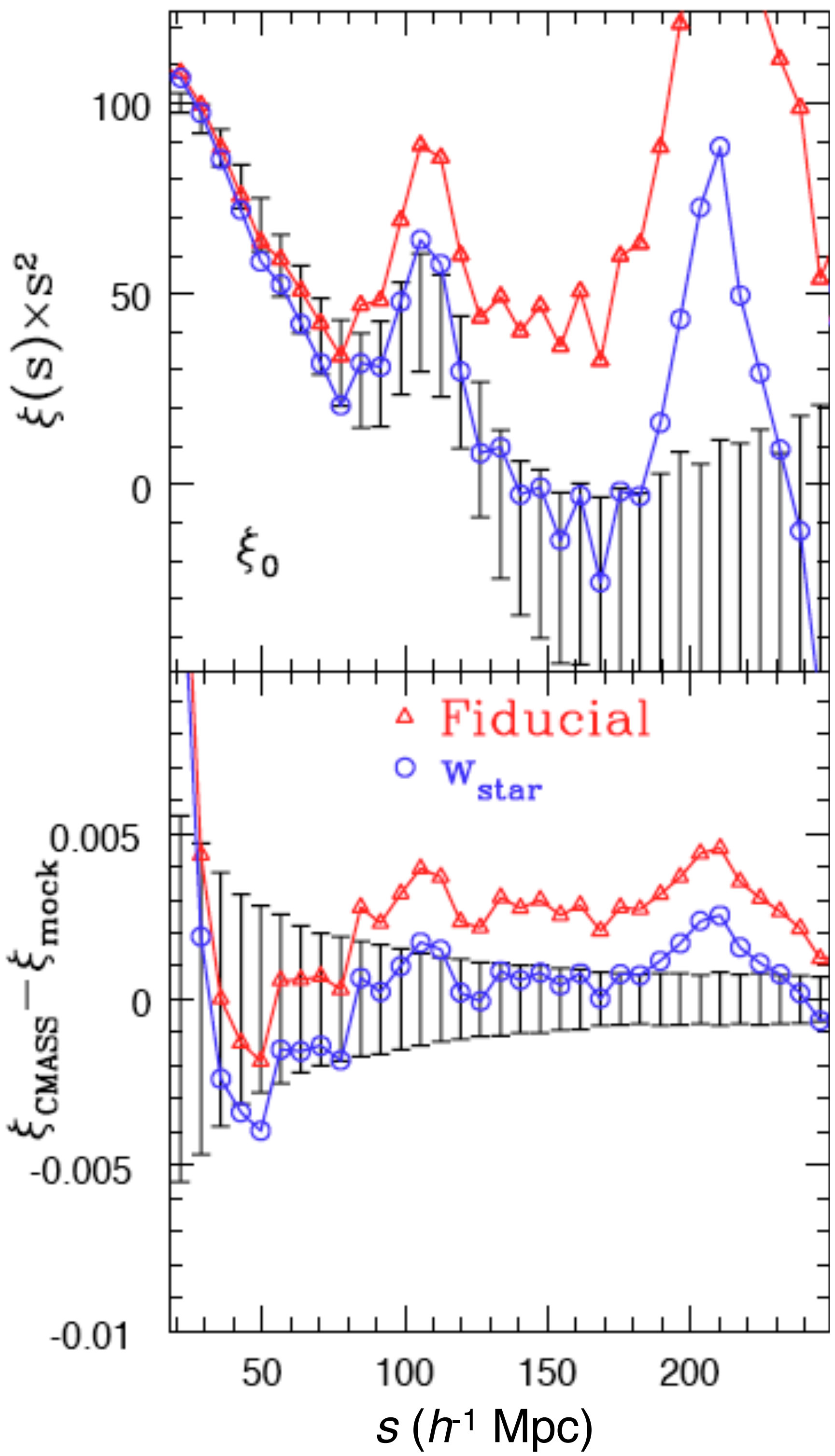


Stars and BOSS Surface Brightness

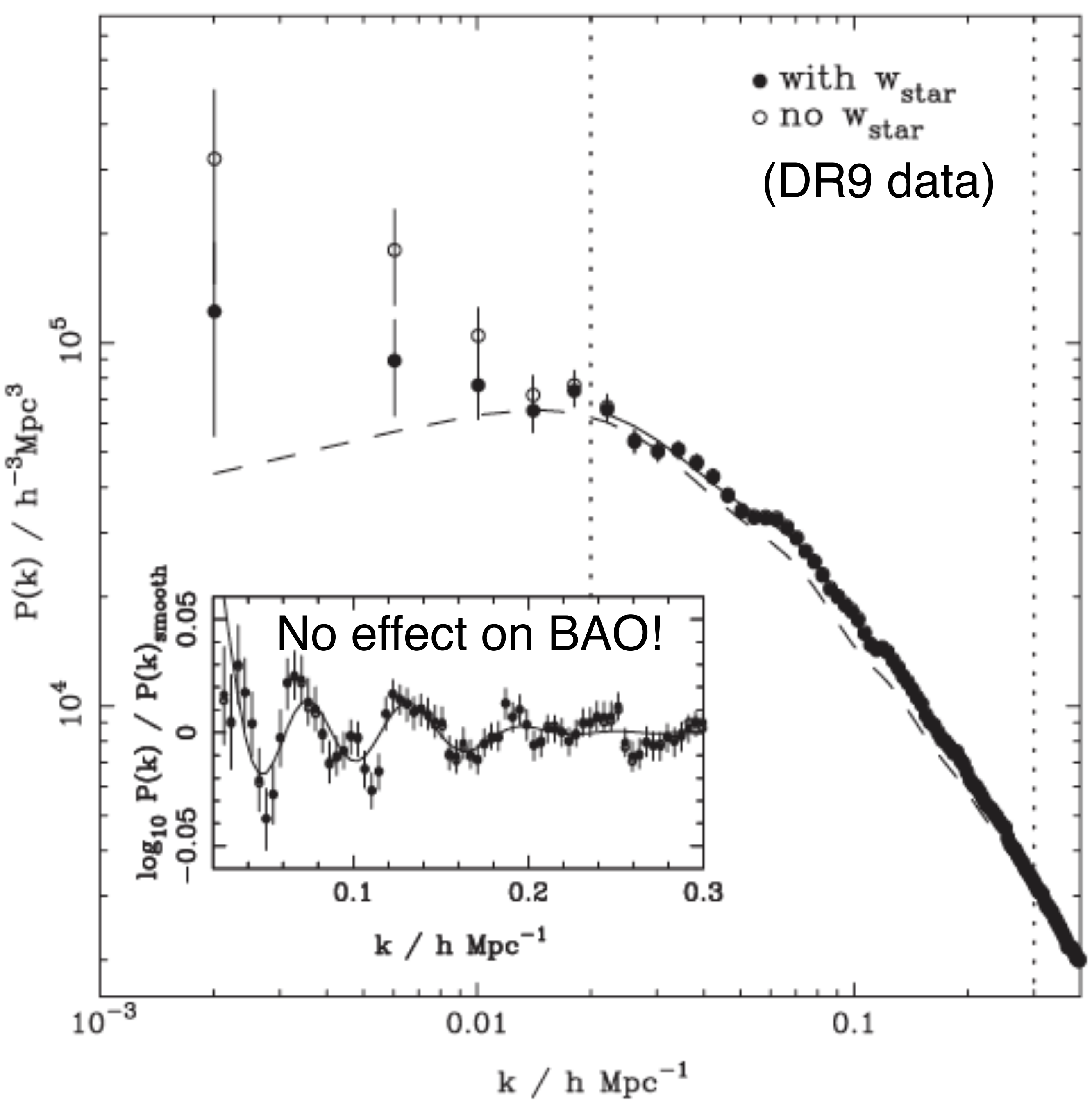
- Spectroscopic results confirm galaxy vs. stellar density relationship
- Depends on surface brightness
- Corrected with weights based on linear fits



Effect on BOSS clustering

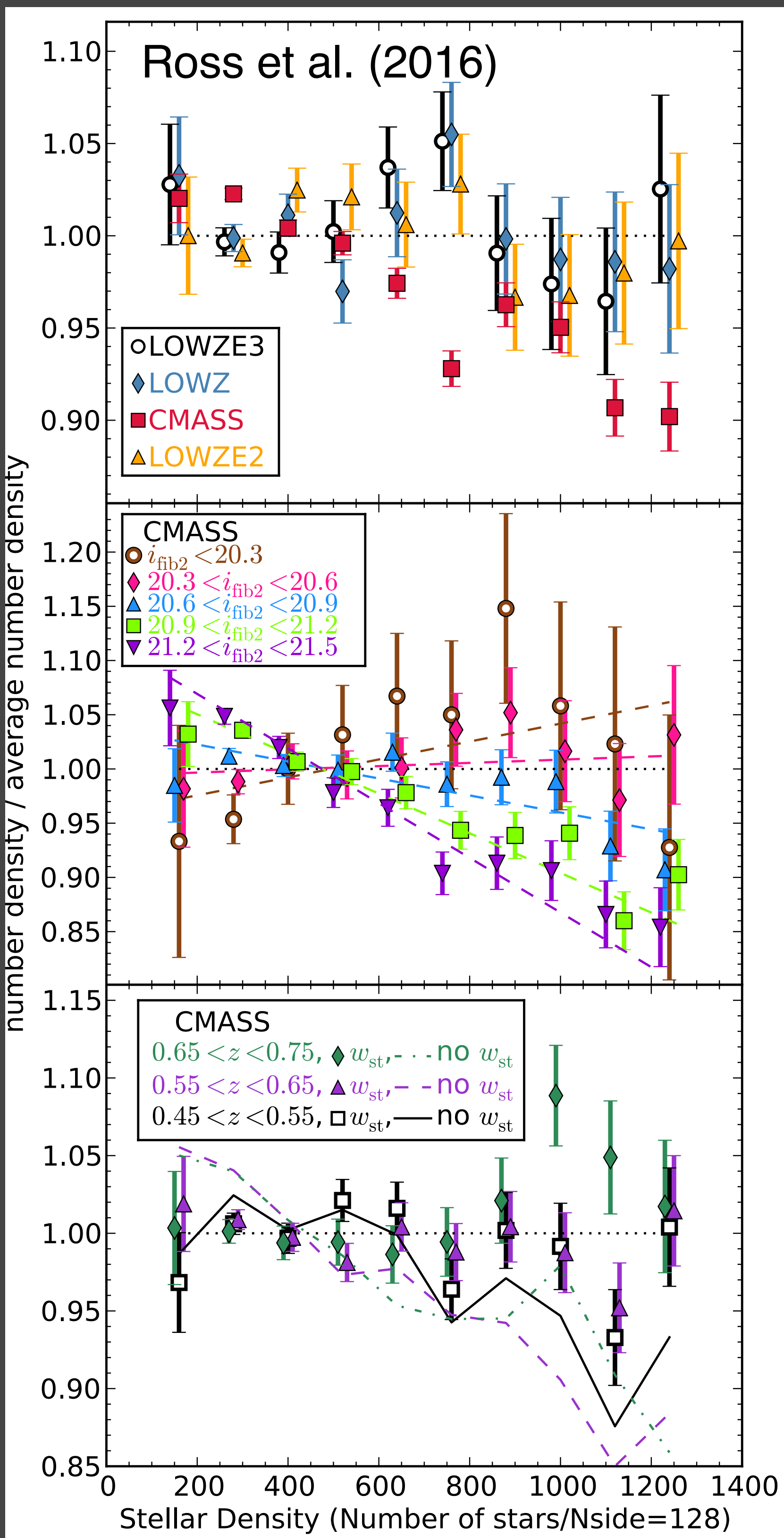


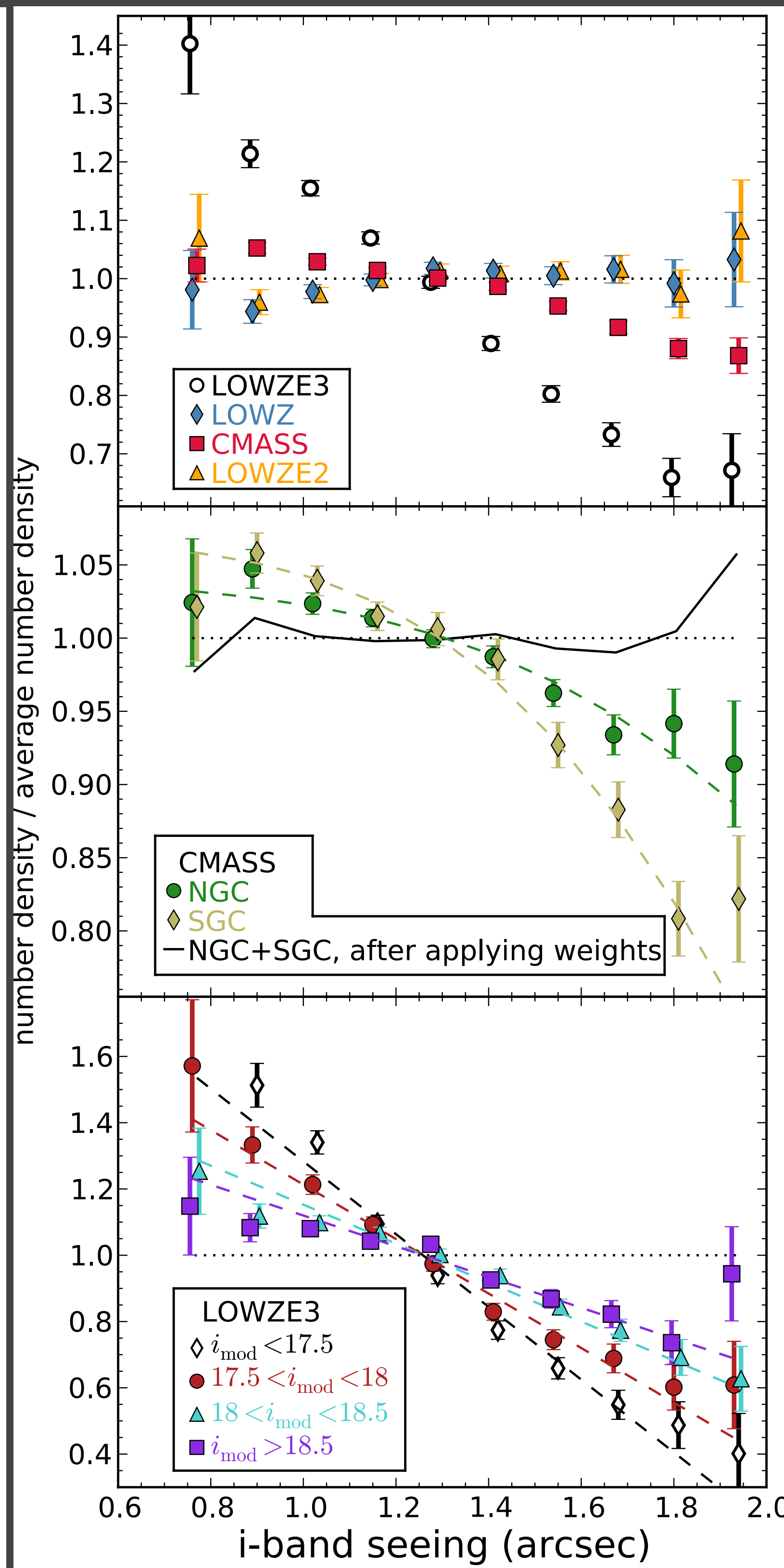
w_{star}: correction for stellar systematic



Ross et al. 2012

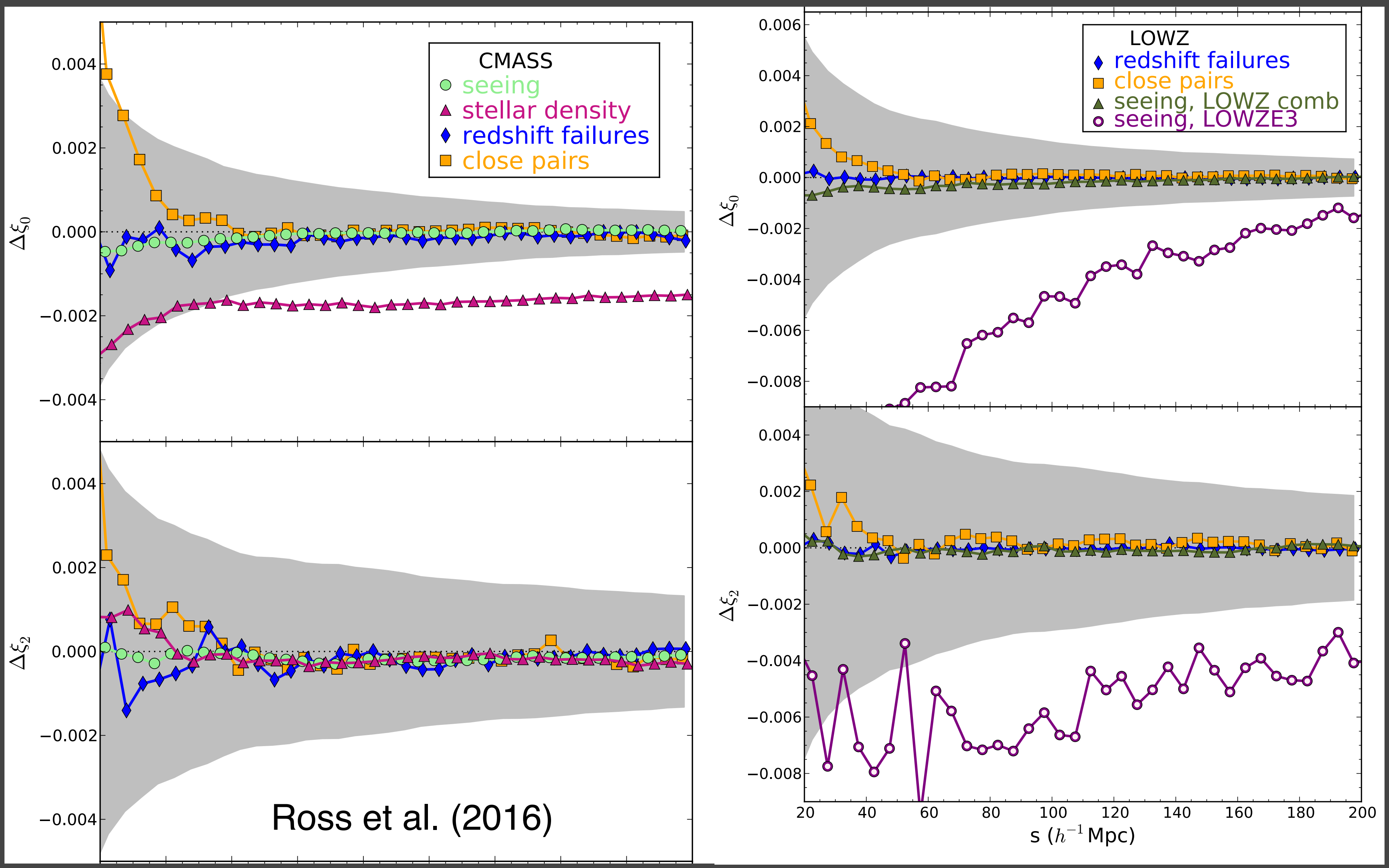
Systematics in final data set





- Stellar density effect remains strong
- Significant effect with seeing due to morphological star/galaxy separation cuts

Systematics in final data set



- Only stellar density has strong effect over full footprint
- (LOWZE3 result is over full footprint, but it is only 660 deg^2 in combined)
- Simulating effects yield no bias in BAO, negligible effect on statistical uncertainty

What BOSS measures

- Pre-reconstruction, full-shape with RSD modeling:
  - $D_V(z)$
  - $F_{AP}(z)$ (with extra information from anisotropic clustering at all scales)
  - $f\sigma_8$