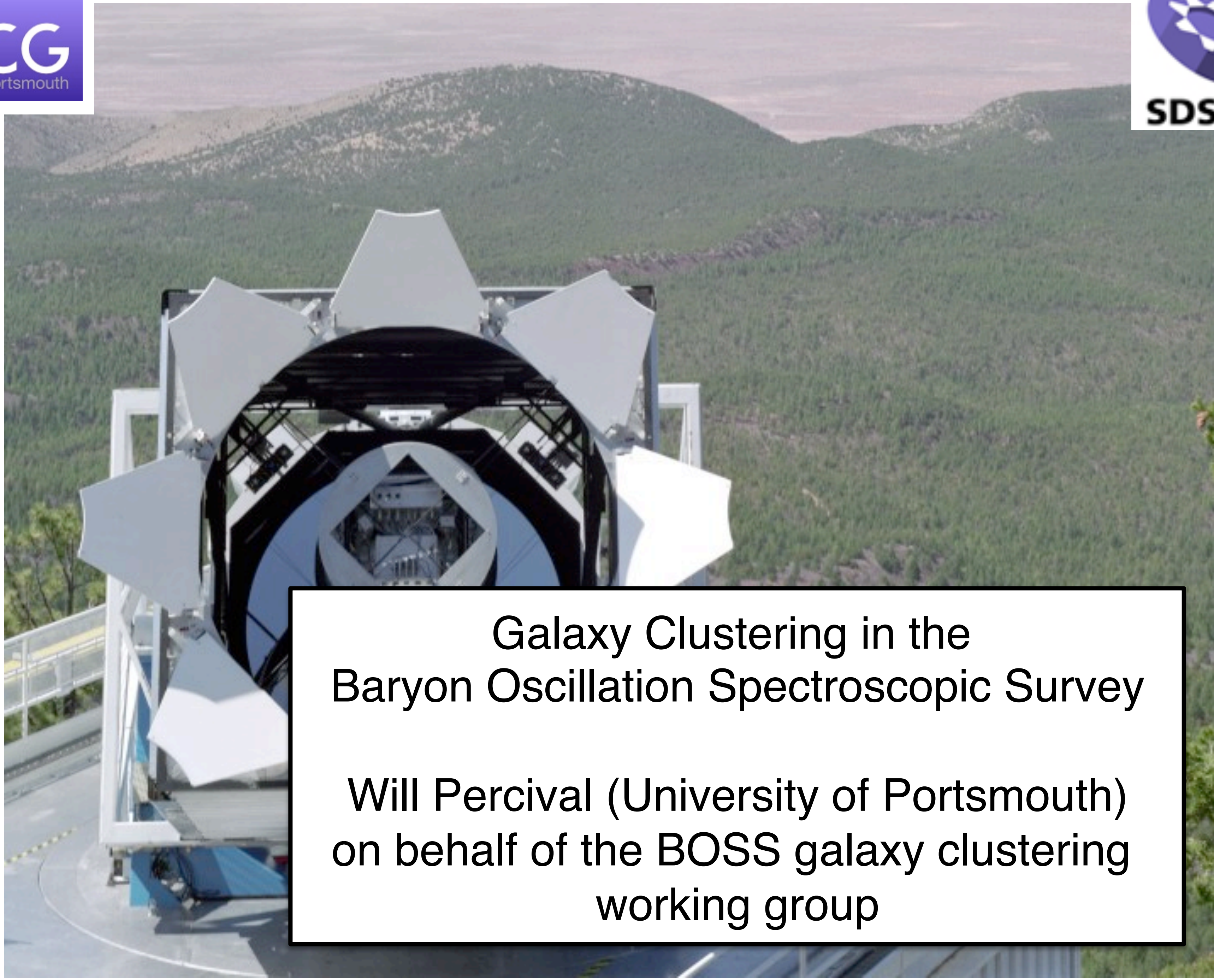
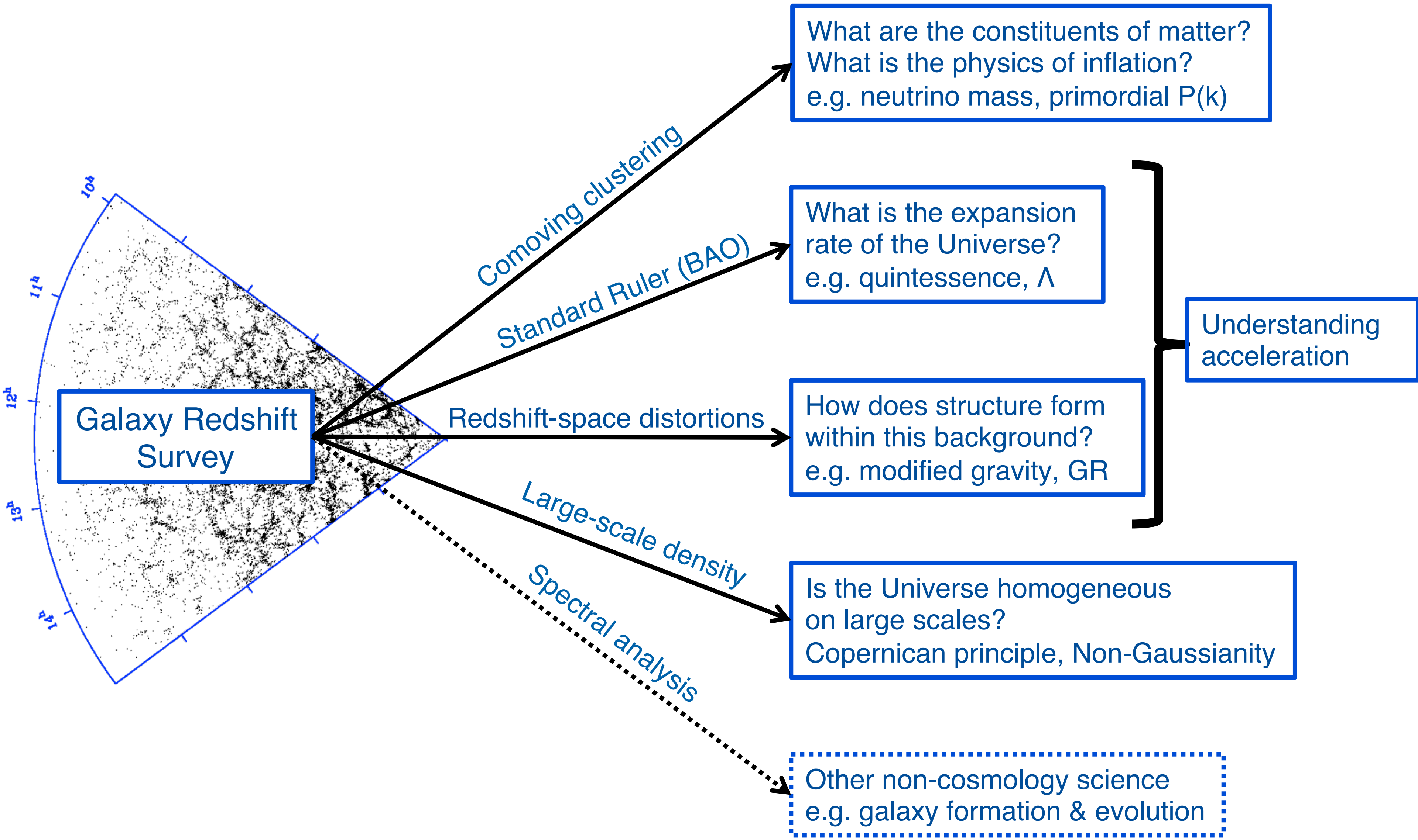


Galaxy Clustering in the Baryon Oscillation Spectroscopic Survey

Will Percival (University of Portsmouth)
on behalf of the BOSS galaxy clustering working group

Cosmology from Spectroscopic Galaxy Surveys



BOSS summary

- 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, $z < 0.7$, $i < 19.9$
  - 1.5×10^5 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 $z = 2.5$

132 pages of science

- **Anderson et al.** (alphabetical) arXiv:1203.6565 - BAO measurement in power-spectrum and correlation function.
- **Reid et al.** arXiv:1203.6641- Anisotropic clustering, redshift-space distortion measurements.
- **Sanchez et al.** arXiv:1203.6616 - Fits to the full shape of the correlation function.
- **Ross et al.** arXiv:1203.6499 - Large-scale systematics.
- **Manera et al.** arXiv:1203.6609 - 600 PTHalo mocks.
- **Tojeiro et al.** arXiv:1203.6565 - Enhanced redshift-space distortion measurements.

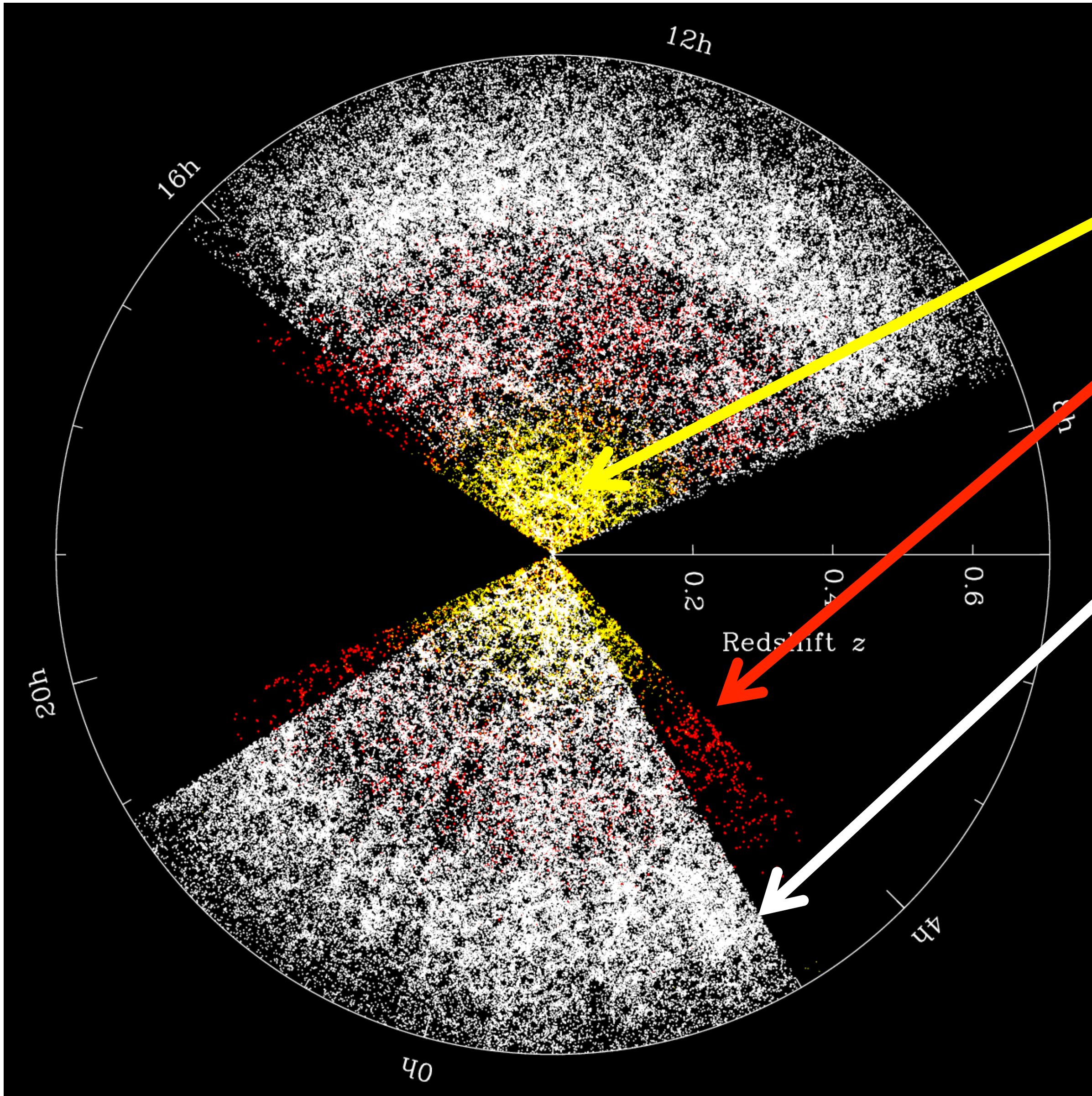
- Plus more to come soon …

A collaborative effort …

Lauren Anderson[1], Eric Aubourg[2], Stephen Bailey[3], Dmitry Bizyaev[4], Michael Blanton[5], Adam S. Bolton[6], J. Brinkmann[4], Joel R. Brownstein[6], Angela Burden[7], Antonio J. Cuesta[8], Luiz N. A. da Costa[9,10], Kyle S. Dawson[6], Roland de Putter[11,12], Daniel J. Eisenstein[13], James E. Gunn[14], Hong Guo[15], Jean-Christophe Hamilton[2], Paul Harding[15], Shirley Ho[3,14], Klaus Honscheid[16], Eyal Kazin[17], D. Kirkby[18], Jean-Paul Kneib[19], Antione Labatie[20], Craig Loomis[21], Robert H. Lupton[14], Elena Malanushenko[4], Viktor Malanushenko[4], Rachel Mandelbaum[14,21], Marc Manera[7], Claudia Maraston[7], Cameron K. McBride[13], Kushal T. Mehta[22], Olga Mena[11], Francesco Montesano[23], Demetri Muna[5], Robert C. Nichol[7], Sebastián E. Nuza[24], Matthew D. Olmstead[6], Daniel Oravetz[4], Nikhil Padmanabhan[8], Nathalie Palanque-Delabrouille[25], Kaike Pan[4], John Parejko[8], Isabelle Pâris[26], Will J. Percival[7], Patrick Petitjean[26], Francisco Prada[27,28,29], Beth Reid[3,30], Natalie A. Roe[3], Ashley J. Ross[7], Nicholas P. Ross[3], Lado Samushia[7,31], Ariel G. Sánchez[23], David J. Schlegel*[3], Donald P. Schneider[32,33], Claudia G. Scóccola[34,35], Hee-Jong Seo[36], Erin S. Sheldon[37], Audrey Simmons[4], Ramin A. Skibba[22], Michael A. Strauss[21], Molly E. C. Swanson[13], Daniel Thomas[7], Jeremy L. Tinker[5], Rita Tojeiro[7], Mariana Vargas Magaña[2], Licia Verde[38], Christian Wagner[12], David A. Wake[39], Benjamin A. Weaver[5], David H. Weinberg[40], Martin White[3,41,42], Xiaoying Xu[22], Christophe Yèche[25], Idit Zehavi[15], Gong-Bo Zhao[7,43]

Anderson et al.

Galaxy distribution



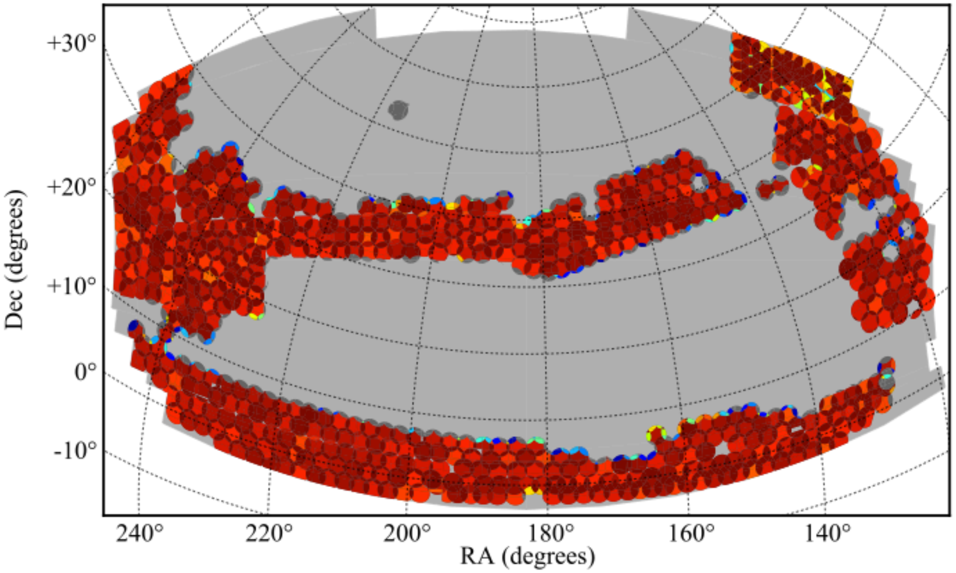
SDSS-II main galaxies

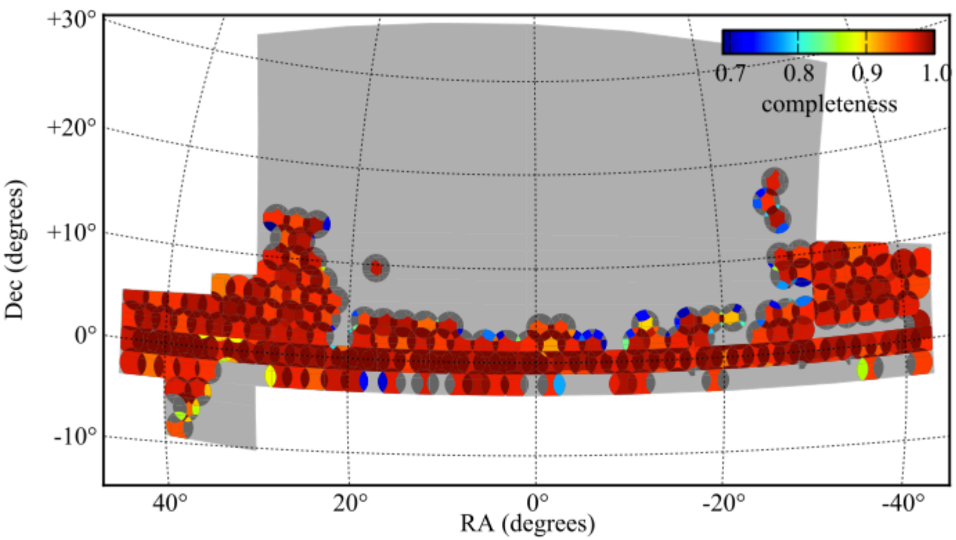
SDSS-II LRGs

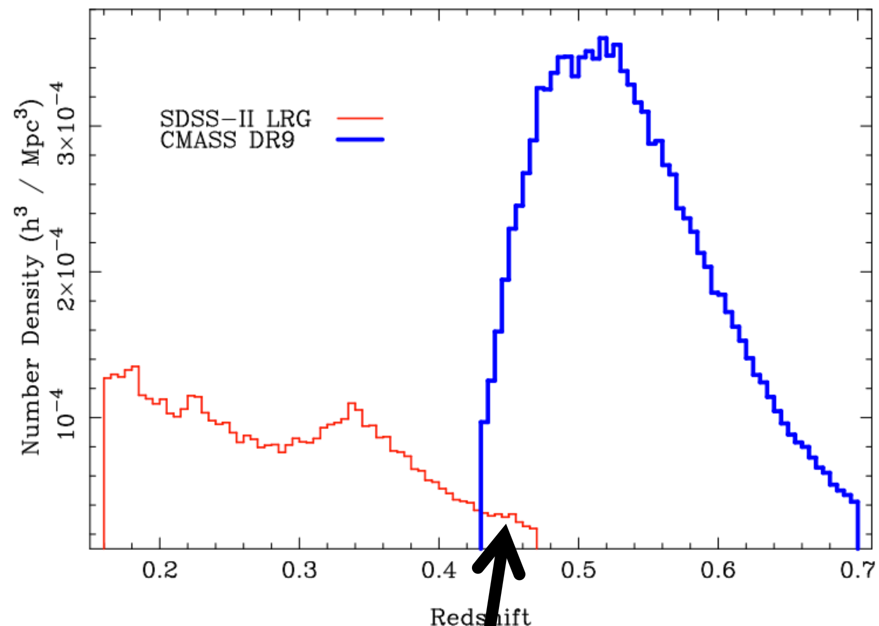
BOSS CMASS galaxies

Image credit: Blanton

Galaxy distribution: DR9

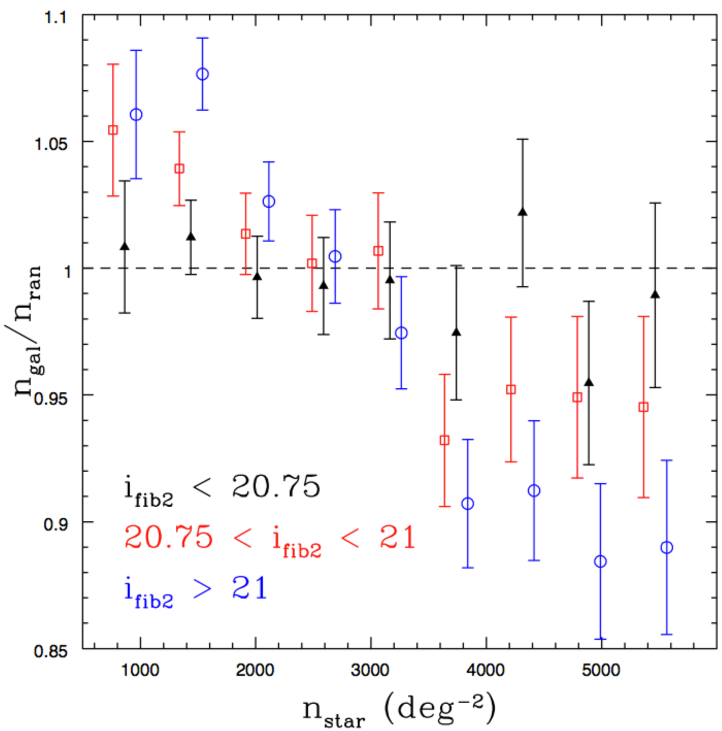




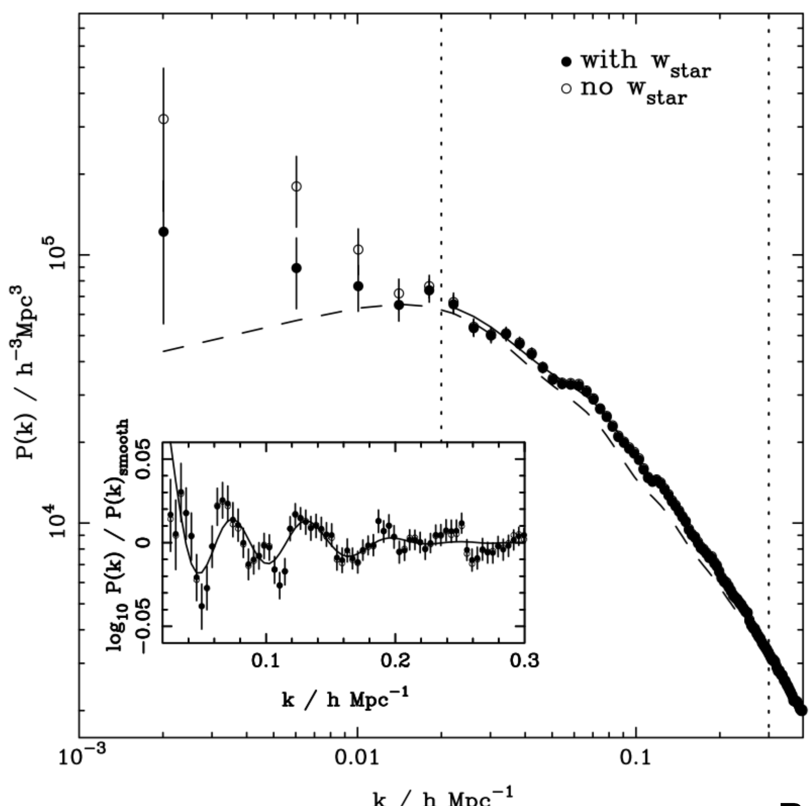


Some of the CMASS galaxies already have known redshifts

Target density fluctuations



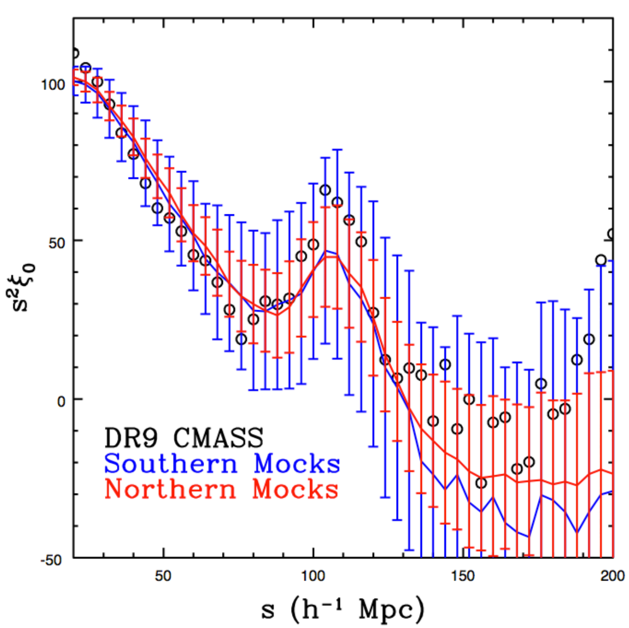
- Target density correlates with stellar density and brightness
- Corrected by weighting
- See Ross et al. for more details

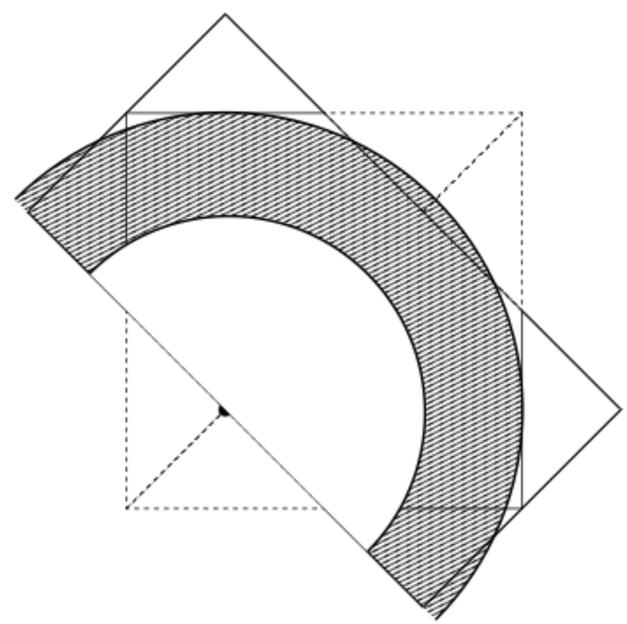


Ross et al.

Mock catalogues

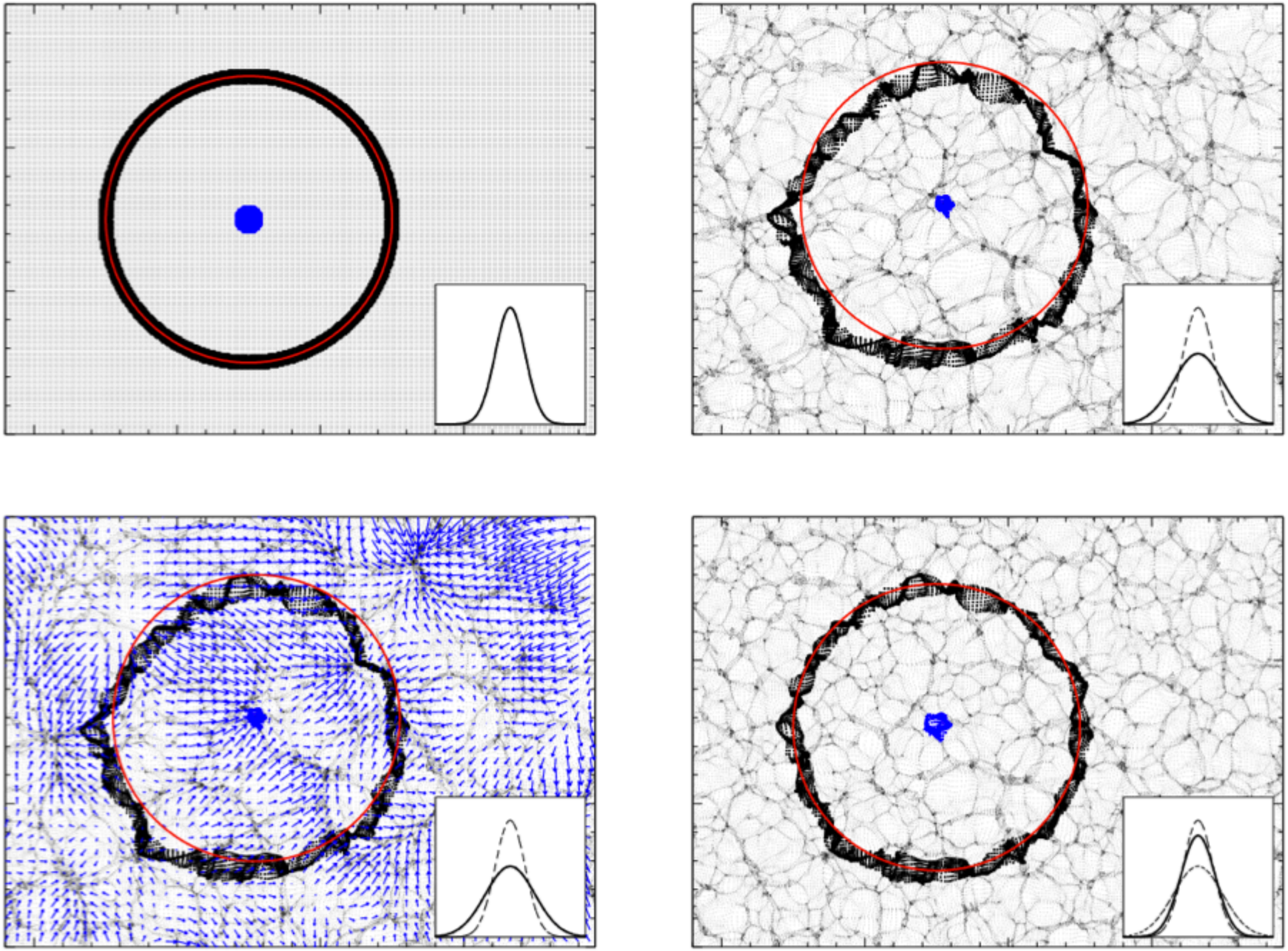
- 600 mocks created by populating 2LPT field using the CMASS HOD
- Redshift-space effects added based on 2LPT velocities
- Matches simulation large-scale clustering at 10% level
- Used to test method and estimate covariances
- See Manera et al. for details





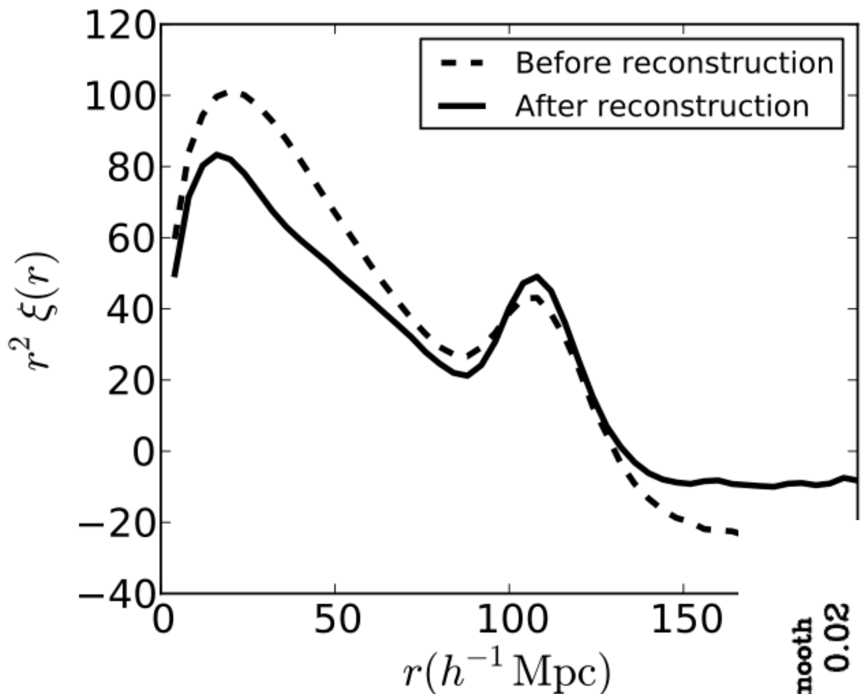
Manera et al.

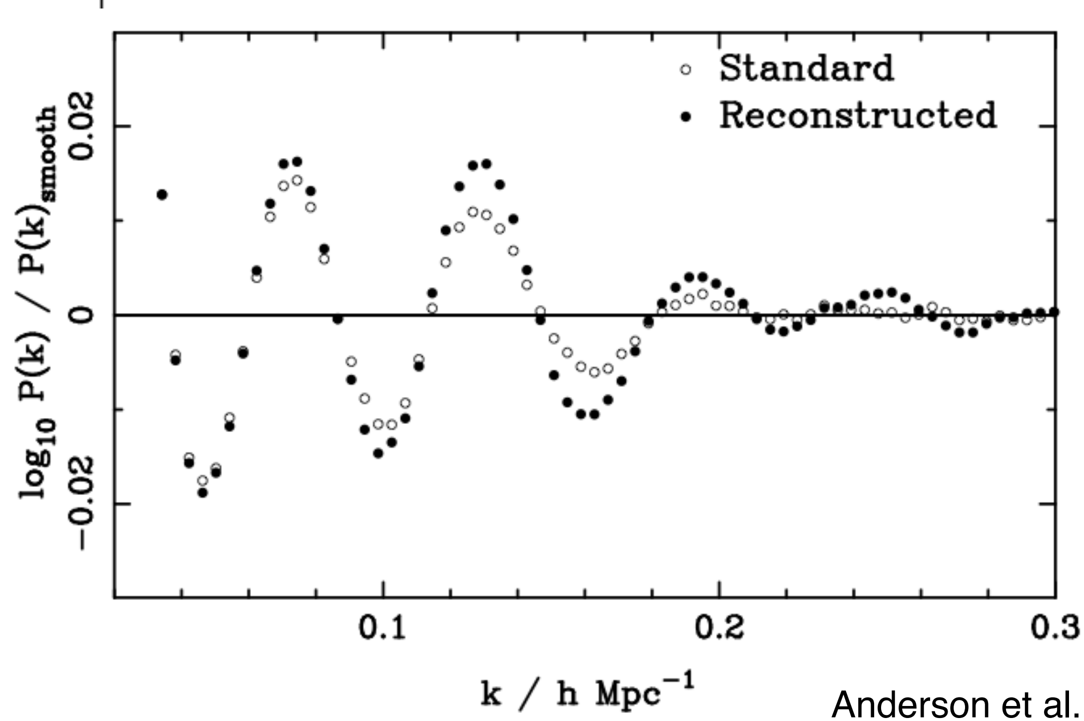
Reconstruction of linear positions



Padmanabhan et al. 2012; arXiv:1202.0090

Reconstruction on CMASS mocks





Anderson et al.

BAO results

Measuring a distance

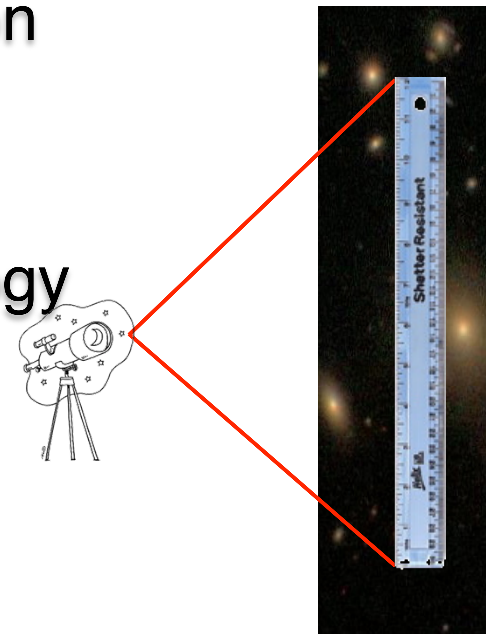
- Fit the observed acoustic feature using some way to parametrize over nuisance broad-band features (different approaches for P(k) and ξ(r))
- Use a fiducial model to compare against observed features in spherically averaged statistics. Departures quantified by dilation scale α:

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

- The dilation scale α depends on cosmology through:

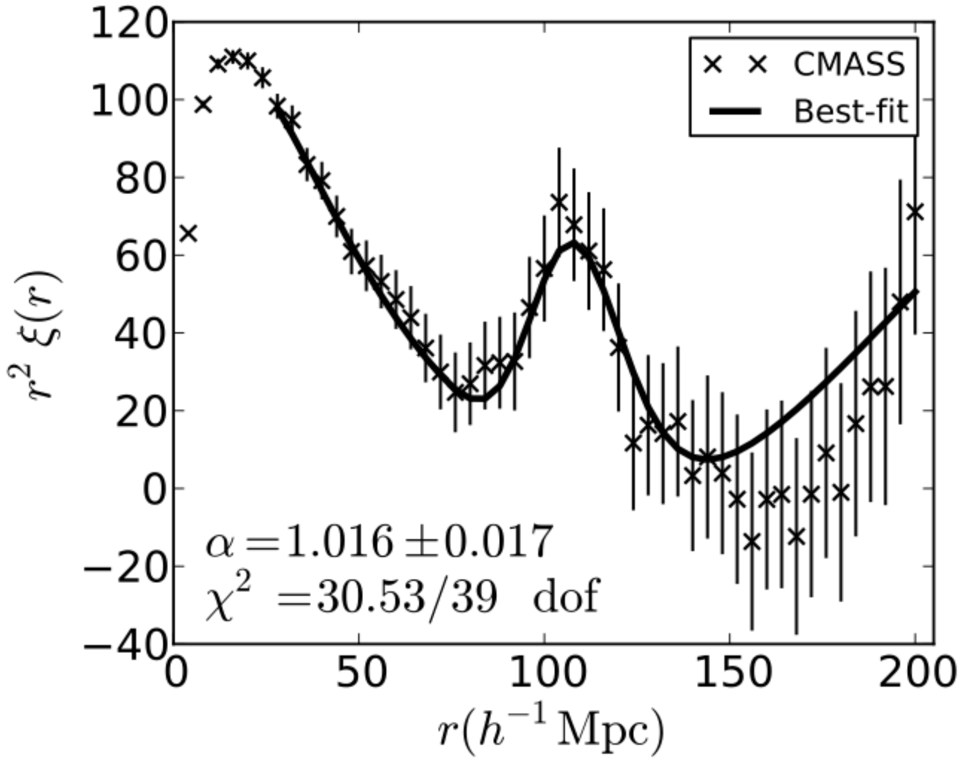
$$D_V / r_s = \alpha (D_V / r_s)_{fid}$$

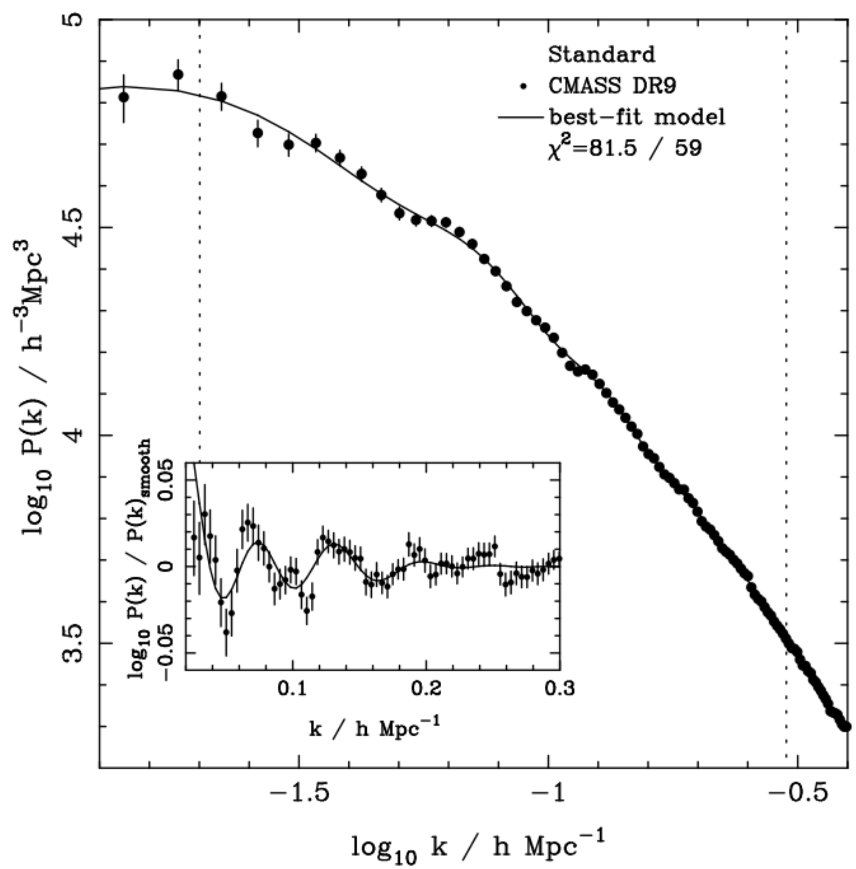
$$D_V = [cz(1 + z)^2 d_A^2 H^{-1}]^{1/3}$$



Anderson et al.

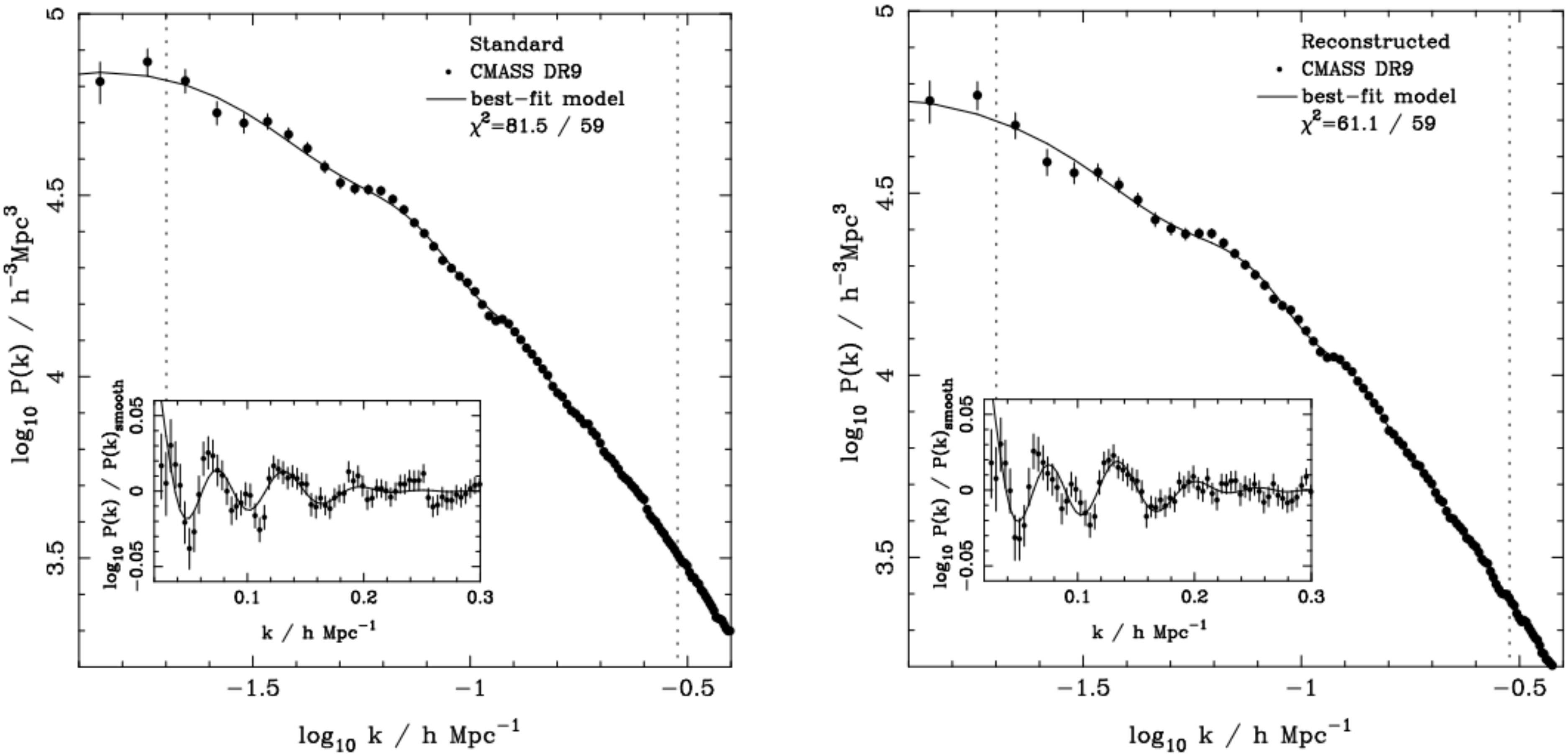
BOSS CMASS clustering measurements





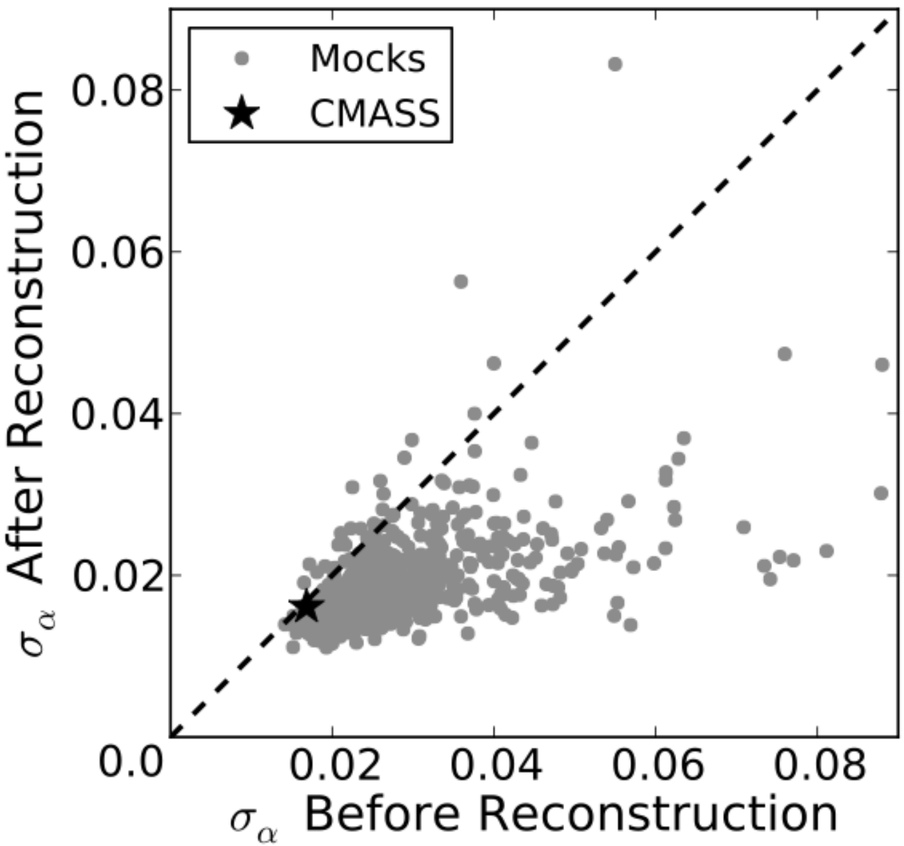
Anderson et al.

Reconstruction on CMASS



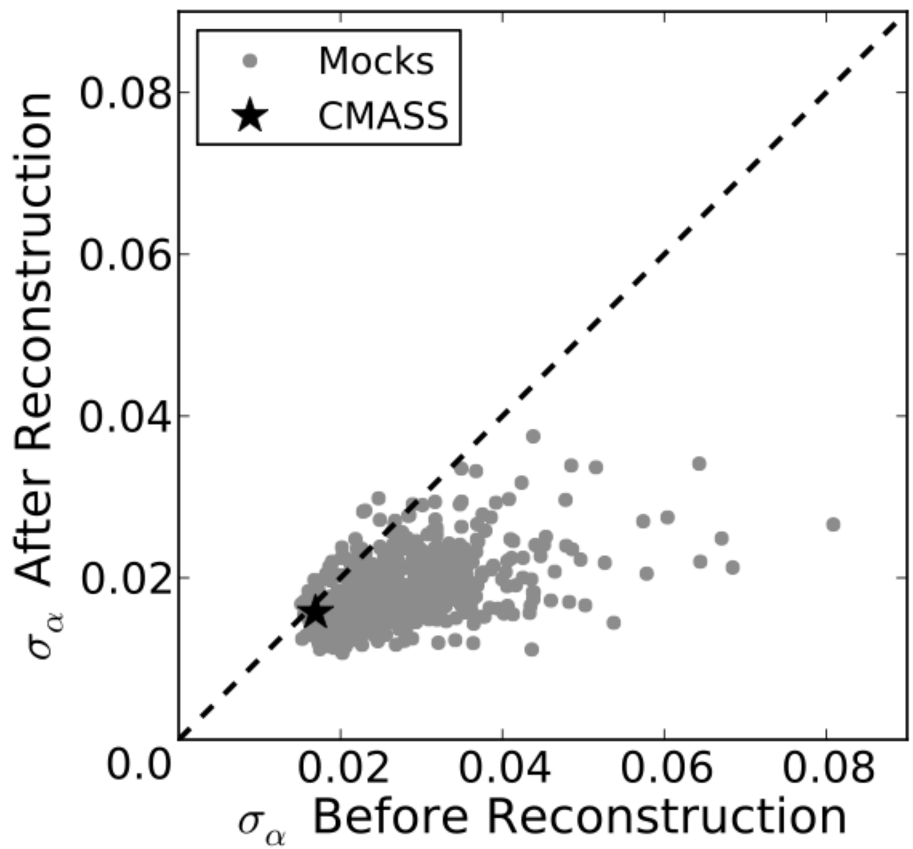
Anderson et al.

Reconstruction: error on α



Correlation function

Power spectrum



Anderson et al.

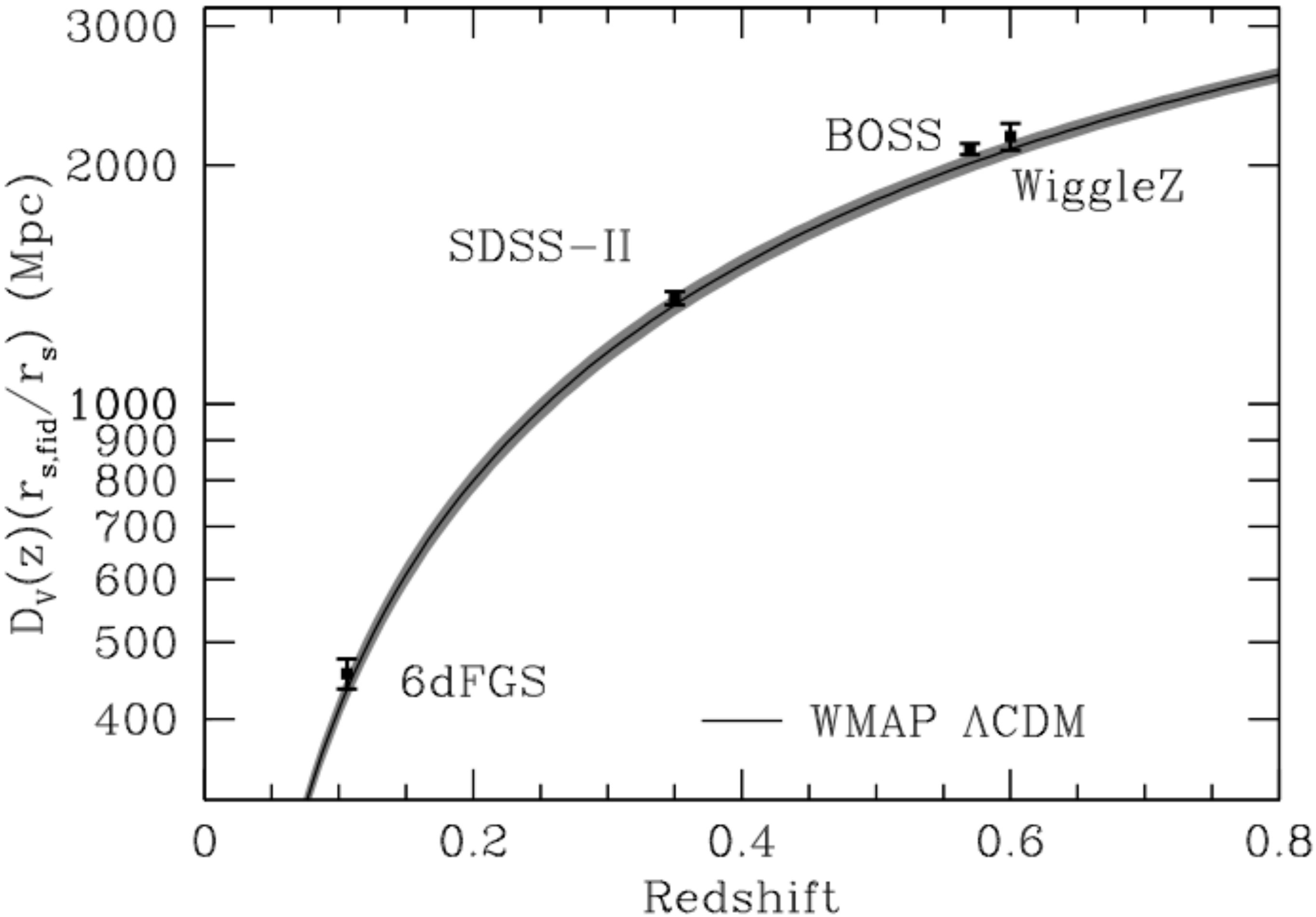
Key BAO measurements

	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.

CMASS results

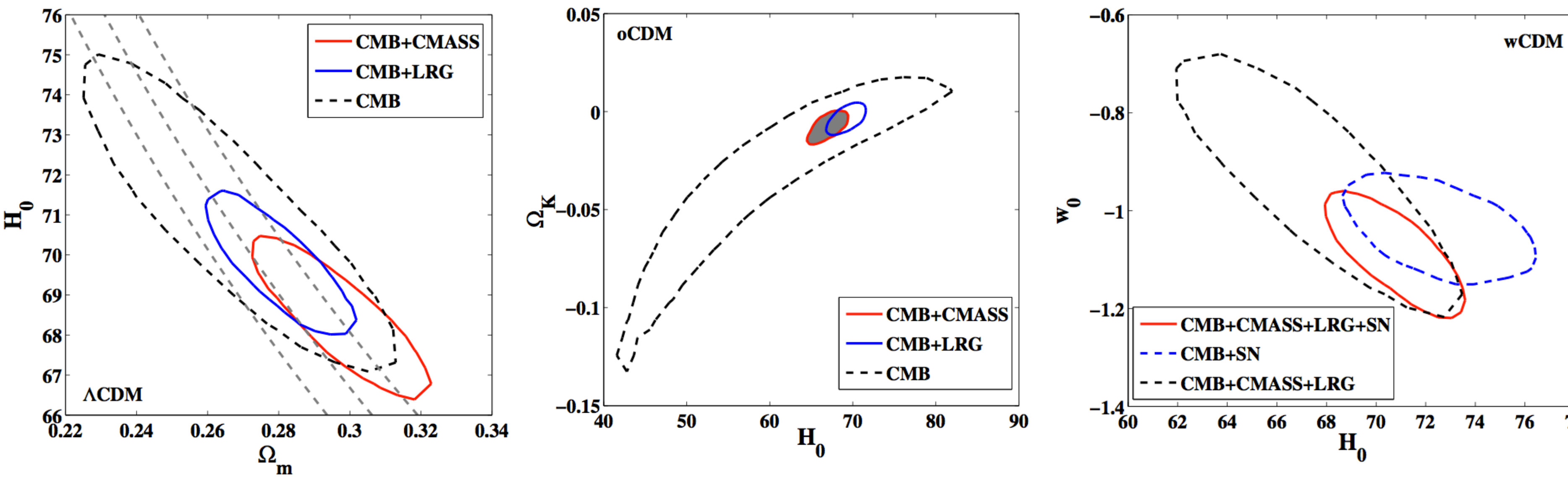


$$D_V(0.57)/r_s = 13.67 \pm 0.22$$

Anderson et al.

Constraints on Friedman equation

$$H^2(a) = H_0^2\Big[\Omega_R a^{-4} + \Omega_M a^{-3} + \Omega_k a^{-2} + \Omega_{DE} \exp\left\{3\int_a^1 \frac{da'}{a'}\left[1+w(a')\right]\right\}\Big]$$



2-param ΛCDM model

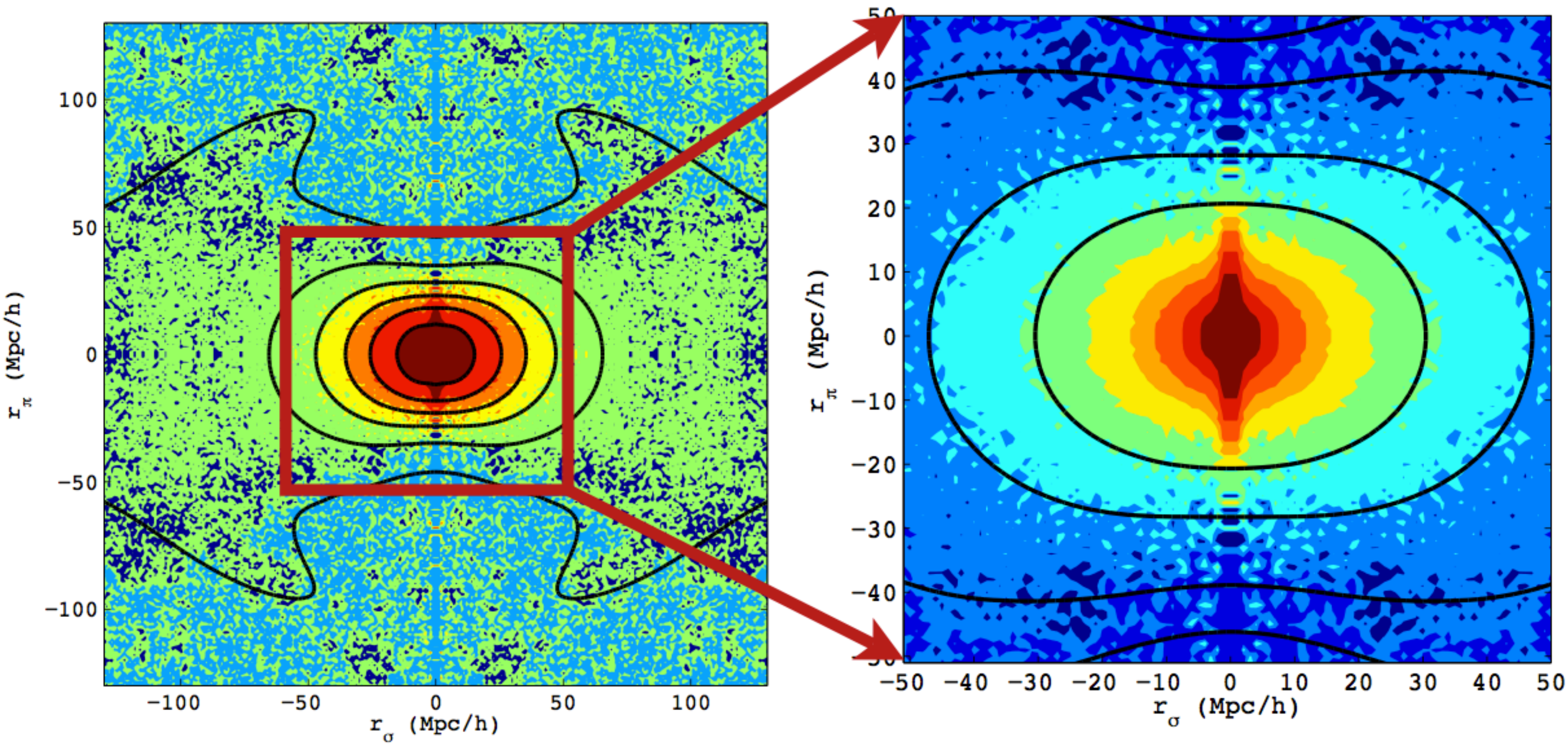
3-param oCDM model

4-param wCDM model

Anderson et al.

Anisotropic clustering results

Anisotropic clustering measurements



Reid et al.

Extra information from anisotropic measurements

- Including the quadrupole allows us to measure H and d_A separately (or include an additional measurement of F)

$$F = (1+z)\, d_A(z) H(z)/c$$

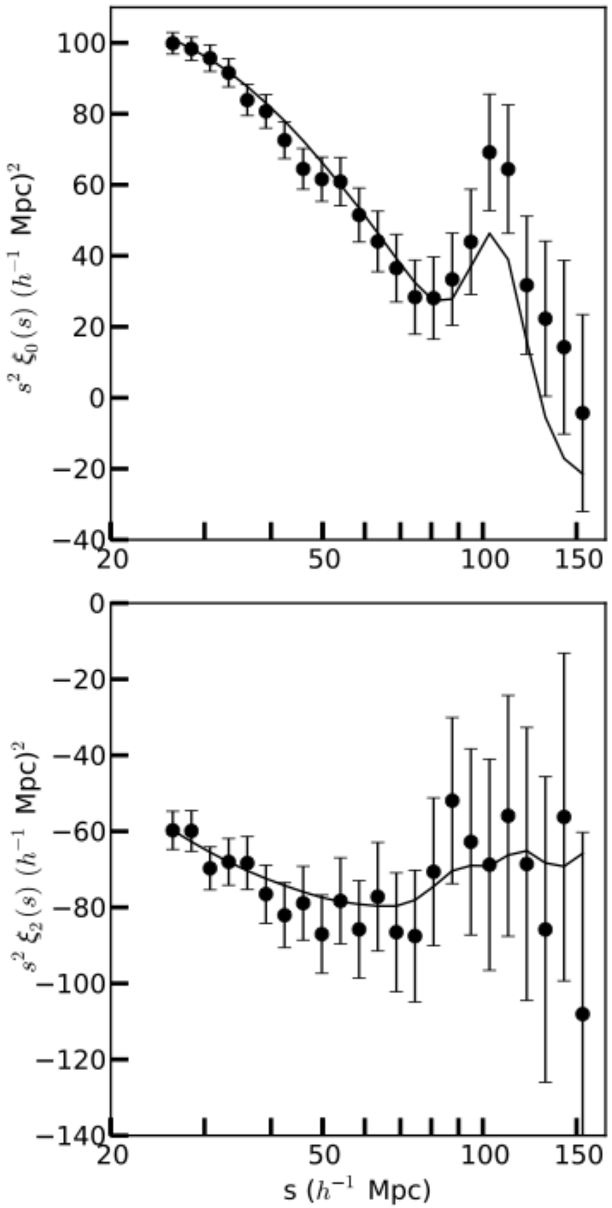
- F is sometimes called the Alcock-Paczynski parameter
- Can also measure the growth rate from the RSD contribution

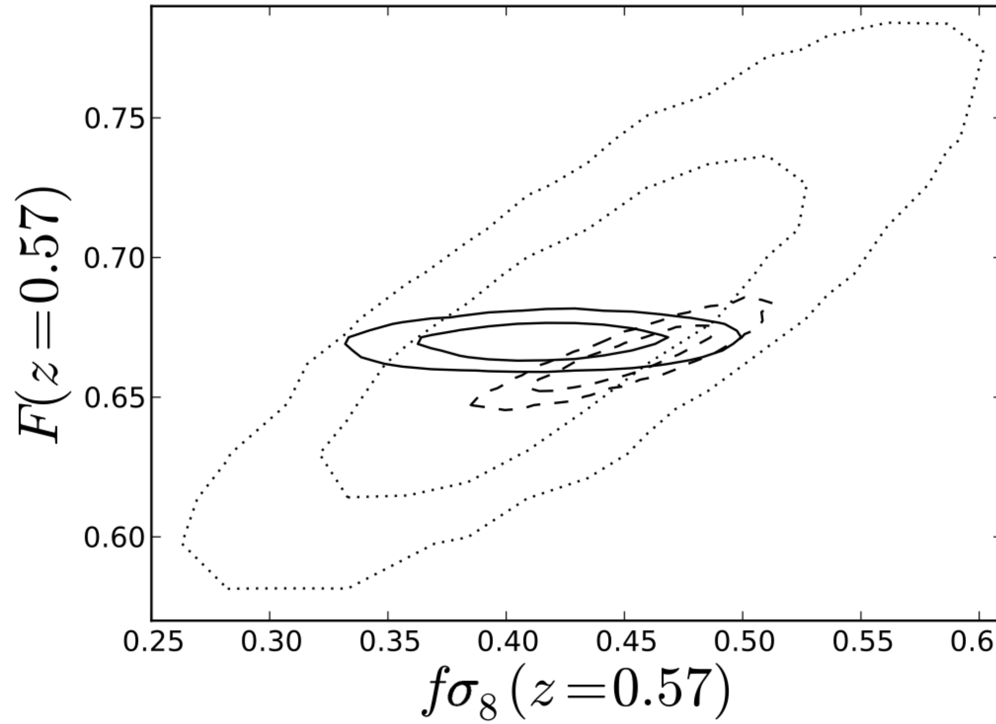
$$f\sigma_8(z=0.57)$$

- These are degenerate, but that degeneracy is not perfect

Reid et al.

Results of the anisotropic fit





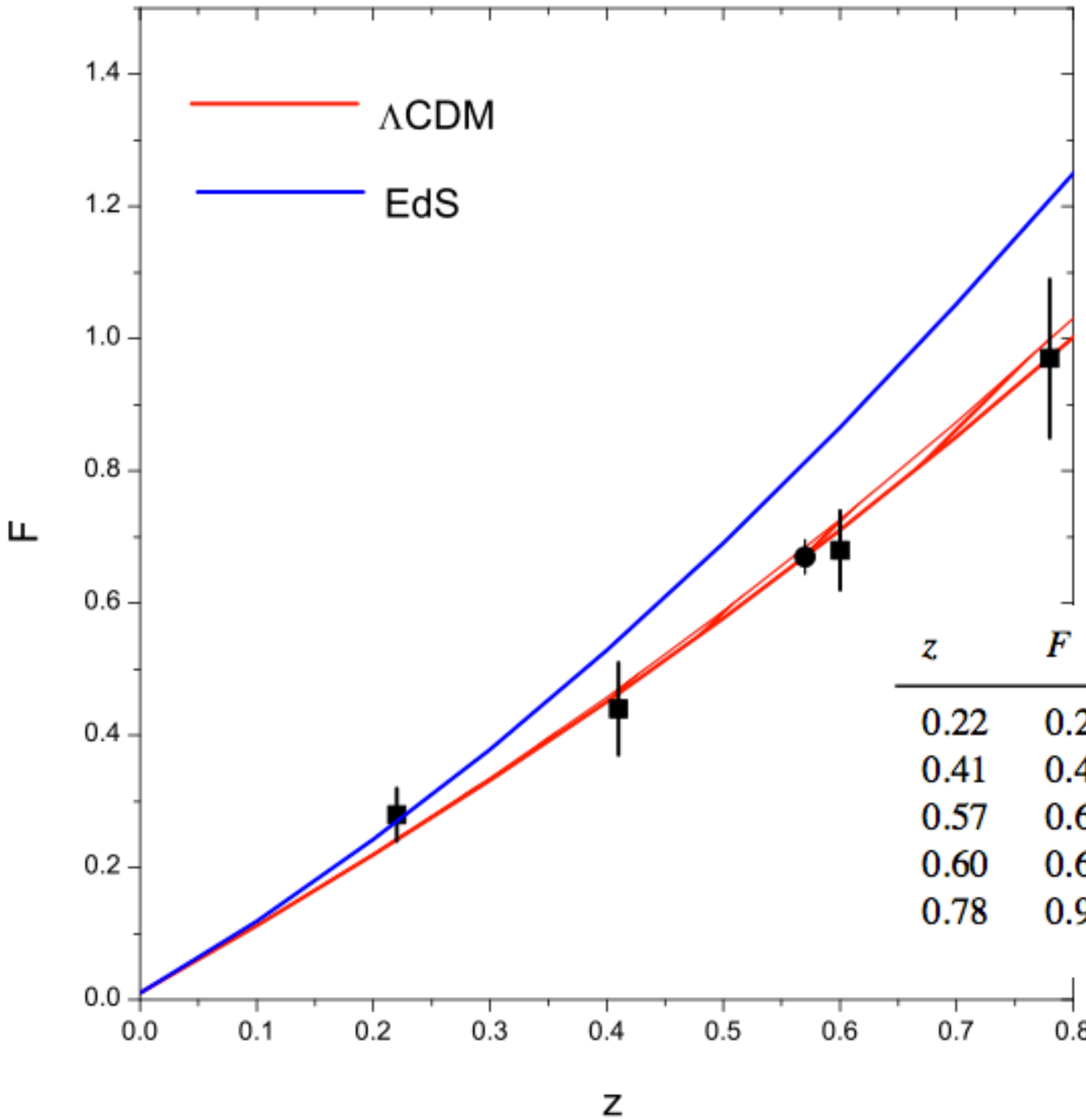
Dotted: free growth, geometry, ΛCDM prior on large-scale linear P(k) shape at z=0.57

Solid: F forced to match ΛCDM model

Dashed: WMAP ΛCDM+GR prediction

Reid et al.

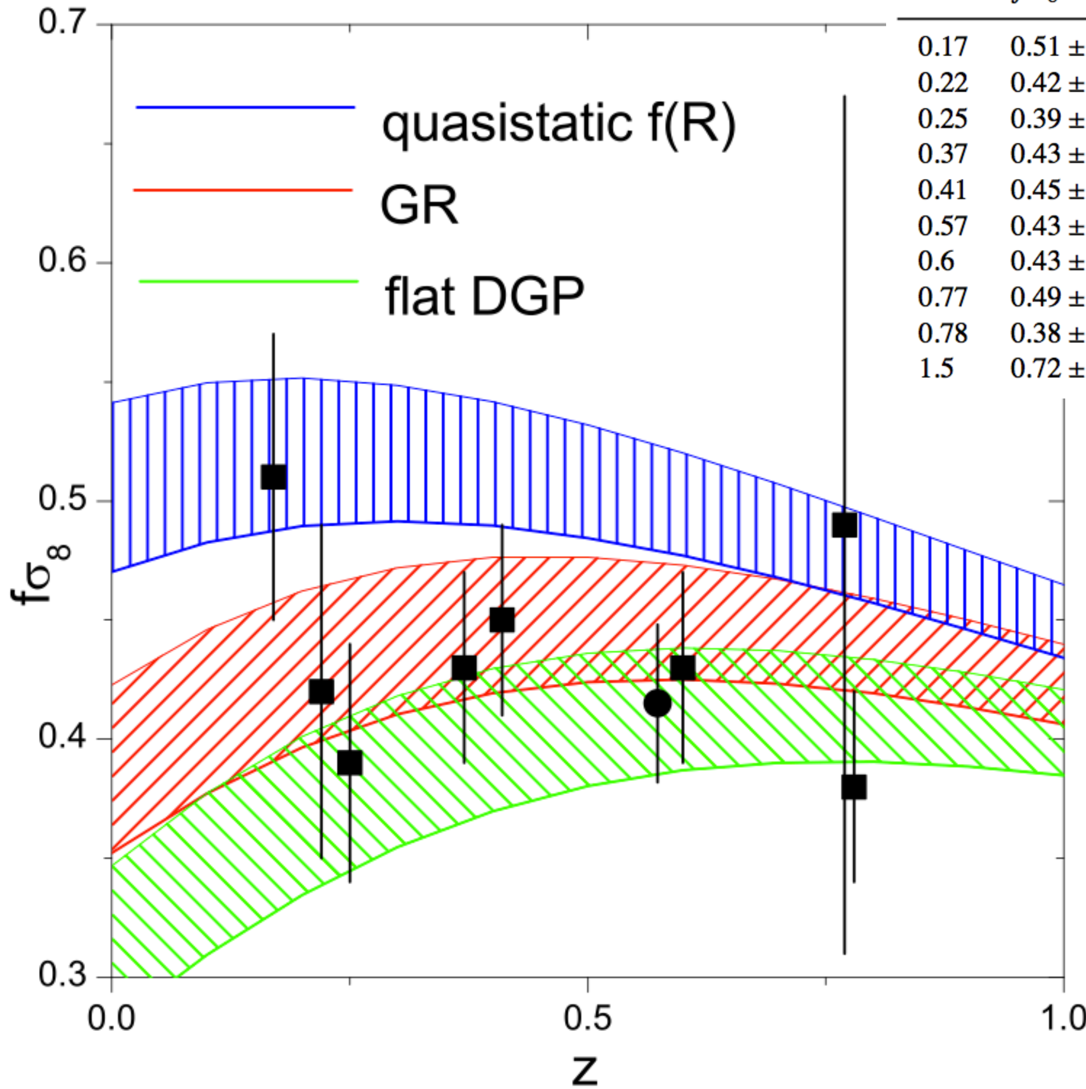
CMASS F measurements in context



z	F	survey	reference
0.22	0.28 ± 0.04	WiggleZ	Blake, et al. (2011c)
0.41	0.44 ± 0.07	WiggleZ	Blake, et al. (2011c)
0.57	0.67 ± 0.026	BOSS	Reid et al. (2012)
0.60	0.68 ± 0.06	WiggleZ	Blake, et al. (2011c)
0.78	0.97 ± 0.12	WiggleZ	Blake, et al. (2011c)

Samushia et al. (in prep), Reid et al.

CMASS RSD measurements in context

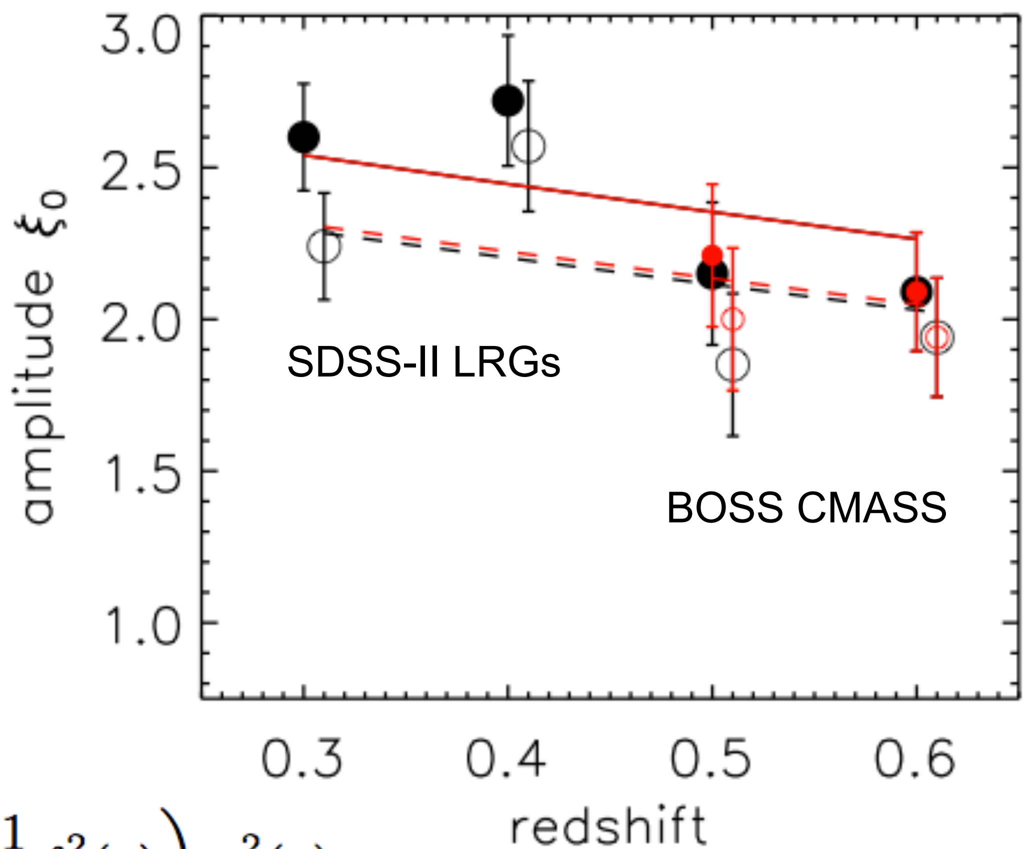


z	$f\sigma_8$	survey	reference
0.17	0.51 ± 0.06	2dFGRS	Percival et al. (2004)
0.22	0.42 ± 0.07	WiggleZ	Blake, et al. (2011b)
0.25	0.39 ± 0.05	SDSS	Samushia, Percival, & Raccanelli (2011)
0.37	0.43 ± 0.04	SDSS	Samushia, Percival, & Raccanelli (2011)
0.41	0.45 ± 0.04	WiggleZ	Blake, et al. (2011b)
0.57	0.43 ± 0.03	BOSS	Reid et al. (2012)
0.6	0.43 ± 0.04	WiggleZ	Blake, et al. (2011b)
0.77	0.49 ± 0.18	VVDS	Guzzo et al. (2007)
0.78	0.38 ± 0.04	WiggleZ	Blake, et al. (2011b)
1.5	0.72 ± 0.15	2SLAQ	da Angela et al. (2008)

Samushia et al. (in prep), Reid et al.

Using passive evolution to enhance RSD measurements

Most luminous 40% of CMASS sample are direct and passive progenitors of the SDSS-II LRG sample to within ~2%



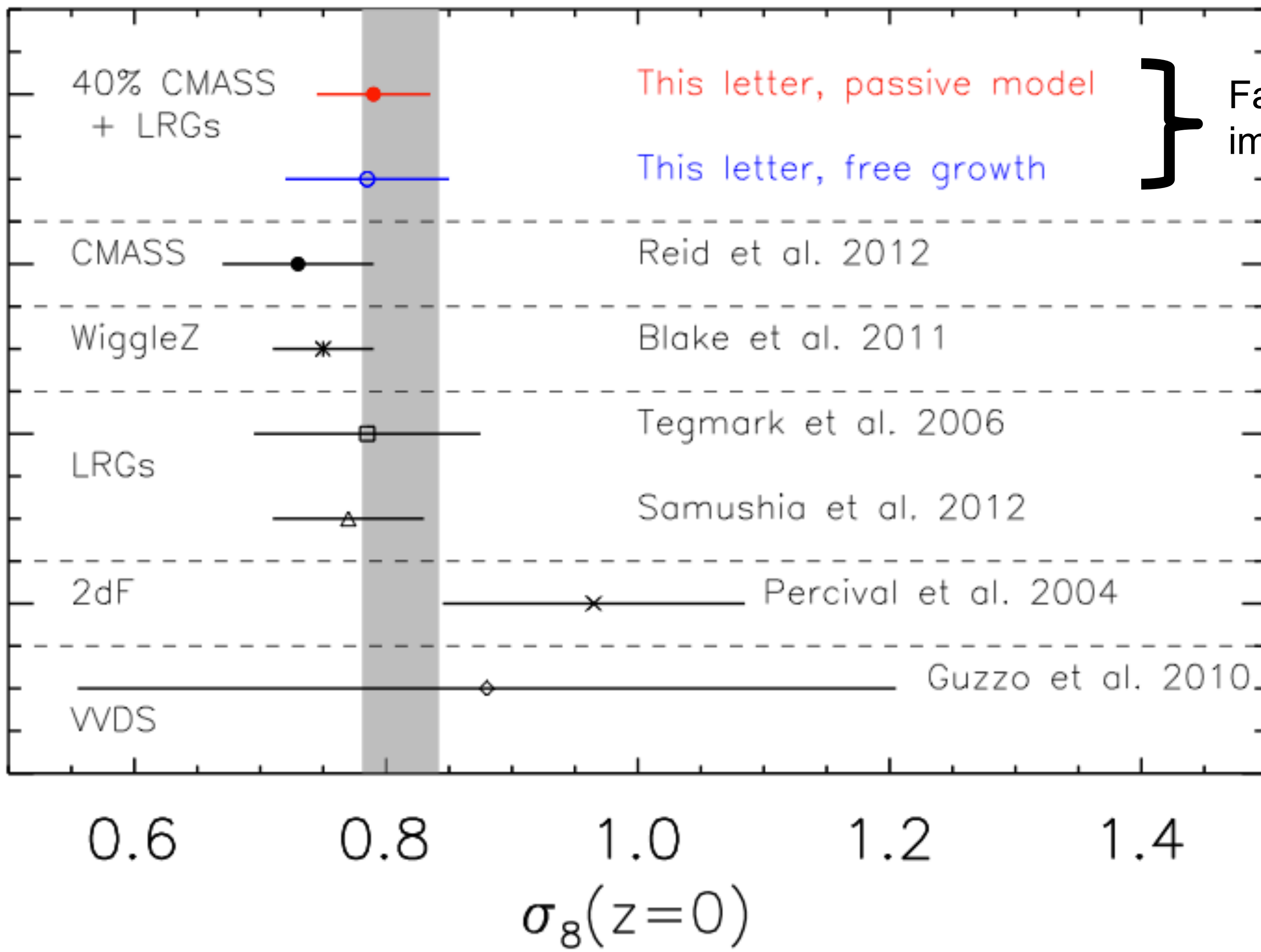
Line shows Fry (1996) model for a passively evolving population

$$A_0(z) = \left(b^2(z) + \frac{2}{3}f(z)b(z) + \frac{1}{5}f^2(z)\right)\sigma_8^2(z)$$

$$b(z) = [b(z_0) - 1]\frac{D(0)}{D(z_0)} + 1$$

Tojeiro et al. 2012; arXiv:1202.6241

Converting to σ_8 measurements

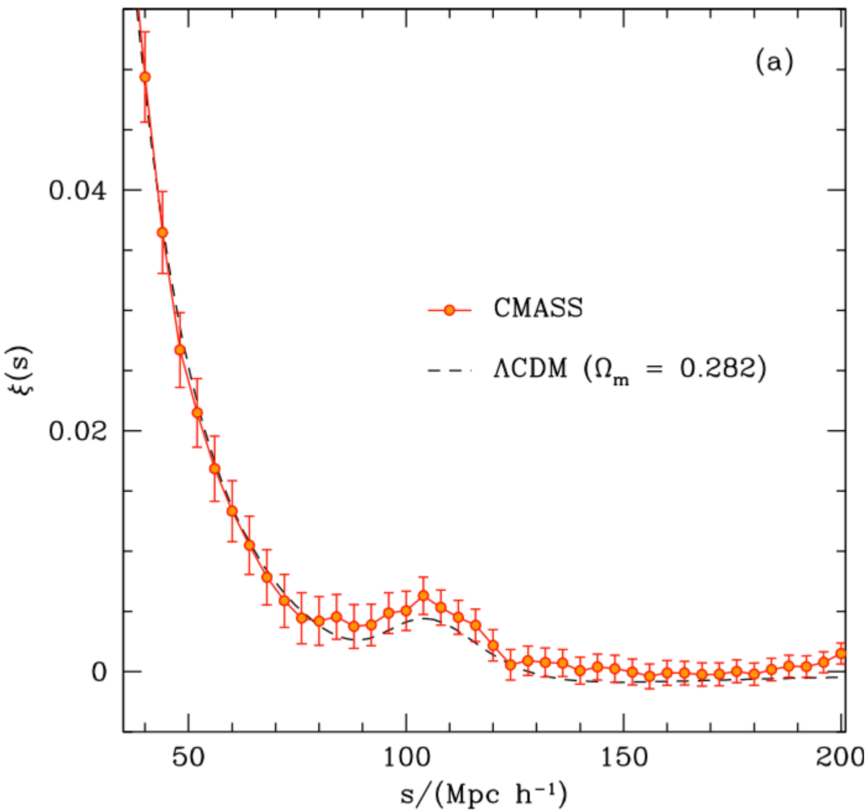


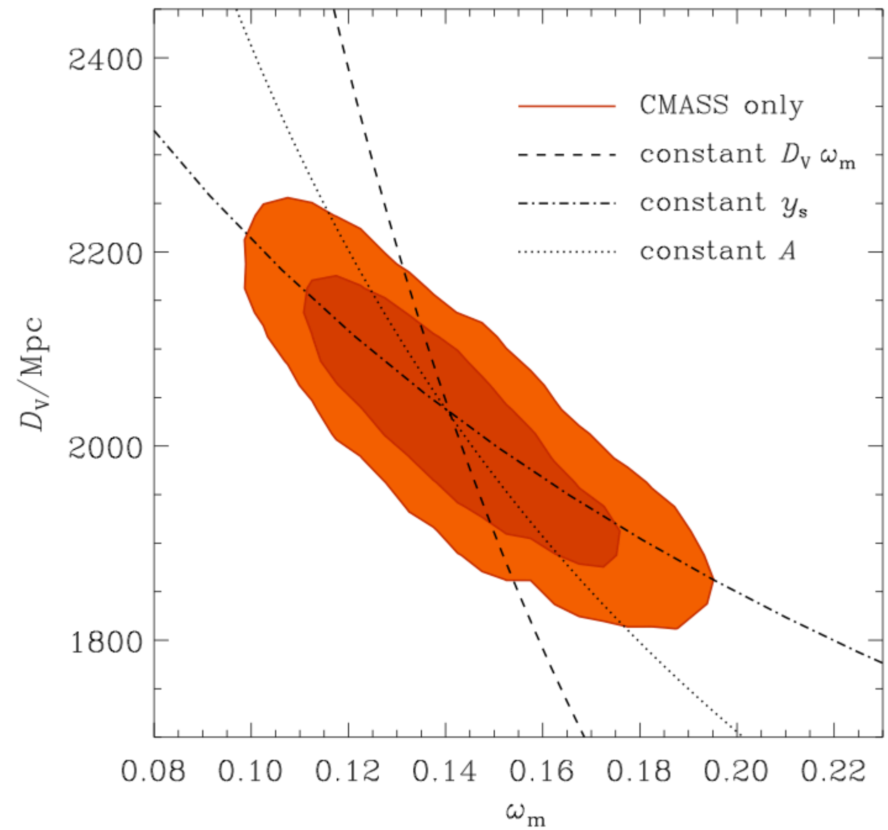
Factor 1.5 improvement

Tojeiro et al.

Fitting the full clustering signal

Fitting the full shape of the correlation function

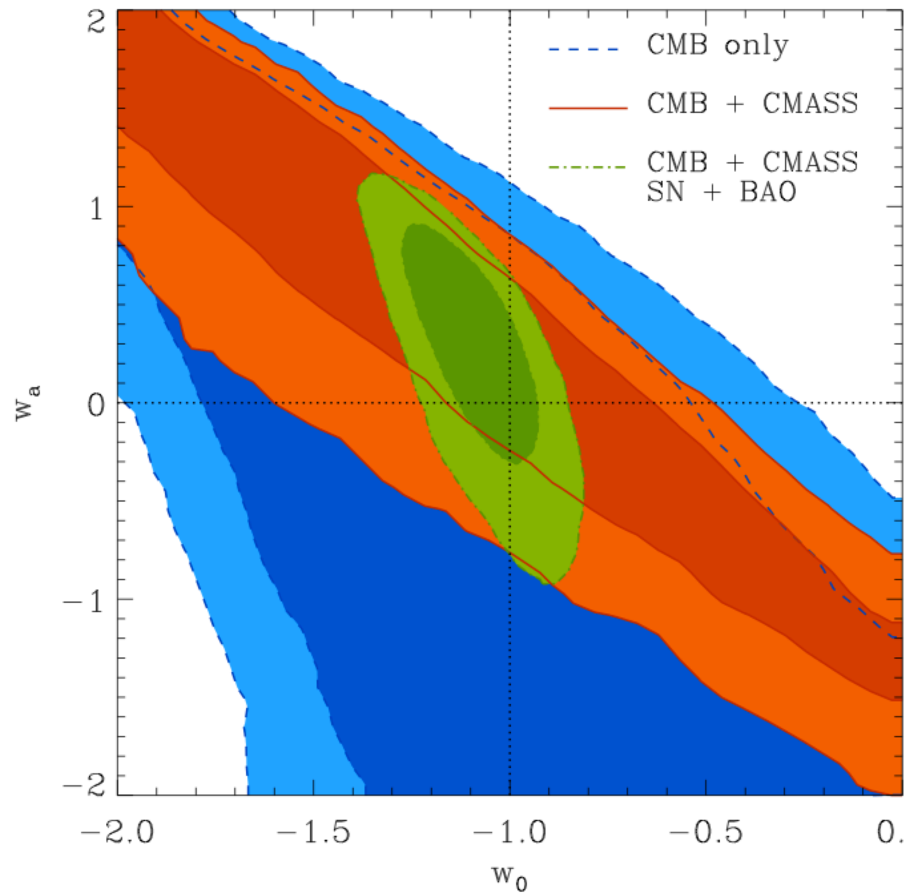




Sanchez et al.

Cosmological constraints from full fit

	CMB	CMB + CMASS	CMB + CMASS +SN	CMB + CMASS +BAO	CMB + CMASS + BAO + SN
w_0	$-1.12^{+0.52}_{-0.51}$	$-1.12^{+0.61}_{-0.58}$	$-1.09^{+0.11}_{-0.11}$	$-0.95^{+0.27}_{-0.27}$	$-1.08^{+0.11}_{-0.11}$
w_a	$-0.3^{+1.2}_{-1.7}$	$0.32^{+0.98}_{-0.99}$	$0.12^{+0.48}_{-0.47}$	$0.05^{+0.62}_{-0.61}$	$0.23^{+0.42}_{-0.42}$
100Θ	$1.0409^{+0.0016}_{-0.0016}$	$1.0409^{+0.0016}_{-0.0016}$	$1.0408^{+0.0015}_{-0.0016}$	$1.0409^{+0.0016}$	$1.0408^{+0.0016}$
$100\omega_b$	$2.219^{+0.042}_{-0.042}$	$2.218^{+0.042}_{-0.041}$	$2.215^{+0.040}_{-0.040}$		
$100\omega_{dm}$	$11.22^{+0.47}_{0.47}$	$11.31^{+0.46}_{-0.46}$	$11.40^{+0.45}_{-0.45}$		
τ	$0.0852^{+0.0061}_{-0.0069}$	$0.0833^{+0.0062}_{0.0067}$	$0.0823^{+0.0058}_{-0.0067}$		
n_s	$0.965^{+0.011}_{-0.011}$	$0.965^{+0.011}_{-0.011}$	$0.963^{+0.011}_{-0.011}$		
$\ln(10^{10}A_s)$	$3.083^{+0.030}_{-0.029}$	$3.082^{+0.030}_{-0.030}$	$3.083^{+0.029}_{-0.029}$		
$\Omega_{\rm DE}$	$0.760^{+0.081}_{-0.087}$	$0.722^{+0.081}_{-0.091}$	$0.730^{+0.016}_{-0.016}$		
$\Omega_{\rm m}$	$0.239^{+0.087}_{-0.081}$	$0.278^{+0.091}_{-0.081}$	$0.269^{+0.016}_{-0.016}$		
σ_8	$0.87^{+0.12}_{-0.12}$	$0.82^{+0.11}_{-0.11}$	$0.832^{+0.049}_{-0.049}$		
$t_0/{\rm Gyr}$	$13.64^{+0.22}_{-0.22}$	$13.79^{+0.16}_{-0.16}$	$13.763^{+0.089}_{-0.091}$		
$z_{\rm re}$	$10.4^{+1.2}_{-1.2}$	$10.3^{+1.2}_{-1.2}$	$10.2^{+1.2}_{-1.2}$		
h	$0.78^{+0.14}_{-0.14}$	$0.72^{+0.11}_{-0.11}$	$0.712^{+0.020}_{-0.020}$		
$D_{\rm V}(z_m)/{\rm Mpc}$	1974^{+86}_{-83}	2040^{+47}_{-45}	2027^{+25}_{-25}		
$f(z_{\rm m})$	$0.733^{+0.077}_{-0.078}$	$0.770^{+0.064}_{-0.069}$	$0.766^{+0.022}_{-0.022}$		



Sanchez et al.

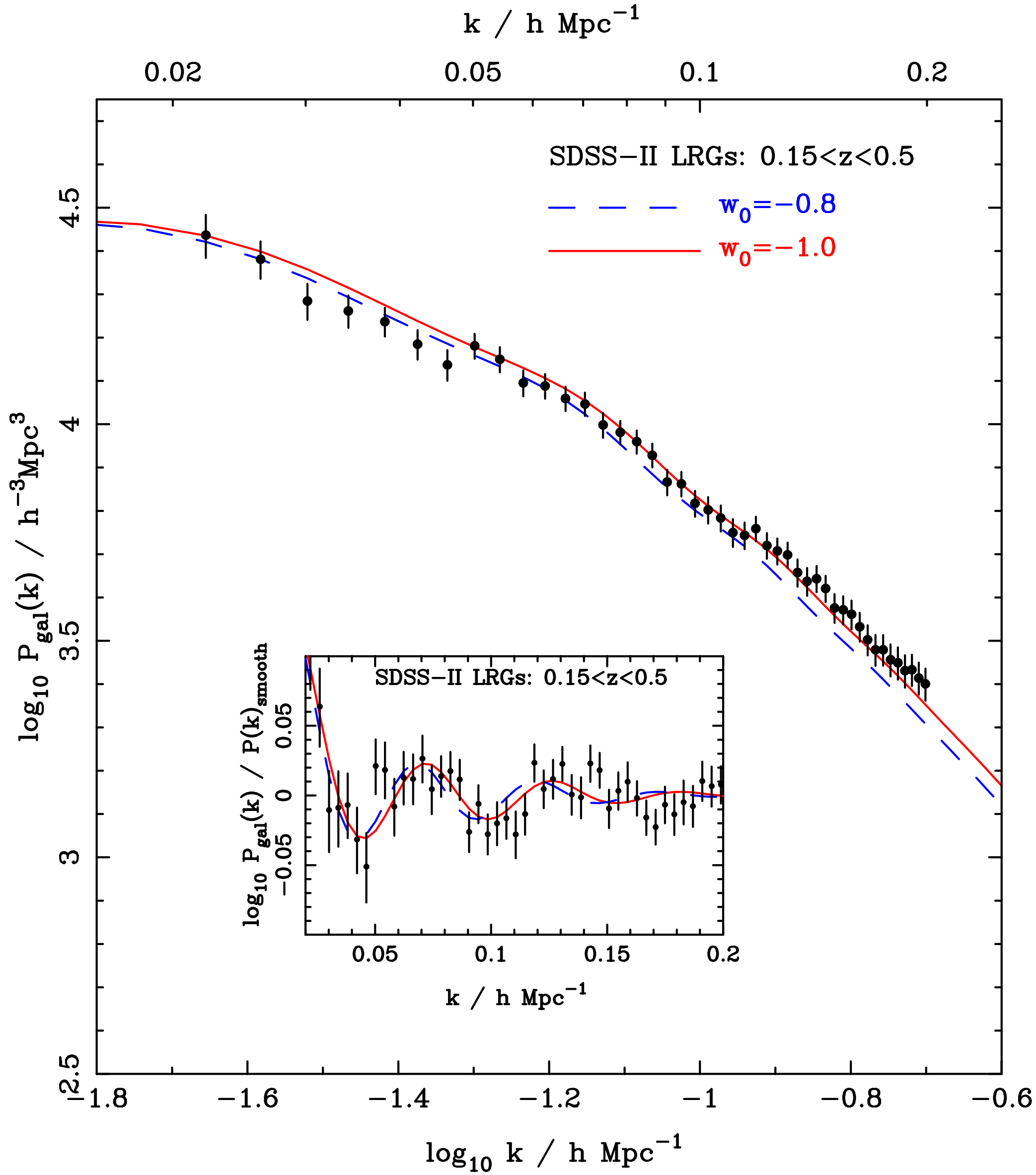
The Future …

SDSS-II LRG clustering

SDSS LRGs at z~0.35

Total effective volume

$V_{eff} = 0.26\ Gpc^3h^{-3}$

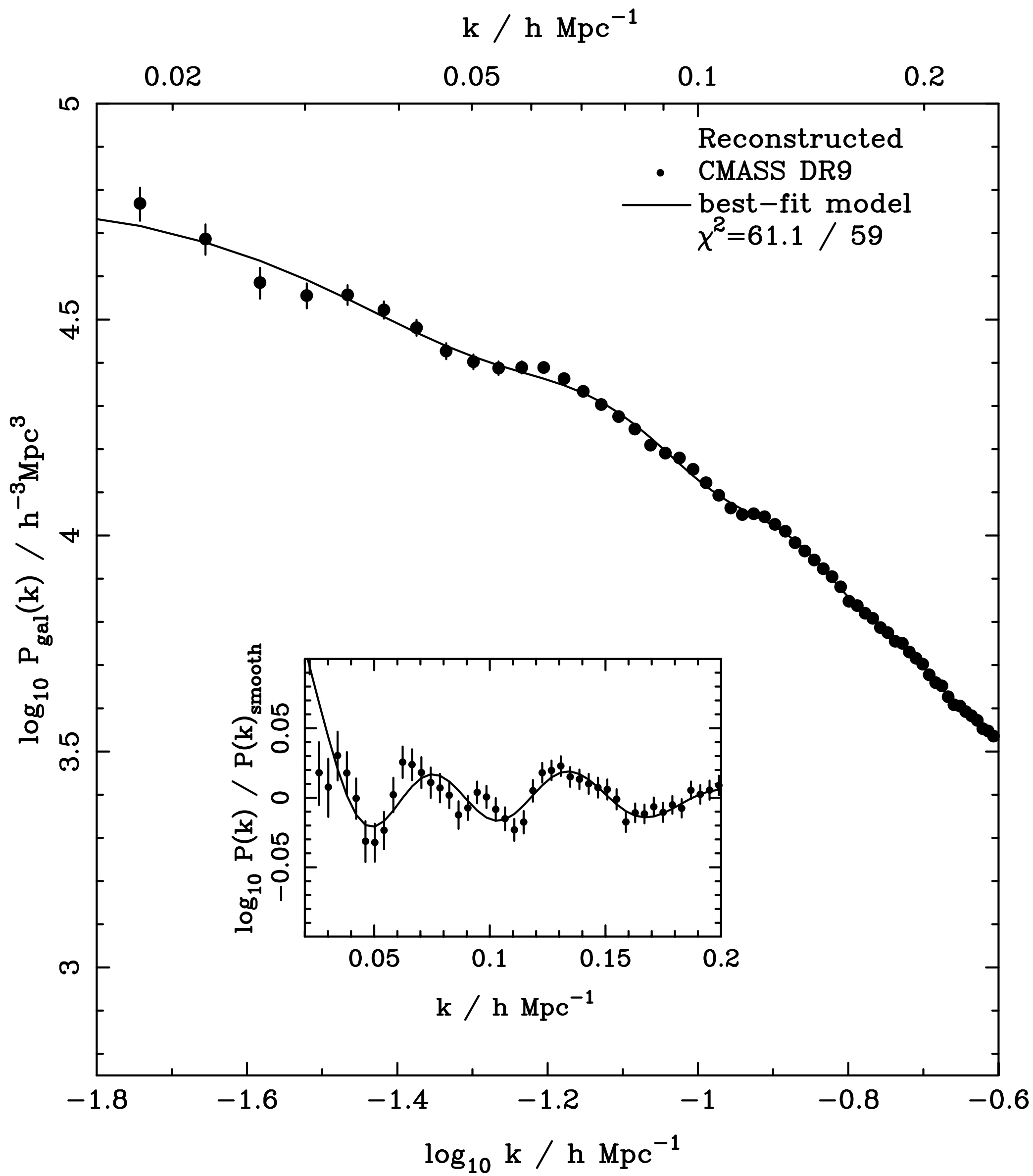


Percival et al. 2009; arXiv:0907.1660

BOSS CMASS DR9 galaxy clustering

BOSS CMASS galaxies at z~0.57

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

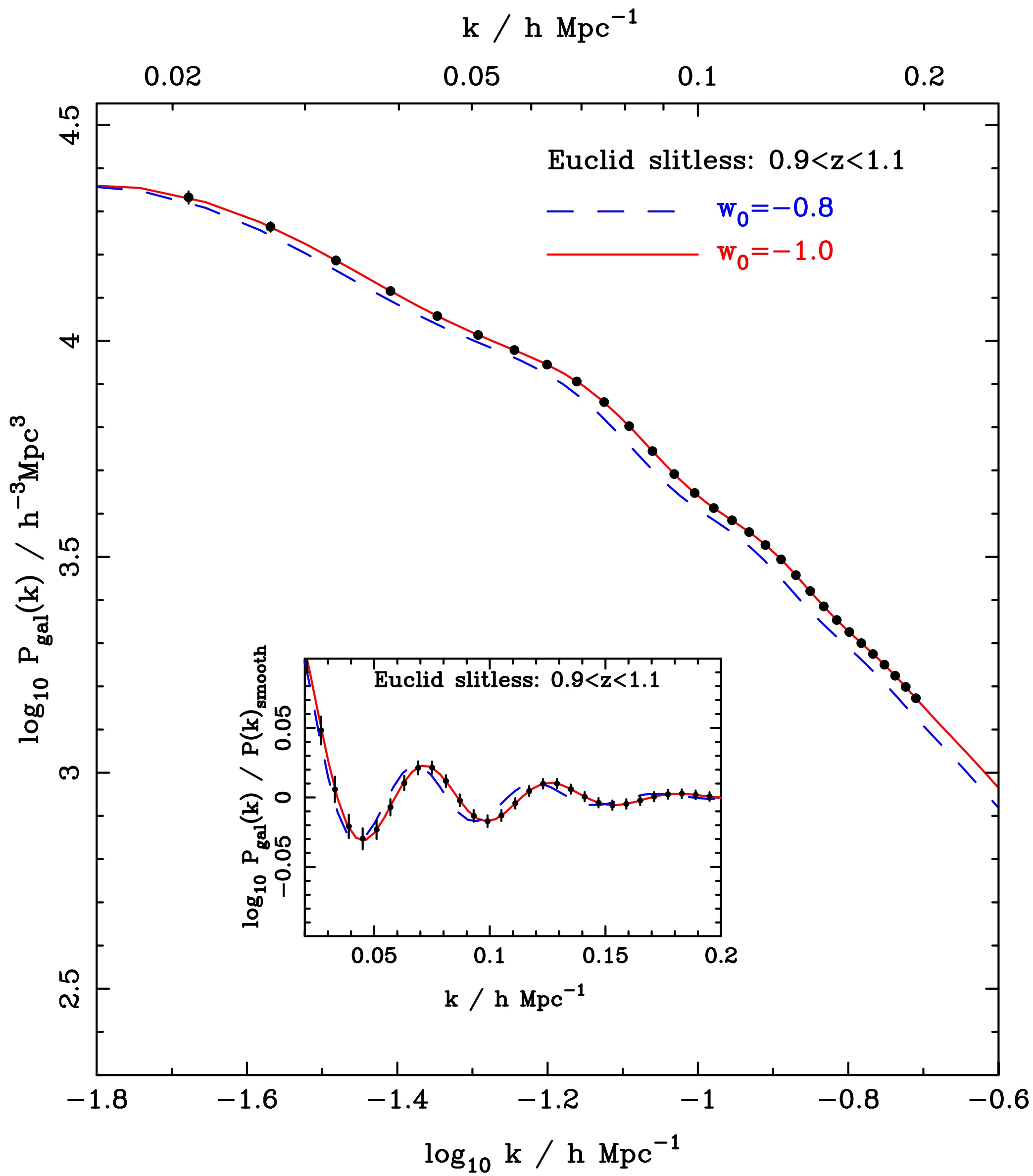


Anderson et al.

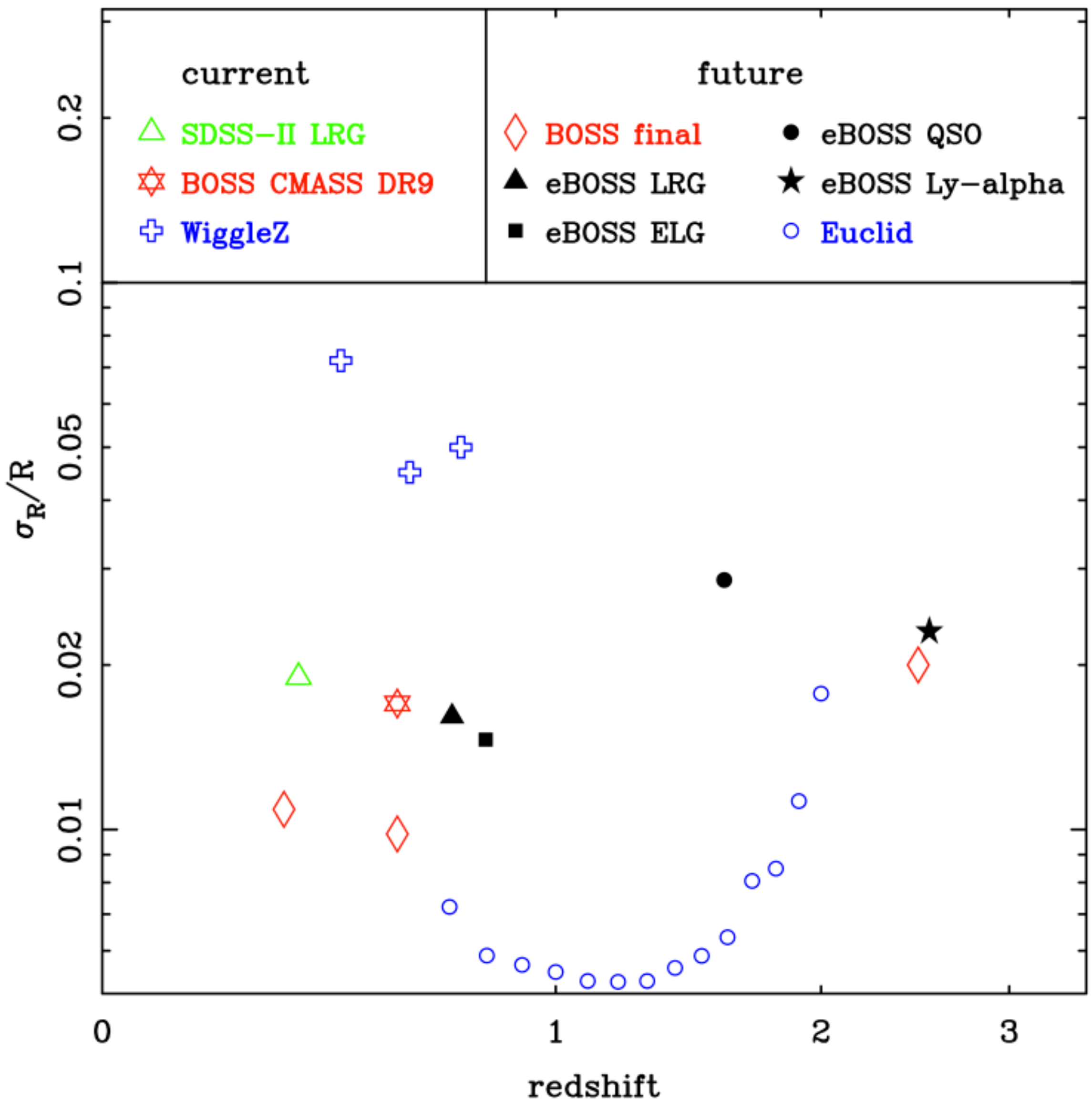
Predicted Euclid galaxy clustering

Redshift slice
$0.9 < z < 1.1$

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



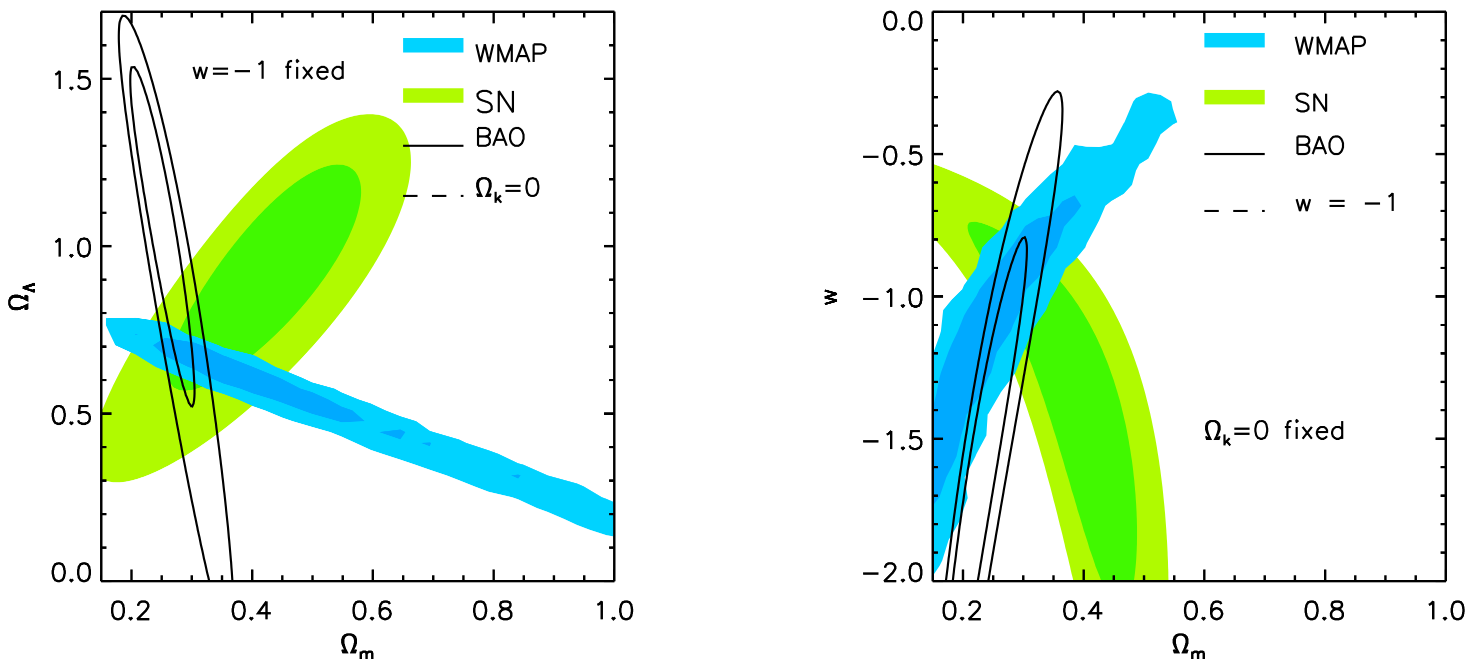
Distance measurements for future surveys



SDSS-II LRG BAO vs other data

ΛCDM models with curvature

flat wCDM models

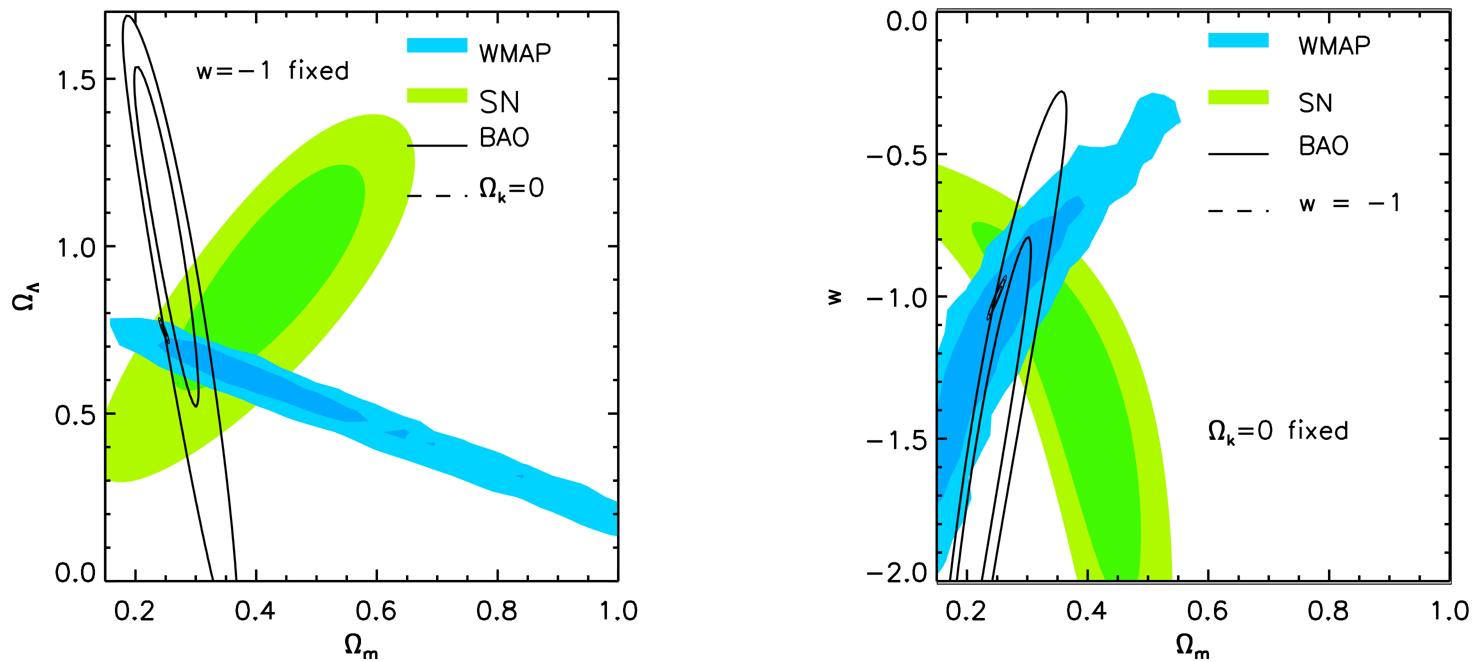


- Union supernovae
- WMAP 5year
- SDSS-II BAO Constraint on $r_s(z_d)/D_V(0.2)$ & $r_s(z_d)/D_V(0.35)$

Percival et al. 2009; arXiv:0907.1660

Euclid BAO predictions

ΛCDM models with curvature | flat wCDM models



- Union supernovae
- WMAP 5year
- SDSS-II BAO Constraint on $r_s(z_d)/D_V(0.2)$ & $r_s(z_d)/D_V(0.35)$

Conclusions

- Anderson et al. (alphabetical) arXiv:1203.6565
- Reid et al. arXiv:1203.6641
- Sanchez et al. arXiv:1203.6616
- Ross et al. arXiv:1203.6499
- Manera et al. arXiv:1203.6609
- Tojeiro et al. arXiv:1203.6565

- Lots more to come …
  - BOSS DR9 papers on GR implications, f_{NL}, Ω_{v}, anisotropic BAO
  - BOSS DR9 is only ~1/3 of the final data set (DR12 Dec 2014)
  - future ground-based surveys (eBOSS, DESpec, BigBOSS, WEAVE, 4MOST, SKA)
  - future space-based surveys (Euclid, WFIRST)