Baryon Oscillation Spectroscopic Survey (BOSS)

The state of the survey

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BOSS

- BOSS is a “new” redshift survey designed to constrain DE using the baryon acoustic oscillation (BAO) method
  - Galaxies z~0.1-0.7
    - 1% d_A, 2% H(z), z~0.4 & 0.6.
  - QSOs (LyAF) z~2-3
    - 1.5% d_A,H at z~2.5
- BOSS is also measuring the growth of structure, galaxy formation and evolution, quasars, …
- BOSS builds upon two success of SDSS-I & II
  - Color selection of luminous galaxies at “high” z
  - Studies of QSO absorption line systems.

Dark energy and cosmic sound

- There are now several independent lines of evidence that the expansion of the Universe is accelerating.
- Measuring the expansion rate essentially involves measuring distances
  - Standard ruler method: suppose we had an object whose length we knew as a function of epoch.
  - By measuring the angle subtended by this ruler as a function of redshift we map out the angular diameter distance d_A.
  - By measuring the redshift interval associated with this distance we map out the Hubble parameter $H(z)$.
- Baryon Acoustic Oscillations:
  - Coupling of baryons and photons in early Universe allows propagation of acoustic waves.
  - Distance waves can propagate before recombination becomes a "standard scale" which can be measured.
  - Features in 2-point function of matter/galaxies/…

BOSS in a nutshell

(Eisenstein et al. 2011)

- BOSS has:
  - ~8,000 deg^2 footprint in Spring
  - ~3,000 deg^2 footprint in Fall
- Upgraded spectrographs (with better throughput c.f. SDSS-I & II)
  - 1000x 2-arcsec fibers in cartridges
  - Increase wavelength range to 3600-10,000A (R=1500-2600)

- Finished ~3,000 deg^2 southern imaging in Fall 2008.
  - Released as part of DR8, published in ApJS (2011).

- Currently doing only spectroscopy
  - 1.3 million galaxies, $i<19.9$, $z<0.8$, over 10,000 deg^2
  - 150,000 QSOs, $g<22$, $2.3<z<3$, over 8,000 deg^2

BOSS data release schedule

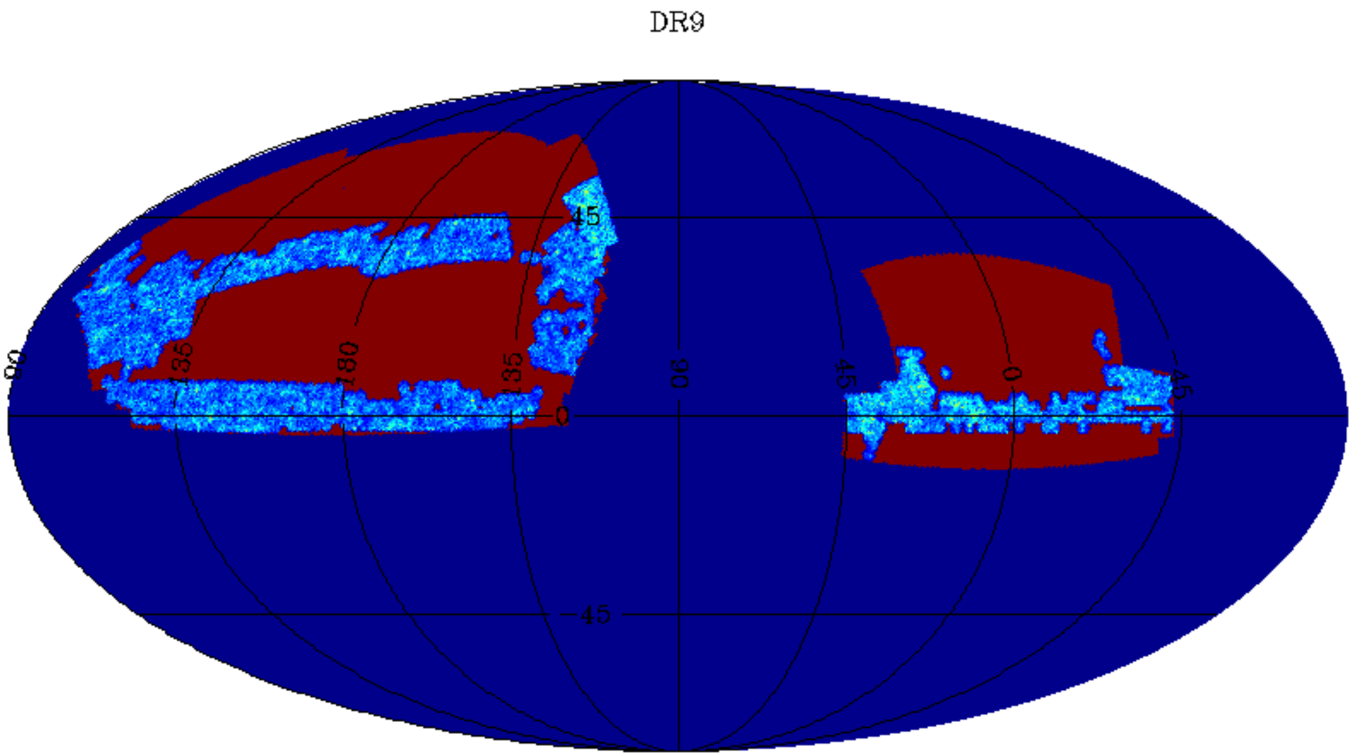
Date	Data release	What
Dec 2010	DR8	Imaging (Jan 2010)
July 2012	DR9	Spectra (July 2011)
July 2013	DR10	Spectra (July 2012)
Dec 2014	DR12	Spectra (Complete)

Outline

Summary of results from DR9

- The galaxy survey
- Constraining dark energy/modified gravity.
  - Baryon acoustic oscillations.
  - Redshift space distortions.
- Constraining quasar demographics.
- The Lyα forest survey.

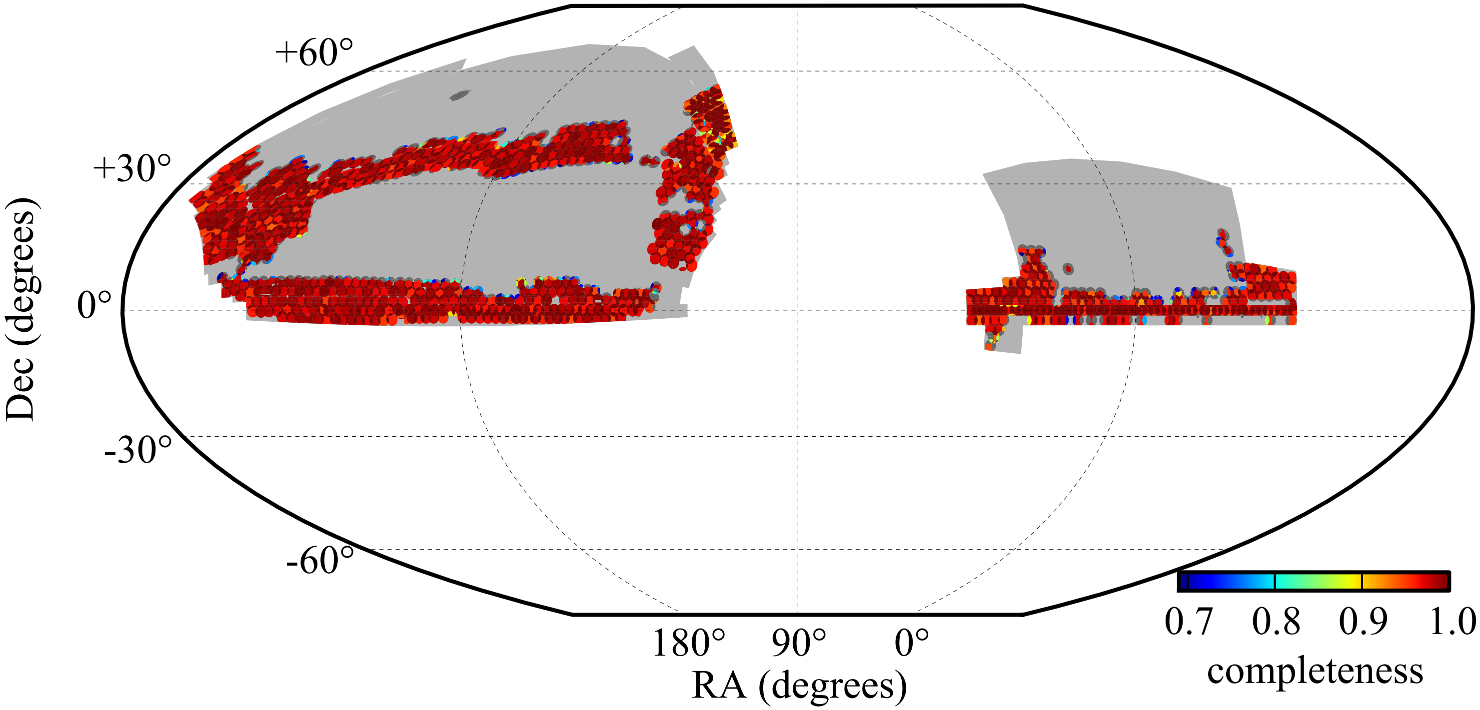
Sky coverage for DR9

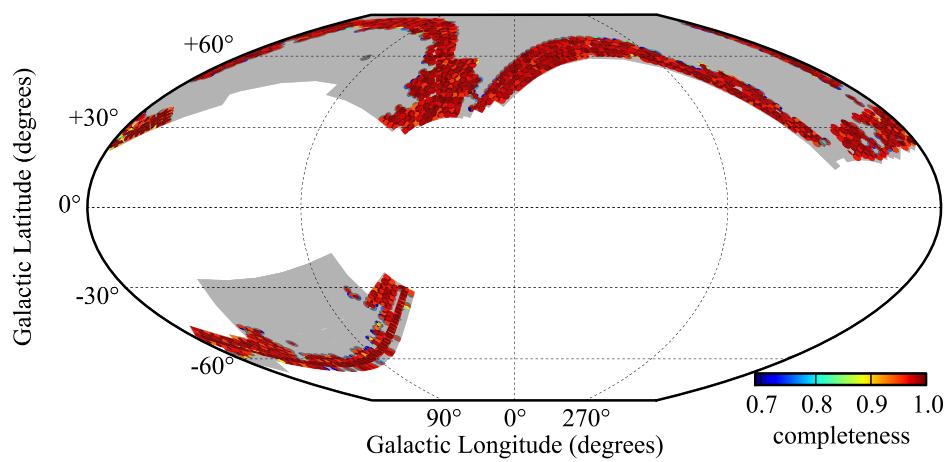


3275 deg^2

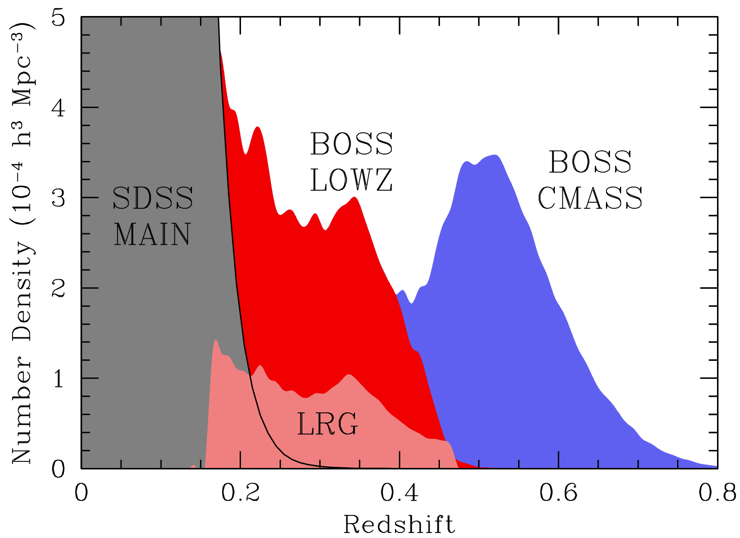
Approximately ~1/3 of the final data, though with a slightly worse geometry …

Sky Coverage of DR9: 3275 deg^2



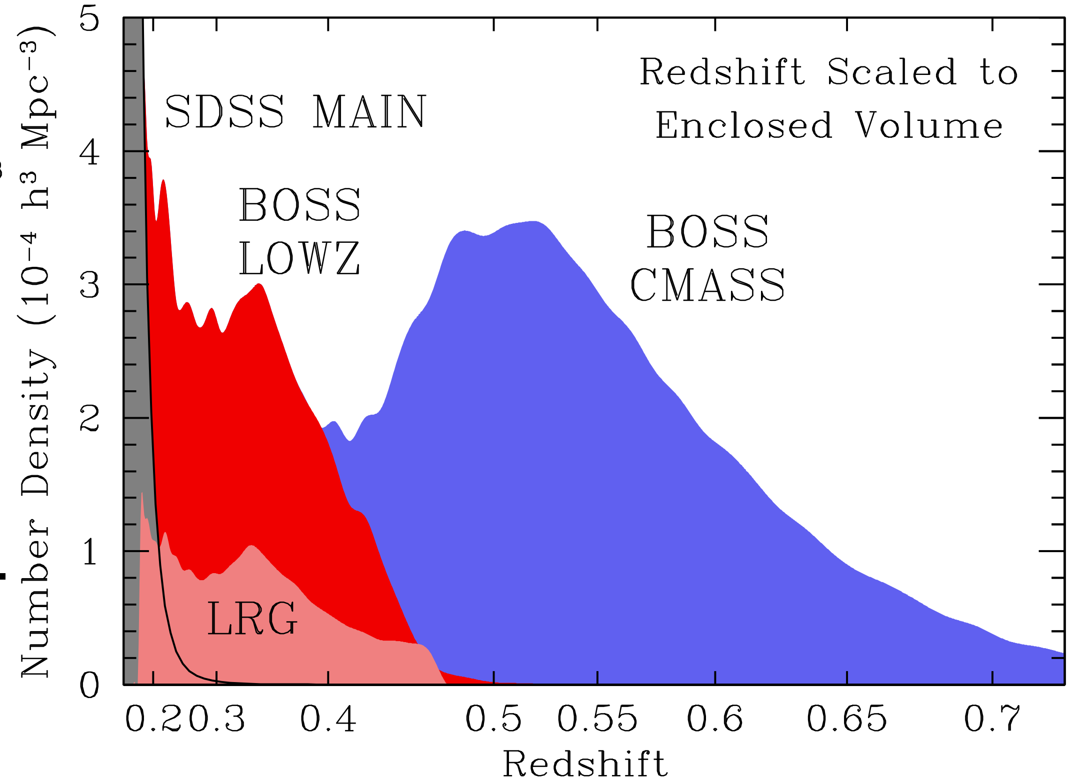


Two galaxy samples



Effective volume of CMASS in DR9 is 2.2Gpc^3

All of the cosmology results for DR9 come from the CMASS sample.
(see Parejko++12 for LOWZ)



CMASS sample

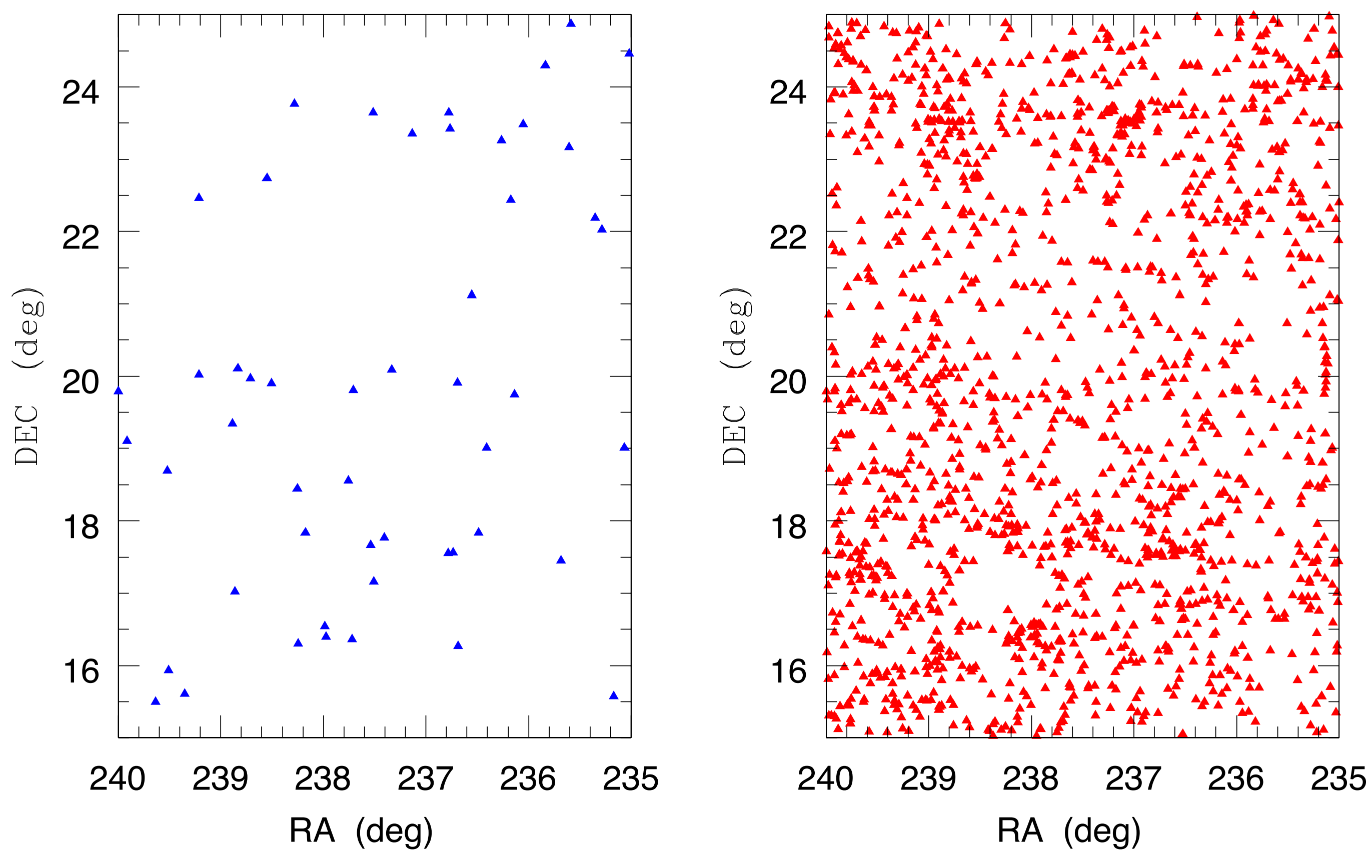
(White et al. 2011)

- Majority of galaxies are central galaxies living in halos of $10^{13}M_{sun}/h$.
- Ten percent are satellites
  - Live in halos 10x more massive
- Broadly agree with trends seen in literature.
- Large scale bias $b\approx 2$ (±10%).
  - $b\sigma_8(z=0.55)=1.3$ [c.f. 1.36 assumed in Science Requirements Doc]
  - Combination of high b and n makes CMASS galaxies a good tracer of LSS.
- Properties all in line with assumptions made in forecasts.

- The data quality was such that 1st clustering results were out within a year of survey start but we didn't have enough volume for a (competitive) BAO measurement at that time …

Tracing large-scale structure

The cosmic web at z~0.5, as traced by luminous galaxies



SDSS BOSS

BOSS DR9 CMASS papers

(264,283 CMASS galaxies over 3275 deg^2 at z_{eff}=0.57)

- Ross et al.: Systematics arXiv:1203.6499
- Anderson et al.: BAO arXiv:1203.6594
- Reid et al.: fits to anisotropic clustering arXiv:1203.6641
- Sanchez et al.: fits to monopole $\xi(s)$ arXiv:1203.6616
- Tojeiro: RSD with passive galaxies arXiv:1203.6565
- Manera et al.: Mock catalogs arXiv:1203.6609
- Samushia et al.: Model constraints arXiv:1206.5309

~150 journal pages!

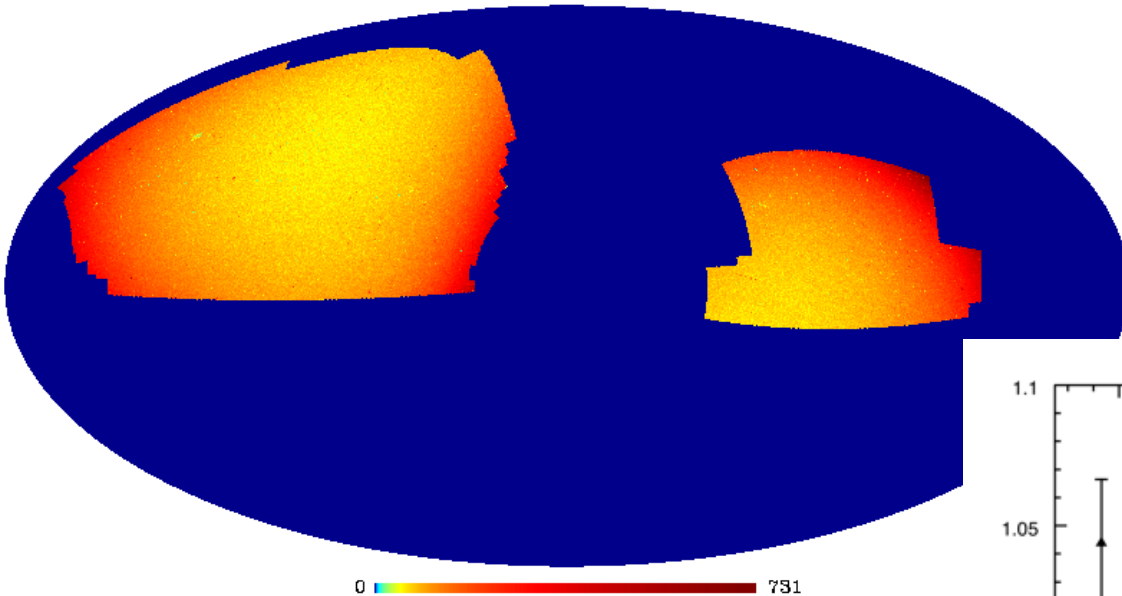
And more on the way …

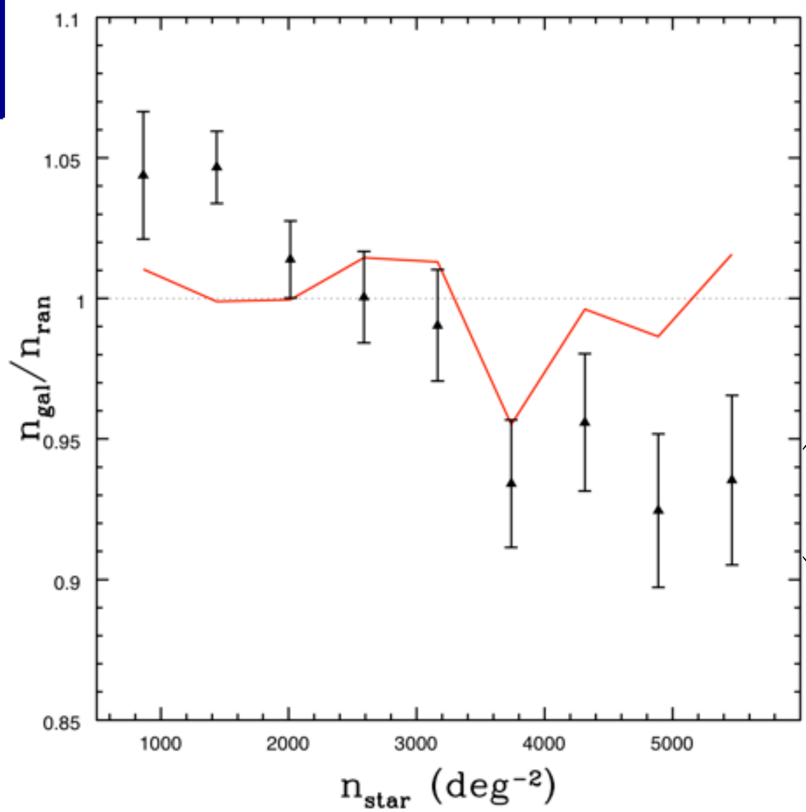
Systematics study

(Ross++12)

- Detailed systematics study.
- We see evidence for large-scale systematic power in the galaxies attributable to photometry.
  - For “CMASS” galaxies we find trends of galaxy number density with stellar density, extinction and seeing (not much with airmass or sky background). Only stellar density really matters for our science.
  - Effects depend on version of code (“Photo”) used for reductions.
  - Need decent mocks to determine statistical significance of effect.
  - Physical origin of the full signal is not understood, but we have a robust scheme for correcting the effect empirically.
    - Density of stars on the sky shows large-scale variations (shape of the galaxy) and this is modulating the power we see on the sky in a measurable way.
    - If we “flatten” this, we remove the systematic.

Stellar/Galaxy density

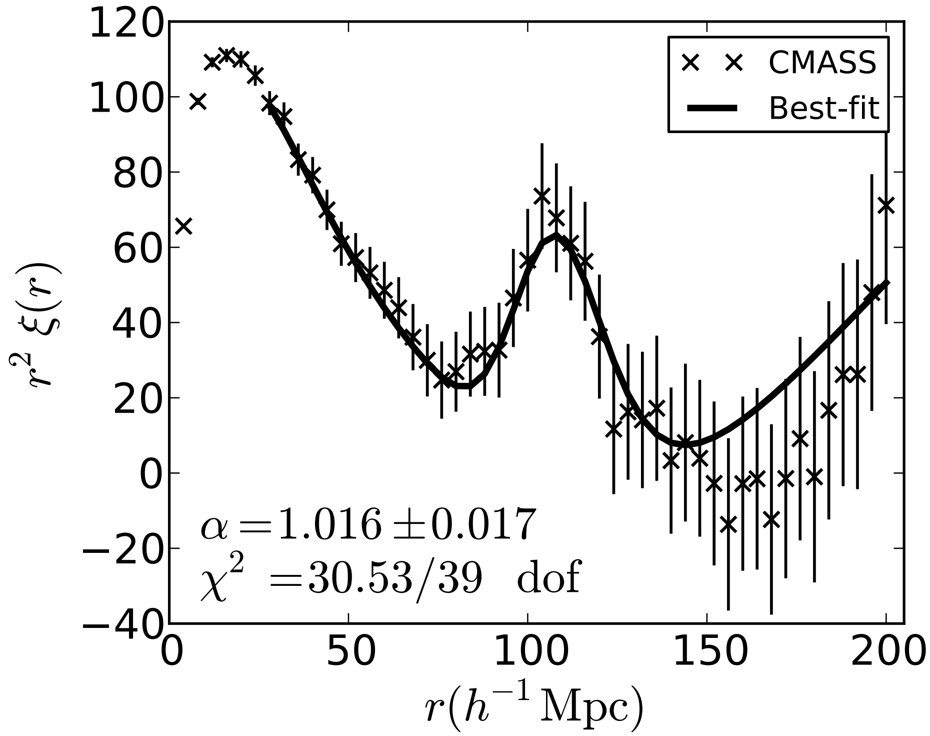


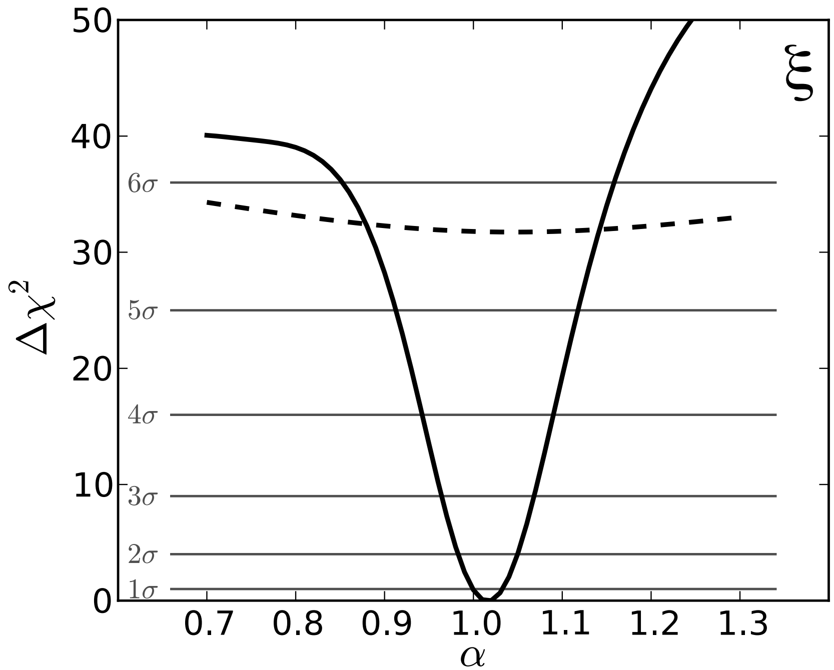


Ross et al. (2011)

BAO detection: Anderson++12

(BAO detected at >5σ in both ξ and P)

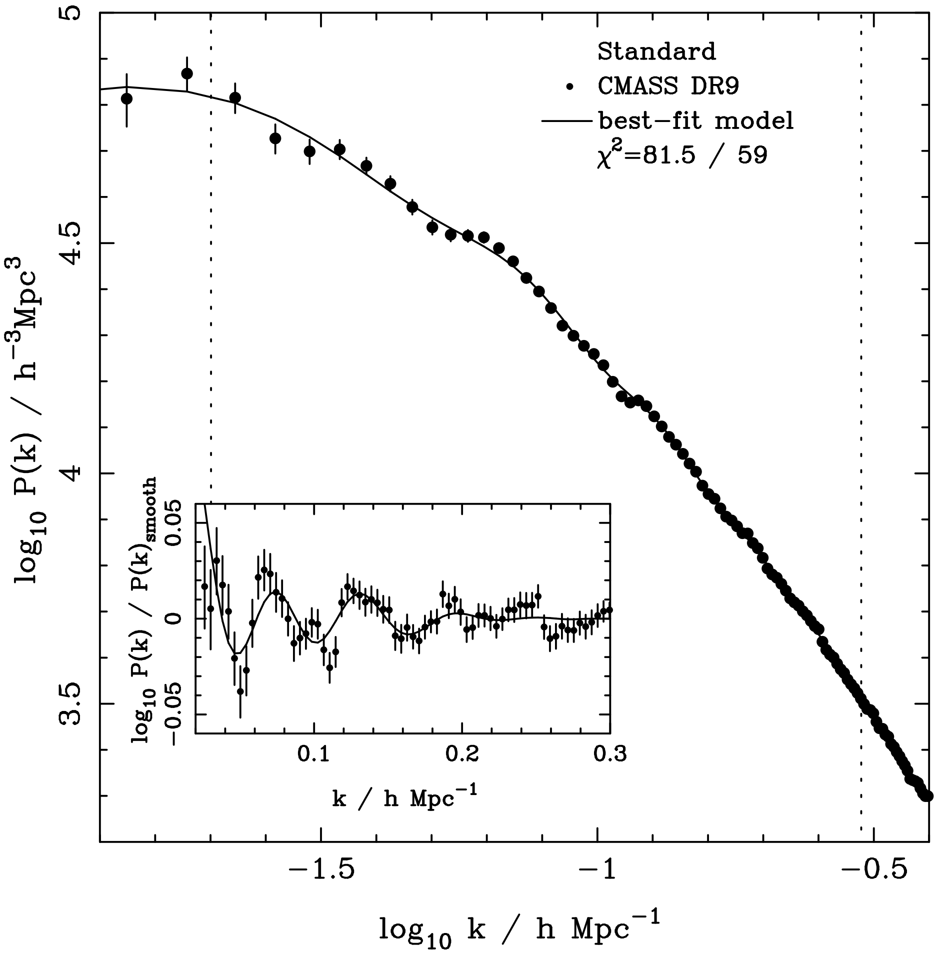


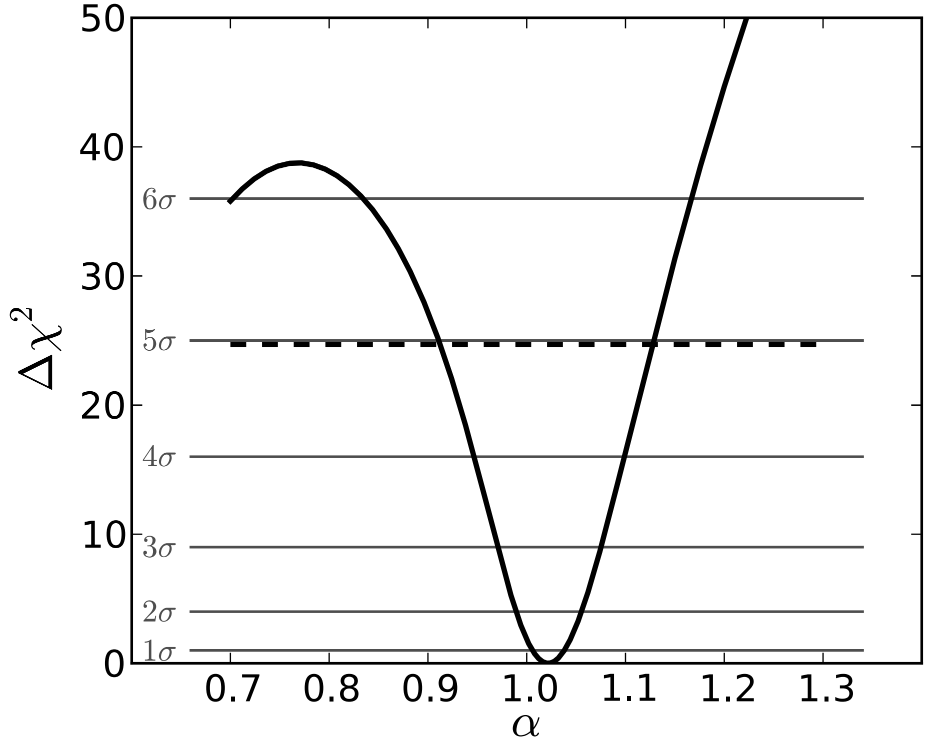


We scale a template by α so that $D_V/r_s = \alpha(D_V/r_s)_{\mathrm{fid}}$

BAO detection: Anderson++12

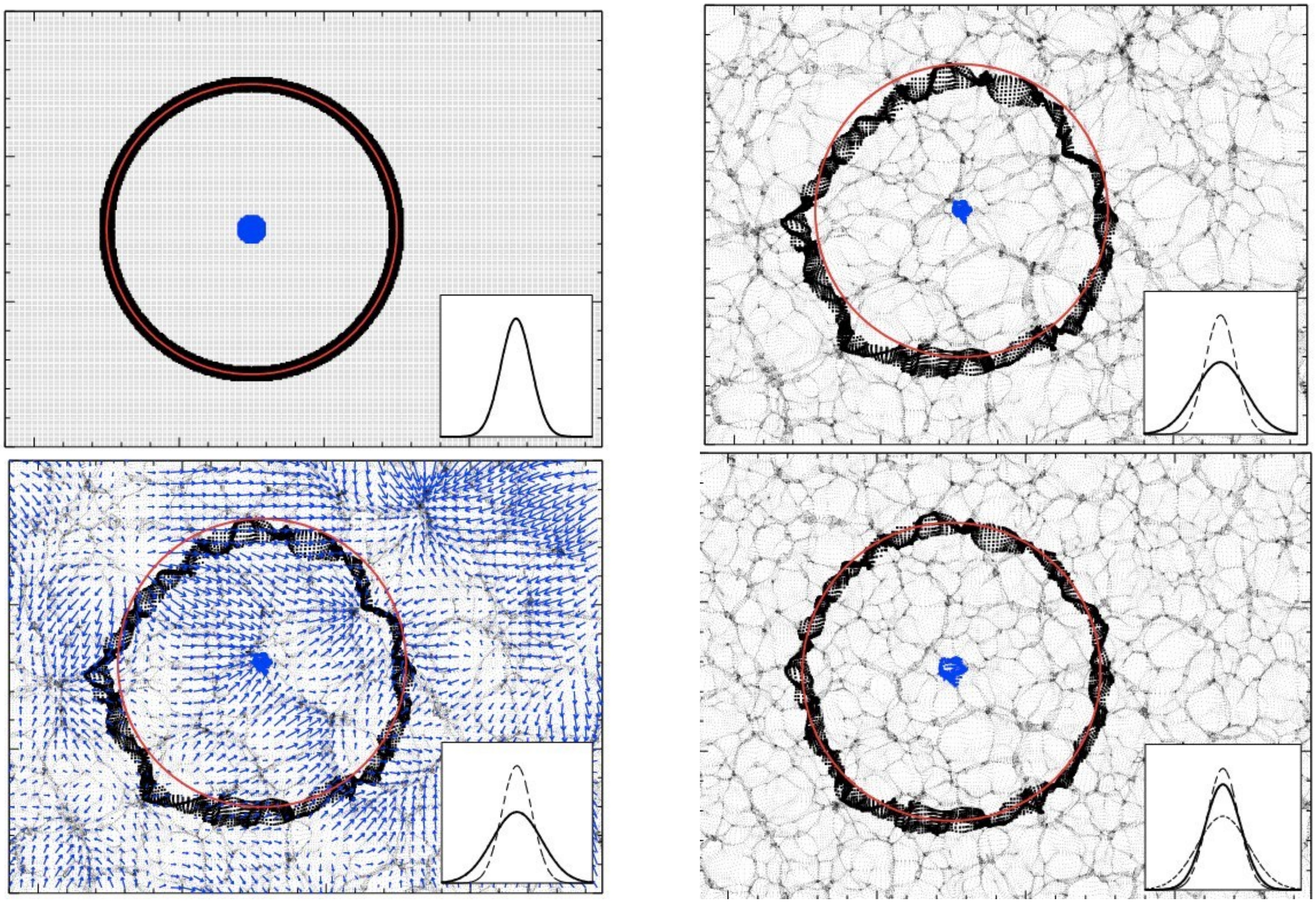
(BAO detected at >5σ in both ξ and P)





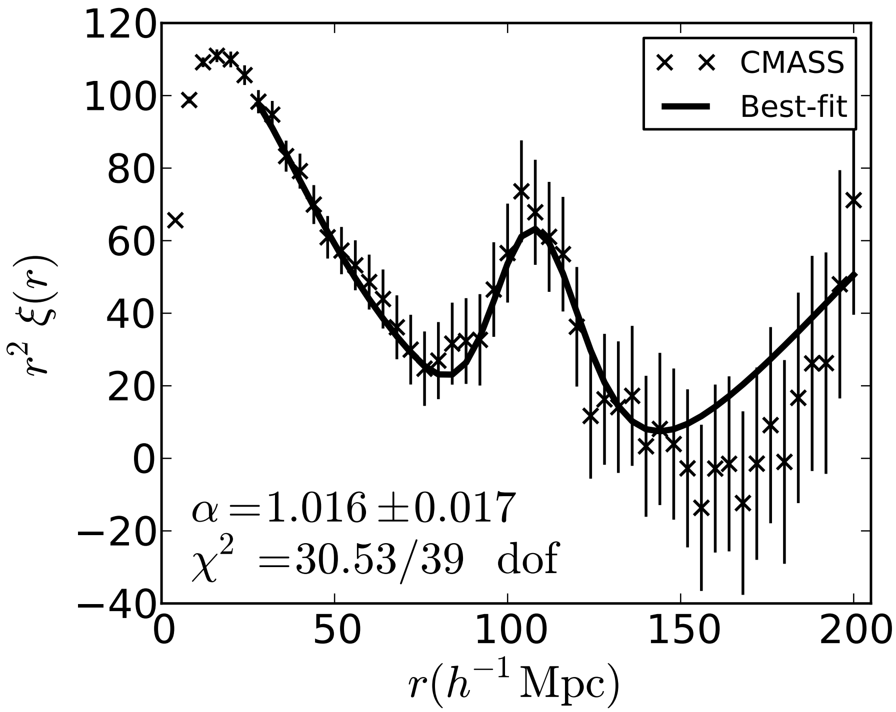
Aside on “reconstruction”

(Eisenstein++07)

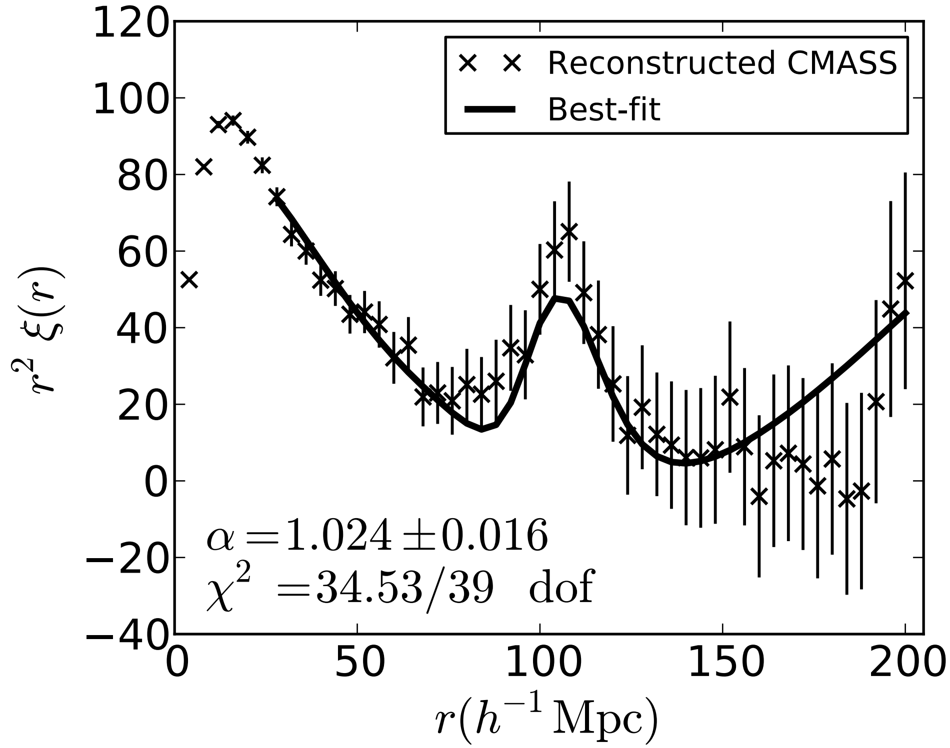


(Padmanabhan++2012)

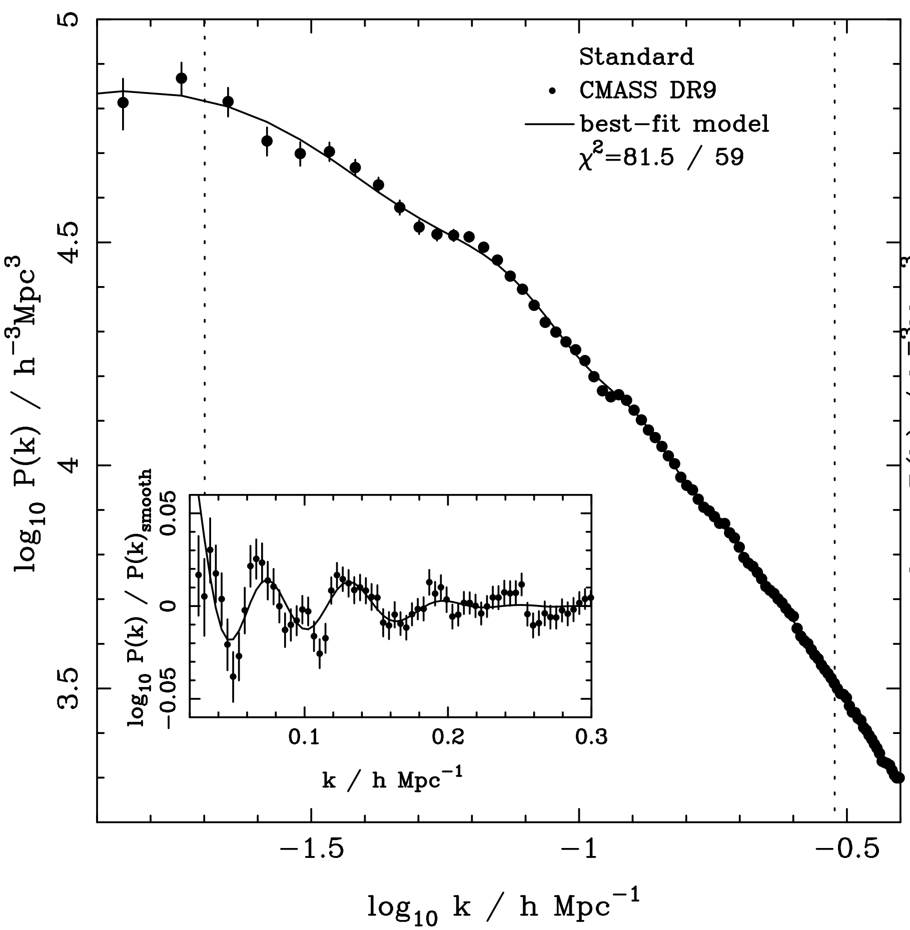
Reconstruction

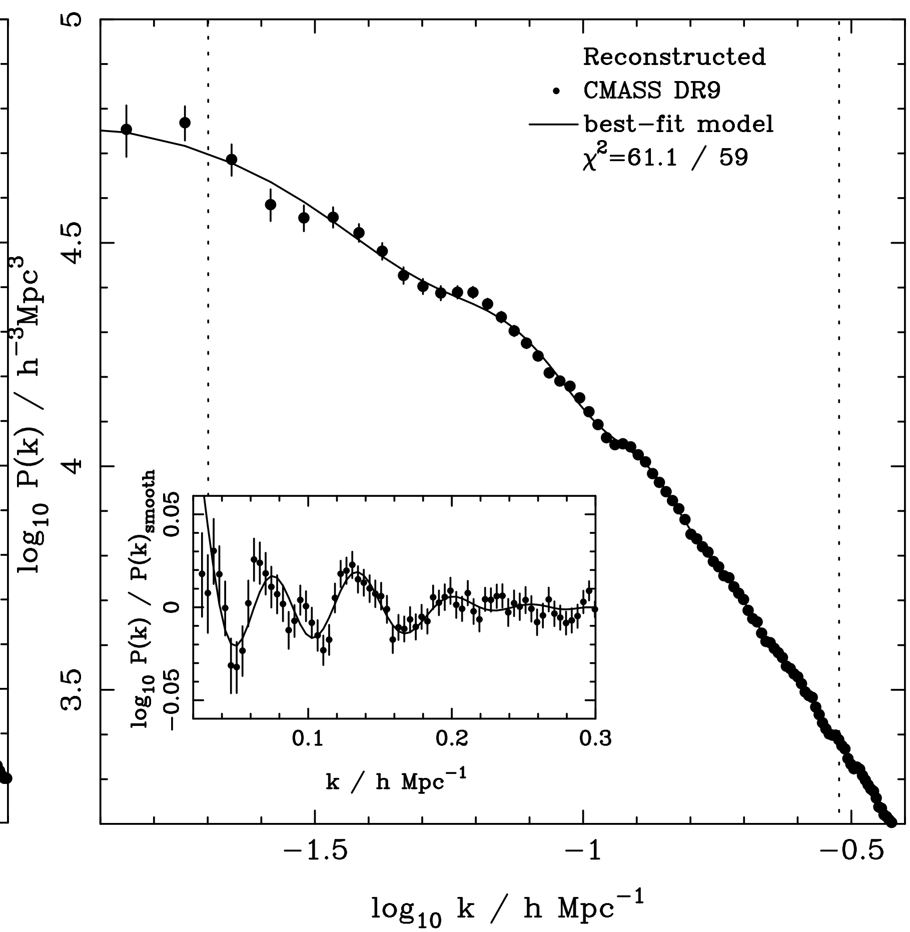


If we use the large-scale structure to "undo" the smearing due to non-linearity we sharpen the peak …

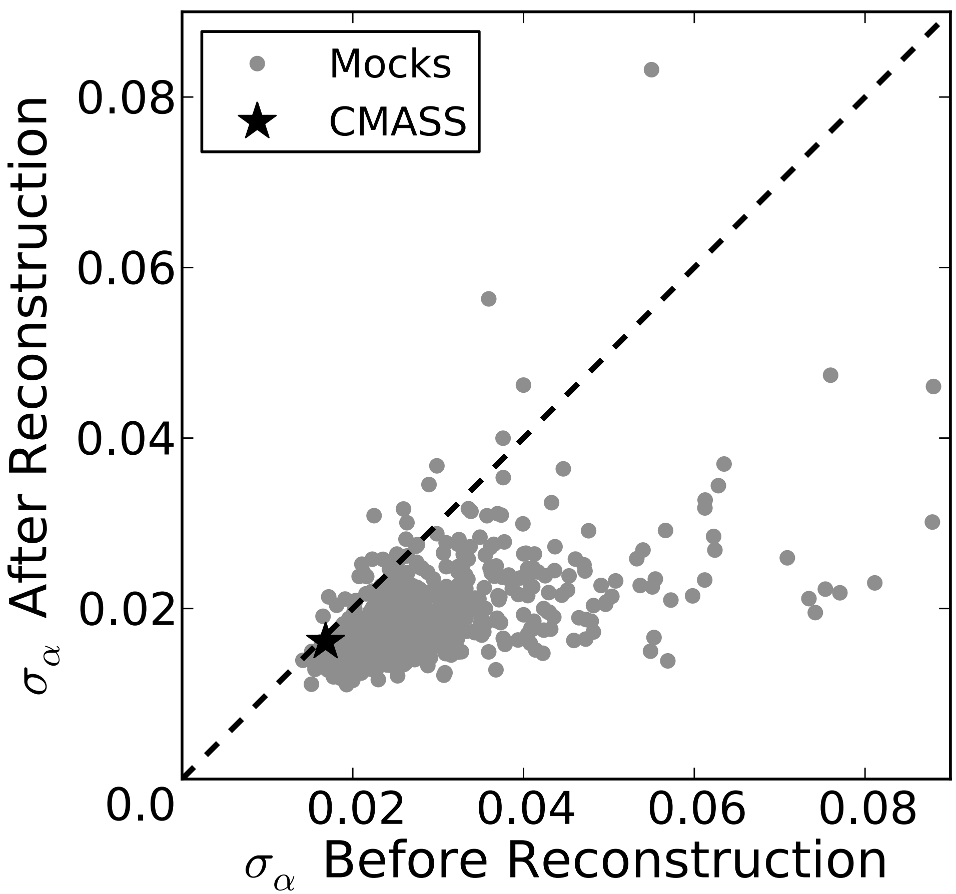


Reconstruction



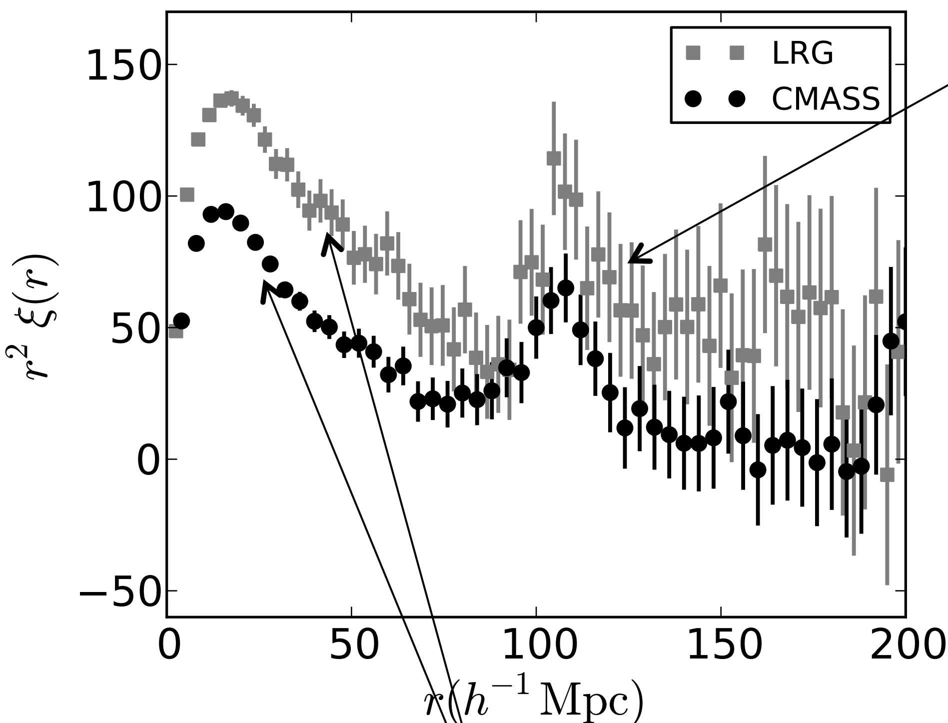


Reconstruction



By a lucky coincidence the peak in the DR9 data was already very "sharp" so our error on α was quite small and reconstruction didn't help all that much …

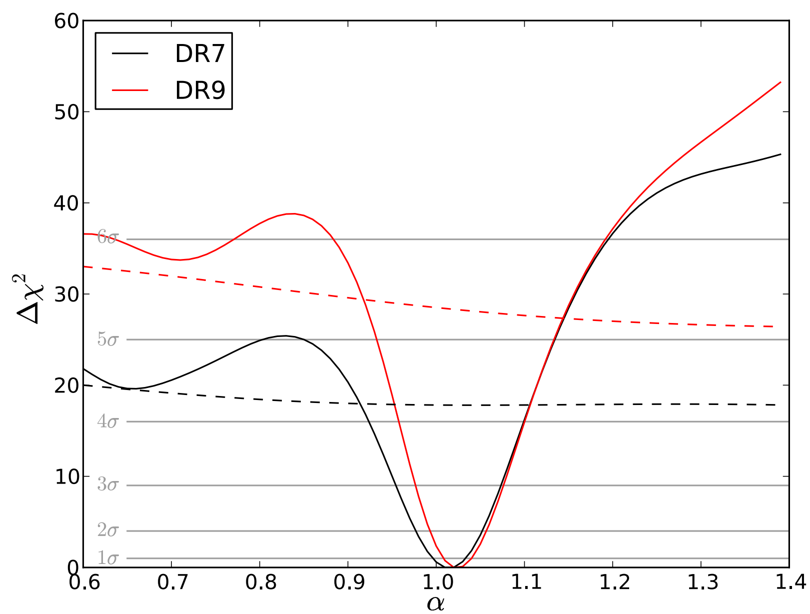
Comparison with SDSS-II



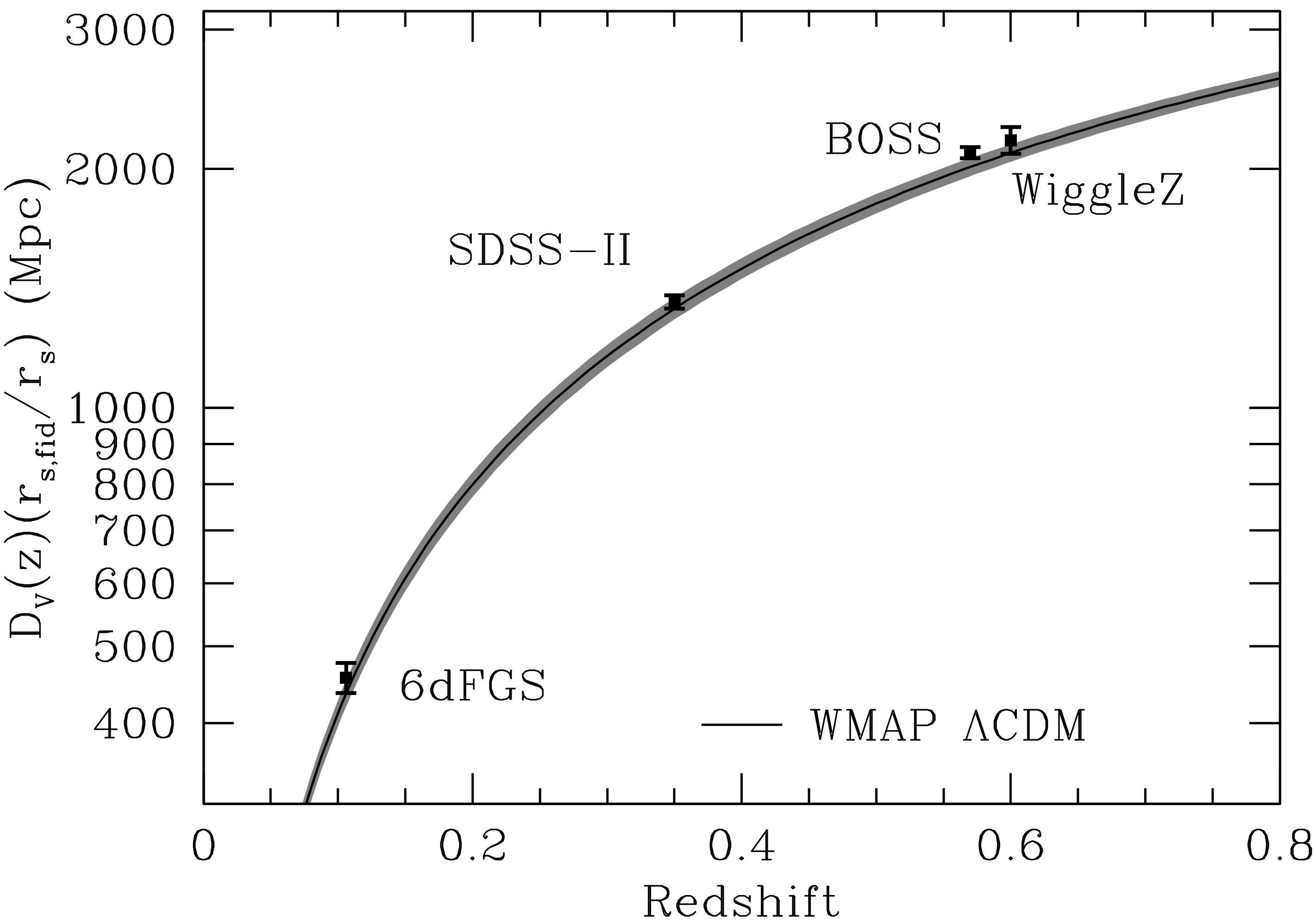
The BAO peak as measured by BOSS and SDSS-II is in the sample place!

The detection is more significant in BOSS.

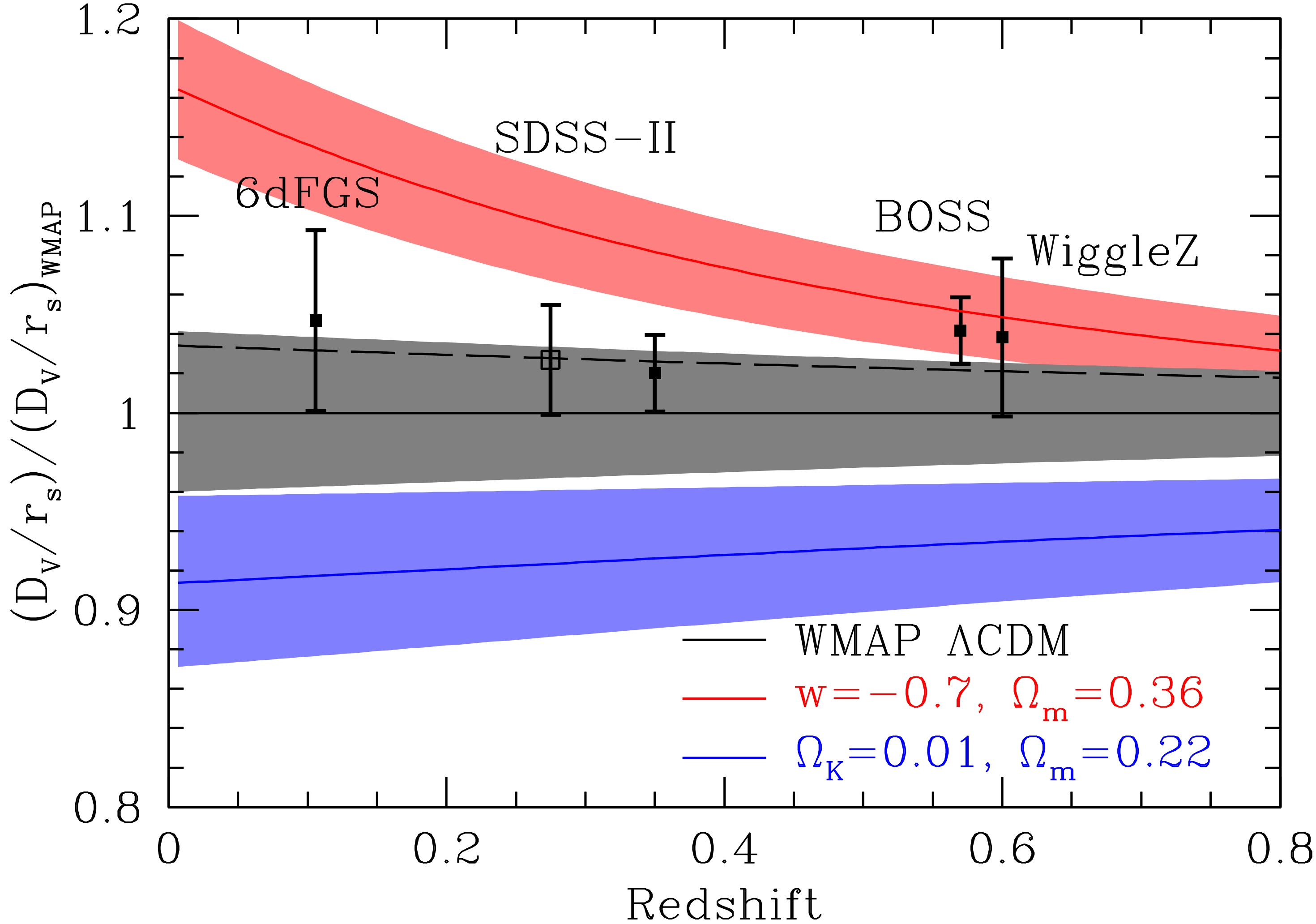
The bias of SDSS-II LRGs and BOSS CMASS galaxies differ.



The distance ladder

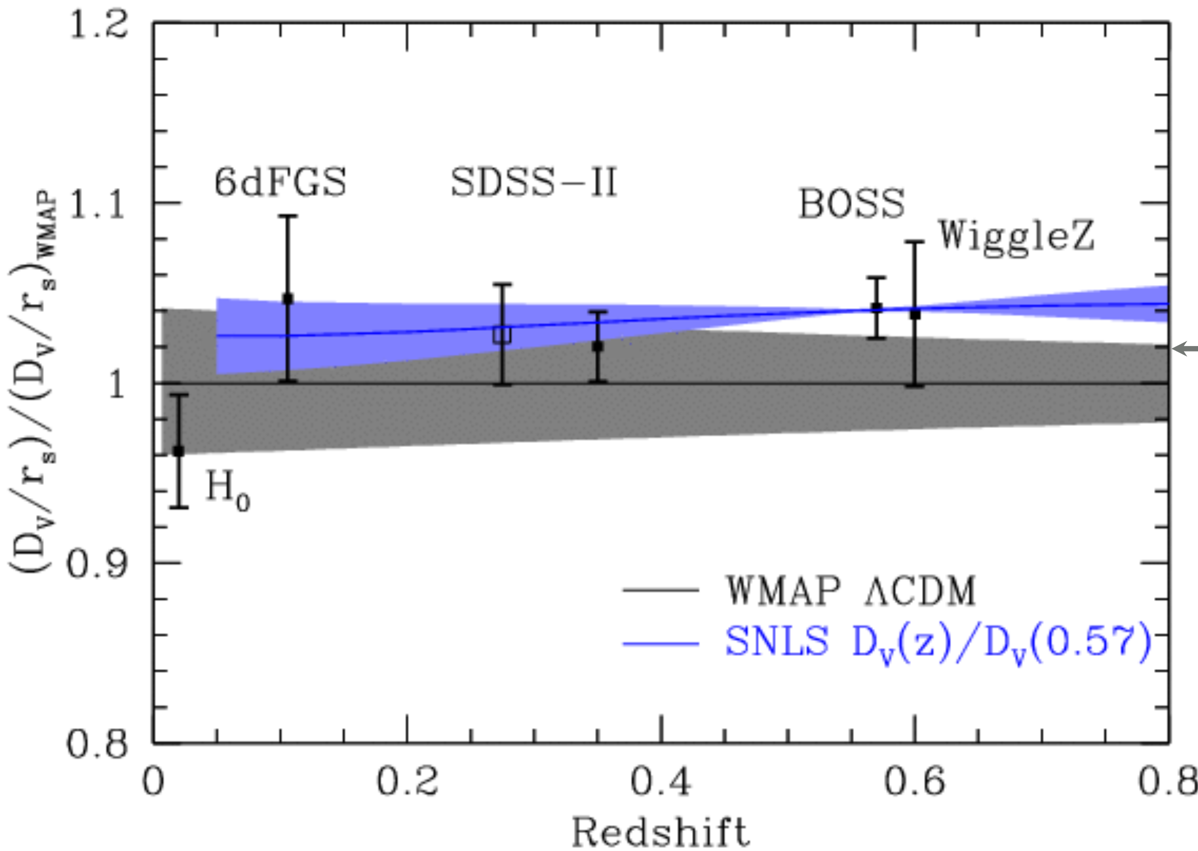


Relative



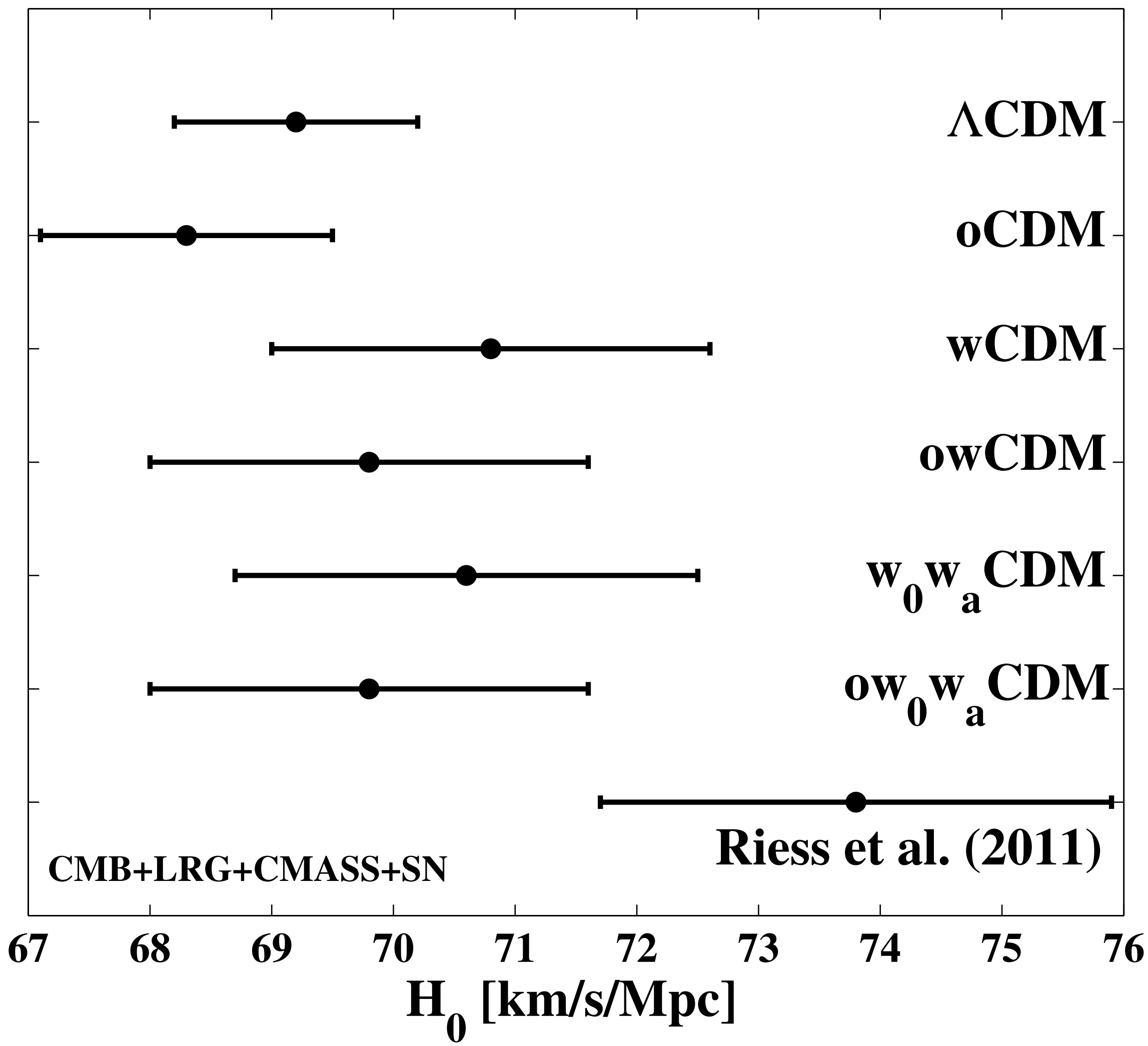
1.2
1.1
1
0.9
0.8
0
0.2
0.4
0.6
0.8
Redshift
$(D_V/r_s)/(D_V/r_s)_{WMAP}$
SDSS−II
6dFGS
BOSS
WiggleZ
WMAP ΛCDM
$w=-0.7,\ \Omega_m=0.36$
$\Omega_K=0.01,\ \Omega_m=0.22$

BAO Hubble Diagram
Comparison with CMB, H_0, and SN



$+1\sigma$ in $\Omega_m h^2$

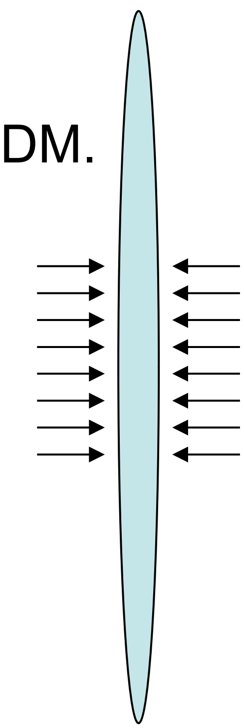
Inferring the Hubble constant



The combination of SN and BAO distances allows us to transfer the CMB distance scale to the local universe and constrain H_0.

Growth of structure

- A key test of dark energy vs. modified gravity models is the growth of structure.
  - Also helps break some DE degeneracies …
- For fixed expansion history/contents, GR makes a unique prediction for the growth of structure (and velocities).
  - Growth predicted to ~1% for a BOSS-like survey for ΛCDM.
- We can measure the growth of structure using redshift space distortions.
  - $z_{obs} = Hr + v_{pec}$.
  - $v_{pec} \sim a\, t \sim (\nabla\Psi)\, t \sim (\nabla\nabla^{-2}\rho)\, t$
  - Distortion correlated with density field.
- Constrain dD/dln(a)~$f\sigma_8$.

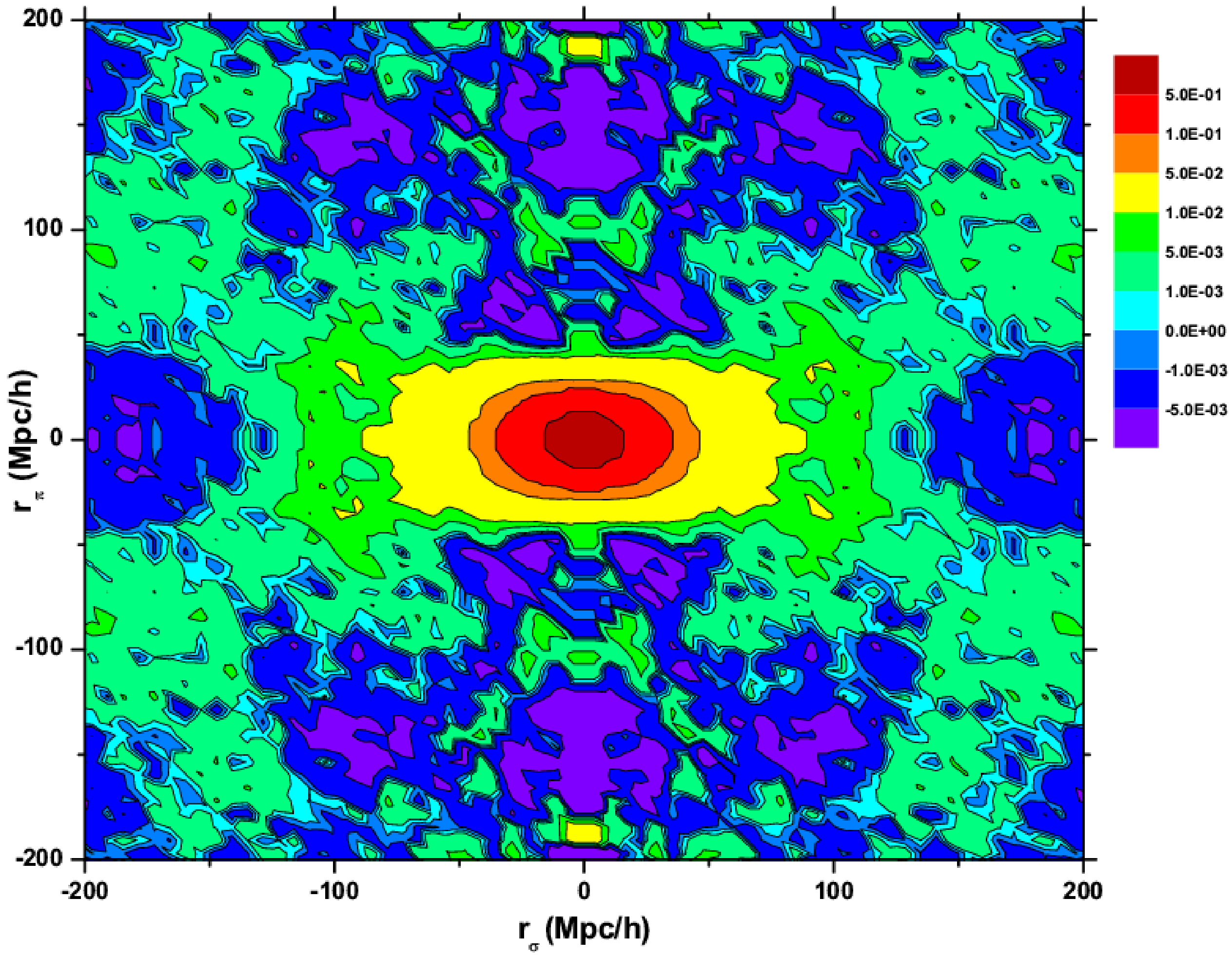


Interest rekindled

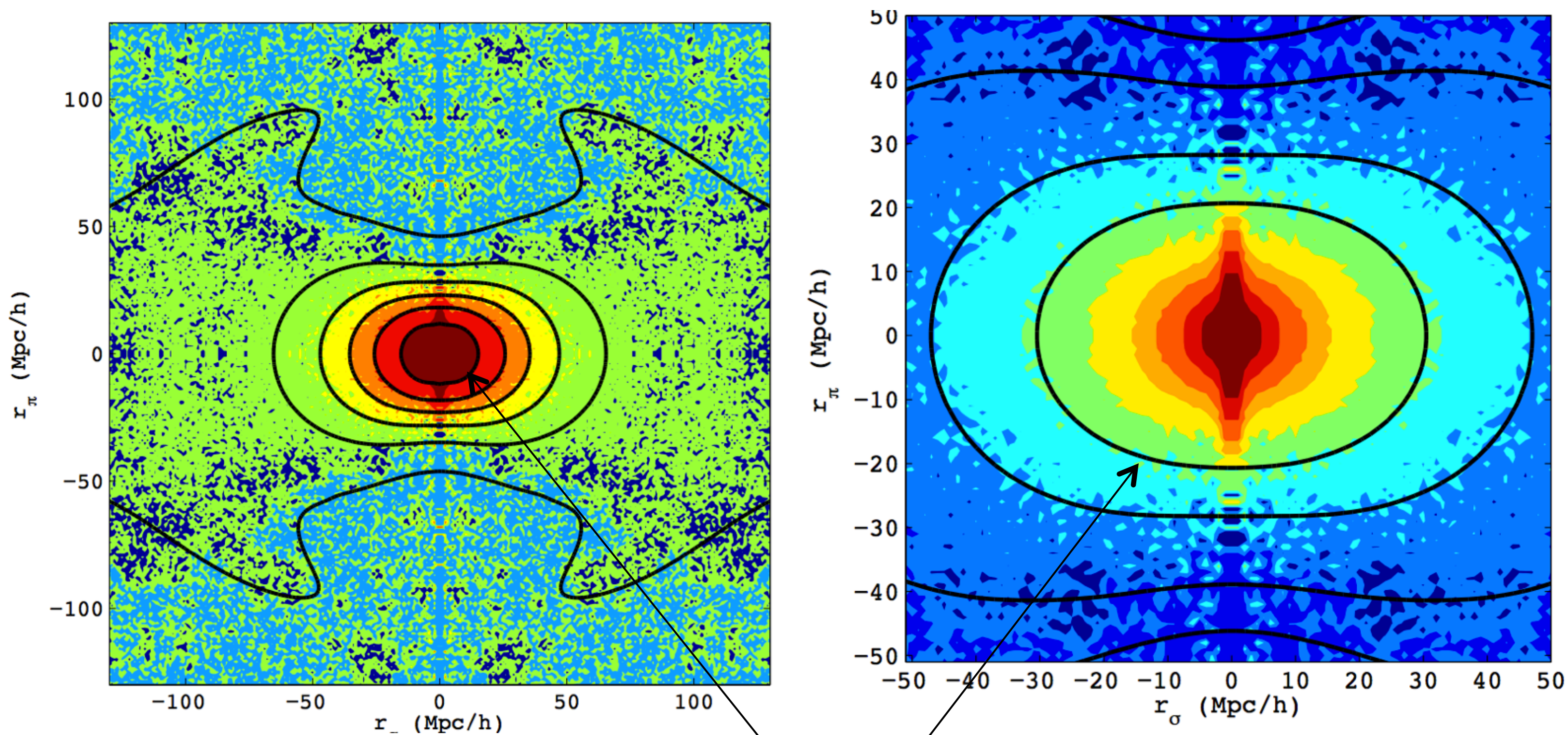
- There has been a lot of theoretical activity pointing out the promise of redshift space distortions recently.
- Rekindled interest in measuring RSD
    - 2dFGRS: Peacock++01, Hawkins++03, Percival++04
    - SDSS: Zehavi++05, Tegmark++06, Cabre++08, Okumura++08, Sanchez++09, …
    - VVDS: LeFevre++05, Garilli++08
    - 2SLAQ: daAngela++08
    - WiggleZ: Blake++11.
    - BOSS: Reid++12.

Two dimensional clustering
(Reid++12)

Anisotropy in the 2-point function due to peculiar velocities allows measurement of the growth of structure and tests of gravity on cosmological scales.

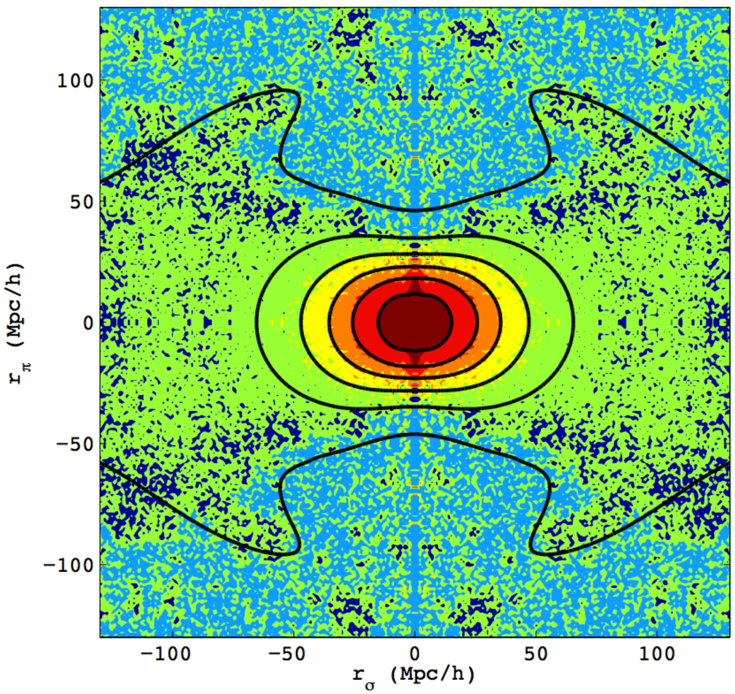


FoG a small correction for us

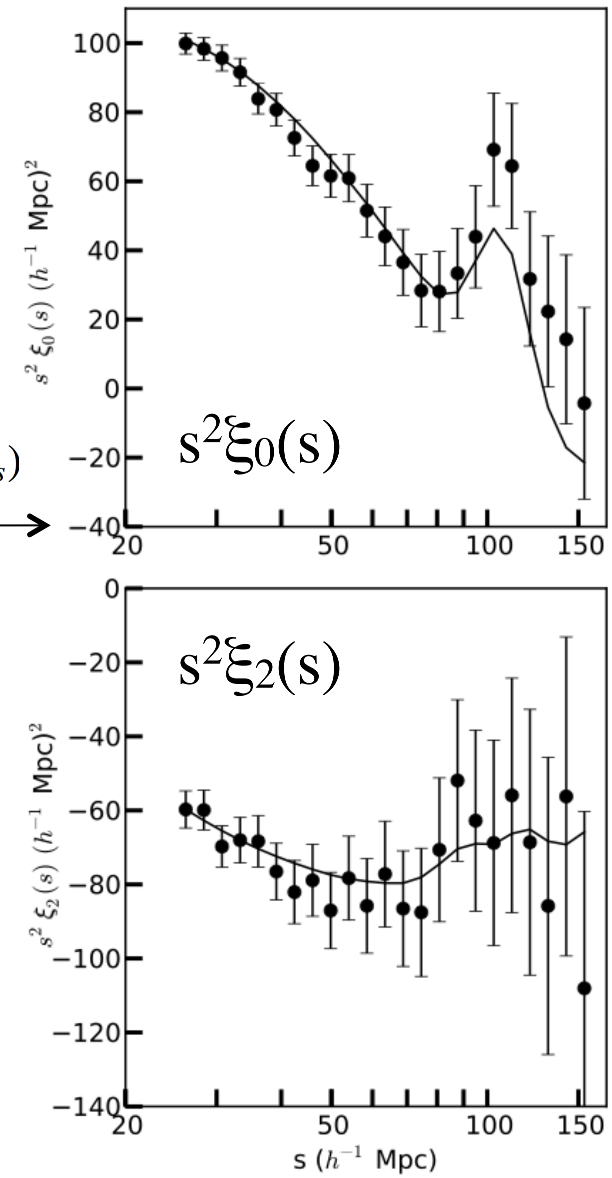


Smallest scale used for analysis

Legendre Polynomial moments: $\xi_\ell(s)$



$$\xi(s,\mu_s) = \sum_\ell \xi_\ell(s) L_\ell(\mu_s)$$



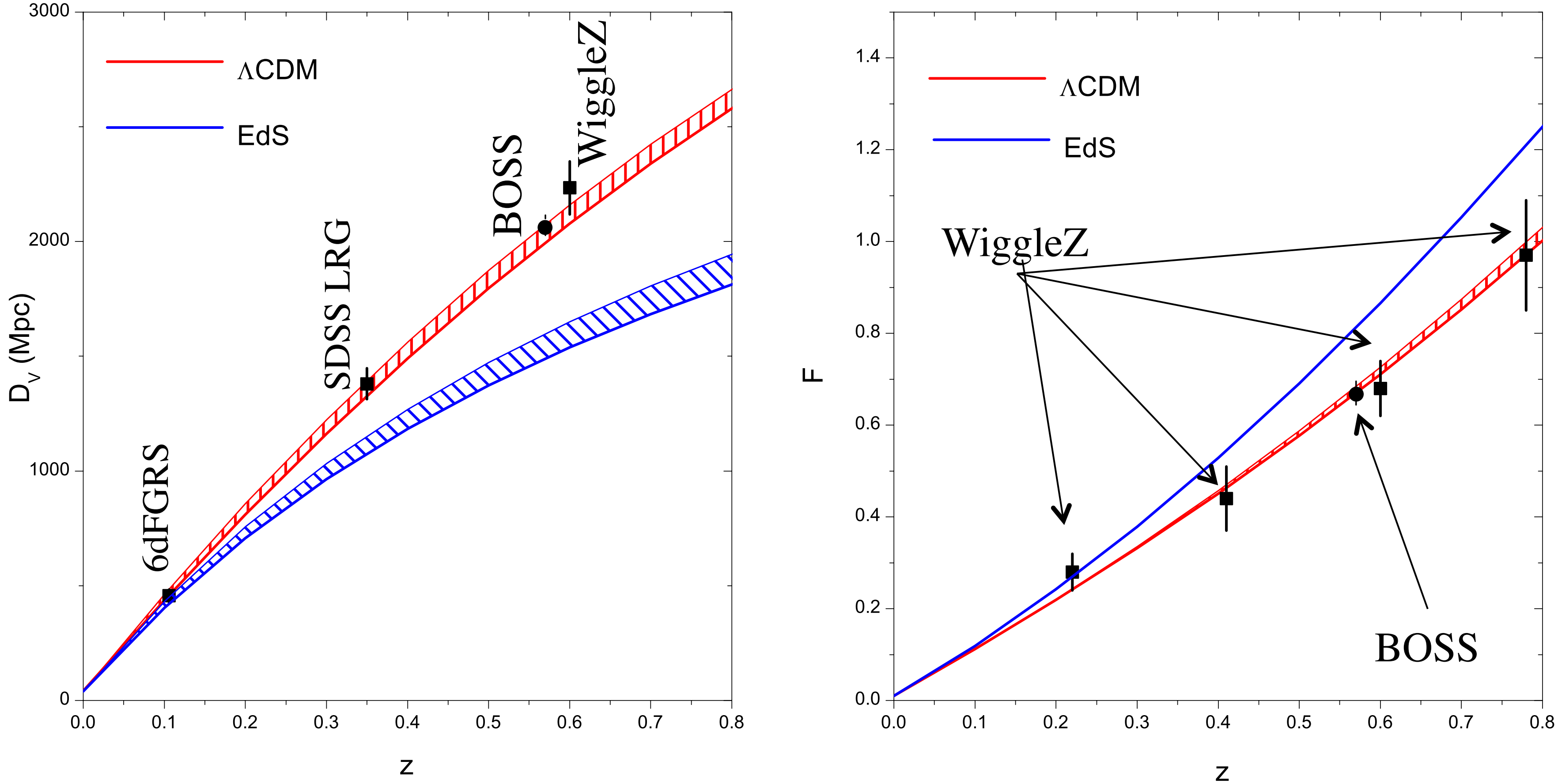
Results: Fitting to 2d clustering

Use full model of $\xi_{0,2}(s \geq 25\ h^{-1}$ Mpc) to constrain:

- $D_V = [\chi^2\, cz/H]^{1/3}$
- Growth of structure ($f\sigma_8$)
- Alcock-Paczynski $F(z) \equiv (1+z)\, D_A(z)\, H(z)/c$
    - Has a different shape-dependence than RSD, distinguishable if have enough dynamic range.
- Marginalize over shape of underlying linear P(k), $b\sigma_8$, σ^2_{FOG}

Results including shape information with our model and the anisotropic clustering is fully consistent with the results using just BAO.

Measure isotropic and distortion parameters

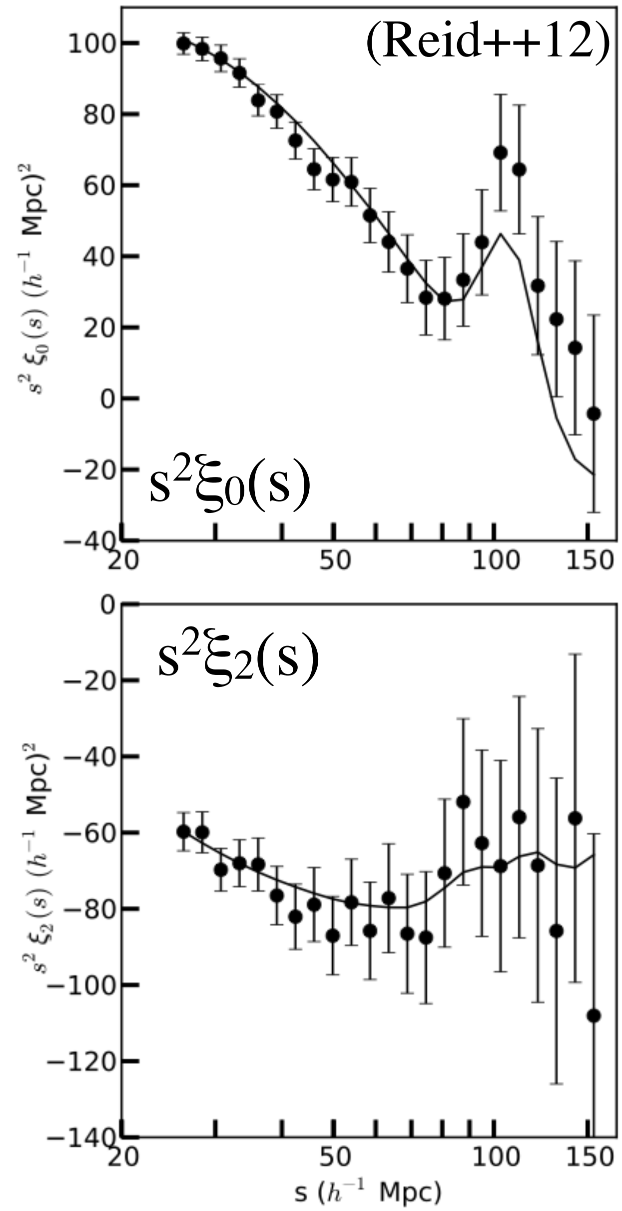


Best fit model: $\chi^2 = 39$ (41 DOF)

ξ_0 BAO + ξ_2: D_A, H, $f\sigma_8$ at z=0.57

Growth & geometry “free”*:
$f\sigma_8$=0.43±0.07
χ=2190±61Mpc
H=92.4±4.5km/s

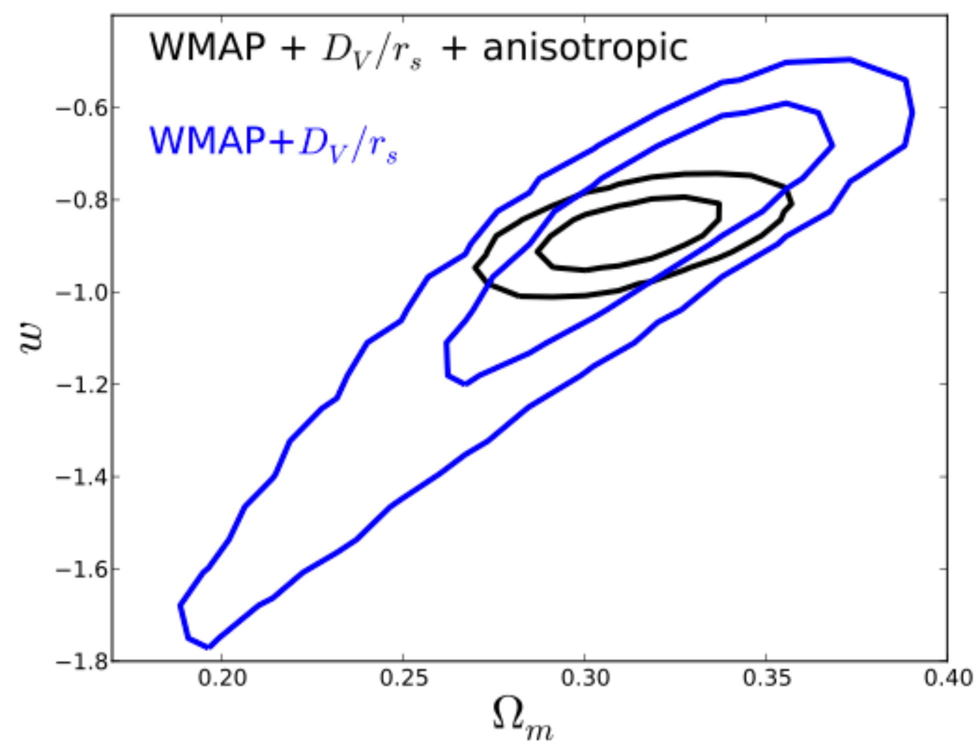
WMAP7 ΛCDM:
$f\sigma_8$=0.45±0.03
χ=2113±53Mpc
H=94.2±1.4km/s



- Can be used to constrain models with arbitrary EoS and growth history providing physics at recombination is unaltered and growth remains scale-independent.
- Approx. almost as good as fitting to ξ_0 and ξ_2 directly.

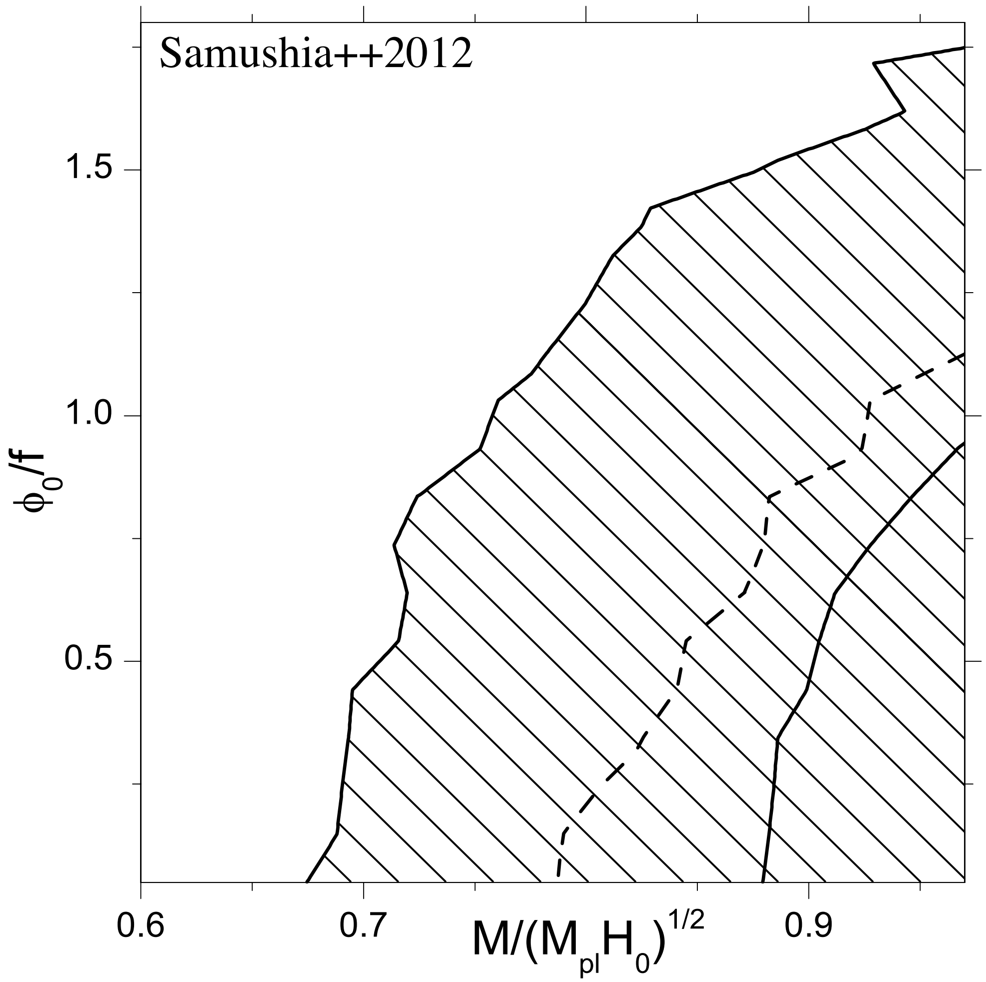
Cosmological implications: flat wCDM
(Samushia++2012)

- 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)
- NB: ΛCDM has $\Delta\chi^2$~2.5 even though w=-1 is ~2σ off.



(* Thanks to fortuitous degeneracy direction between F_{AP} and $f\sigma_8$)

Scalar field model: PNGB



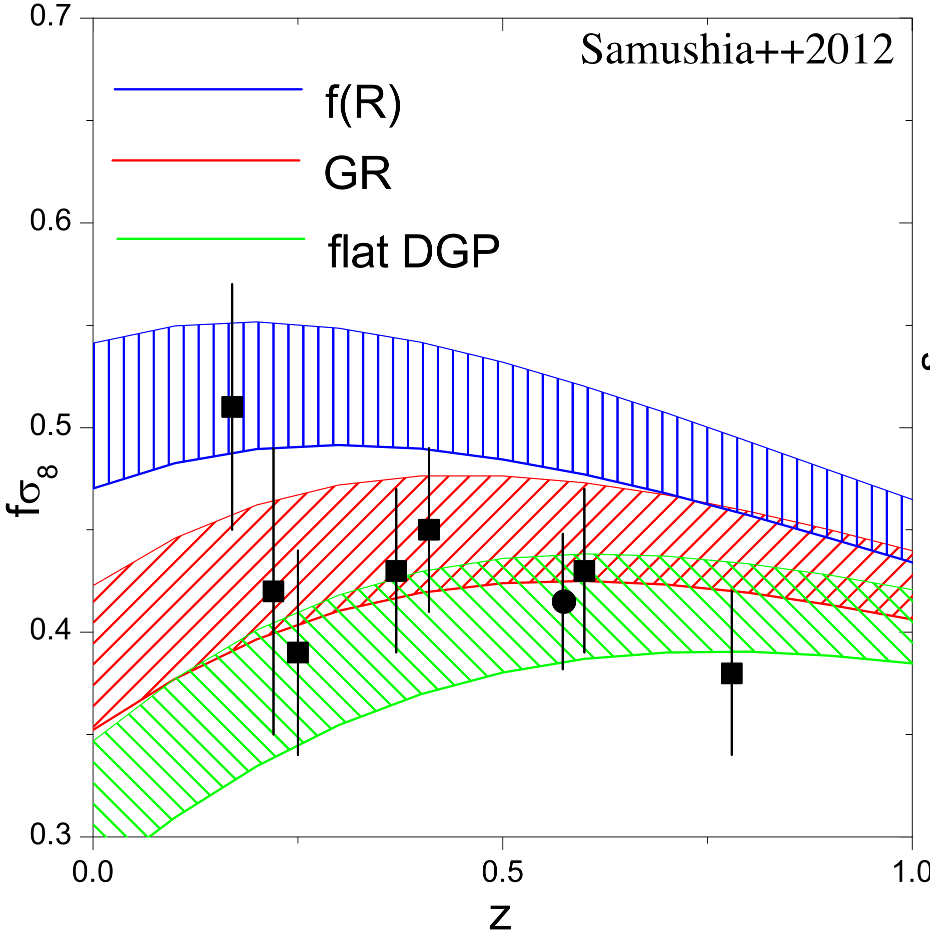
Constraints on a particular scalar-field DE model:

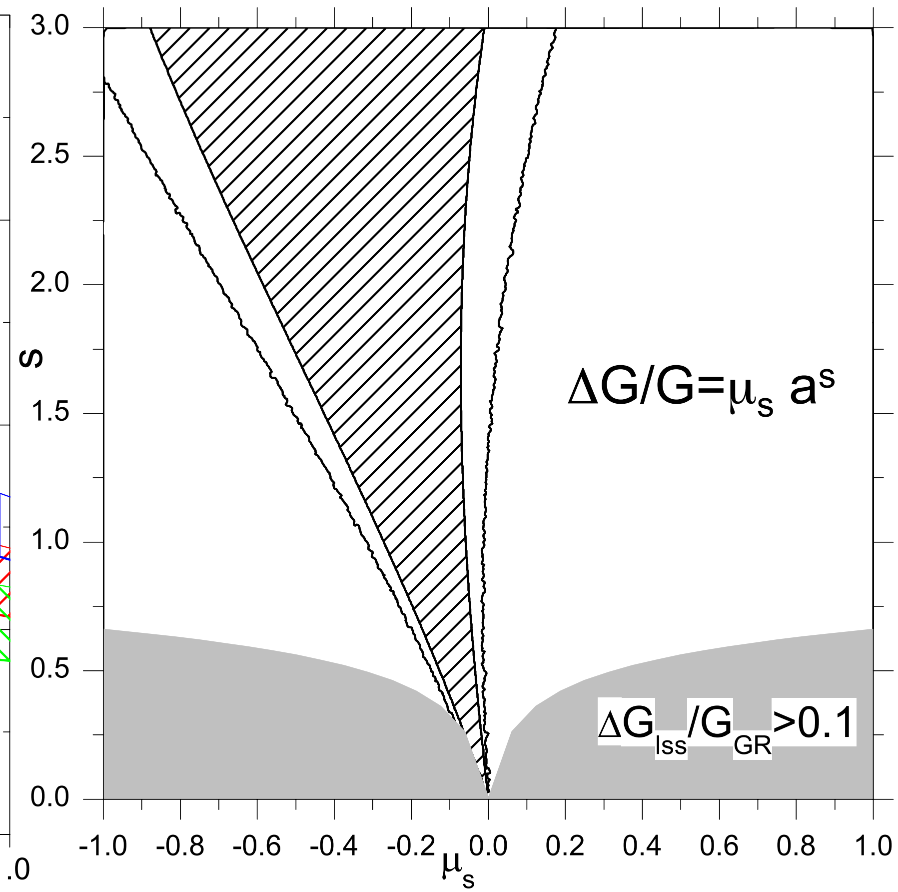
$V(\phi)=M^4[1+\cos(\phi/f)]$

This model is technically "natural" and "explains" the 2nd tooth fairy, that *m~H*, given the 1st tooth fairy, that $M^4 \sim \Lambda$.

The limit f➔∞ is ΛCDM.

Dark Energy or modified gravity?





(Not all analyses make the same assumptions or use the same priors so direct comparison is slightly tricky.)

Future constraints?

- Expect non-negligible increase in volume (and number of galaxies).
  - Roughly factor of 3.
- Get an additional boost by steadily improving survey footprint
  - Fewer “edges” and “gaps”.
- Minor improvements from systematics and reduction improvements, efficiency of survey operations, etc.

Summary

- BOSS BAO has provided the most precise high-z distance in the DE-turn-on epoch to date!
  - $D_V(z=0.57)=2094\pm34$ Mpc (1.7%).
- RSD measurements significantly improve constraining power on models/parameters.
- ρ_{DE}/ρ_m is 4.5x smaller at z=0.57 than z~0.
  - The "why now" problem!
- ΛCDM provides a good fit to the data (χ^2/dof).
- Growth measures show a 2σ preference for w>-1 or MG.
  - Inclusion of other data brings you back closer to ΛCDM.

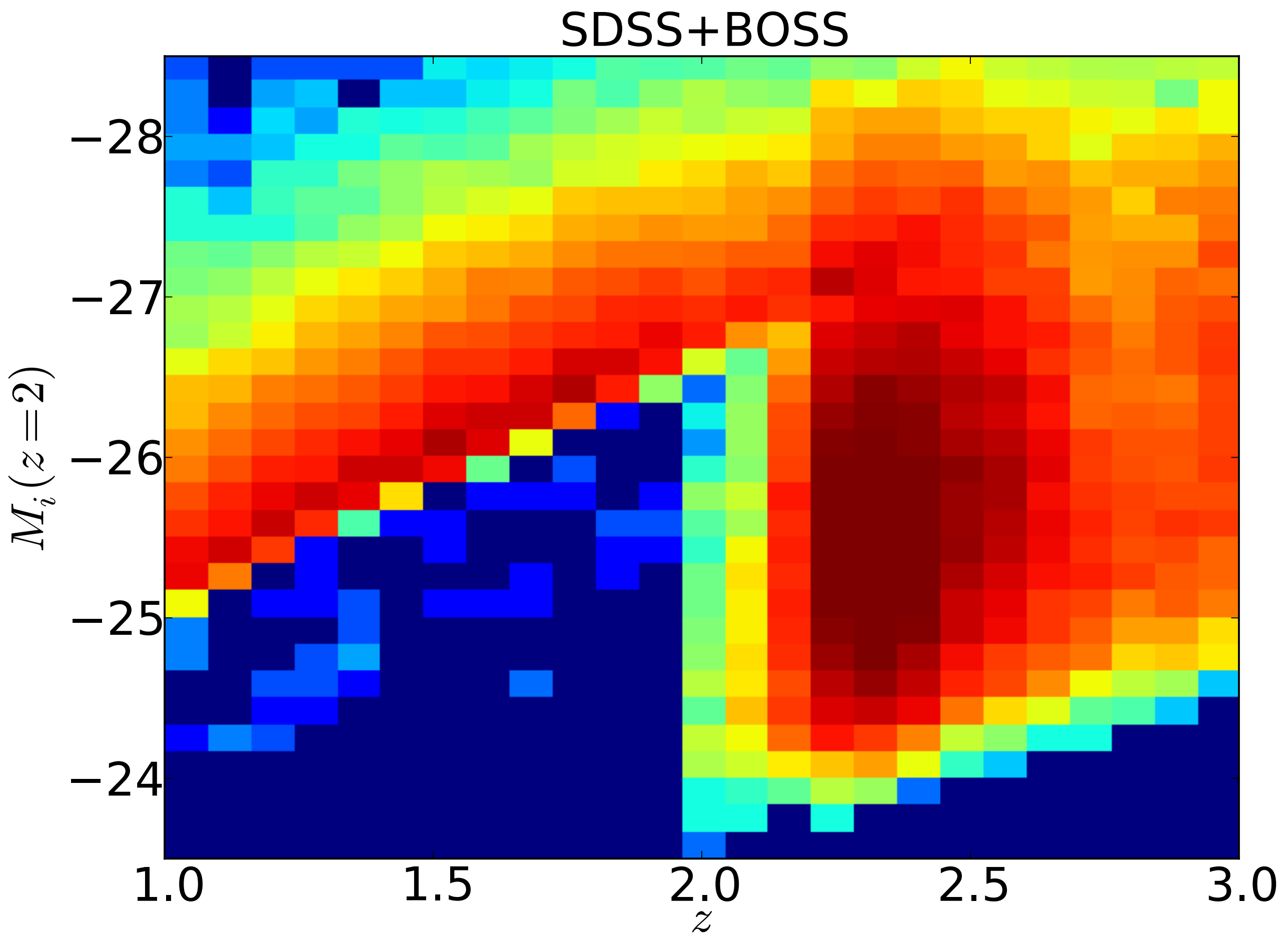
But wait, there's more …

Quasar demographics

- BOSS is providing a large sample of less luminous QSOs at $z\sim2.5$, near peak of QSO dN/dz.
  - Better constraints on faint-end of LF.
  - Better clustering measurements.
    - Which halos? Duty cycle? Triggering?
- Also “double” the number of $z>3.6$ QSOs, reaching ~1 magnitude fainter.
  - Early generations of BHs.
  - Tests of QSO formation.
  - Probes IGM evolution and end of reionization.
- Have multiple QSO selections along Stripe 82.

(BOSS currently has good redshifts for >60K quasars with z>2.2)

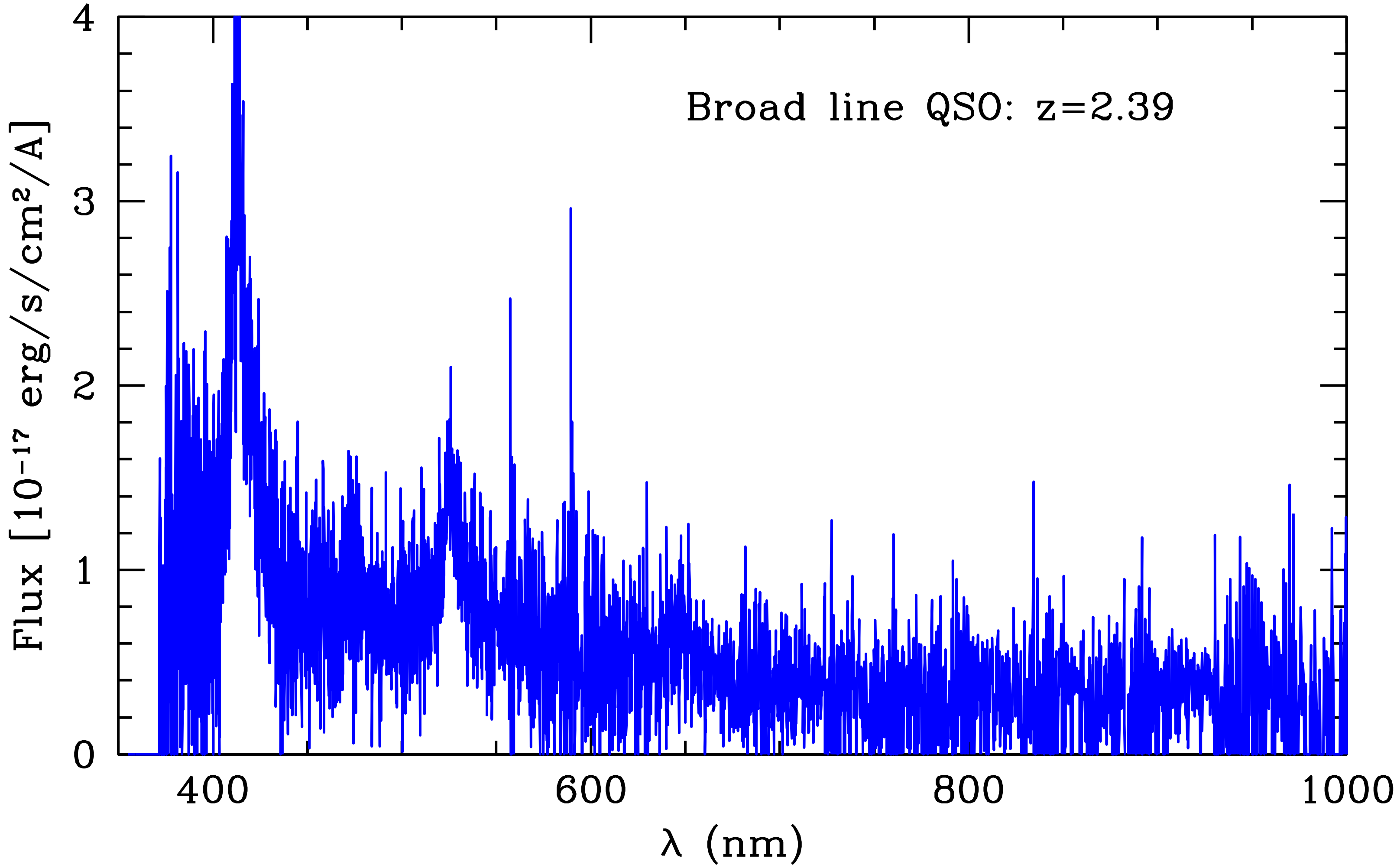
Comparison with SDSS



BOSS probes significantly further down the LF at z>2.2 than did SDSS-I & II.
It is inefficient for 1<z<2.2 by design.

New LF results coming out very soon …

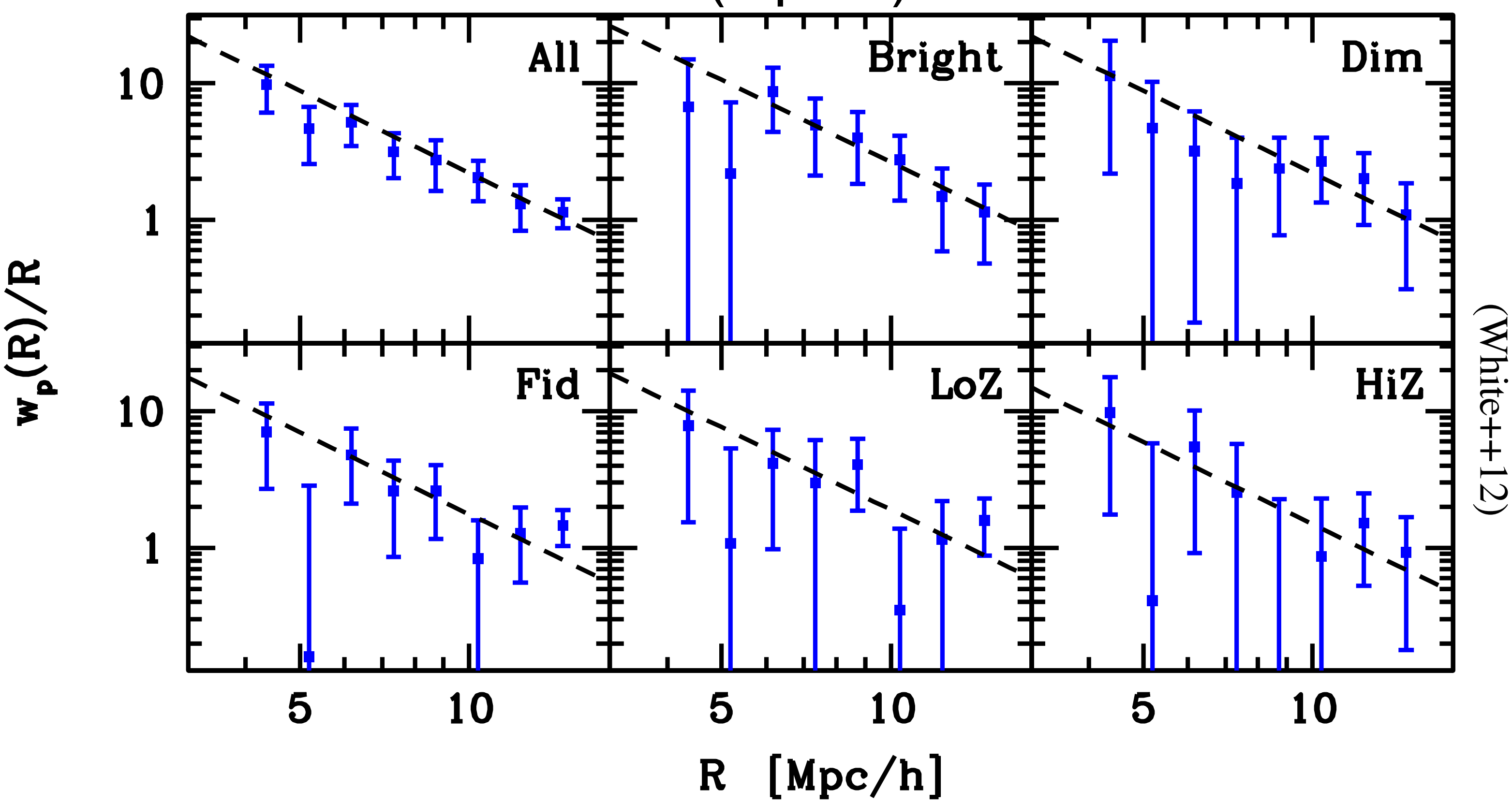
The typical BOSS quasar



Median QSO has $M_i(z=2)=-26$, $L_{bol}=2.5\text{x}10^{39}$W, $M_{BH}=2\text{x}10^8 M_{sun}$

Clustering at z~2.5: Real space

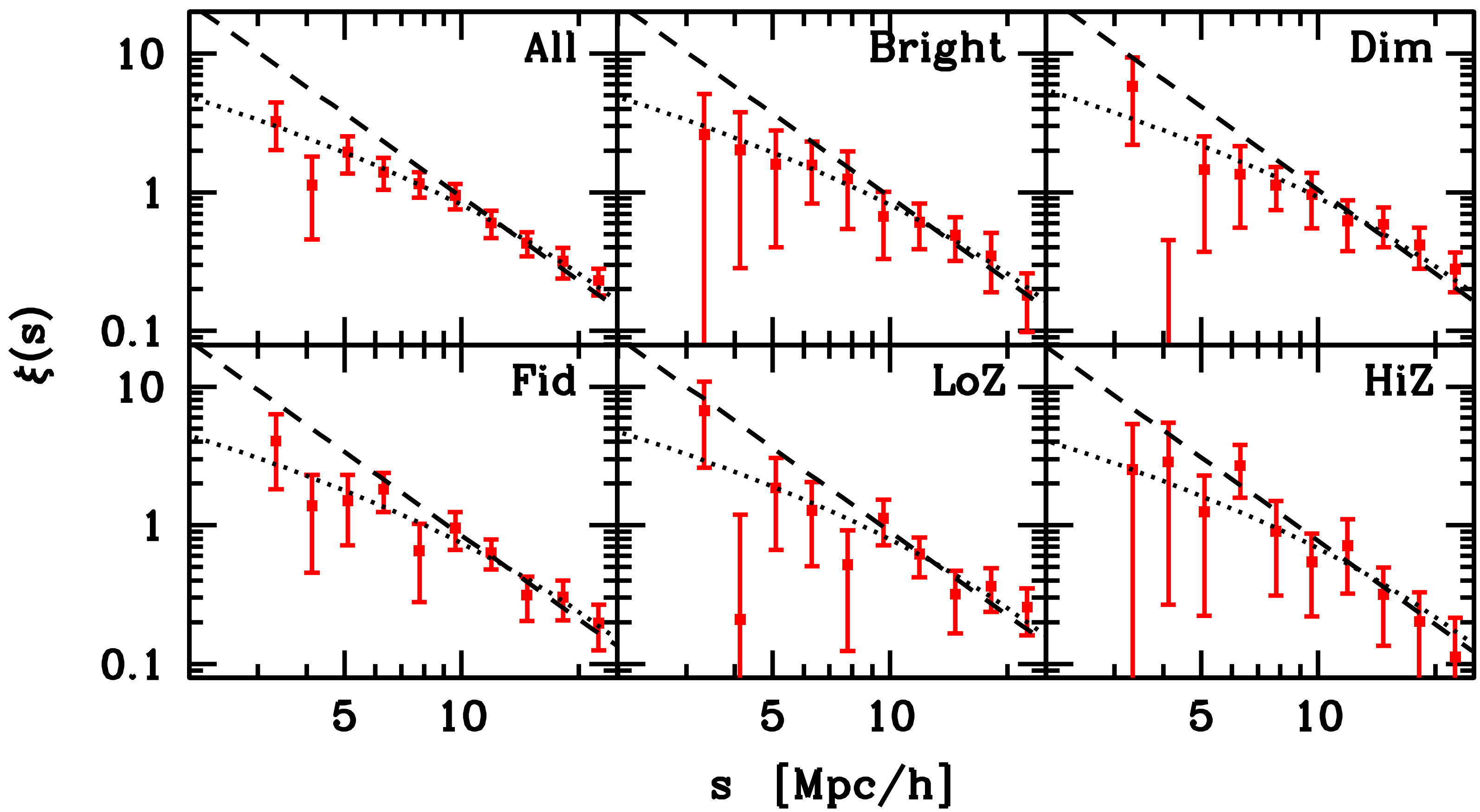
Clustering of 27,129 quasars with 2.2<z<2.8 over 3,600 deg^2 or 9.7(Gpc/h)^3.



No detection of luminosity or redshift dependent clustering: as expected given our dynamic range.

Clustering at z~2.5: Redshift

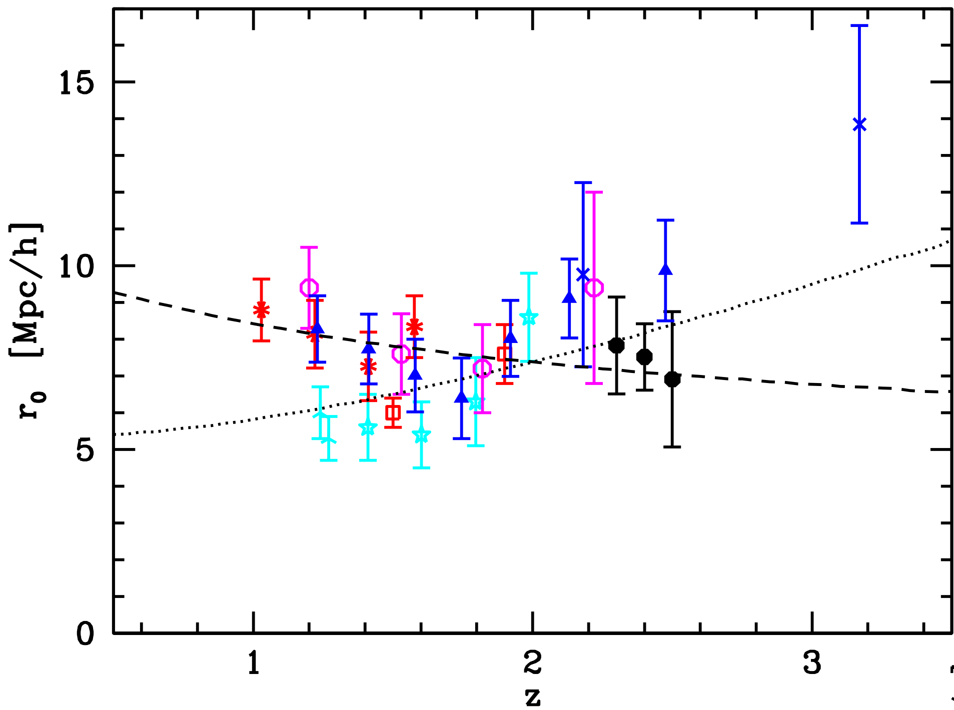
Redshifts very difficult to measure in this range with the BOSS spectrograph (3,600-10,000Å).
End up using broad emission lines in the rest-frame UV (CIII], CIV).



(White++12)

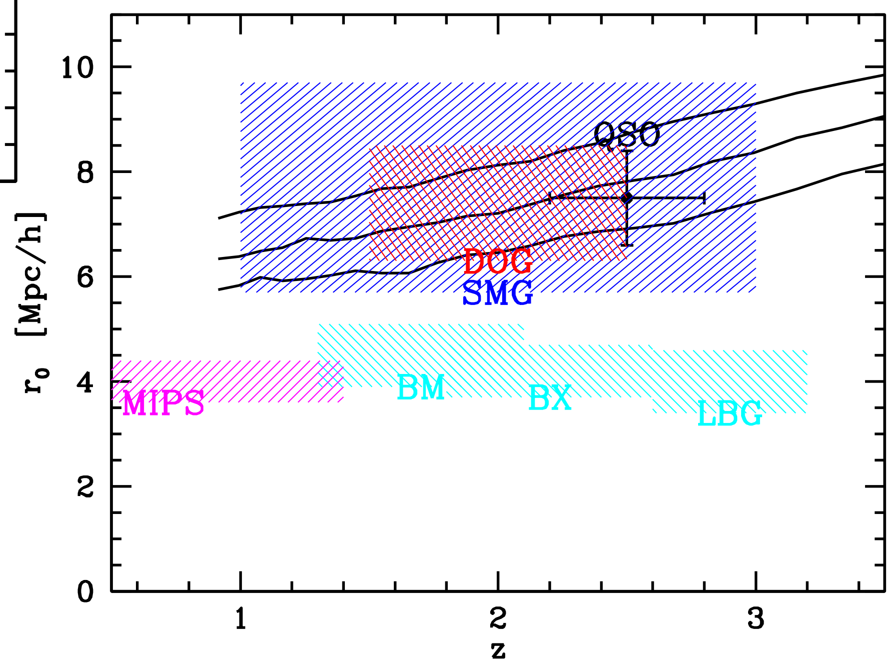
Clustering at z~2.5

(White++12)



b~3.5, M_{halo}~10^{12},
duty cycle ~ 1% (t_Q~10^7yr).

M_{BH}/M_{gal}~5x local relation.



Consistent with "merger scenario" of starburst->submm->QSO.
Wide range of descendents, "typical" descendent is a luminous elliptical galaxy.

QSOs at the peak of the QSO epoch

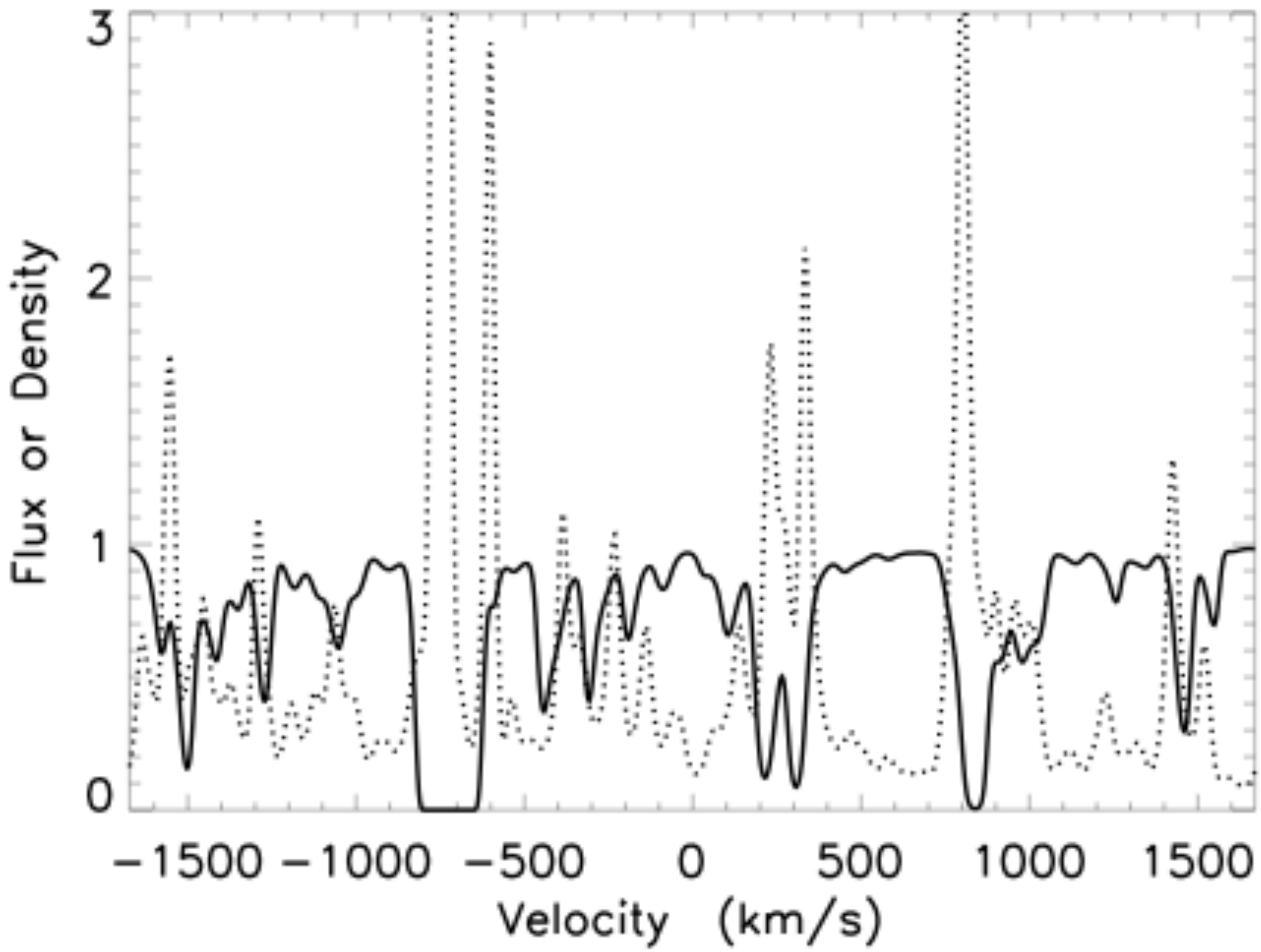
- The diversity of QSO models isn't as large as it might at first seem.
  - Steeply falling mass function.
  - Mostly 2-halo information, and *n* not known.
- If properties of BH set by host galaxy not host halo then LF and clustering easier to explain.
  - $M_{gal}(M_h)$ very steep at low M_h, so flatter faint-end slope and slower run of bias with luminosity.
  - $M_{gal}(M_h)$ very flat at high M_h, may reduce major mergers and suppress high luminosity objects (but other ways…).
- Beware "derived" statistics.
  - Methodological differences can inflate discrepancies.

These quasars also make great backlights …

BAO and the IGM

- Distance constraints become tighter as one moves to higher z
  - More volume per sky area.
  - Less non-linearity.
- Expensive if use galaxies as tracers.
- Any tracer will do: HI
  - 21cm from HI in galaxies: SKA or custom expt.
  - Lyα from IGM as probed by QSOs.
    - Absorption traces mass in a calculable way.
    - A dense grid of QSO sightlines could probe BAO
      - (White 2003, McDonald & Eisenstein 2007, Slosar++09, White++10, McQuinn & White 2011)

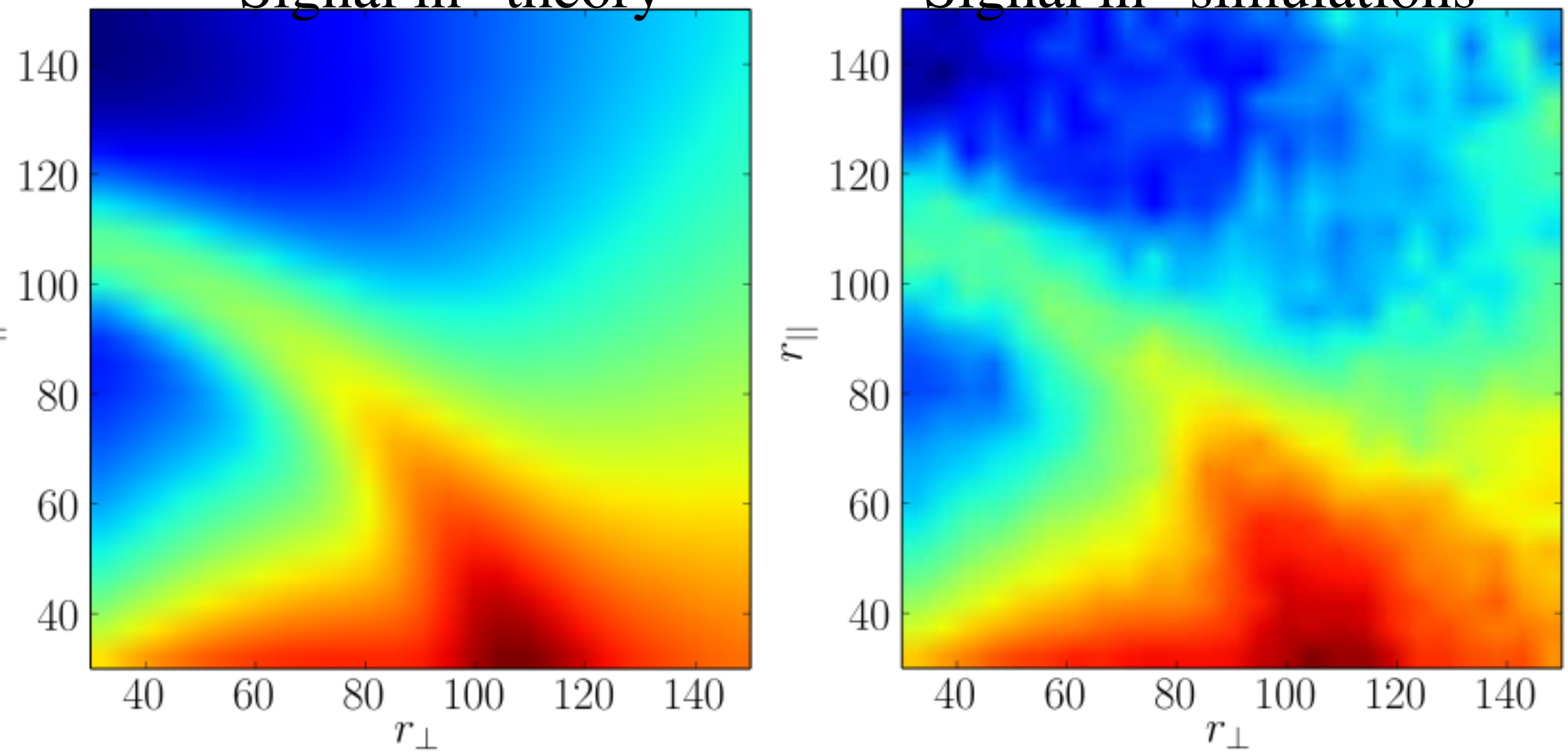
Spectrum ‘=’ density



BAO at high z

Slosar, Ho, White & Louis (2009)

Signal in "theory" Signal in "simulations"



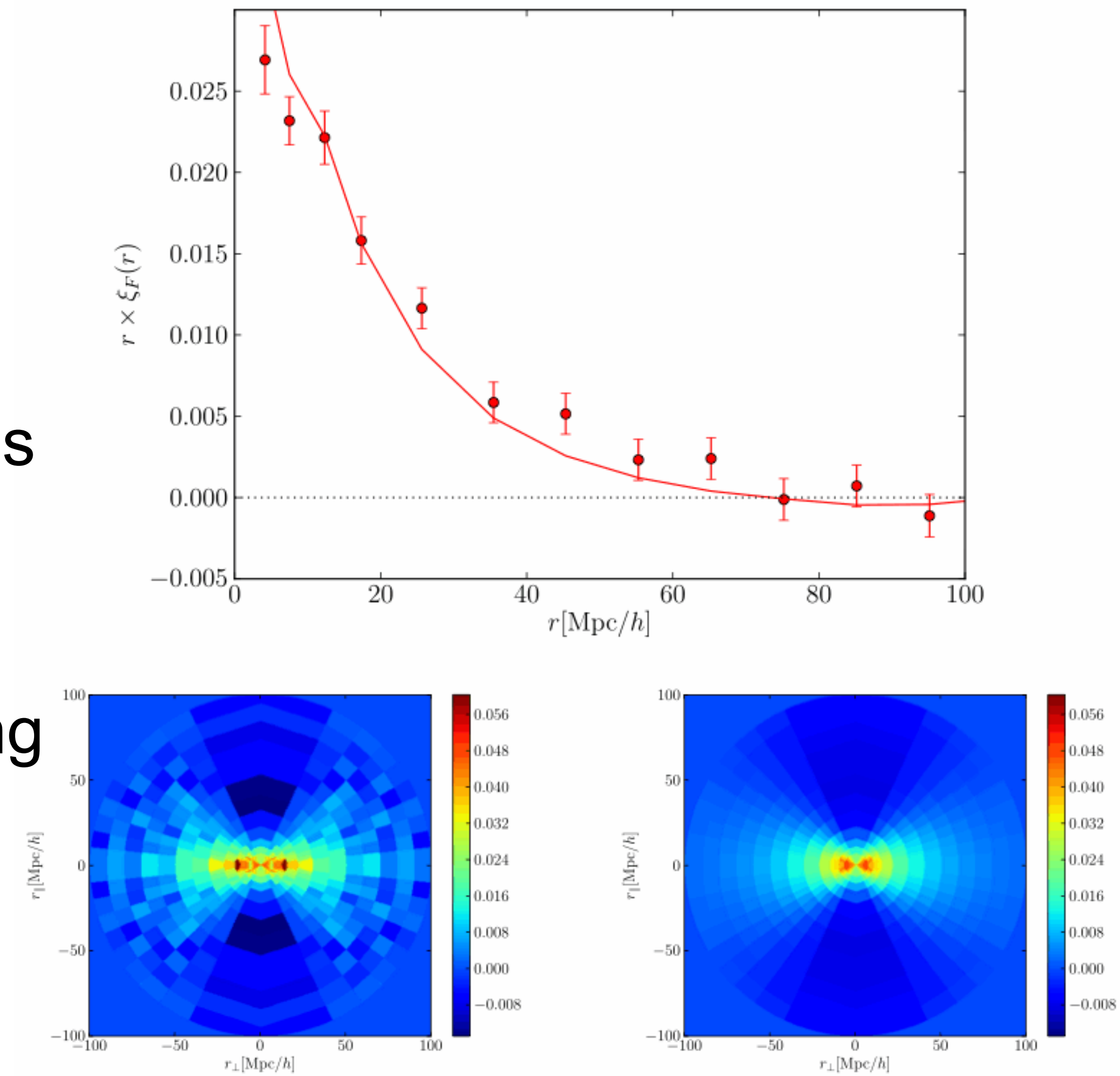
BAO feature survives in the Lyα flux correlation function, because on large scales flux traces density. Relatively insensitive to astrophysical effects.

On large scales

- Differences with the galaxies
  - Not yet a proven technique (but will be *very* soon…)!
  - Signal is $e^{-\tau}$, so downweights high-δ (unlike galaxies which trace high-δ).
  - Need to be slightly careful about redshift space distortions (τ conserved, not *n*, except in line-dominated regime).
  - Noise comes in two forms:
    - Noise in an individual spectrum.
    - Projection/finite sampling: dominant for us and BigBOSS.
    - Balance is important for optimization!
- Additional physics
  - Absorption could be affected by non-gravitational physics
    - Fluctuations in the UV background
    - Temperature fluctuations due to HeII reionization
    - Your favorite astrophysical phenomenon here.

Clustering in the Lyα Forest

- First detection of large-scale clustering of the IGM using cross-correlations between QSO lines of sight.
- Matches ΛCDM prediction well.
- Lyα Forest Working Group has been very active.

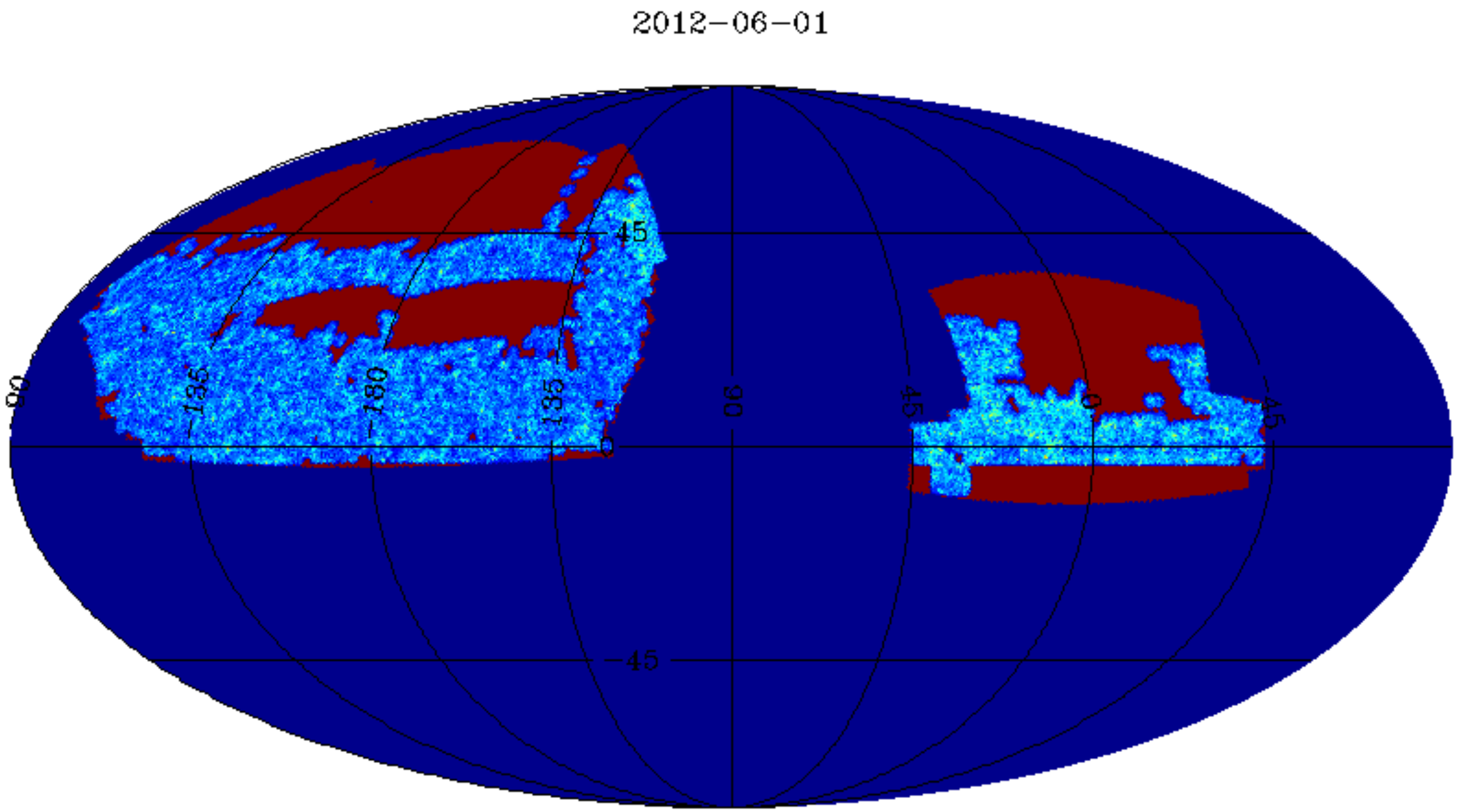


Slosar et al. (2011)

Lyα forest cosmology

- New cosmology paper in few months.
  - Looks very promising for BAO detection.
- Lots of other projects in the early stages
  - "Old fashioned" 1D analysis (for m_ν and inflation, …)
    - Expect ~20x data in McDonald++
- Or in the "thinking about it" stage
  - Lots of cross-correlation projects.
  - …

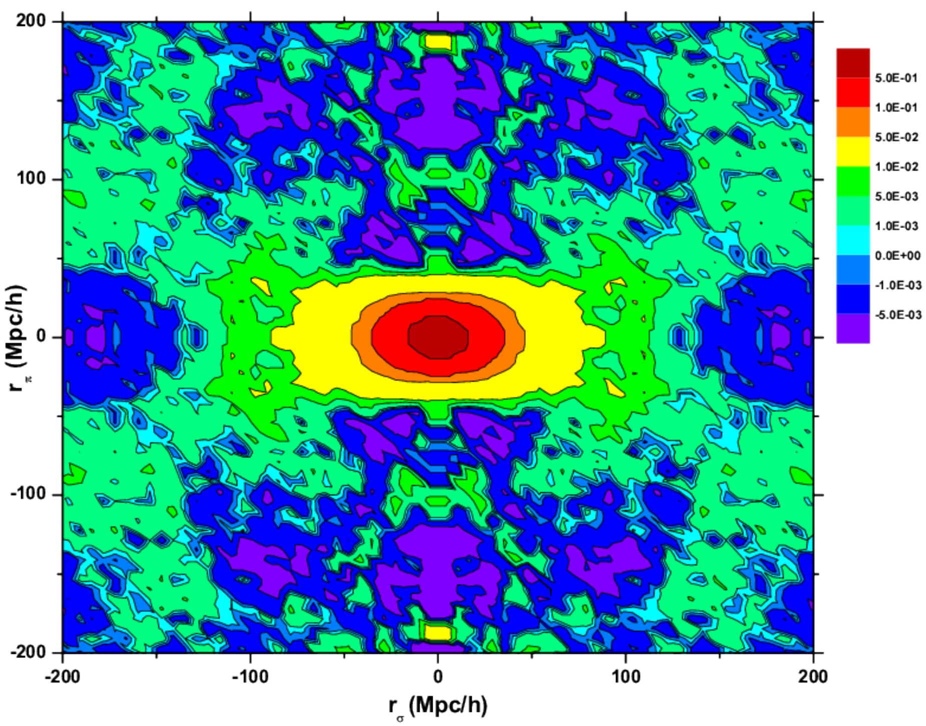
Current status



>500,000 galaxy and >100,000 quasar redshifts, over a million spectra in total!

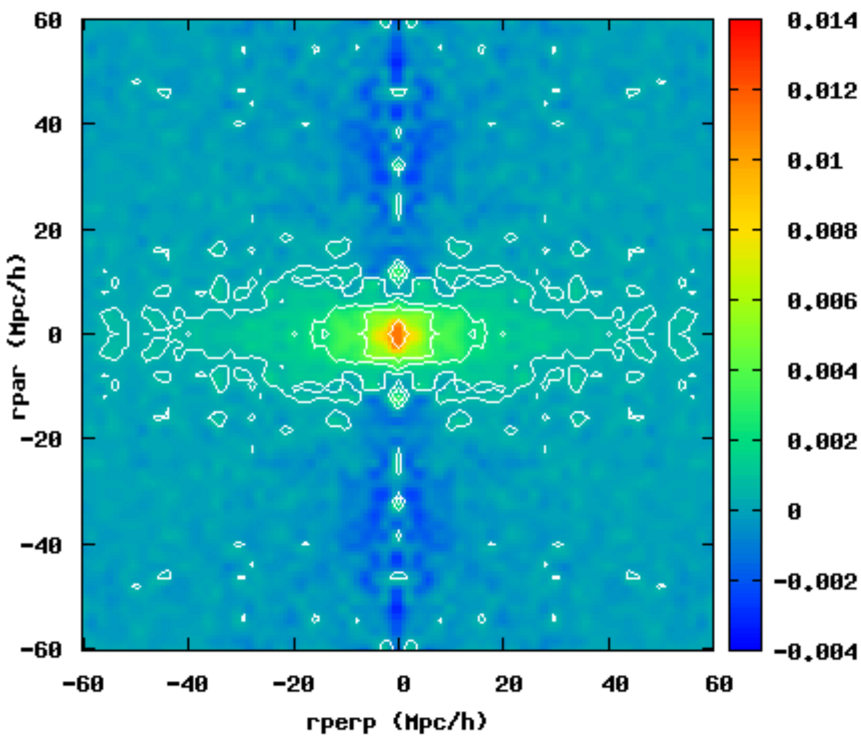
Gravity working at z~0.5 and z~2.5

BOSS galaxies
(years 1+2)



Lado Samushia + galaxy WG

BOSS Lyα
(year 1 only)



Nicolas Busca + Lyα WG

Summary

- BOSS is working extremely well!
- From DR9 we have
  - 1.7% BAO distance constraint at z=0.57
  - (First?) Best measurement of H(z) using BAO + Alcock-Paczynski effect
  - 7% growth rate measurement
- Constraining power on dark energy substantially improved.
- New results on quasar demographics.
- Soon to publish new IGM results.
- Soon to publish new galaxy evolution results.
- Data for DR10 is essentially all “in the can” and we are ahead of schedule …

The End