Testing General Relativity with Redshift Surveys

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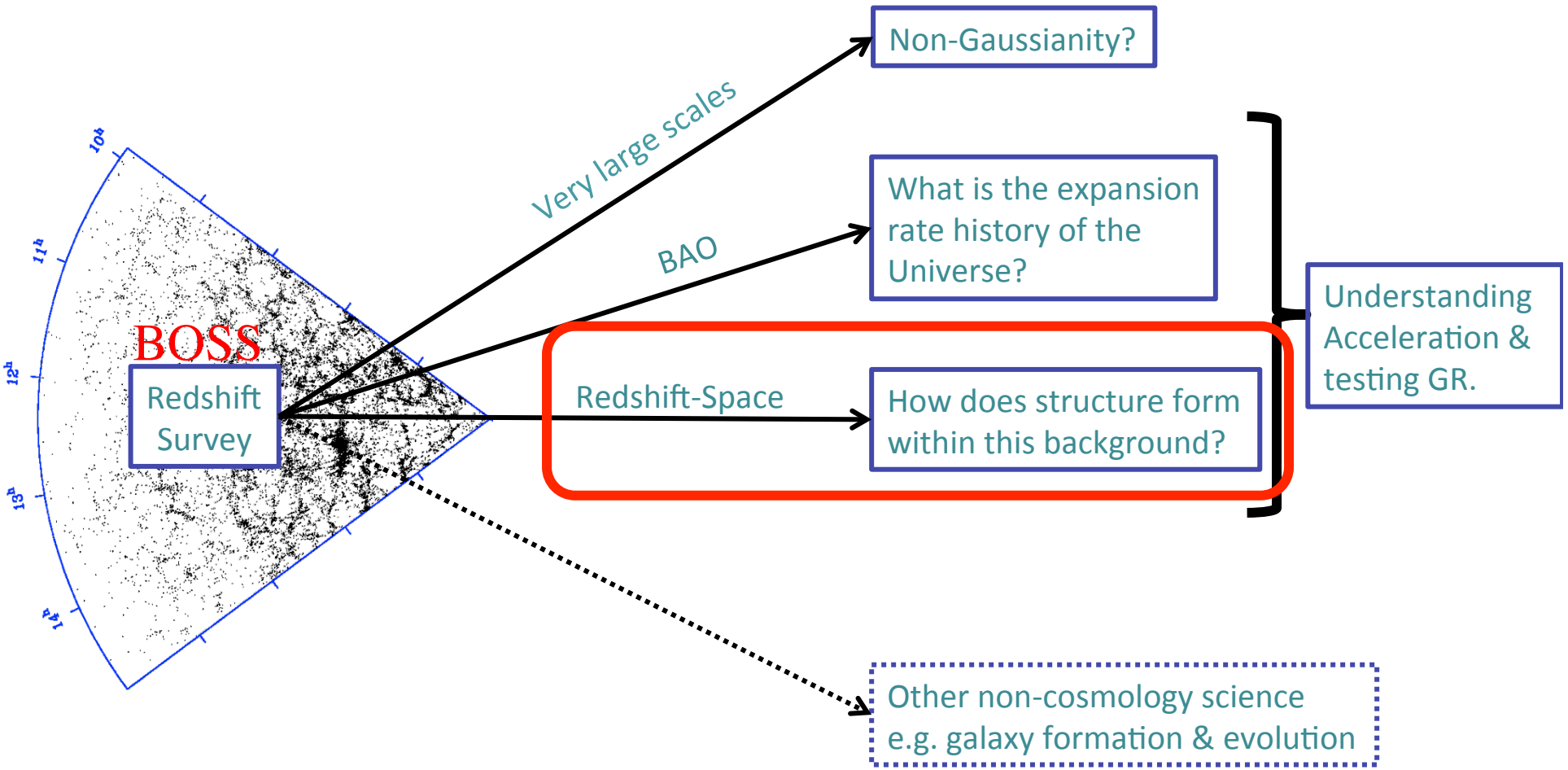
Information from galaxy z-surveys



BOSS

The Baryon Oscillation Spectroscopic Survey was a 6 year program to map the spatial distribution of luminous galaxies and quasars and probe the inter-galactic medium.

SDSS-III and the Baryon Oscillation Spectroscopic Survey (BOSS)

March 21, 2008

Submitted by

PROJECT SUMMARY

Building on the extraordinary legacy of the Sloan Digital Sky Survey (SDSS) and SDSS-II, this proposal presents a five-year project to map the baryon acoustic oscillations (BAO) with unprecedented accuracy to constrain dark energy and other cosmological parameters. The Baryon Oscillation Spectroscopic Survey (BOSS) is the flagship project of SDSS-III, and was awarded five years of dark time (2009 - 2014) in a competitive process conducted by the Astrophysical Research Consortium (ARC) in 2006.

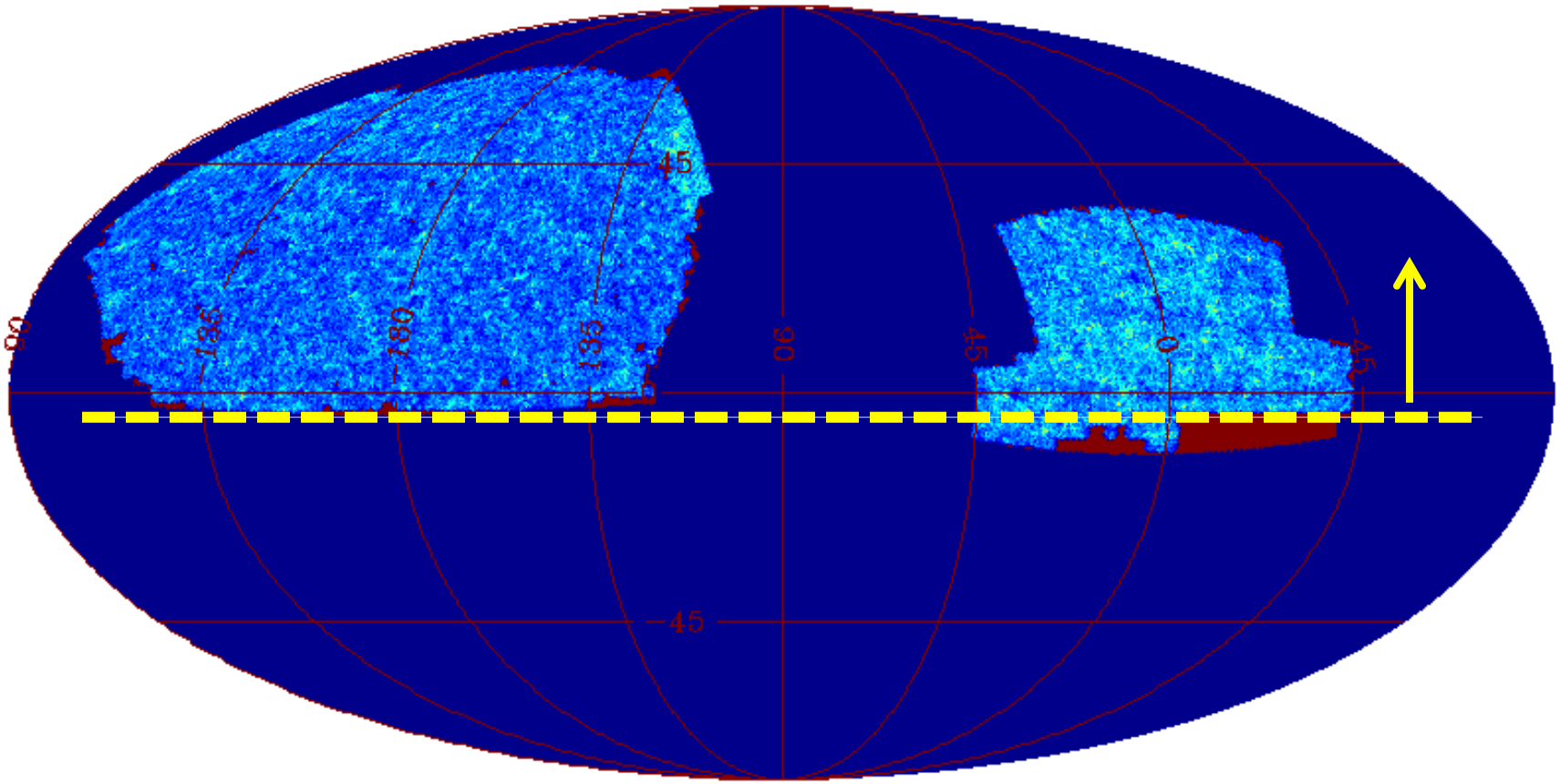
BOSS will carry out a spectroscopic survey of 1.5 million luminous red galaxies (LRGs) and 160,000 high redshift quasars. By using the baryon acoustic oscillation scale as a physically calibrated ruler, BOSS will determine the absolute cosmic distance scale with precision of 1.0% at $z = 0.35$ and 1.1% at $z = 0.6$ from the LRG sample, and 1.5% at $z = 2.5$ from the quasar sample. The combined data set will achieve tight constraints on the equation of state of dark energy, well above what any other planned or proposed BAO experiments could deliver in the same time frame. The high-precision clustering measurements over a wide range of redshifts and length scales will also provide rich insights into the origin of cosmic structure and the matter content of the universe.

How did we do?

- Finished!
  - Early and under budget!
- Redshifts for
  - 0.2+1.35M LRGs ($0.15 < z < 0.7$) and
  - 230K QSOs [of which 169K are at $z > 2.15$]
- over 10,200 deg^2 at $-11<\delta<+69$
- Downtime only 2%!
- Galaxy z-success rate 97%!
- BOSS BAO points are being used in many cosmological fits, especially by CMB expts.

DR12 is now public!

DR12



Redshifts for 1.55M LRGs (0.15<z<0.7) and 230K QSOs [of which 169K are at z>2.15] over 10,200 deg^2 at -11<δ<+69.

RSD: Growth of structure

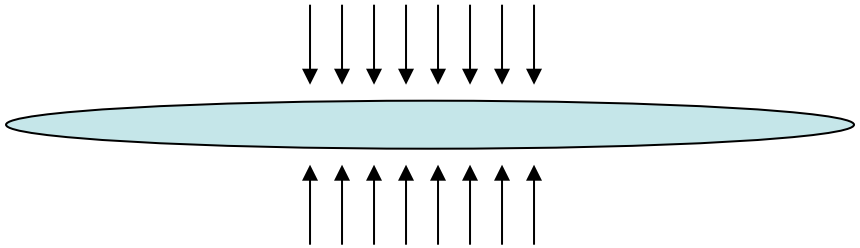
- For fixed expansion history/contents, GR makes a unique prediction for the growth of structure (and velocities).
  - This prediction is at the few percent level – allowing percent level tests of the theory (in principle!).
- Growth of structure could help distinguish dark energy vs. modified gravity models.
  - Also helps break some DE degeneracies …
  - Do we understand how large-scale structure forms?
- We can measure the growth of structure using redshift space distortions.
  - $z_{obs} = Hr + v_{pec}$.
  - $v_{pec} \sim a \sim (\nabla\Psi) \sim (\nabla\nabla^{-2}\rho)$
  - Distortion correlated with density field (i.e. signal).
- We constrain $d\delta/d\ln(a) \sim f\sigma_8$ by measuring the anisotropy in the clustering.

Two regimes

Velocities enhance power on large (linear) scales and suppress power on small scales.

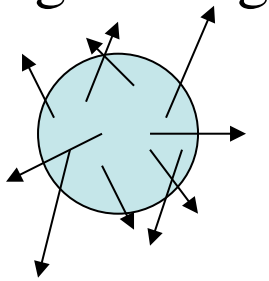
One large scales it's like looking "into the future" along the line-of-sight direction (but not transverse). Induced anisotropy can be used to infer **v** or $d\delta/d\ln(a)$.

Coherent/supercluster infall
(Kaiser effect)

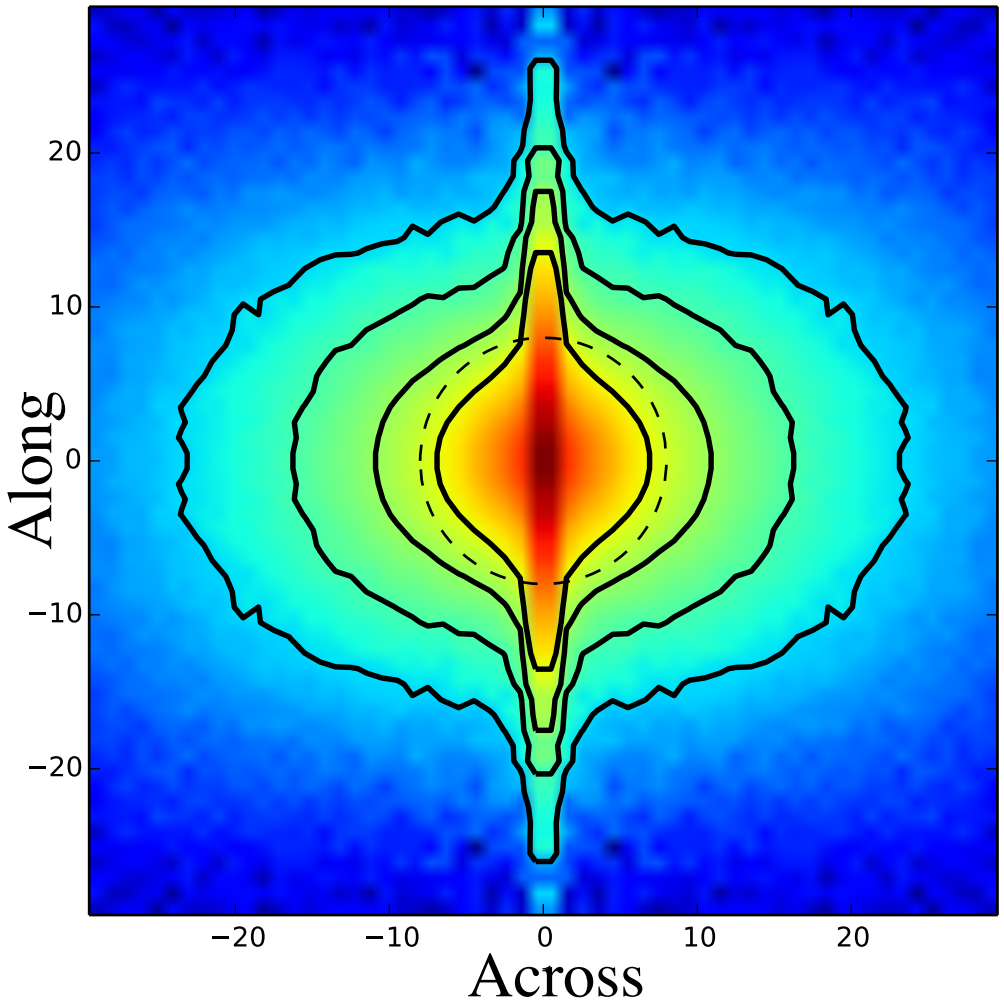


Random (thermal) motion

(fingers-of-god)



2D correlation function

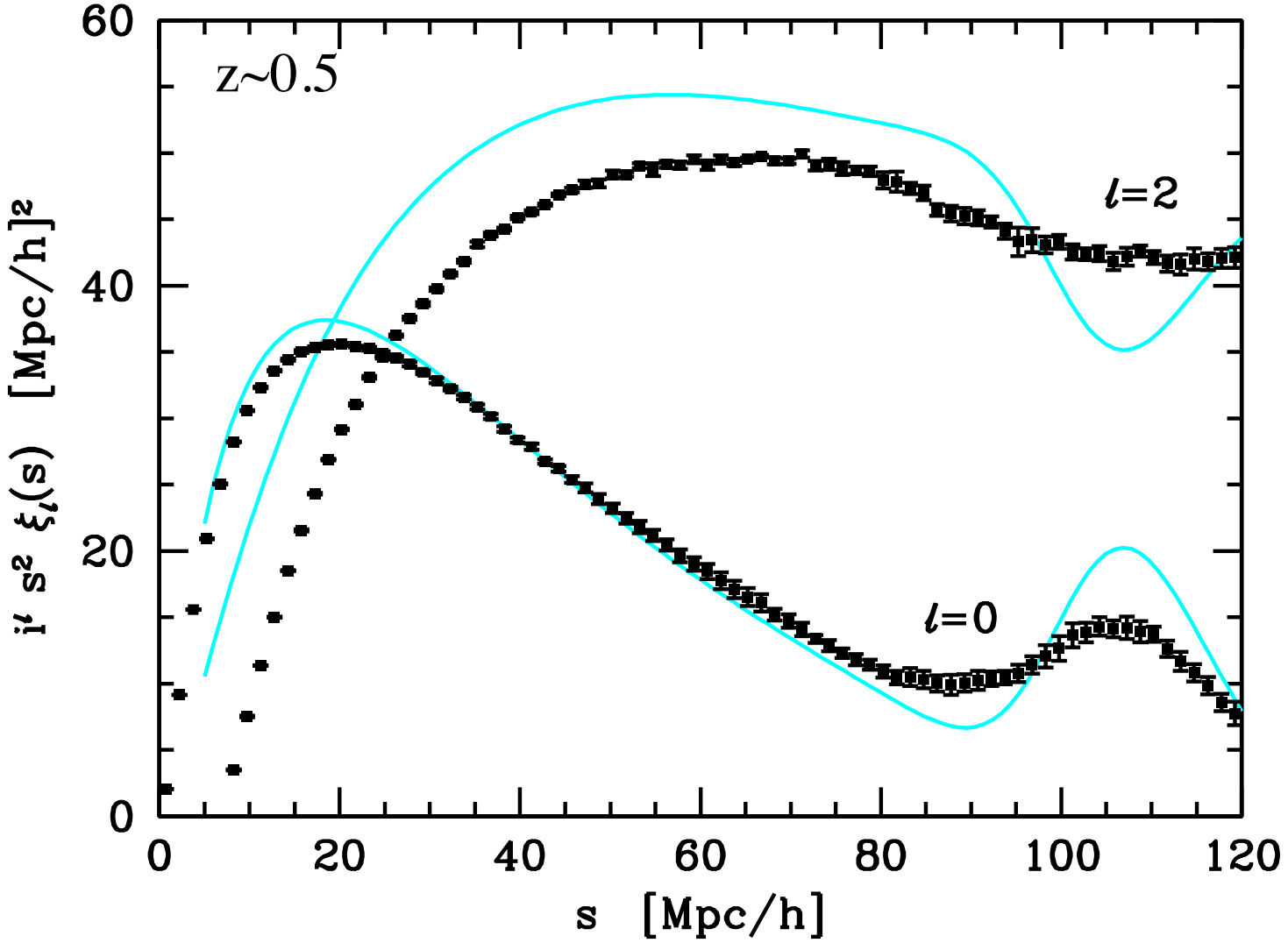


If I plot the counts of pairs of objects, “above random”, in bins of separation across and along the line of sight I get the 2D correlation function.

It is very smooth in angle … usually integrate over the angle, μ, to get the multipole moments (and truncate at low *l*).

Want to model the moments: ξ_l.

Linear theory is not very accurate



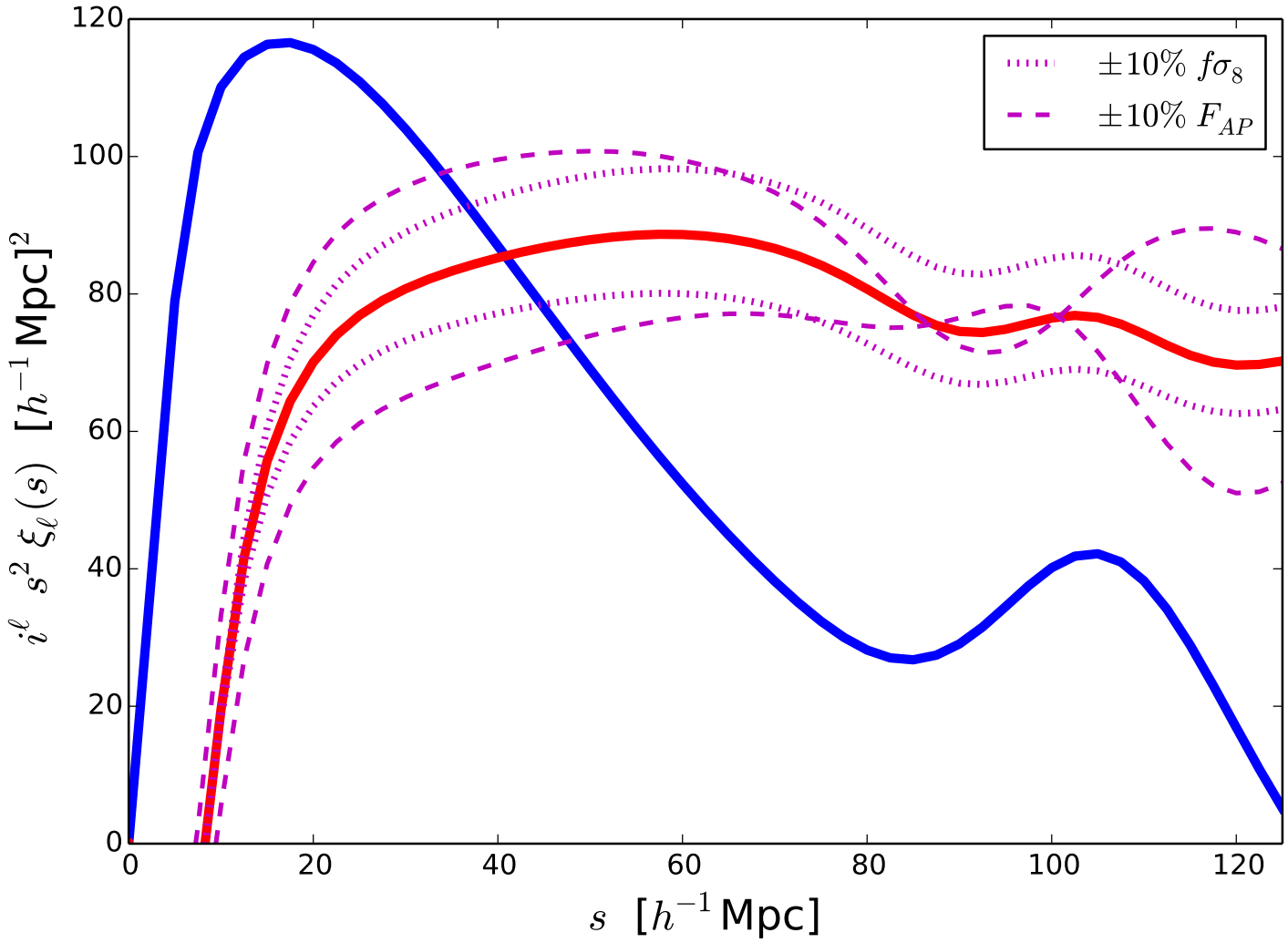
Need higher order

- "Standard" linear perturbation theory is not very accurate.
  - For the monopole, ξ_0, near the BAO peak
  - For the quadrupole, ξ_2, on essentially all scales.
- For RSD part of the difficulty is that we are dealing with two forms of "non-smallness".
  - The density and velocity fields are non-linear.
  - The mapping from real- to redshift-space is "non-small".
- These two forms of "correction" interact (and can partially cancel) and depend on parameters differently.

Need to go beyond linear theory … even on large scales!

Growth-geometry degeneracy

Anisotropies induced by changes in the growth rate can be mistaken for anisotropies induced by having the wrong model to convert θ, z to R, Z (A-P).



This partial "degeneracy" can be broken with a long enough lever arm in scale. But this means we want to fit over a wide range of scales (incl. BAO scale).

BOSS approach(es)

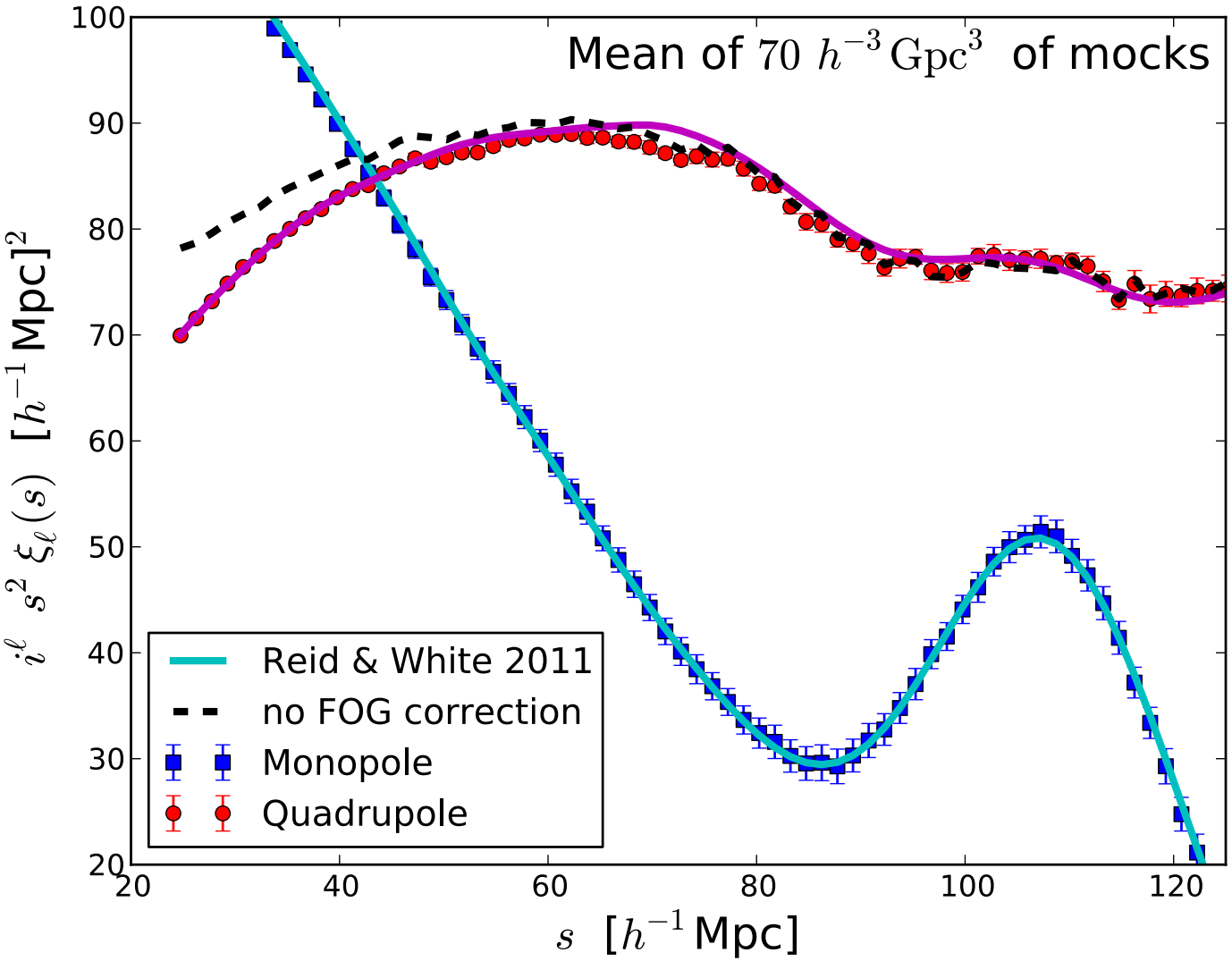
There has been an *enormous* amount of theoretical work on RSD in recent years …

- eTNS [+nonlinear bias].
  - Beutler et al.
- Kaiser + $P_{dewiggled}$.
  - Chuang et al.
- Kaiser + pert. inspired P_{real}.
  - Sanchez et al.
- Distribution function
  - Seljak/McDonald/Hand
- Gaussian streaming models
  - Reid et al., Samushia et al.

Different ways of handling the large (but still not well described by pure linear theory) scales …

All models include some FoG treatment …

FoG a large effect!

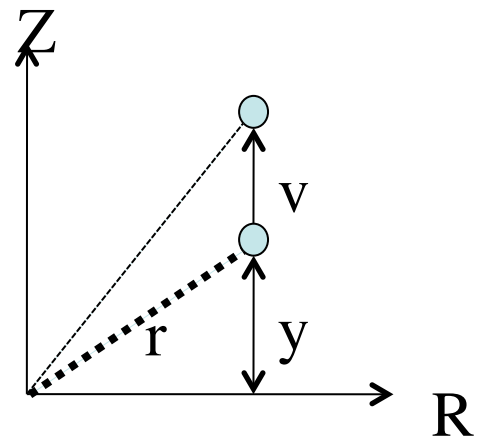


FoG already a 10% effect by s~25Mpc/h [k~0.15].

Gaussian streaming model

- Over the past several years we have developed formalism for fitting the configuration-space, 2-point statistics of biased tracers in redshift-space.
- Based on "streaming" model and perturbation theory, plus a simple 1-parameter model for FoG.
  - Reid & White (2012), Reid et al. (2012), Wang et al. (2014), White (2014), White et al. (2014), ...

$$1 + \xi(R, Z) = \int dy \ [1 + \xi(r)] \, \mathcal{P}\left(v = Z - y, \mathbf{r}\right)$$

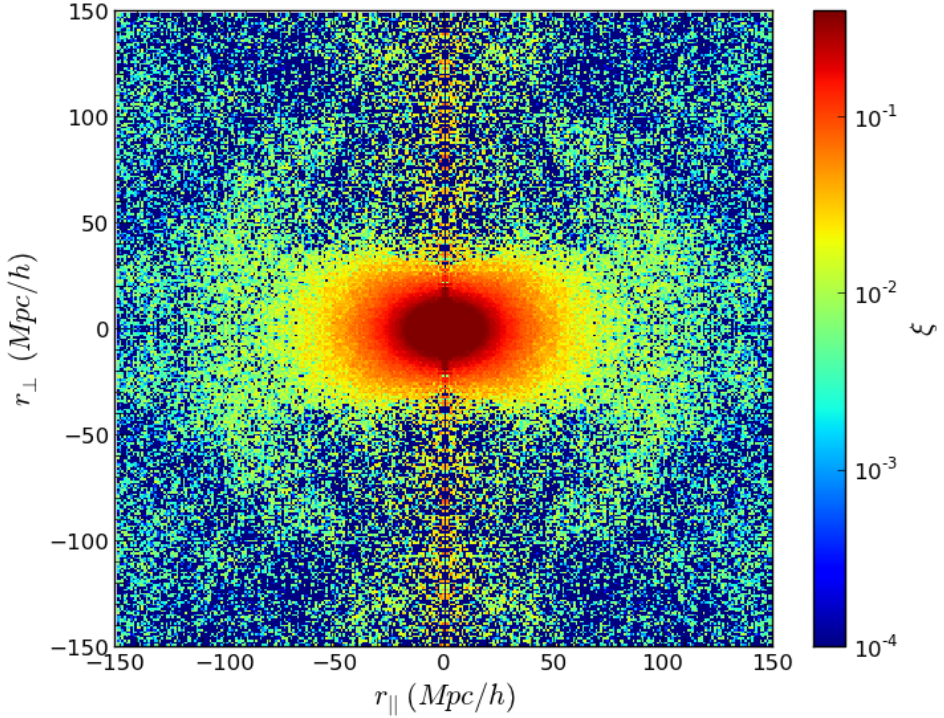


Approximate *P* as a Gaussian with moments set by Eulerian or Lagrangian perturbation theory. Use PT for ξ(r).

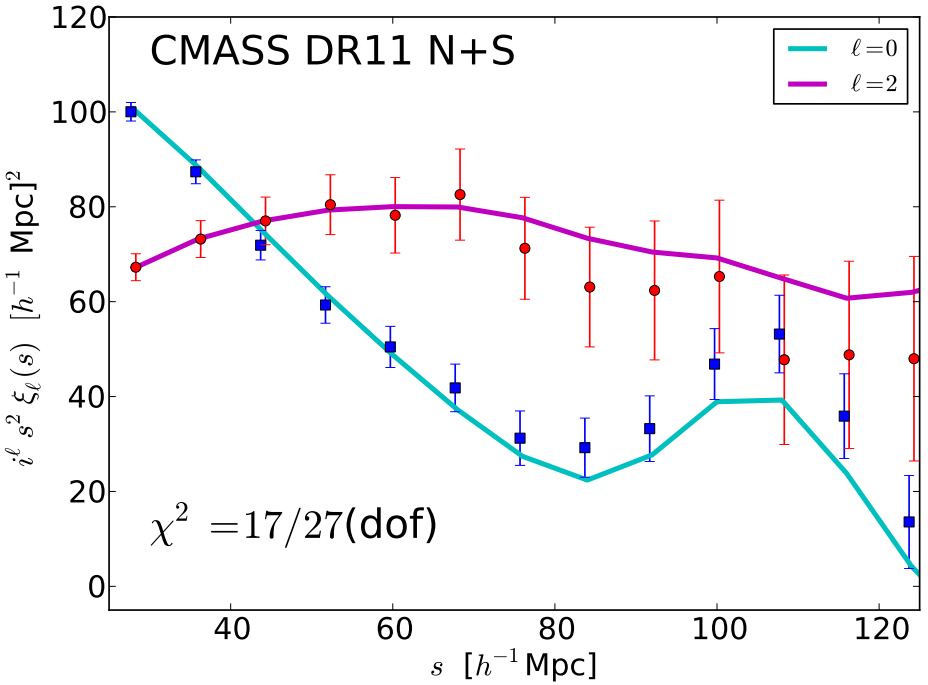
Parameters to fit to anisotropic clustering

- Linear P(k)
  - Known well from Planck, or can marginalize.
- $b\sigma_8$ [unknown galaxy bias]
- $f\sigma_8$ [pec. vel. field norm./growth rate]
- α_{para} ,α_{perp} [geometric params: D_A, H]
- σ_{FoG} [fingers-of-god]

Constraints from DR11

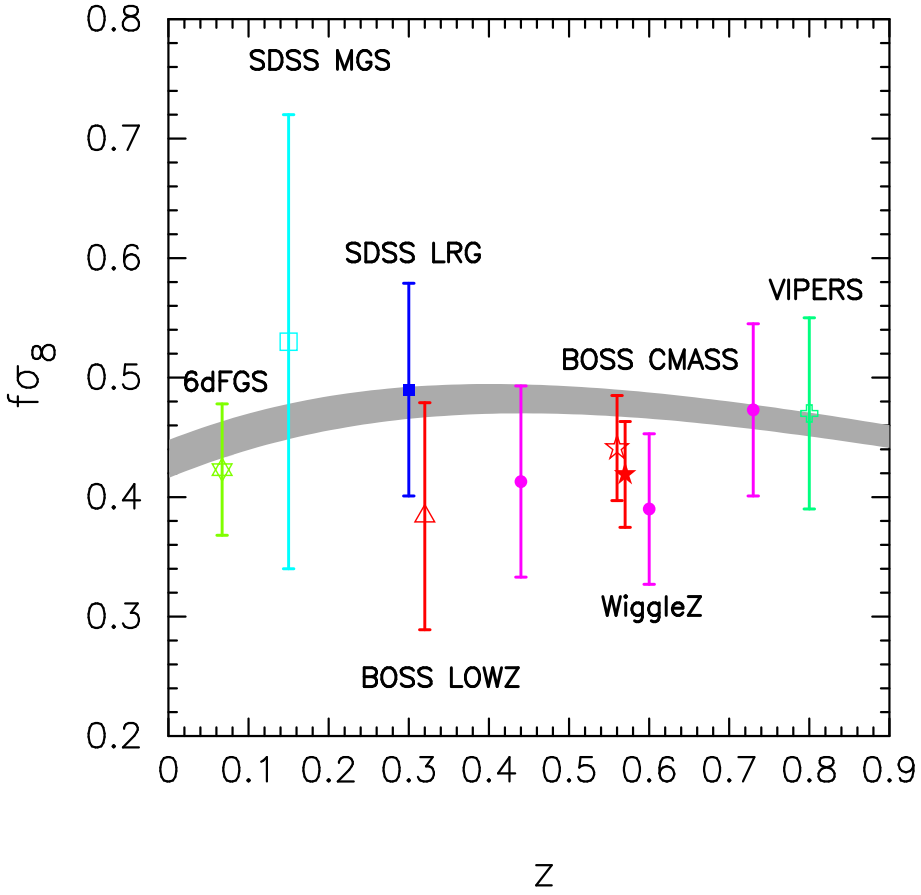


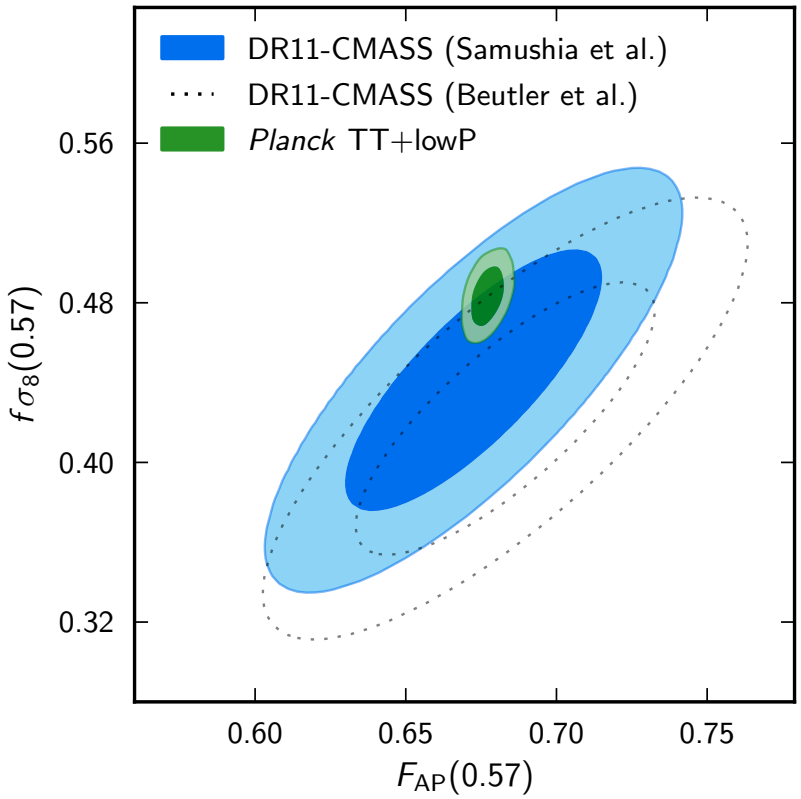
From Samushia et al. (2014), see also Sanchez et al. (2014) and Chuang et al. (2014) and Fourier space analysis in Beutler et al. (2014).



Current constraints …

(compared to Planck)





From the Planck parameters paper: preliminary!

Upcoming BOSS RSD analyses …

- We will be publishing several RSD analyses of DR12.
  - Fourier and configuration space.
  - Straight to cosmological parameters or $f\sigma_8$, F_{AP}, …
- We are planning to combine BAO+RSD, including reconstructed BAO constraints.

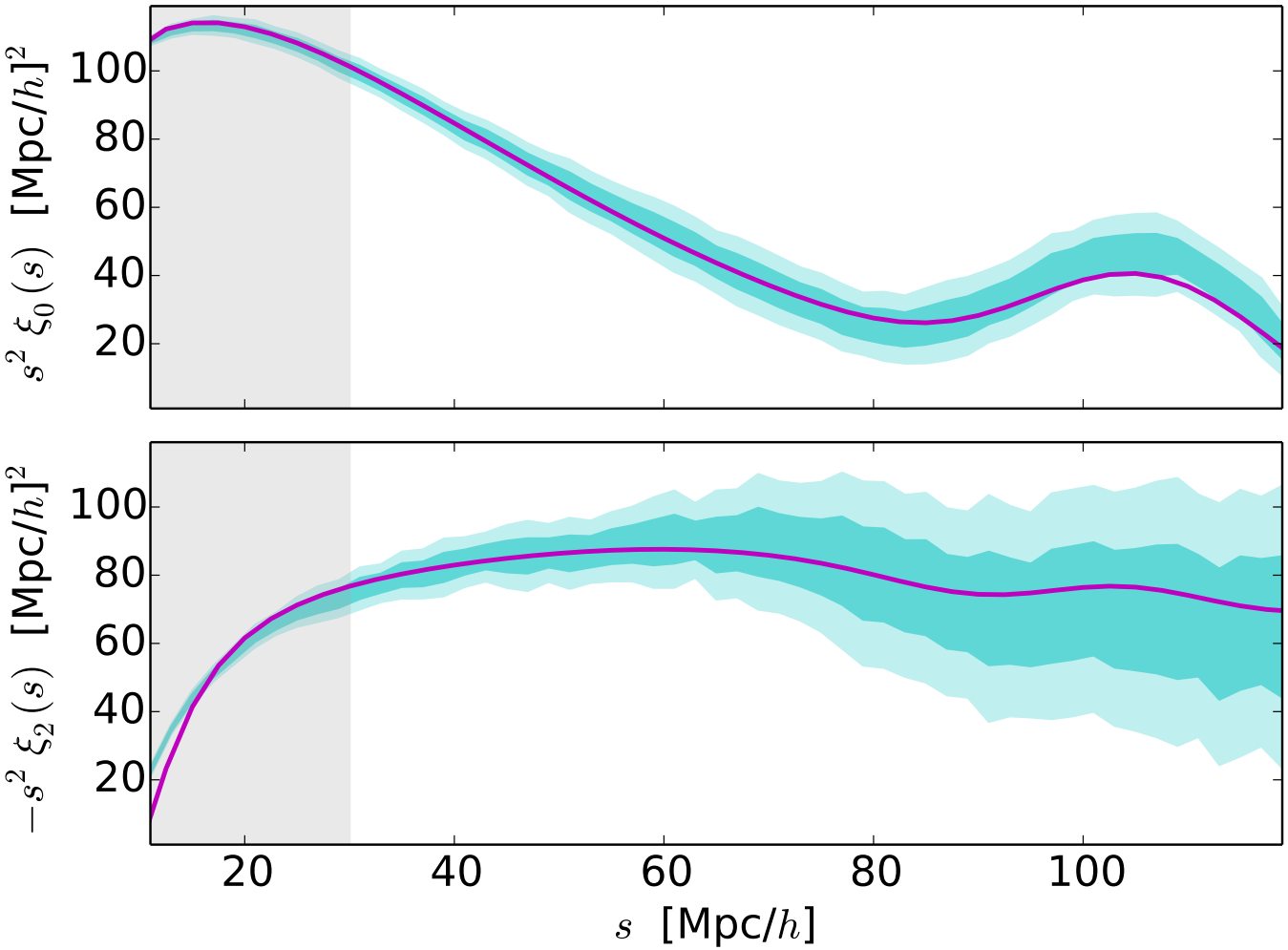
We have just finished a blind mock "challenge" with the goal of a consensus wrap-up paper …

(Beware assembly bias!)

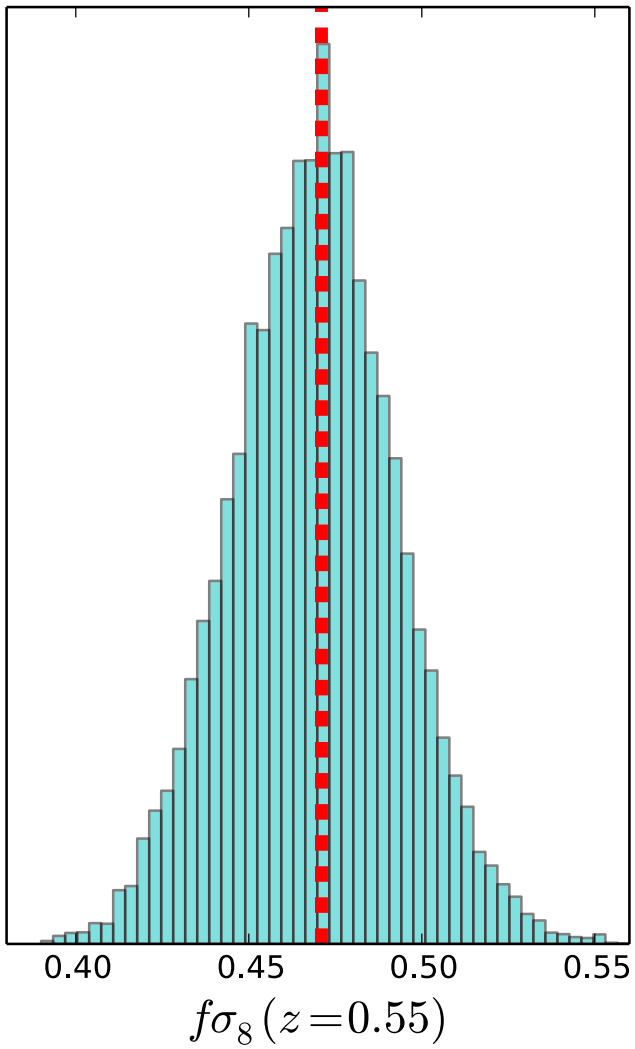
A test unblinded:

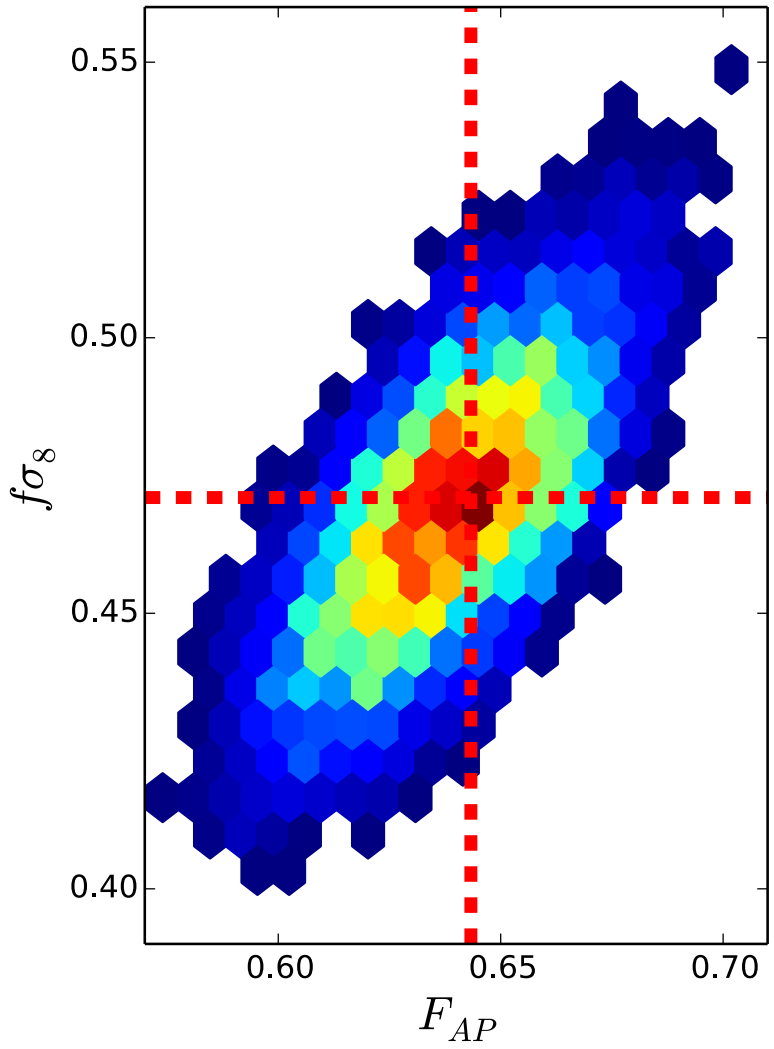
Lagrangian streaming model

(average of ~5 BOSS volumes with 1σ and 2σ bands)



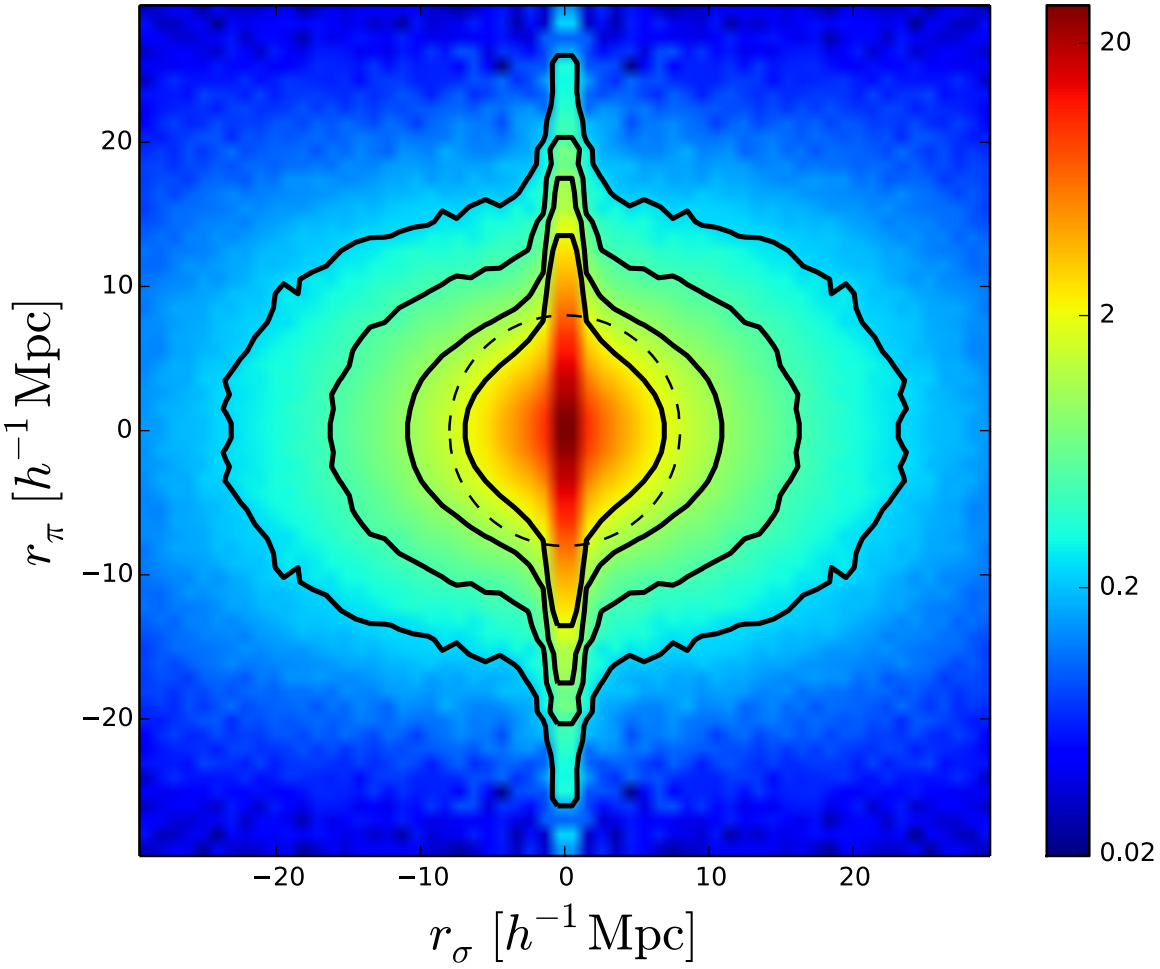
Test on CMASS-like mocks
(average of ~5 BOSS volumes)

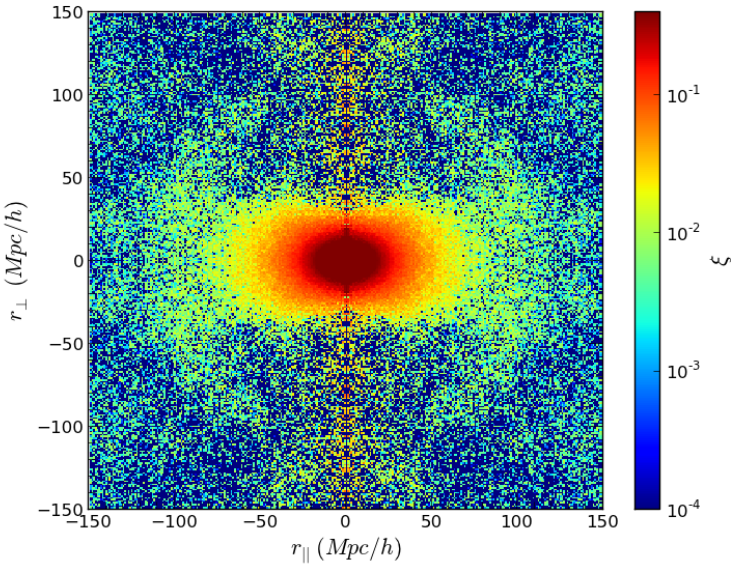




What about small scales?

(Reid et al. 2014)





There's lots of information on small scales, if we can find a way to use it! How much better could we do?

Going to small scales …

- Reid++ show that one can do about a factor of 2 better, with existing data, if you can model things to small scales.
- This is great if your goal is to “test GR” (and galaxy formation, and …).
- Working on small scales requires simulations … makes random exploration hard.

Life after BOSS

- SDSS-III has finished … SDSS-IV has started
  - SDSS-III finished up with “SEQUELS”, looking at LRGs, ELGs and QSOs.
  - eBOSS: probing $0.6<z<2$ with LRGs, ELGs & QSOs over 7,500; 1,500; 7,500 deg^2 respectively.
- Prime Focus Spectrograph (PFS)
- Dark Energy Spectroscopic Instrument (DESI)
- Euclid
- WFIRST-AFTA
- Spherex
- etc.
- 21cm observations …

Coming “soon”: DESI

http://desi.lbl.gov/

- Broad redshift range: 0.5<z<1.6 and 2.2<z<3.5
- Sky area 14,000-18,000 deg^2: 20-35M redshifts!
- Medium resolution spectroscopy (R~3000-5000) from blue to NIR with 4,000 fibers.
- BOSS made two *O*(1%) distance measurements
- DESI will make 35 *O*(1%) BAO distance measurements!
- Plus all of the other science that one can do with redshift surveys!

The End