Applying the Halo Model to Large Scale Structure Measurements of the Luminous Red Galaxies: SDSS DR7 Results

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Outline

- Information in the galaxy P(k): Motivation and Challenges
- Halo Model Review
- Key Insight: Finding Counts-in-Cylinders groups
- Building high-fidelity mock LRG catalogs*
- Modeling the Reconstructed Halo Density Field P(k)
- Cosmological Constraints from SDSS DR7

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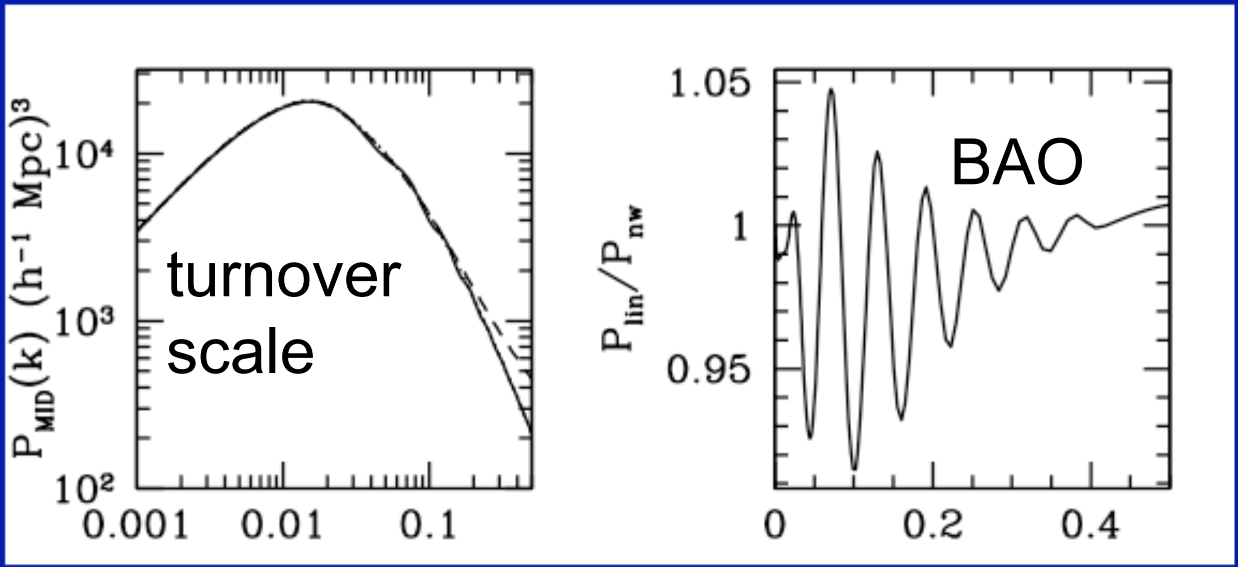
Measuring $P_{gal}(k)$: Motivation

- WMAP5 almost fixes* the expected $P_{lin}(k)$ in **Mpc^{-1}** through $\Omega_c\, h^2$ (6%) and $\Omega_b\, h^2$ (3%), independent of θ_{CMB}



* ignoring the effect of massive neutrinos

k (h Mpc^{-1})

Measuring $P_{gal}(k)$: Motivation

- Given CMB peak height priors, we are mainly constraining $D_V(z_{eff})$ in Mpc:

$$D_V(z) \quad = \quad \left[(1+z)^2 D_A(z)^2 \frac{cz}{H(z)}\right]^{1/3}$$

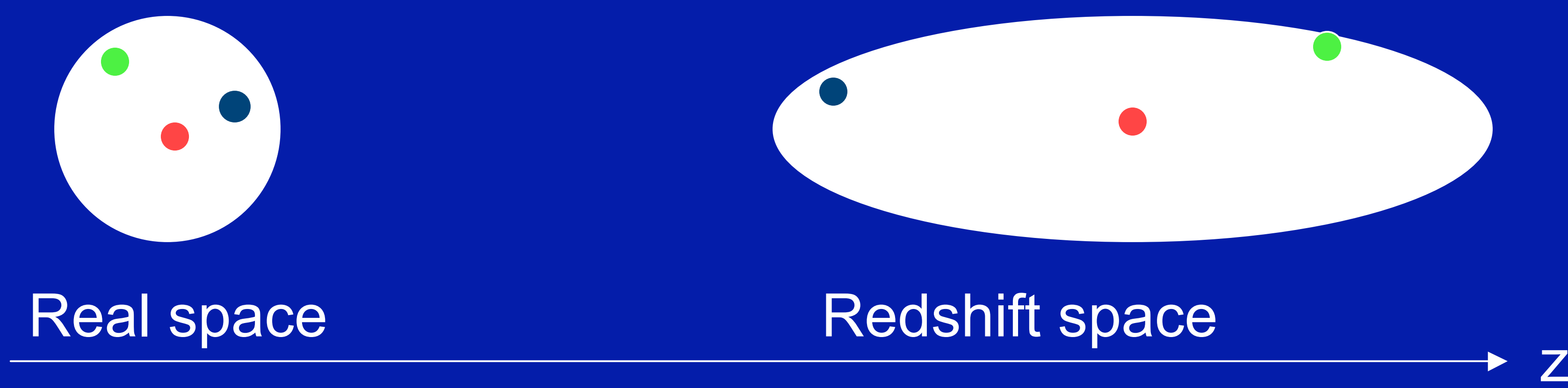
- Constrains one combination of

  Ω_m, H_0, Ω_k, and $w(z_{eff})$

- P(k) shape and BAO provide independent constraints with different sensitivities to CMB priors

Measuring $P_{gal}(k)$: Challenges

- density field δ goes nonlinear
- uncertainty in the mapping between the galaxy and matter density fields
- Galaxy positions observed in redshift space

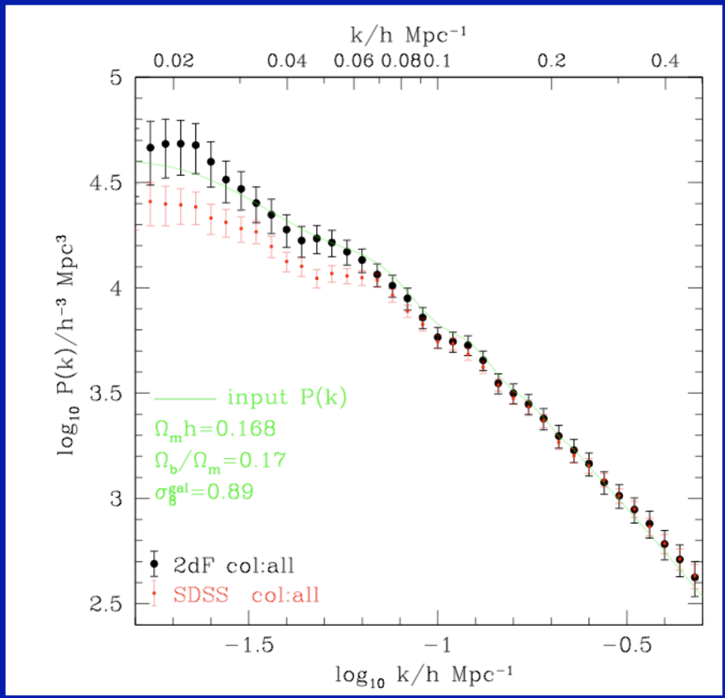


Why Study Galaxy Bias?

- Galaxy bias relates δ_g and δ_m:

$$b^2_{gal}(k) = \frac{P_{gal}(k)}{P_{matter}(k)}$$

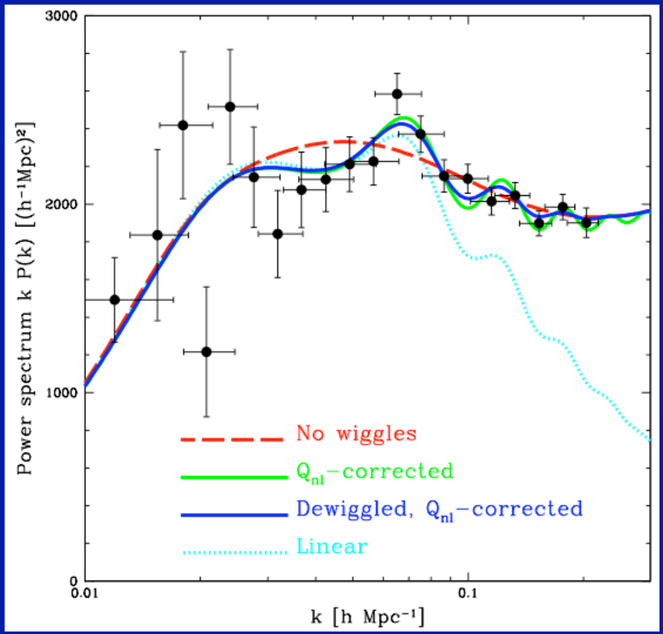
- P(k) and the best fit Ω_m h vary with galaxy type [Sanchez and Cole, 2007]



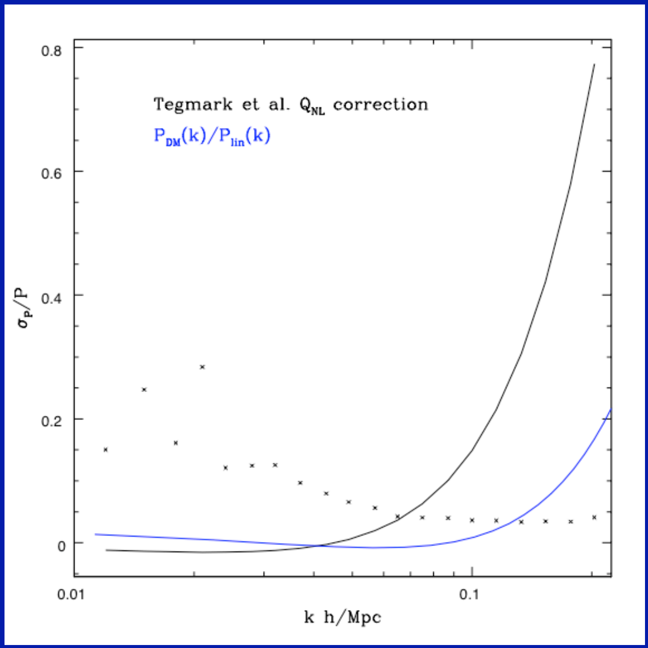
Why Study LRG bias?

- Statistical power compromised by Q_{NL} at k < 0.09! [Dunkley et al 2008, Verde and Peiris 2008]

$$P_g(k) = P_{\text{dewiggled}}(k) b^2 \frac{1 + Q_{nl} k^2}{1 + 1.4k}$$



Tegmark et al 2006

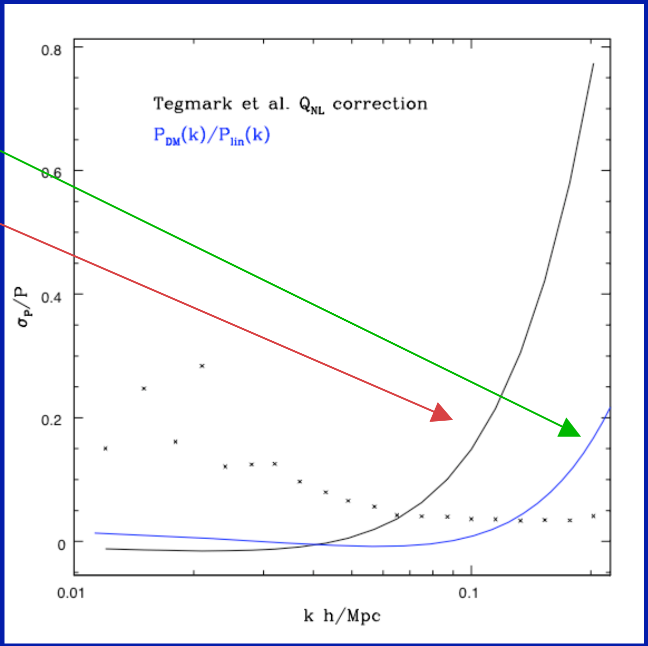


Previous Approaches

- Fit P(k) only on large scales (k < 0.1) and marginalize over nuisance parameter [Tegmark, et al 2006]
- Marginalize over P(k) shape and only extract the BAO information [Percival et al, 2007, prep]

Our Aim

- Use detailed modeling to understand the source of nonlinear LRG bias and eliminate it: Change to !



- Tools: N-body sims + "Halo Model"
- Reward: Fit both Shape and BAO; 8x more modes

Galaxies in the Halo Model

- Halo Model Key Assumptions:
  - Galaxies only form/reside in ‘halos’
  - Halo mass entirely determines key galaxy properties
- Ingredients:
  - halo catalog
  - Halo Occupation Distribution $P(N_{LRG} \mid M)$
  - Galaxy Distribution within halo: ‘central’ and ‘satellite’ galaxies are distinct

Halo Model P(k): real space

$$P_{LRG}(k) = P_{LRG}^{1h}(k) + P_{LRG}^{2h}(k)$$

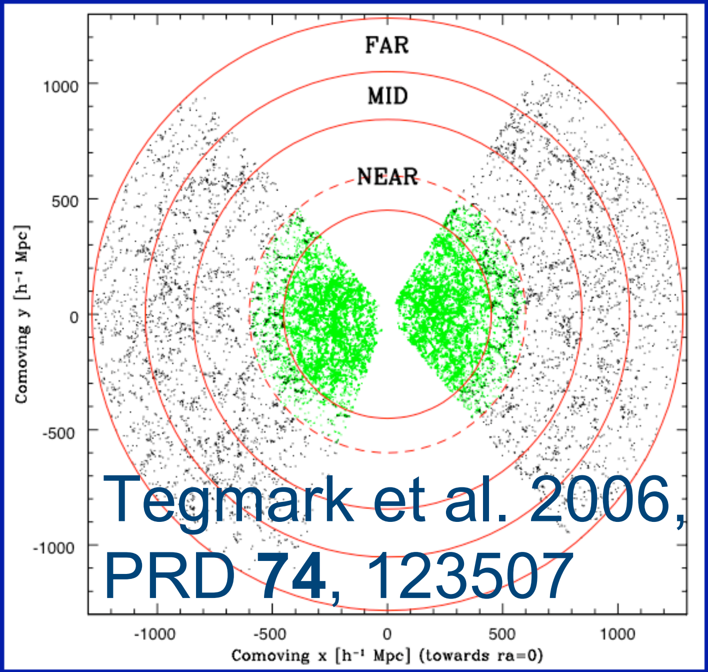
$$P_{LRG}^{1h} = \int dM\, n(M) \frac{\langle N_{LRG}(N_{LRG}-1)|M\rangle}{\bar{n}_{LRG}^2}$$

$$P_{LRG}^{2h}(k) = b_{LRG}^2 P_{DM}(k)$$

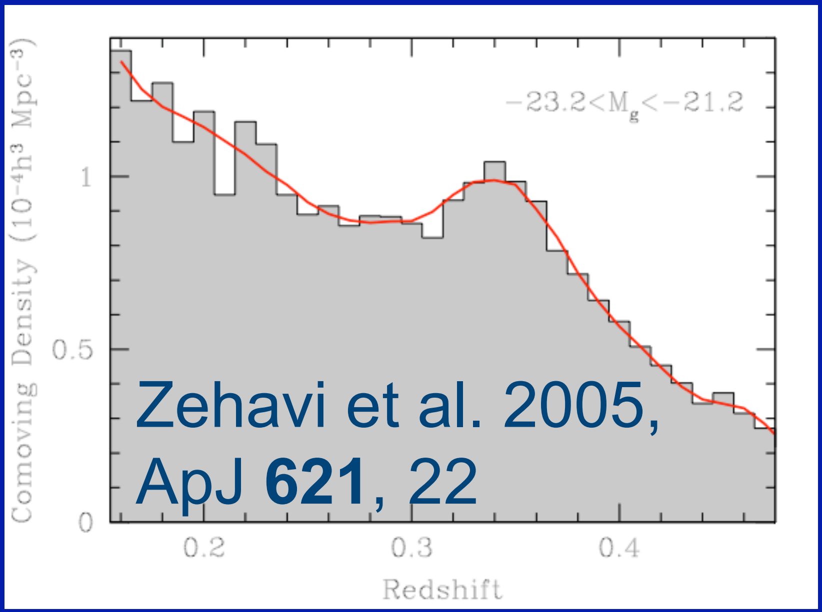
- P^{1h}: major source of ‘nonlinearity’ and variation in $P_{gal}(k)$ with galaxy type [Schulz & White, 2006]
- Redshift space: complicated by FOGs

SDSS LRGs

- Probes largest volume: ~ (Gpc/h)^3
- 3-6% are satellite galaxies
- small $n_{LRG} \longrightarrow 1/n_{LRG}$, P^{1h} corrections large
  – Occupy massive halos $\longrightarrow$ large FOG features



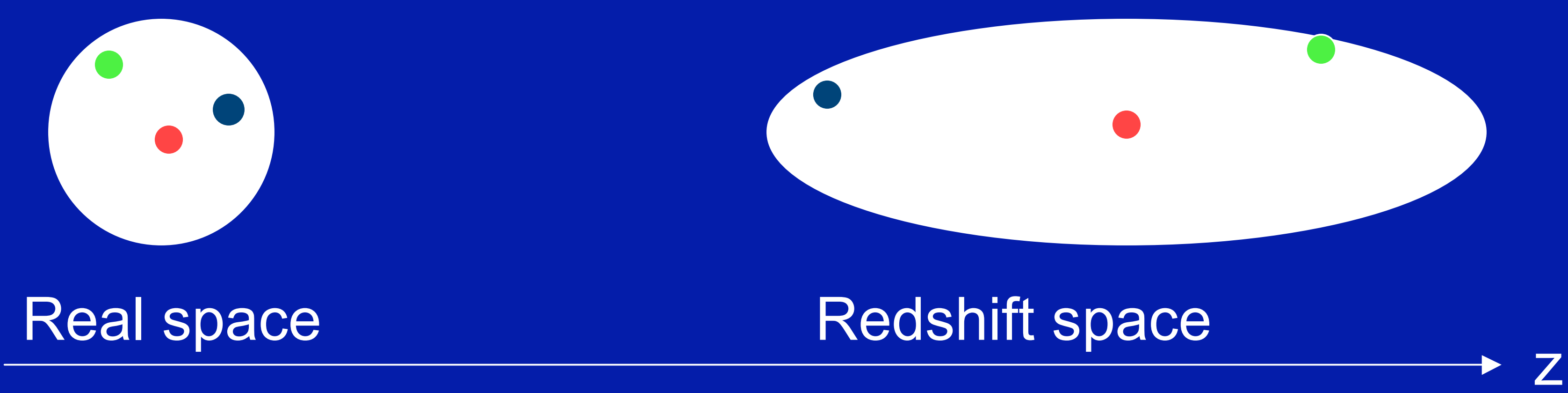
Tegmark et al. 2006, PRD **74**, 123507



Zehavi et al. 2005, ApJ **621**, 22

Key Insight

- Find galaxy groups in the density field using the FOG features ('Counts-in-Cylinders')
  - Measure the group multiplicity function, constrain the HOD $P(N_{LRG} \mid M)$, and make high fidelity mock catalogs
  - Reconstruct the halo density field for P(k) analysis

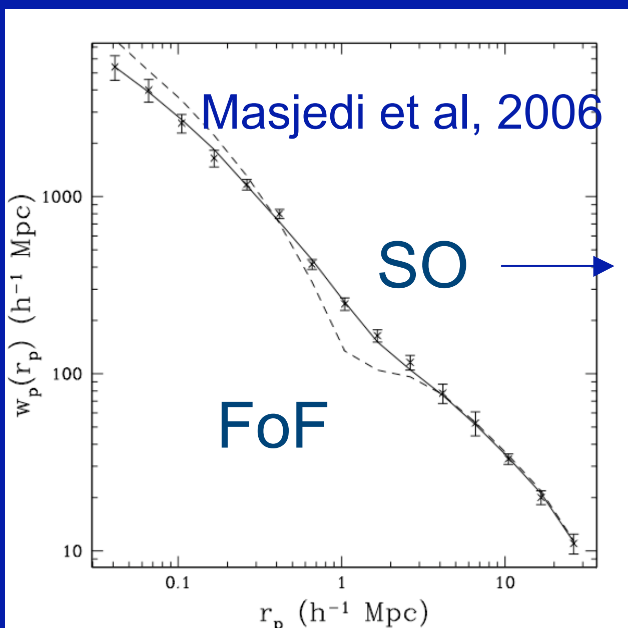


Counts-in-Cylinders Group Finder

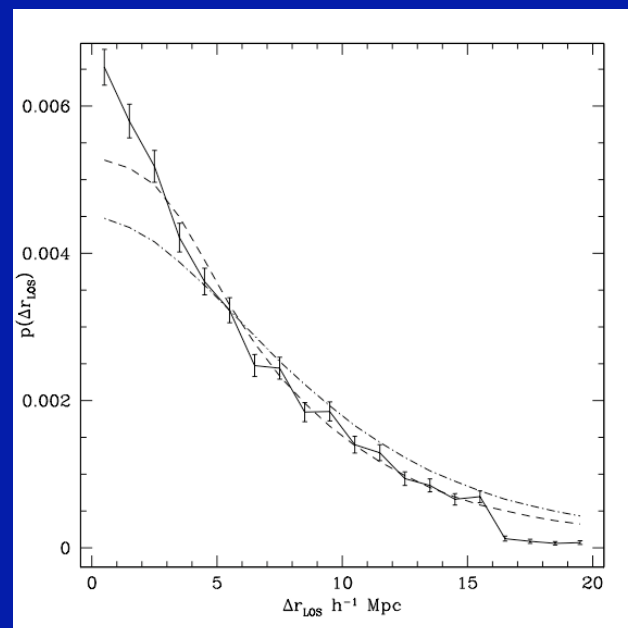
- Identify candidate one-halo pairs of galaxies in cylinders:
  - $\Delta r_{perp} < 0.8$ Mpc/h (set by typical halo size)
  - $\Delta r_{LOS} < 20$ Mpc/h $\longrightarrow \Delta v = 1800$ km/s (set by typical halo velocity dispersion)
- Group pairs into groups with Friends-of-Friends (FoF) algorithm
  - group multiplicity function $N_{CiC}(n)$; must calibrate relation with $N_{HOD}(n)$ to constrain HOD!
- Reconstruct halo density field from the CiC group centers

High Fidelity Mock Catalogs

- Matches 2-pt clustering, higher order statistic $N_{CiC}(n)$, and intragroup velocities
  - can check by changing CiC parameters
  - uncovers systematics in 2-pt fits to HOD



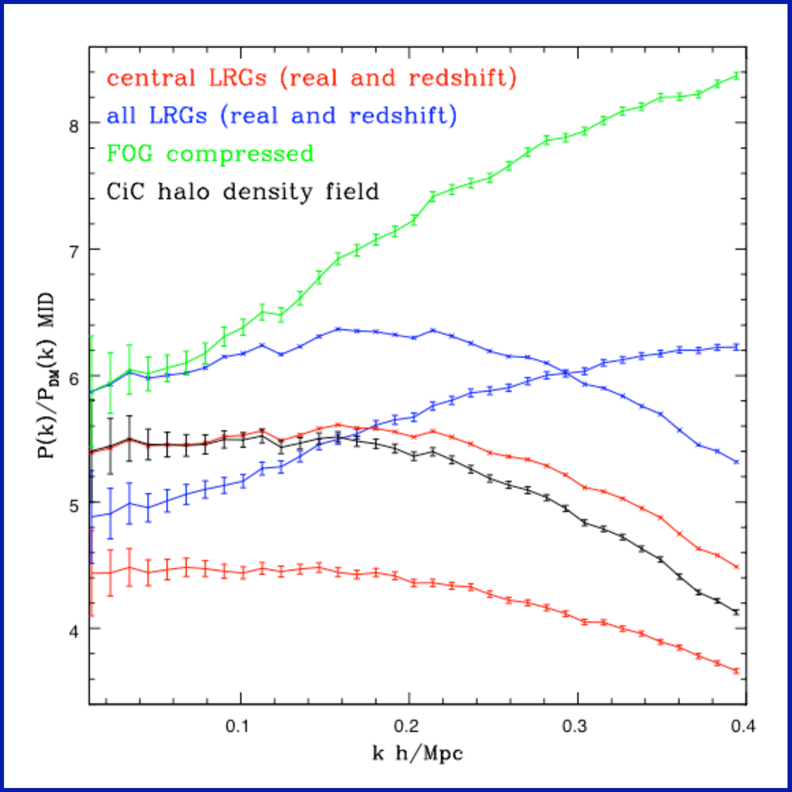
thanks to
Jeremy Tinker



Reid and Spergel, 2009, ApJ accepted, astro-ph/0809.4505

Reconstructed halo density field $P_{halo}(k)$

- Deviation from constant ratio for k < 0.1 (k < 0.2):
  - NEAR: 0% (4%)
  - MID: 0% (2.8%)
  - FAR: 1% (2.5%)
- Tegmark et al 2006 FOG-compressed between k = 0.05 and k = 0.1:
  - NEAR: 6%
  - MID: 7%
  - FAR: 10%



Reid, Spergel, and Bode 2008, ApJ accepted, astro-ph/0811.1025

Model $P_{halo}(k, \mathbf{p})$

- BAO damping

$$P_{\rm damp}(k, \mathbf{p}, \sigma) = P_{\rm lin}(k, \mathbf{p}) e^{-\frac{k^2\sigma^2}{2}} + P_{\rm nw}(k, \mathbf{p}) \left(1 - e^{-\frac{k^2\sigma^2}{2}}\right)$$

Eisenstein, Seo, White 2007

- Nonlinear Growth

$$r_{DM,damp}(k, \mathbf{p}) = \frac{r_{halofit}(k, \mathbf{p})}{r_{halofit}(k, \mathbf{p}_{\rm fid})} \frac{P_{DM}(k, \mathbf{p}_{\rm fid})}{P_{\rm damp}(k, \mathbf{p}_{\rm fid}, \sigma_{DM})}$$

Smith et al 2003

- Reconstructed Halo Bias

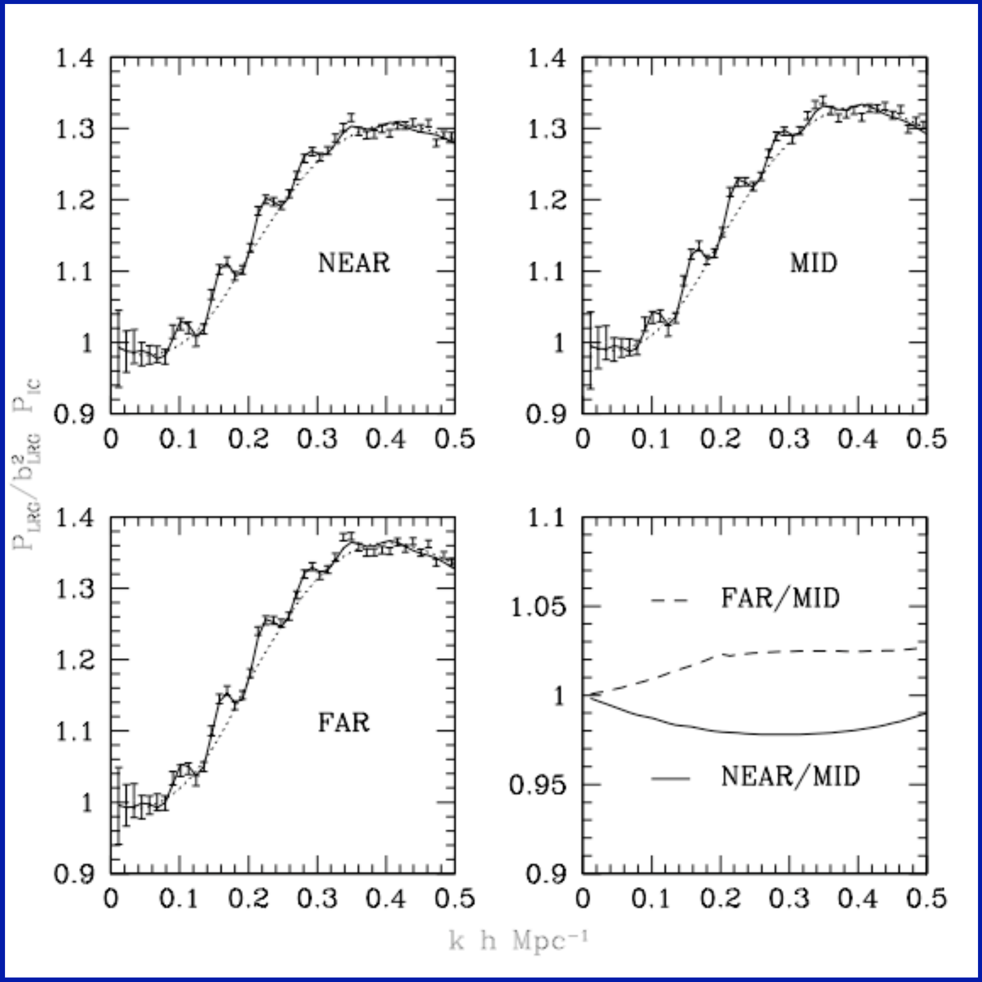
$$r_{halo,DM}(k, \mathbf{p}_{\rm fid}) = \frac{P_{\rm halo}(k, \mathbf{p}_{\rm fid}) / P_{damp}(k, \mathbf{p}, \sigma_{halo})}{P_{\rm DM}(k, \mathbf{p}_{\rm fid}) / P_{damp}(k, \mathbf{p}, \sigma_m)}$$

Model $P_{halo}(k, \mathbf{p})$

$$P_{halo}(k,\mathbf{p}) = b_o^2(1 + a_1 k + a_2 k^2) \times$$
$$\sum_{z_i} P_{damp}(k,\mathbf{p},z_i) r_{DM,damp}(k,\mathbf{p},z_i) r_{halo,DM}(k,z_i)$$

- Weighted sum over NEAR, MID, FAR redshift subsamples
- Remaining uncertainty and cosmological dependence folded into 3 nuisance parameters: b_o, a_1, a_2
- Allow 4% (10%) deviation at k=0.1 (k=0.2); largest systematic uncertainty is central galaxy velocity dispersion

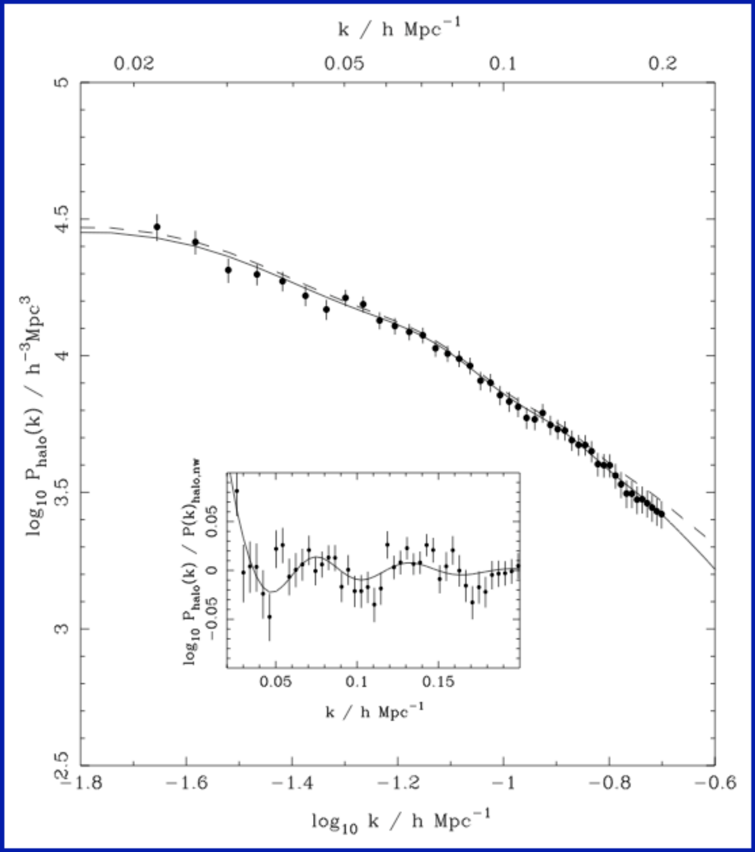
Calibrating model $P_{halo}(k)$ on mocks



Correction to linear theory < 15% at k < 0.2

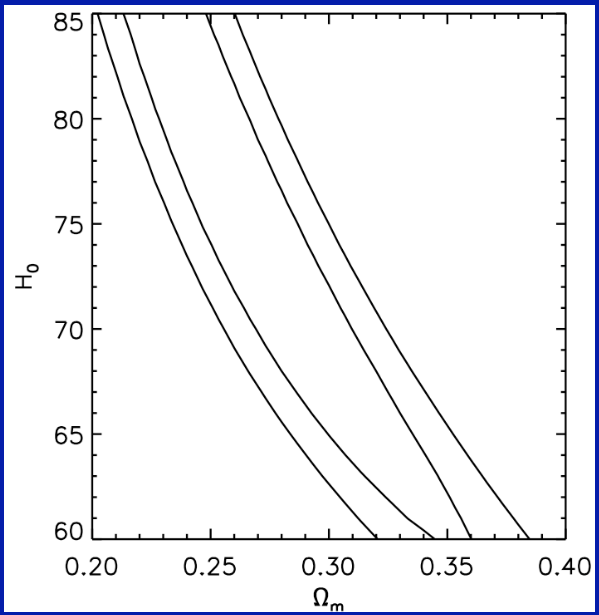
P(k) shape nearly independent of satellite fraction, z

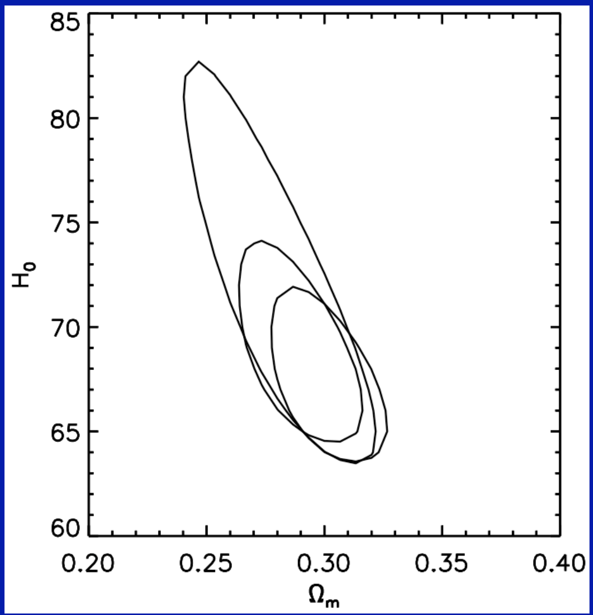
DR7 SDSS LRG $P_{halo}(k)$

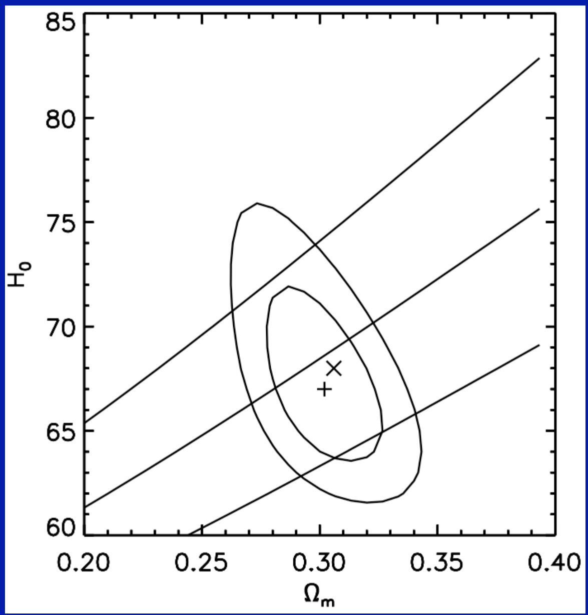


Methodology as in Percival et al 2007 (DR5 analysis)

Constraints From LRGs only







Shape only

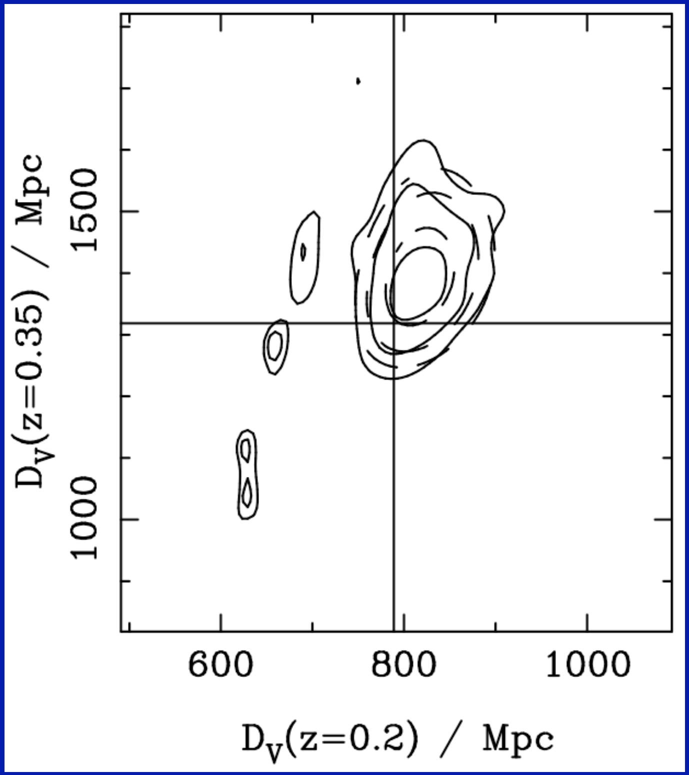
k_{max} = 0.1, 0.15, 0.2

Shape + BAO vs
Percival et al, prep
BAO(z=0.35)

BAO constraints: Percival, Reid, Eisenstein et al, prep

- BAO+SN+CMB priors:
  $\Omega_c h^2 = 0.1099 +/- 0.006$
  $\Omega_b h^2 = 0.0227 +/- 0.0006$

parameter	ΛCDM	oΛCDM	wCDM	owCDM
Ω_k	-	-0.080 ± 0.080	-	$-0.191^{+0.086}_{-0.095}$
w	-	-	-0.946 ± 0.114	$-0.826^{+0.084}_{-0.086}$
Ω_Λ	0.716 ± 0.018	$0.798^{+0.082}_{-0.084}$	$0.715^{+0.017}_{-0.018}$	$0.909^{+0.098}_{-0.087}$
Ω_m	0.284 ± 0.018	0.282 ± 0.018	$0.285^{+0.018}_{-0.017}$	0.282 ± 0.017
H_0	68.7 ± 2.2	69.0 ± 2.2	68.3 ± 2.2	68.7 ± 2.2



Methodology: improved version of Percival et al, MNRAS 381, 1053 (2007)

Summary of our Approach

- Our technique:
  - Eliminates P^{1h} and systematic variation with n_{LRG} or z
  - mitigates FOG effects
- Provides high fidelity mocks and calibrates model in the quasi-linear regime ($k < 0.2$)
  - Constrain both shape and BAO scale
- Use the Halo Model framework to
  - Fix tight constraints on nuisance parameters
  - Propagate uncertainties to understand systematics on cosmological parameters