Beyond Baryon Acoustic Oscillations in the BOSS CMASS galaxy clustering

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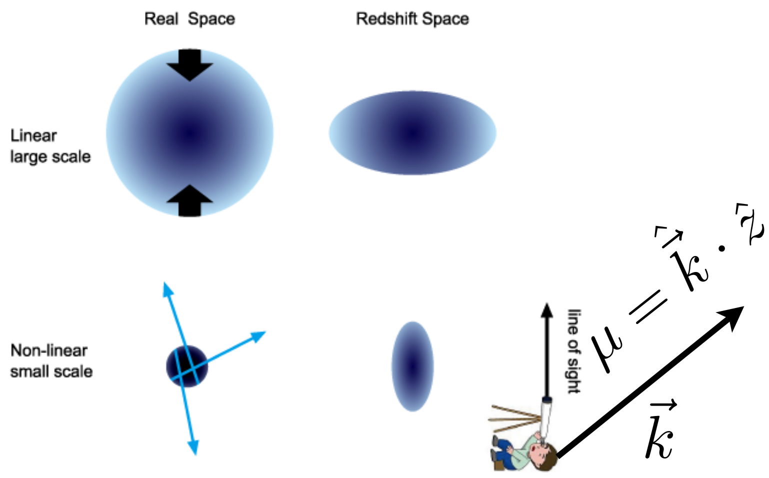
Beyond Baryon Acoustic Oscillations: Two *Anisotropic* Distortion

Redshift-Space Distortion (RSD)

The distance is measured only in 'redshift space'

$$\vec{s} = \vec{r} + \frac{\vec{v}\cdot\hat{z}}{aH(z)}\hat{z}$$

redshift space ($\vec{s}$), real space ($\vec{r}$), line of sight direction ($\hat{z}$)



Linear theory   Kaiser (1987)

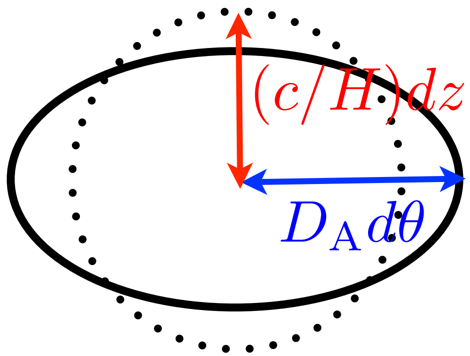
$$P_{\rm g}(k,\mu) = b^2\left(1+\frac{f}{b}\mu^2\right)^2 P^L(k)$$

$$f = \Omega_{\rm m}(z)^{\gamma}\quad \gamma = 0.545 \text{ (GR)} \quad \gamma = 0.68 \text{ (DGP)}$$

see e.g. Jain & Khoury (2010)

Alcock-Paczynski test geometrical distortion

Alcock & Paczynski (1979)



isotropic BAO

$$D_{\rm V} \propto \left(\frac{cD_{\rm A}^2}{H}\right)^{1/3}$$

anisotropic P(k,μ) (including BAO)

RSD → f

AP → $D_{\rm A}, H$

Outline

$$P(k,\mu) = \sum_{\ell} P_\ell(k)\mathcal{L}_\ell(\mu)$$

cosmological information: l=0 (monopole), l=2 (quadrupole), l=4 (hexadecapole) X

Taruya, S.S., Nishimichi (2011)

- *Precise Measurement* of the BOSS CMASS anisotropic galaxy P(k)

  F. Beutler, S.S., H.J. Seo++, coming soon

- *Accurate Modeling* of the anisotropic P(k) based on Perturbation Theory

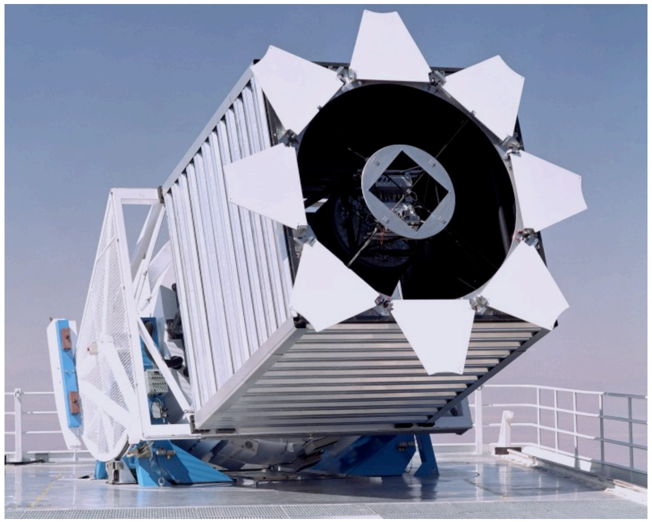
  A. Taruya, T. Nishimichi, S.S. (2010)
  S.S., T. Baludaf, Z. Vlah, U. Seljak++, coming soon
  F. Beutler, S.S., H.J. Seo++, coming soon

- Facing the model with the data → Cosmology Results!

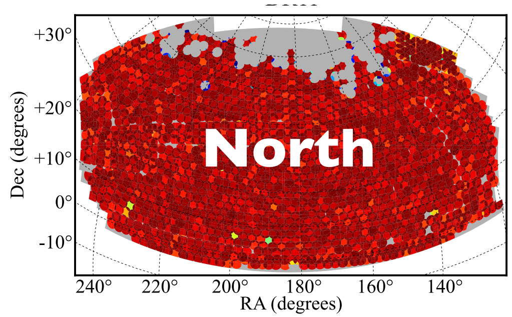
However, I am not allowed to show our results using DR11 P(k) until *Dec 10th*.

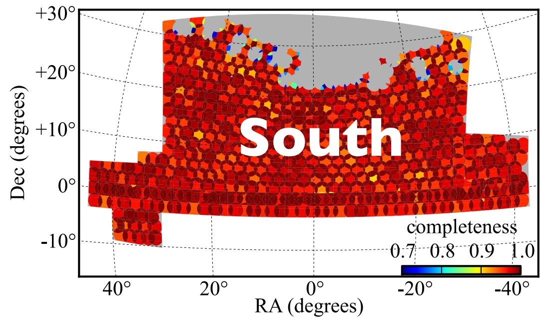
Baryon Oscillation Spectroscopic Survey
Huge improvement from DR9 to DR11

- Sloan Digital Sky Survey III (2009-2014)
  - 2.5m telescope in Apache Point Observatory in NM, USA
  - BOSS (DR9-DR12)aims to measure
    1) 1.5 million galaxies
       LOWZ $0.15 < z < 0.43$
       CMASS $0.43 < z < 0.70$
    2) 150,000 quasars (Ly-α forest)



- BOSS DR11 CMASS galaxy catalog





	DR9	DR11
# of galaxies	264,283	690,827
Area [deg^2]	3,275	8,498
$V_{\rm eff}$ [(Gpc/h)^3]	0.75 →	2.31
when	July, 2012	Dec, 2014

$$\Delta P(k)_{\rm DR9}/\Delta P(k)_{\rm DR11} \sim 1.75$$

How to *measure* the anisotropic P(k)?

- The power spectrum estimator Feldman, Kaiser, Peacock (1994)

$$\hat{P}_\ell(\boldsymbol{k}) = \frac{2\ell+1}{2A_{\rm norm}}\left[D_\ell(\boldsymbol{k})D^*_{\ell=0}(\boldsymbol{k}) - S_\ell\right]$$

where $D_l(k)$ is FT of the density field

$$D_\ell(\boldsymbol{k}) \equiv \sum_i^{N_{\rm g}} \{w_{\rm c}(\boldsymbol{x}_i) - \alpha'\}\, w_{\rm FKP}(\boldsymbol{x}_i) e^{i\boldsymbol{k}\cdot\boldsymbol{x}_i} \mathcal{L}_\ell(\hat{k}\cdot\hat{x}_i),$$

$$A_{\rm norm} = \sum_i^{N_{\rm g}} n'_{\rm g}(\boldsymbol{x}_i) w_{\rm c}(\boldsymbol{x}_i) w^2_{\rm FKP}(\boldsymbol{x}_i).$$

complexity $\mathcal{O}(N^2_{\rm ran} N_c)$

- The standard FKP method

- use FFT to compute $D_l(k)$ with fixed line-of-sight direction $\mathcal{O}(N_c \log N_c)$

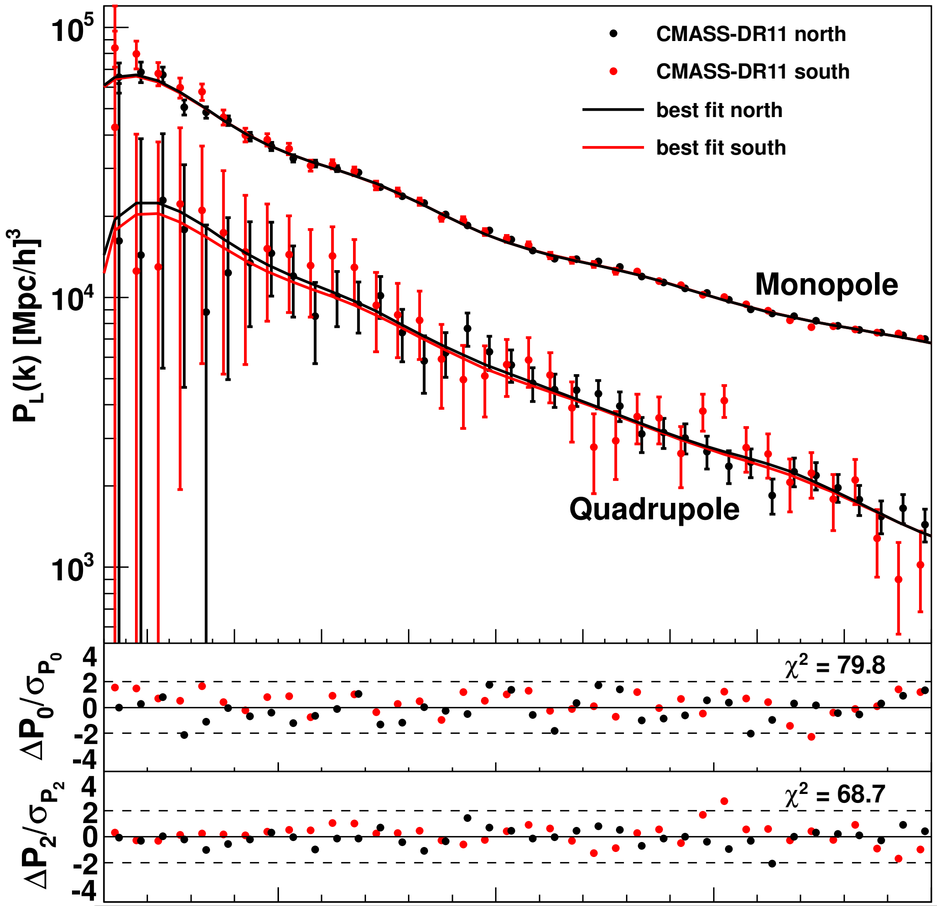
- Therefore, it bias the anisotropic measures. Yoo & Seljak (2013)

Yamamoto et al. (2006) method

- directly sum up the FT coefficients but locally define the line-of-sight
- slow but more suitable to measure higher-order multipole

Measurement of BOSS DR11 P(k)

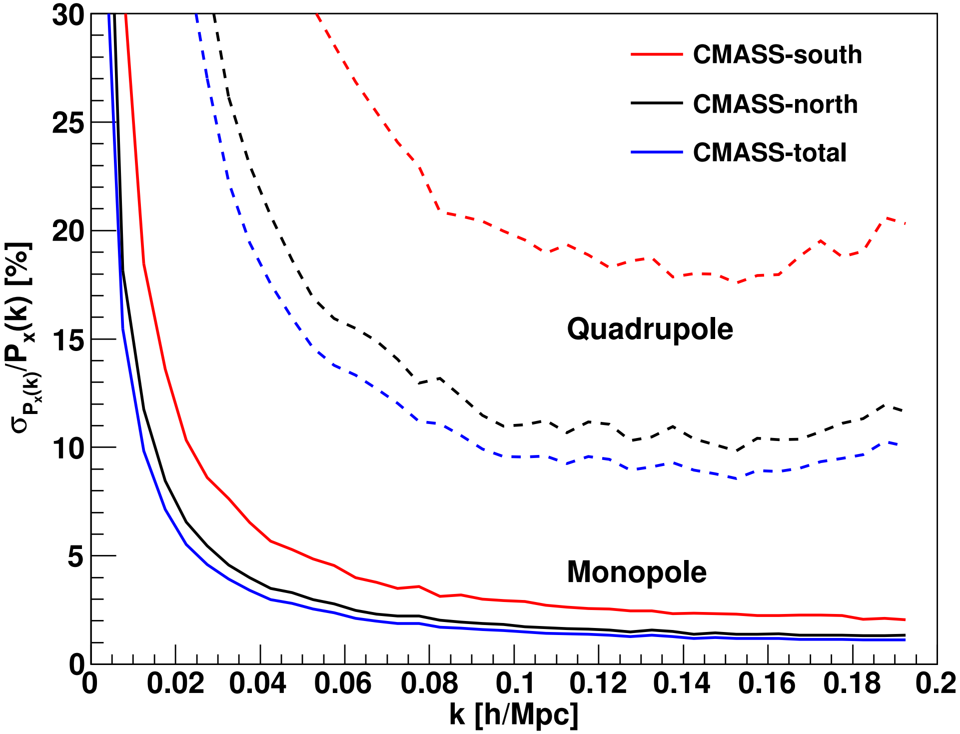
F. Beutler, S.S., H.J. Seo et al., coming on Dec 10th



secret

errors from 1000 QPM mocks

White, Tinker, McBride (2013)



Stay Tuned!

Anisotropic survey window function

- The estimated P(k) is convolved with 'survey window function'

$$P^{\rm conv}(\boldsymbol{k}) = \int \frac{d^3k'}{(2\pi)^3} P^{\rm true}(\boldsymbol{k}') \left|W(\boldsymbol{k}-\boldsymbol{k}')\right|^2 - |W(\boldsymbol{k})|^2 \int \frac{d^3k'}{(2\pi)^3} P^{\rm true}(\boldsymbol{k}') \left|W(\boldsymbol{k}')\right|^2$$

convolution with survey window

integral constraint

where the full window function is

$$\left|W(\boldsymbol{k}-\boldsymbol{k}')\right|^2 = \sum_{i\neq j}^{N_{\rm ran}} w_{\rm FKP}(\boldsymbol{x}_i) w_{\rm FKP}(\boldsymbol{x}_j) e^{i(\boldsymbol{k}-\boldsymbol{k}')\cdot\boldsymbol{x}_i} e^{-i(\boldsymbol{k}-\boldsymbol{k}')\cdot\boldsymbol{x}_j}$$

complexity $\mathcal{O}(N_{\rm ran}^2 N_c^2)$

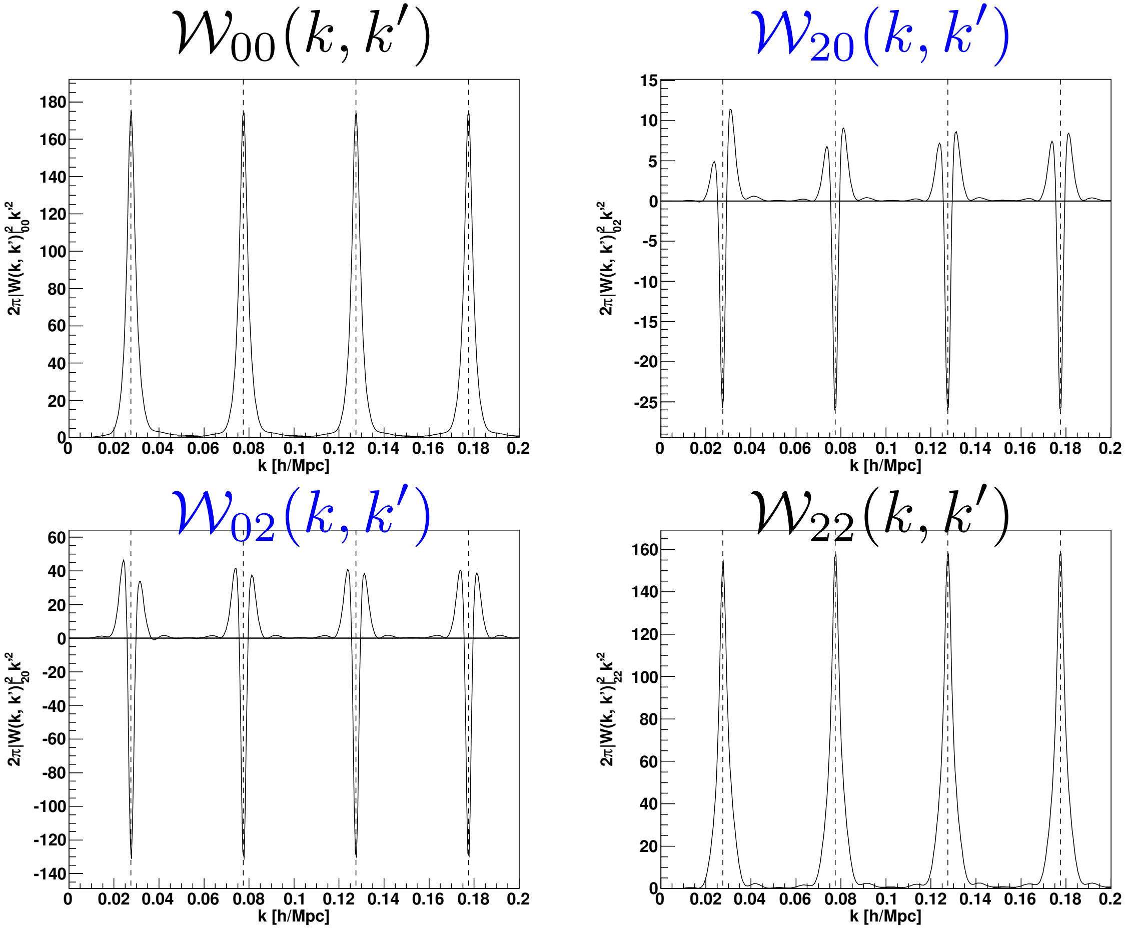
- We derive the formula to efficiently estimate the window function

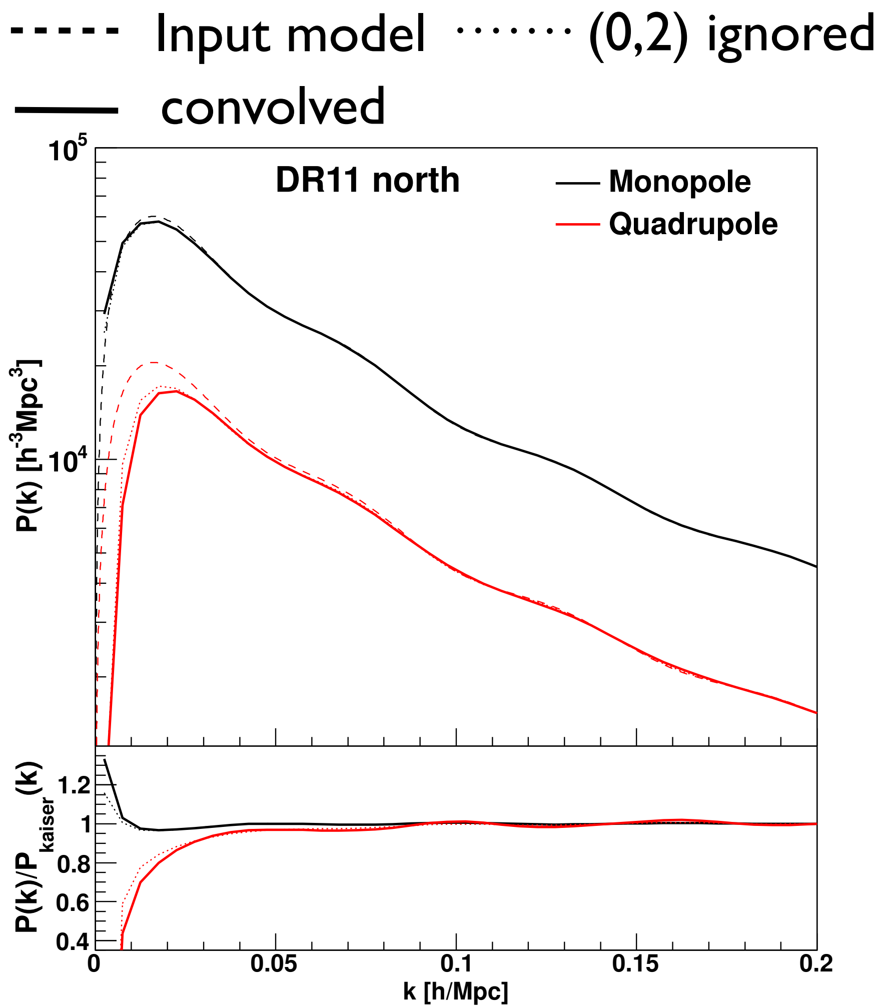
$$P_\ell^{\rm conv}(k) = \int \frac{k'^2 dk'}{2\pi^2} \sum_L P_L(k') \mathcal{W}_{\ell L}(k,k')$$

coupling b/w multipoles

$$\mathcal{W}_{\ell L}(k,k') = 4\pi^2 i^\ell (-i)^L (2\ell+1) \sum_{i\neq j}^{N_{\rm ran}} j_\ell(k\,|\Delta\boldsymbol{x}_{ij}|) j_L(k'\,|\Delta\boldsymbol{x}_{ij}|) L_\ell(\Delta\hat{x}_{ij}\cdot\hat{x}_h) L_L(\Delta\hat{x}_{ij}\cdot\hat{x}_h)$$

Survey window function in CMASS DR11





$\mathcal{W}_{20}(k,k')$ describes the leakage from monopole(L=0) to quadrupole(*l*=2).

The leakage from monopole to quadrupole is ~15%@k=0.01, and ~1%@k=0.05

Modeling nonlinear RSD

- Essentially originating the fact that **mapping is nonlinear**

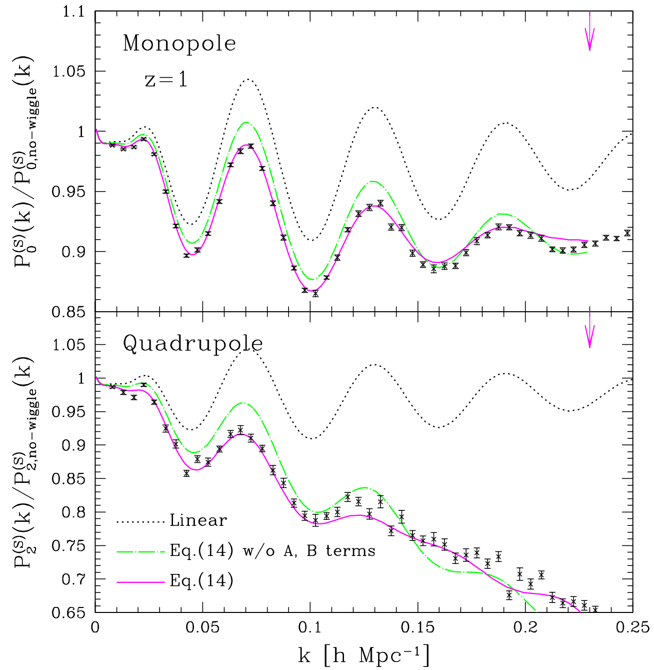
$$J \simeq \left(1 + \frac{\partial}{\partial z}\left[\frac{\vec{v}\cdot\hat{z}}{aH(a)}\right]\right)^{-1}$$

nonlinear w.r.t. velocity field

- Exact form of redshift-space power spectrum

$$P^S(k,\mu) = \int d^3\mathbf{x}\, e^{i\mathbf{k}\cdot\mathbf{x}} \left\langle e^{-ik\mu f \Delta u_z}\{\delta(\mathbf{r}) - f\nabla_z u_z(\mathbf{r})\}\{\delta(\mathbf{r}') - f\nabla_z u_z(\mathbf{r}')\}\right\rangle$$

$$\mathbf{x} = \mathbf{r} - \mathbf{r}' \qquad \Delta u_z = u_z(\mathbf{r}) - u_z(\mathbf{r}') \qquad u_z = (\vec{v}\cdot\hat{z})/(aH)$$



Taruya, Nishimichi, S.S. (2010)

$$P^S(k,\mu) = e^{-k^2 f^2 \sigma_V^2 \mu^2}\left[P_{\delta\delta}(k) + 2f\mu^2 P_{\delta\theta}(k) + f^2\mu^4 P_{\delta\theta}(k) + A(k,\mu) + B(k,\mu)\right]$$

◎ Pros: widely used in mock or real galaxy clustering studies

Blake et al. (2011), de la Torre et al. (2012), Ishikawa et al. (2013), Oka, S.S. et al. (2013) etc.

× Cons: we introduce additional free parameter, σ_V

Modeling Galaxy/Halo Bias

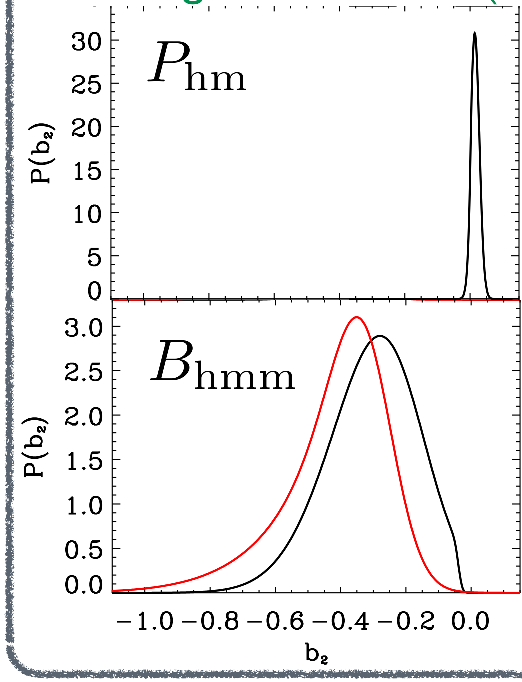
- How to relate $\delta_{\rm h}/\delta_{\rm g}$ with $\delta_{\rm m}$?

  Widely-used assumption is 'local bias'

$$\delta_{\rm h}(\mathbf{x}) = \sum_n \frac{b_n}{n!}\delta_{\rm m}(\mathbf{x})^n$$

Fly & Gaztanaga (1993)
McDonald (2006)
Jeong & Komatsu (2006,2009)
Nishizawa, Takada, Nishimichi (2013) etc

e.g., Pollack et al. (2013)



- How to tackle?

2nd-order $B^{\rm hmm} \sim \langle \delta_{\rm h}^{(2)}\delta_{\rm m}^{(1)}\delta_{\rm m}^{(1)}\rangle$

3rd-order $T^{\rm hmmm} \sim \langle \delta_{\rm h}^{(3)}\delta_{\rm m}^{(1)}\delta_{\rm m}^{(1)}\delta_{\rm m}^{(1)}\rangle$

$$P^{\rm hm} \sim \langle \delta_{\rm h}^{(1)}\delta_{\rm m}^{(1)}\rangle + \langle \delta_{\rm h}^{(1)}\delta_{\rm m}^{(3)}\rangle + \langle \delta_{\rm h}^{(2)}\delta_{\rm m}^{(2)}\rangle + \langle \delta_{\rm h}^{(3)}\delta_{\rm m}^{(1)}\rangle$$

$b_1 \times P^{\rm NL}{\rm m}$

- Nonlinear gravitational evolution naturally induces 'non-local' bias

McDonald & Roy (2010), Matsubara (2011), Chuen Chang et al. (2012)

Renormalization Approach

✔ (halo density)-(matter density) McDonald & Roy (2010)

$$P_{00}^{\rm hm}(k) = \left(c_\delta + \frac{34}{21}c_{\delta^2}\sigma^2 + \frac{1}{2}c_{\delta^3}\sigma^2 + \frac{1}{3}c_{\delta s^2}\sigma^2 + \frac{1}{2}c_{\delta\epsilon^2}\sigma_\epsilon^2 + \frac{68}{63}c_{s^2}\sigma^2 - \frac{16}{63}c_{st}\sigma^2\right)P_{\delta\delta}^{\rm NL}(k)$$

origin: (1)x(1) or (1)x(3)→linear bias

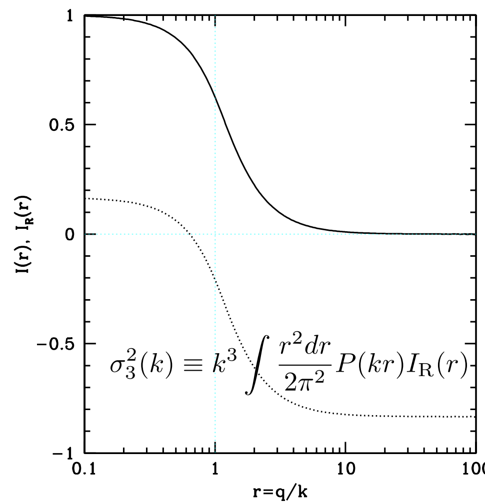
$$+c_{\delta^2}\int\frac{d^3q}{(2\pi)^3}P(q)P(|\boldsymbol{k}-\boldsymbol{q}|)F_{\rm S}^{(2)}(\boldsymbol{q},\boldsymbol{k}-\boldsymbol{q})$$

$$+c_{s^2}\int\frac{d^3q}{(2\pi)^3}P(q)P(|\boldsymbol{k}-\boldsymbol{q}|)F_{\rm S}^{(2)}(\boldsymbol{q},\boldsymbol{k}-\boldsymbol{q})S^{(2)}(\boldsymbol{q},\boldsymbol{k}-\boldsymbol{q})$$

$$+\left(-\frac{16}{21}c_{s^2} + \frac{32}{105}c_{st} + \frac{512}{2205}c_\psi\right)\sigma_3^2(k)P(k)$$

$$= b_1P_{\delta\delta}^{\rm NL}(k) + b_2P_{b2,\delta}(k) + b_{s^2}P_{bs2,\delta}(k) + b_{3\rm nl}\,\sigma_3^2(k)P(k),$$

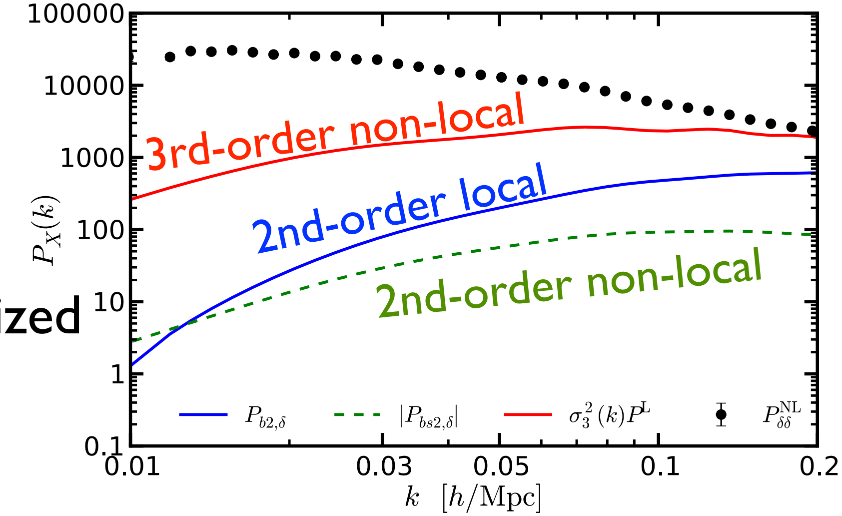
measurable in N-body P(k)!



✔ Bias Renormalization

1) should expect $b_1 \times P(k)$ at $k \to 0$.
No more c_{δ^3} McDonald (2006)

2) After properly subtracting out k→0 limit, the rest of non-local terms can be summarized into only **1** term, '**$b_{3\rm nl}$**'.



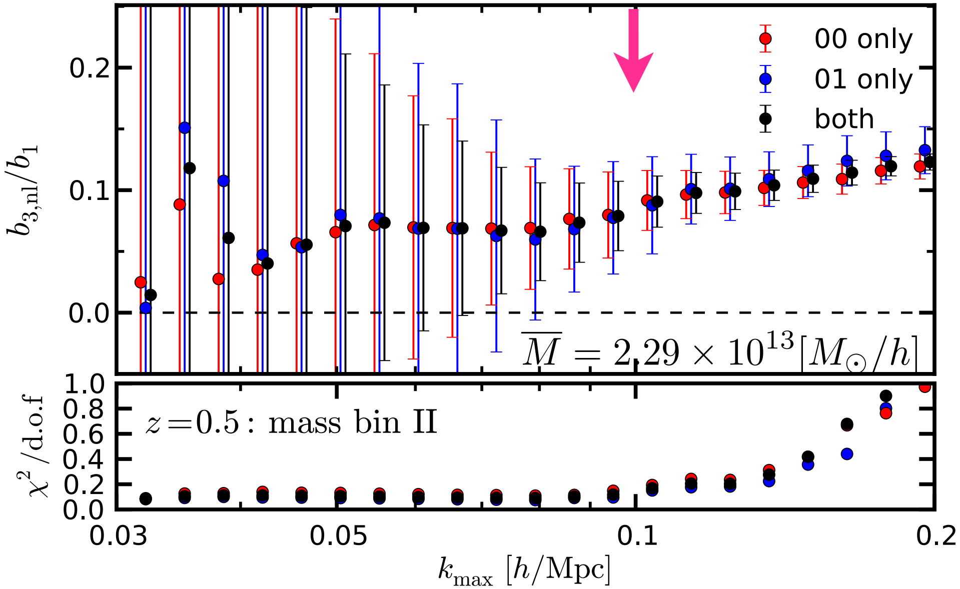
✔ This is also the case for density-momentum

 S.S. et al., in prep

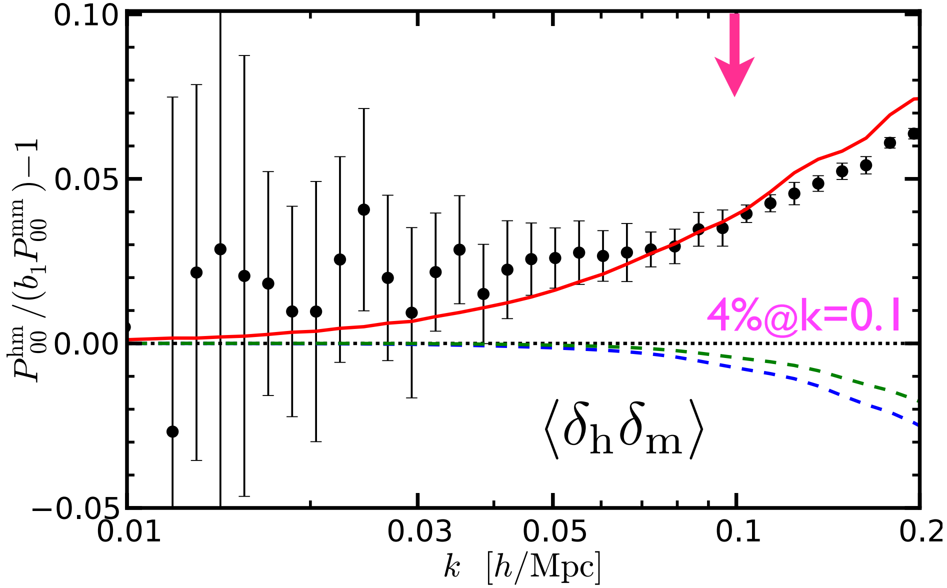
Measurement of “b_{3nl}”

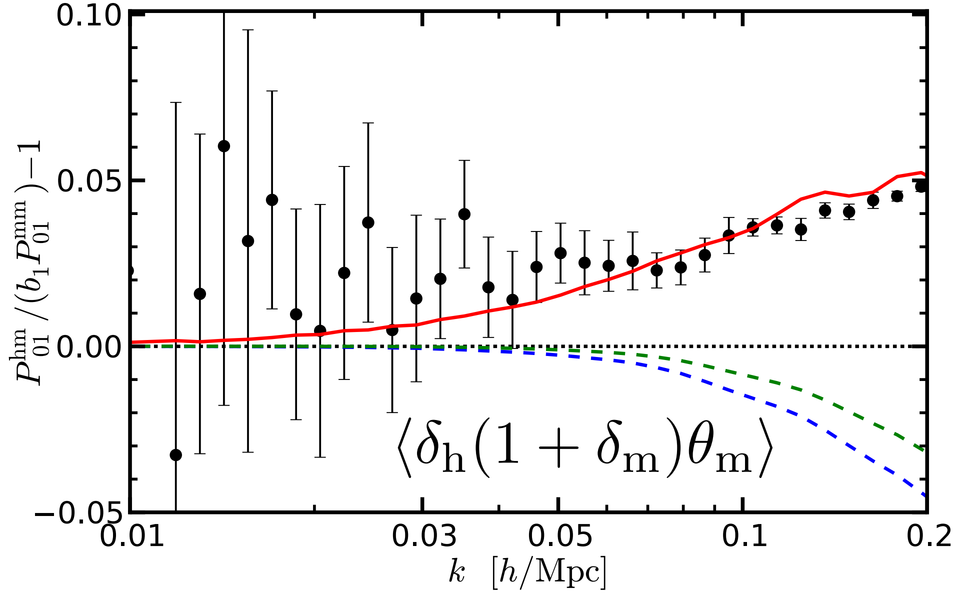
✦ ~halos in BOSS CMASS (z=0.5)

S.S. et al., in prep



- non-zero detection of b_{3nl} for fairly wide range of redshift and mass bin
- the b_{3nl} term can simultaneously explain both of





- Note 1.5^3[(Gpc/h)^3] x 11 realizations.

Theoretical predictions of non-local bias

✔ A simple co-evolution picture of halo's and DM's fields

S.S++ in prep

$$\delta_{\rm h}(\boldsymbol{k},y)' - \theta(\boldsymbol{k},y) = \int \frac{d^3q}{(2\pi)^3}\alpha(\boldsymbol{q},\boldsymbol{k}-\boldsymbol{q})\theta(\boldsymbol{q},y)\delta_{\rm h}(\boldsymbol{k}-\boldsymbol{q},y),$$

$$\delta_{\rm m}(\boldsymbol{k},y)' - \theta(\boldsymbol{k},y) = \int \frac{d^3q}{(2\pi)^3}\alpha(\boldsymbol{q},\boldsymbol{k}-\boldsymbol{q})\theta(\boldsymbol{q},y)\delta_{\rm m}(\boldsymbol{k}-\boldsymbol{q},y),$$

$$\{f\theta(\boldsymbol{k},\eta)\}' + \left(1+\frac{\mathcal{H}'}{\mathcal{H}^2}\right)\theta(\boldsymbol{k},y) - \frac{3}{2f}\Omega_{\rm m}(y)\delta_{\rm m}(\boldsymbol{k},y) = f\int \frac{d^3q}{(2\pi)^3}\beta(\boldsymbol{q},\boldsymbol{k}-\boldsymbol{q})\theta(\boldsymbol{q},\eta)\theta(\boldsymbol{k}-\boldsymbol{q},\eta),$$

see also,
Baldauf++(2012)
Chen-Chan++(2012)
Sheth++(2013)

where $y \equiv d\ln D(a)$

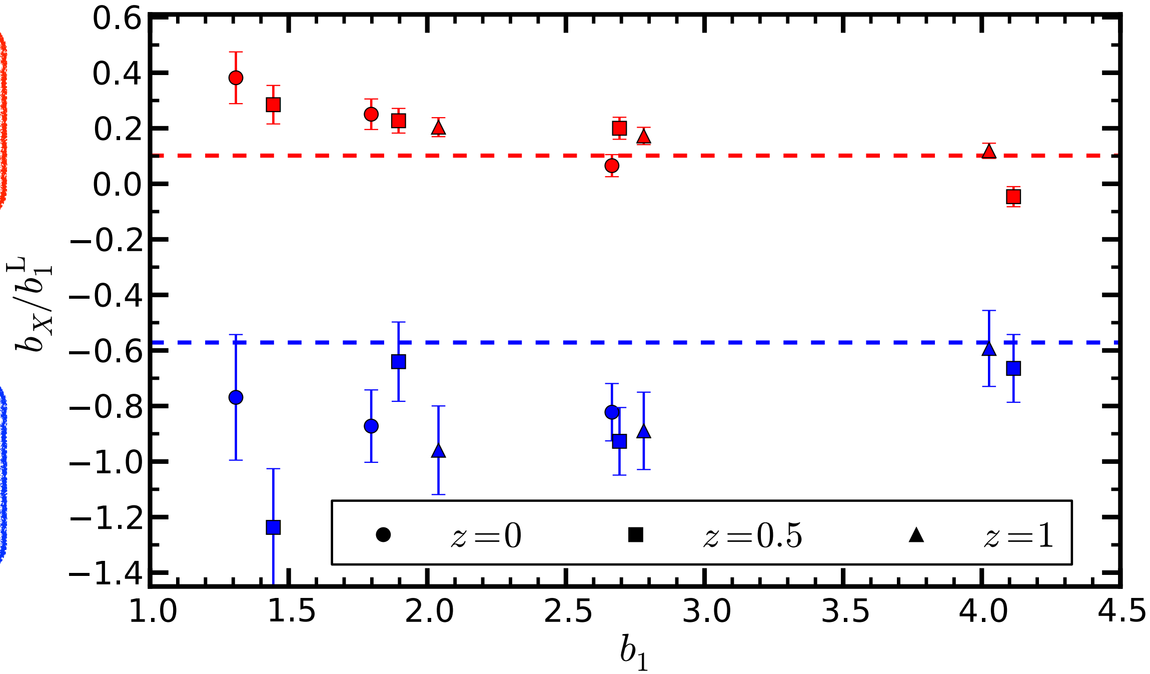
✔ Comparison b/w simulation results and co-evolution prediction

3rd order

$$b_{3\rm nl} = \frac{32}{315}b_1^{\rm L} = \frac{32}{315}(b_1^{\rm E}-1)$$

2nd order

$$b_{s^2} = -\frac{4}{7}b_1^{\rm L} = -\frac{4}{7}(b_1^{\rm E}-1)$$



Does this model work against CMASS P(k)?

F. Beutler, S.S., H.J. Seo++

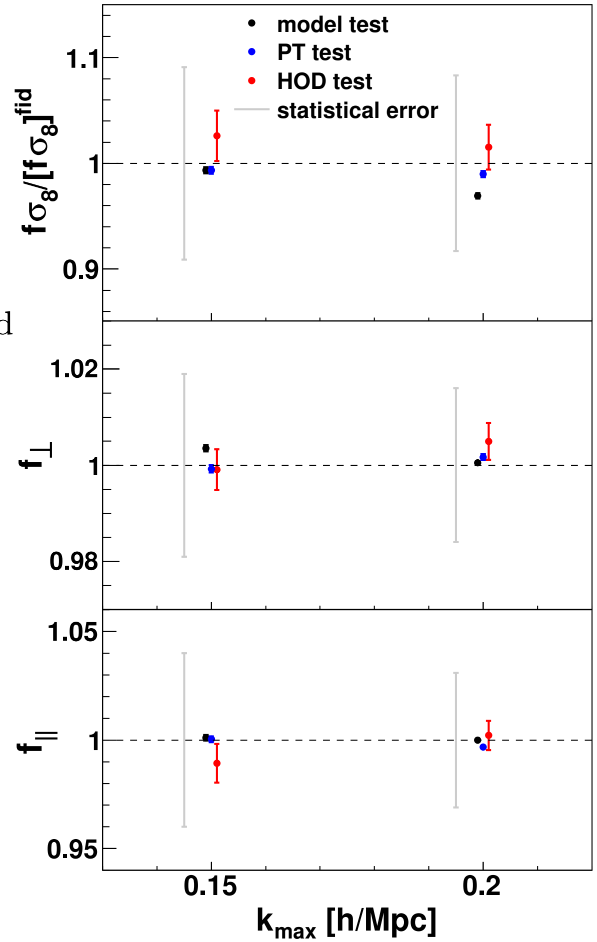
✔ Against mock catalog (LCDM simulation+HOD)

✔ 7 Free parameters $z_{\rm eff} = 0.57$

- parameters of interest: $f\sigma_8, f_\perp = H^{\rm fid}/H, f_\parallel = D_{\rm A}/D_{\rm A}^{\rm fid}$
- galaxy bias: b_1, b_2, N
- FoG suppression: $\sigma_{\rm v}$

✔ Passed 3 types of tests

- our fiducial model (also WMAP/Planck)
- PT uncertainties in theoretical modeling
- HOD uncertainties in mock catalog



source	$f_\parallel$ $[H(z_{\rm eff})]$		$f_\perp$ $[D_A(z_{\rm eff})]$		$f(z_{\rm eff})\sigma_8(z_{\rm eff})$	
$k_{\rm max}$ $[h/{\rm Mpc}]$	0.15	0.20	0.15	0.20	0.15	0.20
model test	$0.11 \pm 0.13\%$	$0.00 \pm 0.10\%$	$0.352 \pm 0.061\%$	$0.052 \pm 0.049\%$	$-0.66 \pm 0.29\%$	$-3.08 \pm 0.26\%$
PT test	$0.04 \pm 0.14\%$	$-0.32 \pm 0.12\%$	$-0.075 \pm 0.074\%$	$0.168 \pm 0.060\%$	$-0.65 \pm 0.33\%$	$-1.01 \pm 0.30\%$
HOD test	$-1.07 \pm 0.89\%$	$0.21 \pm 0.67\%$	$-0.09 \pm 0.42\%$	$0.50 \pm 0.38\%$	$2.6 \pm 2.4\%$	$1.5 \pm 2.1\%$
statistical error	4.0%	3.1%	1.9%	1.6%	9.1%	8.3%

Conclusion

- The anisotropic P(k) in BOSS DR11 provides us with a great opportunity to tackle cosmic acceleration via RSDs & AP test.

- We measured the multipole $P_l(k)$ for the first time (*) in a consistent manner in the sense of the survey window.

- We showed that non-local bias, naturally induced by nonlinear gravitational evolution, can simultaneously explain P(k) & B(k). The model seems to work against the CMASS mock catalog.

BOSS DR11 Galaxy Clustering Papers will come out on *~Dec 10th*

- Aadowolf et al.: main alphabetical BAO paper

- Beutler, S.S., Seo et al.: RSD & AP in Fourier space

- Samushia et al., Chuang et al.: RSD & AP in configuration space

- Percival et al.: Inverse covariance matrix & optimal binning
  -already submitted and (almost-)accepted to MNRAS

Renormalization in density-momentum P(k)

✔ Also, interesting to see momentum power spectrum, $P_{LL'}(k)$

$$P^{\rm S}(\boldsymbol{k}) = \sum_{LL'} \frac{(-1)^{L'}}{L!L'!}(ik_\parallel)^{L+L'} P_{LL'}(\boldsymbol{k})$$

$$T_\parallel^L(\boldsymbol{x}) \equiv \{1+\delta(\boldsymbol{x})\}\, v_\parallel(\boldsymbol{x})^L,$$

$$P_{LL'}(\boldsymbol{k})(2\pi)^3\delta_D(\boldsymbol{k}+\boldsymbol{k}') \equiv \langle T_\parallel^L(\boldsymbol{k}) T_\parallel^{L'}(\boldsymbol{k}')\rangle$$

- ingredient of redshift-space power spectrum e.g., Seljak & McDonald (2011)
- more well-defined quantity in simulations Okumura et al. (2011,2012)
- can be similarly renormalized if assuming no velocity bias S.S++ in prep

(halo density)-(matter momentum) $\langle \delta_{\rm h}(1+\delta)\theta\rangle$

measurable in N-body P(k)!

$$P_{01}^{\rm hm}(k) = b_1\left\{P_{\delta\theta}^{\rm NL}(k) + B_{b1}(k)\right\} + b_2\left\{P_{b2,\theta}(k) + B_{b2}(k)\right\}$$
$$+ b_{s^2}\left\{P_{bs2,\theta}(k) + B_{bs2}(k)\right\} + b_{3\rm nl}\,\sigma_3^2(k)P(k).$$

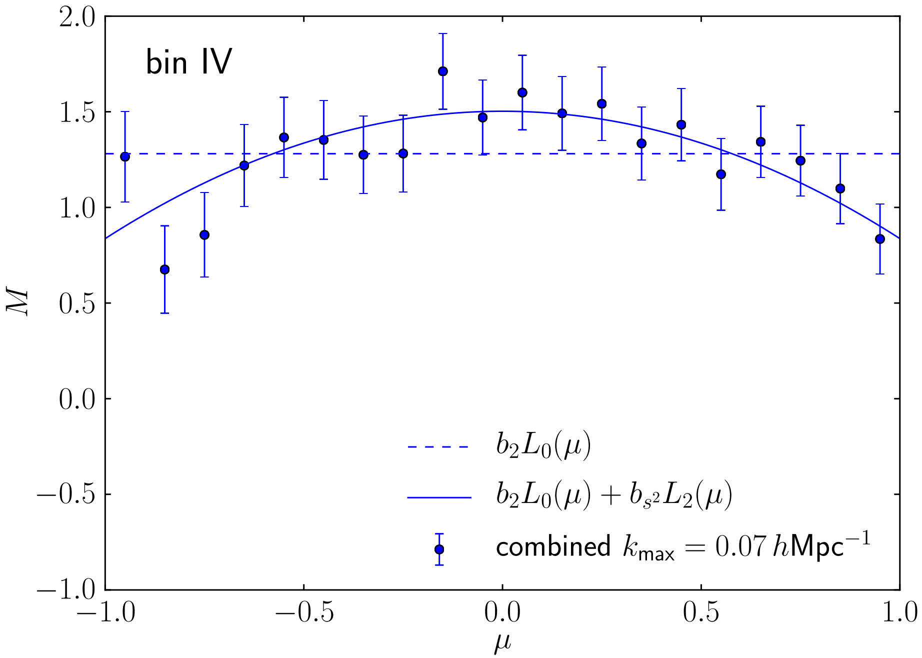
Renormalization & Bispectrum

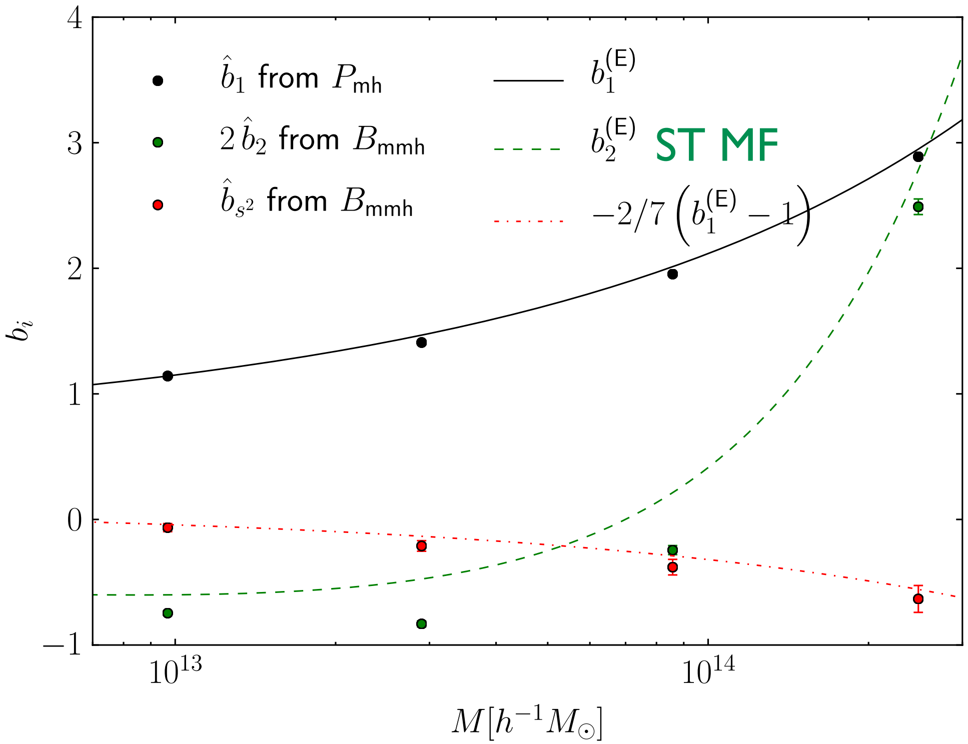
✔ Bispectrum SHOULD be described by renormalized bias

Baldauf et al. (2012)

$$B_{000}^{\rm hmm}(\boldsymbol{k}_1,\boldsymbol{k}_2,\boldsymbol{k}_3) = b_1 B_{000}^{\rm mmm}(\boldsymbol{k}_1,\boldsymbol{k}_2,\boldsymbol{k}_3) + P(k_1)P(k_2)\left[b_2 + b_{s^2}\left(\mu_{k_1,k_2}^2 - \frac{1}{3}\right)\right]$$

✔ Stable measurements of 2nd-order bias (b_2, b_{s2}) from $B^{hmm}(k)$





see Nishizawa, Nishimichi, Takada (2013)