RSD adventures in the non-linear regime

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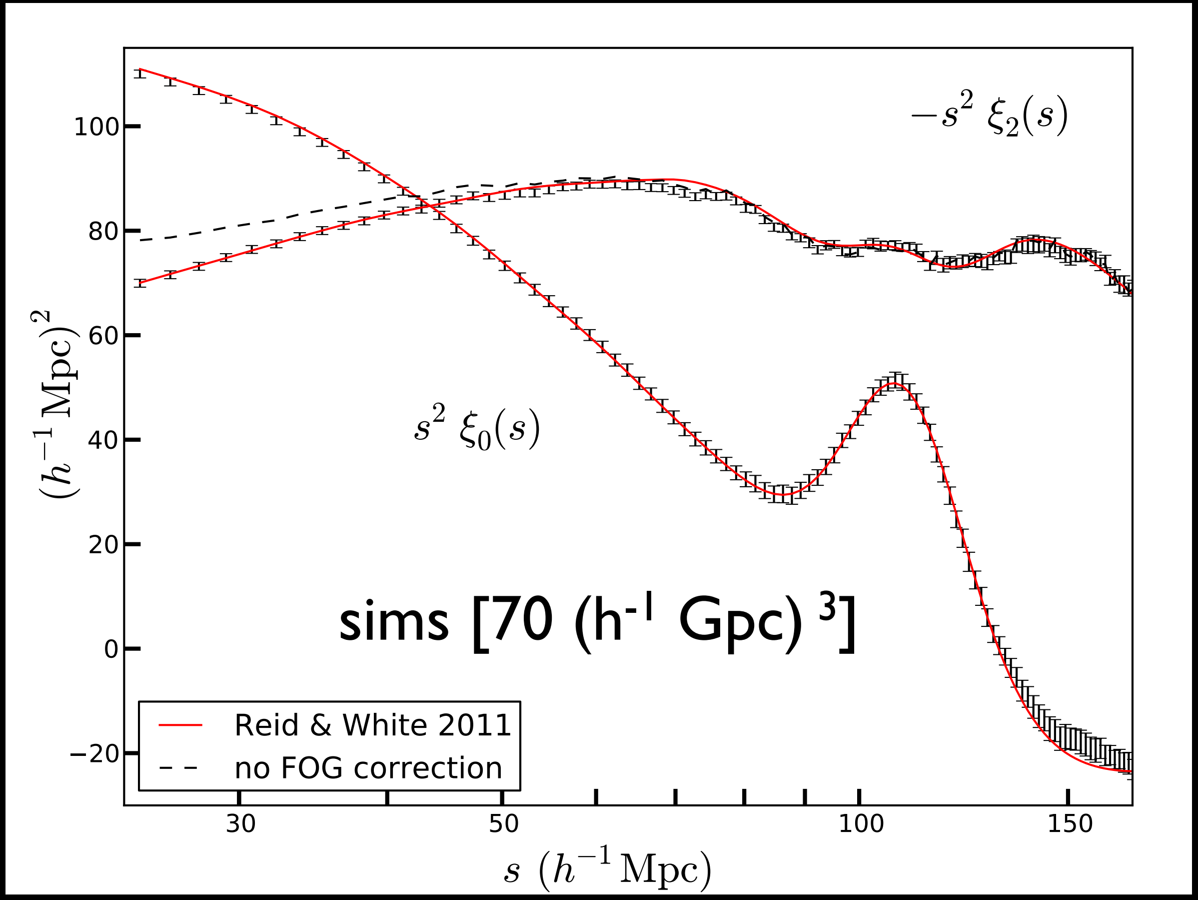
in collaboration with Hee-Jong Seo, Alexie Leauthaud, Jeremy Tinker, Martin White and the Baryon Oscillation Spectroscopic Survey [BOSS] collaboration

Outline

- Perturbation theory -- the end of the line?
- Measurements of small-scale clustering
- A fully non-linear model using simulations
- Results: central galaxy motions, halo occupation distribution (HOD), and $f\sigma_8$
- Conservative interpretation: constraint on σ^2_{FOG} + validation of its parametrization

State-of-the-art in BOSS: $\xi(r,\mu)$

- Fits to $\xi_{0,2}(s)$ restricted to s > 25 h^{-1} Mpc; $f\sigma_8$ = 0.447 ± 0.028 (ΛCDM + GR)
- Perturbation theory for halo clustering breaks down surprisingly early ($\xi \approx$ 0.14!)
- FOGs already important (~10%!)
- For those who think in Fourier space, s_{min} = 25 h^{-1} Mpc corresponds to k_{max} = 0.15 h Mpc^{-1}
- Not much promise for going to smaller scales with this approach
- [Chuang et al., Sanchez et al. 2014 analyses restricted to even larger scales]



Adapted from Reid & White 2011

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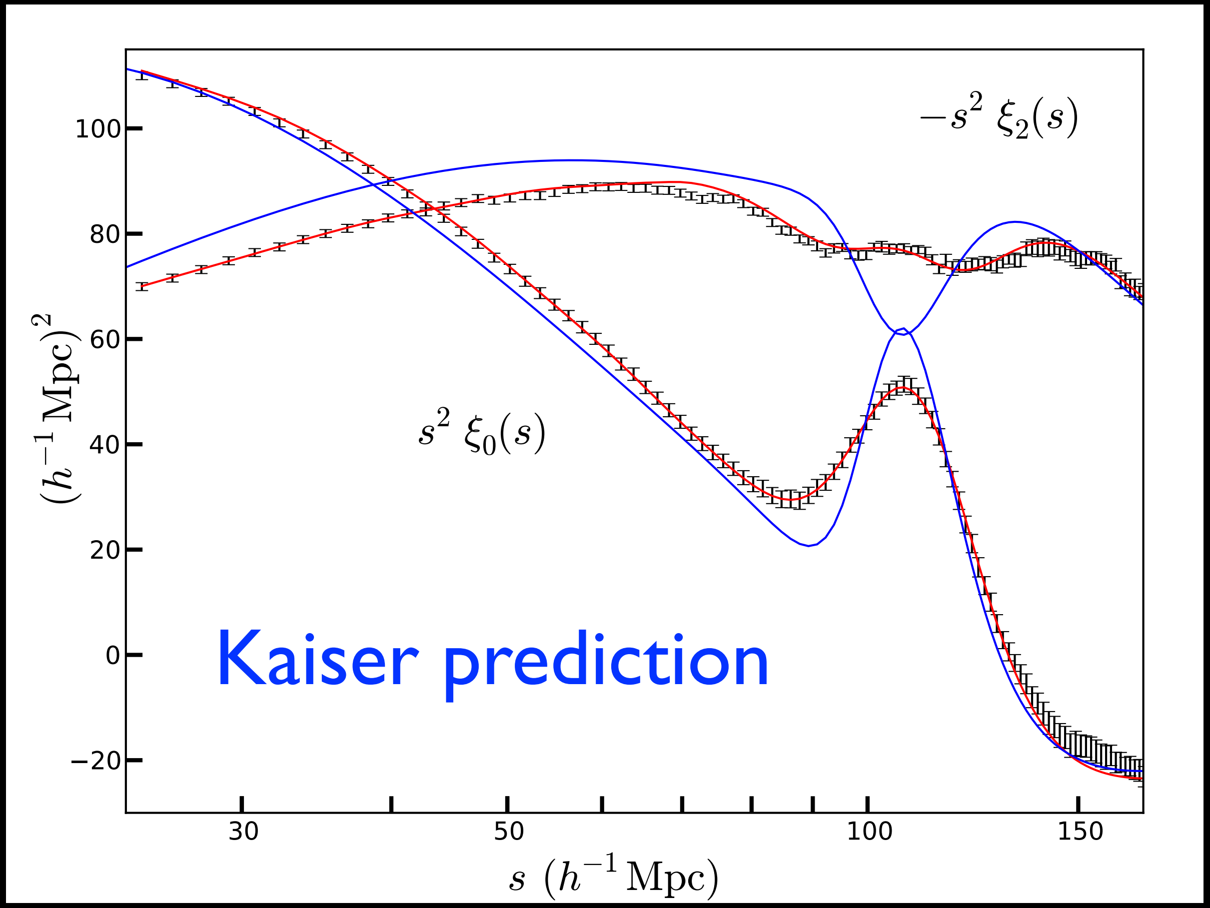

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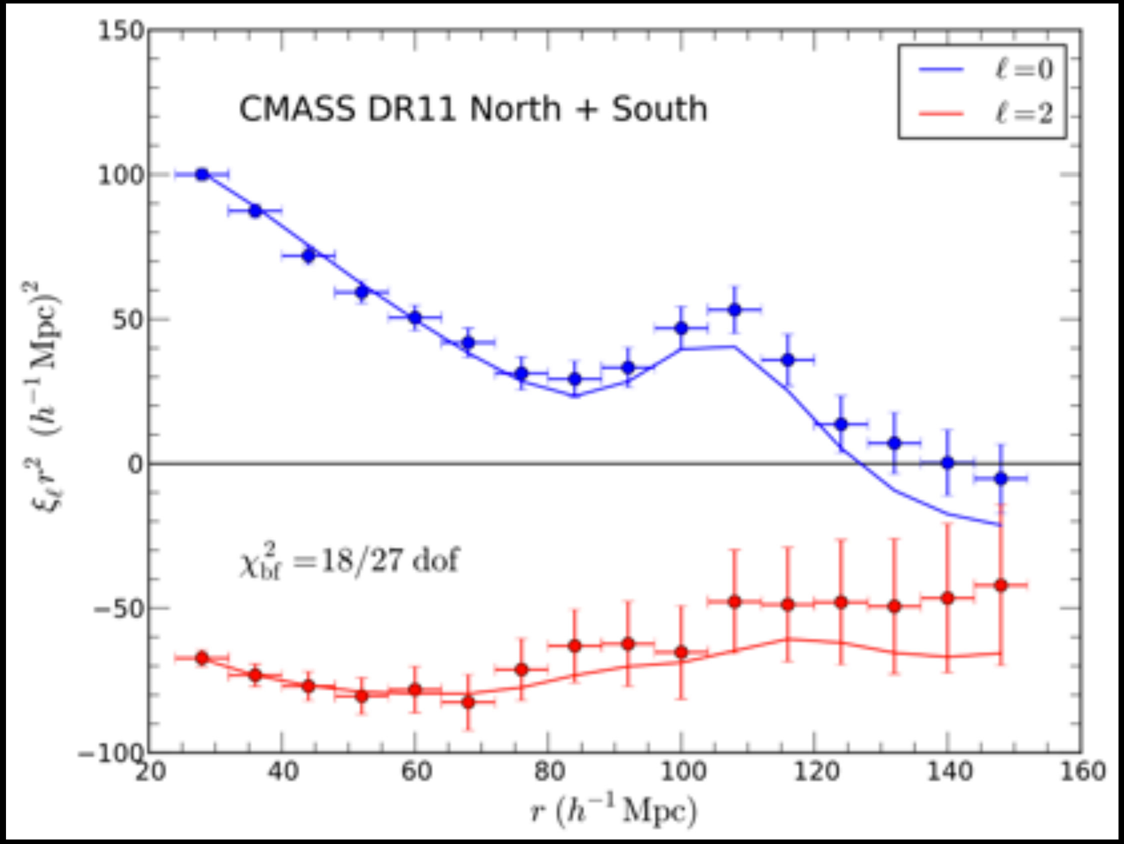
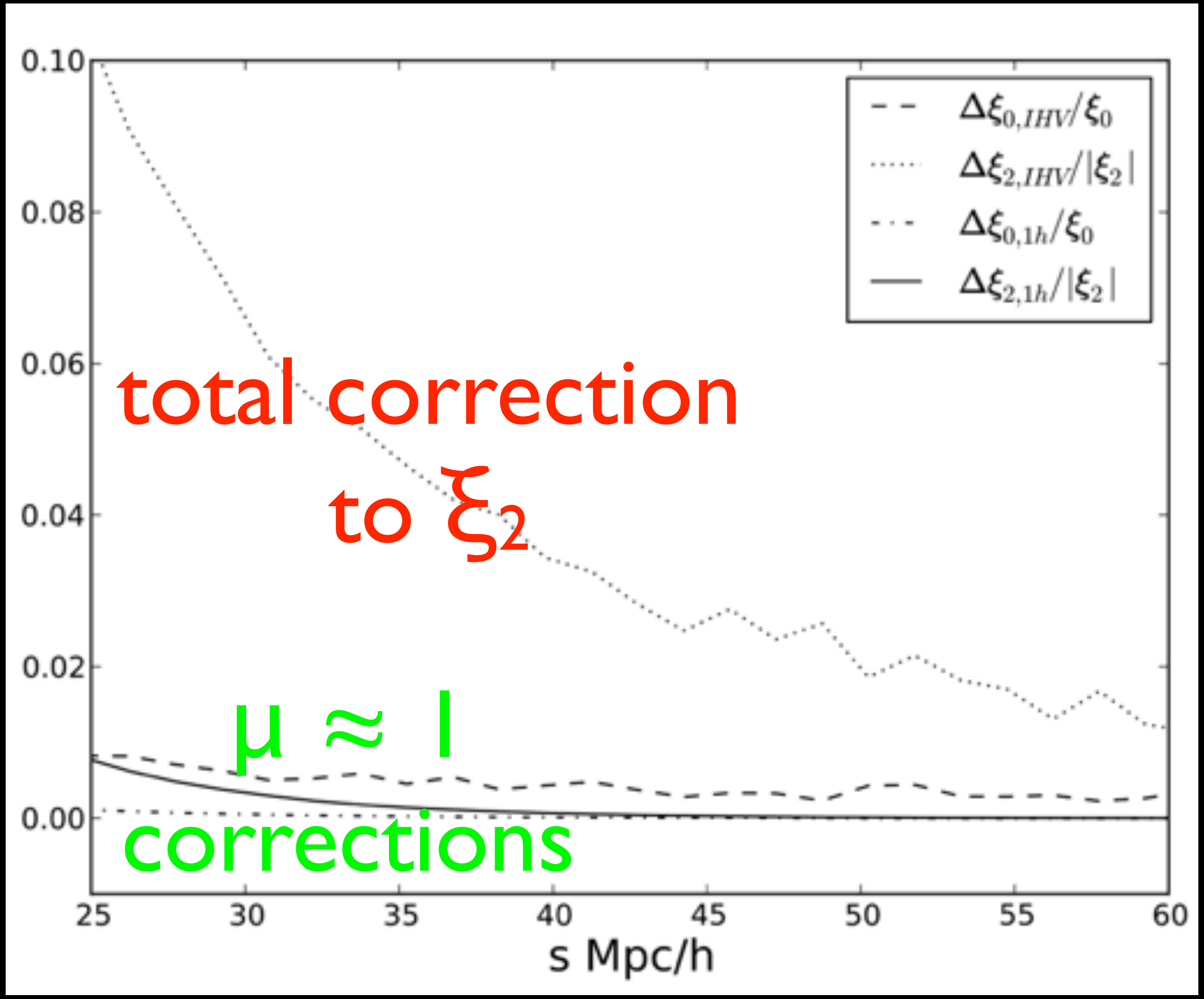


Samushia, Reid, et al. 2014

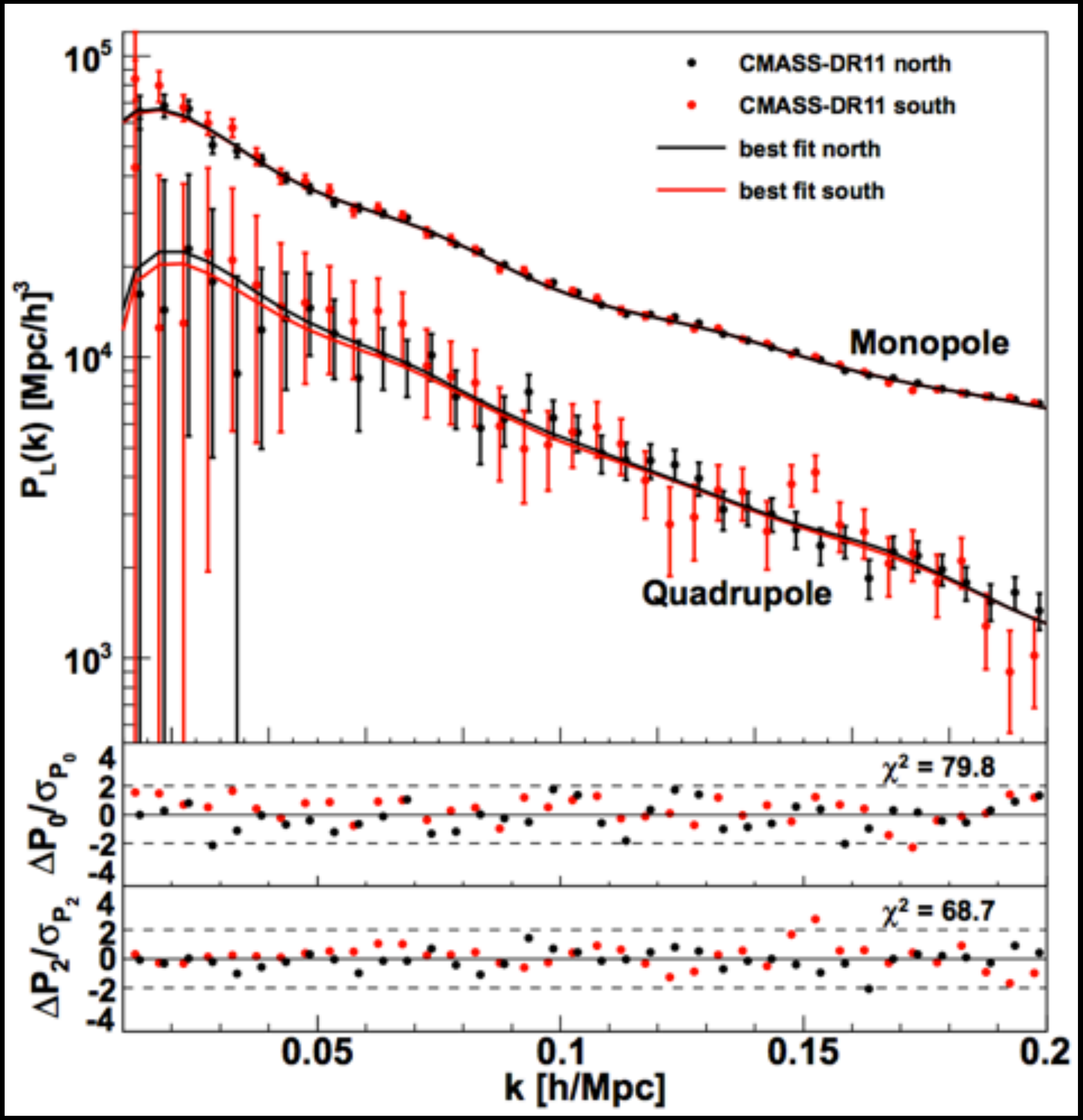
Note the FOG are dominated by "2-halo" term on these scales, cannot remove them just by excising the LOS



Reid et al. 2012

State-of-the-art in BOSS: P(k,μ)

- Fits to $P_{0,2}(k)$ restricted to $k_{max} < 0.2\ h\ \mathrm{Mpc}^{-1}$
- $f\sigma_8 = 0.422^* \pm 0.028$ (ΛCDM + GR) [* biased low by ~0.5σ]; same precision as $\xi_{0,2}$ analysis
- Model: TNS + additional bias and shot noise terms

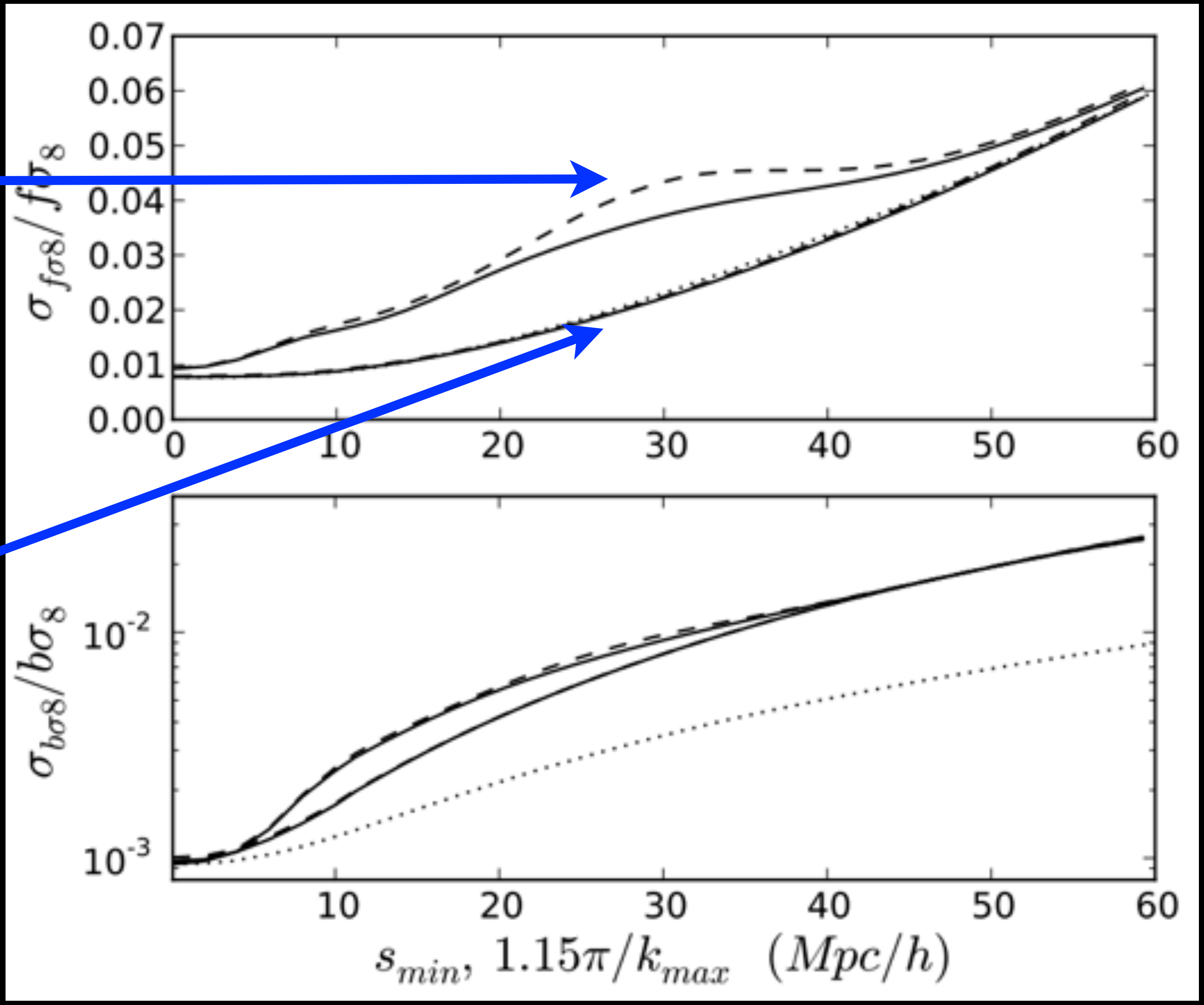


Beutler et al. 2014

Degeneracy between σ^2_{FOG} and $f\sigma_8$ in Fisher Matrix projections

Constraints from $\xi_{0,2}$ flatten between 25 and 40 h^{-1} Mpc as σ^2_{FOG} becomes important but not well-constrained

Knowing σ^2_{FOG} would put us on this curve. That information is encoded in the small-scale clustering!

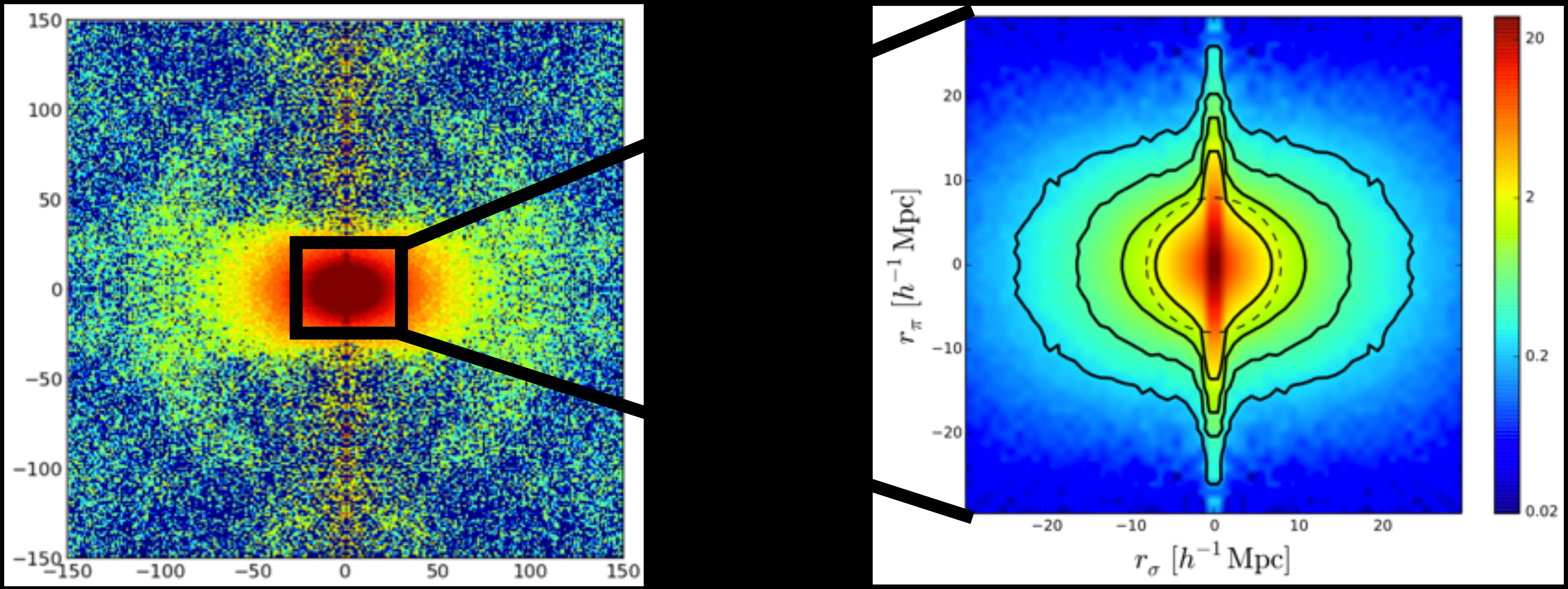


Reid and White 2011

Measurements of small-scale clustering

$\xi(r_\perp, r_\parallel)$

$r_\parallel$ (h^{-1} Mpc)



$r_\perp$ (h^{-1} Mpc)

BOSS DR11, Samushia, Reid et al. 2013

Reid et al. 2014

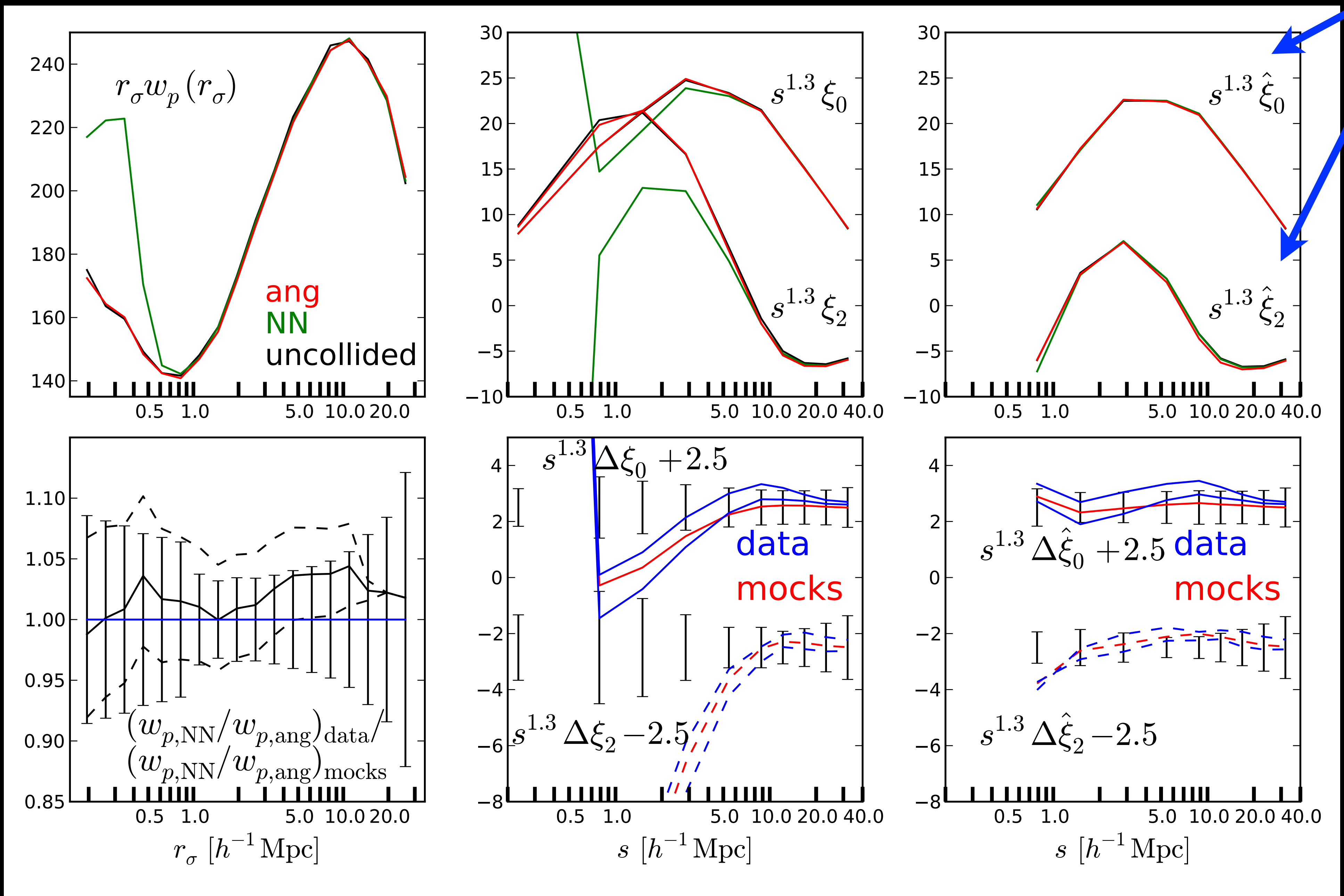
Measurements of small-scale clustering

- Dominant systematic uncertainty for small-scale measurements is "fiber-collisions": θ_{FB} = 62" = 0.53 h^{-1} Mpc at z=0.7
- We mitigate this uncertainty in two ways.
  - Mock Tile -- Generate a mock catalog with clustering matched to BOSS; apply BOSS tiling algorithm to reproduce typical tile-density correlations. Derive measurement biases and their uncertainties.
  - Select clustering statistics for which the fiber collision correction uncertainties are minimized but relevant information retained

Measurements of small-scale clustering

- We consider two fiber collision "correction" methodologies.
  - "ang": DD pairs are upweighted based on the angular clustering of the parent target sample compared with the spectroscopic sample:
  - "NN": Nearest neighbor redshift assignment
- Angular upweighting empirically works well on small scales; not easily generalizable to subsamples
- NN should be correct on large scales, though $\mu \approx 1$ always wrong.
- More complicated schemes exist (Guo et al. 2012); not clear they're correct with realistic tile-density correlations

Measurements of small-scale clustering



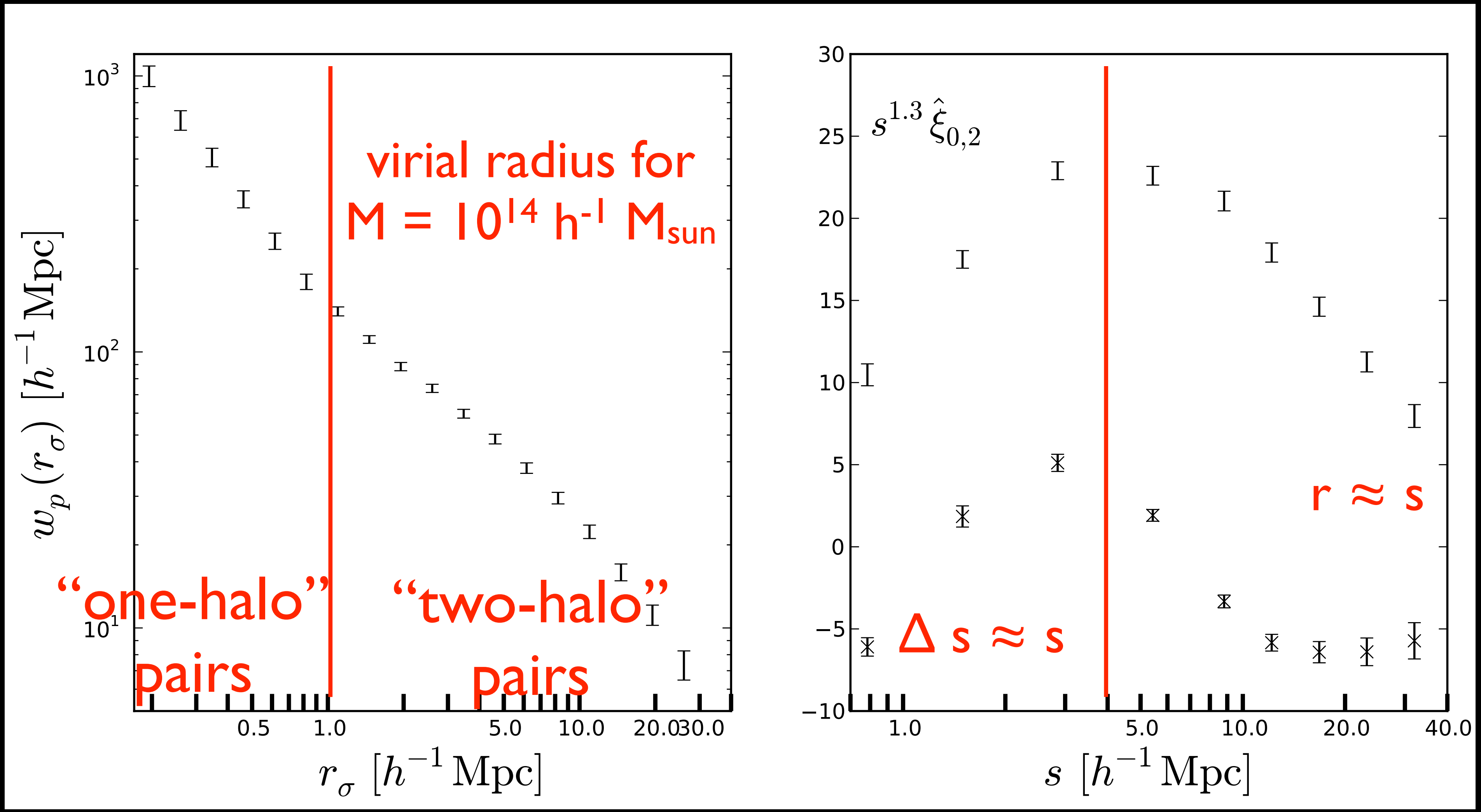
New statistics excise pairs with $r_\sigma < 0.53$ h^{-1} Mpc; approach $\xi_{0,2}$ on large scales. Difference between “truth” and “corrected” small

Difference between “ang” and NN corrected statistics agree between mocks and data

Measurements of small-scale clustering

Final data vector: $w_p(r_\sigma < 2\ h^{-1}\ \mathrm{Mpc}) + \xi_{0,2}$ [27 points]

Projected Clustering

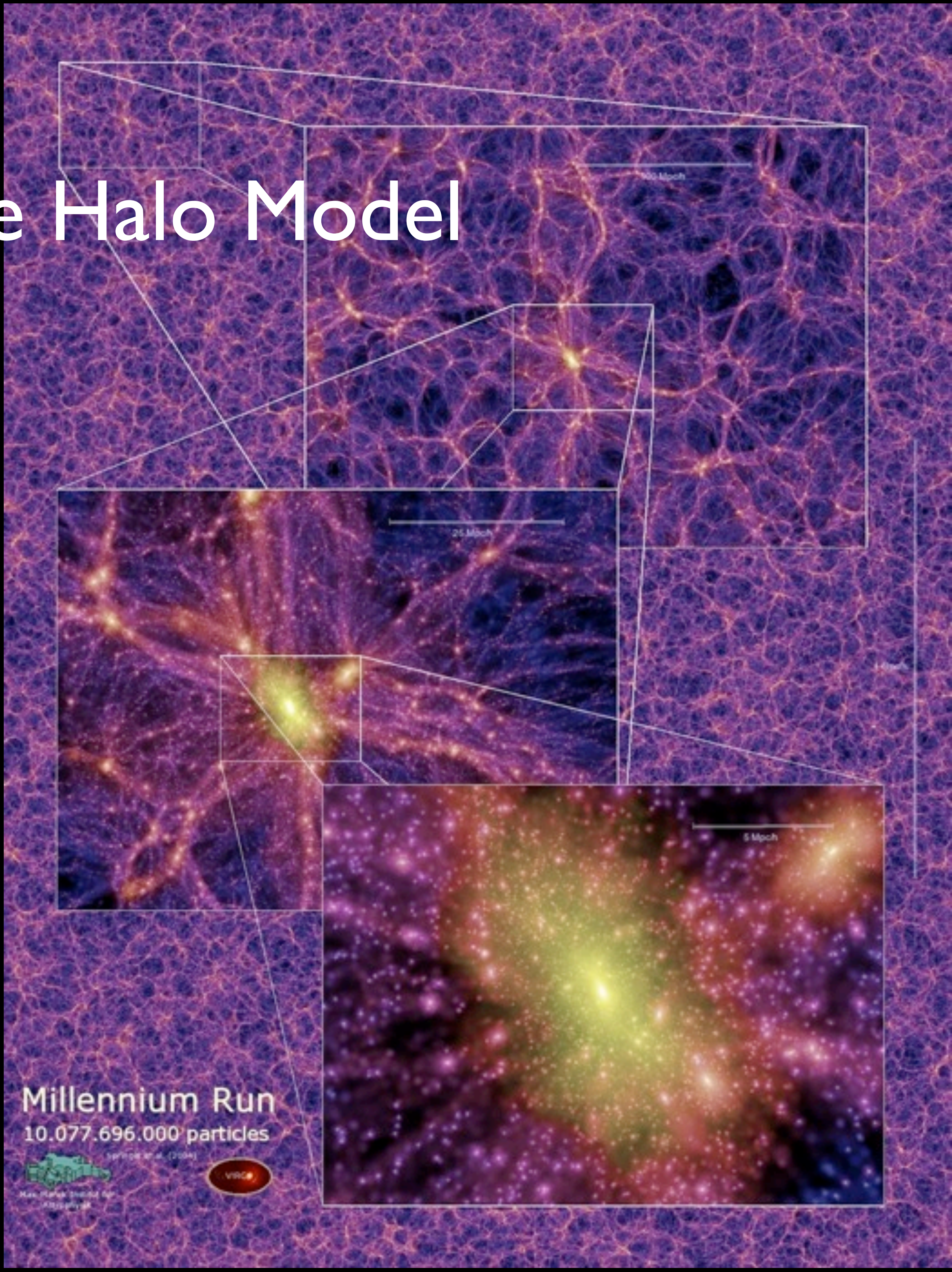


$s^{1.3}\xi_{0,2}$

$r_\perp$ (h^{-1} Mpc) s (h^{-1} Mpc)

Theory: The Halo Model

- Gas accumulates in gravitationally-bound dark matter halos, forms galaxies
- Halo mass determines P(N_{gal})
- "Fingers-of-God" are virial motions within halos



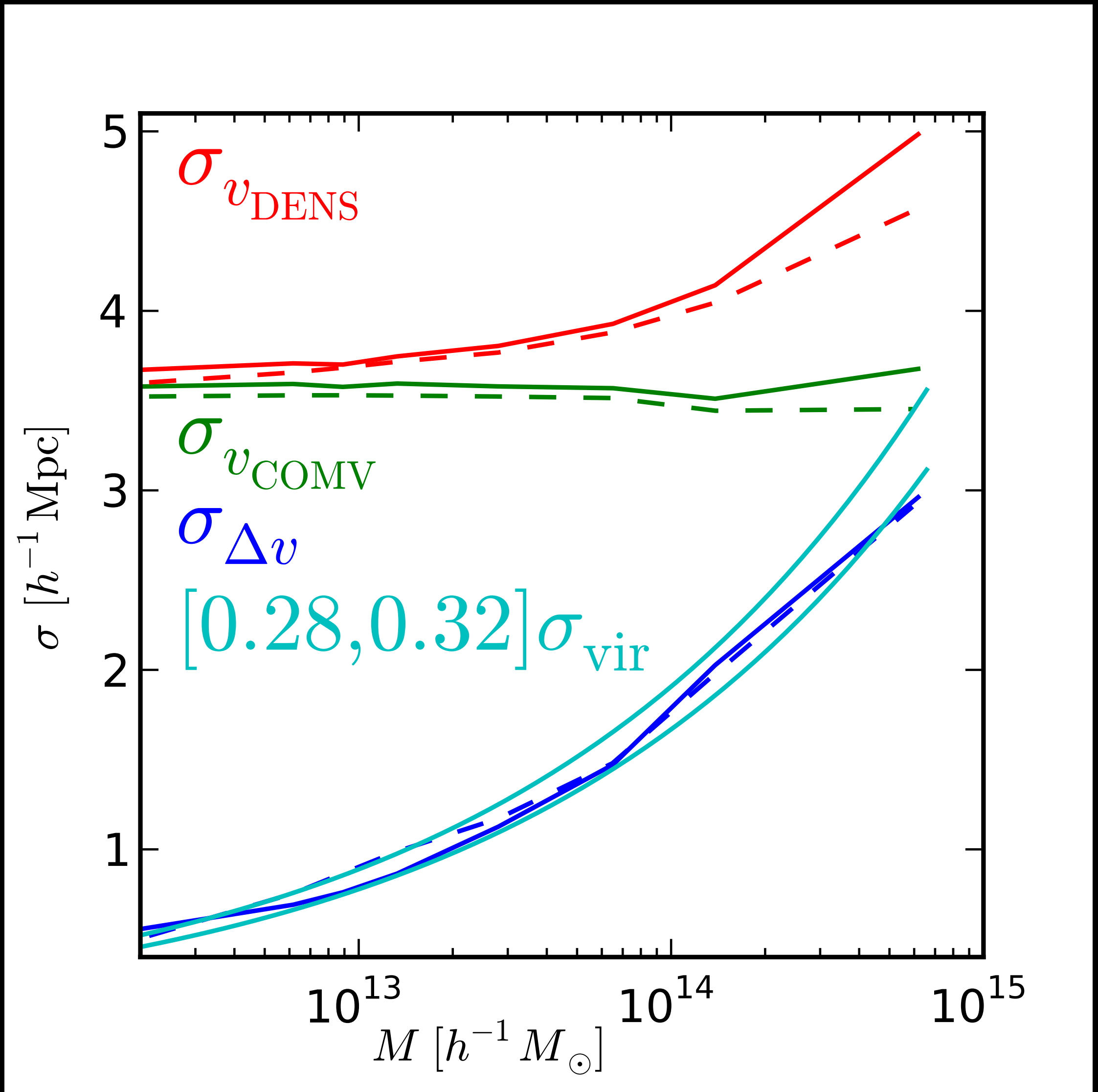
Theory Implementation

- "Standard" 5-parameter HOD parametrization

$$N_{\rm cen}(M) = 0.5\left[1 + {\rm erf}\left(\frac{\log_{10} M - \log_{10} M_{\rm min}}{\sigma_{\log_{10} M}}\right)\right] \qquad N_{\rm sat}(M) = \left(\frac{M - M_{\rm cut}}{M_1}\right)^{\alpha}$$

- Two extra "velocity parameters"
  - γ_{IHV} [rescales all intra-halo velocities]
  - γ_{cenv} [random central galaxy velocity dispersion, rms $\gamma_{cenv}*\sigma_{vir}$]
- Redshift errors included [estimated from pipeline errors + repeat observations; see Bolton et al 2012]
- Theory computed directly from simulations using Neistein & Khochfar (2012) trick

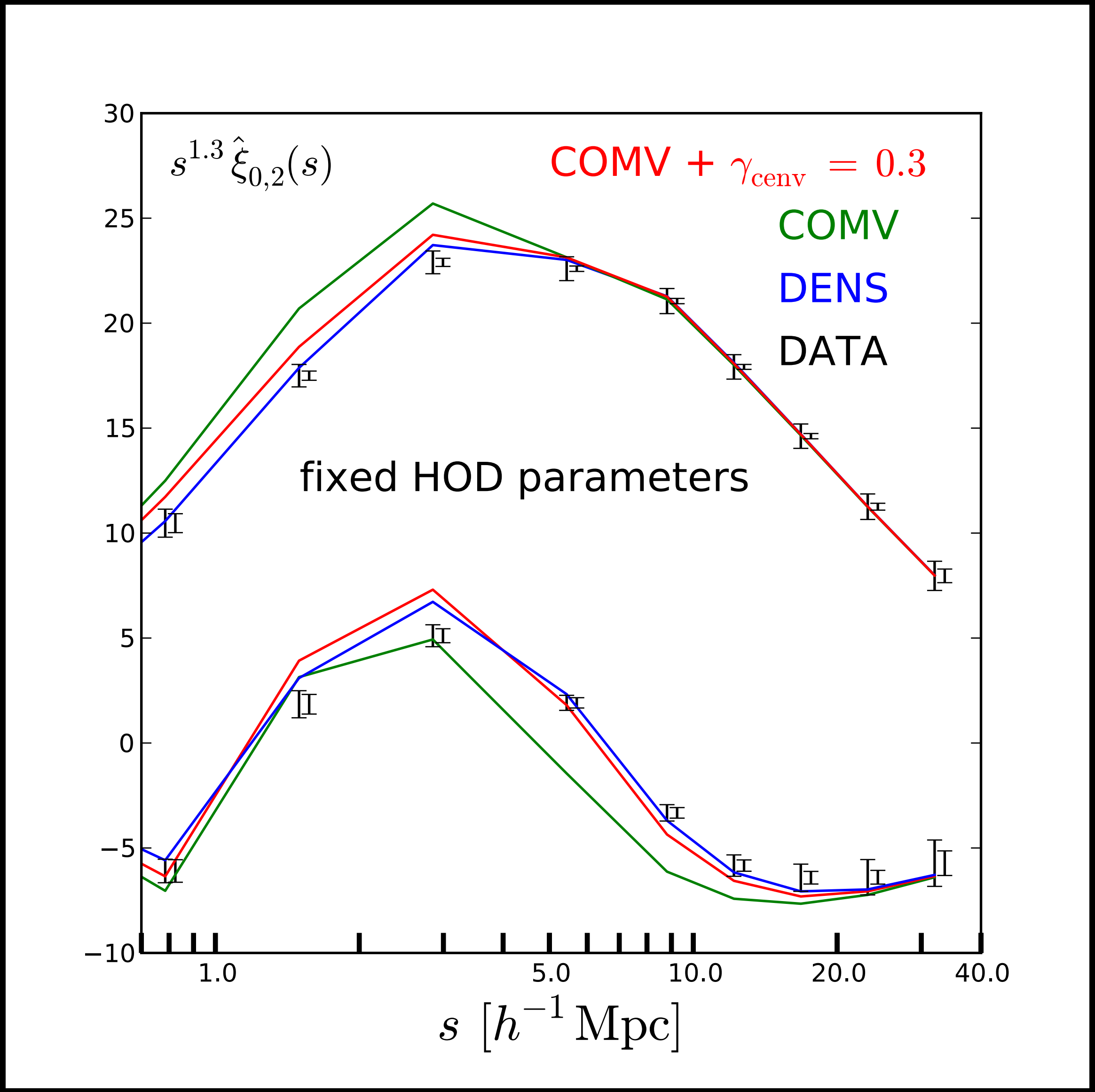
Result I: central galaxy is moving wrt the halo center of mass velocity ("COMV")



$\mathbf{v}_{\rm DENS}$ computed by averaging a small fraction of dark matter halo particles at the density peak, roughly the size of a CMASS galaxy

$|\mathbf{v}_{\rm DENS} - \mathbf{v}_{\rm COMV}| \sim 0.3\sigma_{\rm vir}$

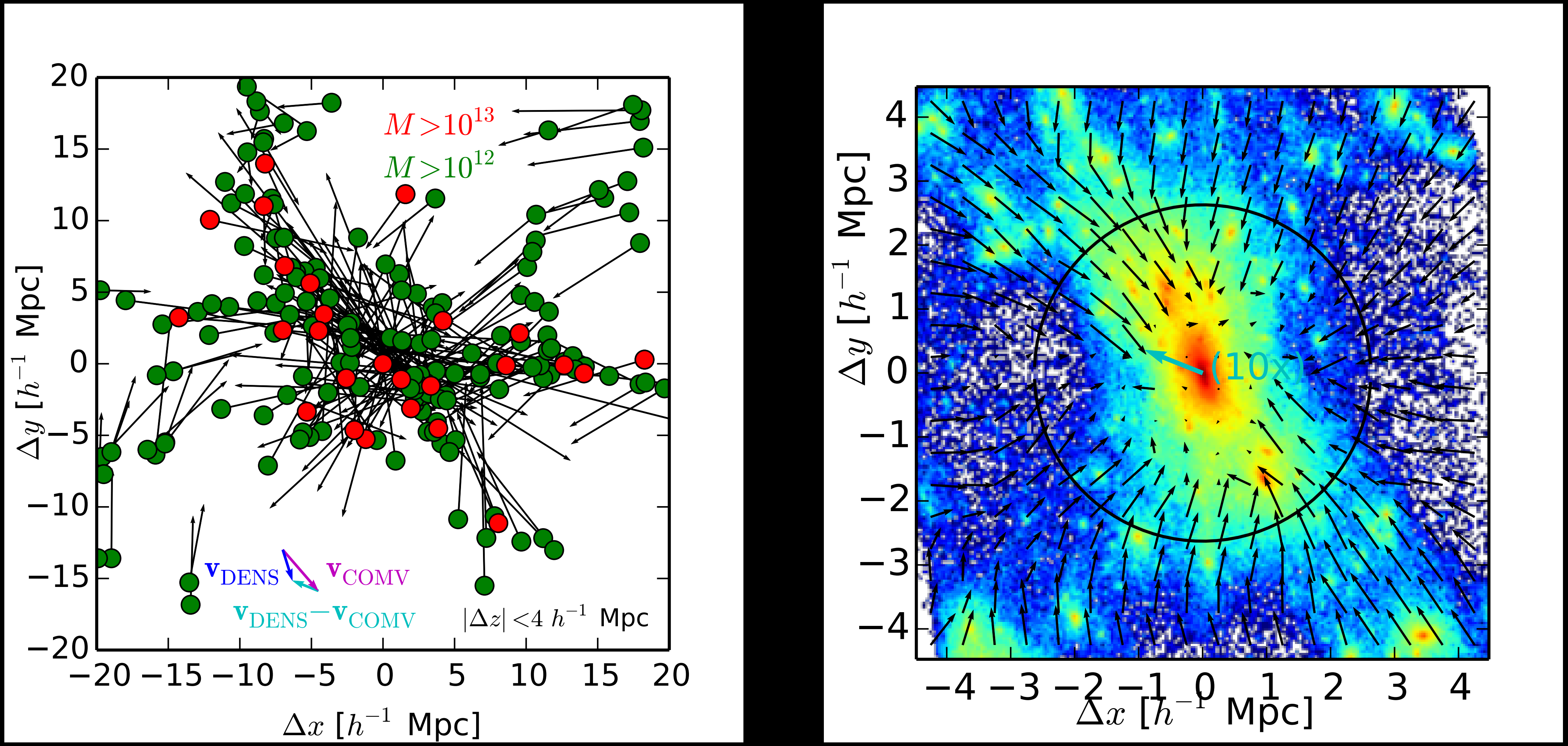
Result I: central galaxy is moving wrt the halo center of mass velocity ("COMV")



$\mathbf{v}_{\rm DENS}$ computed by averaging a small fraction of dark matter halo particles at the density peak, roughly the size of a CMASS galaxy

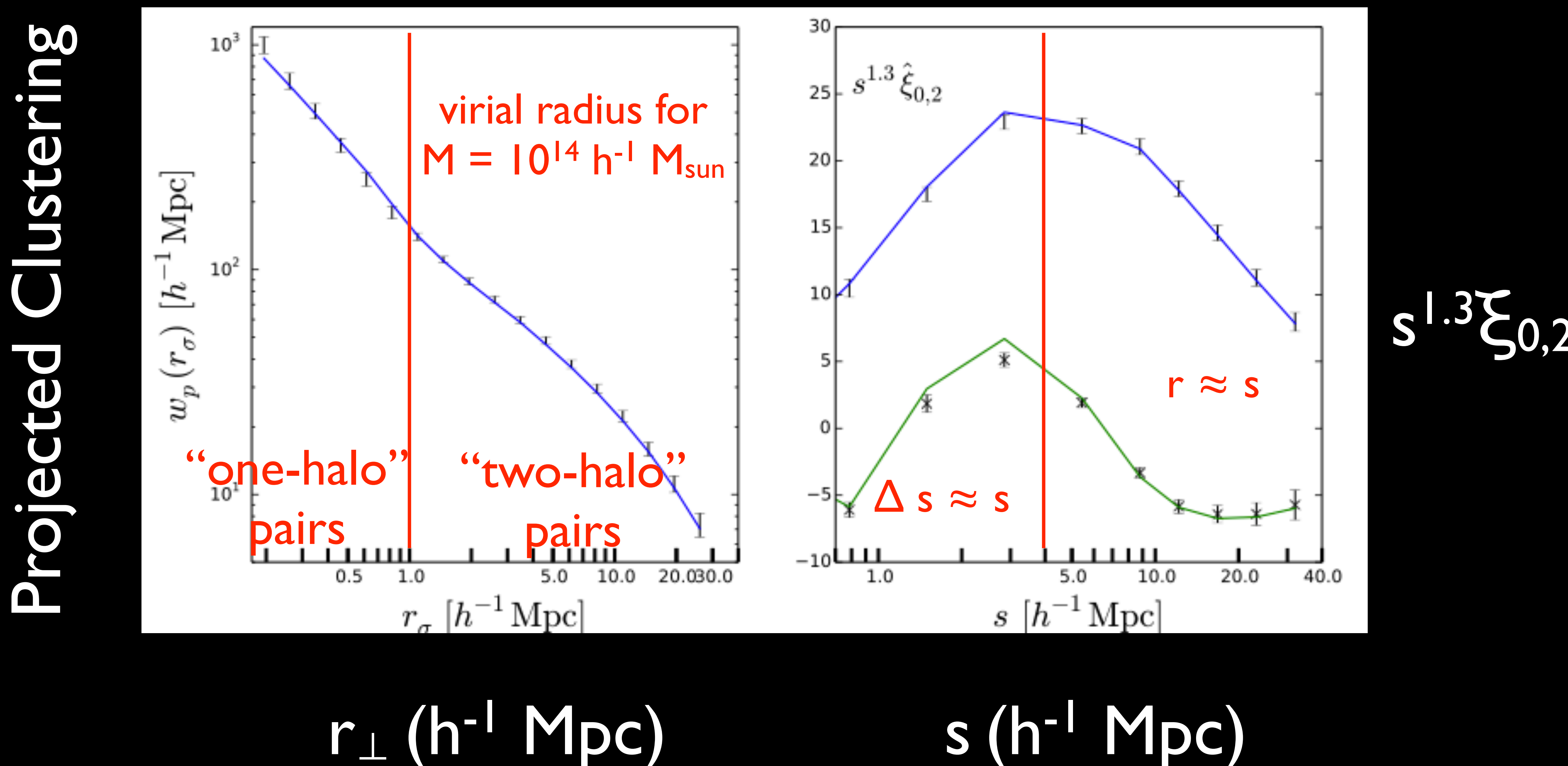
$\mathbf{v}_{\rm DENS}$ preferred by $\Delta\chi^2 = 31$ (13) when HOD parameters vary; $\mathbf{v}_{\rm DENS} - \mathbf{v}_{\rm COMV}$ must be correlated with the local environment

Result I: central galaxy is moving wrt the halo center of mass velocity ("COMV") Correlated with local environment?



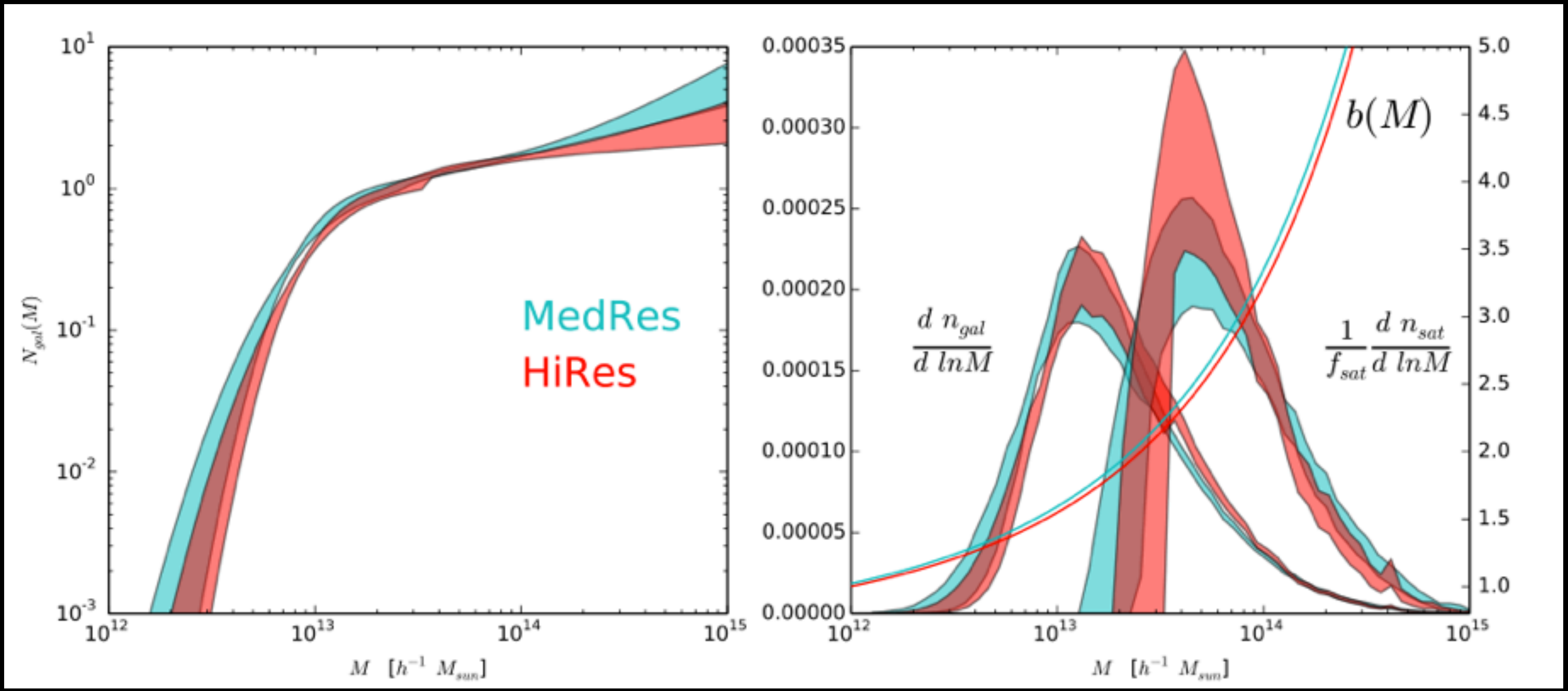
Environment of most massive halo in simulation

Best fit HOD model to small-scale clustering



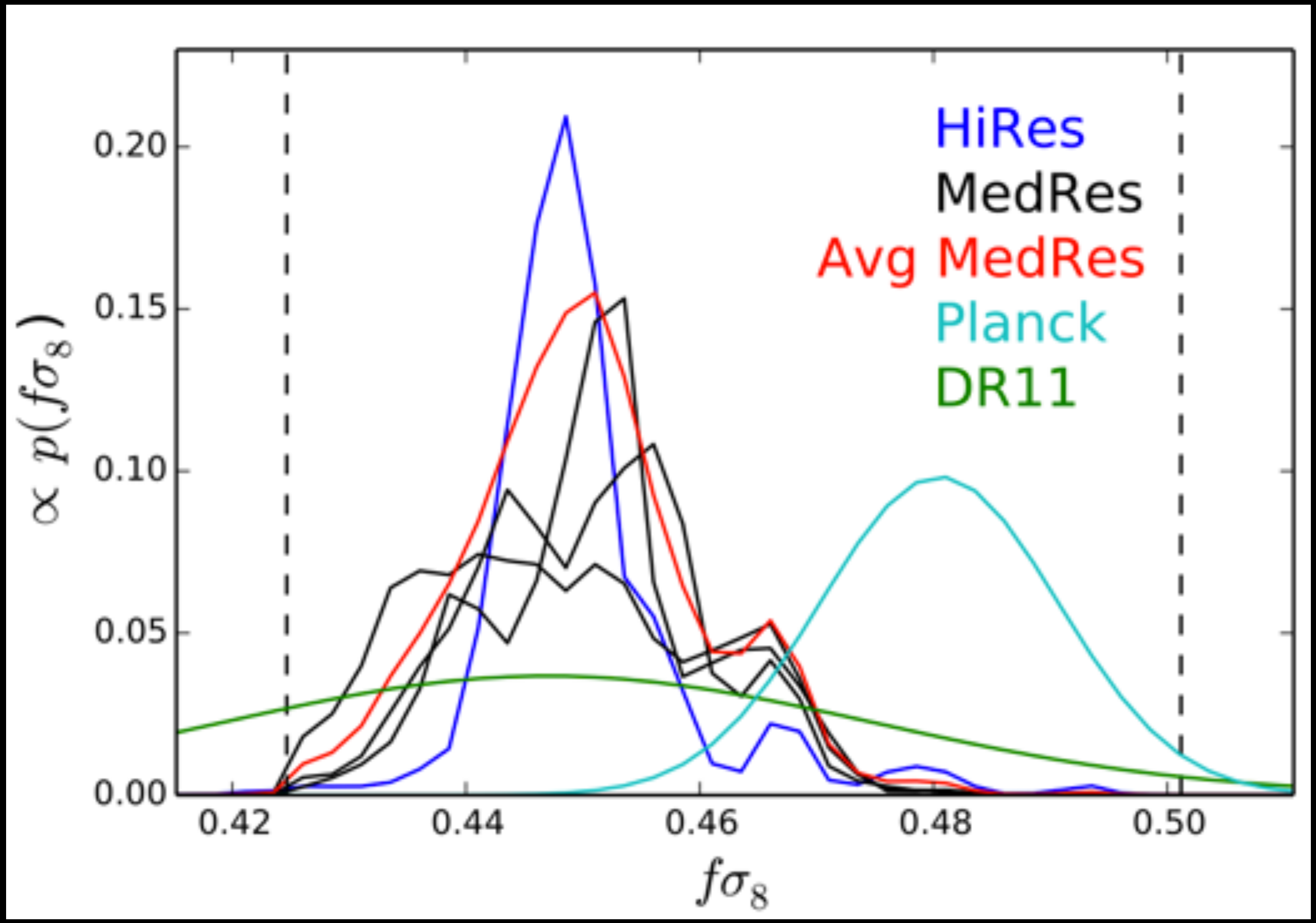
Reasonably good fit: $\chi^2 = 32$ for 21 dof

Result II: Constraints on the HOD



- "satellite" fraction = 10%
- bias $\approx$ 2

Result III: Constraints on the growth rate $f\sigma_8$



- DR11 large scales: $f\sigma_8 = 0.447 \pm 0.028$
- DR10 small scales: $f\sigma_8 = 0.450 \pm 0.011$
- Planck ΛCDM prediction: $f\sigma_8 = 0.480 \pm 0.010$

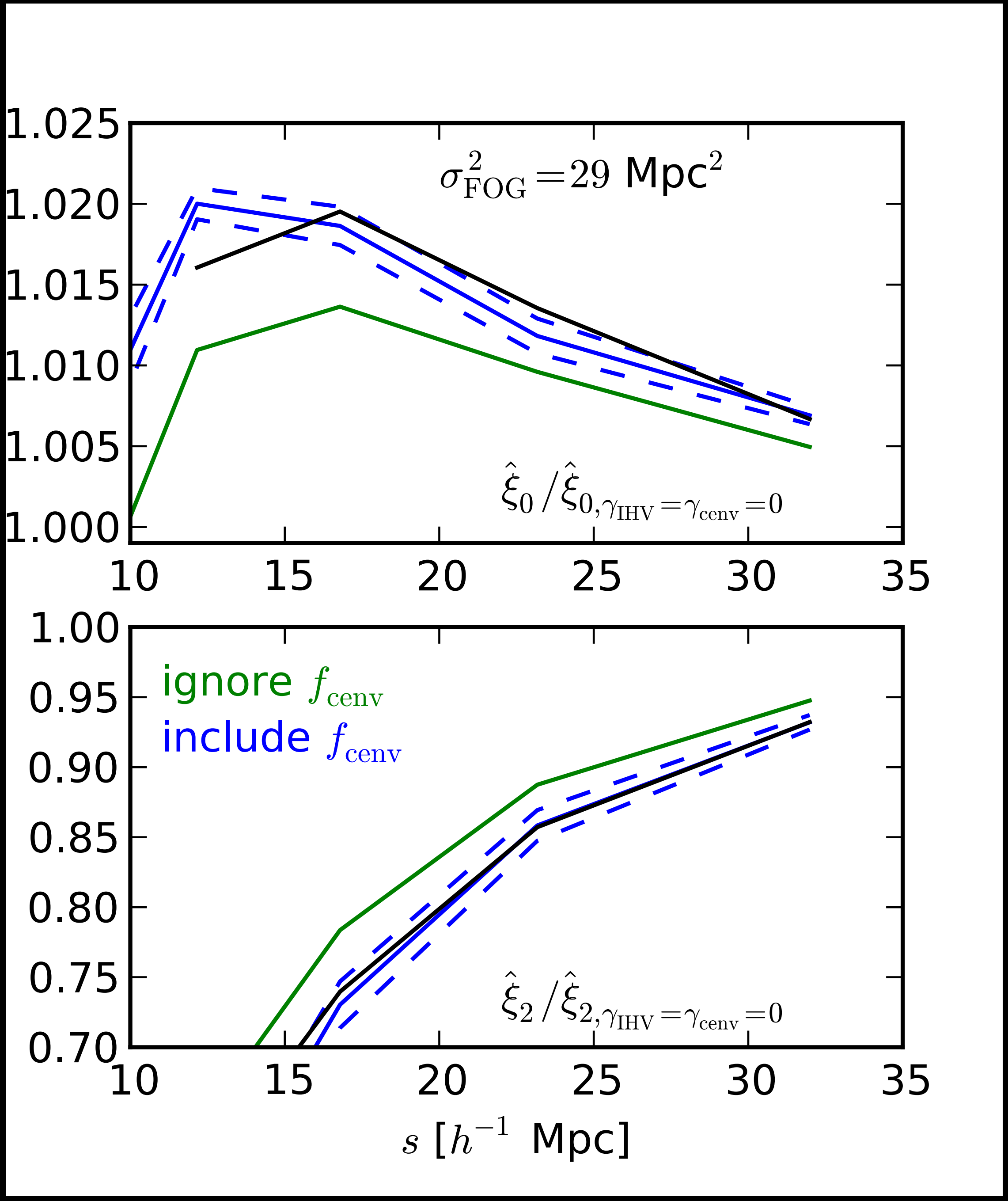
Result IV: σ^2_{FOG} = 29 ± 10 Mpc^2

Simple Gaussian dispersion nuisance parameter σ^2_{FOG} describes the difference in mock catalogs with and without intrahalo velocities

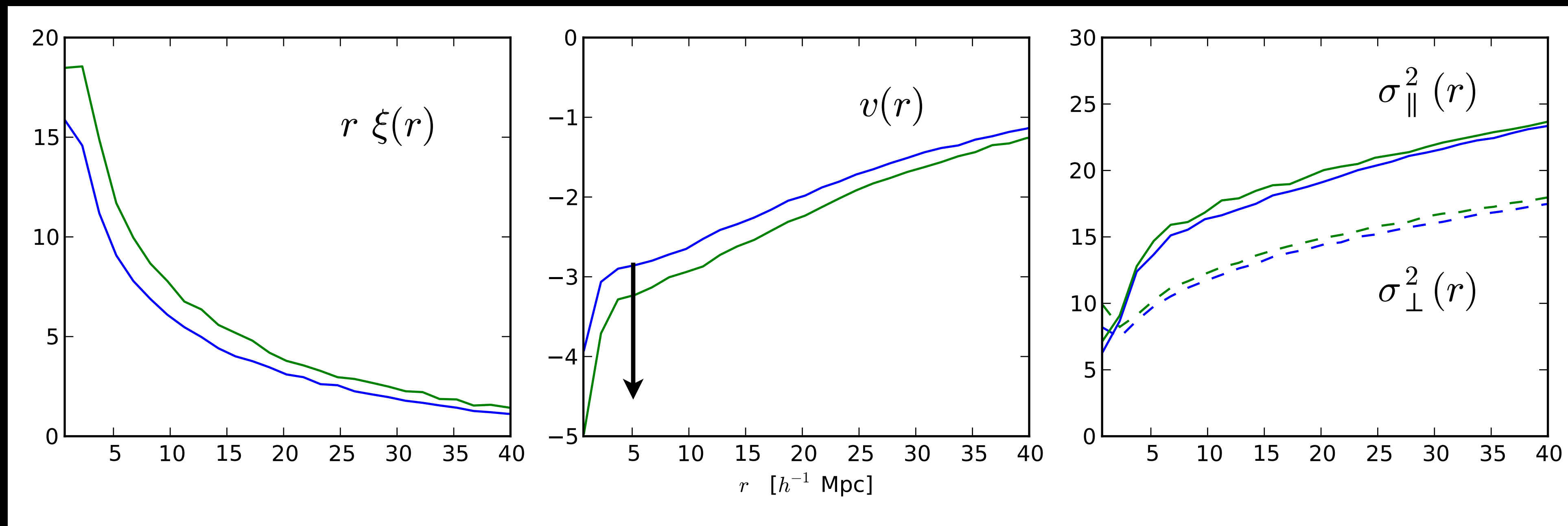
Application to DR11:
$f\sigma_8 = 0.447 \pm 0.028$

↓

$f\sigma_8 = 0.457 \pm 0.025$
$f\sigma_8$ shifts up when $\sigma^2_{FOG} \approx 0$ is disfavored



Modified gravity implications: effects on $P(v_{12},r)$



~1-2 h^{-1} Mpc enhancement in $v(r)$ at $r = 5\ h^{-1}$ Mpc for both f(R) and Galileon simulations [Zu et al. 2013]

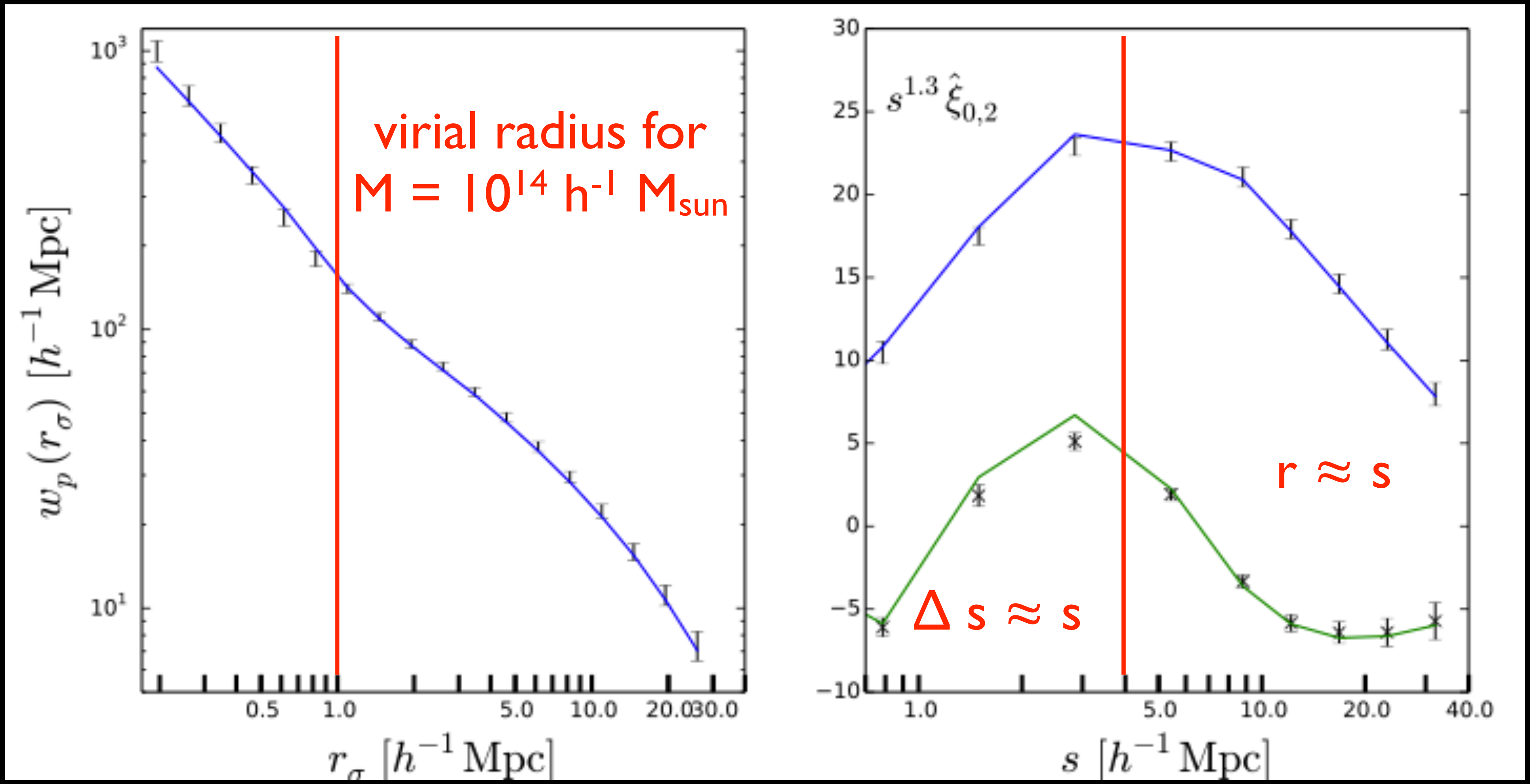
SHOULD be easily ruled out by our measurements (2.5% accuracy!) but modified gravity simulations needed for a quantitative comparison

Map to redshift space:

$$1 + \xi_s(r_\sigma, r_\pi) = \int_{-\infty}^{\infty} dy\, [1 + \xi(r)]\, \mathcal{P}(v_z \equiv r_\pi - y, \mathbf{r})$$

Best fit HOD model to small-scale clustering

Projected Clustering



$s^{1.3}\xi_{0,2}$

$r_\perp$ (h^{-1} Mpc)   s (h^{-1} Mpc)

No room for ~30% enhancement of velocities!

Tests

	fiducial	HiRes	HiRes	MedRes	COMV	COMV	high $\bar{n}_{\rm HOD}$
$\log_{10} M_{\rm min}$	$\mathbf{13.031 \pm 0.029}$	13.055 ± 0.022	13.089 ± 0.027	13.004 ± 0.025	13.152 ± 0.027	13.027 ± 0.027	12.926 ± 0.022
$\sigma_{\log_{10} M}$	$\mathbf{0.38 \pm 0.06}$	0.31 ± 0.05	0.38 ± 0.05	0.32 ± 0.07	0.61 ± 0.03	0.37 ± 0.06	0.16 ± 0.12
$\log_{10} M_{\rm cut}$	$\mathbf{13.27 \pm 0.13}$	13.43 ± 0.13	13.36 ± 0.13	13.27 ± 0.14	13.07 ± 0.15	13.19 ± 0.13	13.01 ± 0.58
$\log_{10} M_1$	$\mathbf{14.08 \pm 0.06}$	14.33 ± 0.32	14.24 ± 0.18	14.09 ± 0.07	14.05 ± 0.04	14.05 ± 0.04	14.09 ± 0.05
α	$\mathbf{0.76 \pm 0.18}$	0.40 ± 0.22	0.53 ± 0.22	0.73 ± 0.20	1.03 ± 0.13	0.90 ± 0.14	0.93 ± 0.22
$\bar{n}_{\rm HOD}$	$\mathbf{4.12 \pm 0.13}$	4.14 ± 0.11	4.08 ± 0.16	4.16 ± 0.09	4.05 ± 0.17	4.14 ± 0.11	4.64 ± 0.11
$f_{\rm sat}$	$\mathbf{0.1016 \pm 0.0069}$	0.0997 ± 0.0068	0.1015 ± 0.0069	0.1015 ± 0.0071	0.1038 ± 0.0065	0.1037 ± 0.0072	0.1152 ± 0.0076
$f\sigma_8$	$\mathbf{0.452 \pm 0.011}$	**0.482**	0.449 ± 0.006	**0.472**	**0.472**	**0.472**	**0.472**
$\gamma_{\rm IHV}$	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**	**1.00**
$\gamma_{\rm cenv}$	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.30**	**0.00**
$\chi^2_{w_p}$ (18)	**12.4**	9.5	9.7	11.5	28.9	15.5	8.6
$\chi^2_{\hat{\xi}_{0,2}}$ (18)	**27.5**	31.0	24.4	30.6	65.0	49.4	27.1
$\chi^2_{w_p+\hat{\xi}_{0,2}}$ (27)	**32.3**	34.1	26.4	36.8	68.5	50.0	30.0

	MedRes1	MedRes2	high $\bar{n}_{\rm HOD}$	cen/sat test	MedRes0	MedRes0	MedRes0
$\log_{10} M_{\rm min}$	13.035 ± 0.032	13.037 ± 0.030	12.951 ± 0.030	12.983 ± 0.060	13.034 ± 0.030	13.017 ± 0.028	13.024 ± 0.030
$\sigma_{\log_{10} M}$	0.39 ± 0.06	0.39 ± 0.06	0.26 ± 0.10	0.31 ± 0.11	0.40 ± 0.07	0.34 ± 0.06	0.36 ± 0.06
$\log_{10} M_{\rm cut}$	13.26 ± 0.14	13.28 ± 0.13	13.08 ± 0.15	11.89 ± 0.99	13.24 ± 0.13	13.24 ± 0.14	13.25 ± 0.14
$\log_{10} M_1$	14.09 ± 0.06	14.07 ± 0.06	14.06 ± 0.05	14.23 ± 0.05	14.03 ± 0.05	14.17 ± 0.10	14.08 ± 0.06
α	0.75 ± 0.19	0.75 ± 0.19	0.88 ± 0.16	1.15 ± 0.10	0.89 ± 0.15	0.67 ± 0.22	0.77 ± 0.18
$\bar{n}_{\rm HOD}$	4.11 ± 0.14	4.11 ± 0.13	4.60 ± 0.13	3.67 ± 0.28	4.16 ± 0.09	4.10 ± 0.14	4.13 ± 0.12
$f_{\rm sat}$	0.1016 ± 0.0070	0.1017 ± 0.0068	0.1140 ± 0.0074	0.1536 ± 0.0222	0.0998 ± 0.0069	0.1024 ± 0.0068	0.1021 ± 0.0070
$f\sigma_8$	0.447 ± 0.014	0.451 ± 0.010	0.458 ± 0.010	0.455 ± 0.009	0.460 ± 0.013	0.453 ± 0.011	0.445 ± 0.009
$\gamma_{\rm IHV}$	**1.00**	**1.00**	**1.00**	**1.00**	**0.80**	**1.20**	**1.00**
$\gamma_{\rm cenv}$	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	**0.00**	0.06 ± 0.05
$\chi^2_{w_p}$ (18)	10.9	12.5	9.9	8.3	17.4	8.4	13.4
$\chi^2_{\hat{\xi}_{0,2}}$ (18)	28.2	27.3	27.0	22.4	55.0	21.1	27.2
$\chi^2_{w_p+\hat{\xi}_{0,2}}$ (27)	31.9	32.1	28.4	22.1	57.3	24.4	32.7

Caveats

- We have neglected the Alcock-Paczynski effect, so this measurement cannot be used to constrain dark energy (yet)
- We use amplitude-matched halo catalogs from different redshifts to validate our determination of $f\sigma_8$ as an overall scaling of the simulation halo velocity field.

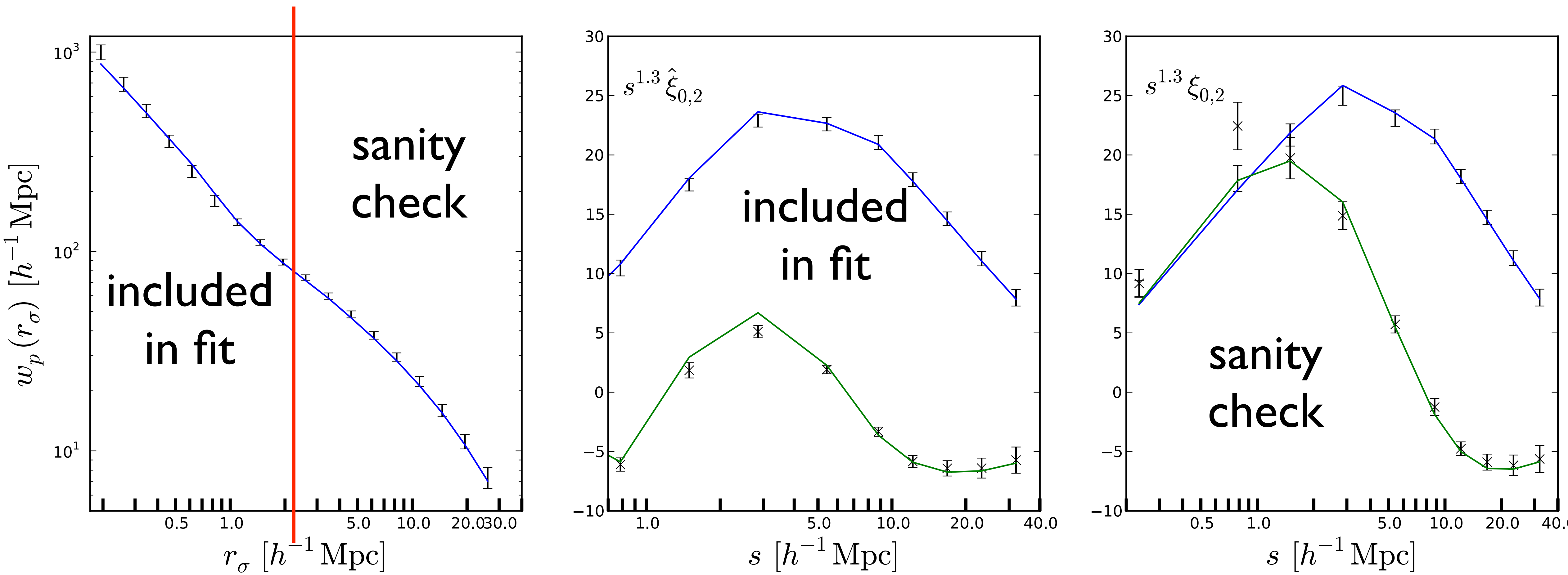
Conclusions

- The anisotropic clustering in the highly non-linear regime for CMASS galaxies can be reasonably well understood in the HOD framework + ΛCDM cosmology (a quantitative first!)
- These measurements provide a 2.5% constraint on $f\sigma_8$ that is robust to a variety of HOD model extensions
- The central galaxies are moving wrt their halo center-of-mass! The best way to extract it from dark matter simulations is unclear; need to marginalize over available choices here! See forthcoming BOSS Guo et al. paper.
- We constrained σ^2_{FOG} from small-scale clustering, which can be applied to large-scale RSD analyses.
- This *should* be a useful measurement for modified gravity constraints.

EXTRAS

Measurements of small-scale clustering

Final data vector: $w_p(r_\sigma < 2\ h^{-1}\ \mathrm{Mpc}) + \xi_{0,2}$ [27 points]



Brief model description

- 2LPT (Matsubara et al. 2008) s > 100 Mpc
- s < 100 Mpc: Gaussian streaming approximation

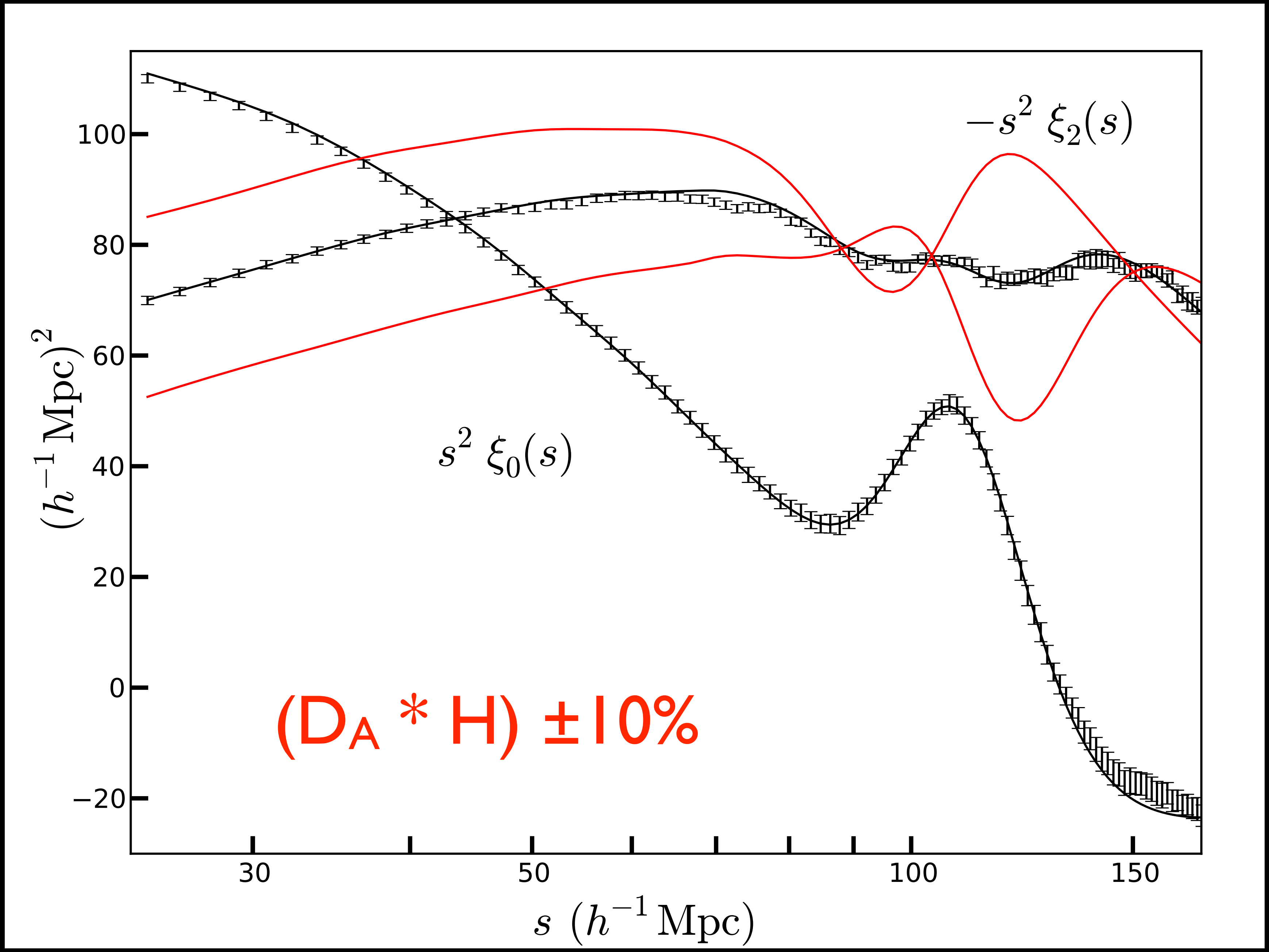
$$1+\xi_g^s(r_\sigma,r_\pi)=\int\left[1+\xi_g^r(r)\right]e^{-[r_\pi-y-\mu v_{12}(r)]^2/2\sigma_{12}^2(r,\mu)}\frac{dy}{\sqrt{2\pi\sigma_{12}^2(r,\mu)}}$$

2LPT
2nd order bias included

2SPT
1st order bias only

- FOGs included with additive isotropic σ^2_{FOG}

Alcock-Paczynski has different scale-dependence, distinguishable from RSD



Dv stretches s axis