

Toward Accurate Modeling of Galaxy Clustering on Small Scales: Halo Model Extensions & Lingering Tension

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Constraining Cosmology with Small-Scale Clustering

Run DMO simulation
& identify halos



Apply halo model to
DMO halos



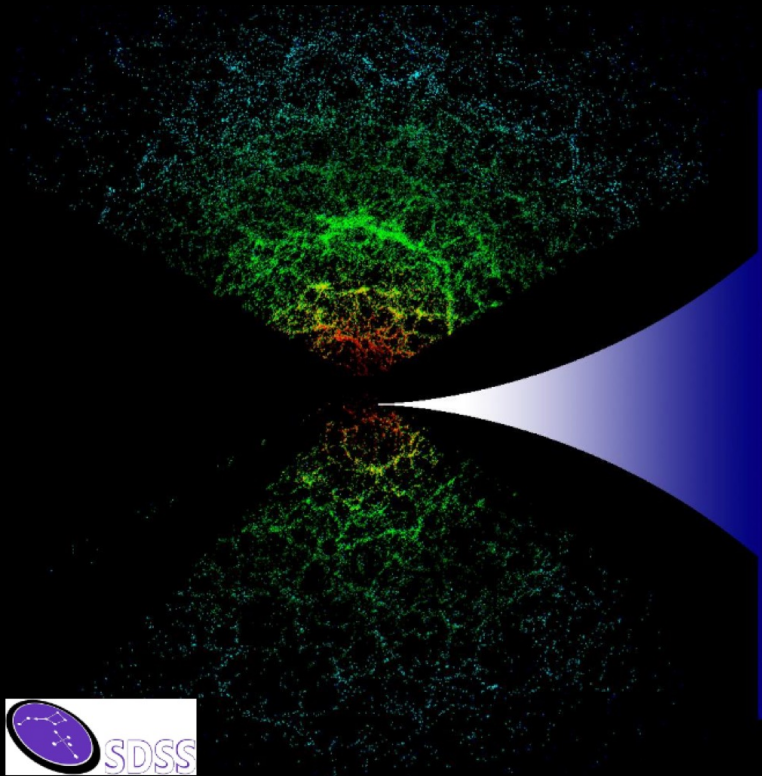
Construct realistic
mock galaxy catalogs



Measure clustering statistics
and compare to data

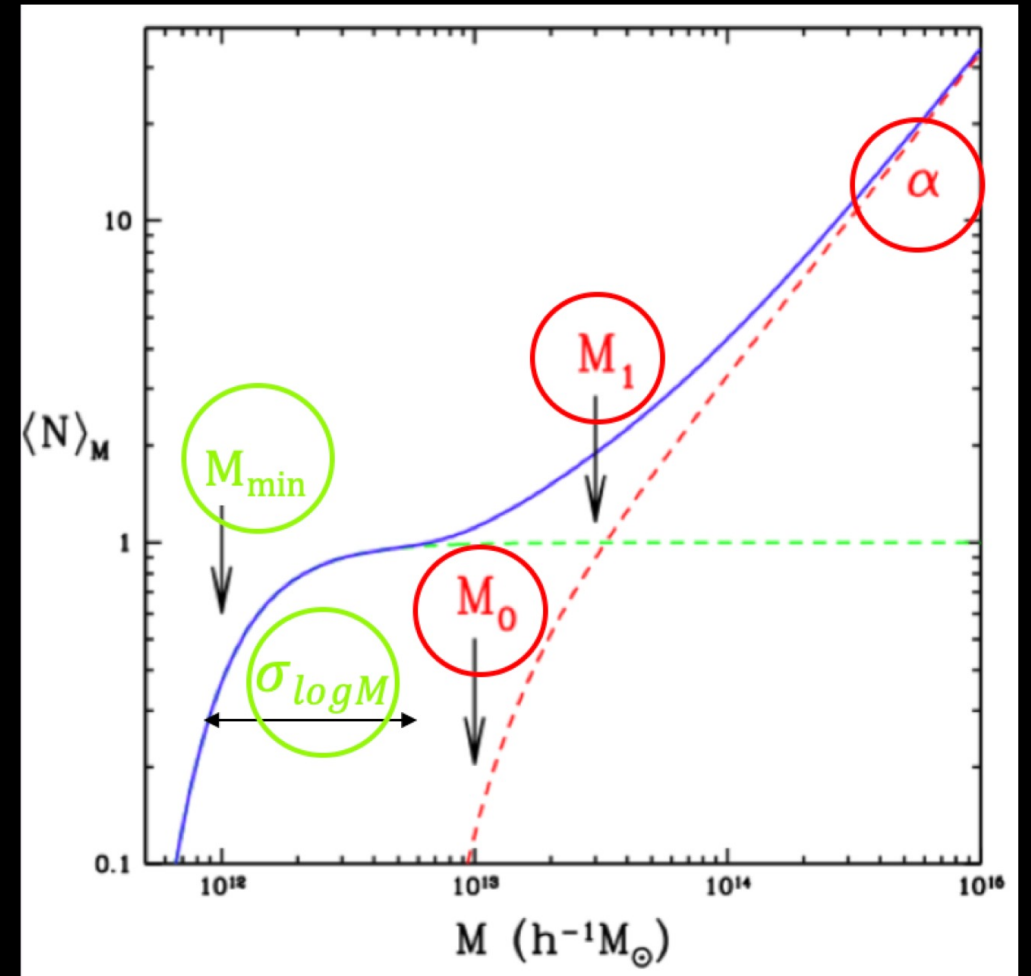


Constrain halo model &
cosmological parameters



Standard Halo Occupation Distribution Model

- Assign a number of central and satellite galaxies to a halo of mass M using 5 parameters
 - Central parameters: M_{\min} and $\sigma_{\log M}$
 - Satellite parameters: M_0 , M_1 , and α
 - Number of galaxies assigned to halo is based only on halo mass (**no galaxy assembly bias**)
- Central galaxy is placed at the center of the halo and is at rest with respect to the halo
- Satellite galaxies are given the positions and velocities of random dark matter particles within the halo (**no spatial or velocity bias**)



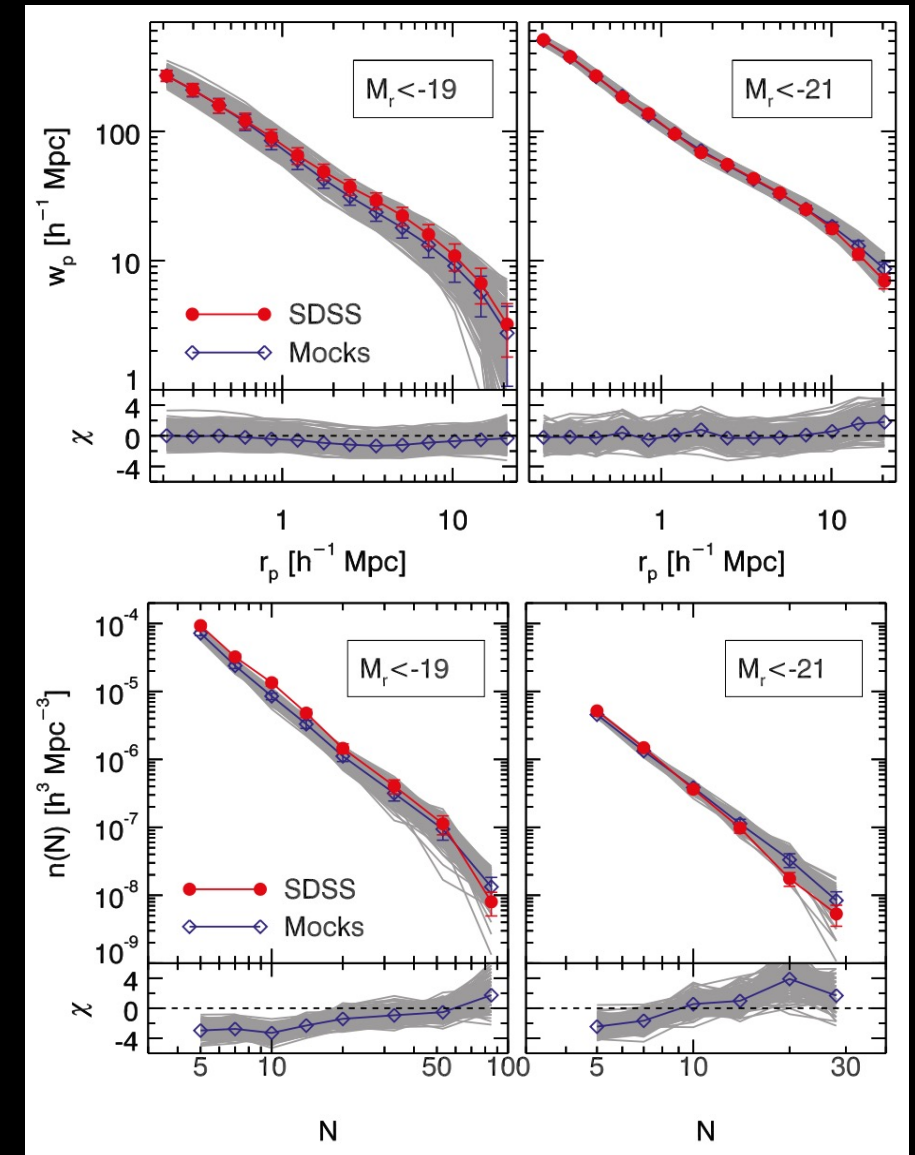
Berlind & Weinberg (2002), Kravtsov et al. (2004),
Zheng et al. (2005), Zheng et al. (2007)

Planck Λ CDM + Standard HOD Model

- Has been tested on large scales & with standard clustering statistics
- Sinha et al. (2018) used a fully numerical, mock-based modeling procedure to test the Planck Λ CDM + Standard HOD Model
 - Galaxy number density
 - Projected correlation function
 - **Group Multiplicity Function**
 - Found slight tension with SDSS

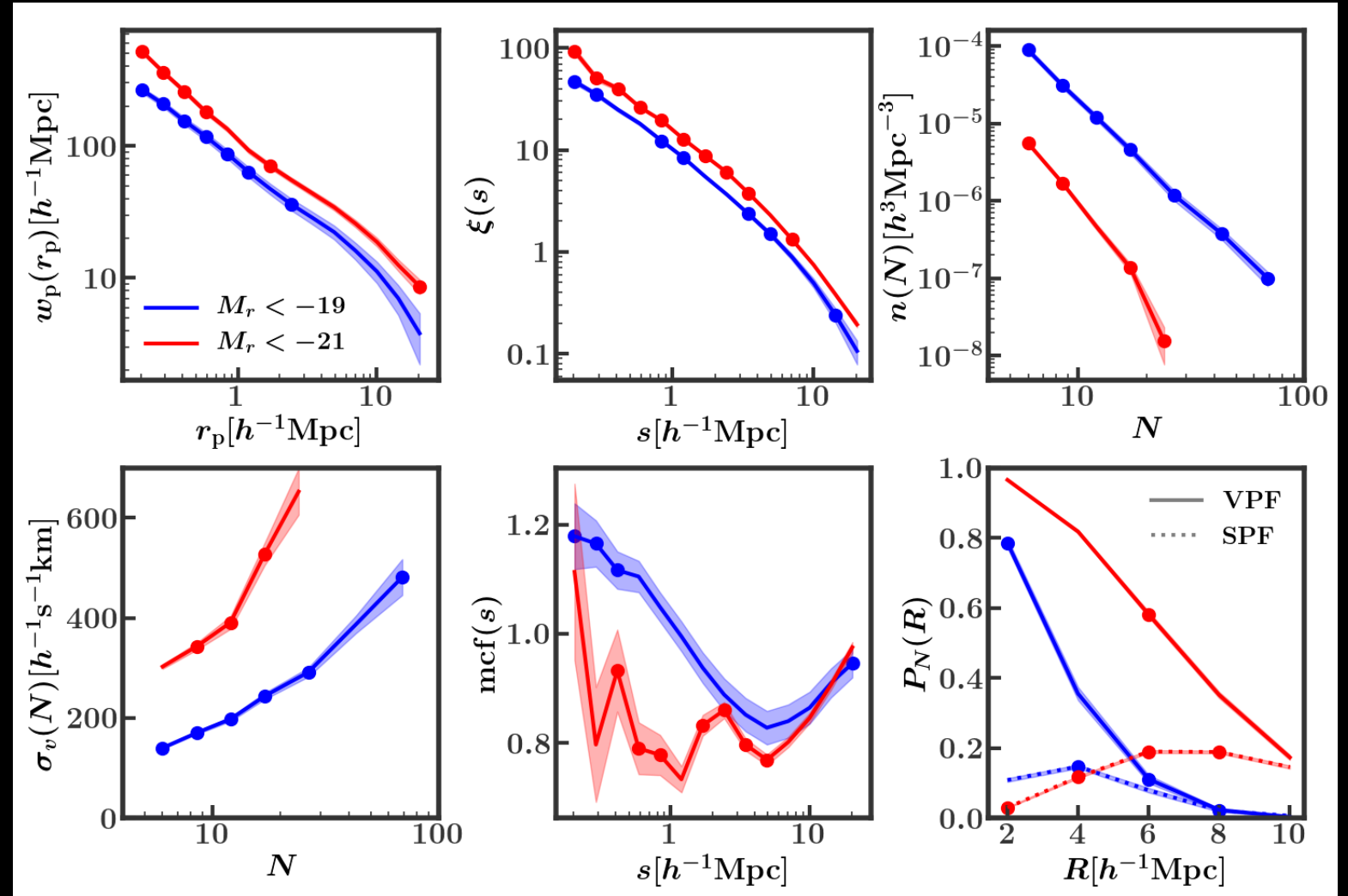
M_r^{lim}	z_{min}	z_{max}	z_{median}	V_{eff} ($10^6 h^{-3} \text{Mpc}^3$)	n_g ($h^3 \text{Mpc}^{-3}$)
-19	0.02	0.067	0.054	5.555	0.0149
-21	0.02	0.165	0.132	78.374	0.0012

Sinha et al. (2018)



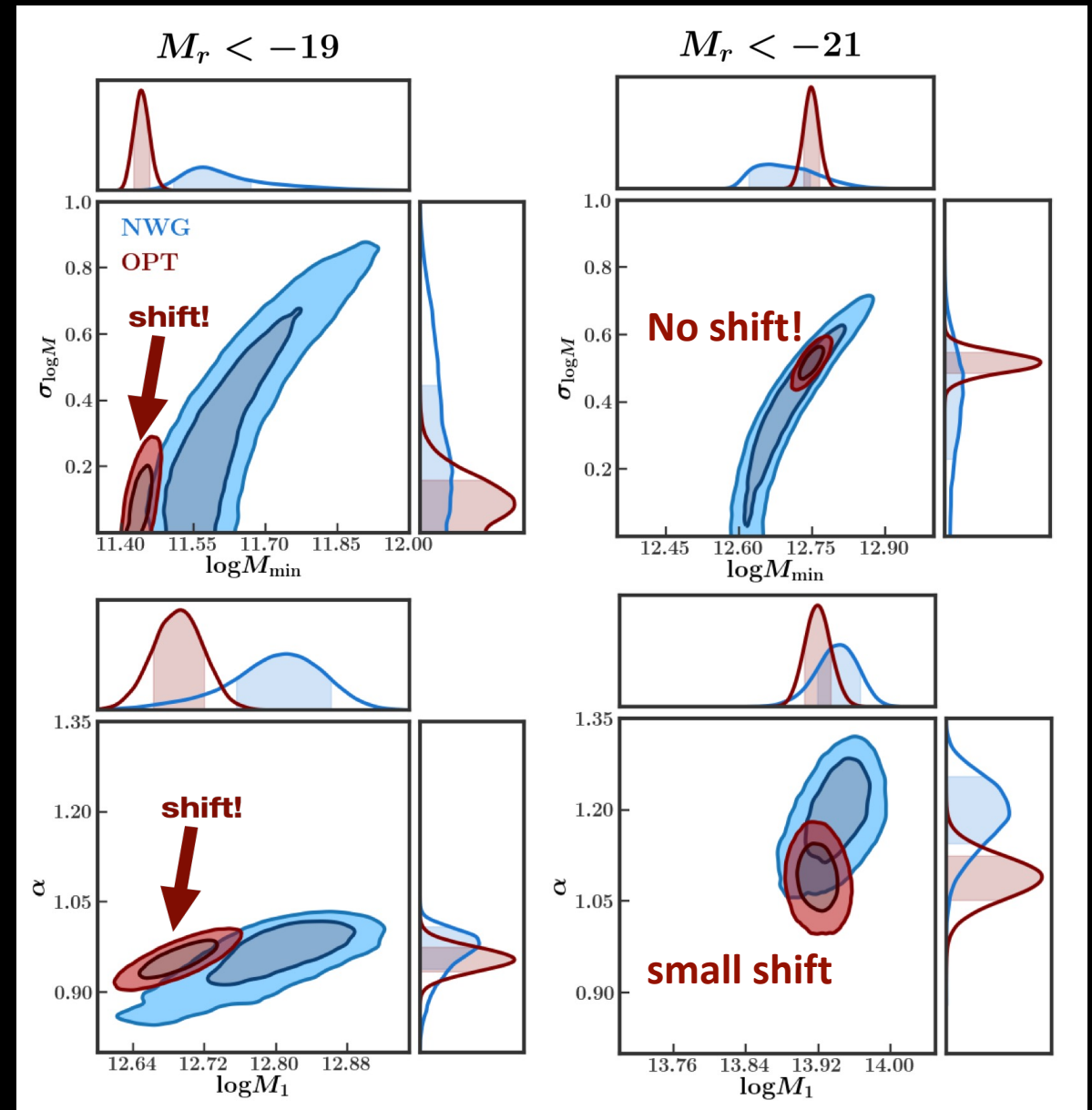
Optimal Clustering Measurements

- Szewciw et al. (2022) added:
 - **Redshift-space Correlation Function**
 - **Average group velocity dispersion function**
 - **Mark Correlation Function**
 - **Counts-in-cells statistics**
- Select a combination of different scales of each clustering statistic that yields optimal constraining power and minimal noise



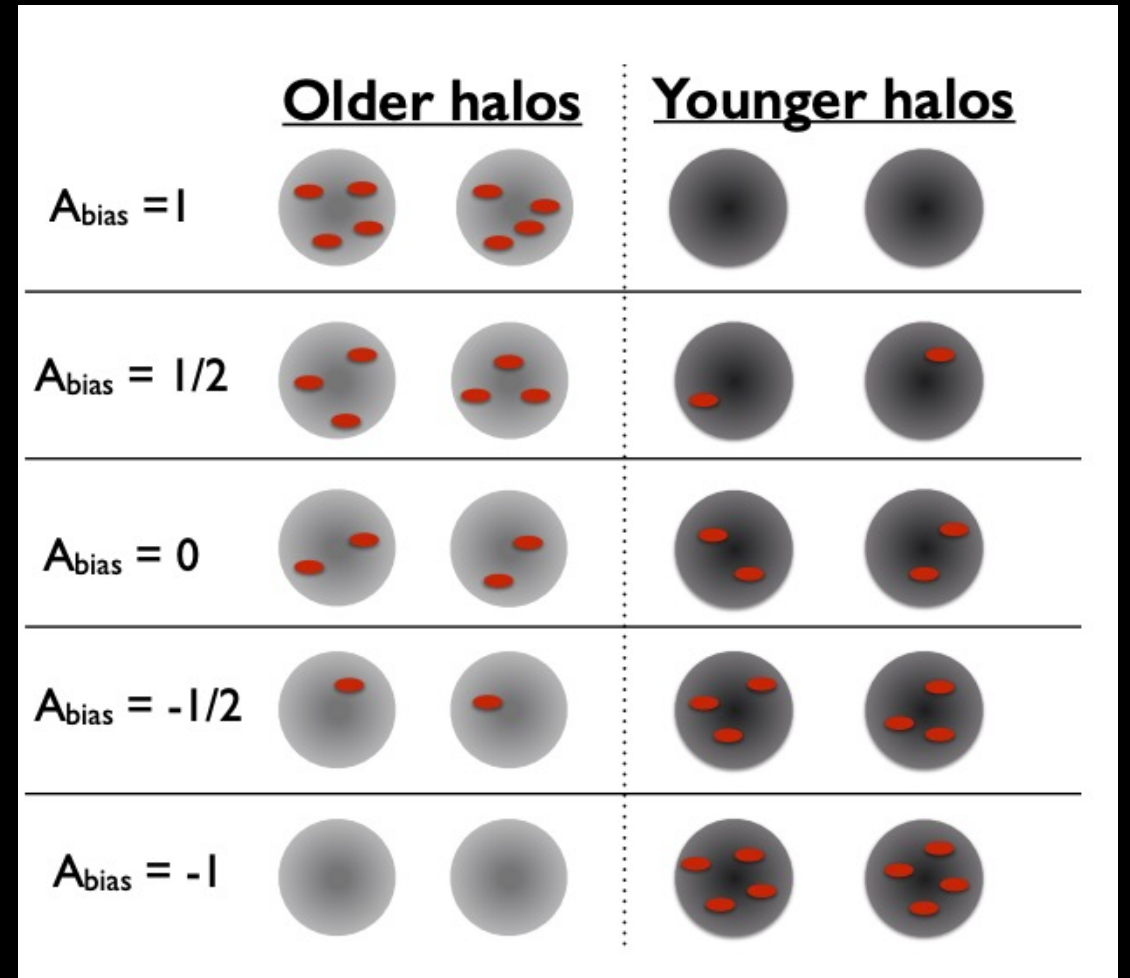
Constraining the Galaxy-Halo Connection with Optimal Statistics

- Major shifts seen in best-fit parameter values compared to previous results
 - Shifts probably due to the inclusion of clustering statistics that are sensitive to non-standard effects (e.g. assembly bias)
 - Comparisons with hydro simulations indicate presence of these effects, particularly among low-luminosity galaxies
- Major increase in constraining power
 - $>4\sigma$ tension for both samples



Decorated HOD Model

- Expanded standard HOD model from to include parameters for **central and satellite galaxy assembly bias (A_{cen} & A_{sat})**
- “Decorated HOD” model from Hearin et al. (2016)
- Galaxies are assigned to halos based on both halo mass and a secondary halo property
 - e.g. age, **concentration, environment**
- Identify a new set of optimal clustering measurements to constrain this model

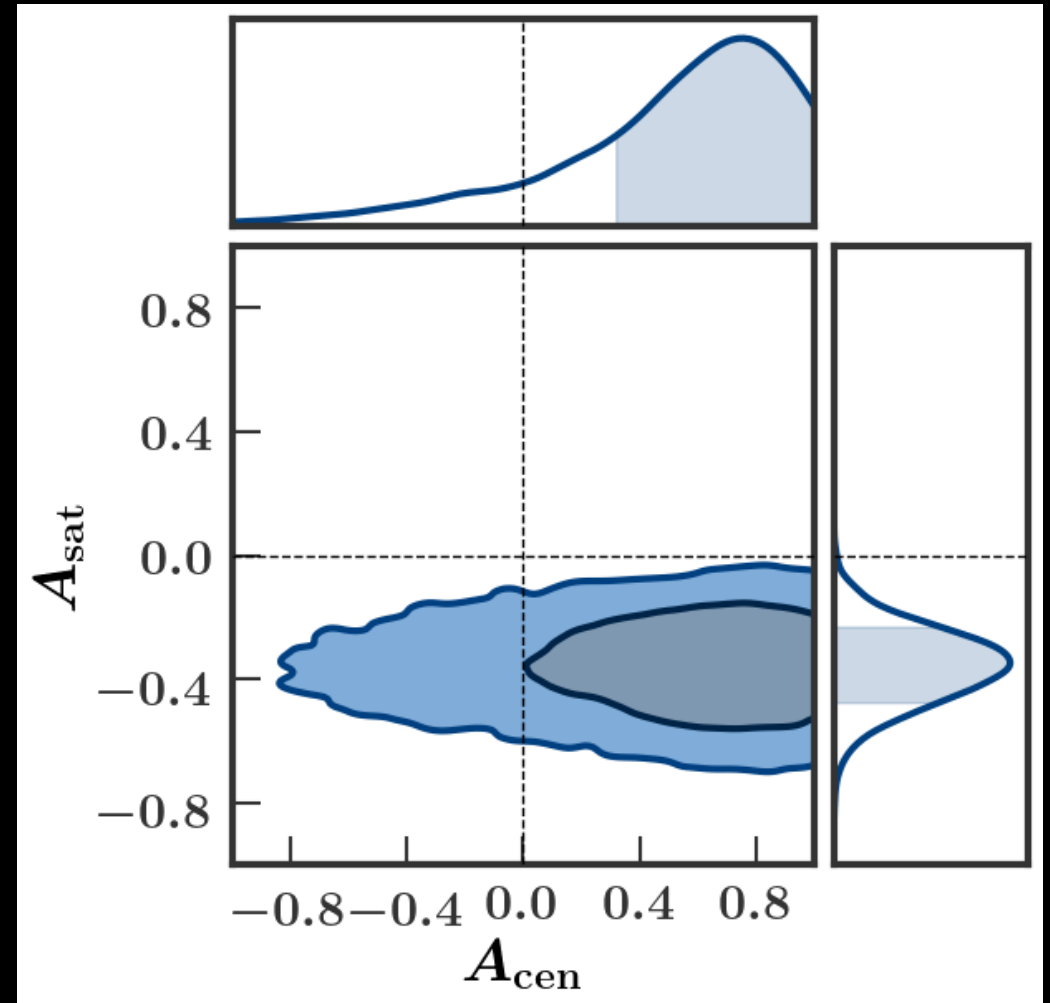
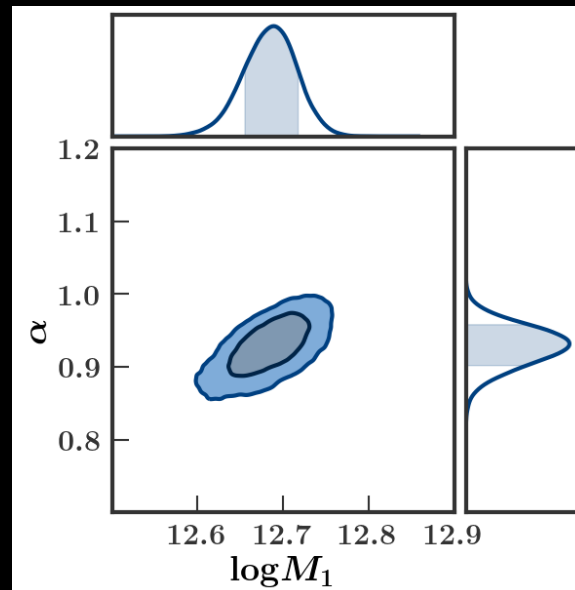
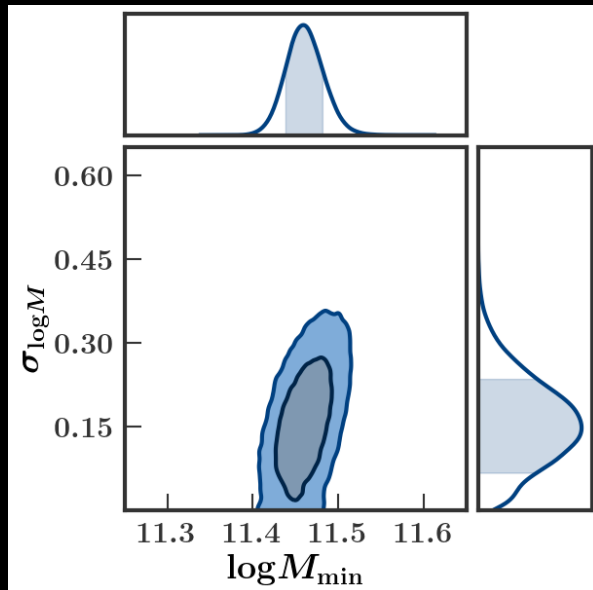


Hearin et al. (2016)

Results: Assembly Bias (Concentration)

-19 sample:

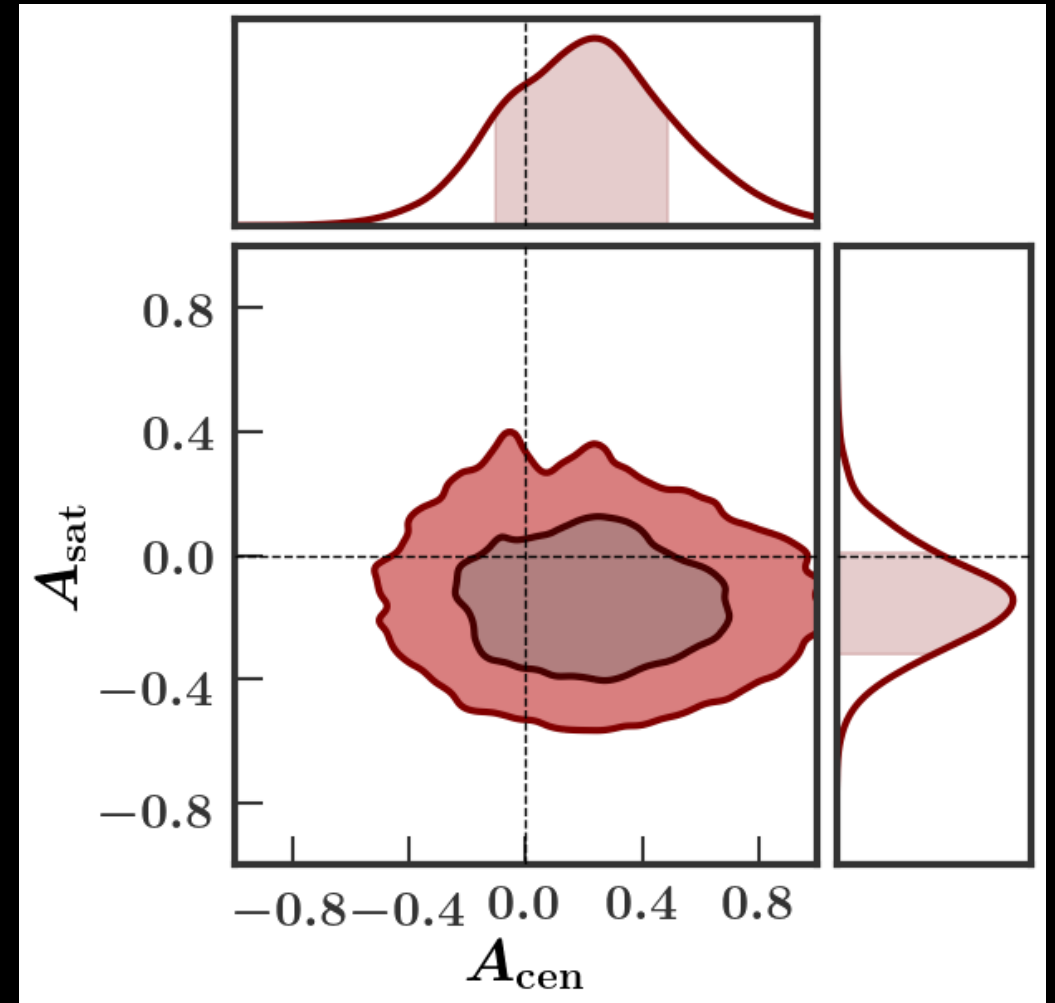
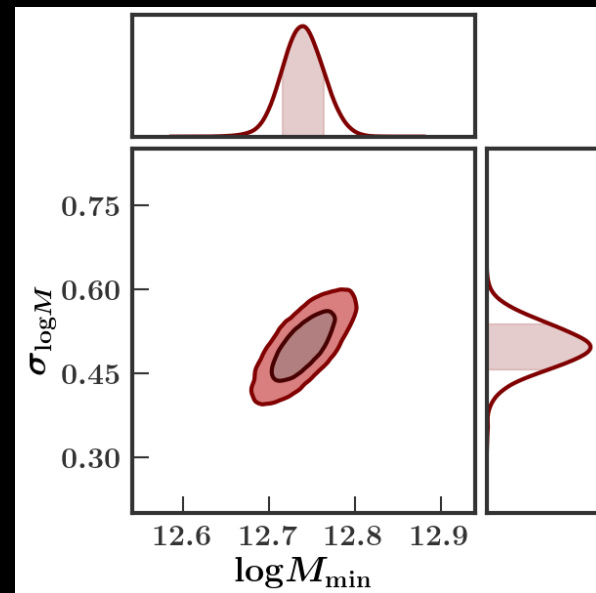
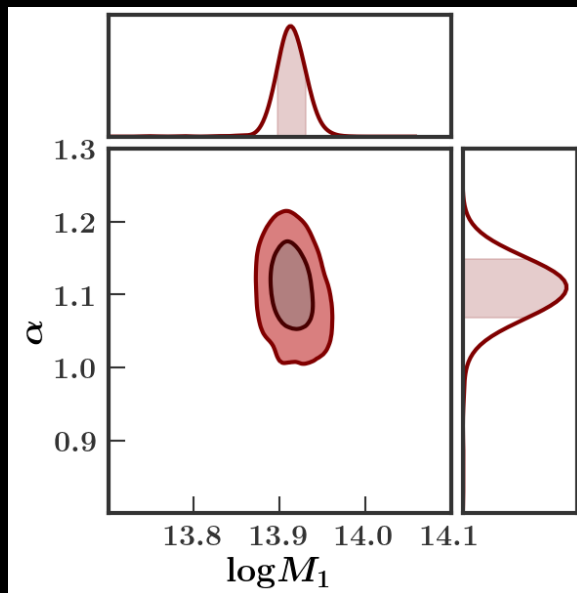
- Can rule out a model with zero assembly bias
- Evidence for negative satellite assembly bias at the 99.8% confidence level
- Improvement in tension with SDSS (4σ to 2σ)



Results: Assembly Bias (Concentration)

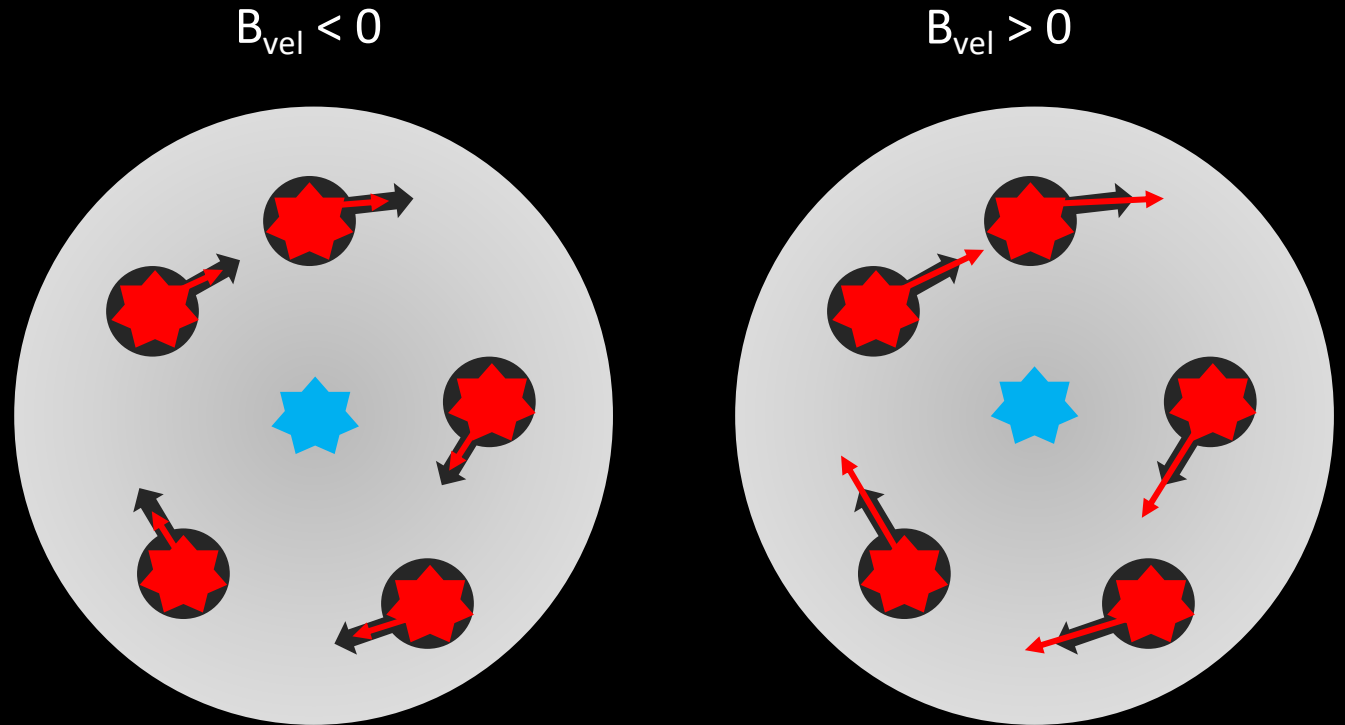
-21 sample:

- No detection of central or satellite assembly bias
- No improvement in tension with SDSS (4.5σ)



Satellite Galaxy Velocity Bias

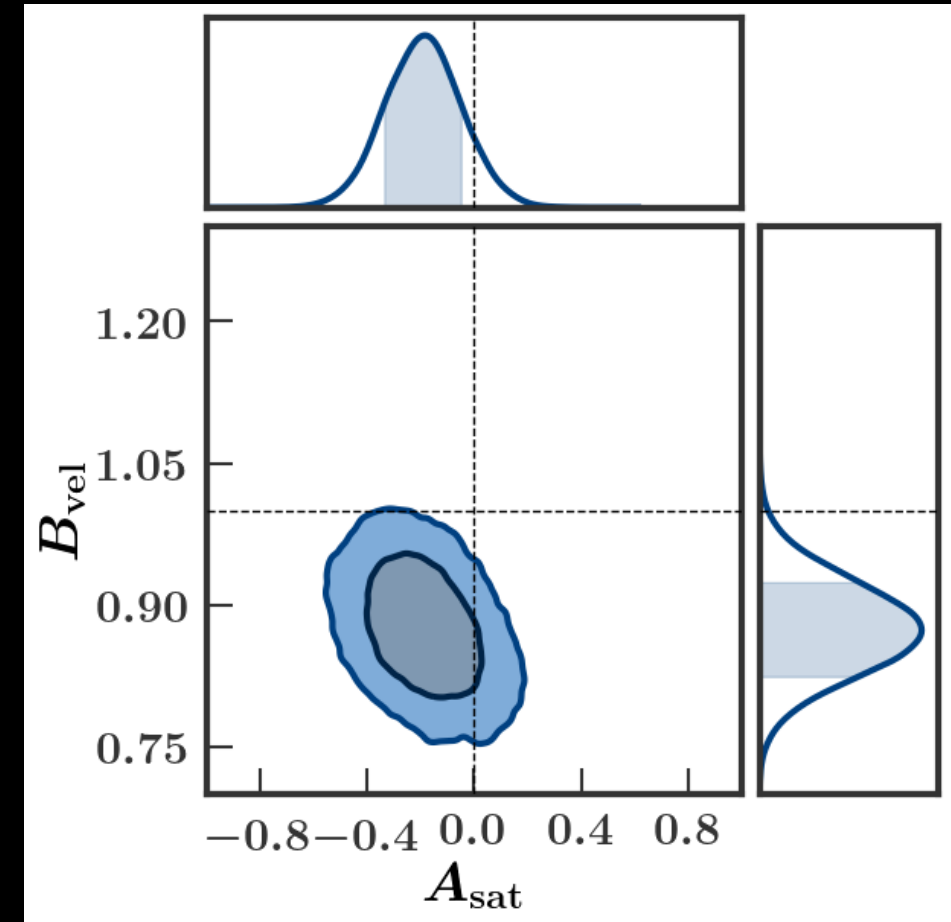
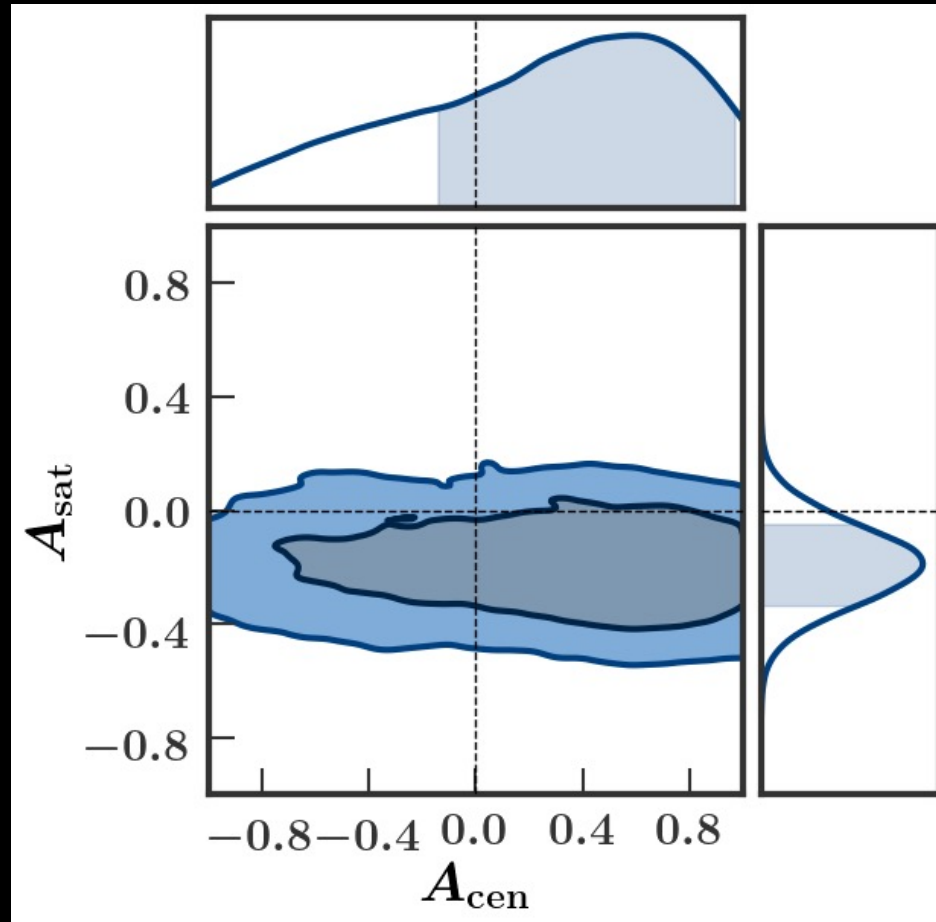
- Added parameter for **satellite galaxy velocity bias**, B_{vel}
- Indicates how much faster or slower galaxies move relative to dark matter
- Central galaxy still at rest with respect to halo (no central velocity bias)
- No spatial bias
- Did not identify new optimal clustering statistics



Results: Assembly Bias (Concentration) + Velocity Bias

-19 sample:

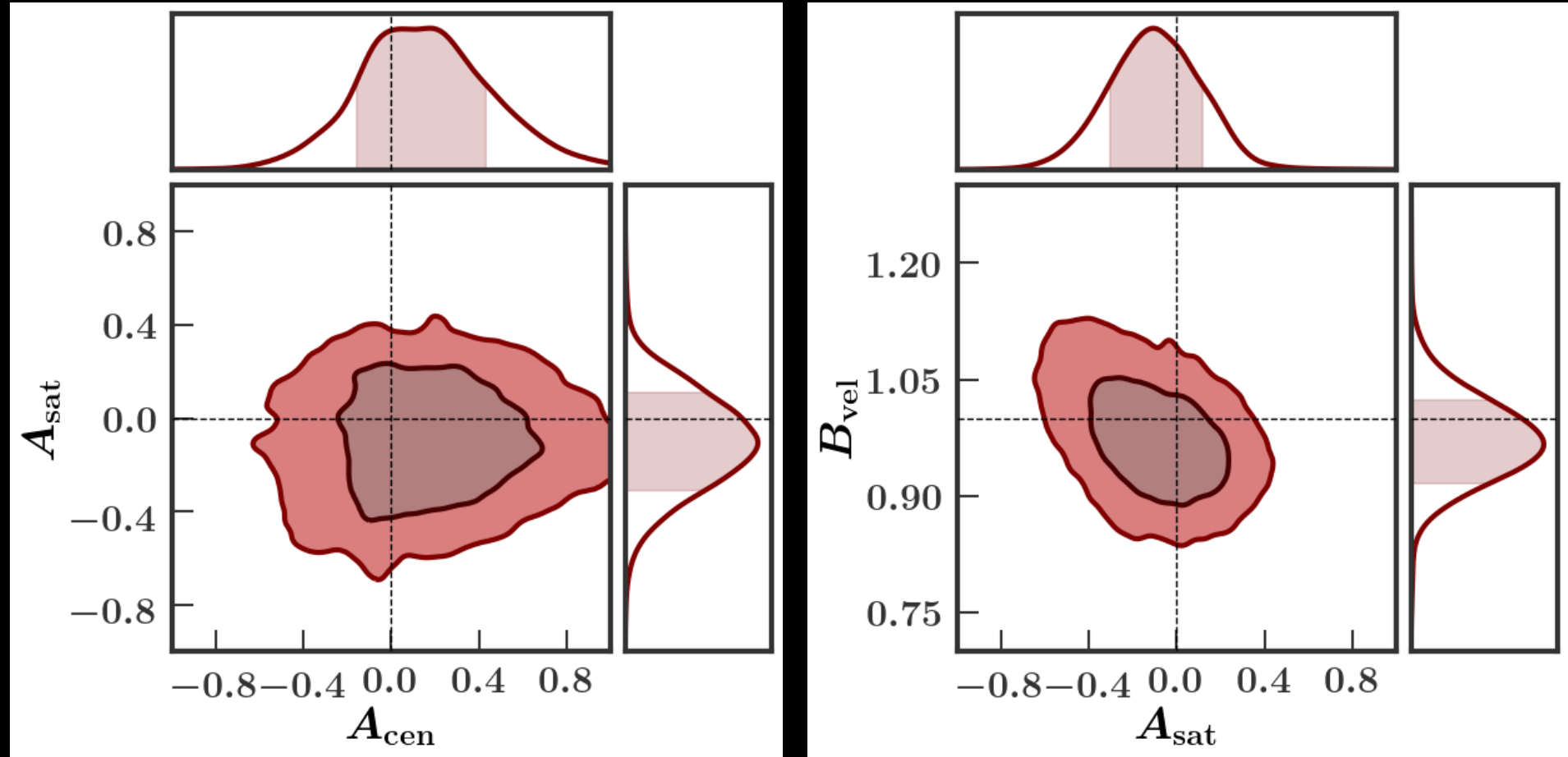
- Weaker constraints on A_{cen} & A_{sat}
- Detect moderate satellite velocity bias at the 99.8% confidence level
- Further improvement in tension with SDSS ($< 2\sigma$)



Results: Assembly Bias (Concentration) + Velocity Bias

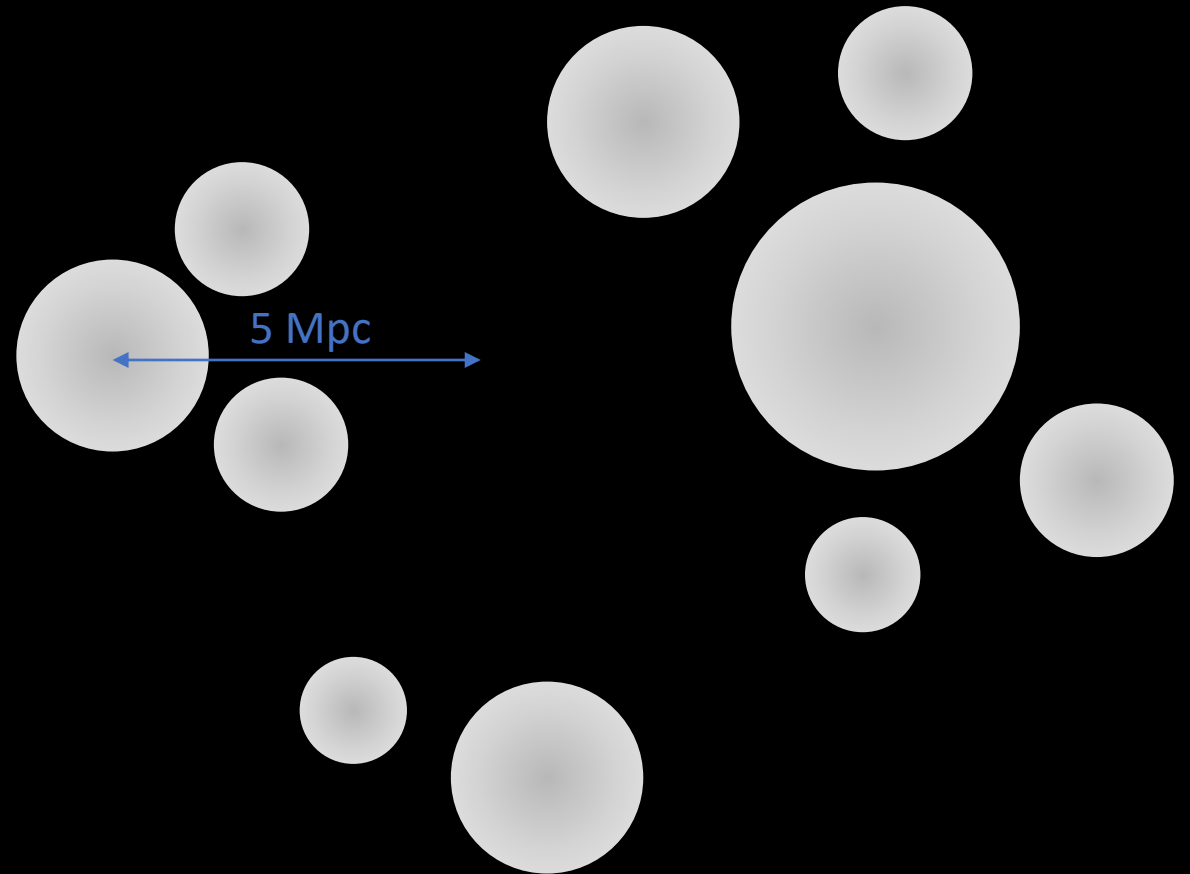
-21 sample:

- No detection of assembly bias or velocity bias
- No relief of tension with SDSS (still 4.5σ)



Assembly Bias – Local Halo Environment

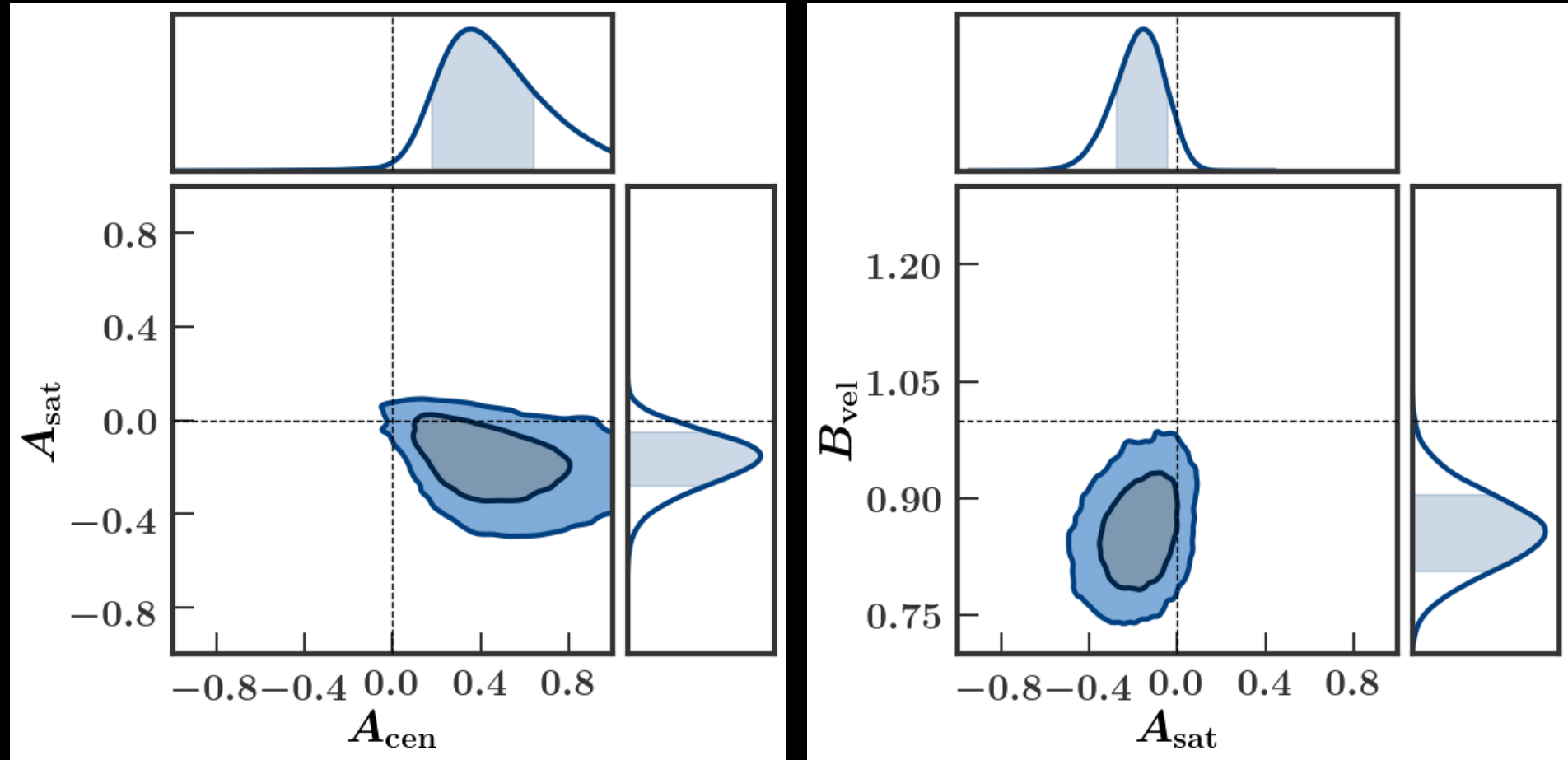
- New assembly bias property: **local halo environment**
- Note: we are not claiming that environment is the **cause** of assembly bias, but rather that the **true** assembly bias property correlates strongly with environment
- Mass (in halos) in 5 Mpc/h region around halo
- Did not identify new optimal clustering statistics



Results: Assembly Bias (Environment) + Velocity Bias

-19 sample:

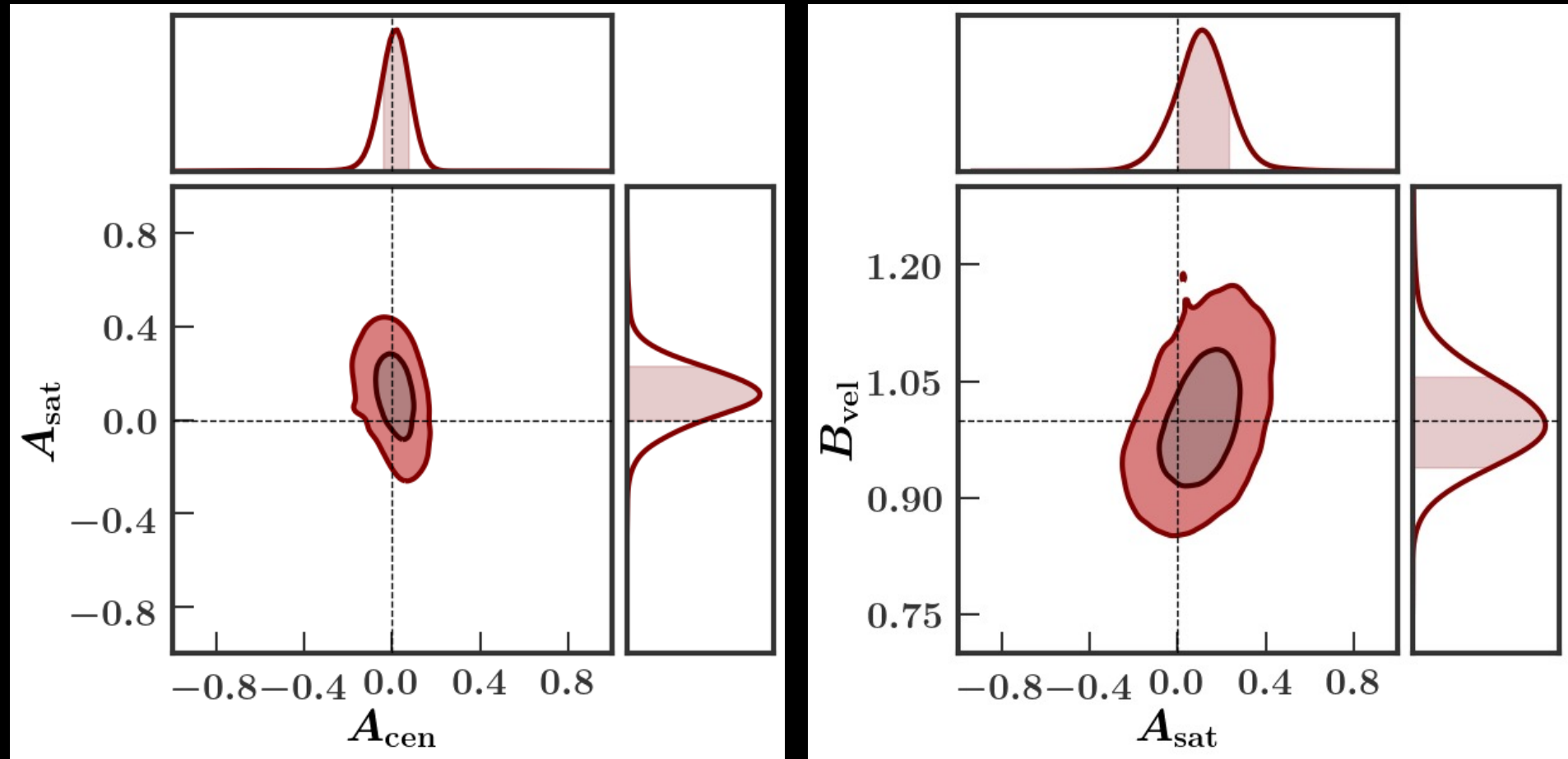
- Tight constraints on A_{cen} , A_{sat} , & B_{vel}
- Detect central and satellite assembly bias at the 99% and 95% confidence levels
- Detect satellite velocity bias at the 99.9% confidence level
- No remaining tension with SDSS



Results: Assembly Bias (Environment) + Velocity Bias

-21 sample:

- No detection of assembly bias or velocity bias
- No relief of tension with SDSS (still 4.5σ)



Conclusions

- Low-luminosity galaxies in SDSS exhibit central and satellite galaxy assembly bias, as well as satellite velocity bias
 - Best fitting model uses environment-based assembly bias
 - Satellite galaxies preferentially reside in less dense environments (95%)
 - Central galaxies preferentially reside in denser environments (99%)
 - Satellite galaxies move 10-15% slower than the dark matter (99.9%)
 - Essentially no remaining tension with SDSS
- High-luminosity galaxies exhibit negligible assembly bias when using either concentration or local environment as the assembly bias property
 - They also exhibit negligible satellite velocity bias
 - None of these models yield good agreement with SDSS (4.5σ tension)
- These results are consistent with comparisons to hydrodynamic simulations (e.g., Beltz-Mohrmann et. al 2020)
- Tension in -21 sample is potentially indicative of an issue with our cosmological model
 - This would be consistent with several recent works that have found tension between their best-fit cosmological parameters and Planck (e.g. Zhai et al. 2022, Lange et al. 2022)

Best-fit results

Table 5. SDSS best-fit results for different halo models

M_r^{lim}	Model	Obs.	$\log M_{\text{min}}$	$\sigma_{\log M}$	$\log M_0$	$\log M_1$	α	A_{cen}	A_{sat}	B_{vel}	p-value
-19	Standard HOD	S22	11.445	0.099	11.651	12.703	0.958	–	–	–	$6.8 \cdot 10^{-6}$
	ABcon	BM22	11.455	0.141	11.757	12.685	0.925	0.793	-0.368	–	0.047
	ABcon + VB	BM22	11.474	0.132	11.877	12.715	0.950	0.825	-0.251	0.898	0.155
	ABenv + VB	BM22	11.490	0.125	11.855	12.783	0.985	0.533	-0.224	0.826	0.364
-21	Standard HOD	S22	12.728	0.467	9.015	13.929	1.112	–	–	–	$3.5 \cdot 10^{-5}$
	ABcon	BM22	12.774	0.554	9.447	13.926	1.067	-0.090	-0.240	–	$2.6 \cdot 10^{-6}$
	ABcon + VB	BM22	12.756	0.525	9.804	13.915	1.108	0.144	-0.198	0.976	$1.8 \cdot 10^{-6}$
	ABenv + VB	BM22	12.740	0.495	9.984	13.917	1.079	-0.025	0.165	1.011	$4.1 \cdot 10^{-6}$

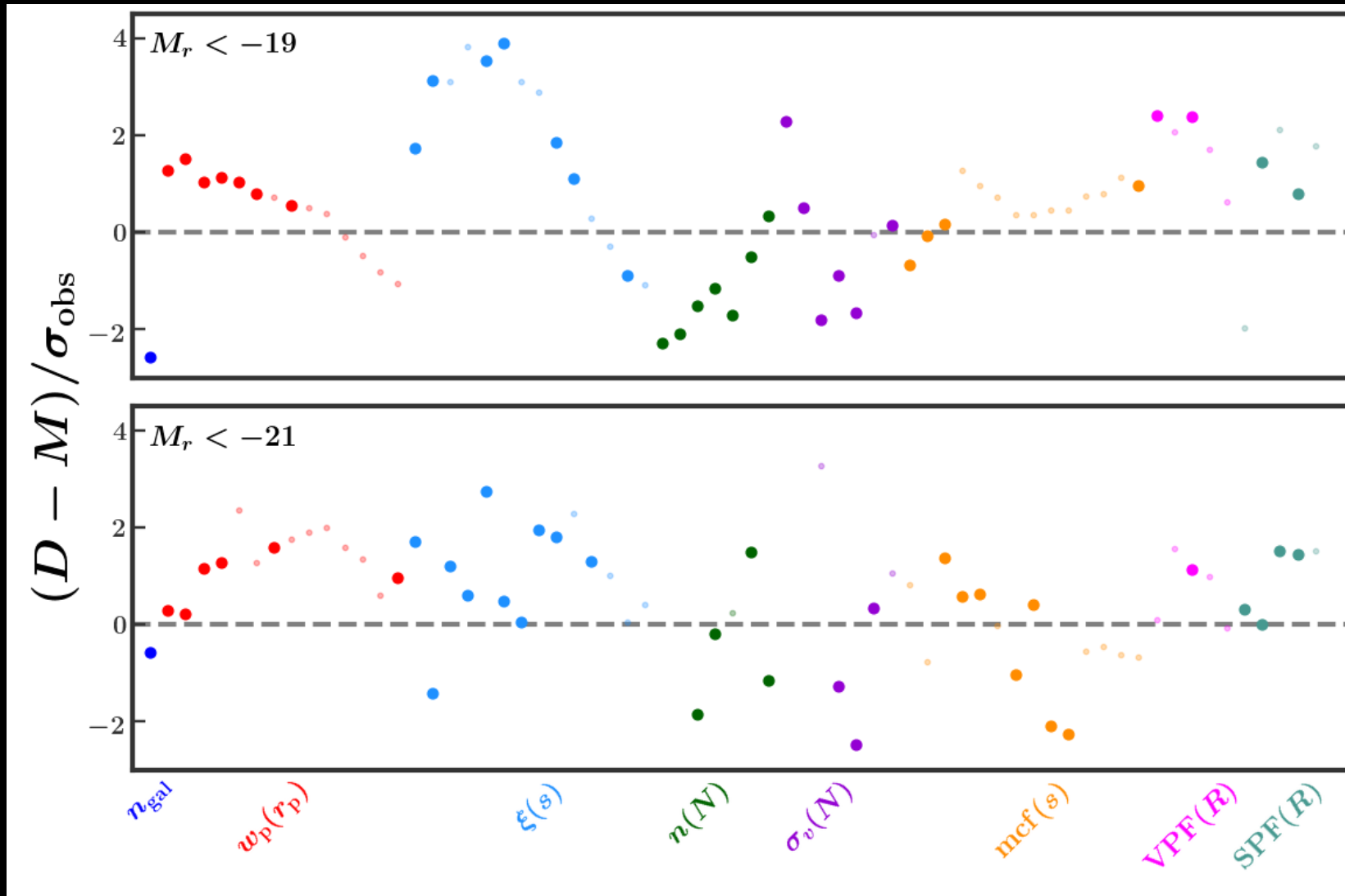
NOTE—Best-fit HOD parameters for each SDSS sample using four different models: the standard 5-parameter model, a model with concentration-based assembly bias (“ABcon”), a model with concentration-based assembly bias plus satellite velocity bias (“ABcon + VB”), and a model with environment-based assembly bias plus satellite velocity bias (“ABenv + VB”). The Standard HOD results are taken from S22 and thus use the S22 observables, while the chains using extended HOD models use the optimal observables identified in this work (listed in Table 4). We indicate the goodness-of-fit of each parameter combination with a p-value.

Optimal Clustering Measurements

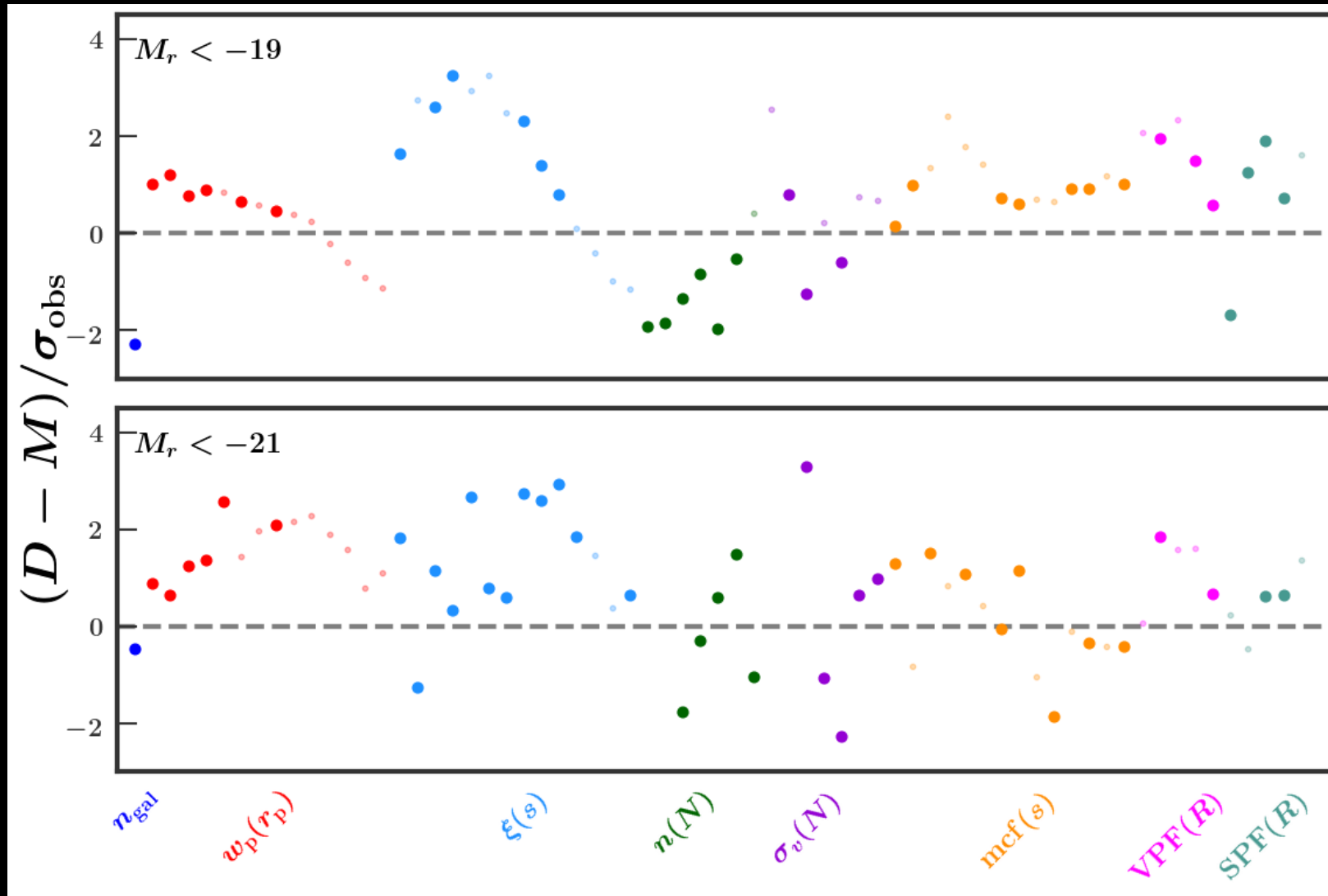
Index	-19 sHOD	-19 dHOD	-21 sHOD	-21 dHOD
1	n_{gal}	n_{gal}	n_{gal}	n_{gal}
2	$w_p(r_p)$ 2	$w_p(r_p)$ 2	$w_p(r_p)$ 2	$w_p(r_p)$ 2
3	$w_p(r_p)$ 4	$\sigma_v(N)$ 3	$\xi(s)$ 8	$\sigma_v(N)$ 1
4	VPF(R) 3	$\xi(s)$ 8	$w_p(r_p)$ 4	$\xi(s)$ 9
5	$w_p(r_p)$ 8	$n(N)$ 3	mcf(s) 9	$\xi(s)$ 3
6	$\xi(s)$ 1	SPF(R) 1	$w_p(r_p)$ 1	mcf(s) 10
7	$n(N)$ 3	$w_p(r_p)$ 3	$\xi(s)$ 9	$w_p(r_p)$ 5
8	$\xi(s)$ 5	$n(N)$ 2	mcf(s) 7	$n(N)$ 1
9	$n(N)$ 2	$w_p(r_p)$ 8	$\xi(s)$ 4	$\sigma_v(N)$ 3
10	$n(N)$ 4	$\xi(s)$ 1	$\xi(s)$ 7	mcf(s) 3
11	$n(N)$ 1	$w_p(r_p)$ 4	mcf(s) 10	$\xi(s)$ 1
12	SPF(R) 4	VPF(R) 2	$\xi(s)$ 1	$\xi(s)$ 8
13	$\xi(s)$ 13	mcf(s) 1	$w_p(r_p)$ 14	$\xi(s)$ 5
14	mcf(s) 14	$\xi(s)$ 10	$n(N)$ 1	$w_p(r_p)$ 1
15	$\xi(s)$ 6	SPF(R) 2	SPF(R) 4	$n(N)$ 2
16	$n(N)$ 5	$\xi(s)$ 4	mcf(s) 3	SPF(R) 4
17	$\xi(s)$ 2	$n(N)$ 1	$\xi(s)$ 6	mcf(s) 5
18	SPF(R) 2	$n(N)$ 5	$\sigma_v(N)$ 4	$\sigma_v(N)$ 4
19	$\xi(s)$ 10	$w_p(r_p)$ 1	$\xi(s)$ 5	mcf(s) 14
20	mcf(s) 2	SPF(R) 4	$\xi(s)$ 3	SPF(R) 3
21	mcf(s) 3	mcf(s) 7	$n(N)$ 4	$w_p(r_p)$ 3

22	$\sigma_v(N)$ 1	mcf(s) 11	$w_p(r_p)$ 7	$\sigma_v(N)$ 5
23	$\sigma_v(N)$ 3	$\sigma_v(N)$ 5	$w_p(r_p)$ 3	$\sigma_v(N)$ 2
24	$\xi(s)$ 9	SPF(R) 3	mcf(s) 8	$\xi(s)$ 7
25	$\sigma_v(N)$ 4	$\xi(s)$ 3	VPF(R) 3	$n(N)$ 3
26	mcf(s) 1	$n(N)$ 4	$\xi(s)$ 2	$n(N)$ 4
27	$\sigma_v(N)$ 2	mcf(s) 2	$n(N)$ 5	$\xi(s)$ 4
28	$n(N)$ 6	$\sigma_v(N)$ 2	$n(N)$ 2	$\xi(s)$ 2
29	VPF(R) 1	VPF(R) 4	$\xi(s)$ 11	$n(N)$ 5
30	$w_p(r_p)$ 1	mcf(s) 8	$\sigma_v(N)$ 3	$w_p(r_p)$ 8
31	$w_p(r_p)$ 6	$w_p(r_p)$ 6	$\sigma_v(N)$ 2	$w_p(r_p)$ 4
32	$w_p(r_p)$ 5	$\xi(s)$ 9	SPF(R) 2	$\xi(s)$ 6
33	$\sigma_v(N)$ 5	$n(N)$ 6	mcf(s) 5	mcf(s) 8
34	$w_p(r_p)$ 3	mcf(s) 14	SPF(R) 3	$\xi(s)$ 10
35	$\sigma_v(N)$ 7	VPF(R) 5	mcf(s) 4	$\xi(s)$ 11
36	$n(N)$ 7	mcf(s) 12	SPF(R) 1	mcf(s) 7
37	–	–	–	mcf(s) 12
38	–	–	–	$\xi(s)$ 14
39	–	–	–	VPF(R) 5
40	–	–	–	VPF(R) 2
41	–	–	–	mcf(s) 1

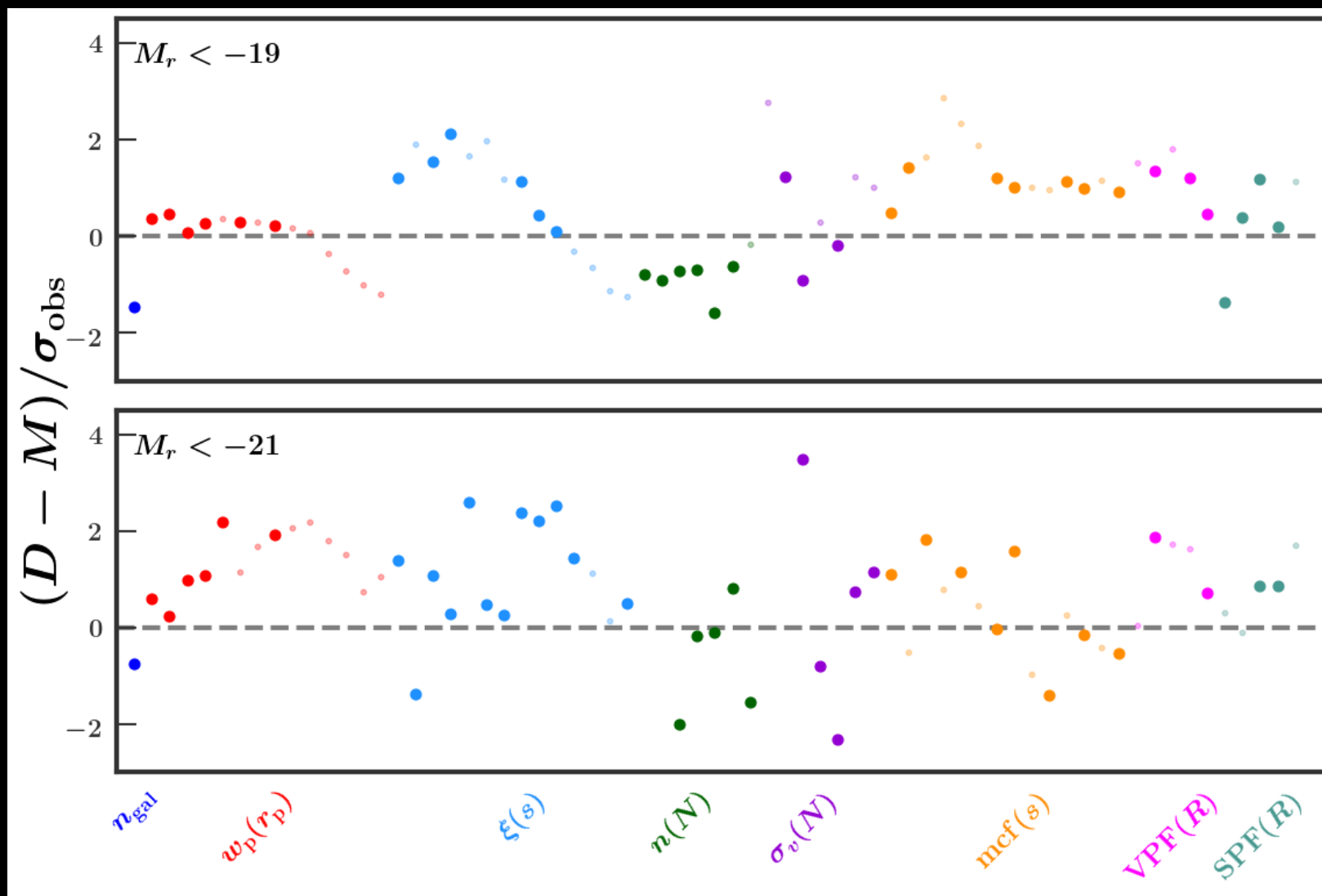
Results: Standard Model



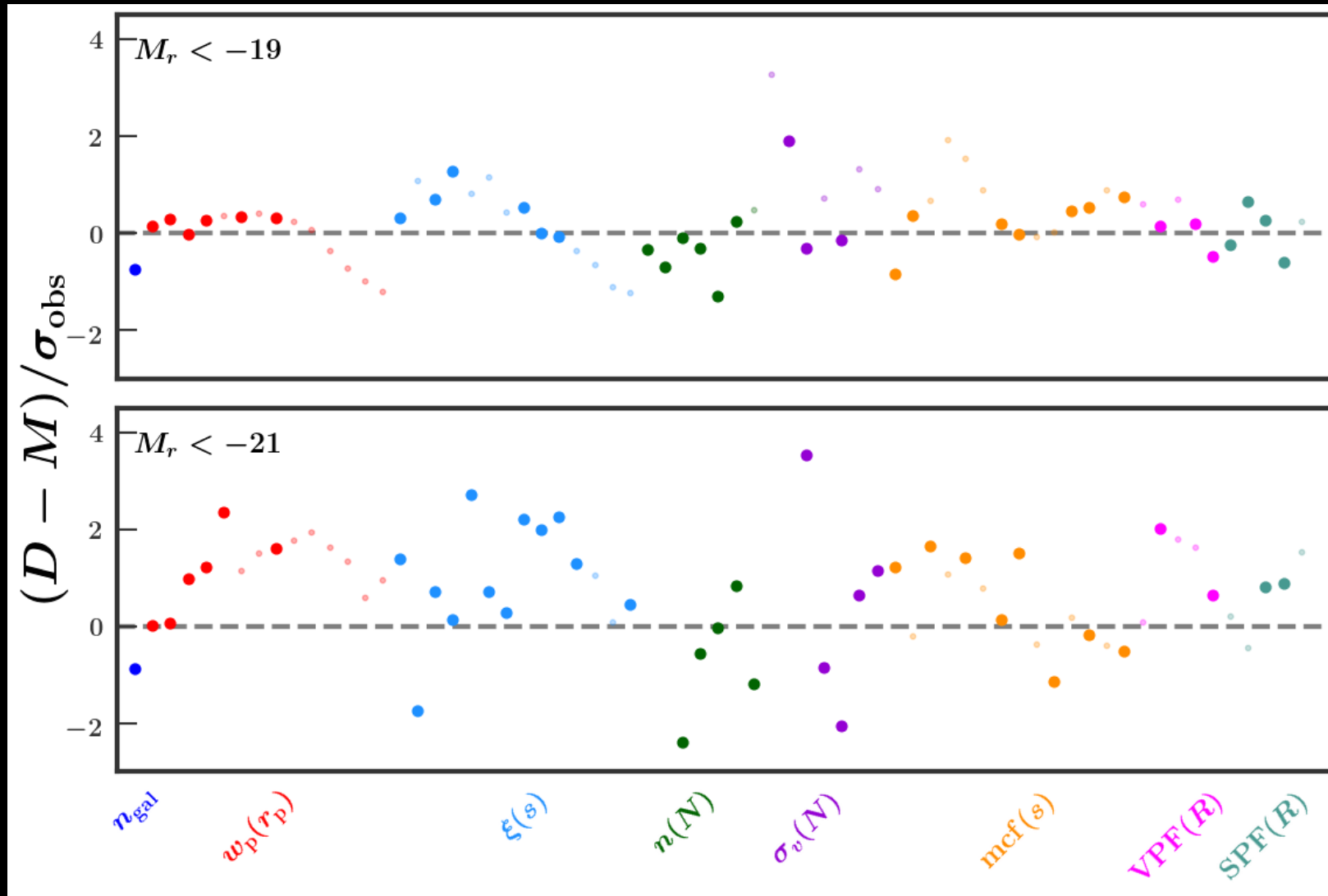
Results: Assembly Bias (Concentration)



Results: Assembly Bias (Concentration) + Velocity Bias

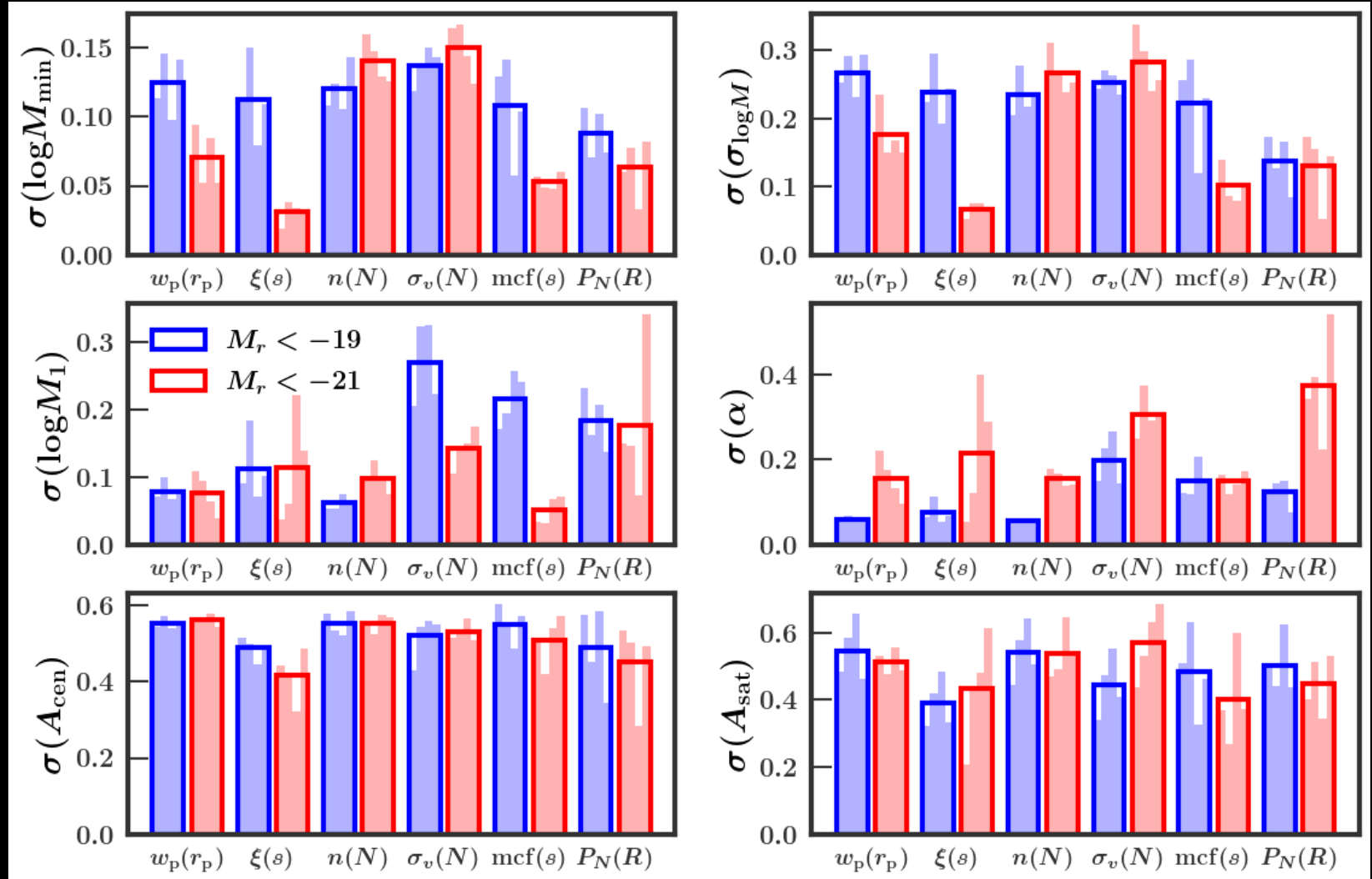


Results: Assembly Bias (Environment) + Velocity Bias

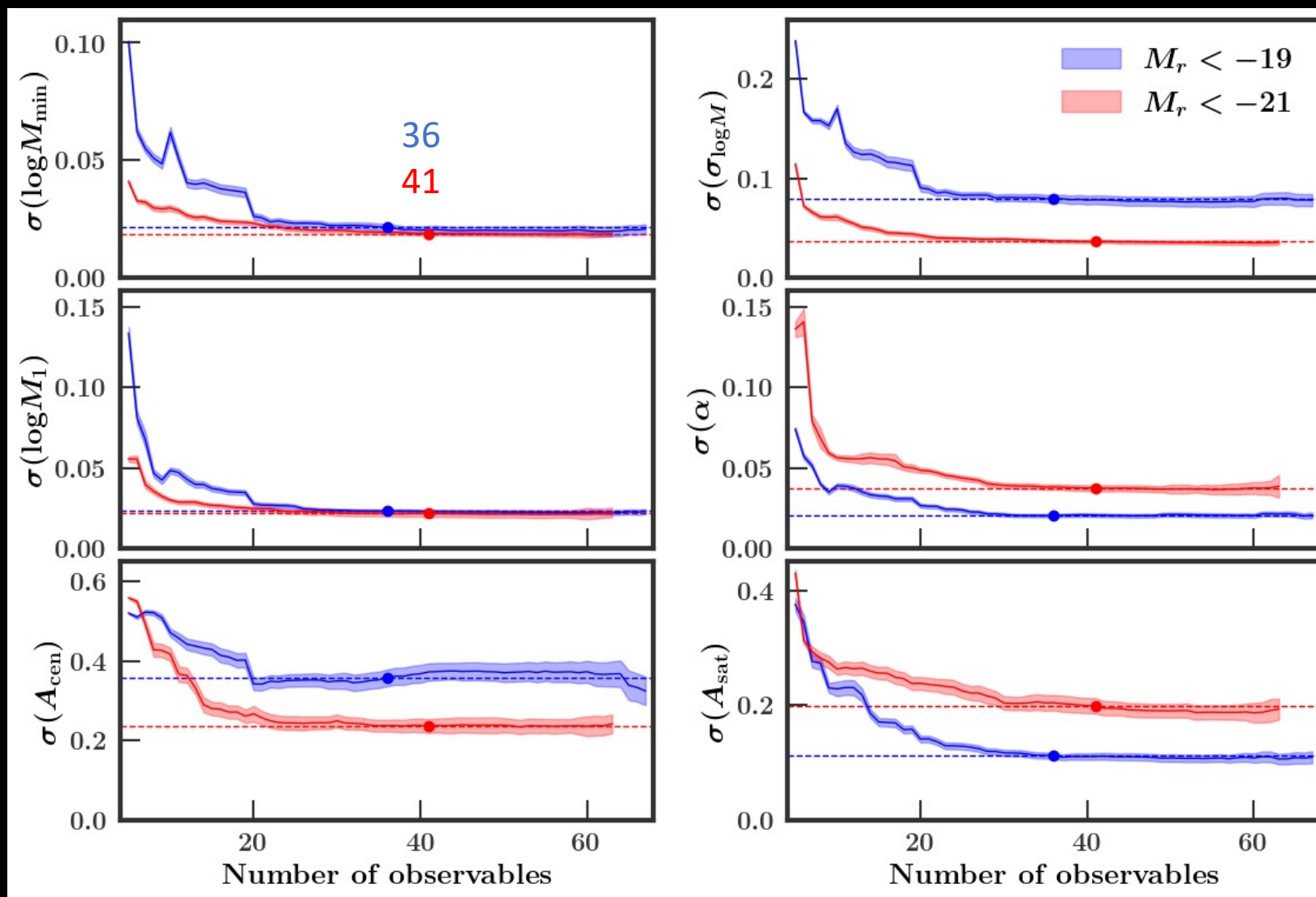


Identifying Optimal Clustering Statistics

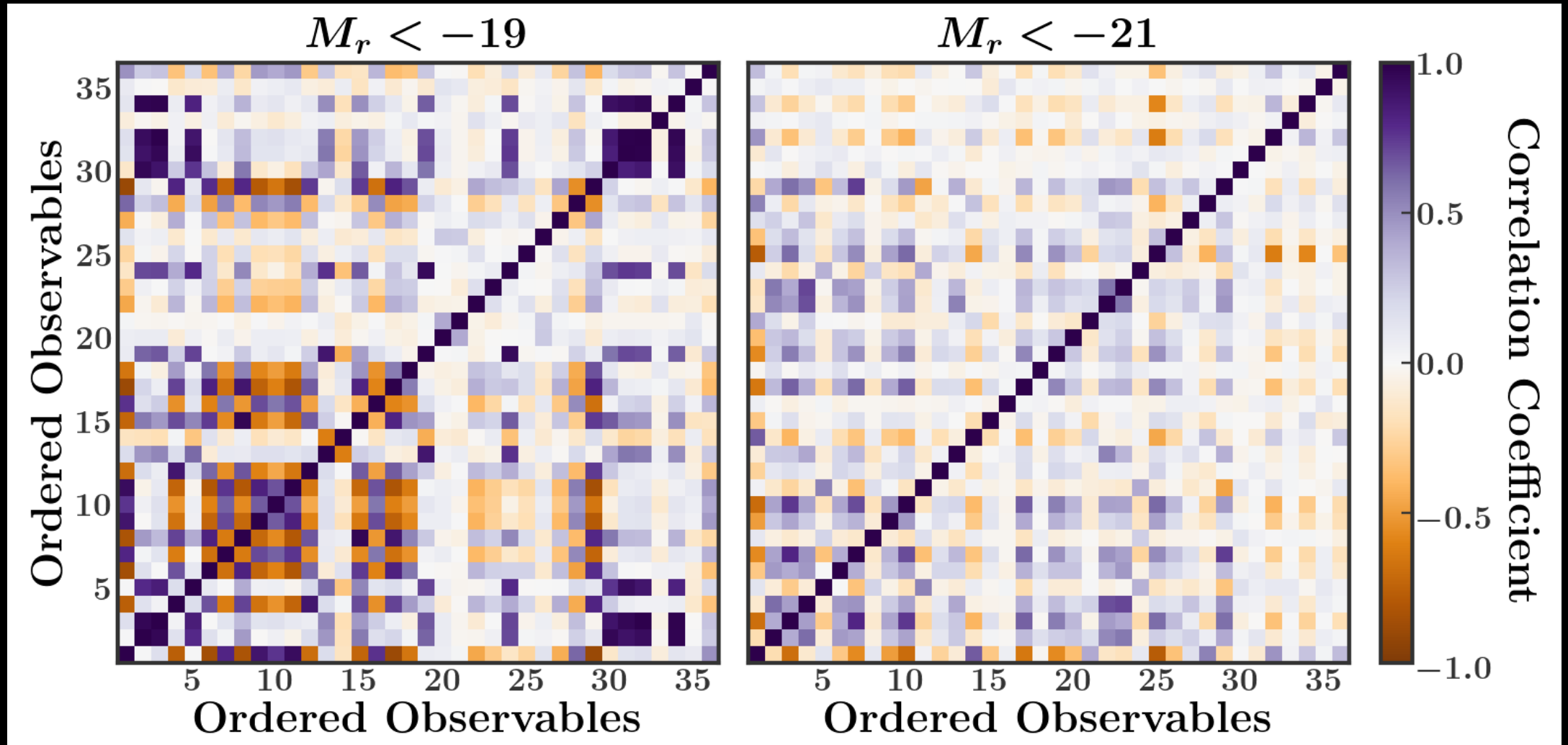
- Constraining power of each clustering statistic (plus number density) for each HOD parameter



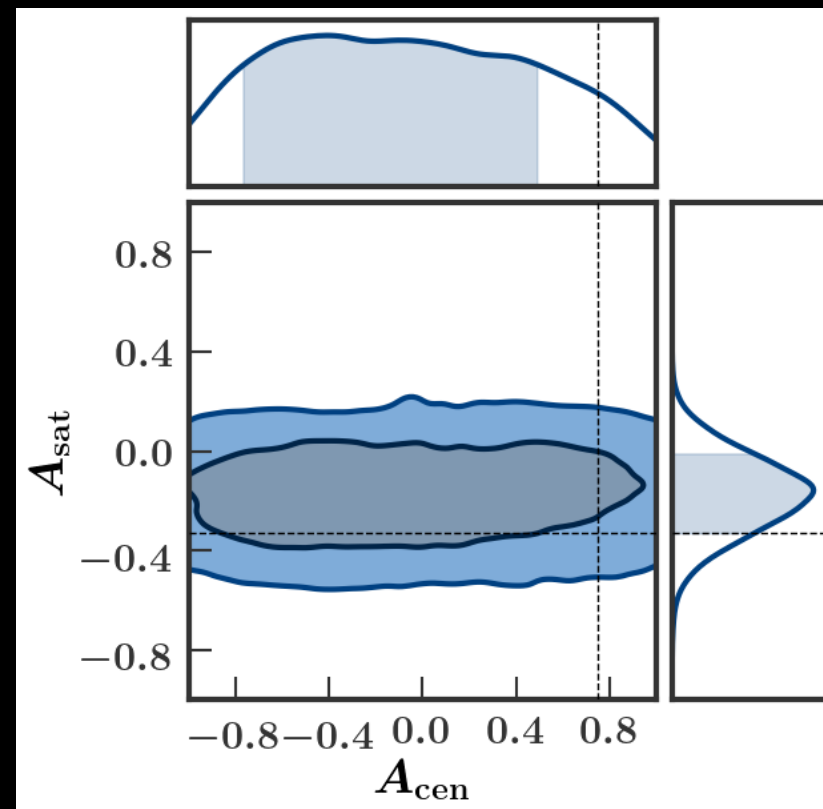
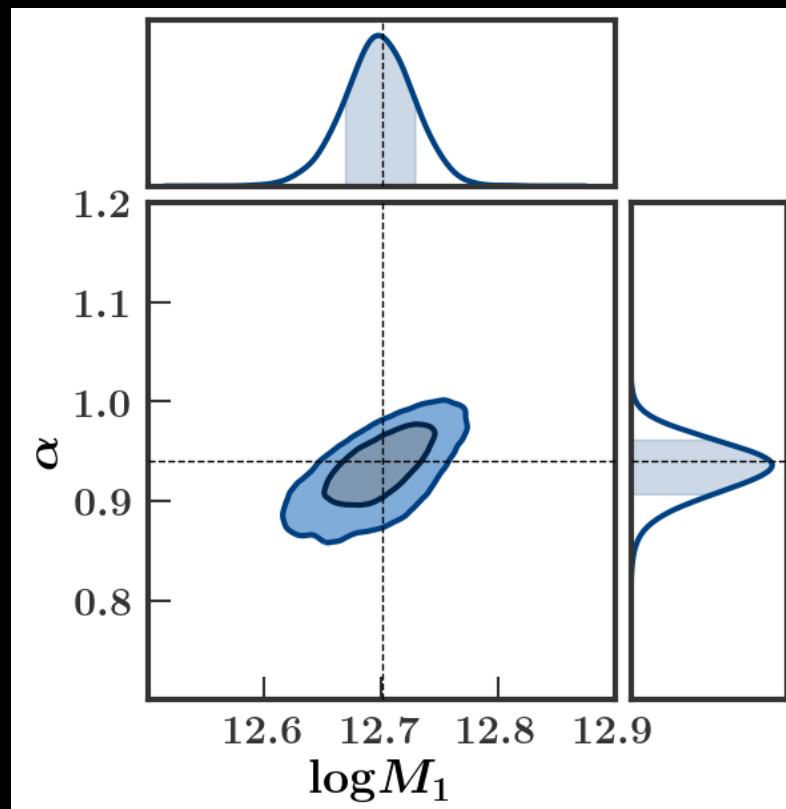
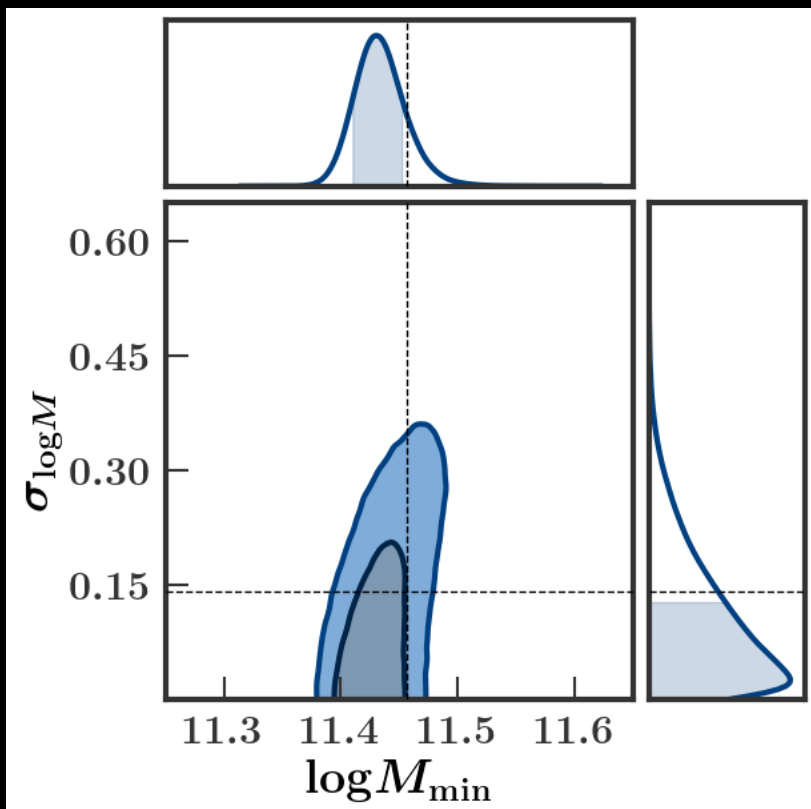
Identifying Optimal Clustering Statistics



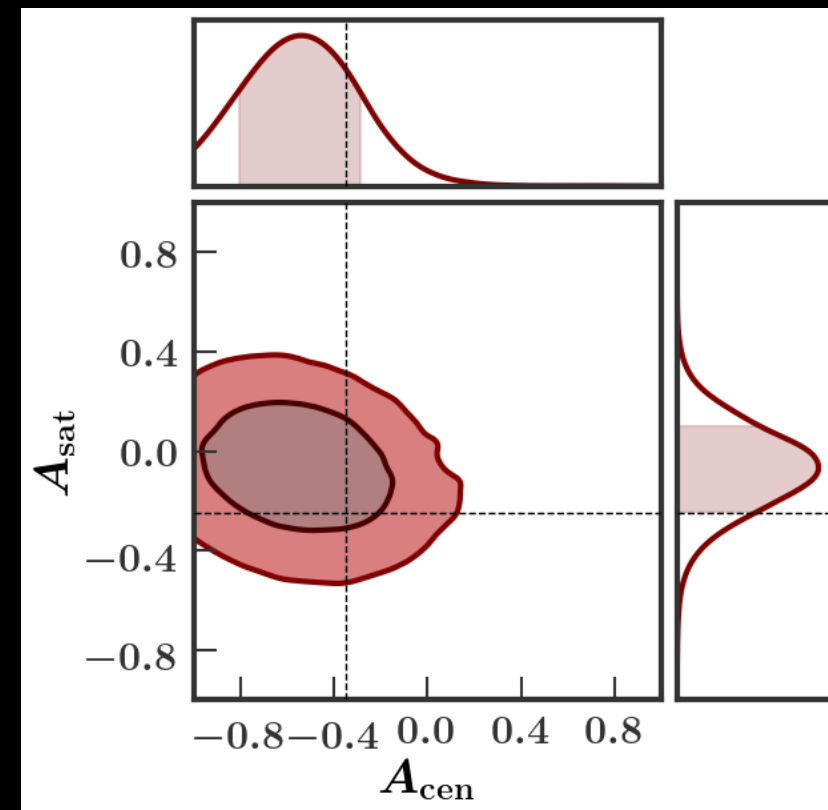
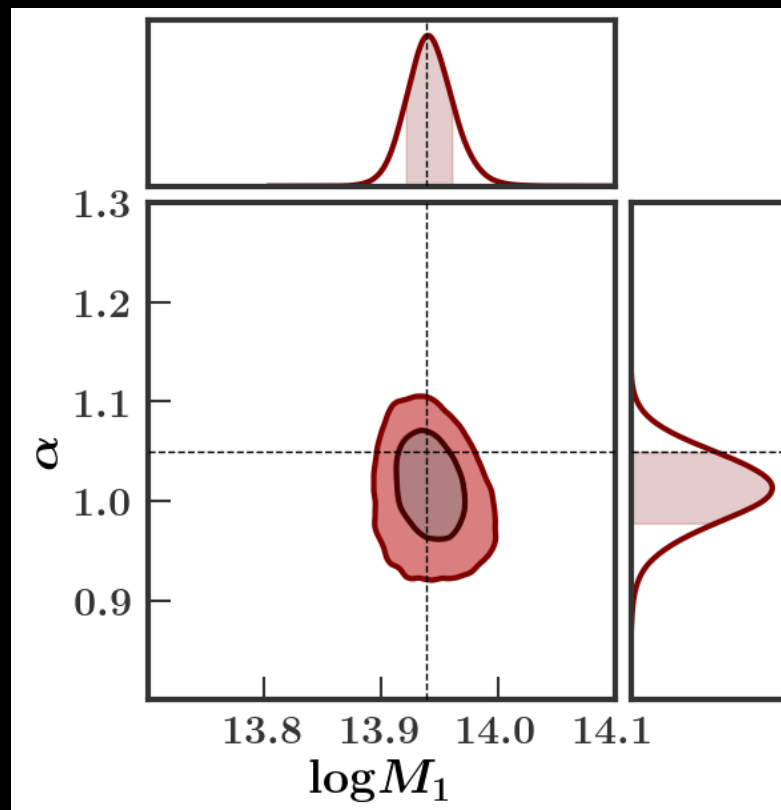
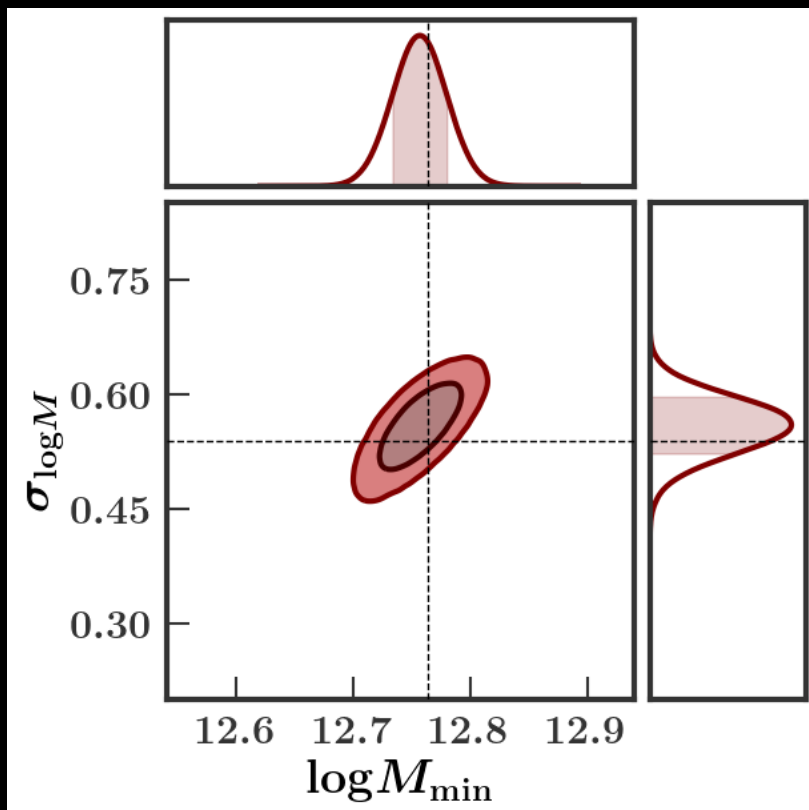
Mock-based Covariance Matrices



Mock Validation

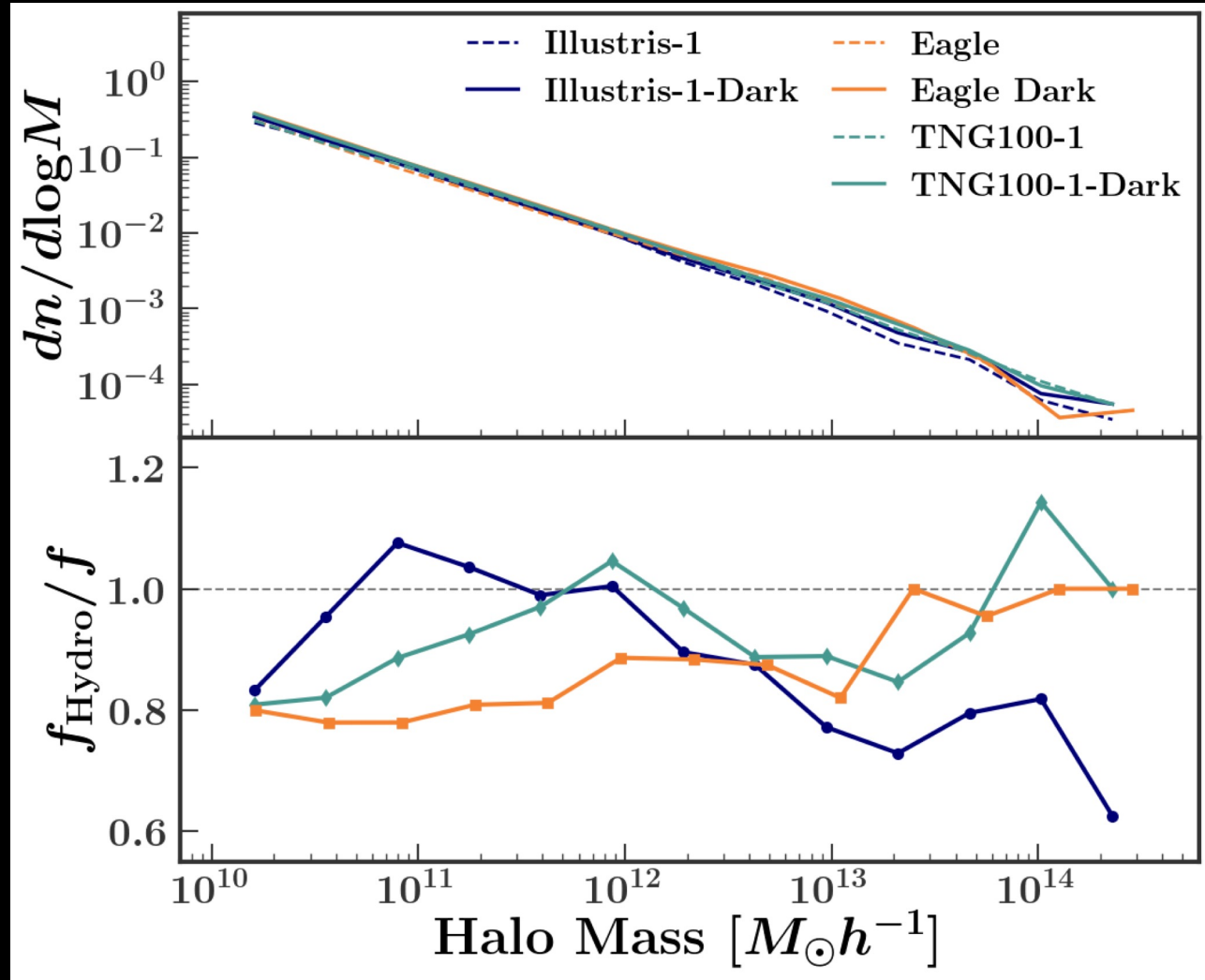


Mock Validation



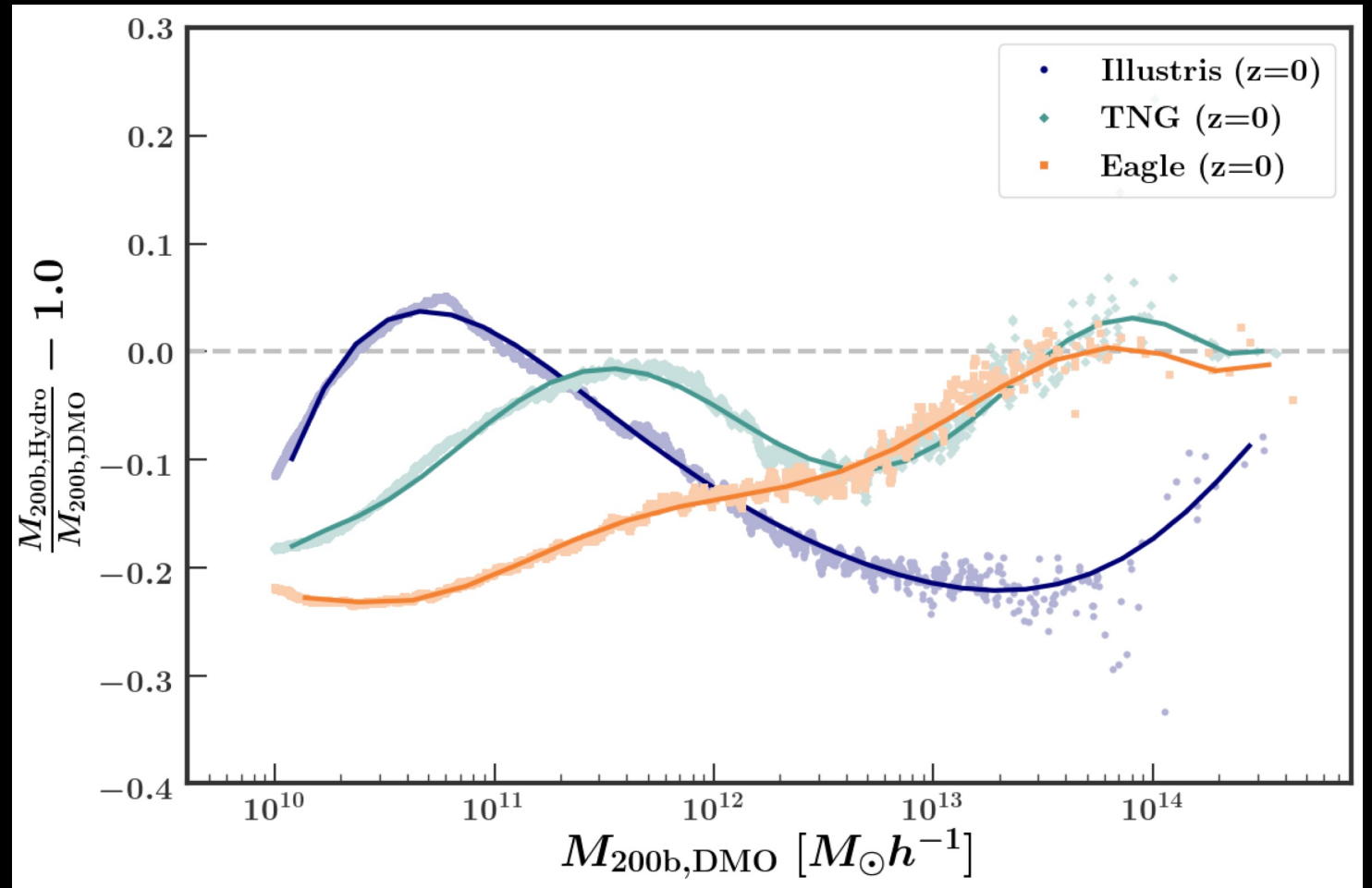
Correcting the halo mass function

- Halo mass function is shifted to lower masses in hydro compared to DMO due to baryonic physics



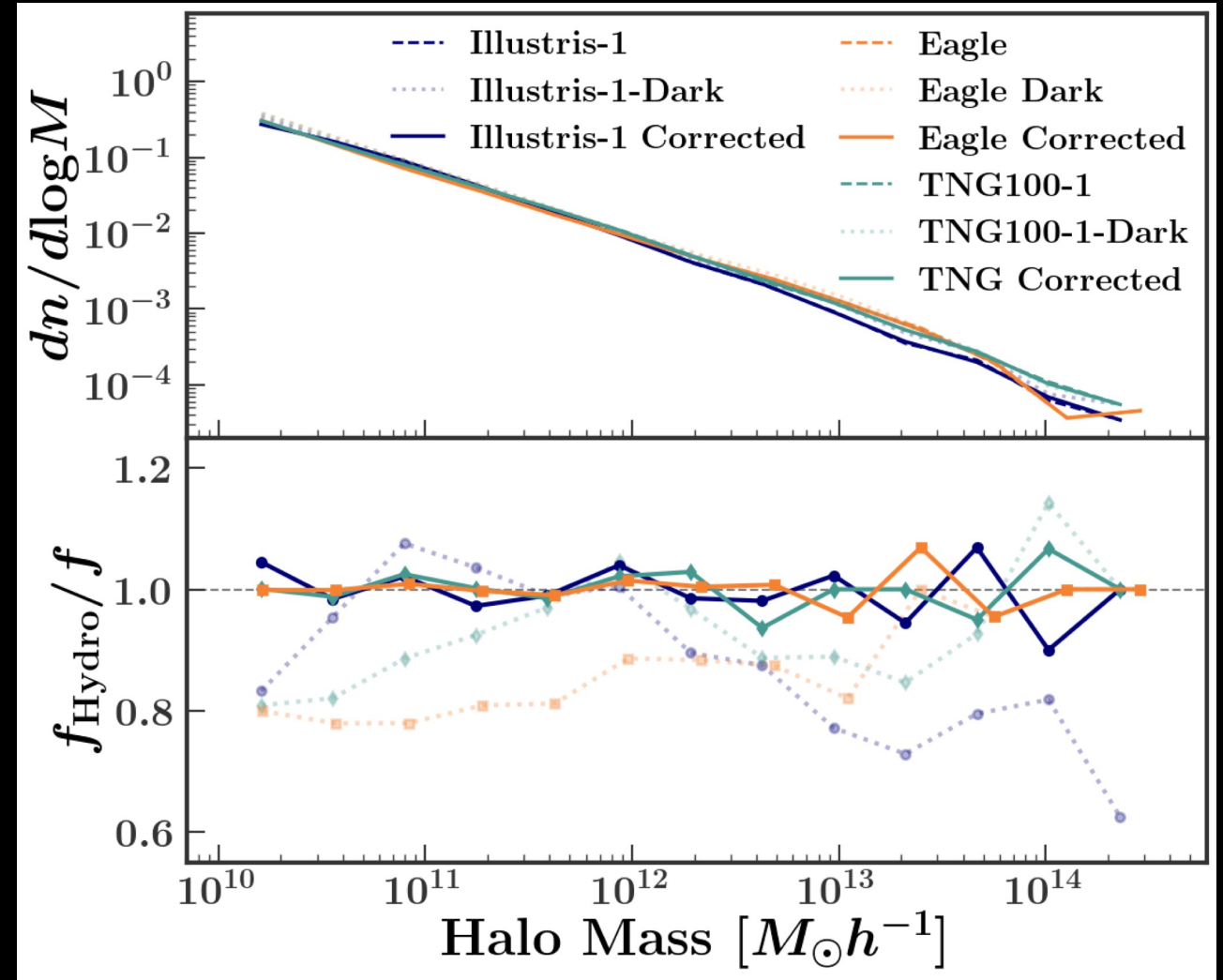
Halo Mass Corrections

- Match halos between DMO and hydro according to mass
- Use this relationship to correct DMO halo mass function



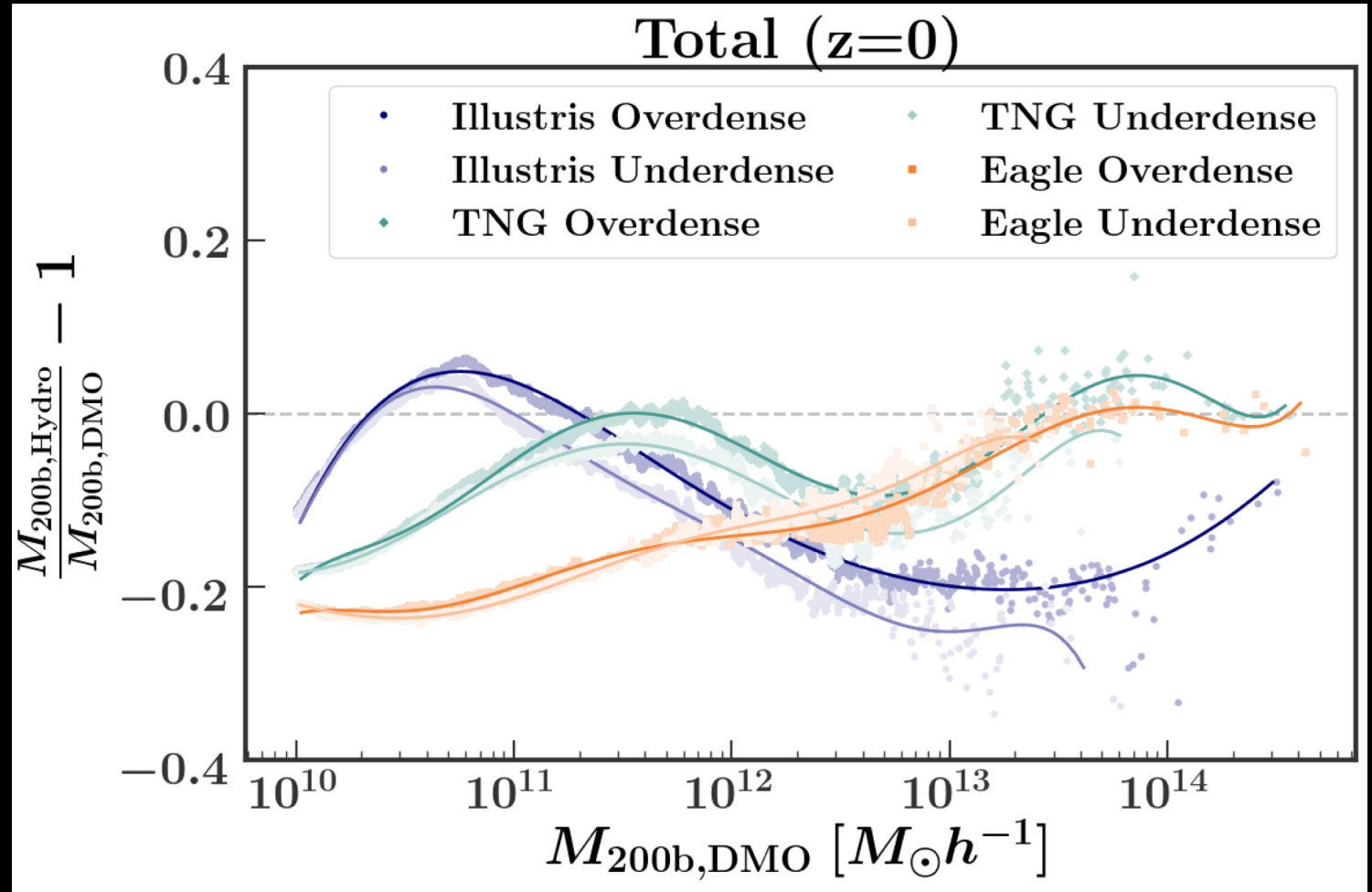
Halo Mass Corrections

- This correction accounts for the impact of baryonic physics on the mass function

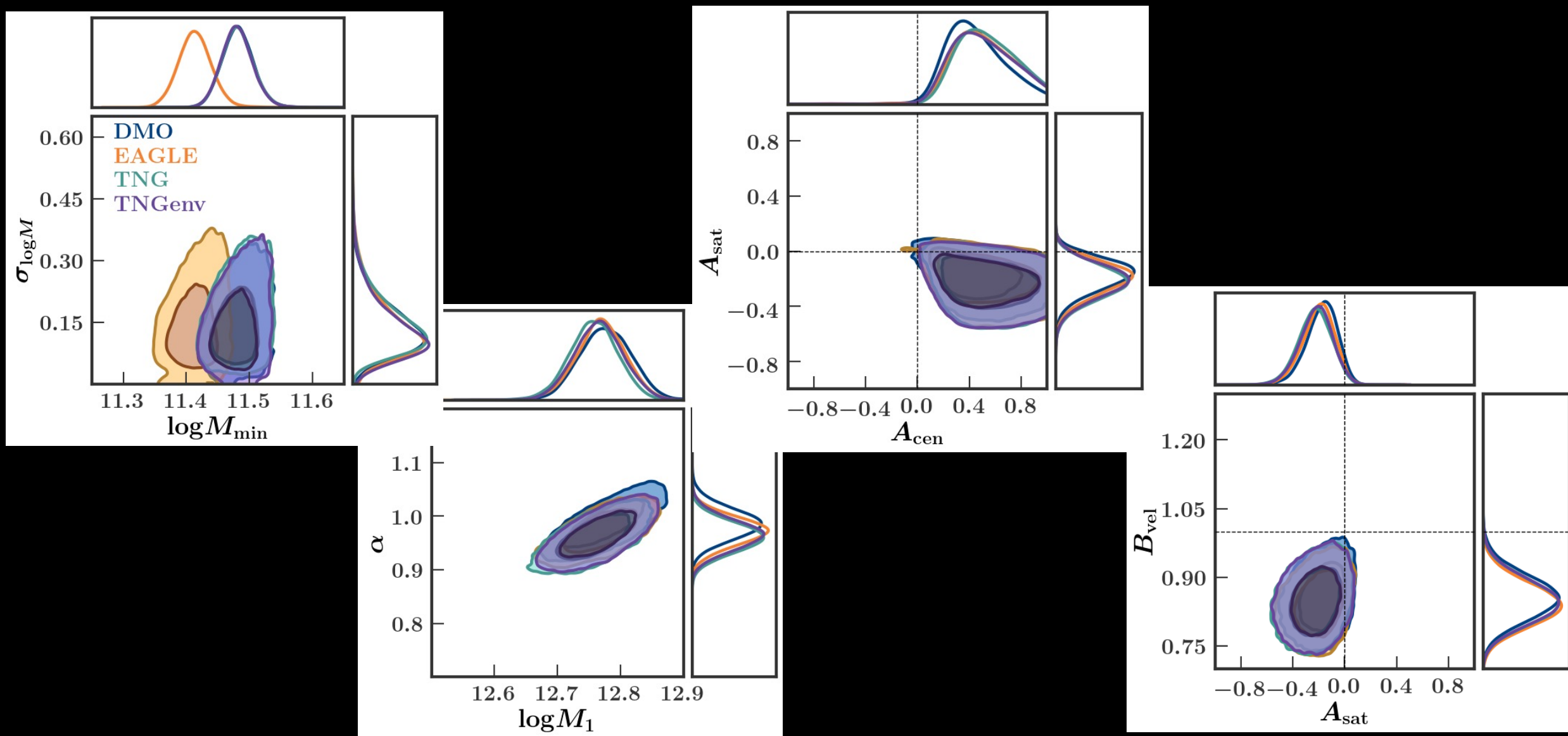


Halo Mass Corrections

- Match halos by mass and environment



Results: Halo Mass Corrections



Results: Halo Mass Corrections

