

Assembly Bias and the Application of the Galaxy-Halo Connection in Cosmological Studies

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What Is Assembly Bias

Halo assembly bias: the effect that the clustering of halos at fixed mass has a dependence on properties other than M_h .

Galaxy Assembly Bias: At fixed halo mass, the galaxy properties or number of galaxies within halos may depend on secondary halo properties that themselves show a halo assembly bias signature.

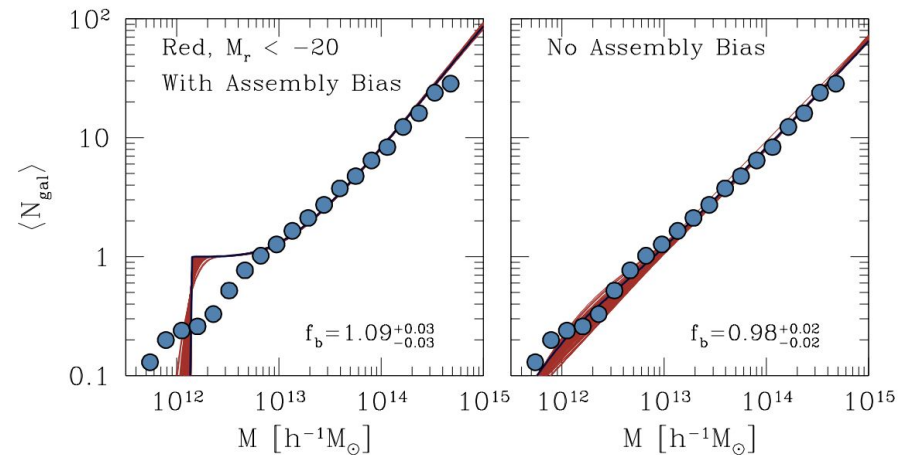


HOD secondary dependences

$$P(N_g|M, x)$$

Why Do We Care

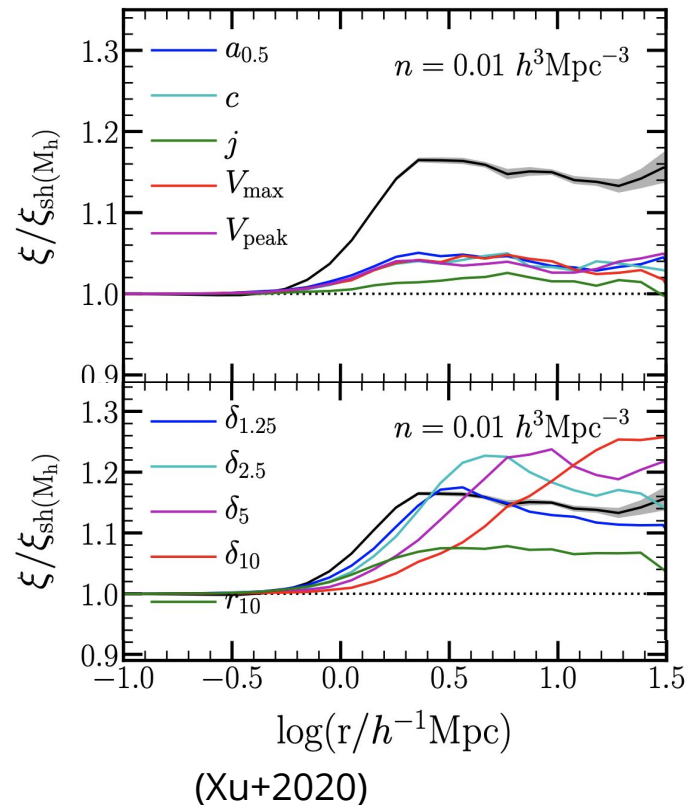
- Understanding galaxy formation.
- Ignoring assembly bias can yield significant errors in galaxy-halo connection constraints.
- Ignoring assembly bias can bias cosmology inferences.



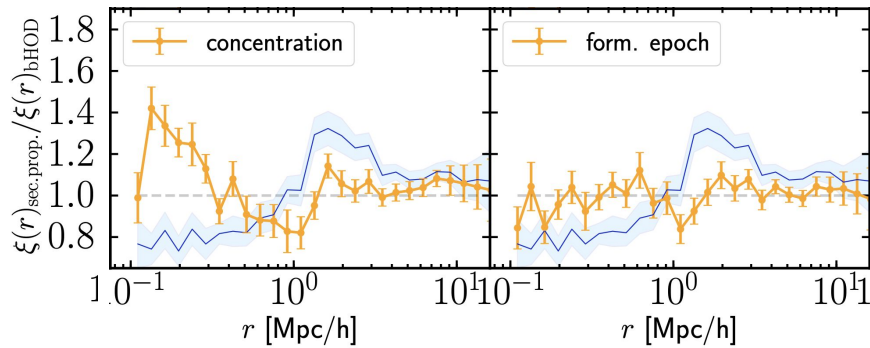
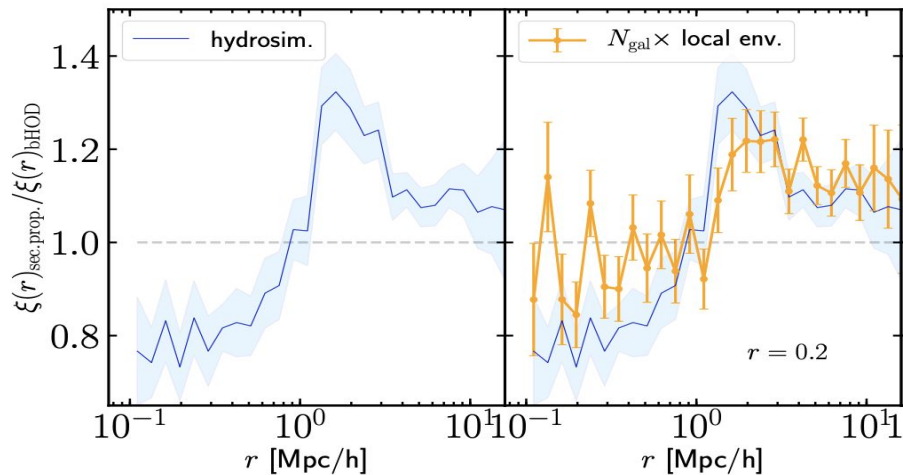
(Zentner+2014)

Identifying the secondary property

- What halo property best captures assembly bias?
- The most informative halo property is halo environment.
 - Xu+2020 with semi-analytic models.
 - Hadzhiyska+2019 with hydrosims.



Identifying the secondary property



(Hadzhiyska et al 2019)

Extending HODs with secondary property

- How do we generalize the HOD to account for a secondary dependence?

Galaxy swapping:

$$\begin{aligned}\langle N_{\text{gal}} | M_{\text{vir}}, c_{\text{high}} \rangle &= \langle N_{\text{gal}} | M_{\text{vir}} \rangle + \delta N_{\text{gal}} \\ \langle N_{\text{gal}} | M_{\text{vir}}, c_{\text{low}} \rangle &= \langle N_{\text{gal}} | M_{\text{vir}} \rangle - \delta N_{\text{gal}}\end{aligned}\quad (\text{Hearin+2016})$$

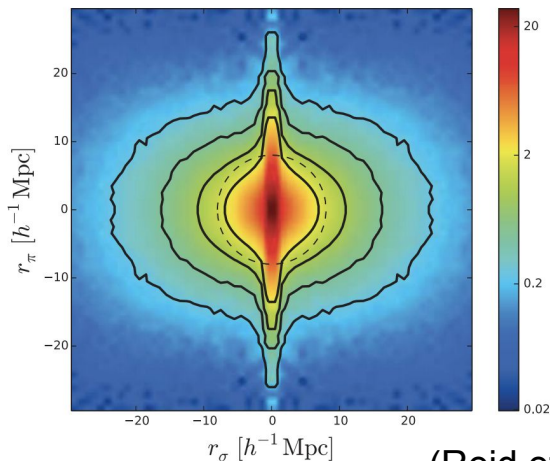
Inject secondary dependence into HOD parameters:

$$\begin{aligned}\log M_{\text{min}}(\delta_{1.25}^{\text{rank}}) &= \log M_{\text{min}}^0 + B_{\text{cen}} \times [\delta_{1.25}^{\text{rank}} - 0.5] \\ \log M_1(\delta_{1.25}^{\text{rank}}) &= \log M_1^0 + B_{\text{sat}} \times [\delta_{1.25}^{\text{rank}} - 0.5].\end{aligned}\quad (\text{Xu+2020})$$

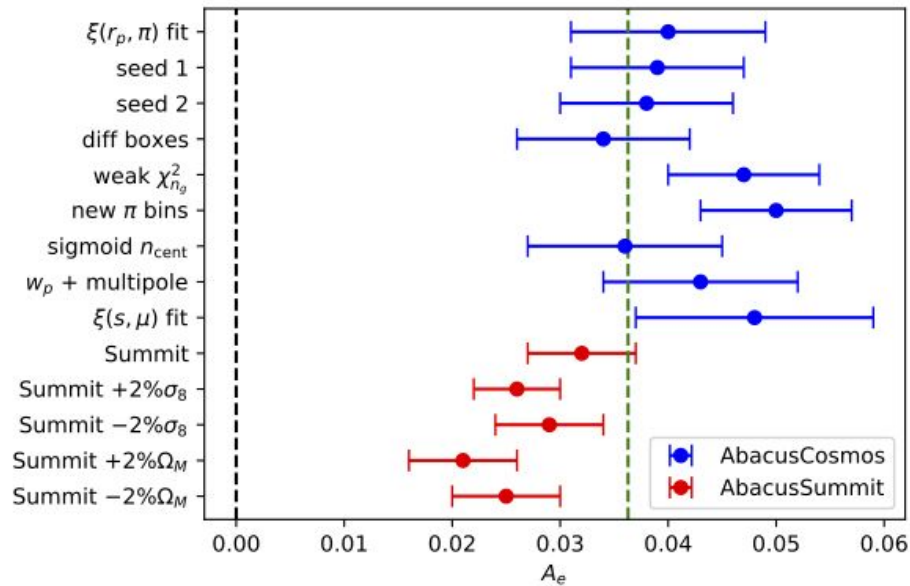
Also Walsh & Tinker 2019 and Yuan+2018.

Fitting the BOSS redshift-space 2PCF

- Evidence for a positive environment based assembly bias.
- The best-fit $\chi^2 = 50$ (d.o.f = 37).
- Including A_e : $\Delta \text{BIC} = 13$.



(Reid et al. 2014)

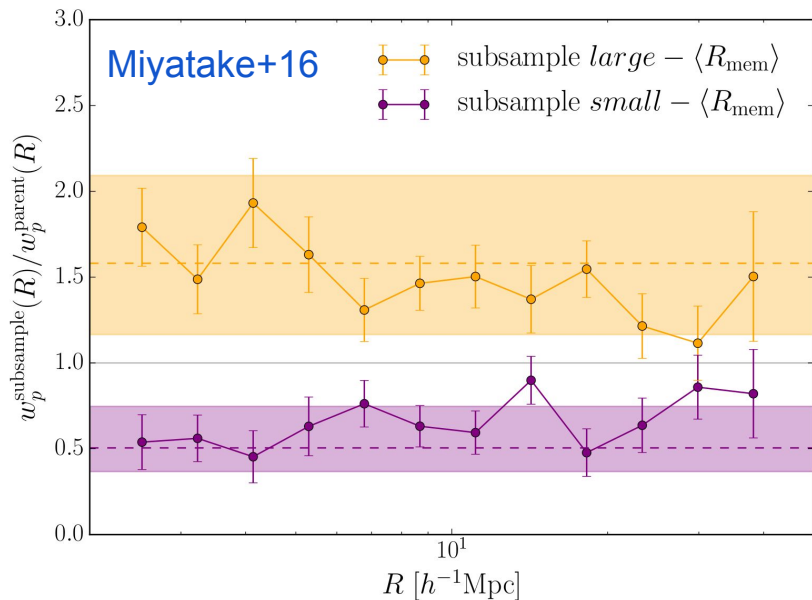


(Yuan et al. in prep)

Observational Evidence for Galaxy Assembly Bias

Direct Evidence for Galaxy Assembly Bias

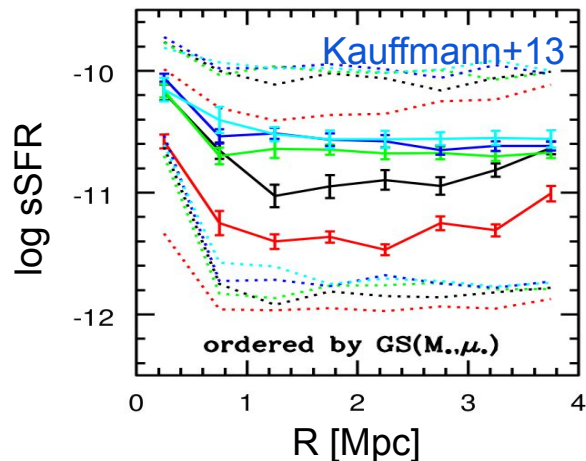
Assembly Bias in redMaPPer Clusters



2-Halo Galactic Conformity

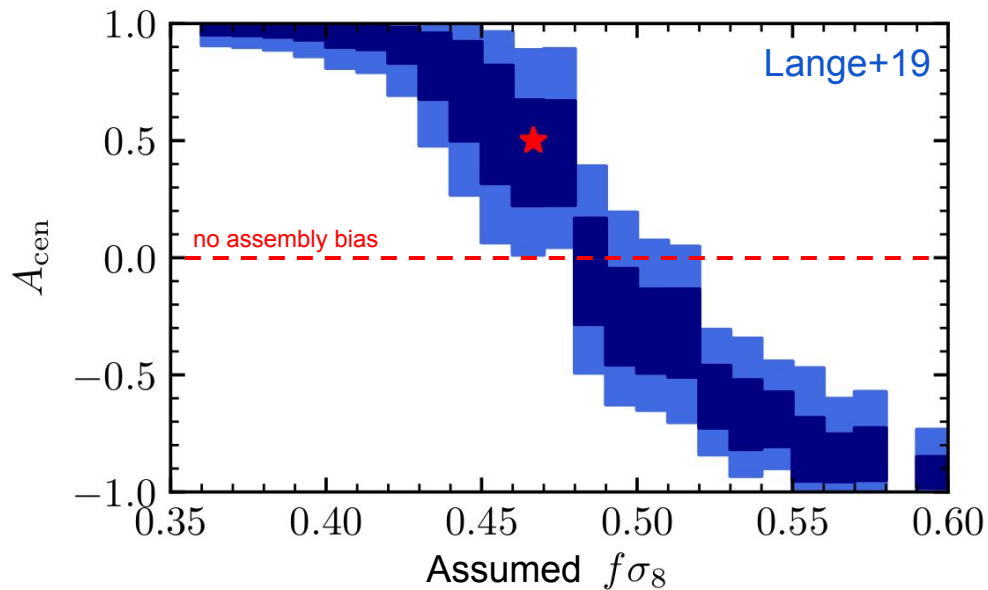
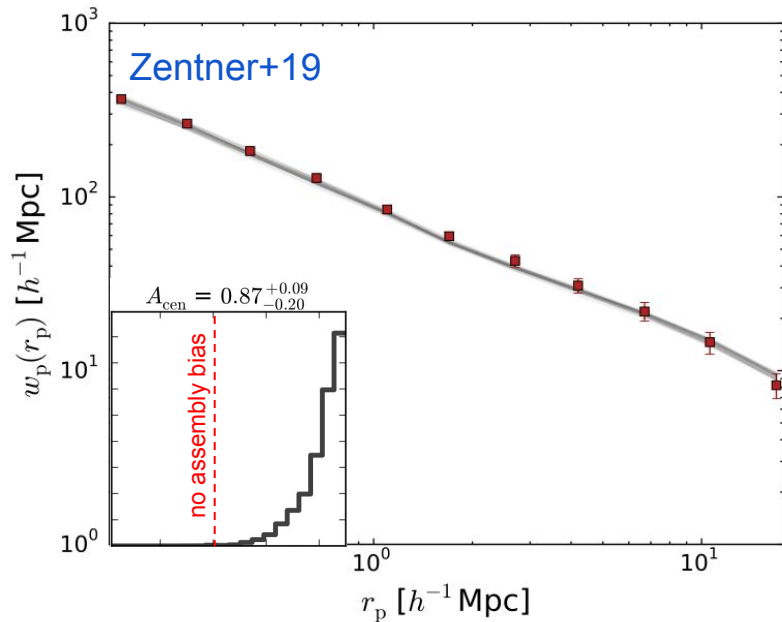
Beyond halo mass: galactic conformity as a smoking gun of central galaxy assembly bias

Andrew P. Hearin, Douglas F. Watson, Frank C. van den Bosch



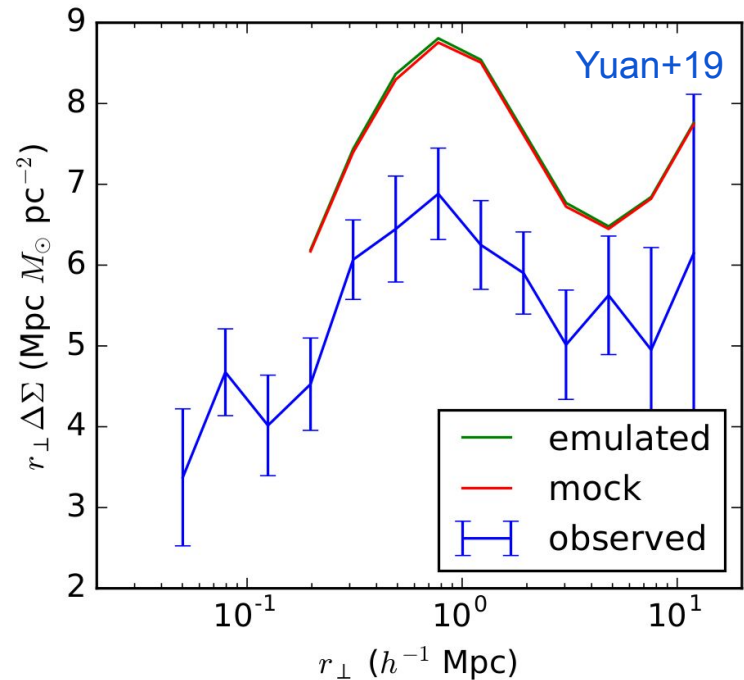
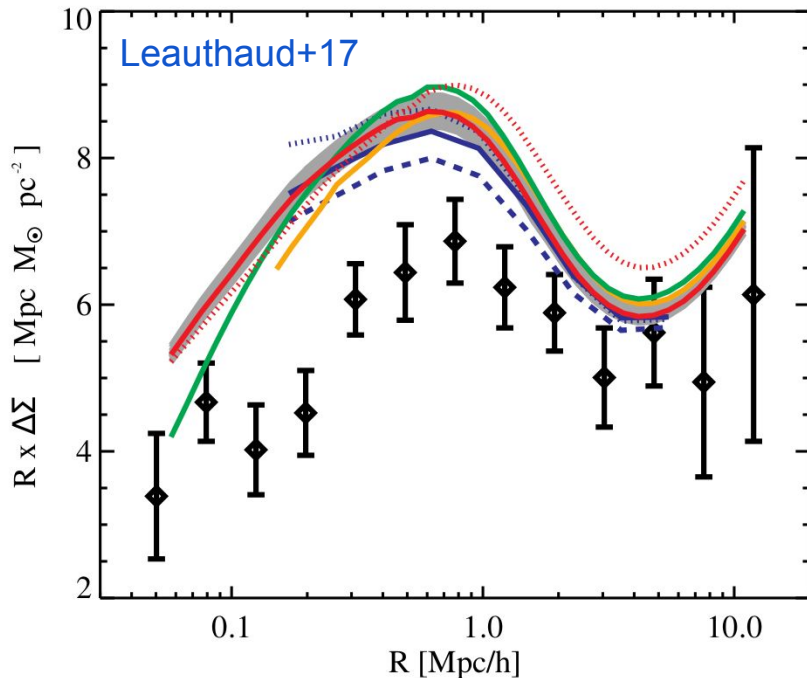
Most direct evidence for galaxy assembly bias can be explained by systematic errors (Busch+17, Zu+17, Tinker+17, Calderon+18, Sunayama+20).

Indirect Evidence from Galaxy Clustering



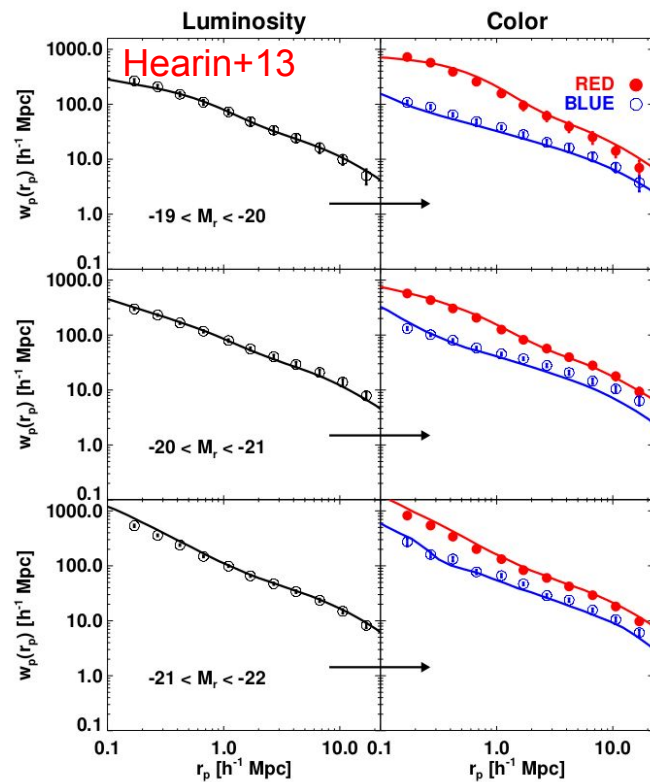
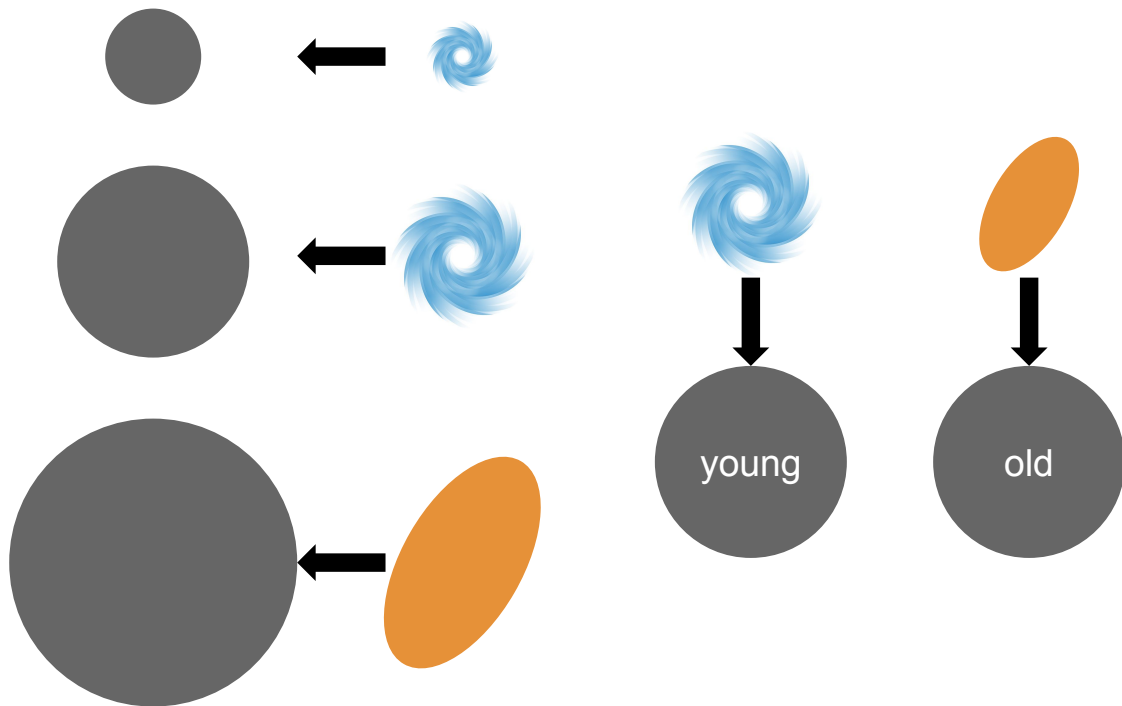
Challenge: Galaxy assembly bias can be degenerate with other model variations.

Lensing is Low: Evidence for Assembly Bias?

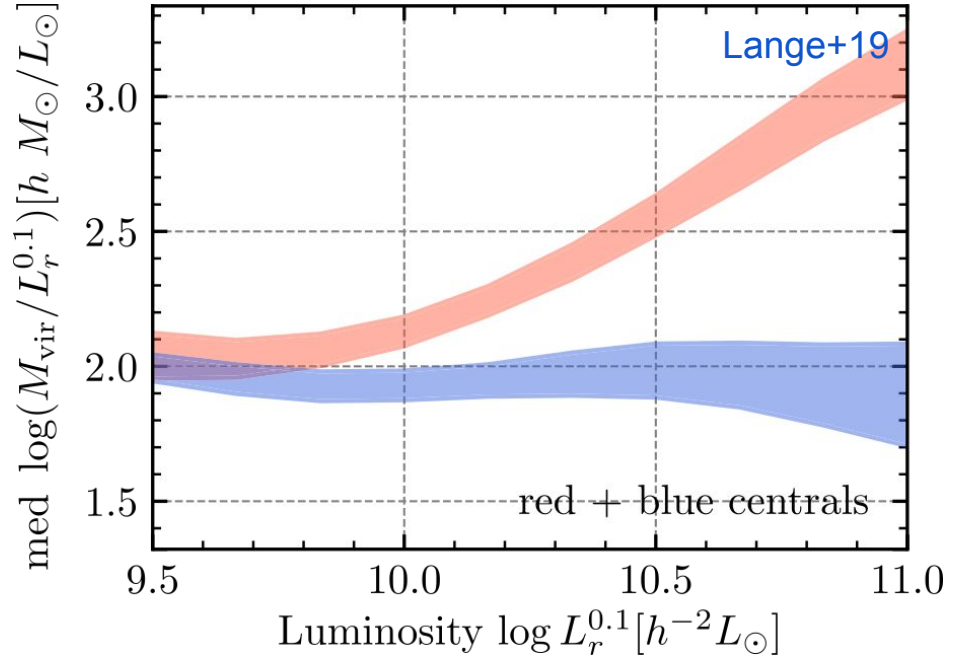
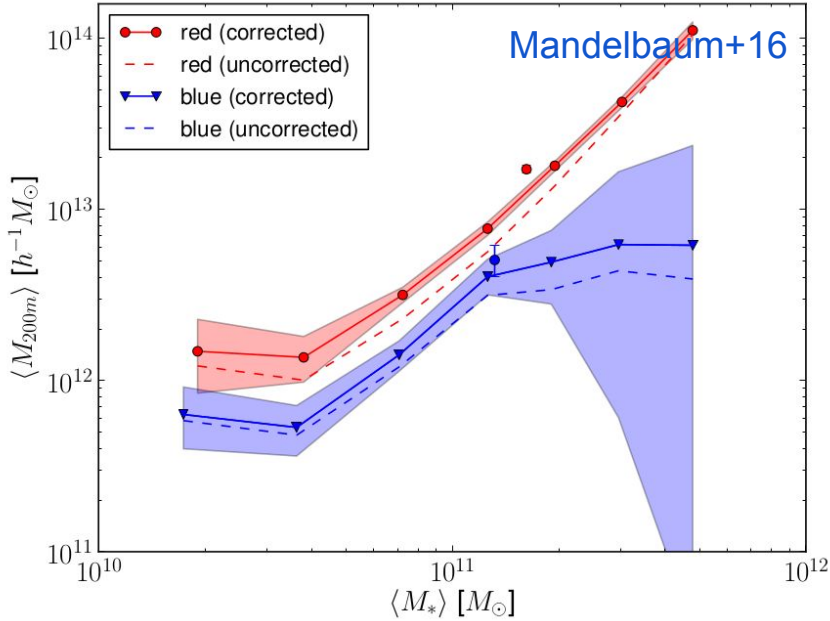


Clustering+Lensing mismatch cannot be explained by galaxy assembly bias.

Example: Age Matching



Example: Age Matching



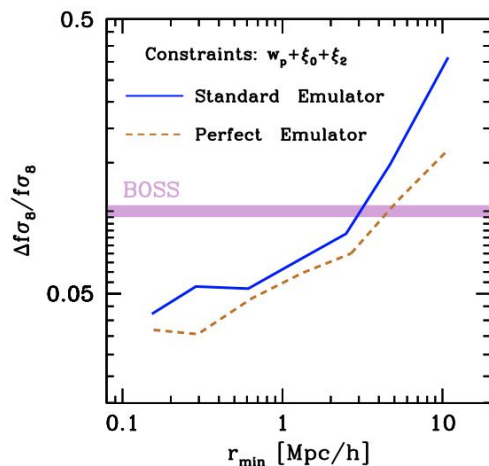
“Extreme” models of galaxy assembly bias can often be excluded.

Galaxy Assembly Bias and Cosmology

- There is a benefit to trying to extract cosmological information from non-linear clustering.
 - It requires a more complicated bias model (usually halo modeling), but early results show an upgrade in constraints over perturbation theory.
- Any robust analysis that uses halo occupation should incorporate secondary correlations.
- However, early efforts with LRG-type samples show positive results
 - Small effects (which are more physically realistic) have small impact on cosmology.
 - Different ways to incorporate assembly bias show consistent results on mocks.

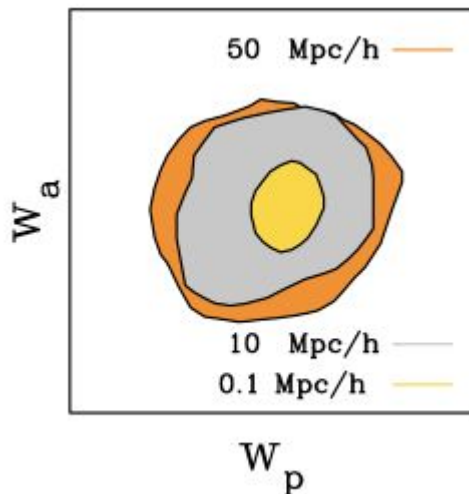
Constraining Power of Small Scales

Growth rate of structure from redshift-space clustering



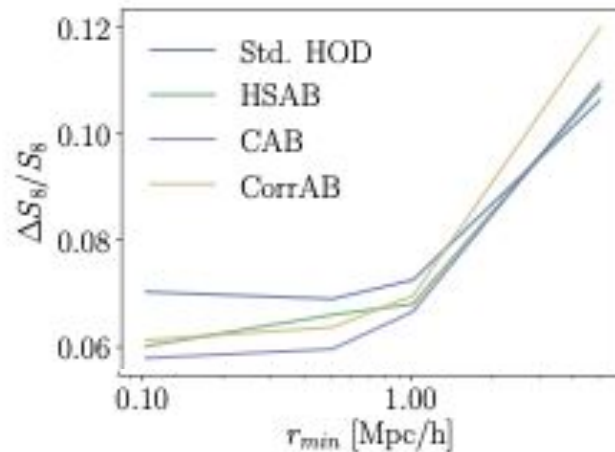
From Zhai et al (2019)
(Aemulus III)

Dark energy constraints using 3x2pt from a lensing survey.



From Kraus & Eifler (2017)

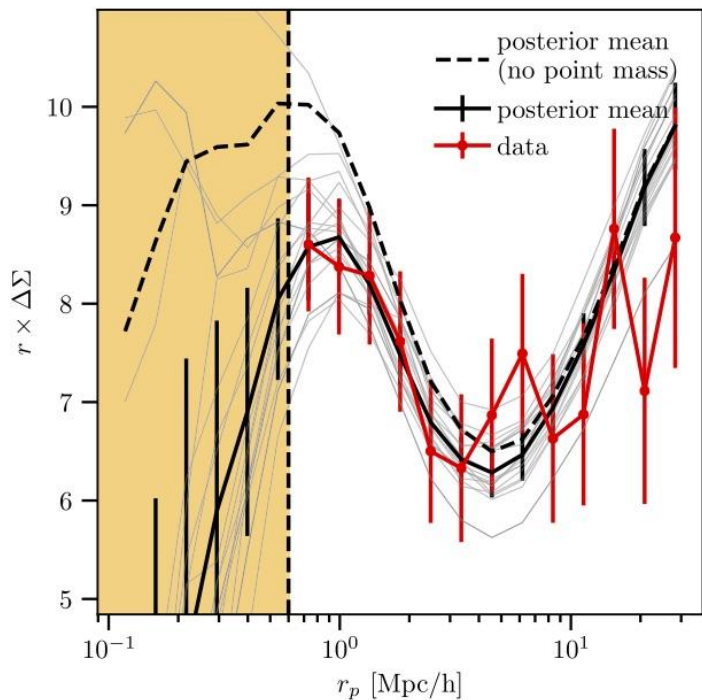
Cluster normalization from galaxy clustering and galaxy-galaxy lensing.



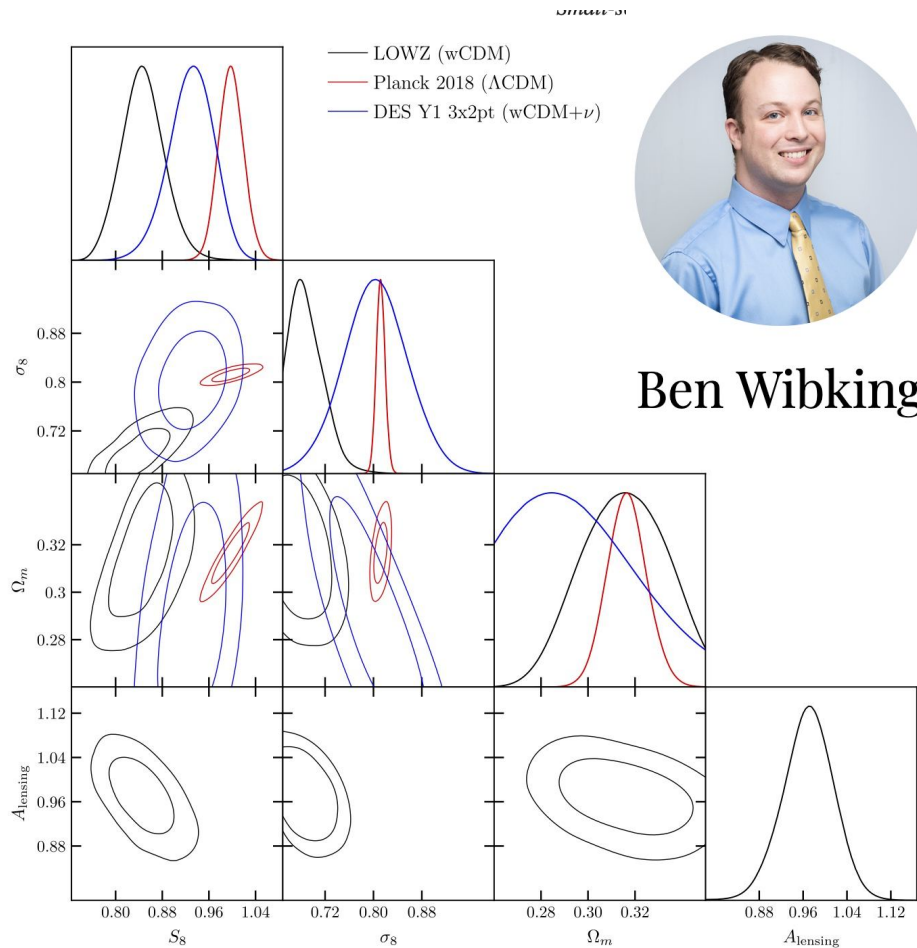
From McLaughlin et al (2020)
(Aemulus V)

Includes assembly bias!

The Era of Emulators is Upon Us!



Wibking et al 2020: Clustering+lensing analysis of BOSS LOWZ sample

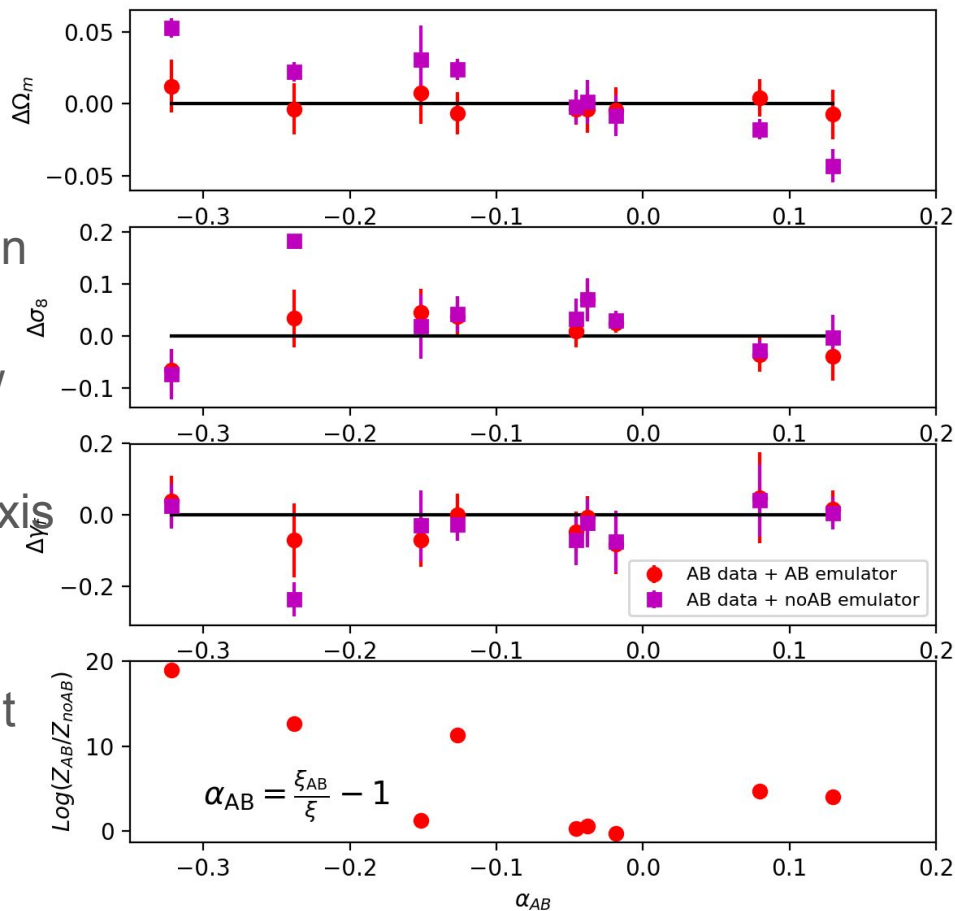


Ben Wibking

RSD Analysis: Upcoming Aemulus Project (Zhongxu Zhai)

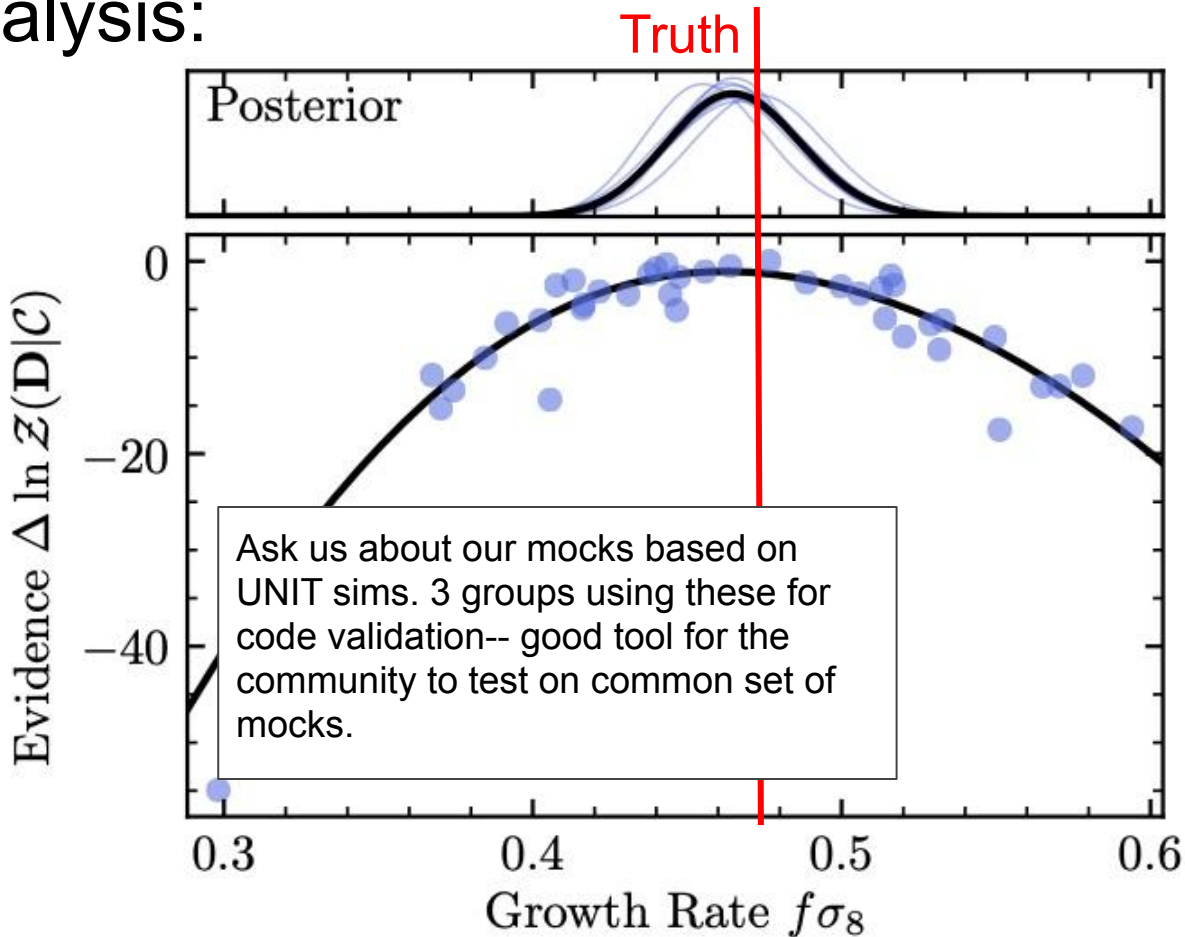


- Incorporating Assembly Bias (AB) in a galaxy clustering model.
- HOD is now $f(M, \rho_{10})$, adding 3 new parameters.
- Test on mocks that include AB: x-axis is change in b^2 due to AB.
- Small AB=no impact on results.
- Large AB=highly biased results, but new HOD model recovers proper cosmology.



BOSS-like RSD Analysis: Johannes Lange

- Uses Aemulus simulations, but different modeling approaches.
- Decorated HOD to incorporate AB.
- Results from abundance matching mocks with Lehmann et al (2017)-type AB.

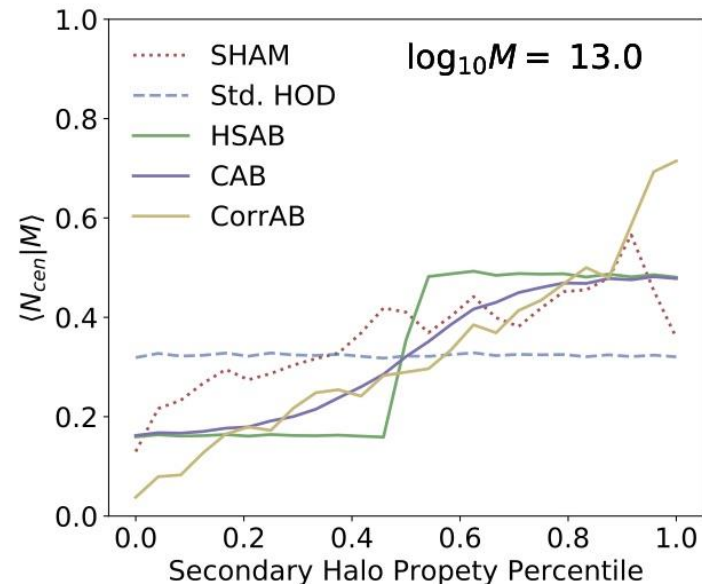


Lensing Analysis: Aemulus V (arriving soon)

Sean McLaughlin



- Comprehensive look at various assembly bias implementations.
 - Standard HOD
 - Decorated HODs, Heaviside form (ie, step functions in halo occupation)
 - Decorated HODs, continuous form
 - Correlating N_{gal} with secondary property (analogous to conditional abundance matching)
- Different secondary properties.
 - Halo concentration
 - Matter density at 10 Mpc/h scale



Mock data vector:

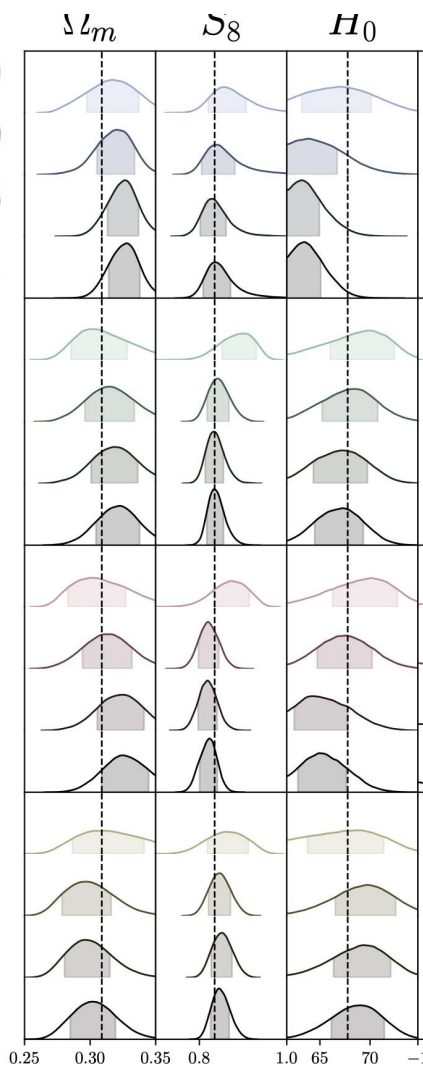
- Galaxy clustering
- Gal-Gal lensing
- RedMagic-like sample

Analysis

- Emulator using Aemulus simulations
- For emulator, AB is with density.
- Mock created from MDPL, including AB.
- In mock, AB uses concentration.



Std. HOD $r_{min} = 5.0$
Std. HOD $r_{min} = 1.0$
Std. HOD $r_{min} = 0.5$
Std. HOD $r_{min} = 0.1$
HSAB $r_{min} = 5.0$
HSAB $r_{min} = 1.0$
HSAB $r_{min} = 0.5$
HSAB $r_{min} = 0.1$
CAB $r_{min} = 5.0$
CAB $r_{min} = 1.0$
CAB $r_{min} = 0.5$
CAB $r_{min} = 0.1$
CorrAB $r_{min} = 5.0$
CorrAB $r_{min} = 1.0$
CorrAB $r_{min} = 0.5$
CorrAB $r_{min} = 0.1$



Standard HOD (halo mass only parameterization)

Decorated HOD, step-function occupation

Decorated HOD, continuously varying N_{gal}

Correlated HOD with secondary property

Galaxy Assembly Bias and Cosmology

- There is a benefit to trying to extract cosmological information from non-linear clustering.
- Any robust analysis that uses halo occupation should incorporate secondary correlations.
- However, early efforts with LRG-type samples show positive results

Caveats (future work)

- This is the beginning, not the end, of this type of work.
- As we transition to ELGs, ALL of this needs to be redone. Bringing SFR into target selection may open Pandora's Box.
- As we transition to sub-percent precision (DESI, DES, EUCLID, WFIRST), we need to re-do all these tests.