New Insights into Cosmology and the Galaxy-Halo Connection from non-linear Scales

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LUX ET VERITAS

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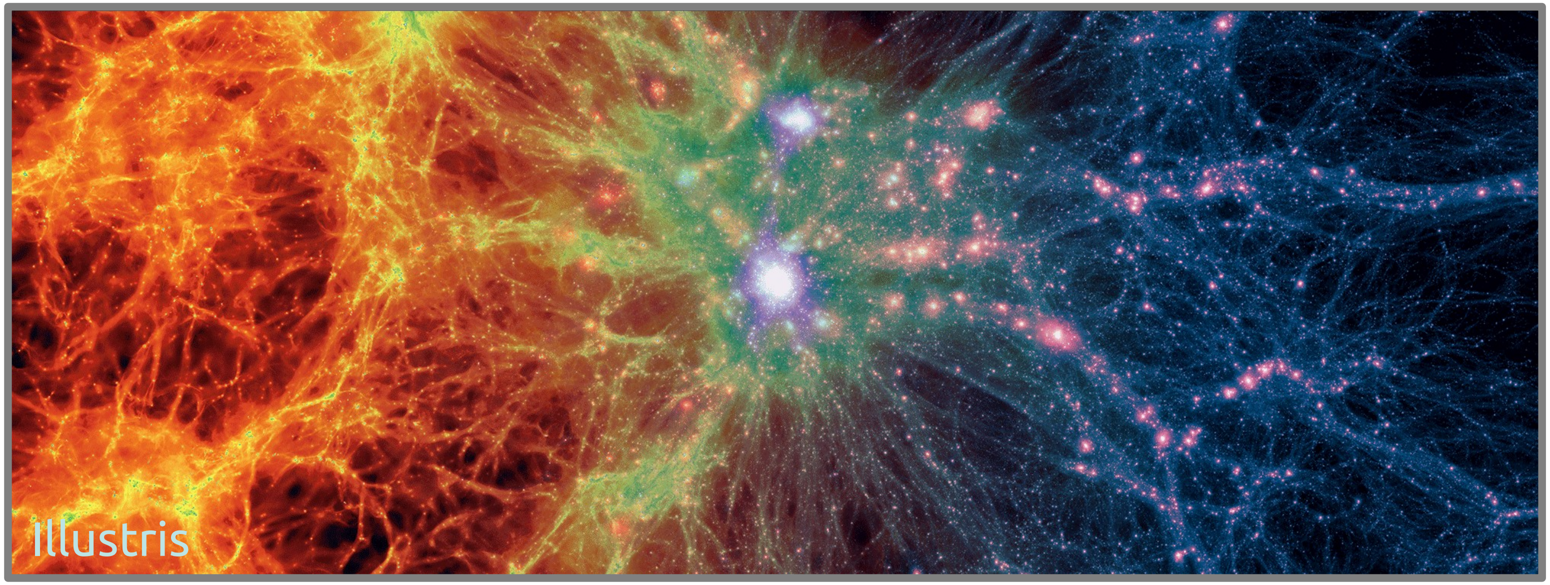
Galaxy Formation – A tale of two approaches



Simulations

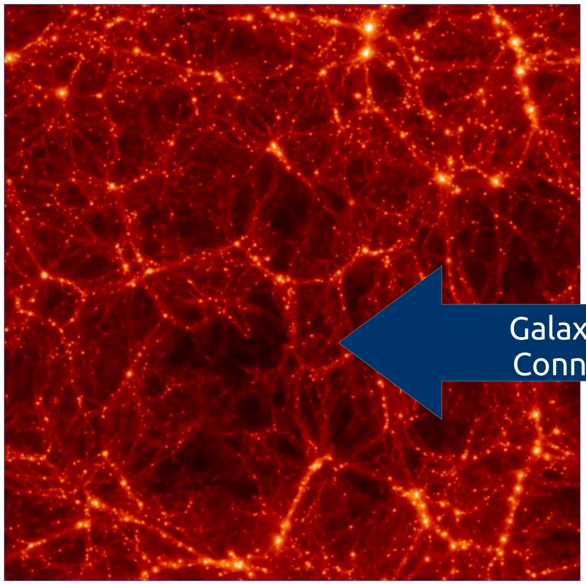
- semi-analytic models (SAMs), hydro. simulations
- predict observables from first principles*
- *many free parameters (sub-grid physics) to tune

Empirical Modeling

- galaxy-dark matter halo connection through observations (reverse engineering)
- little galaxy physics priors
- can also constrain cosmology

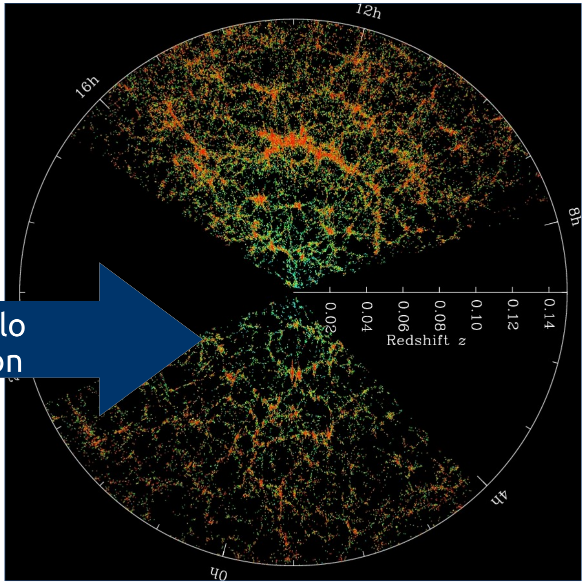
Empirical Modeling - Basics

Dark Matter Field



Galaxy-Halo Connection

Galaxy Distribution



Galaxy-Halo Connection:

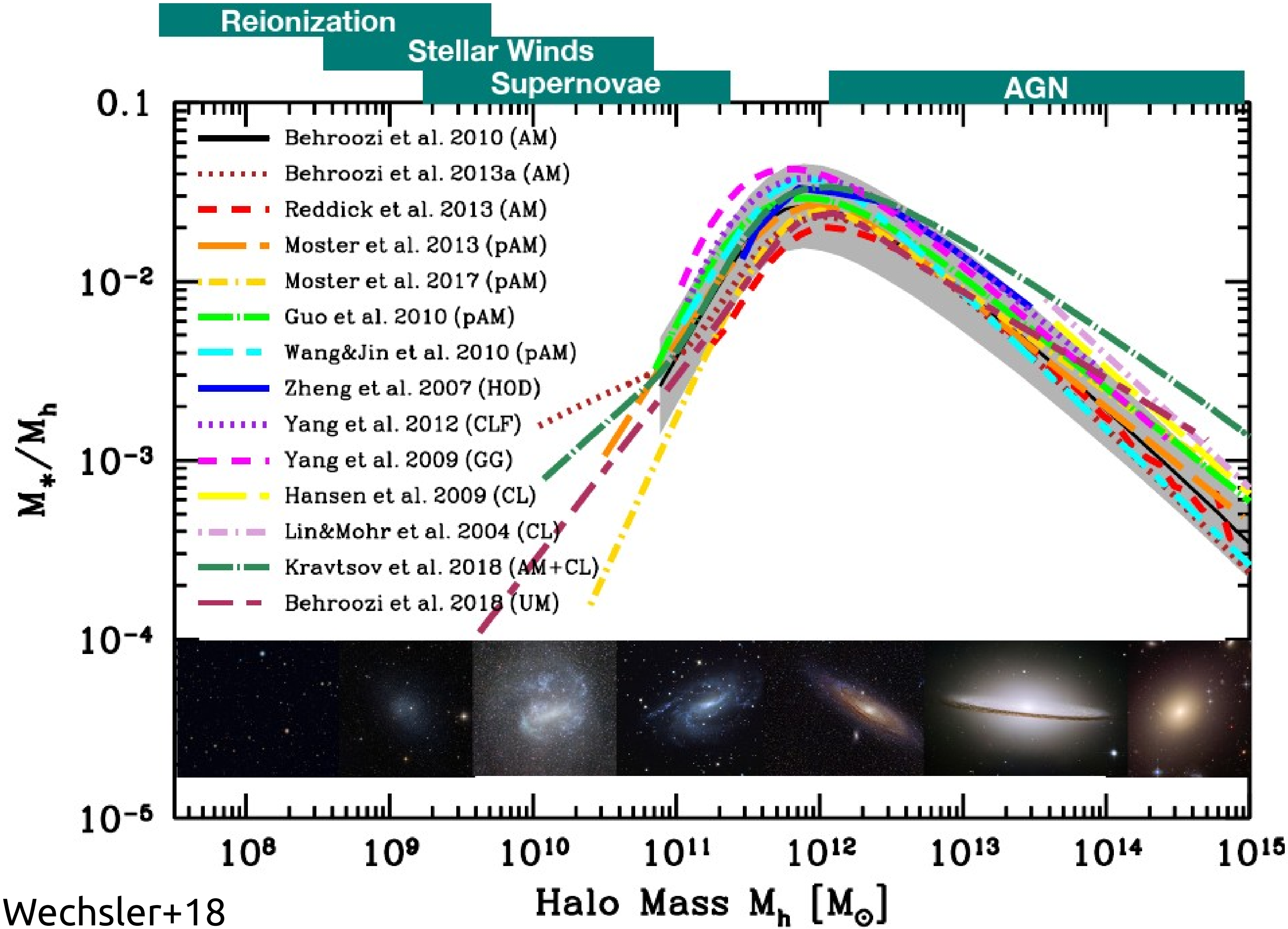
- $N_{gal}(M_{halo})$ aka HOD
- mass-luminosity relation
- satellite radial profile
- velocity bias
- ...

(projected) Galaxy Clustering

Galaxy-Galaxy Lensing

Satellite Kinematics (FoG effect)

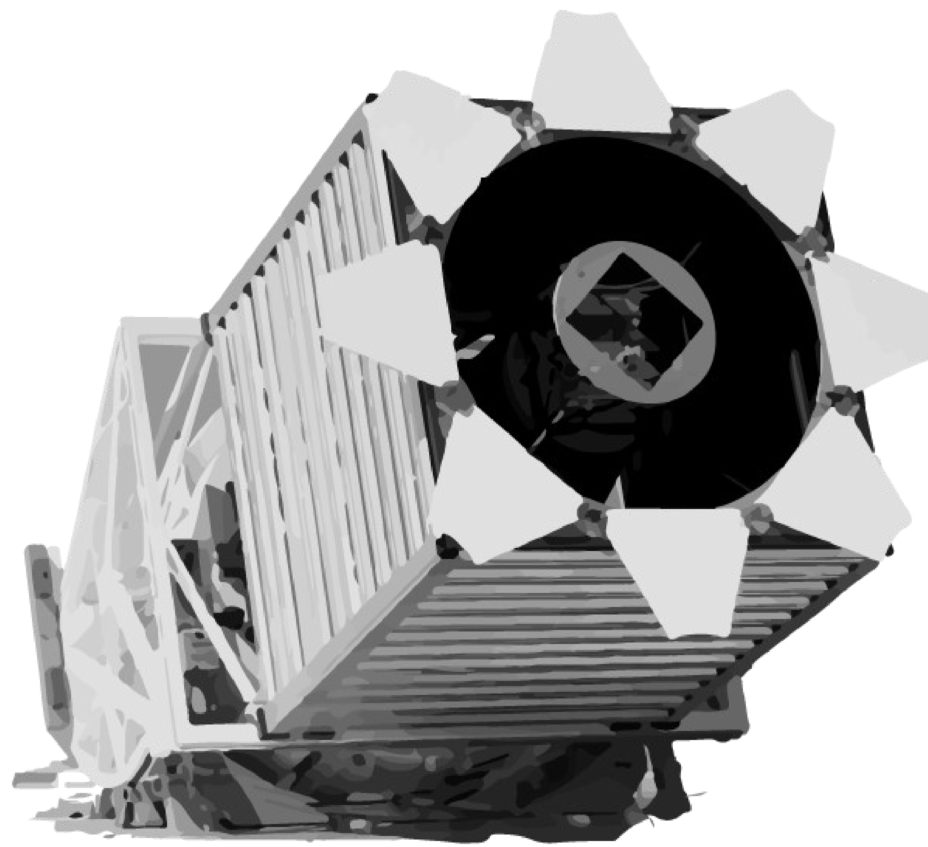
Empirical Modeling – A Success Story



Wechsler+18

Outline

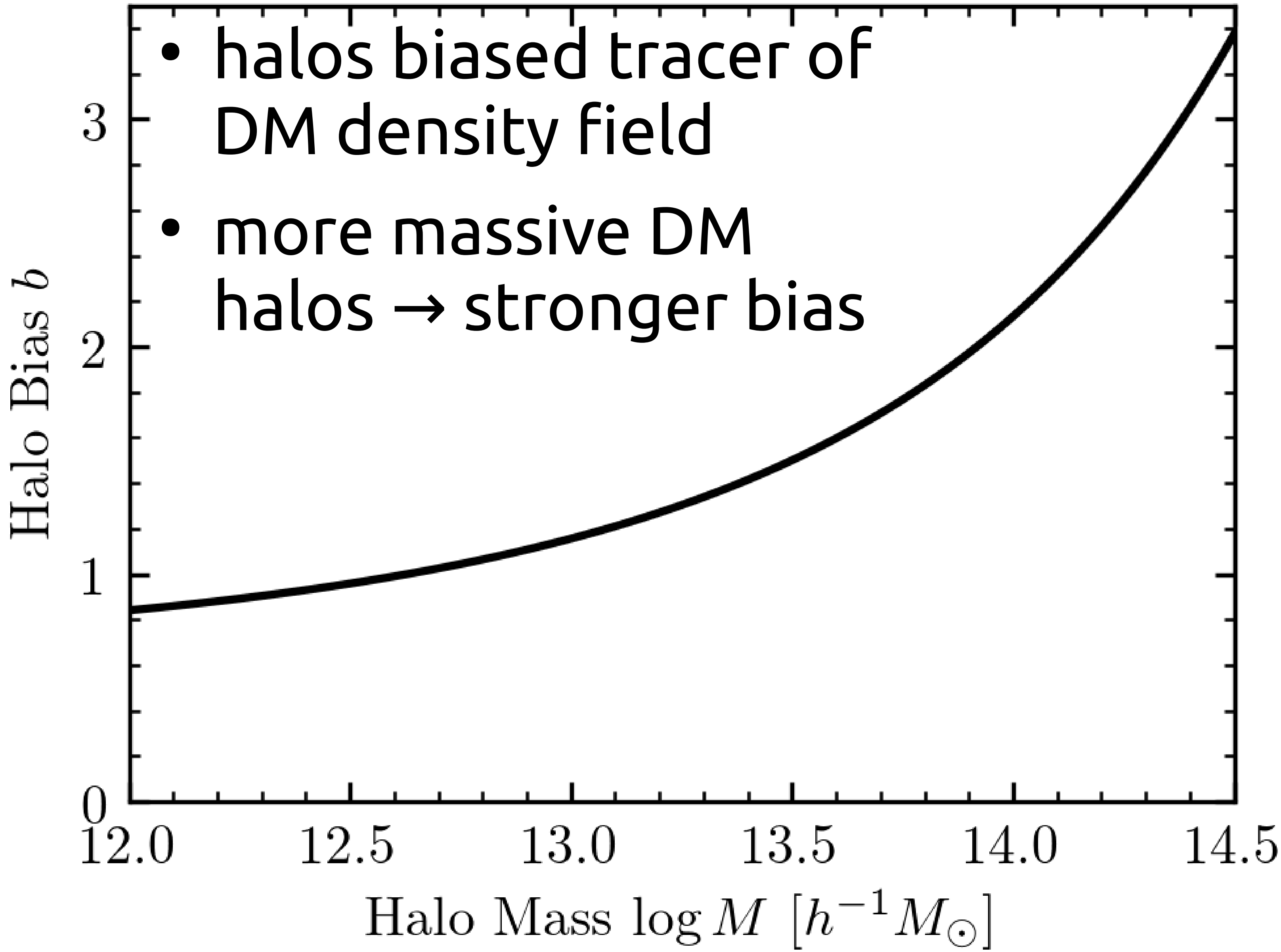
- Empirical Modeling in galaxy surveys
- Clustering + Lensing Discrepancy in BOSS
- New Methods for Satellite Kinematics
- SDSS Constraints from Satellite Kinematics
- Future Work



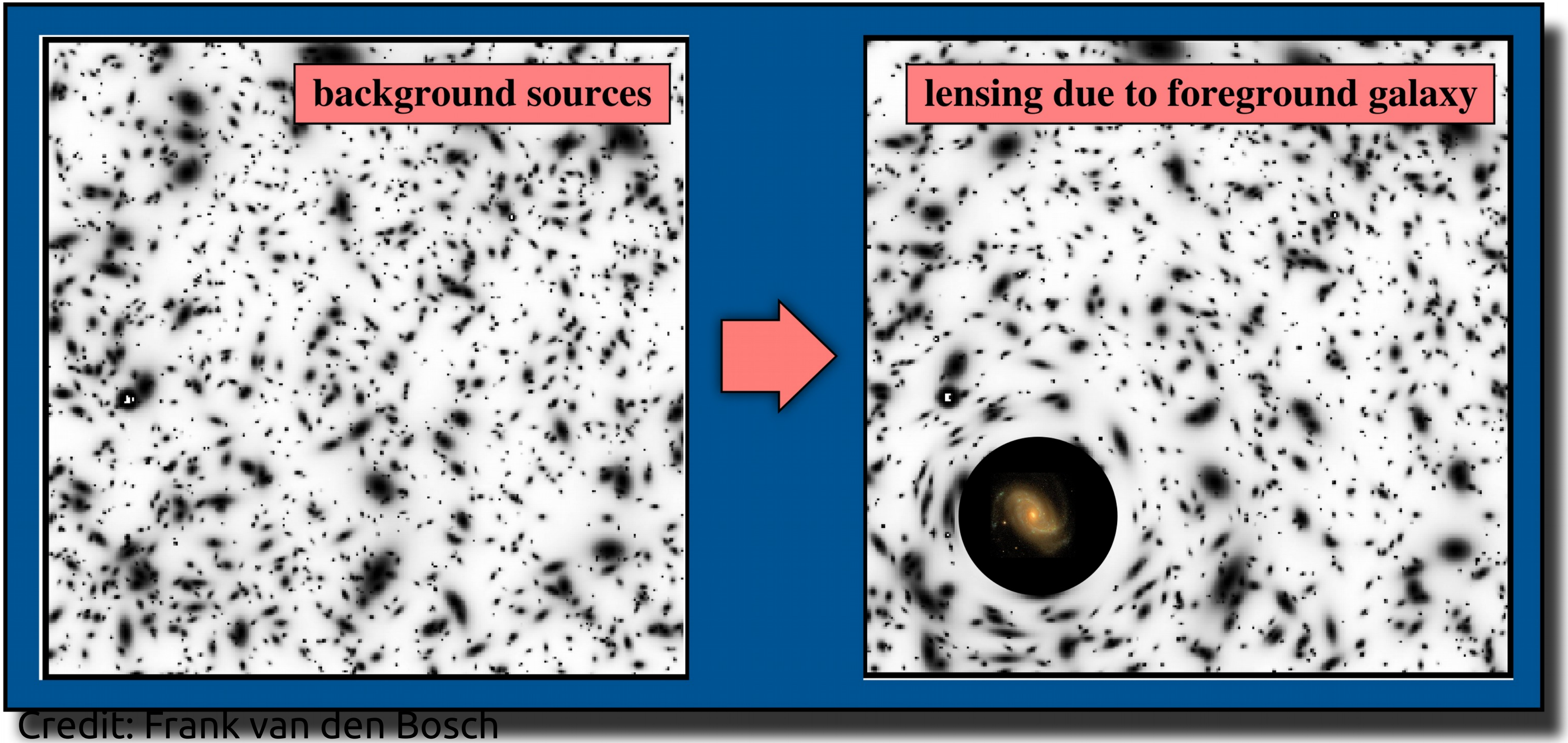
Reconciling Clustering + Lensing

Galaxy Clustering – Indirect Halo Masses

- halos biased tracer of DM density field
- more massive DM halos → stronger bias

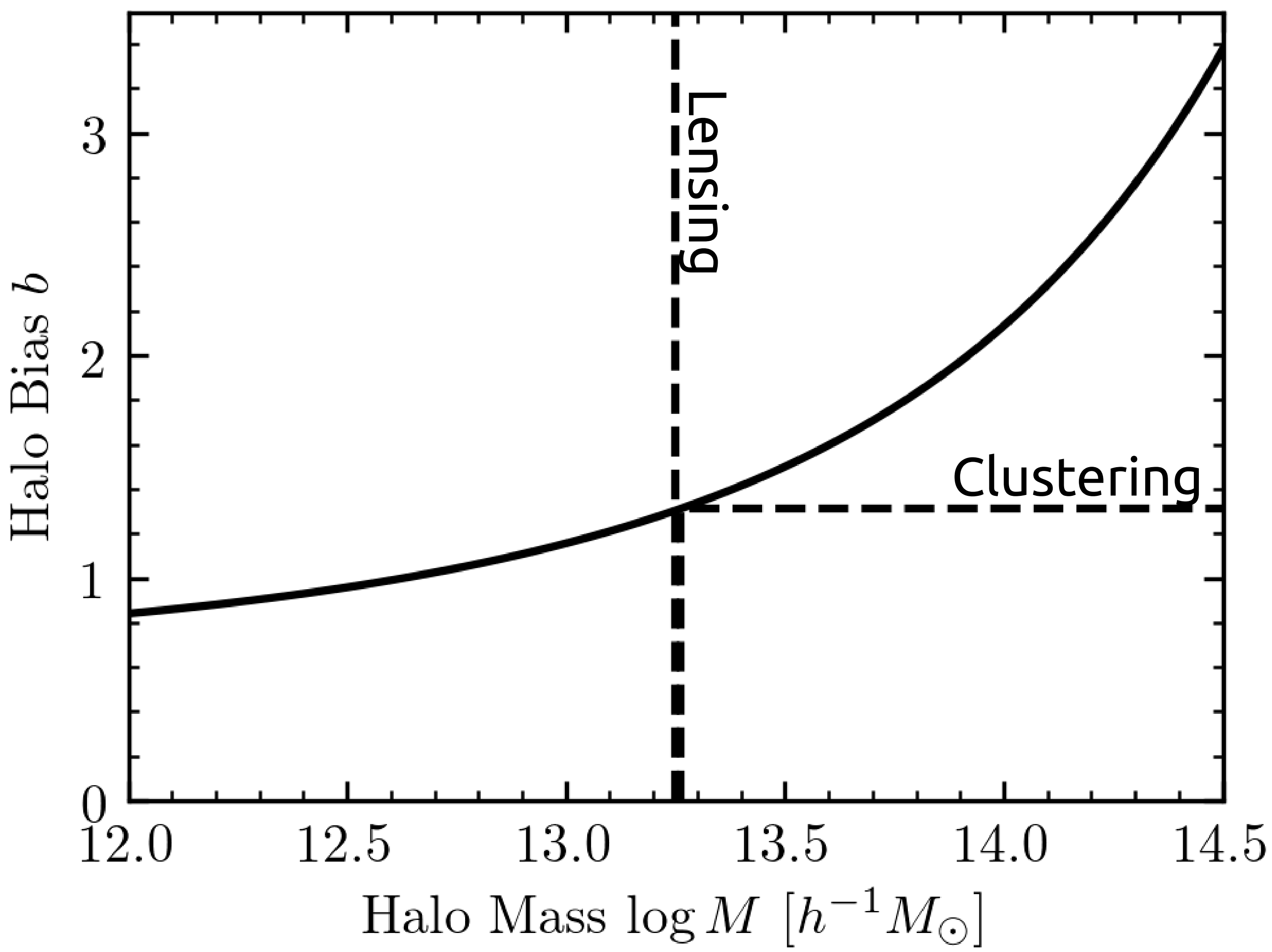


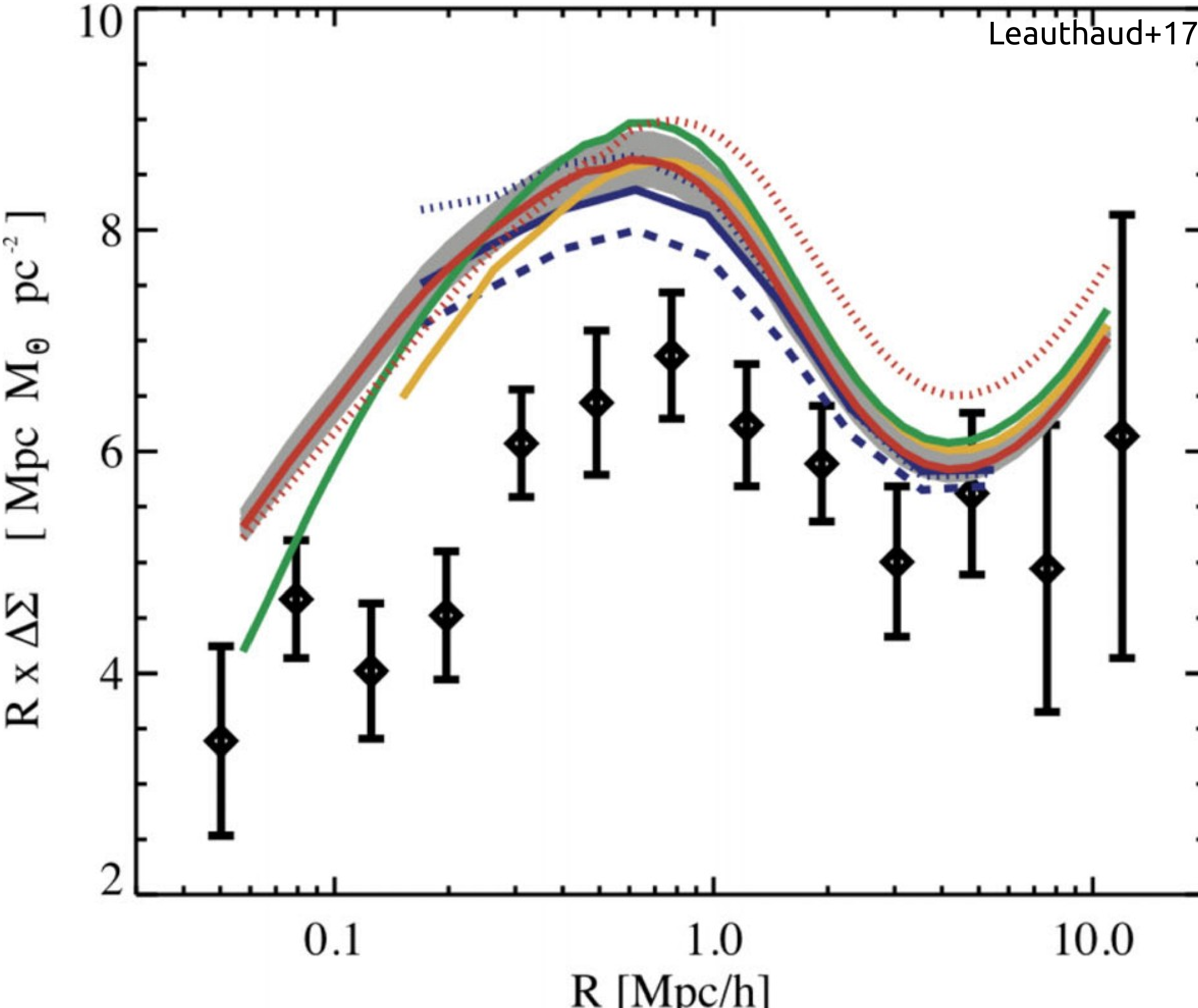
Galaxy-Galaxy Lensing – Direct Halo Masses



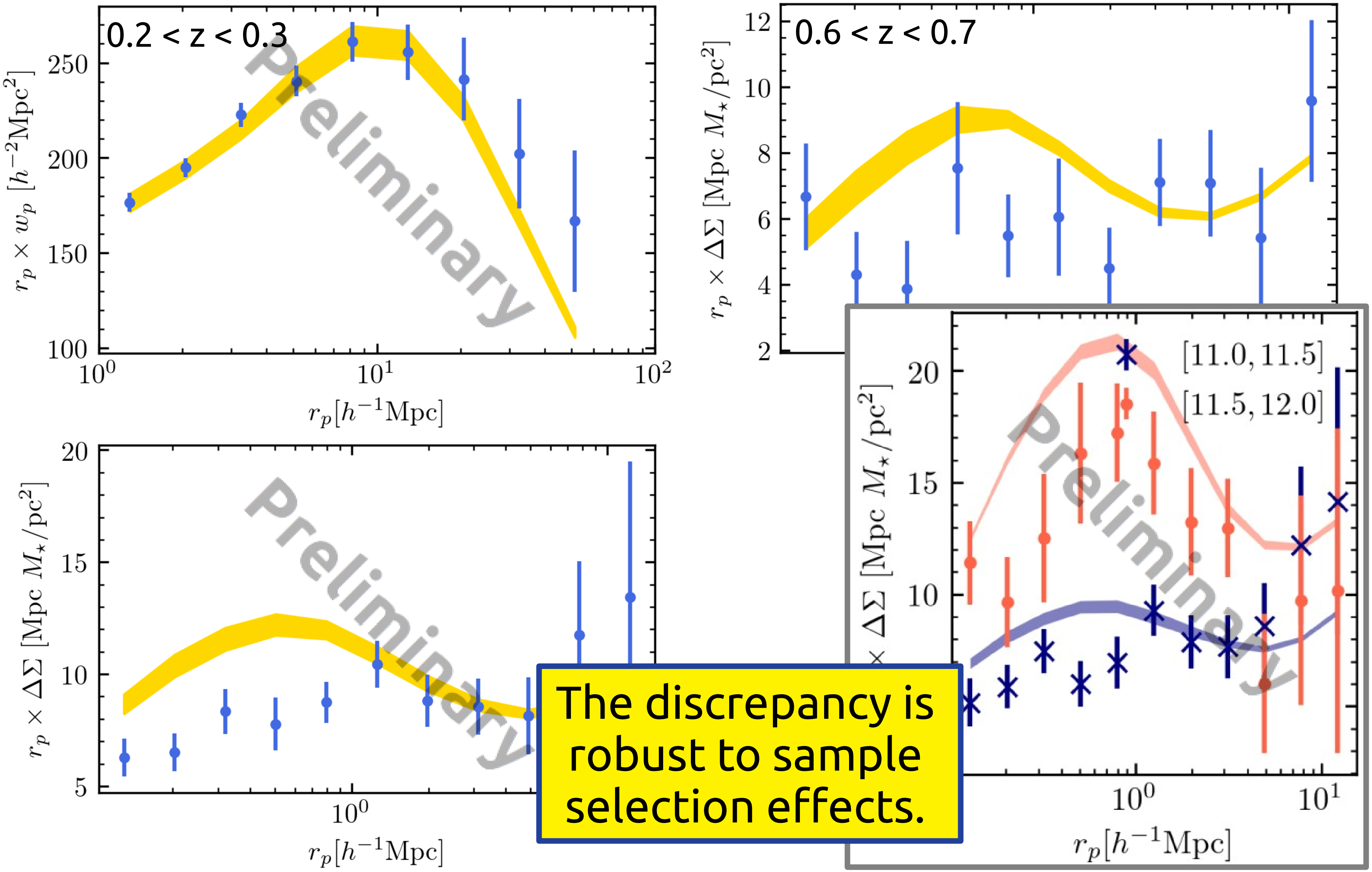
Credit: Frank van den Bosch

Combining Clustering and Lensing




Leauthaud+17
10
8
6
4
2
R x ΔΣ [Mpc M⊙ pc⁻²]
0.1
1.0
10.0
R [Mpc/h]

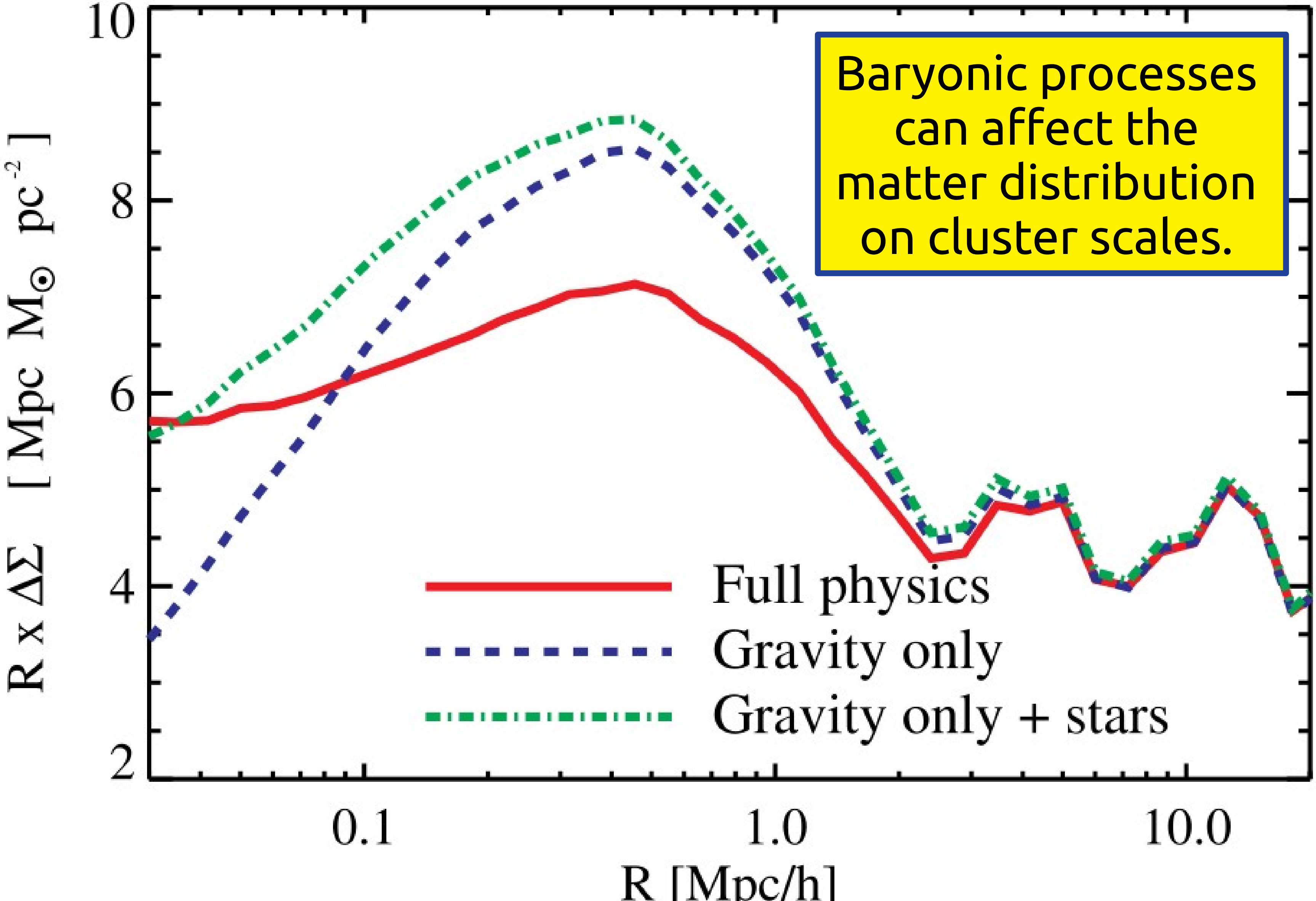
Dissecting the Lensing Discrepancy



The discrepancy is robust to sample selection effects.

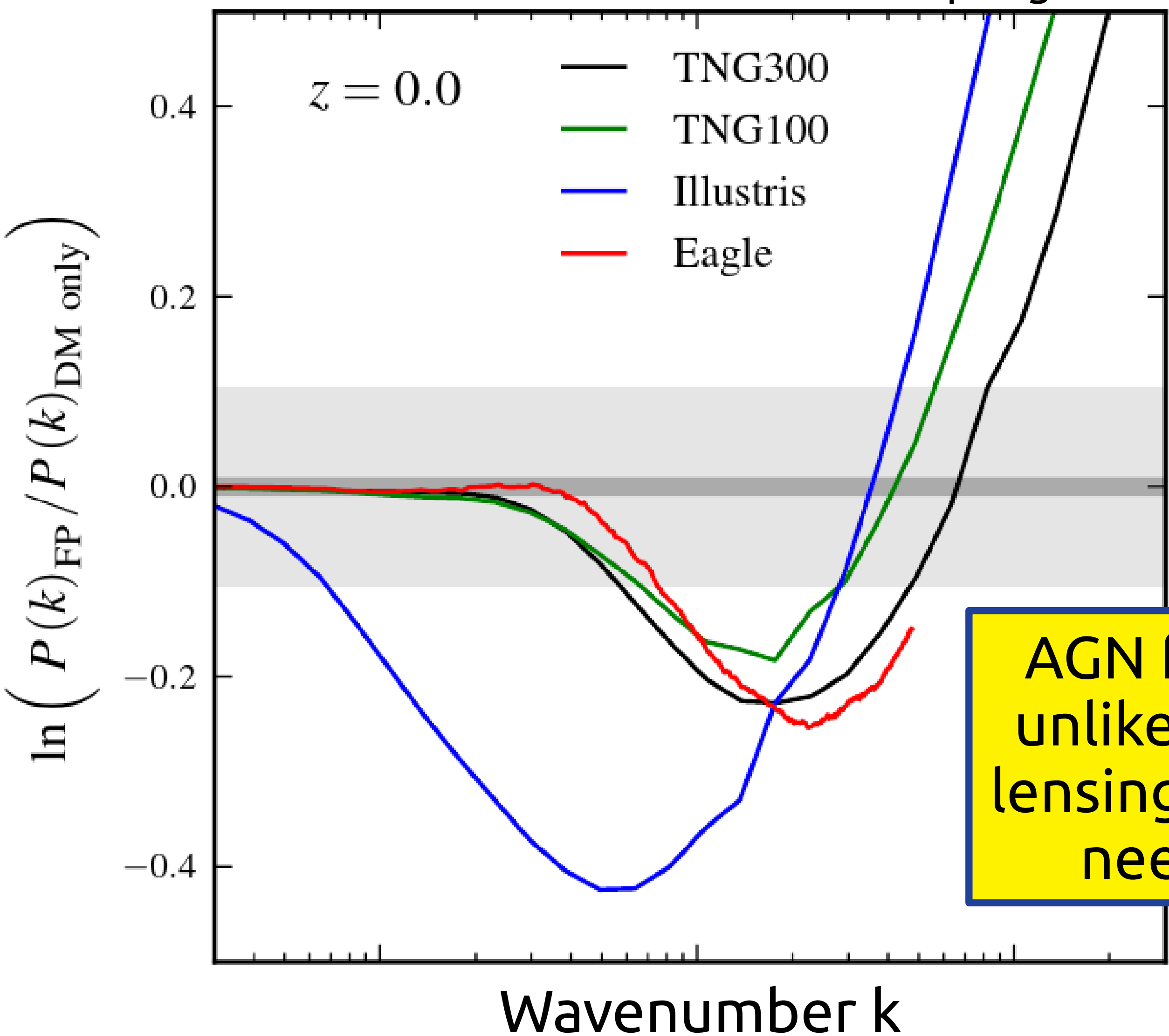
Lensing Discrepancy – Baryonic feedback?

Leauthaud+17



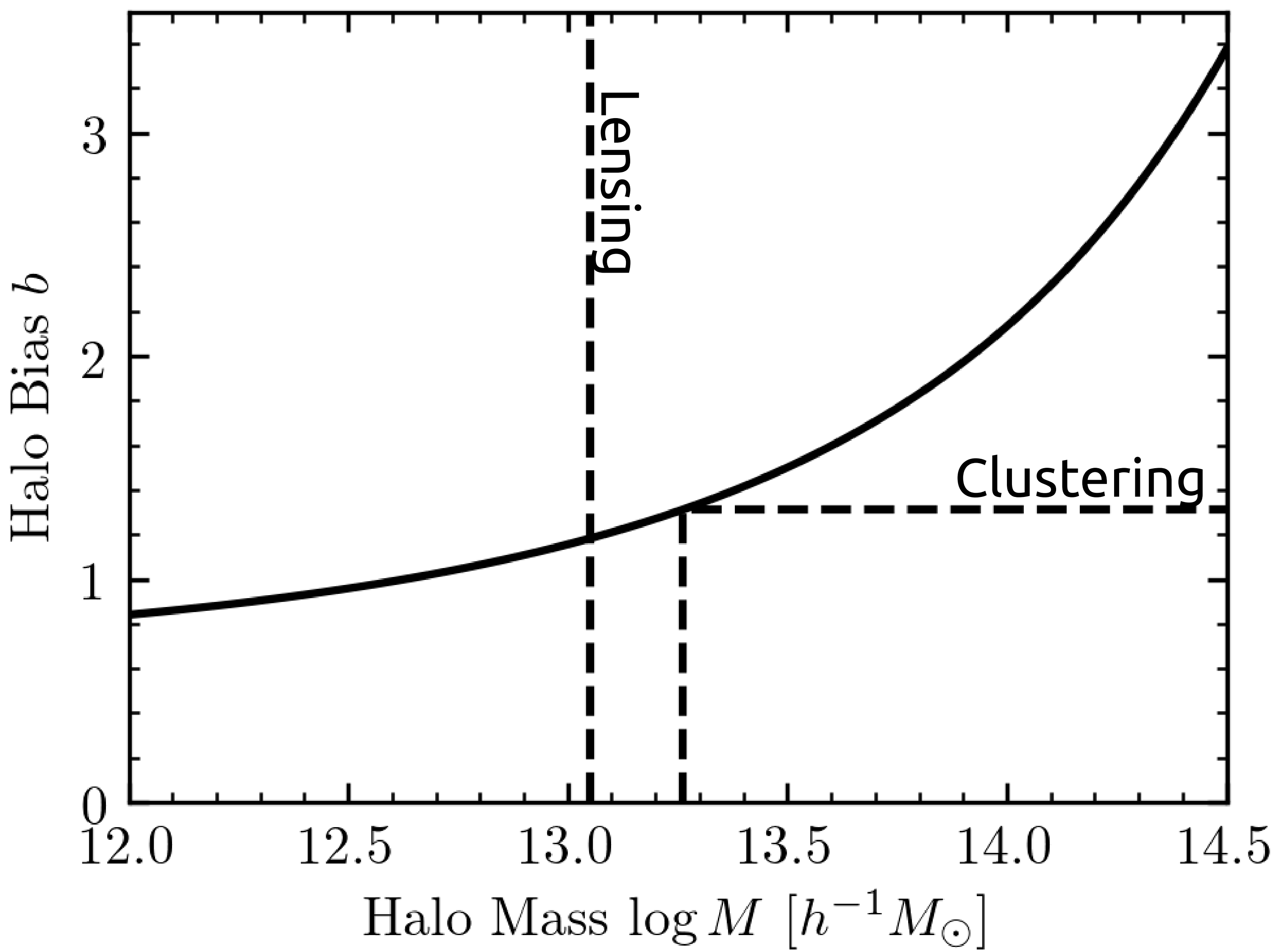
Lensing Discrepancy – Baryonic feedback?

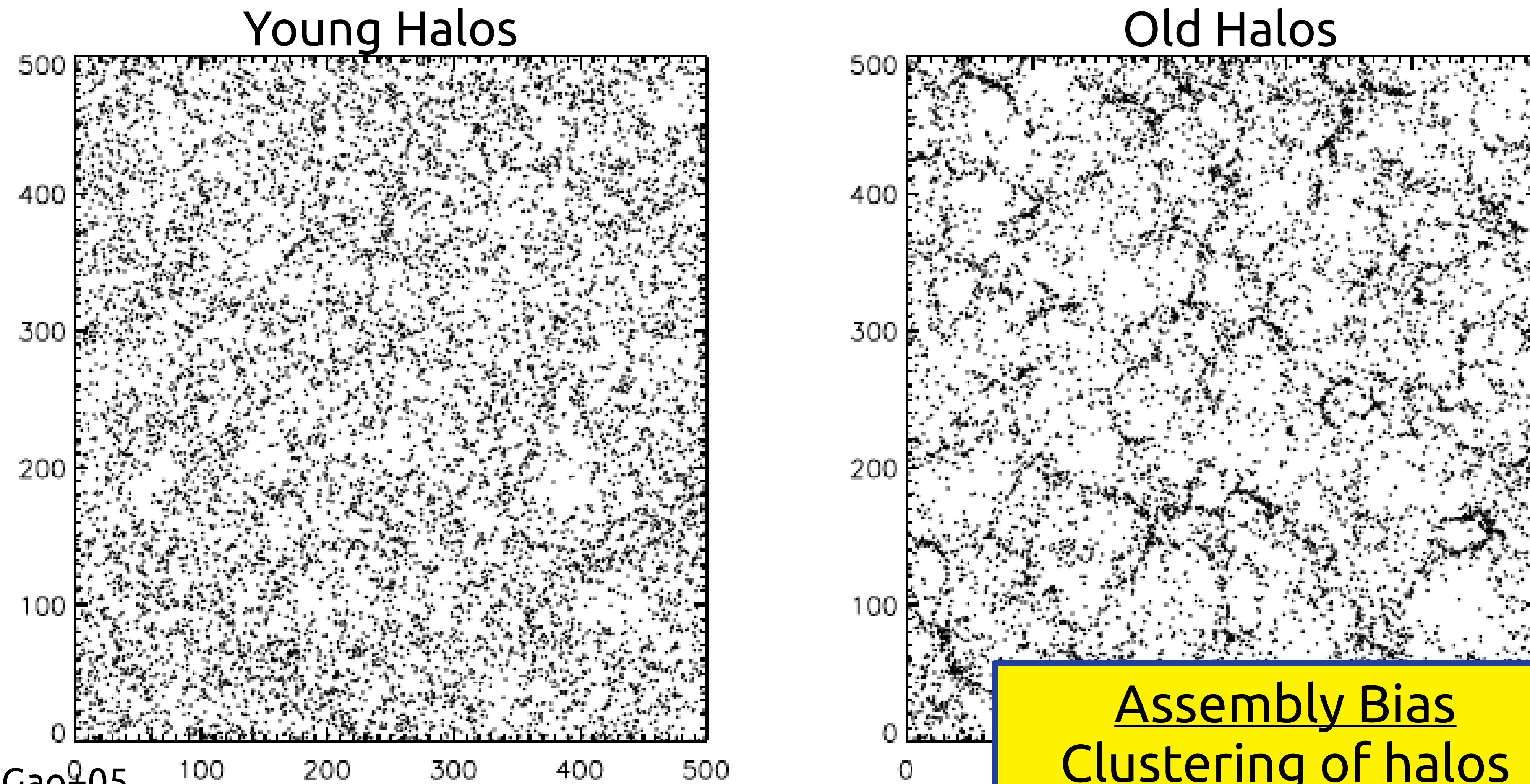
Springel+17



AGN feedback alone seem unlikely to fully explain the lensing discrepancy. It would need to be "extreme".

Lensing Discrepancy – Assembly Bias?





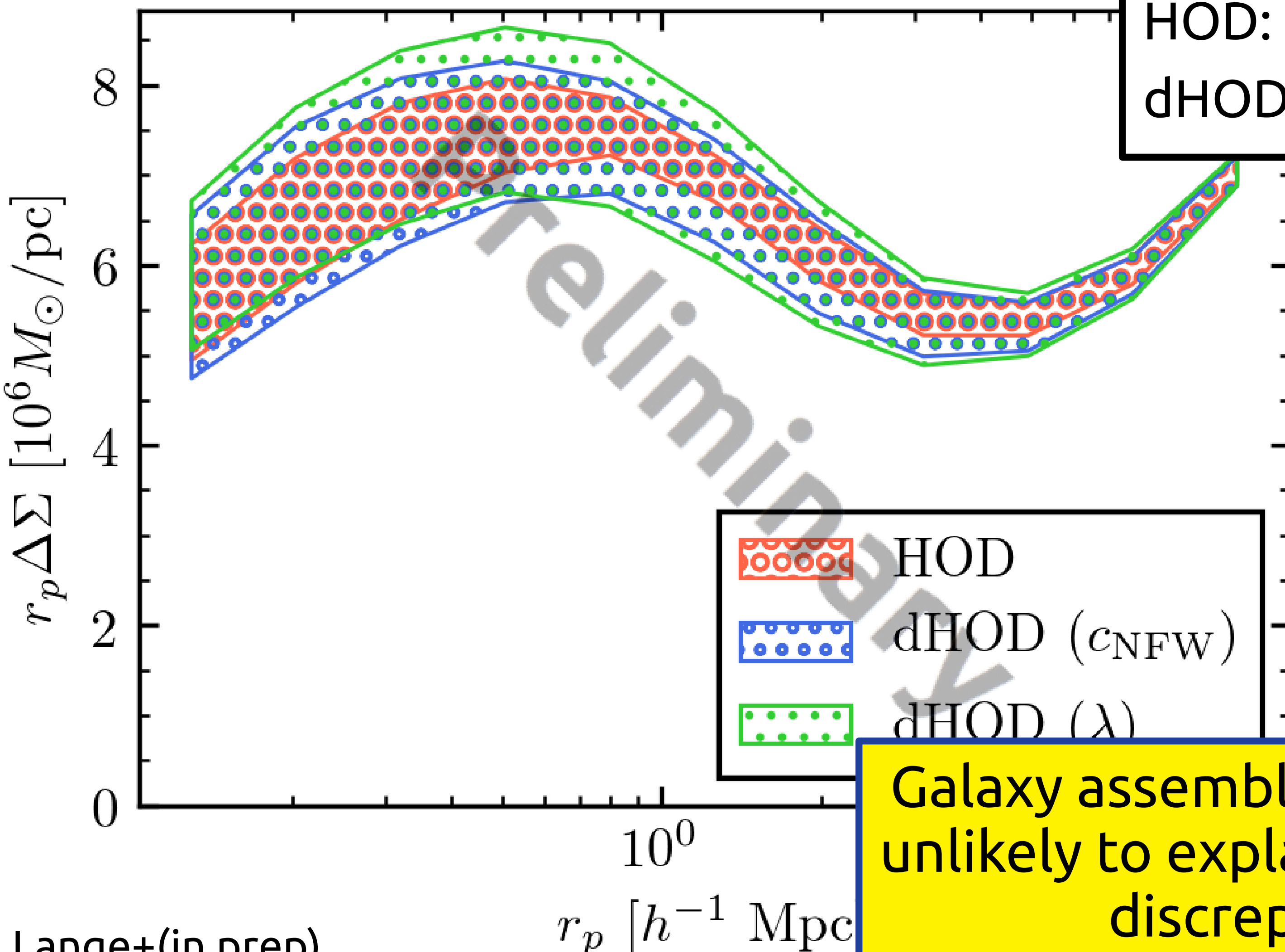
Gao+05

<u>Assembly Bias</u>
Clustering of halos depends on properties other than halo mass.

Lensing Discrepancy – Assembly Bias?

HOD: $N_{gal}(M_{halo})$

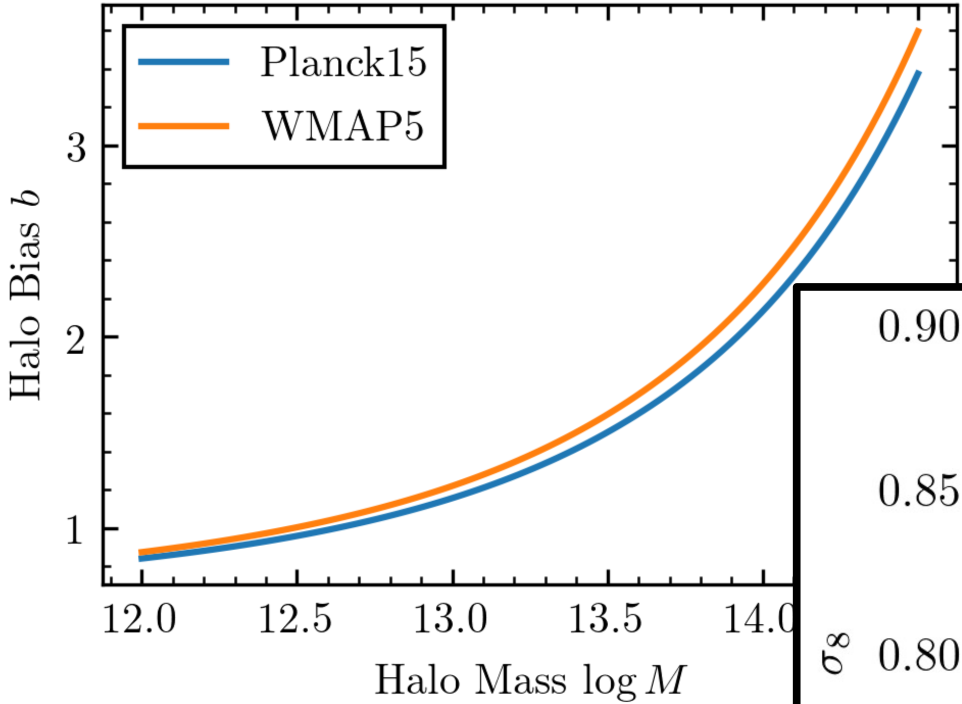
dHOD: $N_{gal}(M_{halo}, x_{halo})$

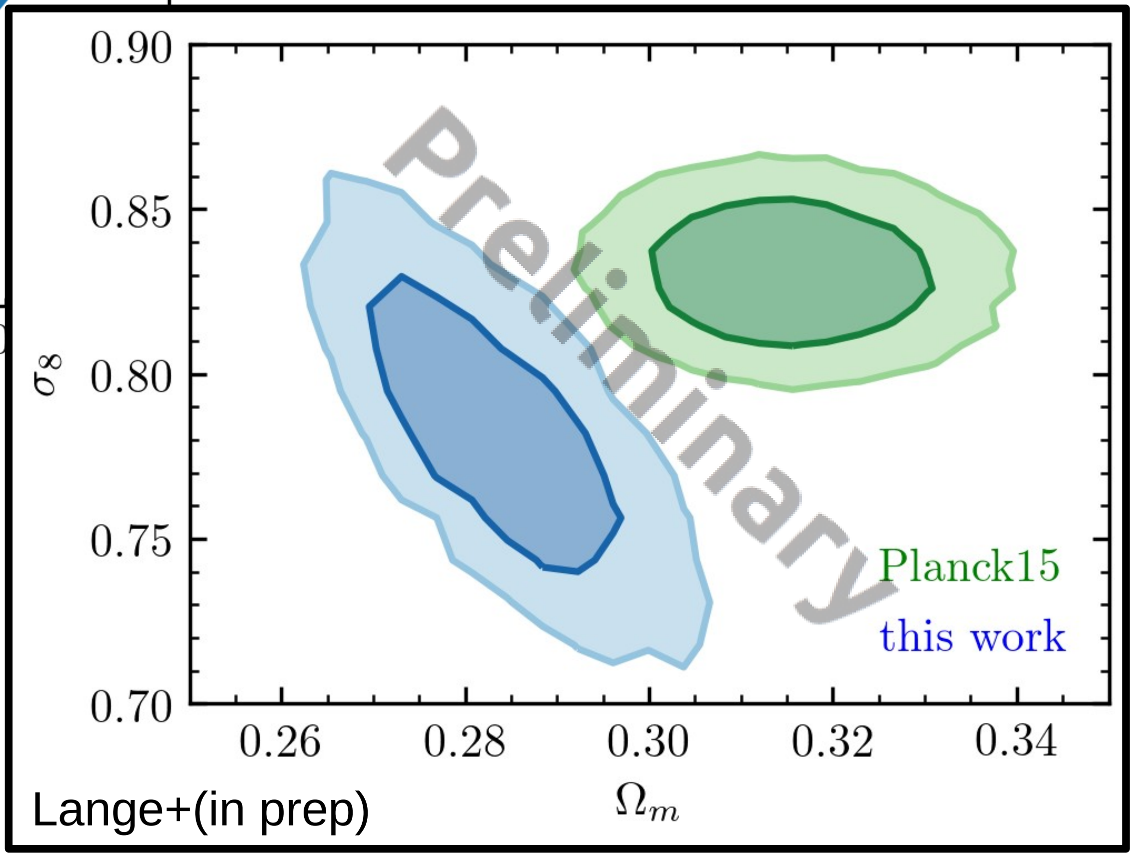


Lange+(in prep)

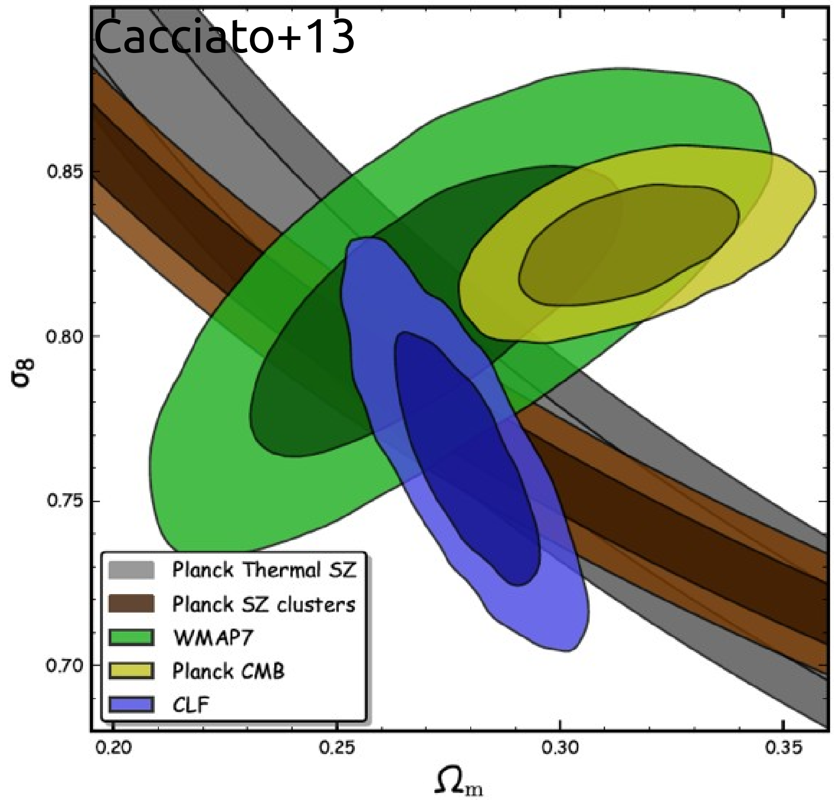
Galaxy assembly bias alone is unlikely to explain the lensing discrepancy.

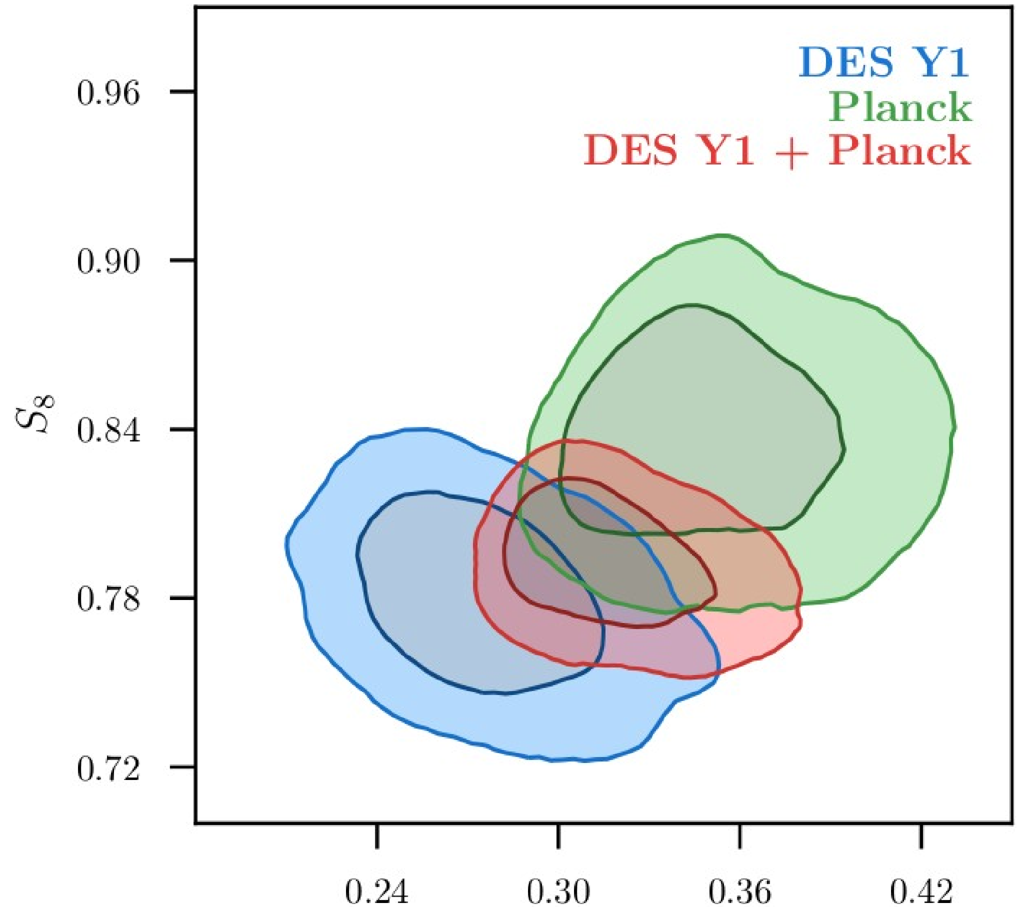
Lensing Discrepancy – Cosmology?





Lensing Discrepancy – Cosmology?



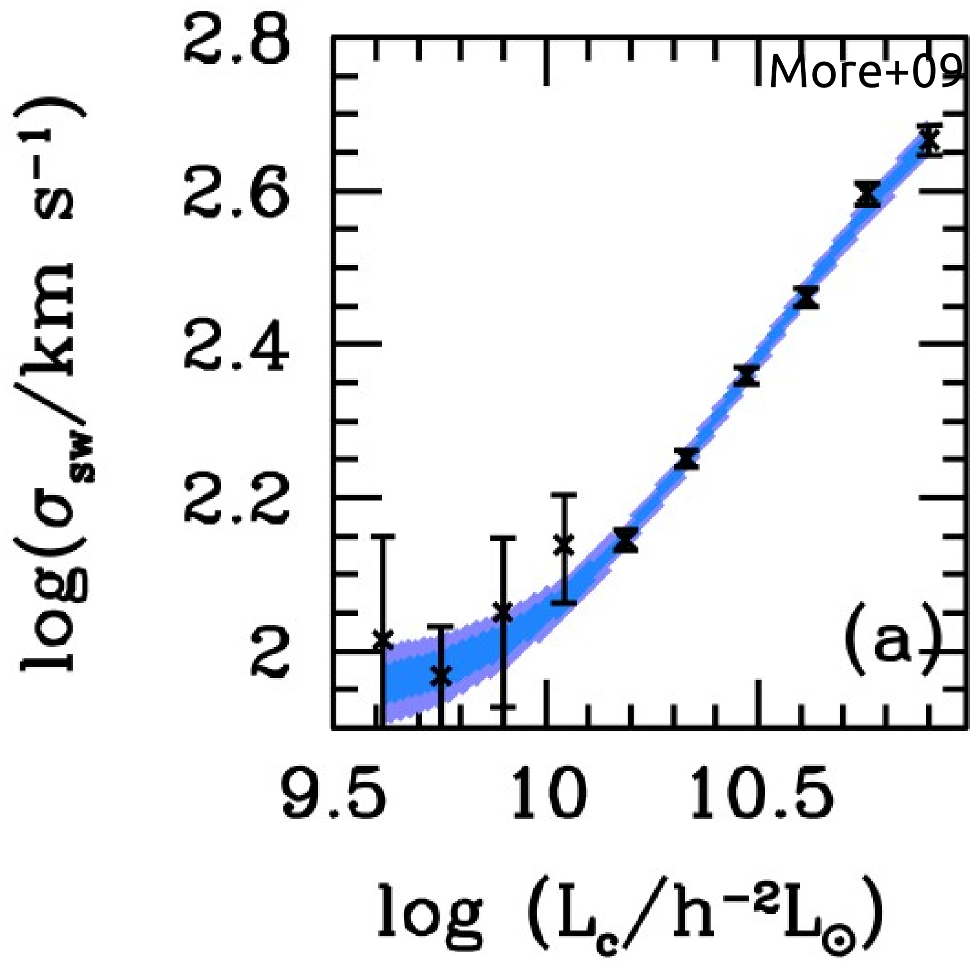


There might be tension between CMB and lensing.

Maturing
Satellite Kinematics

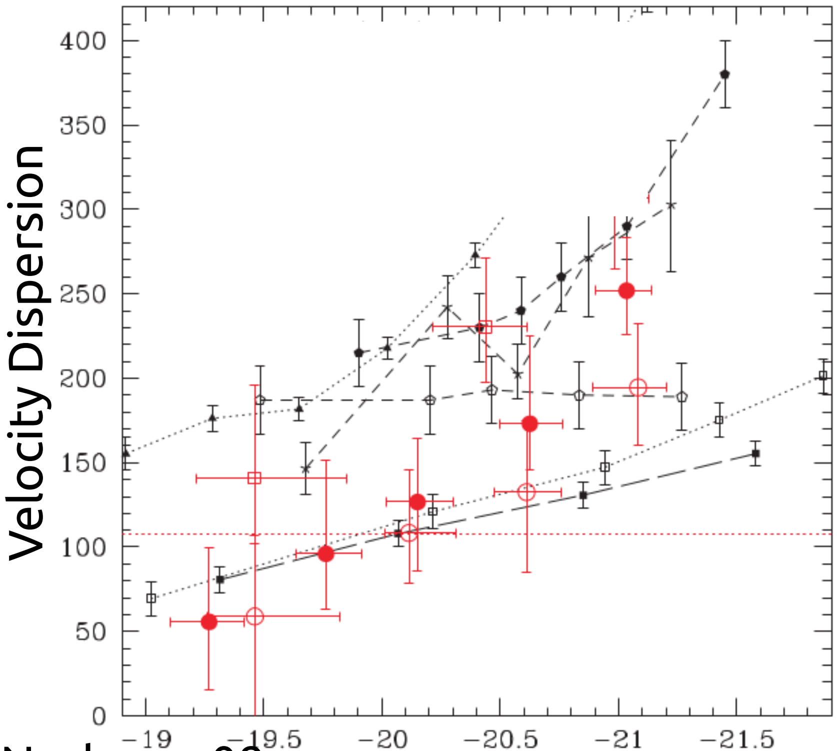
Satellite Kinematics Recipe

1) Identify central and satellite candidates
2) Bin centrals in luminosity, color etc.
3) Stack satellites in each central bin
4) Measure velocity dispersion in each bin
5) Model galaxy-halo connection



$$\sigma^2 \propto M_{vir}/R \quad \text{and} \quad R \propto M_{vir}^{1/3}$$
$$\rightarrow \quad \sigma^2 \propto M_{vir}^{2/3}$$

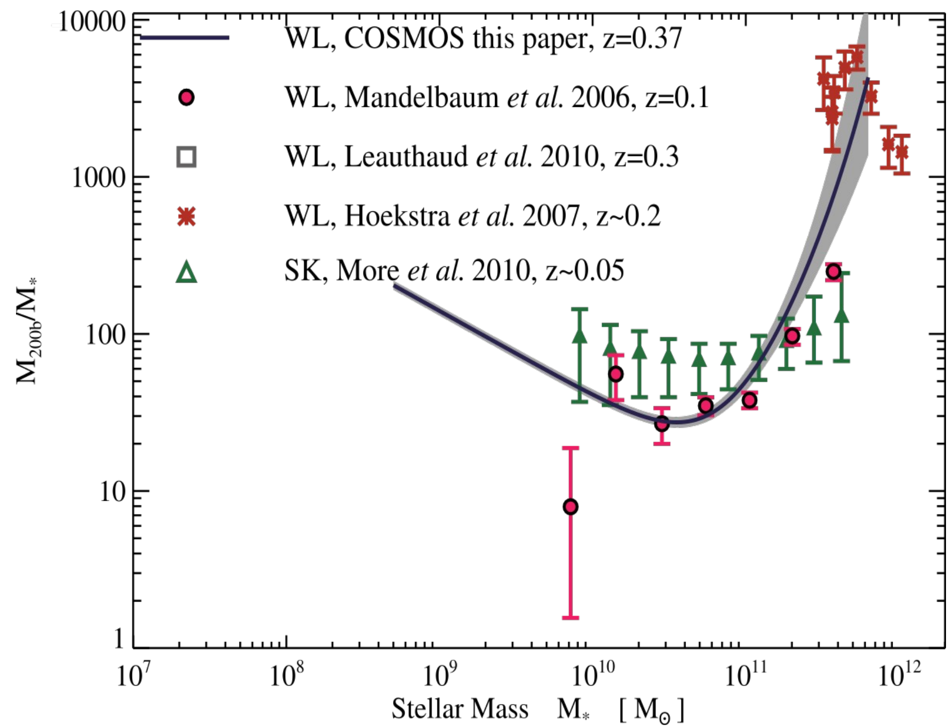
Satellite Kinematics: Where are we now?



Norberg+08

“All the […] methods introduce biases and unless one applies the same selection criterion to […] mock galaxy catalogues […] the results remain questionable.” (Norberg+08)

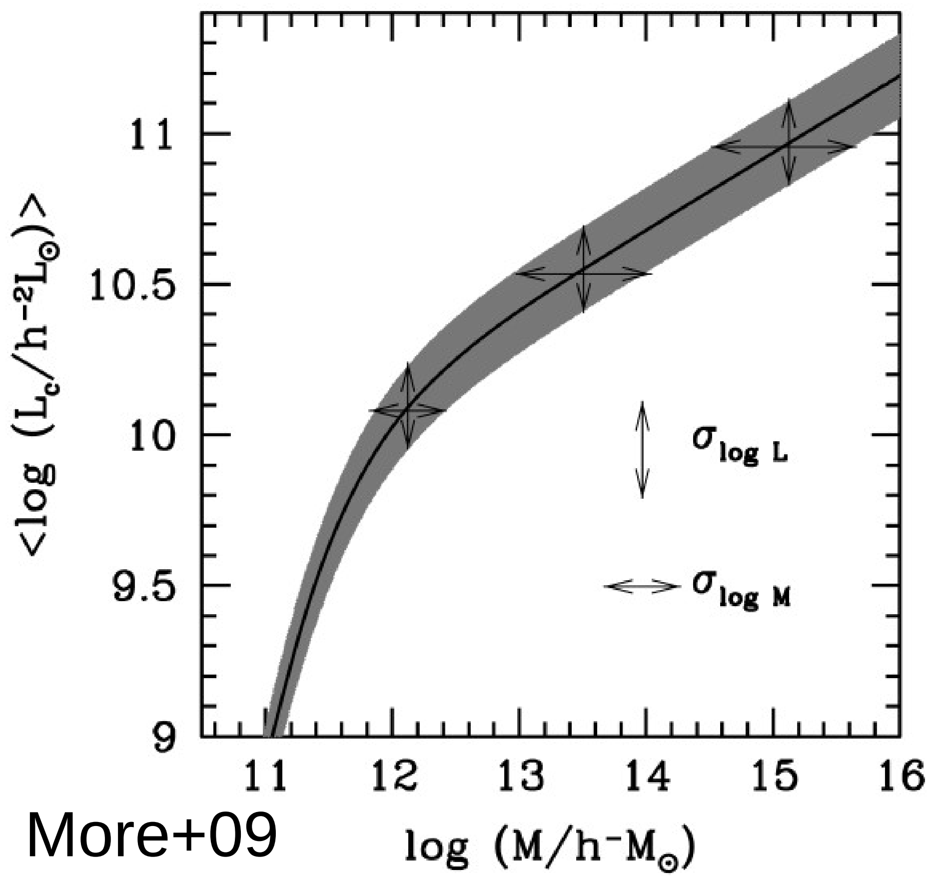
“We observe a clear tension with the results from satellite kinematics (More et al. 2011) […].” (Mandelbaum+15)



Leauthaud+12

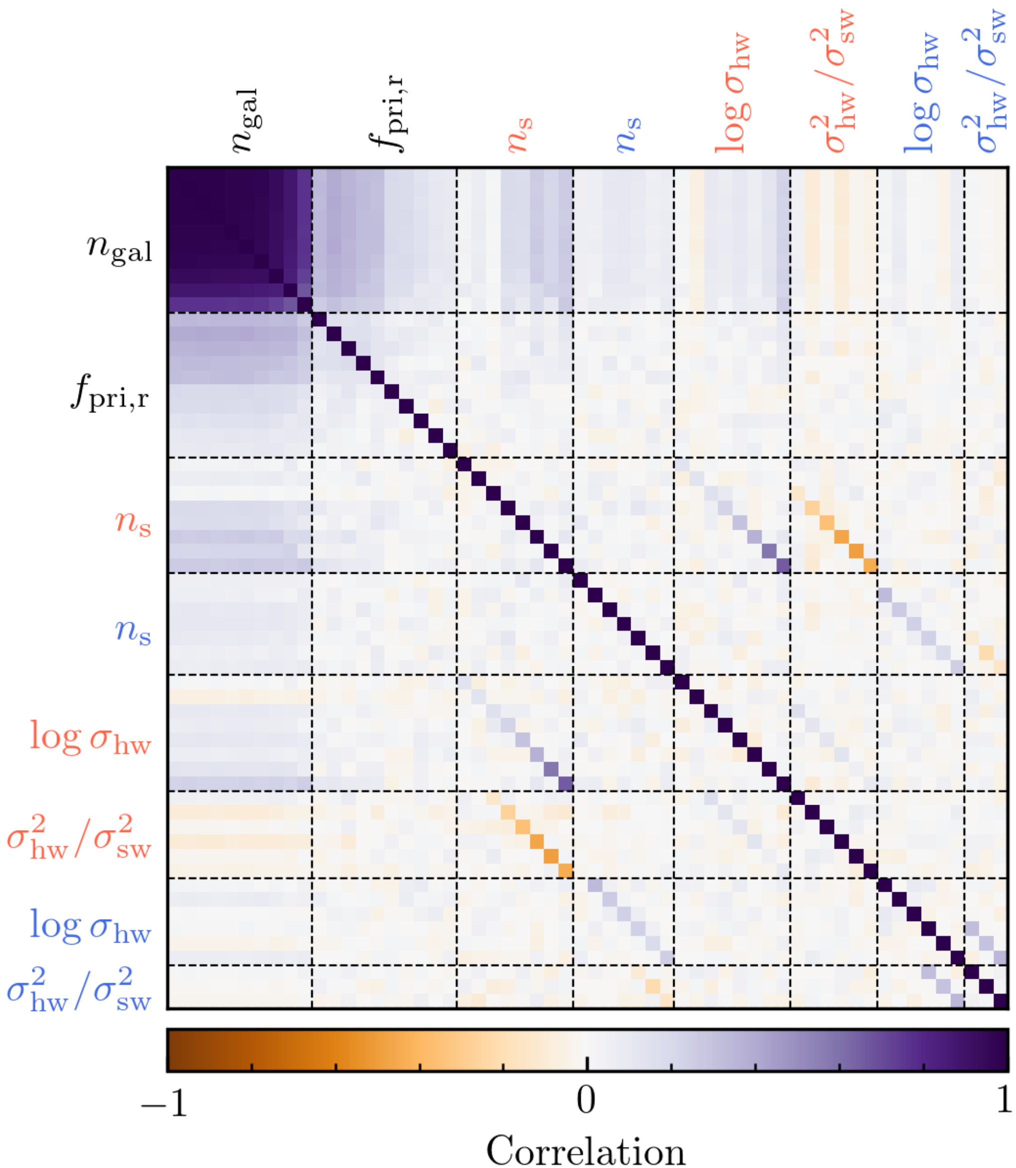
Way of stacking satellites matters!

- not all centrals live in halos of same mass
- satellite weighting (sw): equal weight for each satellite
- host weighting (hw): equal weight for each central
- $\sigma_{hw}/\sigma_{sw} < 1$ measures scatter in halo mass



More+09

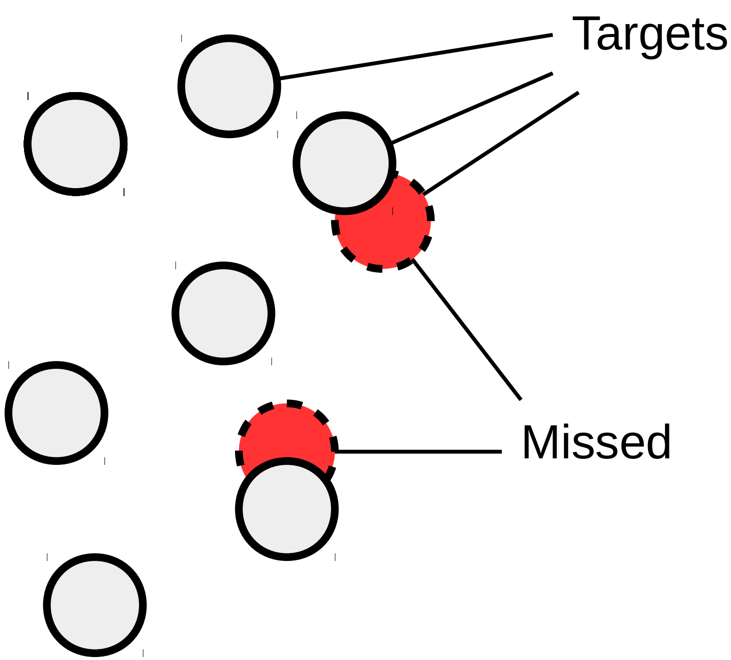
Ways to improve constraining power

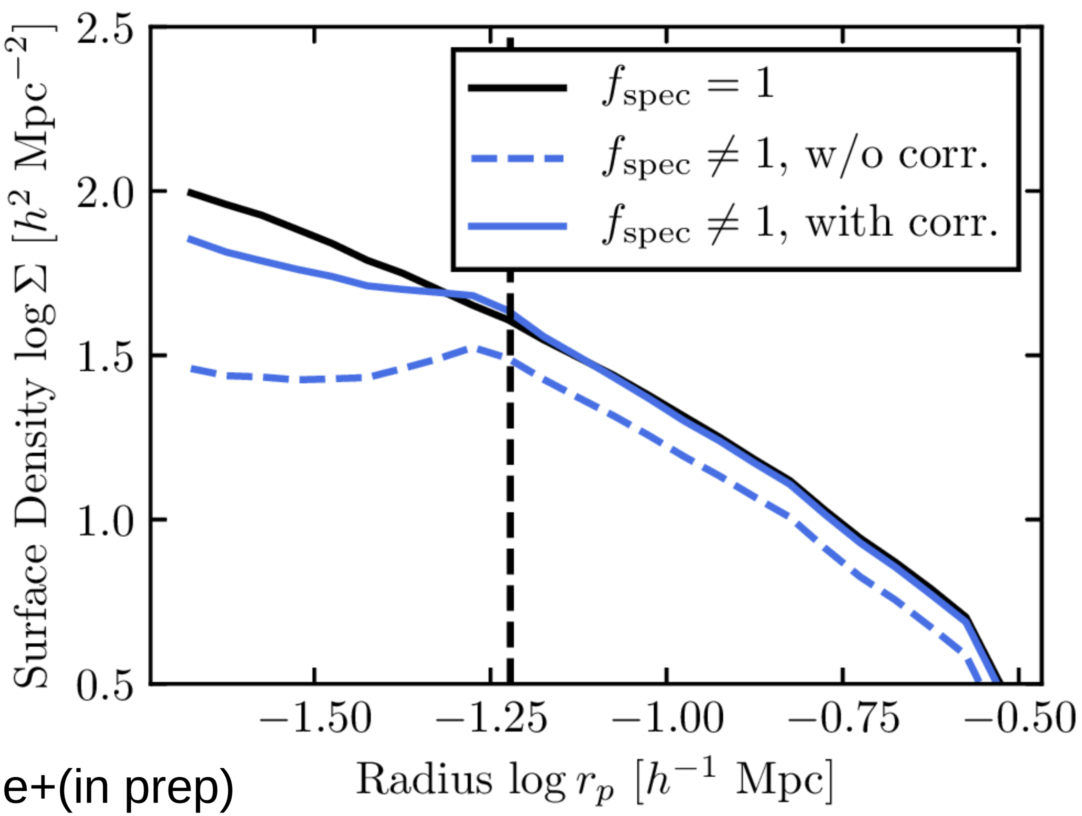


- uncertainties estimated from mock catalogs
- σ_{sw} and σ_{hw} highly correlated

  → better constraint on halo mass scatter

Fiber collisions are an issue!





Lange+(in prep)

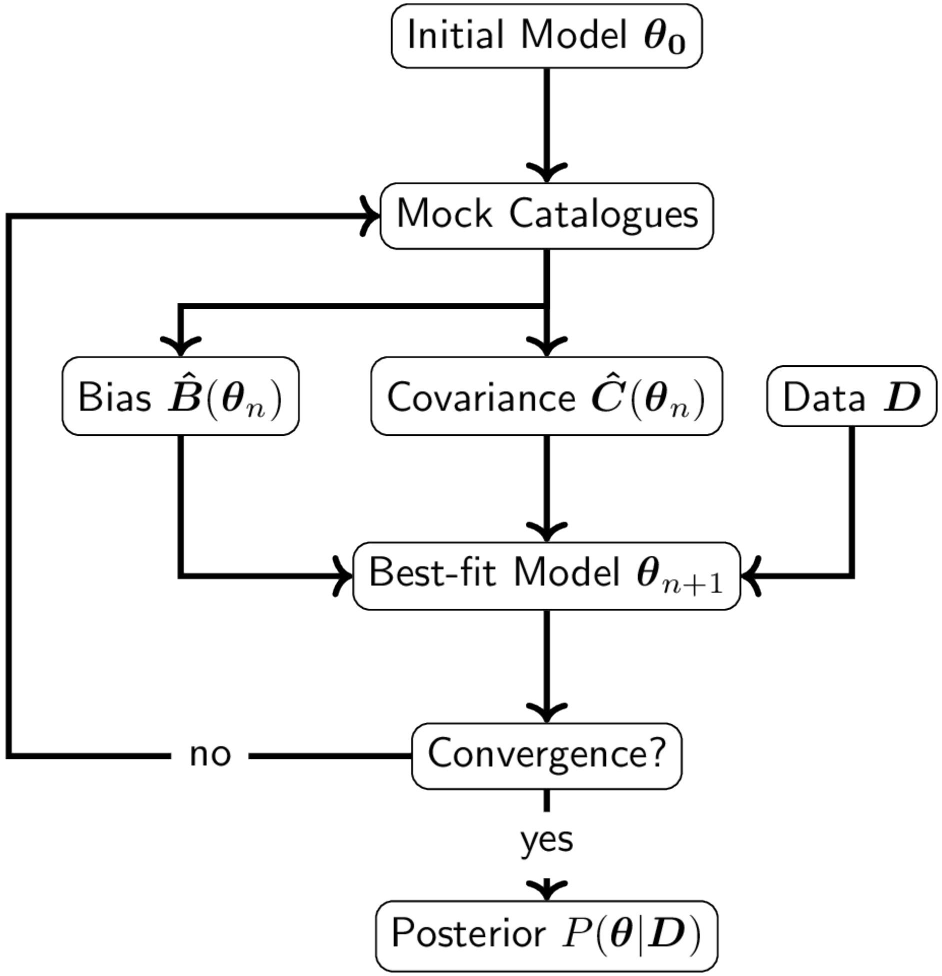
Not correcting for fiber collisions leads to systematically underestimated halo masses.

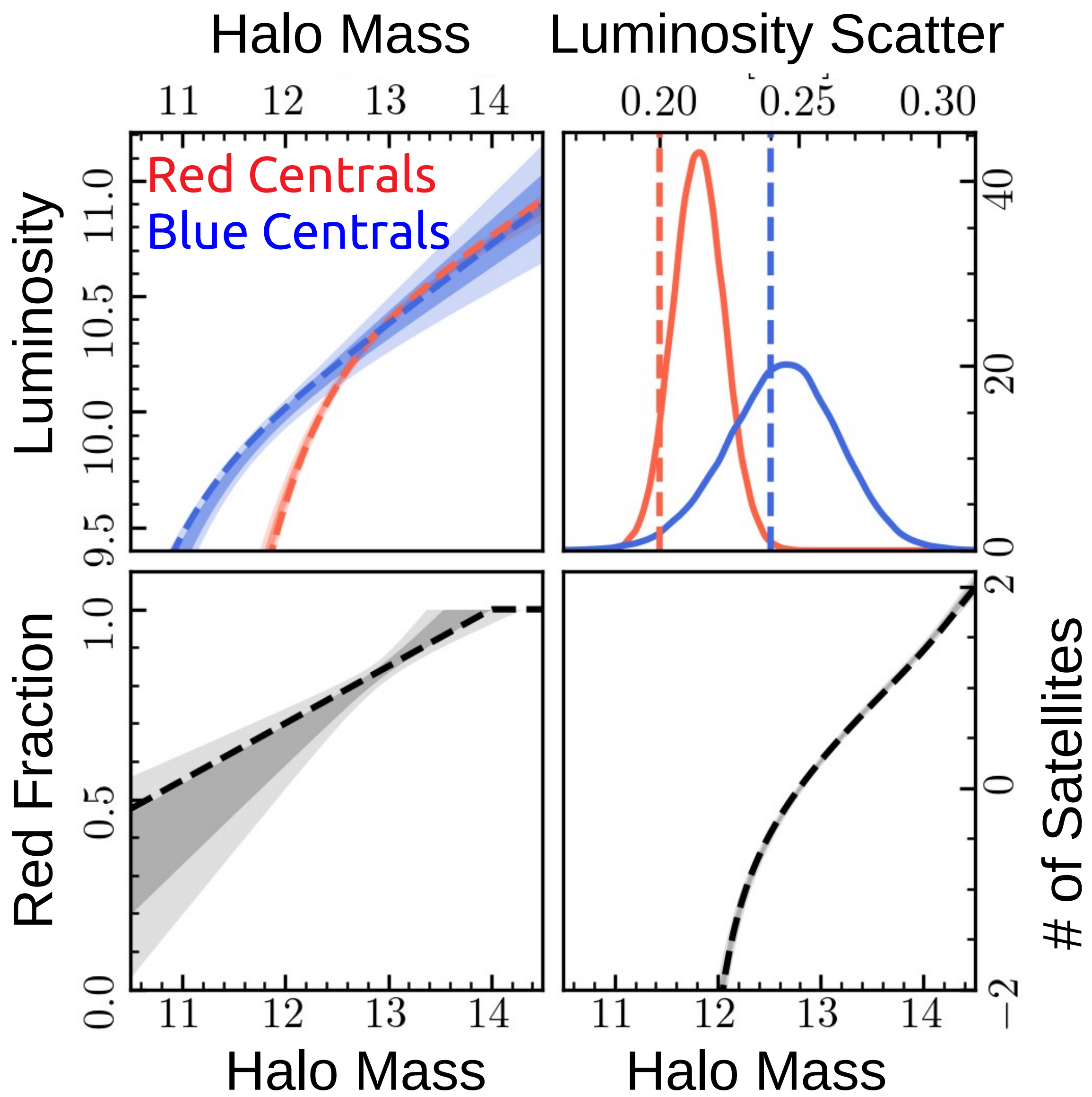
Correcting for Bias of Analytical Model

- analytic model for velocity dispersion

$$\sigma^2(L_1, L_2) \approx \frac{\int_{L_1}^{L_2}\int_0^{\infty} w(L,M)\,\sigma_{\mathrm{ap}}^2(L,M)\,n_{\mathrm{h}}(M)\,\Phi_{\mathrm{c}}(L|M)\,\mathrm{d}M\,\mathrm{d}L}{\int_{L_1}^{L_2}\int_0^{\infty} w(L,M)\,n_{\mathrm{h}}(M)\,\Phi_{\mathrm{c}}(L|M)\,\mathrm{d}M\,\mathrm{d}L}$$

- various biases exist
- calibration with best fit model (recursive)



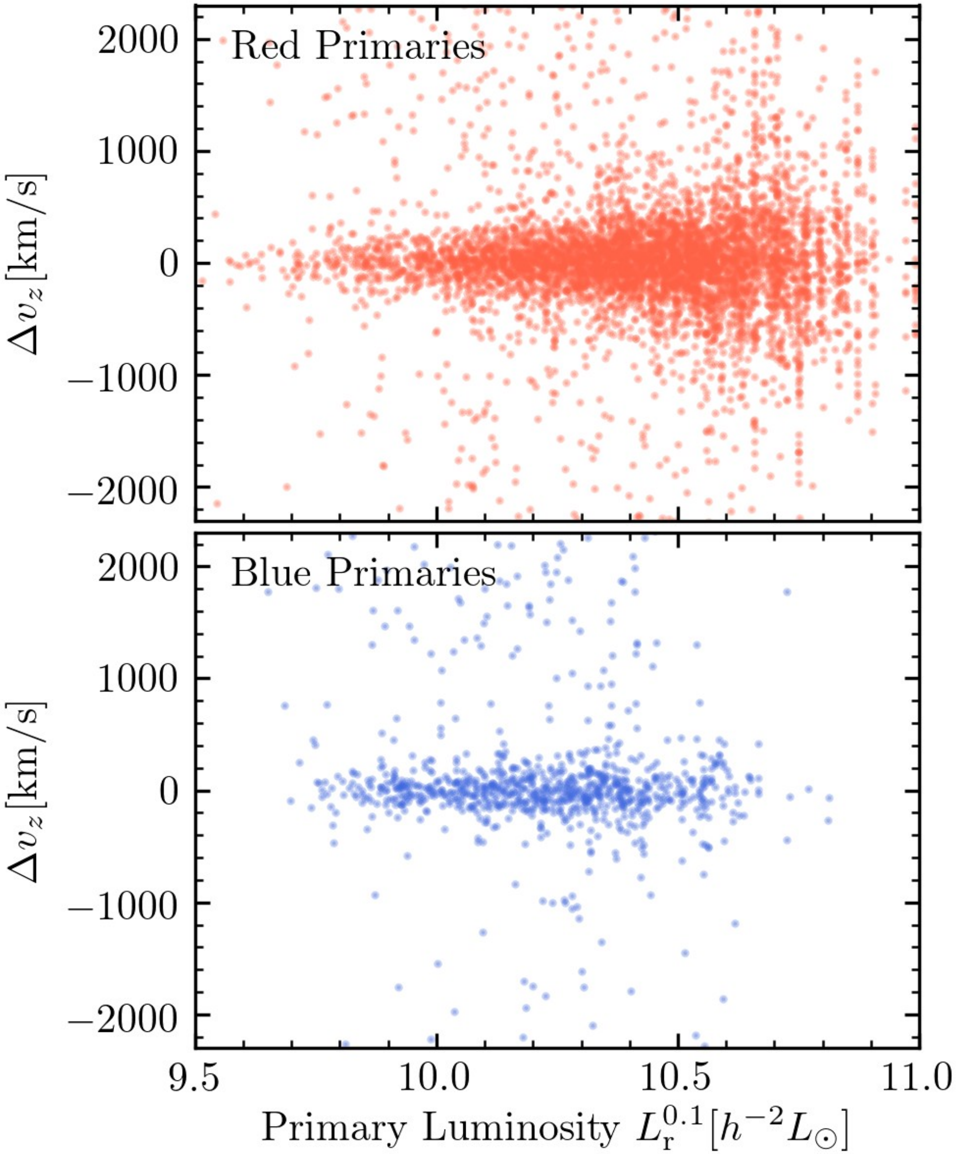


Satellite kinematics constraints are close to unbiased and very competitive compared to clustering + lensing.

Satellite Kinematics in SDSS DR7

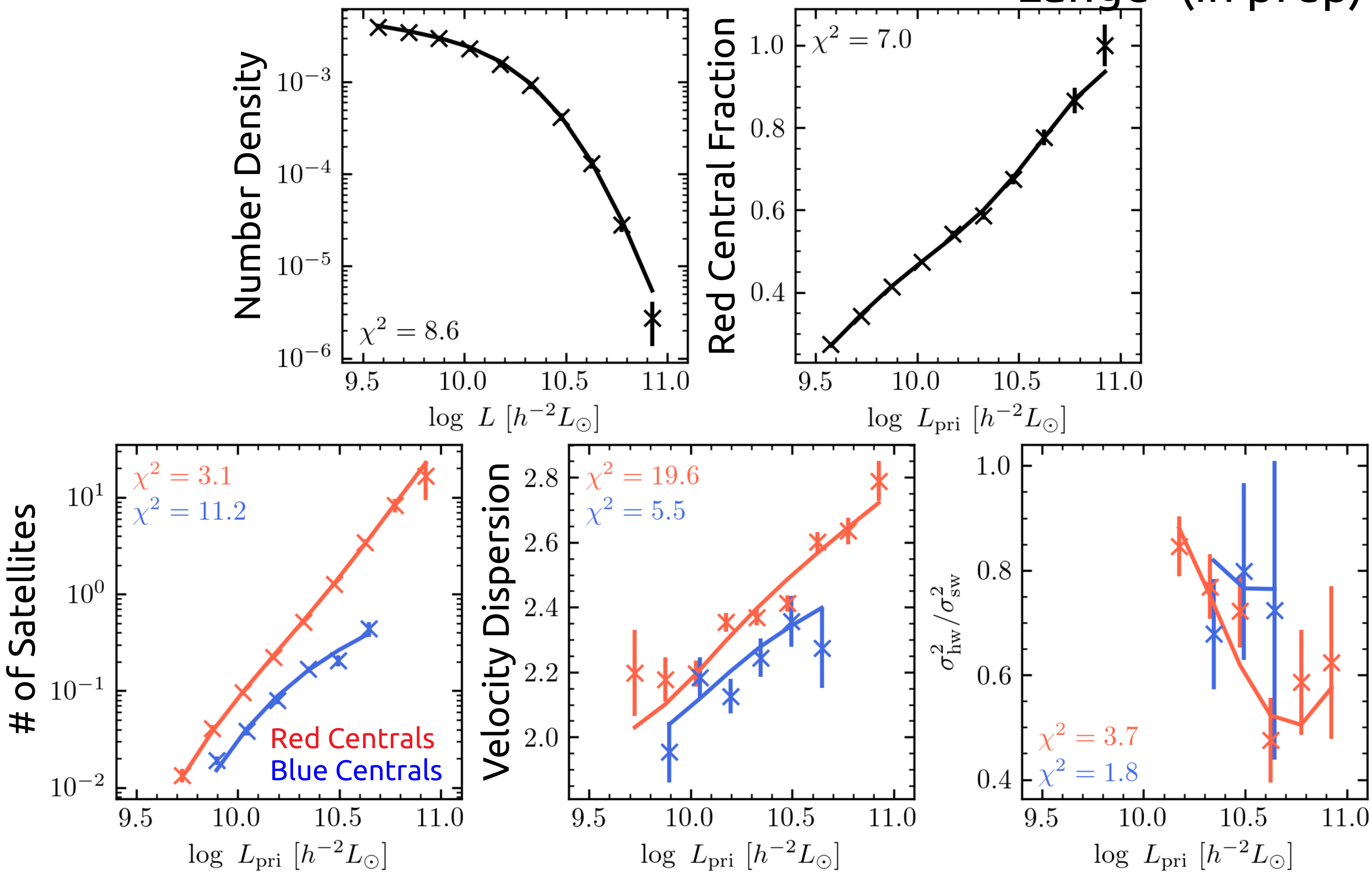
New Constraints from SDSS DR7

- DR7, galaxies with 0.02 < z < 0.067, L > $10^{9.5}$
- ~45,000 centrals, ~7,000 satellites
- red galaxies at fixed luminosity have more satellites/higher velocity dispersion

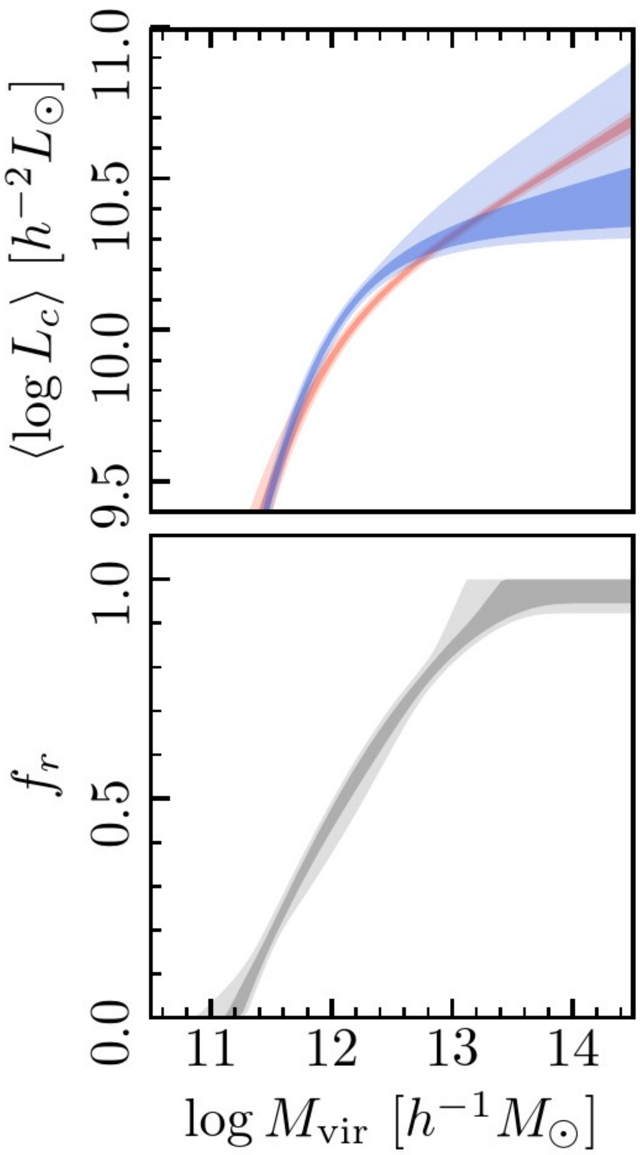


Model can accurately fit SDSS DR7

Lange+(in prep)



Mass-Luminosity Relation

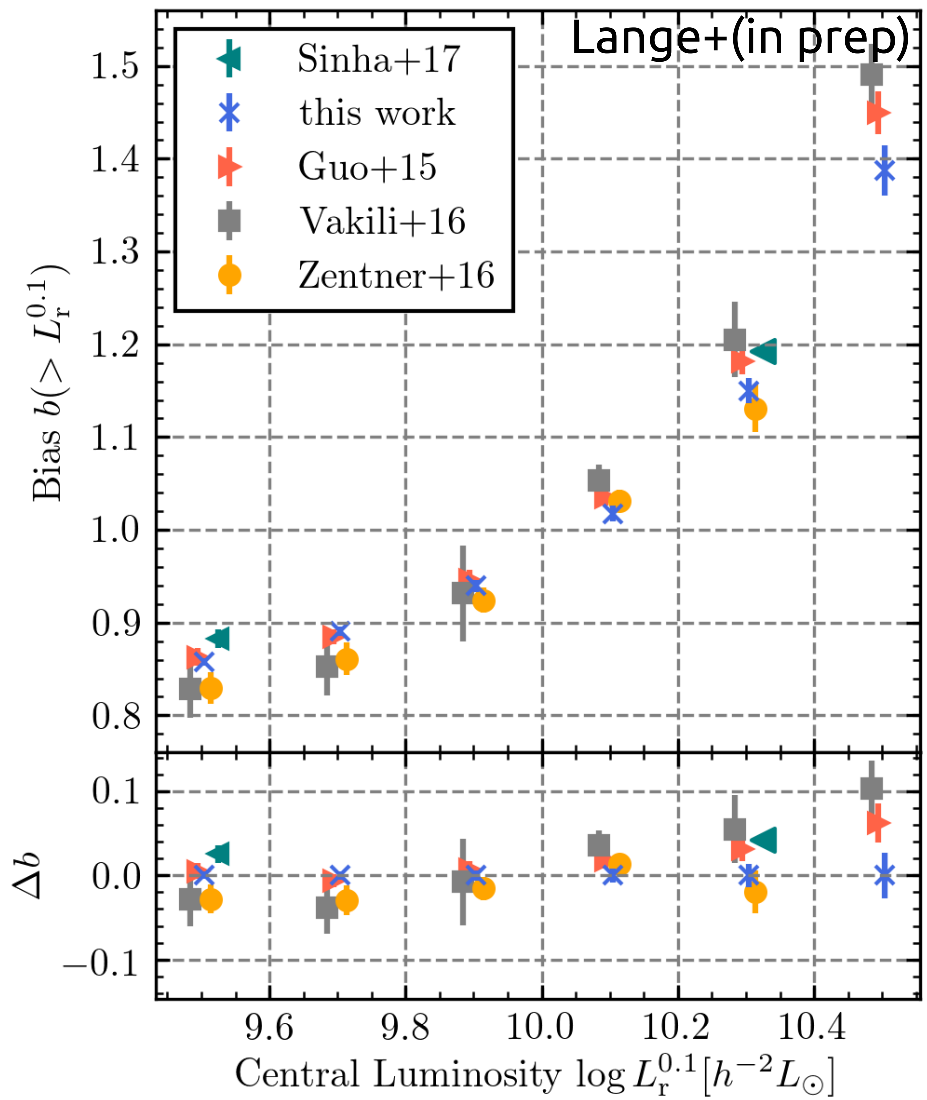


- red centrals live in more massive halos than blue ones
- but, red and blue centrals have similar mass-luminosity relations
- solution: red fraction of centrals increases with halo mass

Halo mass is a main driver of galaxy quenching.

see also e.g. More+11, Zu+15, Mandelbaum+16

Comparison with previous studies



- Bias b ↔ Mass M, determines clustering
- sat. kin. in blue, other results from clustering/group cat.
- total mass increases with cen. luminosity

Results from sat. kin. are in good agreement with other studies.

Summary

- tension between results from (projected) clustering, lensing and satellite kinematics on small scales
- clustering + lensing tension unlikely explained by AGN feedback or assembly bias alone, tension with Planck CMB?
- matured satellite kinematics into competitive probe, good agreement with projected clustering results
- future work:
  - comparison lensing – kinematics
  - stellar-to-halo mass relation and scatter
  - secondary galaxy / halo properties