# Probing Galaxy Formation and Cosmology in the Non-Linear Regime

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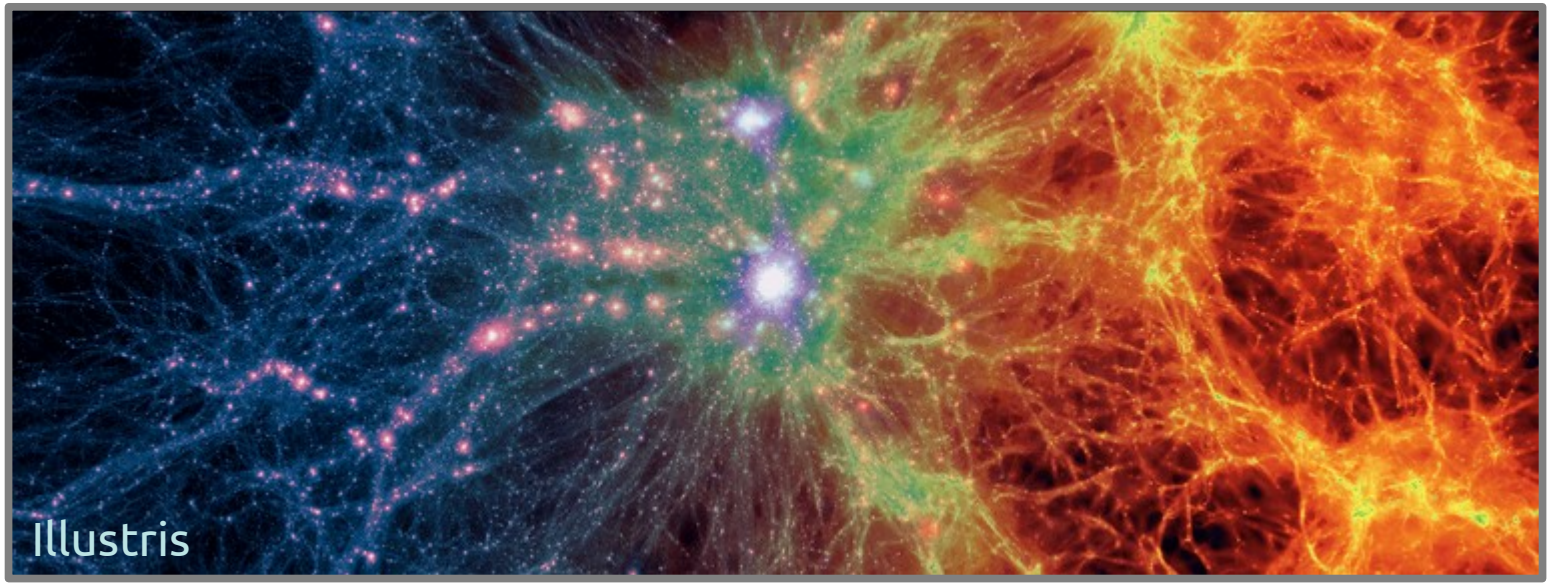
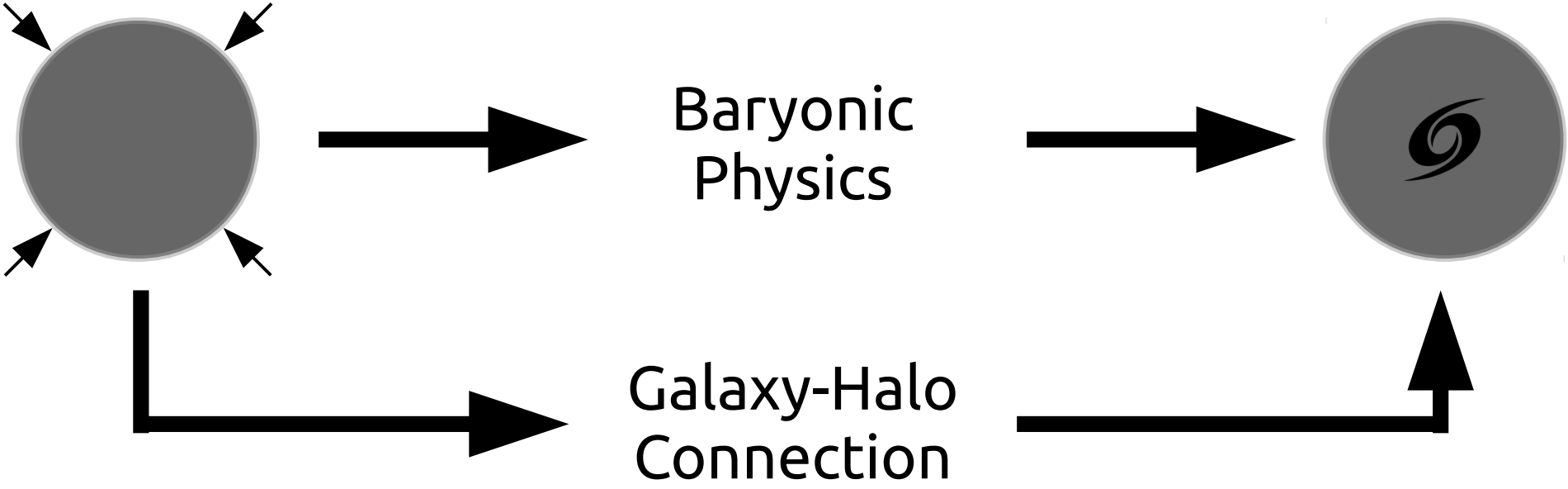
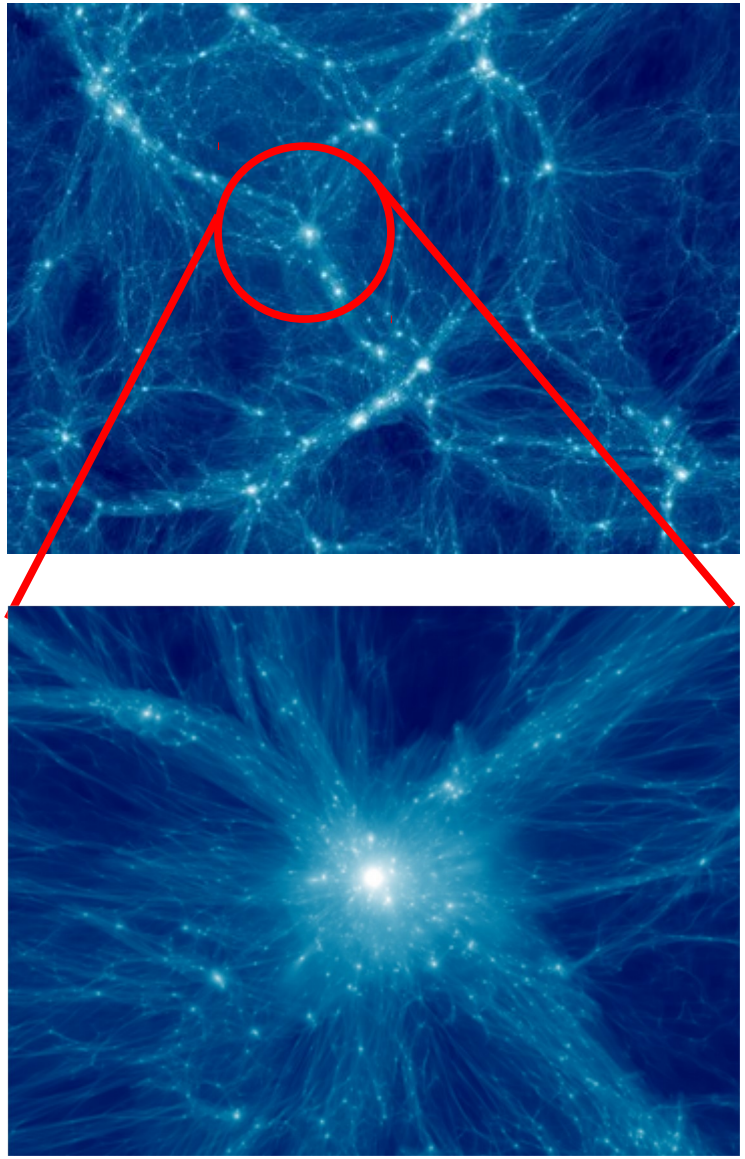
# The ΛCDM Paradigm



# Non-Linear Scales



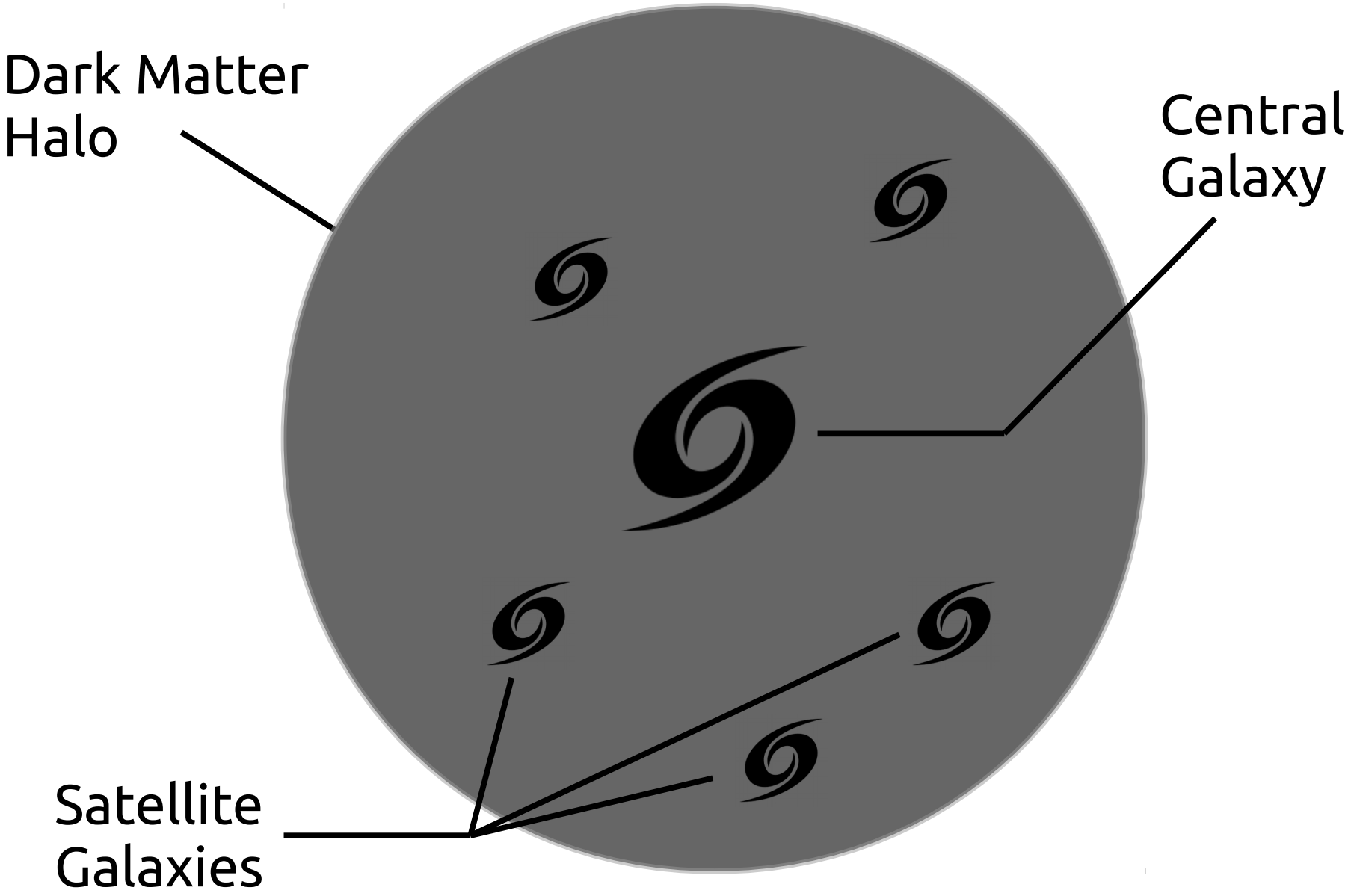
(Quasi-)Linear Scales:

- density contrast < O(1)
- cross-correlation $r_{gm} = 1$
- structure formation analytically tractable

Non-Linear Scales:

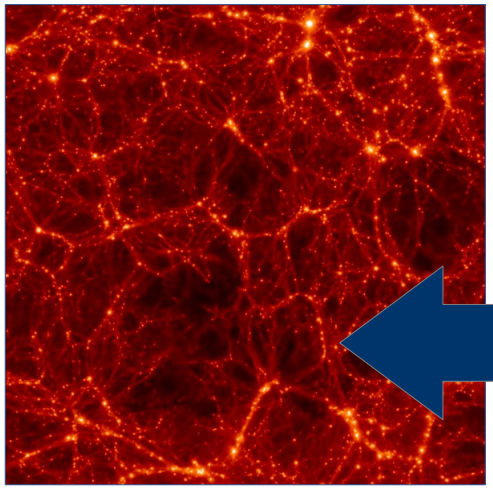
- density contrast ≥ O(1)
- cross-correlation $r_{gm} \neq 1$
- requires N-body simulations

# The Dark Matter Halo

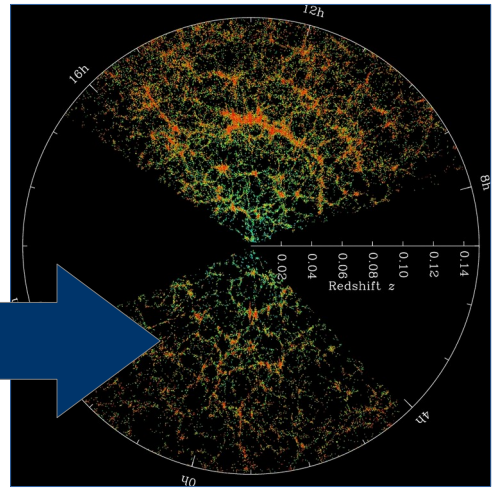


# Galaxy-Halo Connection - Basics

Dark Matter Field



Galaxy Distribution

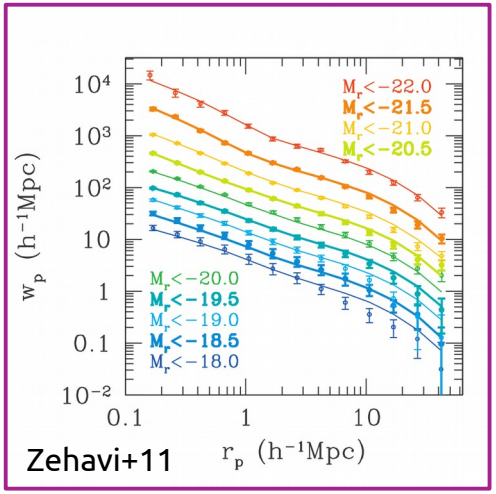



Galaxy-Halo Connection

Galaxy-Halo Connection:

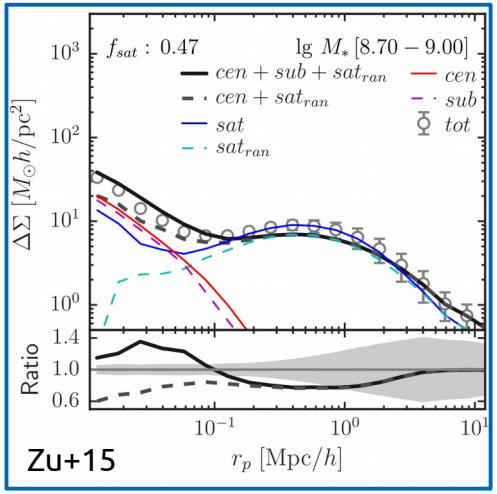
- $N_{gal}(M_{halo})$ aka HOD
- $<L_{gal}>(M_{halo})$
- satellite radial profile
- ...

Galaxy Clustering



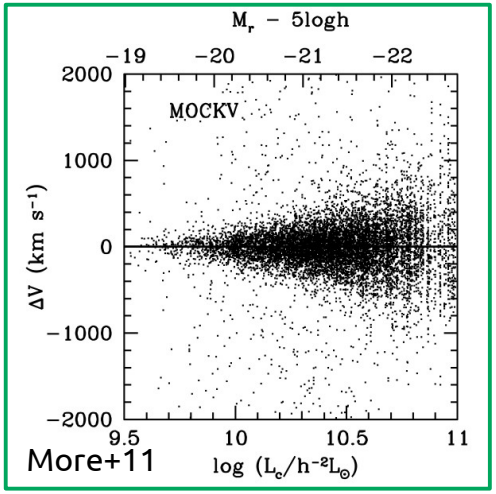

Zehavi+11

Galaxy-Galaxy Lensing




Zu+15

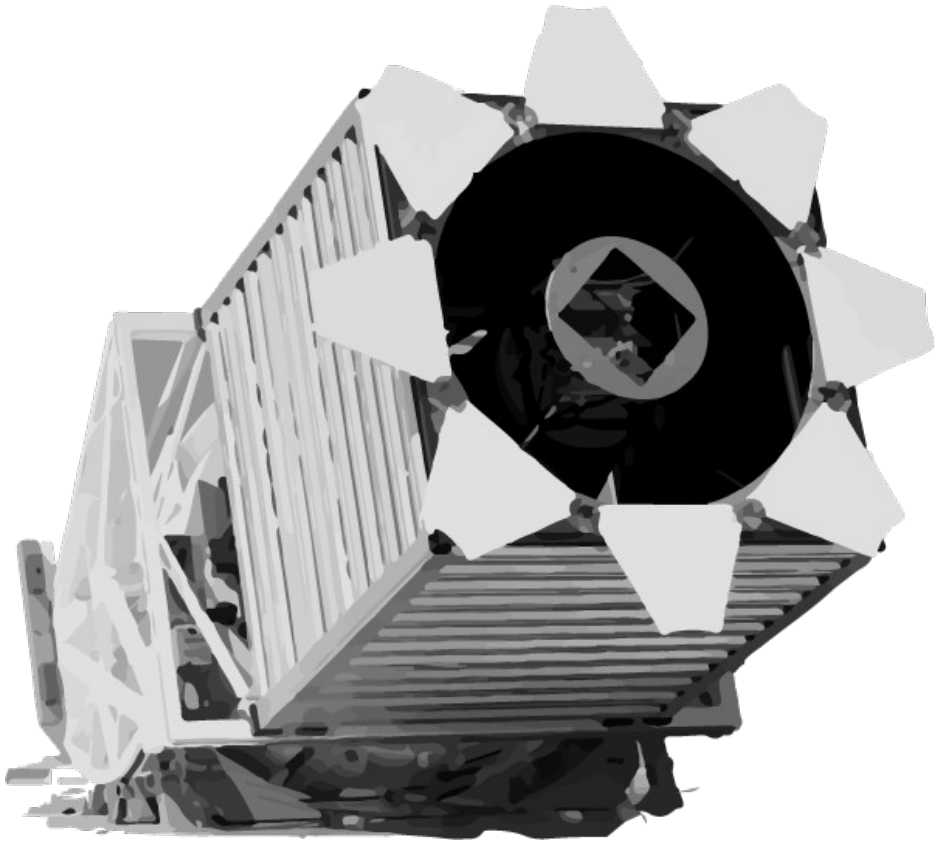
Satellite Kinematics




More+11

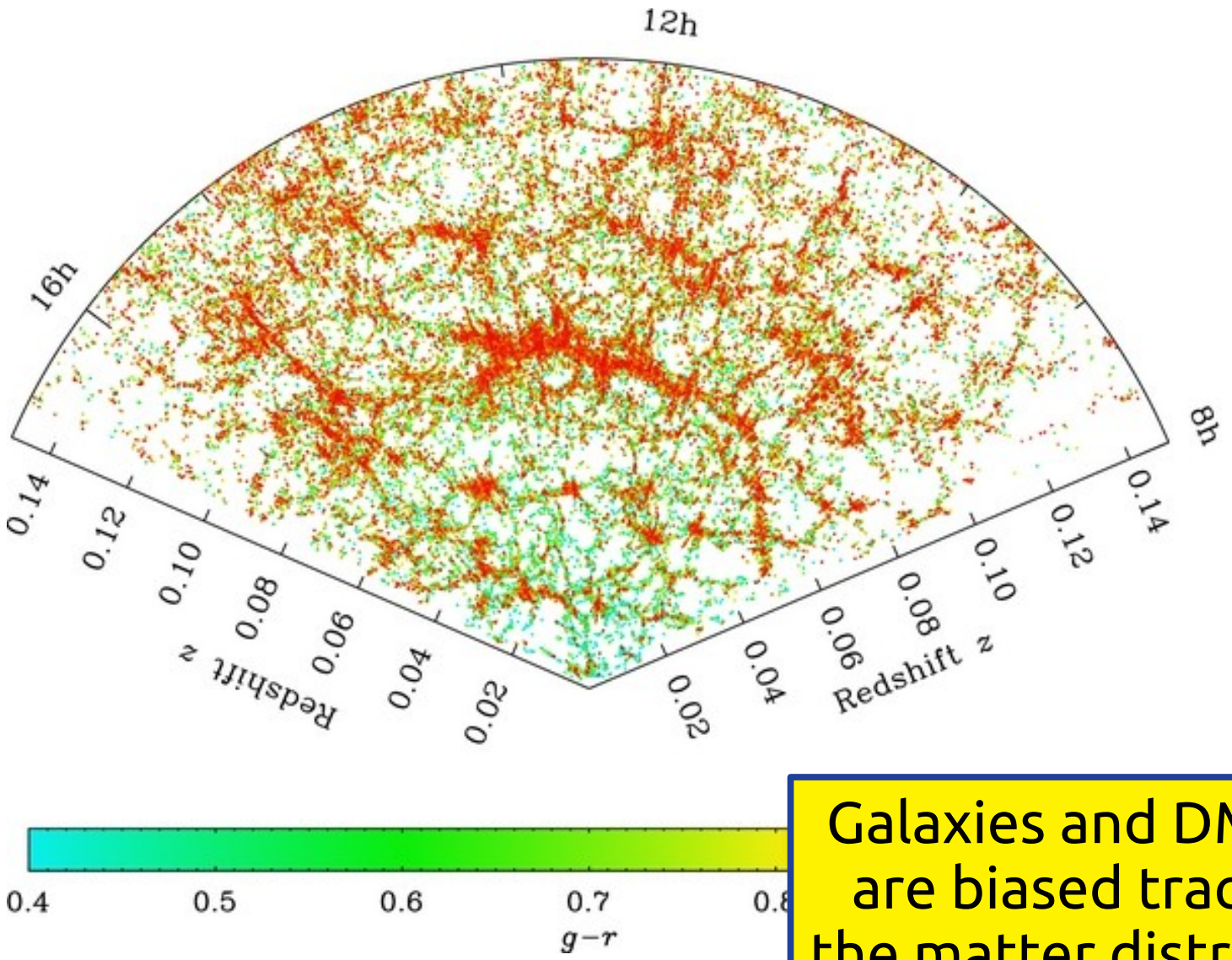
# Outline

- Empirical Modeling of the Galaxy-Halo Connection
- BOSS Clustering + Lensing Discrepancy
- New Methods for Satellite Kinematics
- SDSS Constraints from Satellite Kinematics
- Future of Non-Linear Scales



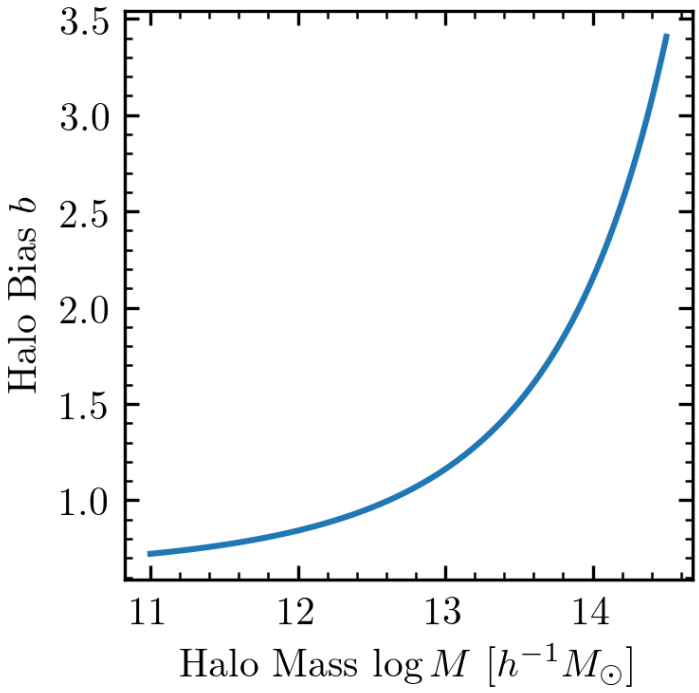
# BOSS Lensing Discrepancy

# Inferences from Galaxy Clustering

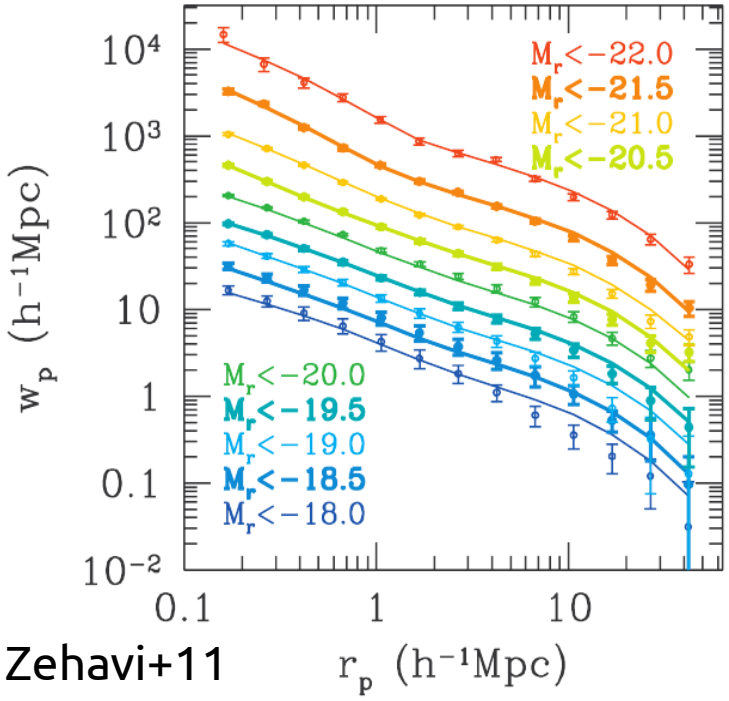



Galaxies and DM halos are biased tracers of the matter distribution.

# Inferences from Galaxy Clustering




More massive halos are more strongly clustered.

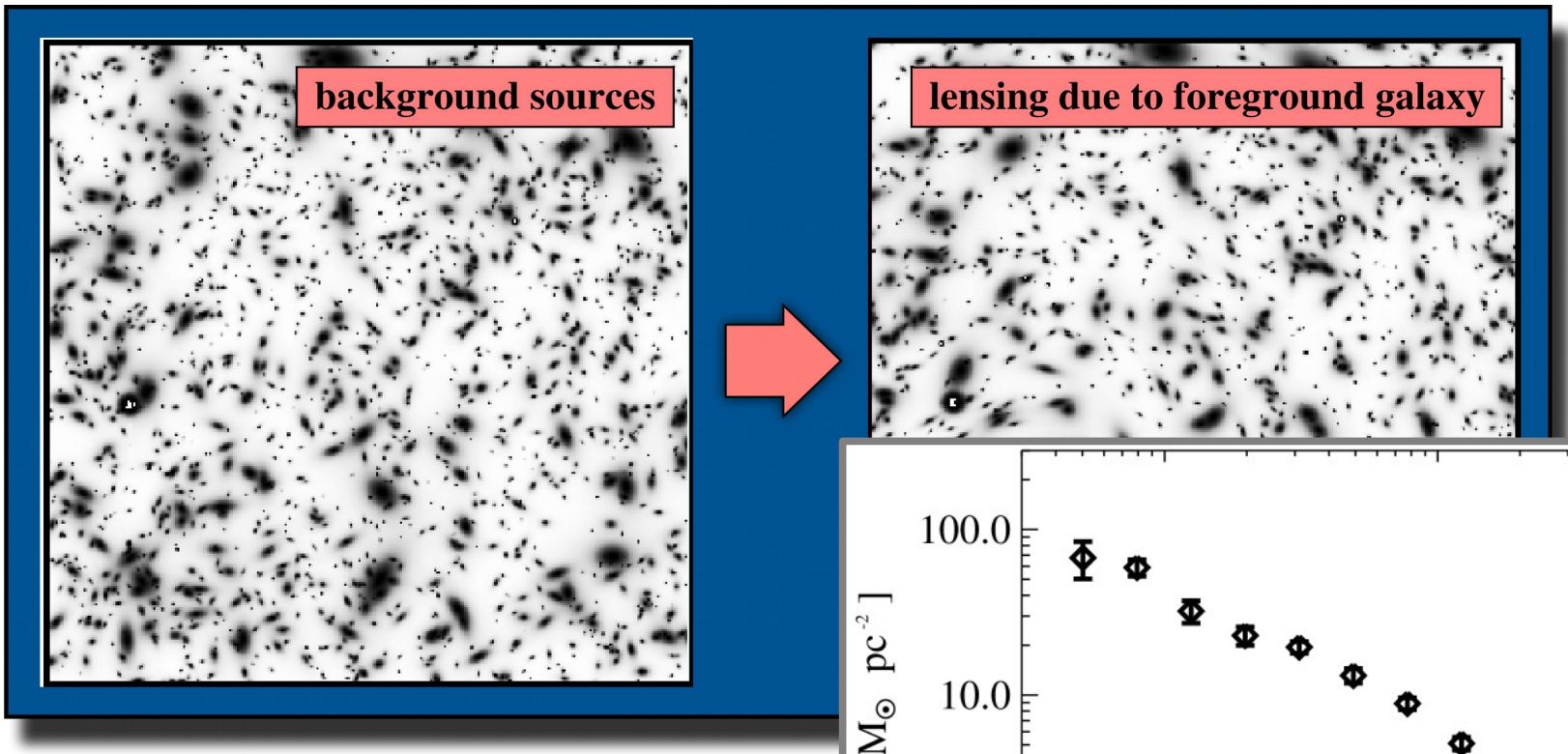


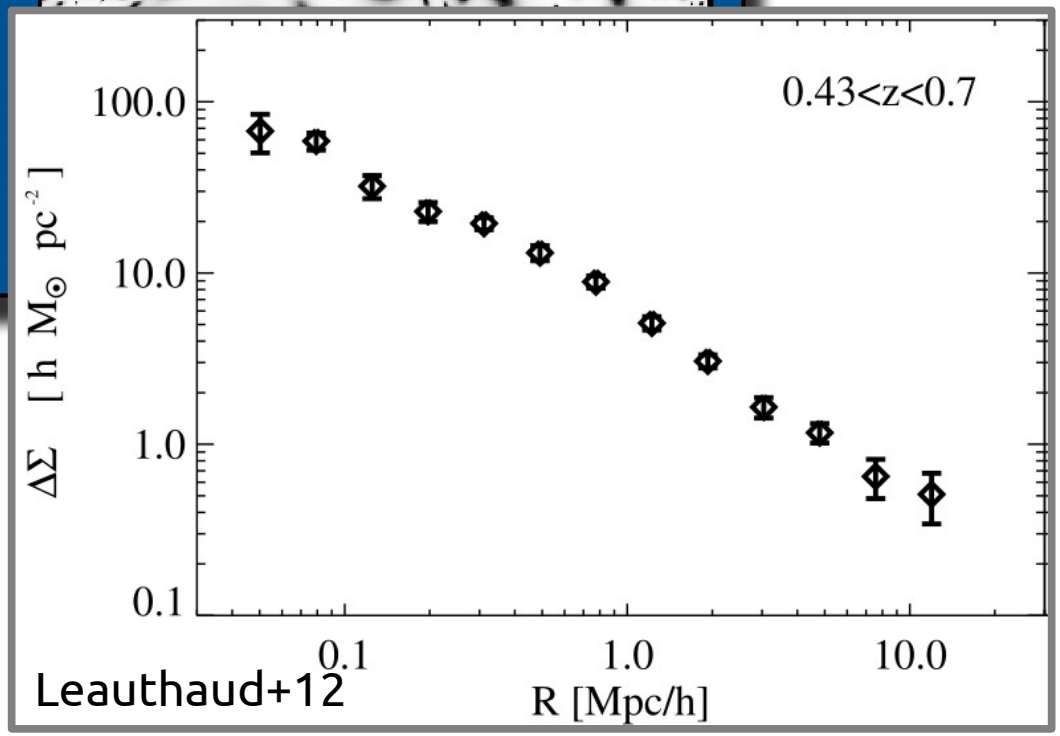

Zehavi+11

More luminous galaxies are more strongly clustered.

More luminous galaxies live in more massive DM halos.

# Inferences from Galaxy-Galaxy Lensing

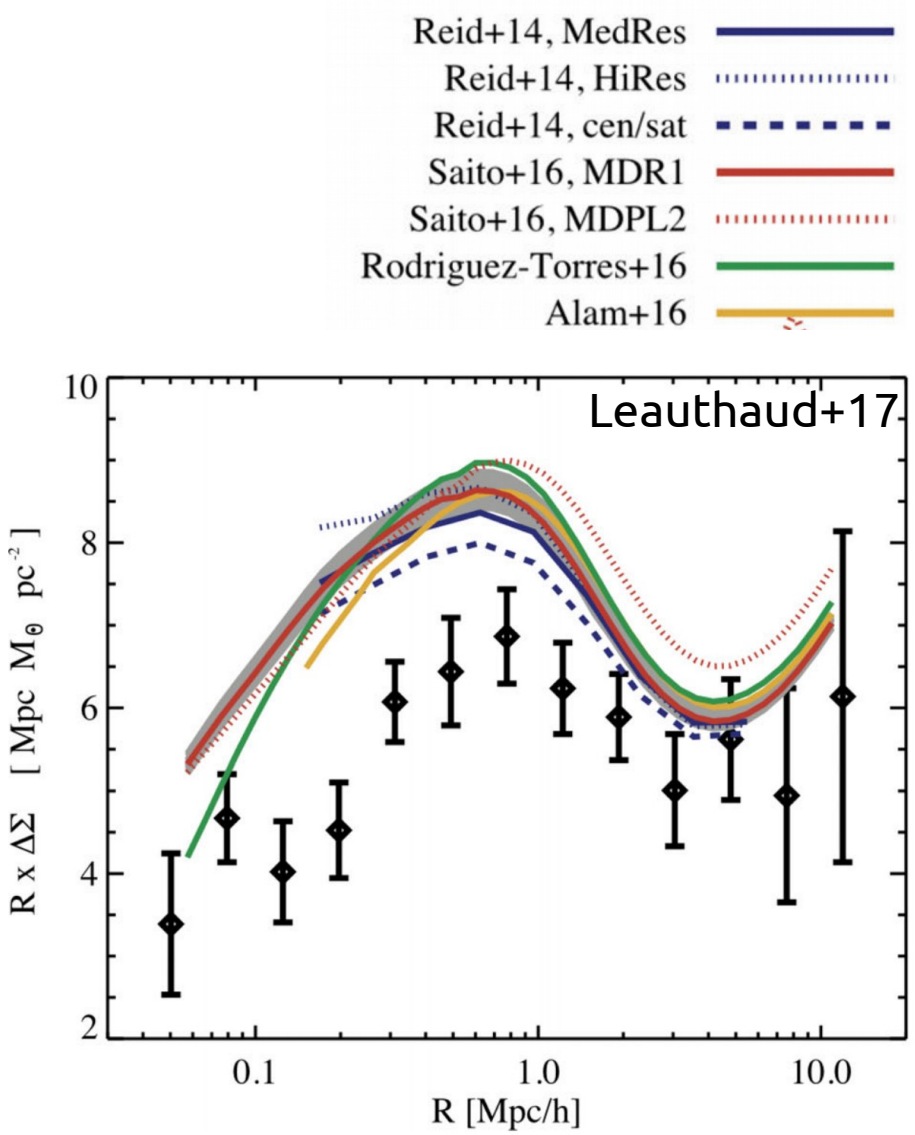


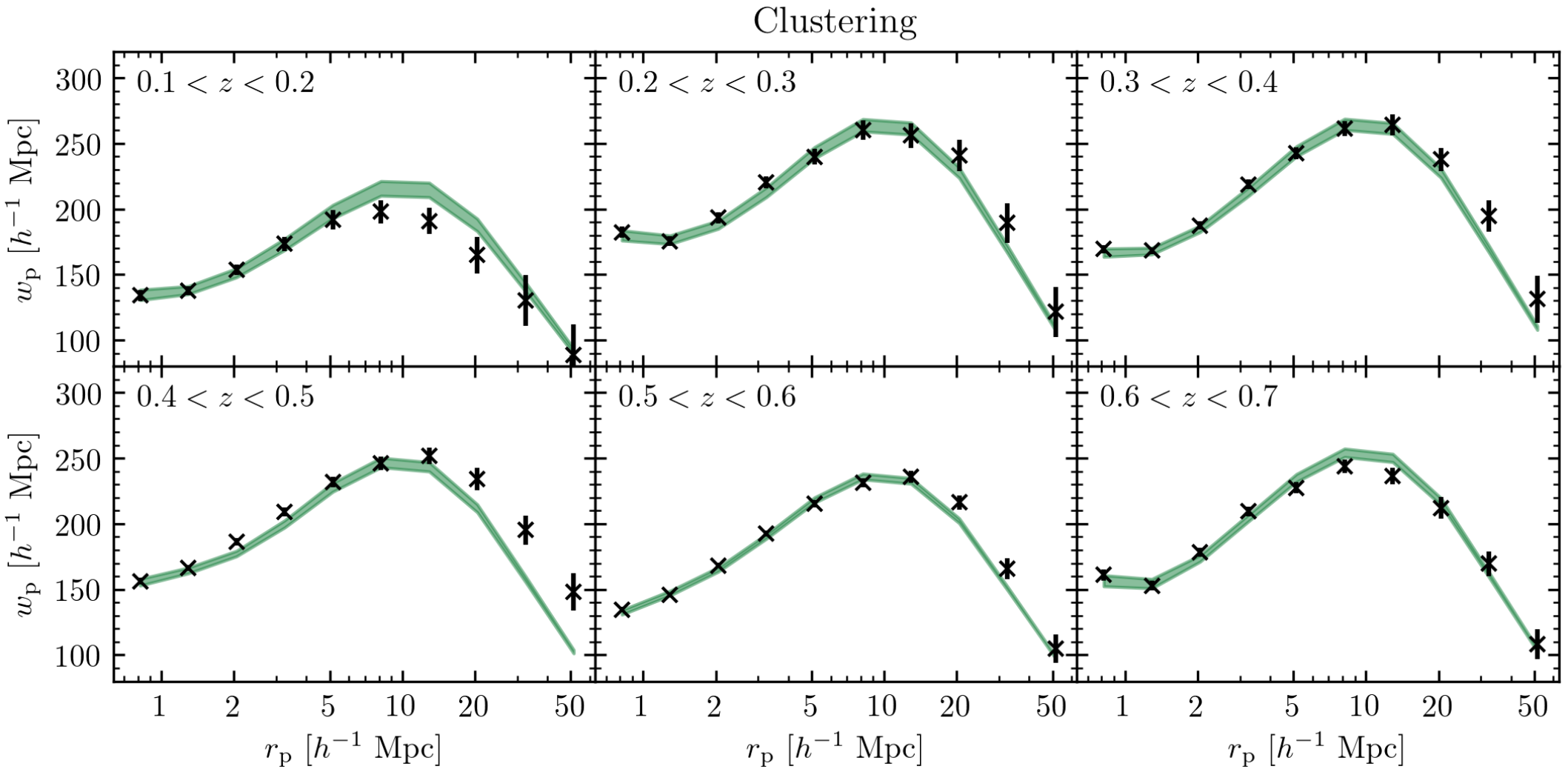

More luminous galaxies live in more massive DM halos.

# Problem: Lensing is low

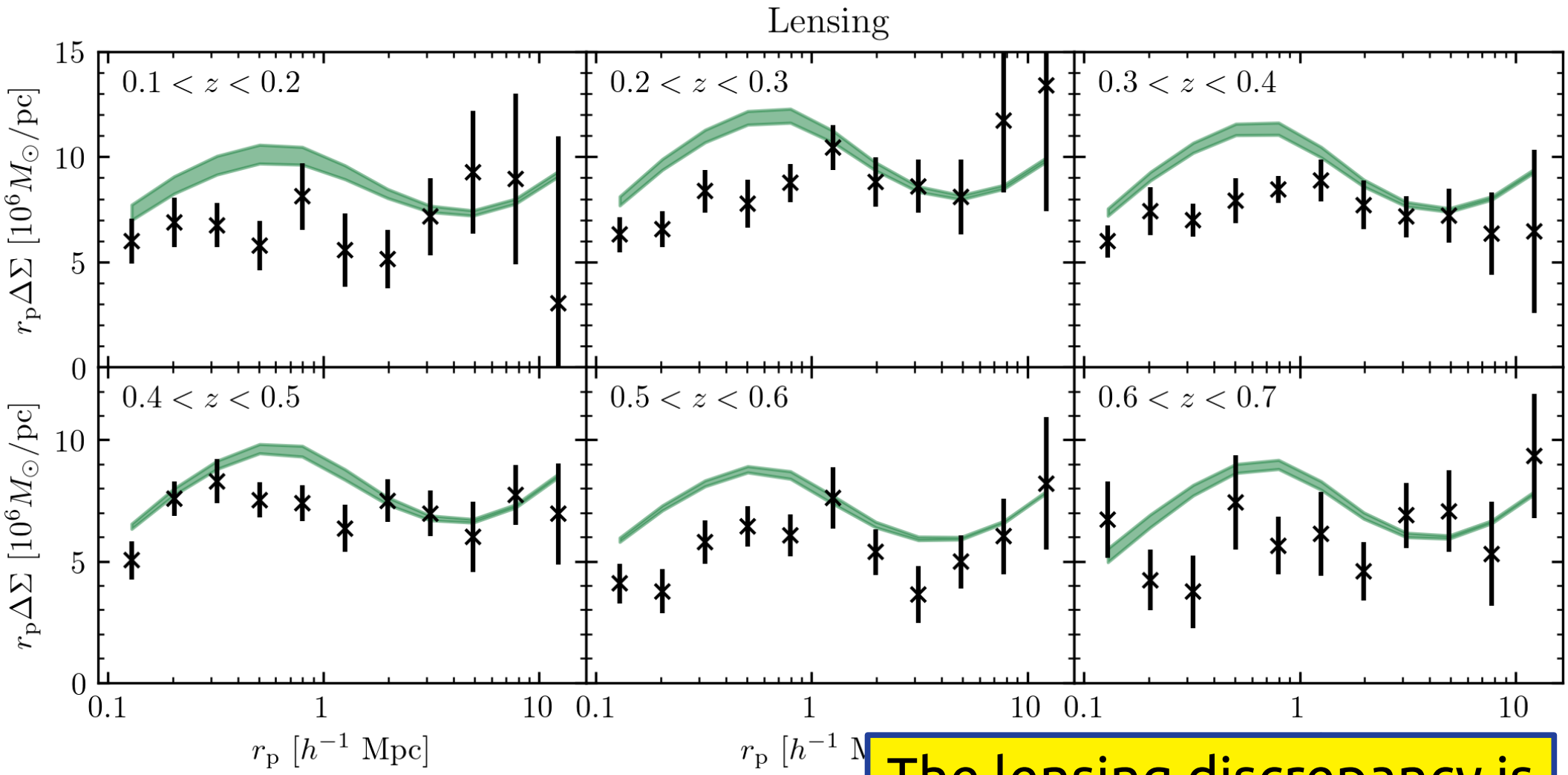
- independent studies analyzed clustering of BOSS CMASS
- consistent predictions for lensing
- higher than what is observed with CFHTLenS/SDSS



# Lensing Discrepancy: Redshift Dependence

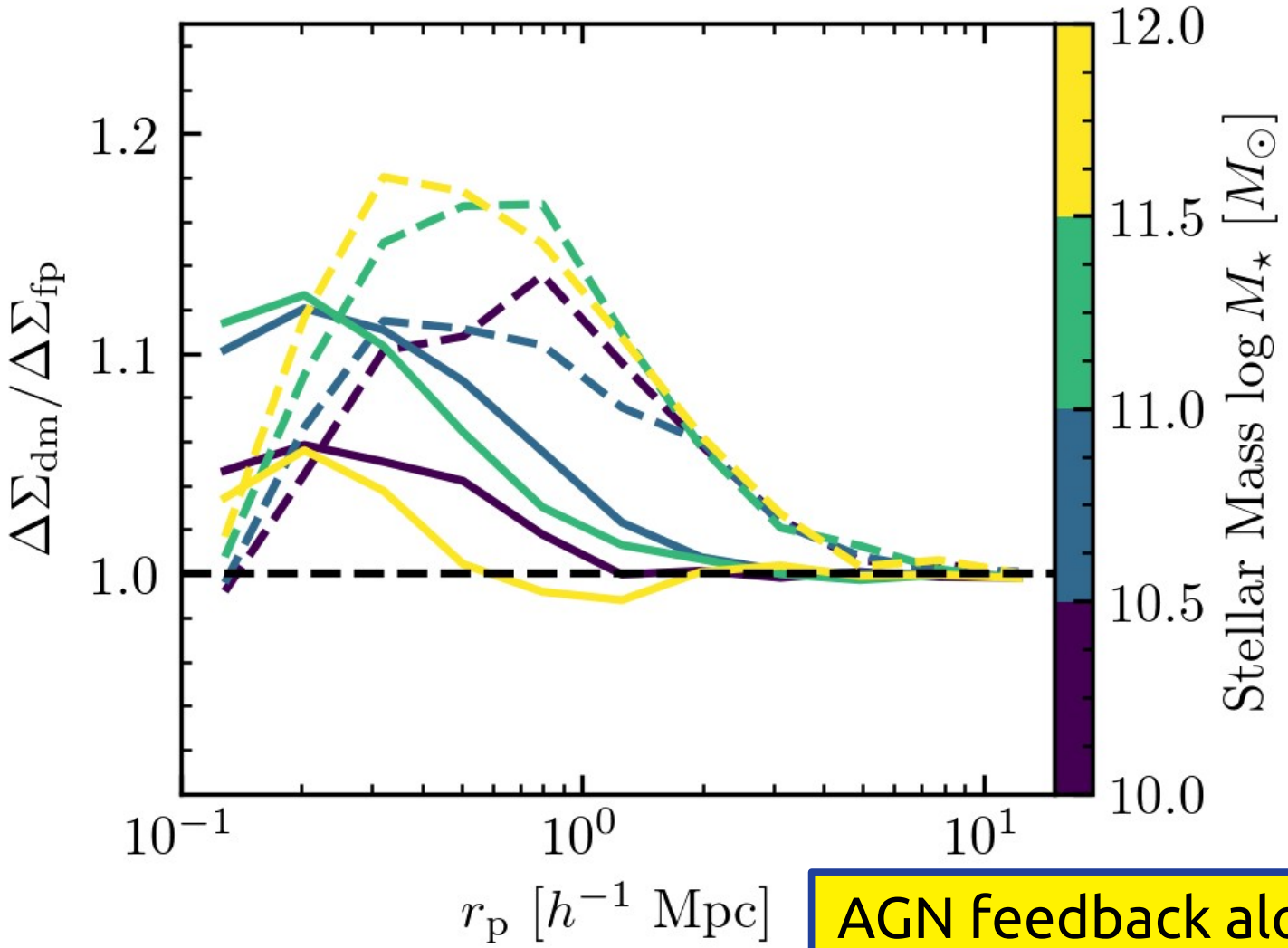


# Lensing Discrepancy: Redshift Dependence



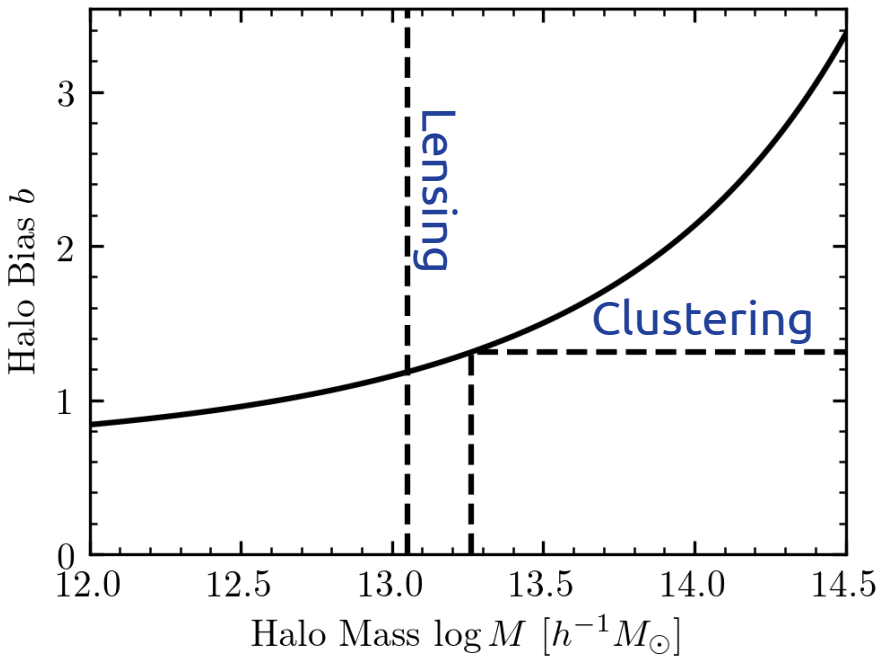

The lensing discrepancy is independent of redshift.

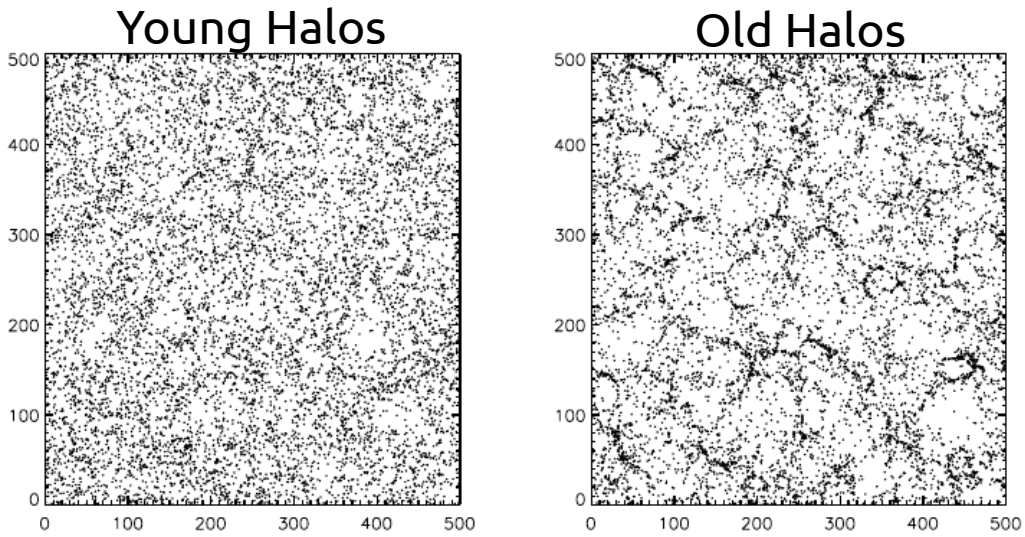
# Lensing Discrepancy: AGN feedback?



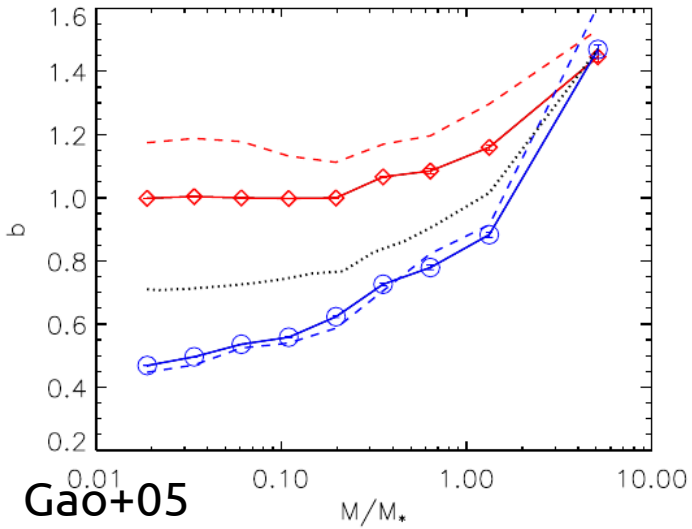

AGN feedback alone seems unlikely to fully explain the lensing discrepancy.

# Lensing Discrepancy: Assembly Bias?



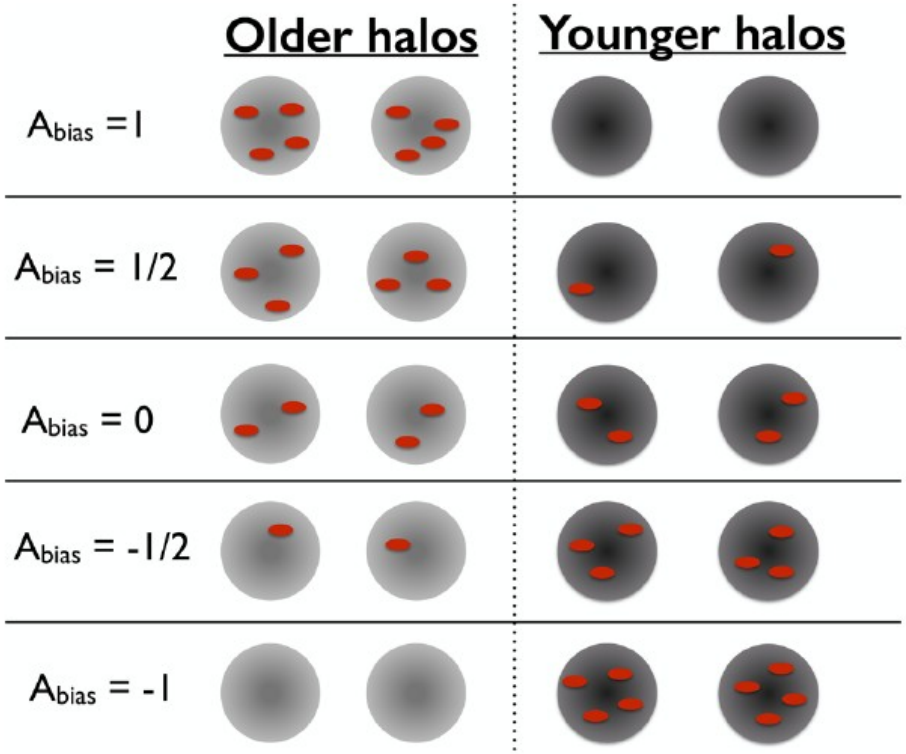




**Assembly Bias**
Clustering of halos depends on properties other than halo mass.




Gao+05

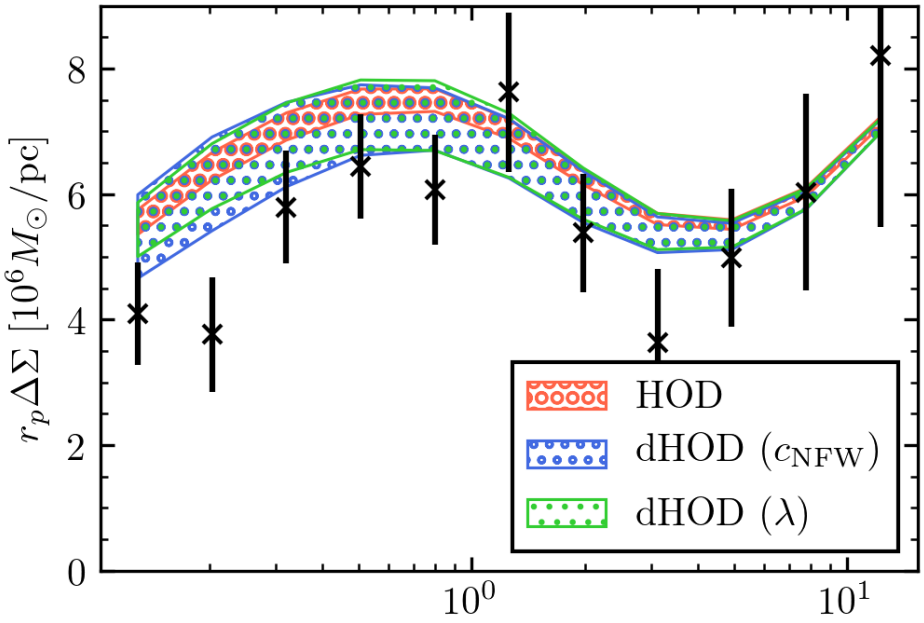
# Lensing Discrepancy: Assembly Bias?




Hearin+16

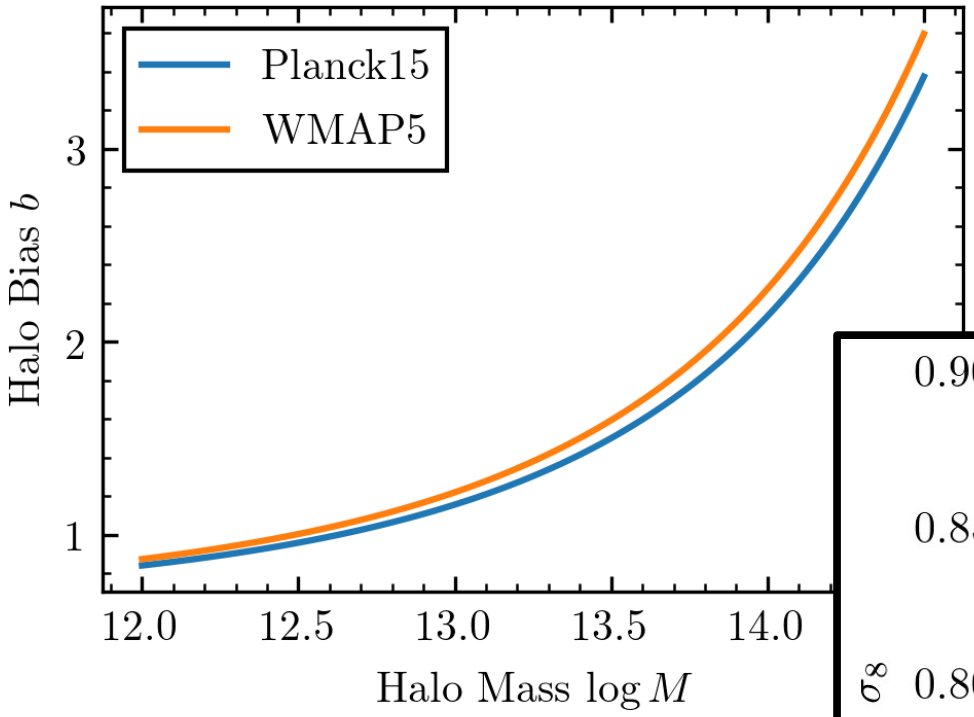
HOD: mass-only galaxy occupation
dHOD: additional dependence on secondary halo property

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

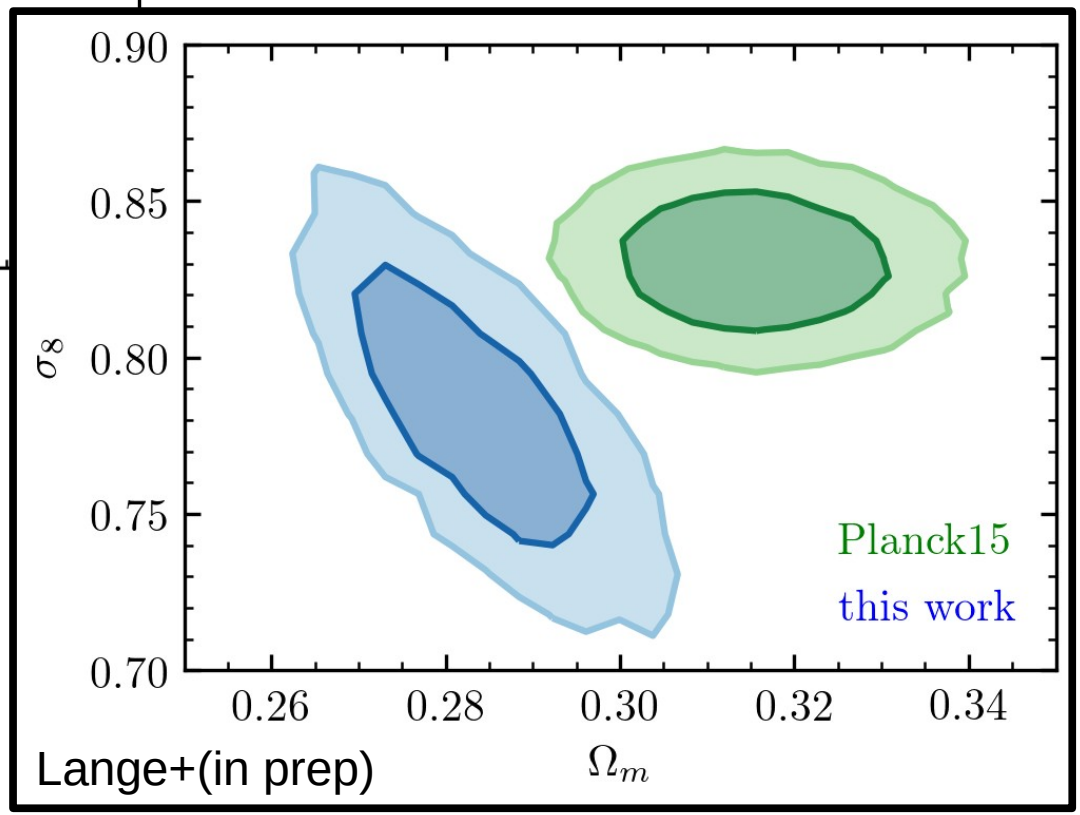



Lange+(in prep)

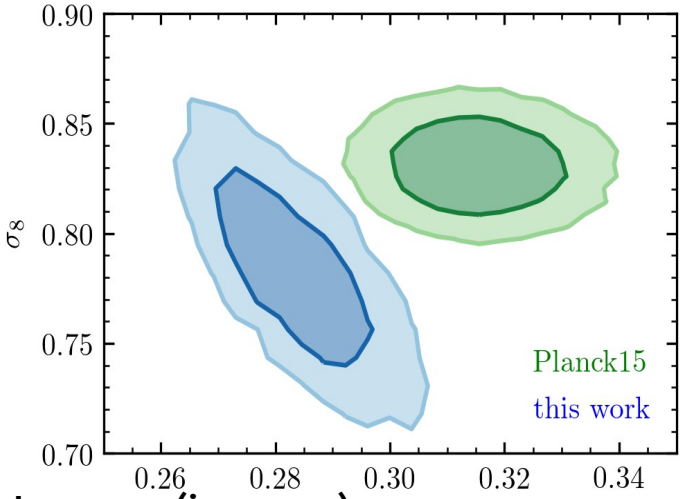
# Lensing Discrepancy: Cosmology



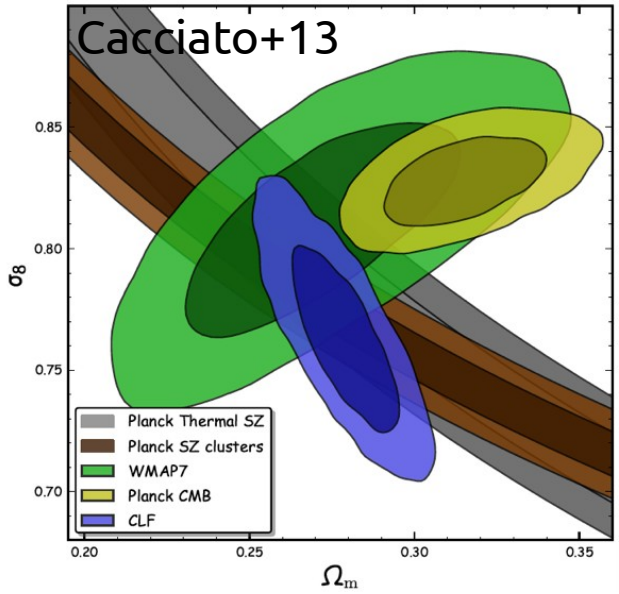

A change in cosmology can resolve the discrepancy.

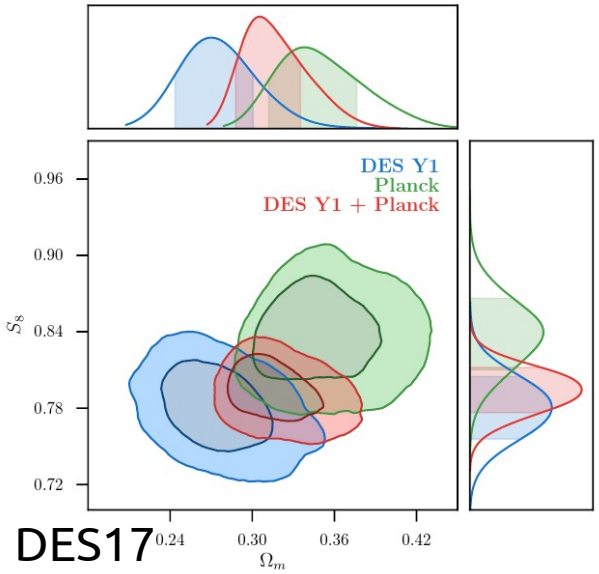


# Lensing Discrepancy: Cosmology




Lange+(in prep)



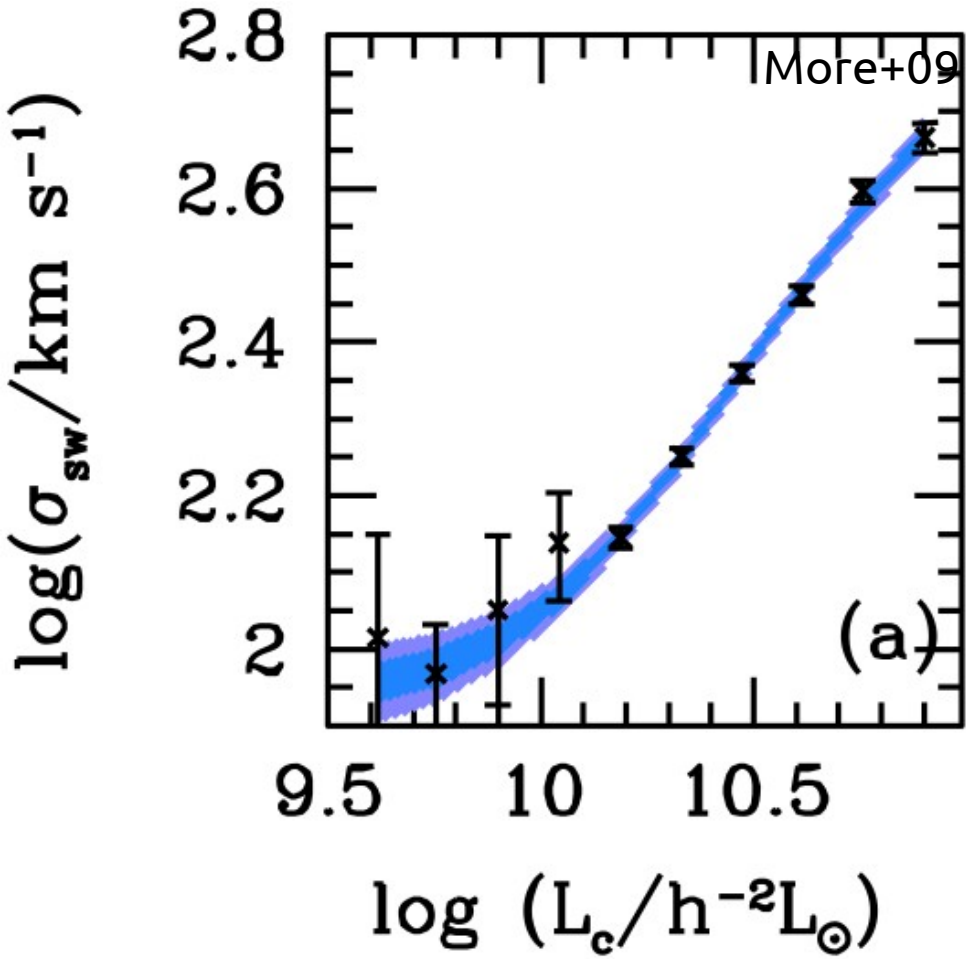

DES17

There might be tension between observations of the low-redshift Universe and Planck CMB results.

# Maturing Satellite Kinematics

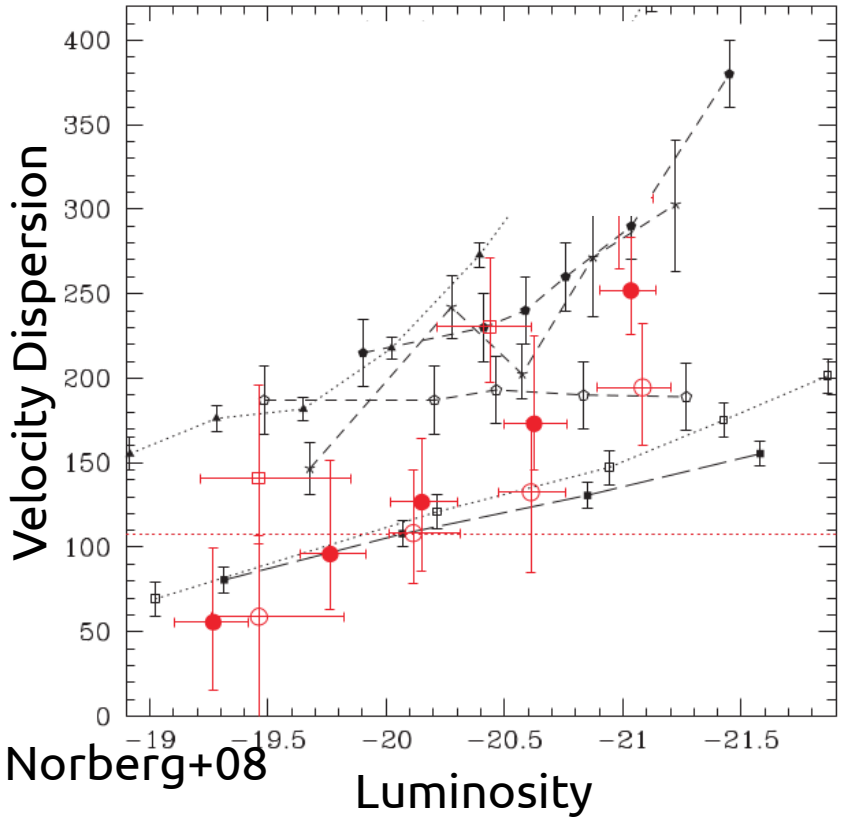
# Satellite Kinematics Recipe

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




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

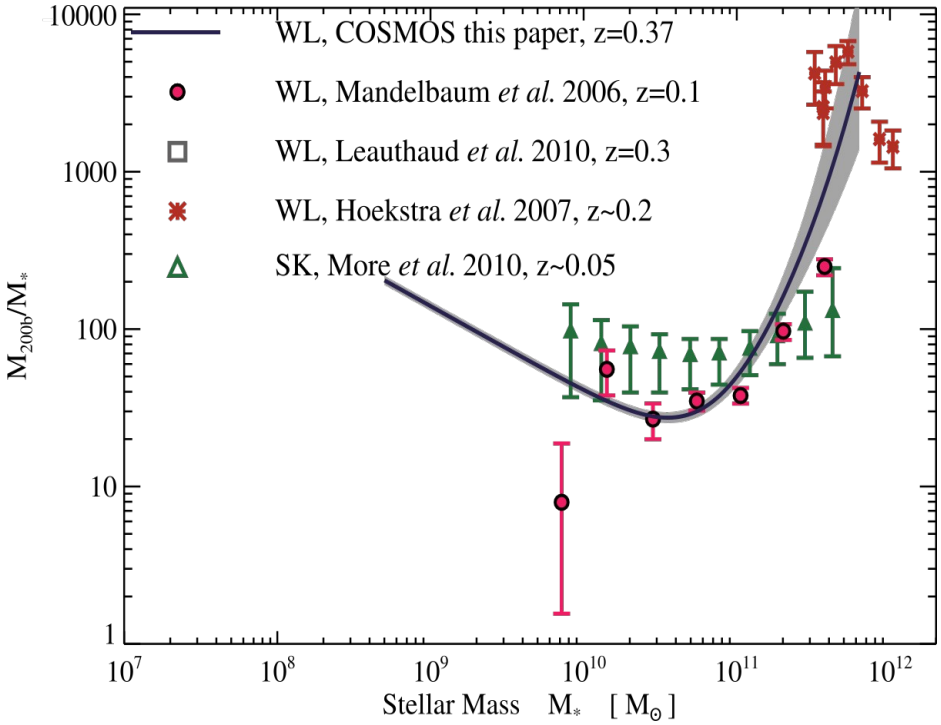
# Satellite Kinematics: Where are we now?




Norberg+08

"We observe a clear tension with the results from satellite kinematics [...]." (Mandelbaum+15)

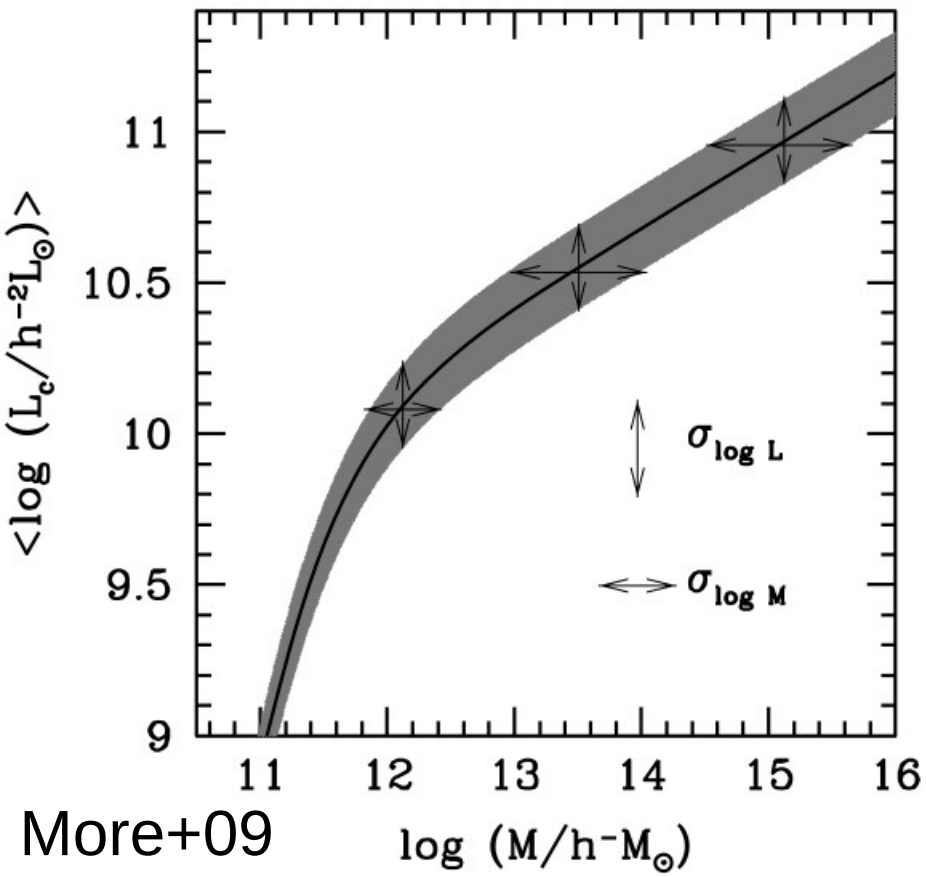
"All the [...] methods introduce biases and unless one applies the same selection criterion to [...] mock galaxy catalogues [...] the results remain questionable." (Norberg+08)




Leauthaud+12

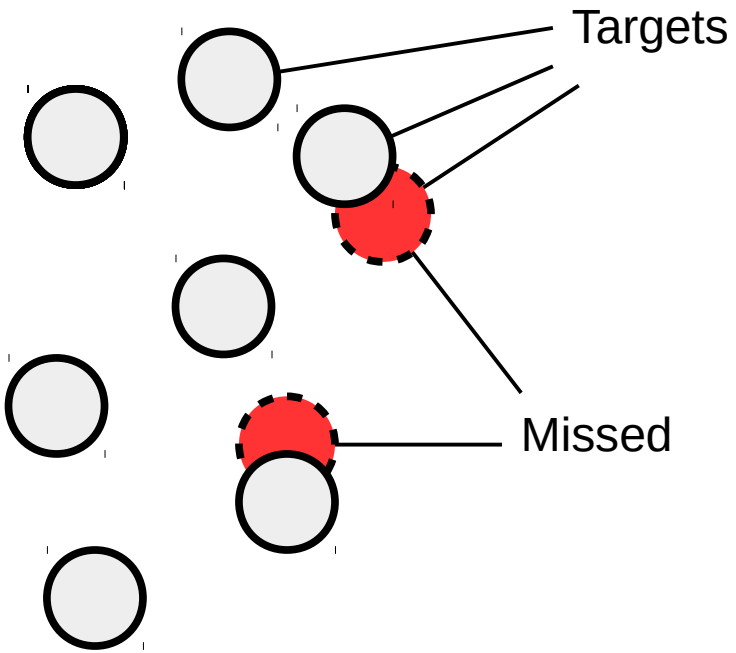
# Way of stacking satellites matters!

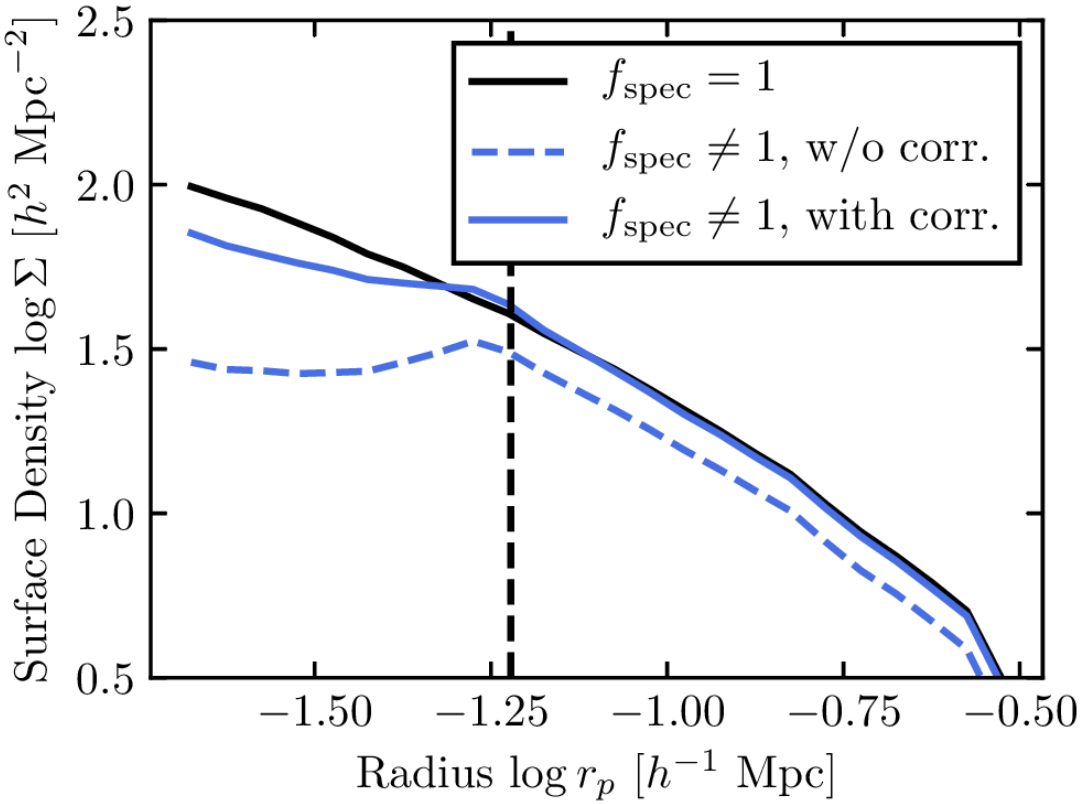
- not all centrals live in halos of same mass
- satellite weighting (sw): equal weight for each satellite
- host weighting (hw): equal weight for each central
- $\sigma_{hw}/\sigma_{sw} < 1$ measures scatter in halo mass




More+09

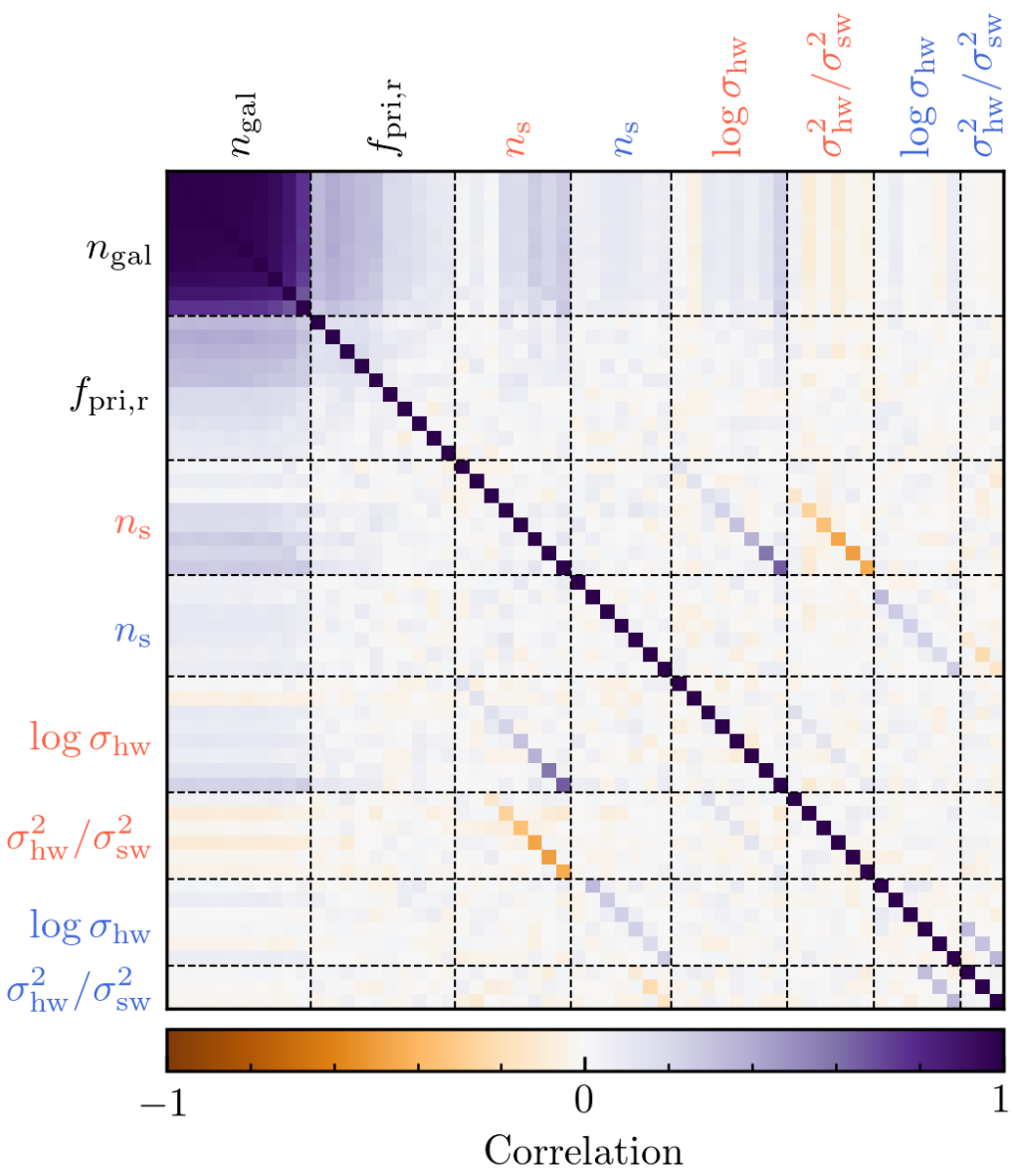
# Fiber collisions are an issue!



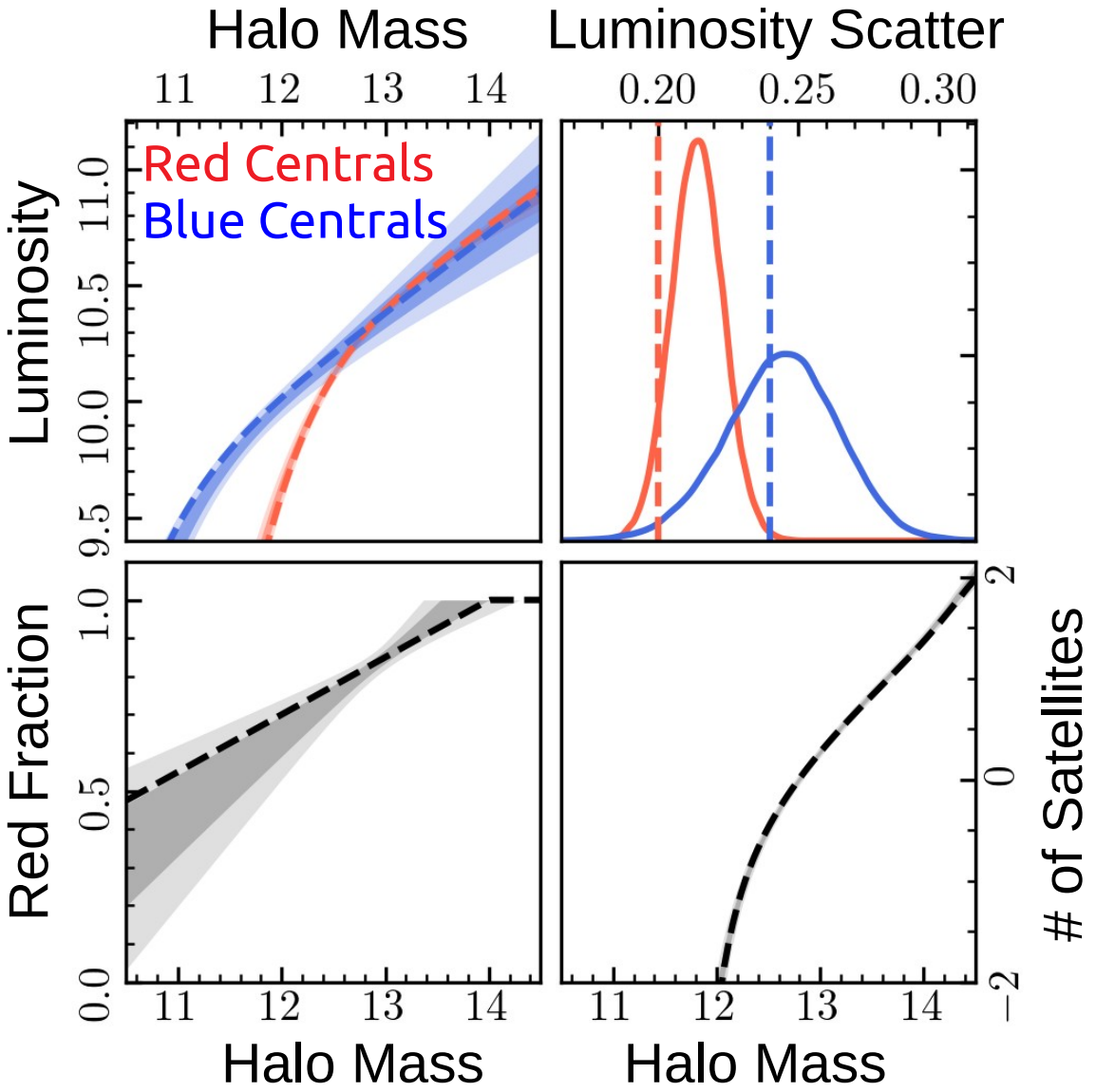

Not correcting for fiber collisions leads to systematically underestimated halo masses.

# Forward modeling of observational effects




- uncertainties estimated from mock catalogs
- $\sigma_{sw}$ and $\sigma_{hw}$ highly correlated

  → better constraint on halo mass scatter
- calibration of analytic model with mock catalogs



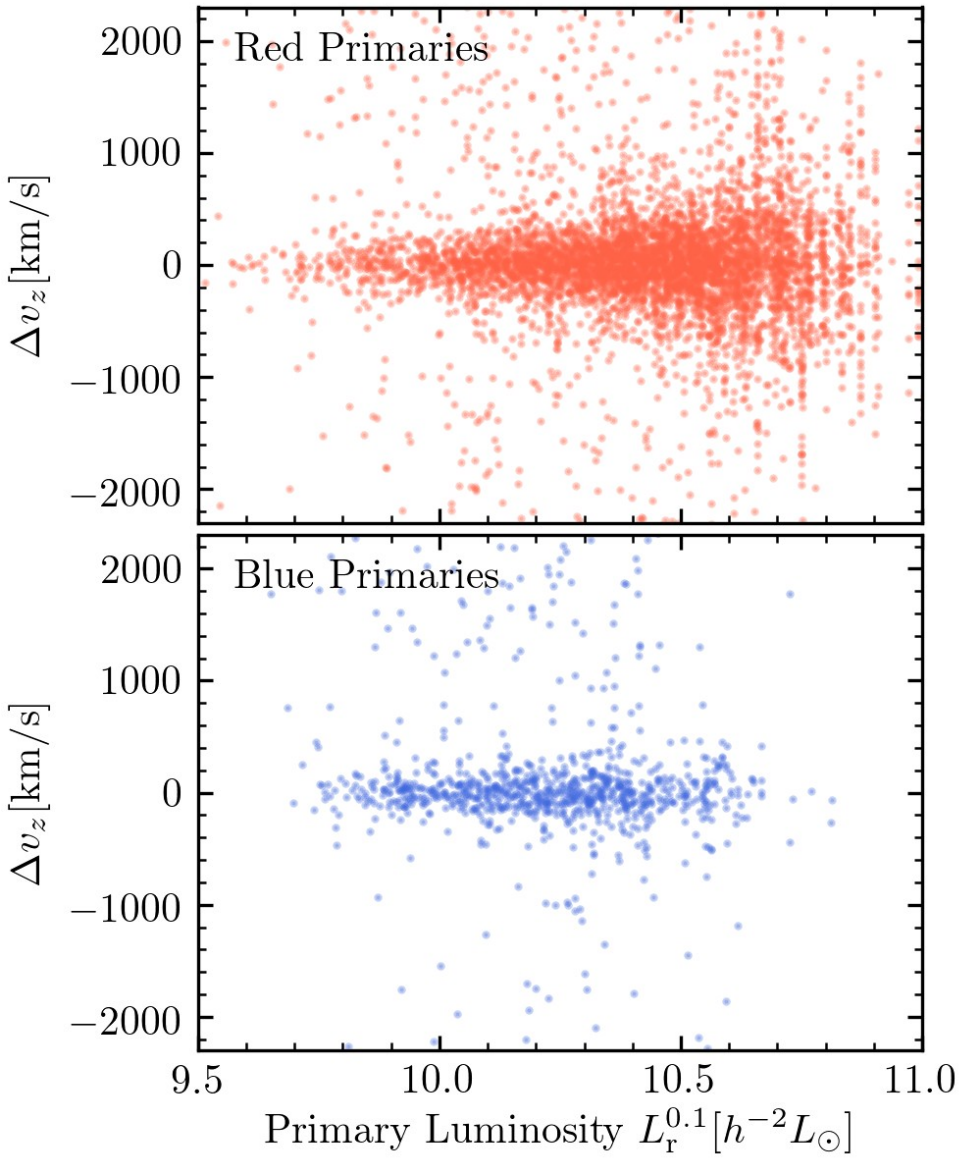

Satellite kinematics constraints are close to unbiased and very competitive compared to clustering + lensing.

# Satellite Kinematics in SDSS DR7

# New Constraints from SDSS DR7

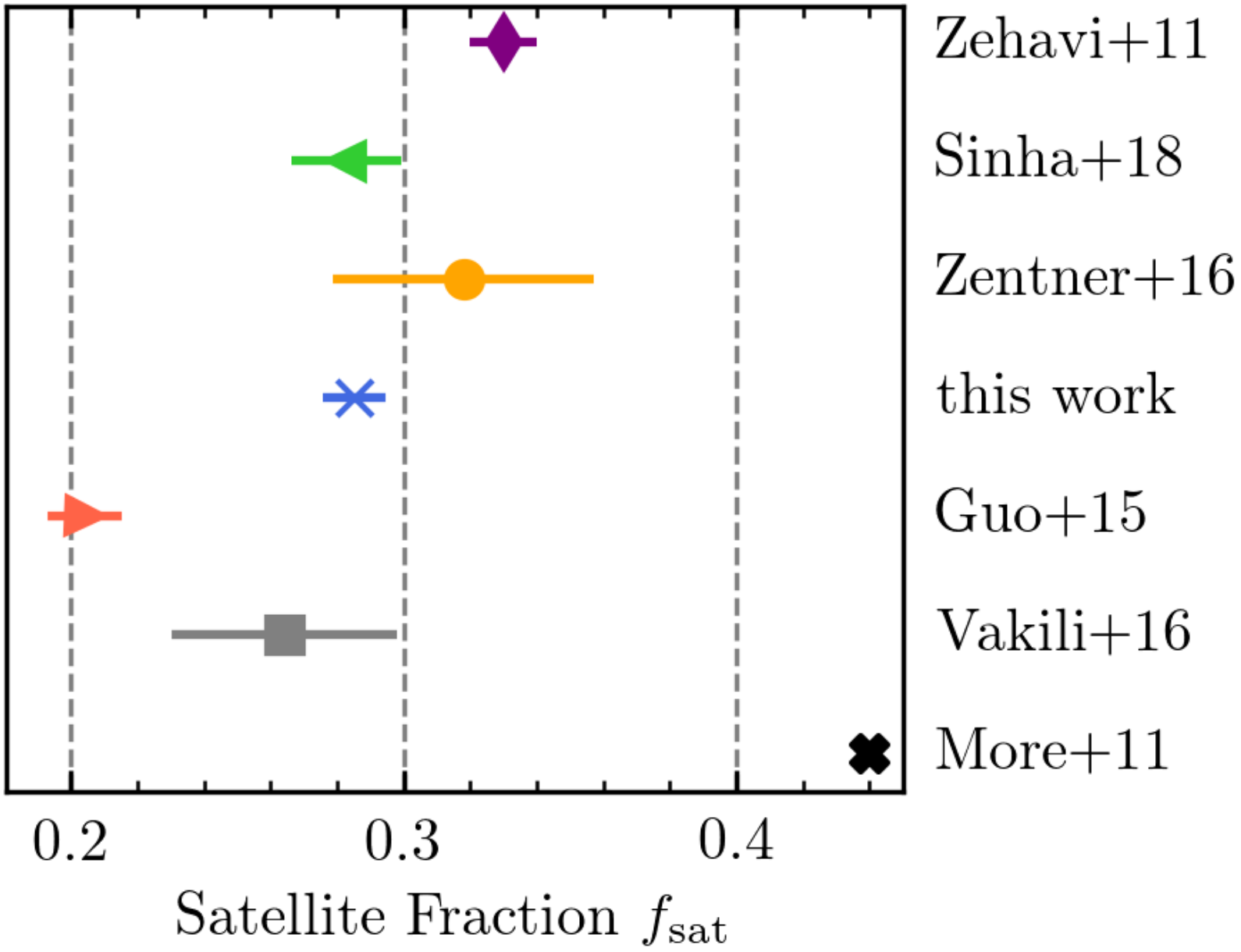
- DR7, galaxies with 0.02 < z < 0.067, L > $10^{9.5}$
- ~45,000 centrals,

  ~7,000 satellites
- red galaxies at fixed luminosity have more satellites/higher velocity dispersion



# Model can accurately fit SDSS DR7

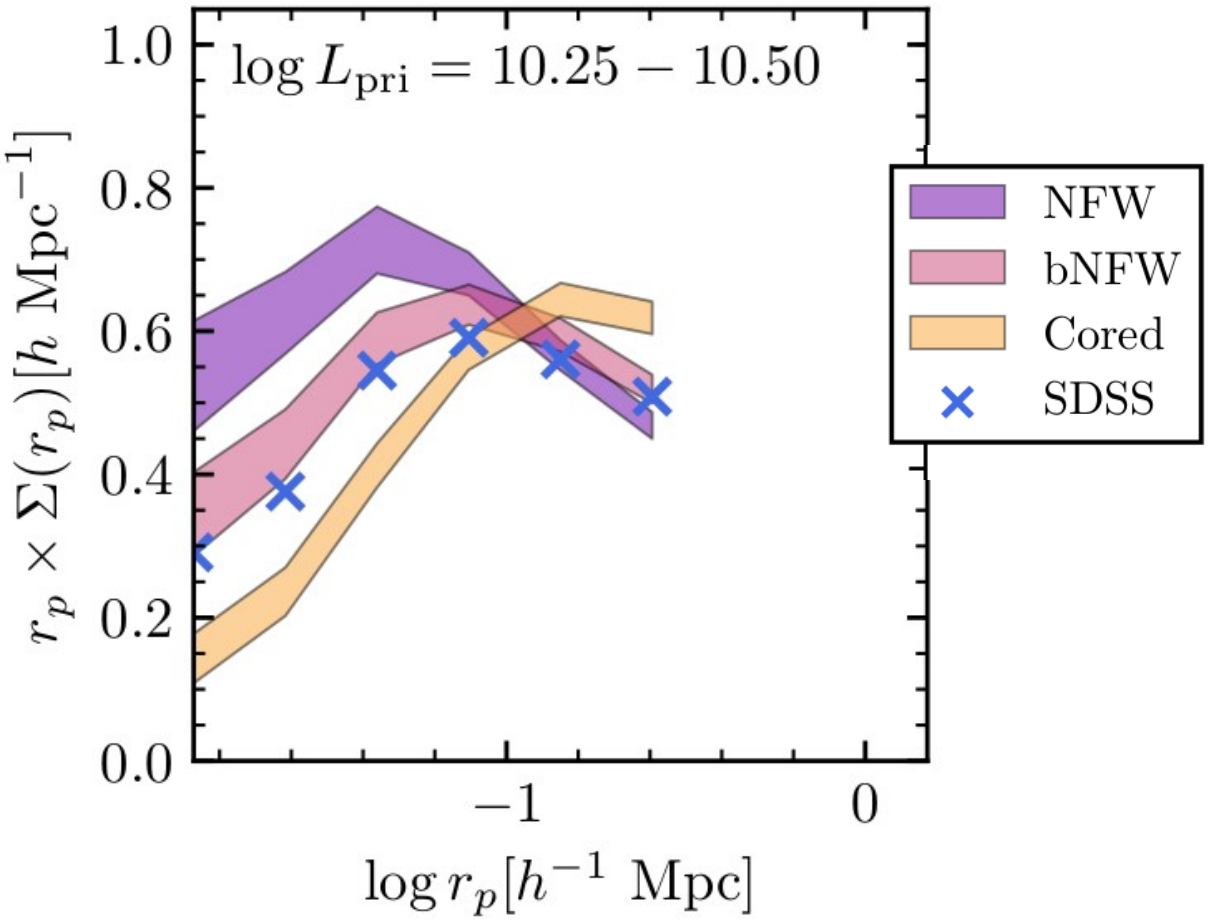
# Comparison with previous studies



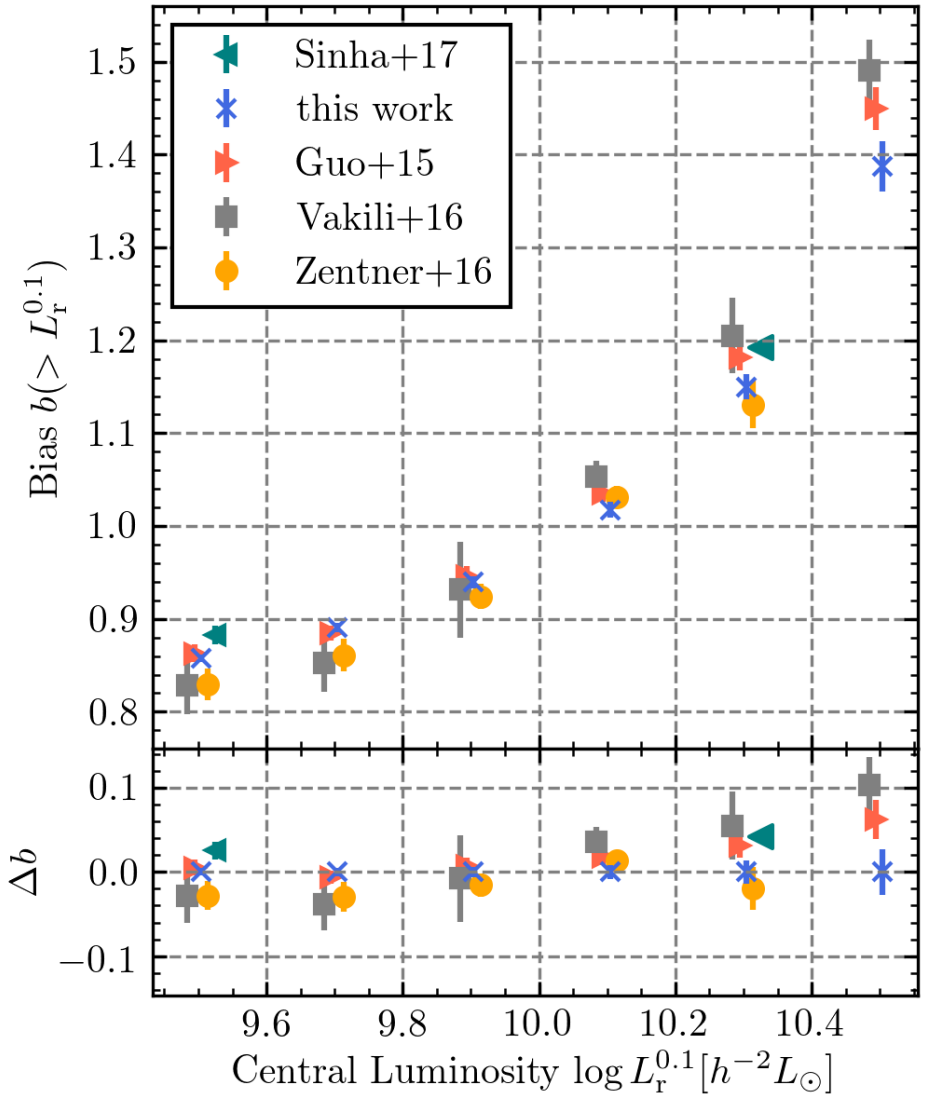
# Satellites follow a low-concentration NFW profile

- dark matter follows NFW profile
- subhalos have cored profile

Satellites in SDSS have a radial profile in between that of dark matter and subhalos.



# Comparison with previous studies

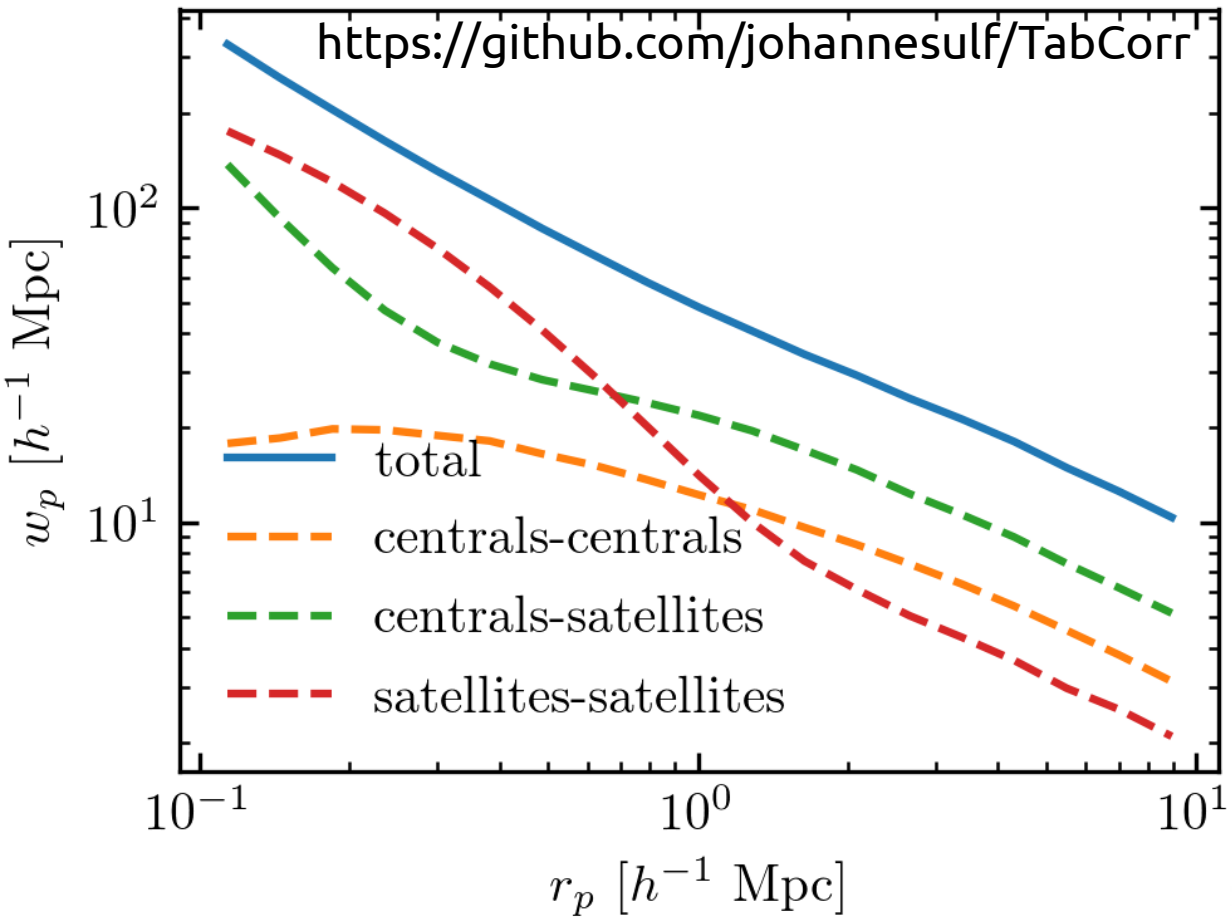


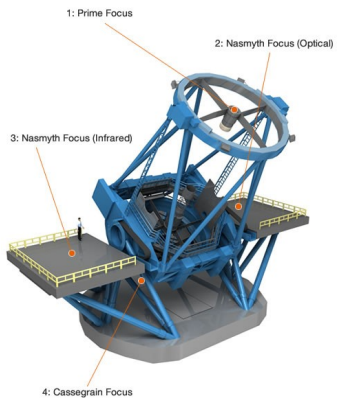

- Bias b ↔ Mass M, determines clustering
- sat. kin. in blue, other results from clustering/group cat.
- total mass increases with cen. luminosity

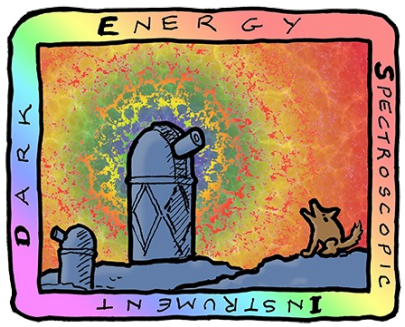
Results from sat. kin. are in good agreement with other studies.

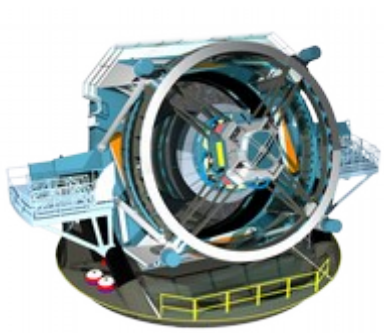
# High-Precision Modeling of Non-Linear Scales

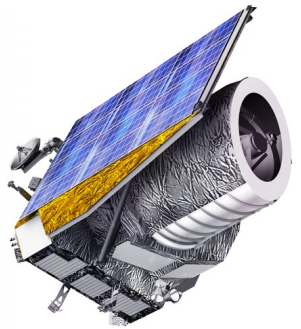
# Cosmology in the Non-Linear Regime





Problem: The accuracy of analytic models for the matter and galaxy distribution on non-linear scales is insufficient for future surveys.

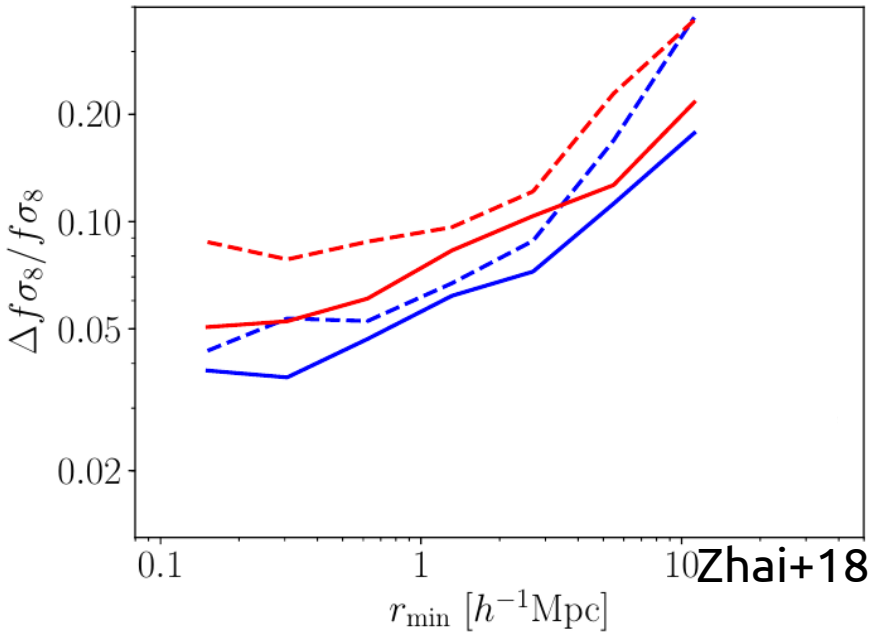
# Solutions?

Option 1:

ignore non-linear scales

→ Problem:

huge information loss

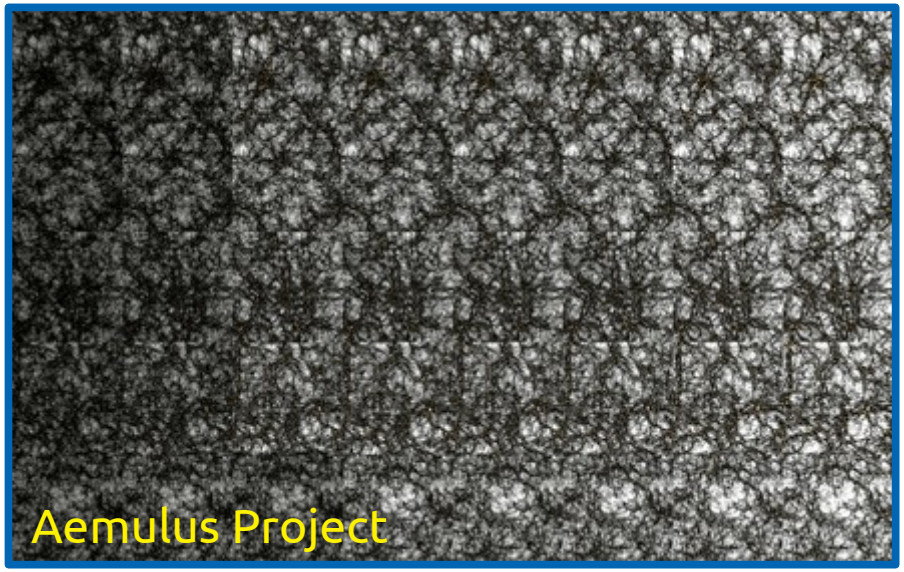



Option 2:

simulation-based approach

→ Problem:

computational cost



# Future Directions

Emulating galaxy clustering and galaxy-galaxy lensing into the deeply nonlinear regime: methodology, information, and forecasts

Benjamin L
Lehman H.
Marc Metch

DARK QUEST. I. FAST AND ACCURATE EMULATION OF HALO CLUSTERING STATISTICS AND ITS APPLICATION TO GALAXY CLUSTERING

Takahiro Nishimich

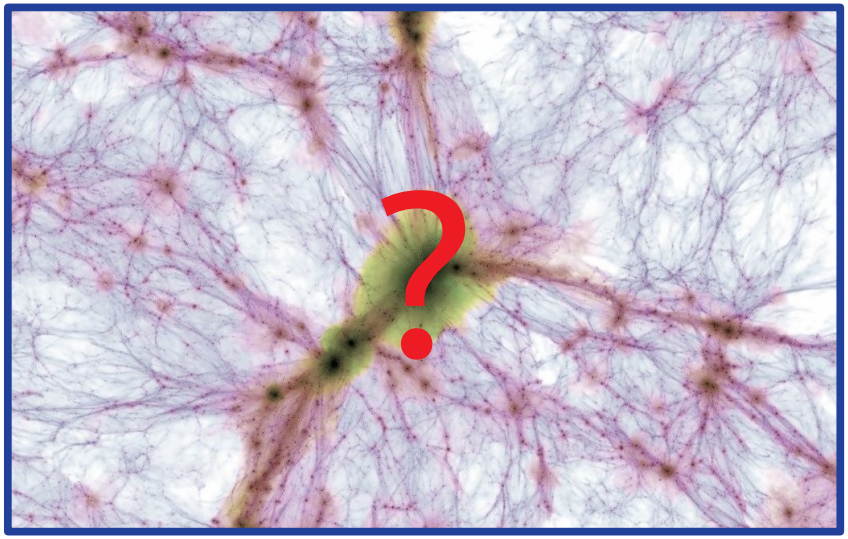
The Aemulus Project I: Numerical Simulations for Precision Cosmology

Joseph DeRose,[1,2] Risa H. Wechsler,[1,2] Jeremy L. Tinker,[3] Matthew R. Becker,[1,2,4] Yao-Yuan Mao,[5] Thomas McClintock,[6] Sean McLaughlin,[1,2] Eduardo Rozo,[6] and Zhongxu Zhai[3]

$$L(H,C|D) \propto p(H,C)\, p(D|M(H,C))$$

H: galaxy-halo connection
C: cosmology
D: measurements
M: predictions

Emulation of observables might be the way forward. However, this is still not a completely solved problem.



# Summary

- The BOSS lensing discrepancy suggests a revision of galaxy formation or cosmological models.
- Satellite kinematics can now be used as robust tool to probe the galaxy-halo connection.
- Satellite kinematics constraints from SDSS are among the most stringent and agree with other methods.
- In the future, simulation-based approaches are needed to probe non-linear scales. New methods need to be developed.