Title: Tackling the challenges of galaxy-dark matter connection modeling and new insights into secondary (assembly) biases

Speakers: Sihan Yuan

Series: Cosmology & Gravitation

Date: February 09, 2021 - 1:30 PM

URL: http://pirsa.org/21020022

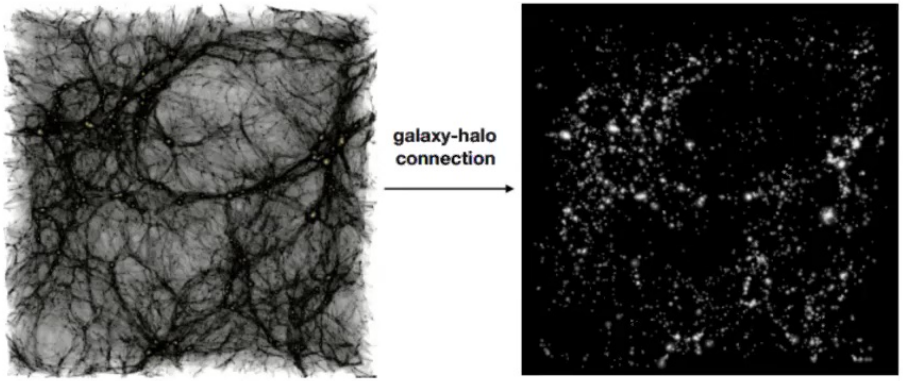
Abstract: Modeling galaxy-dark matter connection is essential in deriving unbiased cosmological constraints from galaxy clustering observations. We show that a more physically motivated galaxy-dark matter incorporating secondary (assembly) biases results in more accurate predictions of galaxy clustering, yields novel insights into effects such as baryonic feedback, and significantly reduces the tension in galaxy lensing. We further present progress and opportunities in building a multi-tracer galaxy-dark matter connection framework that is rich in features and highly efficient, enabling more robust cosmological analyses with upcoming DESI data.

Tackling challenges in galaxy-dark matter connection modeling and secondary biases

Sihan Yuan

with Daniel Eisenstein, Lehman Garrison, Alexie Leauthaud,
Boryana Hadzhiyska, Hong Guo, and Sownak Bose

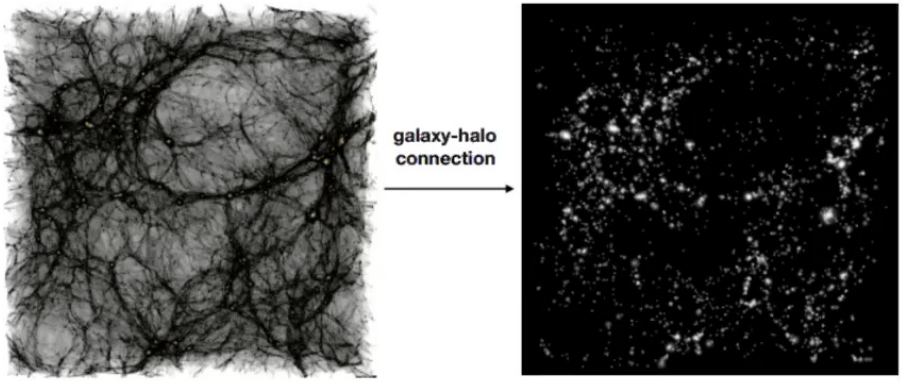
The importance of galaxy-dark matter connection



Wechsler & Tinker 2018

- Inferring cosmological parameters.
- Understanding the physics of galaxy formation.
- Probing the structure and properties of dark matter.

The various approaches

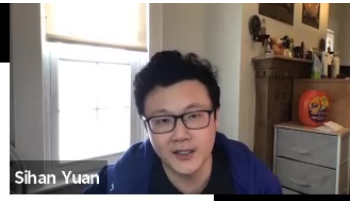


Wechsler & Tinker 2018

Approaches to modeling the galaxy-halo connection

← physical models			empirical models →	
Hydrodynamical Simulations	**Semi-analytic Models**	**Empirical Forward Modeling**	**Subhalo Abundance Modeling**	**Halo Occupation Models**
Simulate halos & gas; Star formation & feedback recipes	Evolution of density peaks plus recipes for gas cooling, star formation, feedback	Evolution of density peaks plus parameterized star formation rates	Density peaks (halos & subhalos) plus assumptions about galaxy—(sub)halo connection	Collapsed objects (halos) plus model for distribution of galaxy number given host halo properties

Expensive ← Computation cost → Cheap

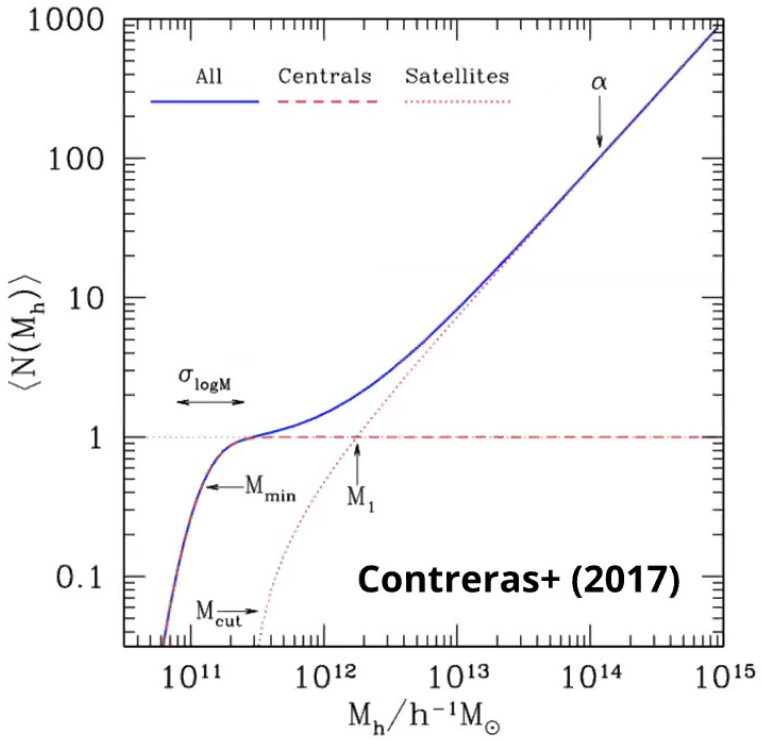


The Halo Occupation Distribution (HOD) model

- The HOD abstracts dark matter into gravitationally bound halos, which are then analytically associated with galaxies.

- The HOD is essential for large high resolution surveys such as DESI.
  - Cheap enough to process very large simulation volumes.
  - Takes advantage of the subscale physics built into simulations.

The Halo Occupation Distribution (HOD) model



$$\langle N_{\rm gal}(M_{\rm halo})\rangle = \langle N_{\rm cen}(M_{\rm halo})\rangle + \langle N_{\rm sat}(M_{\rm halo})\rangle$$

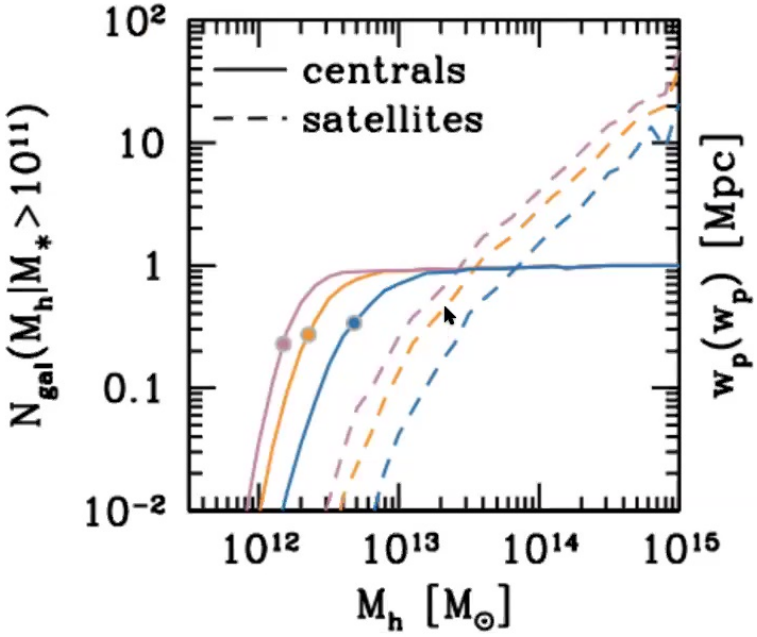
$$\langle N_{\rm cen}(M_{\rm halo})\rangle = \frac{1}{2}\left[1 + {\rm erf}\left(\frac{\log {\rm M}_{\rm halo} - \log {\rm M}_{\rm min}}{\sigma_{\log {\rm M}}}\right)\right]$$

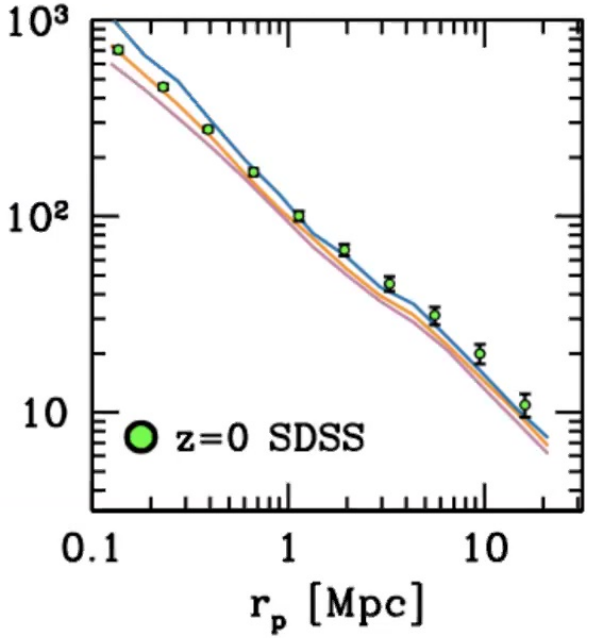
$$\langle N_{\rm sat}(M_{\rm halo})\rangle = \left(\frac{M_{\rm halo} - M_{\rm cut}}{M_1}\right)^{\alpha}$$

Jing, Mo & Börner (1998); Benson+ (2000); Peacock & Smith (2000); Berlind & Weinberg (2002), Zheng+ (2005) ....

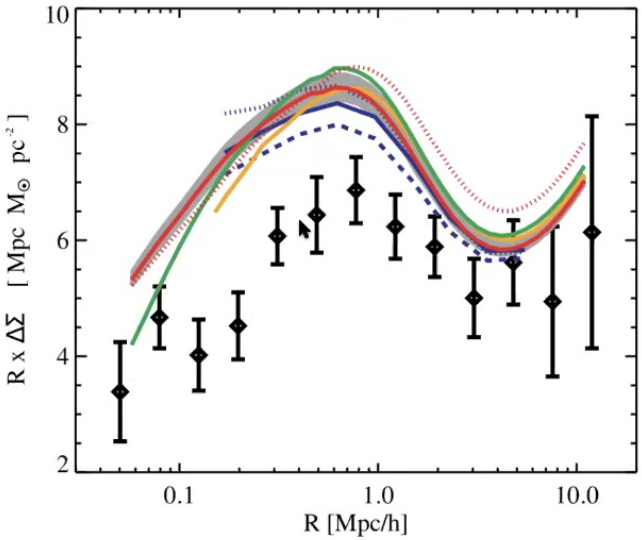
The Halo Occupation Distribution (HOD) model

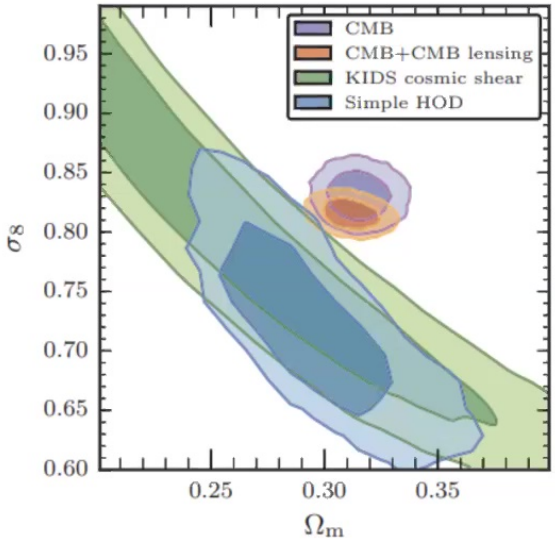
Wechsler & Tinker 2018





The lensing tension

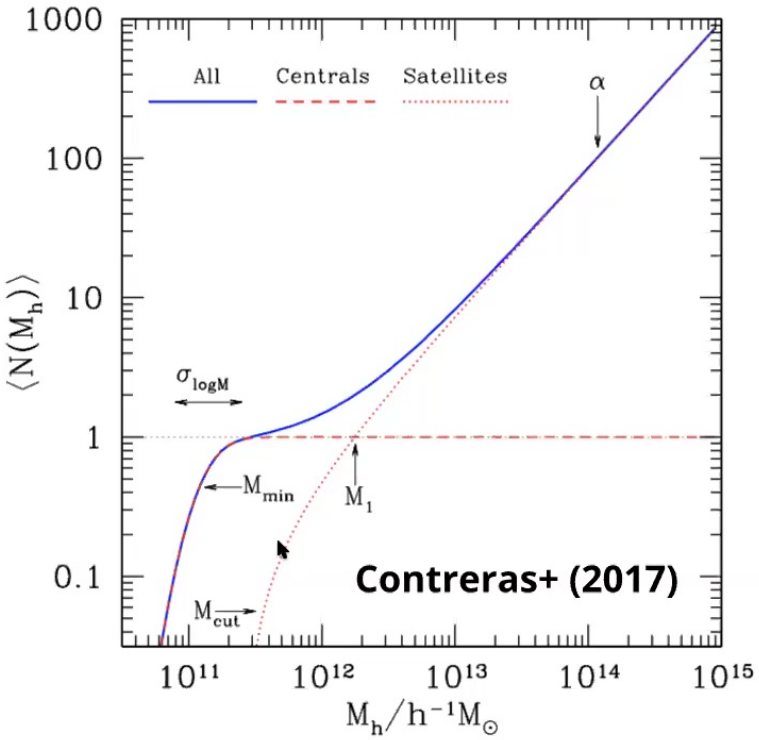




Leauthaud+17

Systematics? Modeling? Cosmology?

The Halo Occupation Distribution (HOD) model



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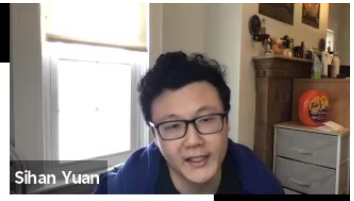

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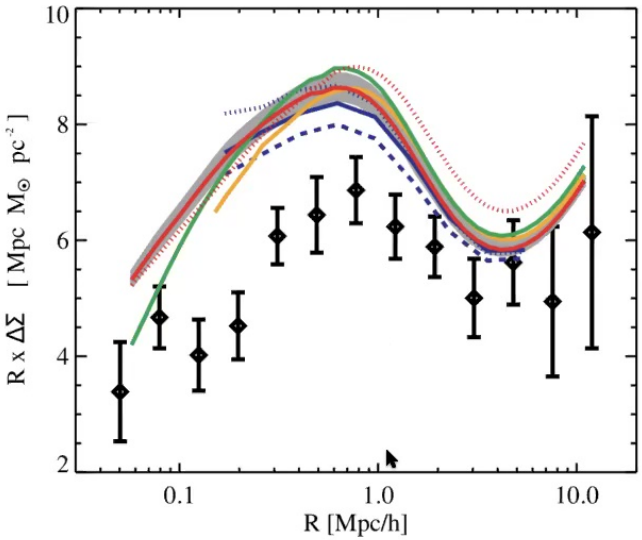

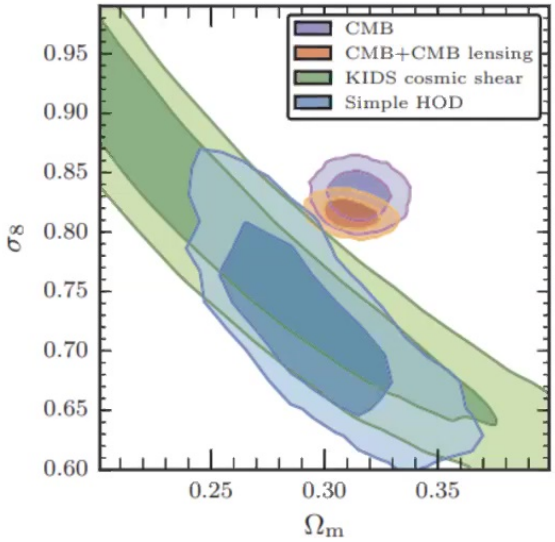

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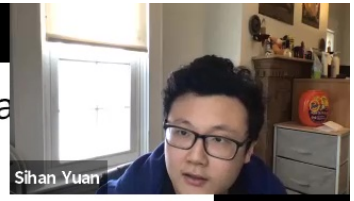
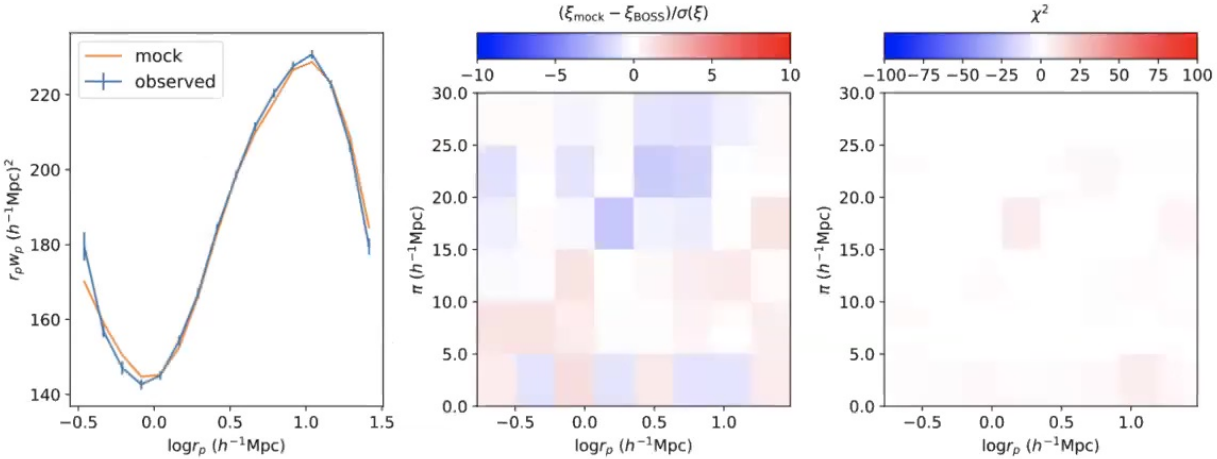


Yuan et. a

Fitting the BOSS redshift-space 2PCF



Best fit:
A = -0.7± 0.2
Ae = 0.04 ± 0.01

- Preference for including both secondary biases:
  - Include A: ΔBIC = 21.
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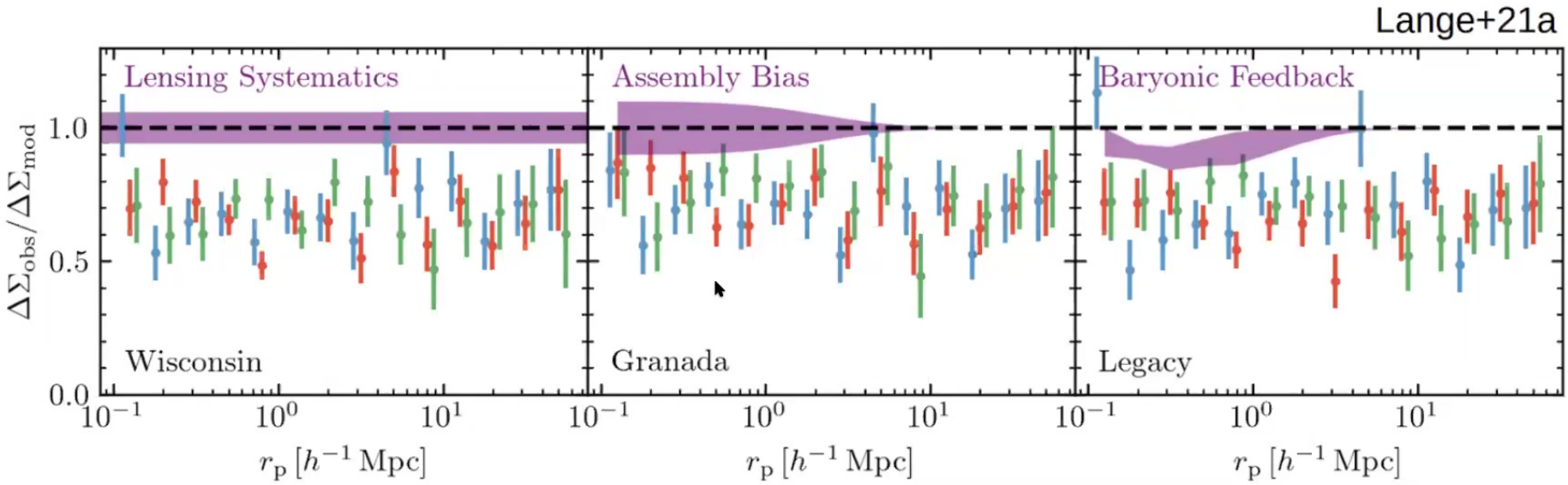
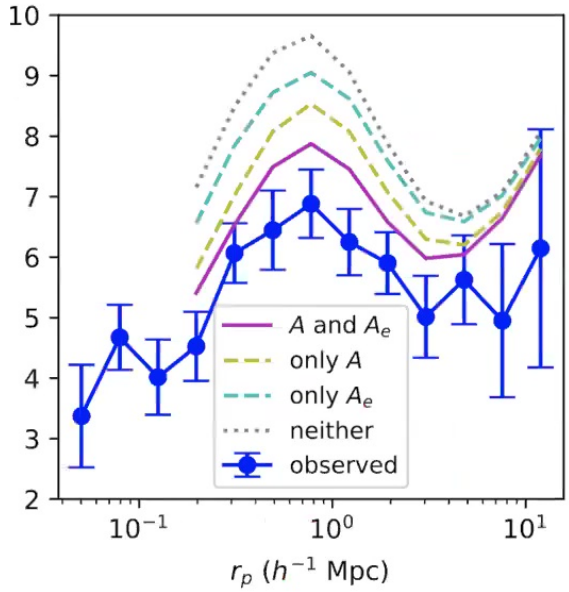
  - Combined: ΔBIC = 36.

Different assembly bias models produce different results



Yuan et. a

A path towards resolving the lensing tension?



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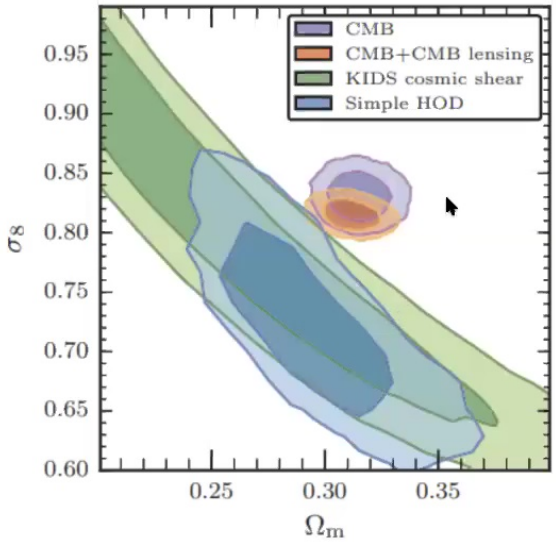
The lensing tension

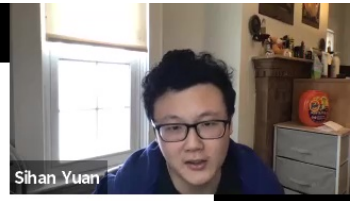


Linder 2005:

$\sigma_8(\gamma)$

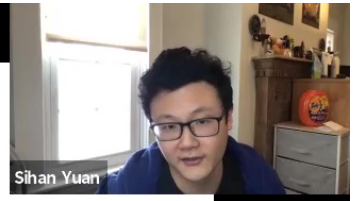
γ --- Growth index, derived from GR

Growth rate informs underlying gravity models.



The lensing tension can be significantly remedied with more realistic HOD models

(Yuan et al. 2020b)



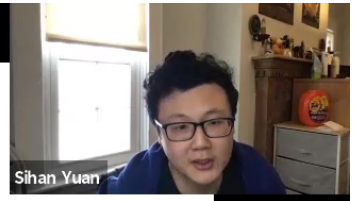
Assembly bias

- *Assembly bias* is the phenomenon when the clustering of halos/galaxies at fixed mass depends on additional properties of the halo (i.e. other than mass)

Formation time
Concentration
Spin
Velocity dispersion
… and so on

- Early forming halos have more time to undergo mergers and tidal disruption.
- Leads to fewer but more luminous galaxies.

- Can significantly bias cosmology/HOD inference (Lange+2019).
- Observational evidence: Zentner+2014, Miyatake+2016.

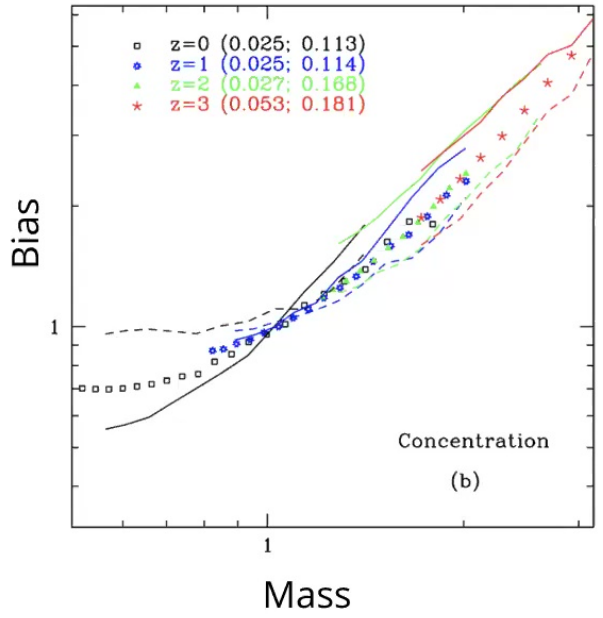


Assembly bias

- Halo concentration has been the most popular marker of assembly bias.

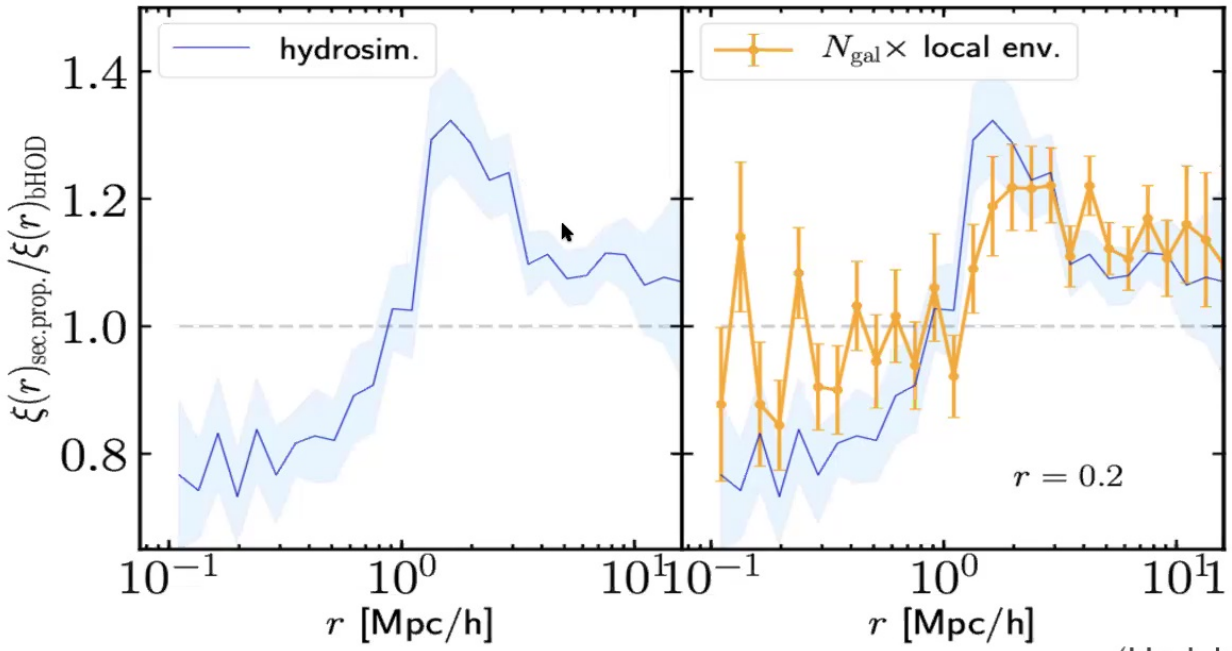
$$c = \frac{r_{\rm vir}}{r_s}$$

  - Concentration correlates well with formation time.
- In the HOD model: $P(N_g \mid M, c)$.



Gao & White 2007

Environment-based secondary bias



(Hadzhiyska et al 2020)

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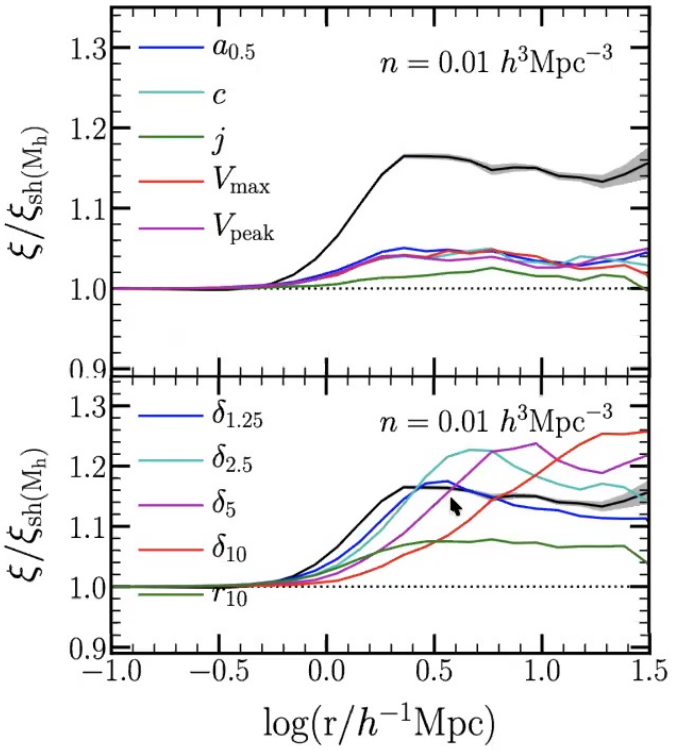
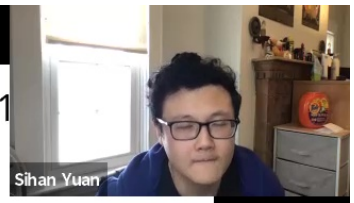


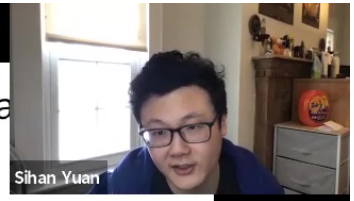
(Xu+2020)



Yuan et. al. 201

Extended HOD including secondary biases

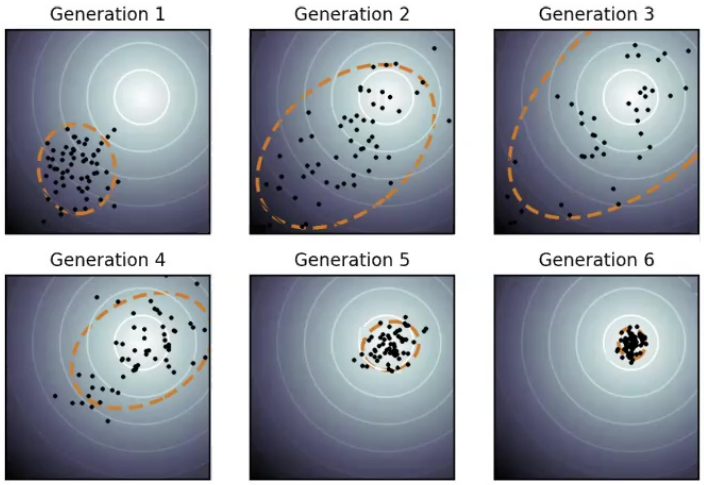
- Vanilla parameters. $\rightarrow [M_{\rm cut}, M_1, \sigma, \alpha, \kappa]$
- Generalized parameters:
  - Assembly bias based on concentration and environment. $\rightarrow [A, A_e]$
  - Satellite radial distribution parameters. $\rightarrow [s, s_p]$
  - Velocity bias parameters for centrals and satellites. $\rightarrow [\alpha_c, s_v, s_r]$



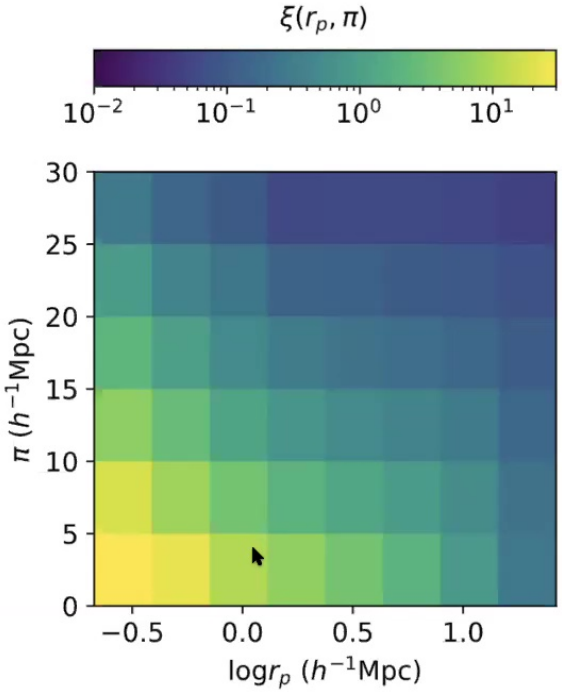
Yuan et. a

Fitting the BOSS clustering with extended HOD

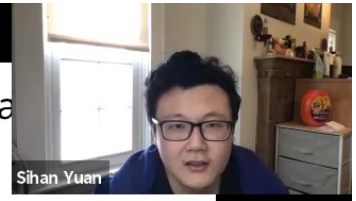
- Data:
  - BOSS CMASS galaxies within 0.46 < z < 0.61 (DR12).
  - Fiber-collision corrected.
- Algorithm:
  - Evolutionary global optimization routine (CMAES).



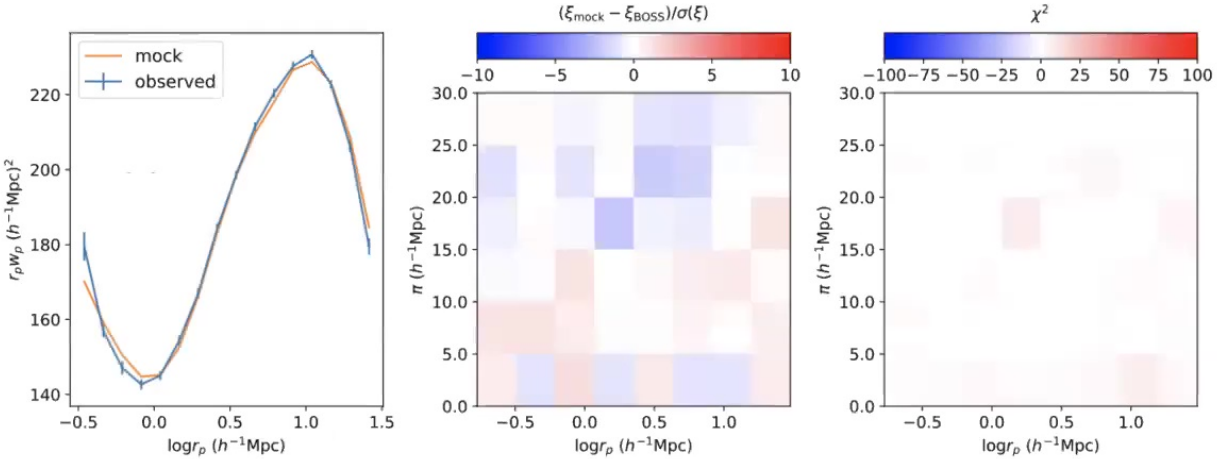
(wikipedia)



Yuan et. a



Fitting the BOSS redshift-space 2PCF



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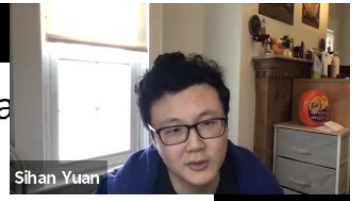
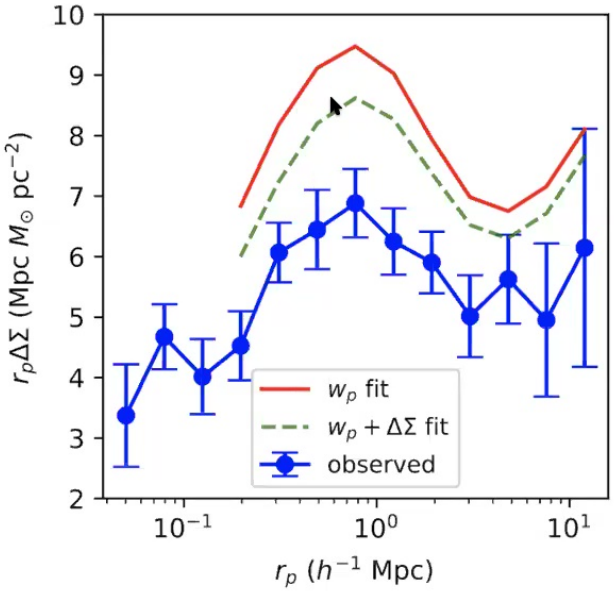
The lensing prediction

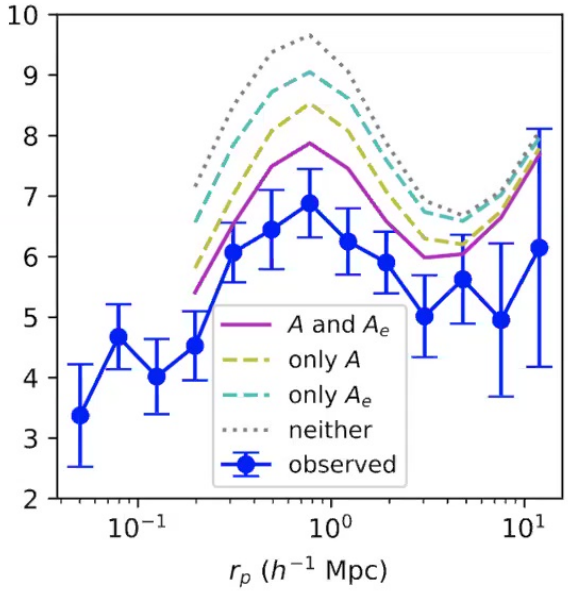
Yuan et. a



Previous predictions

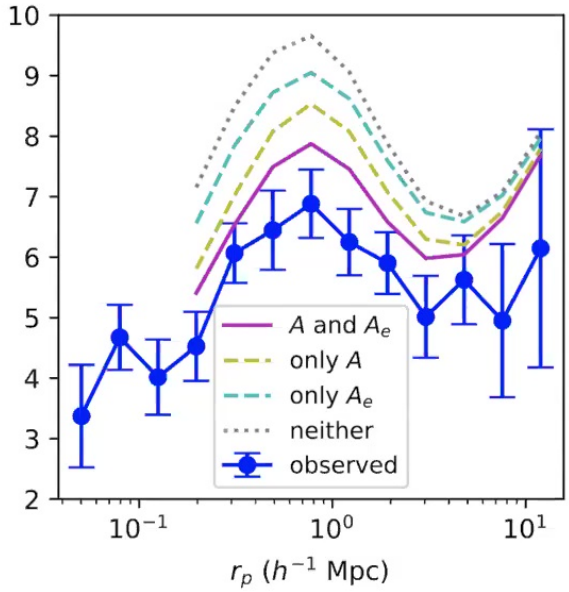


New predictions



Yuan et. al. 2020b

A path towards resolving the lensing tension?



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The LOS structure of the 2PCF is pushing galaxies into lower mass halos.

The lensing prediction

Yuan et. al. 2020a, b

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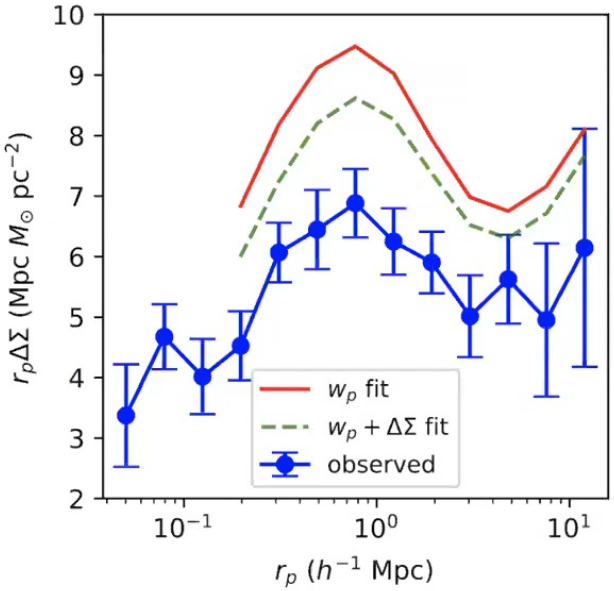

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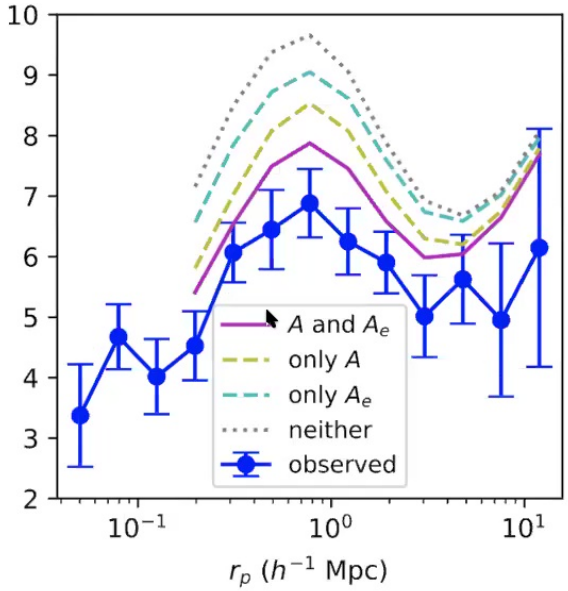

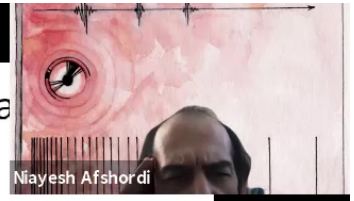

Yuan et. a

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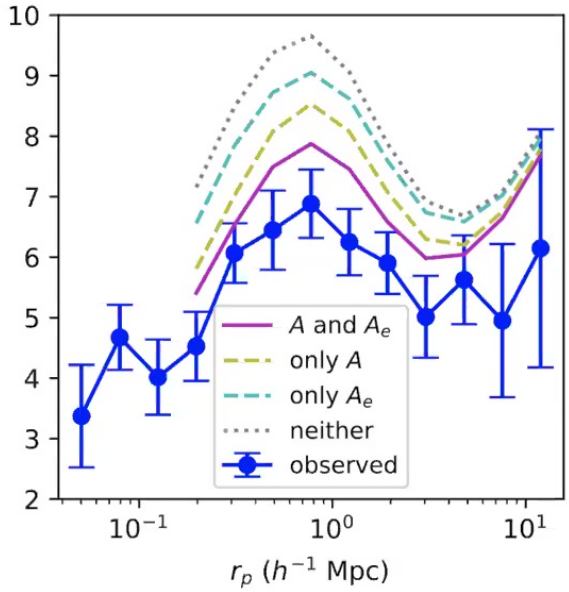

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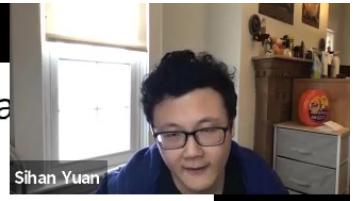

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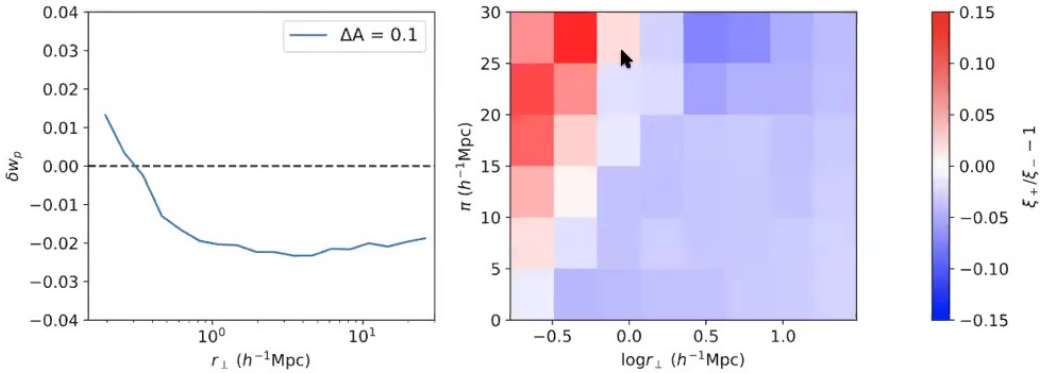
What is exactly driving these secondary biases?

Projected 2PCF

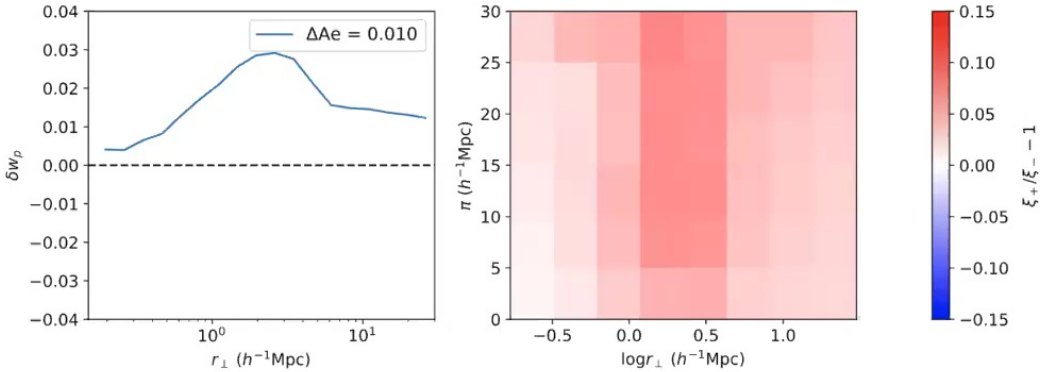
Redshift-space 2PCF

Concentration-based assembly bias **A**:

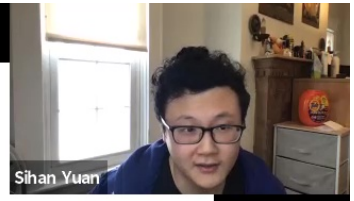


A < 0:
colder halos.

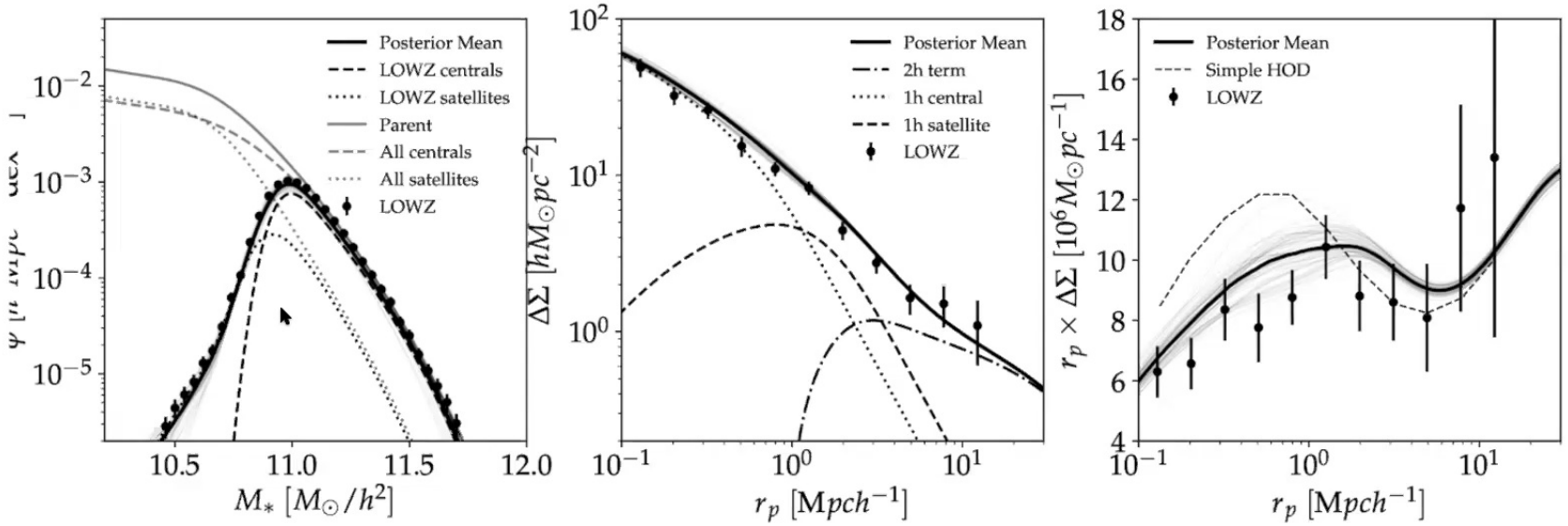
Environment-based secondary bias **Ae**:



Ae > 0:
Extended profiles.



Other solutions to “lensing is low”?

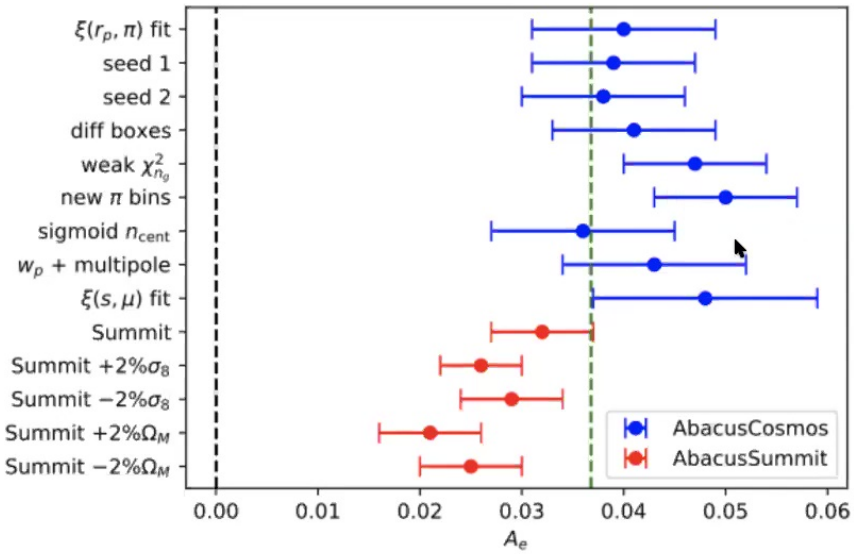


Issues: 1) satellite fraction 80% :(

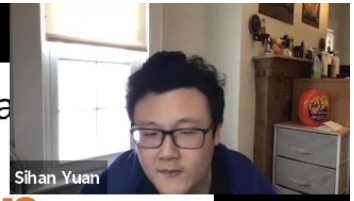
Zu Ying 2020

A positive detection of Ae

Yuan et. a



- A consistent detection of Ae across all fits:
- Ae might depend on cosmology (need more testing).



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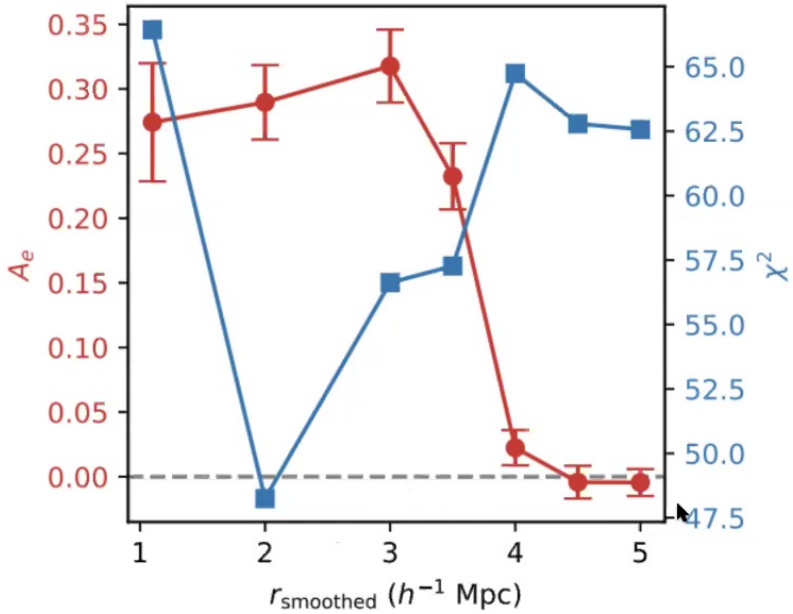
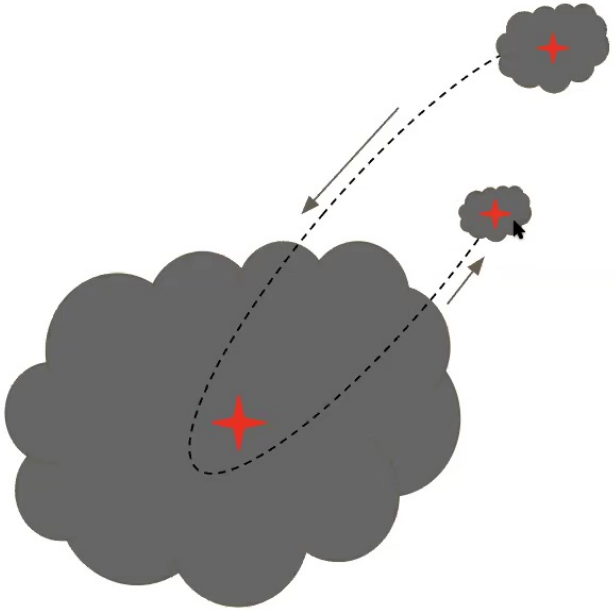
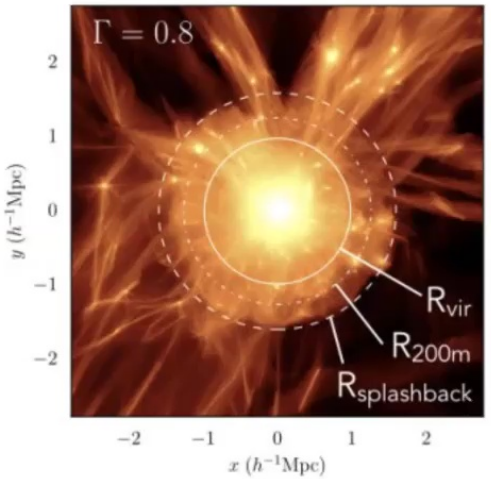
The dependence of Ae on environment definition



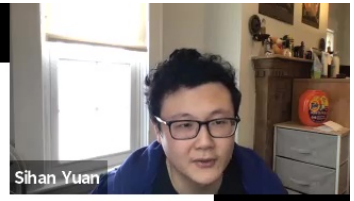
Yuan et. a

Evidence for splashback?

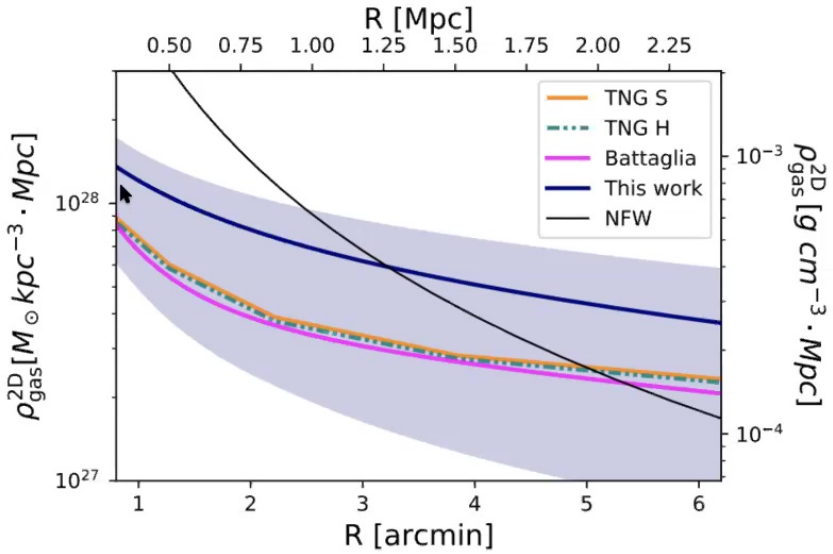


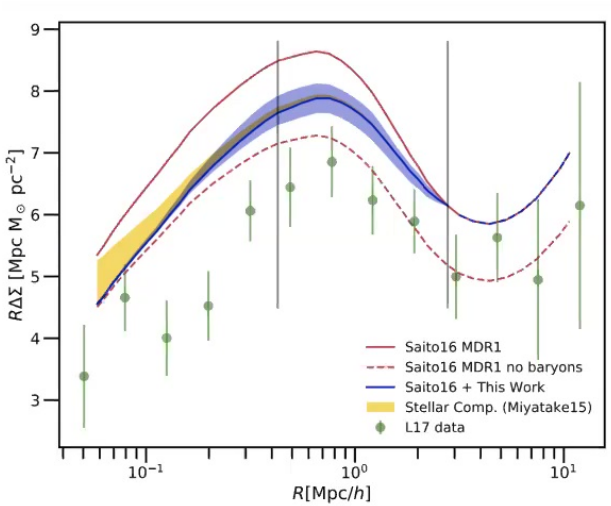


Credit: Benedikt Diemer



Evidence for extended baryon profile?

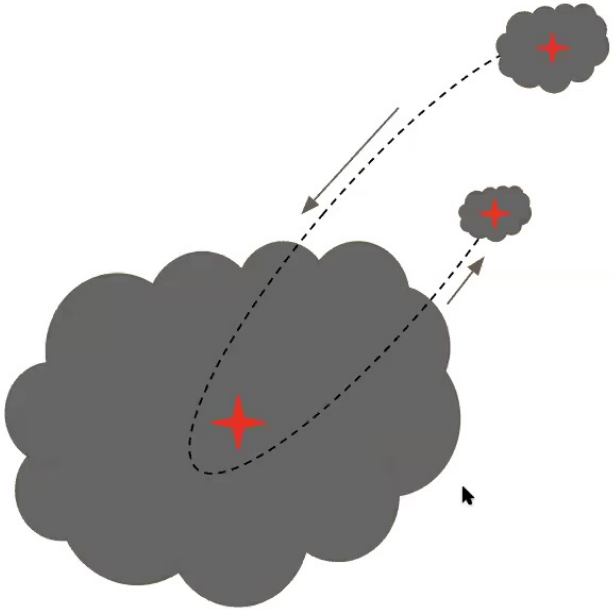


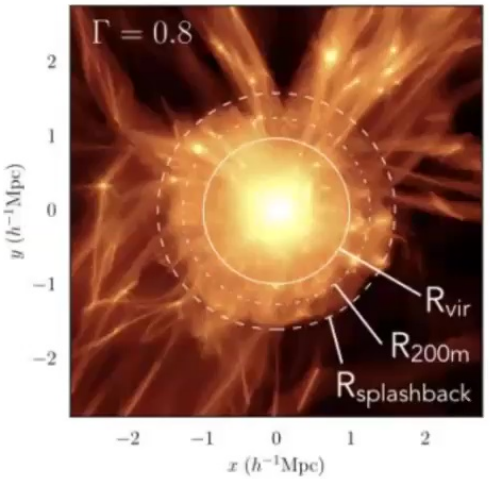


Amodeo et al. 2020

Yuan et. al. 2020b

Evidence for splashback?





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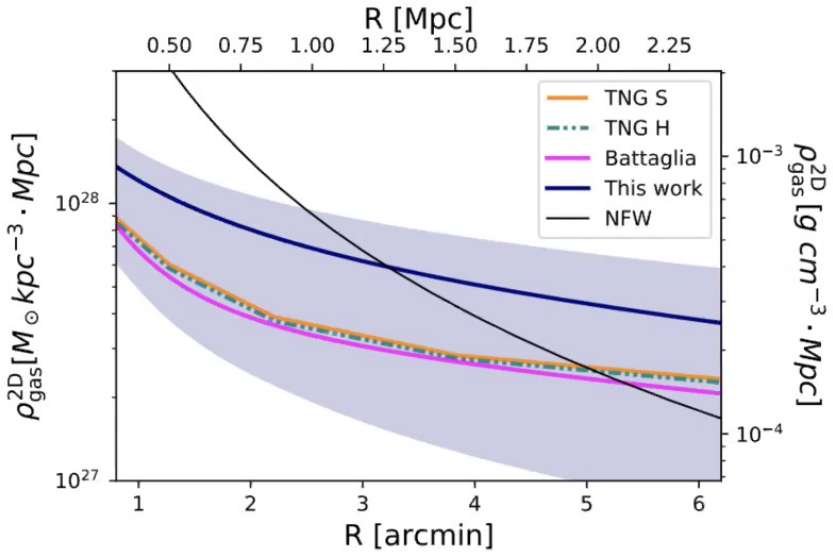
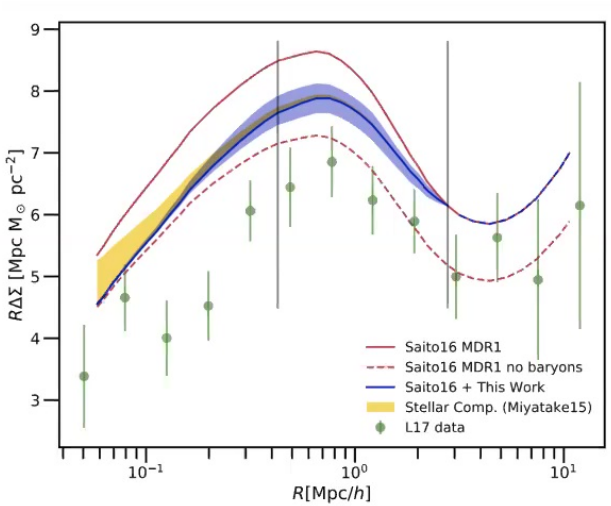
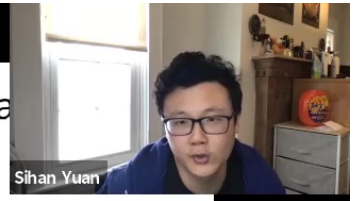




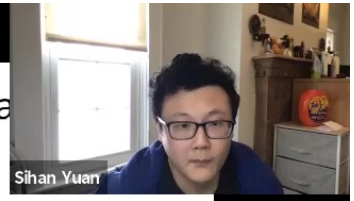
Amodeo et al. 2020



Yuan et. a

Current work: AbacusHOD (DESI-HOD)

- Highly Efficient
  - **Performance**: 80ms/tracer to populate a 2Gpc box on a 32 core desktop. Scalable to more cores and nodes.
  - **Optimizations**:
    - Mass-dependent subsampling.
    - Preloading halo and particle data in memory.
    - Memory in-place implementation with numba parallel.
- Multi-tracer (LRG, ELG, QSO)
  - ELG/QSO HOD based on Shadab's eBOSS fits.
  - Performance is 2x slower when ELG/QSO is enabled.
- Feature Rich
  - HOD extensions: secondary biases, velocity biases, satellite distribution flexibilities, RSD.
  - Interface with Abacus merger tree outputs.
  - Includes fast (0.1 second) 2-point calculators.



Yuan et. a

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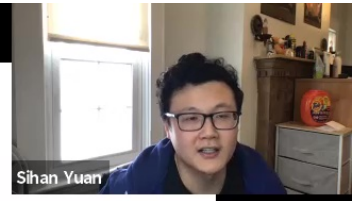
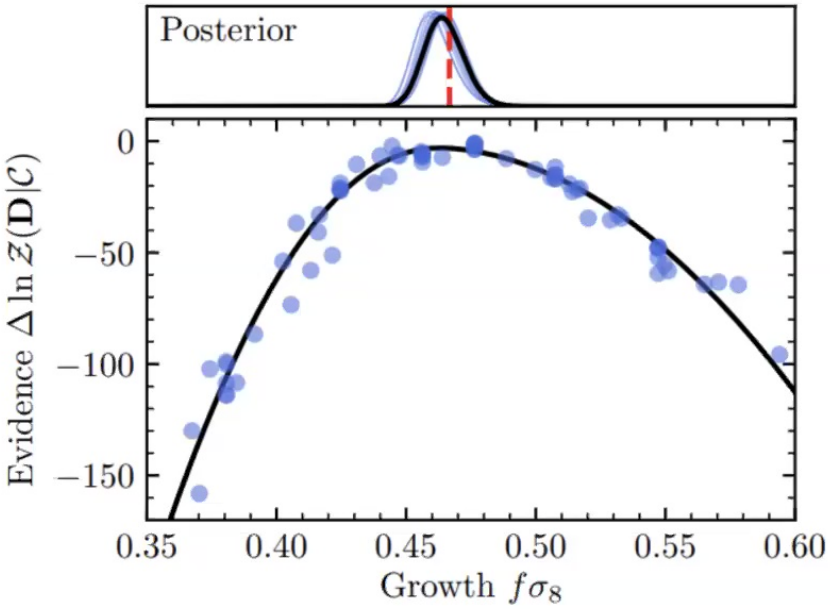
Evidence modeling with AbacusHOD + DESI

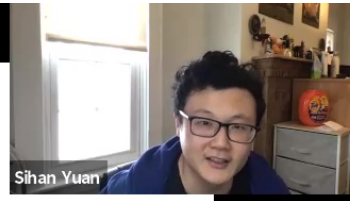


$$P(\mathcal{C}|\mathbf{D}) = \int P(\mathcal{C},\mathcal{G}|\mathbf{D})\,\mathrm{d}\mathcal{G}$$
$$= \frac{1}{\mathcal{Z}(\mathbf{D})}\int P\left(\mathbf{D}|\hat{\mathbf{D}}(\mathcal{C},\mathcal{G})\right)P(\mathcal{C})P(\mathcal{G})\mathrm{d}\mathcal{G}$$
$$= \frac{\mathcal{Z}(\mathbf{D}|\mathcal{C})P(\mathcal{C})}{\mathcal{Z}(\mathbf{D})}.$$

- AbacusSummit (155 cosmologies) + AbacusHOD (extended and fast) is very well suited for this!

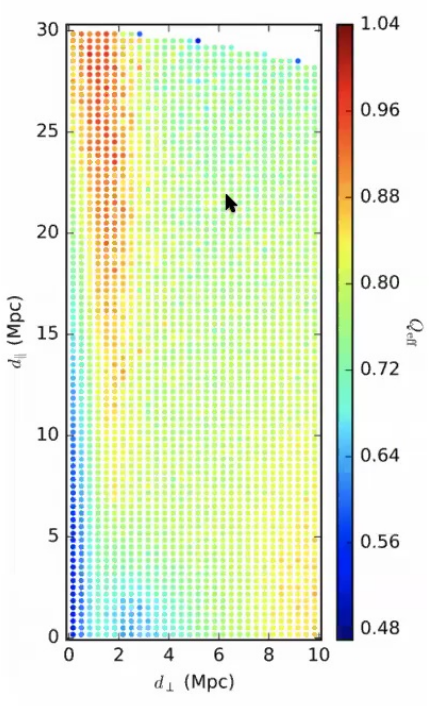


Credit: Lange+19

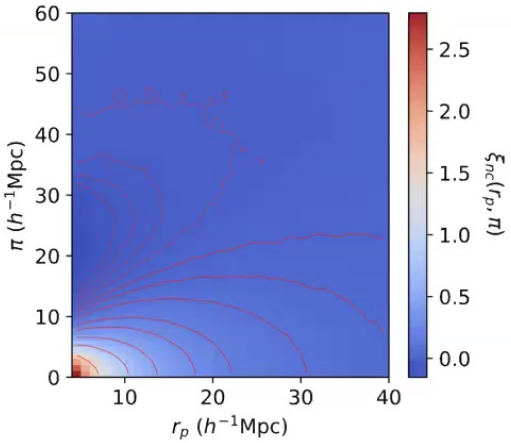


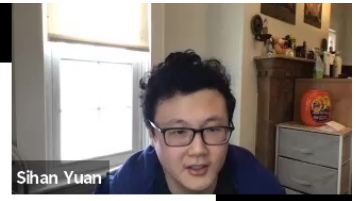
Novel statistics?

- Squeezed 3PCF (Yuan et al 2017, 2018).



- SZ-marked group correlation function (work in progress).





Summary

- We find strong evidence for extended HOD models with secondary biases.
- The corresponding lensing prediction is significantly more consistent with data than previous predictions.
- Redshift-space clustering offers a lot more information.
- The secondary biases have interesting implications ranging from dark matter structure, to CGM, to GR.
- Currently developing a fast extended HOD that will enable robust HOD and cosmology analyses, especially within DESI.

Different assembly bias models produce different results