

A visualization of the cosmic web, showing a complex network of filaments and nodes of matter. The central node is particularly bright and dense, with many filaments radiating outwards. The background is dark blue, and the filaments are a golden-yellow color.

Modeling Galaxies in the Era of Precision Cosmology

An open-source approach with Halotools

Andrew Hearin

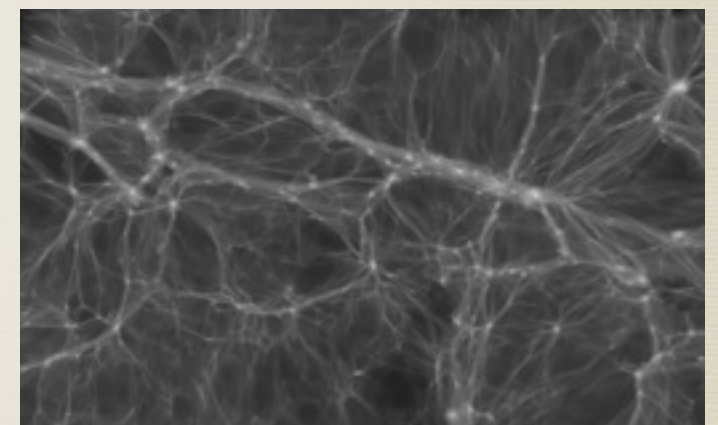
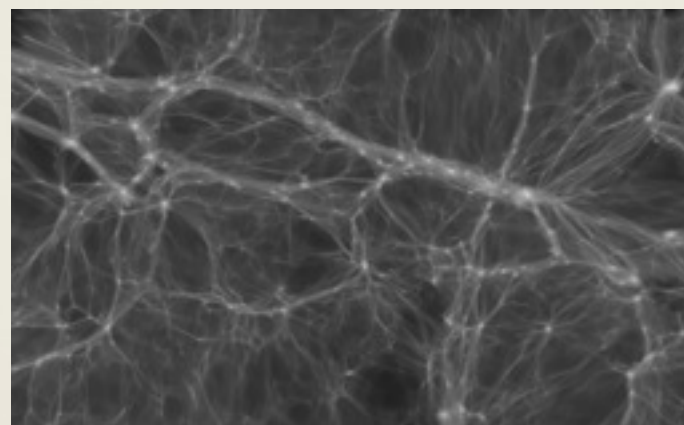
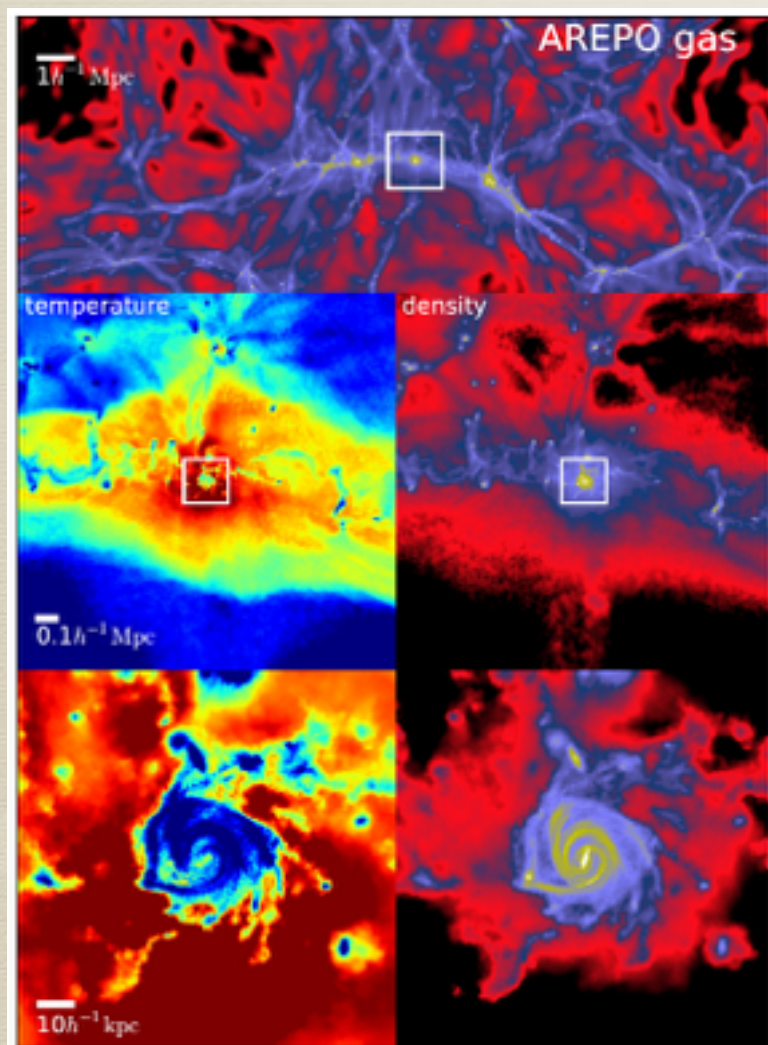
Modeling Galaxy Evolution

Three complementary approaches

Hydro sim

Semi-analytic model

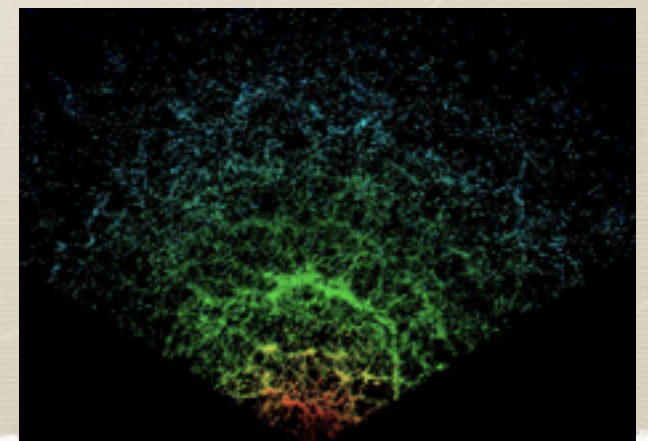
Empirical model



+

+

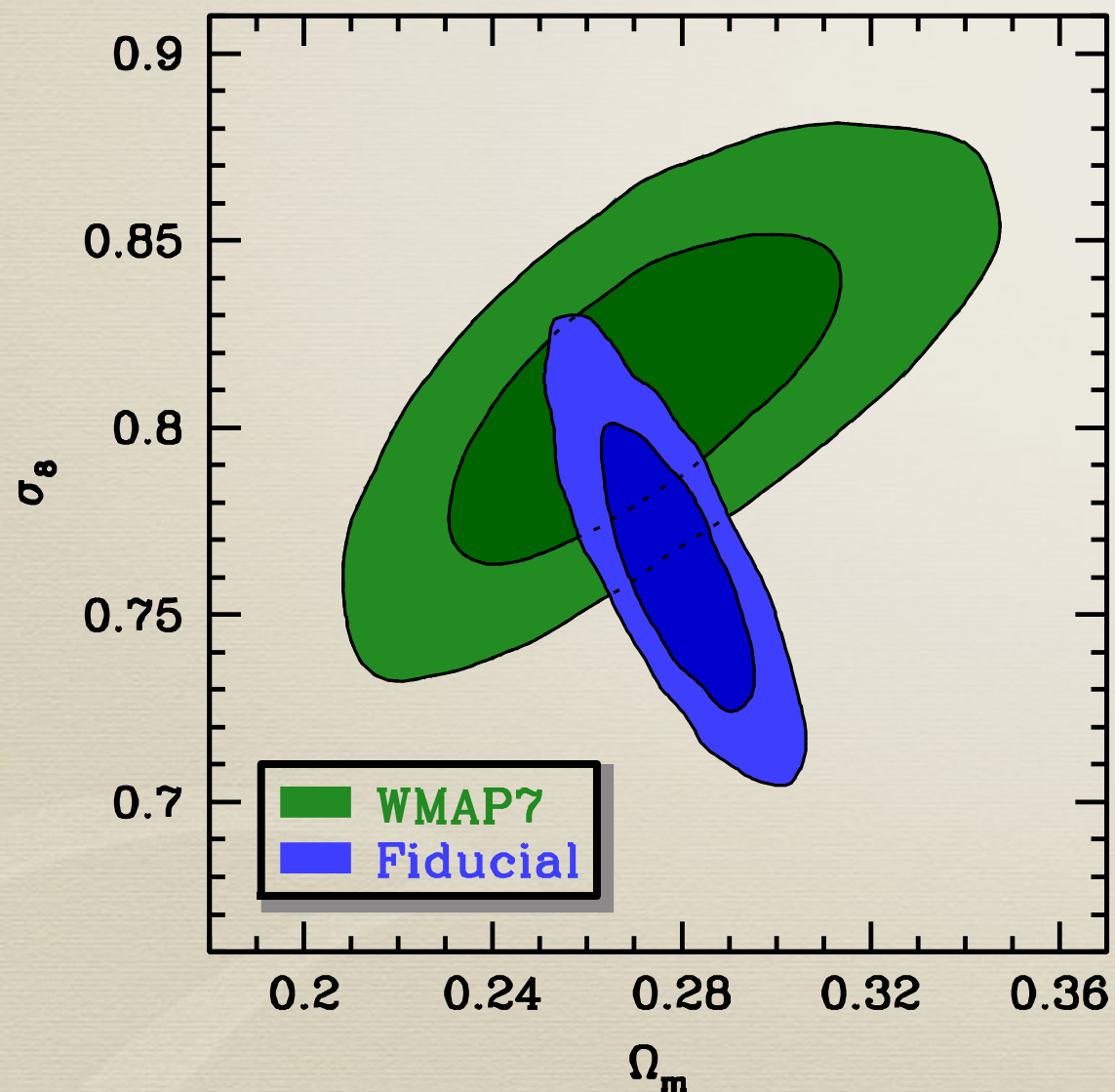
$$\begin{aligned}
 \lambda &= \frac{J|E|^{1/2}}{GM^{5/2}} \\
 \frac{dM_{\text{baryon}}}{dt} &= \epsilon(M_{\text{halo}}) \frac{dM_{\text{DM}}}{dt} \\
 \frac{dM_{\text{gas}}}{dt} &= -\Psi_{\text{SFR}}(t) + \mathcal{E}_{\text{wind}}^*(t) \\
 \dots &= \dots
 \end{aligned}$$



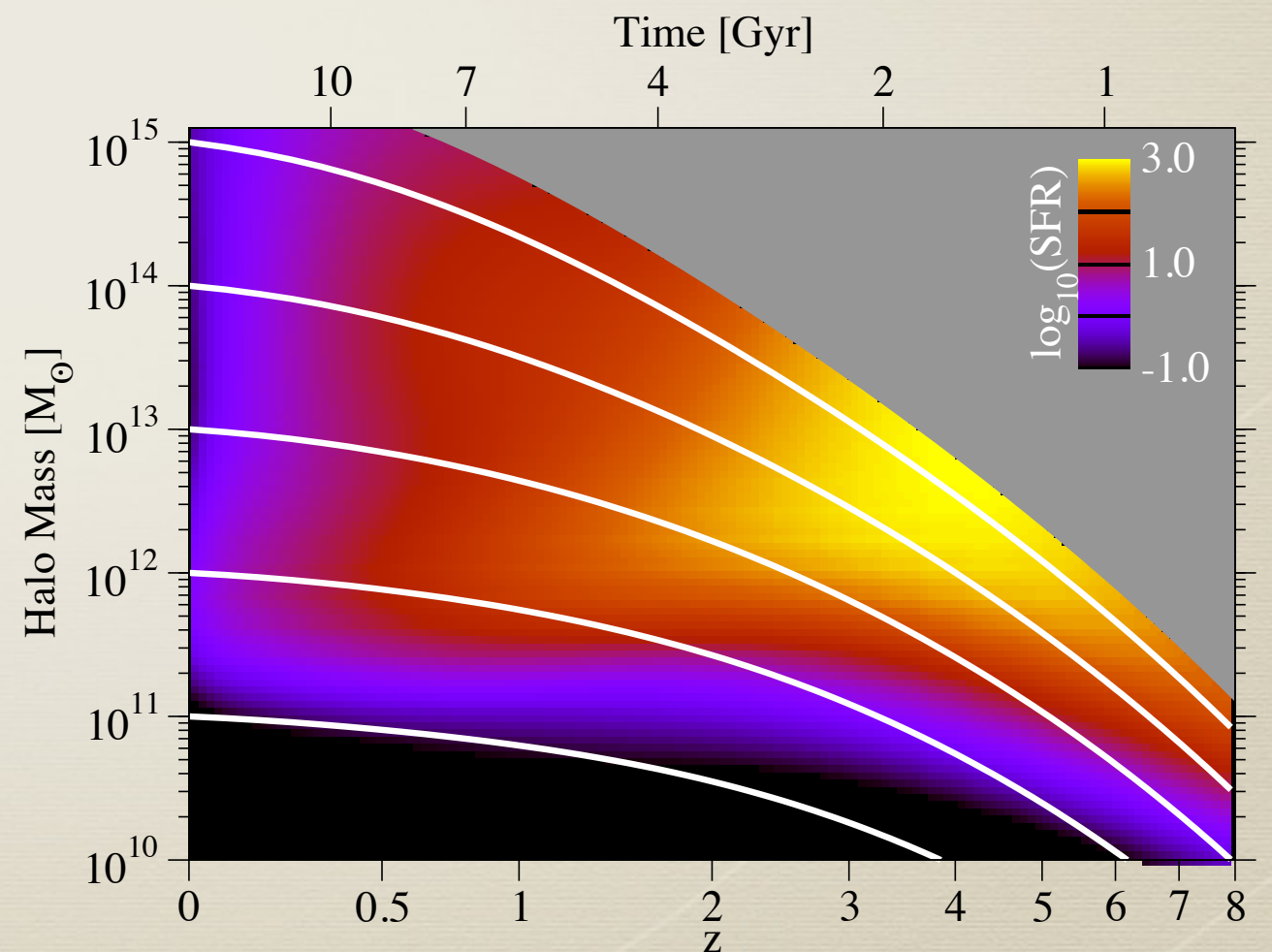
Modeling Galaxy Evolution

The promise of empirical modeling

Cosmology



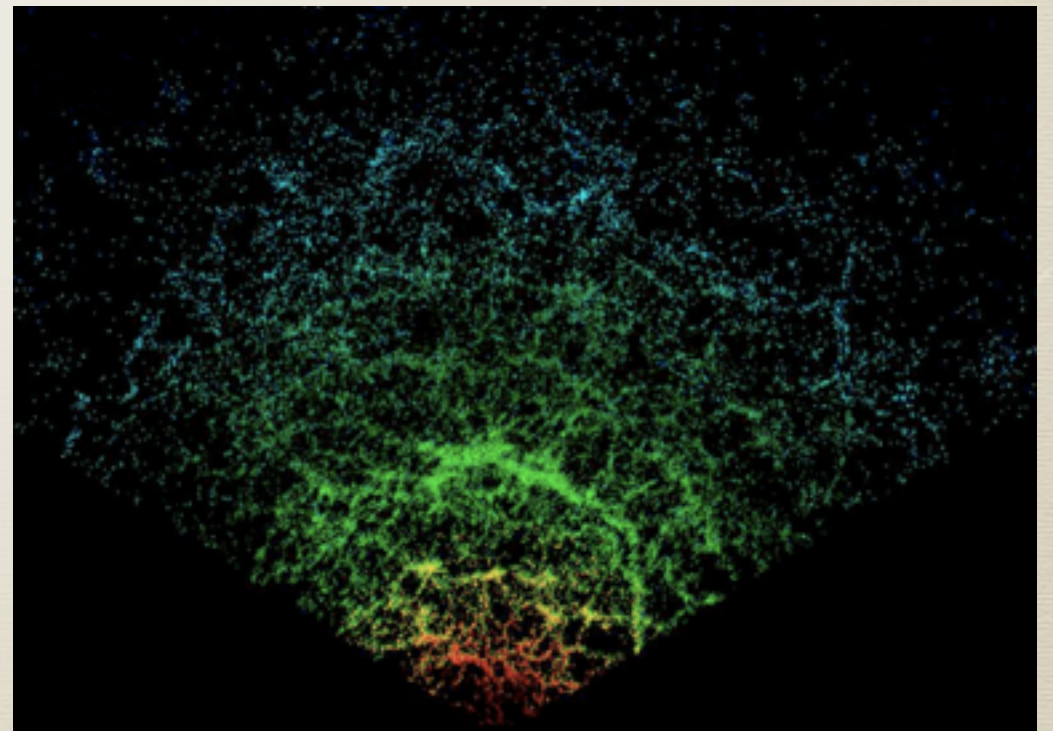
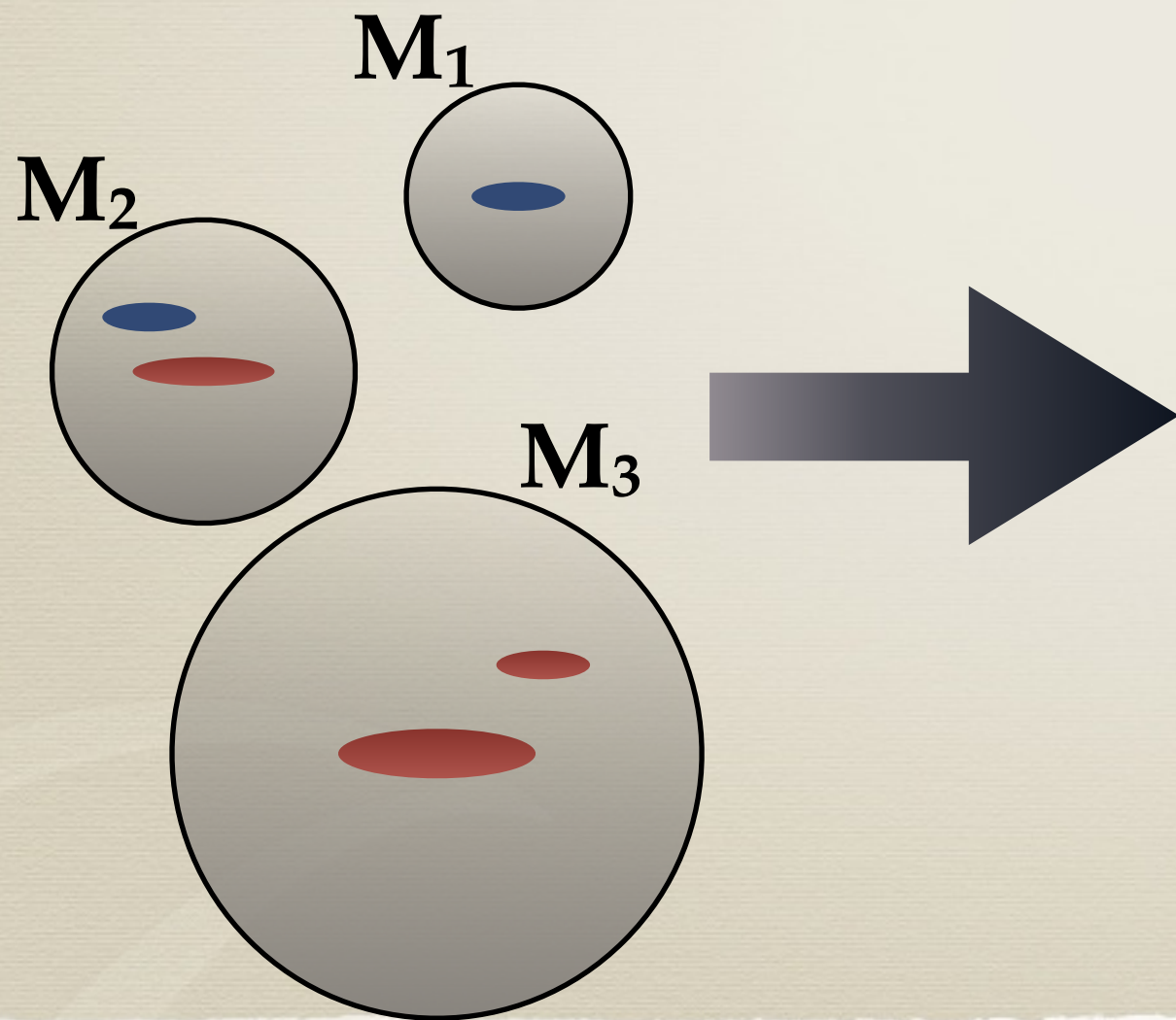
Galaxy evolution



The Promise of Empirical Modeling

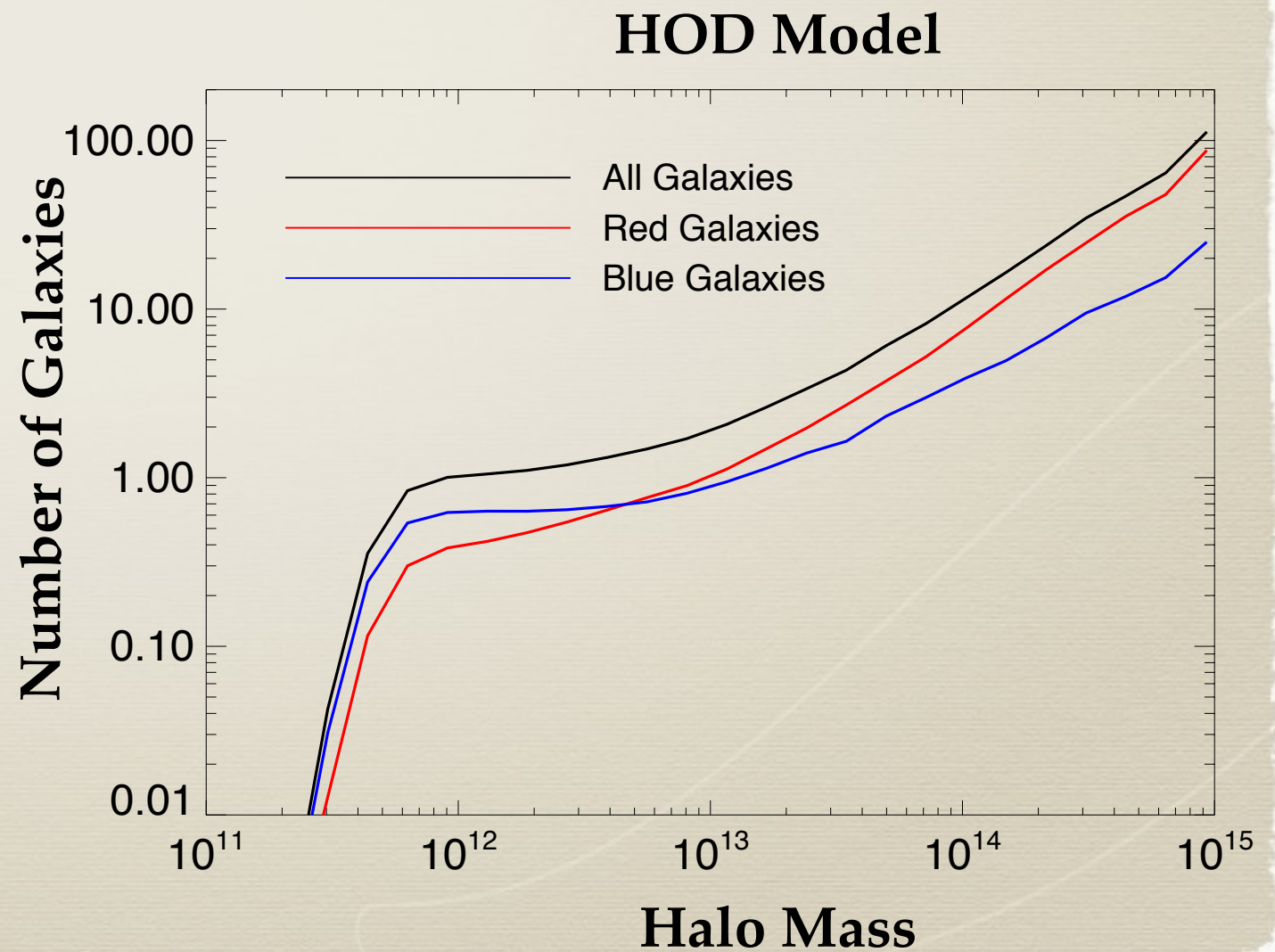
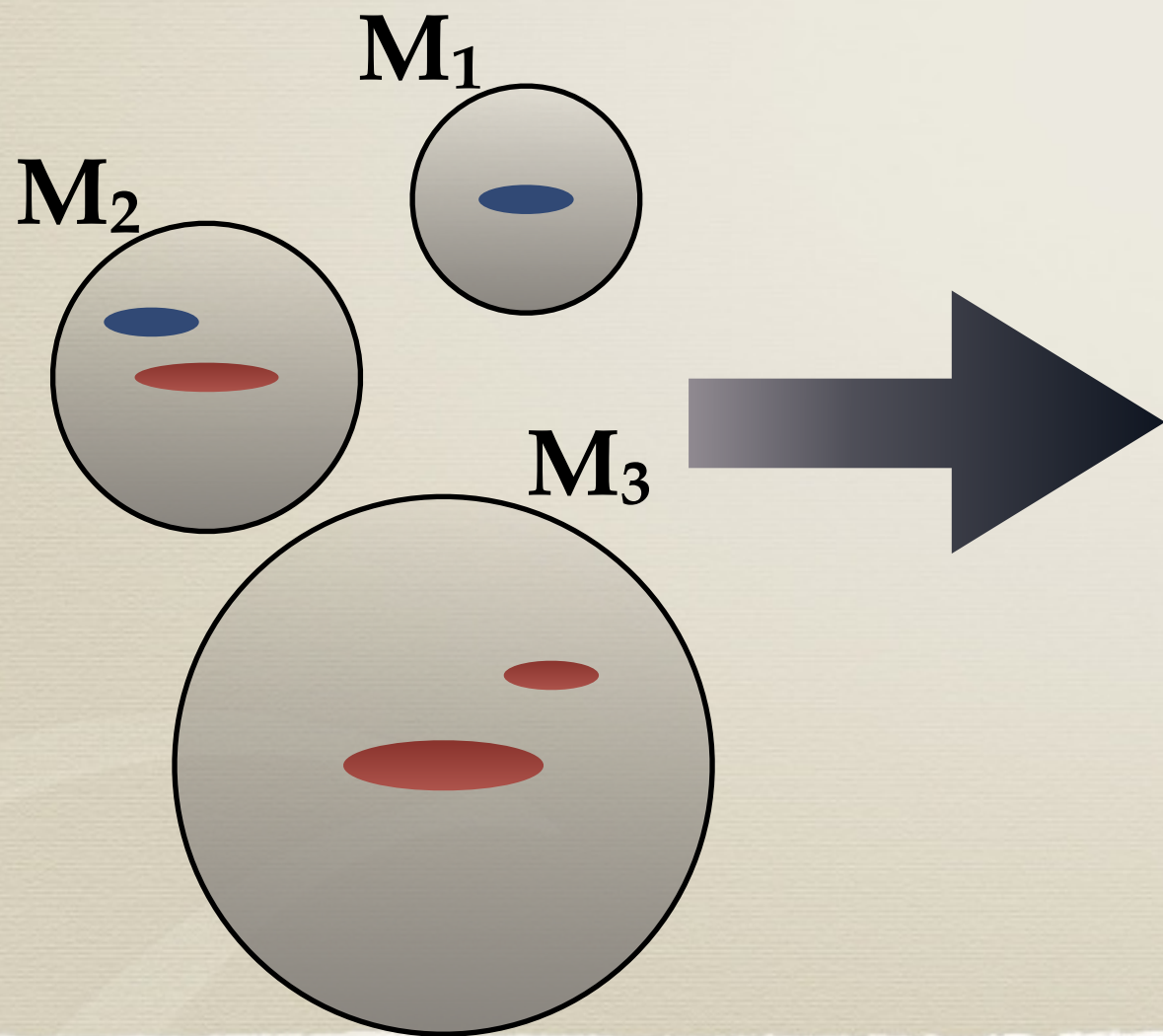
Ten years of empirical modeling
in one glib cartoon

Halo mass is king!



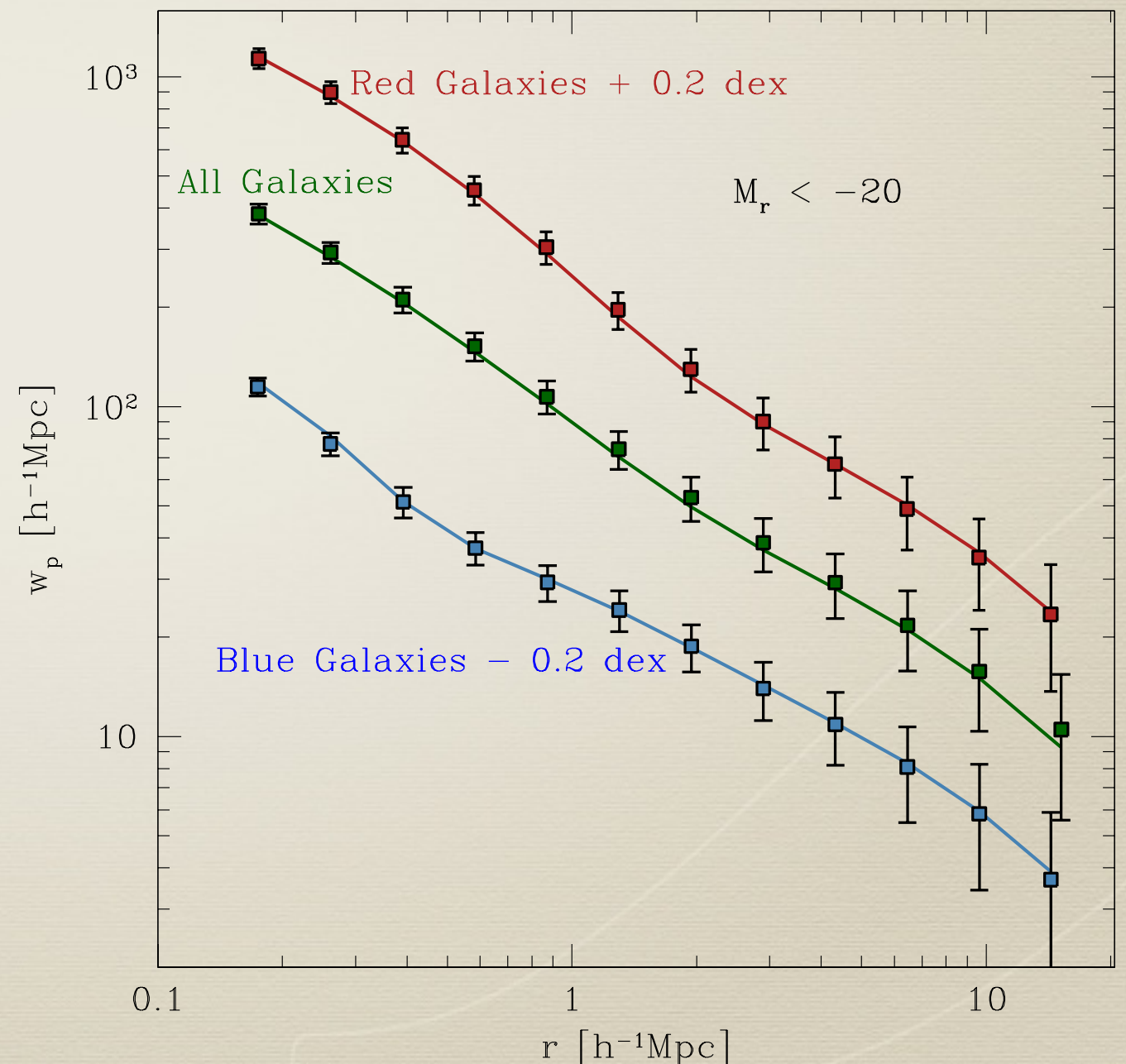
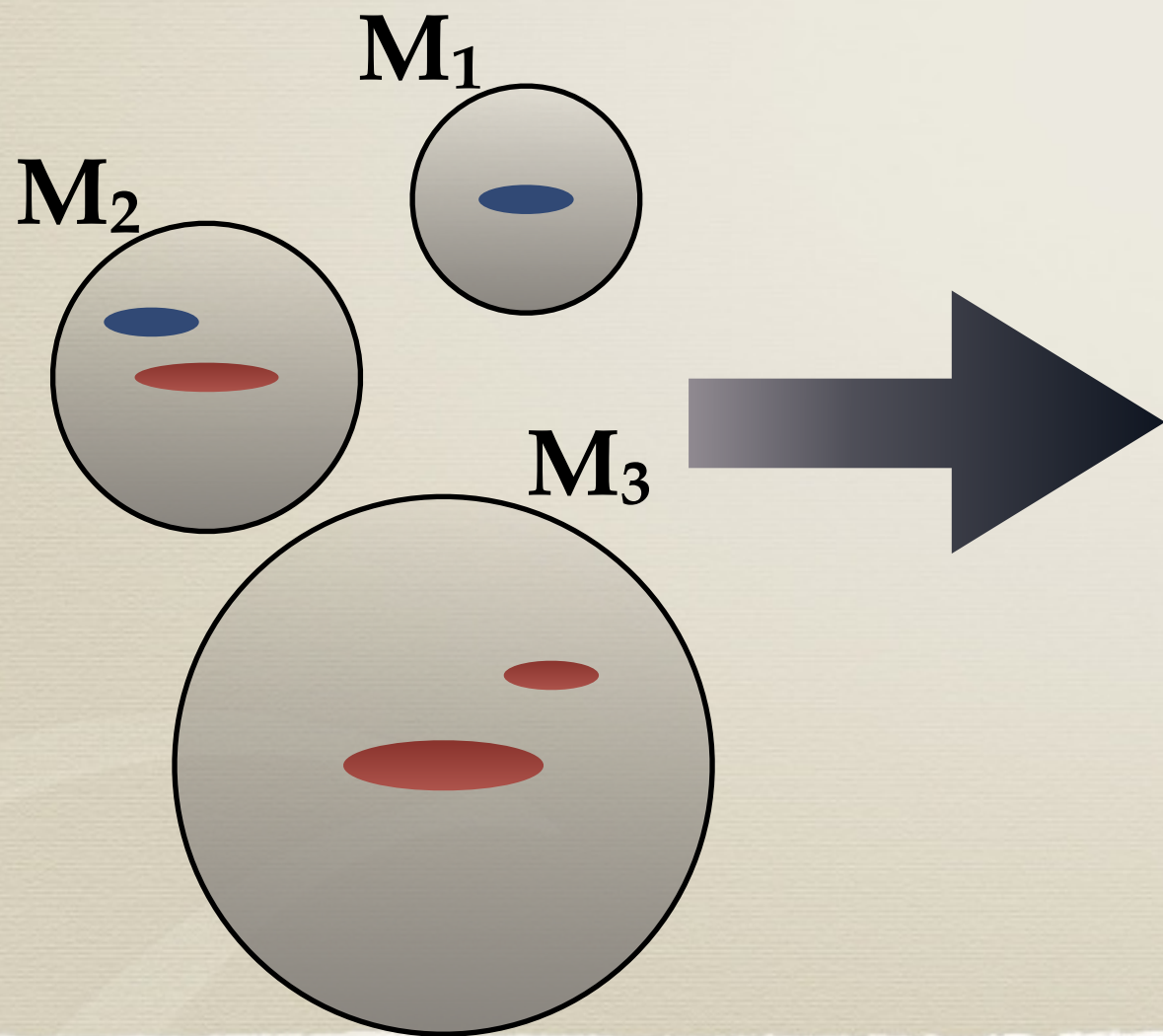
The Promise of Empirical Modeling

HOD as a specific example



The Promise of Empirical Modeling

HOD + simulation fitting functions \Rightarrow
large-scale structure predictions



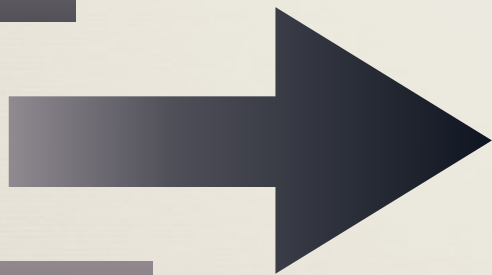
The Promise of Empirical Modeling

Cosmology from clustering + gg-lensing

HOD model

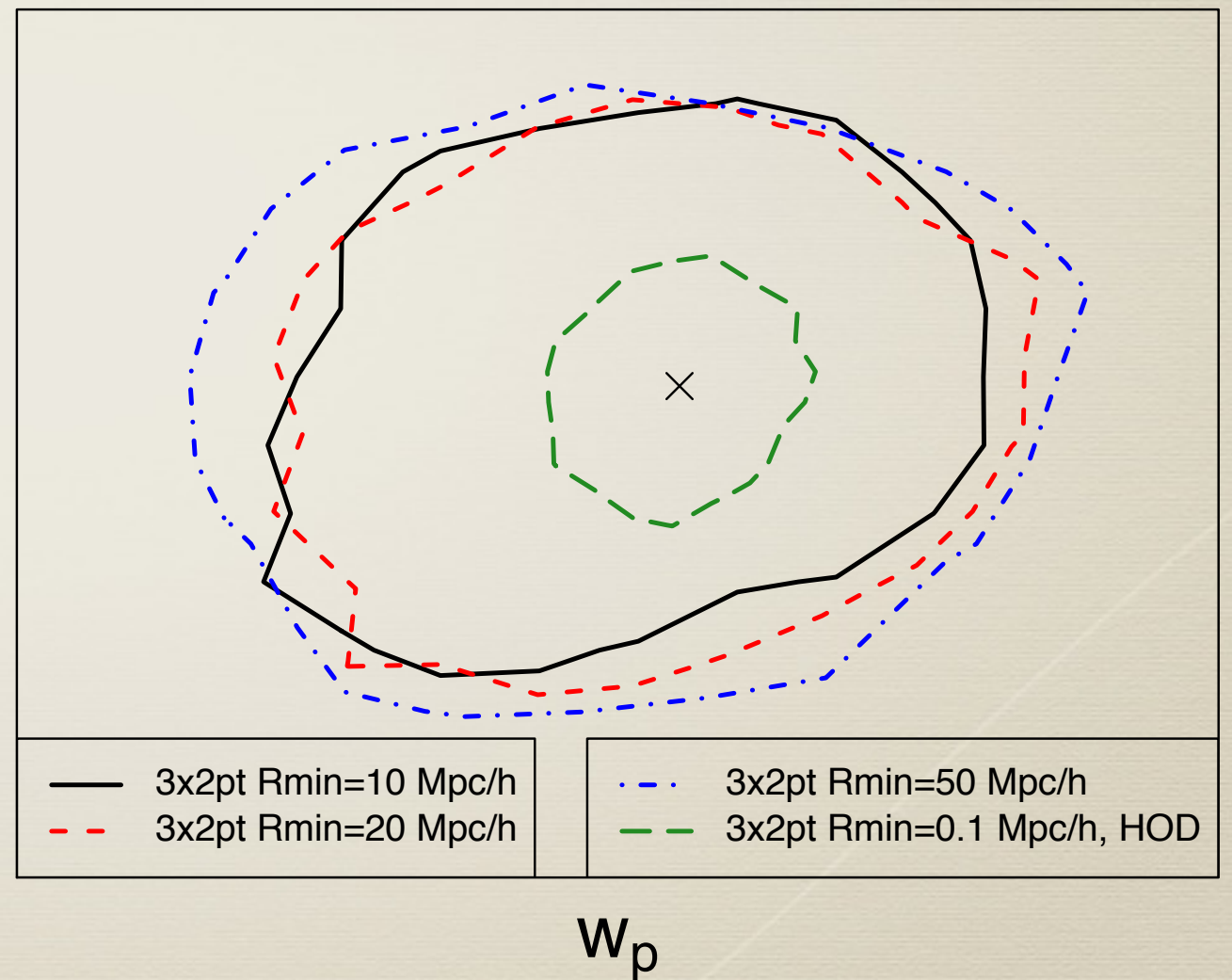
+

halo
fitting functions



w_a

CosmoLike



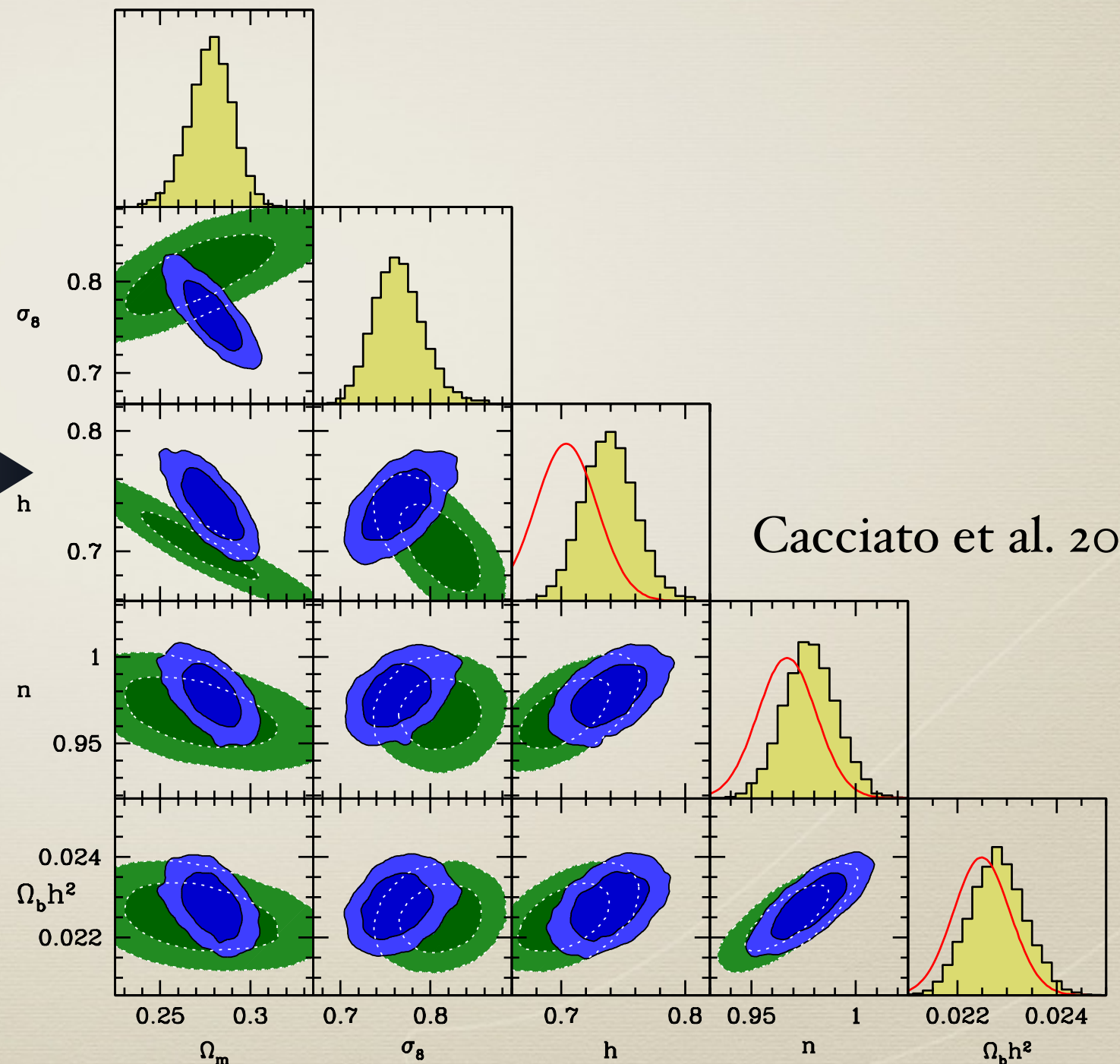
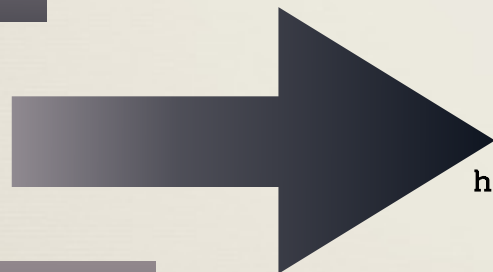
The Promise of Empirical Modeling

Cosmology from clustering + gg-lensing

CLF model

+

halo
fitting functions

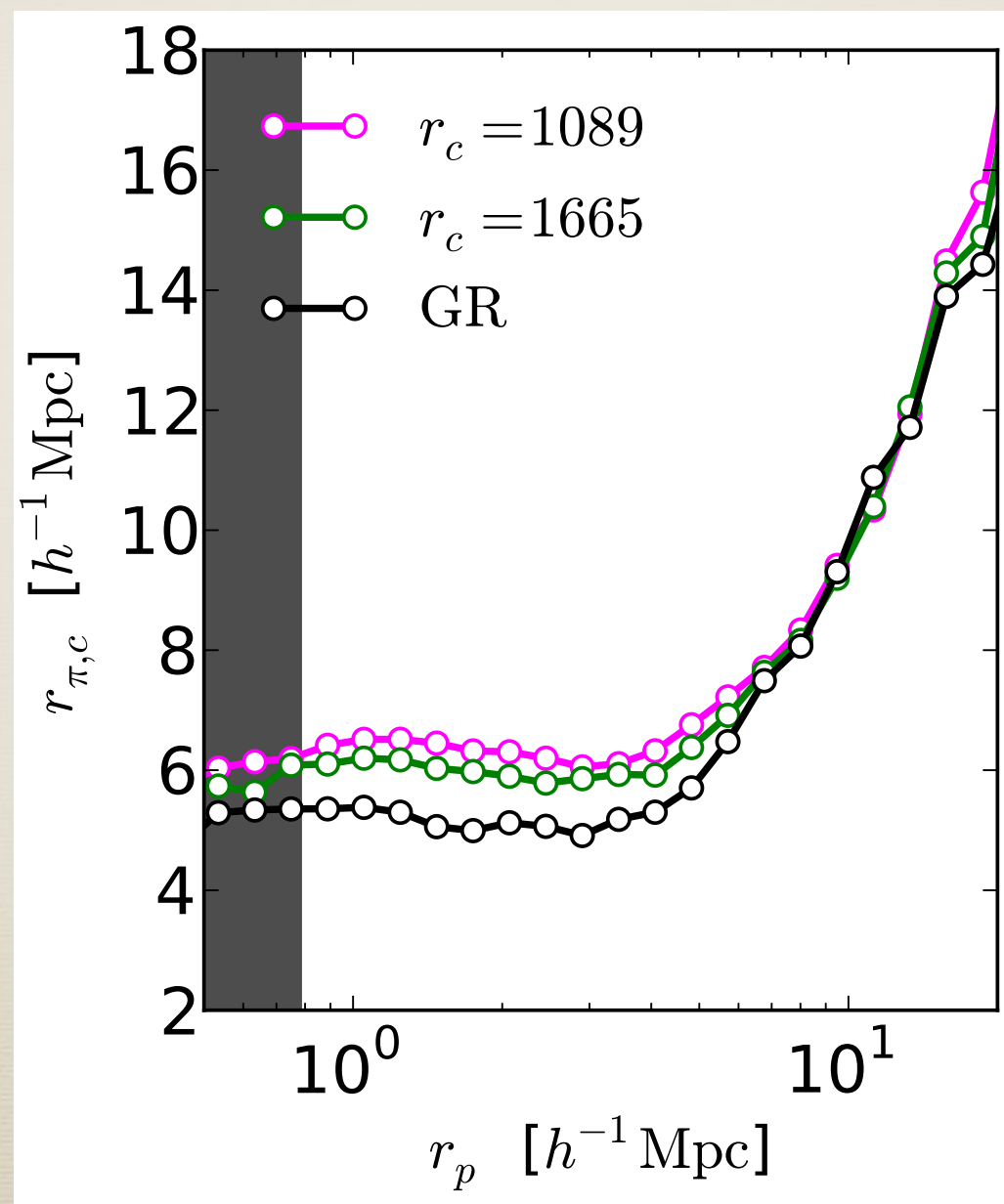


Cacciato et al. 2013

The Promise of Empirical Modeling

Modified GR from redshift-space distortions

Zu & Weinberg 2013



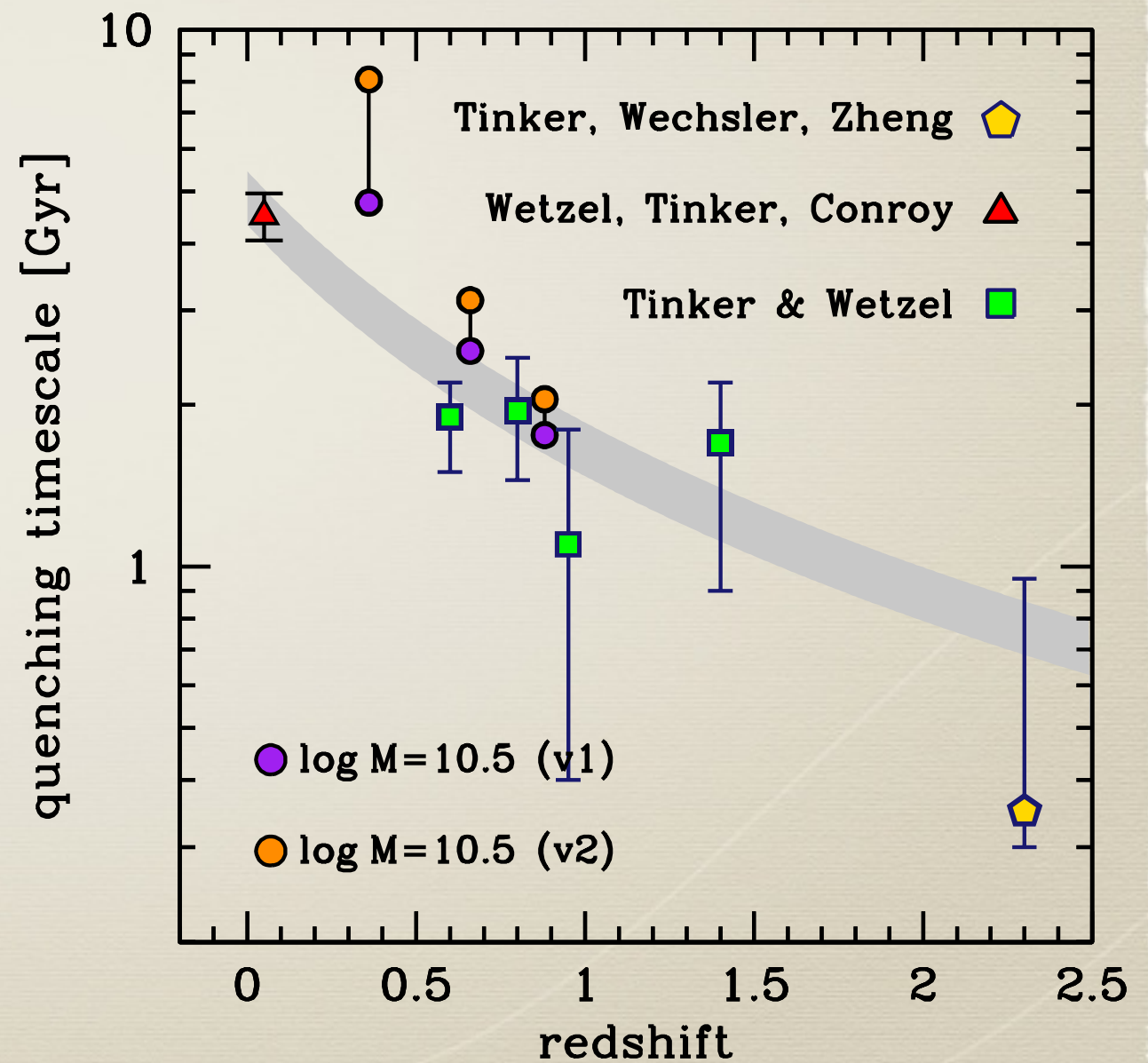
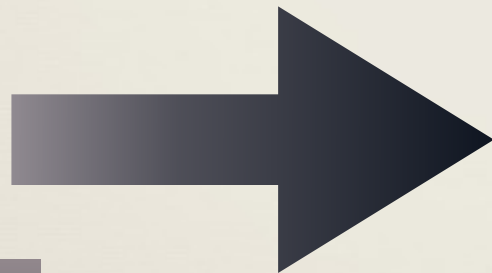
The Promise of Empirical Modeling

Satellite quenching timescales
from clustering + lensing

HOD model

+

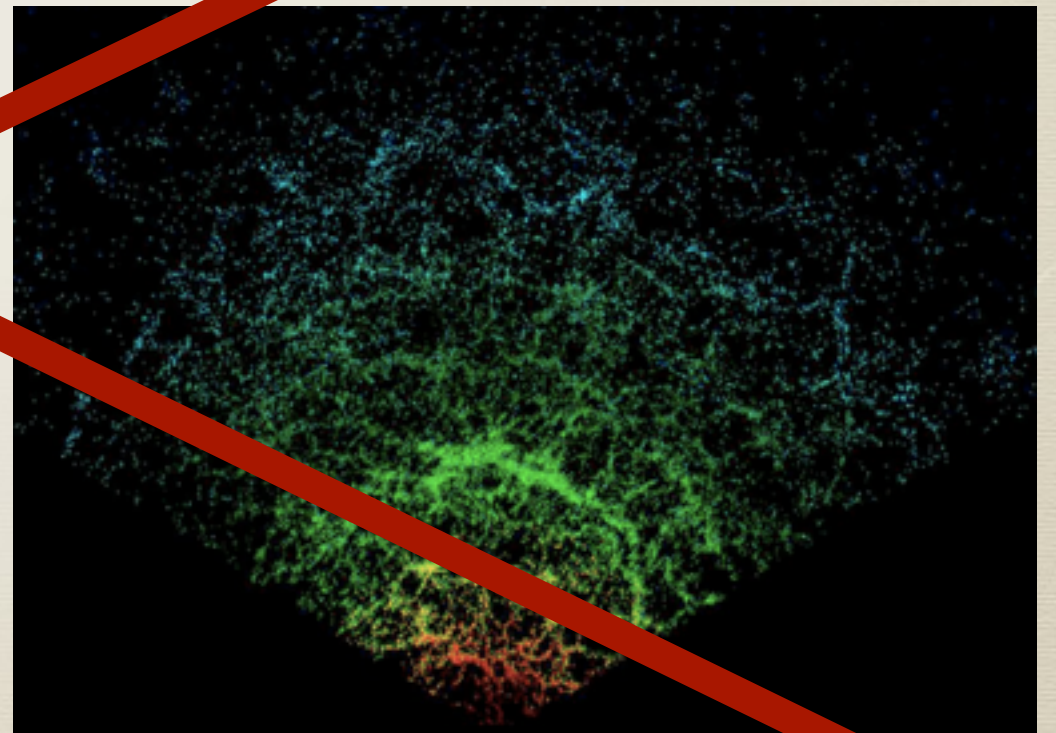
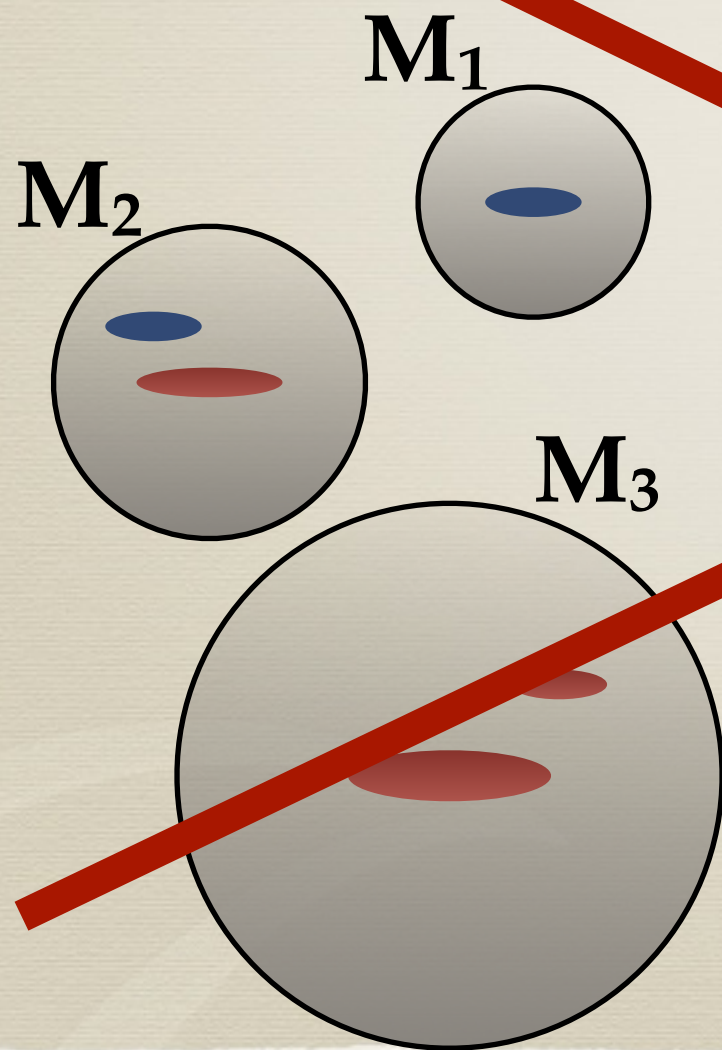
halo
fitting functions



Tinker et al. 2013

A Wrench in the Works

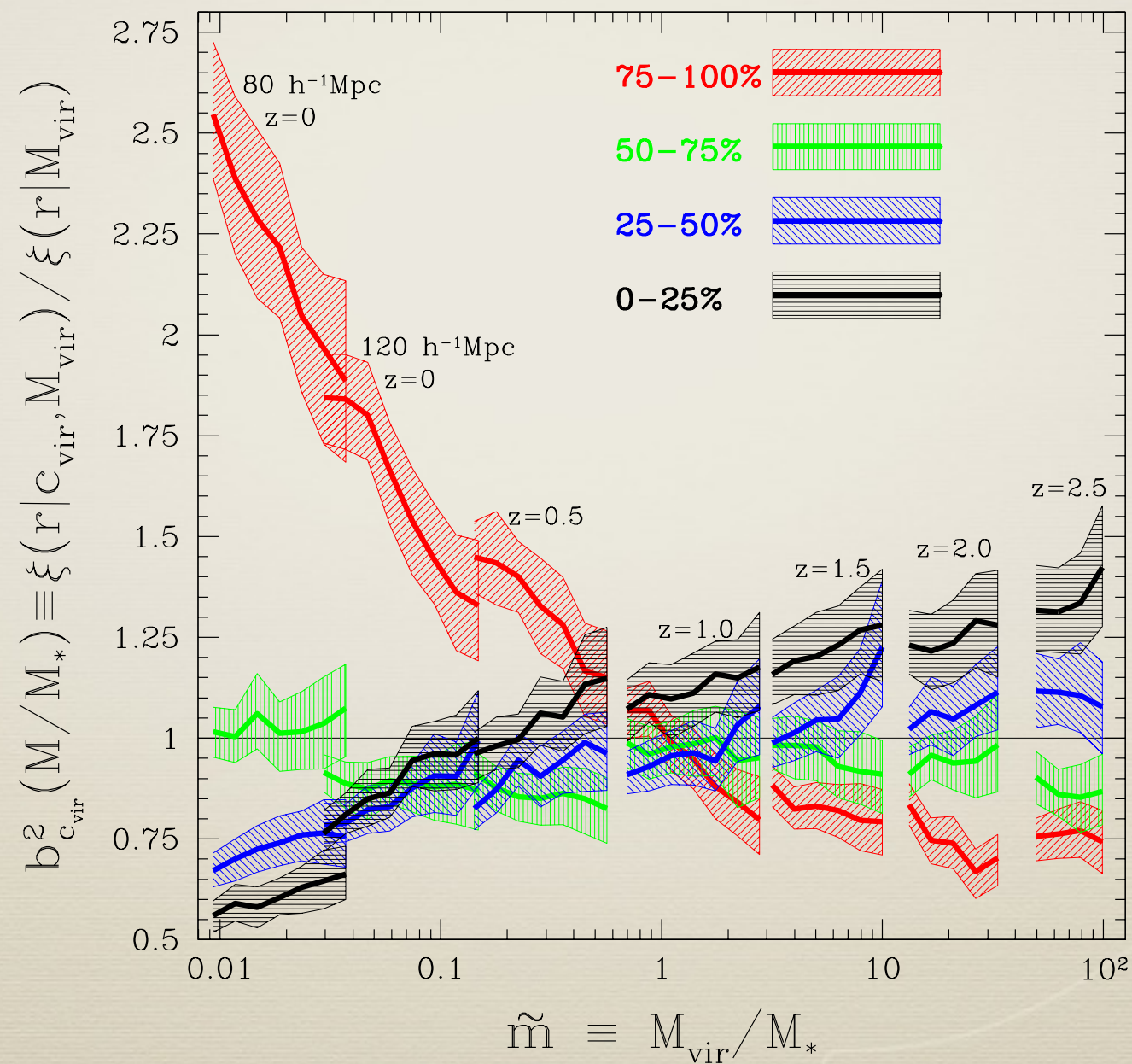
The threat of assembly bias



The Threat of Assembly Bias

Halo mass alone does not determine clustering

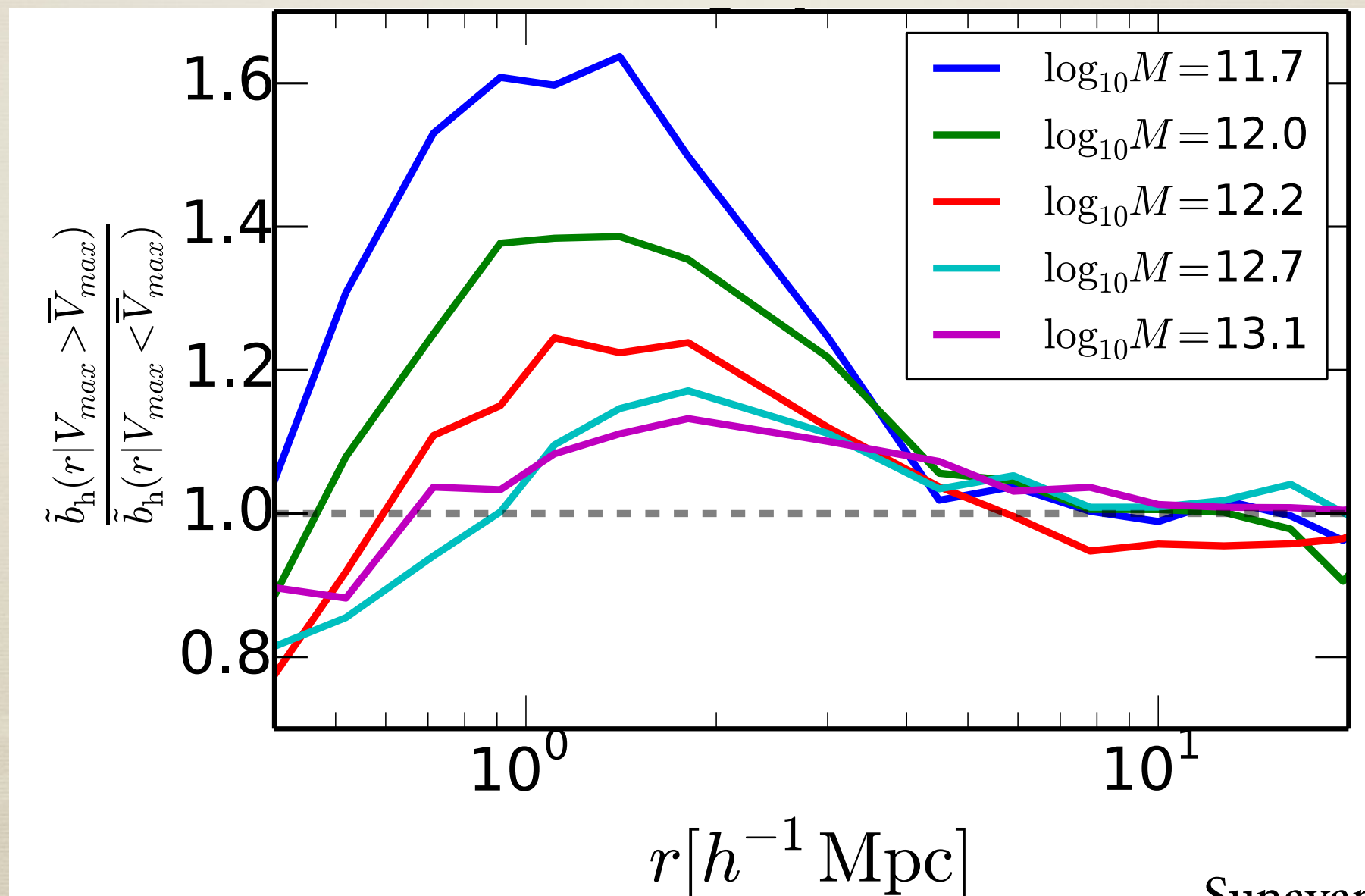
Not even in the linear regime!



The Threat of Assembly Bias

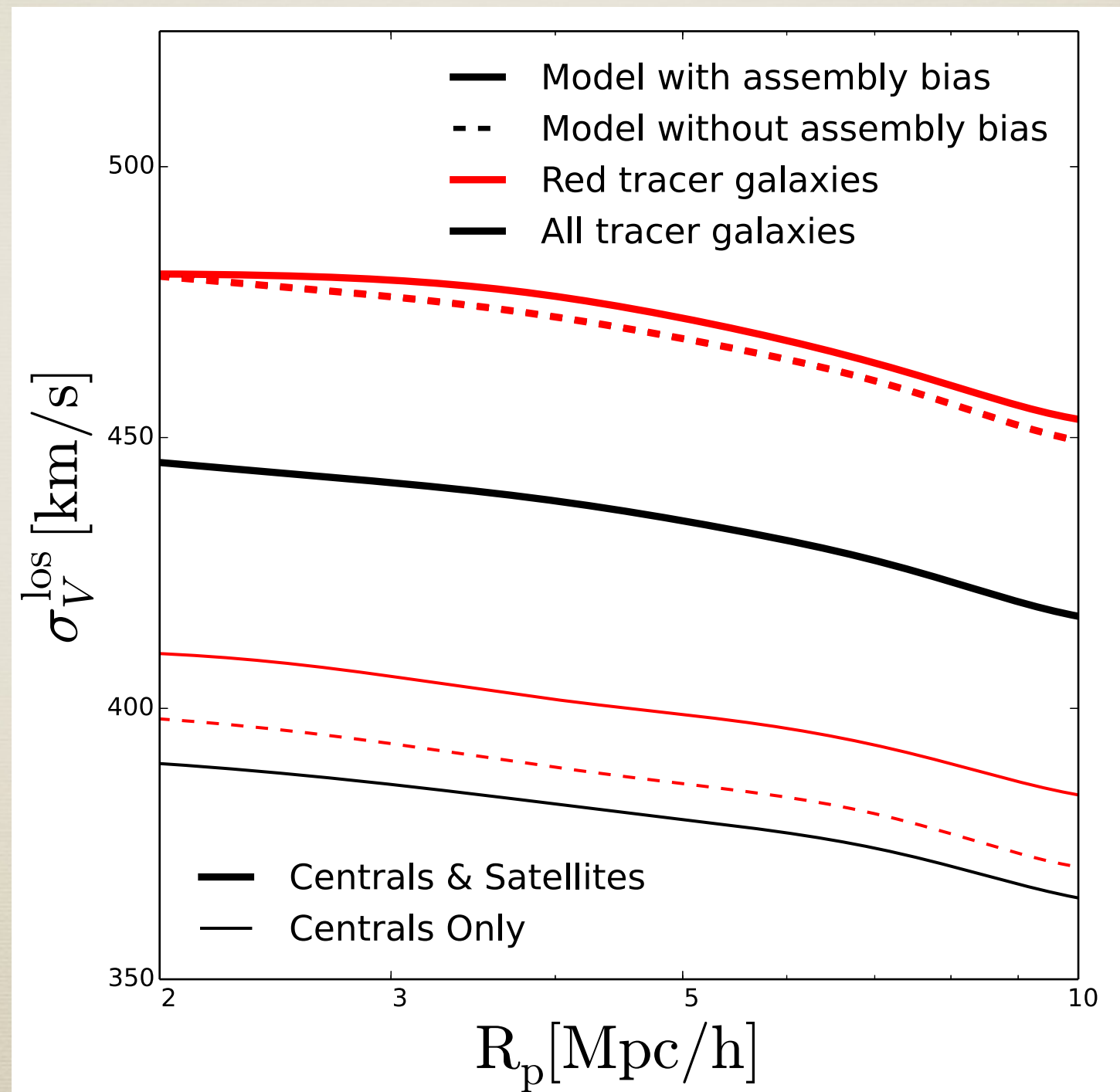
Halo mass alone does not determine clustering

Effects are highly scale-dependent



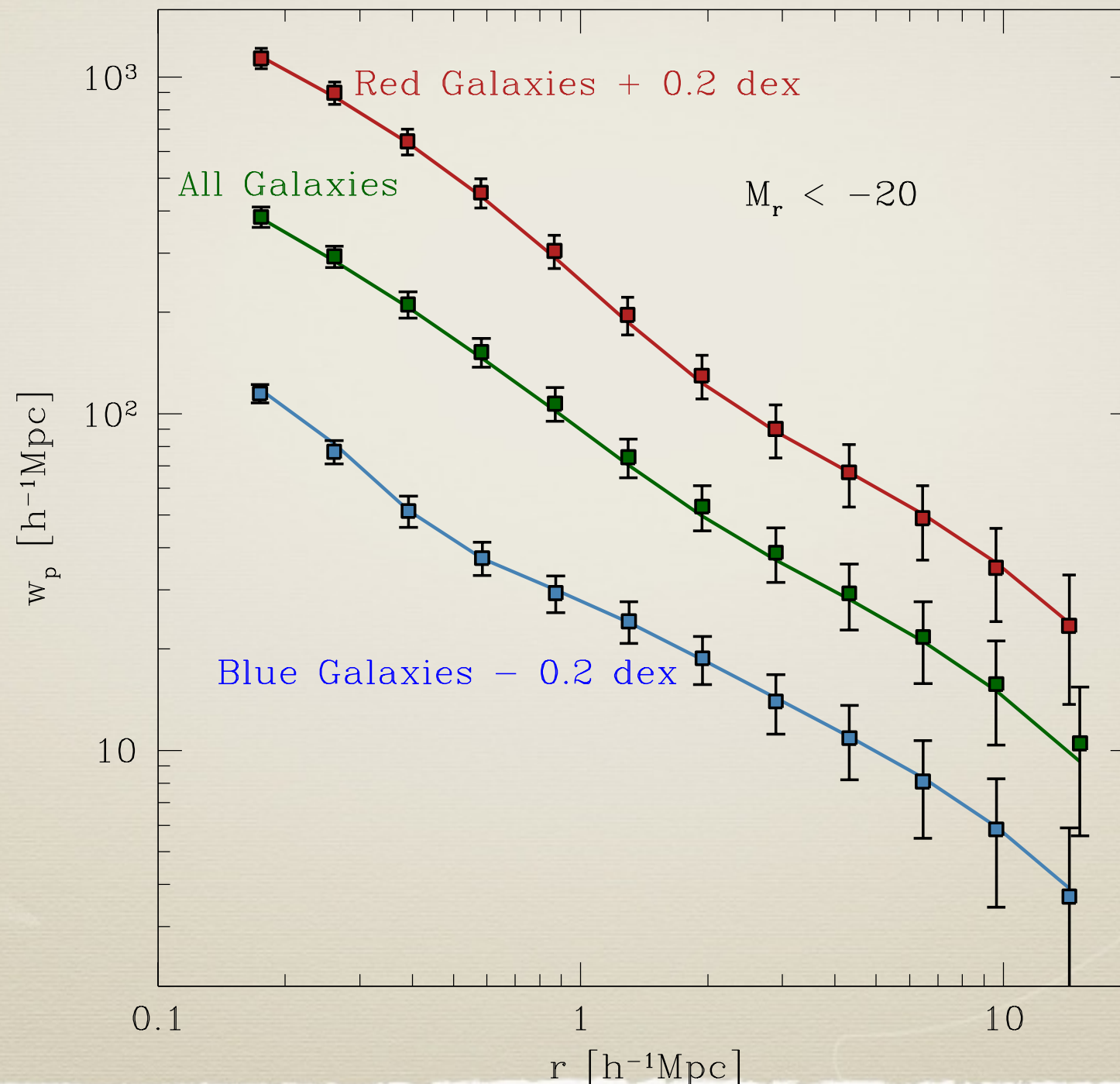
The Threat of Assembly Bias

Potentially disastrous consequences



The Threat of Assembly Bias

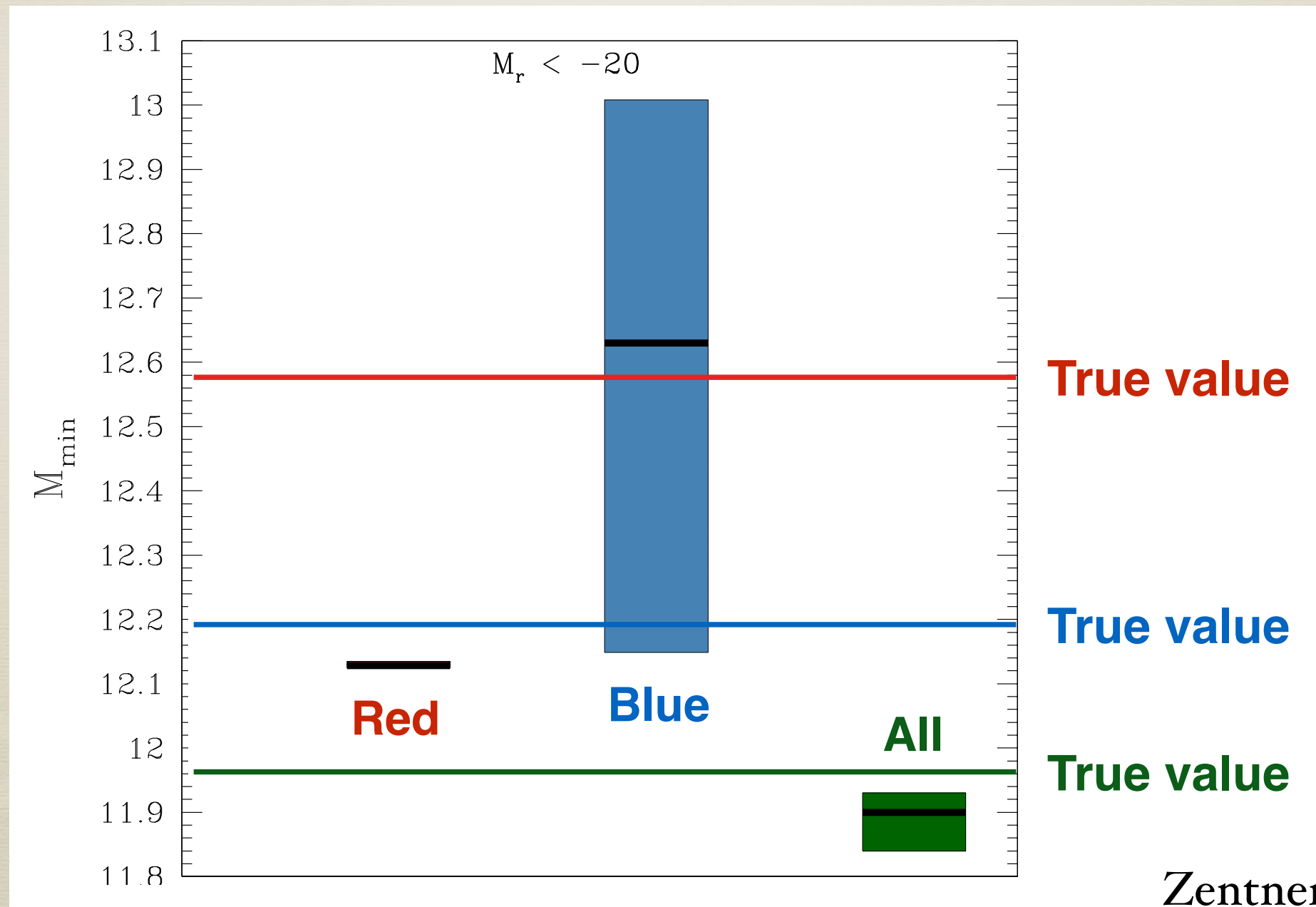
Potentially disastrous consequences



Zentner et al. 2013

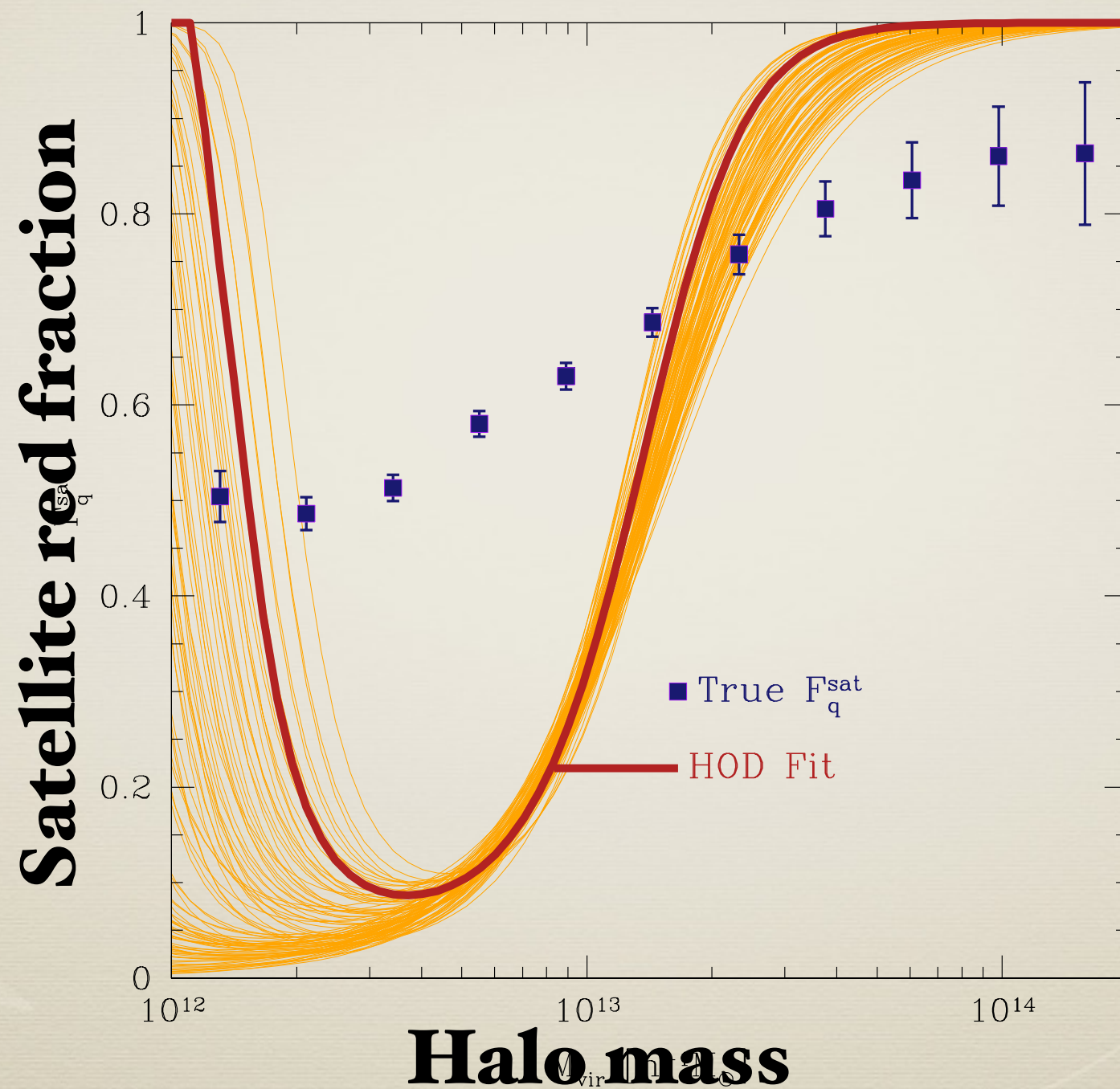
The Threat of Assembly Bias

Potentially disastrous consequences



The Threat of Assembly Bias

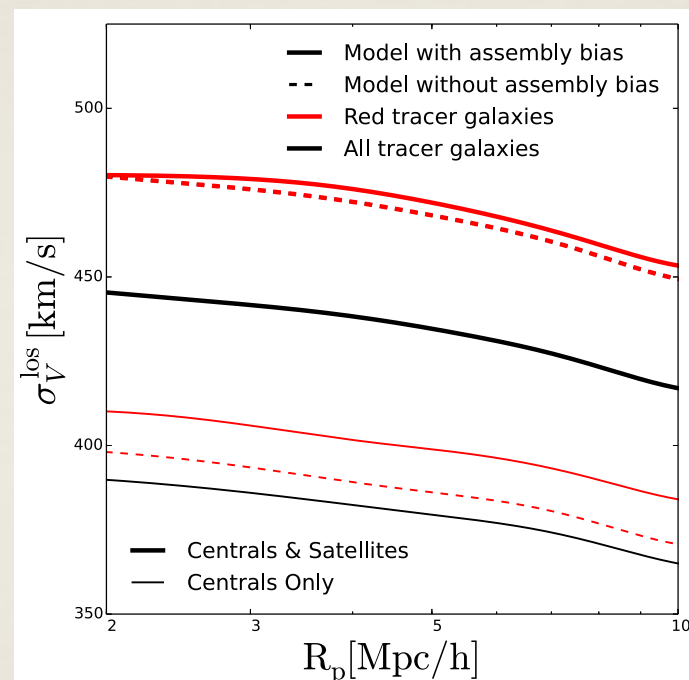
Potentially disastrous consequences



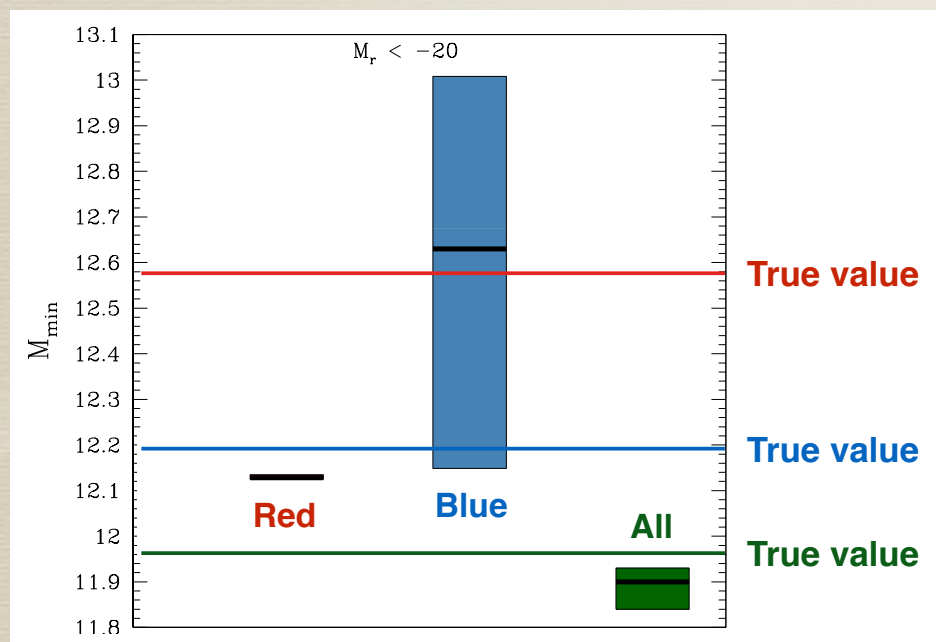
The Threat of Assembly Bias

Potentially disastrous consequences

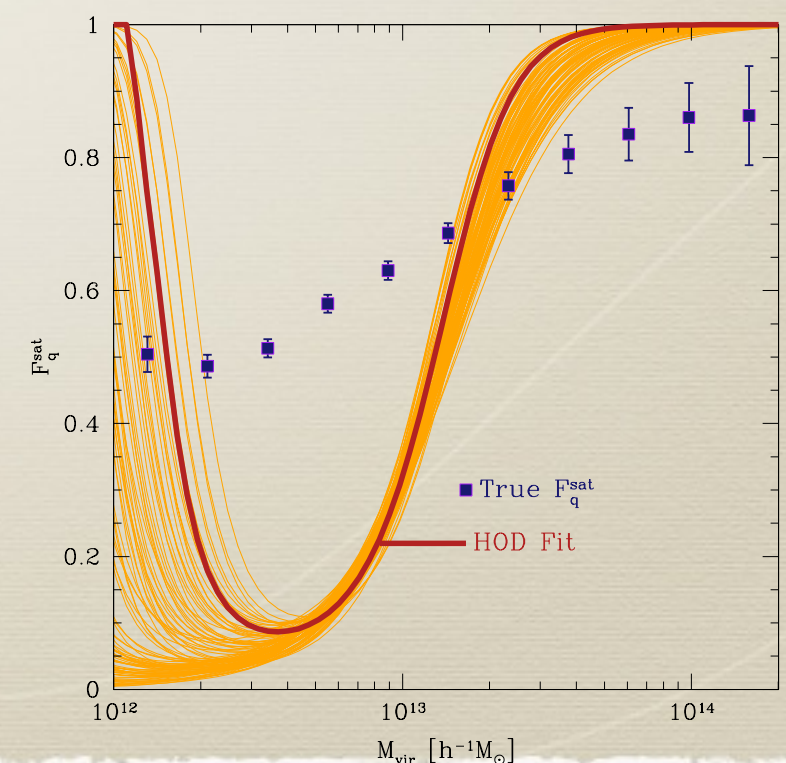
modified GR



Λ CDM

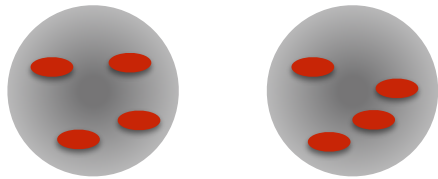

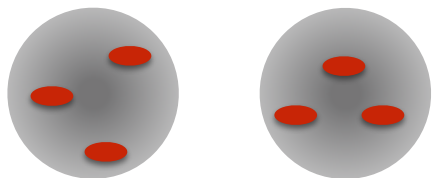

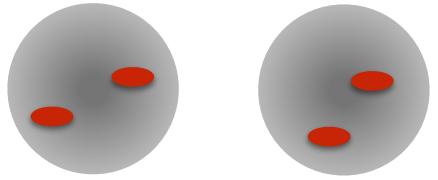

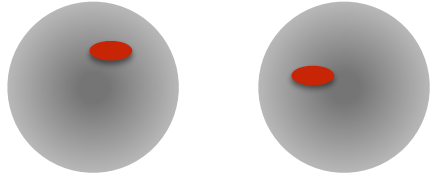
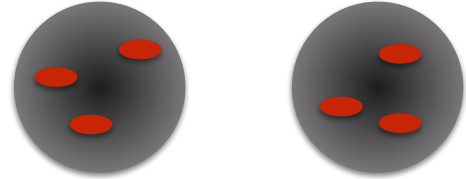
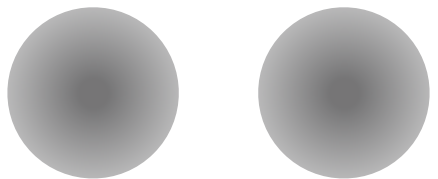



quenching physics



A new approach to the problem

Direct modeling with decorated HODs

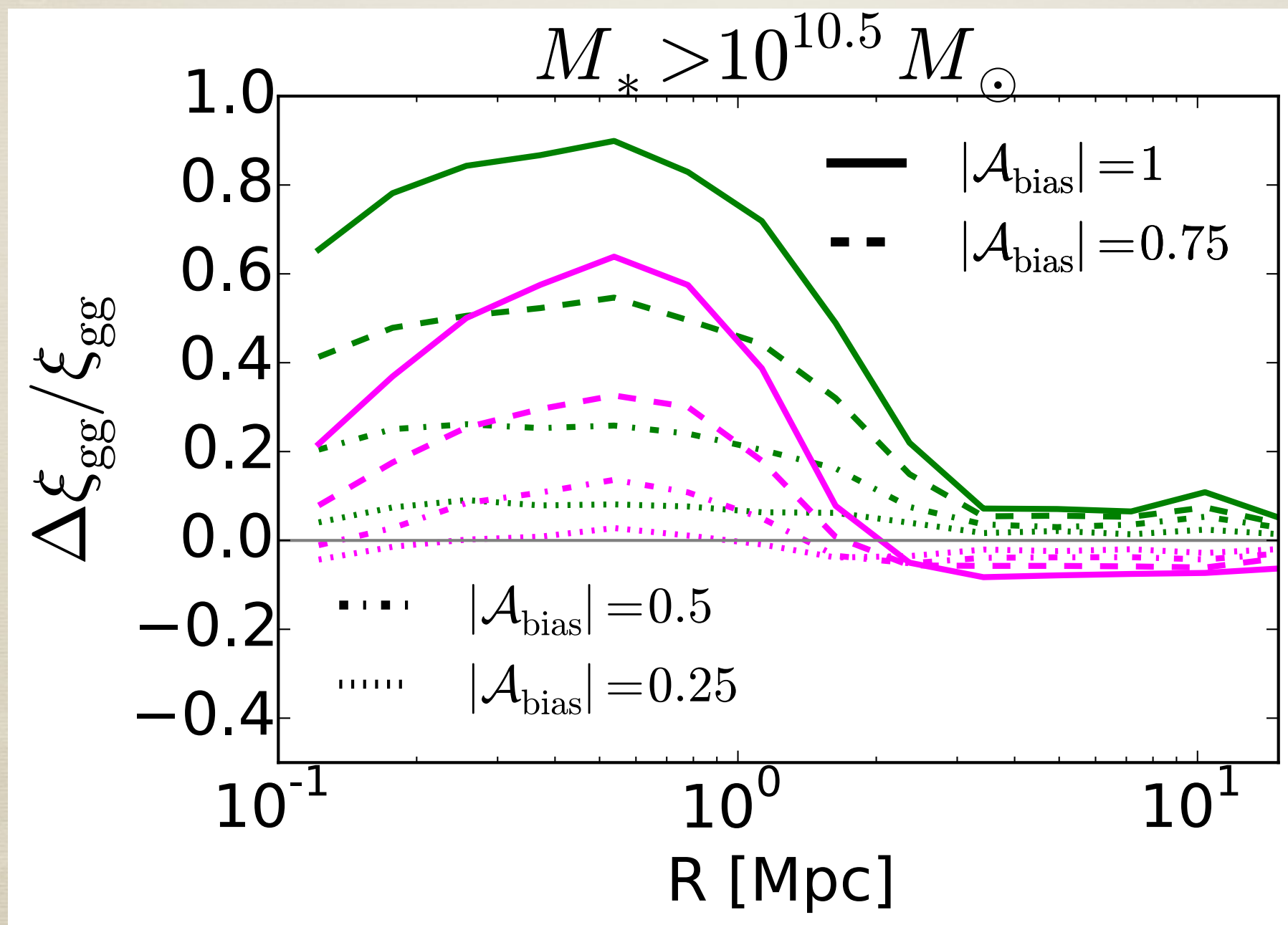
	<u>Older halos</u>	<u>Younger halos</u>
$A_{\text{bias}} = 1$		
$A_{\text{bias}} = 1/2$		
$A_{\text{bias}} = 0$		
$A_{\text{bias}} = -1/2$		
$A_{\text{bias}} = -1$		

See also
Mao et al. 2015,
Lehmann et al. 2015

Hearin et al. 2015

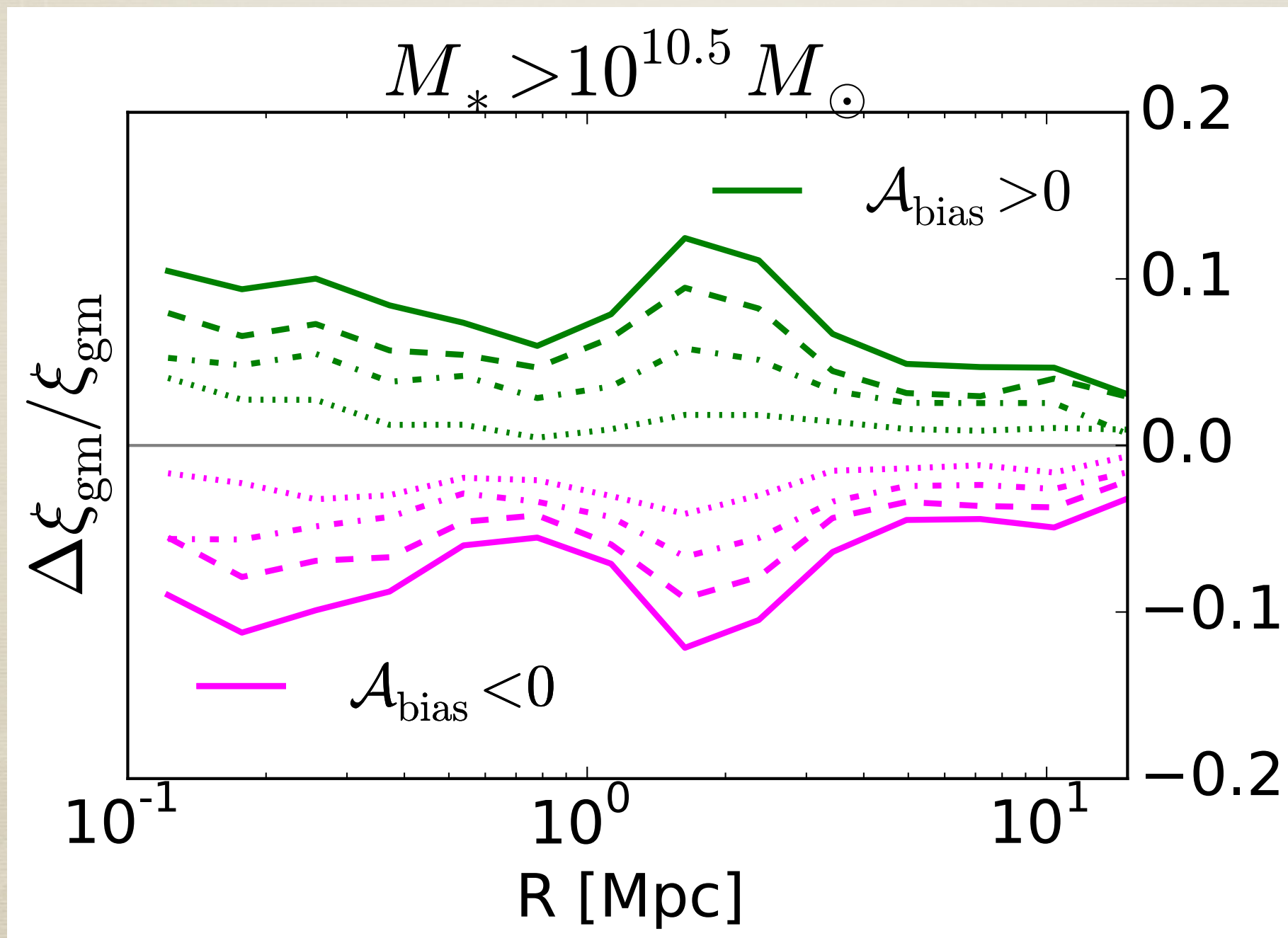
Accounting for Assembly Bias

Decorated HOD and galaxy clustering



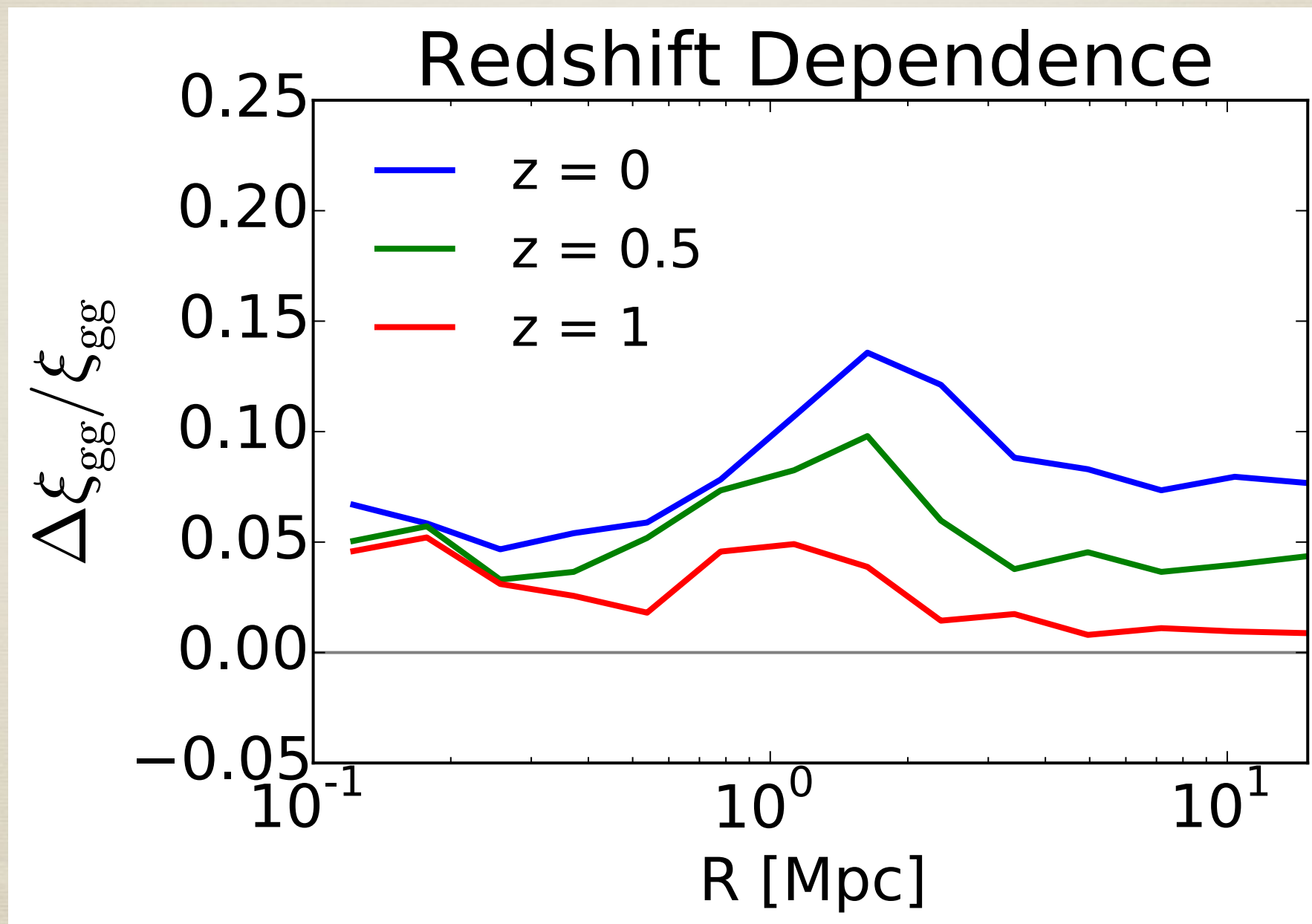
Accounting for Assembly Bias

Decorated HOD and gg-lensing



Accounting for Assembly Bias

Time evolution of the signal



Introducing Halotools

Open-source python package for LSS modeling

Batteries included

- HODs (traditional and decorated)
- Abundance matching
- Stellar-to-halo mass relations
- color- and quenching-models
- Many more

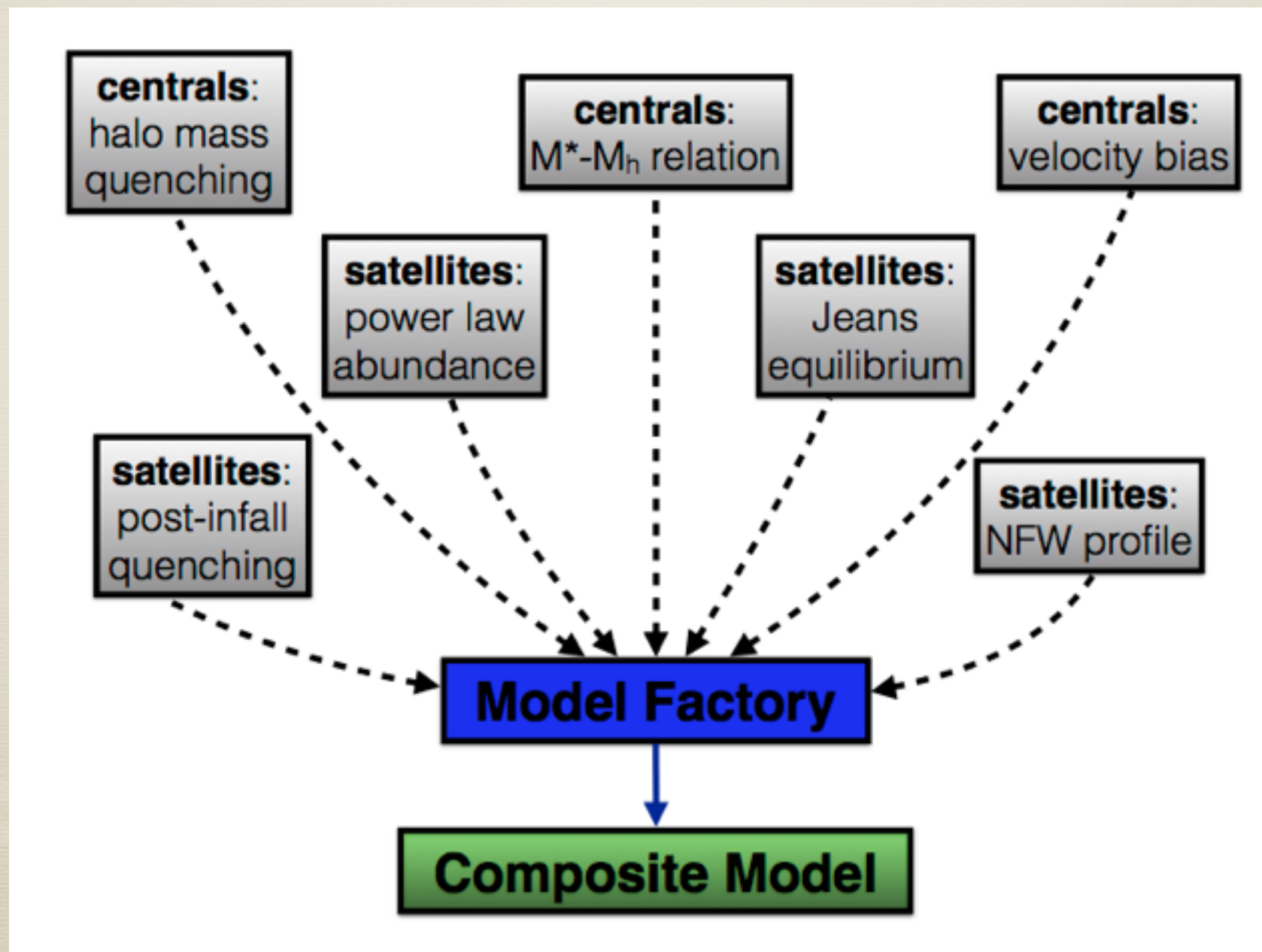
Making Universes with Halotools

Direct mock-population approach

- Relax/test conventional modeling assumptions
 - Assembly bias, halo exclusion, etc.
 - fitting function approximations
- Easy to explore wide range of alternative statistics
 - Marked correlation functions
 - Group- and void-based statistics
 - Cluster RSD
- Precision calculations of covariance matrices
 - Easily tailorable for each statistic

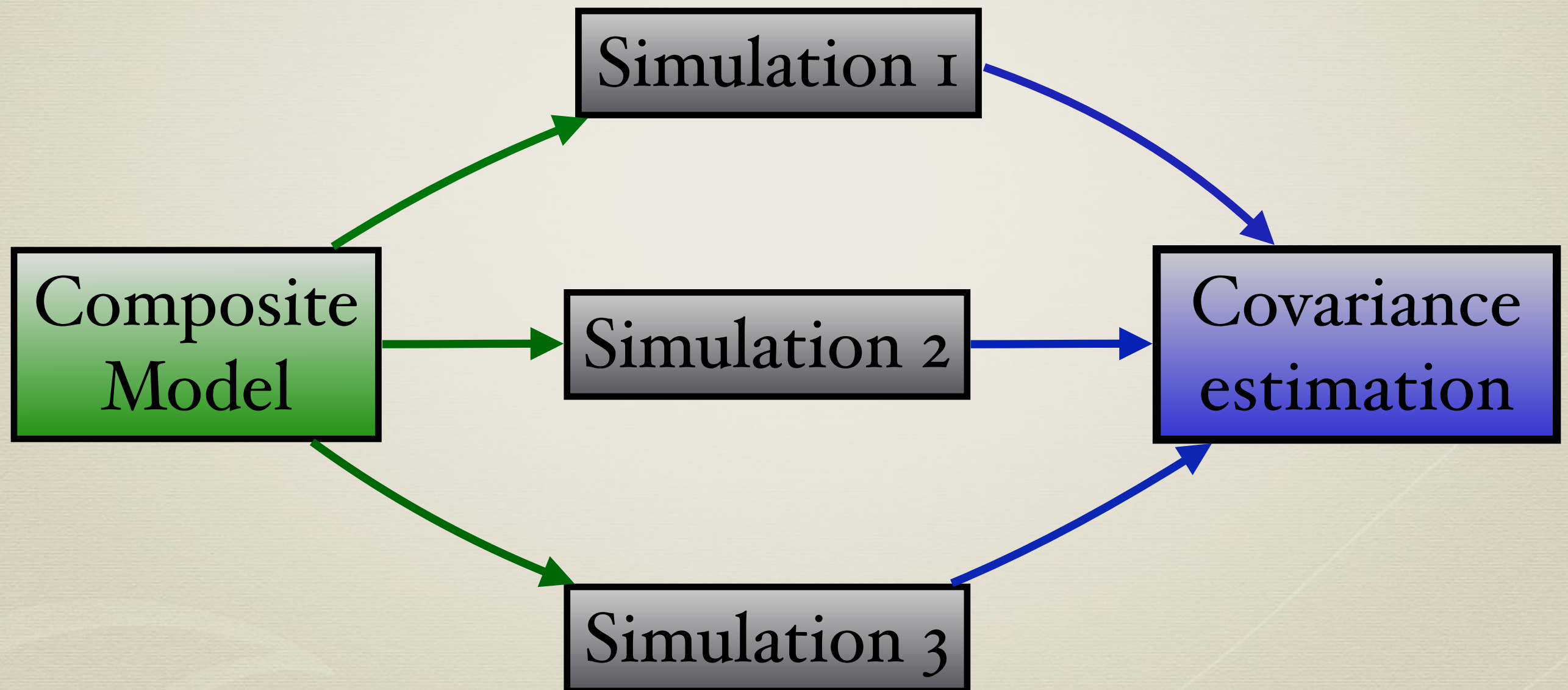
Modeling Galaxies with Halotools

Flexible object-oriented platform
to build your own model



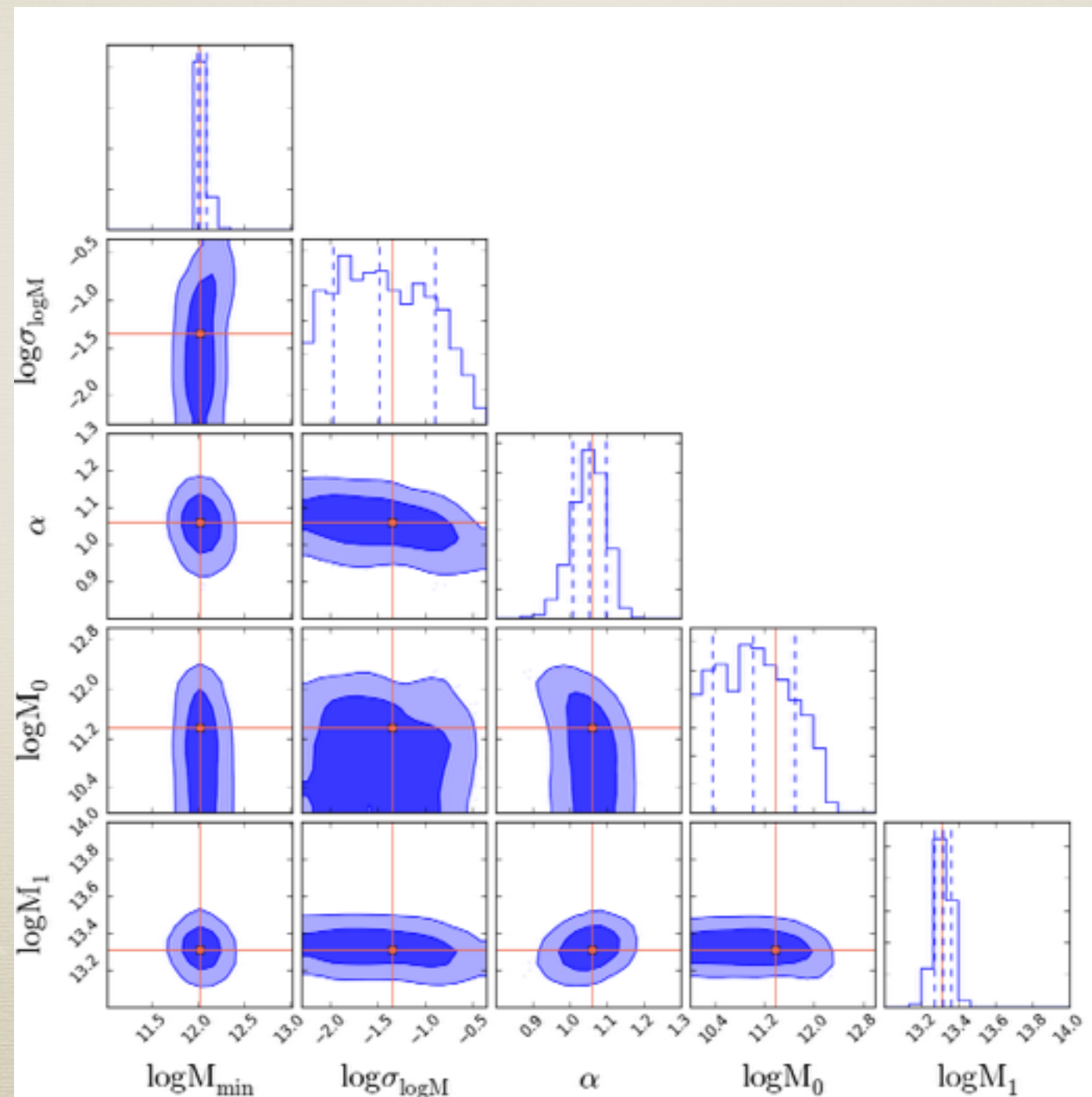
Covariance Matrices with Halotools

Plug-and-play with any simulation
and any summary statistic



Constraining Models with Halotools

Optimized for expansive MCMC-type analyses



Chang, Vakili et al.,
in prep.

Reproducibility with Halotools

Exhaustive documentation, tutorials and automated test suite

halotools.readthedocs.org
github.com/astropy/halotools

The screenshot shows the Halotools documentation website. The header includes the 'halotools:docs' logo, the 'astropy' logo, and navigation links for 'Index' and 'Modules'. A search bar is also present. Below the header, the version 'halotools v0.0.dev1043' is displayed. The main content area is titled 'Halotools Documentation' and provides an overview of the package. A left sidebar contains a 'Page Contents' menu with links to 'User Documentation', 'Halotools Overview', 'Mock-Making Tools', 'Model-Building Tools', 'Simulation Analysis Tools', 'Tutorials', and 'Developer Documentation'. The main content area lists these sections with their respective sub-topics: 'User Documentation' (Halotools Overview, Mock-Making Tools, Model-Building Tools, Simulation Analysis Tools, Tutorials), 'Mock-Making Tools' (Quickstart Guide to Making Mocks, Overview of mock-making methods), 'Model-Building Tools' (Quickstart Guide to Modeling the Galaxy-Halo Connection, Building models of the Galaxy-Halo connection), 'Simulation Analysis Tools' (Overview of simulation analysis tools, Halo catalog management, Halo analysis, Merger tree analysis), and 'Tutorials'.

halotools:docs **astropy** Index Modules Search

halotools v0.0.dev1043 next »

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- Halotools Documentation
 - User Documentation
 - Halotools Overview
 - Mock-Making Tools
 - Model-Building Tools
 - Simulation Analysis Tools
 - Tutorials
 - Developer Documentation

Halotools Documentation

Halotools is a python package designed to study large-scale structure, cosmology, and galaxy evolution using N-body simulations and halo models. The code is publicly available at <https://github.com/astropy/halotools>. You can find the latest build of the documentation at halotools.readthedocs.org.

User Documentation

Halotools Overview

- Halotools Science Overview
- Package Installation
- Getting Started with Halotools

Mock-Making Tools

- Quickstart Guide to Making Mocks
- Overview of mock-making methods

Model-Building Tools

- Quickstart Guide to Modeling the Galaxy-Halo Connection
- Building models of the Galaxy-Halo connection

Simulation Analysis Tools

- Overview of simulation analysis tools
- Halo catalog management
- Halo analysis
- Merger tree analysis

Tutorials

v: master

Conclusions

- Empirical modeling has great potential for both cosmology and galaxy evolution science
- Program is severely threatened by assembly bias
- Halotools offers an open-source way forward

halotools.readthedocs.org

Some additional information

Modeling Galaxy Evolution

The empirical modeling approach

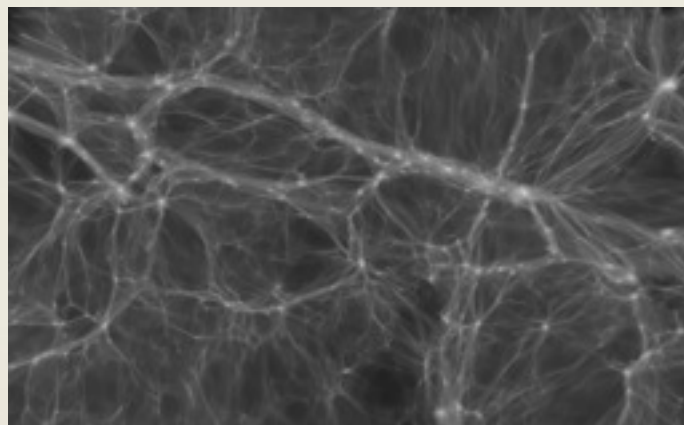
Run dark matter-only simulation,
build simplest possible statistical model warranted by data

Advantages

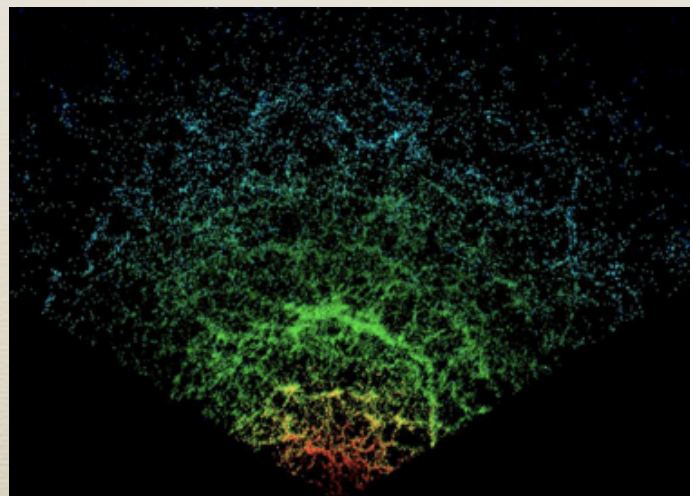
Clearly-defined
modeling assumptions

Quantitatively successful

Dirt cheap



+



Disadvantages

Contact lost with
fine-grained physics

Highly restrictive:
can only predict a few
galaxy properties at a time
(usually)

Modeling Galaxy Evolution

The hydro sim approach

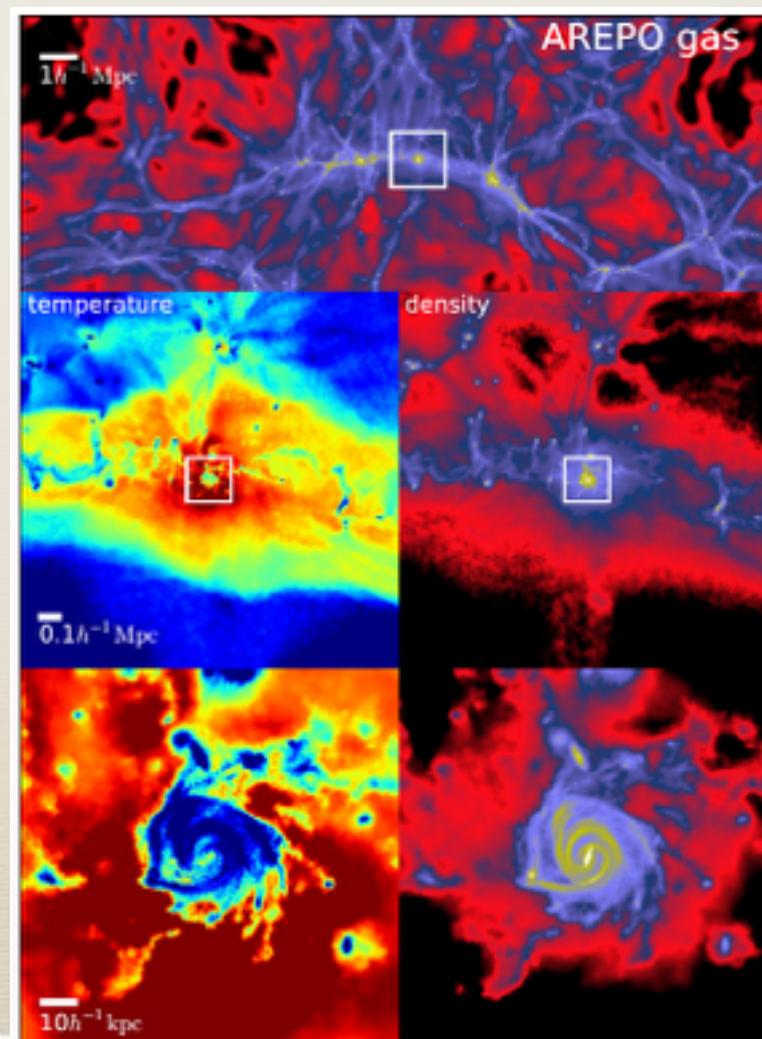
Run simulations that simultaneously
includes dark matter and gas

Advantages

Self-consistent!

Most fundamental

Direct connection to
underlying physics



Disadvantages

Extremely expensive!
(~100 million CPU hours)

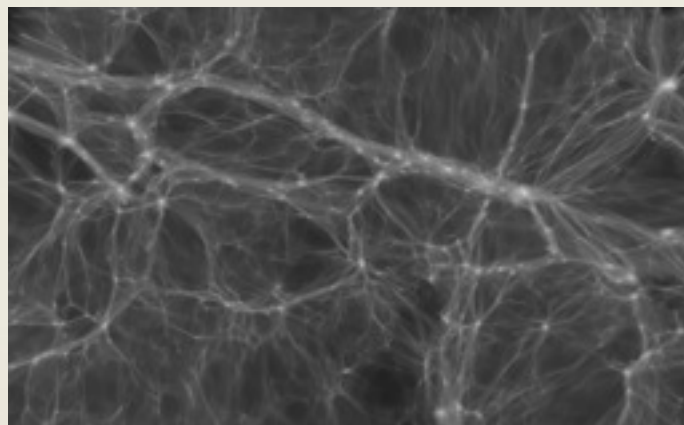
Whoops, wrong model:
Gotta run it all over again!

Grossly incorrect predictions
without fine-tuning
(usually)

Modeling Galaxy Evolution

The semi-analytic modeling approach

Run dark matter-only simulation,
apply hydrodynamics in post-processing phase



Advantages

Less expensive than hydro
(~1 million CPU hours
for N-body sim)

Close connection
to true gas physics
(we hope)

Disadvantages

Too many parameters
to properly Monte Carlo
(usually)

Not self-consistent

$$\begin{aligned} \lambda &= \frac{J|E|^{1/2}}{GM^{5/2}} \\ \frac{dM_{\text{baryon}}}{dt} &= \epsilon(M_{\text{halo}}) \frac{dM_{\text{DM}}}{dt} \\ \frac{dM_{\text{gas}}}{dt} &= -\Psi_{\text{SFR}}(t) + \mathcal{E}_{\text{wind}}^*(t) \\ \dots &= \dots \end{aligned}$$