

*Andrew Hearin, Argonne National Lab*

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# Galaxy—Halo Modeling of Large-Scale Structure

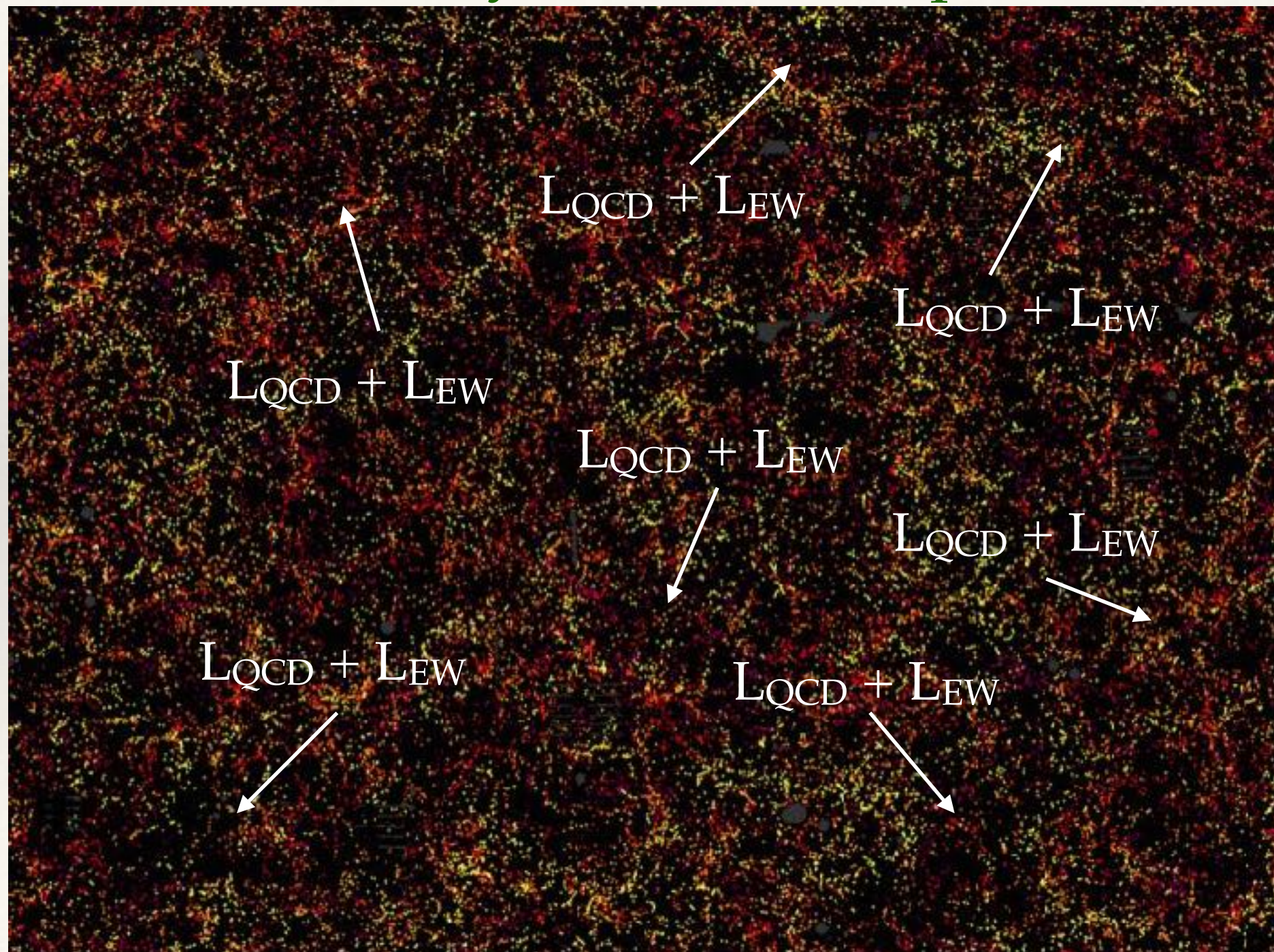
Theory overview, lessons from  
previous successes,  
and guidelines for a future of  
forward-modeling diverse  
datasets

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# Galaxy Formation Theory

“Fundamental” theory has been complete for decades

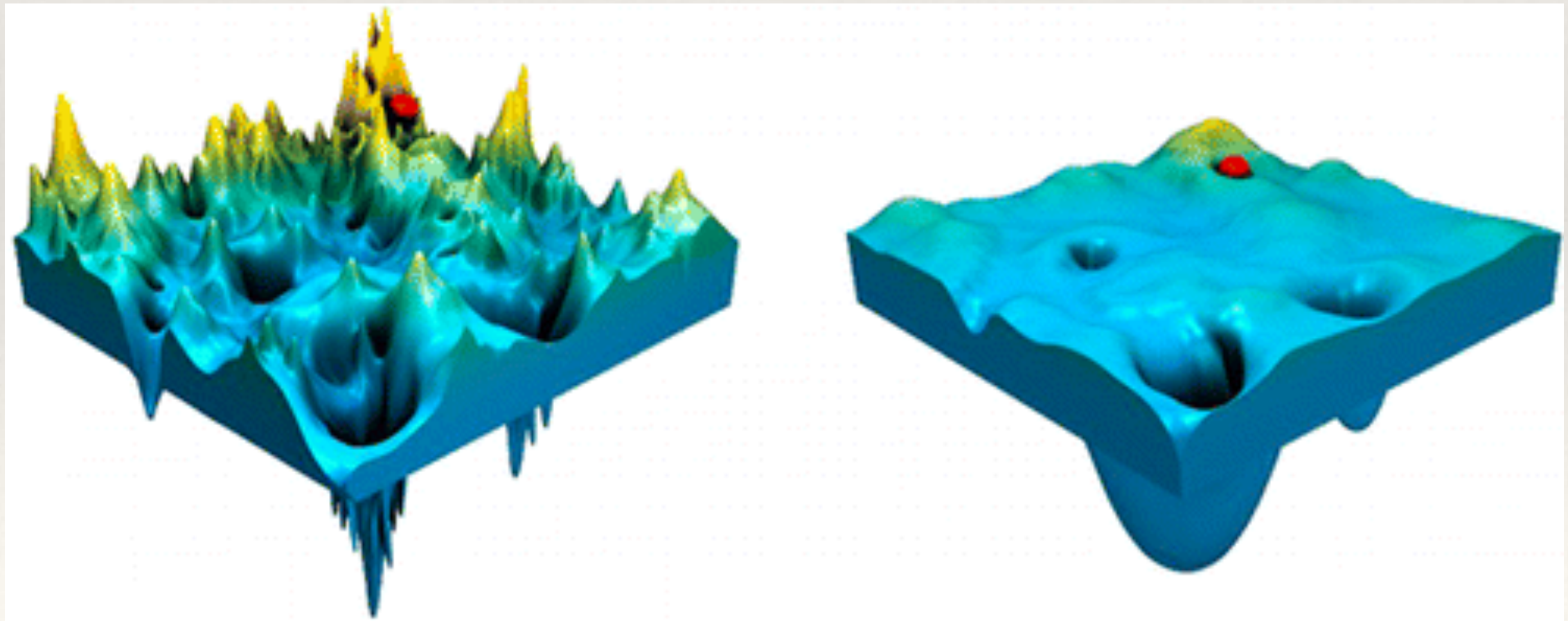




# Coarse Grained Models

“Fundamental” theory is hopeless

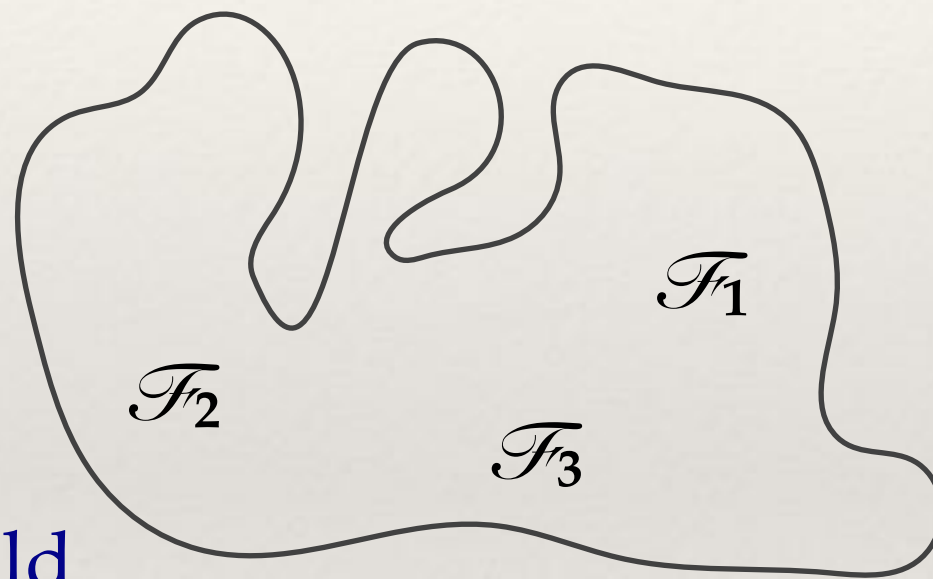
Hydro sims, SAMs, empirical models  
are coarse-grained models of the fundamental theory



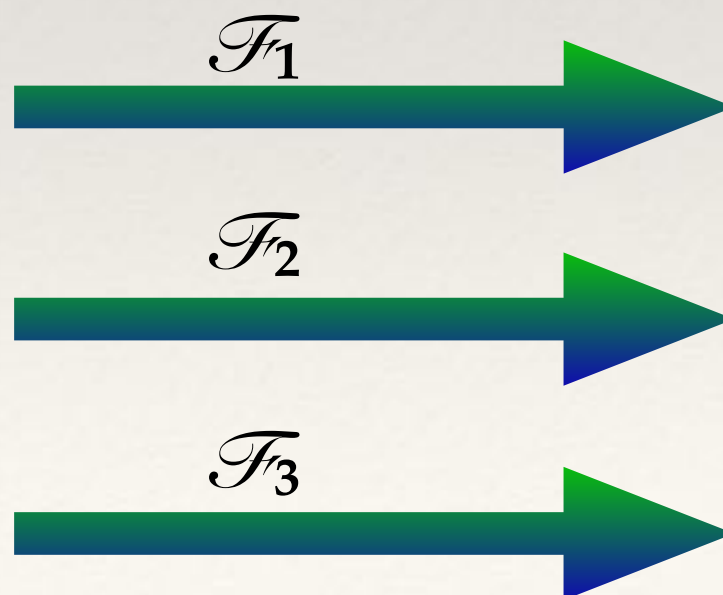
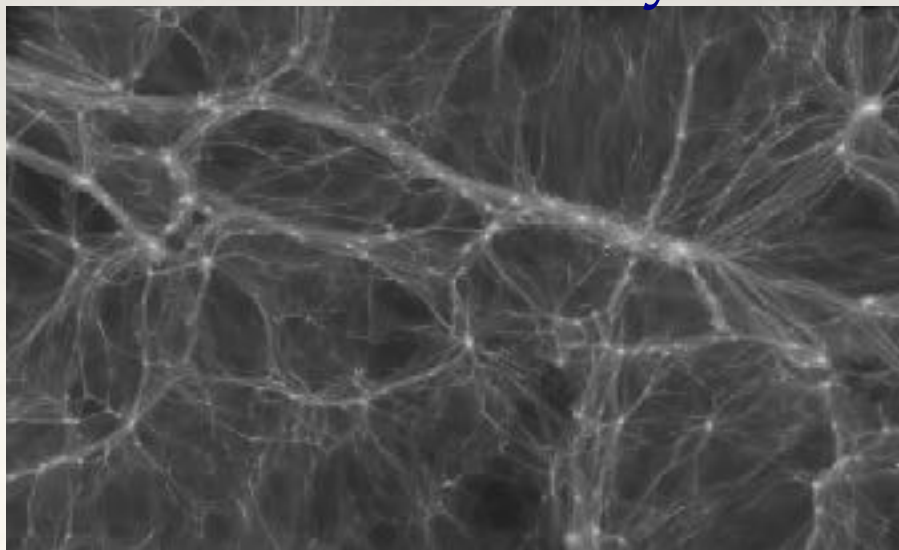
# Mapping Simulated to Real Quantities

An extremely high-dimensional problem

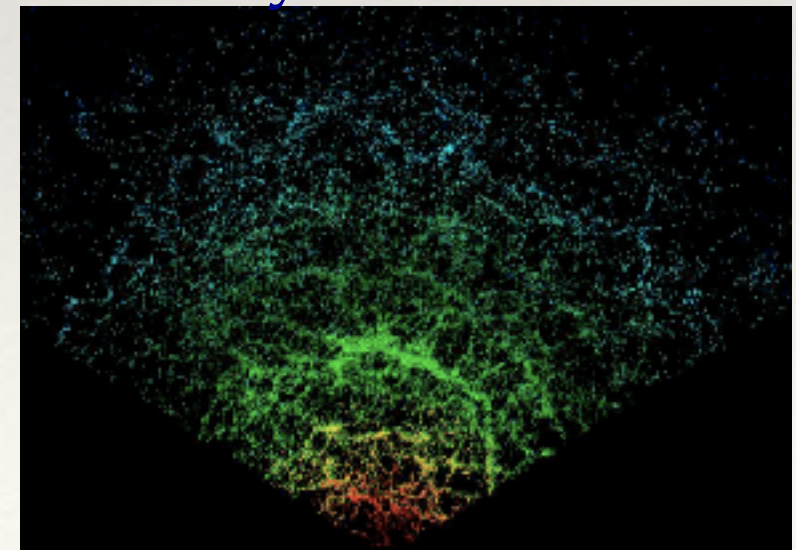
High-dimensional space of possible functions



Simulated density field



Galaxy distribution





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# Simplifying the Problem

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Dark Matter Halos:

Fundamental building blocks of large-scale structure

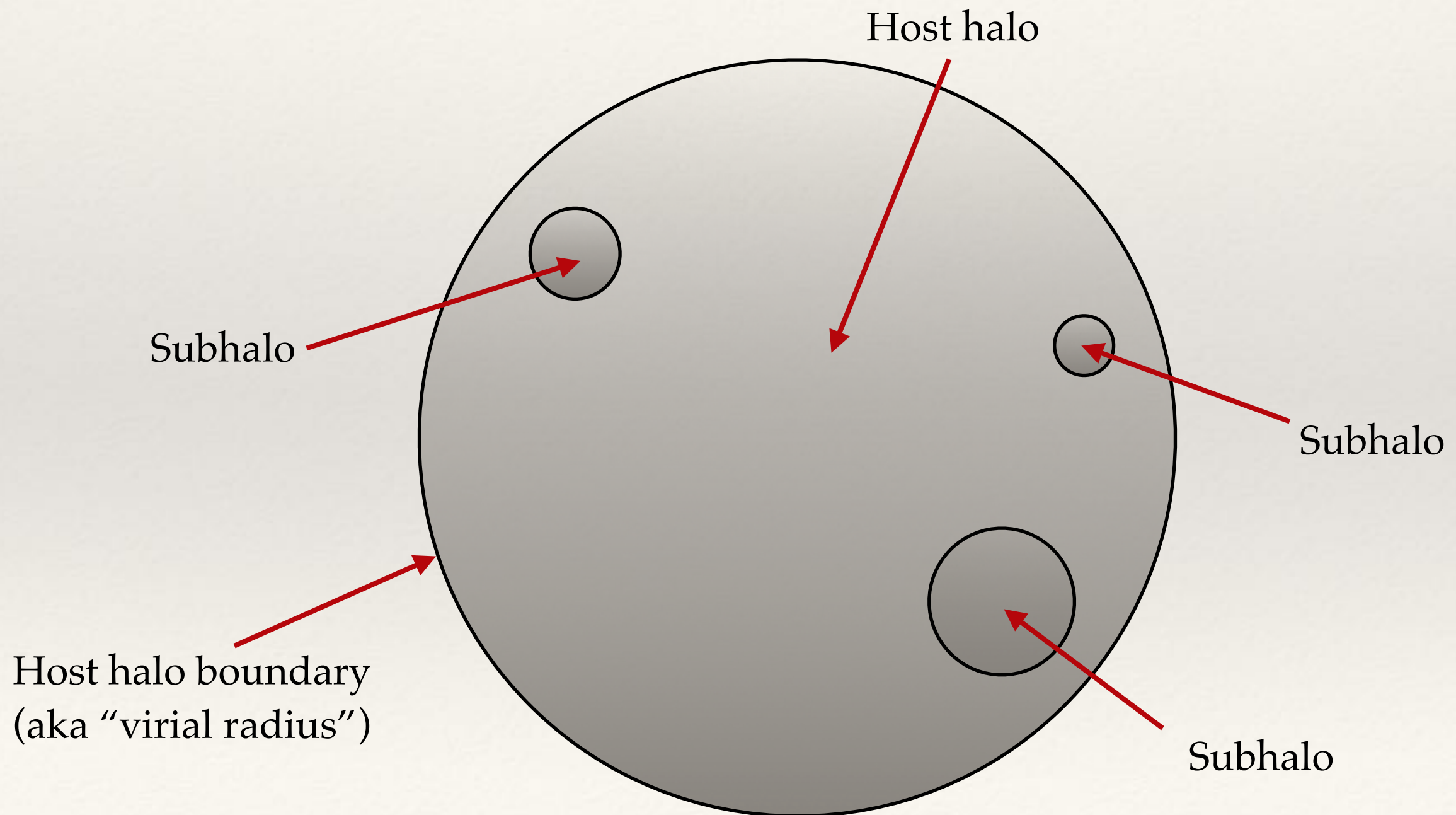


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# Dark Matter Halos

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## Host halos and subhalos

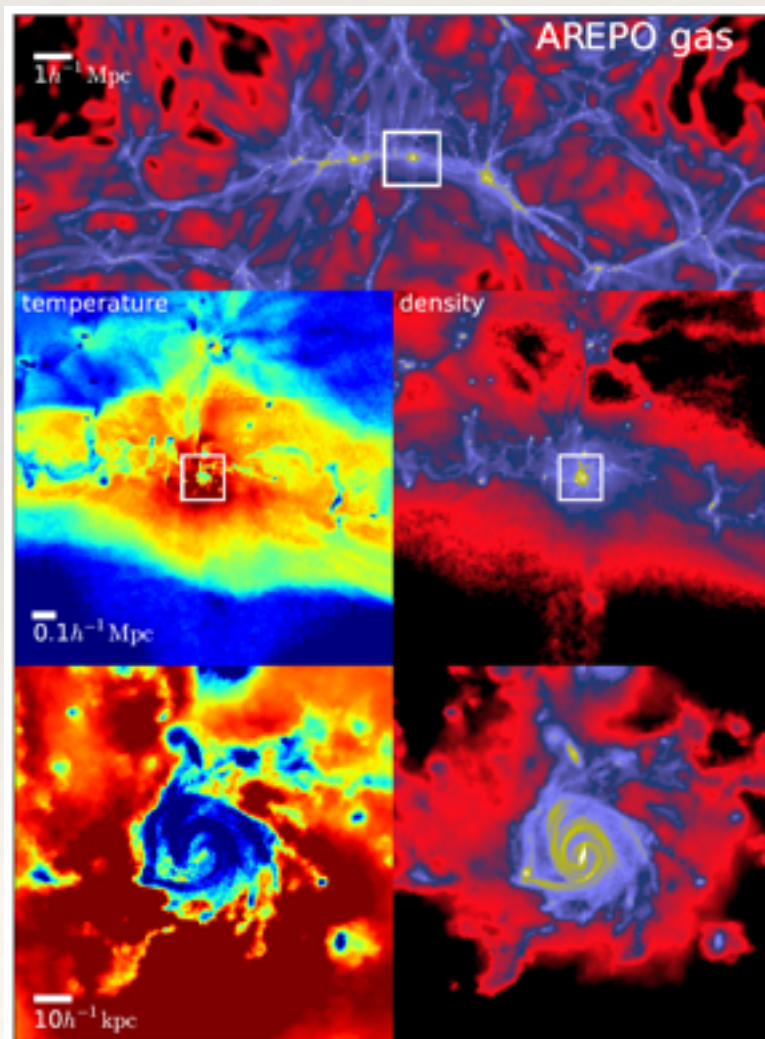




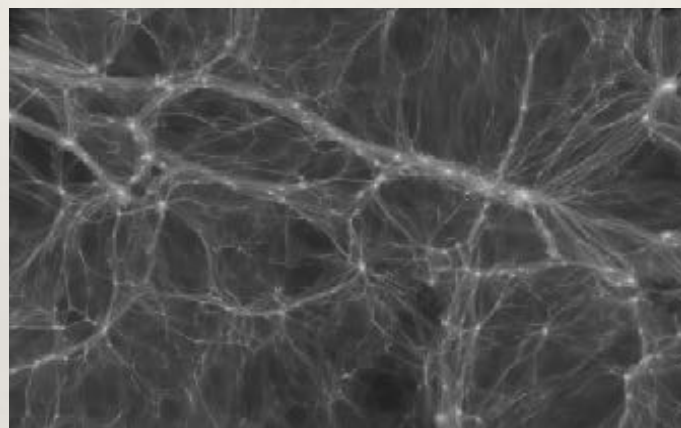
# Coarse Grained Models

Three complementary approaches

## Hydro



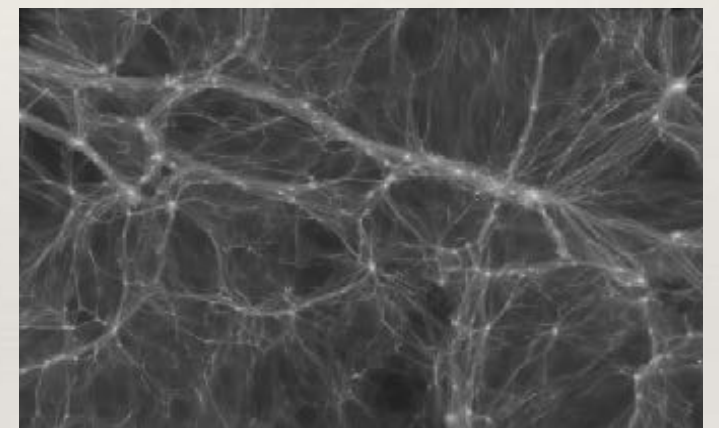
## Semi-analytic model



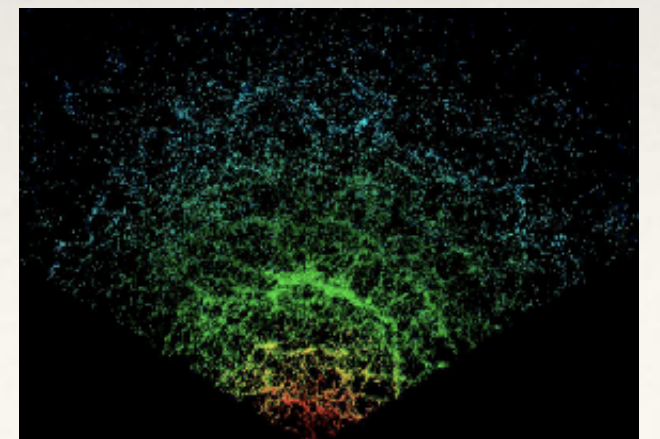
+

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

## Empirical model



+

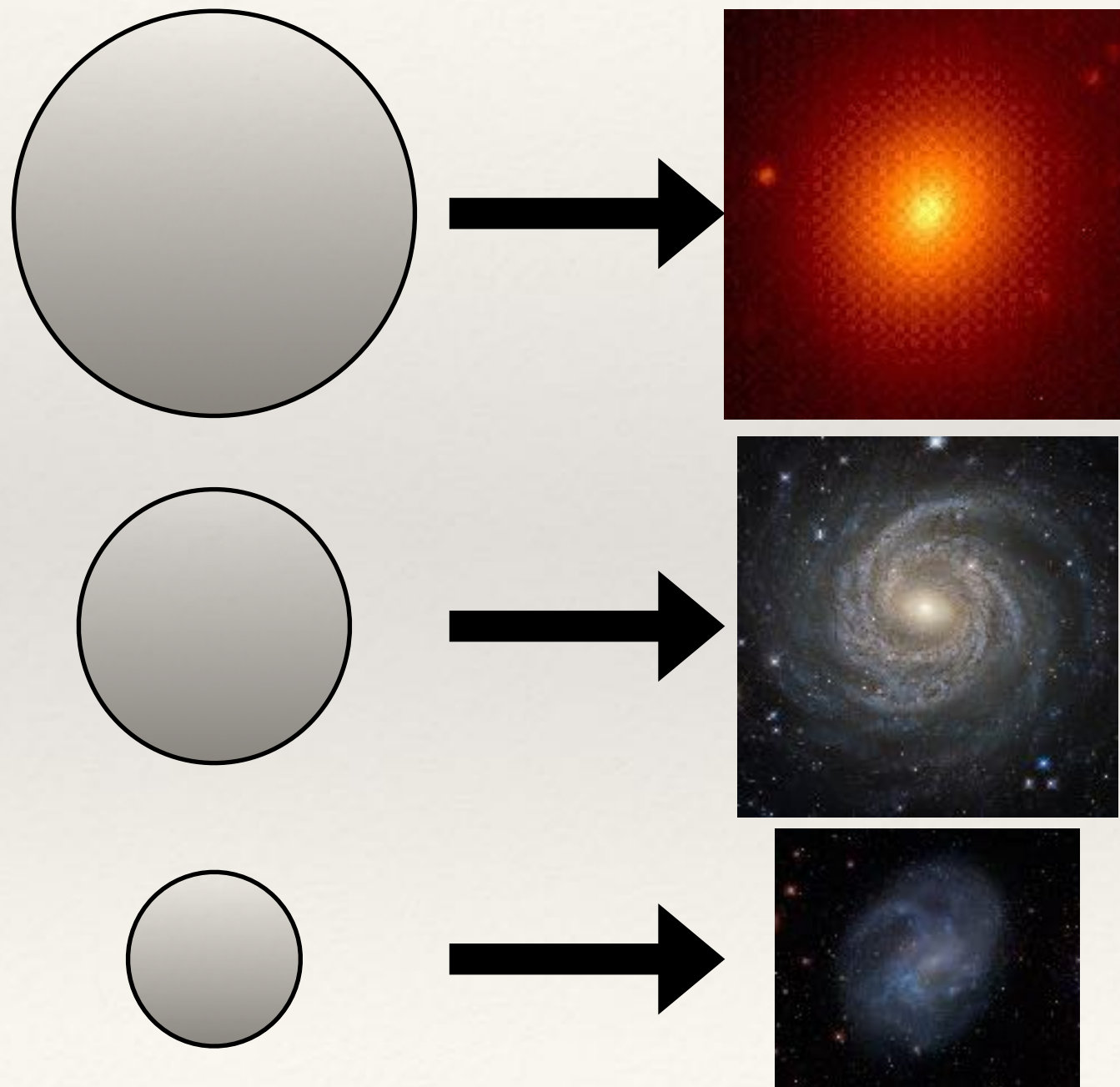


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# Mapping Simulated to Real Quantities

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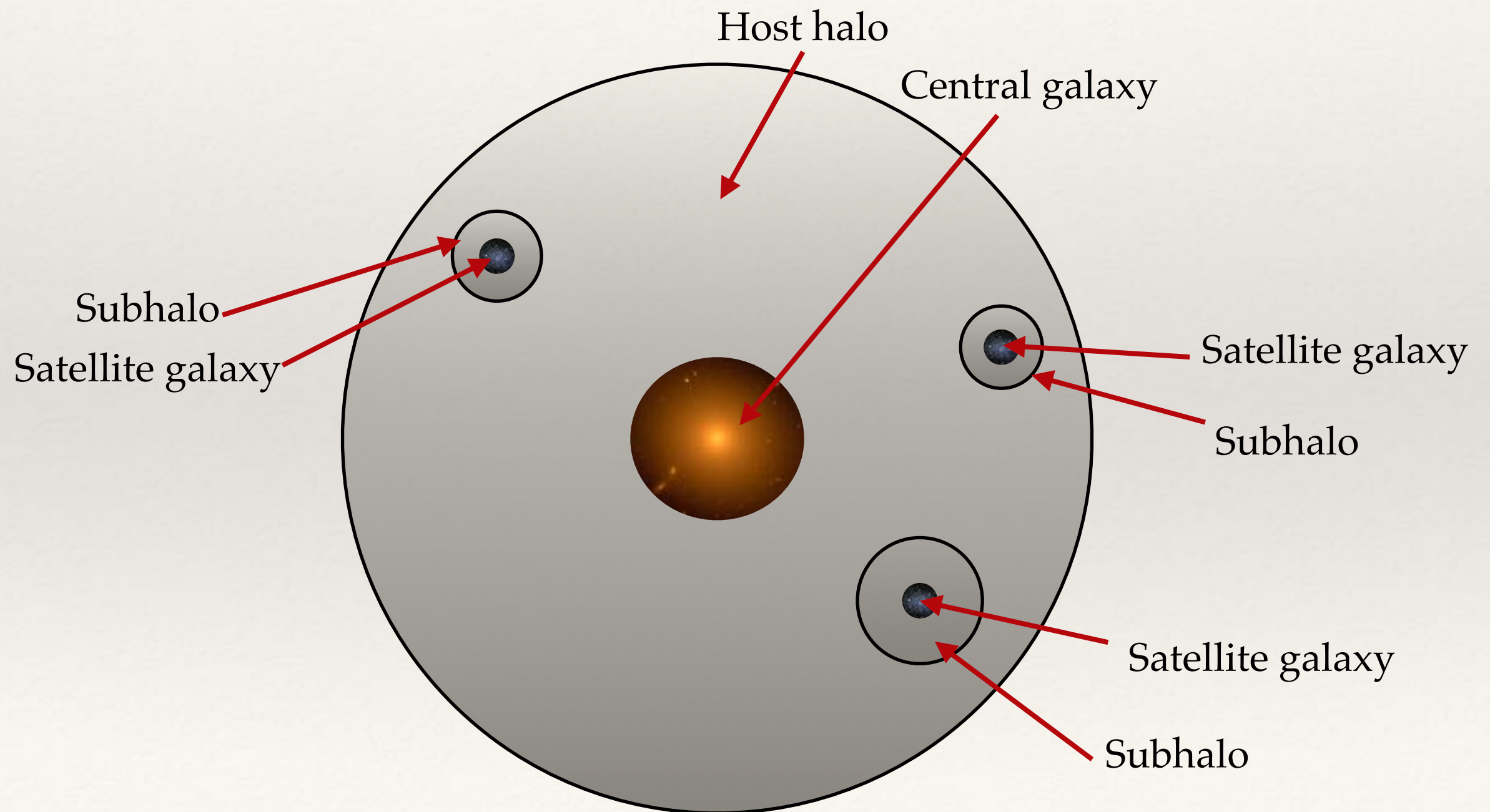
Basic Approach: Determine map from (sub)halos  $\longrightarrow$  galaxies





# Building a Galaxy–Halo Model

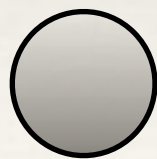
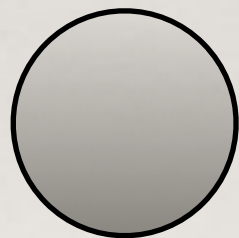
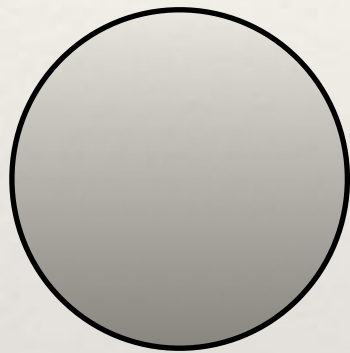
Simple abundance matching ansatz



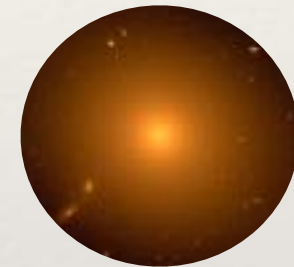
# Building a Galaxy–Halo Model

Simple abundance matching ansatz

Bigger (sub)halos

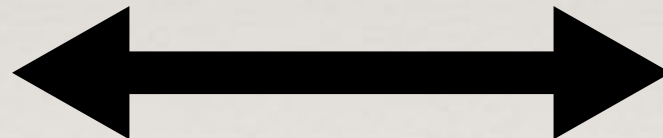
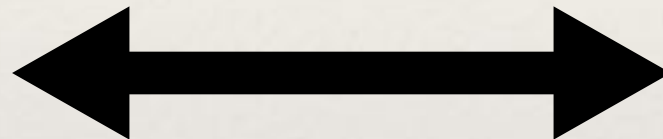


Bigger galaxies



Smaller (sub)halos

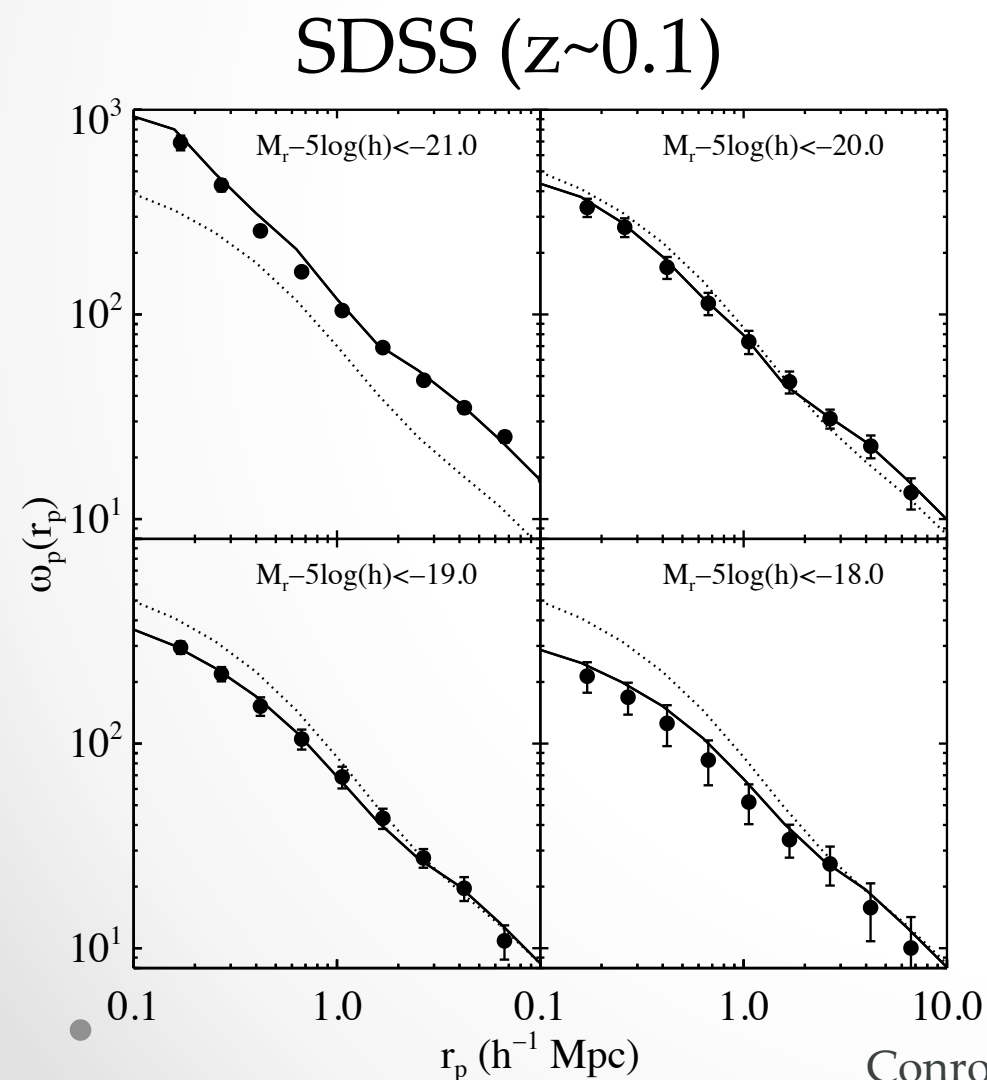
Smaller galaxies



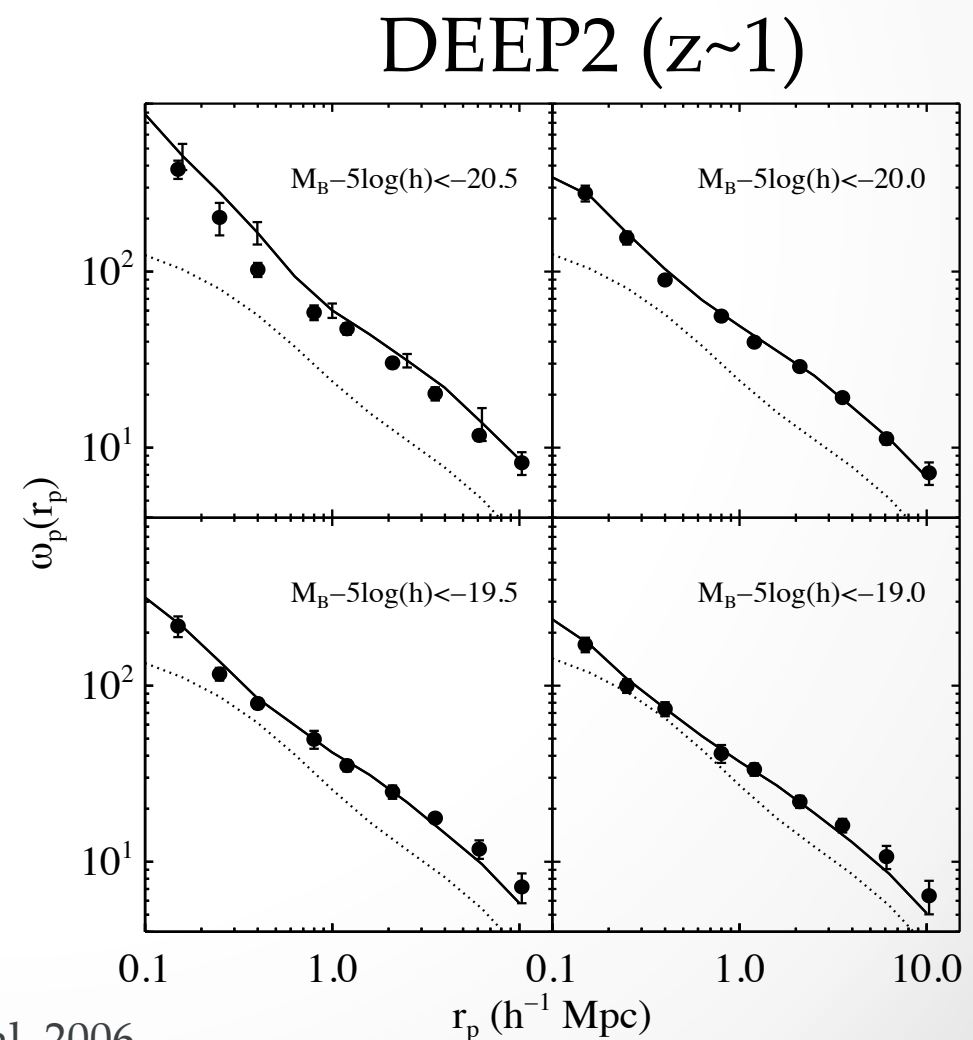


# Simple Abundance Matching

Quantitative level of success is (should be) startling!



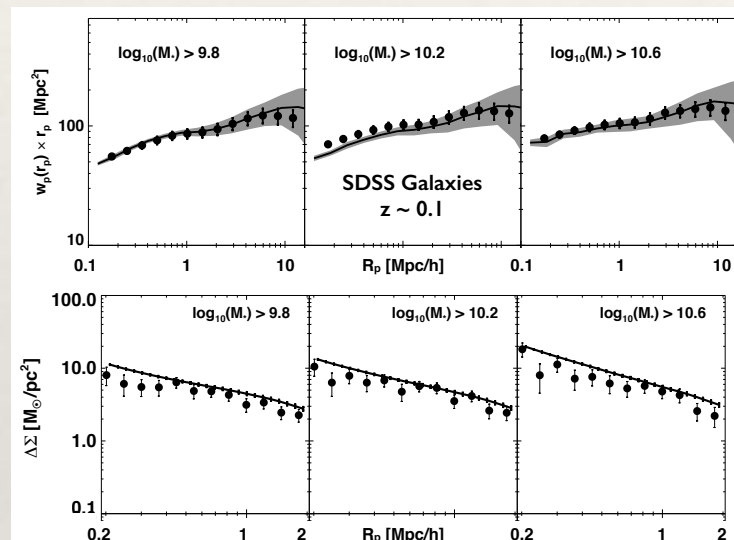
Conroy et al. 2006



# Simple Abundance Matching

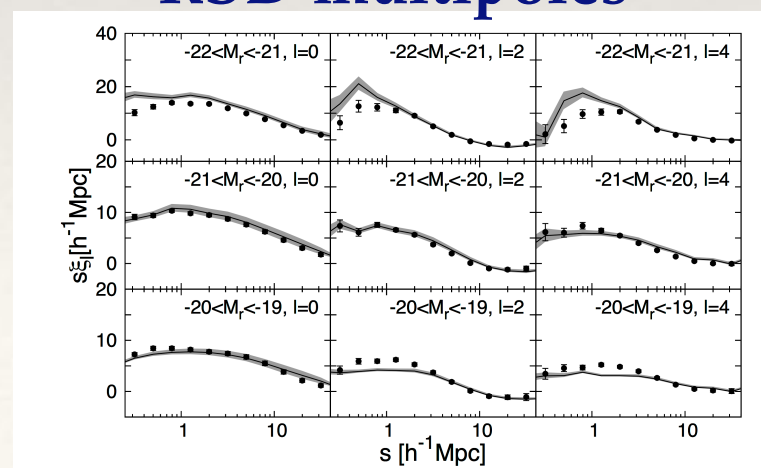
Large-scale structure success is diverse

## galaxy-galaxy lensing



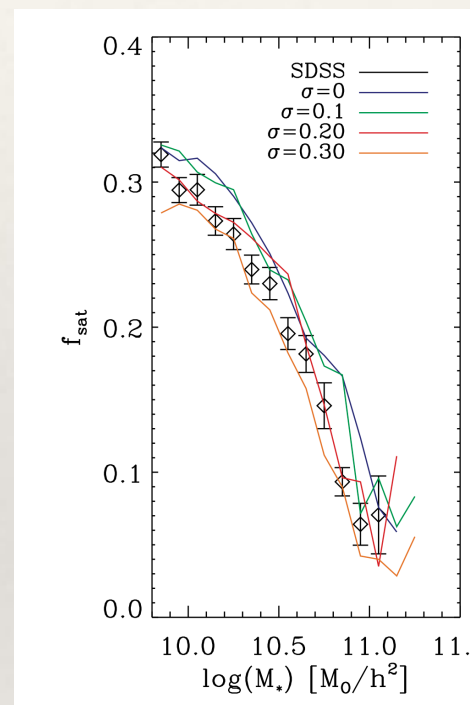
Hearin+14

## RSD multipoles



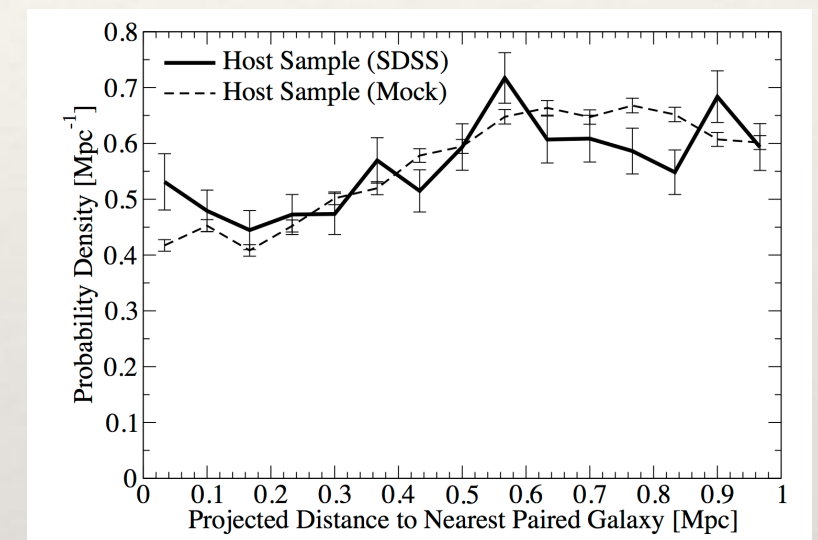
Yamamoto+15

## satellite fractions



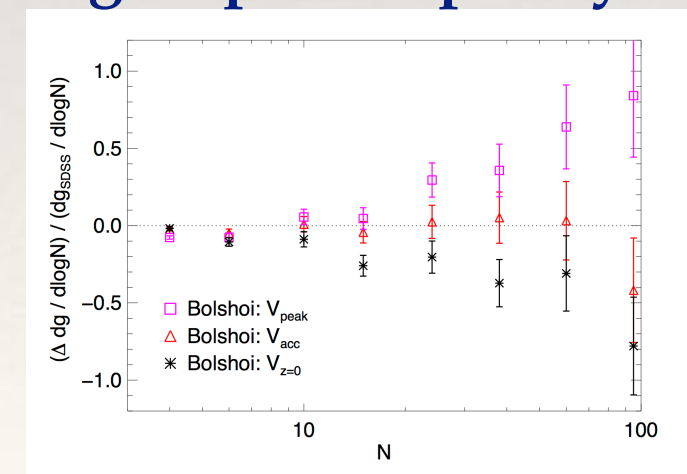
Reddick+13

## Distribution of close pairs



Behroozi+15

## group multiplicity



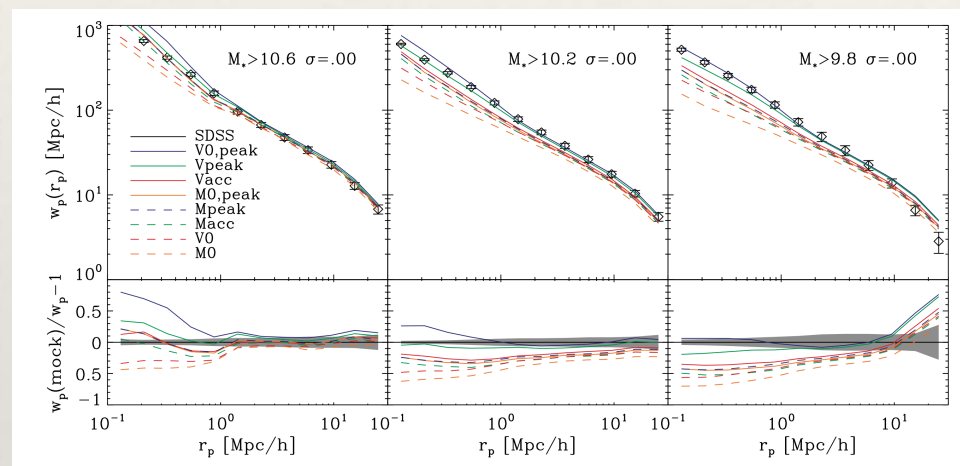
Hearin+12



# Simple Abundance Matching

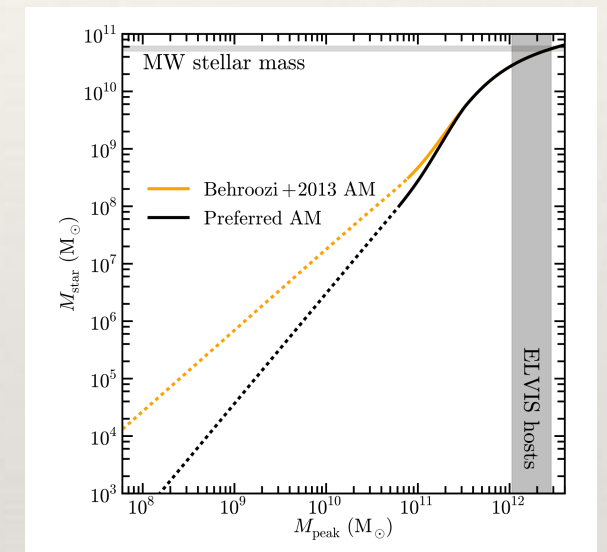
Formulation details significantly impact level of success

Which subhalo property?



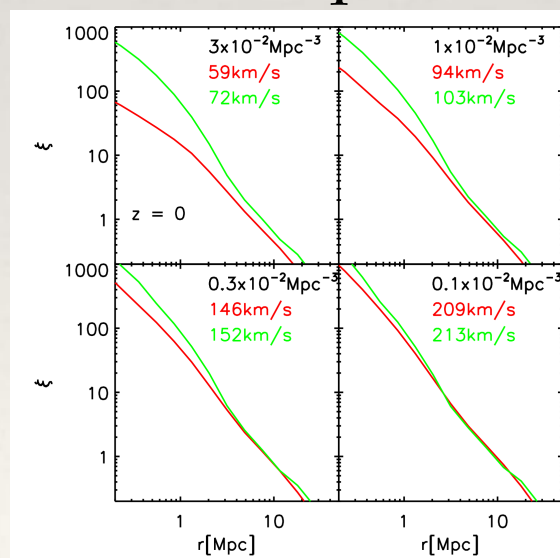
Reddick+12

How far down the mass function?



Garrison-Kimmel+13

Resolution requirements?



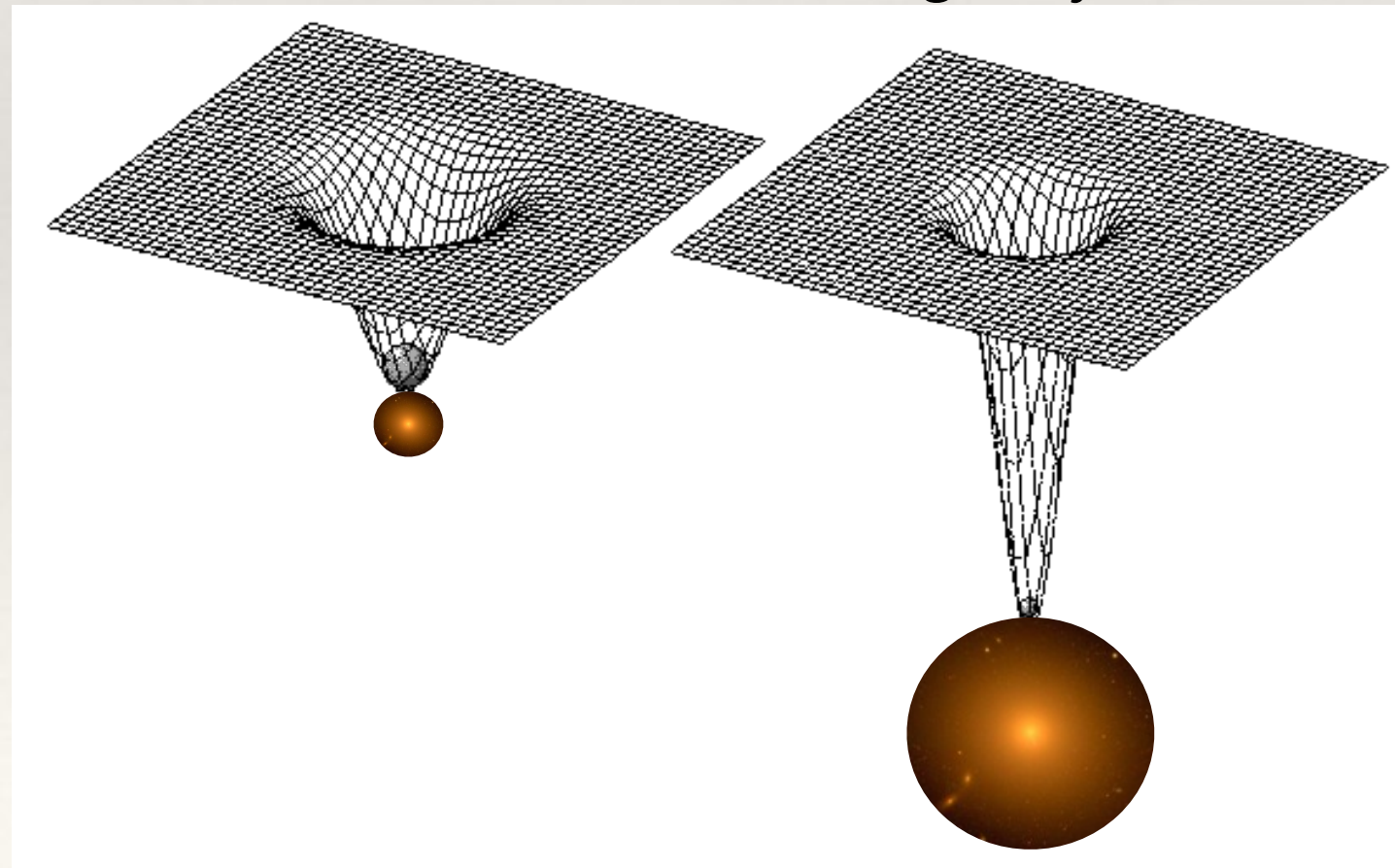
Guo & White 2013

# What do we learn from abundance matching?

Whenever you get so much for so little, nature is telling you your assumptions must be reasonably correct

## Basic lesson:

Depth of the gravitational potential well is the coarse-grained halo property with the dominant influence on galaxy mass

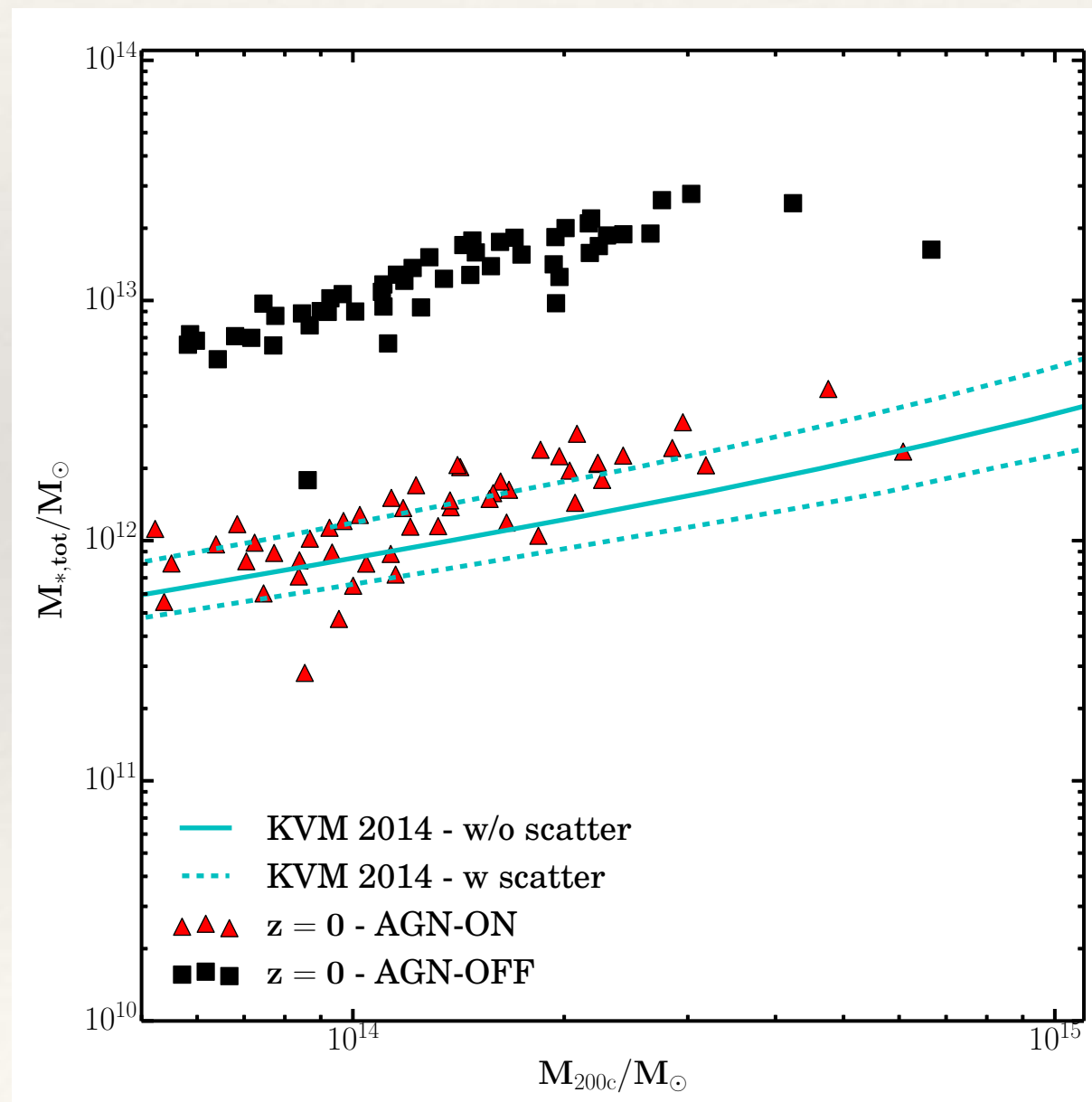




# What do we learn from abundance matching?

Model parameters have universal translation

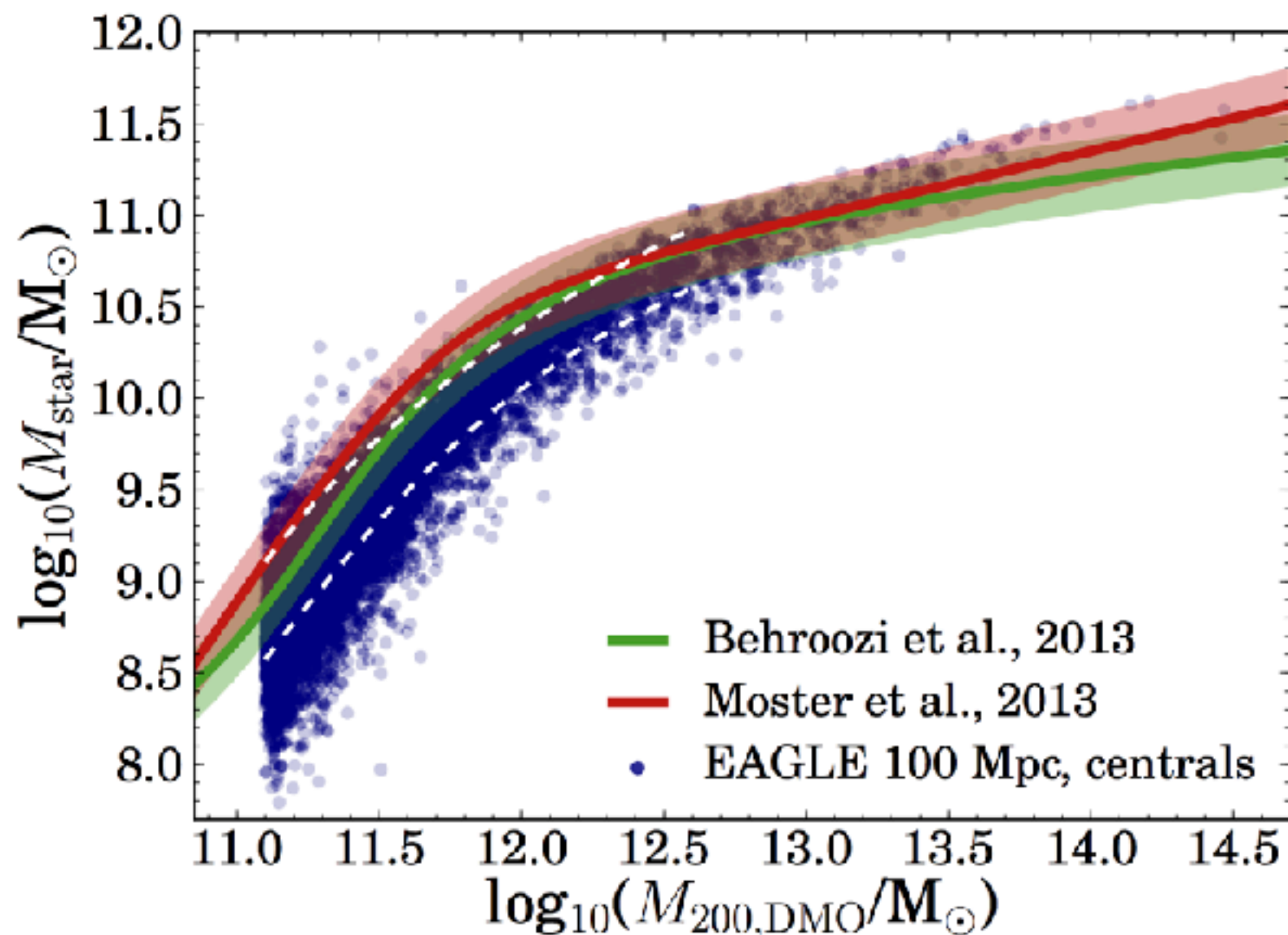
Provides boundary conditions for more fine-grained models



# What do we learn from abundance matching?

Model parameters have universal translation

Provides boundary conditions for more fine-grained models

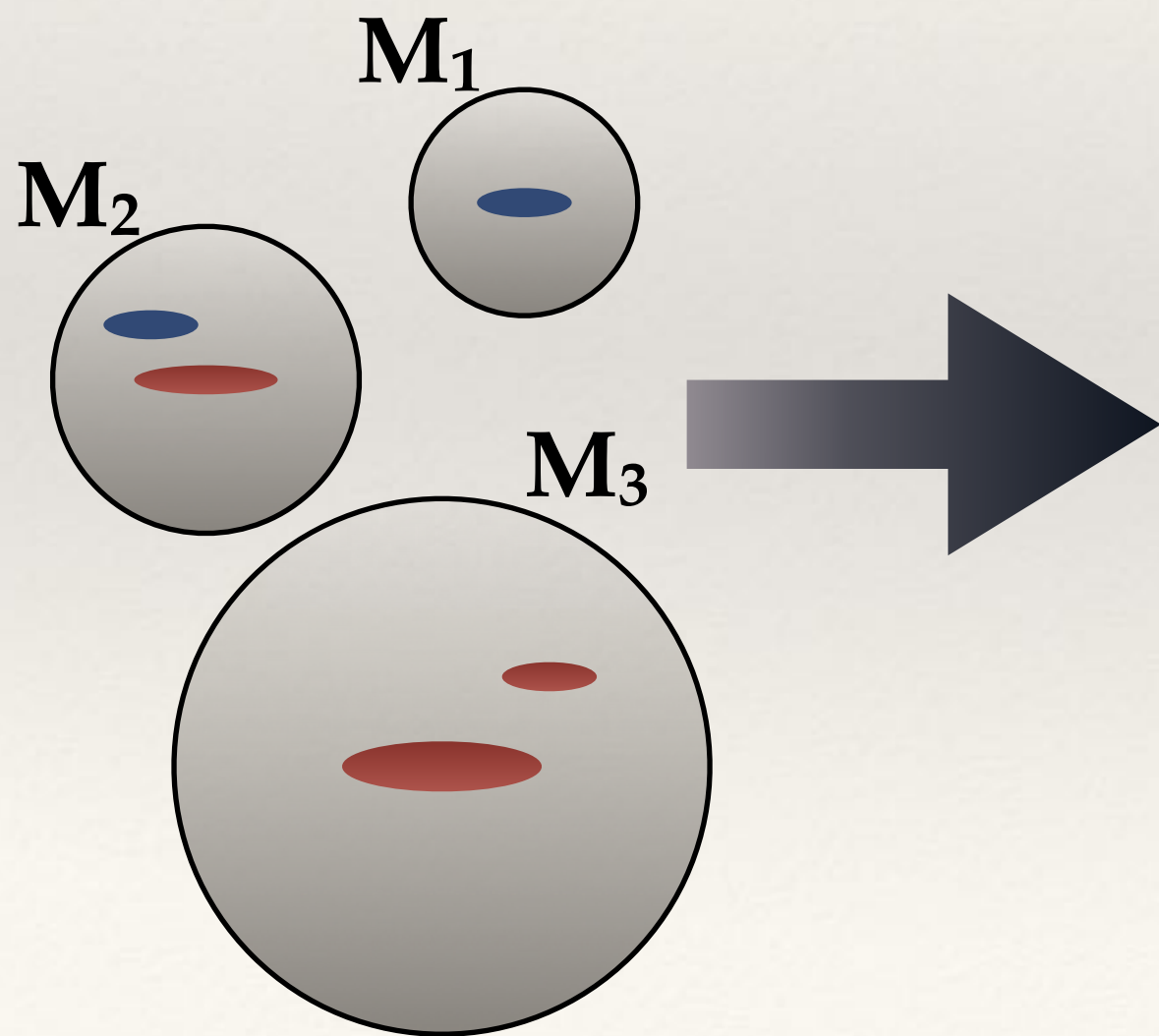




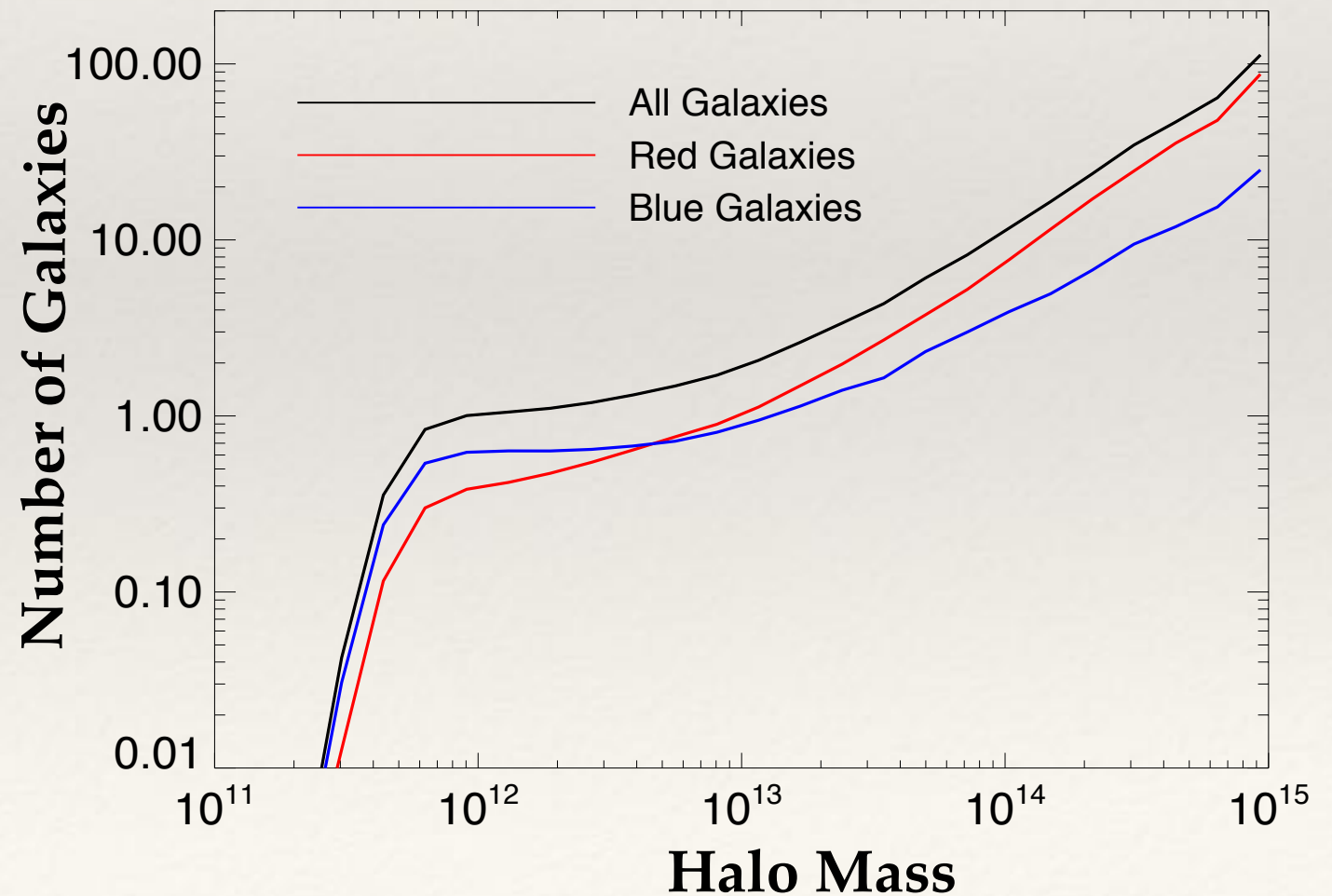
# Halo Occupation Distribution

Based on host halos only

Parameterized form of  $P(N_{\text{cen}} | M_{\text{halo}})$  &  $P(N_{\text{sat}} | M_{\text{halo}})$

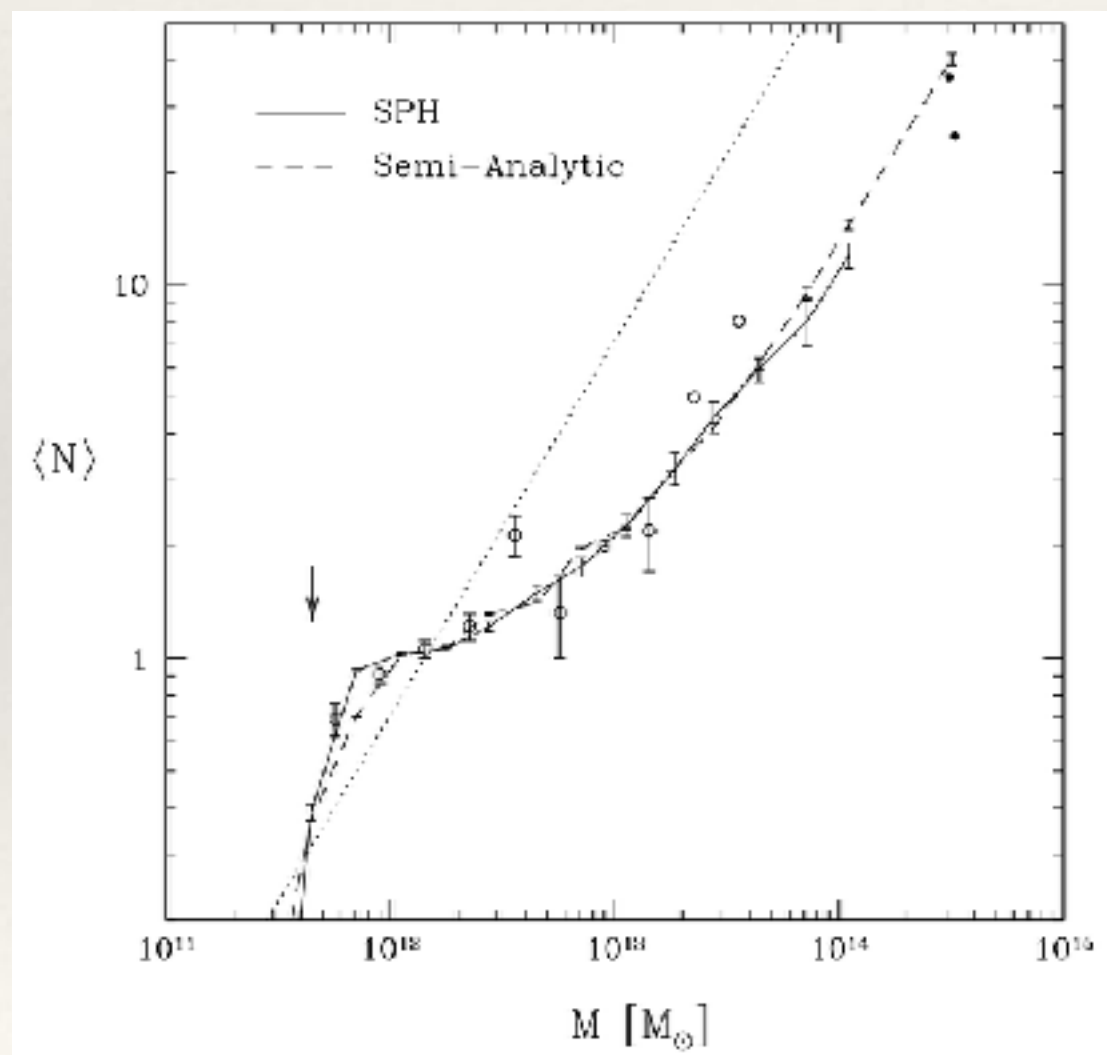


## HOD Model

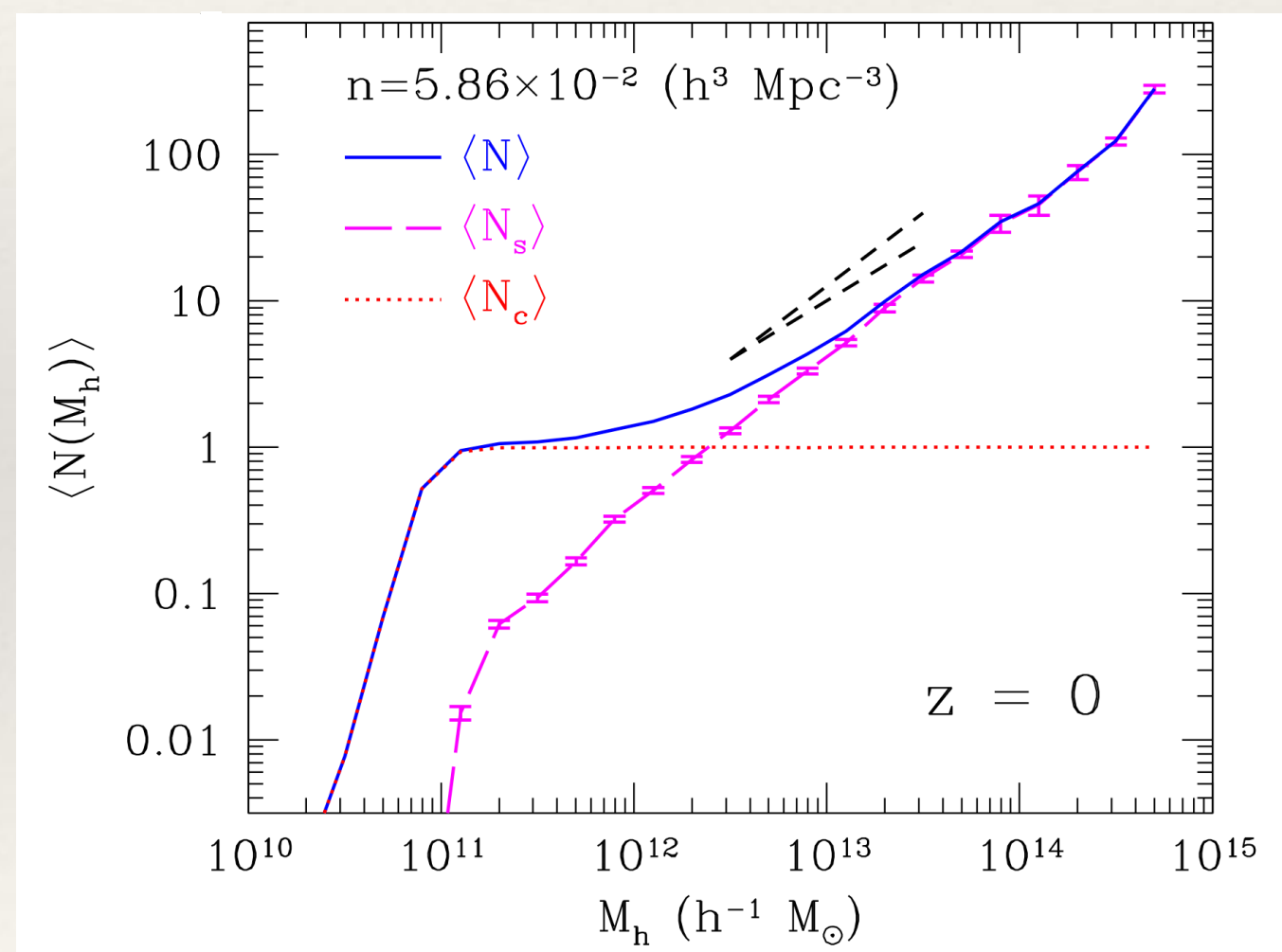


# Halo Occupation Distribution

HOD functional forms physically motivated by hydro sims, SAMs, and subhalo occupations



Berlind et al. (2003)

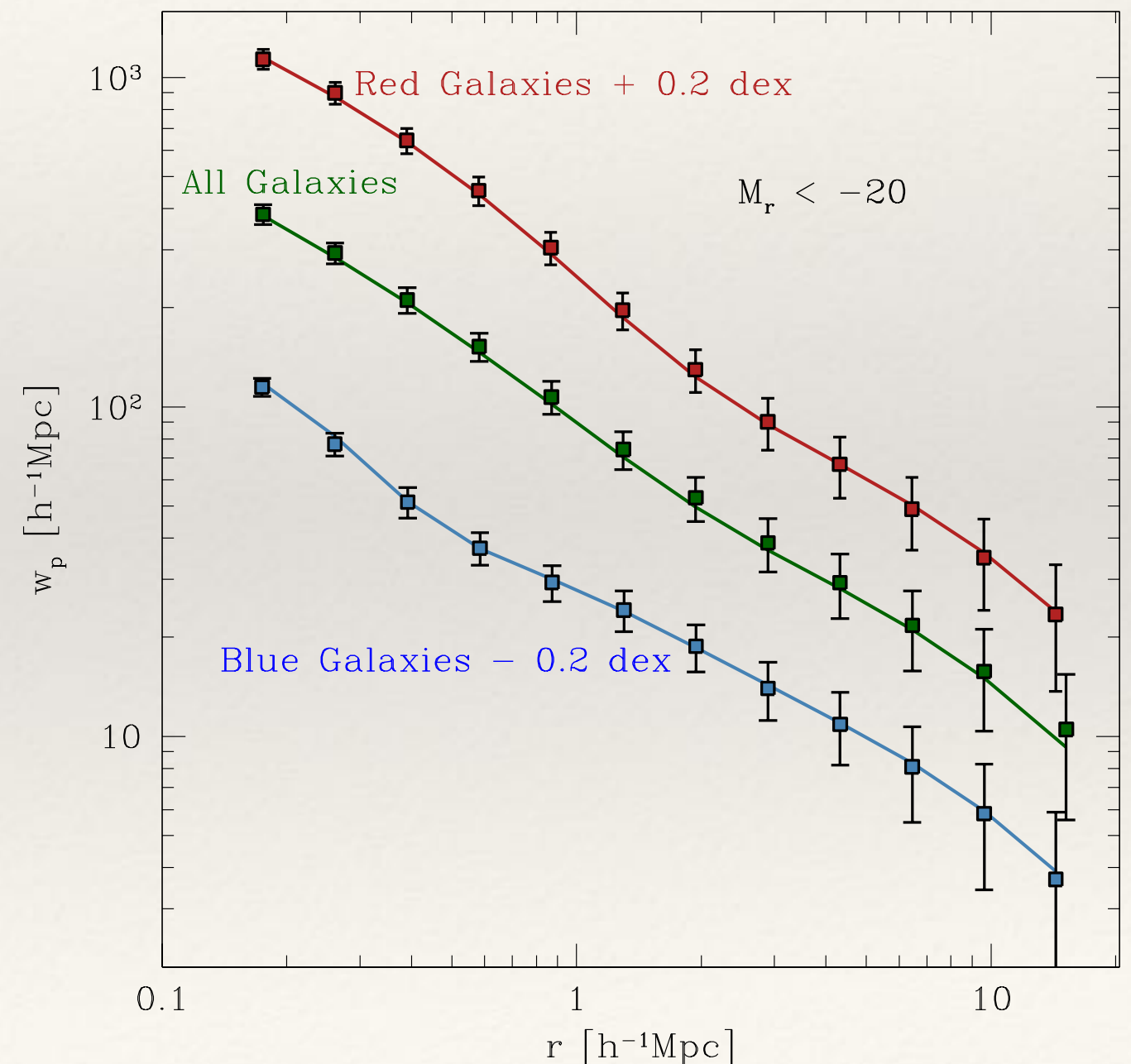
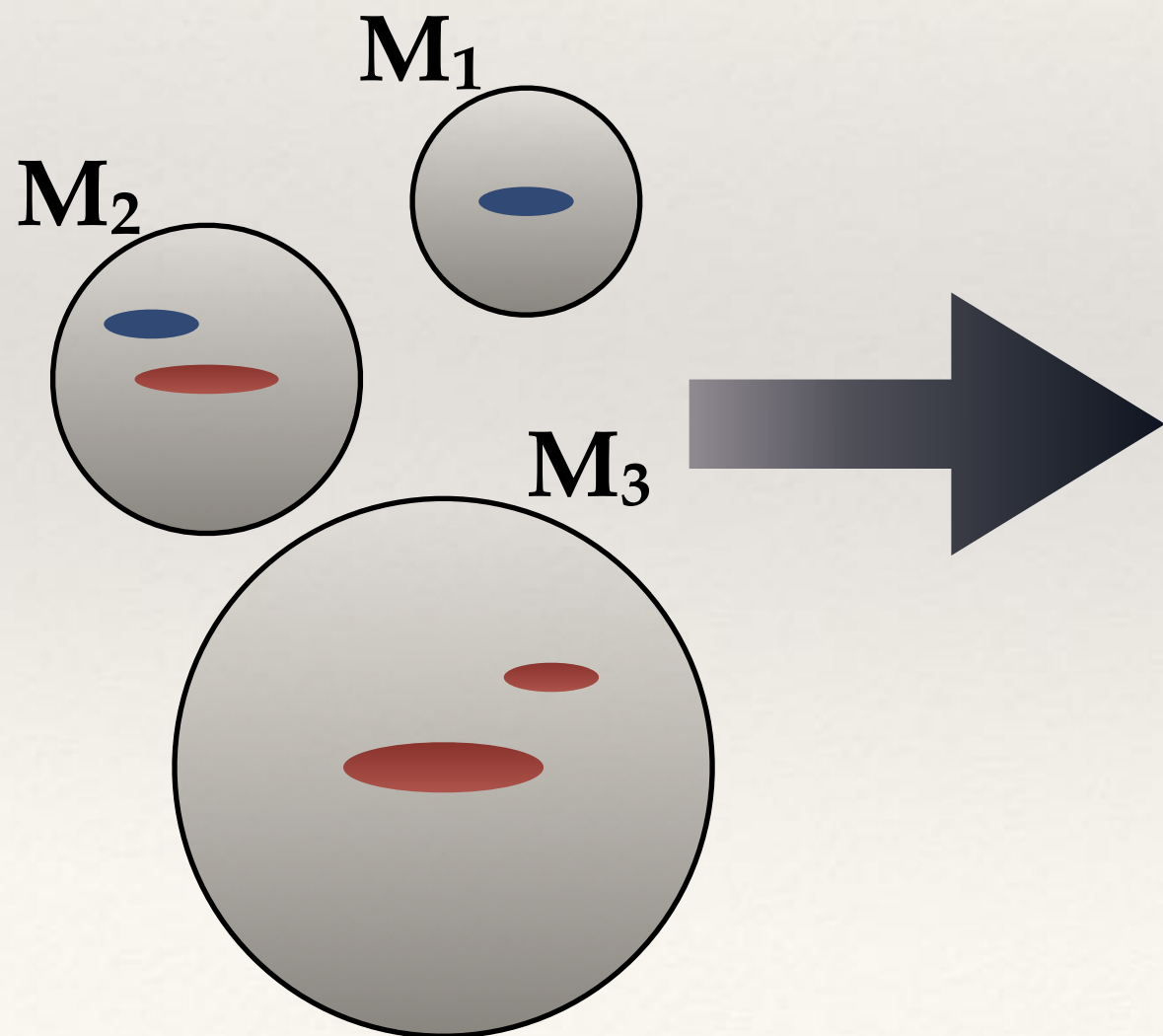


Kravtsov et al. (2004)



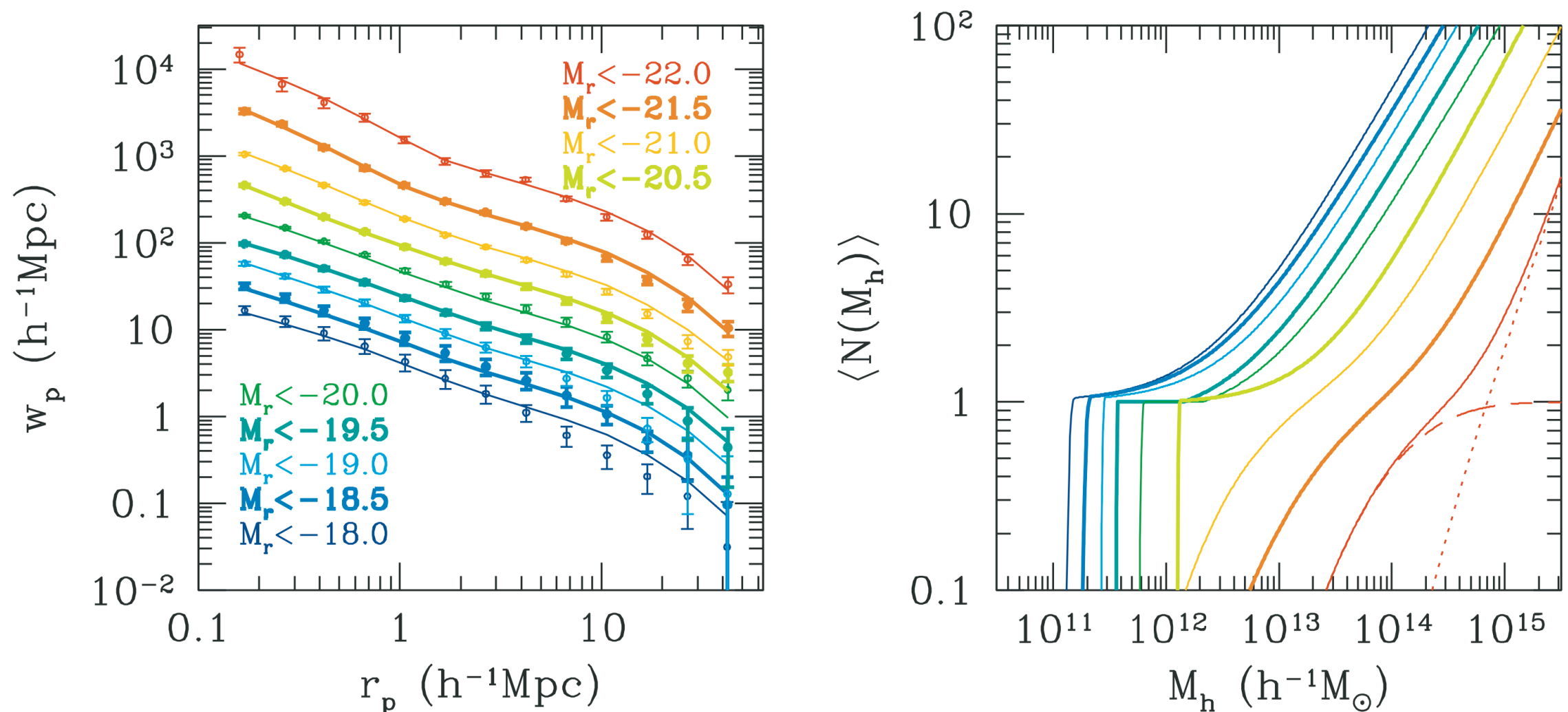
# Halo Occupation Distribution

Occupation statistics  $\Rightarrow$  galaxy clustering



# Halo Occupation Distribution

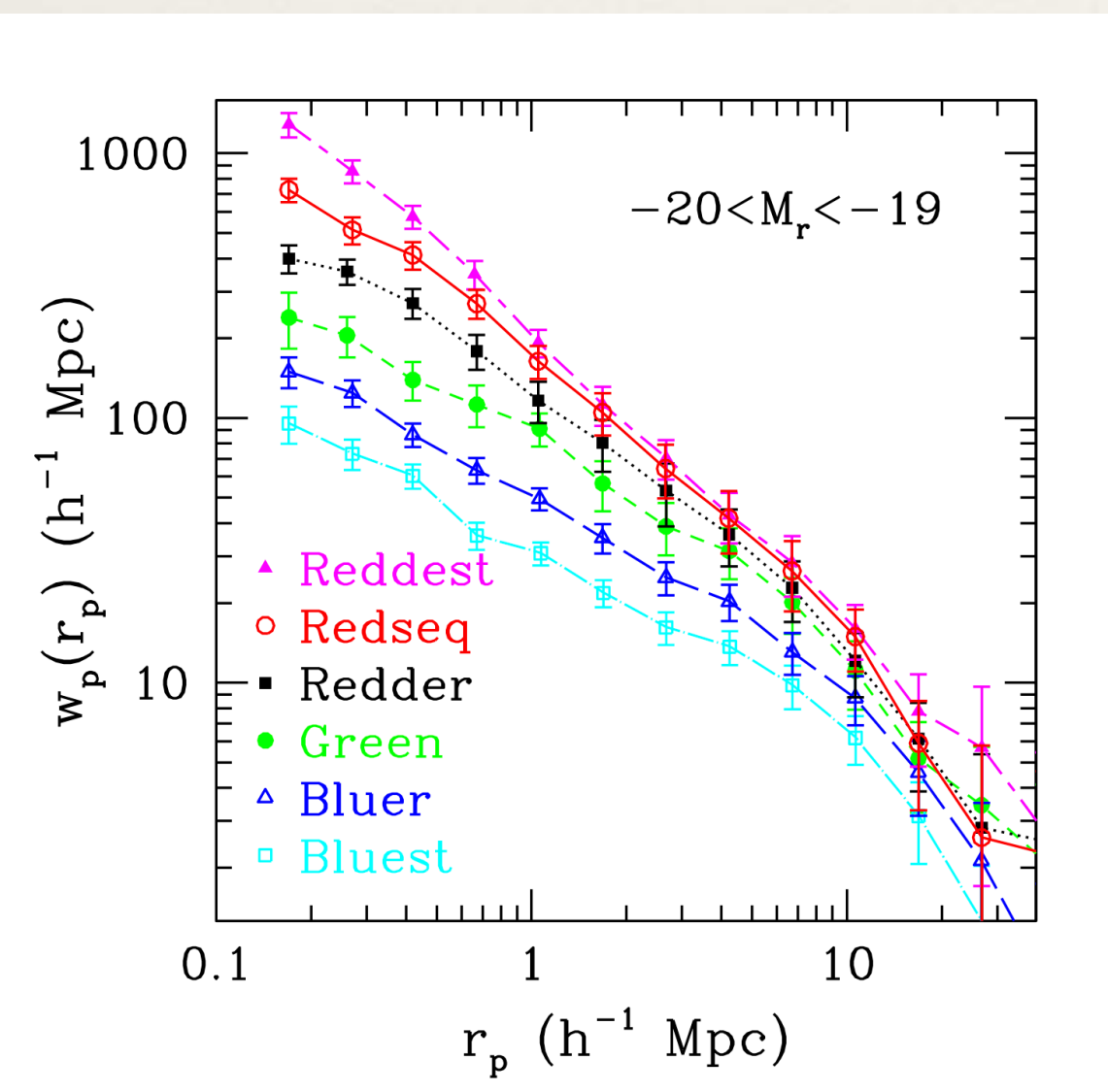
Successful fits to galaxy clustering,  
including dependence on  $M_r$  brightness



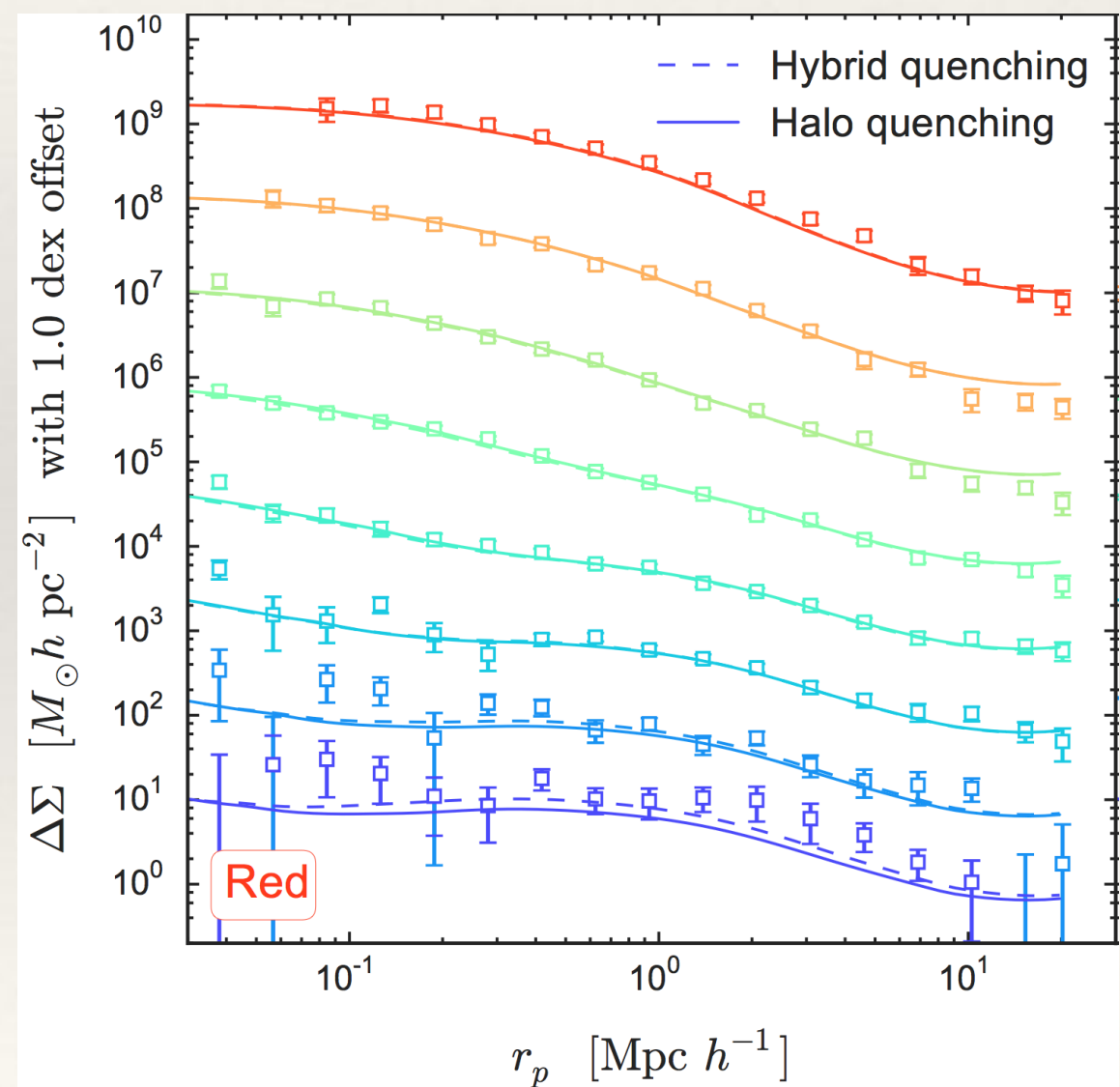


# Halo Occupation Distribution

Successful fits to galaxy clustering and lensing,  
including dependence on g-r color



Zehavi+11

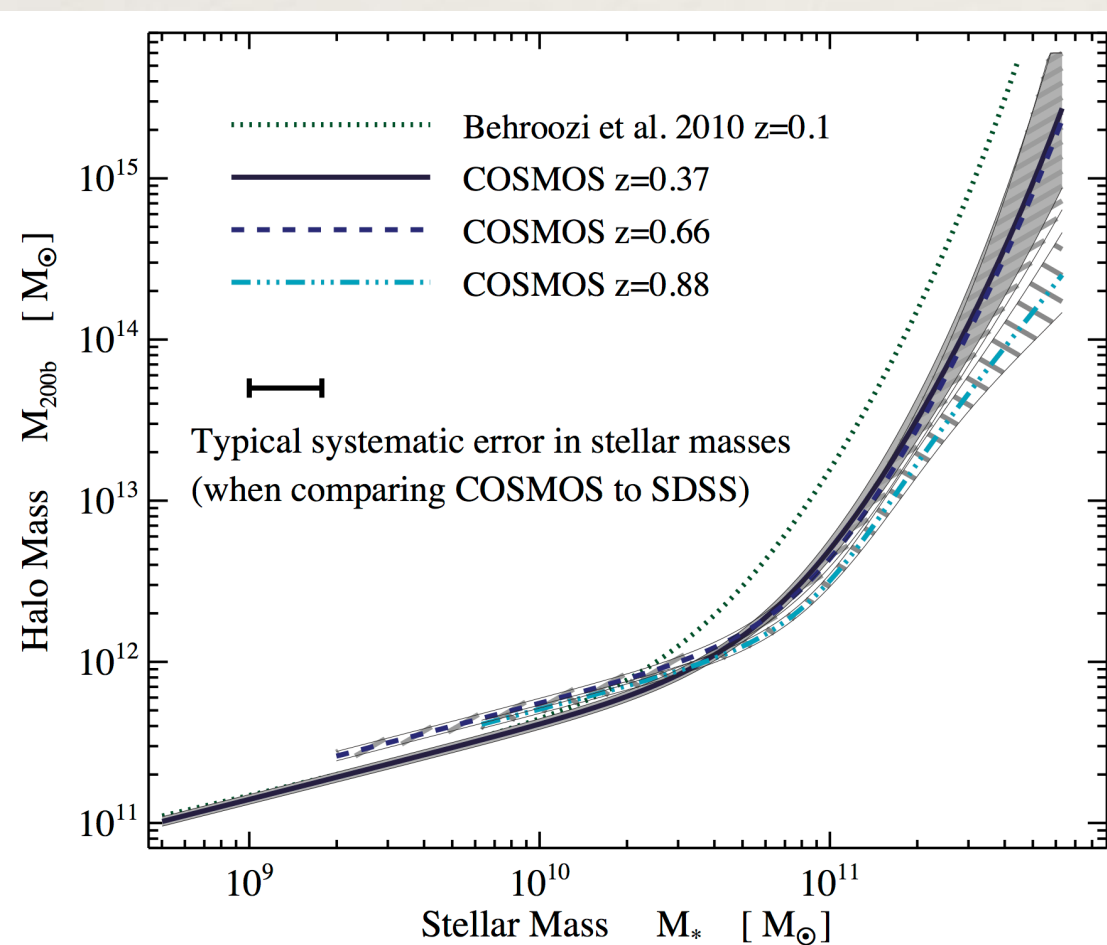


Zu & Mandelbaum (2016)

# Halo Occupation Distribution

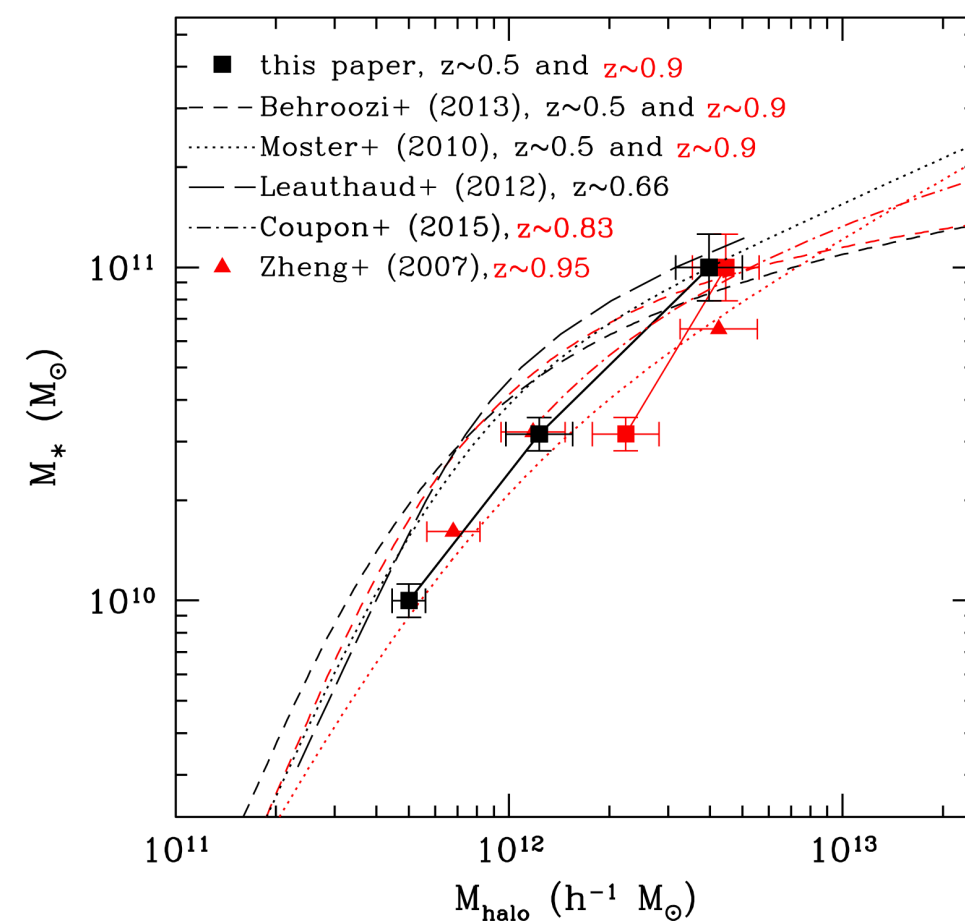
Successful fits to galaxy clustering,  
including dependence on redshift

## COSMOS



Leauthaud, Tinker et al. (2011)

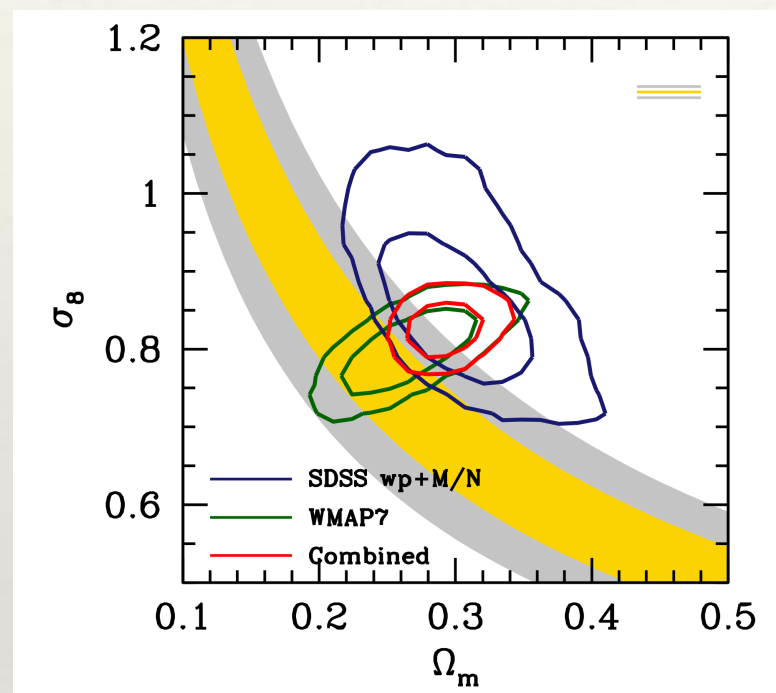
## PRIMUS



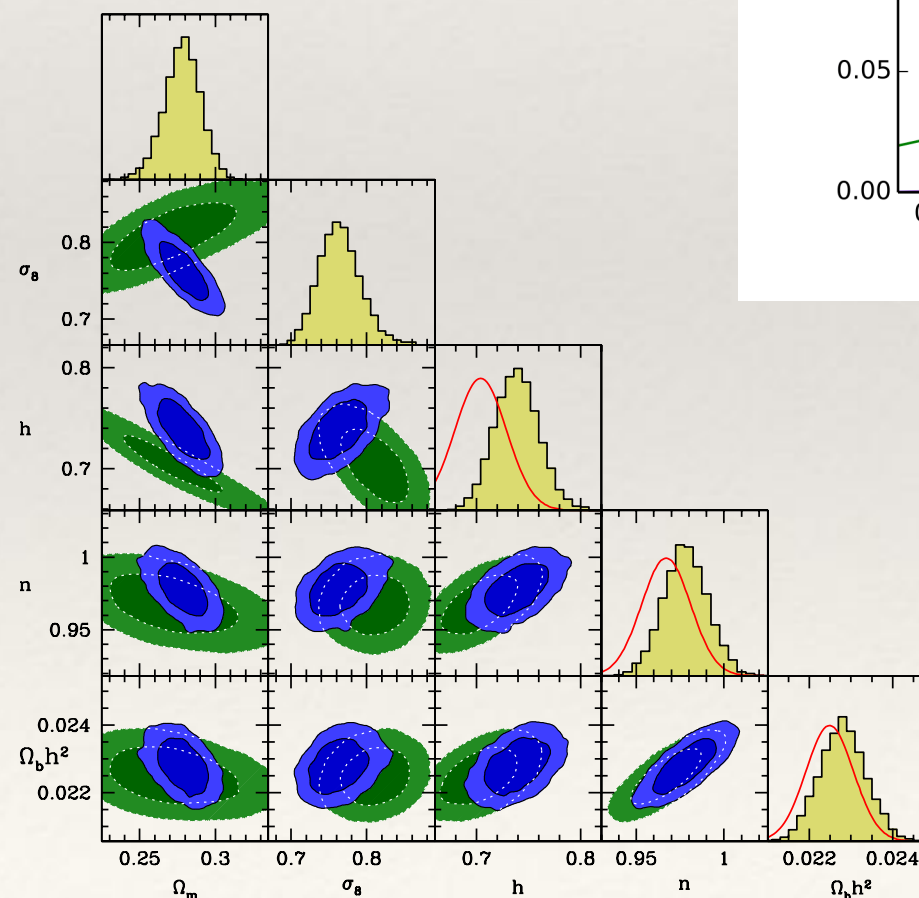
Skibba, Coil et al. (2015)

# Halo Occupation Distribution

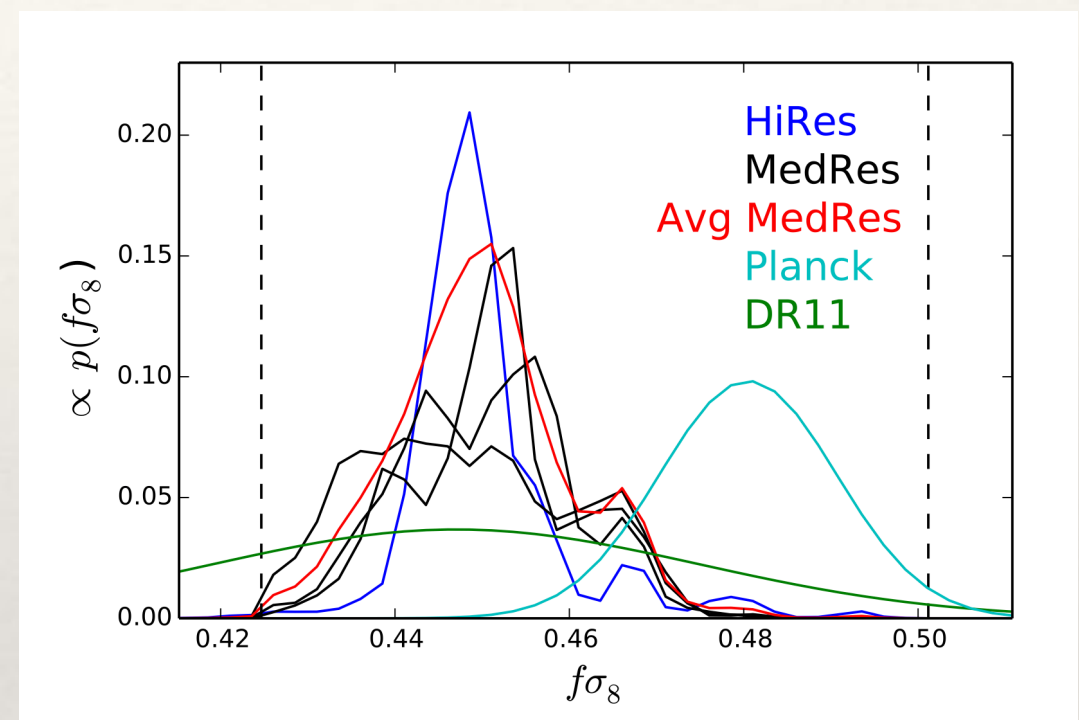
## Cosmological parameter estimation



Tinker+11



Cacciato+12



Reid+14

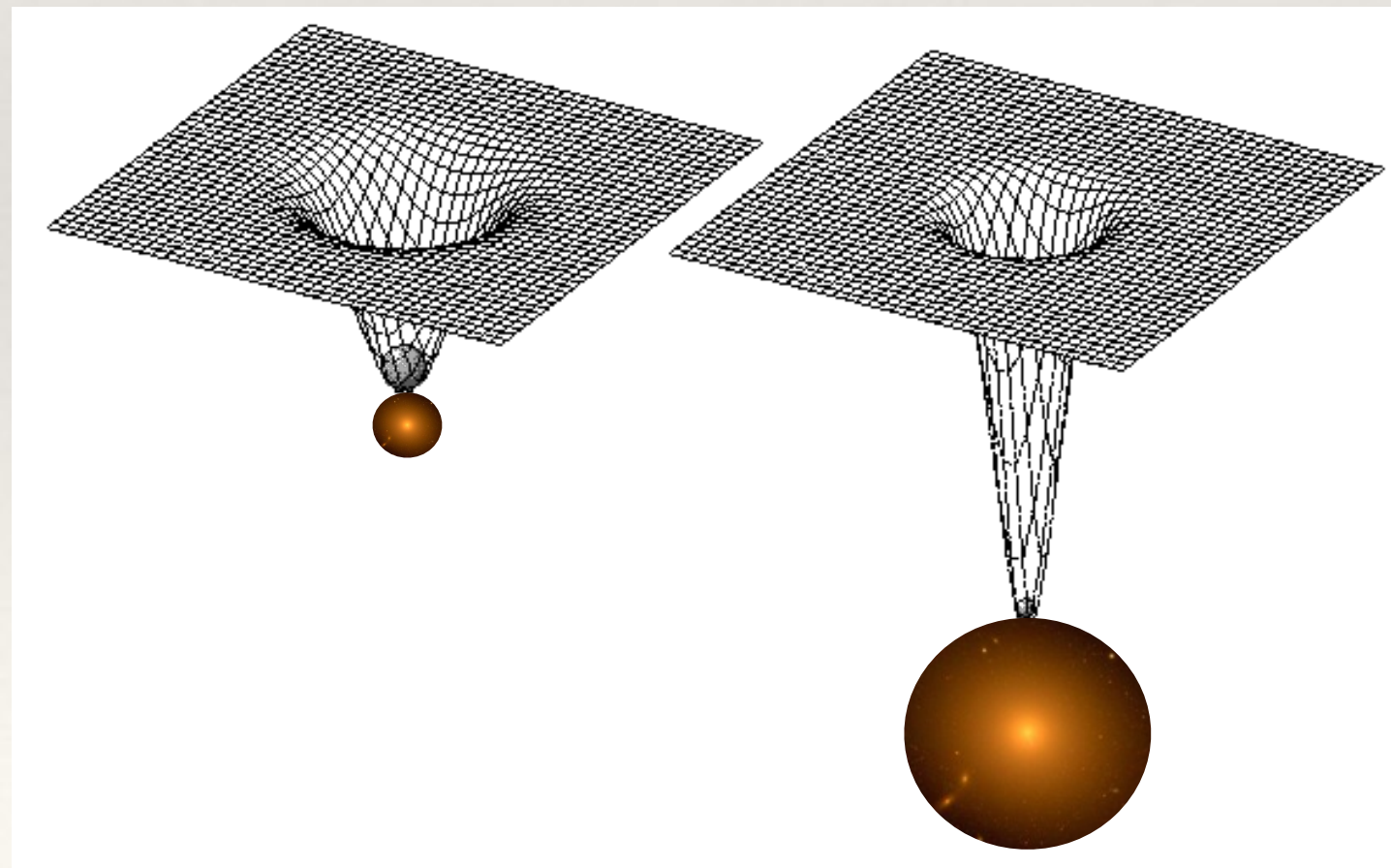


# What do we learn from the HOD?

Whenever you get so much for so little, nature is telling you your assumptions must be reasonably correct

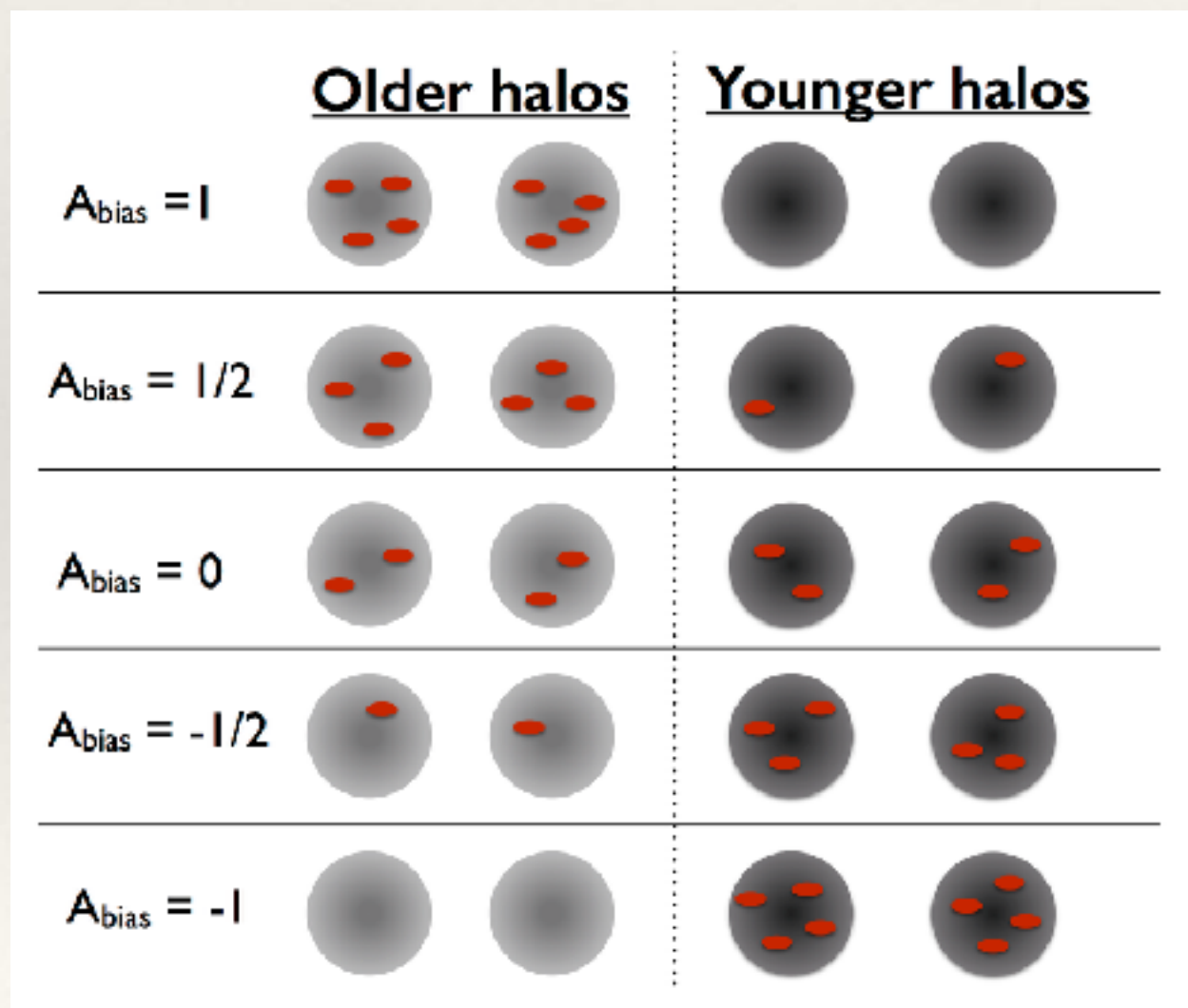
## Basic lesson:

Depth of the gravitational potential well  
has the dominant influence on galaxy mass *and color/SFR*



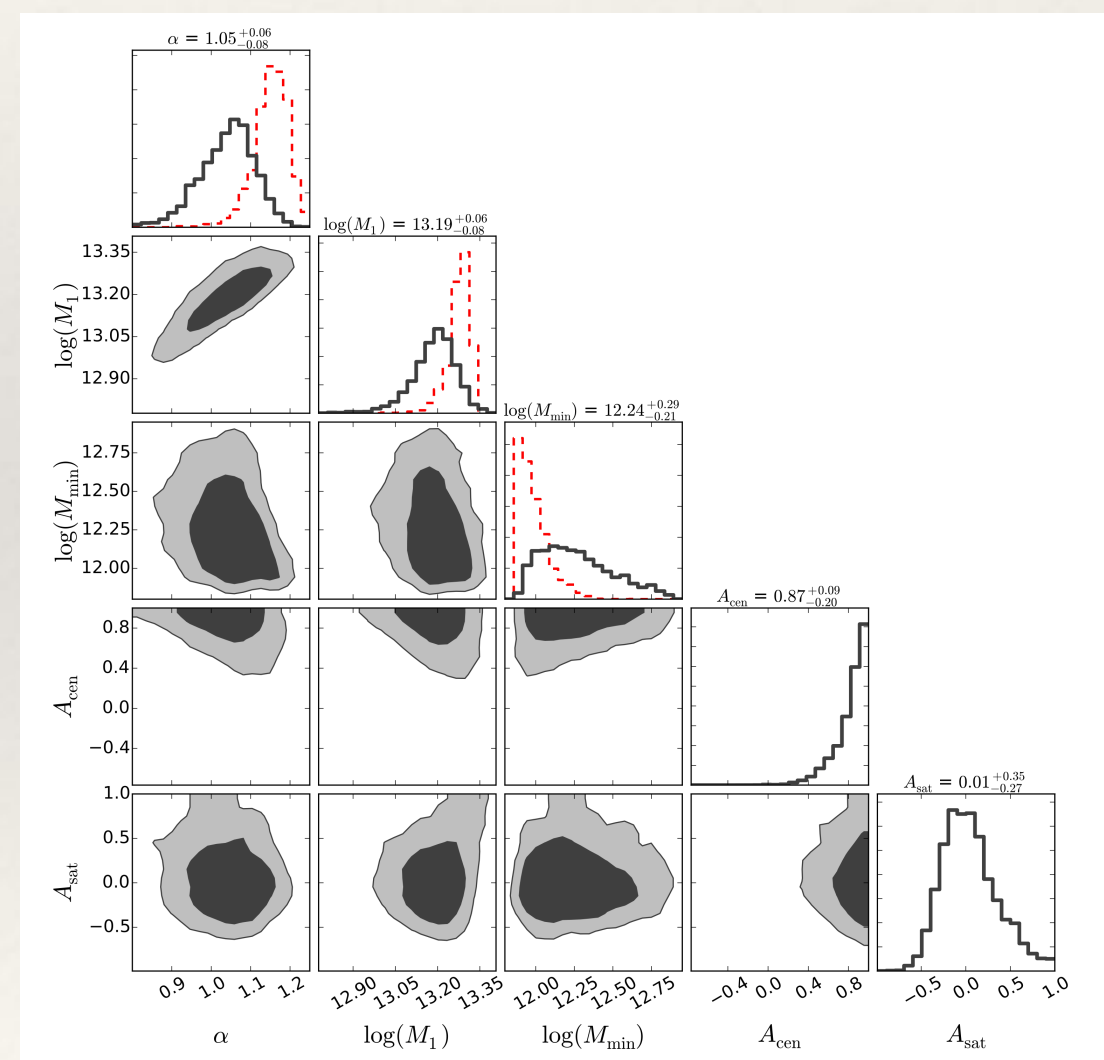
# Halo Occupation Distribution

Quantitative constraints on the strength of assembly bias with the Decorated HOD



Hearin+15

(see Halotools for python implementation)

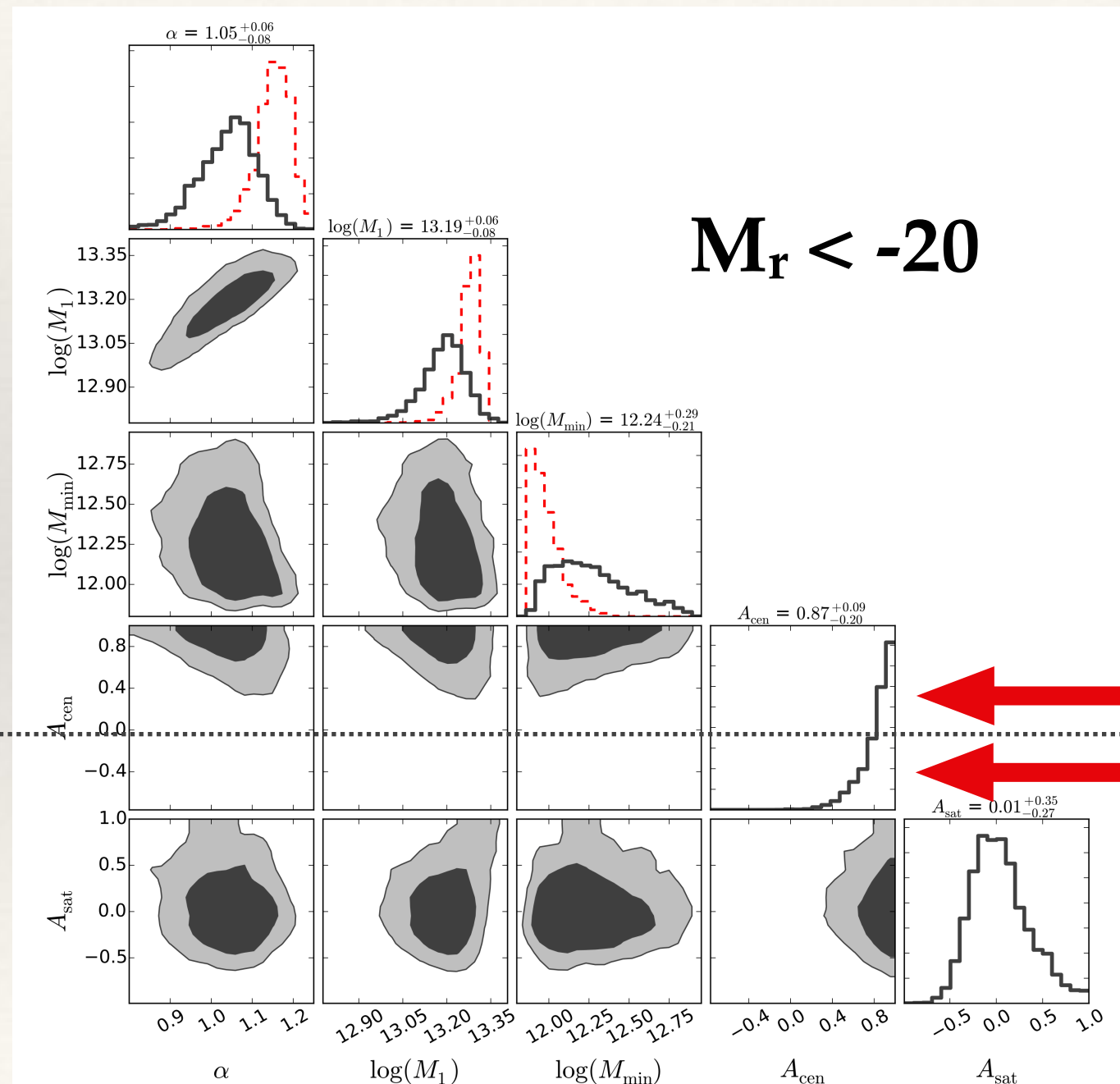


Zentner+16

# Halo Occupation Distribution

Central assembly bias well-constrained away from zero

Zero assembly bias



Central galaxy  
assembly bias strength  
parameter constraints

Zentner+16

See also Vakili & Hahn 2016



# Halotools

Open-source python library for galaxy—halo modeling  
of large-scale structure

[halotools.readthedocs.io](http://halotools.readthedocs.io)

The screenshot shows the Halotools documentation website. The header includes the 'halotools:docs' logo, navigation links for 'astropy', 'index', and 'modules', and a search bar. Below the header, the page is divided into a left sidebar and a main content area. The sidebar, titled 'Page Contents', lists the following sections: Halotools Documentation, User Documentation (with sub-links for Overview, Mock-Making Tools, Model-Building Tools, Simulation Analysis Tools, and Tutorials), and Developer Documentation. The main content area, titled 'Halotools Documentation', contains a paragraph about the library's purpose and a link to the GitHub repository. Below this, there are sections for 'User Documentation', 'Halotools Overview' (with sub-links for Science Overview, Package Installation, and Getting Started), 'Mock-Making Tools' (with sub-links for Quickstart Guide and Overview of methods), 'Model-Building Tools' (with sub-links for Quickstart Guide and Building models), 'Simulation Analysis Tools' (with sub-links for Overview, Halo catalog management, Halo analysis, and Merger tree analysis), and 'Tutorials'. A 'next' link is visible in the top right corner of the main content area. At the bottom right, there is a 'v. master' dropdown menu.

halotools:docs

astropy index modules Search

halotools v0.6.0dev1043

next

## Page Contents

- 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](http://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

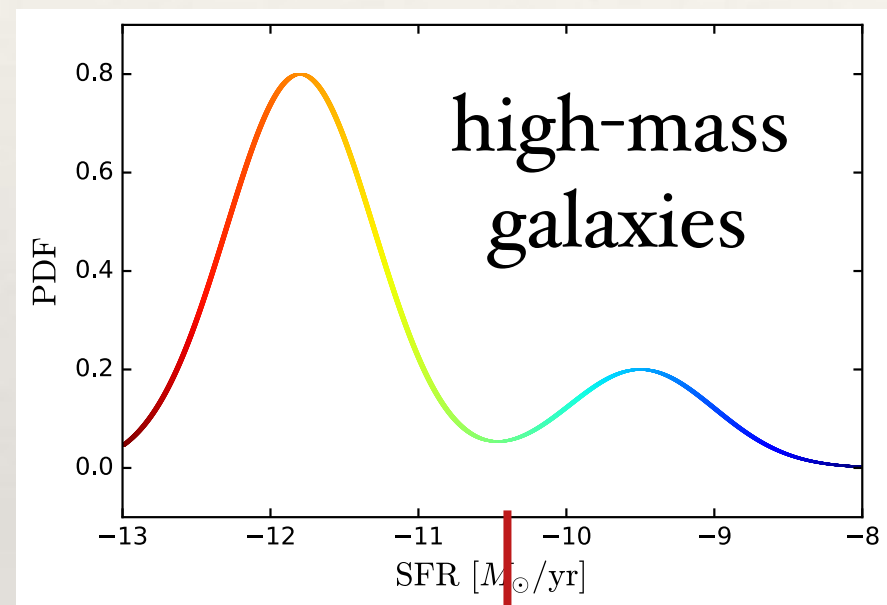
### Tutorials

v. master

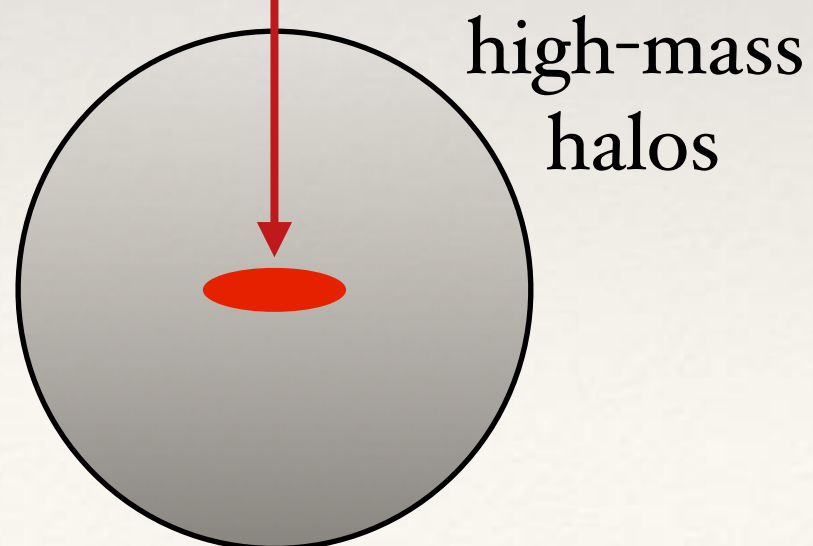
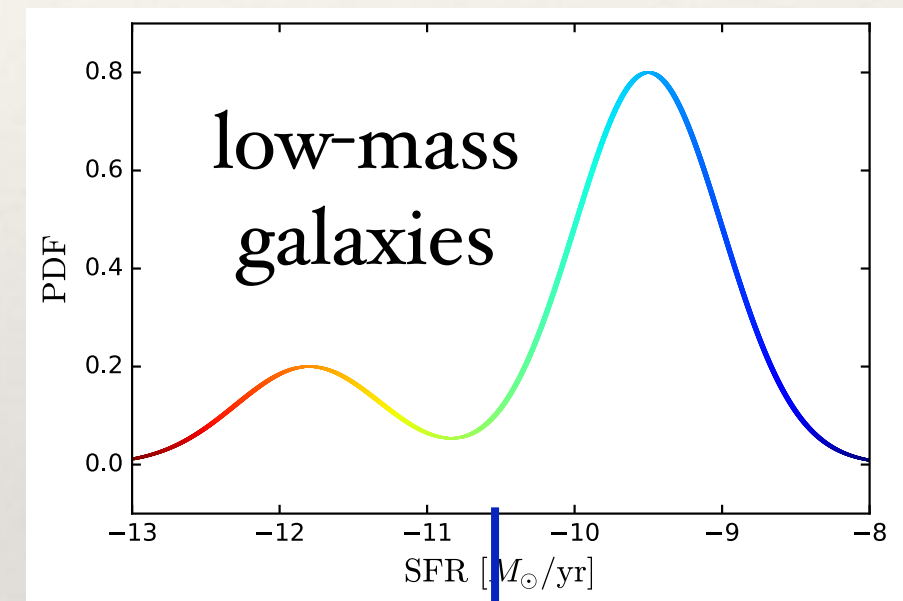
# Simple Age Matching

## Construction of the Halo--SFR map

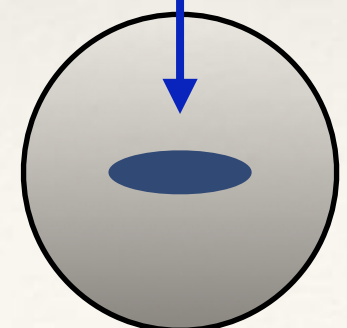
Formulation has direct mathematical analogy to simple abundance matching



Ingredient 1:  
Halo mass  
regulates available SFR



low-mass  
halos

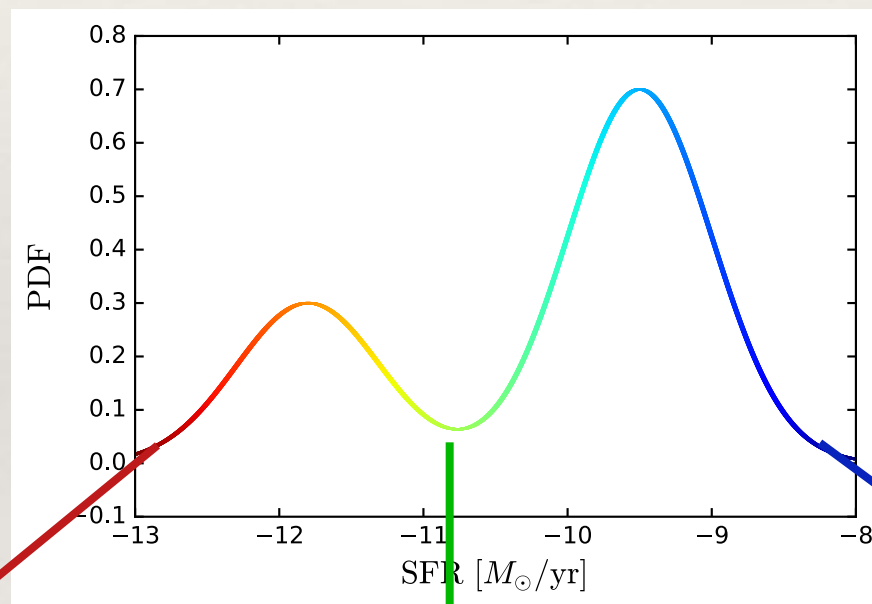


# Simple Age Matching

## Construction of the Halo--SFR map

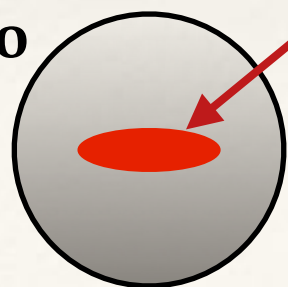
### Ingredient 2:

Galaxy SFR  $\propto$  Halo “age”  
at fixed halo mass

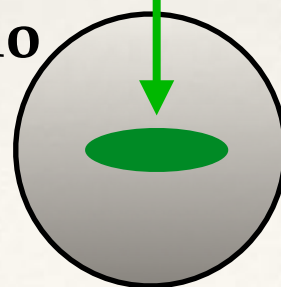


old, slow-accreting,  
early-forming  
halos

$M_{\text{halo}}$

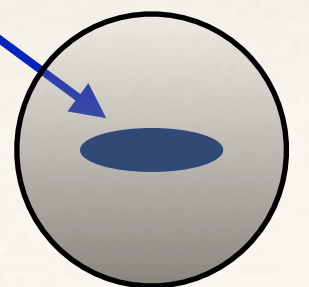


$M_{\text{halo}}$



young, fast-accreting,  
actively-forming  
halos

$M_{\text{halo}}$

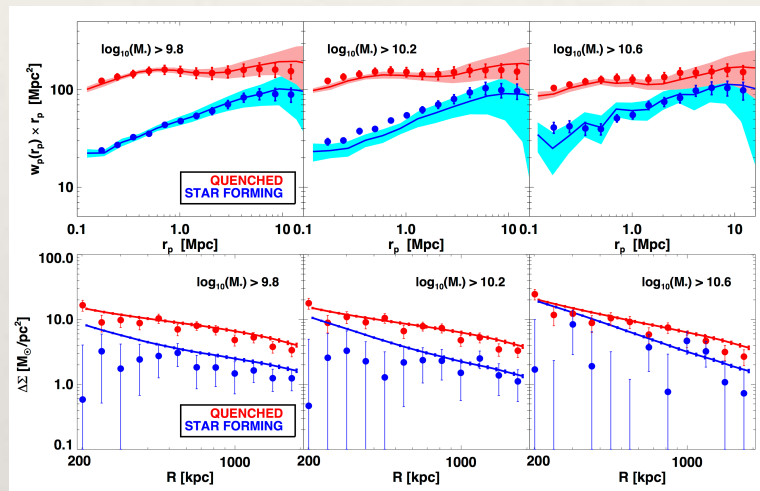




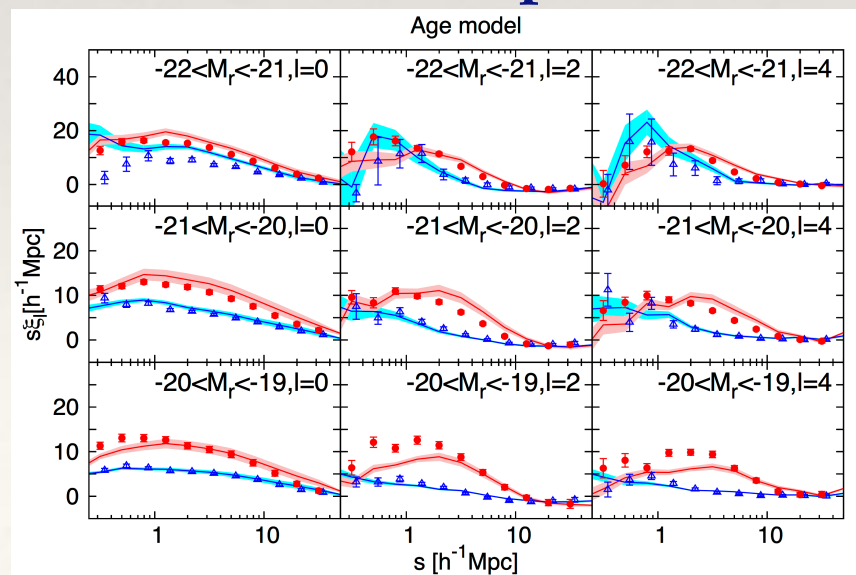
# Simple Age Matching

Many different successful predictions  
with few parameters and two simple ingredients

galaxy clustering & lensing

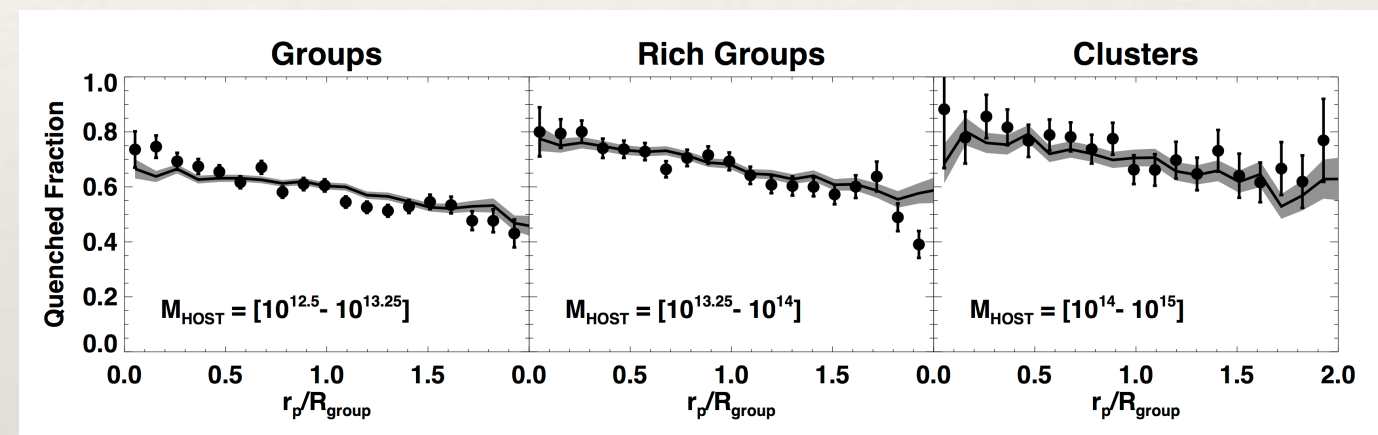


RSD multipoles



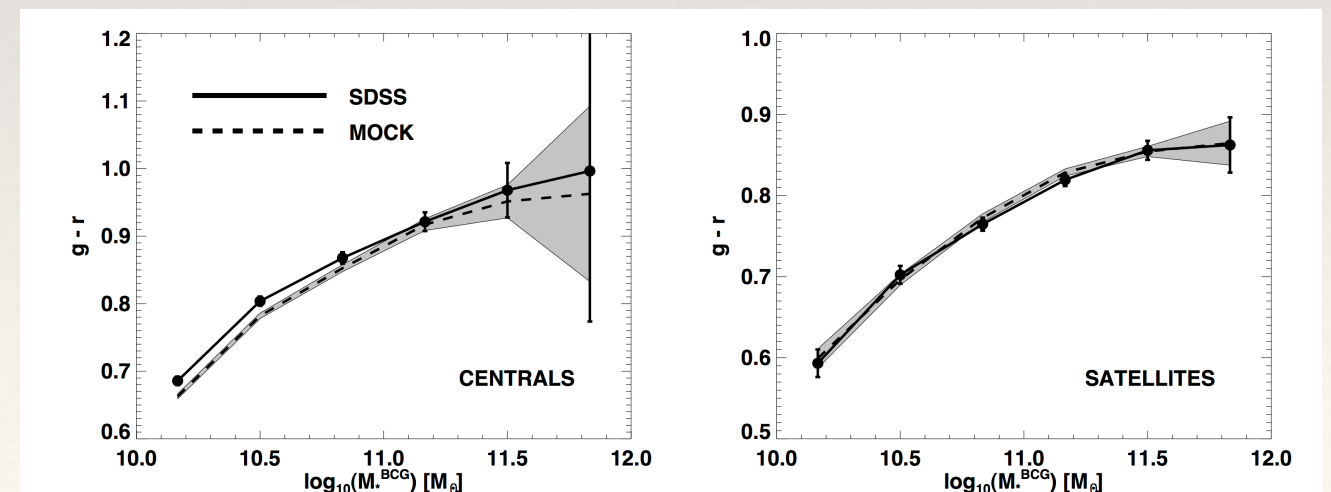
Yamamoto et al. 2016

satellite quenching profiles



Watson et al. 2015

Central & satellite color vs. group mass

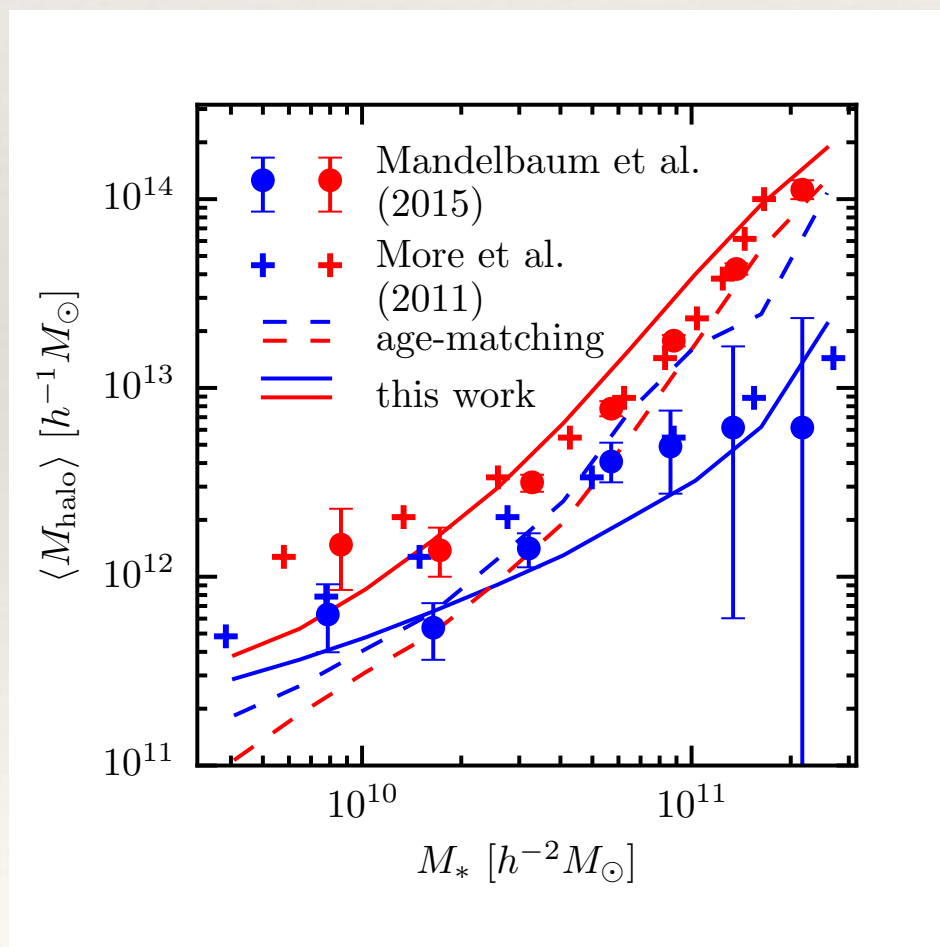


Hearin et al. 2014

# Simple Age Matching

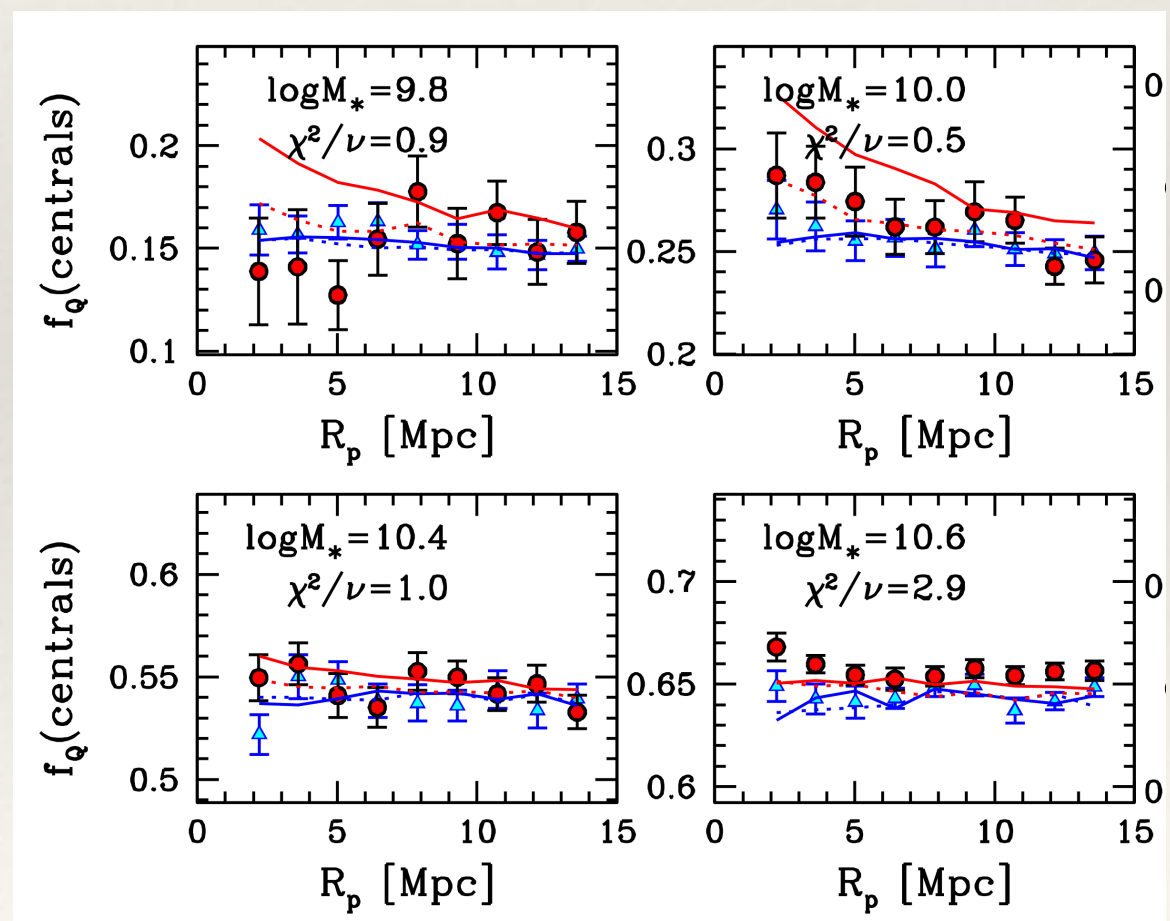
Formulation details significantly impact level of success

Red/blue SHMR



Campbell+17, in prep

Galactic Conformity



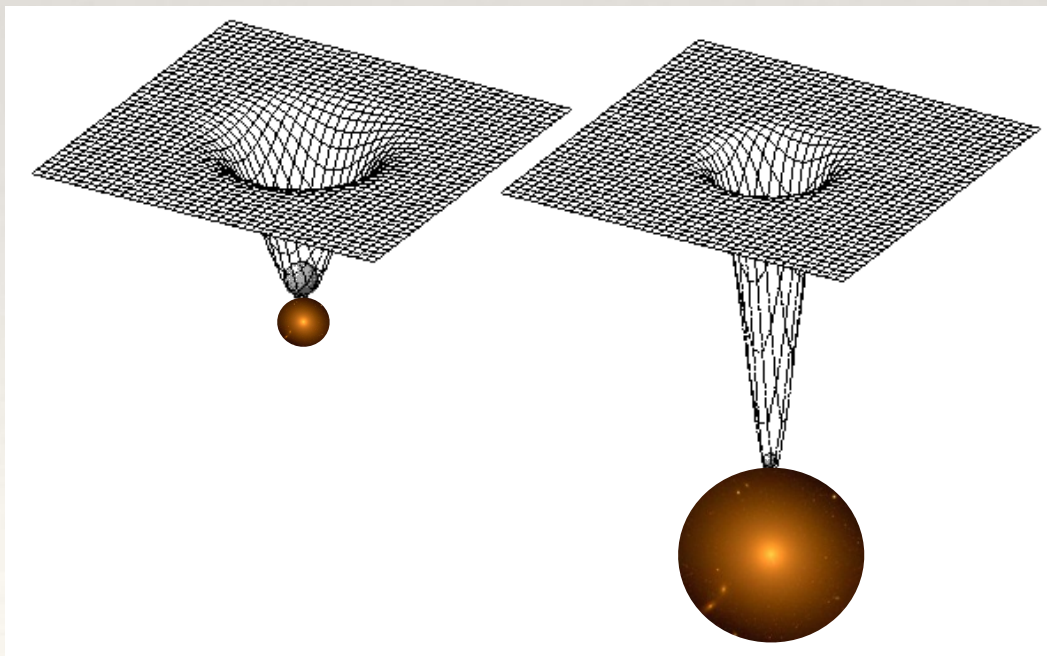
Tinker+17

# What do we learn from age matching?

Whenever you get so much for so little, nature is telling you  
your assumptions must be reasonably correct

## Basic lesson:

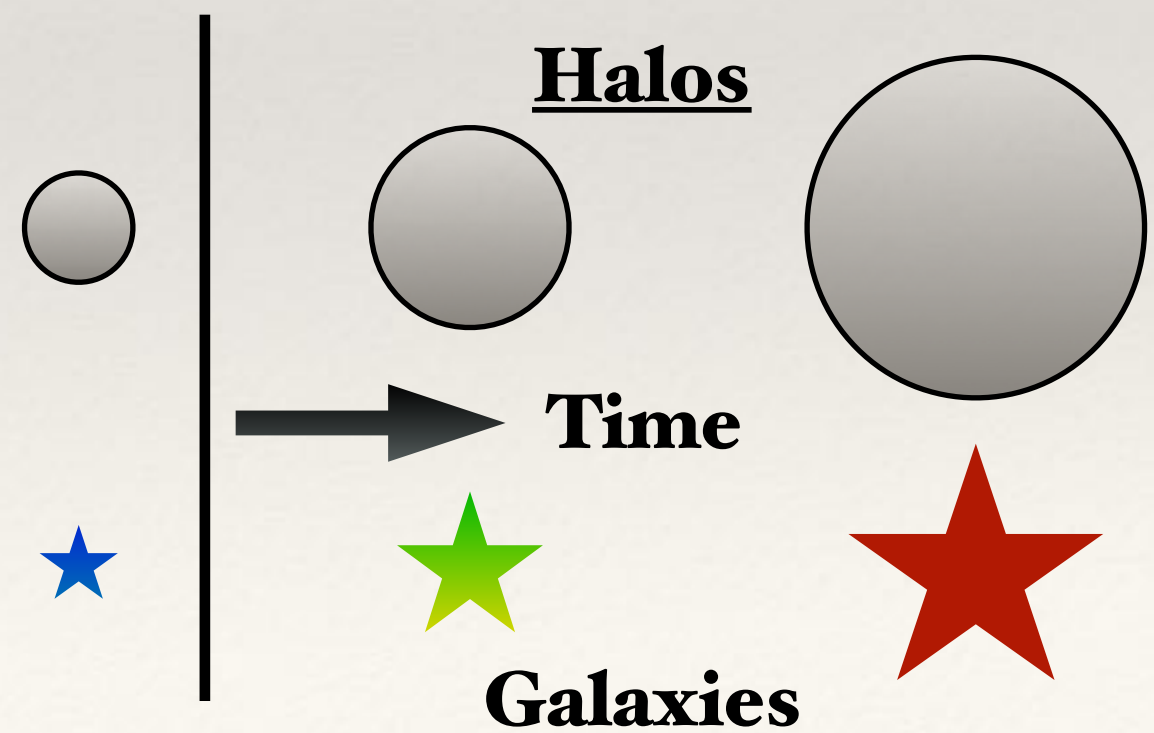
Depth of gravitational potential well  
has the dominant influence on galaxies



## Basic lesson:

Galaxy—halo co-evolution

Halo assembly has important additional influence  
Dramatic modeling simplifications from exploiting this!





# SHAM/HOD Foundation: A severe problem

Conventional empirical models construct maps  
for the *integrated* galaxy quantity ( $M_r$  or  $M^*$ )

## Fundamental & irreducible technical problem

How to compute cross-correlations between different tracers?  
Need to know which *particular* galaxies are in which *particular* halos

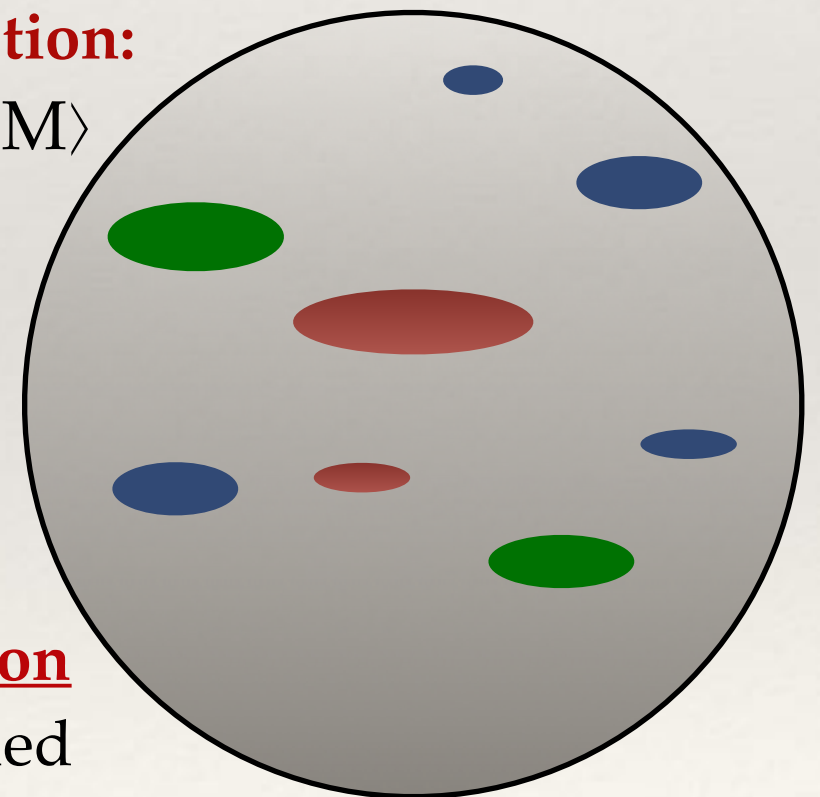
**No justification for common assumption:**

$$\langle N_{\text{red}} N_{\text{blue}} | M \rangle = \langle N_{\text{red}} | M \rangle \langle N_{\text{blue}} | M \rangle$$

$M_{\text{halo}}$   
(+ conc,  $\lambda$ , etc.)



$N_{\text{gal}}$  (HOD)  
 $M^*$  (SHAM)



**Catastrophic parameter proliferation**

Only gets *worse* as more data is added

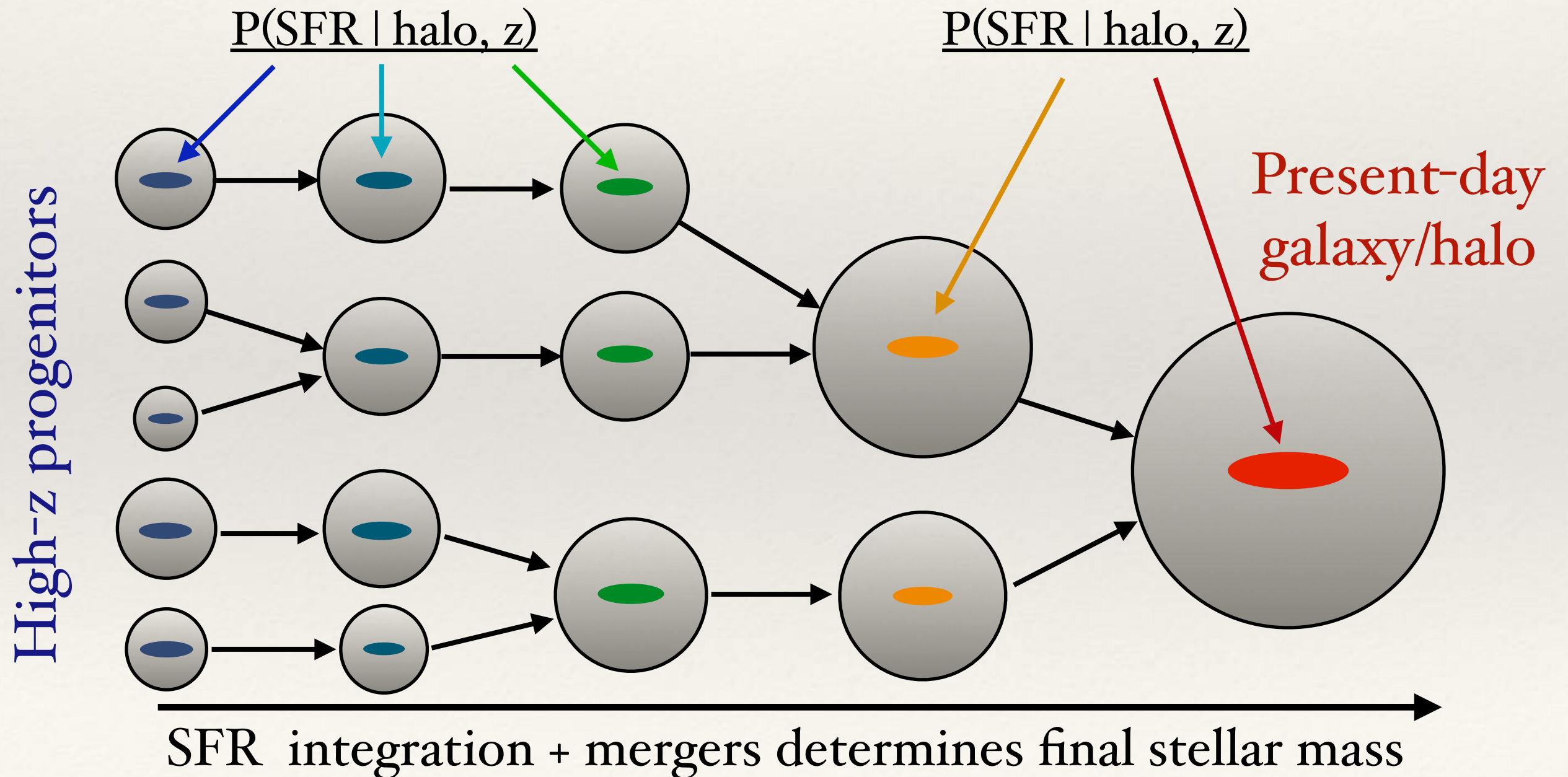
But cross-correlations of multiple datasets are the future of large-scale structure!

**Conventional models are doomed to a future of single datasets**

# A Proposed Remedy

Alternative direction: parameterize the *differential* quantity (SFR) instead

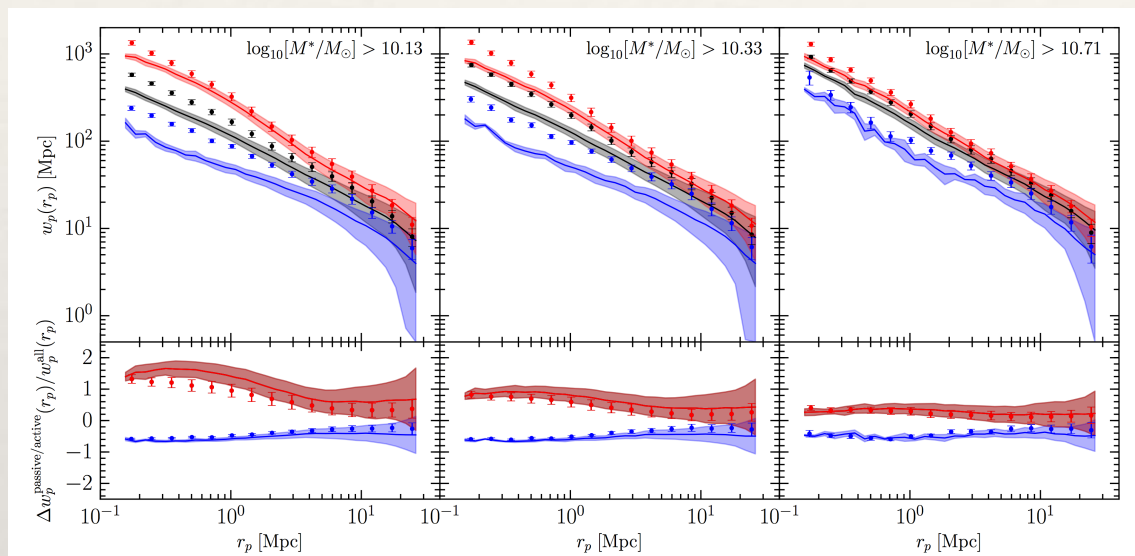
Now can use *far* more available data, forward-modeling survey selection functions



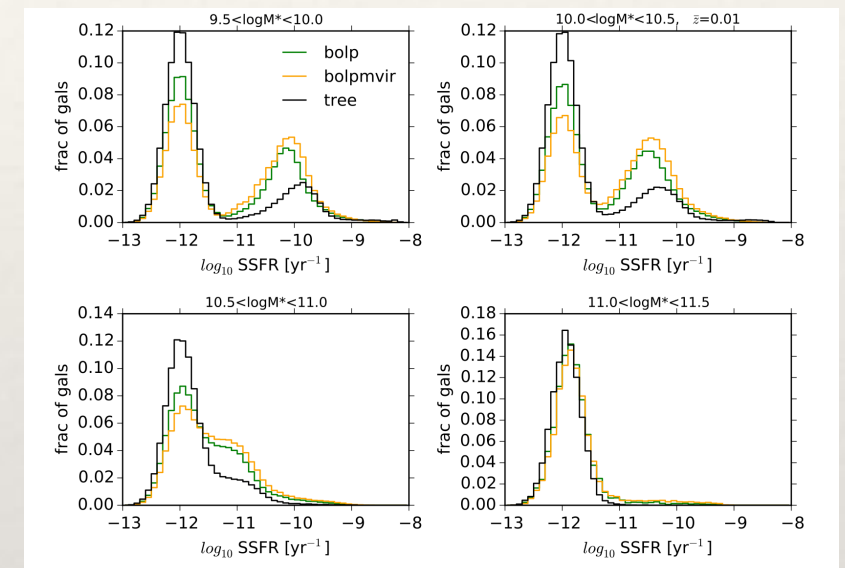
# A Proposed Remedy

New generation of forward models already moving in this direction

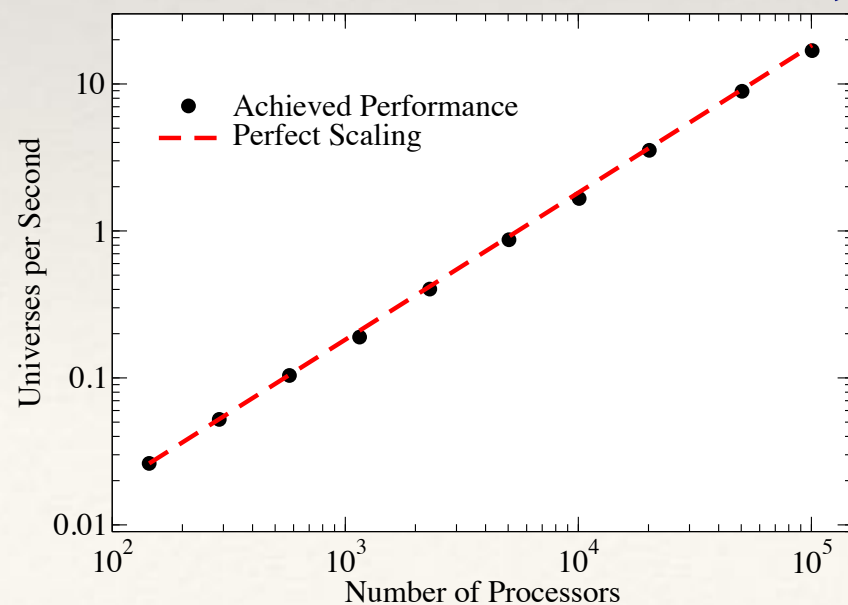
Becker 2015



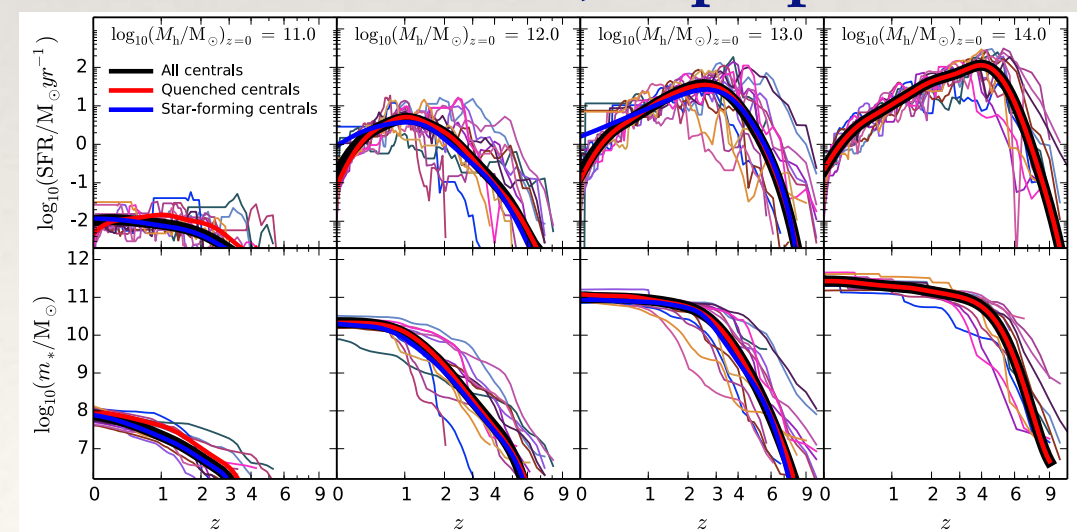
Cohn 2016



Universe Machine: Behroozi+17, in prep



Moster+17, in prep





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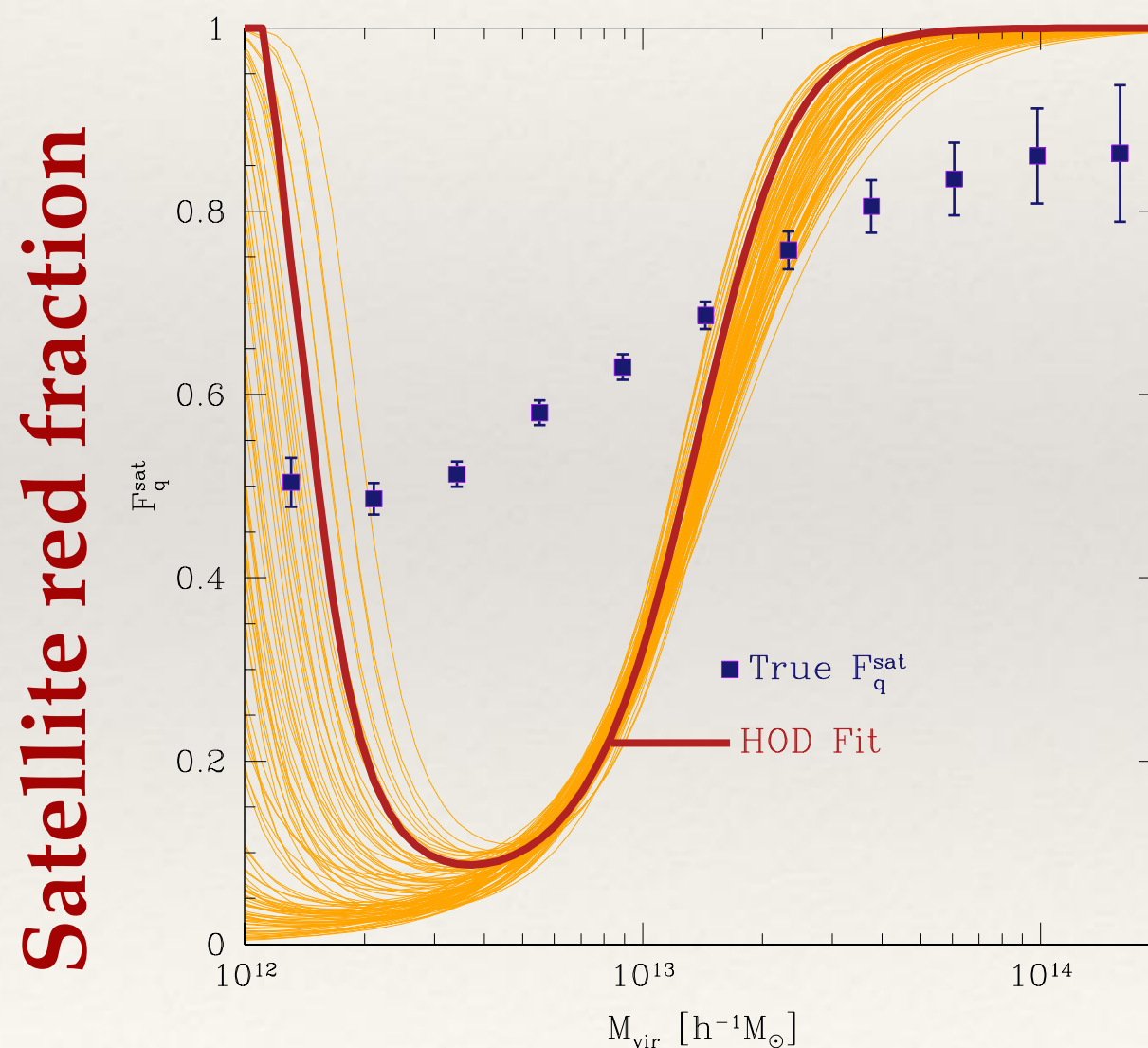
# Additional Slides

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# Assembly Bias Consequences

Are interesting conclusions about galaxies threatened by potentially incorrect HOD assumptions?

**Yes, they most certainly are!**



**Halo Mass**

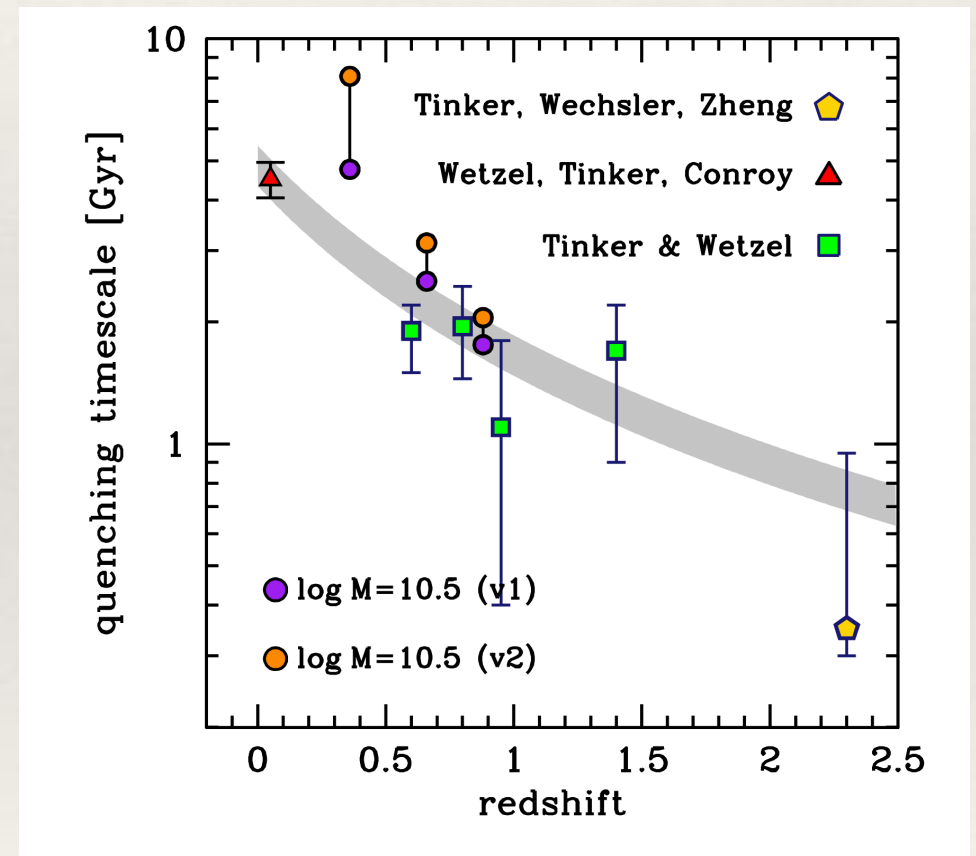
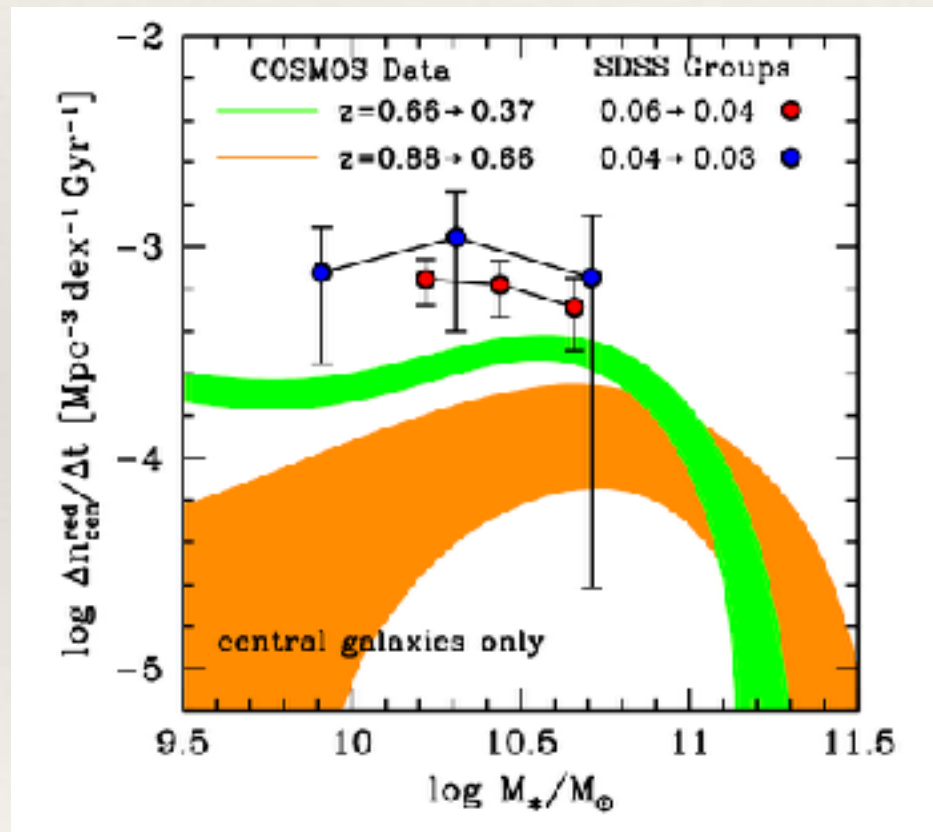
# Color Dependent HODs

## Upshot:

Rich information can be extracted about galaxy evolution  
using HOD fits to e.g., COSMOS data

Tinker, Leauthaud, et al 2013

Red sequence migration rate



## Downside:

Parameter proliferation rapidly becomes unmanagable

COSMOS fits required  $27 \times 3 = 81$  parameters for binary red/blue designation alone