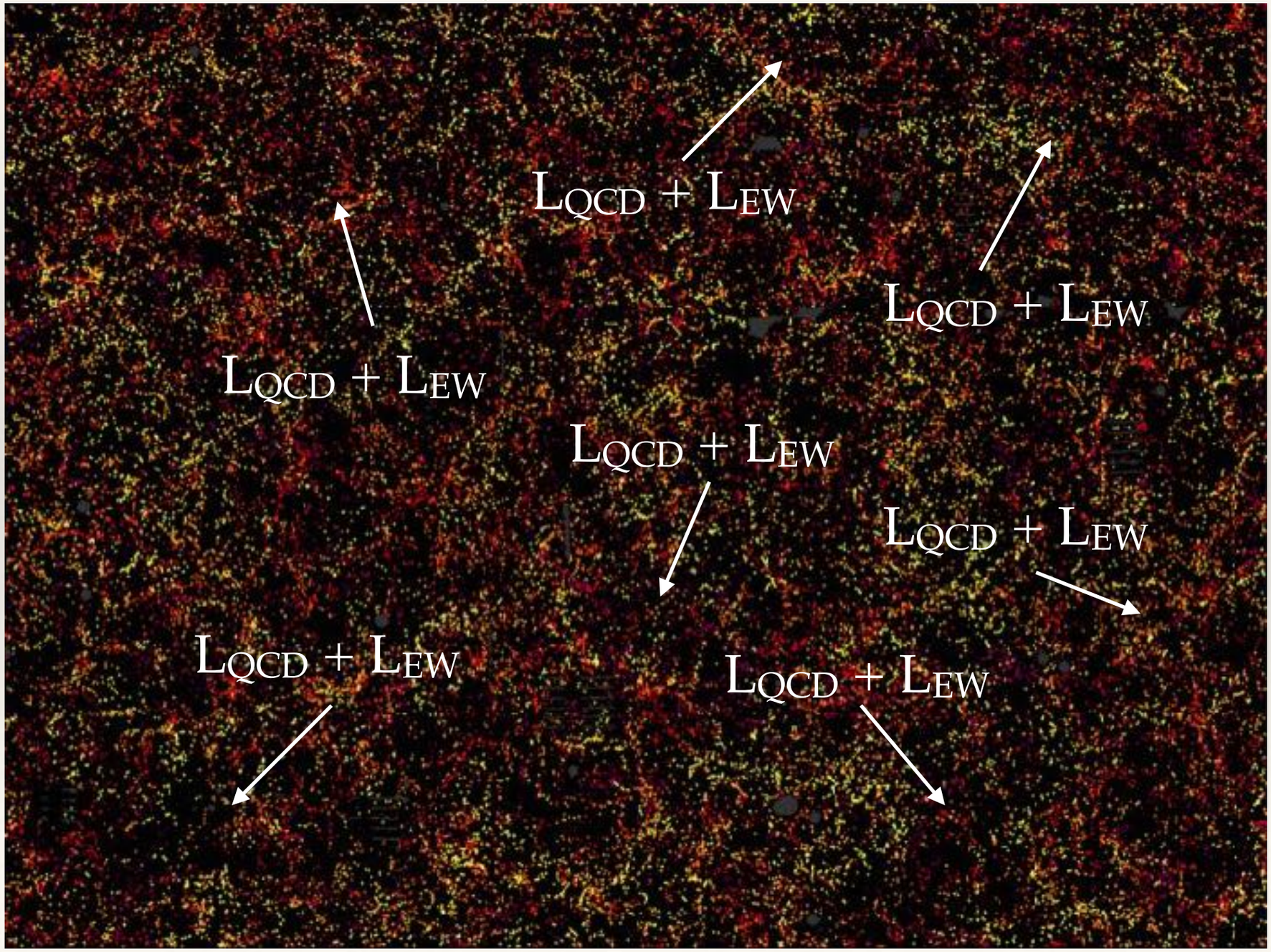
Andrew Hearin, Argonne National Lab

Galaxy–Halo Modeling of Large-Scale Structure

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

Galaxy Formation Theory

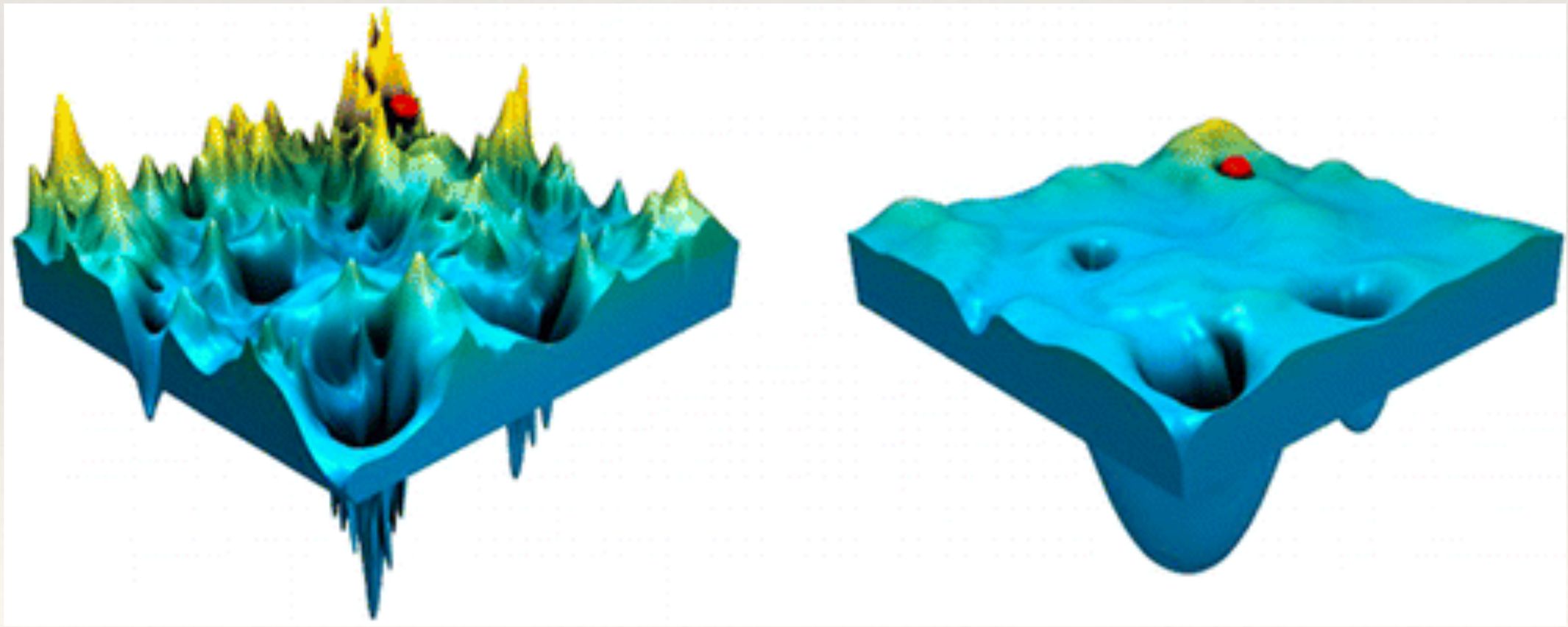
"Fundamental" theory has been complete for decades



Coarse Grained Models

"Fundamental" theory is hopeless

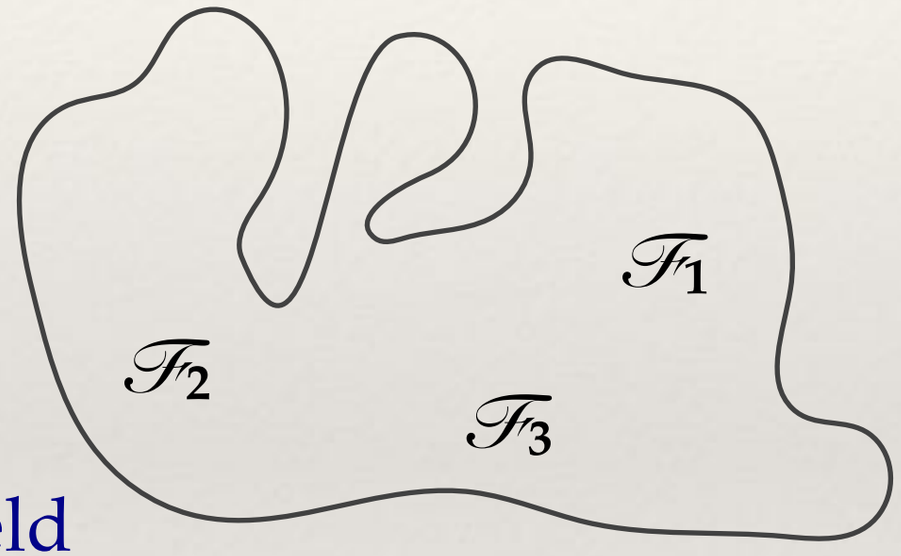
Hydro sims, SAMs, empirical models
are coarse-grained models of the fundamental theory



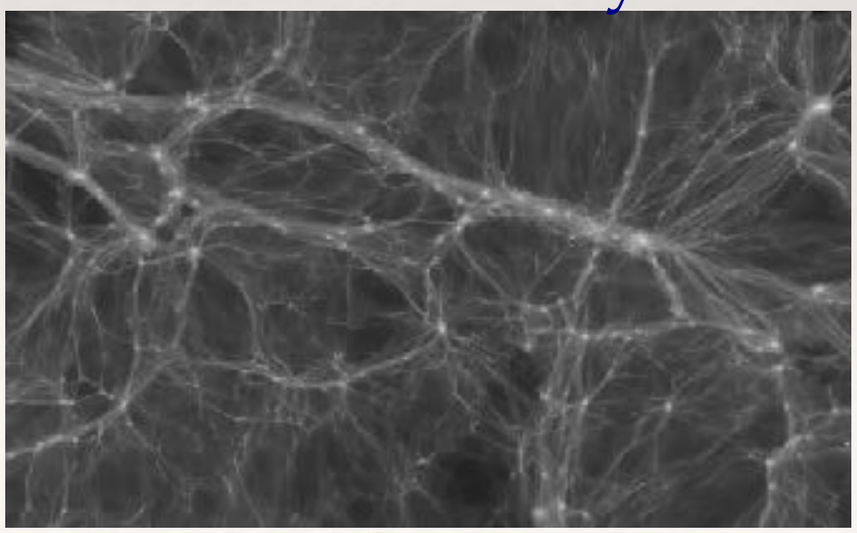
Mapping Simulated to Real Quantities

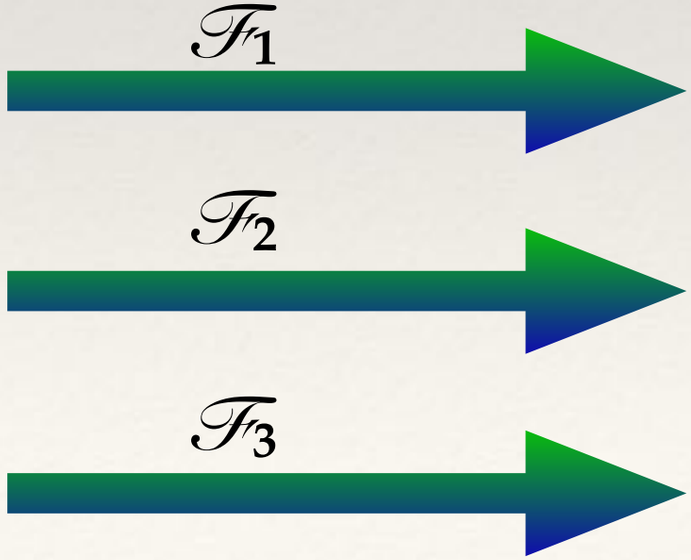
An extremely high-dimensional problem

High-dimensional space of possible functions

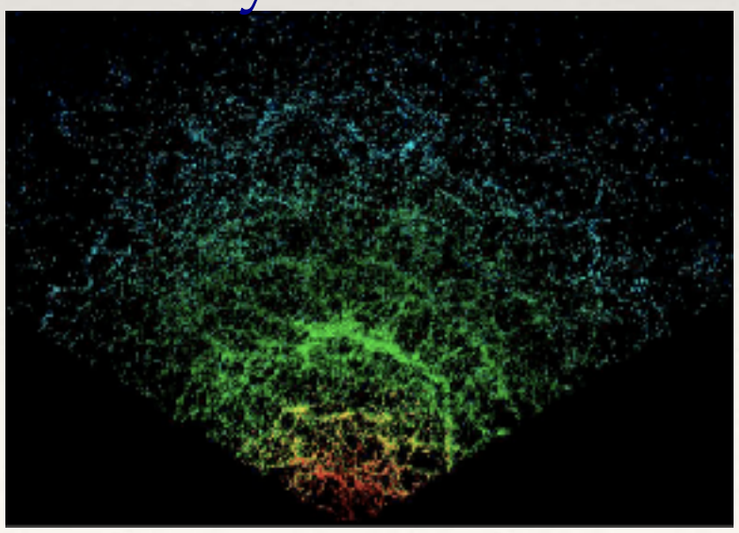


Simulated density field



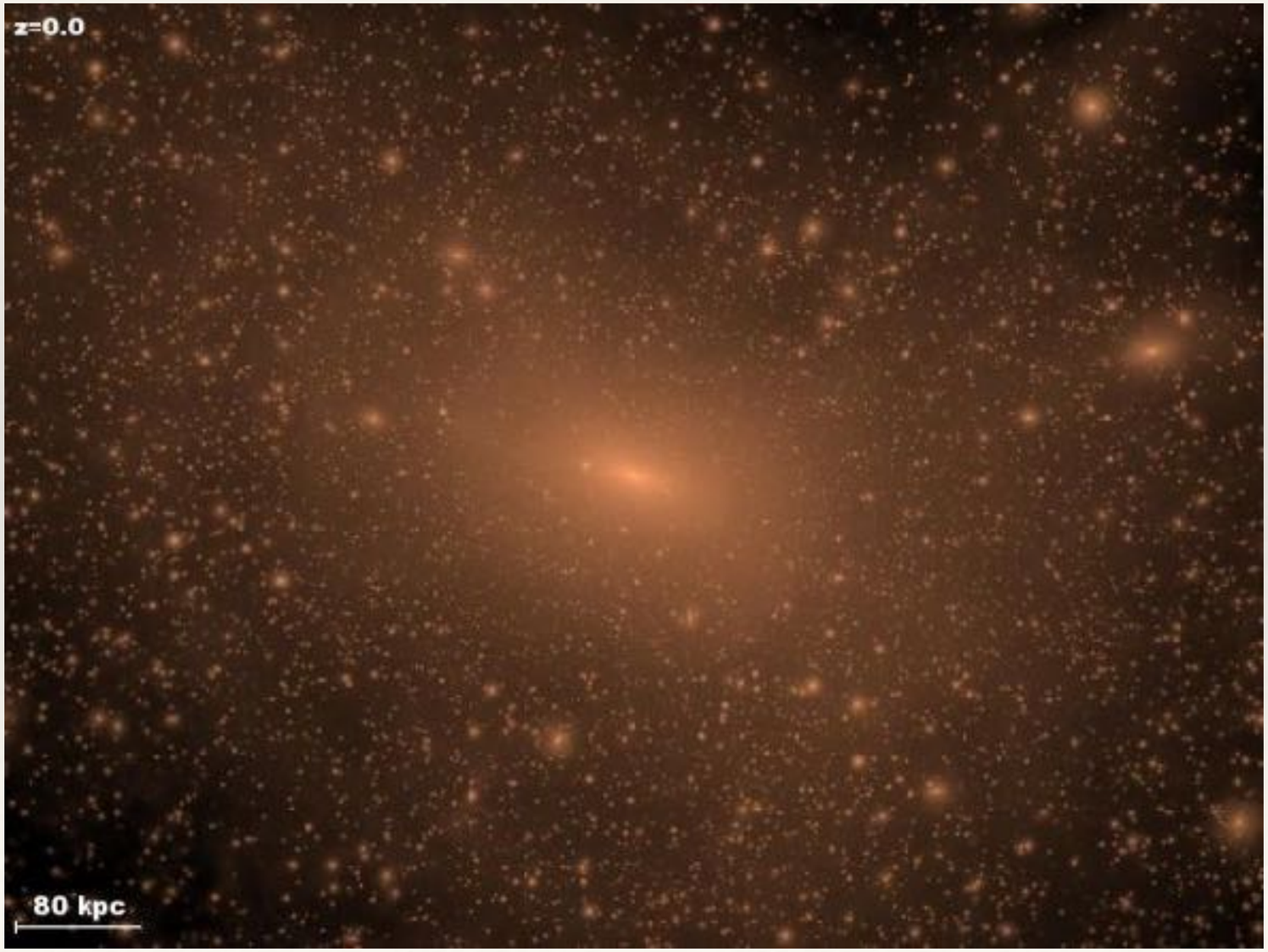


Galaxy distribution



Simplifying the Problem

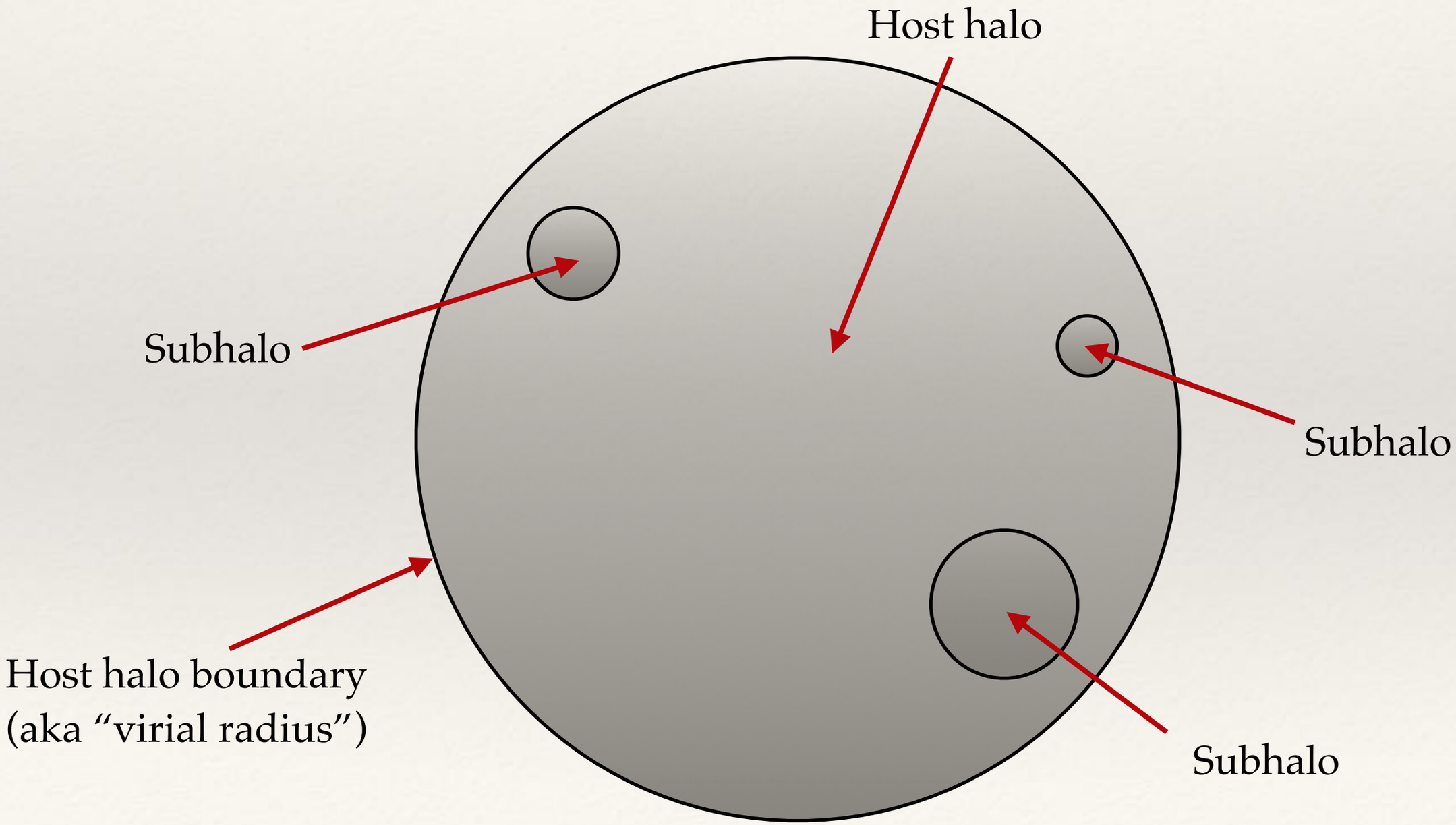
Dark Matter Halos:
Fundamental building blocks of large-scale structure



e.g. White & Rees 78

Dark Matter Halos

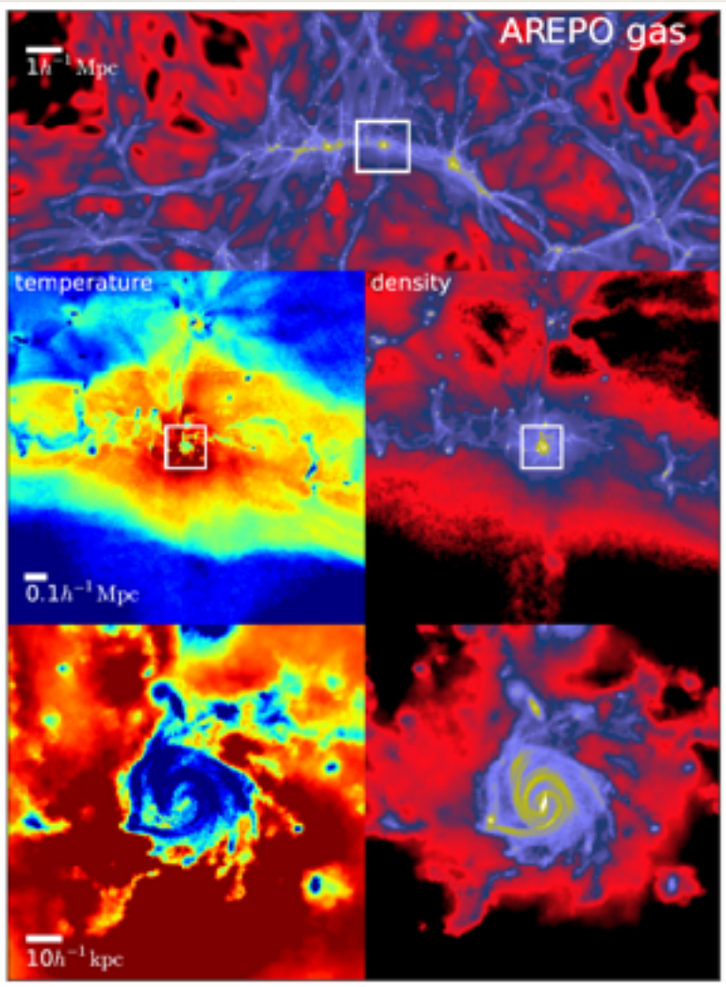
Host halos and subhalos



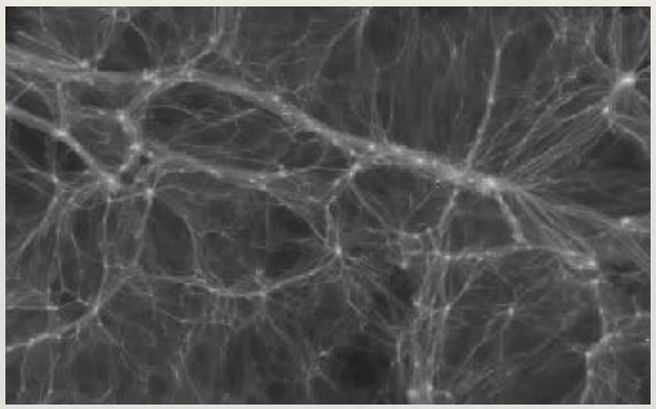
Coarse Grained Models

Three complementary approaches

Hydro



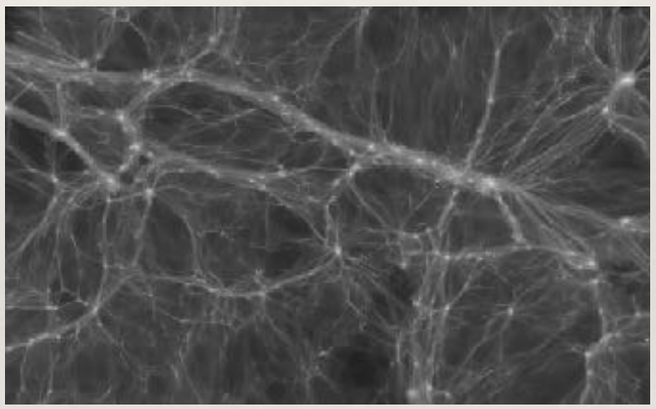
Semi-analytic model



+

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

Empirical model



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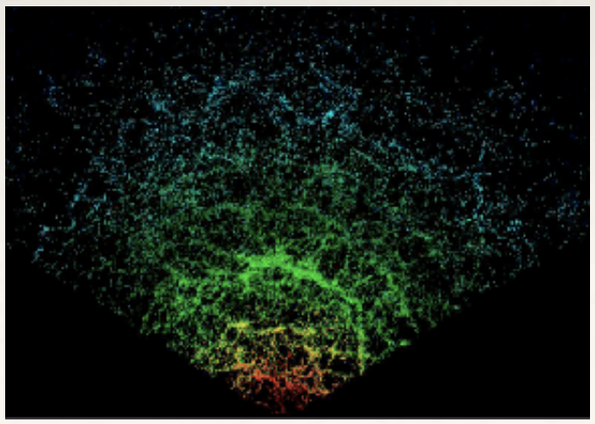
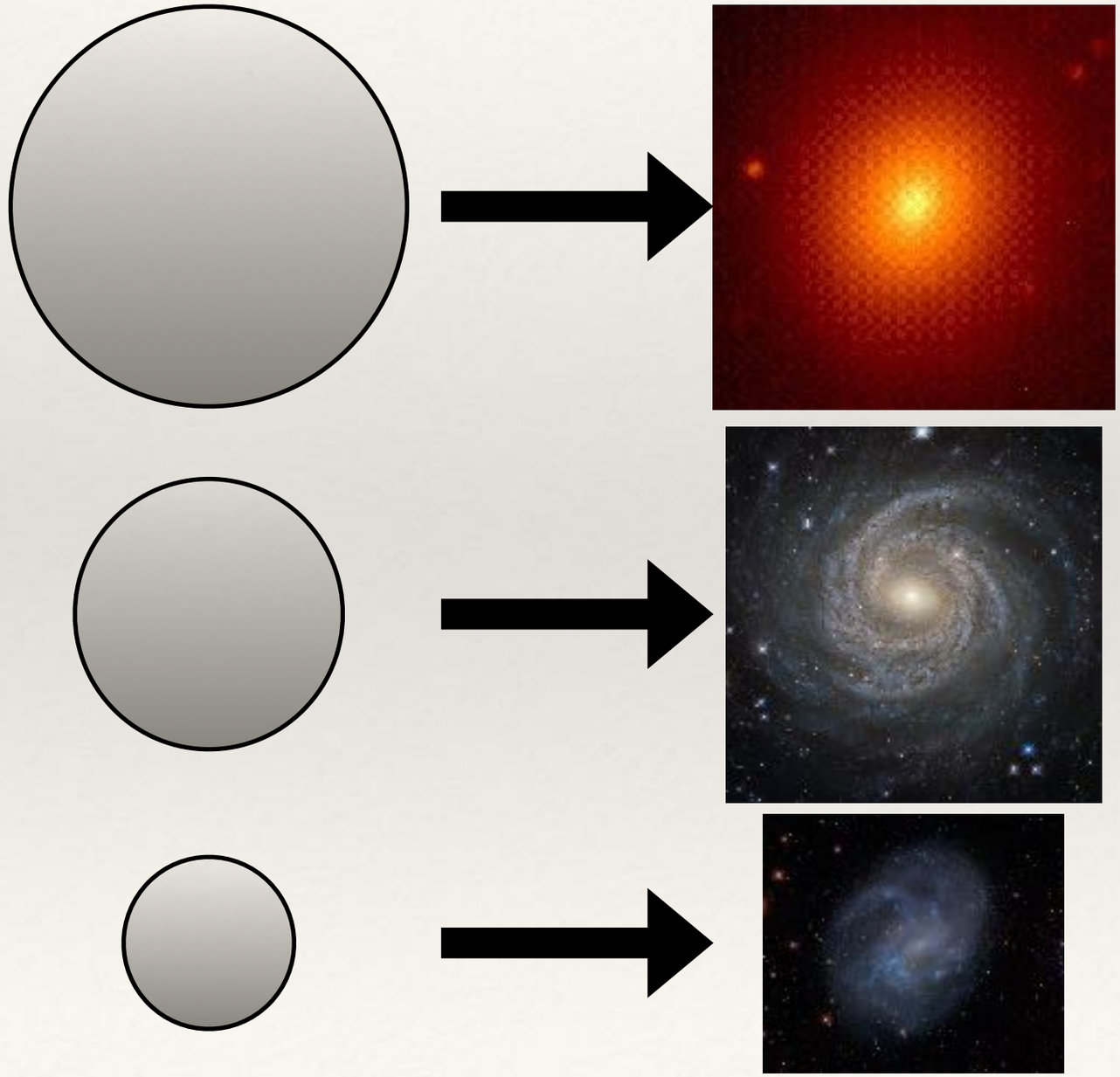


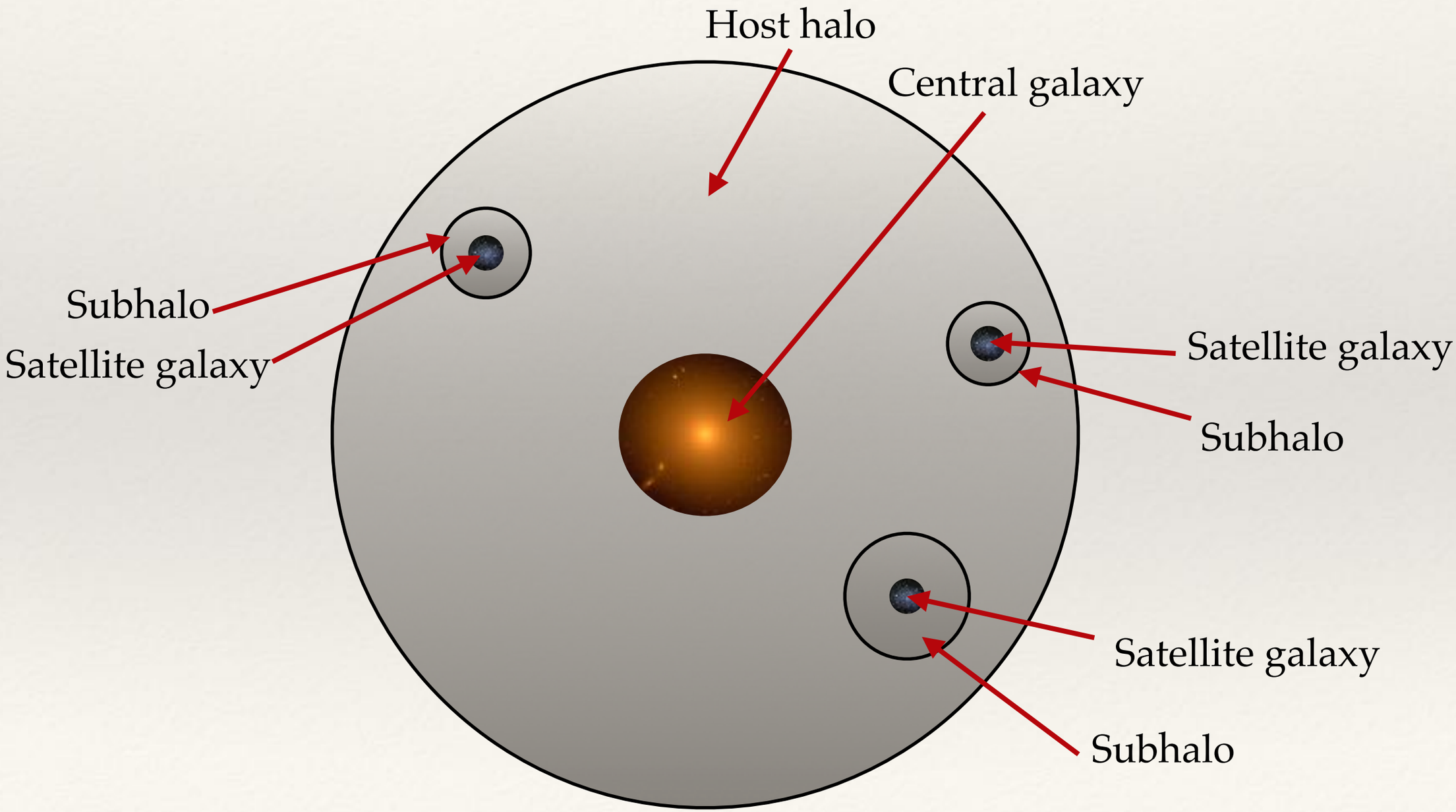
Mapping Simulated to Real Quantities

Basic Approach: Determine map from (sub)halos —> galaxies



Building a Galaxy–Halo Model

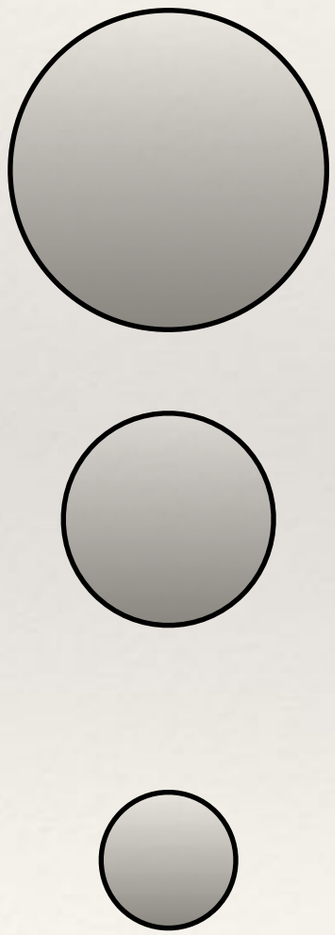
Simple abundance matching ansatz



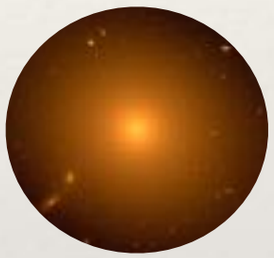
Building a Galaxy–Halo Model

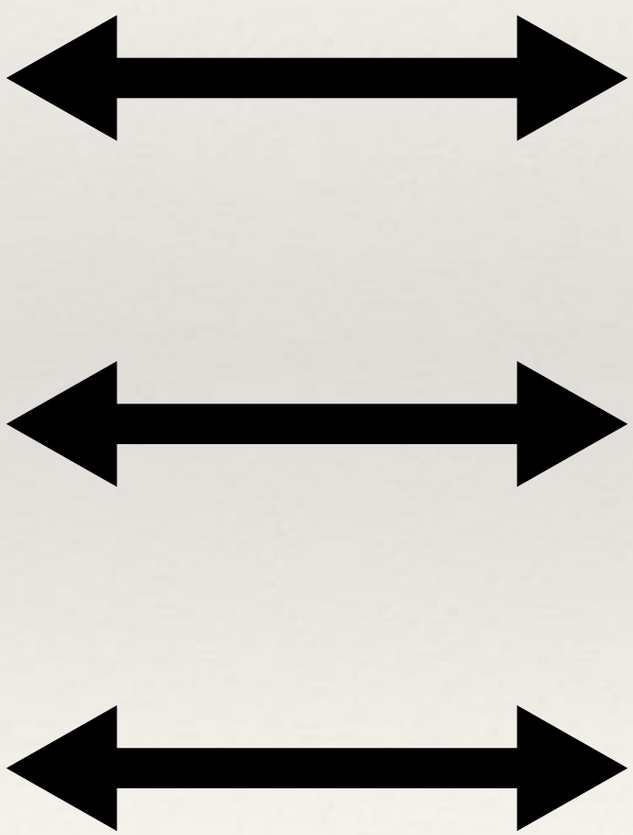
Simple abundance matching ansatz

Bigger (sub)halos



Bigger galaxies



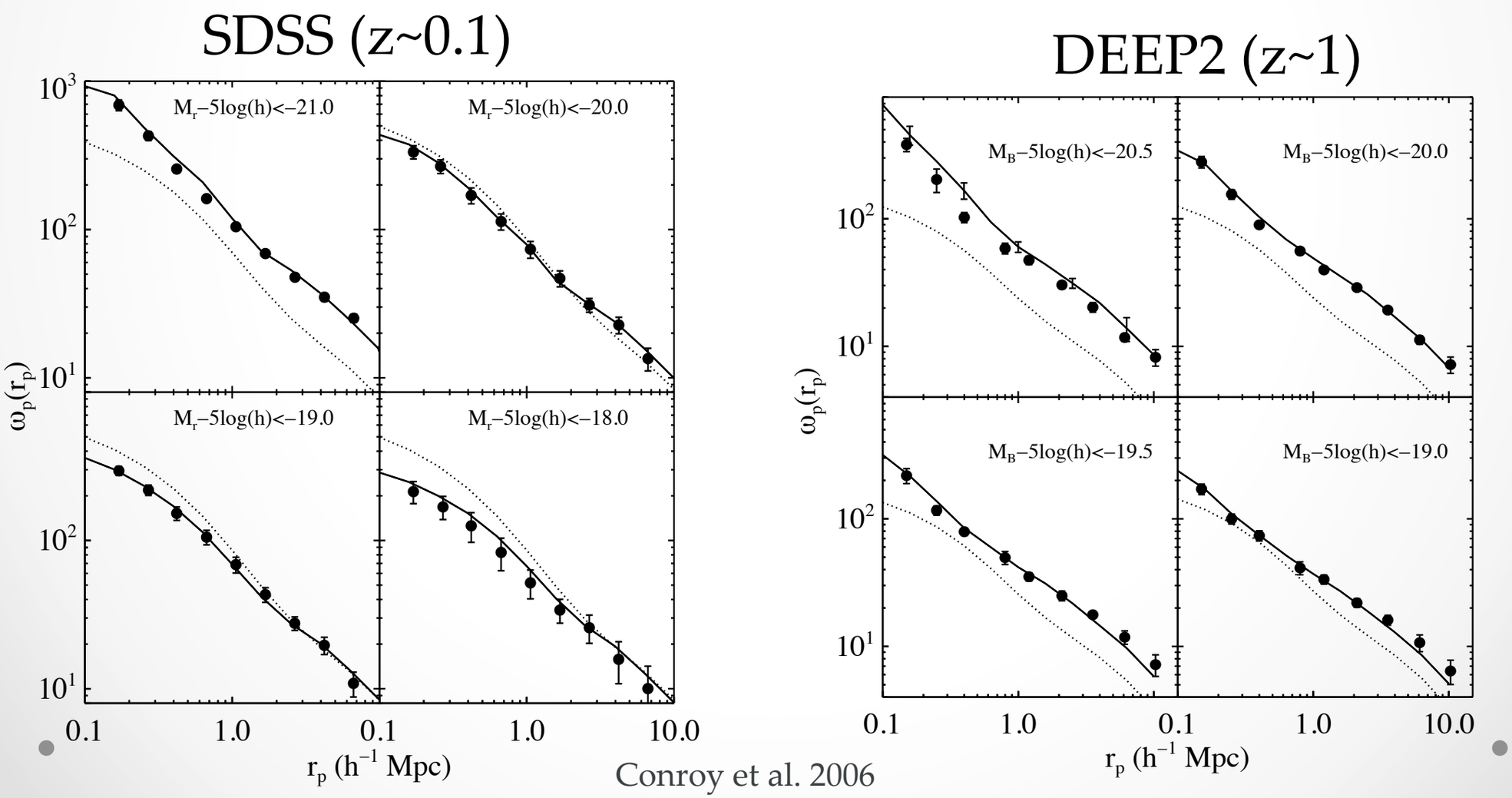


Smaller (sub)halos

Smaller galaxies

Simple Abundance Matching

Quantitative level of success is (should be) startling!

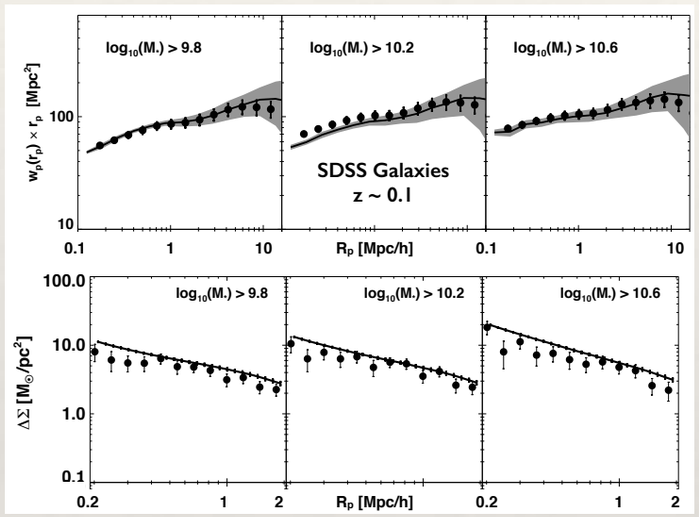


Conroy et al. 2006

Simple Abundance Matching

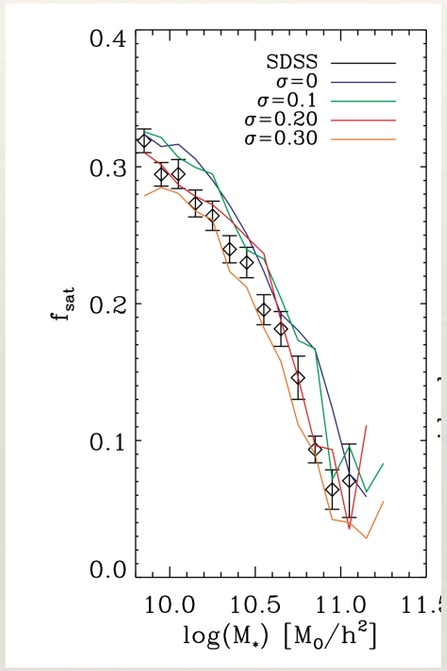
Large-scale structure success is diverse

galaxy-galaxy lensing



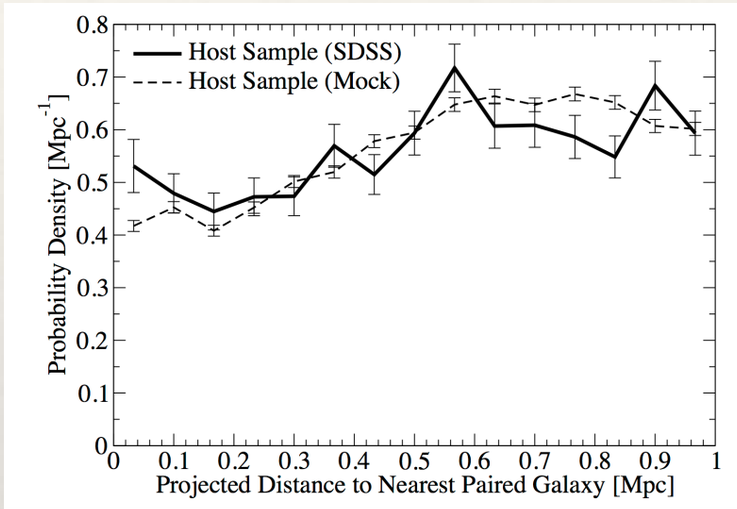
Hearin+14

satellite fractions



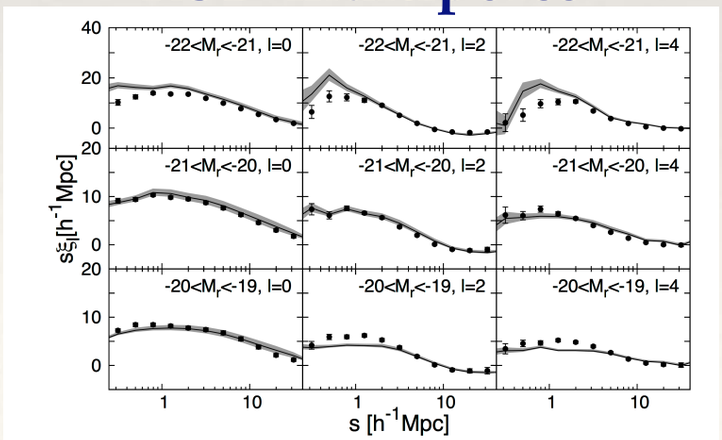
Reddick+13

Distribution of close pairs



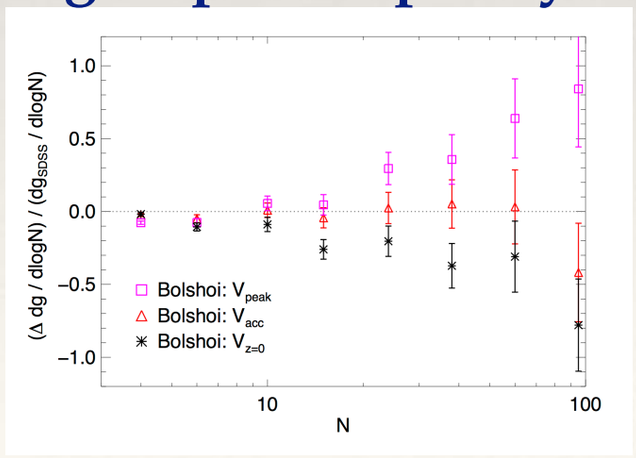
Behroozi+15

RSD multipoles



Yamamoto+15

group multiplicity

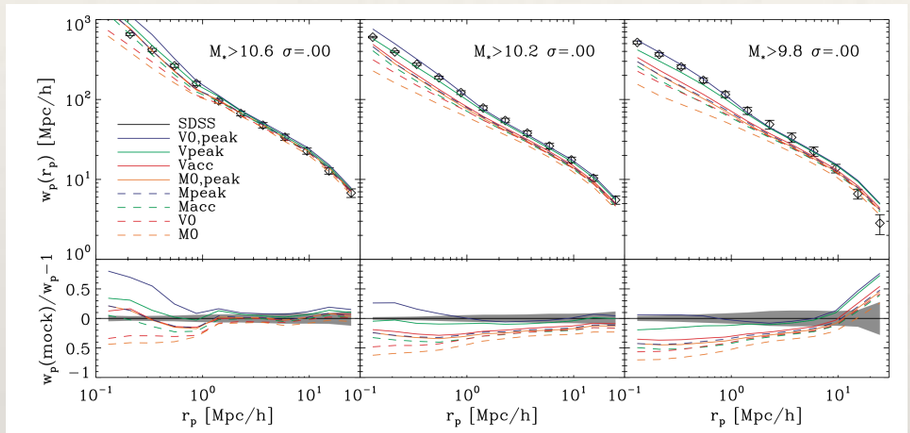


Hearin+12

Simple Abundance Matching

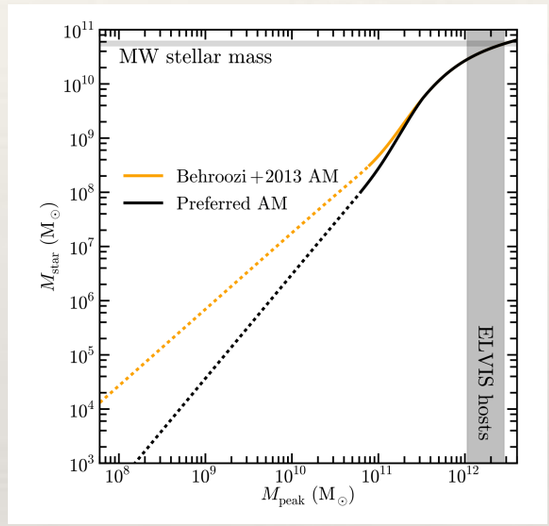
Formulation details significantly impact level of success

Which subhalo property?



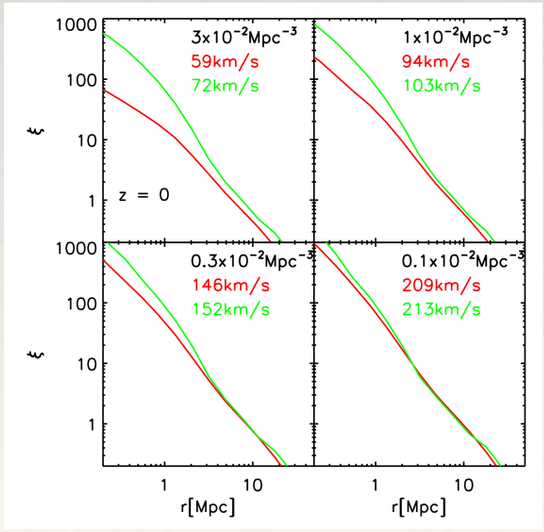
Reddick+12

How far down the mass function?



Garrison-Kimmel+13

Resolution requirements?



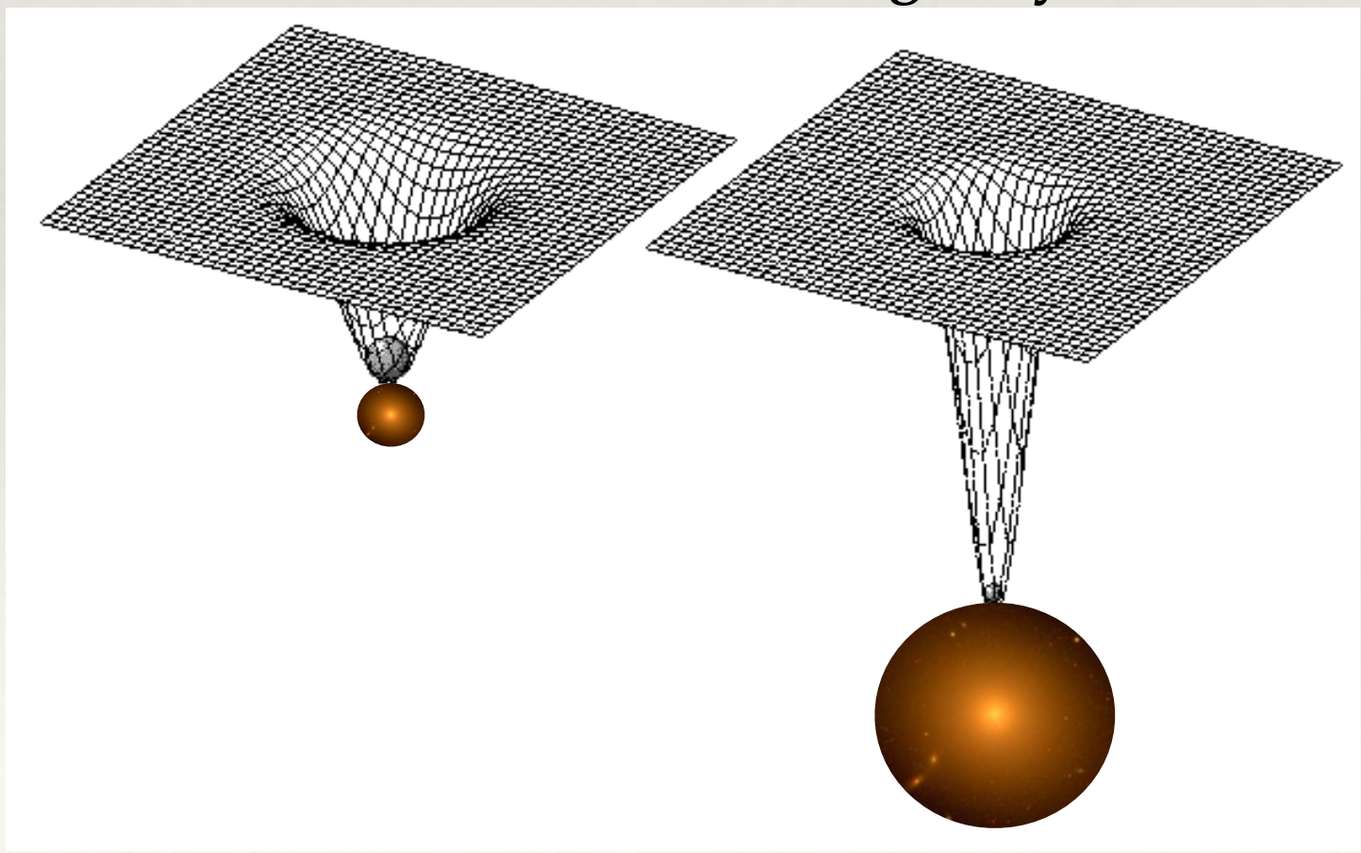
Guo & White 2013

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:

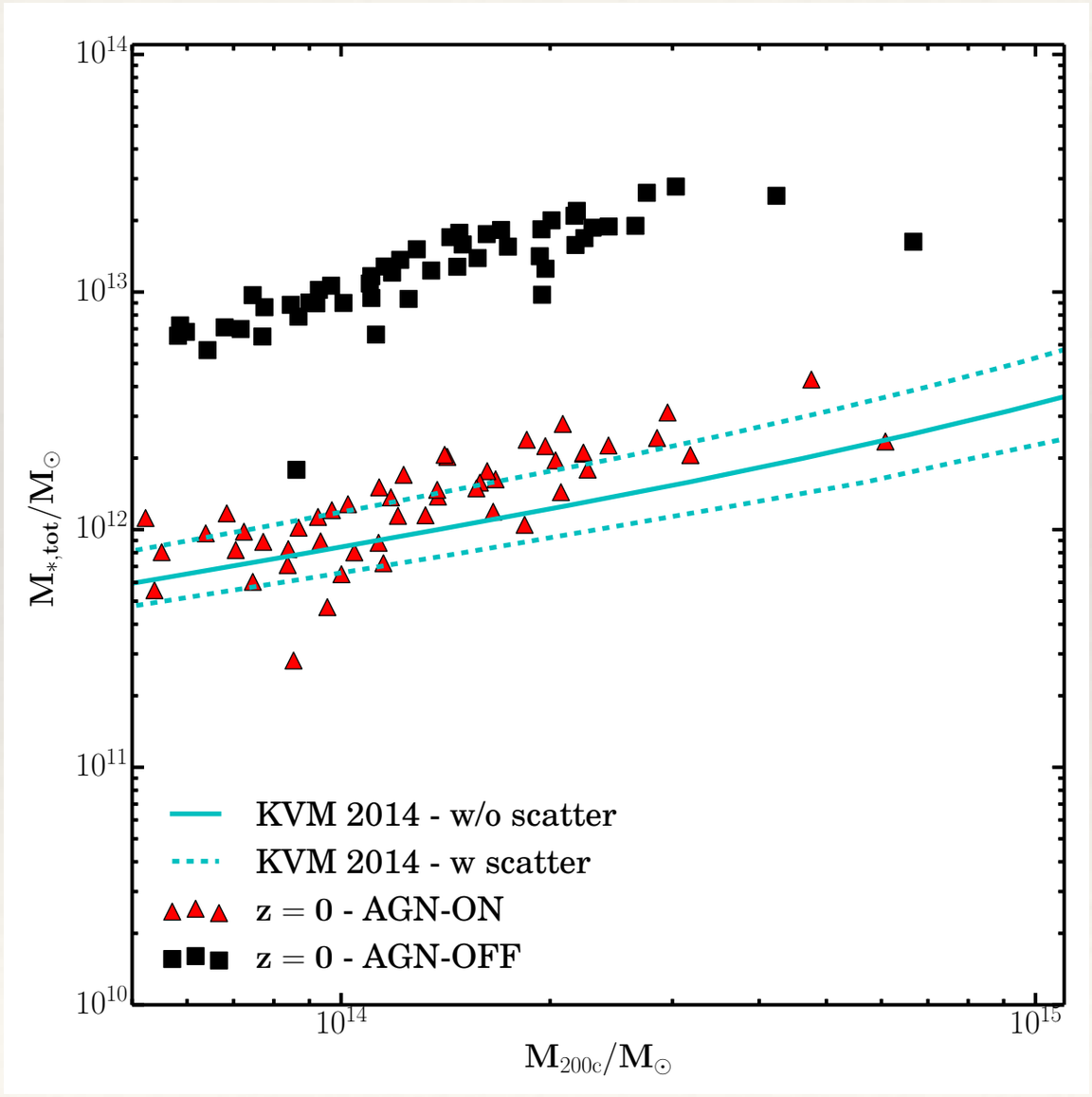
Depth of the gravitational potential well
is the coarse-grained halo property with
the dominant influence on galaxy mass



What do we learn from abundance matching?

Model parameters have universal translation

Provides boundary conditions for more fine-grained models



Martizzi+14

What do we learn from abundance matching?

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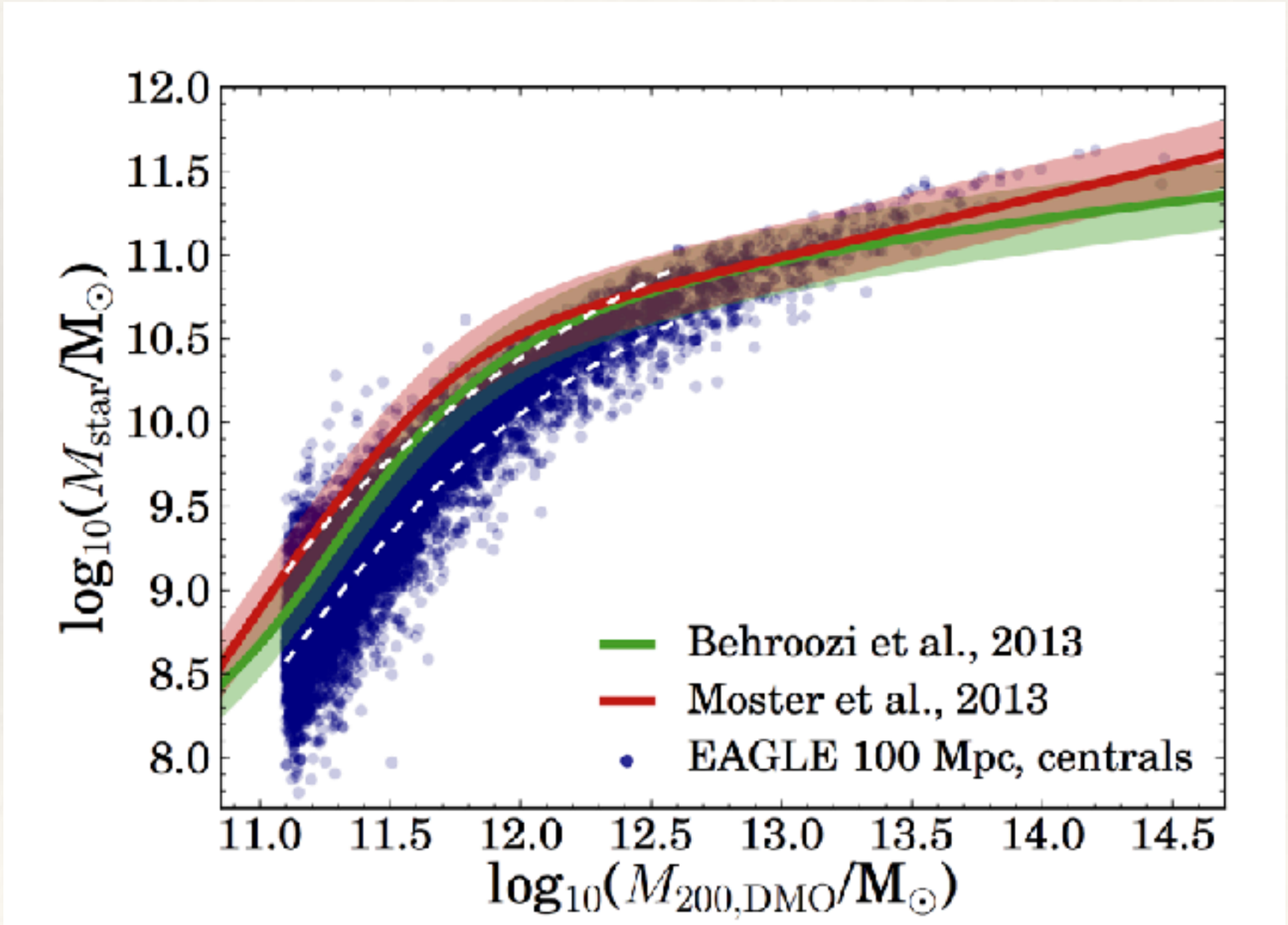
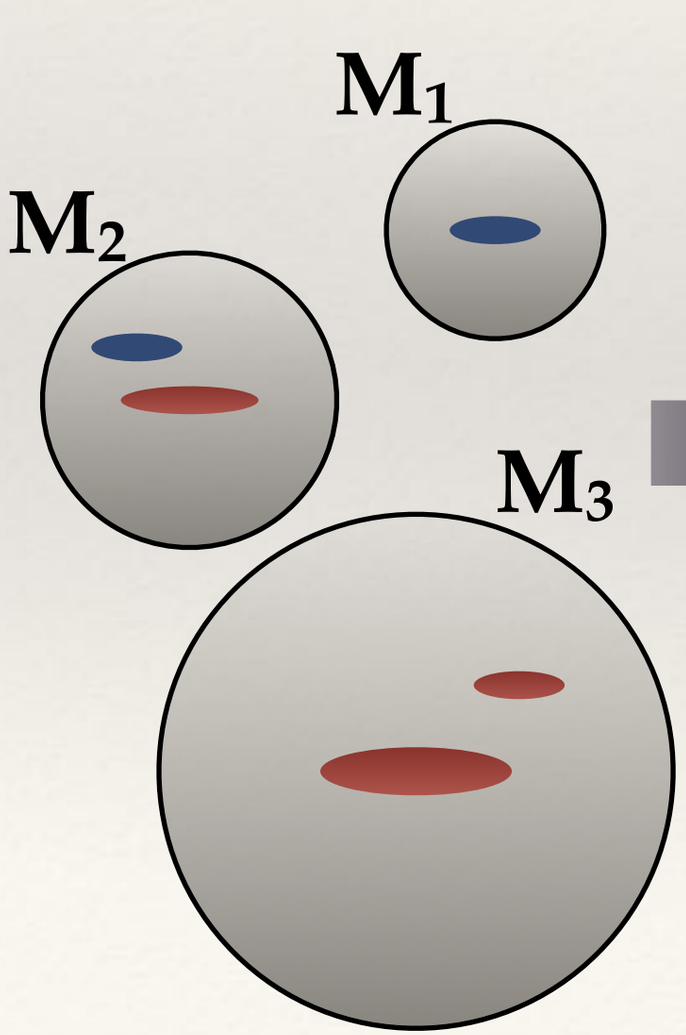


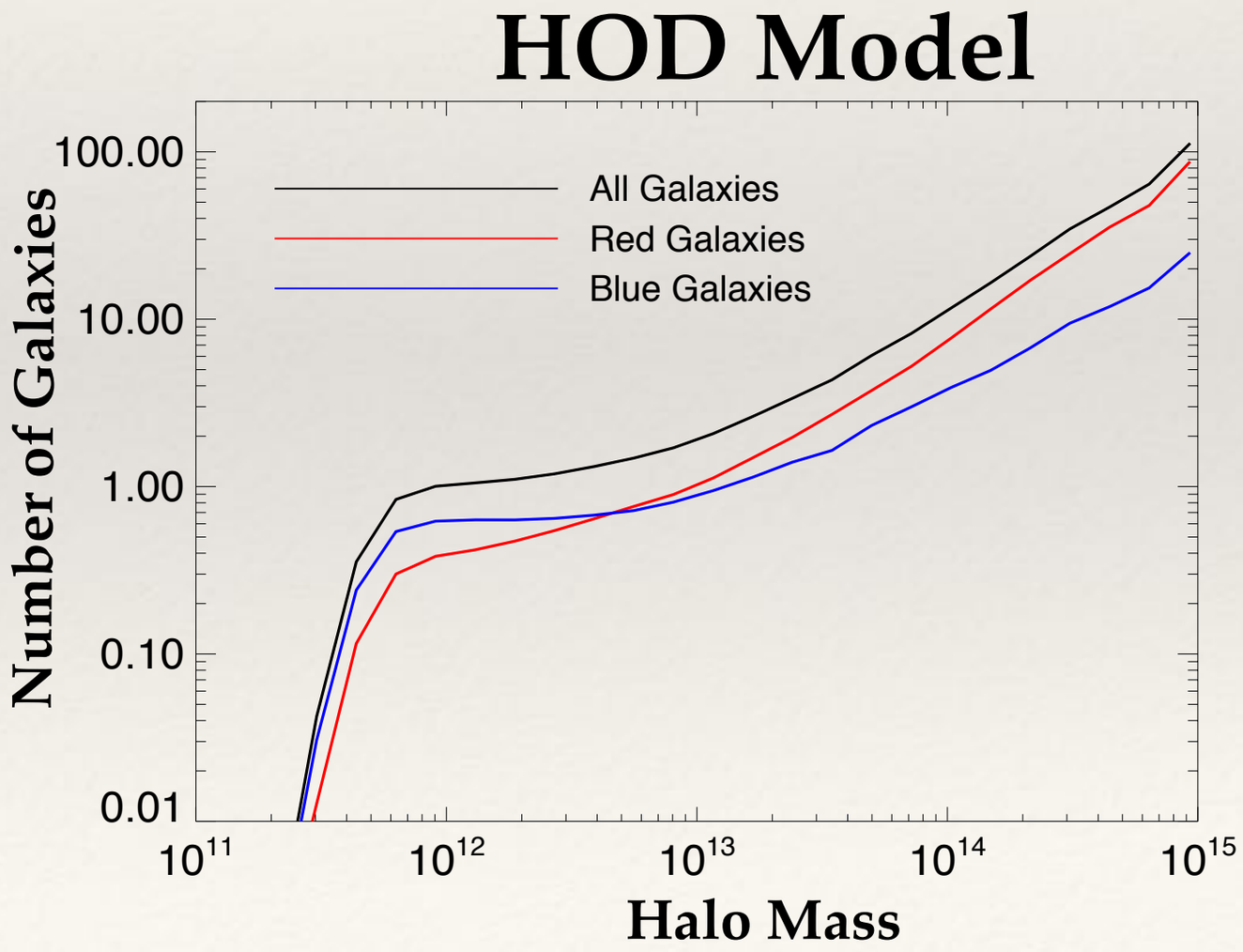
Matthee+16

Halo Occupation Distribution

Based on host halos only

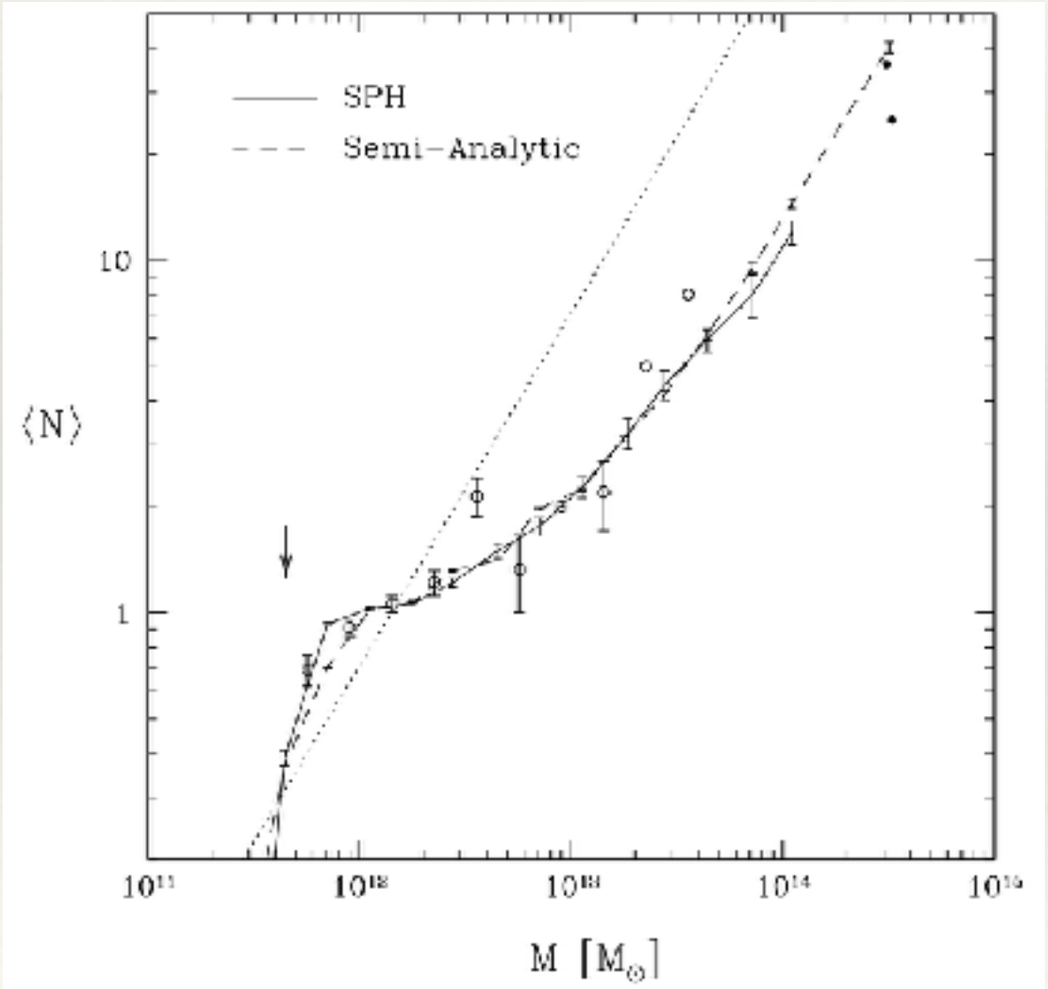
Parameterized form of $P(N_{cen} \mid M_{halo})$ & $P(N_{sat} \mid M_{halo})$



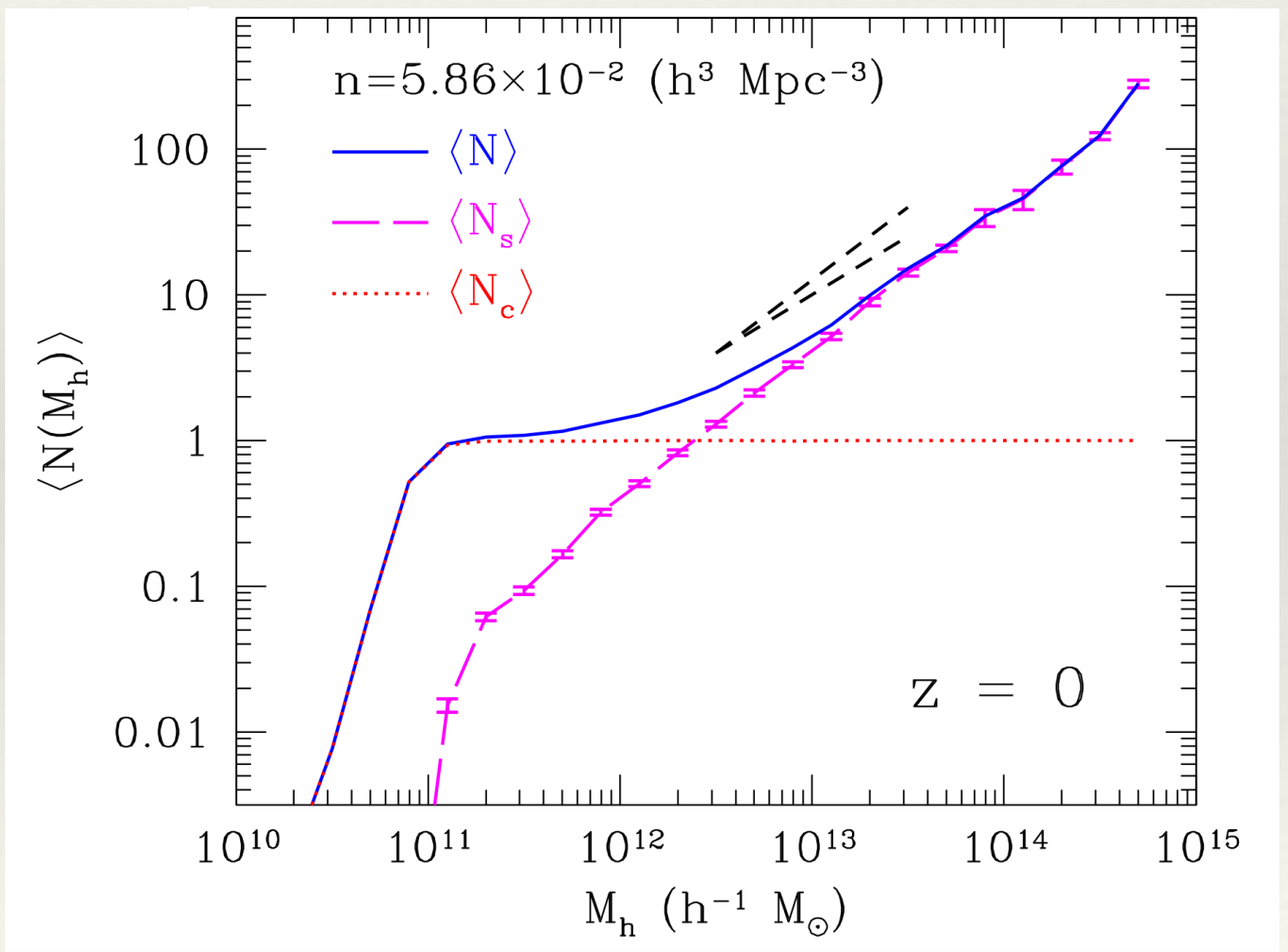


Halo Occupation Distribution

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



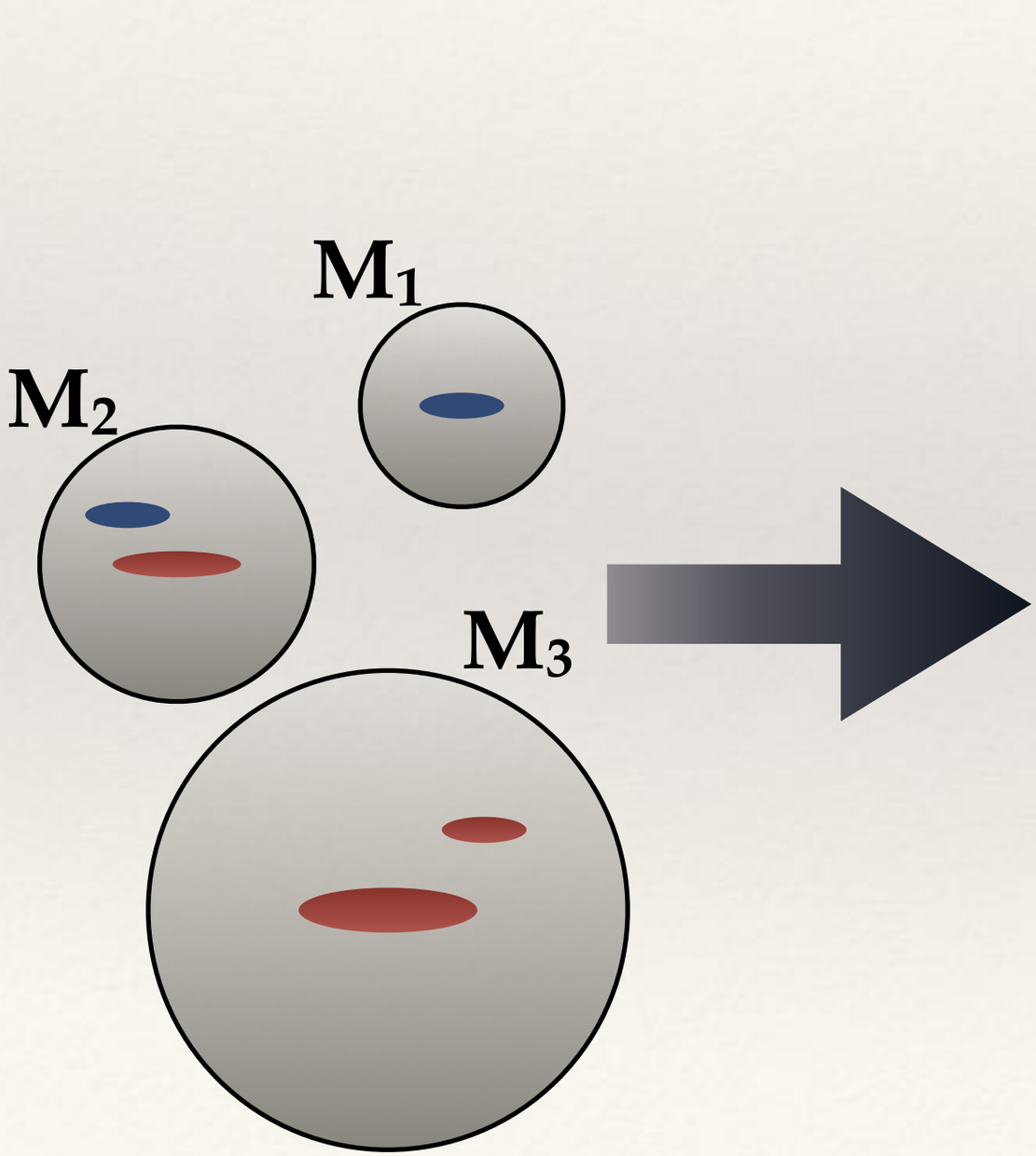
Berlind et al. (2003)

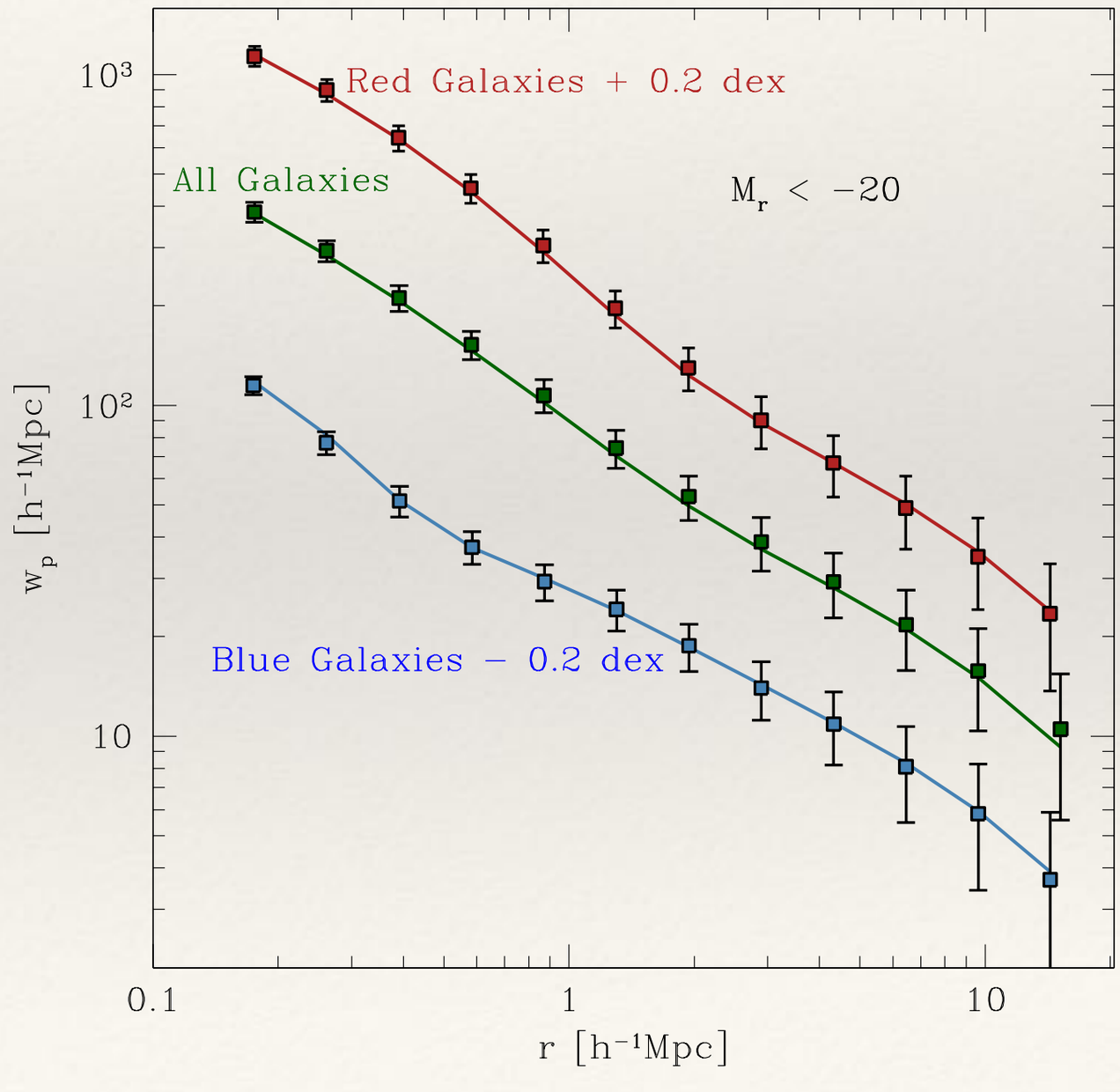


Kravtsov et al. (2004)

Halo Occupation Distribution

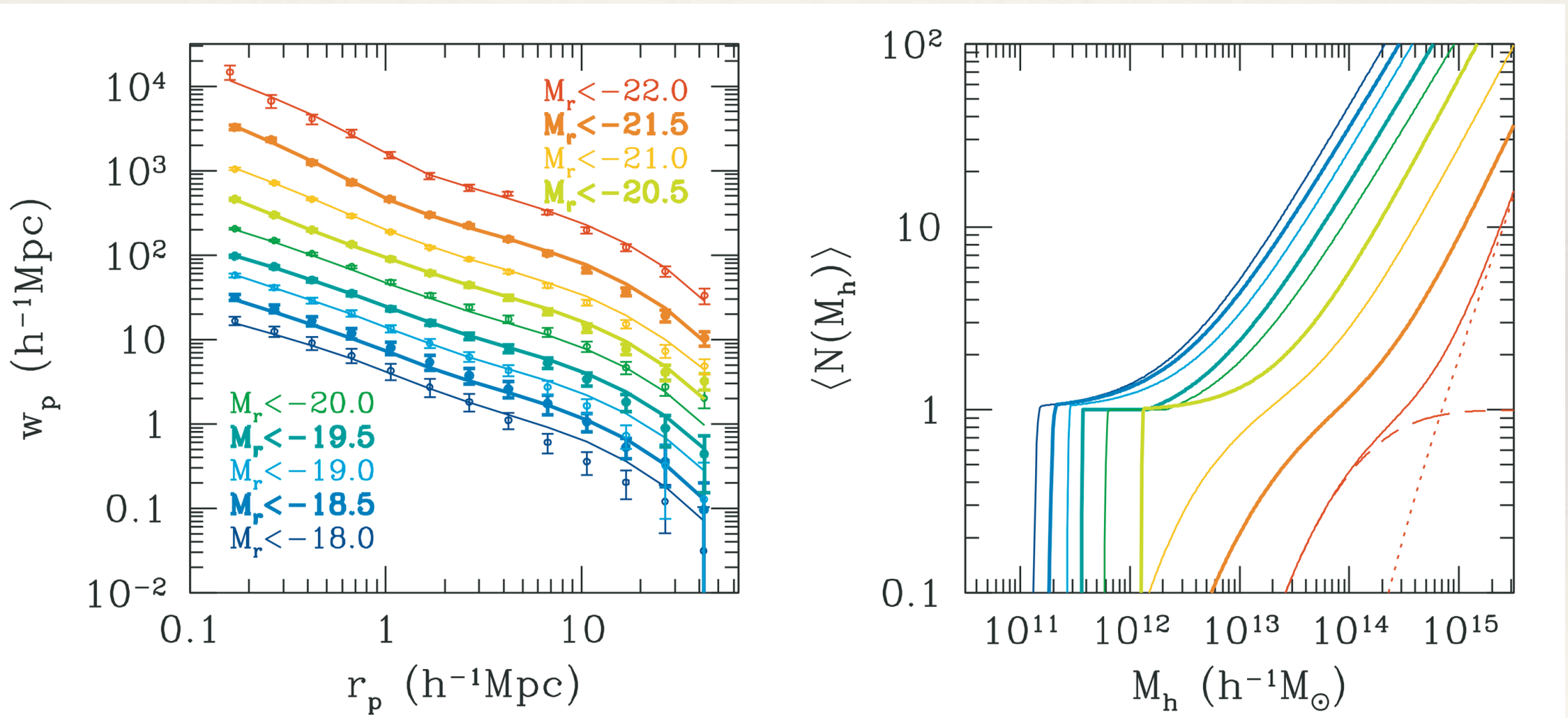
Occupation statistics ==> galaxy clustering





Halo Occupation Distribution

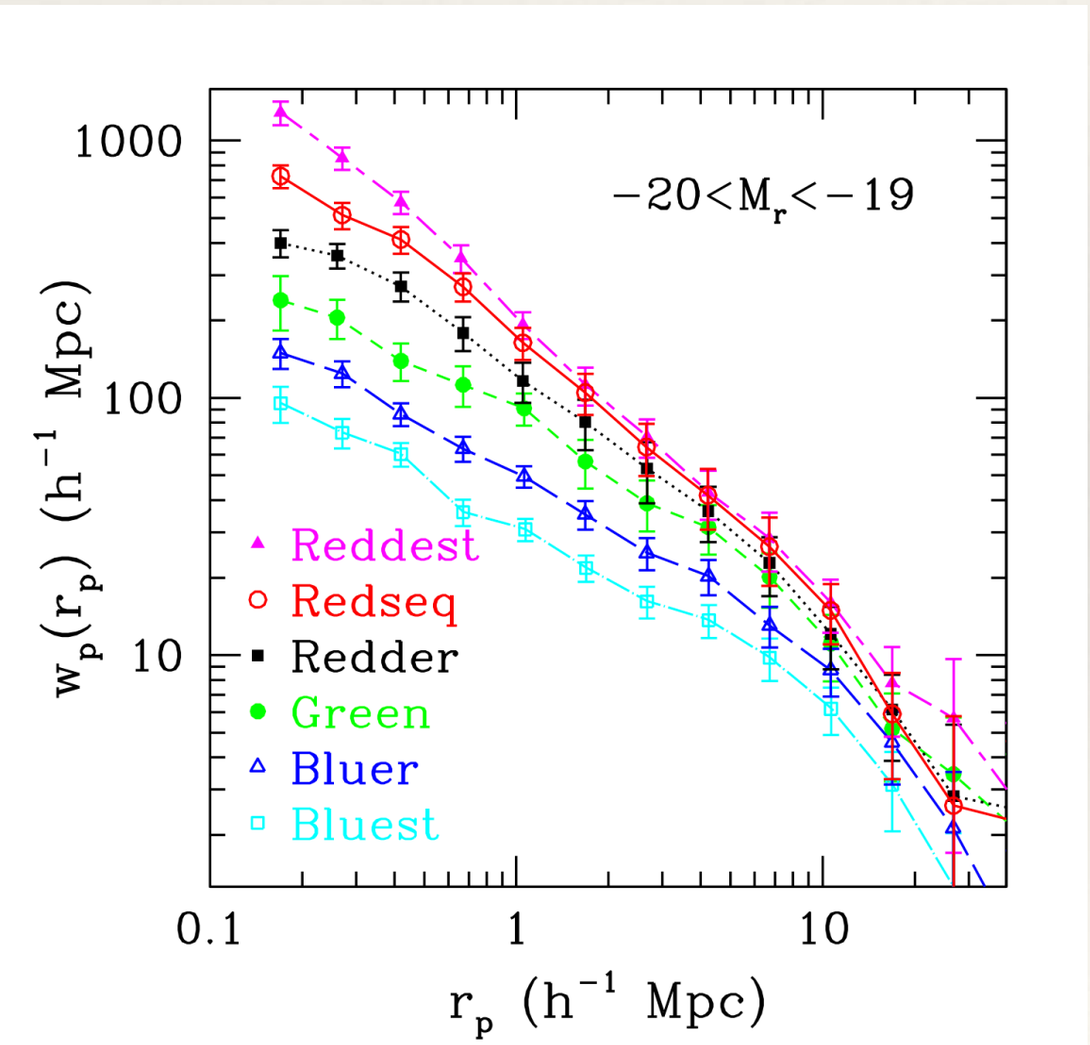
Successful fits to galaxy clustering, including dependence on M_r brightness



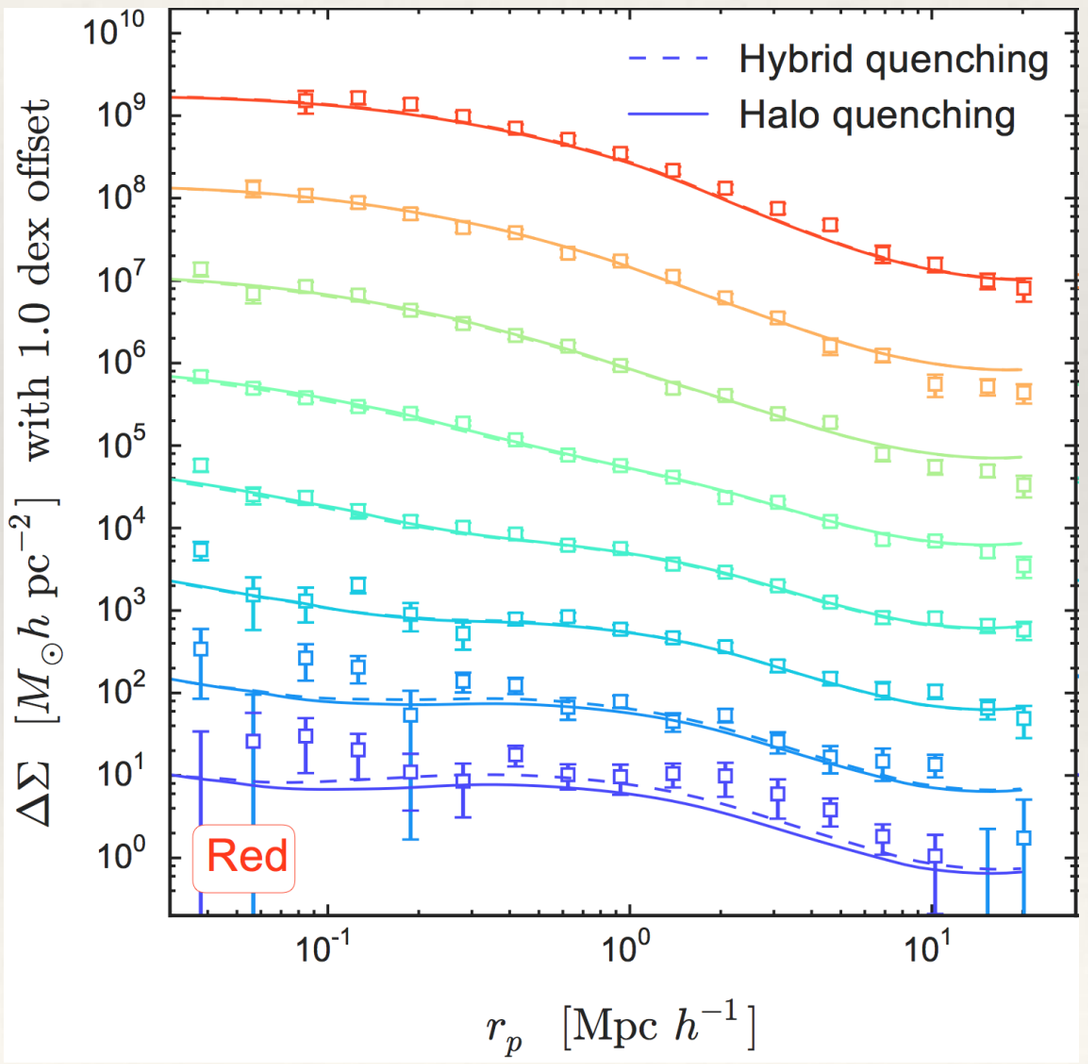
Zehavi+11

Halo Occupation Distribution

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



Zehavi+11

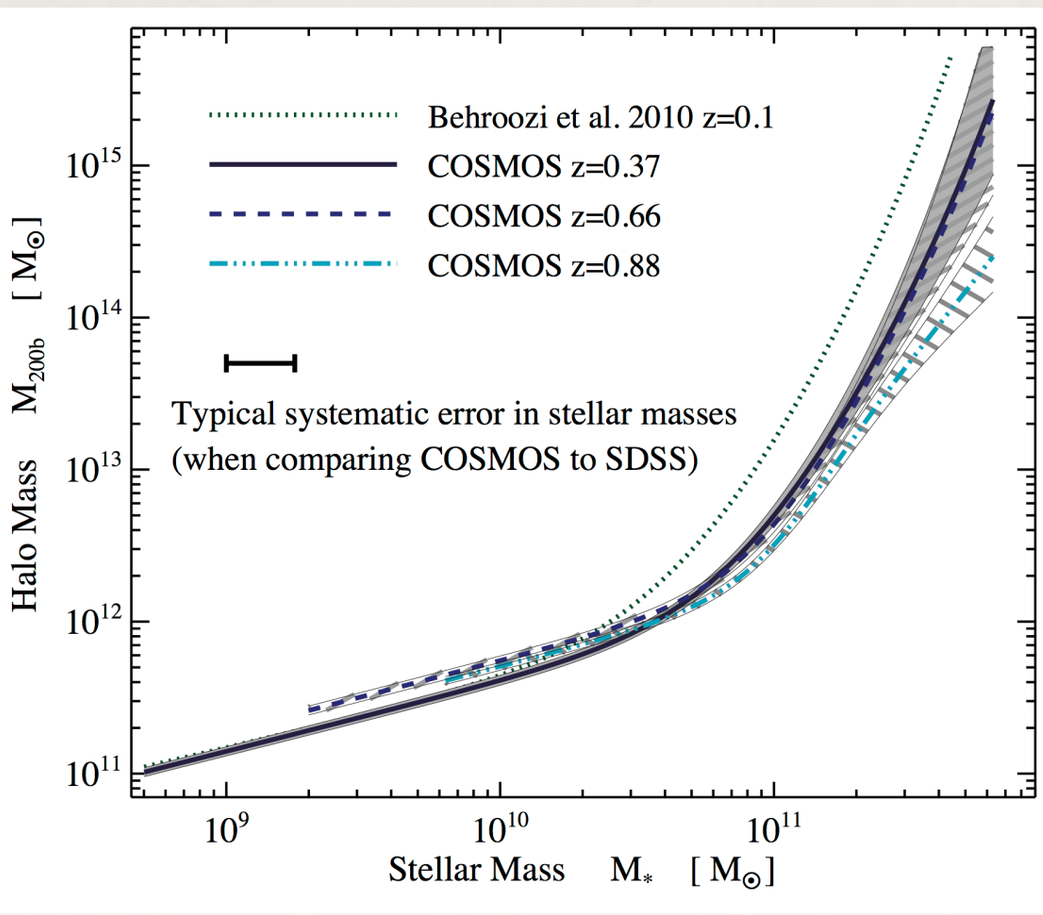


Zu & Mandelbaum (2016)

Halo Occupation Distribution

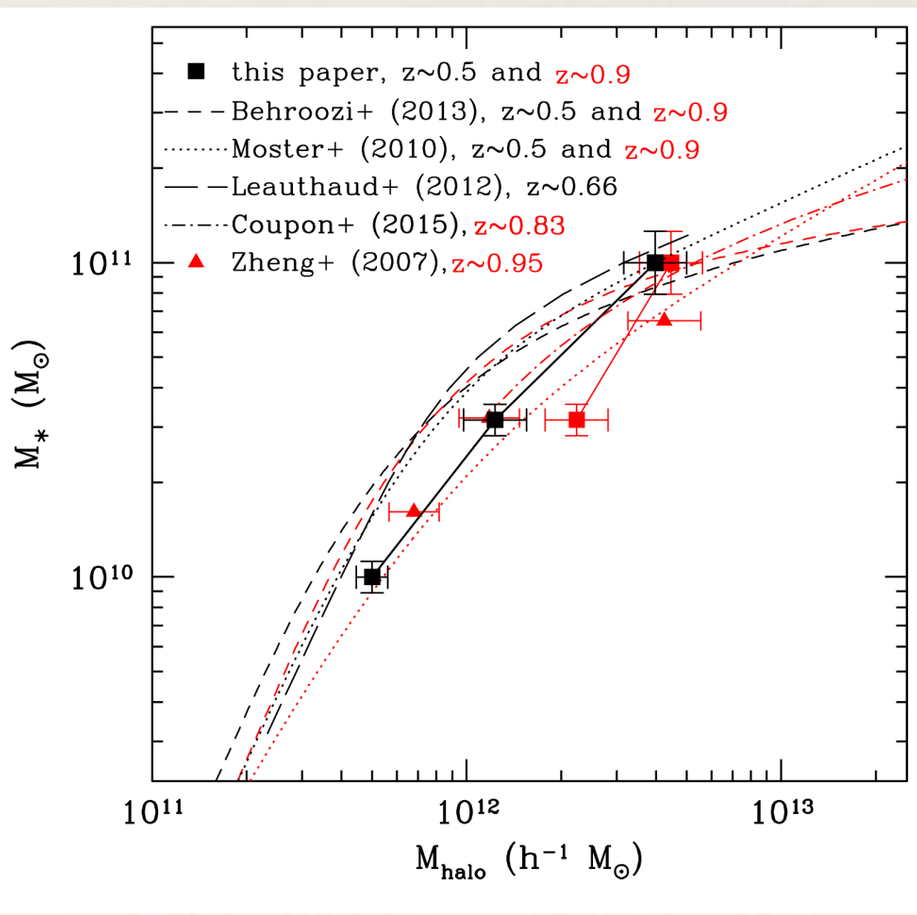
Successful fits to galaxy clustering,
including dependence on redshift

COSMOS



Leauthaud, Tinker et al. (2011)

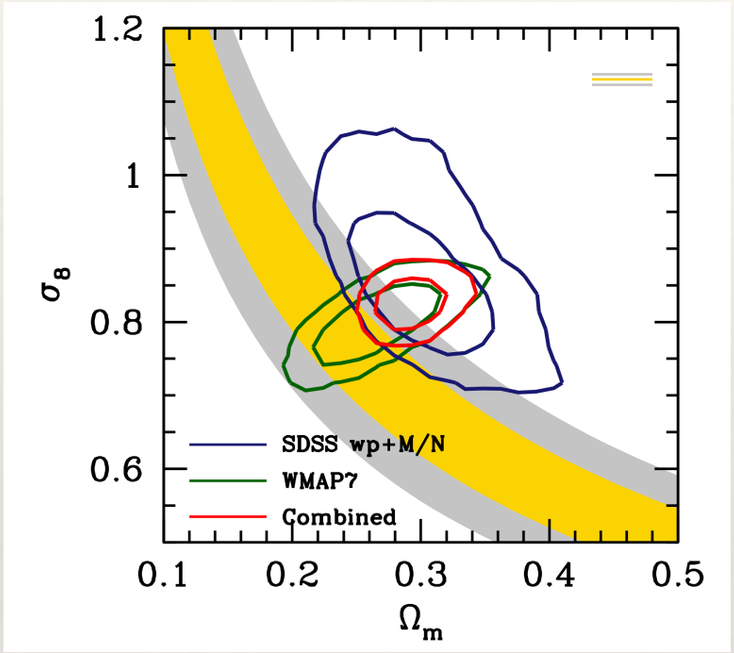
PRIMUS



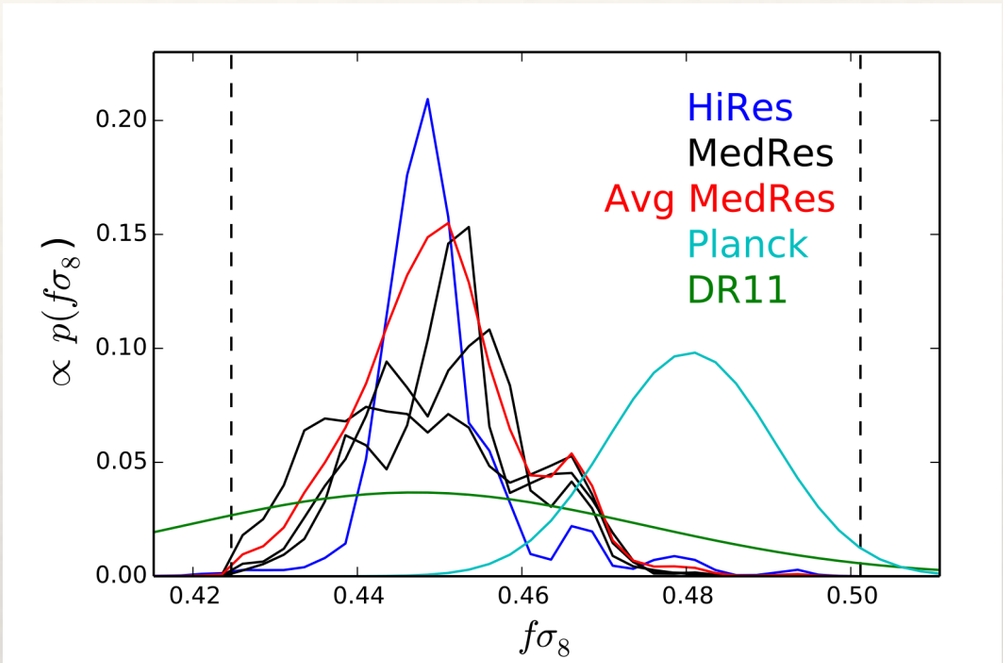
Skibba, Coil et al. (2015)

Halo Occupation Distribution

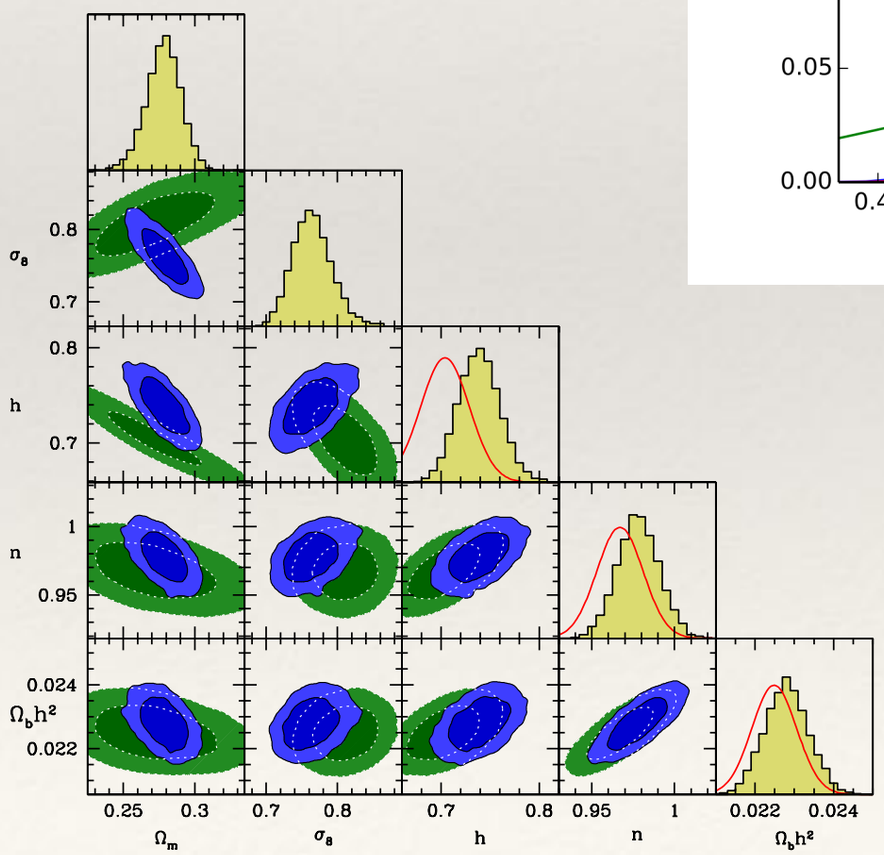
Cosmological parameter estimation



Tinker+11



Reid+14



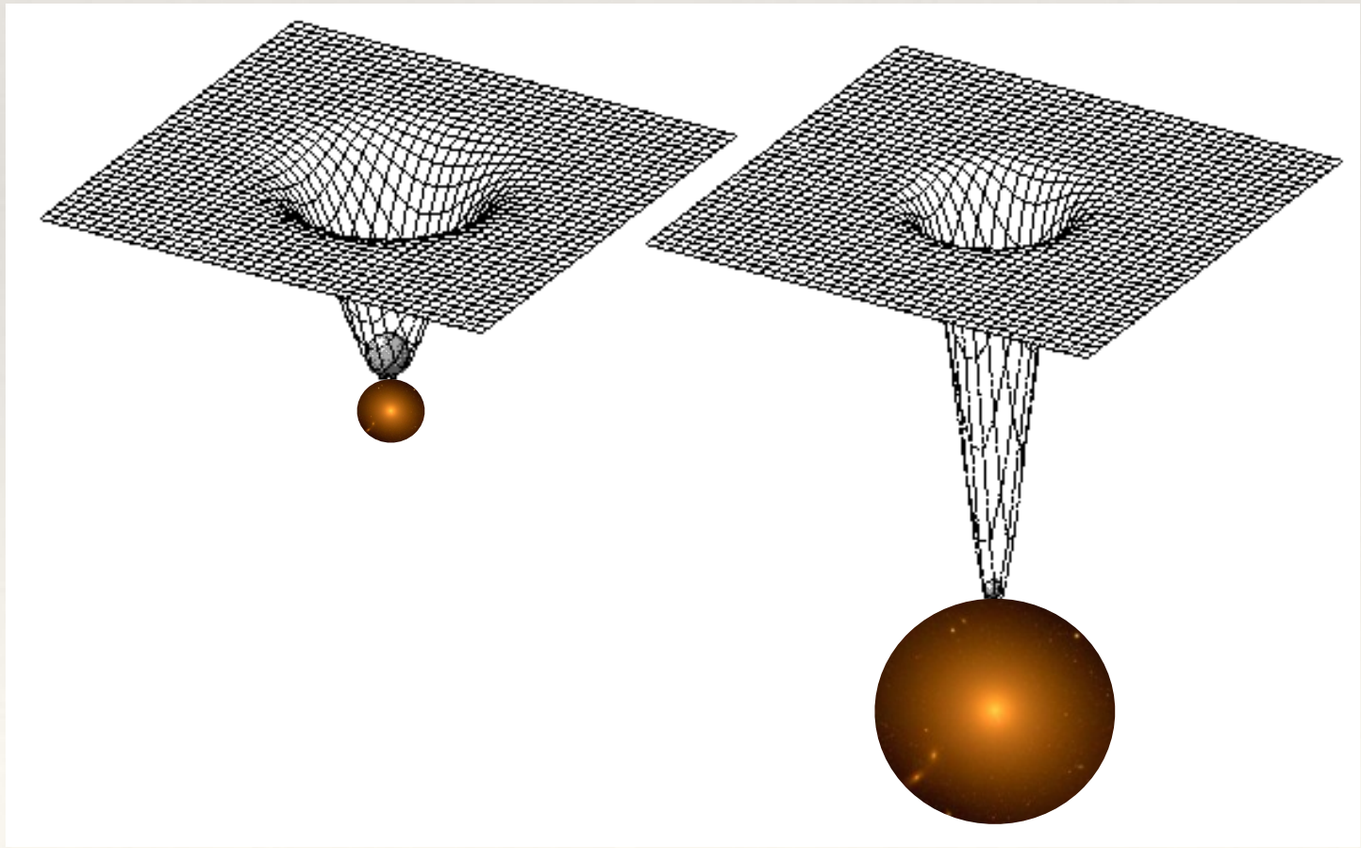
Cacciato+12

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

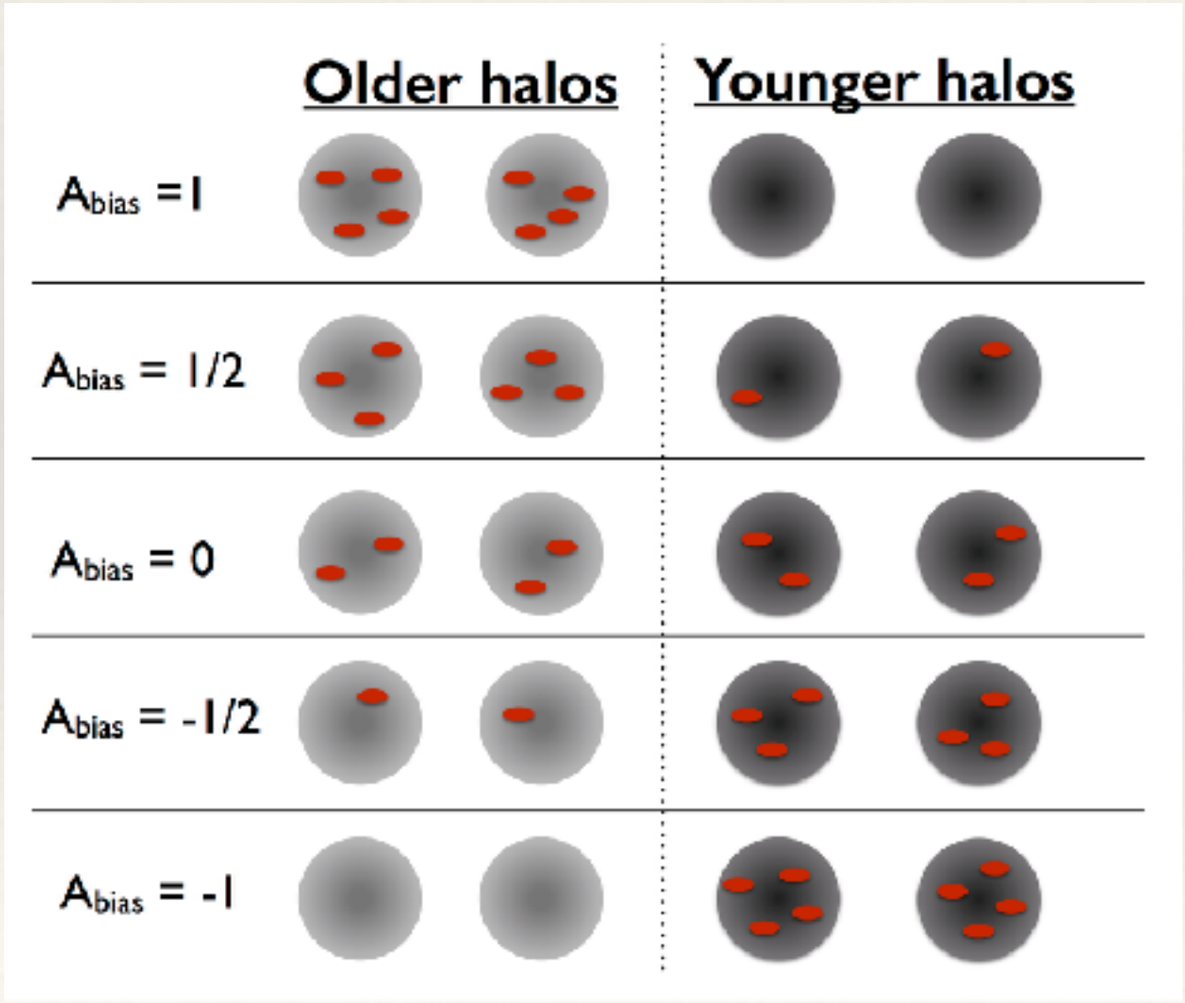
Basic lesson:

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

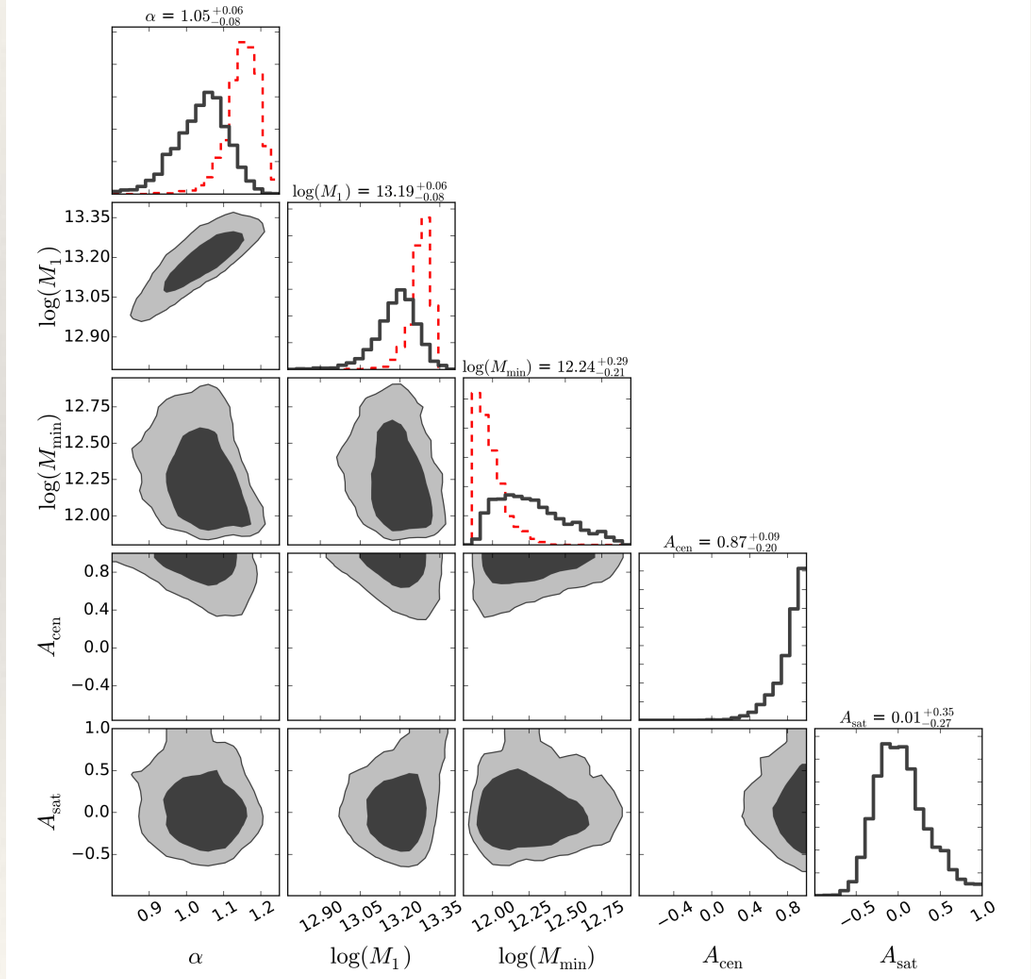


Halo Occupation Distribution

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



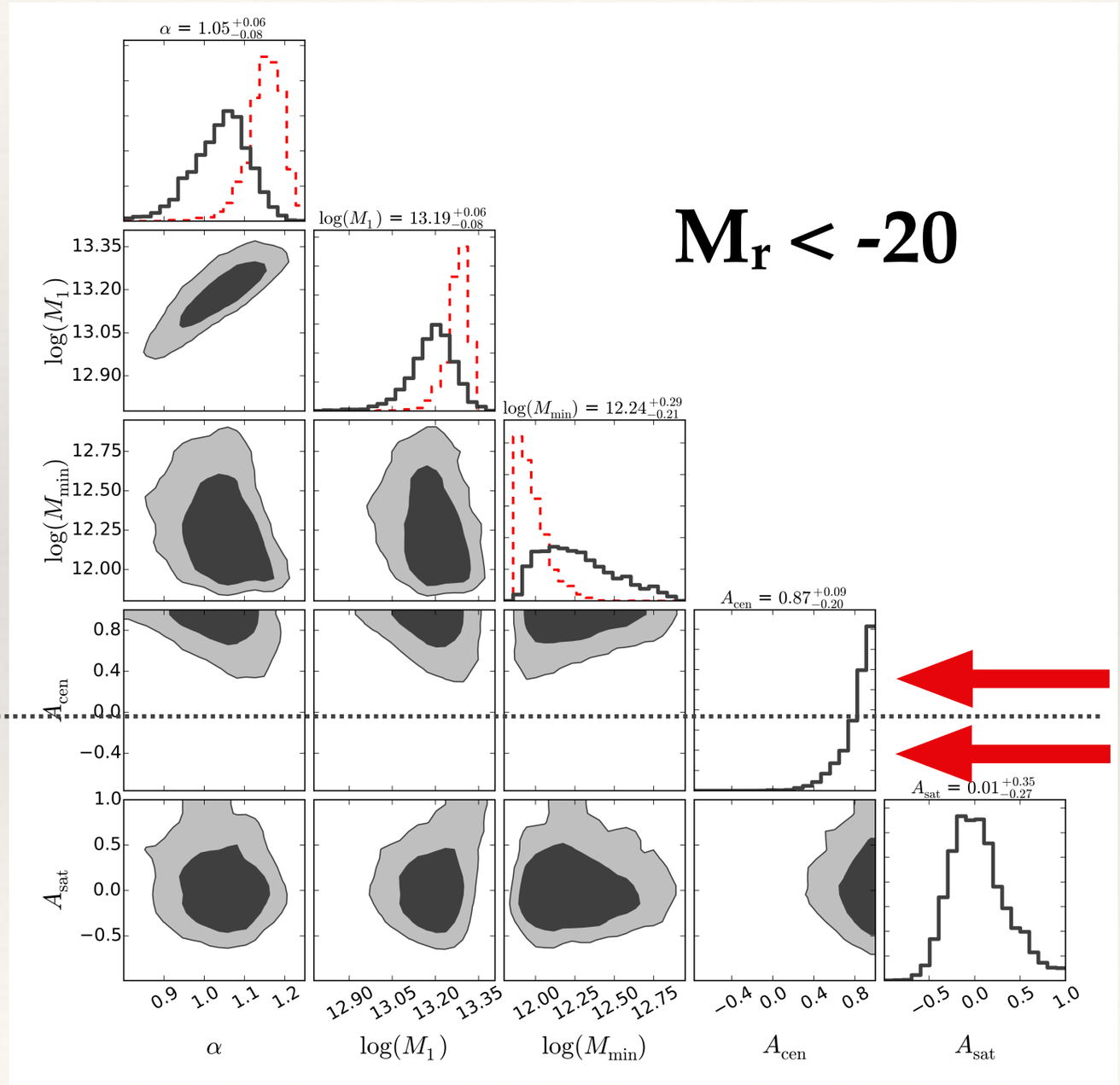
Hearin+15
(see Halotools for python implementation)



Zentner+16

Halo Occupation Distribution

Central assembly bias well-constrained away from zero



M_r < -20

Zero assembly bias

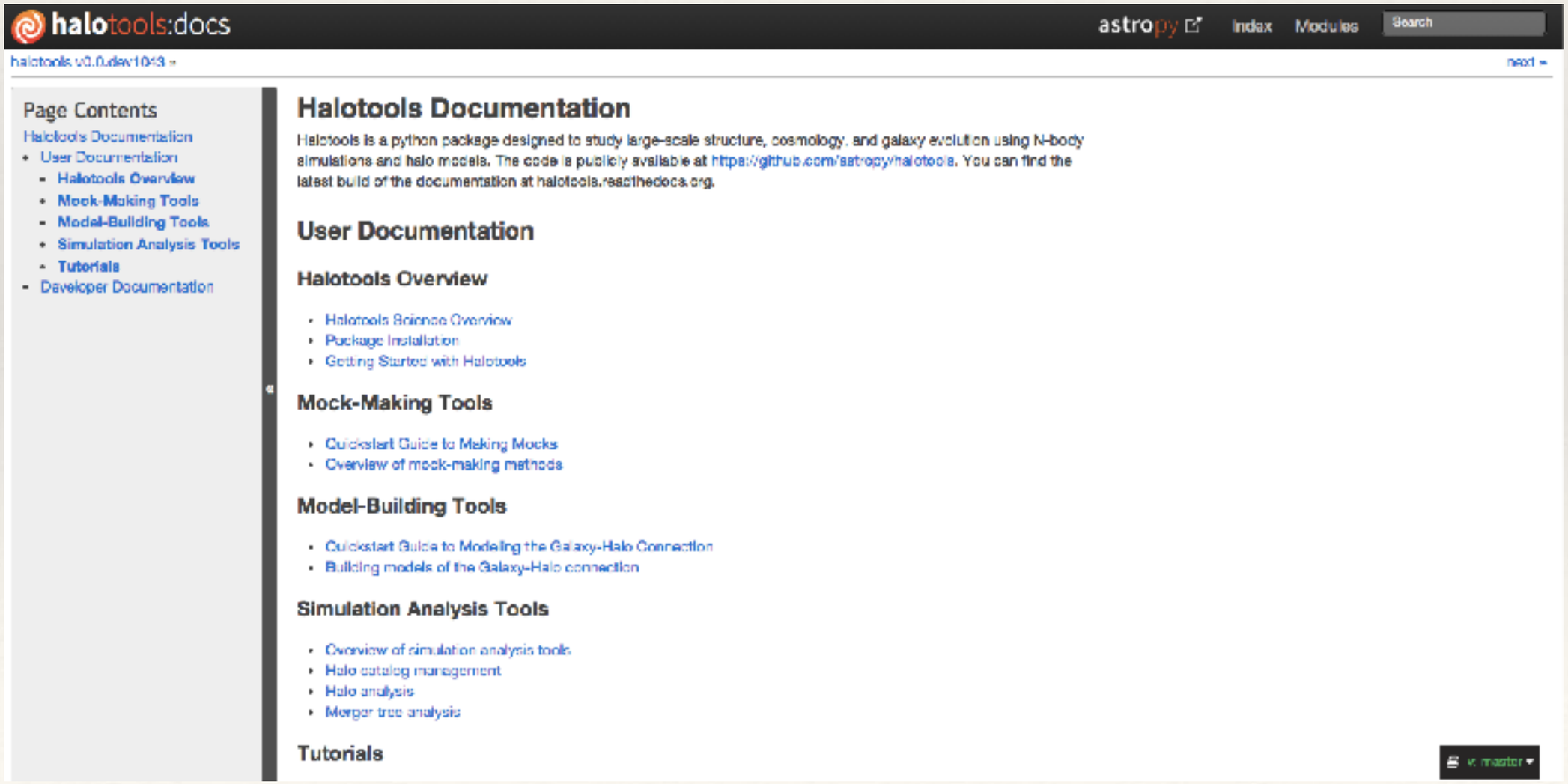
Central galaxy assembly bias strength parameter constraints

Zentner+16
See also Vakili & Hahn 2016

Halotools

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

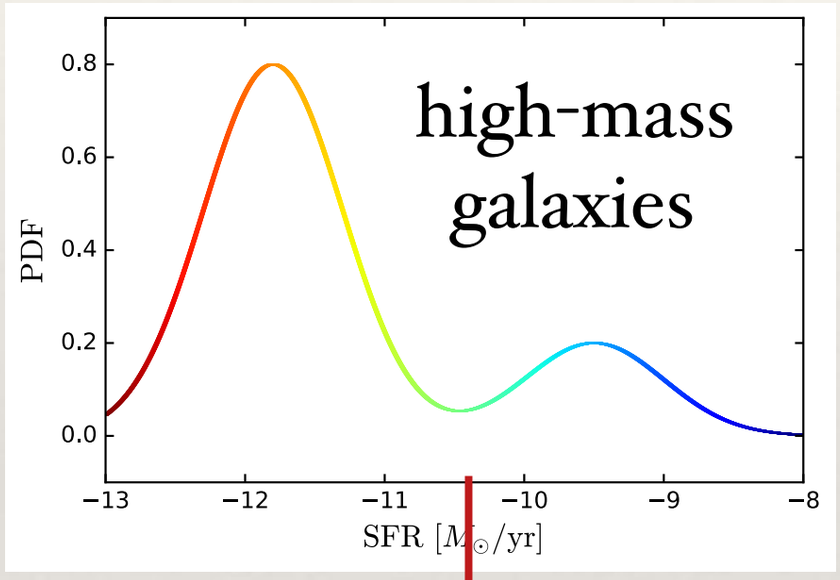
halotools.readthedocs.io



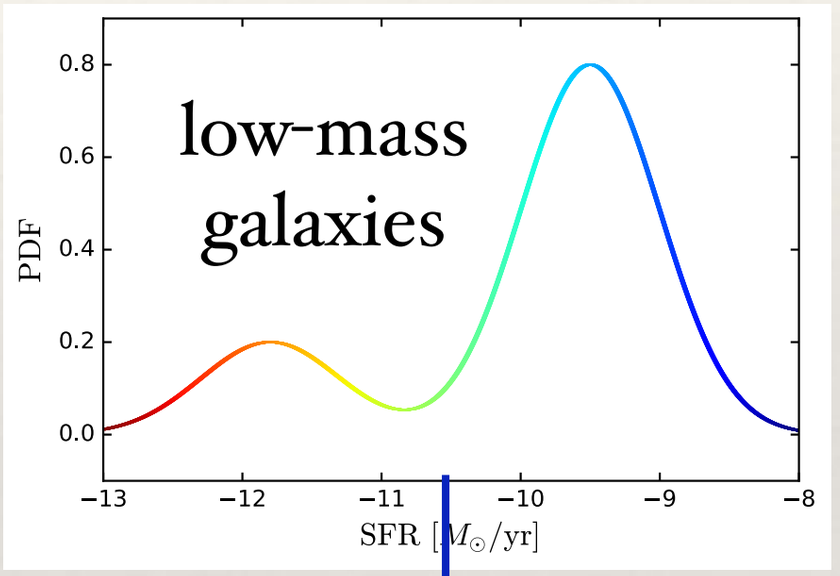
Simple Age Matching

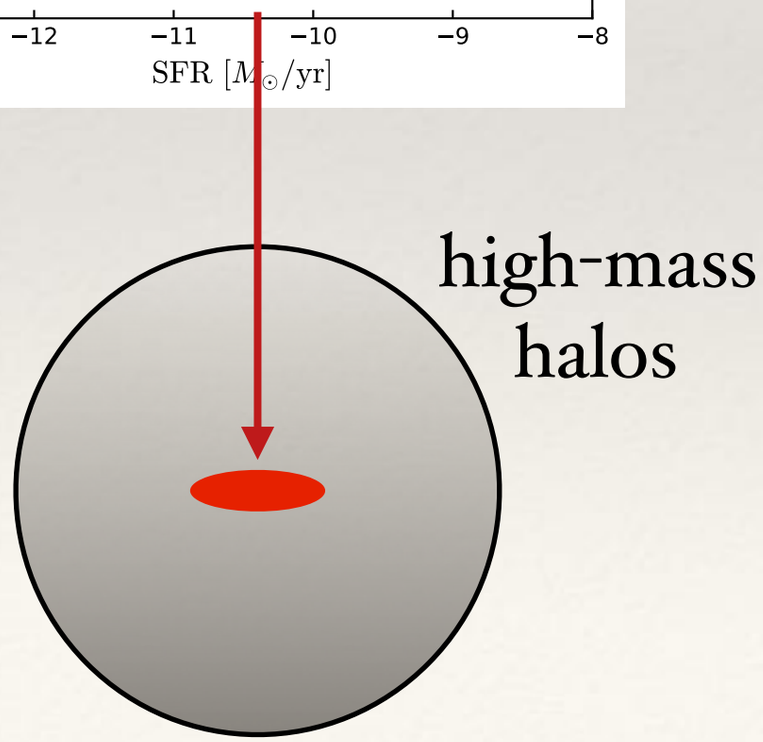
Construction of the Halo--SFR map

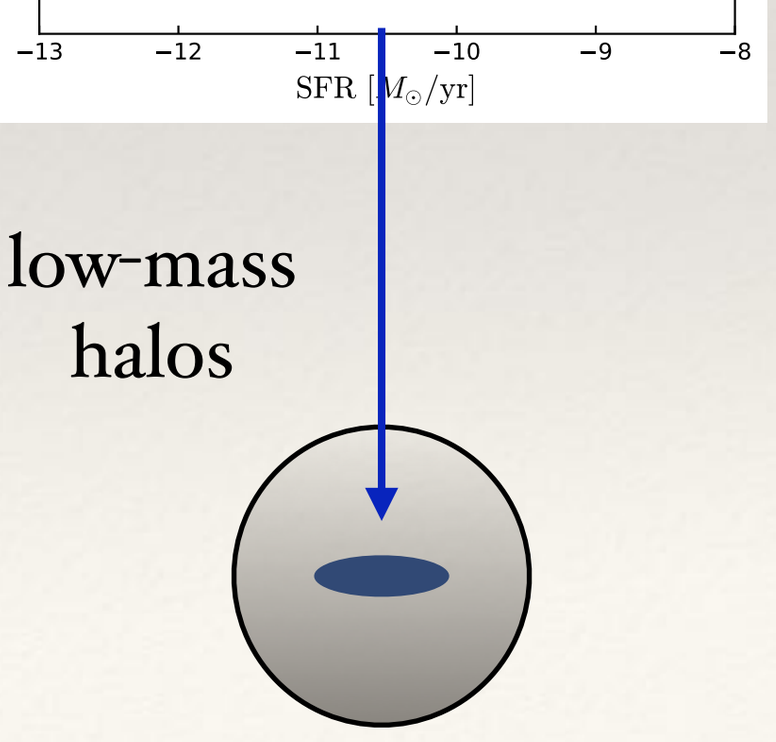
Formulation has direct mathematical analogy to simple abundance matching



Ingredient 1:
Halo mass regulates available SFR







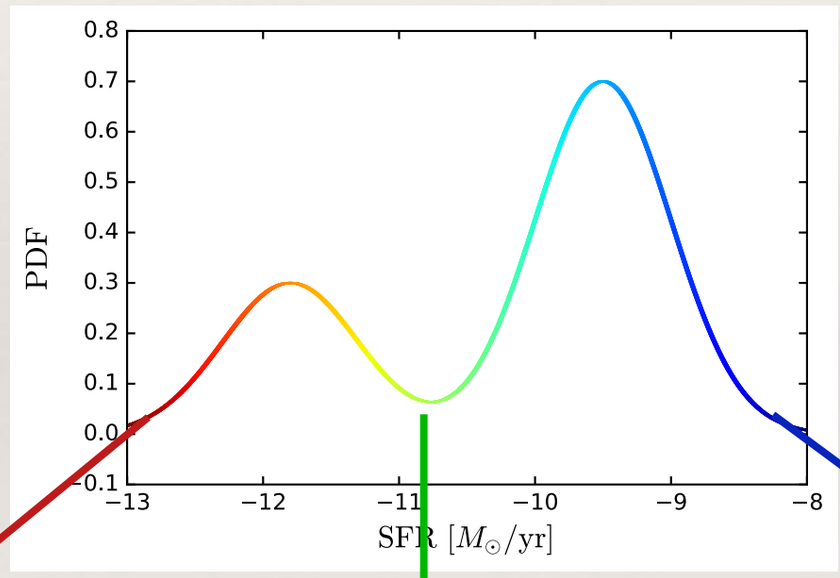
Simple Age Matching

Construction of the Halo--SFR map

Ingredient 2:

Galaxy SFR ∝ Halo "age"

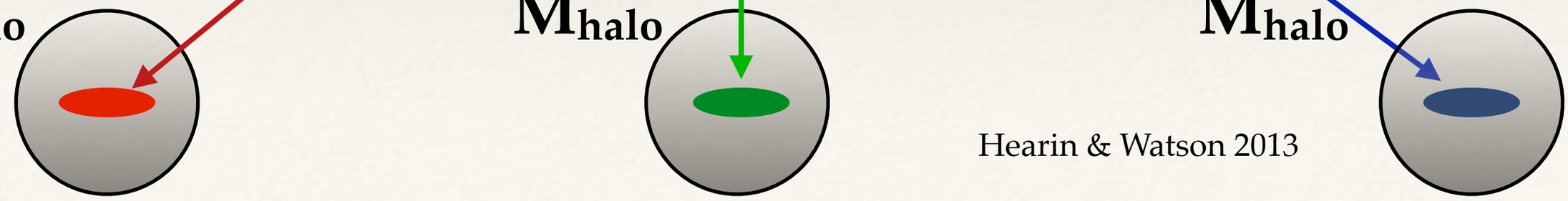
at fixed halo mass



old, slow-accreting, early-forming halos

young, fast-accreting, actively-forming halos

M_{halo} M_{halo} M_{halo}

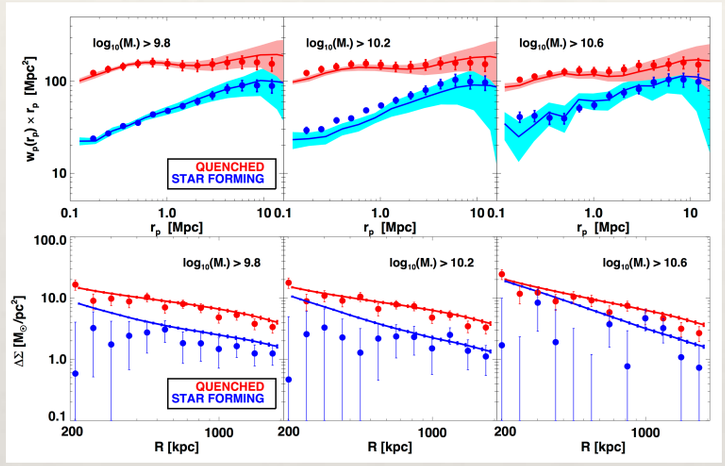


Hearin & Watson 2013

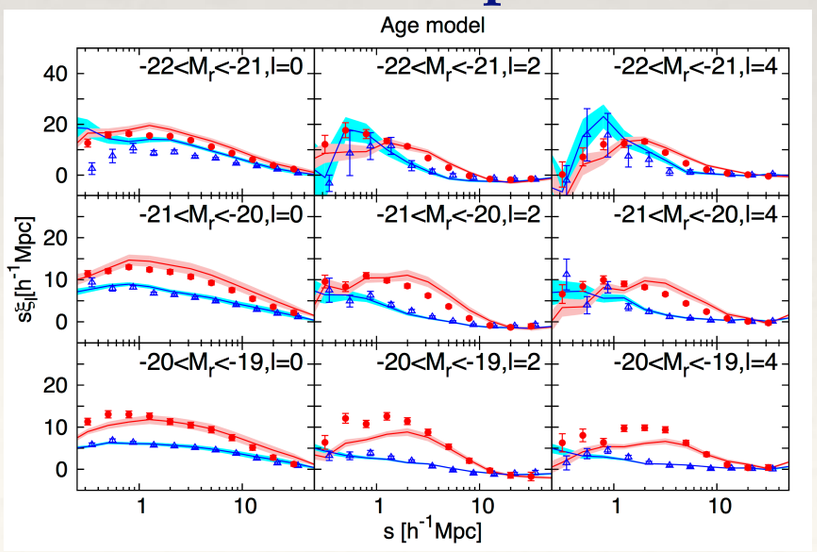
Simple Age Matching

Many different successful predictions with few parameters and two simple ingredients

galaxy clustering & lensing

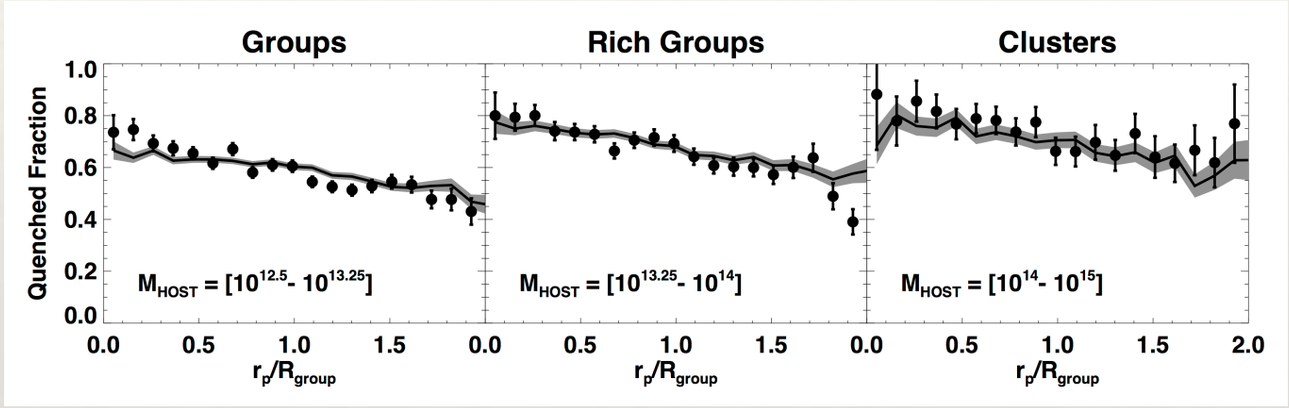


RSD multipoles



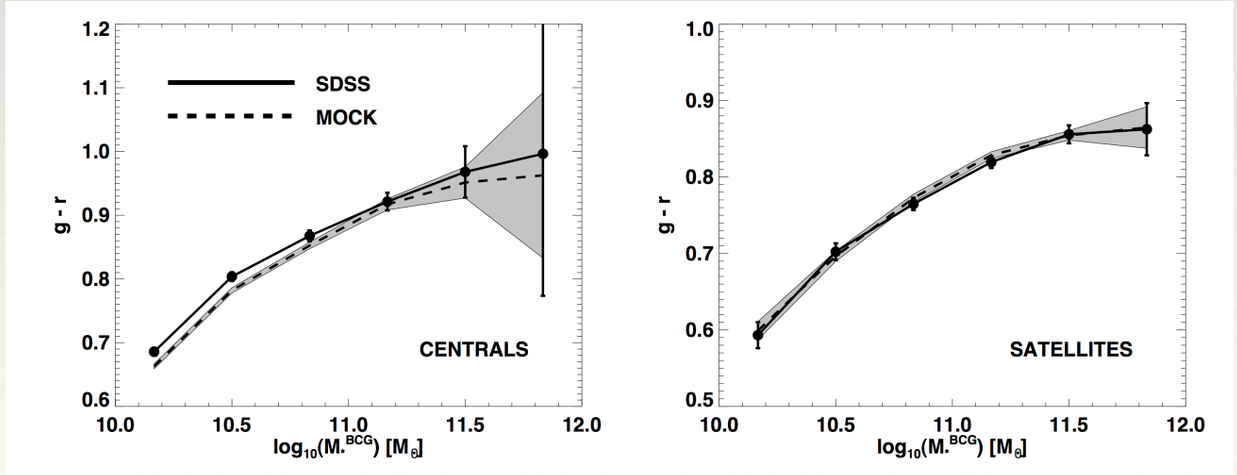
Yamamoto et al. 2016

satellite quenching profiles



Watson et al. 2015

Central & satellite color vs. group mass

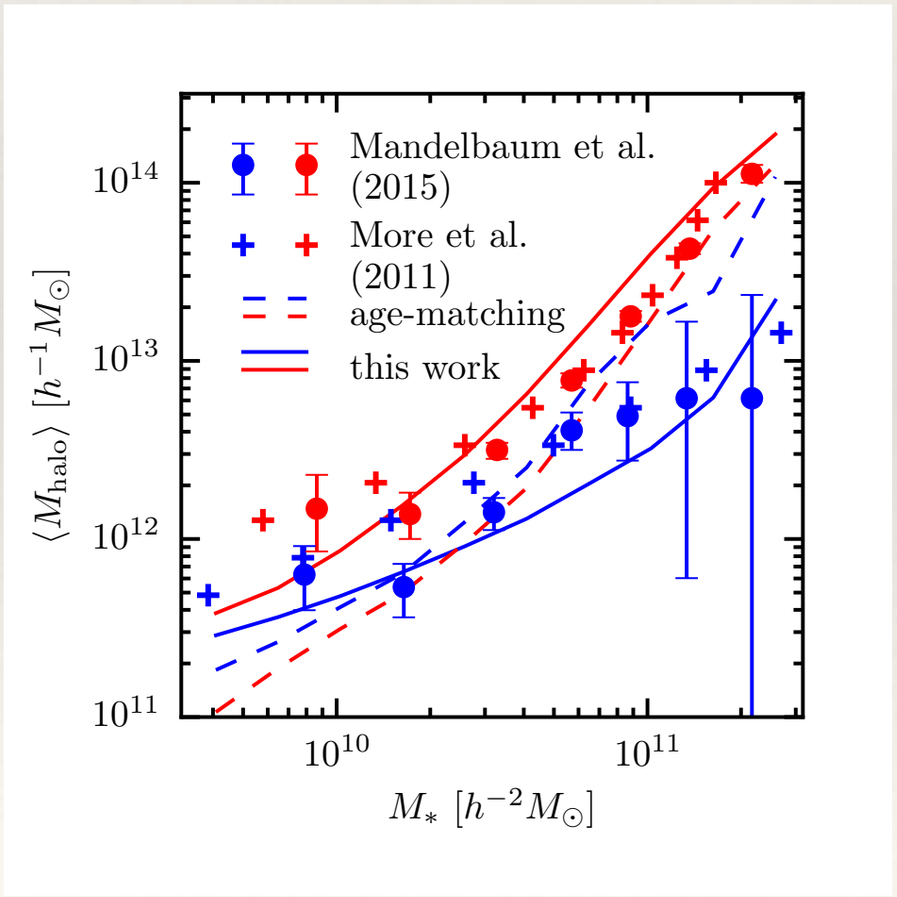


Hearin et al. 2014

Simple Age Matching

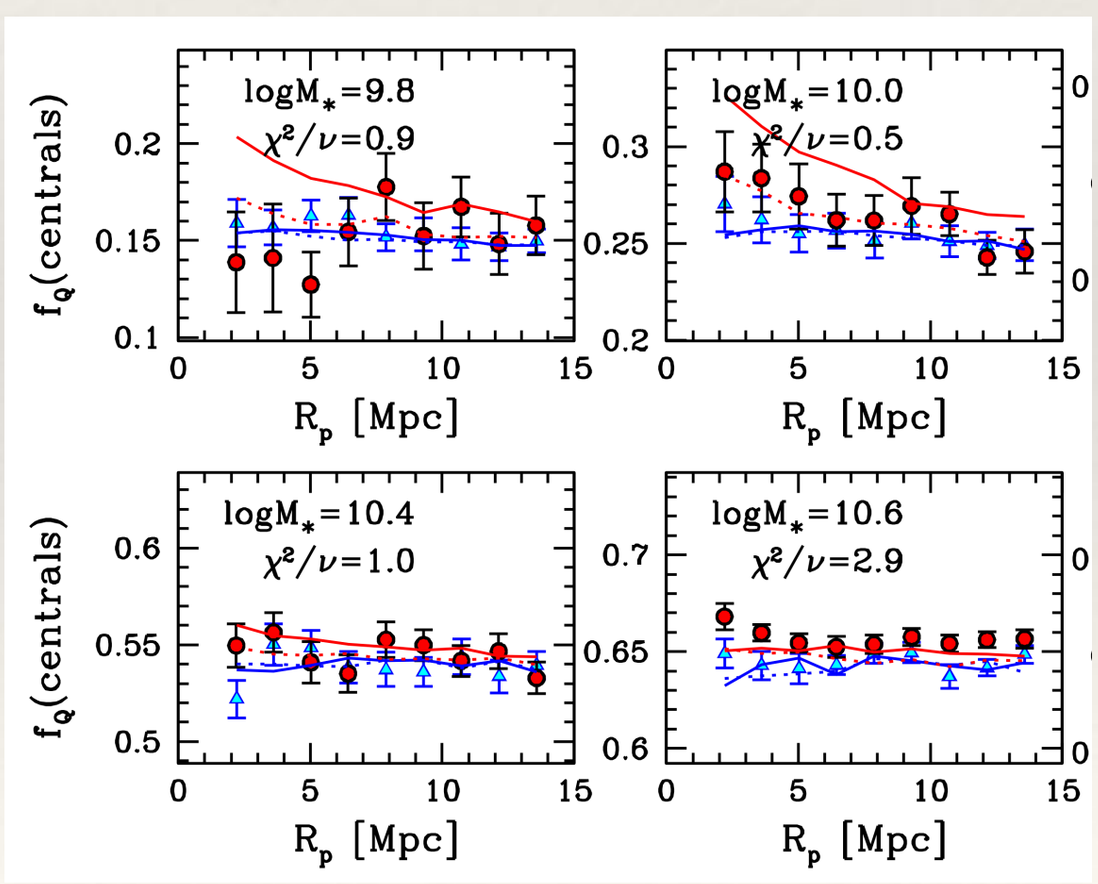
Formulation details significantly impact level of success

Red/blue SHMR



Campbell+17, in prep

Galactic Conformity



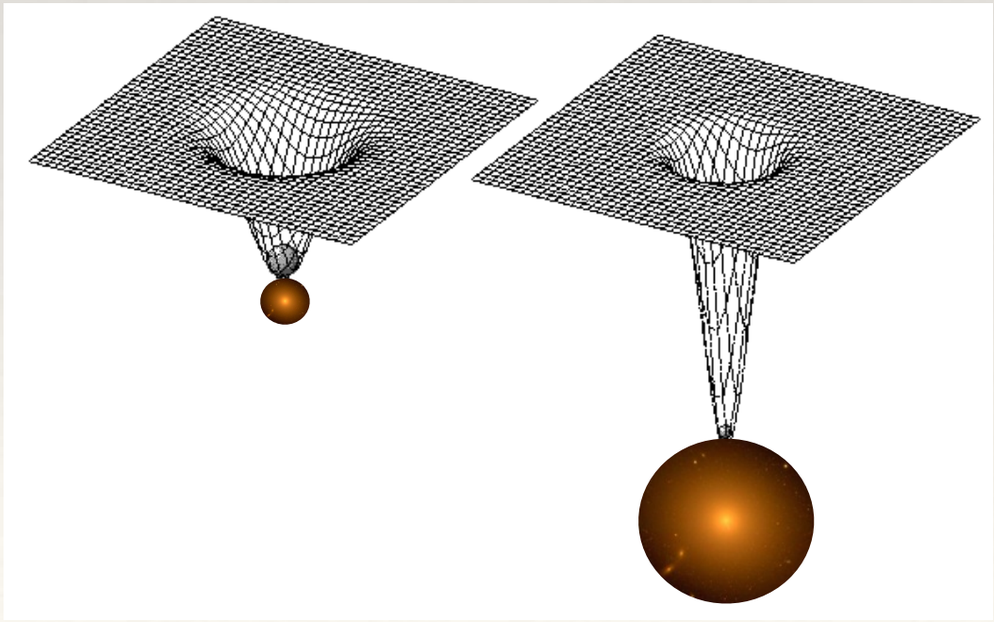
Tinker+17

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:

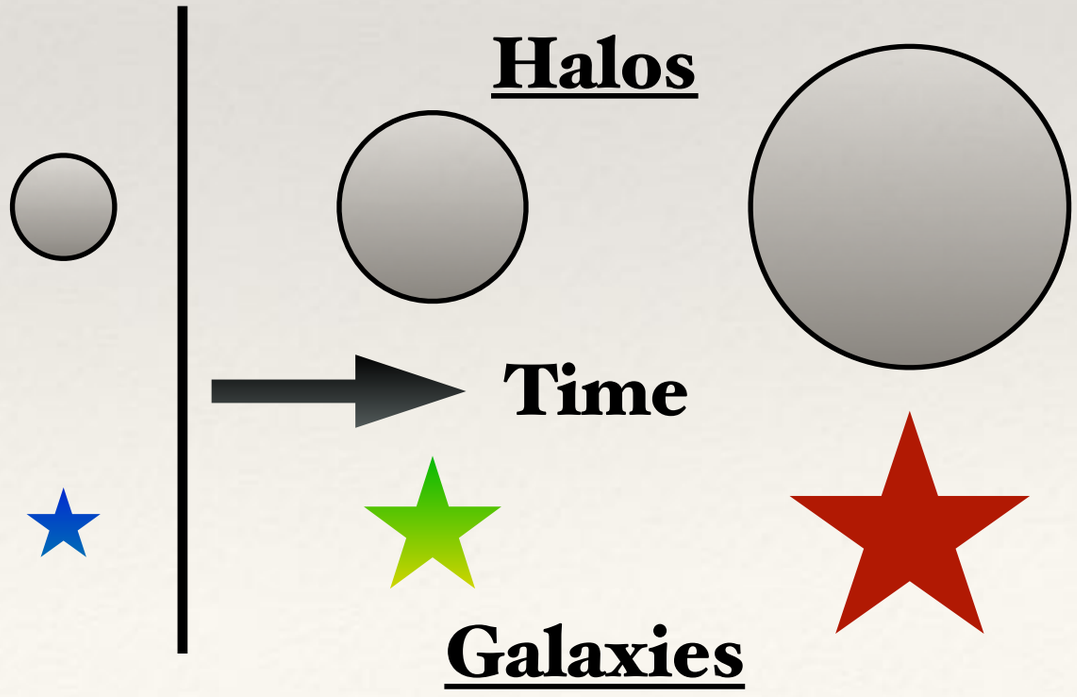
Depth of gravitational potential well has the dominant influence on galaxies



Basic lesson:

Galaxy—halo co-evolution

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



SHAM/HOD Foundation: A severe problem

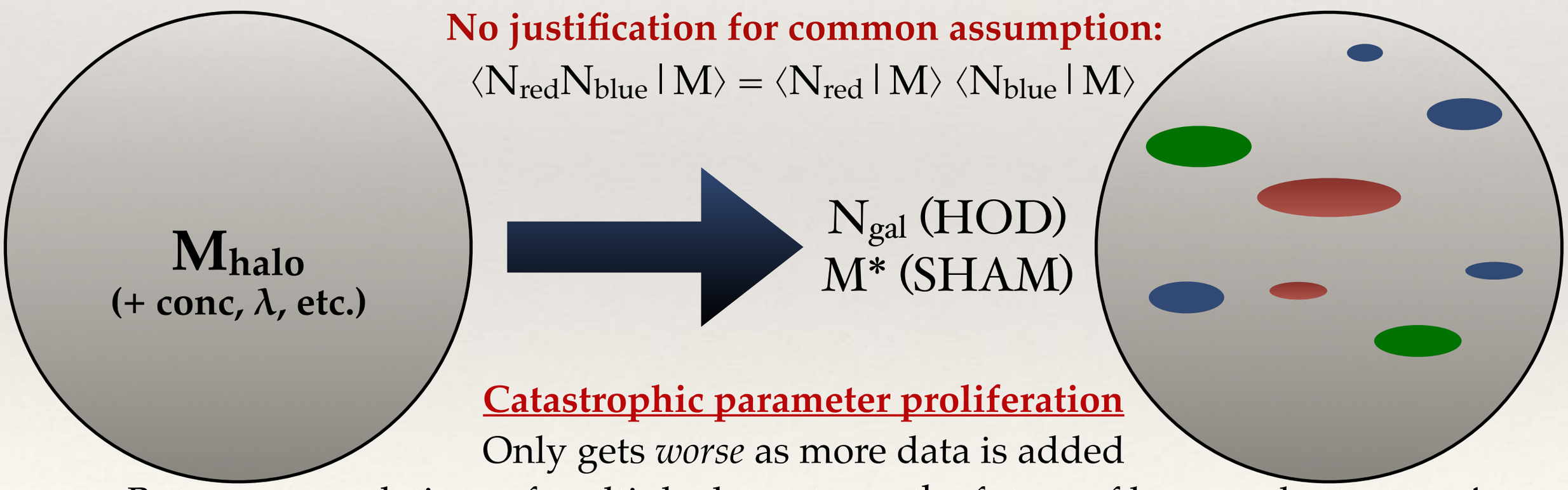
Conventional empirical models construct maps
for the *integrated* galaxy quantity (M_r or M^*)

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:

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



Catastrophic parameter proliferation

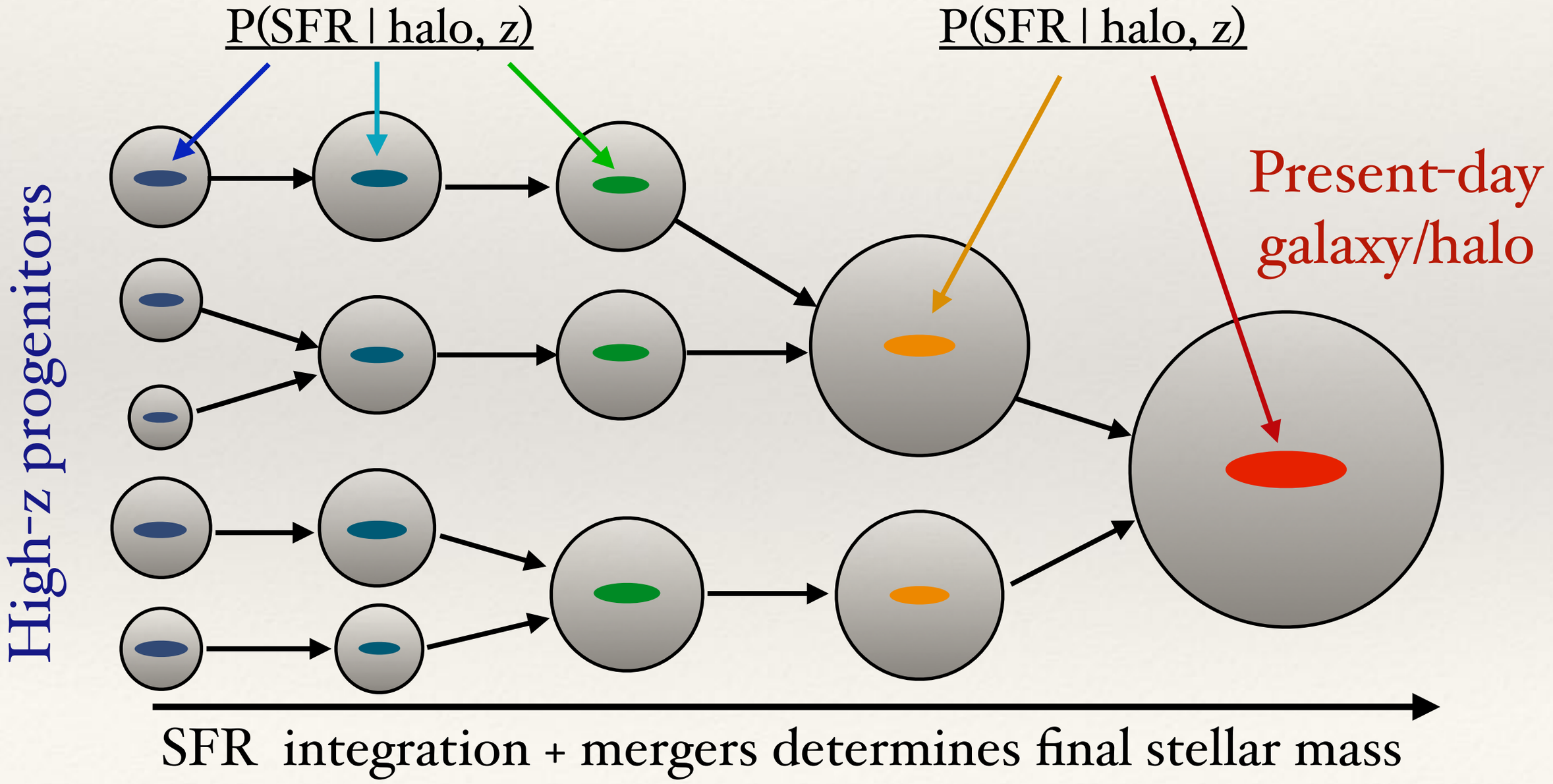
Only gets *worse* as more data is added
But cross-correlations of multiple datasets are the future of large-scale structure!

Conventional models are doomed to a future of single datasets

A Proposed Remedy

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

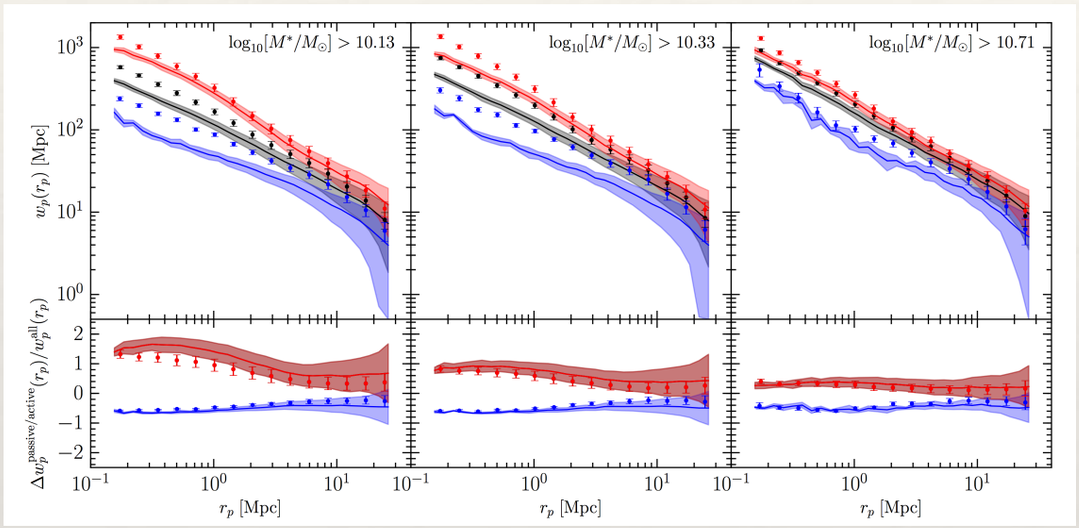
Now can use *far* more available data, forward-modeling survey selection functions



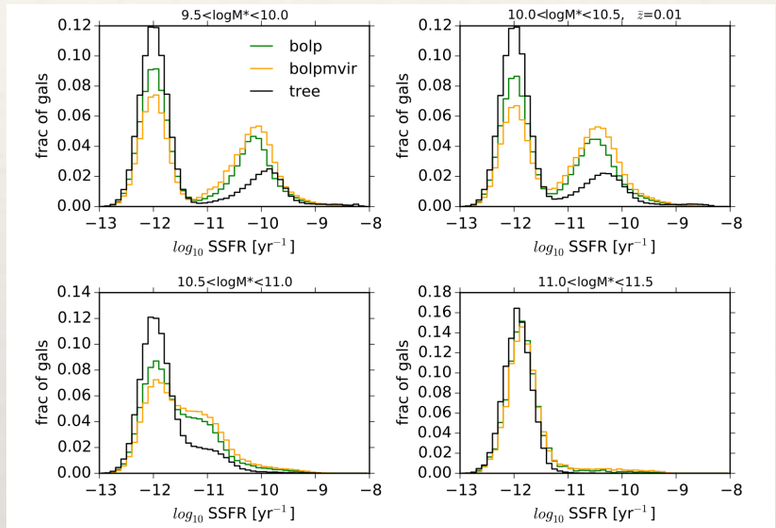
A Proposed Remedy

New generation of forward models already moving in this direction

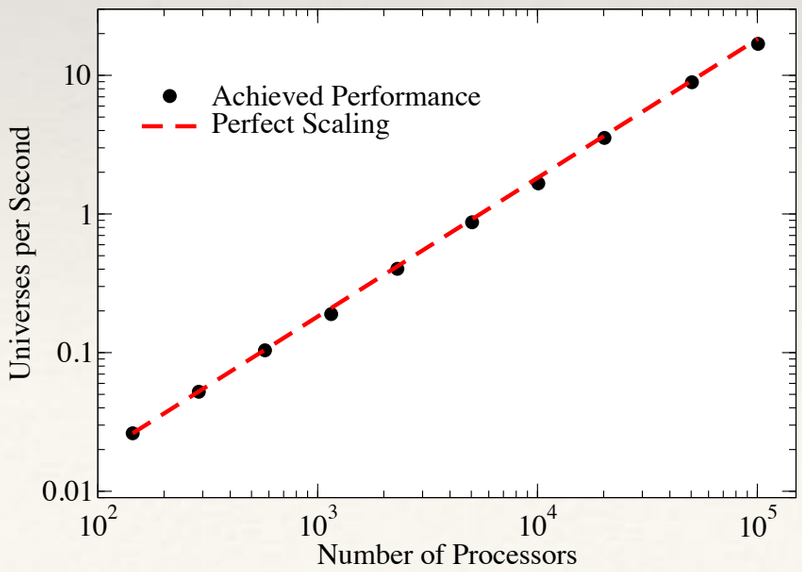
Becker 2015



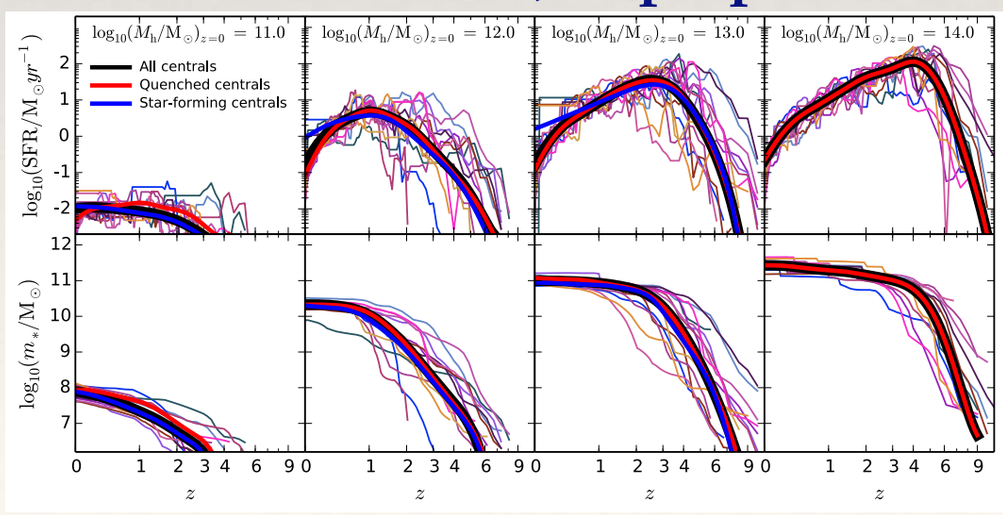
Cohn 2016



Universe Machine: Behroozi+17, in prep



Moster+17, in prep



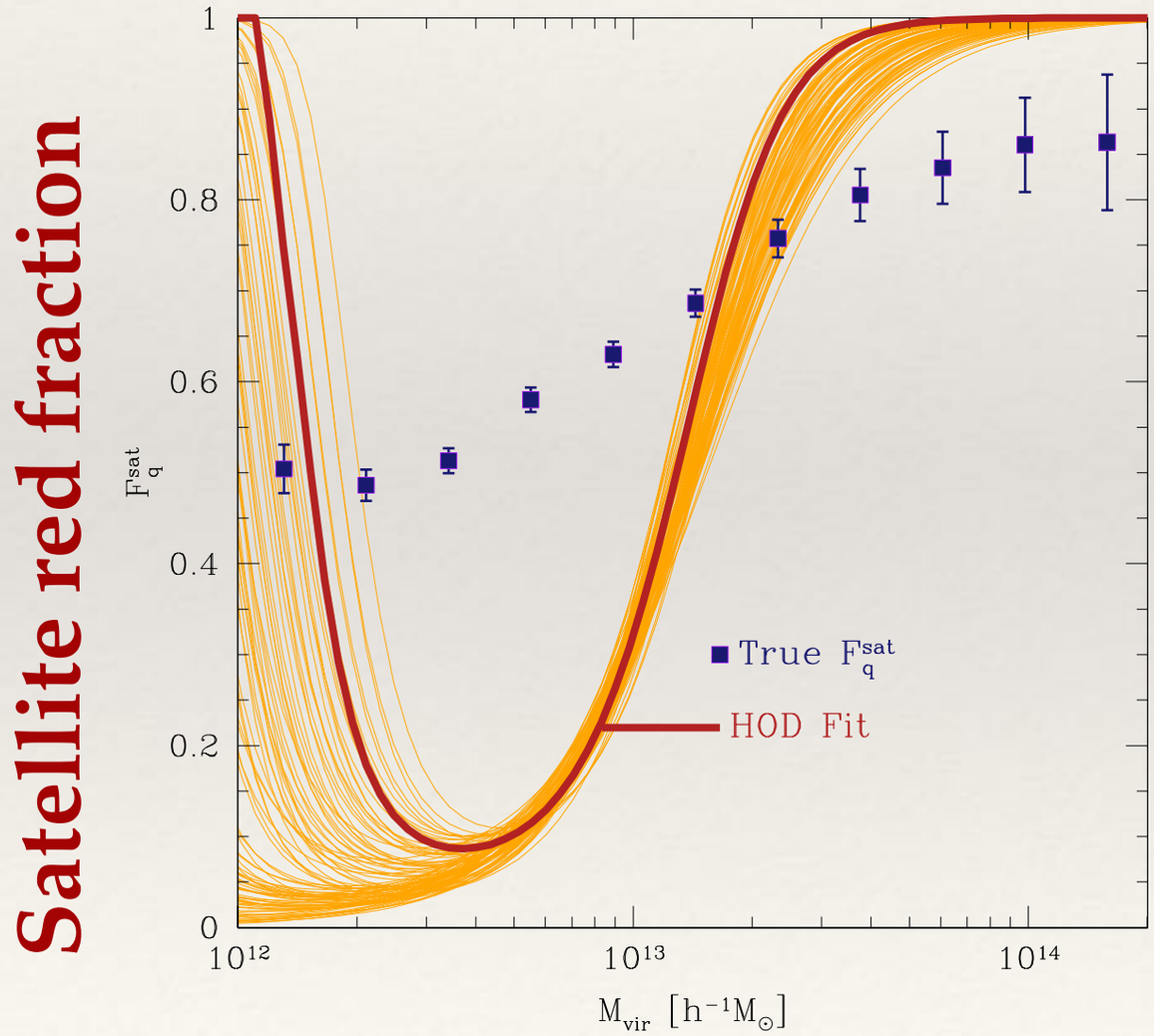
Additional Slides

e.g. White & Rees 78

Assembly Bias Consequences

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

Yes, they most certainly are!



Halo Mass

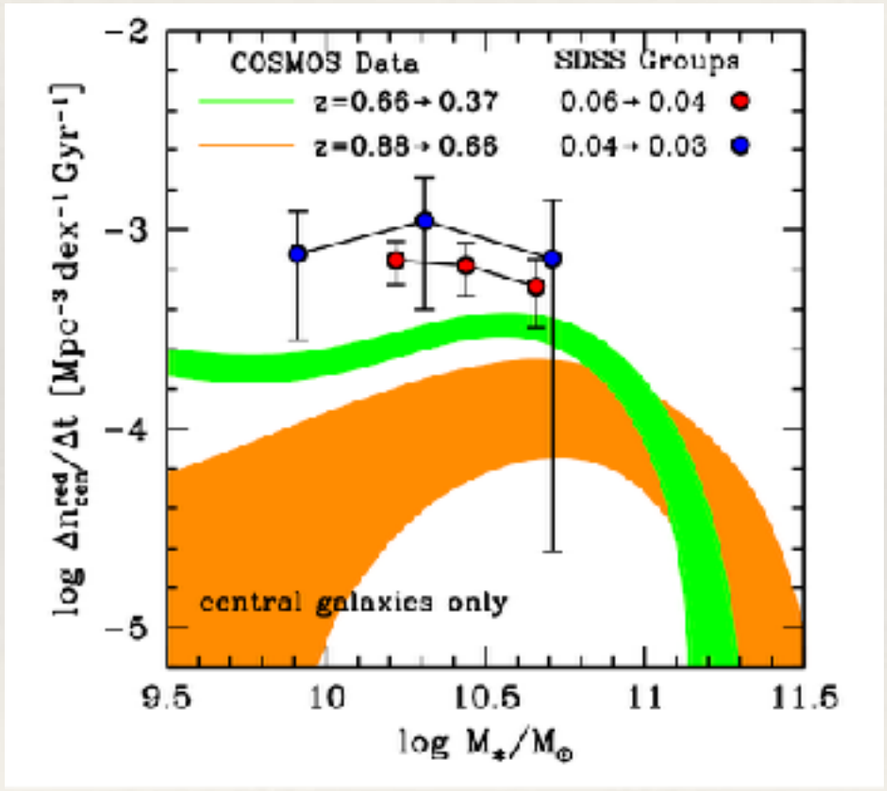
Zentner+13

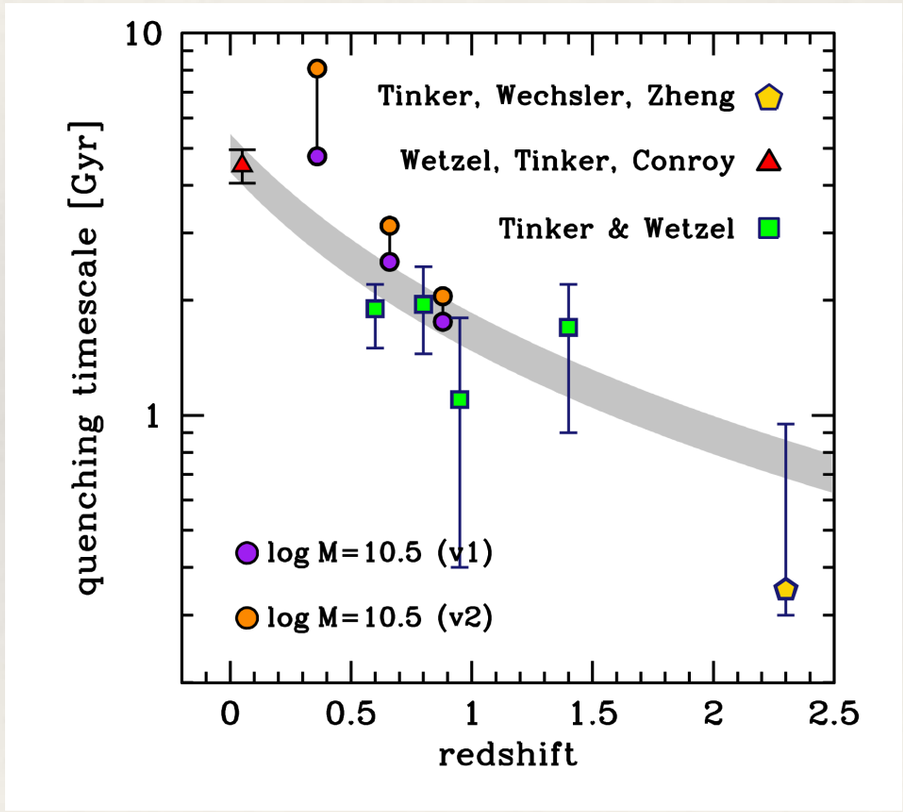
Color Dependent HODs

Upshot:

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

Tinker, Leauthaud, et al 2013





Downside:

Parameter proliferation rapidly becomes unmanagable

COSMOS fits required 27 x 3 = 81 parameters for binary red/blue designation alone