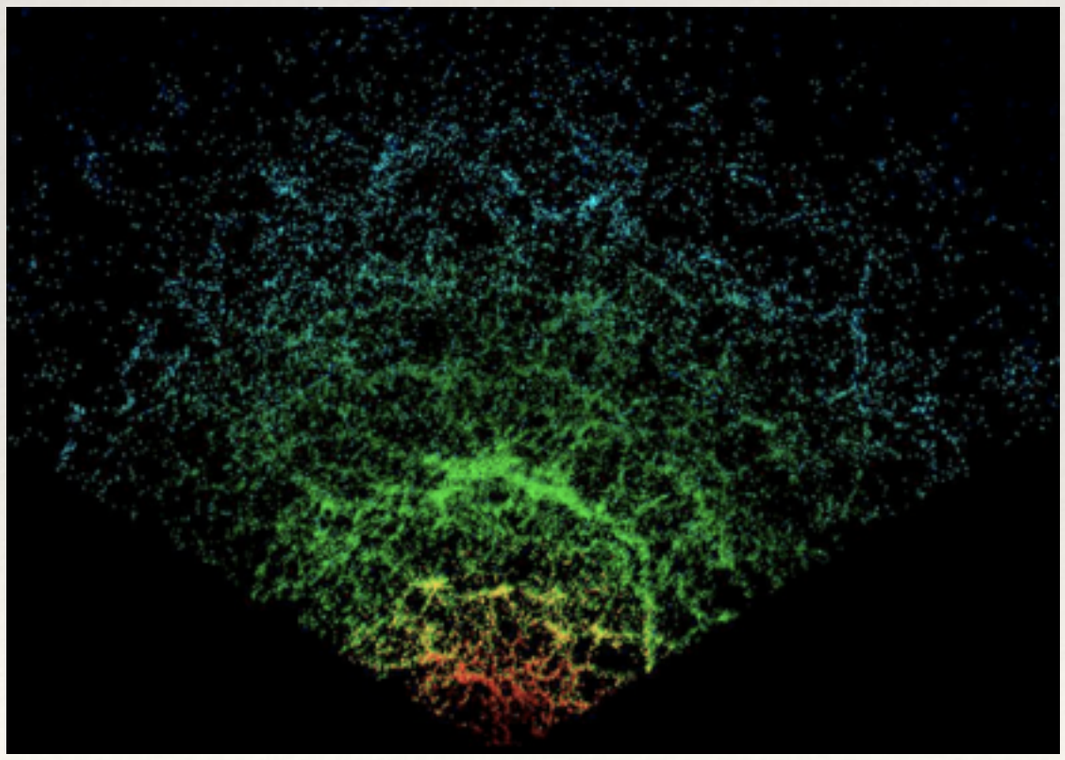
The Dark Side of Galaxy Evolution

Andrew Hearin
Yale University

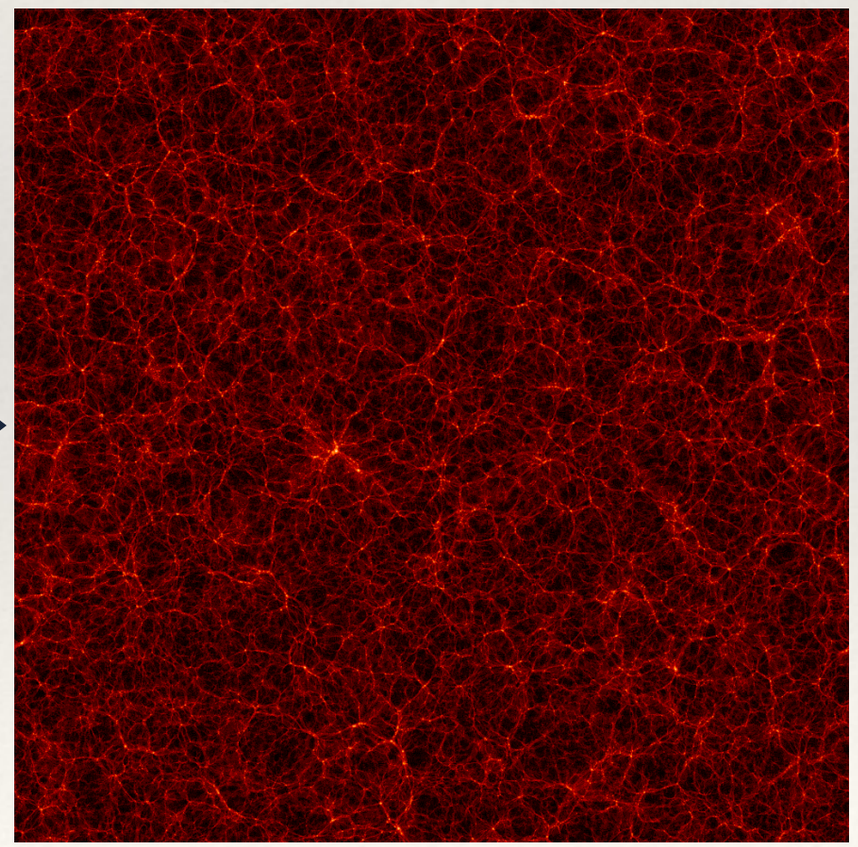
Basic Goal

Connect Galaxies to Dark Matter Halos

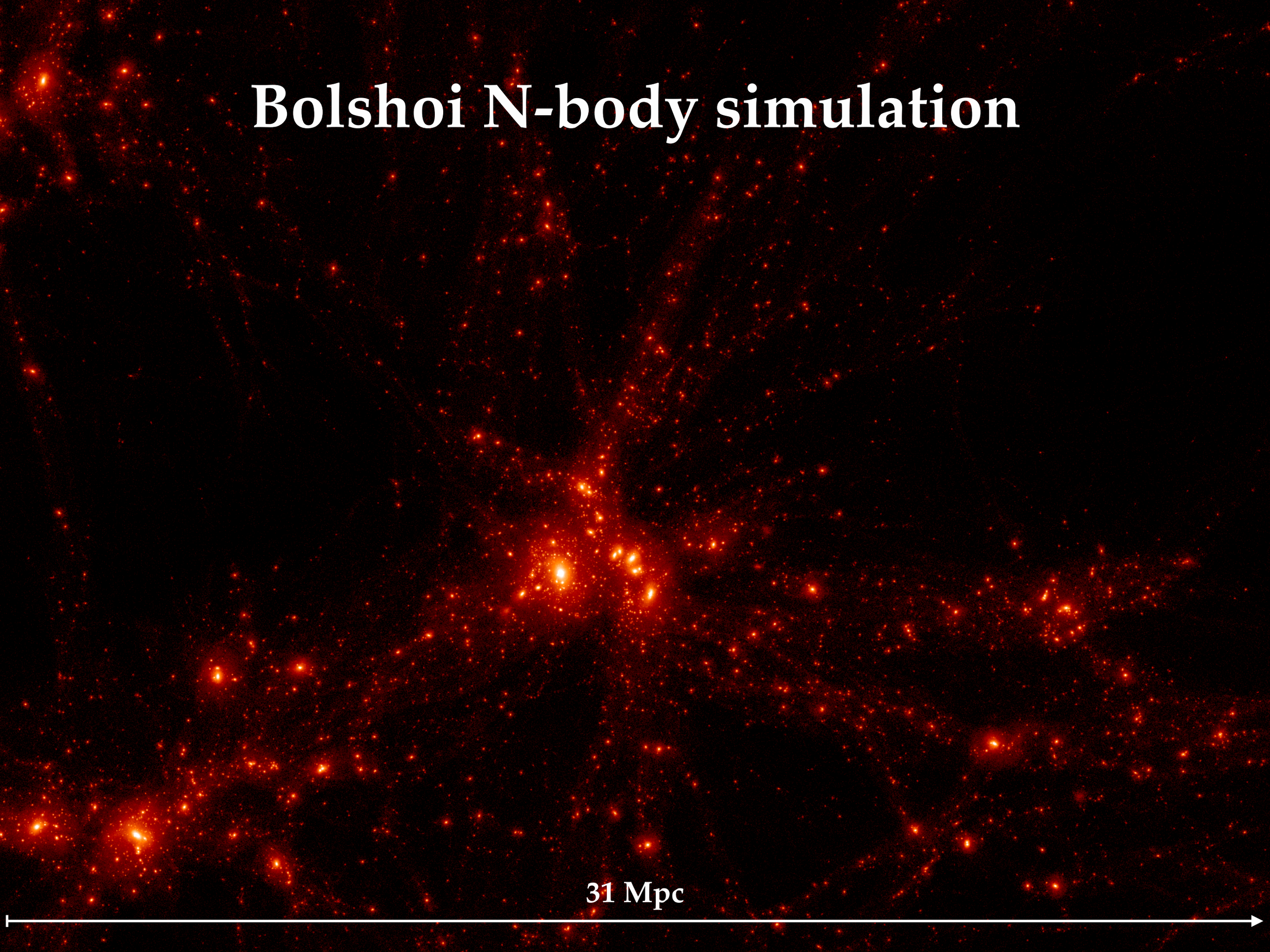
Observed Galaxies



Dark Matter Halos



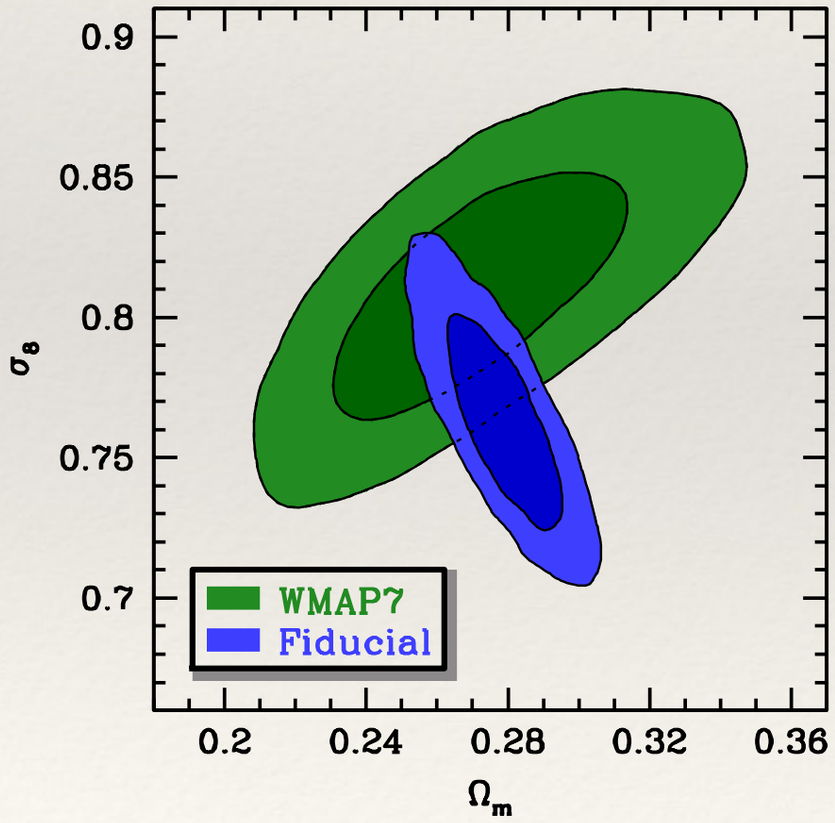
Bolshoi N-body simulation



Motivation

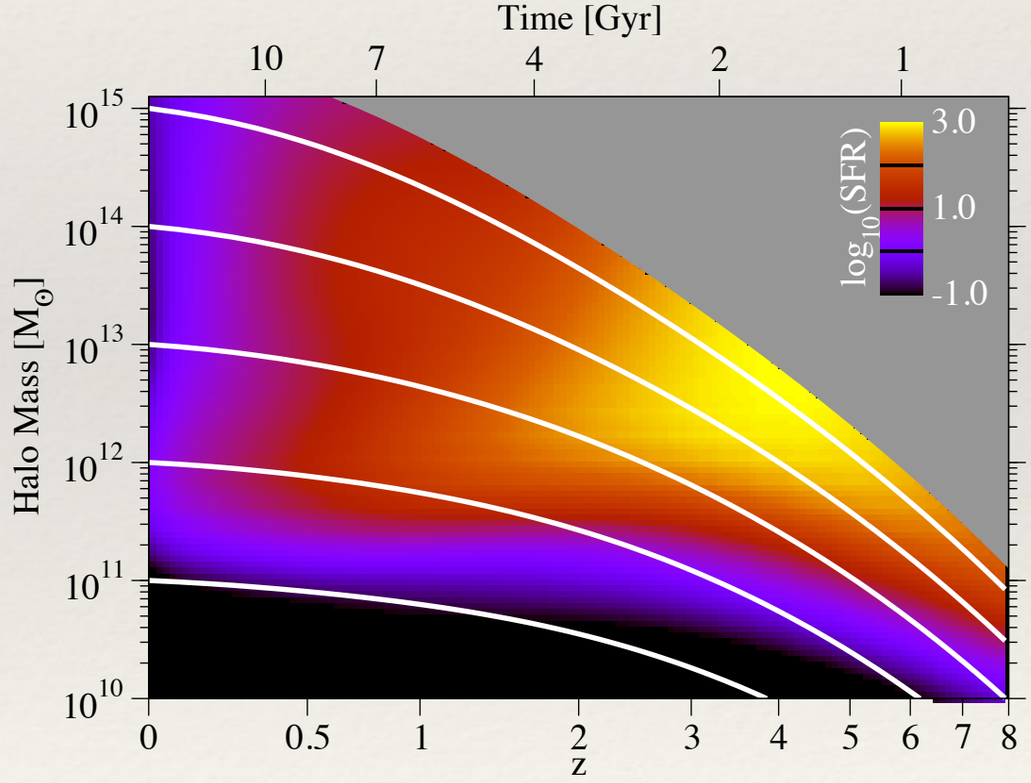
Connect Galaxies to Dark Matter Halos

Cosmological Constraints:



Cacciato et al. 2013

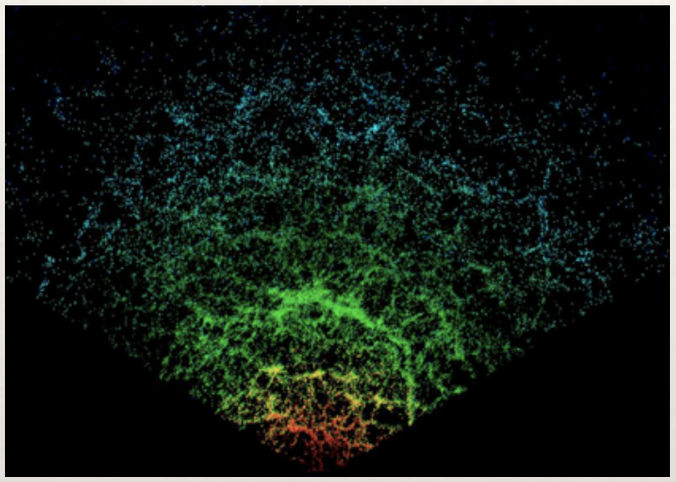
Galaxy Evolution:



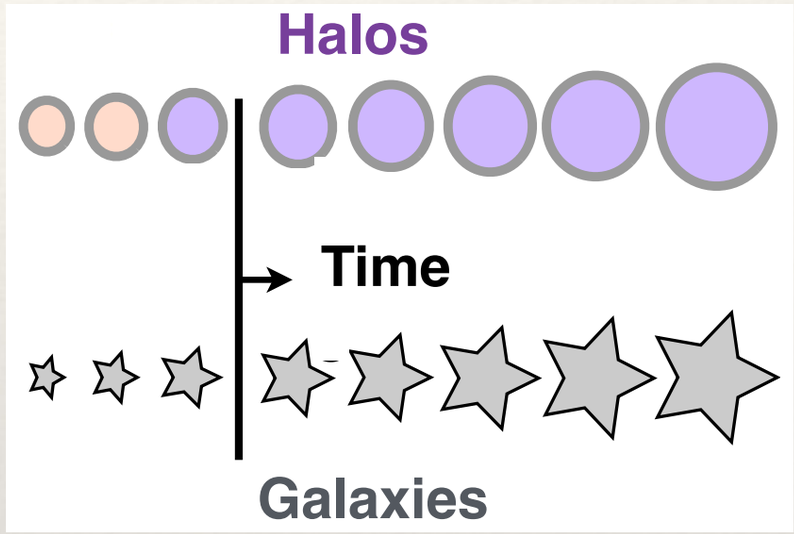
Behroozi et al. 2012

Outline

1. Basic Galaxy Phenomenology

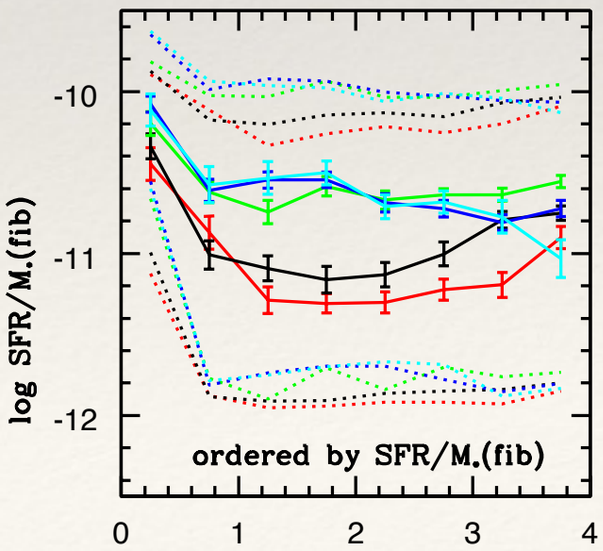


2. Galaxy & Halo Co-Evolution



3. The Threat of Assembly Bias

4. Model Discrimination



Cast of Characters

Doug Watson

Peter Behroozi

Matt Becker

Reina Reyes

Ramin Skibba

Andrey Kravtsov

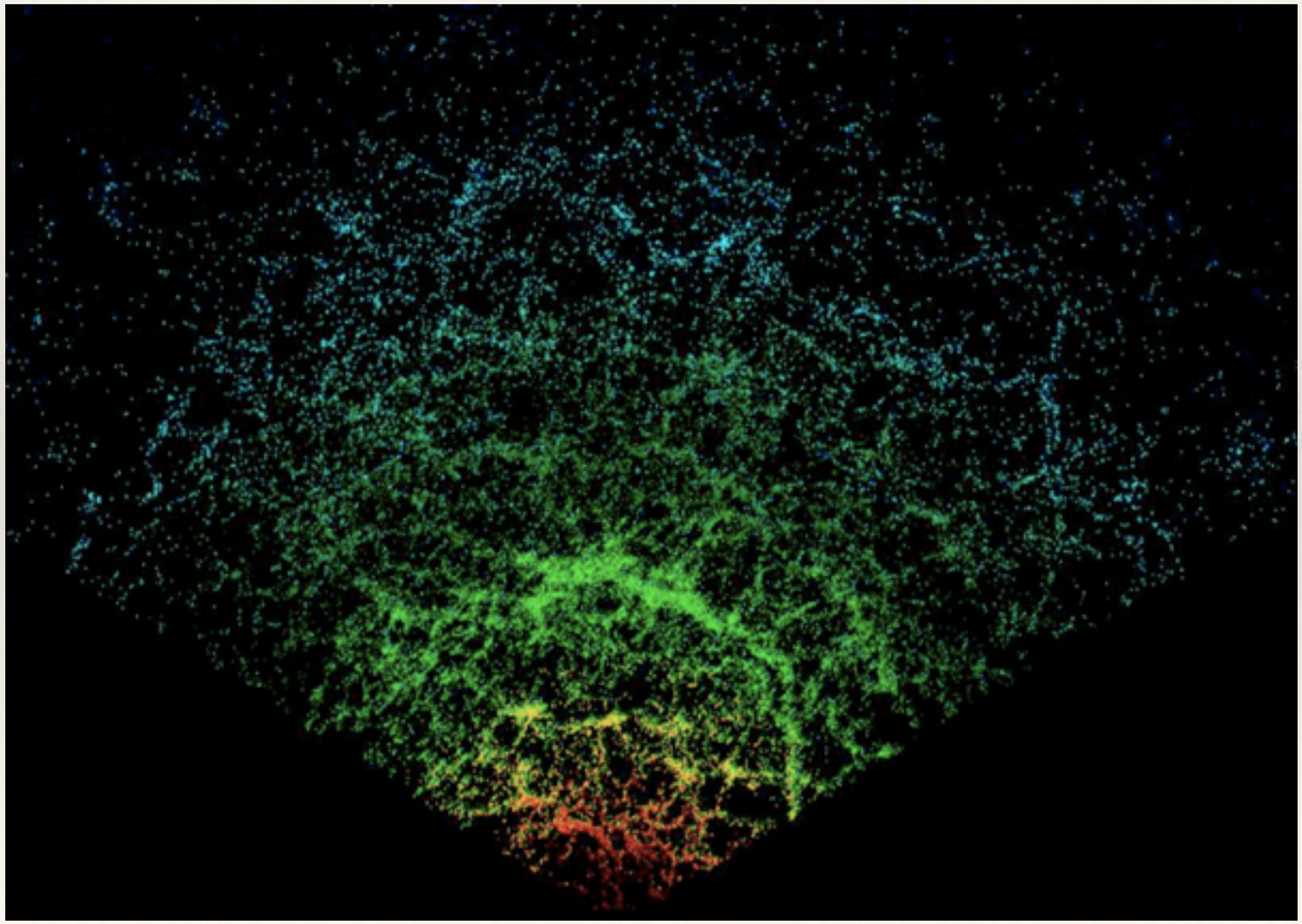
Andreas Berlind

Andrew Zentner

Frank van den Bosch

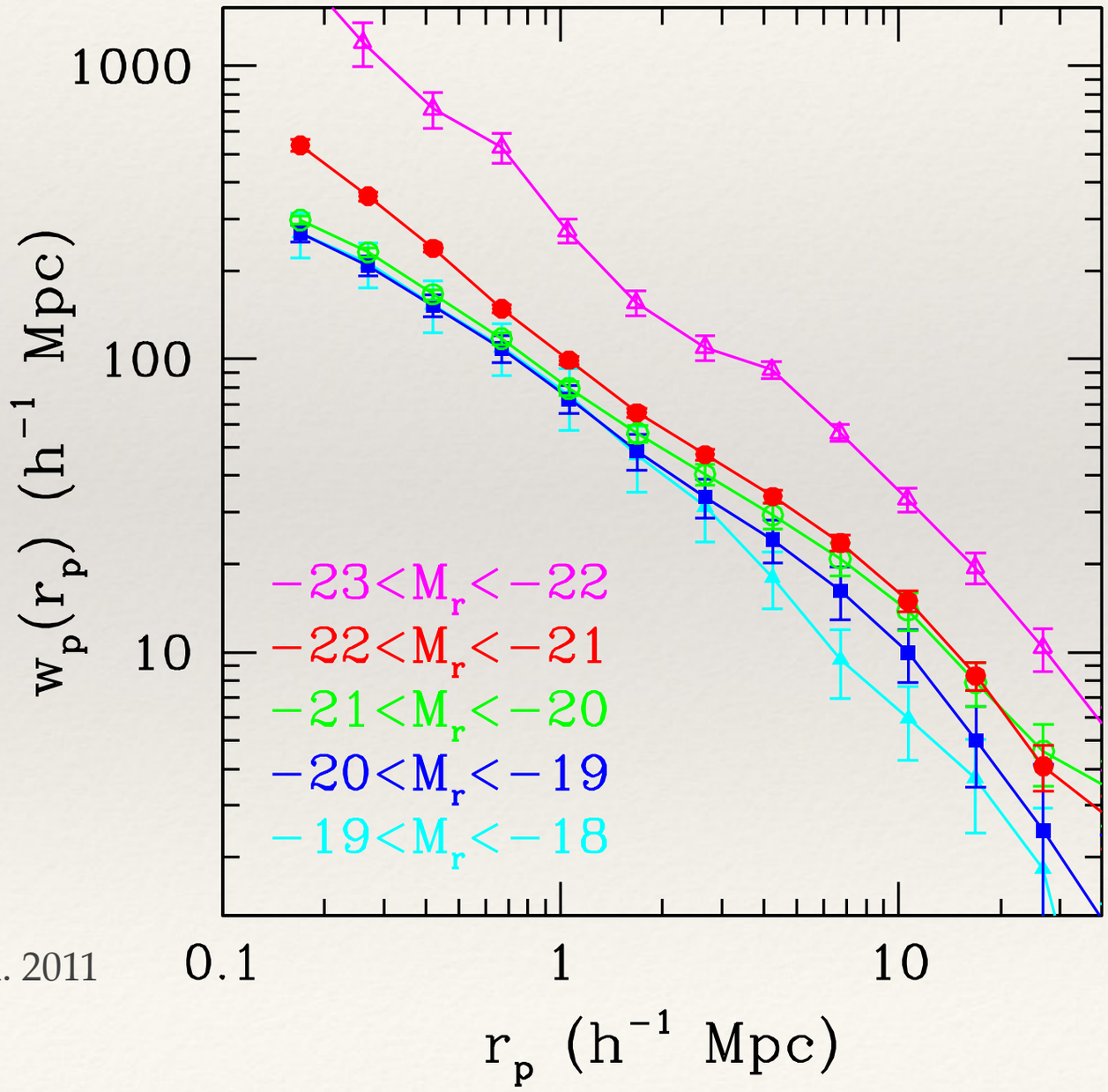
Part I

A Lightning Tour of Galaxy Phenomenology



Galaxy Evolution Phenomenology

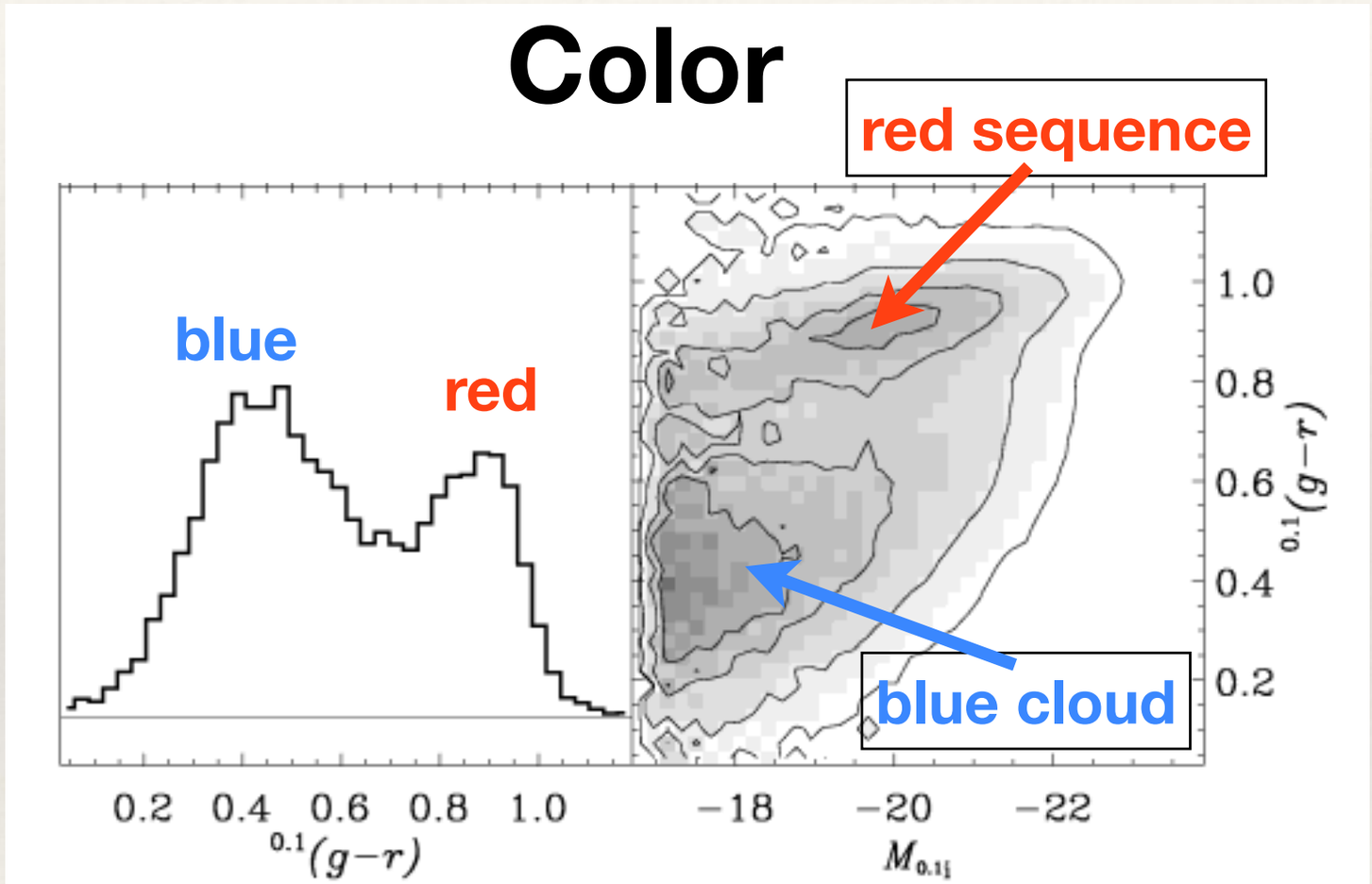
Luminosity-Dependent Clustering



Zehavi et al. 2011

Galaxy Evolution Phenomenology

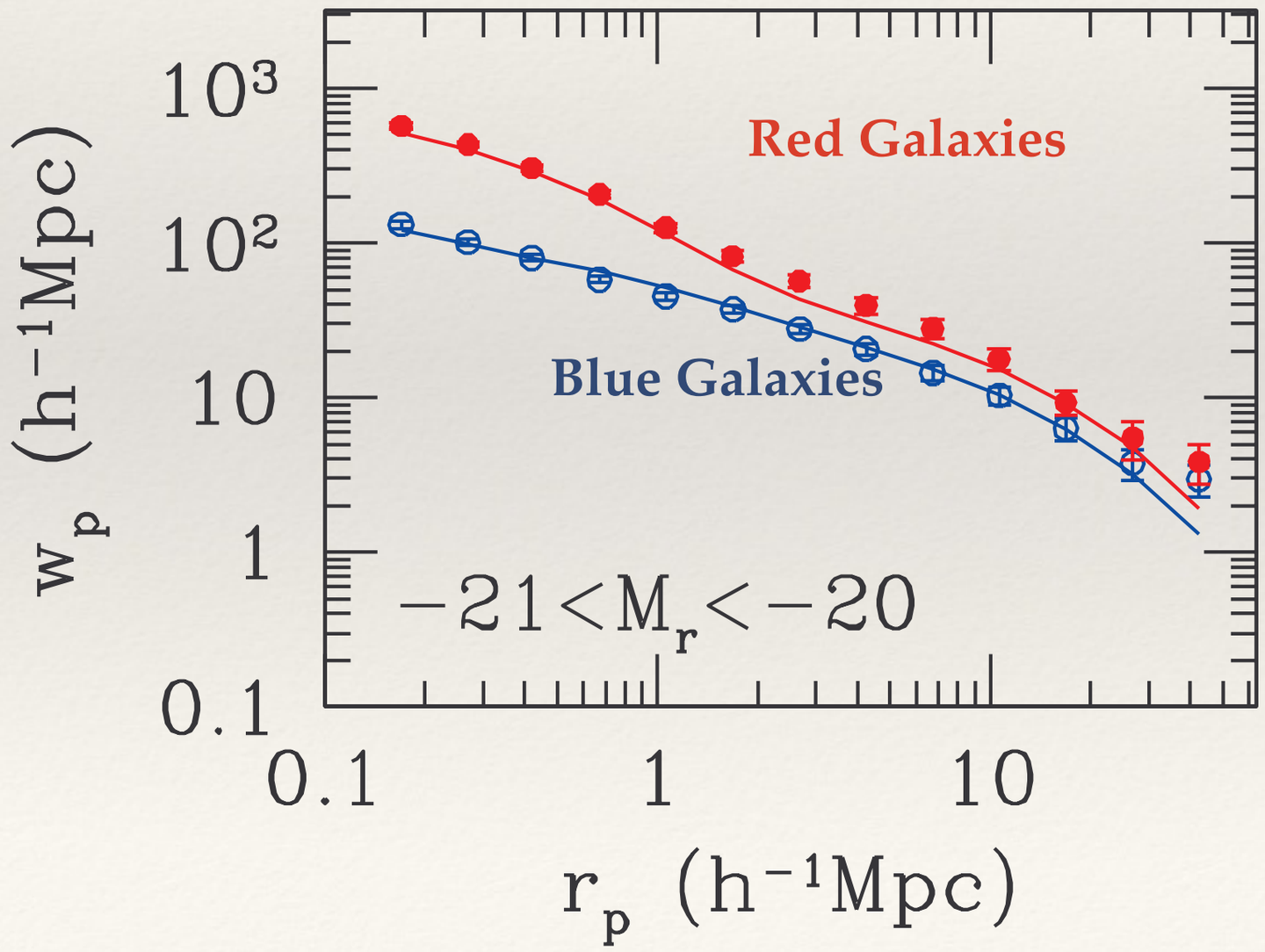
Bi-modality in color



Blanton et al. (2003)

Galaxy Evolution Phenomenology

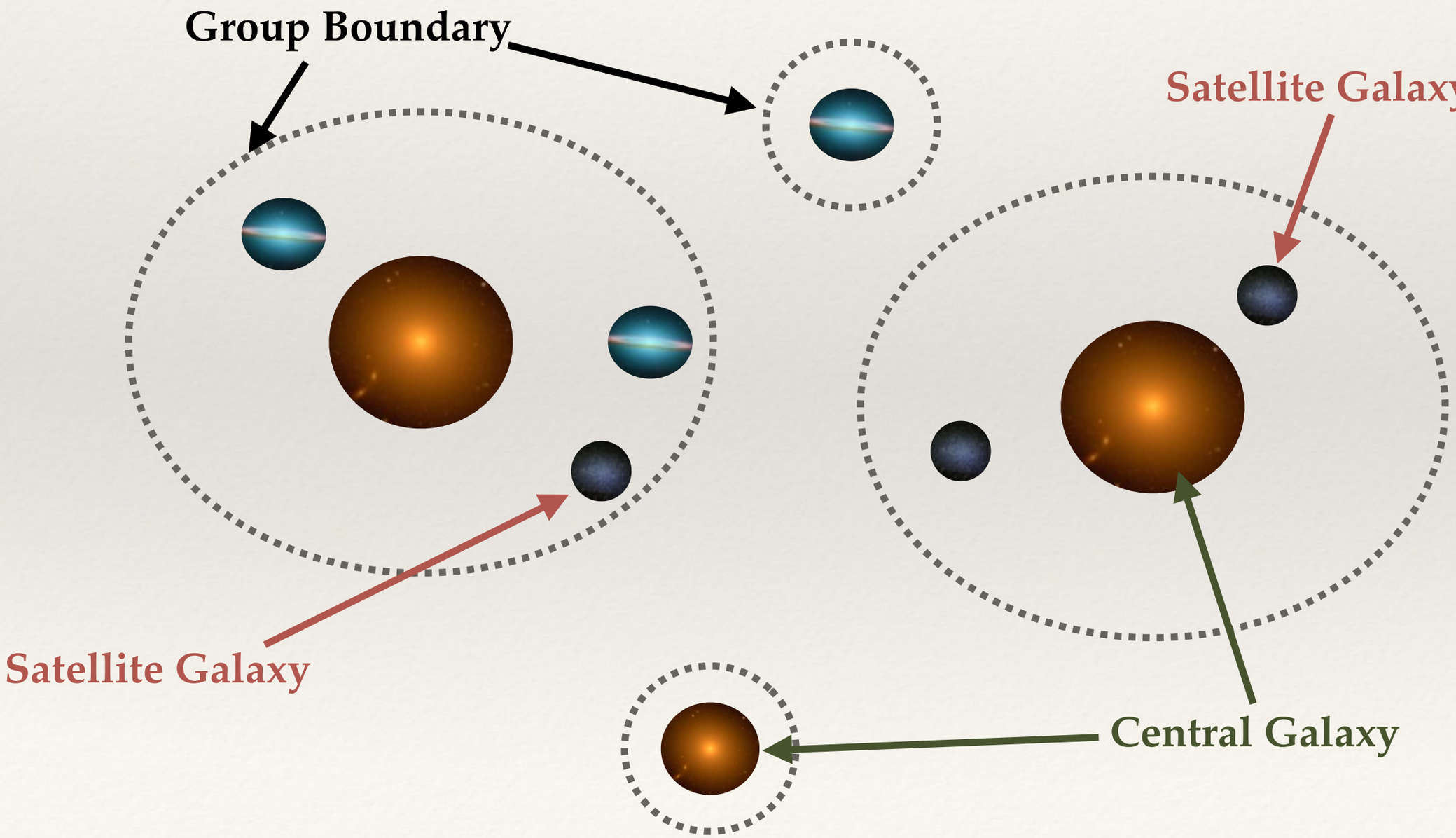
Color-Dependent Clustering



Zehavi et al. 2011

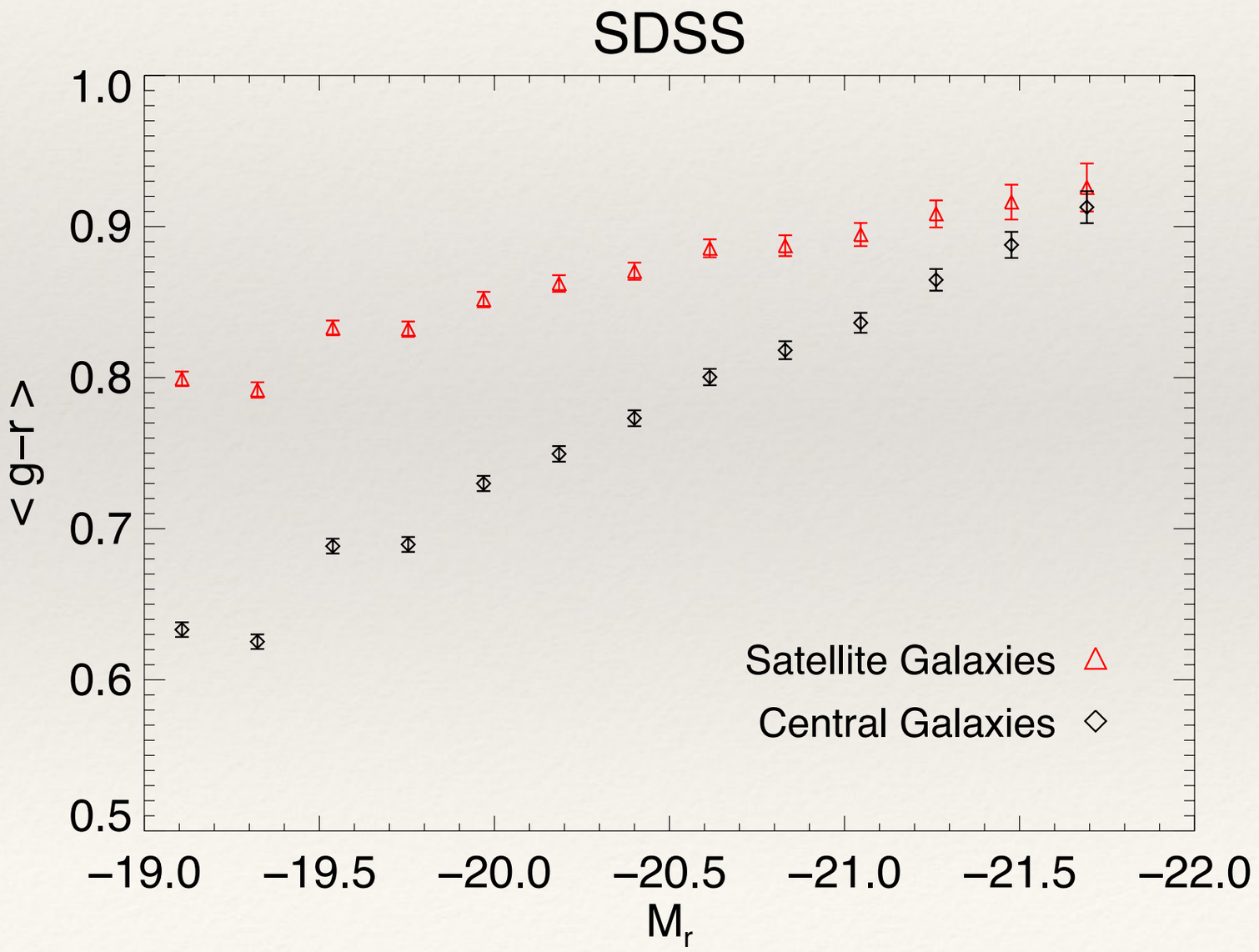
Galaxy Evolution Phenomenology

Central and Satellite Galaxies



Galaxy Evolution Phenomenology

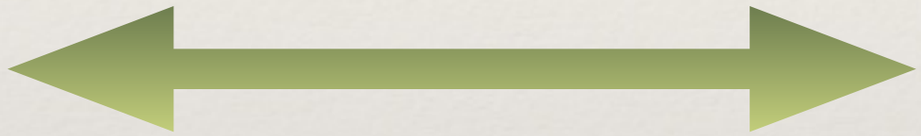
Central & Satellite Quenching



Adapted from
Hearin & Watson 2013,
arXiv:1304.5557

Galaxy Evolution Phenomenology

A technical aside

Luminosity (L)  **Stellar Mass (M*)**

Color (g-r)  **Specific Star Formation Rate (sSFR)**

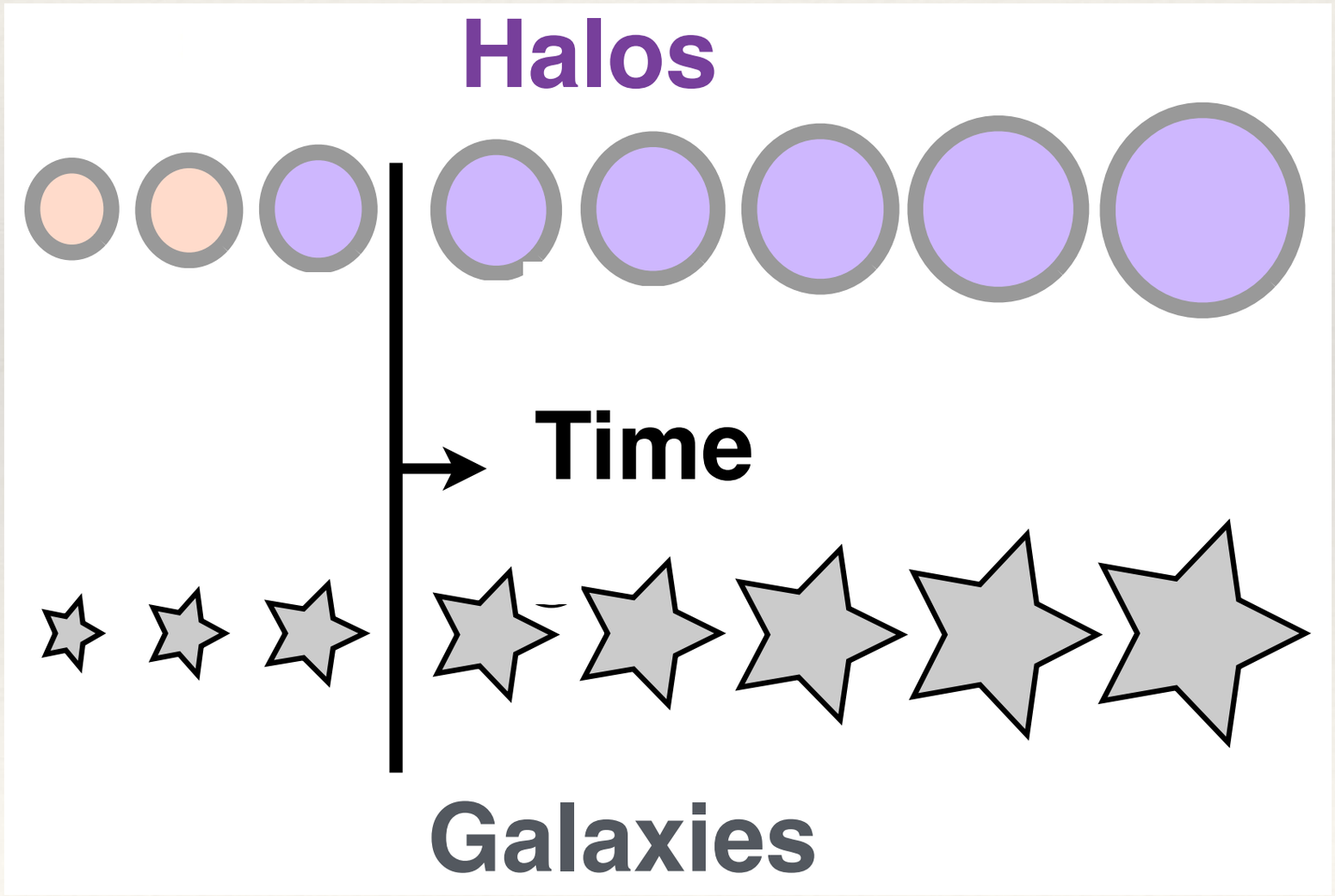
Galaxy Evolution Phenomenology

A One-Slide Recap

1. **Bright, Large-M* galaxies cluster more strongly than faint, low-M* galaxies**
2. **Red "quenched" galaxies cluster more strongly than blue "star-forming" galaxies**
3. **"Satellite" galaxies are redder and more quenched than "central" galaxies**

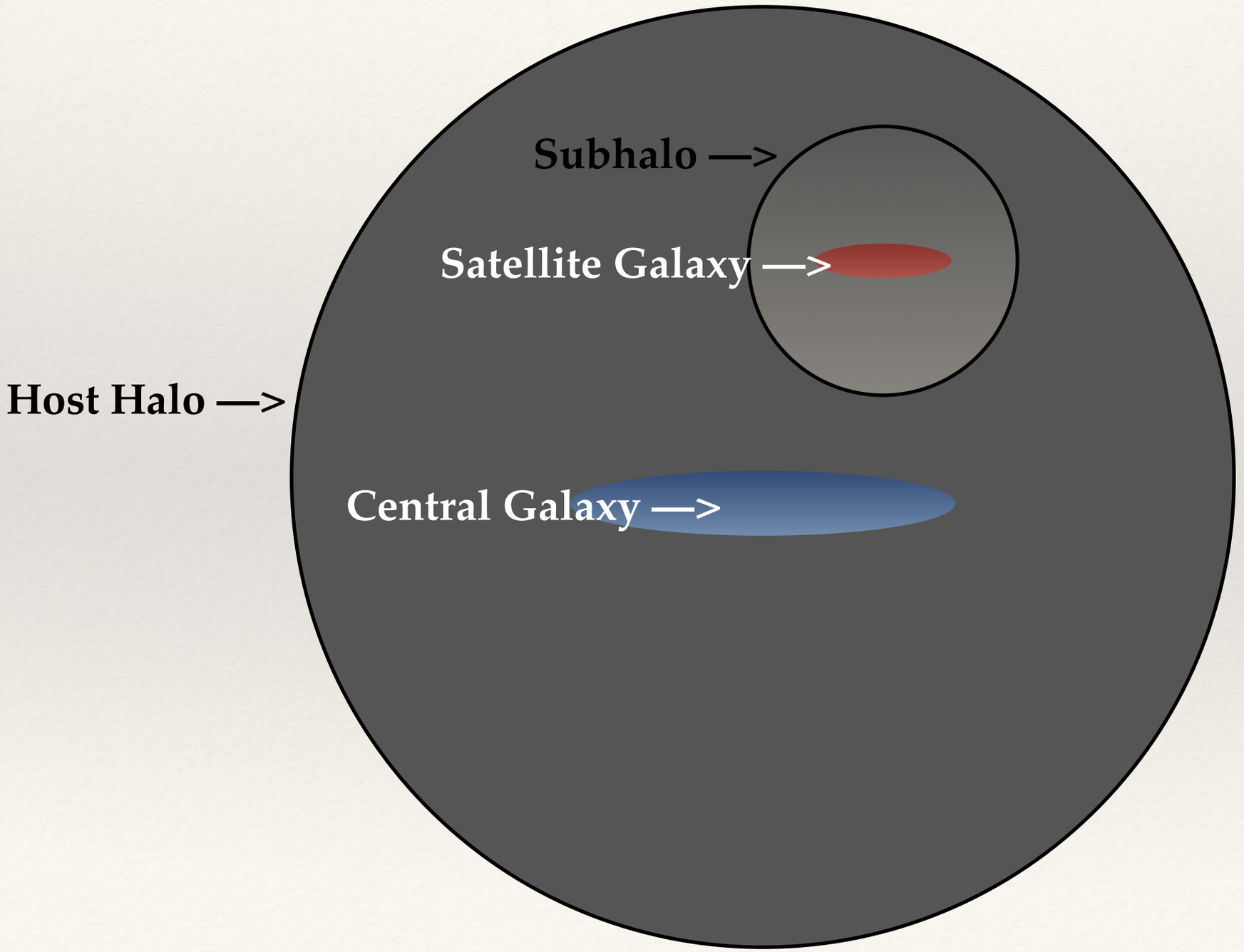
Part II

Modeling the Co-Evolution of Galaxies and Dark Matter Halos



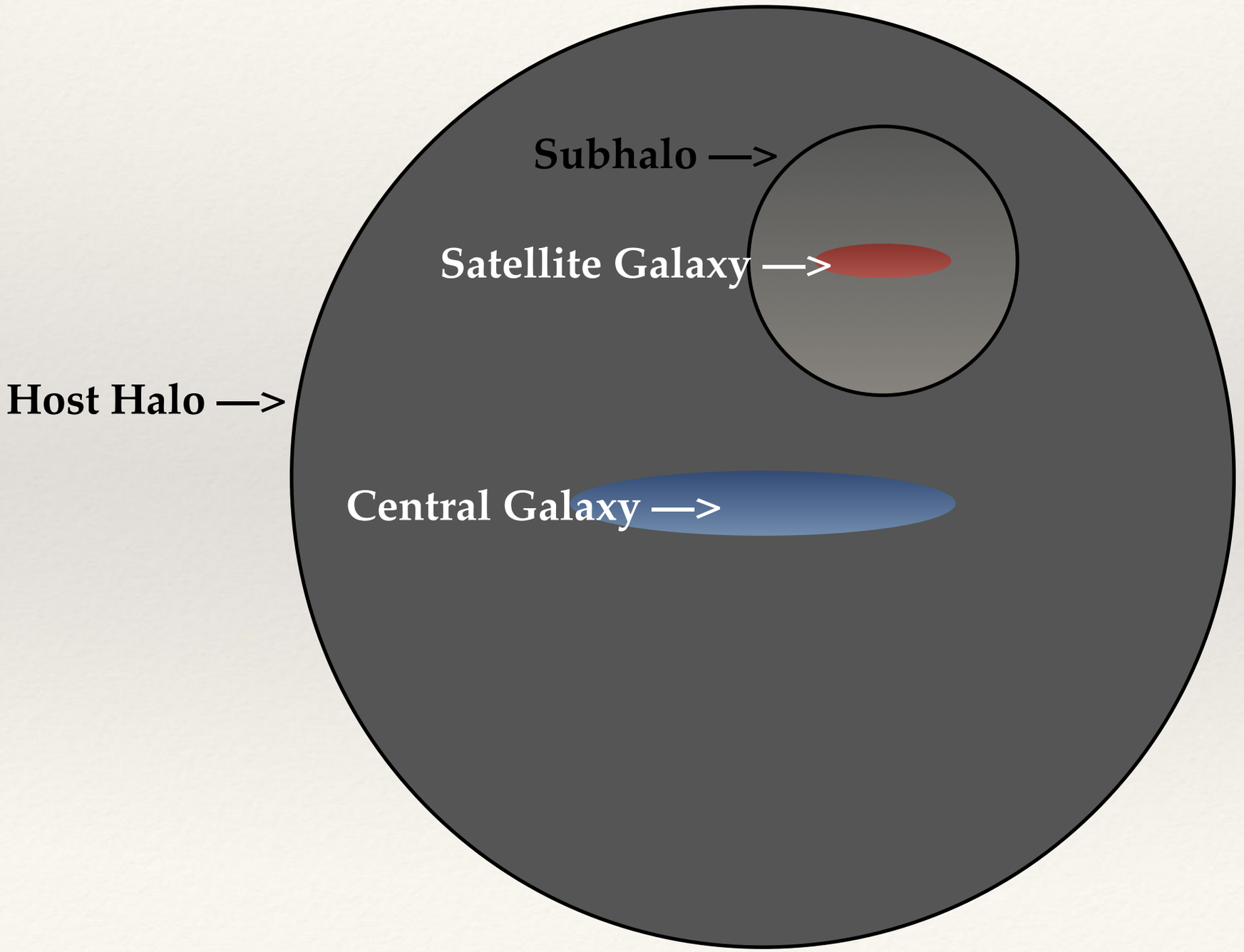
Galaxy & Halo Co-Evolution

Fundamental Tenet



Galaxy & Halo Co-Evolution

Which galaxies live in which (sub)halos?

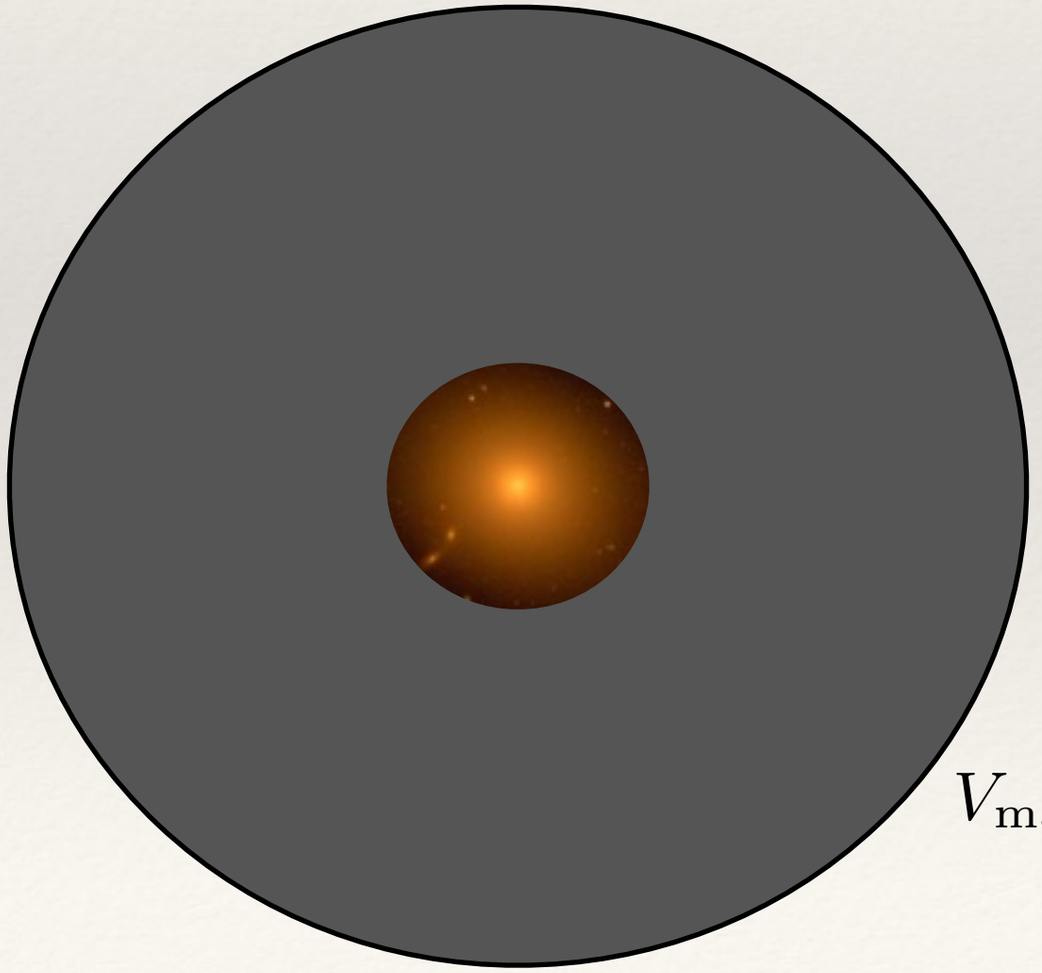


Galaxy & Halo Co-Evolution

How bright is the galaxy in a dark matter halo?

<u>Goal</u>:

Construct a mapping: V_{max} <—> M_r



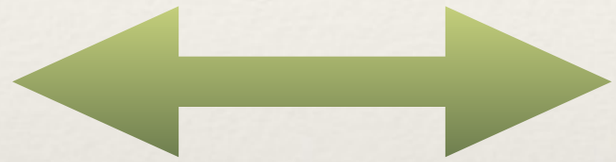
$$V_{\rm max} = GM(< R)/R$$

Galaxy & Halo Co-Evolution

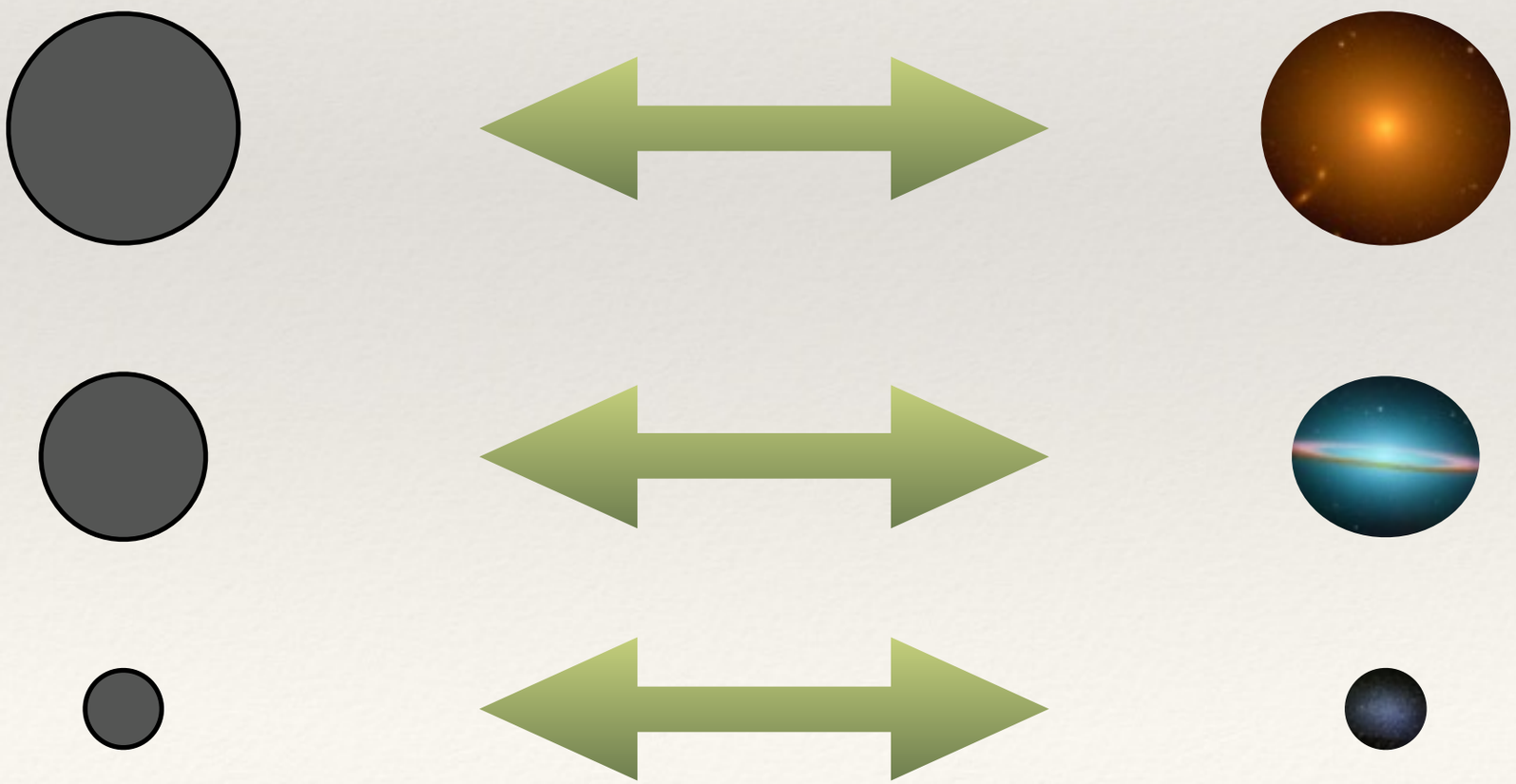
How bright is the galaxy in a dark matter halo?

Abundance Matching Ansatz

Biggest Halos
(Largest Vmax)



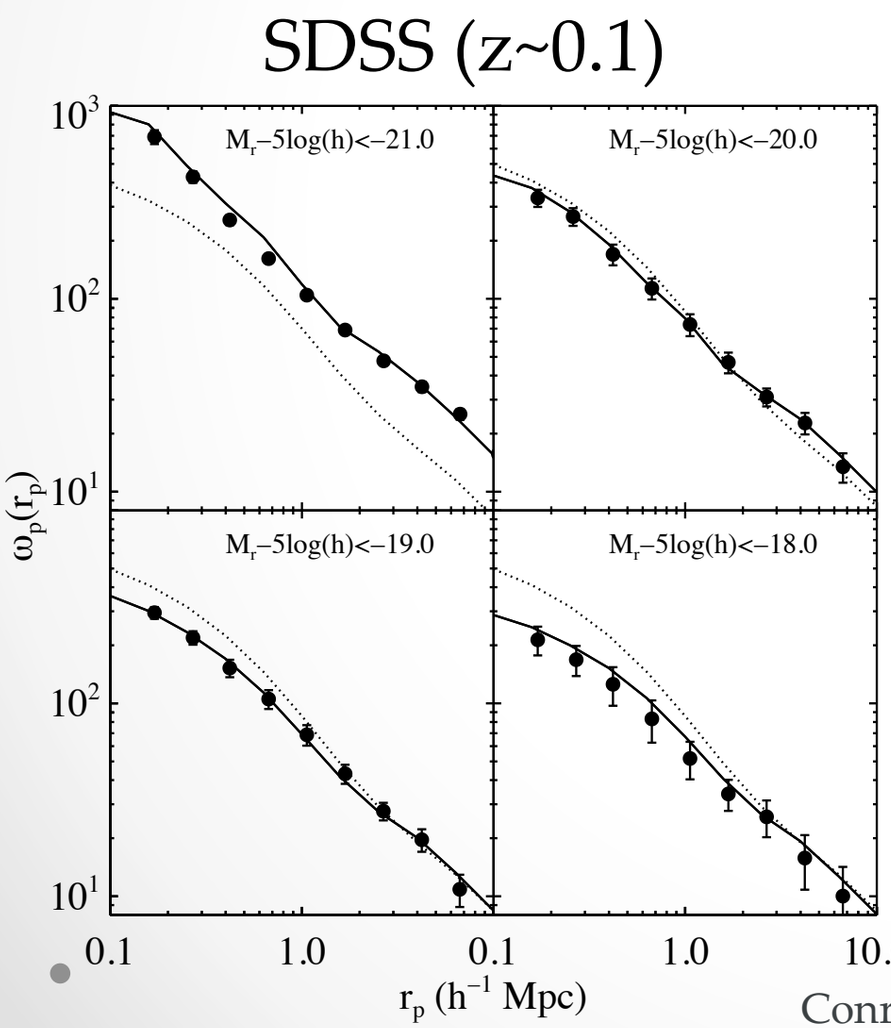
Biggest Galaxies
(Brightest Luminosity)

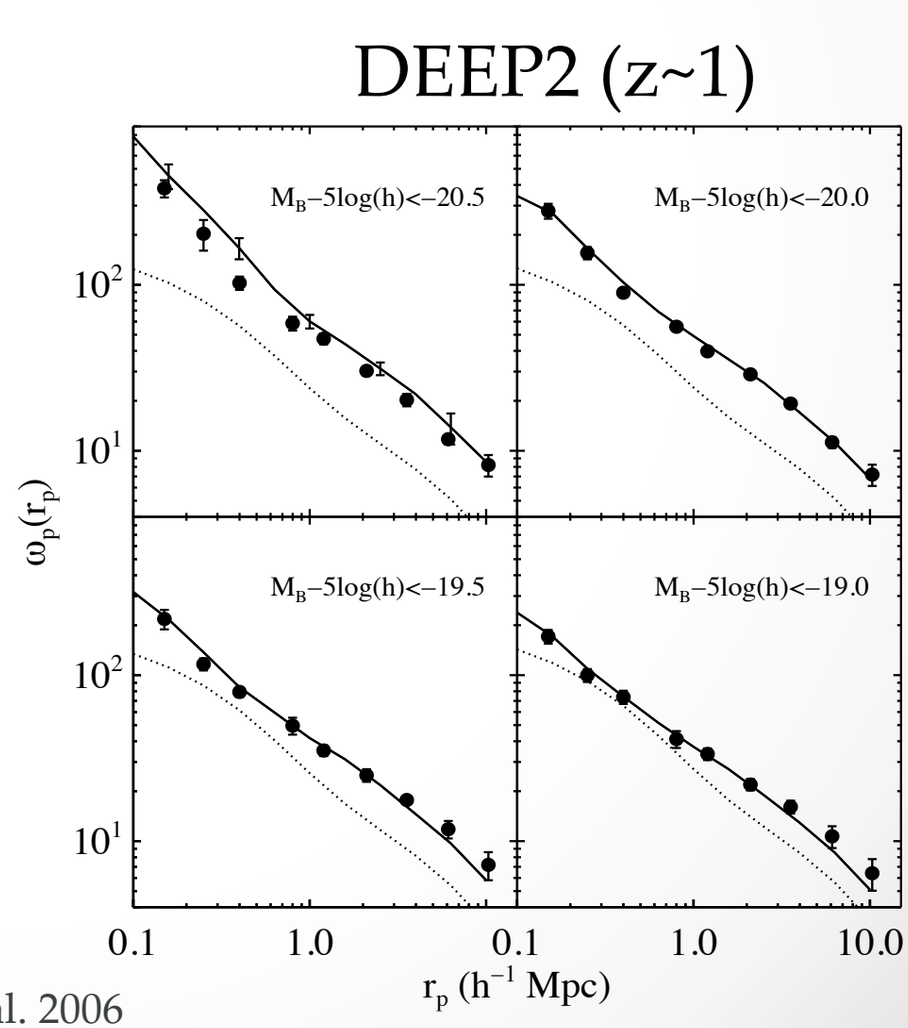


Galaxy & Halo Co-Evolution

How bright is the galaxy in a dark matter halo?

Astounding success across cosmic time!



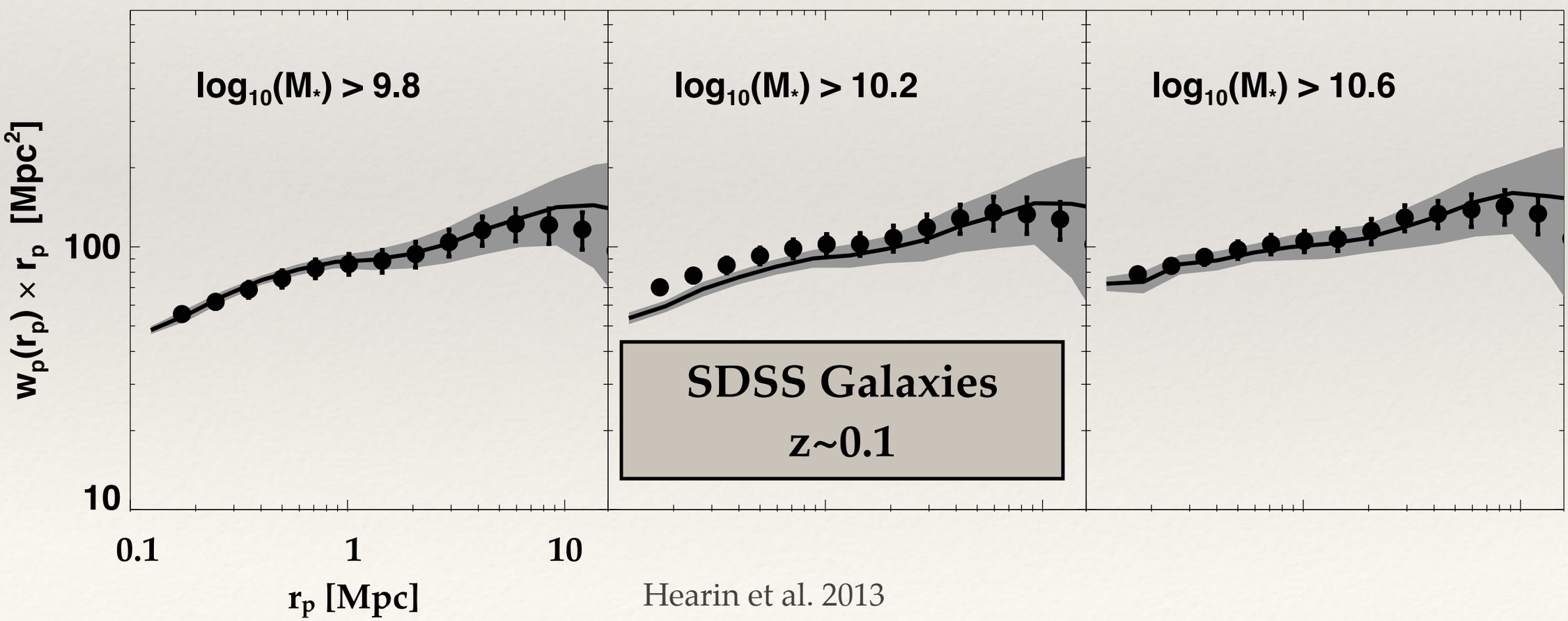


Conroy et al. 2006

Galaxy & Halo Co-Evolution

How much stellar mass fits inside a halo?

Abundance Matching works equally well for M*!

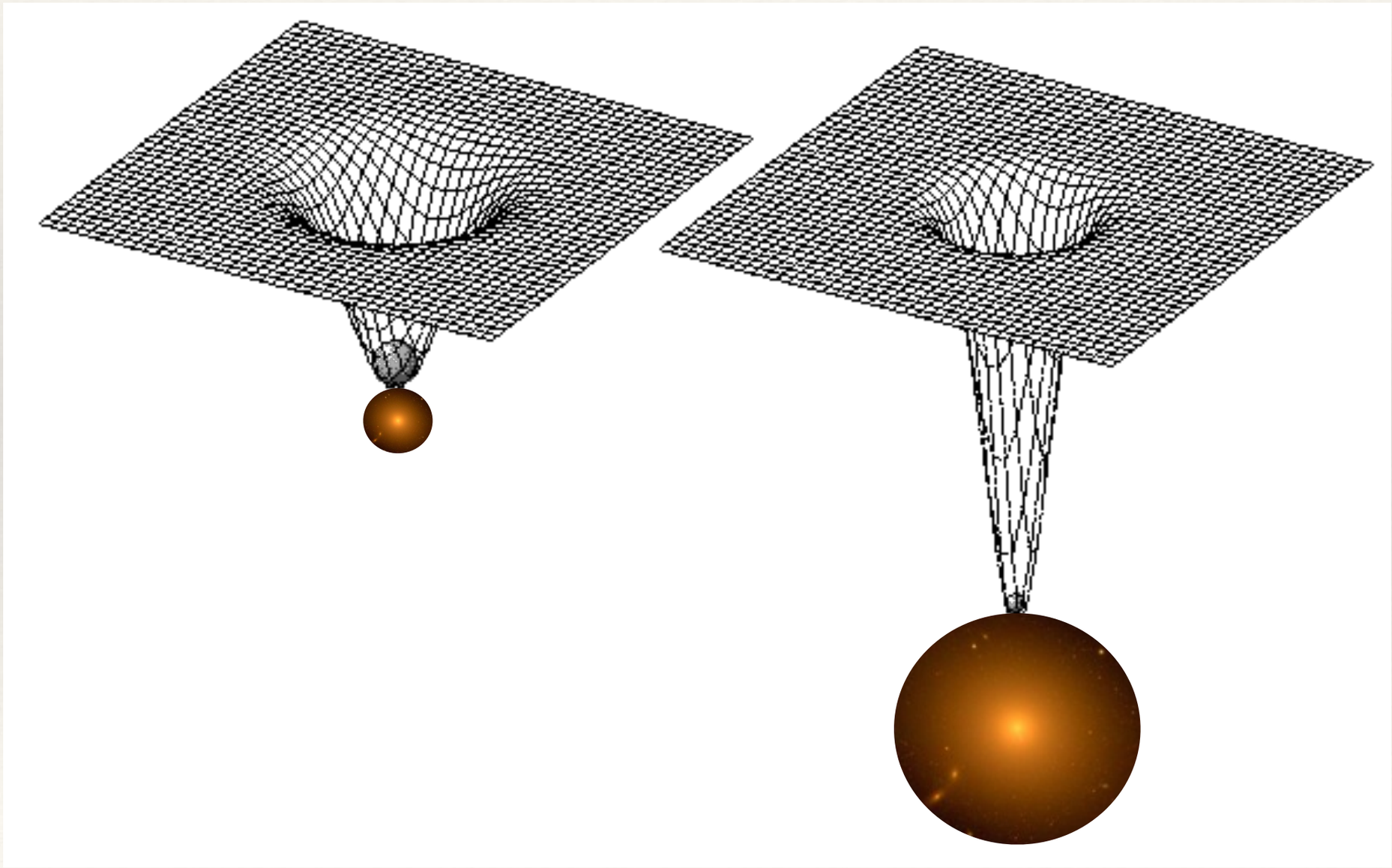


Hearin et al. 2013
arXiv:1310.6747

(See also Behroozi et al. 2012; Reddick et al. 2013)

Galaxy & Halo Co-Evolution

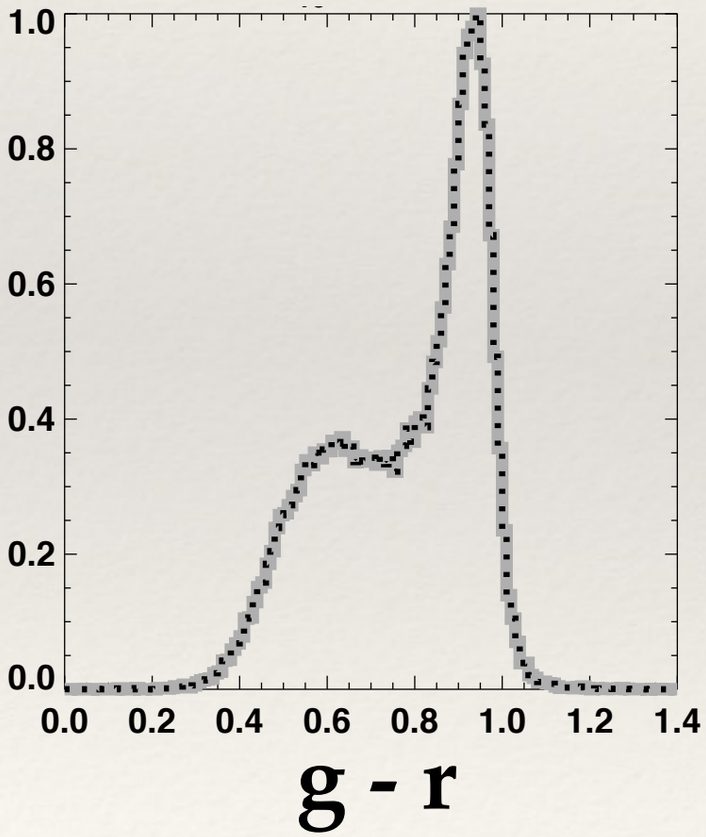
Upshot of Abundance Matching



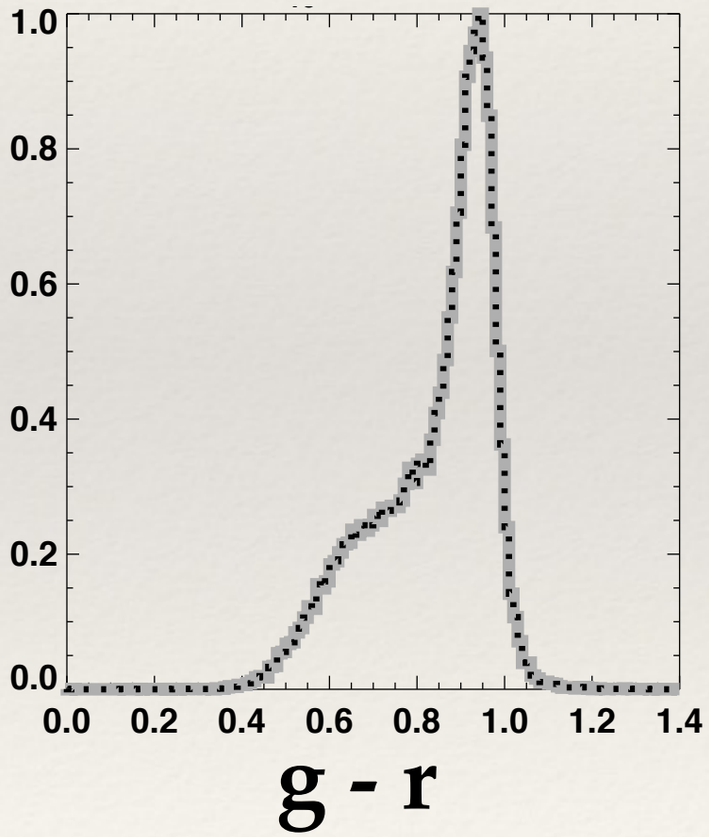
Galaxy & Halo Co-Evolution

What color is the galaxy in a dark matter halo?

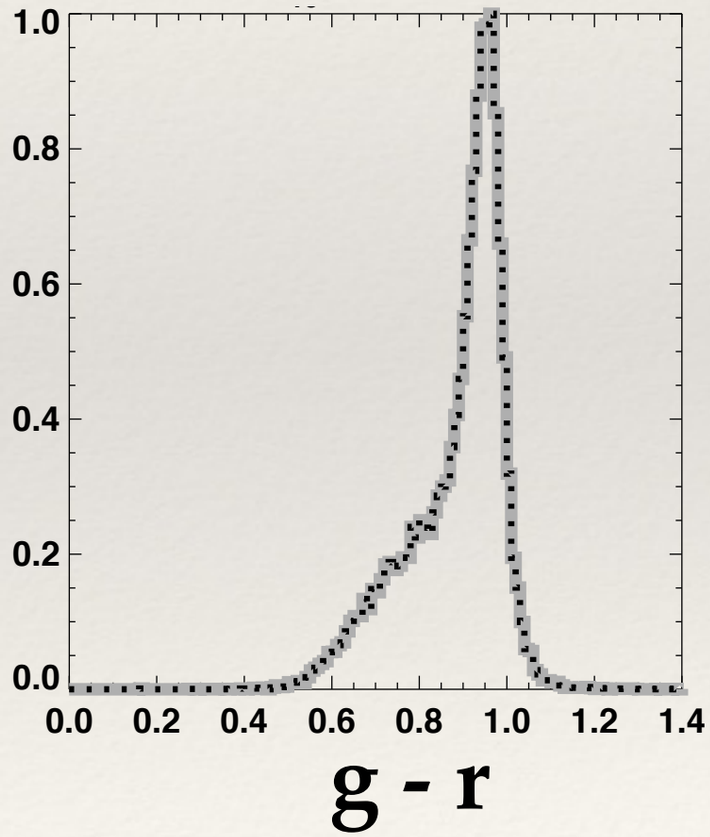
$M_* \sim 10^{10} M_\odot$



$M_* \sim 10^{10.5} M_\odot$



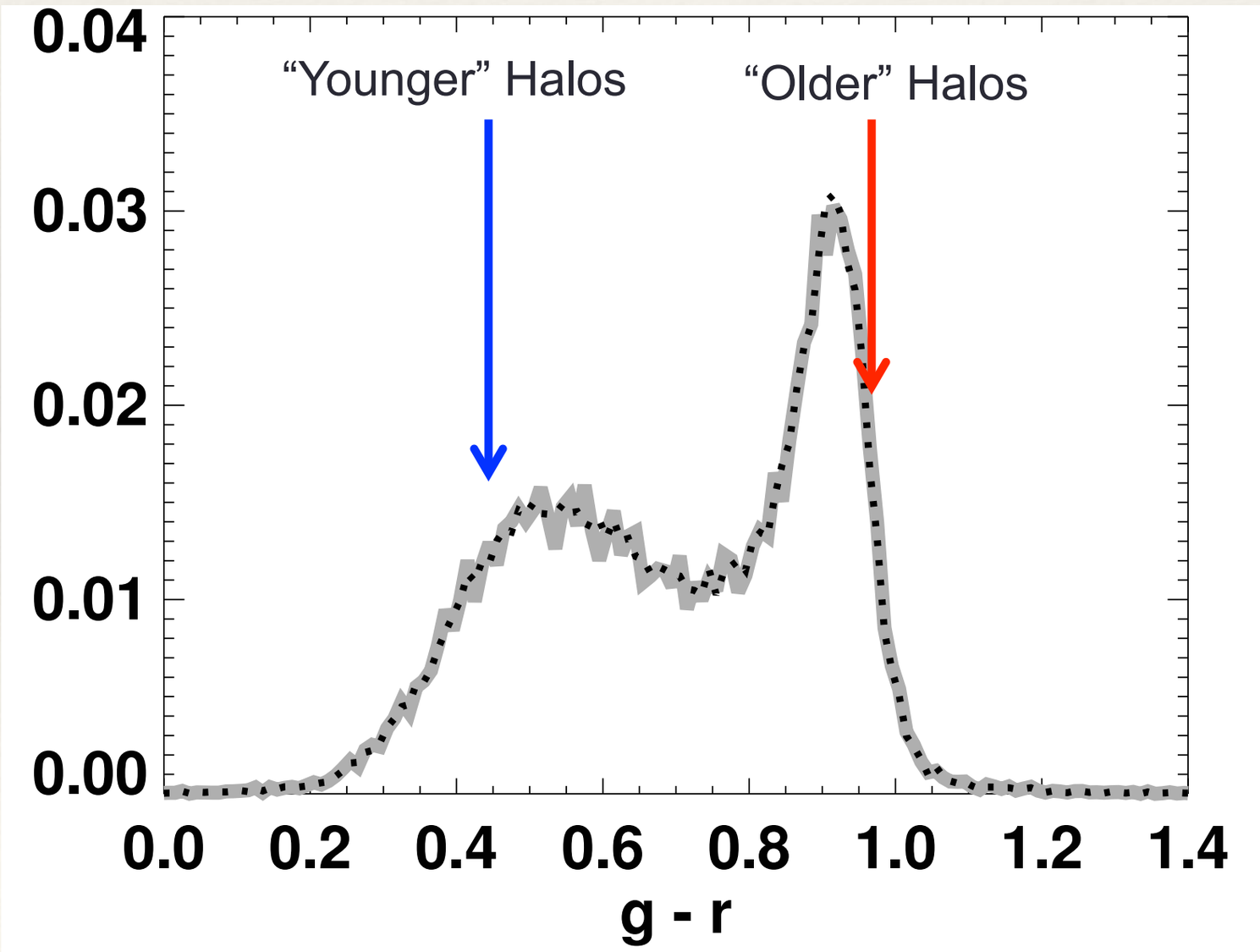
$M_* \sim 10^{11} M_\odot$



Galaxy & Halo Co-Evolution

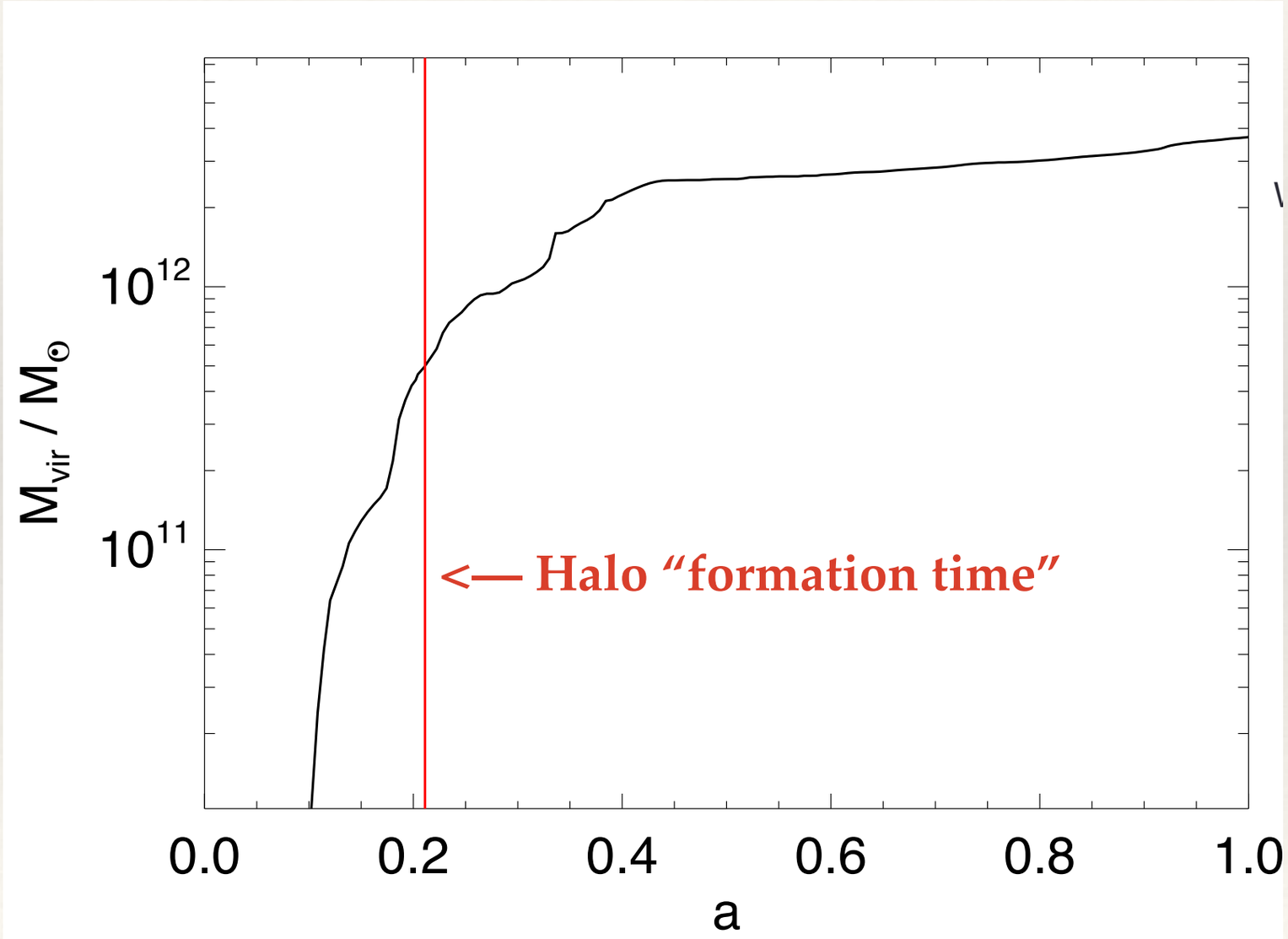
What color is the galaxy in a dark matter halo?

Age Matching Ansatz



Galaxy & Halo Co-Evolution

How old is a dark matter halo?

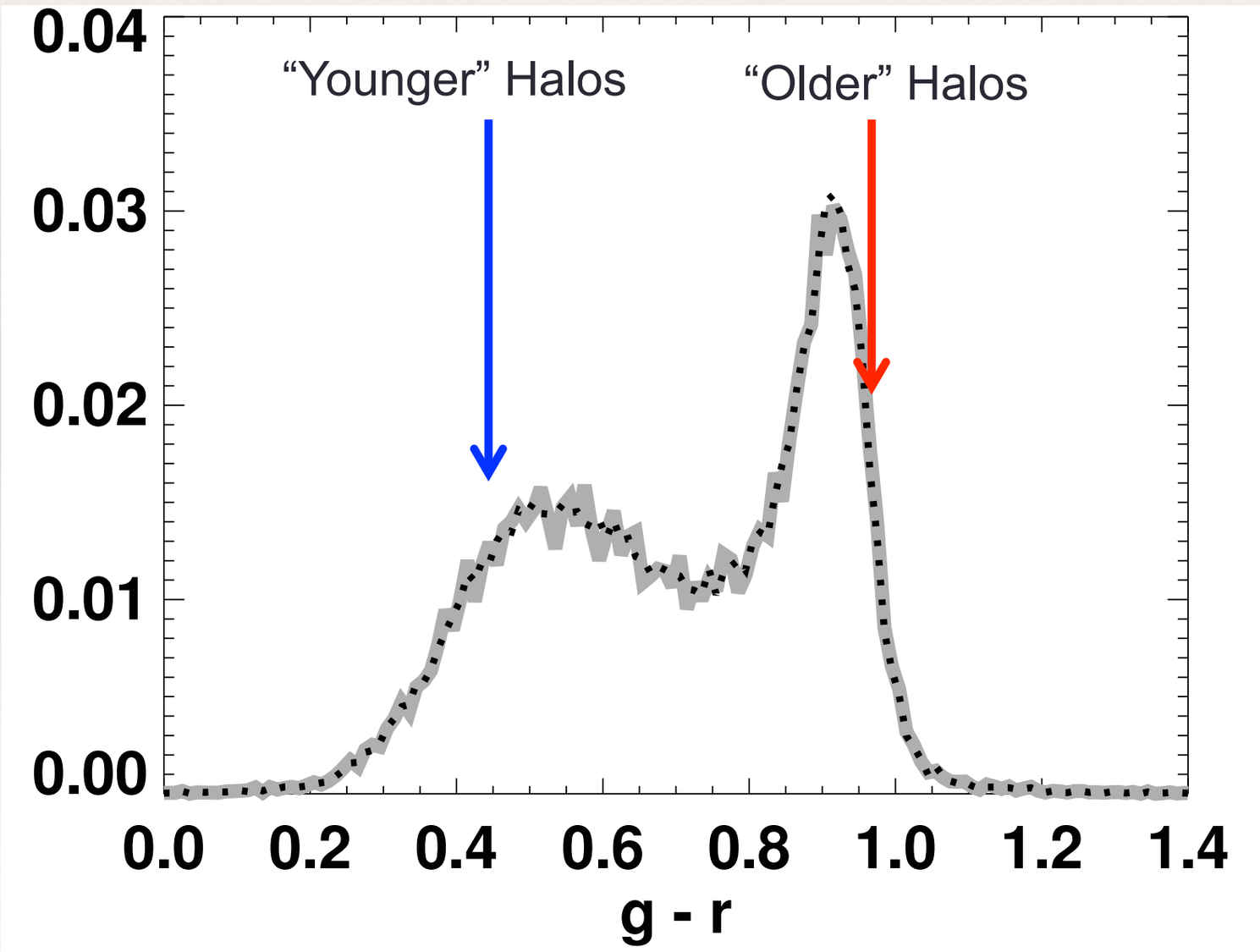


See e.g., Wechsler 2002; Zhao 2003

Galaxy & Halo Co-Evolution

What color is the galaxy in a dark matter halo?

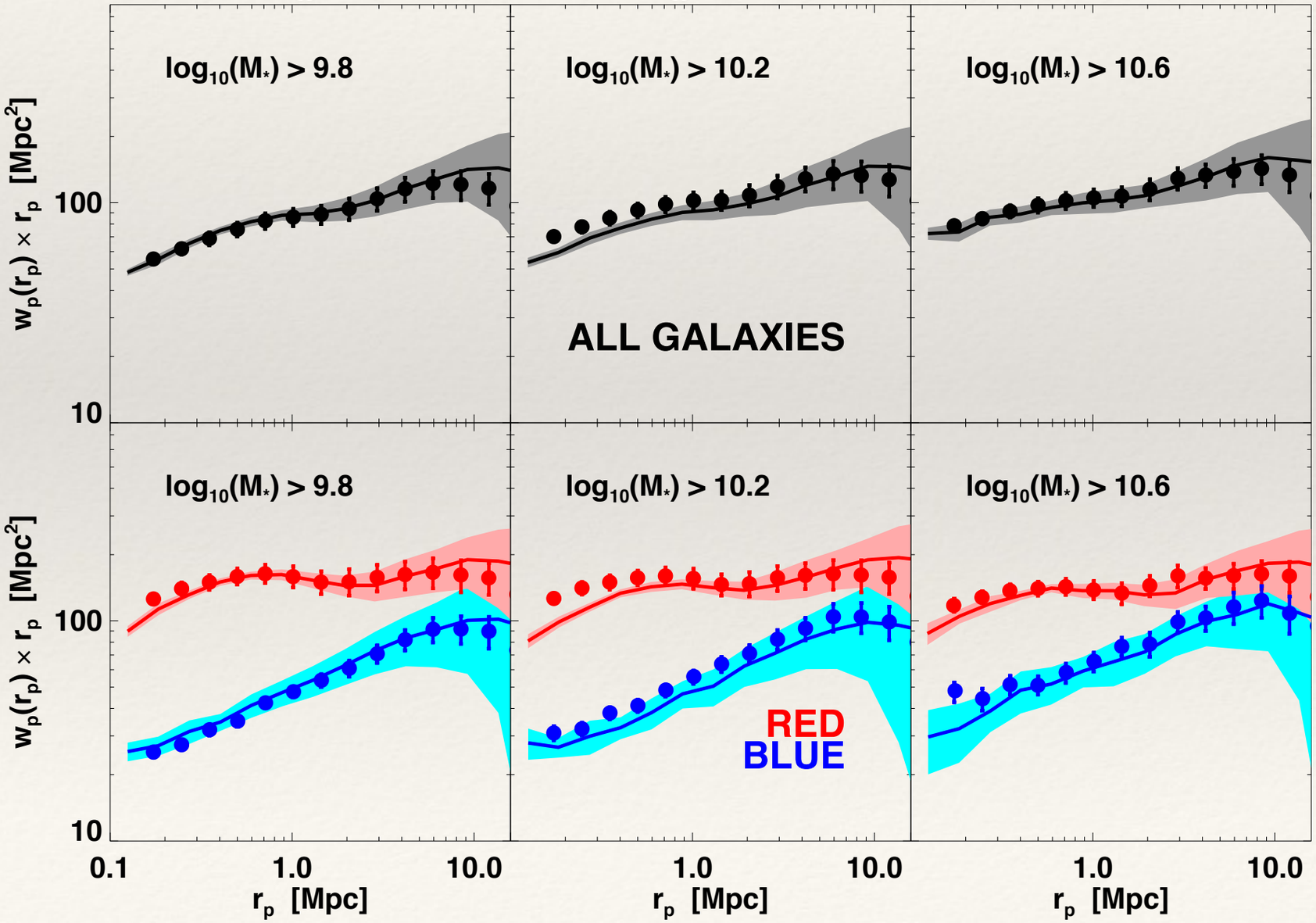
Age Matching Ansatz



Galaxy & Halo Co-Evolution

What color is the galaxy in a dark matter halo?

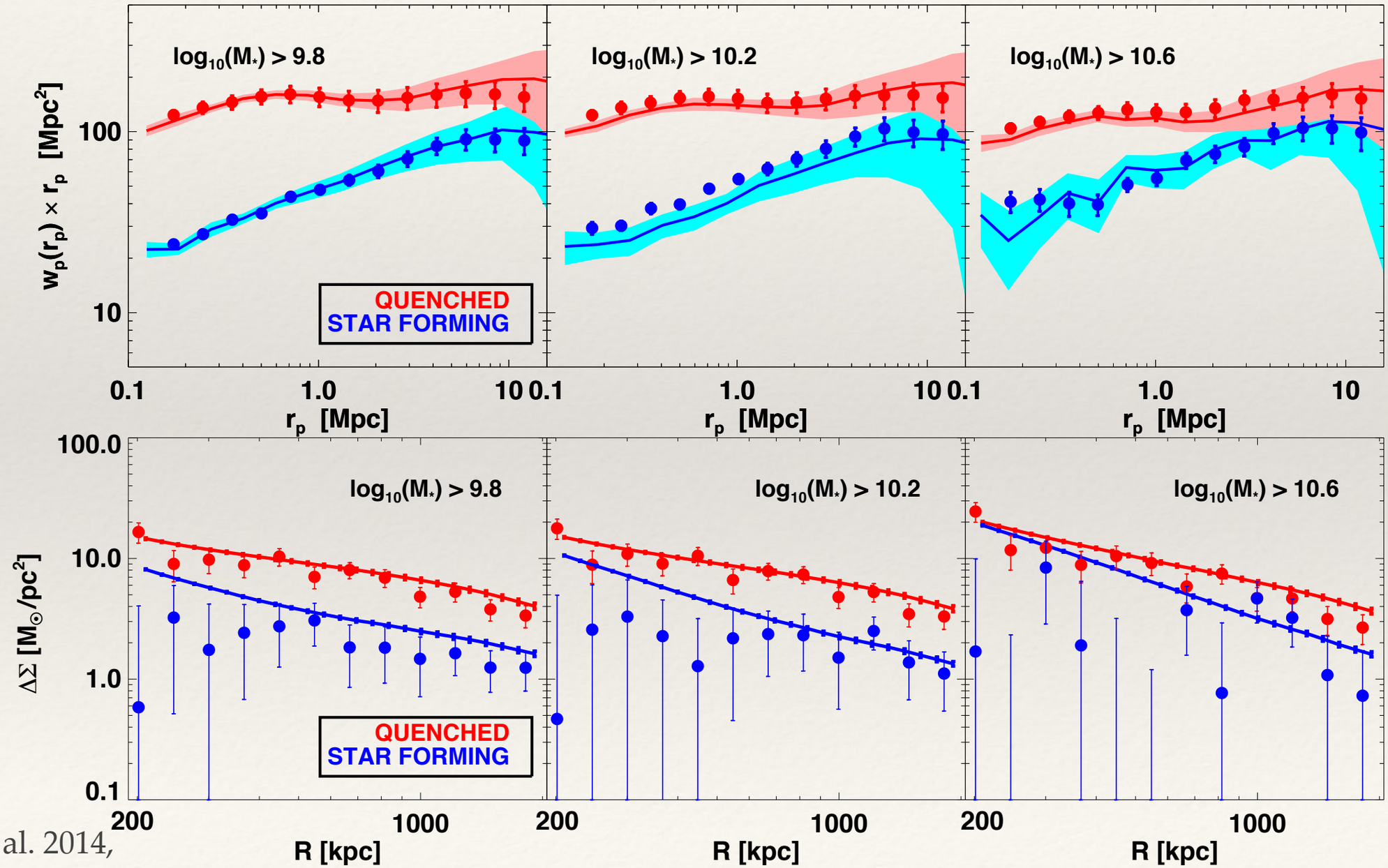
Age Matching Prediction



Hearin et al. 2013
arXiv:1310.6747

Galaxy & Halo Co-Evolution

From Color to Star Formation Rate

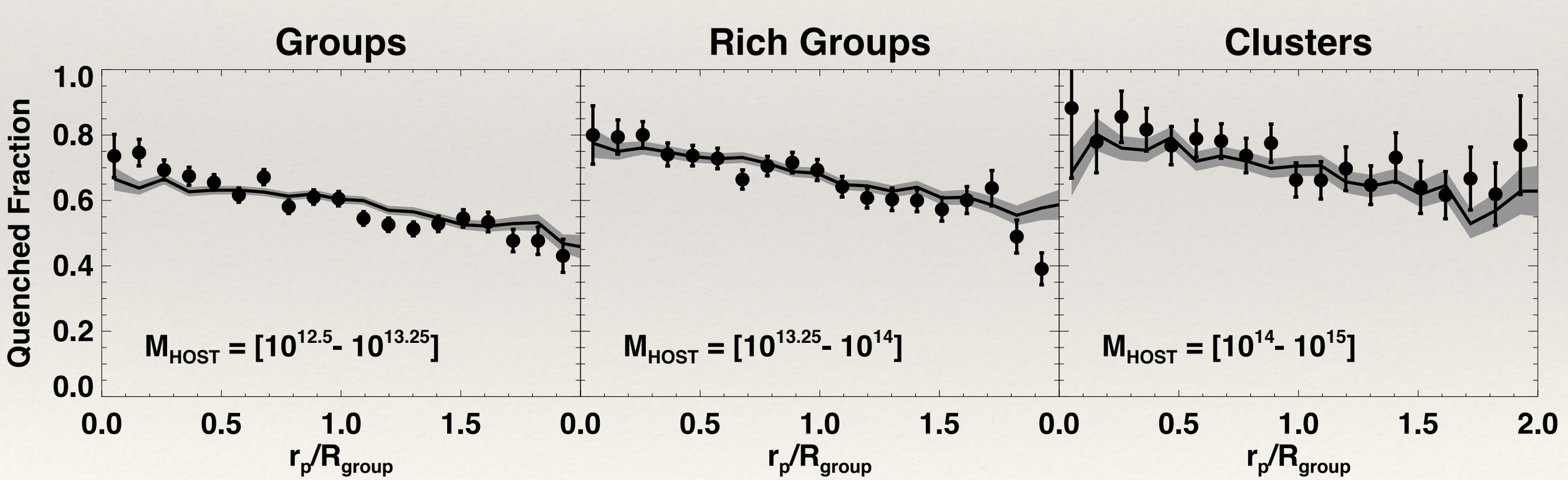


Watson et al. 2014,
arXiv:1403.1578

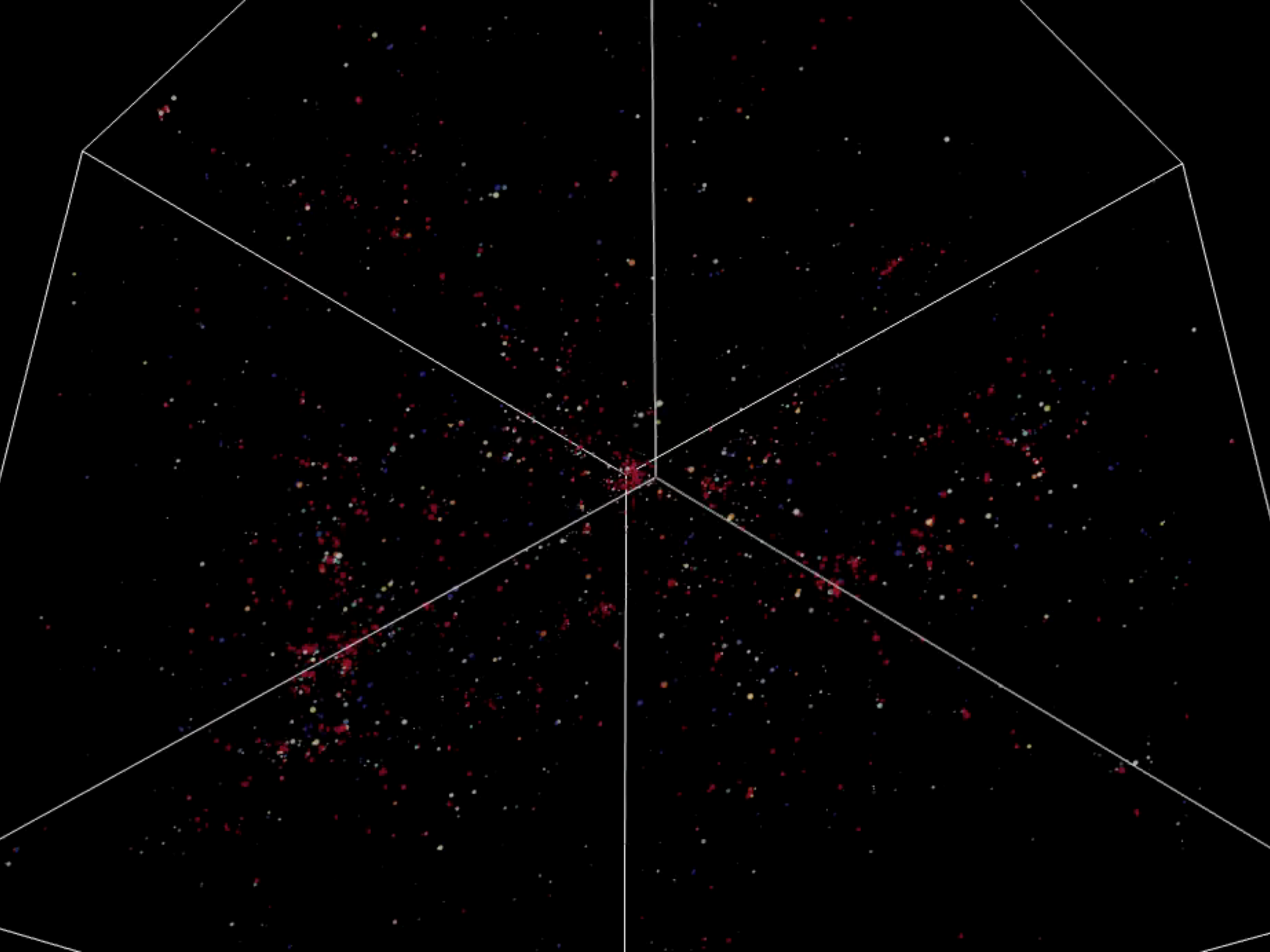
Galaxy & Halo Co-Evolution

Satellite Quenching Profiles

Age Matching Prediction



Watson et al. 2014,
arXiv:1403.1578



Galaxy & Halo Co-Evolution

Age Matching mocks publicly available at:

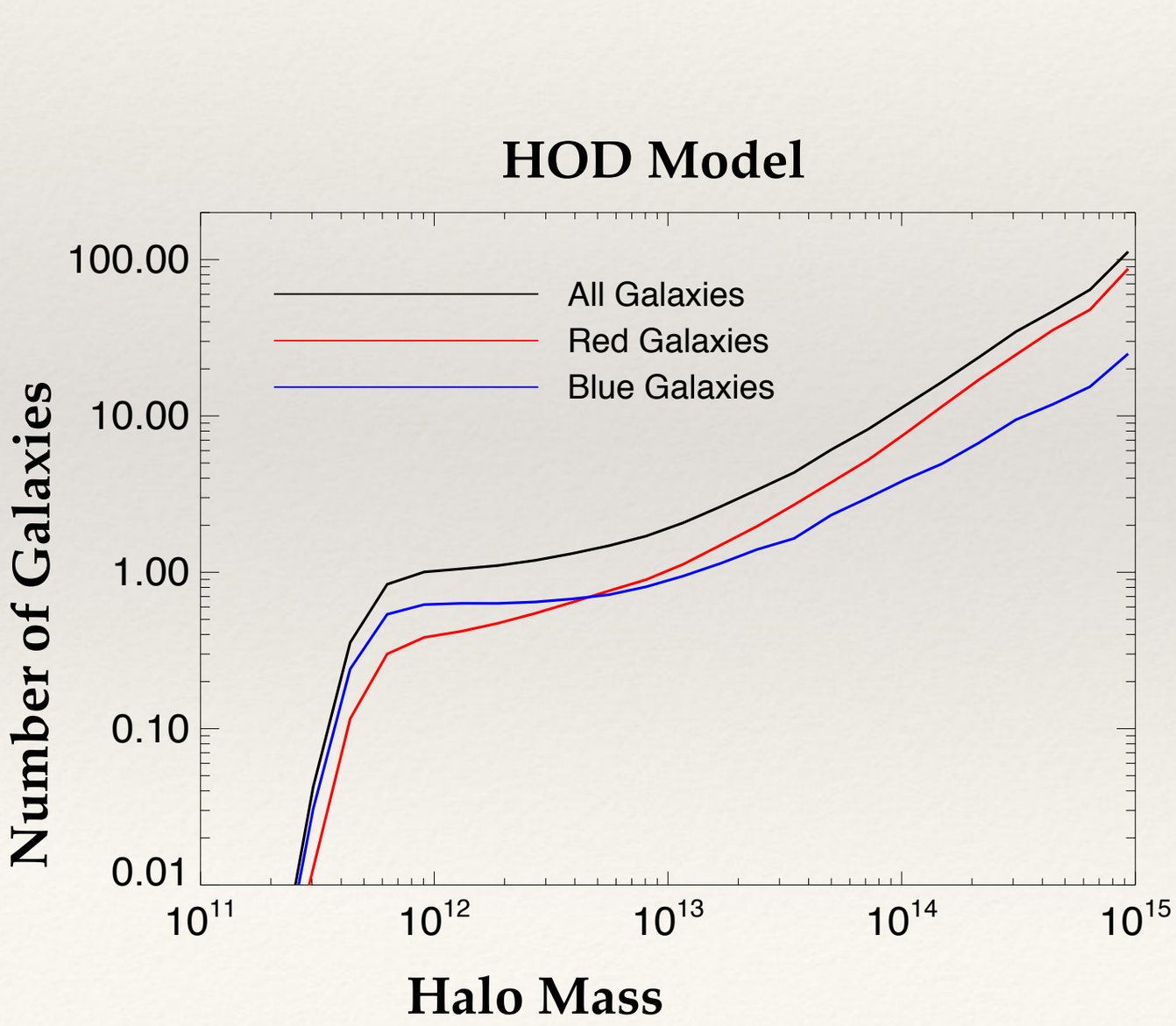
http://logrus.uchicago.edu/~aphearin

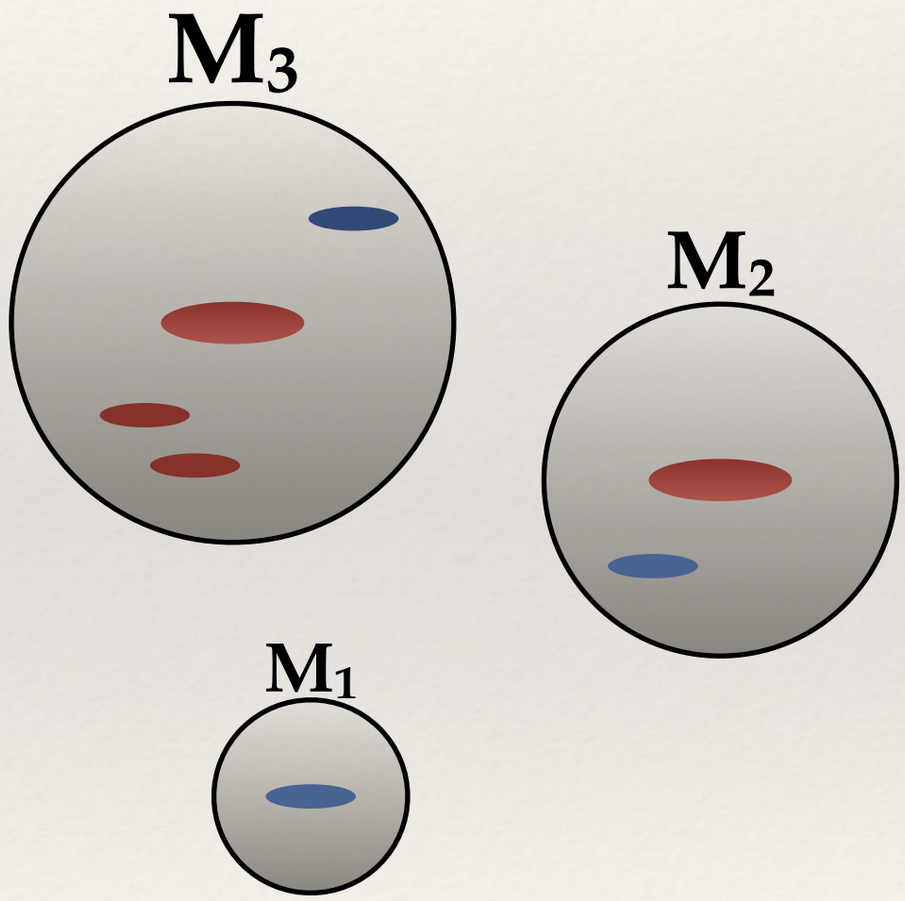
Part III

The Threat of Assembly Bias

The Threat of Assembly Bias

The Halo Occupation Distribution (HOD) in a Nutshell



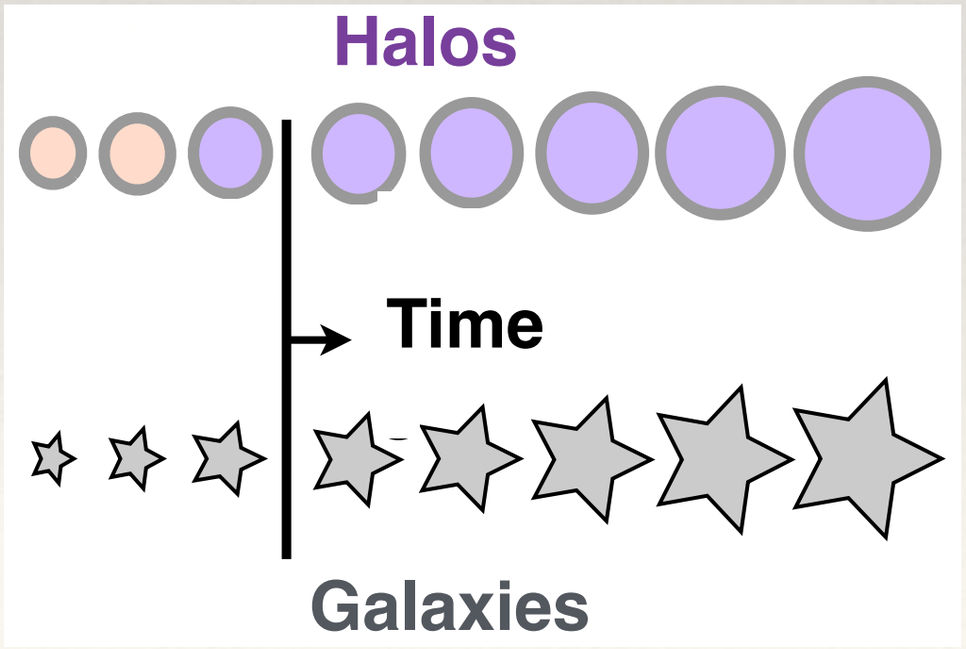


The Threat of Assembly Bias

Age Matching and the HOD: Mutually Incompatible Assumptions

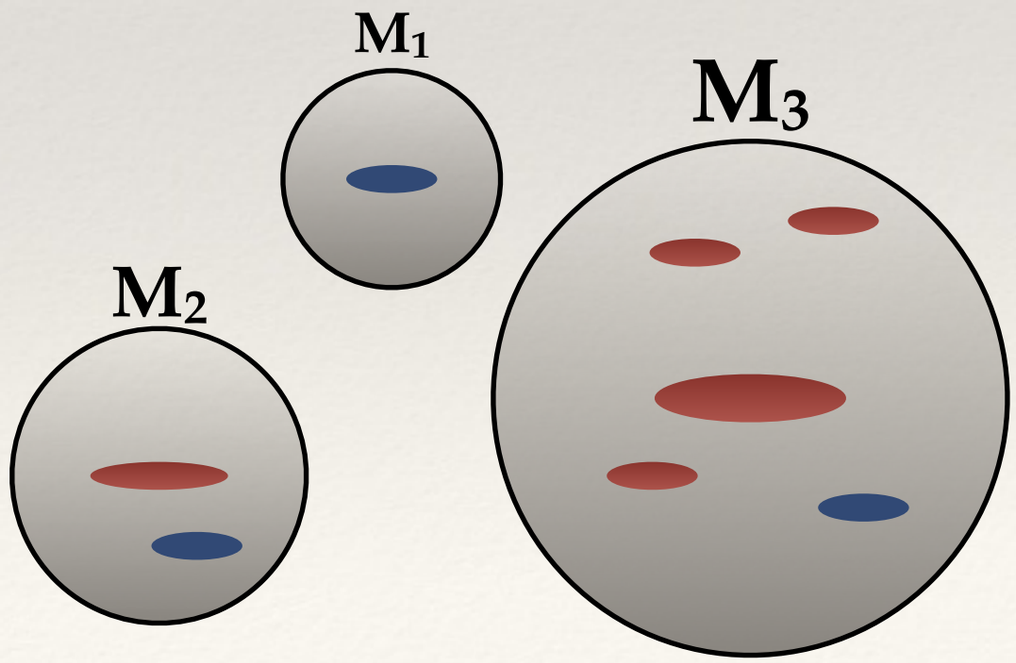
Age Matching:

Galaxies & halos co-evolve



HOD:

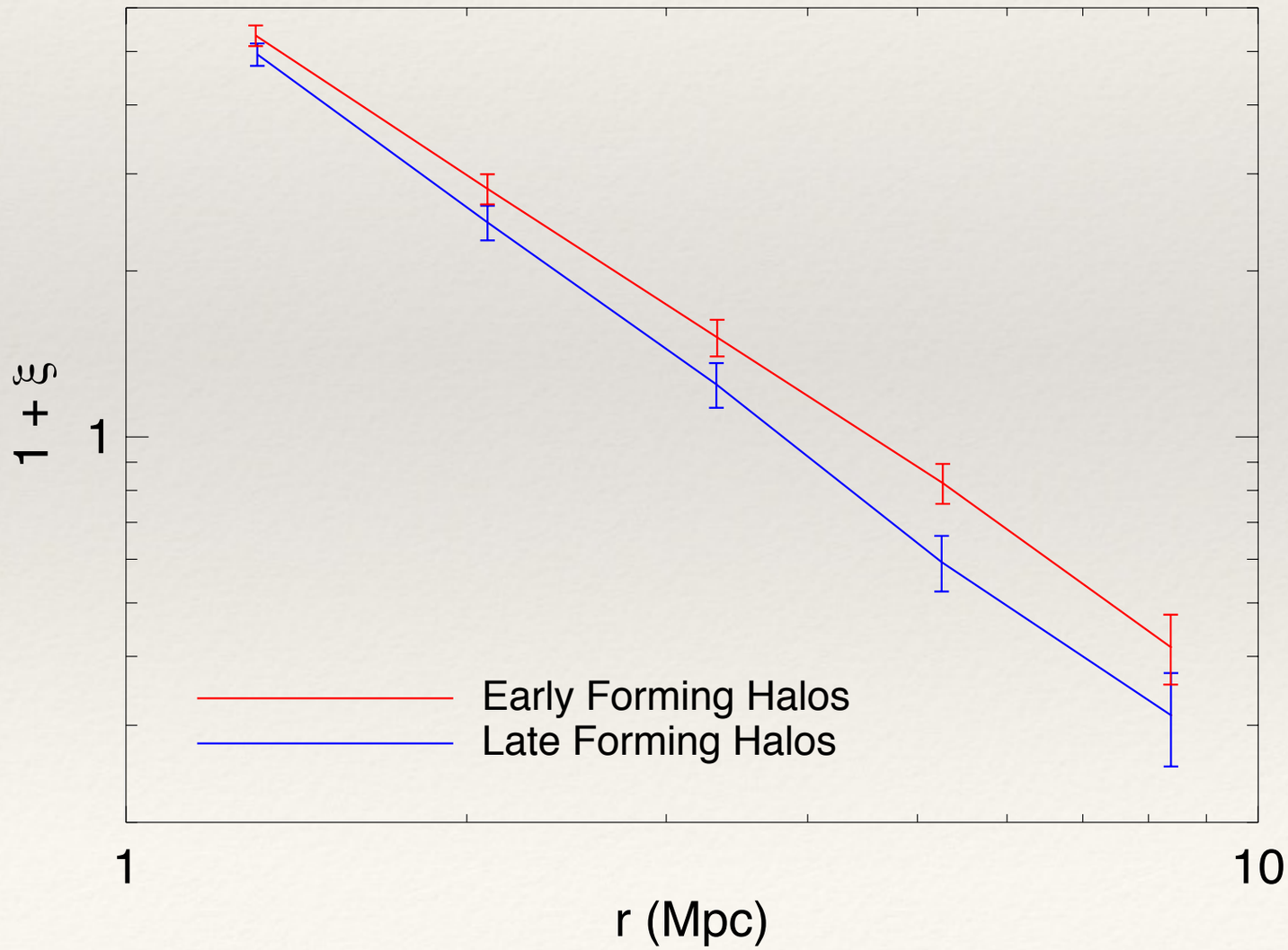
"Halo mass is king"



The Threat of Assembly Bias

Why do these differences matter?

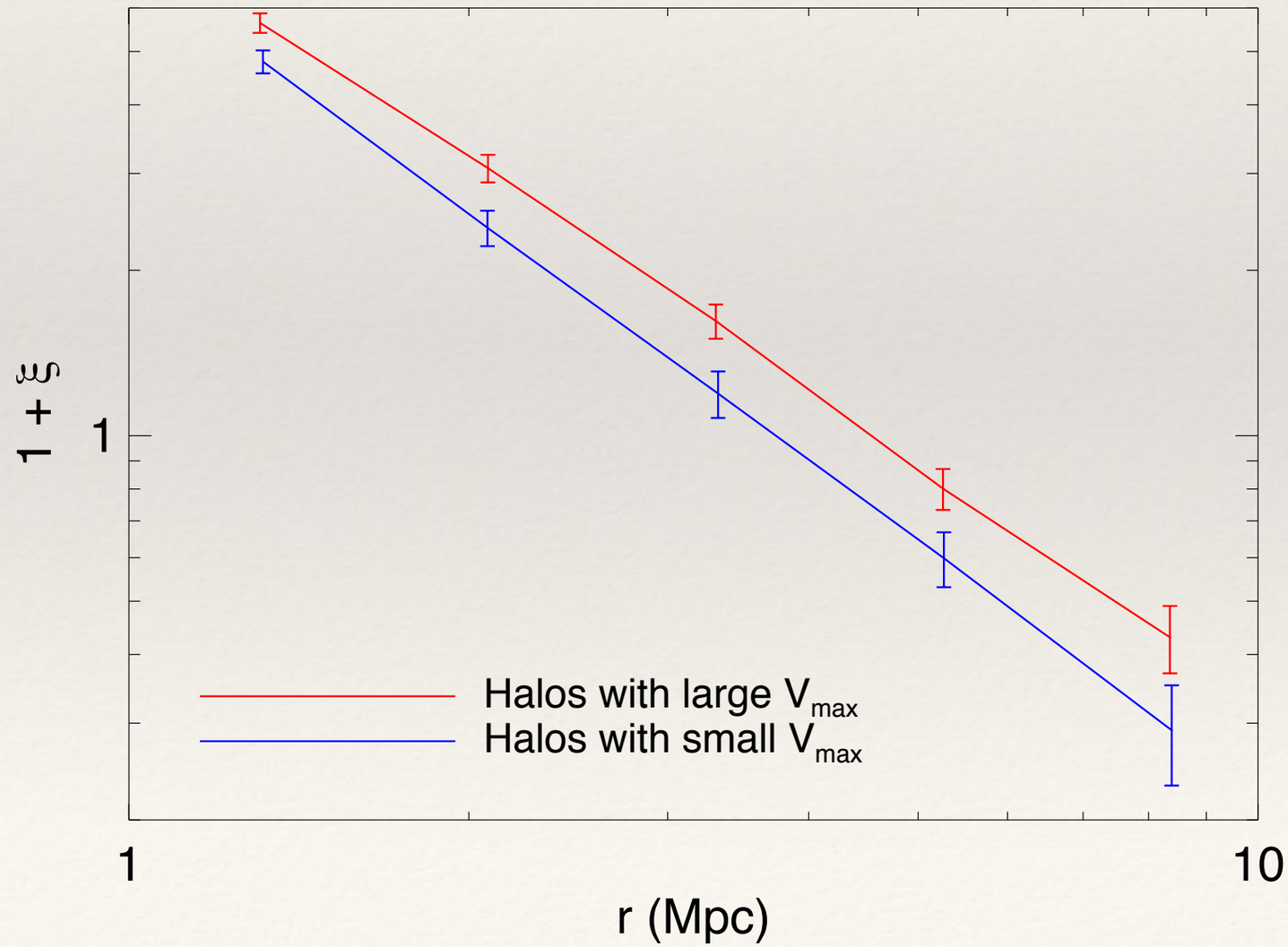
Formation time impacts halo clustering *at fixed mass*



The Threat of Assembly Bias

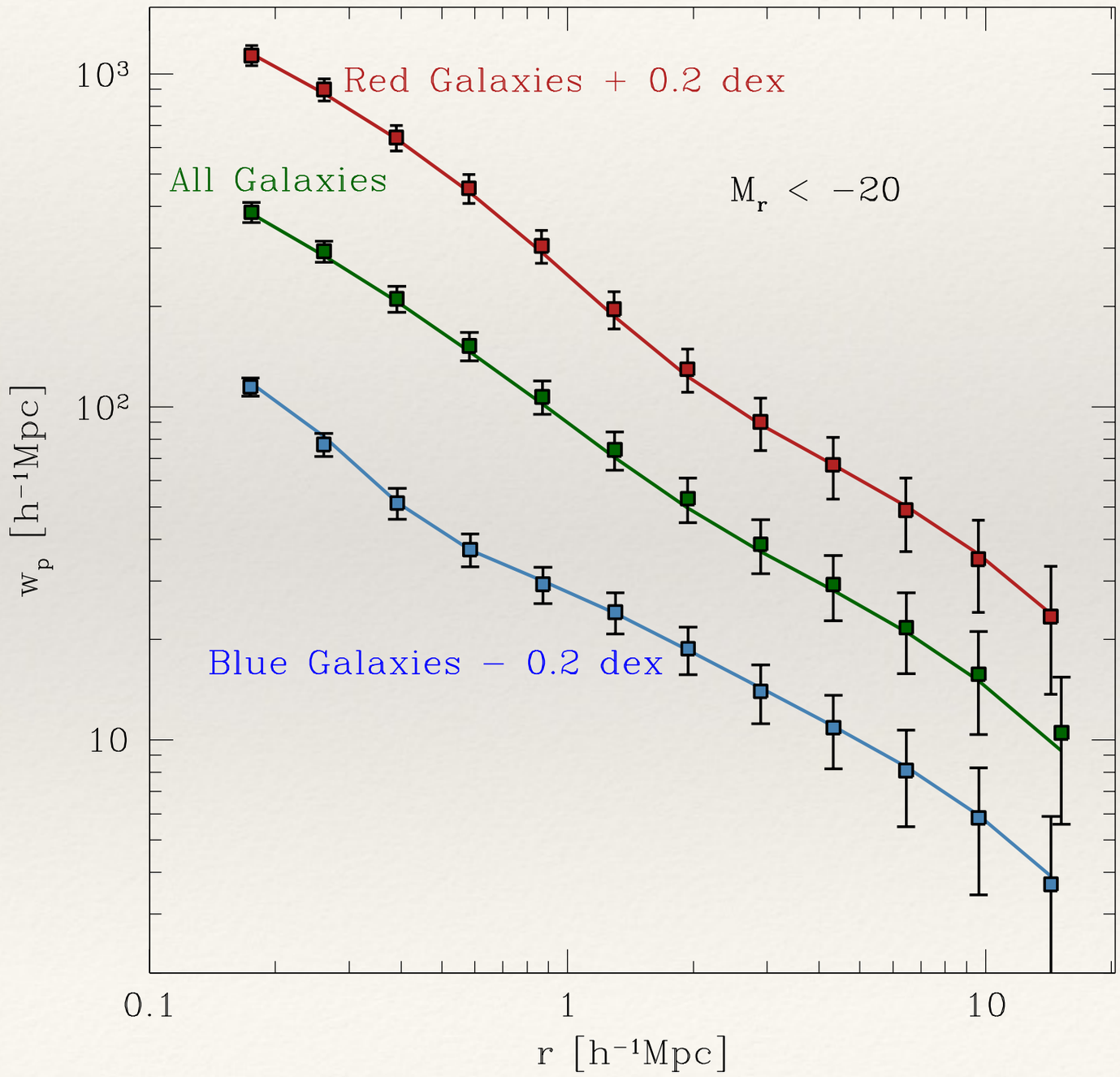
Why do these differences matter?

Potential well depth impacts halo clustering *at fixed mass*



The Threat of Assembly Bias

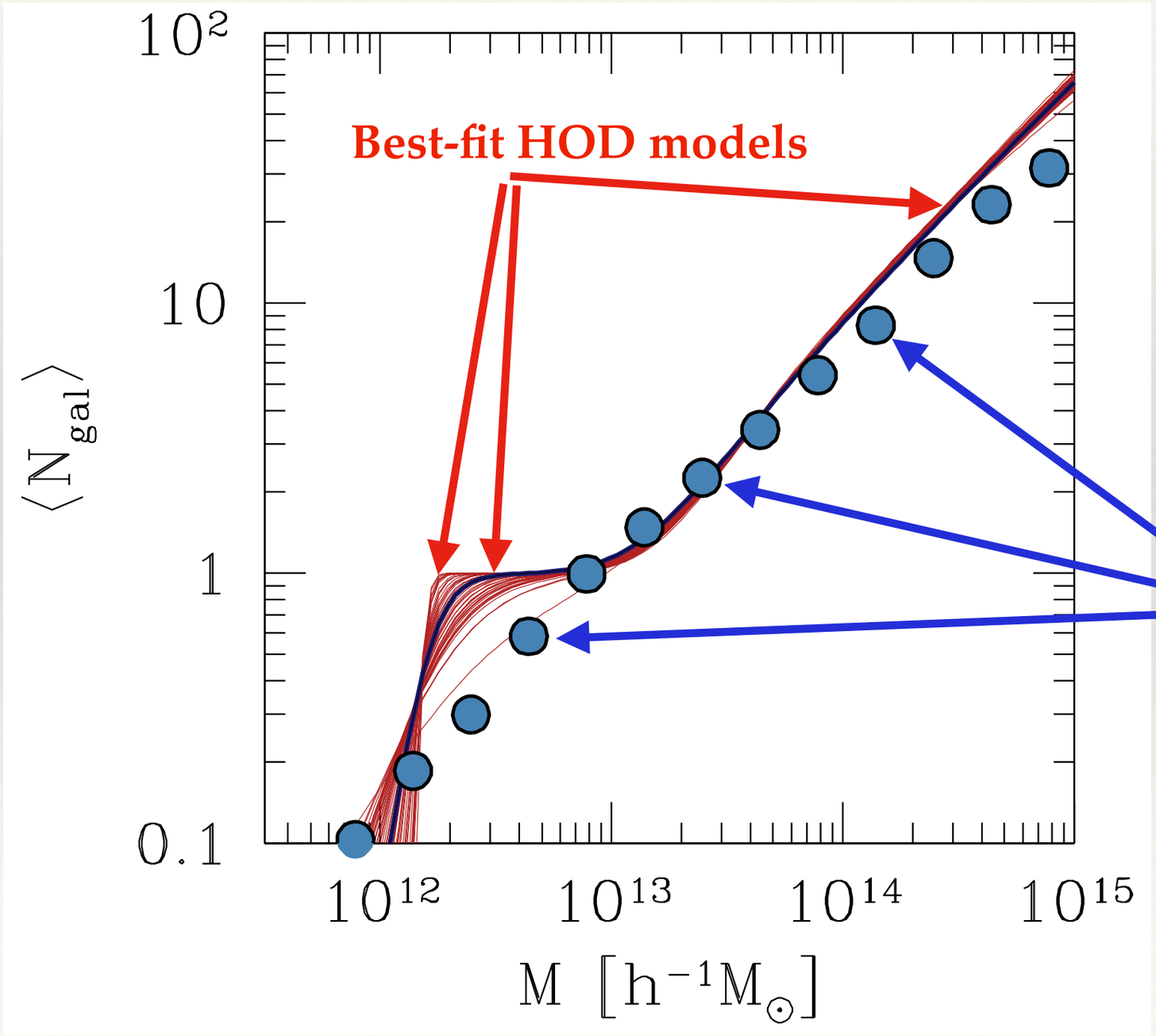
HOD fit to Age Matching mock



Zentner et al. 2013
arXiv:1311.1818

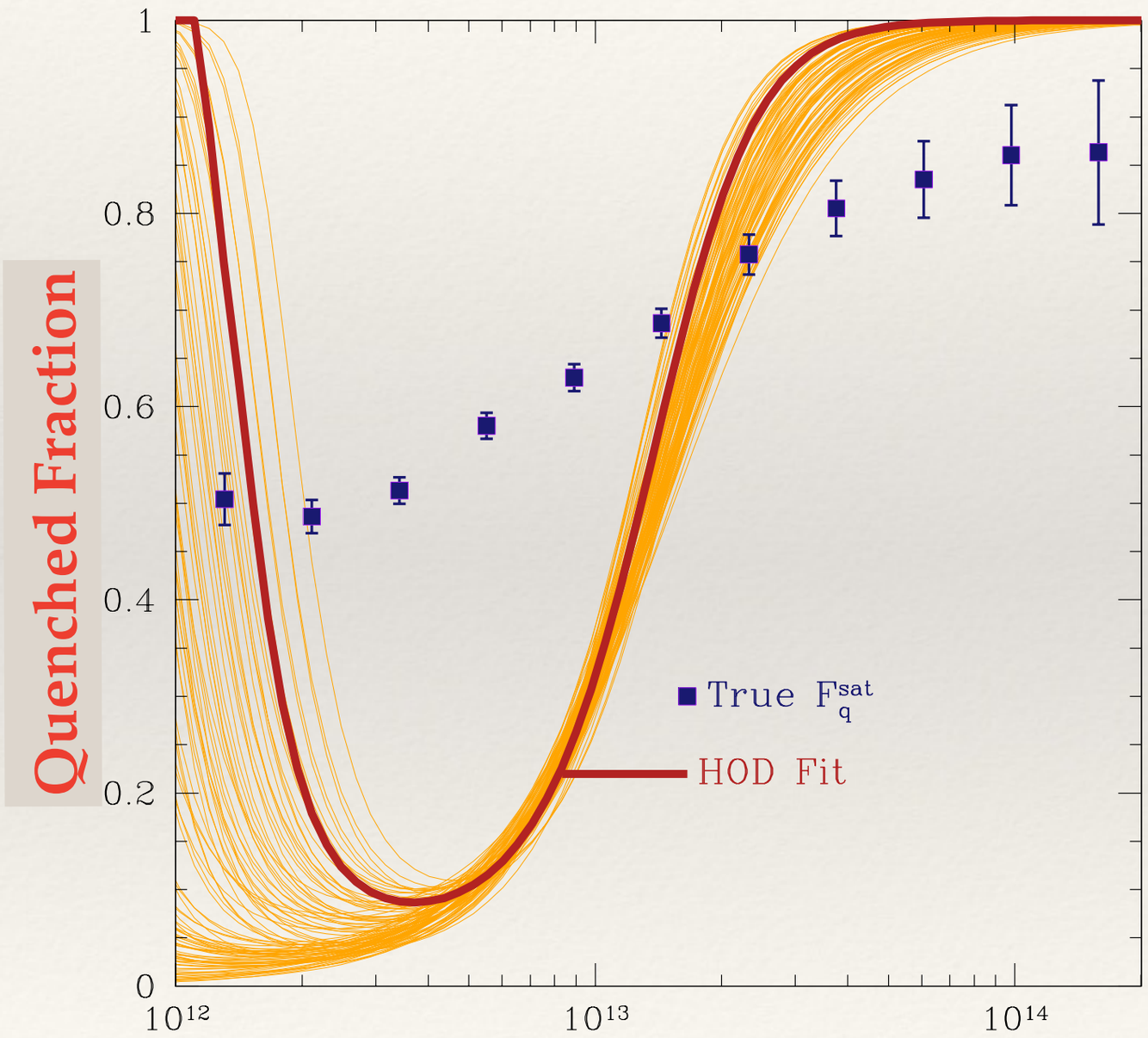
The Threat of Assembly Bias

Best-fitting HOD is Systematically Biased!



The Threat of Assembly Bias

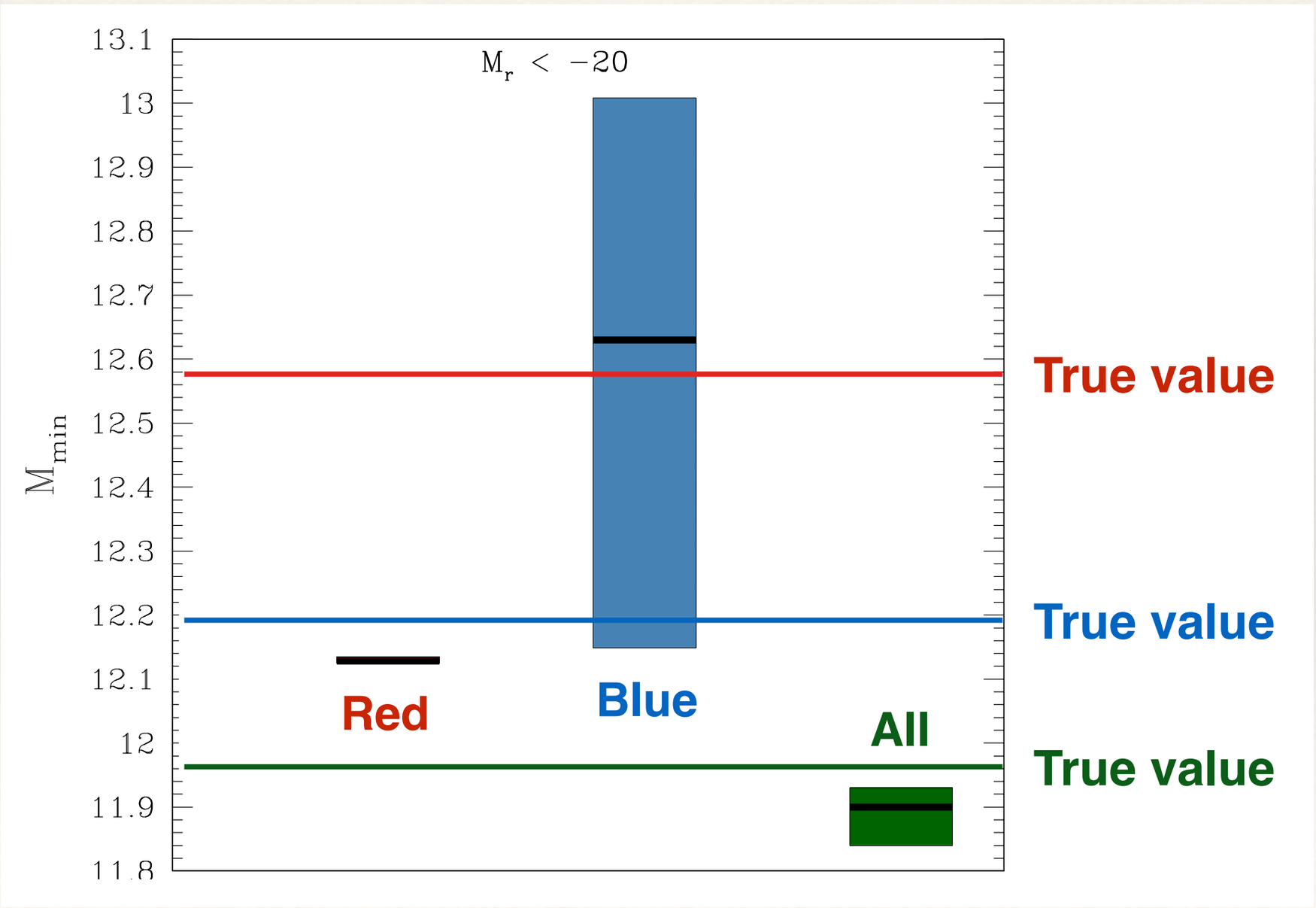
Systematic error on satellite quenching



Zentner et al. 2013
arXiv:1311.1818

The Threat of Assembly Bias

Systematic error on M_{min}

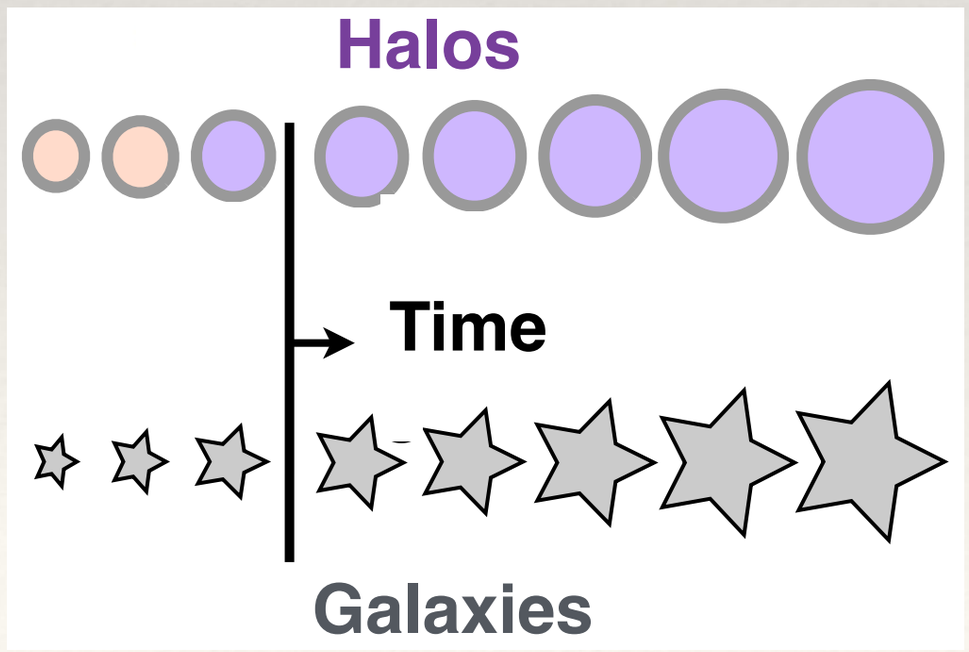


Zentner et al. 2013
arXiv:1311.1818

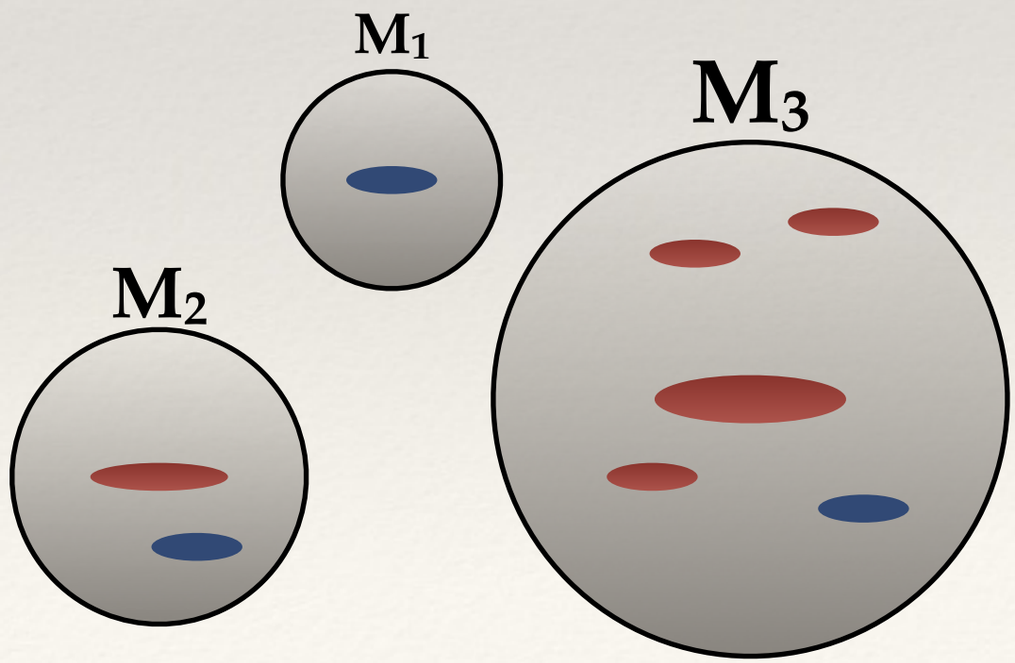
Part IV

Model Discrimination: Observations of Assembly Bias

Age Matching

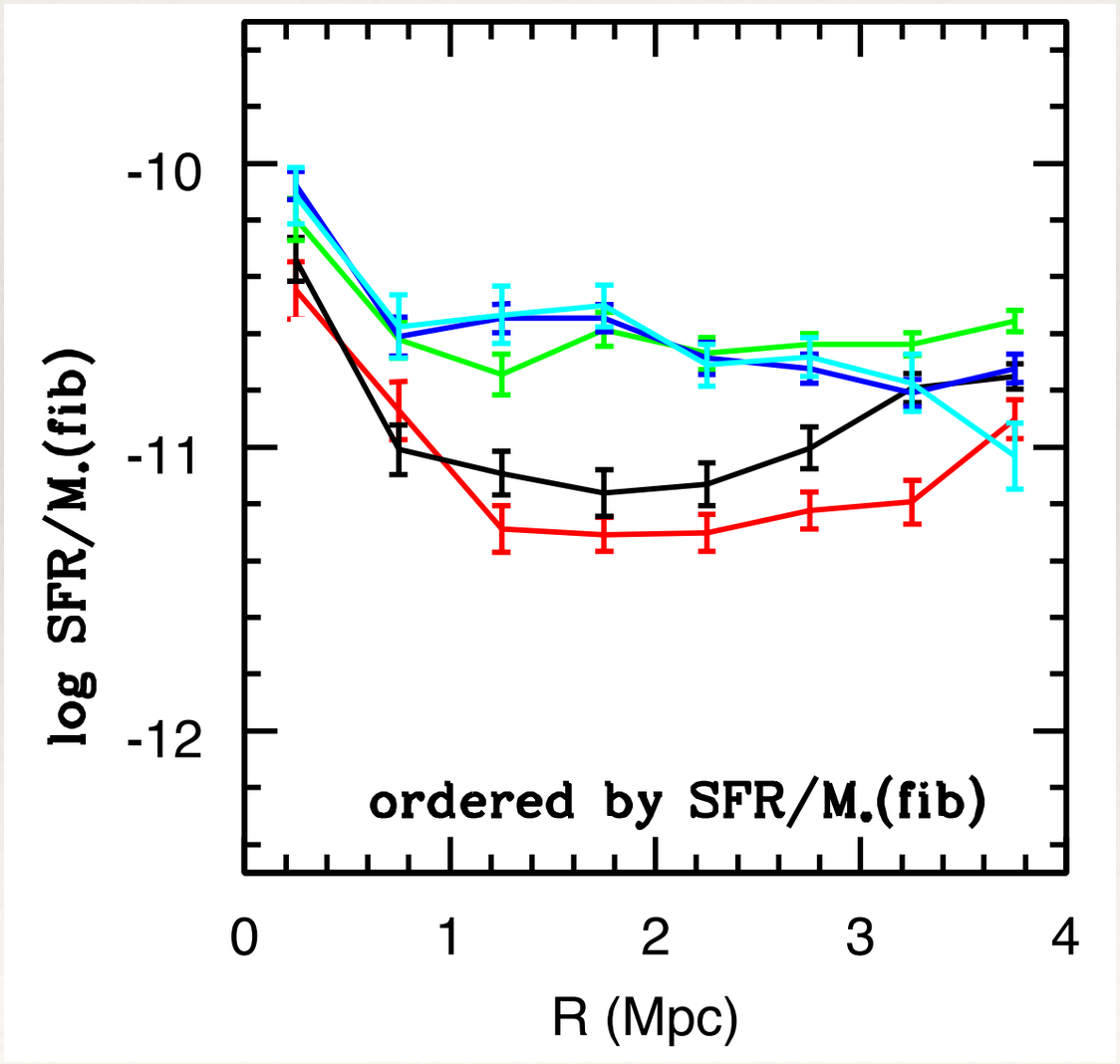


HOD



Model Discrimination

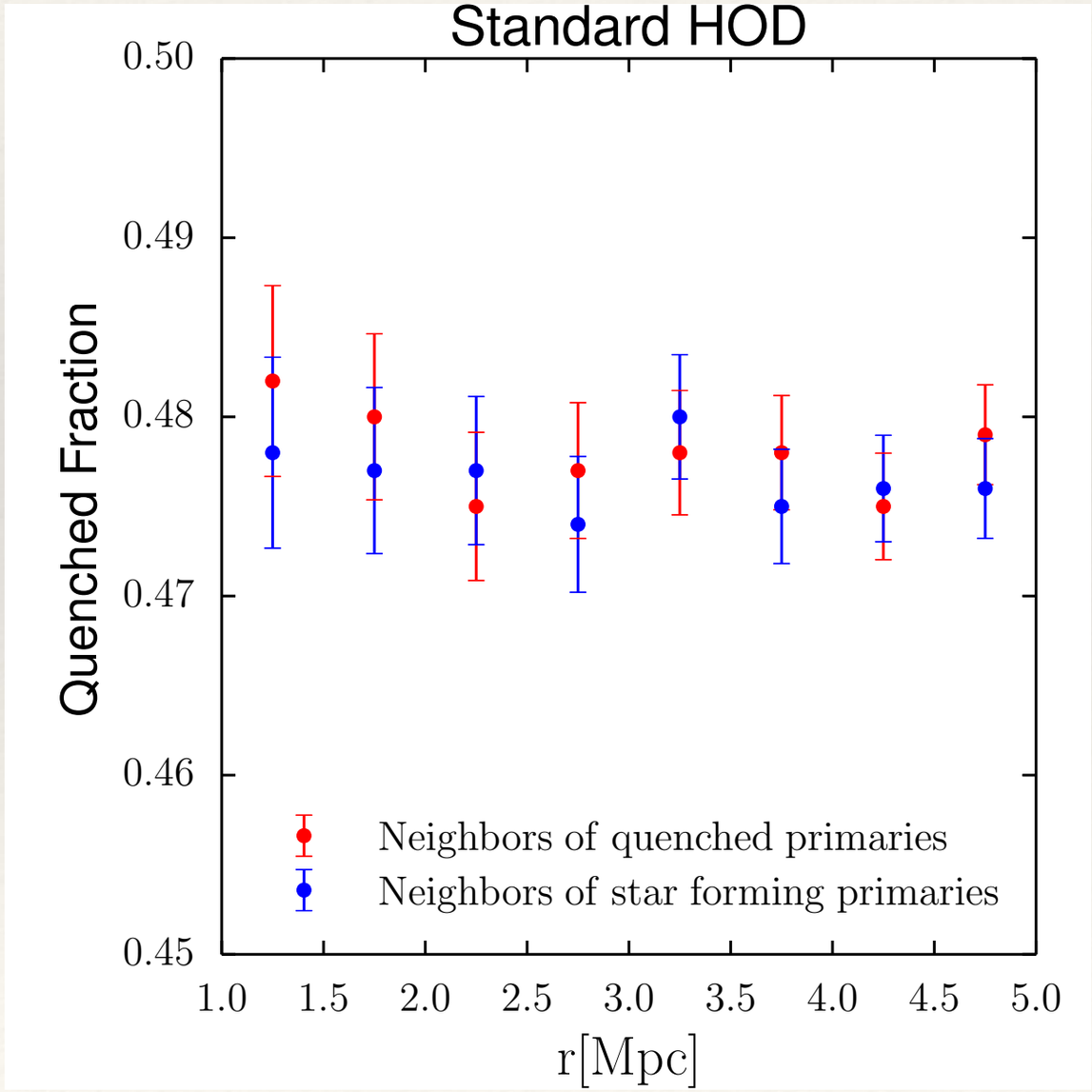
Galactic Conformity: SFR Correlations outside R_{vir}



Kauffman et al. 2013
arXiv:1209.3306

Model Discrimination

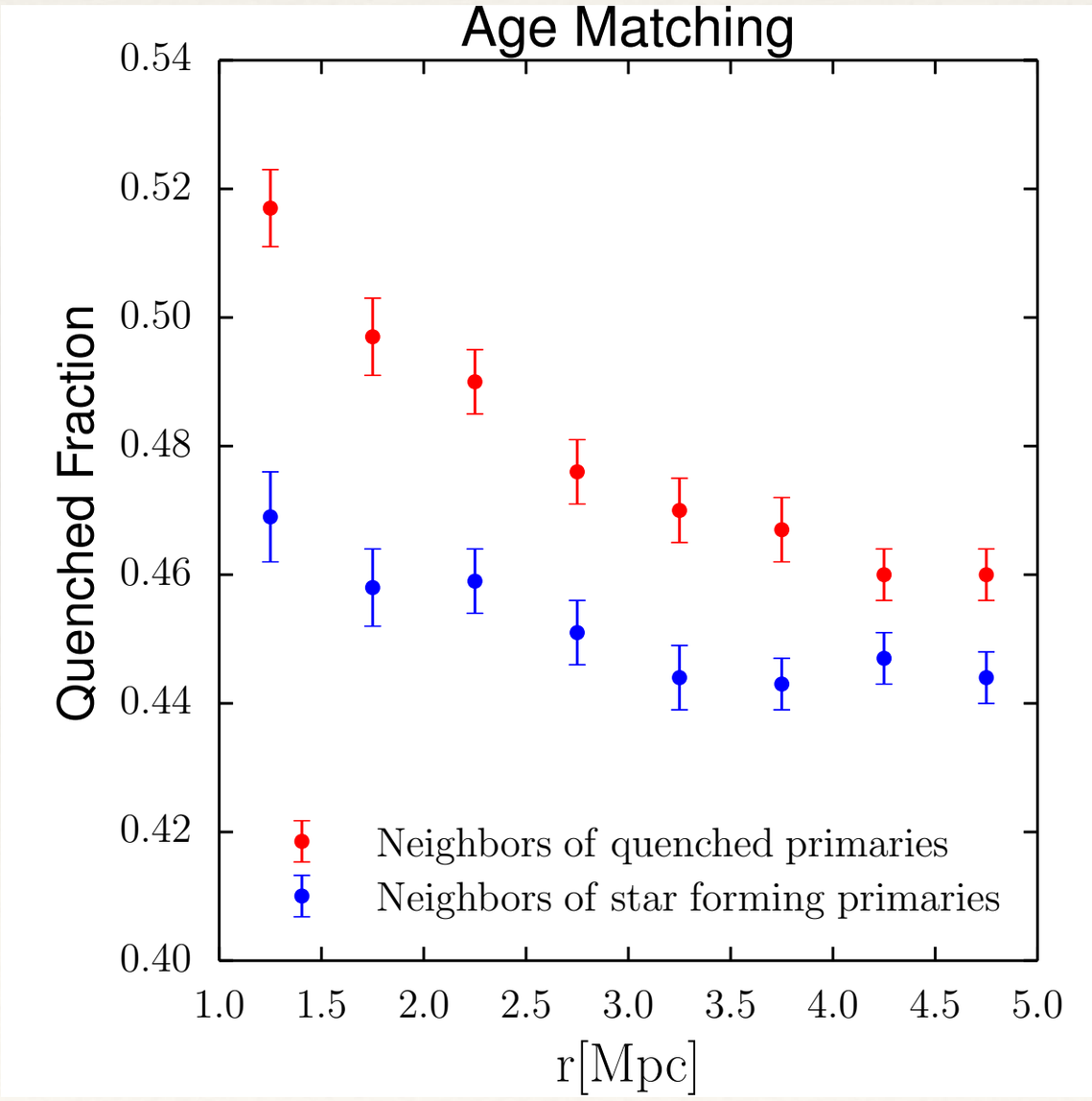
Galactic Conformity:
HOD predicts identically zero signal



Hearin 2014, in prep

Model Discrimination

Galactic Conformity:
Age Matching *does* predict signal



Hearin 2014, in prep

Conclusions

1. **Age Matching** is a new, simple, accurate model for the **co-evolution** of galaxies and their halos

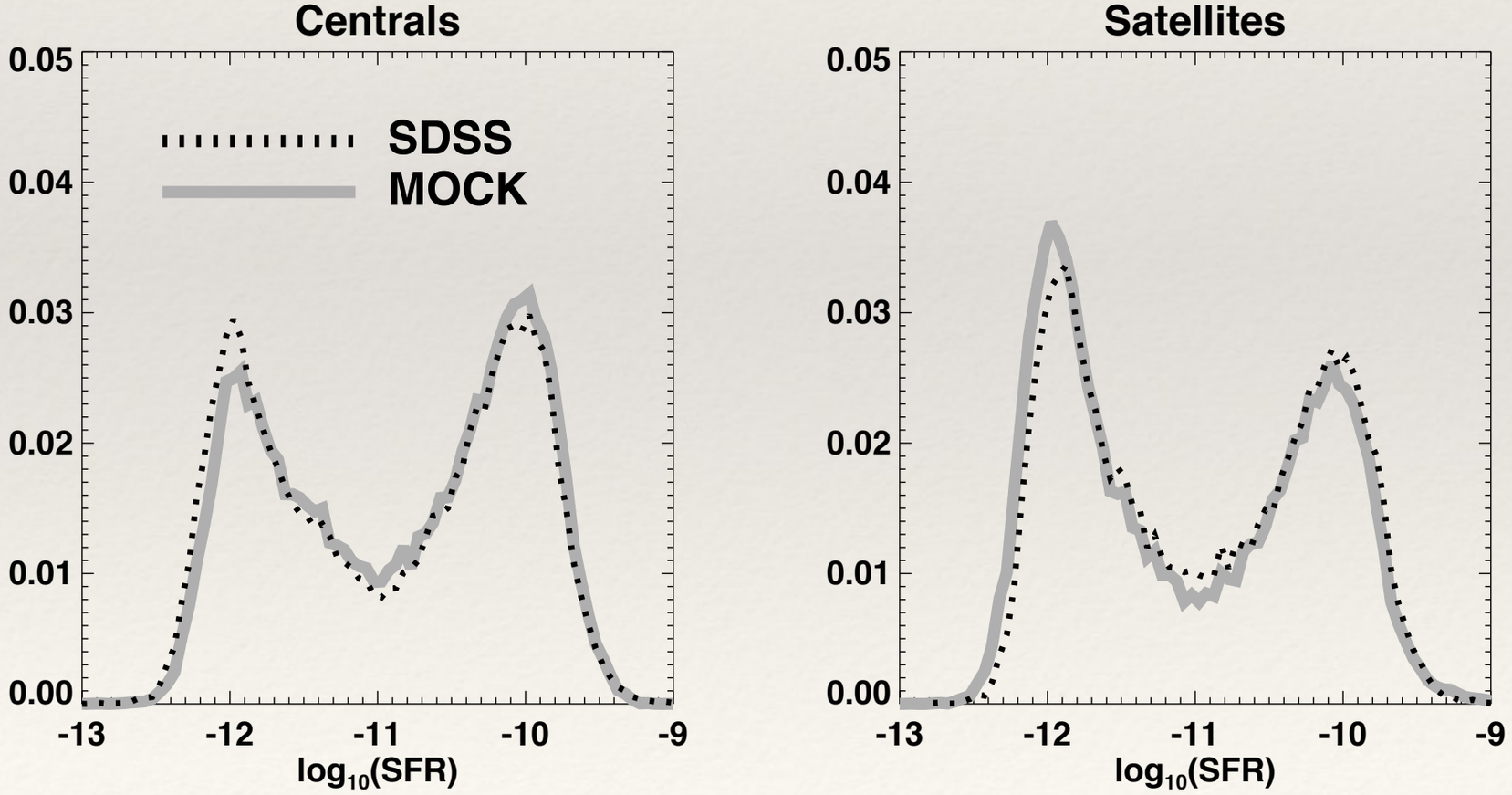
2. Importance of post-infall physics to satellite quenching has likely been **over-estimated**

3. A **new generation** of galaxy-halo models is required to robustly constrain cosmology and galaxy evolution

Some Additional Information

Some Additional Information

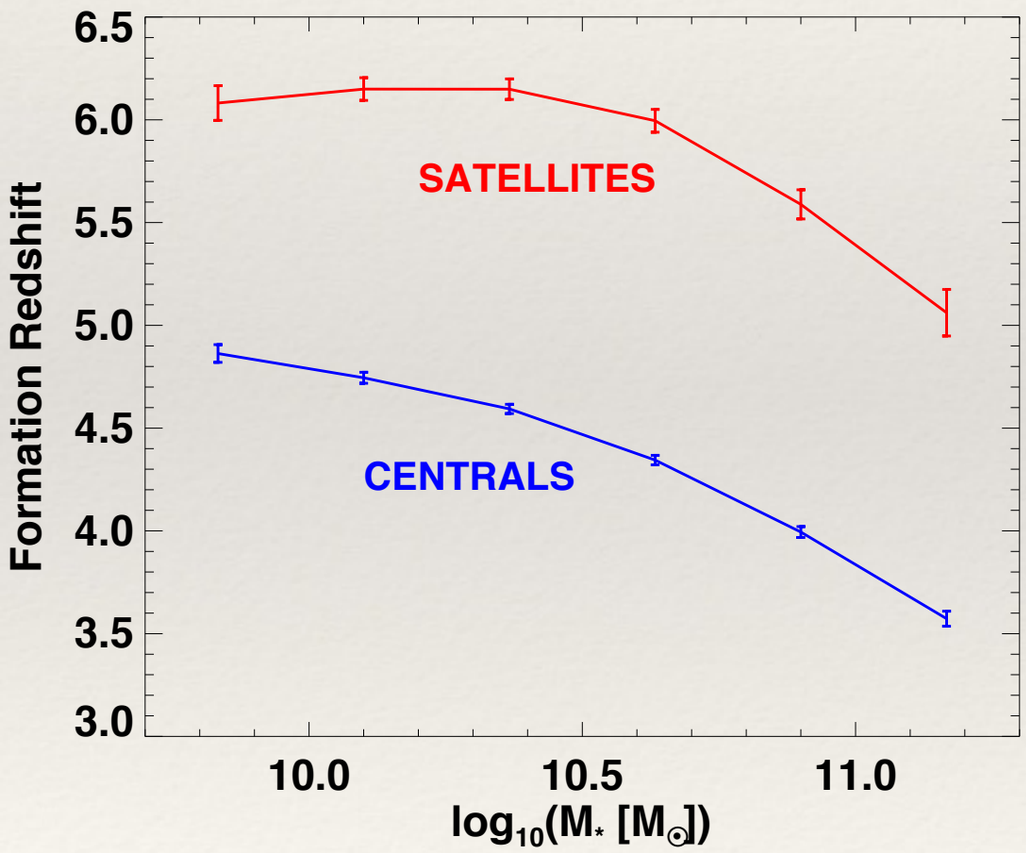
Satellite Quenching
with no modeling of post-infall processes

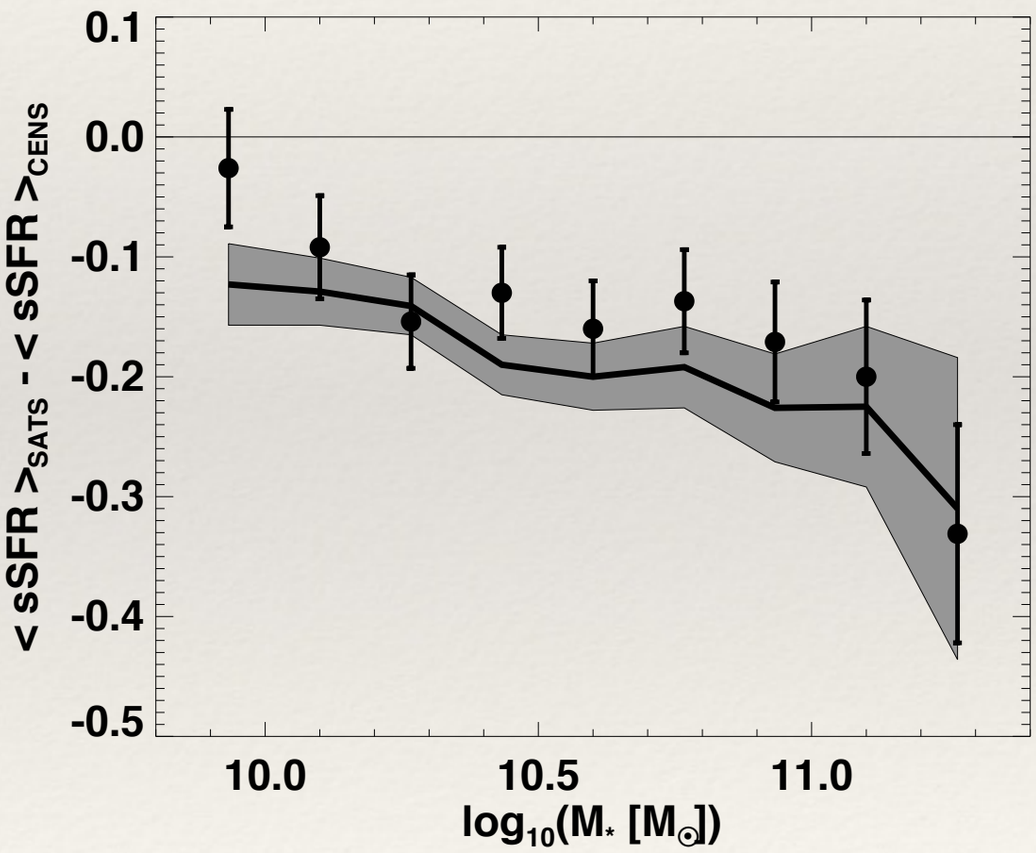


Watson et al. 2014,
arXiv:1403.1578

Some Additional Information

Satellite Quenching with no modeling of post-infall processes

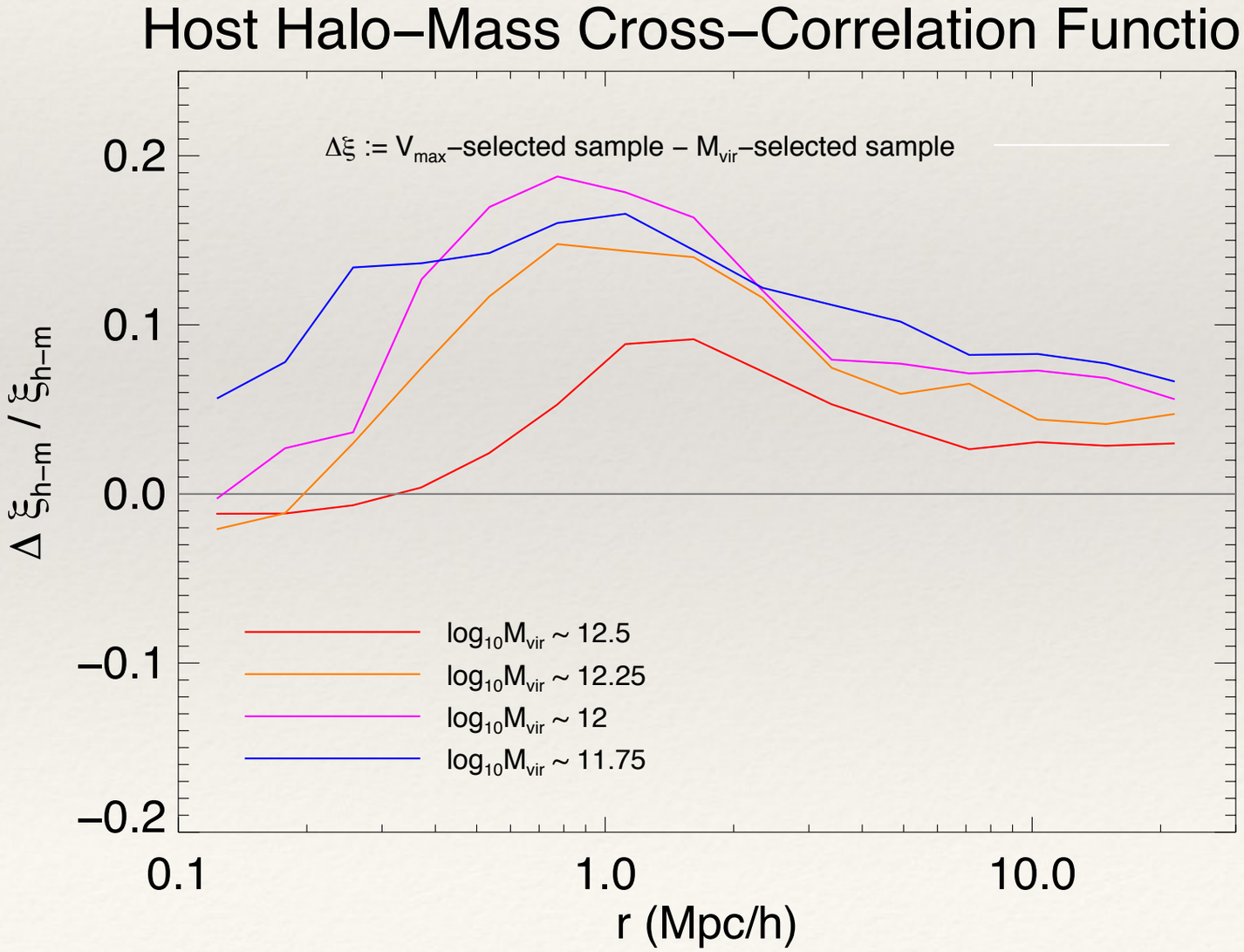




Watson et al. 2014,
arXiv:1403.1578

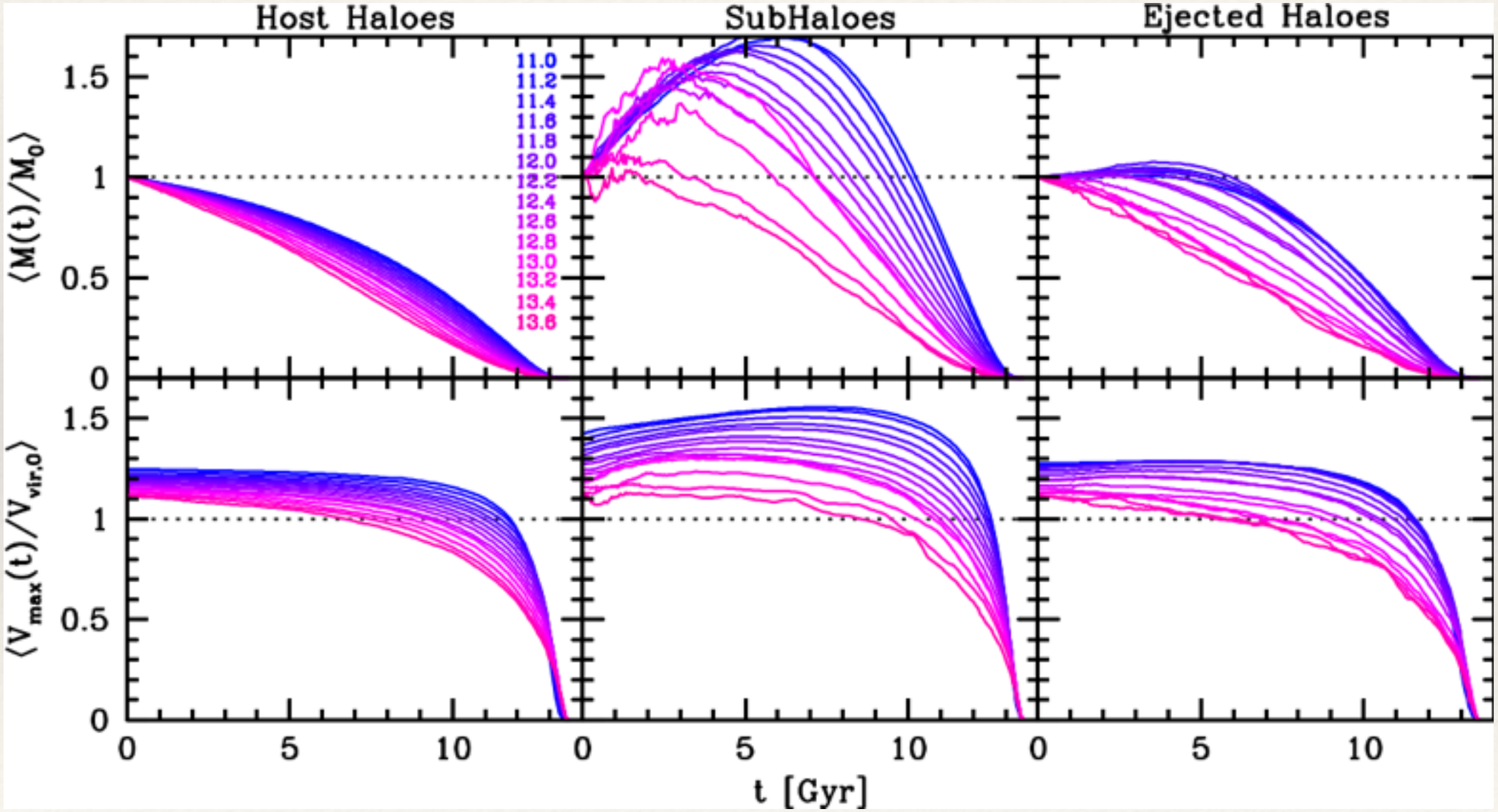
Some Additional Information

Assembly Bias is scale-dependent, even on large scales!



Some Additional Information

An in-depth look at halo assembly history



van den Bosch et al.,
in prep.

Some Additional Information

Subhalo infall time and formation time are correlated