Modeling Galaxies in the Era of Precision Cosmology

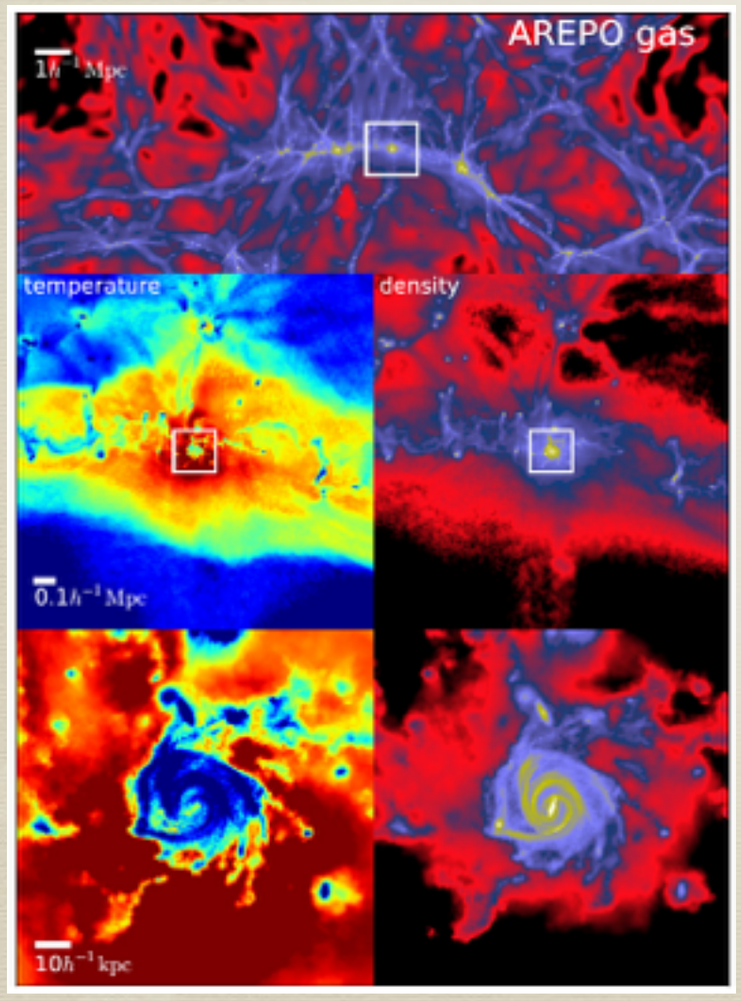
An open-source approach with Halotools

Andrew Hearin

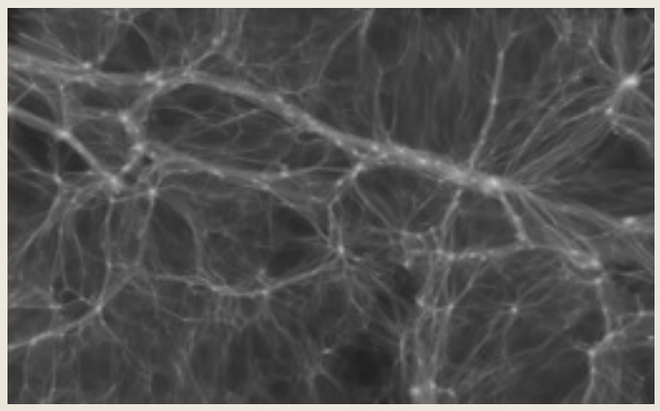
Modeling Galaxy Evolution

Three complementary approaches

Hydro sim



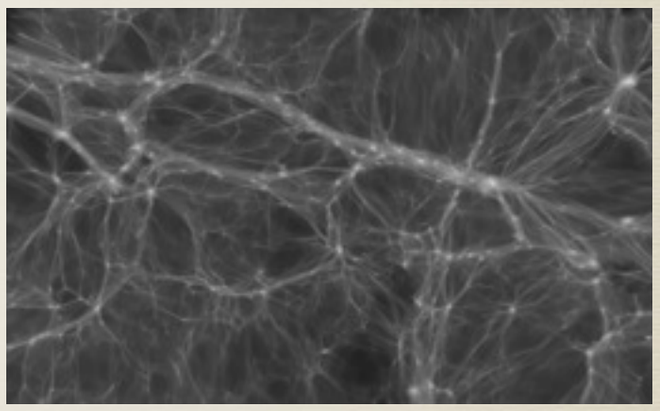
Semi-analytic model



+

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

Empirical model



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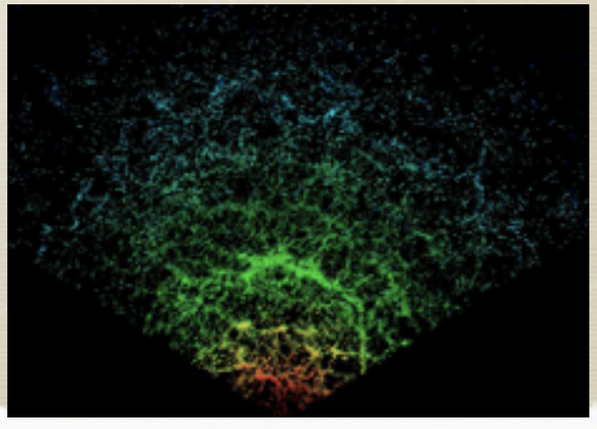
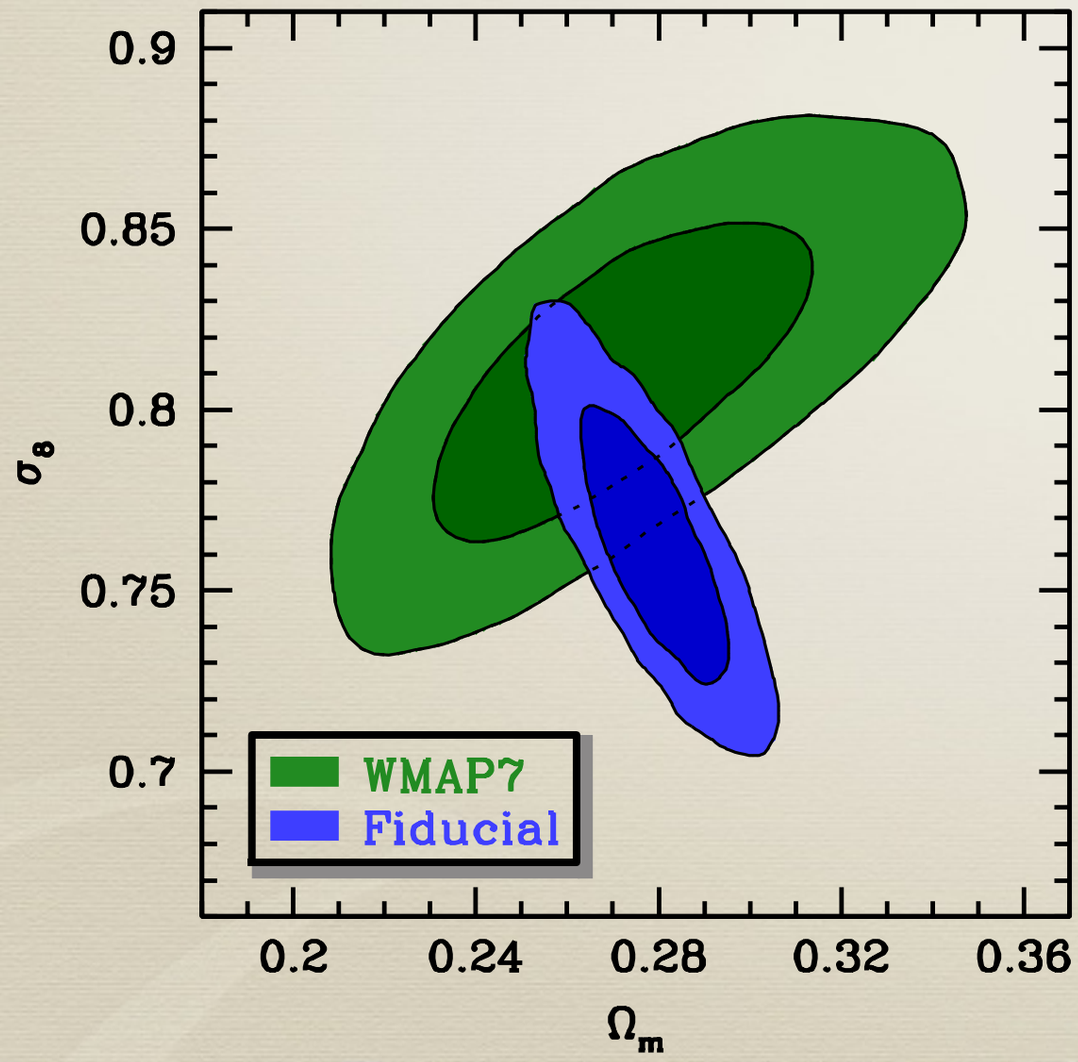


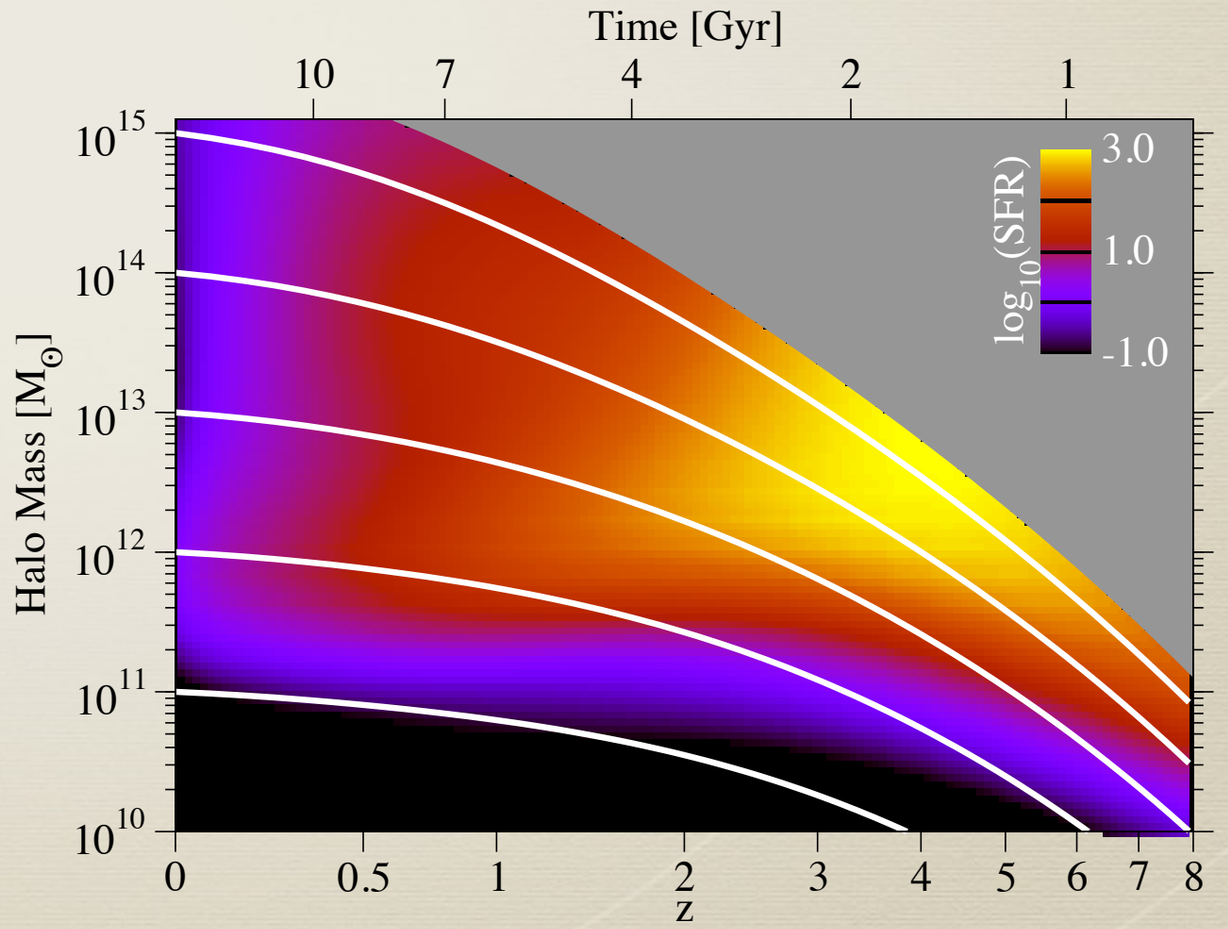
Modeling Galaxy Evolution

The promise of empirical modeling

Cosmology



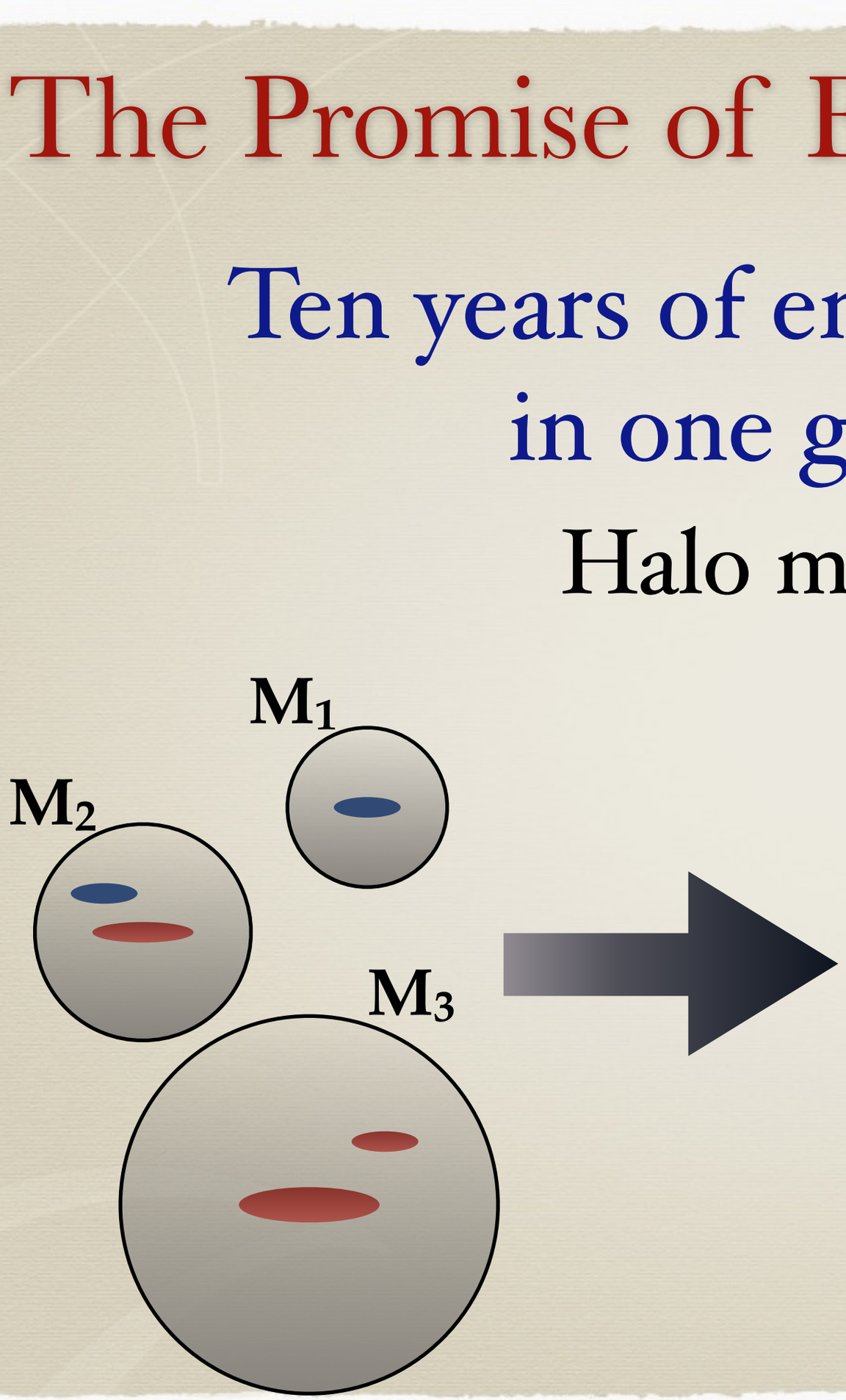
Galaxy evolution

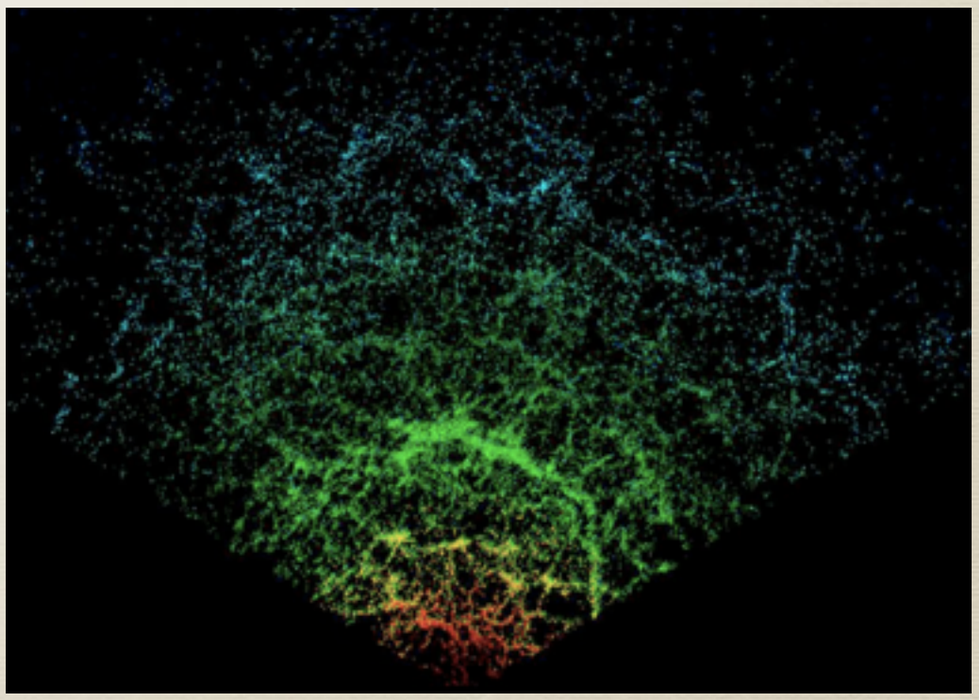


The Promise of Empirical Modeling

Ten years of empirical modeling in one glib cartoon

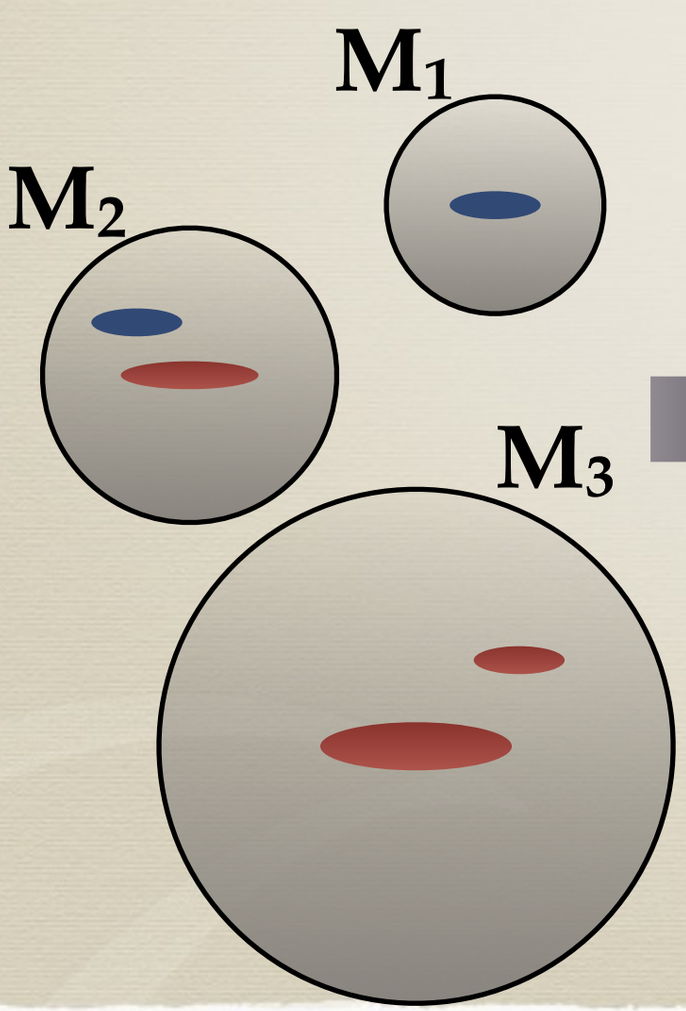
Halo mass is king!

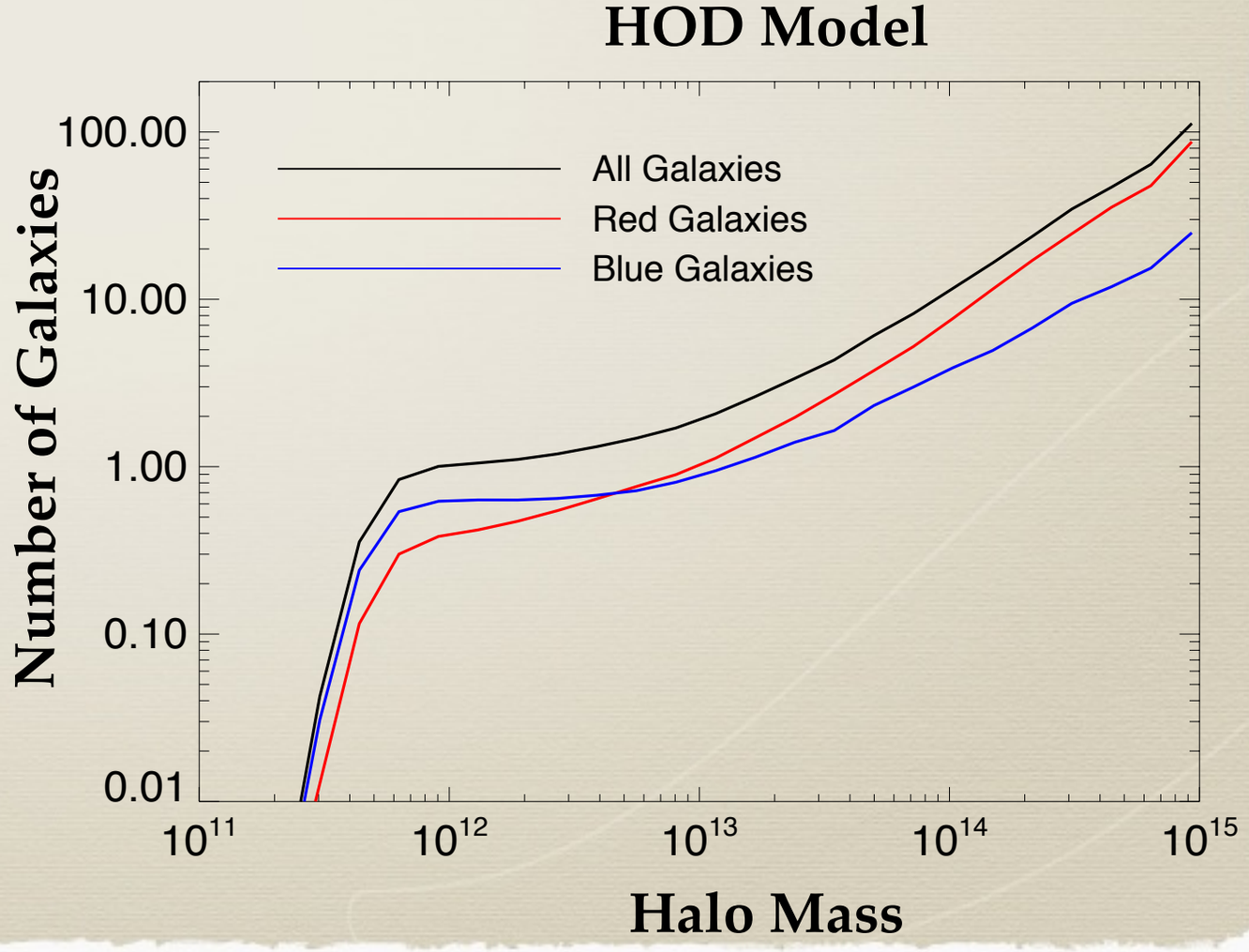




The Promise of Empirical Modeling

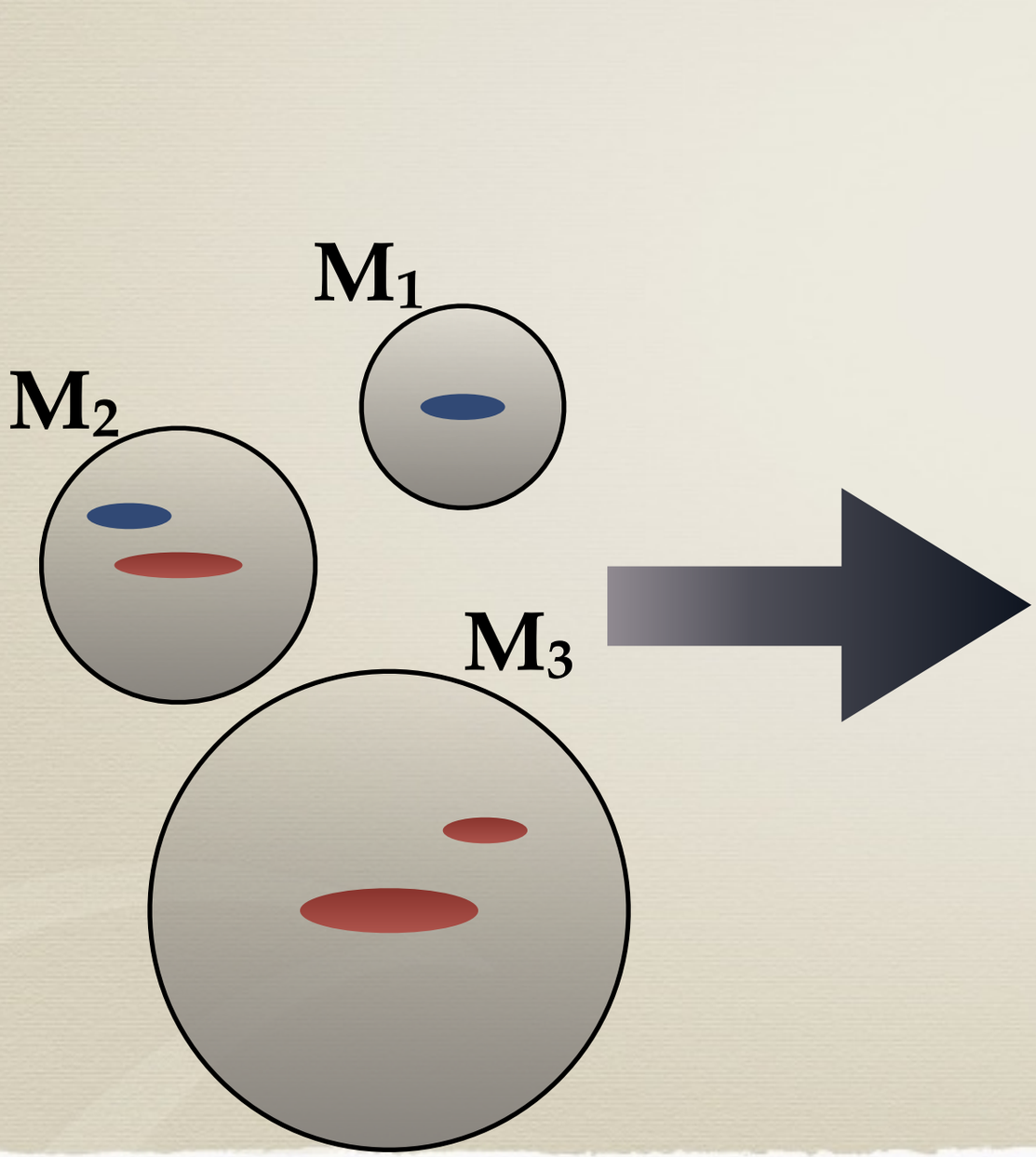
HOD as a specific example

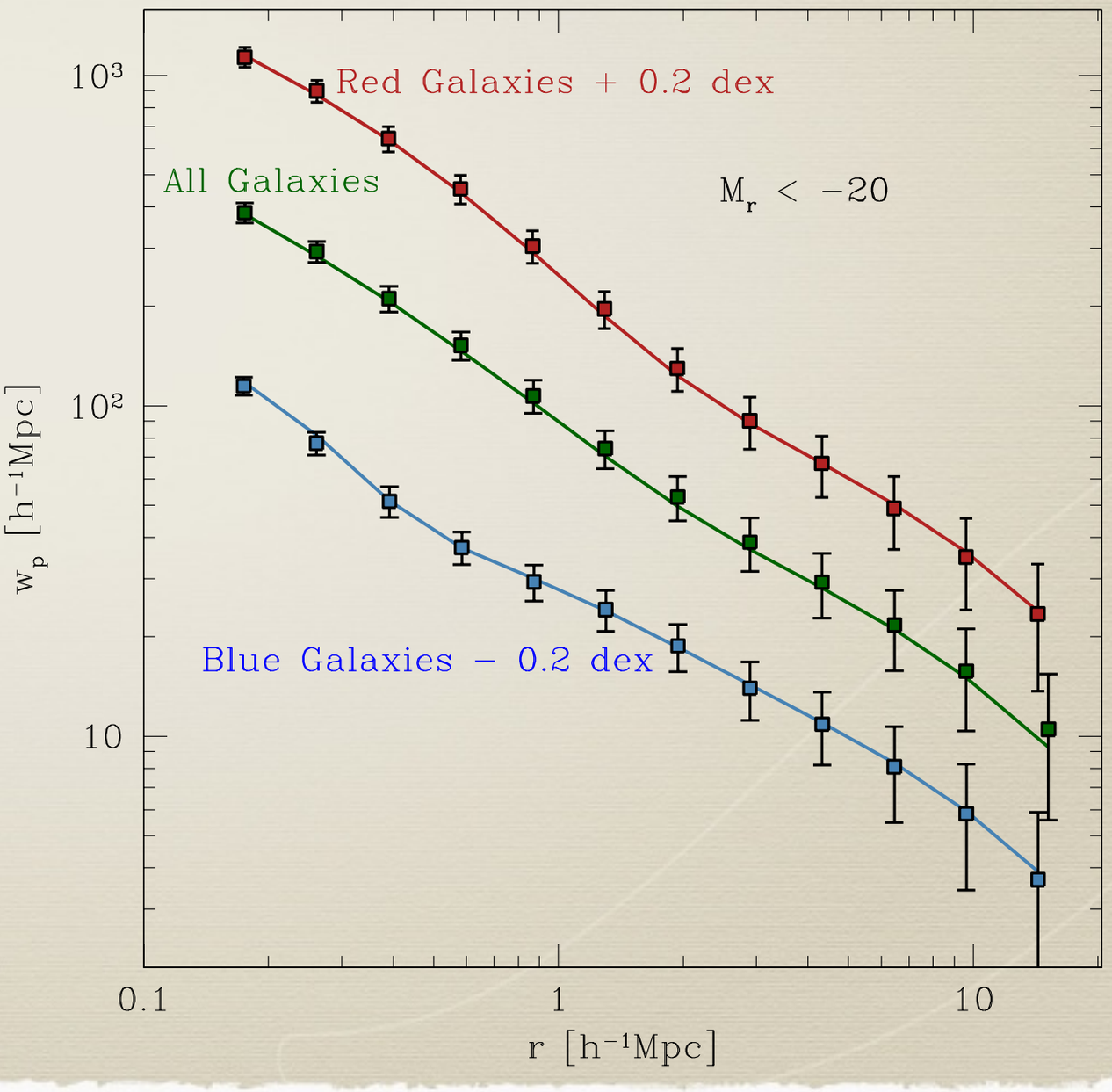




The Promise of Empirical Modeling

HOD + simulation fitting functions ==> large-scale structure predictions





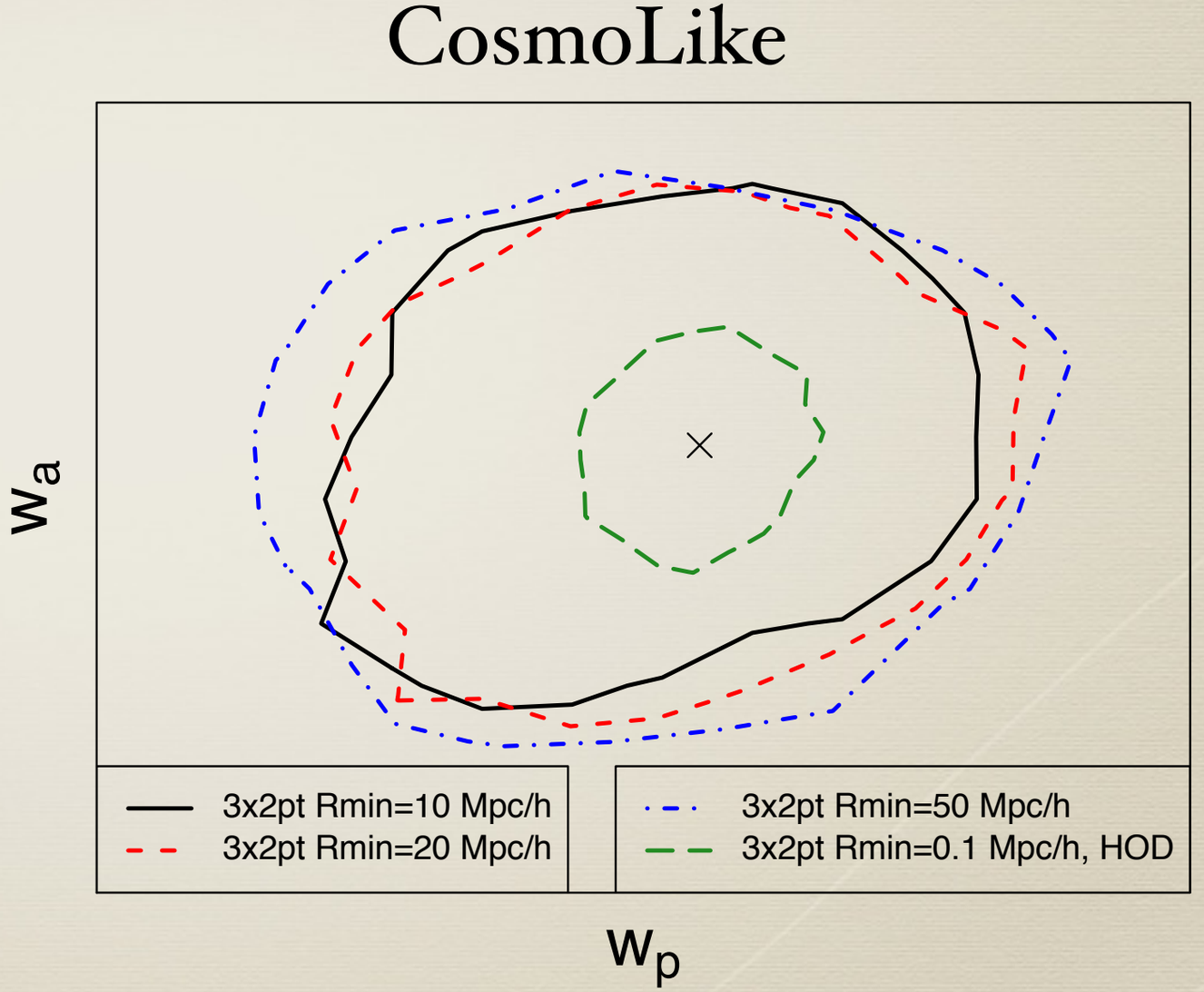
The Promise of Empirical Modeling

Cosmology from clustering + gg-lensing

HOD model

+

halo
fitting functions



Krause & Eifler 2016

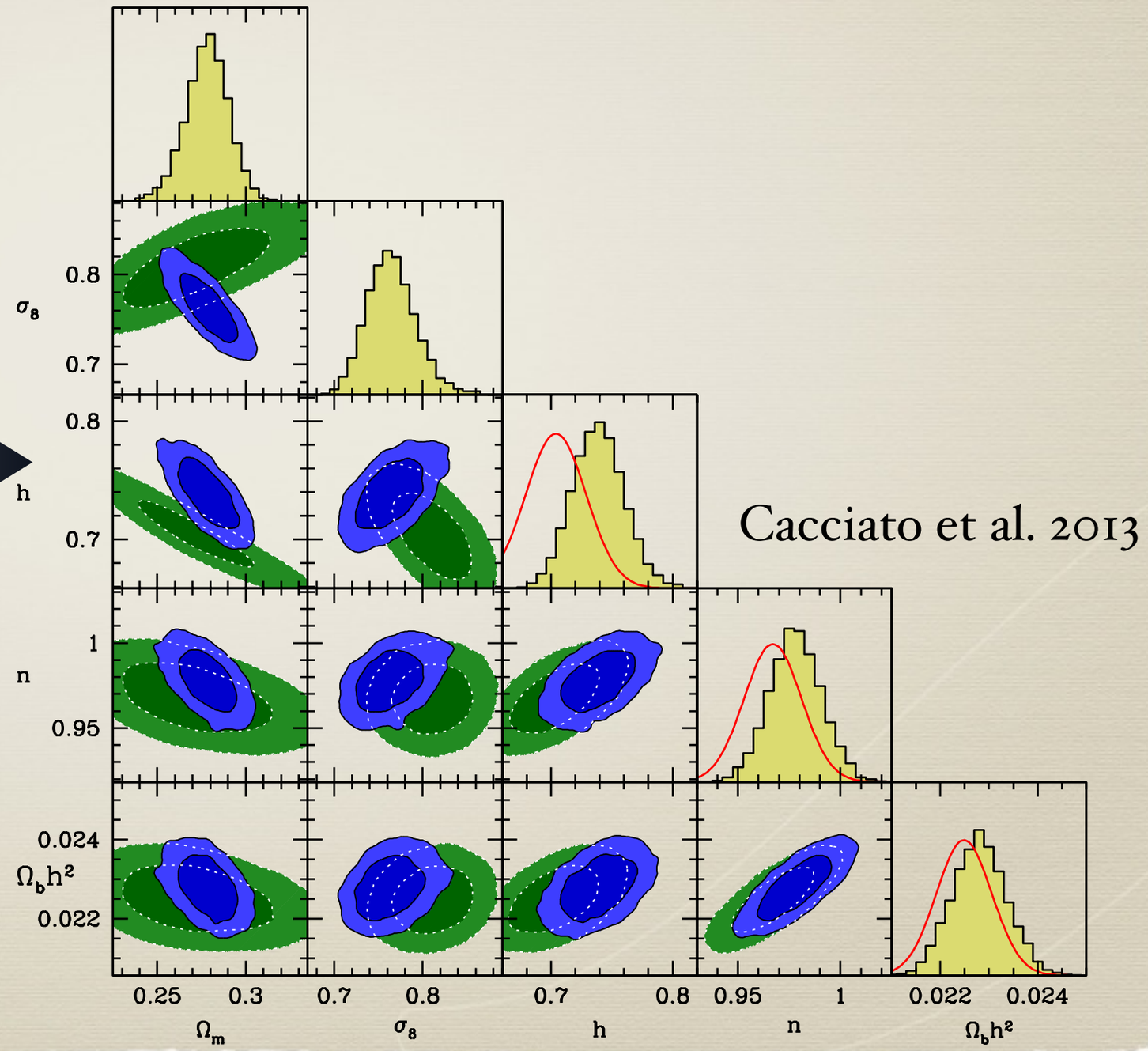
The Promise of Empirical Modeling

Cosmology from clustering + gg-lensing

CLF model

+

halo fitting functions

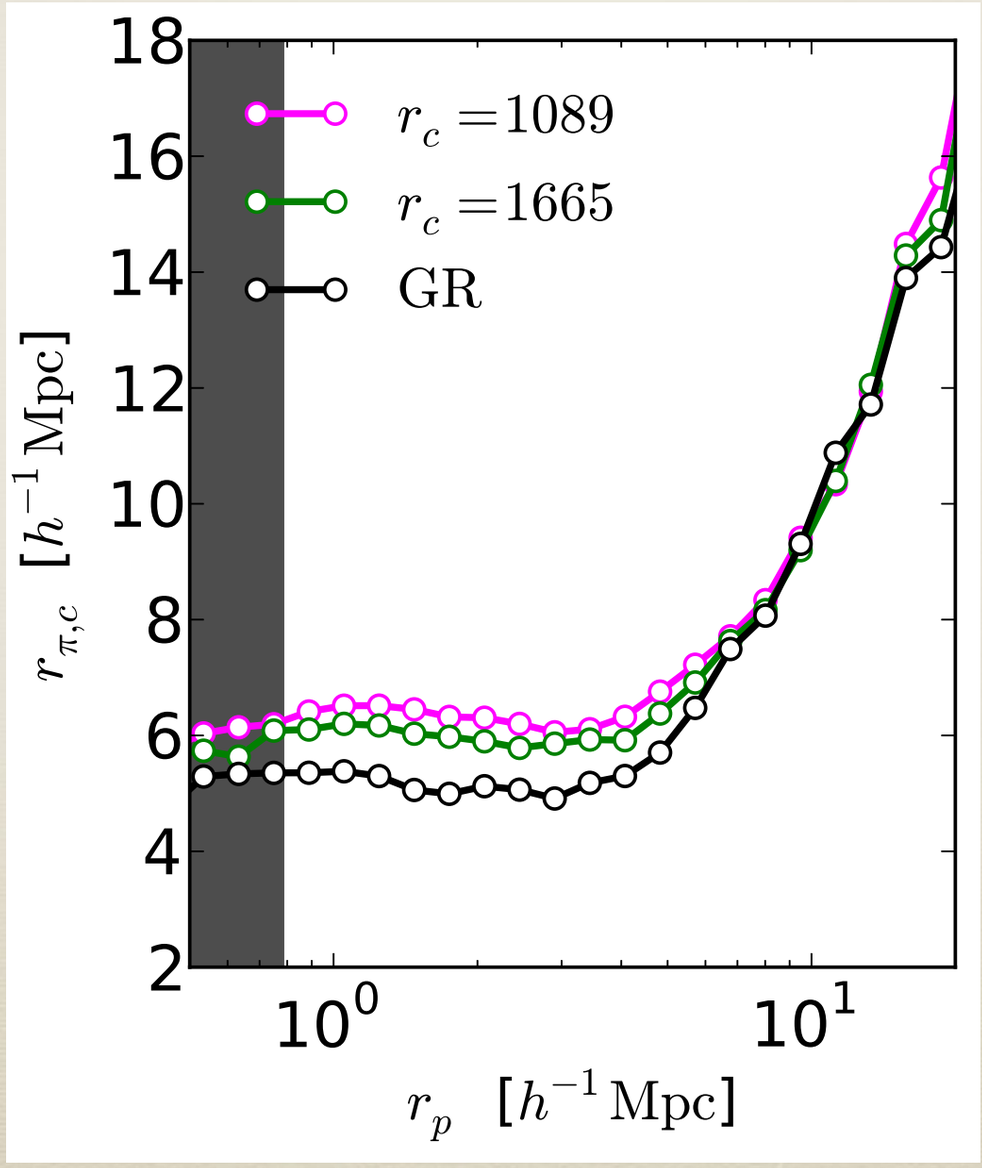


Cacciato et al. 2013

The Promise of Empirical Modeling

Modified GR from redshift-space distortions

Zu & Weinberg 2013



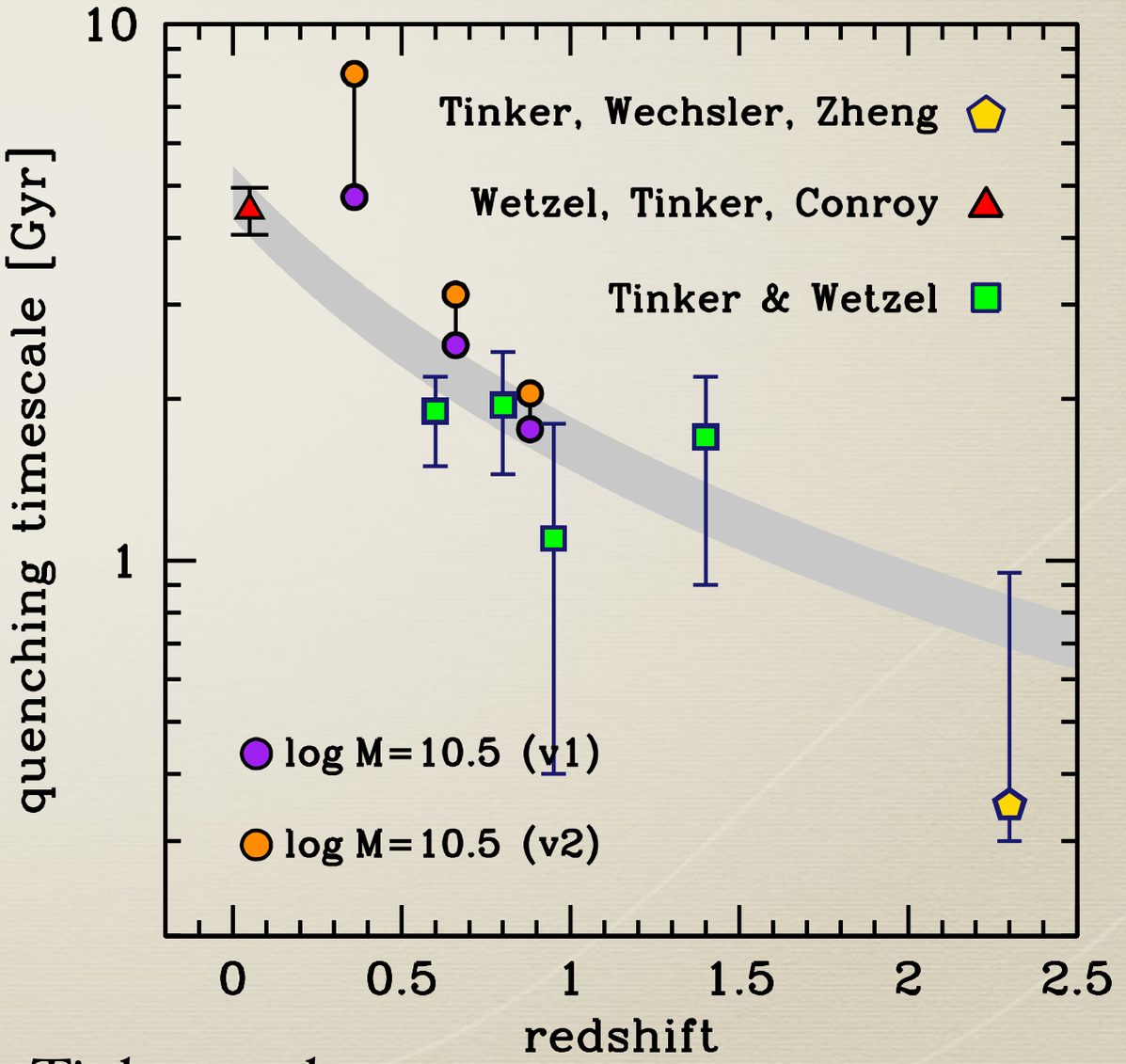
The Promise of Empirical Modeling

Satellite quenching timescales from clustering + lensing

HOD model

+

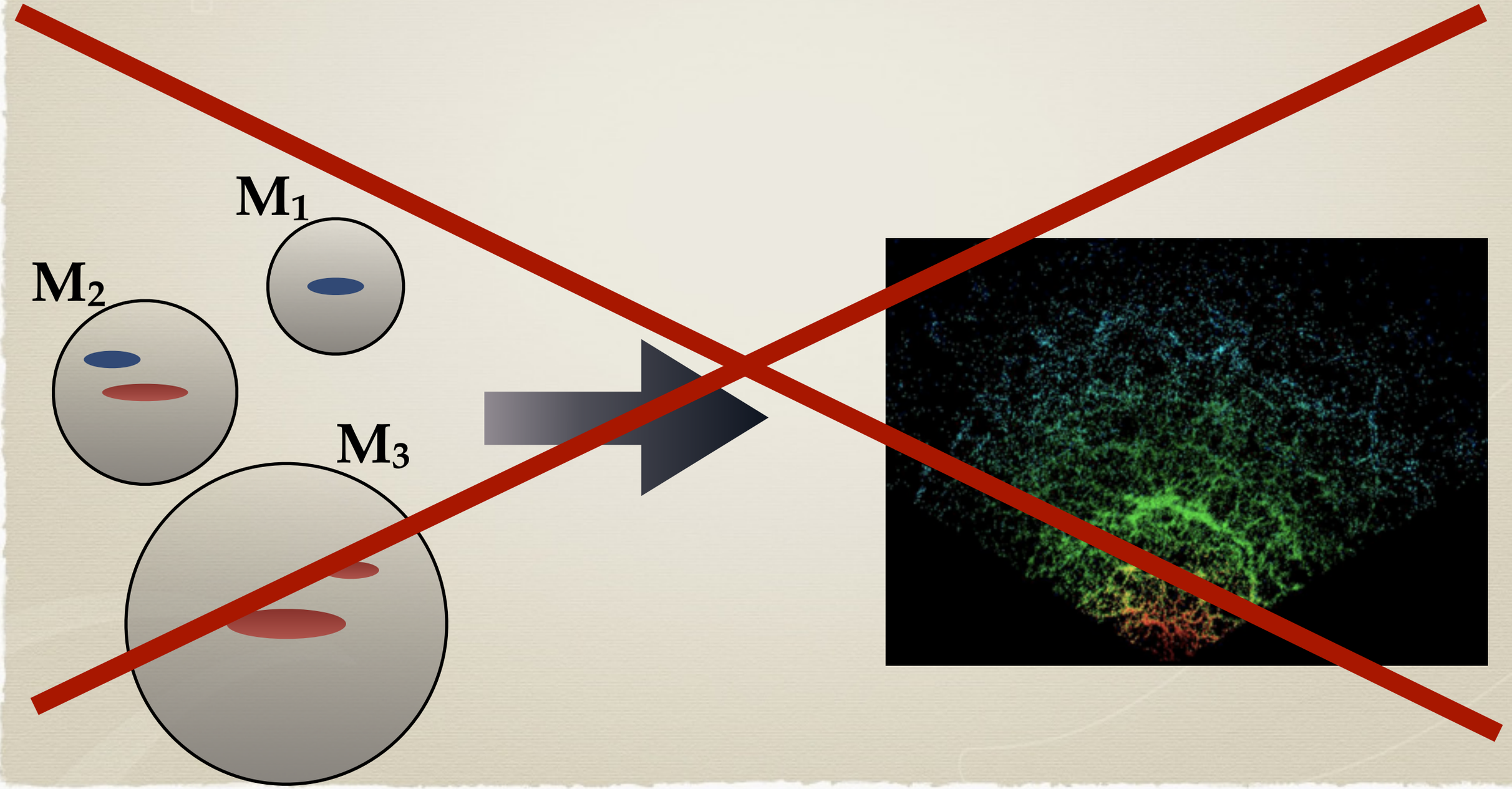
halo fitting functions



Tinker et al. 2013

A Wrench in the Works

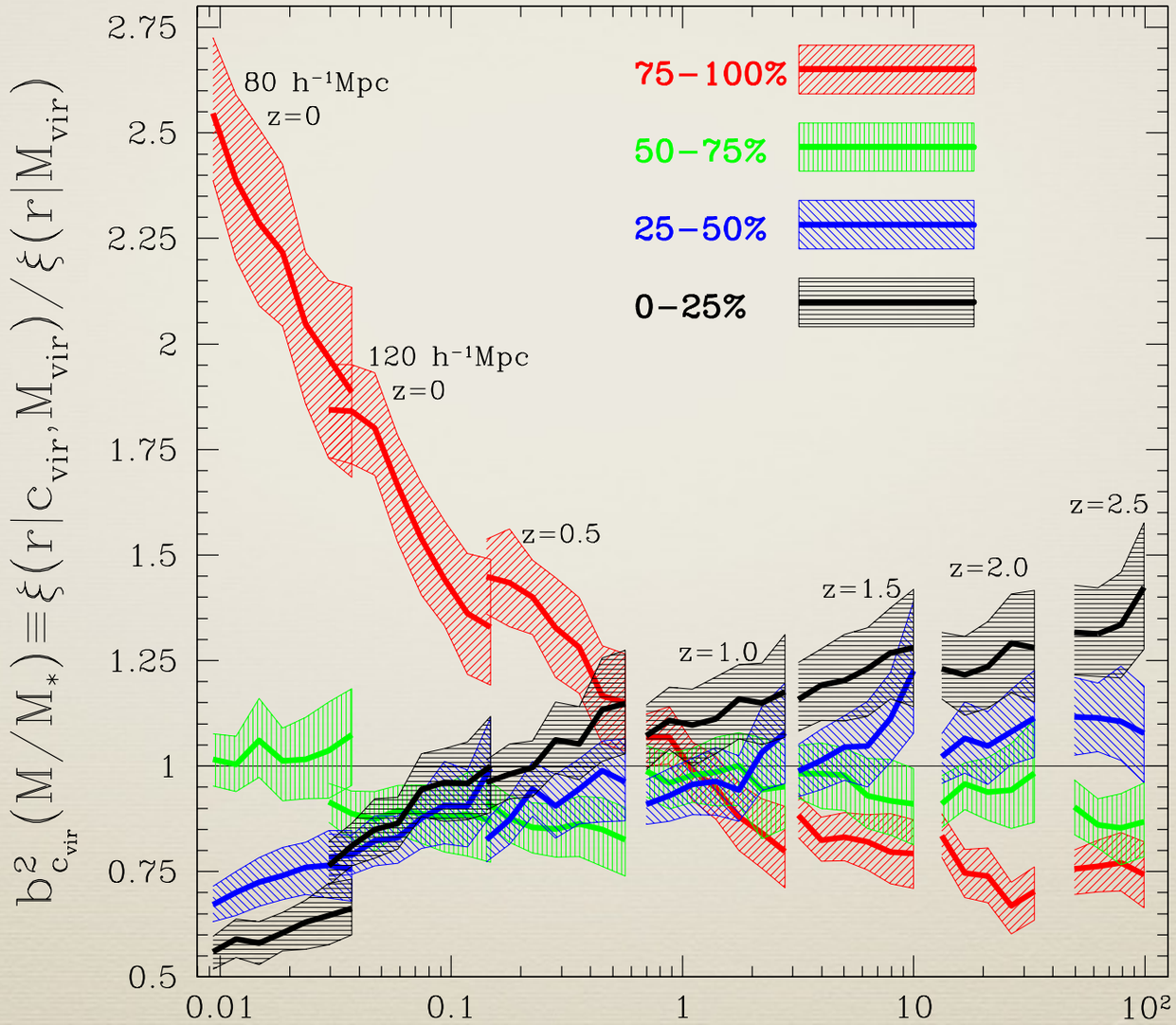
The threat of assembly bias



The Threat of Assembly Bias

Halo mass alone does not determine clustering

Not even in the linear regime!

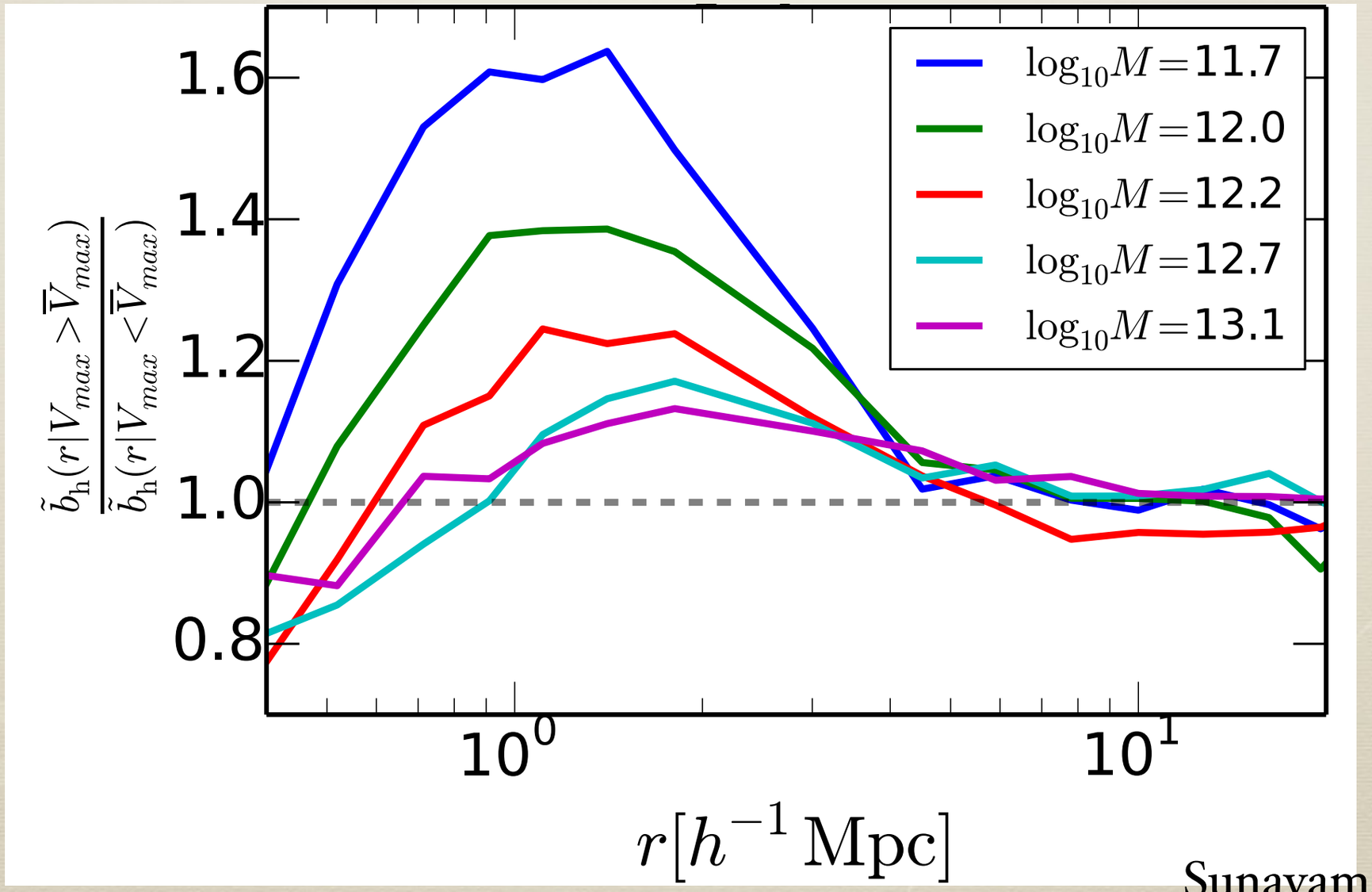


Wechsler et al. 2006

The Threat of Assembly Bias

Halo mass alone does not determine clustering

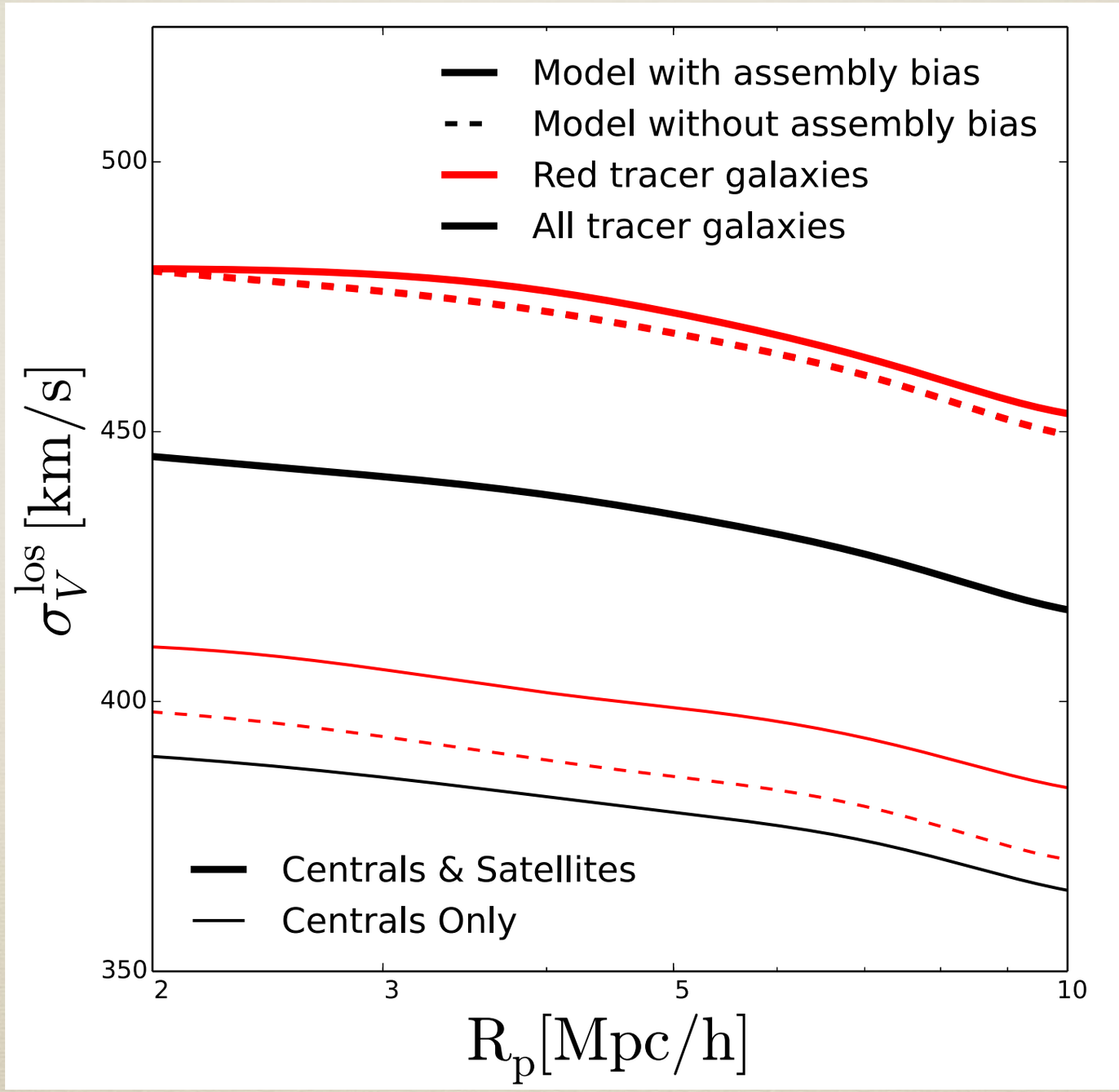
Effects are highly scale-dependent



Sunayama et al. 2015

The Threat of Assembly Bias

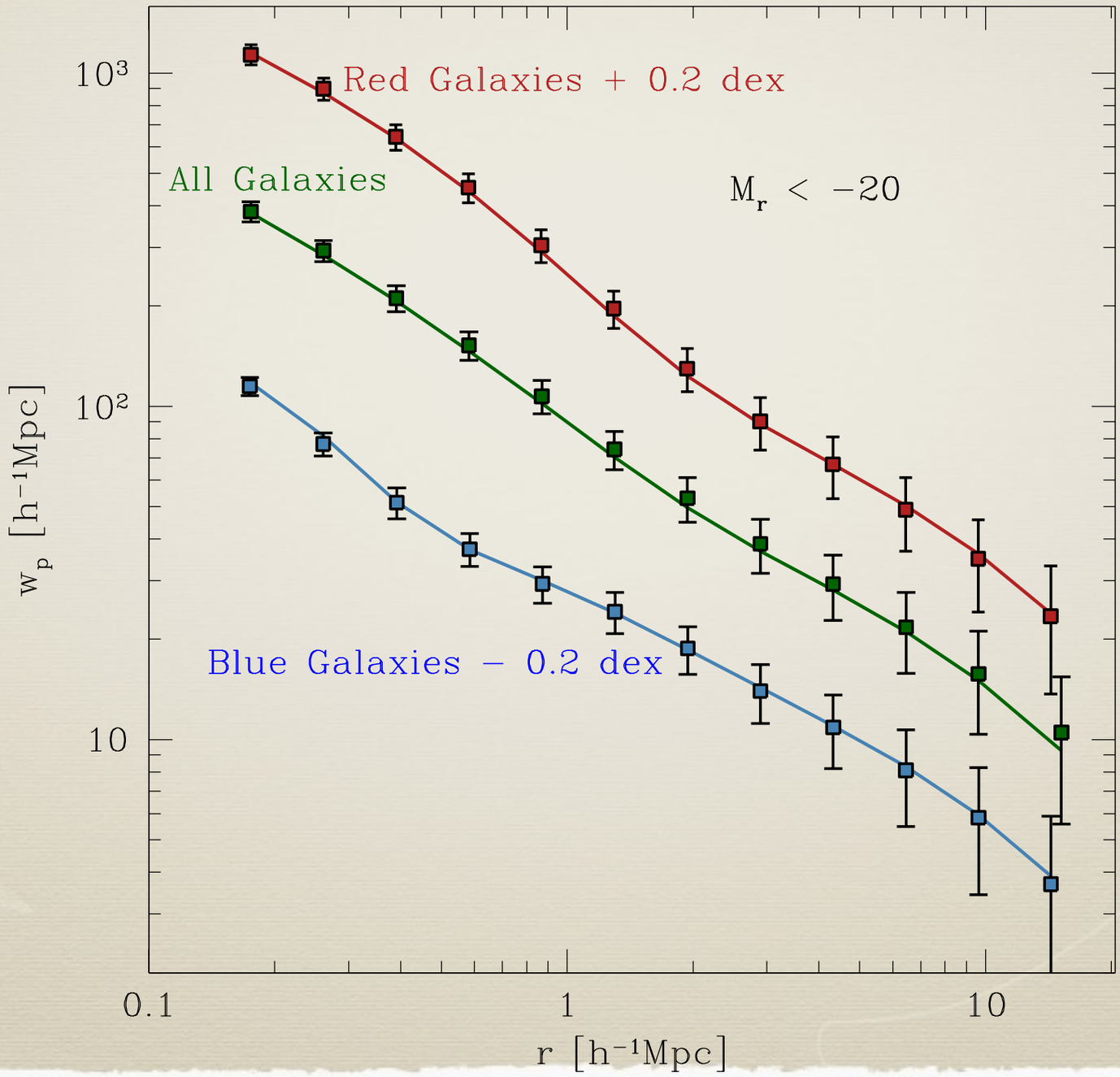
Potentially disastrous consequences



Hearin 2015

The Threat of Assembly Bias

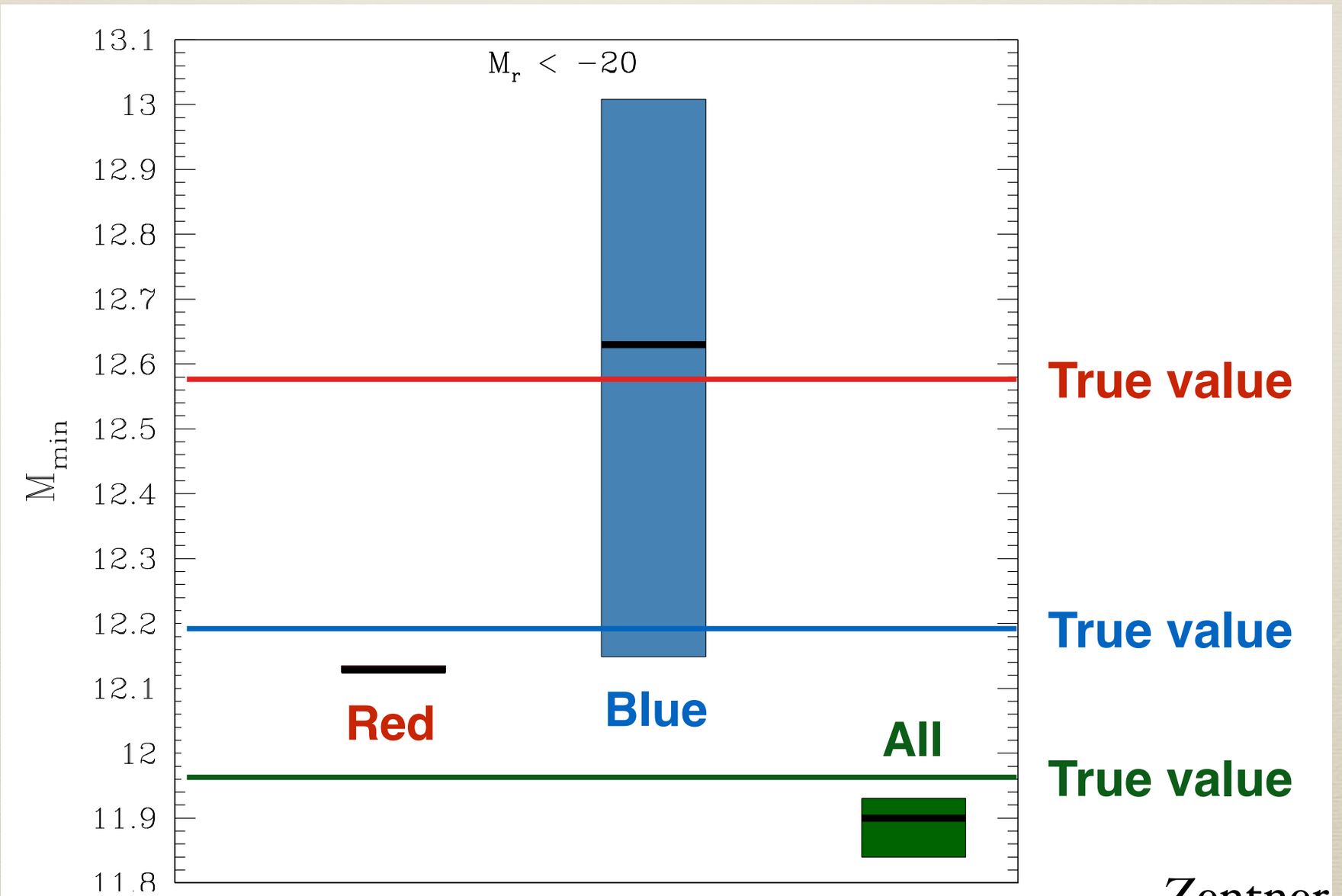
Potentially disastrous consequences



Zentner et al. 2013

The Threat of Assembly Bias

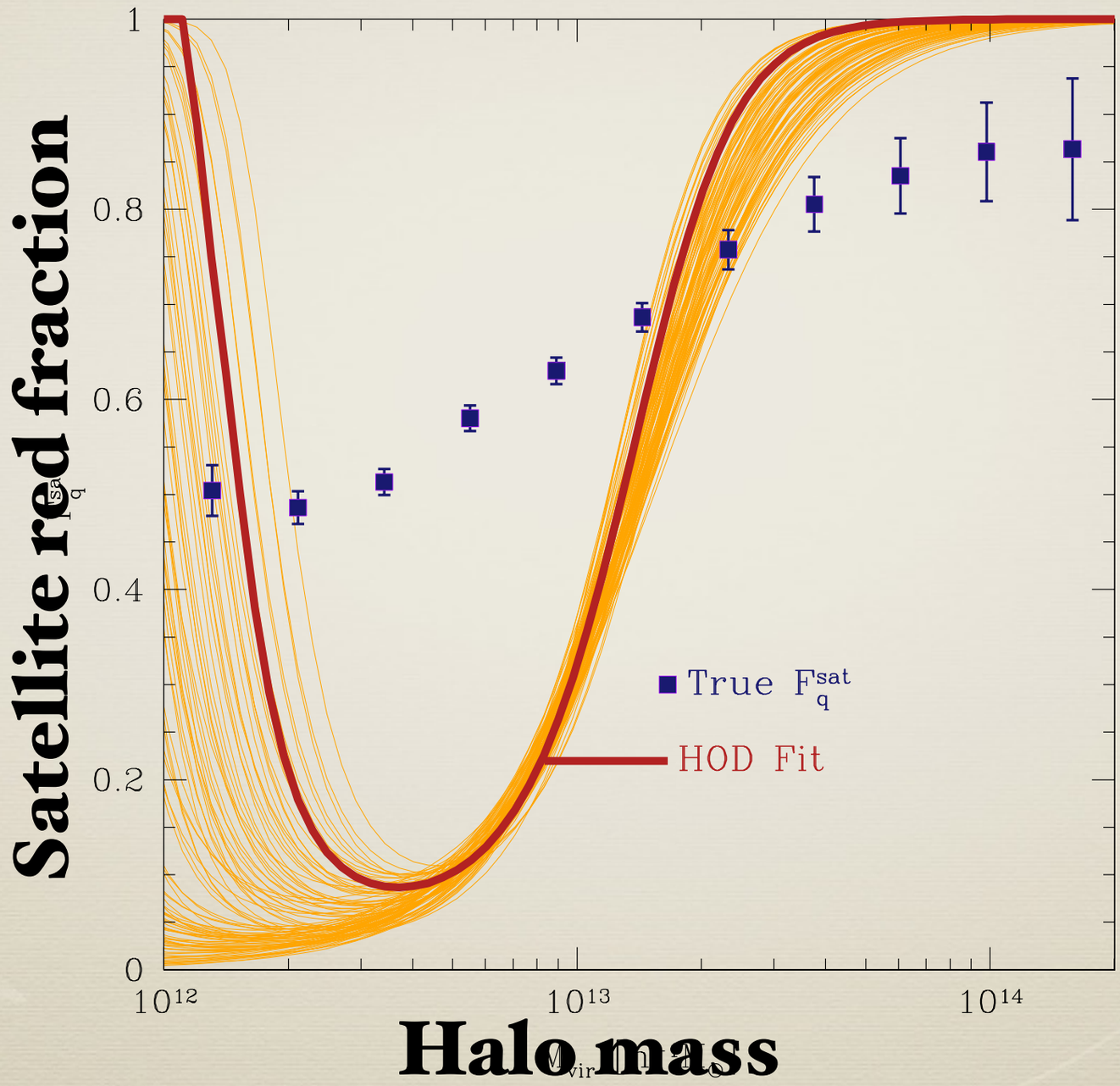
Potentially disastrous consequences



Zentner et al. 2013

The Threat of Assembly Bias

Potentially disastrous consequences

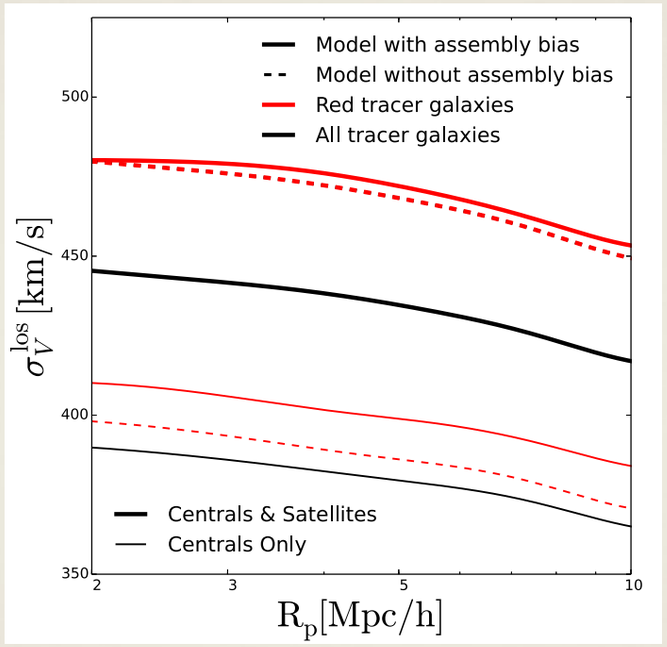


Zentner et al. 2013

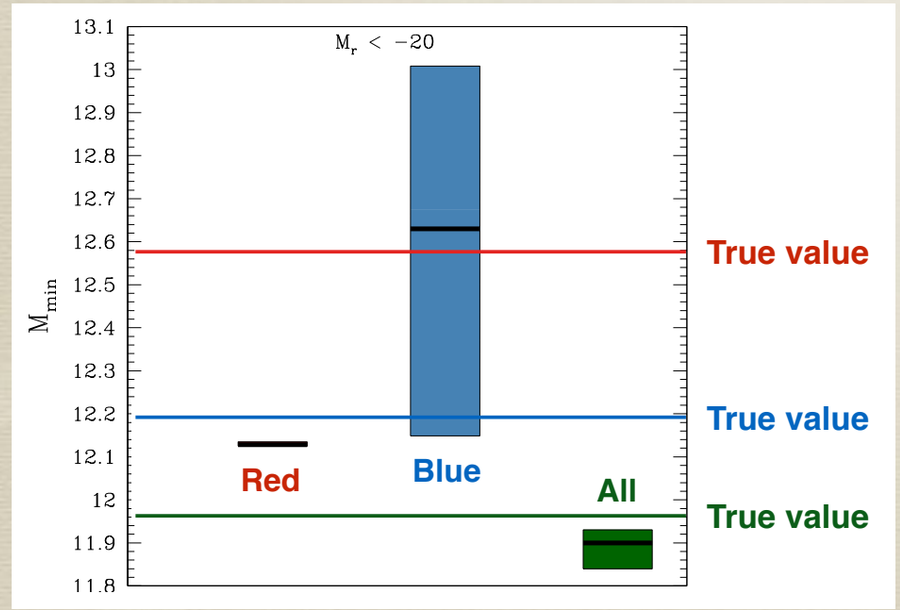
The Threat of Assembly Bias

Potentially disastrous consequences

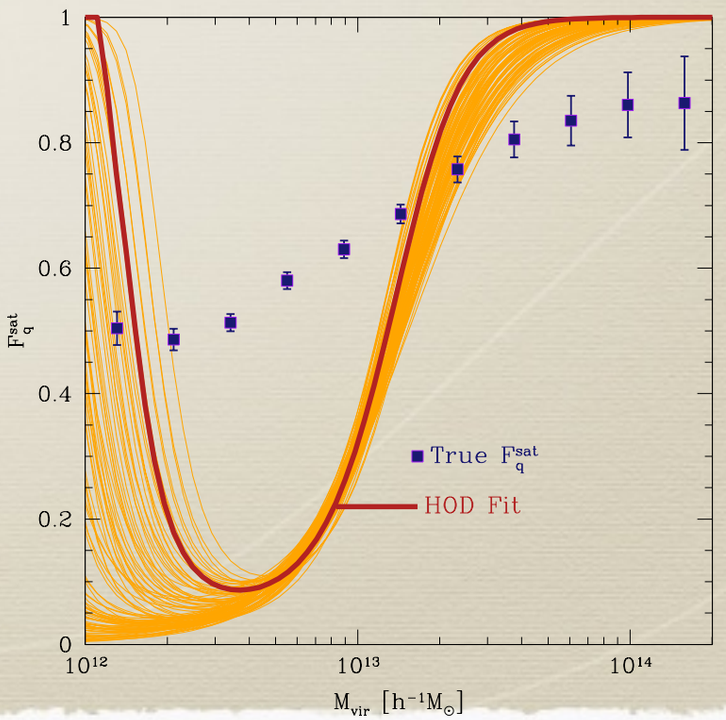
modified GR



ΛCDM

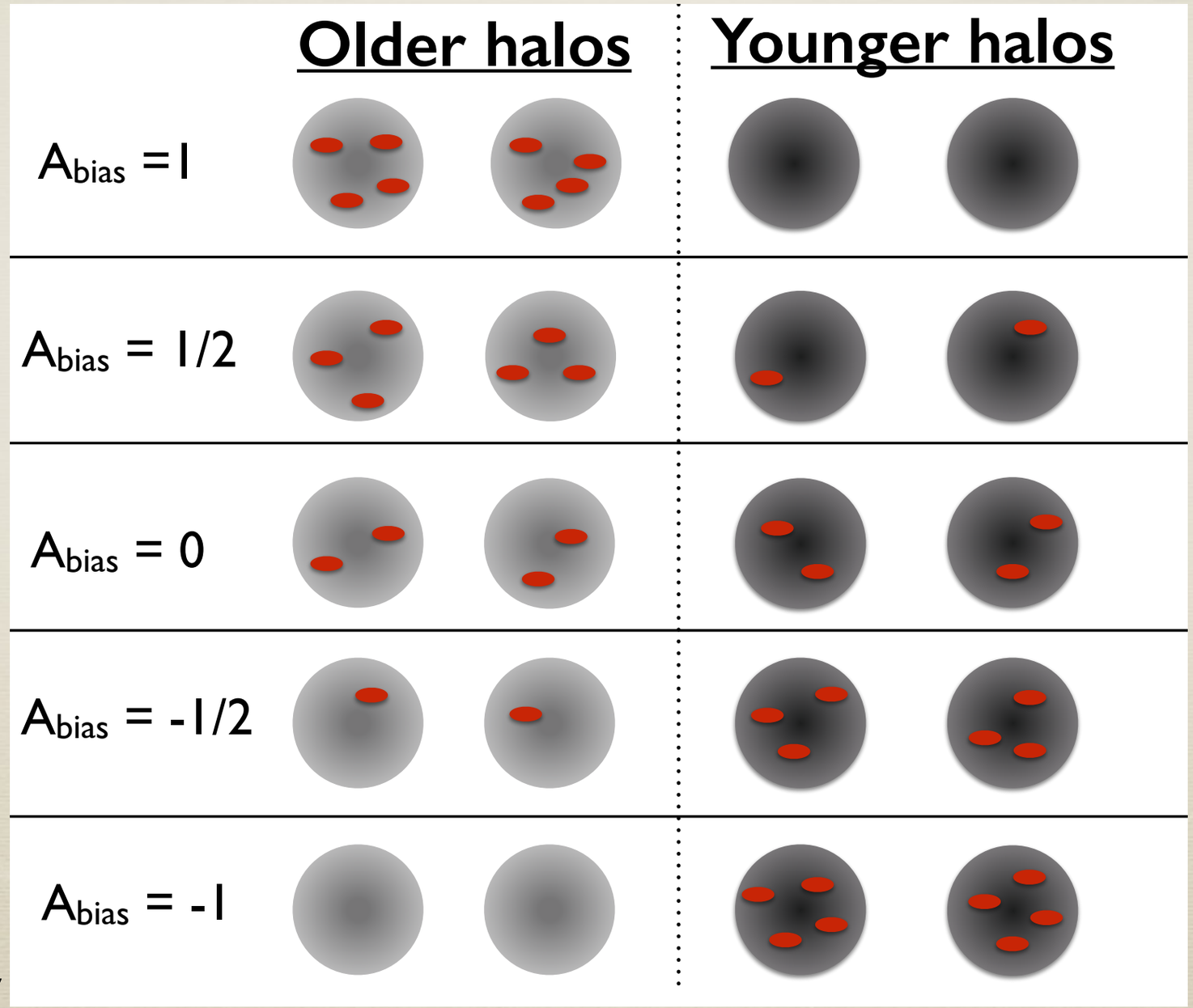


quenching physics



A new approach to the problem

Direct modeling with decorated HODs

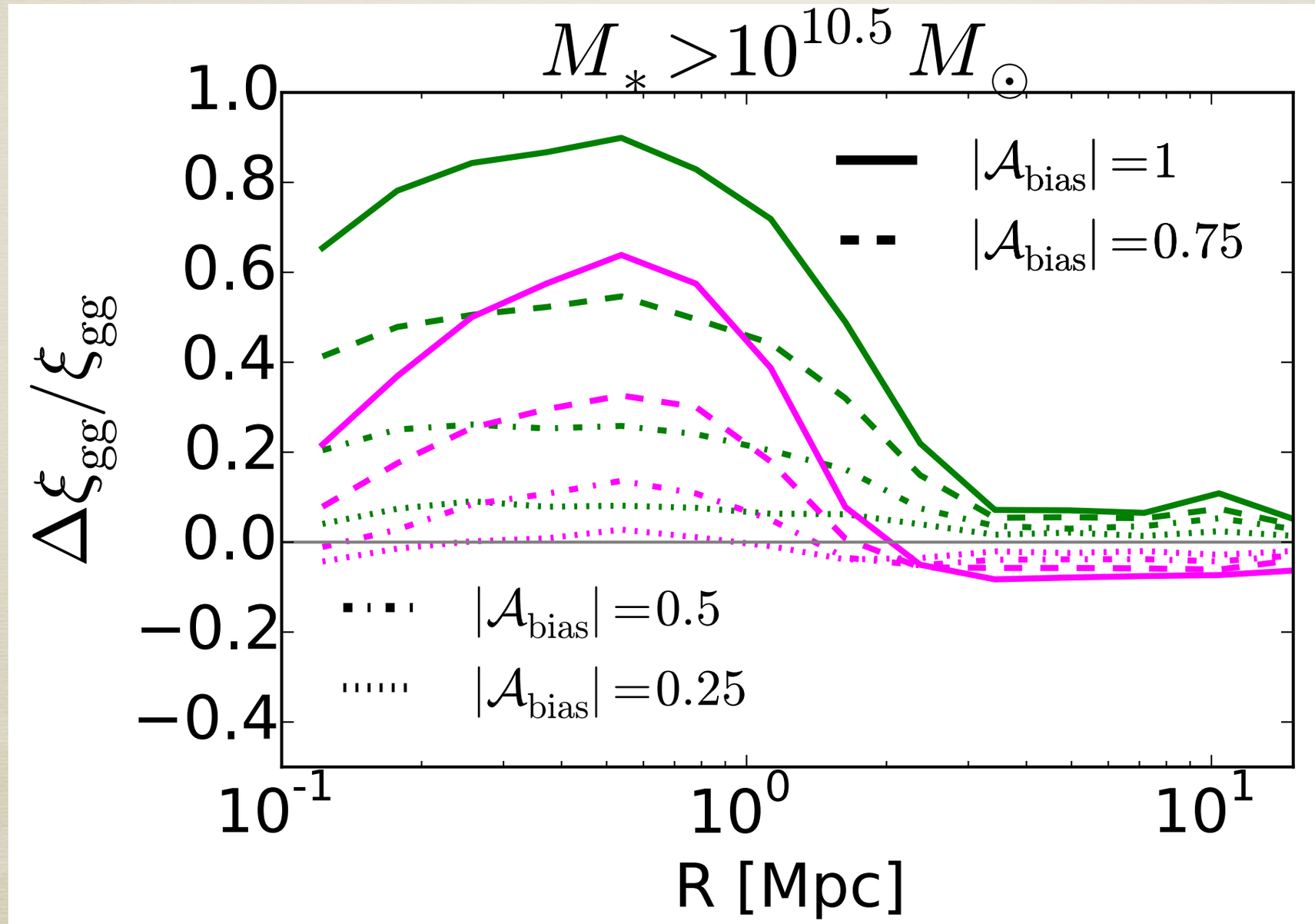


See also
Mao et al. 2015,
Lehmann et al. 2015

Hearin et al. 2015

Accounting for Assembly Bias

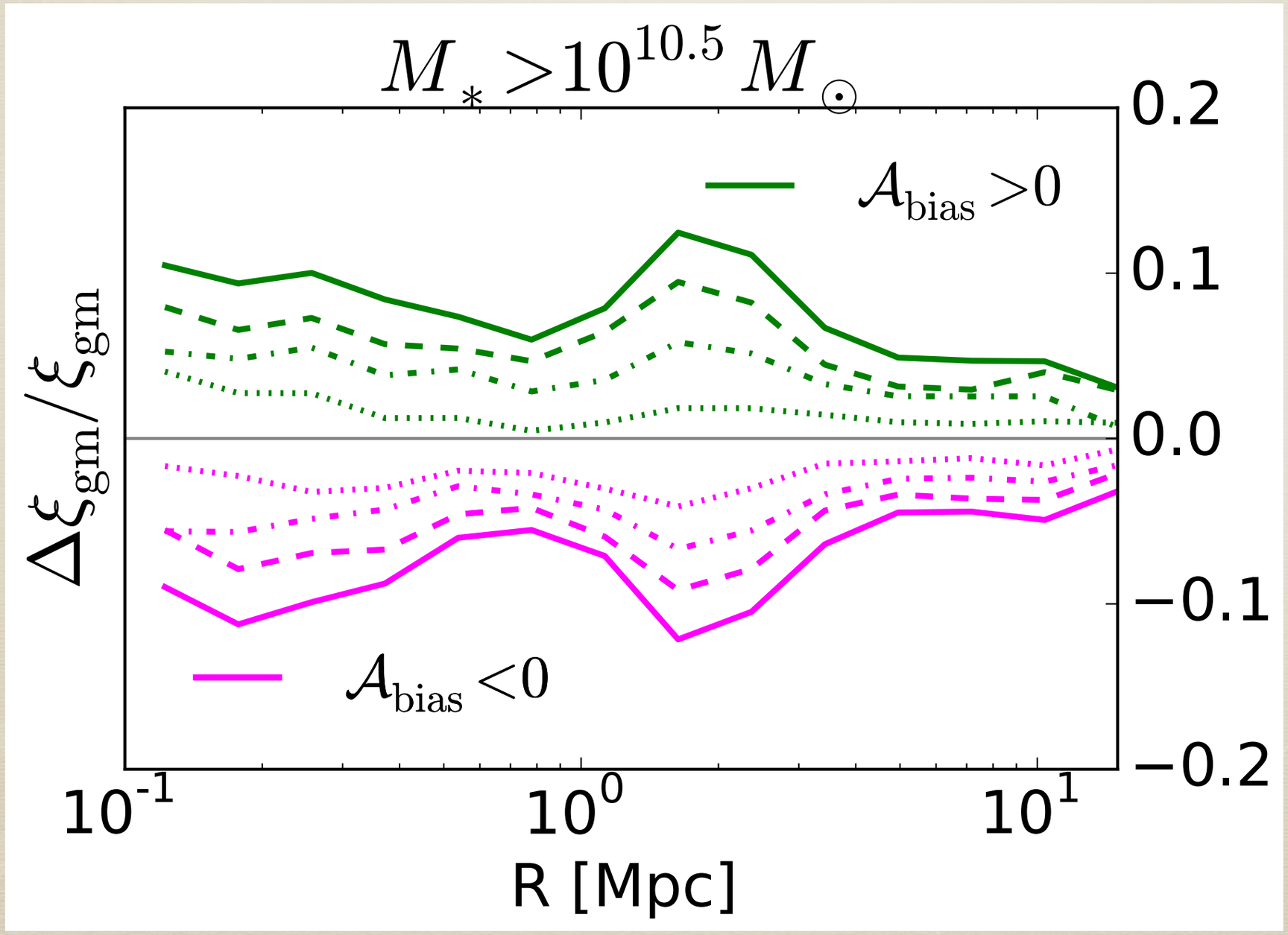
Decorated HOD and galaxy clustering



Hearin et al. 2015

Accounting for Assembly Bias

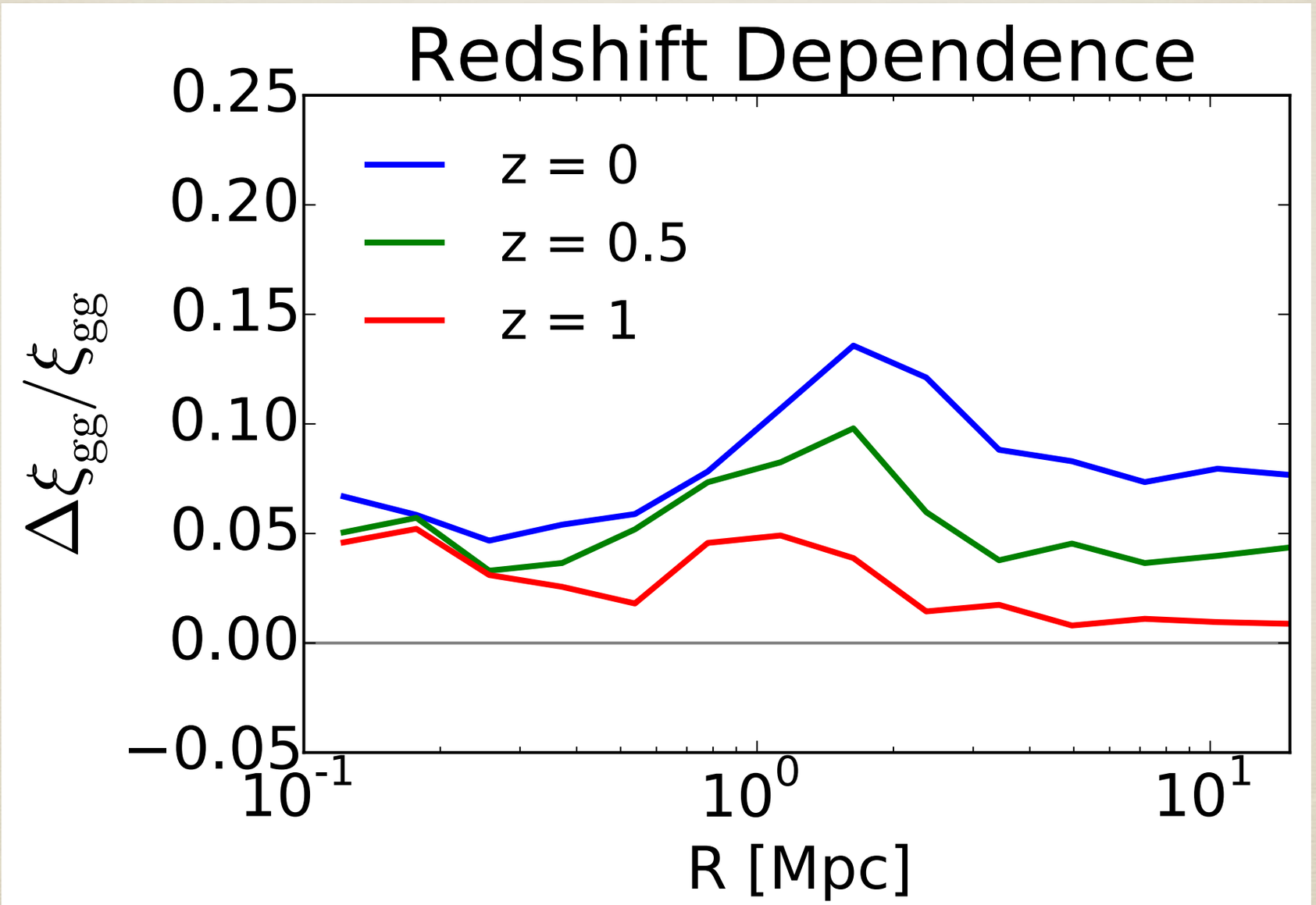
Decorated HOD and gg-lensing



Hearin et al. 2015

Accounting for Assembly Bias

Time evolution of the signal



Hearin et al. 2015

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

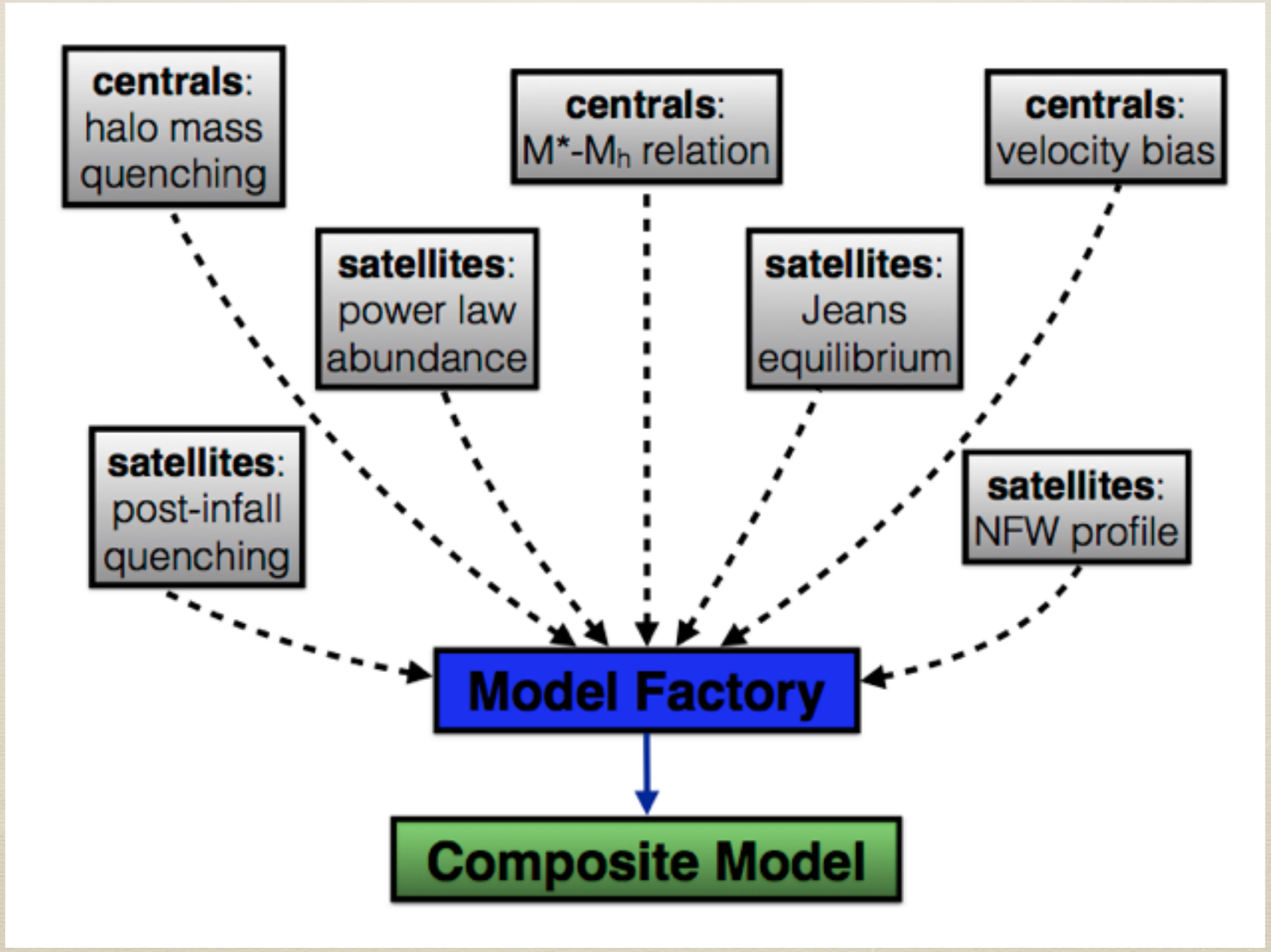
Making Universes with Halotools

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

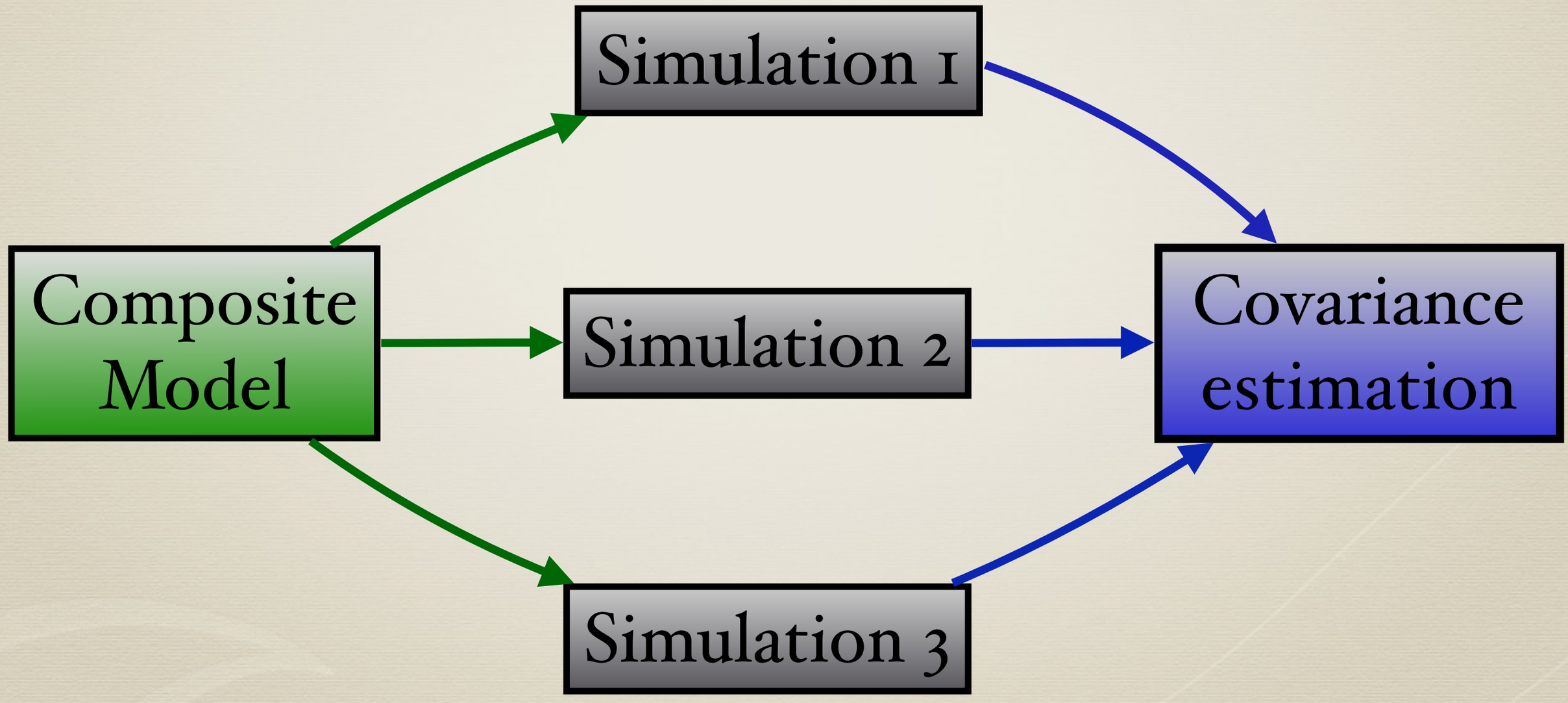
Modeling Galaxies with Halotools

Flexible object-oriented platform to build your own model



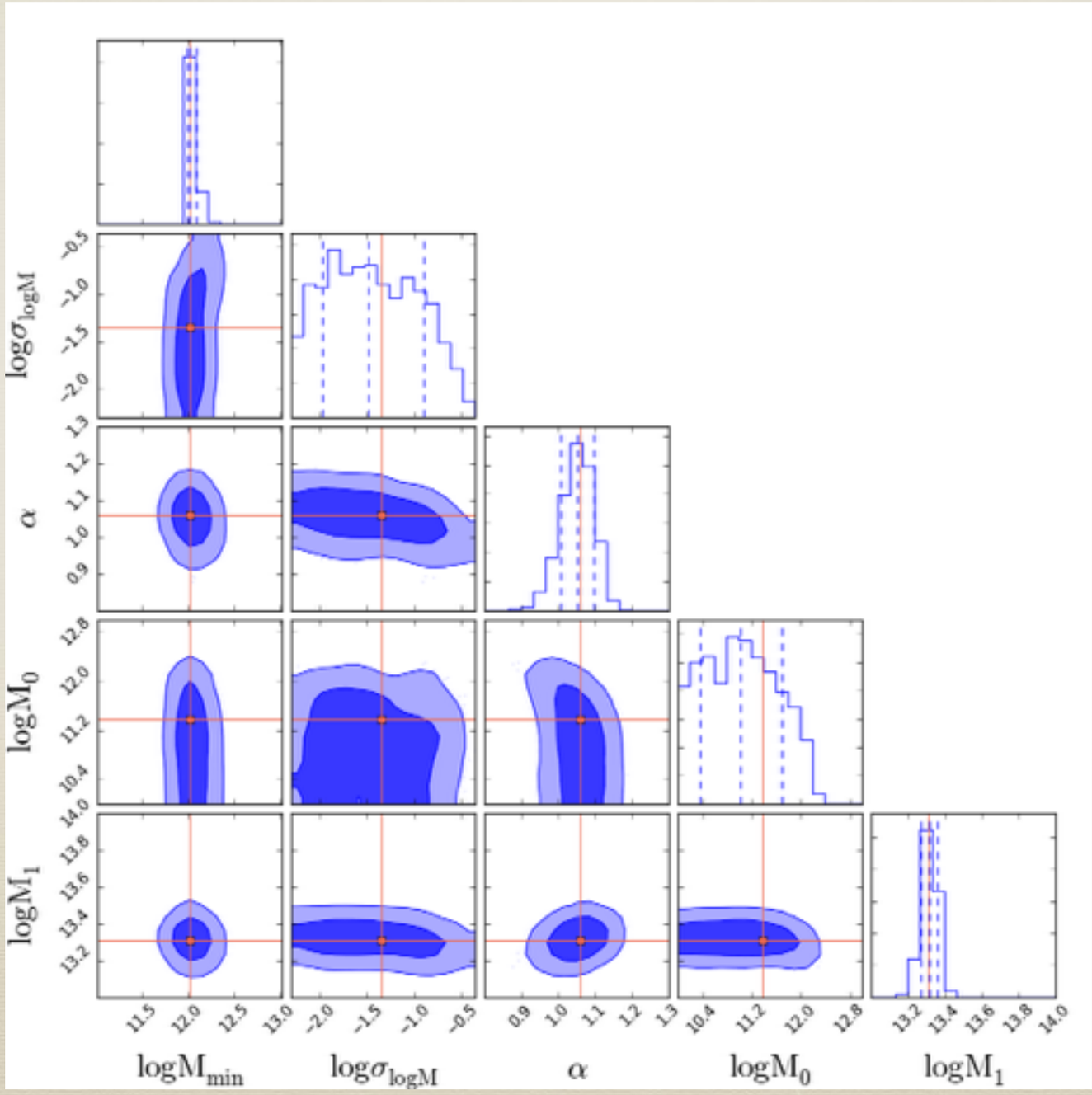
Covariance Matrices with Halotools

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



Constraining Models with Halotools

Optimized for expansive MCMC-type analyses



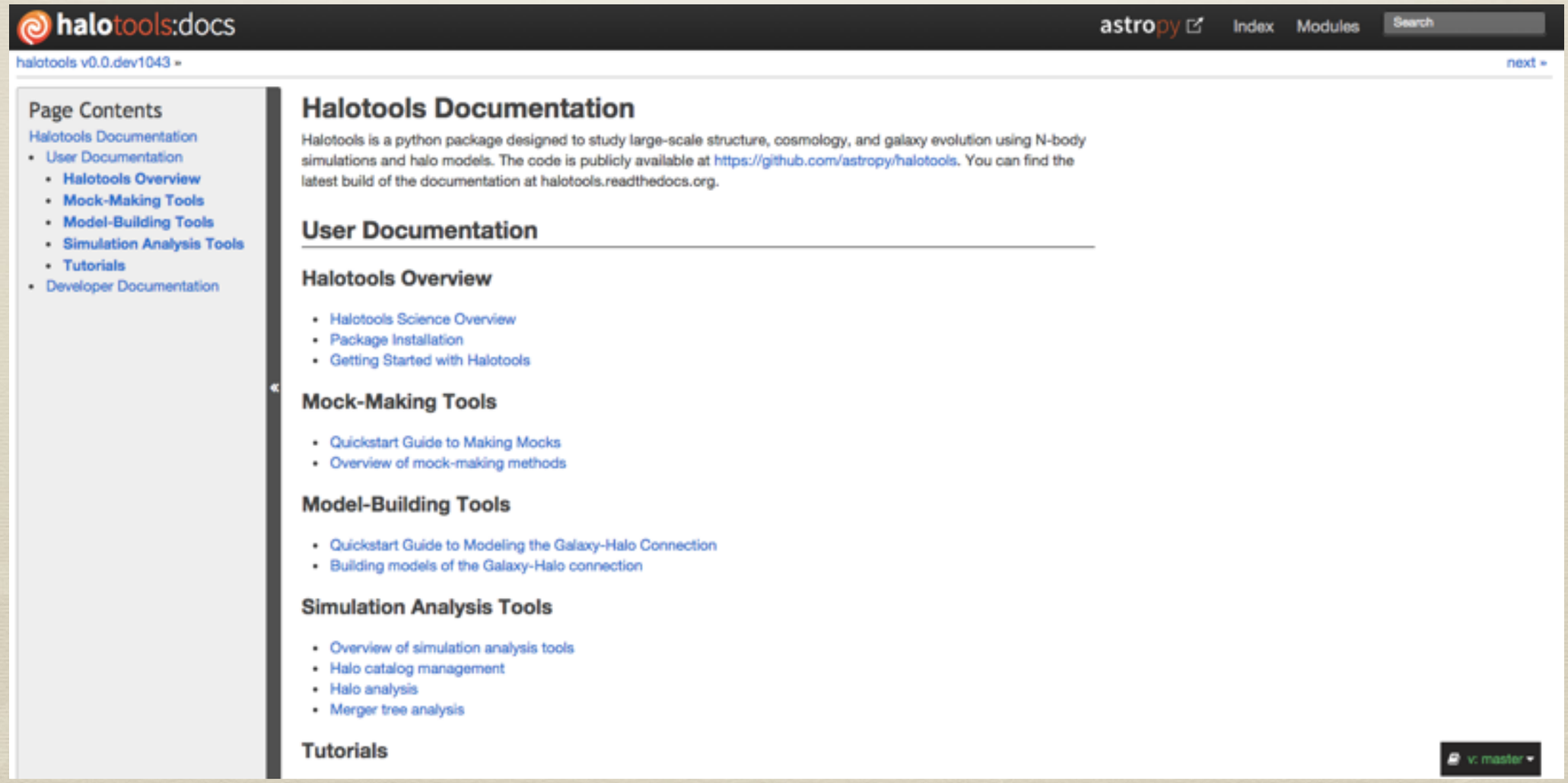
Chang, Vakili et al., in prep.

Reproducibility with Halotools

Exhaustive documentation, tutorials and automated test suite

halotools.readthedocs.org

github.com/astropy/halotools



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

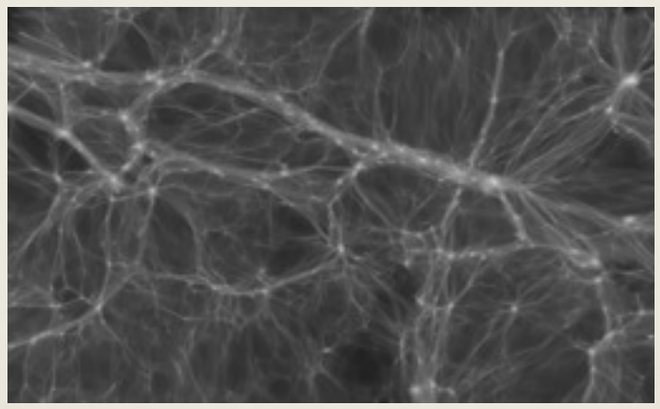
halotools.readthedocs.org

Some additional information

Modeling Galaxy Evolution

The empirical modeling approach

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



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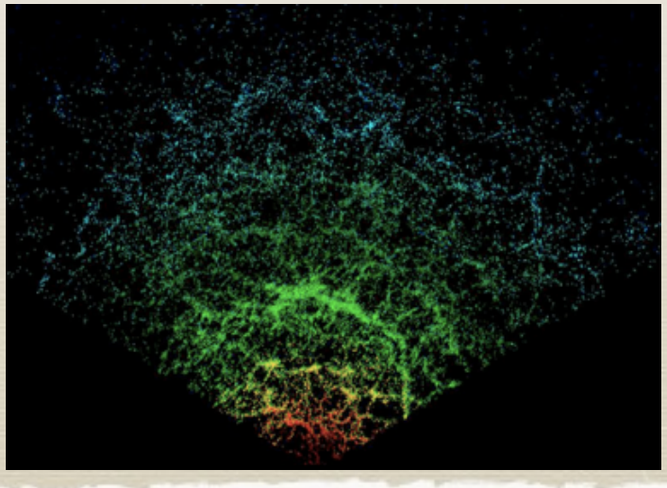


Advantages

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

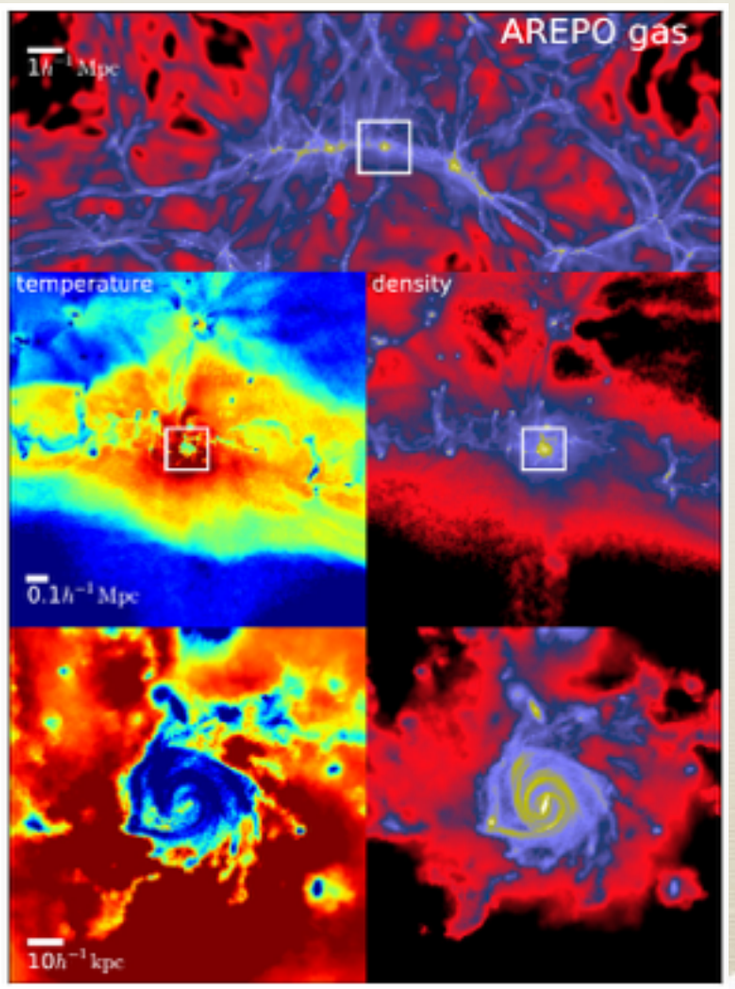
Run simulations that simultaneously
includes dark matter and gas

Advantages

Self-consistent!

Most fundamental

Direct connection to
underlying physics



Disadvantages

Extremely expensive!
(~100 million CPU hours)

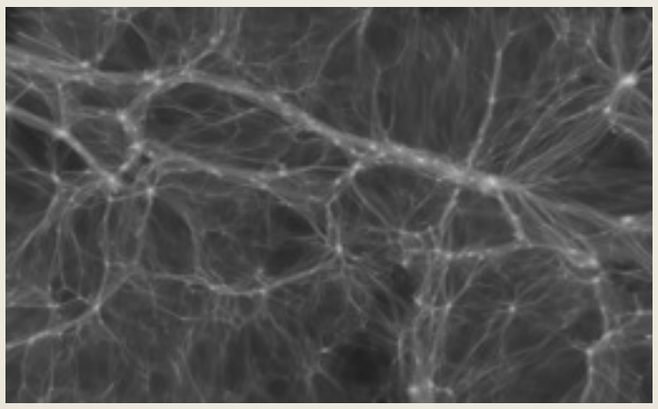
Whoops, wrong model:
Gotta run it all over again!

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)

+

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

Disadvantages

Too many parameters
to properly Monte Carlo
(usually)

Not self-consistent