# STAR FORMATION HISTORIES FROM Z=0 TO Z=8

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IPMU - October 13th, 2011

# Some Motivation

*Hundreds* of papers published on

how many galaxies there are of a given mass,

the cosmic star formation rate,

the star formation rates of individual galaxies.

# Some Motivation

The current best galaxy simulations can match:

~~how many galaxies there are of a given mass,~~

~~the cosmic star formation rate,~~

the star formation rates of individual galaxies.*

*Only sometimes.

# Some Motivation

If we knew something how quickly galaxies
in simulations were *supposed* to form stars,
we could better understand how to fix this (subgrid models).

LMC; Hubble Heritage Team

# Introduction

How do galaxies build up their stellar populations?

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Two main ways to gain stars:

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Stars reaching the end of the stellar life cycle.

Stars ejected into the ICL during galaxy mergers.

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## Current State of Research

**Two main ways to gain stars:**

Star formation internal to the galaxy.

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## Current State of Research

Two main ways to gain stars:

Star formation internal to the galaxy.

Stars deposited by merging galaxies.

Two main ways to lose stars:

KNOWN *

Stars reaching the end of the stellar life cycle.

Stars ejected into the ICL during galaxy mergers.

* e.g., Bruzual & Charlot 2003, Le Borgne 2004, Maraston 2005, Charlot & Bruzual 2020

# Introduction

## Current State of Research

Two main ways to gain stars:

Star formation internal to the galaxy.

Stars deposited by merging galaxies.

MOSTLY KNOWN*

Two main ways to lose stars:

Stars reaching the end of the stellar life cycle.

KNOWN

Stars ejected into the ICL during galaxy mergers.

* e.g., Fakhouri et al. 2010, Wetzel & White 2009, Cole et al. 2008, Allgood 2005, all the way to Lacey & Cole 1994

# Introduction

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Stars ejected into the ICL during galaxy mergers. *

UNDER INVESTIGATION

* e.g., Dolag et al. 2009, Purcell et al. 2007, Conroy et al. 2007

# Introduction

## Current State of Research

Star formation internal to the galaxy.

NO ONE CAN MEASURE, EXCEPT INSTANTANEOUSLY

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Current State of Research

Star formation internal to the galaxy.

NO ONE CAN MEASURE, EXCEPT INSTANTANEOUSLY

Simulations and semi-analytic models, while useful for comparing models to observations, are not guaranteed to explore the full range of physical models relevant for the actual universe.

# Introduction

What else do we know that might be useful?

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Galaxy Stellar Masses as a Function of Time*

* e.g., Drory et al. 2009, Illingworth et al. 2009, Li & White 2009, Perez-Gonzalez et al. 2008, Fontana et al. 2006

# Introduction

What else do we know that might be useful?

Galaxy Stellar Masses as a Function of Time

How to Populate Halos in Simulations With Galaxies*

* e.g., Behroozi et al. 2010, Moster et al. 2009, Hansen et al. 2009, Yang et al. 2007, Zheng et al. 2007, Cooray 2006, Mandelbaum et al. 2006

# Introduction

What else do we know that might be useful?

Galaxy Stellar Masses as a Function of Time

+

How to Populate Halos in Simulations With Galaxies

=

Galaxy Stellar Mass Histories

# Introduction

What else do we know that might be useful?

$$\frac{d \text{ Galaxy Stellar Mass}}{dt} =$$

Two main ways to gain stars:

- Star formation internal to the galaxy.
- Stars deposited by merging galaxies. MOSTLY KNOWN

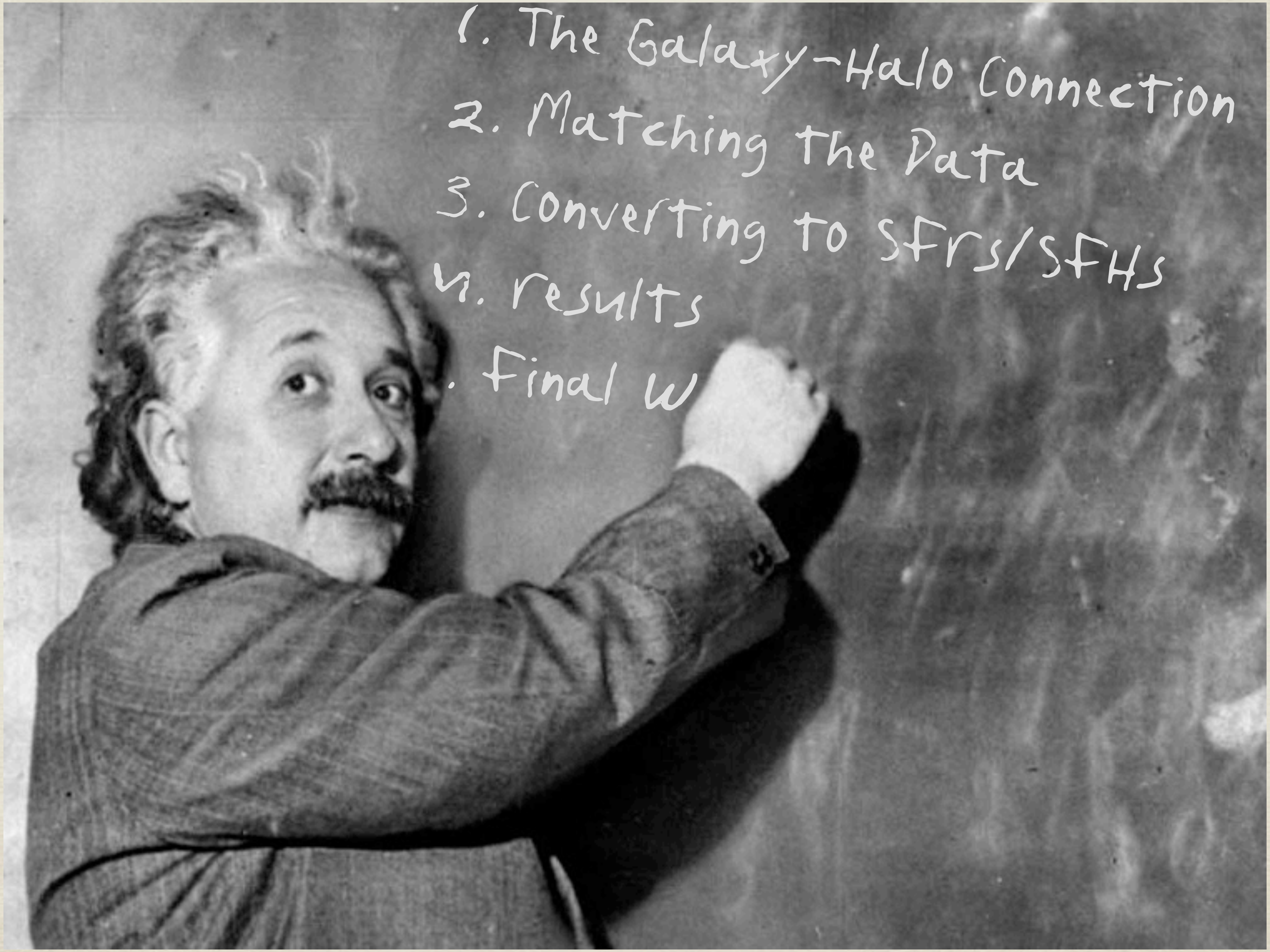
Two main ways to lose stars:

- Stars reaching the end of the stellar life cycle. KNOWN
- Stars ejected into the ICL during galaxy mergers. UNDER INVESTIGATION

# Introduction

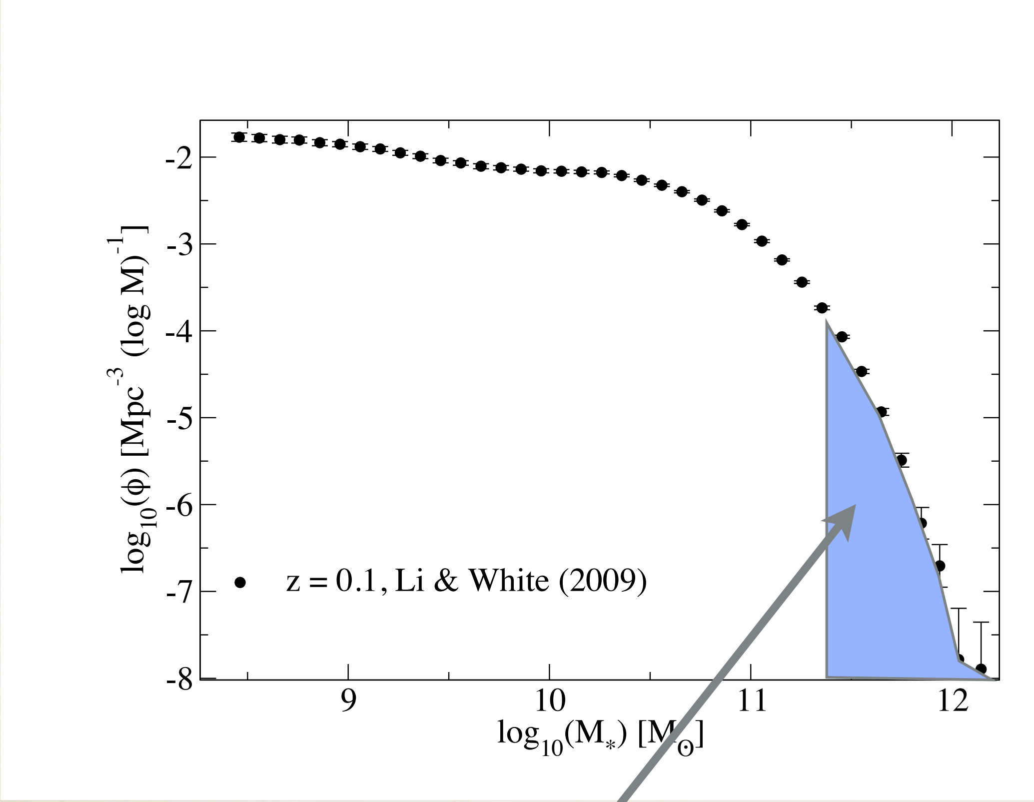
Hence, we have the possibility
of constraining galaxy star formation
*as a function of time*
*and dark matter halo properties*
by connecting observed galaxies
with their likely progenitors
and merger histories
through dark matter simulations.

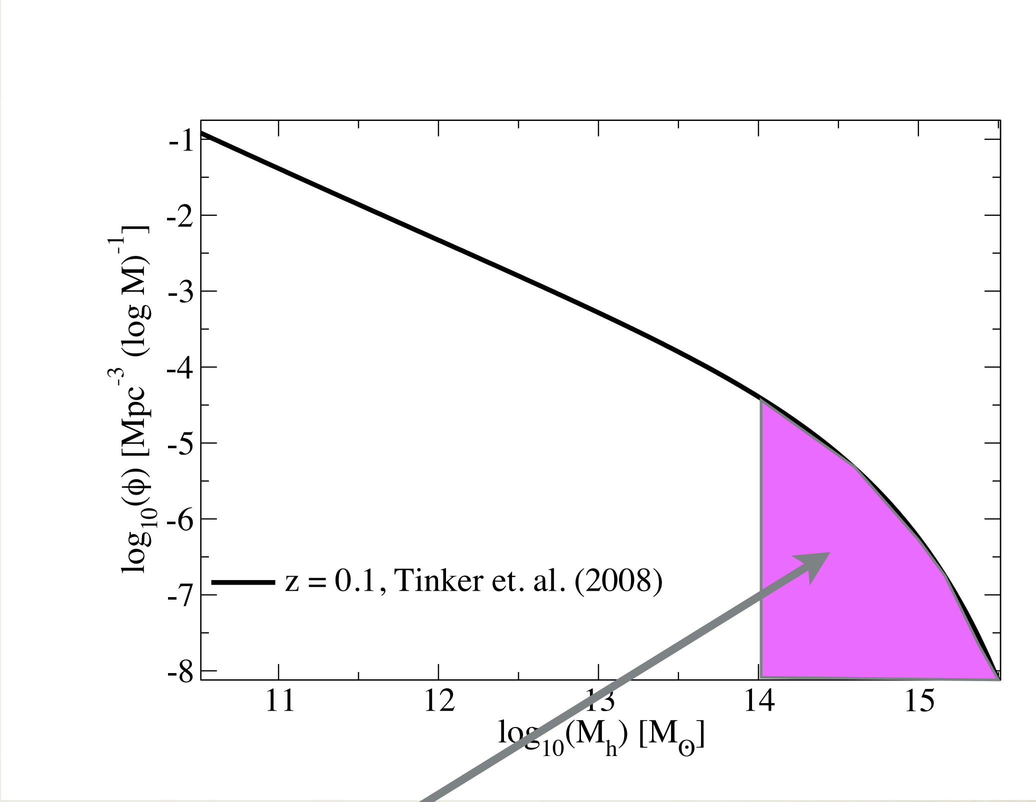
# Outline


1. The Galaxy-Halo Connection
2. Matching the Data
3. Converting to SFRs/SFHs
4. results
. Final W

# The Galaxy-Halo Connection

General principle of abundance matching:
The largest galaxies live in the largest halos.



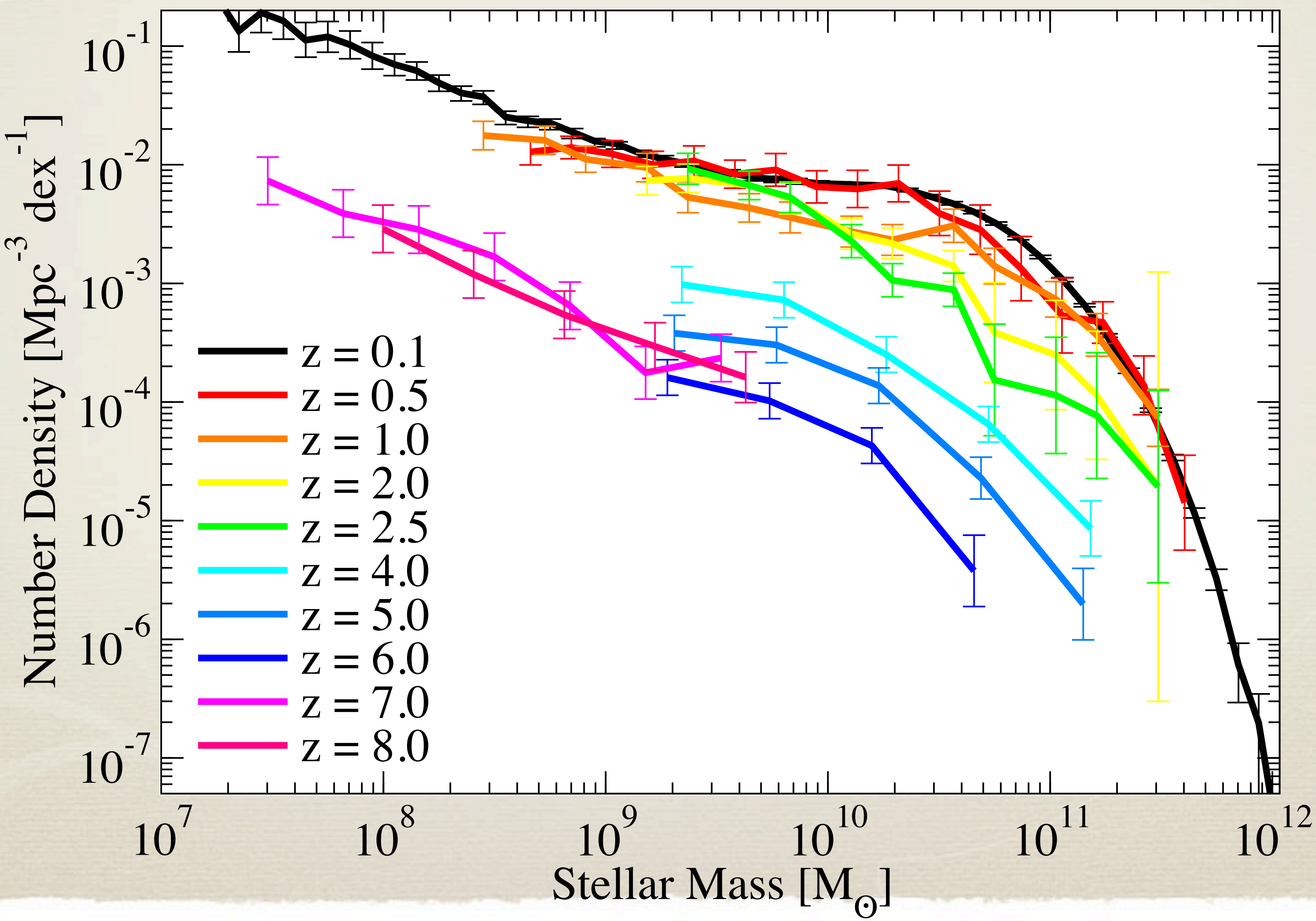

E.g.:

$$N_{SM}(>10^{11.4}M_\odot) = N_M(>10^{14}M_\odot)$$

$$\rightarrow SM(M_h = 10^{14}M_\odot) = 10^{11.4}M_\odot$$

# The Galaxy-Halo Connection

There's an important issue: stellar mass functions aren't good enough by themselves to constrain stellar mass histories.



# The Galaxy-Halo Connection

Workaround: constrain stellar mass histories also with specific star formation rates and the cosmic star formation rate.

(What about the tension between the cosmic SFR and the cosmic stellar mass density?*)

* e.g., Wilkins et al. 2008, Hopkins & Beacom 2006

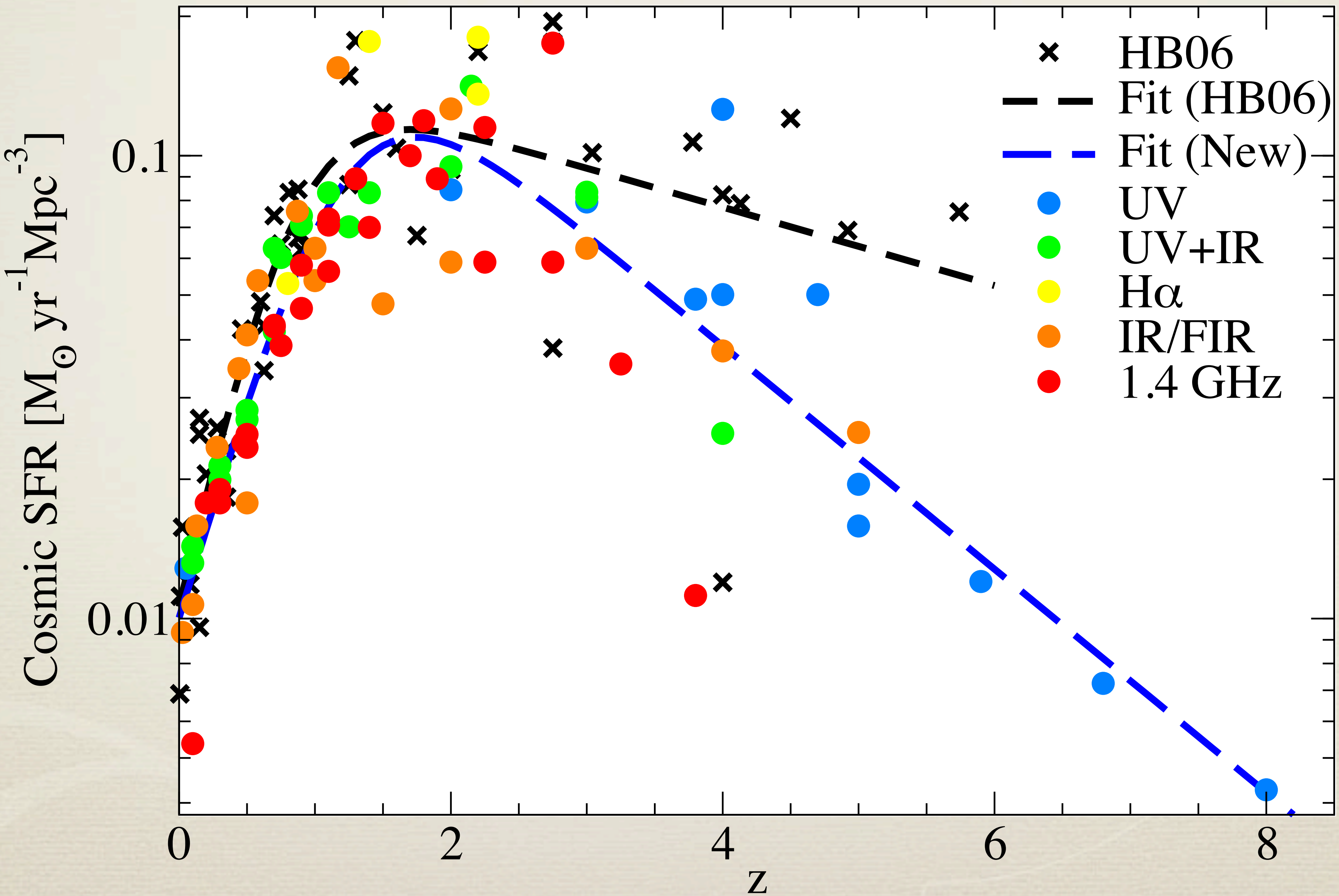
# The Galaxy-Halo Connection

There's been lots of new data since then, however:

| Publication | Redshifts | Technique | Area | Notes |
|---|---|---|---|---|
| Robotham & Driver (2011) | 0.013 – 0.1 | UV | 833 $deg^2$ | I |
| Salim et al. (2007) | 0.005 – 0.2 | UV | 741 $deg^2$ | A |
| Ly et al. (2011a) | 0.8 | $H\alpha$ | 0.8 $deg^2$ | I |
| Zheng et al. (2007a) | 0.2 – 1 | UV/IR | 0.458 $deg^2$ | I |
| Rujopakarn et al. (2010) | 0 – 1.2 | FIR | 0.389 - 9 $deg^2$ | I |
| Smolčić et al. (2009) | 0.2 – 1.3 | 1.4 GHz | 2 $deg^2$ | I |
| Shim et al. (2009) | 0.7 – 1.9 | $H\alpha$ | 0.029 $deg^2$ | I |
| Tadaki et al. (2011) | 2.2 | $H\alpha$ | 0.0156 $deg^2$ | I |
| Hayes et al. (2010) | 2.2 | $H\alpha$ | 0.0156 $deg^2$ | I |
| Magnelli et al. (2011) | 1.3-2.3 | IR | 0.0786 $deg^2$ | I |
| Karim et al. (2011) | 0.2 – 3 | 1.4 GHz | 2 $deg^2$ | |
| Ly et al. (2011b) | 1 – 3 | UV | 0.241 $deg^2$ | AI |
| Kajisawa et al. (2010) | 0.5 – 3.5 | UV/IR | 0.029 $deg^2$ | AI |
| Dunne et al. (2009) | 0 – 4 | 1.4 GHz | 0.8 $deg^2$ | I |
| Cucciati et al. (2011) | 0 – 5 | UV | 0.611 $deg^2$ | I |
| Le Borgne et al. (2009) | 0 – 5 | IR-mm | varies | I |
| van der Burg et al. (2010) | 3 – 5 | UV | 4 $deg^2$ | I |
| Yoshida et al. (2006) | 4 – 5 | UV | 0.243 $deg^2$ | I |
| Bouwens et al. (2011a) | 4 – 8 | UV | 0.040 $deg^2$ | I |

# The Galaxy-Halo Connection

High-redshift SFR data has actually changed dramatically since Hopkins & Beacom!*



# The Galaxy-Halo Connection

High-redshift SFR data has actually changed dramatically since Hopkins & Beacom!*

So it in fact is now possible to self-consistently match cosmic star formation rates and the cosmic stellar mass density without any special tricks like an evolving IMF!

# Uncertainties...

How much can we trust the data which observers give us, especially at high redshifts?

# Main Uncertainties

* Stellar Mass Functions:
  * Uniform Mass Errors (IMF, SPS, Dust, Pop.)
  * Nonuniform Mass Errors
  * Scatter (Eddington) Bias
  * Cosmic Variance
  * Redshift Errors
  * Magnification Bias

Behroozi et al. 2010

# Main Uncertainties

- Star Formation Rates:
  - Dust Obscuration
  - Intrinsic Scatter Corrections
  - Survey Completeness
  - Cosmic Variance
  - Redshift Errors
- SFRs, cont'd:
  - SED libraries
  - AGNs
  - Dust Temperature
  - 1.4GHz SFR Calibration
  - IMF
- Specific Star Formation Rates:
  - All of the above, plus all of the uncertainties for SMs.

# Uncertainties Summary

Stellar masses: 0.25 dex
(Mostly from SPS/dust/population model assumptions)

Star formation rates: 0.13 dex ($z=0$) to 0.27 dex ($z>3$)
(Mostly from dust modeling issues, but also population, and redshift issues linked to stellar masses)

Specific star formation rates: 0.28 dex at all redshifts
(Combinations of the above effects)

Plus, an additional 0.3 dex from the IMF.

# Uncertainties Summary

Even at high redshifts, systematic uncertainties
now dominate over statistical ones.

A note for those on TACs:
future galaxy surveys will only help our understanding
of the stellar mass growth of the universe
only if they have targeted, specific methods to
address systematic errors!

# Matching the Data

We constrain everything at the same time by parametrizing the stellar mass / halo mass relationship and its redshift evolution:

low-mass slope

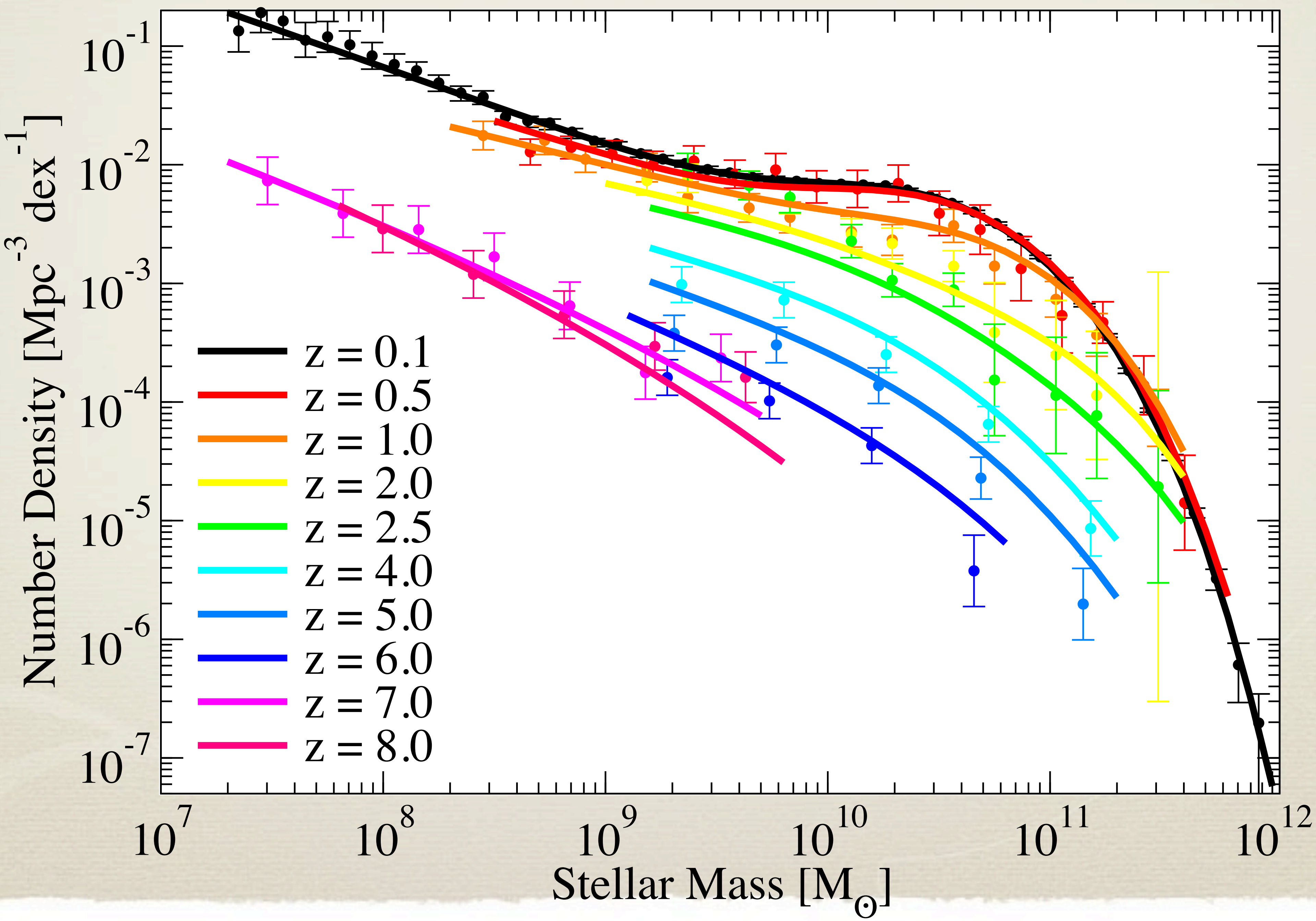
high-mass cutoff

$$\log_{10}(M_h(M_*)) = \log_{10}(M_1) + \beta \log_{10}\left(\frac{M_*}{M_{*,0}}\right) + \frac{\left(\frac{M_*}{M_{*,0}}\right)^{\delta}}{1+\left(\frac{M_*}{M_{*,0}}\right)^{-1}} - \frac{1}{2}$$
$$-\lambda\left(\exp\left[-\gamma \log_{10}\left(\frac{M_*}{M_{*,0}}\right)^{2}\right] - 1\right)$$

transition region

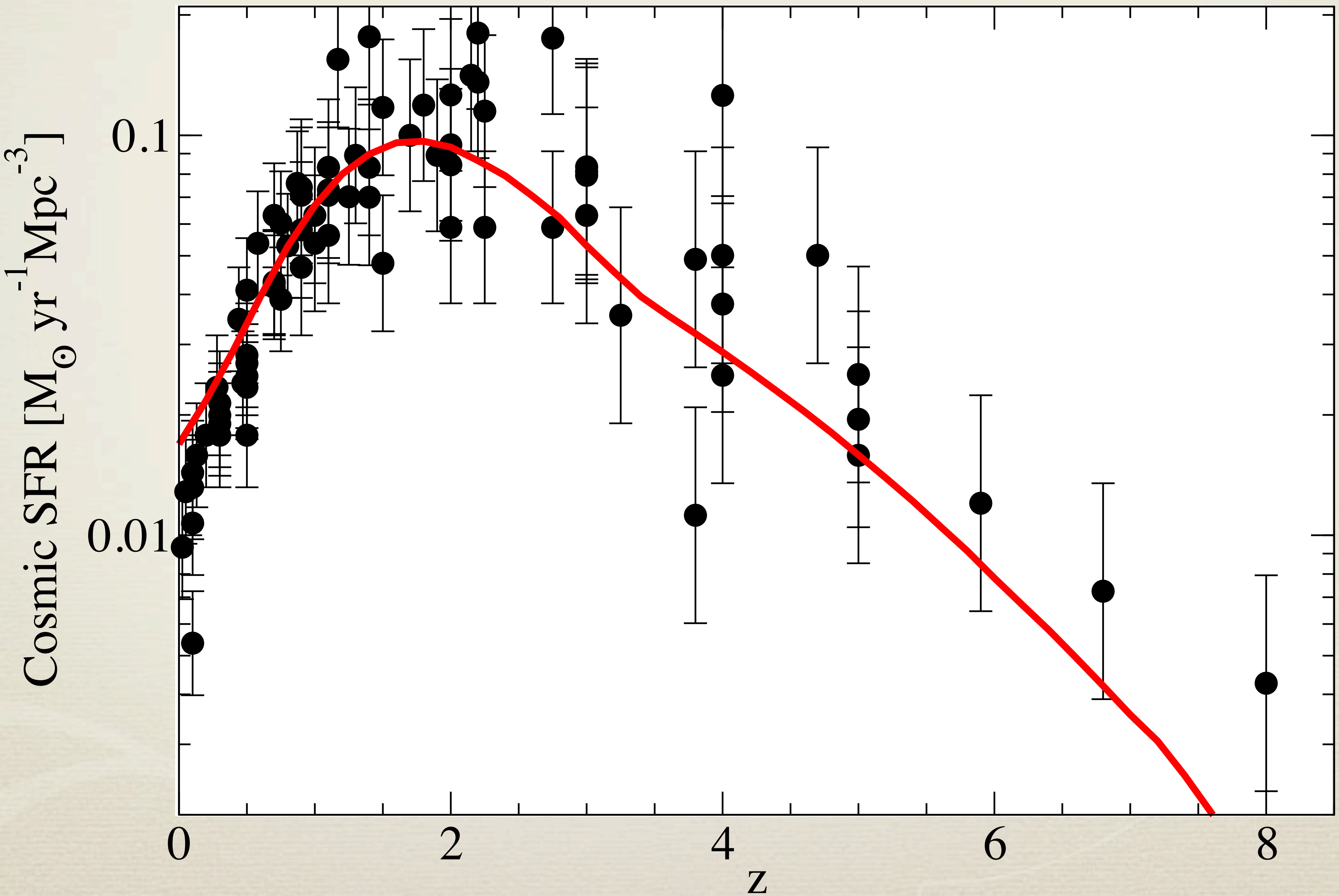
# Matching the Data

With an MCMC search, we can match the galaxy stellar mass functions, ...



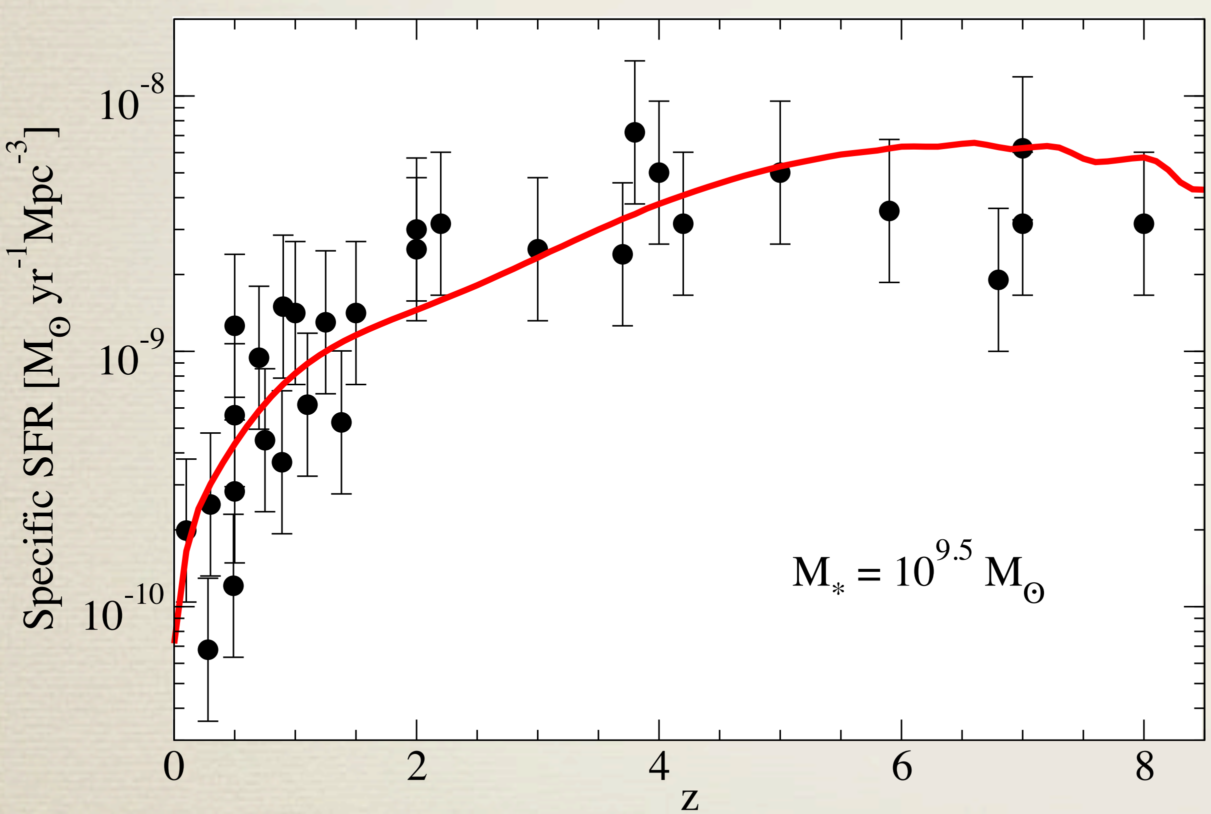
# Matching the Data

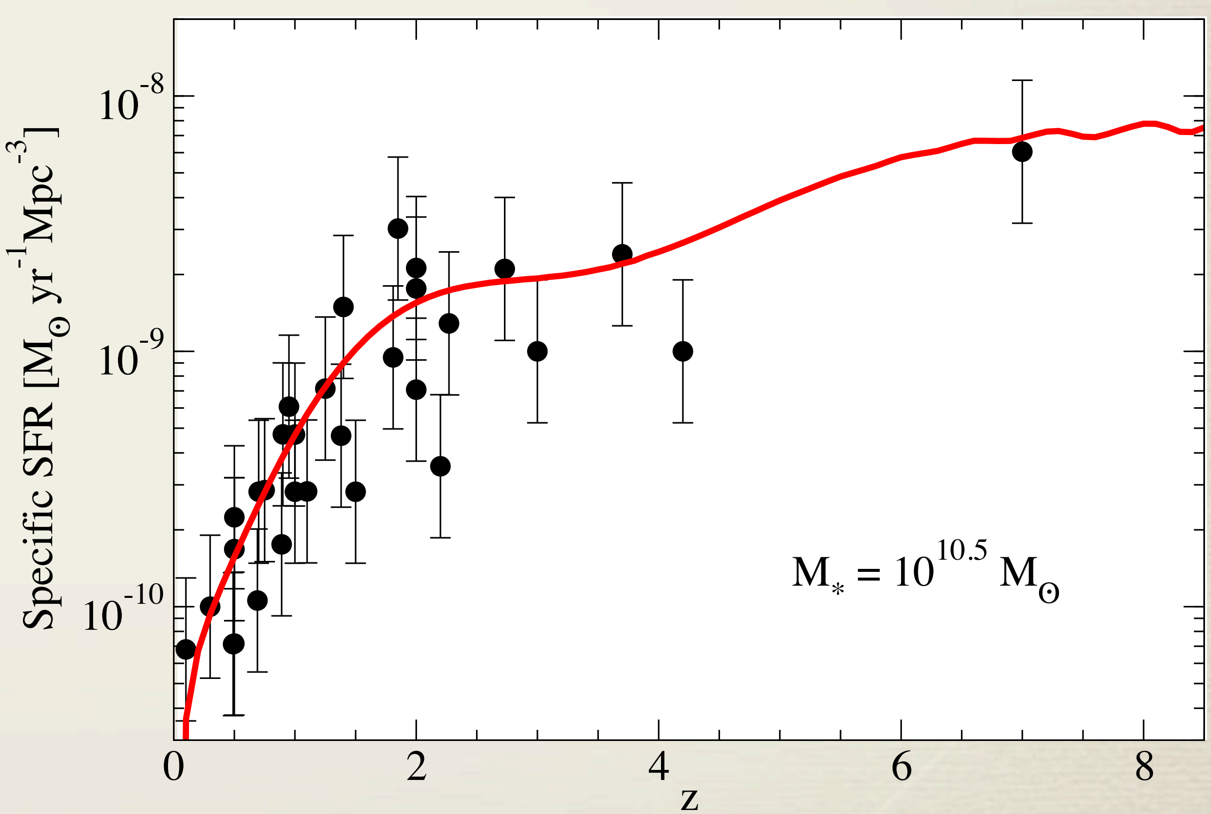
...the cosmic Star Formation Rates:



# Matching the Data

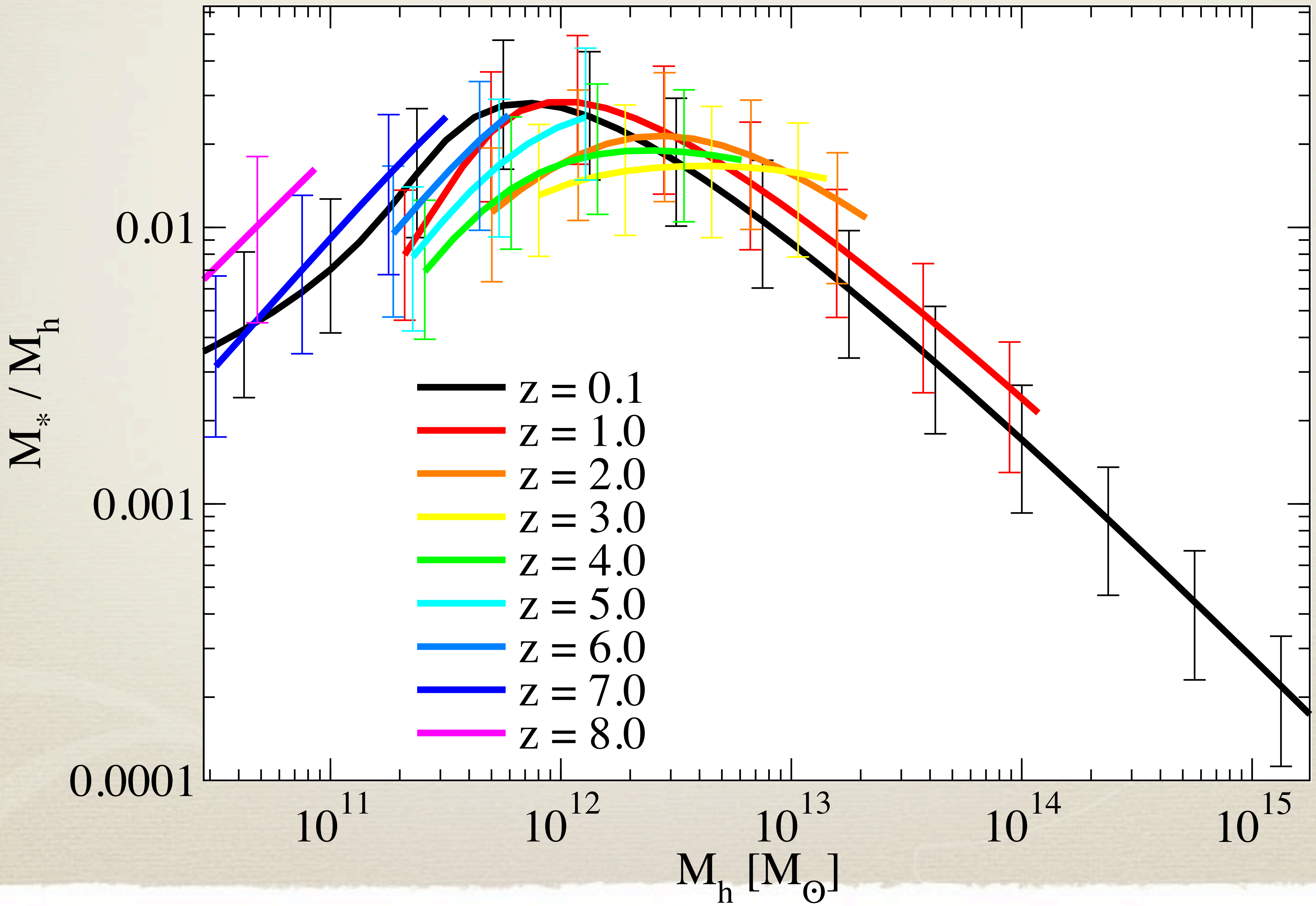
...and the specific Star Formation Rates:



# Matching the Data

We thus obtain stellar masses as a function of redshift and halo mass along with their uncertainties!



# Converting to SFRs

$$\frac{d\text{ Galaxy Stellar Mass}}{dt} =$$

Two main ways to gain stars:

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# Converting to SFRs

Use the conservation equation to determine how changes in stellar mass over time relate to the star formation rate.

$$(\Delta t) \cdot SFR_{m_d}(t_{now}) =$$

(new stars)

$$SM_{m_d}(t_{now})$$

(expected stellar mass)

$$-\left(MMP_{m_p,m_d} + SUBS_{m_p,m_d} \cdot (1 - ICL(m_p, m_d))\right)$$

(number of contributing progenitors, corrected for ICL losses)

$$\times\ SFH^{m_p,t}(t_{now})(1 - SL_t(t_{now}))$$

(stellar population of progenitors, corrected for stellar death)

# Converting to SFRs

Some small hangups:

The halo mass function has not been precisely calibrated to z=8.*

Especially not including satellites!

No-one has ever calibrated the galaxy-galaxy merger rate to z=8, either!*

*Reed et al. 2006 go to z=30, but they use Zel'dovich IC's instead of 2LPT, which makes an enormous difference.

*F+M 2010 do go to z=8, but only for FOF-FOF mergers.

# Converting to SFRs

Solutions: (advertisements)

~~The halo mass function has not been precisely calibrated to z=8.~~
we provide a recalibration of Tinker et al. (2008) at high redshift

~~Especially not including satellites!~~
we wrote a new phase space + time (7D) halo finder (Rockstar)

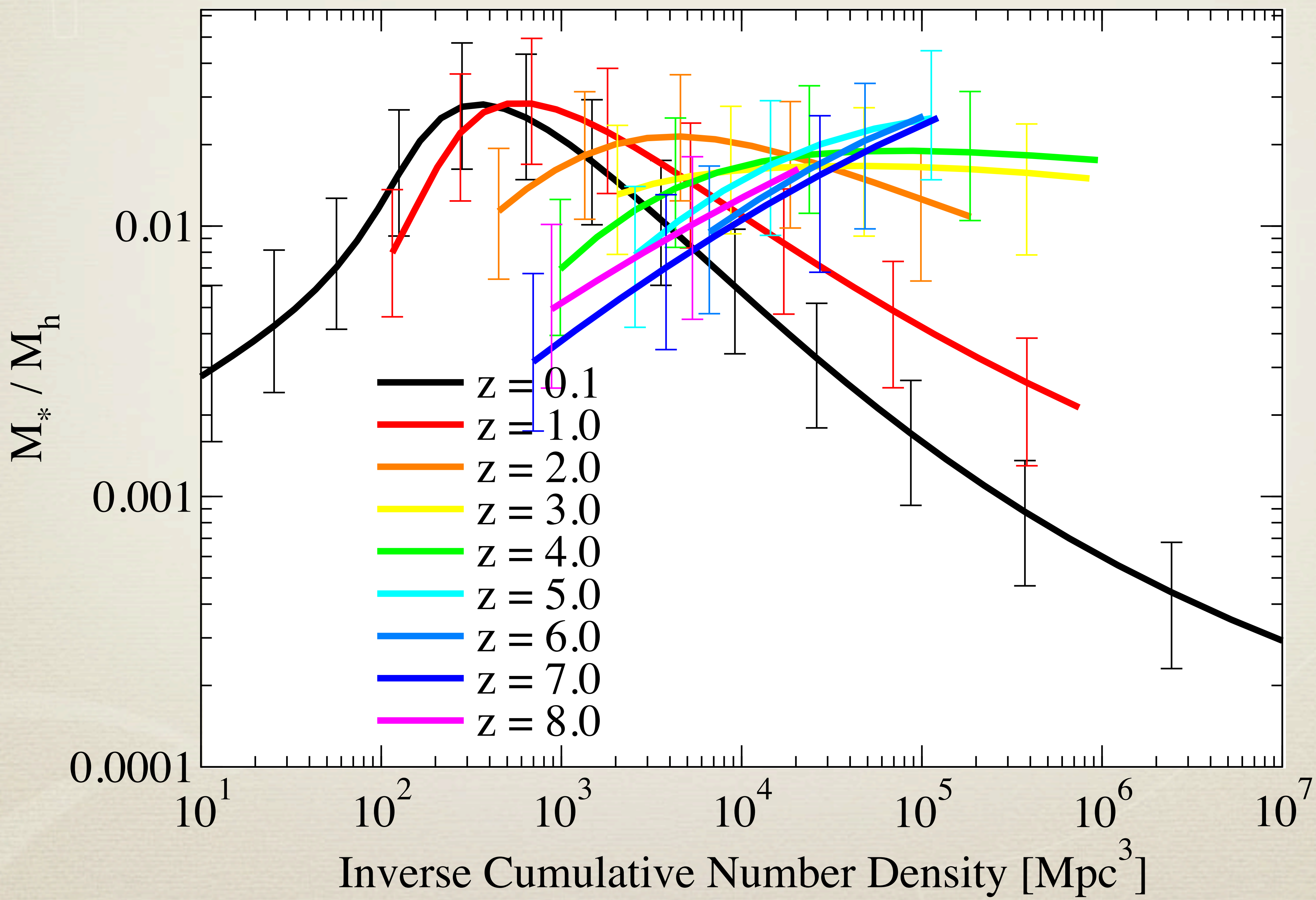
~~No-one has ever calibrated the galaxy-galaxy merger rate to z=8, either!*~~

we wrote a new merger tree algorithm to significantly improve tracking of satellite galaxies and provide a recalibration of the F+M 2010 result for galaxy-galaxy mergers from z=0 to z=8.

(Will discuss more at end if time).

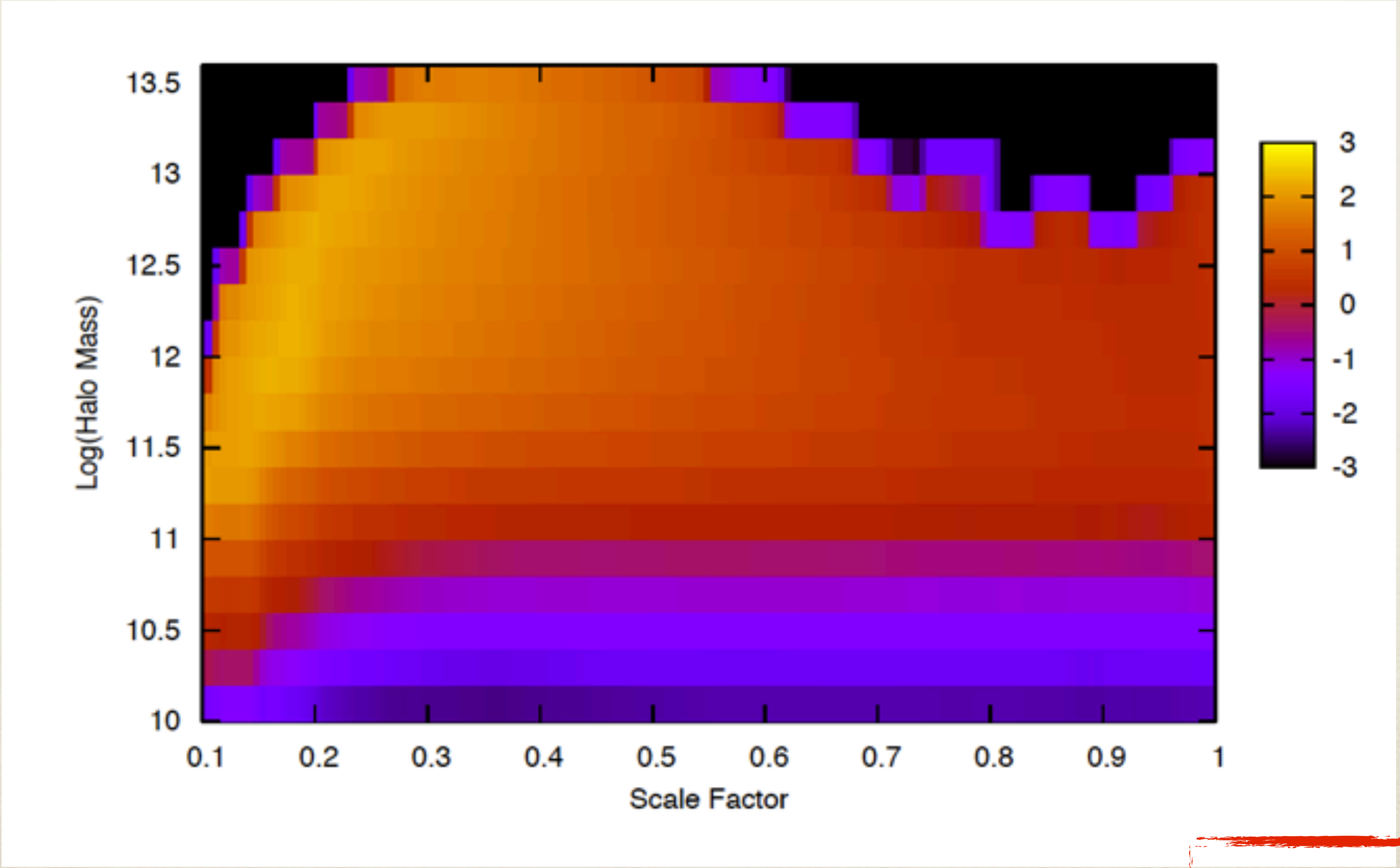
# Results

We find a significant change in the evolution of massive halos after z=2:



# Results

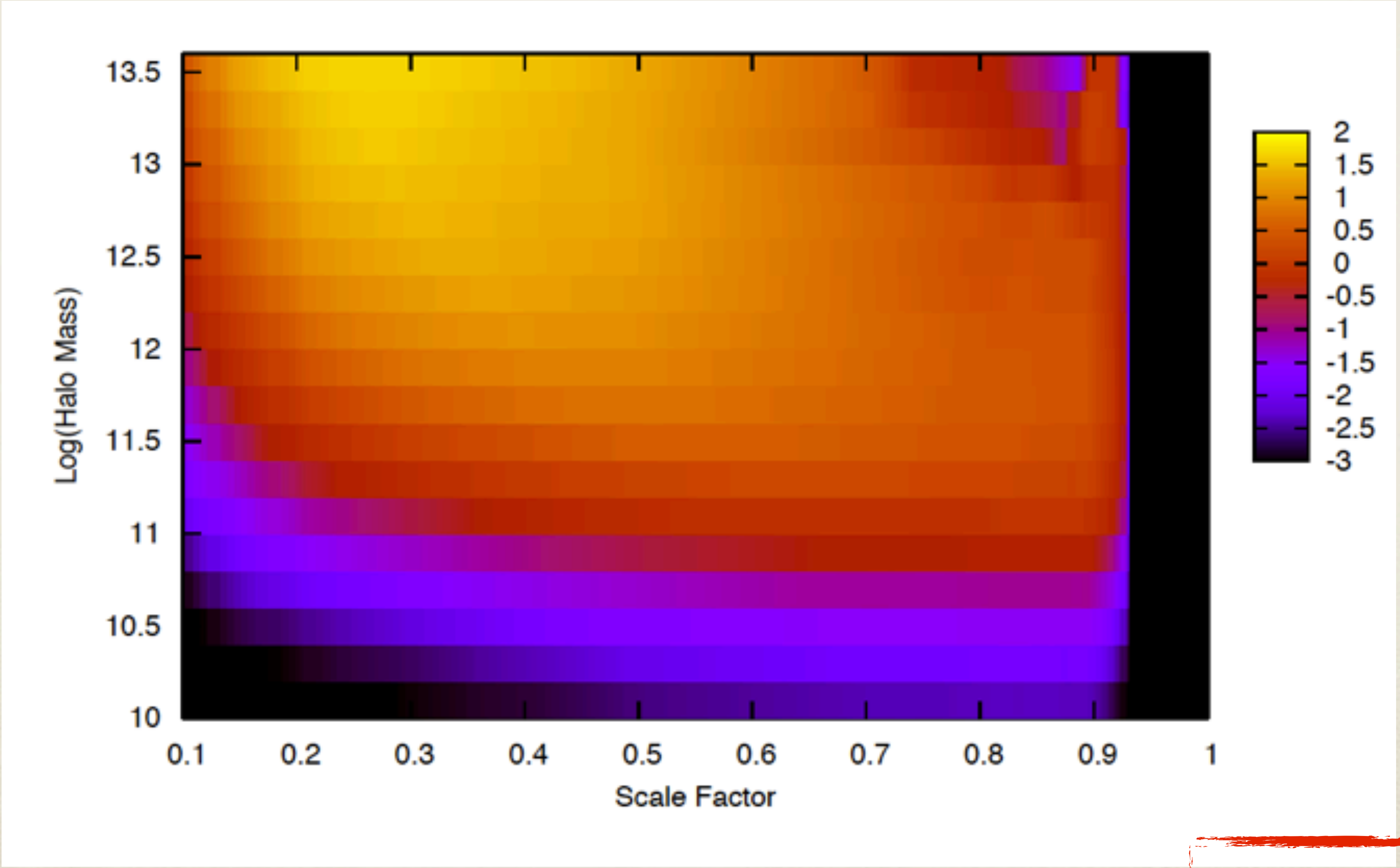
At high redshifts, there appears to be no upper cutoff in halo mass for the star formation rate; this is not true at low redshifts:




Preliminary

# Star Formation Histories

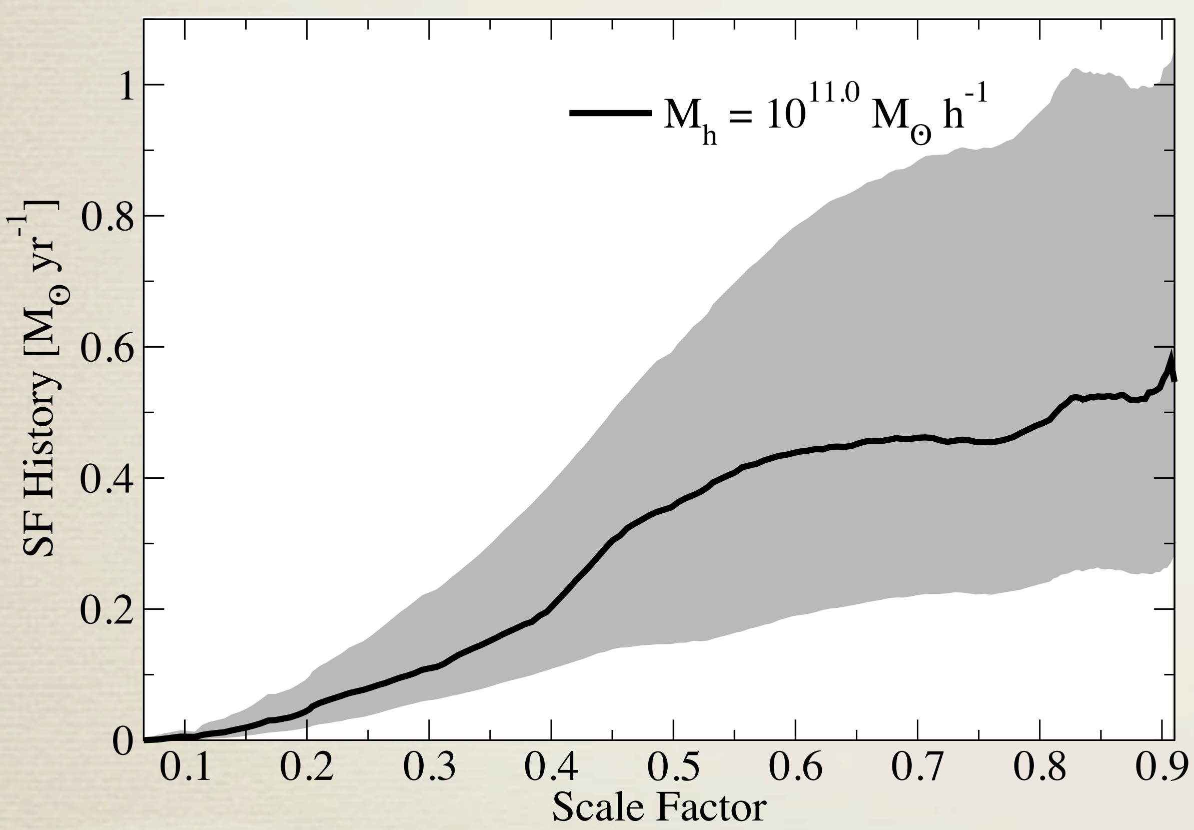
These features are echoed in the star formation histories:

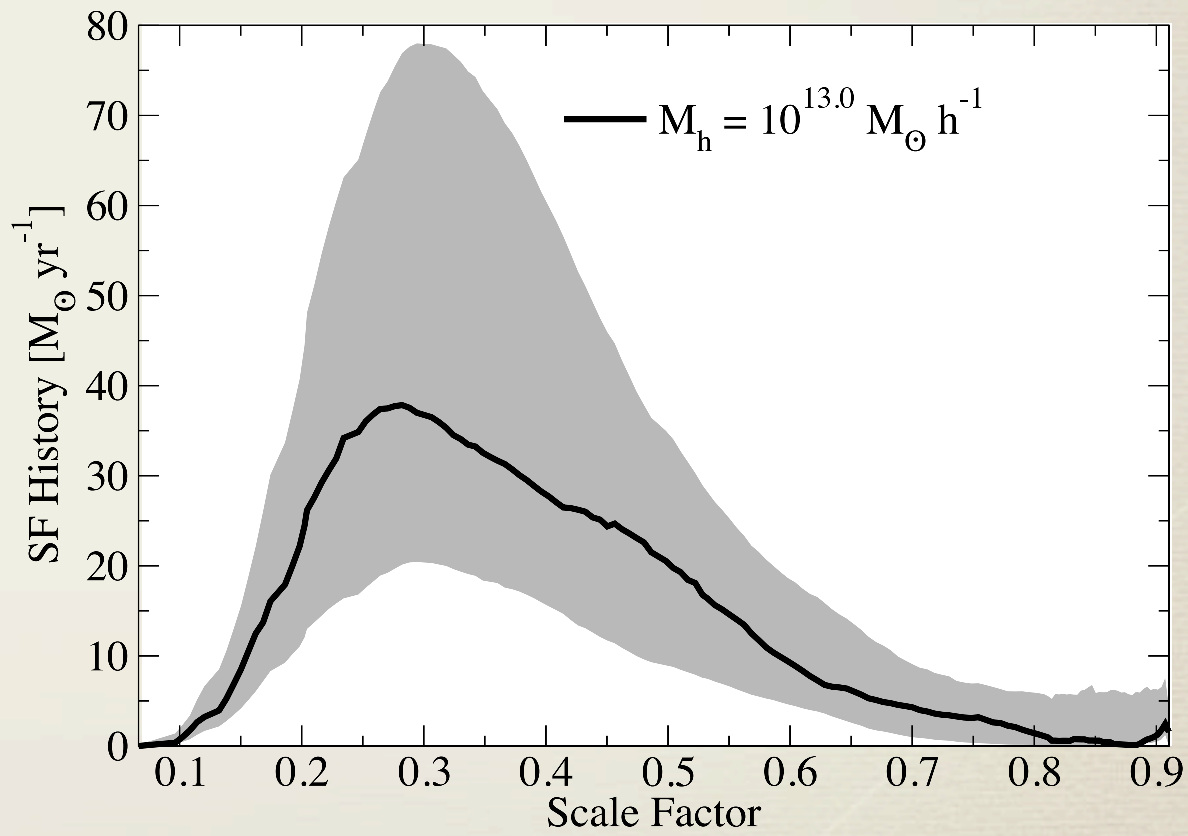



Preliminary

# Star Formation Histories

The rate at which the stellar population grew in low-mass galaxies has always been increasing; whereas for high-mass galaxies, the rate peaked at an early redshift and then declined.

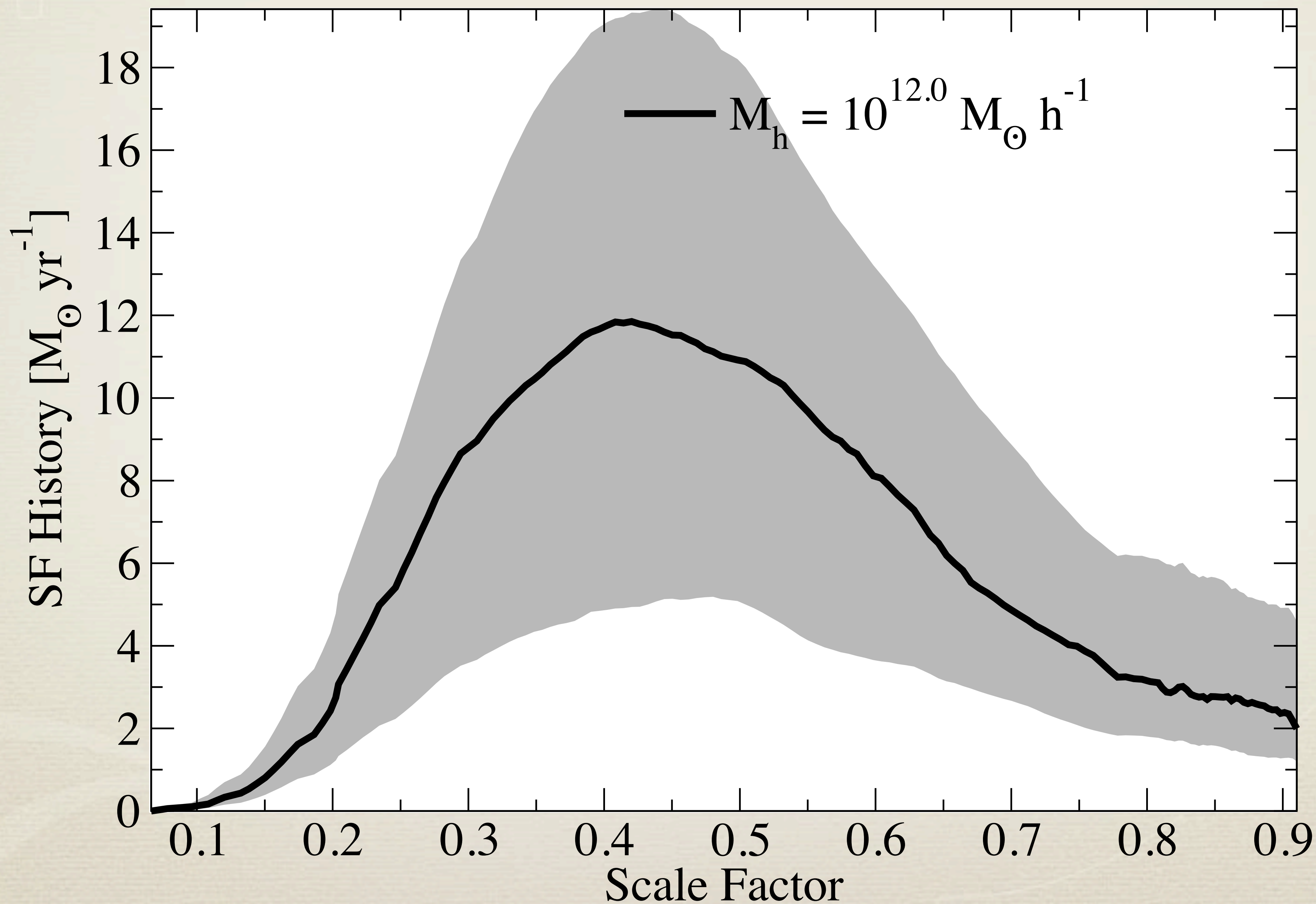



PRELIMINARY

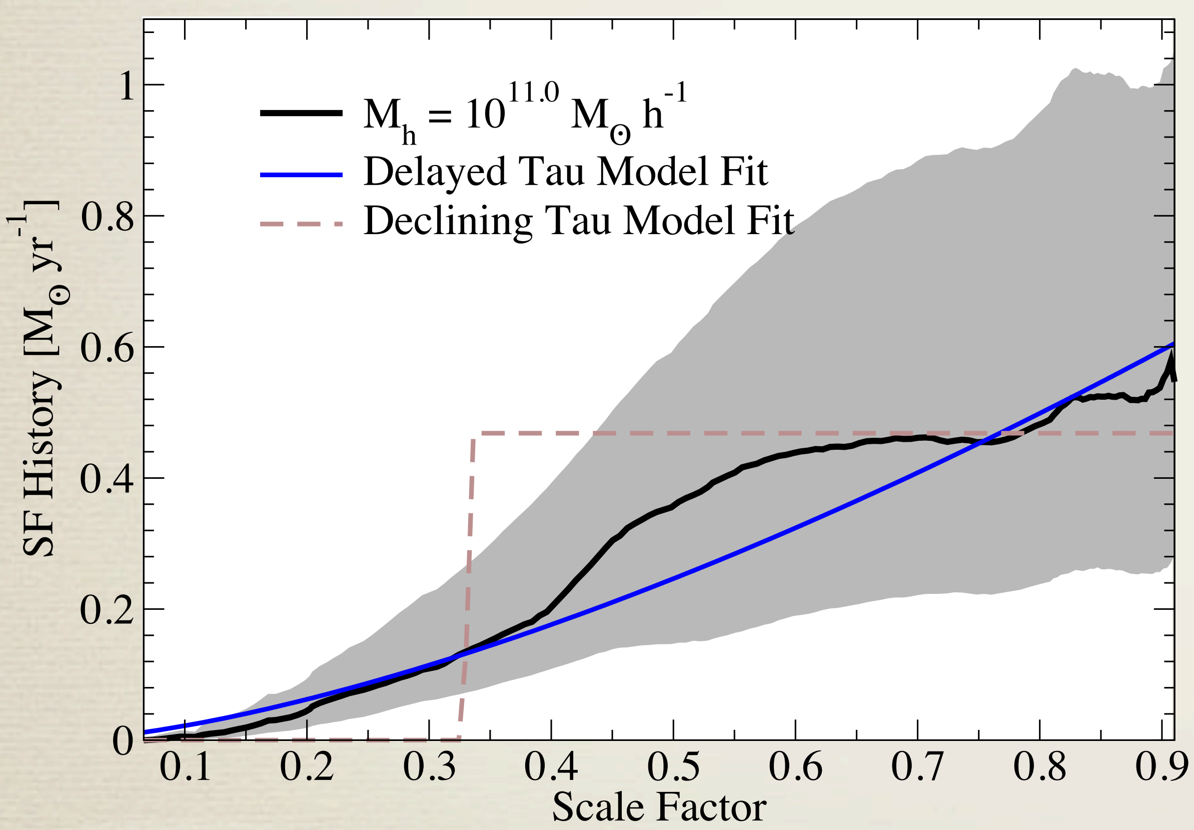
# Star Formation Histories

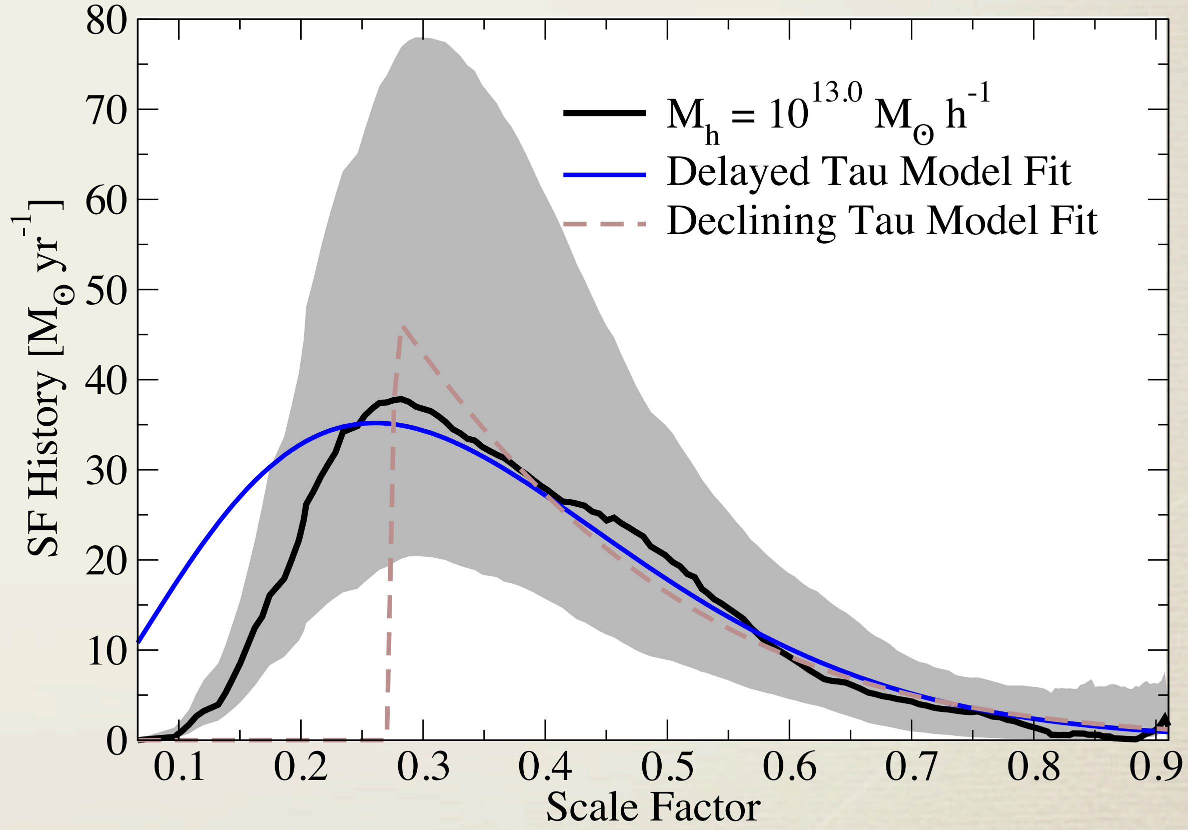
For a Milky-Way-sized galaxy, peak star formation happened at z~1-1.5, and declined to ~2 Msun/year at z=0.1.



# Star Formation Histories

While a declining tau model is a good fit for high-mass galaxies at z=0, it is a terrible fit for low-mass galaxies at z=0 or for galaxies at z>1.



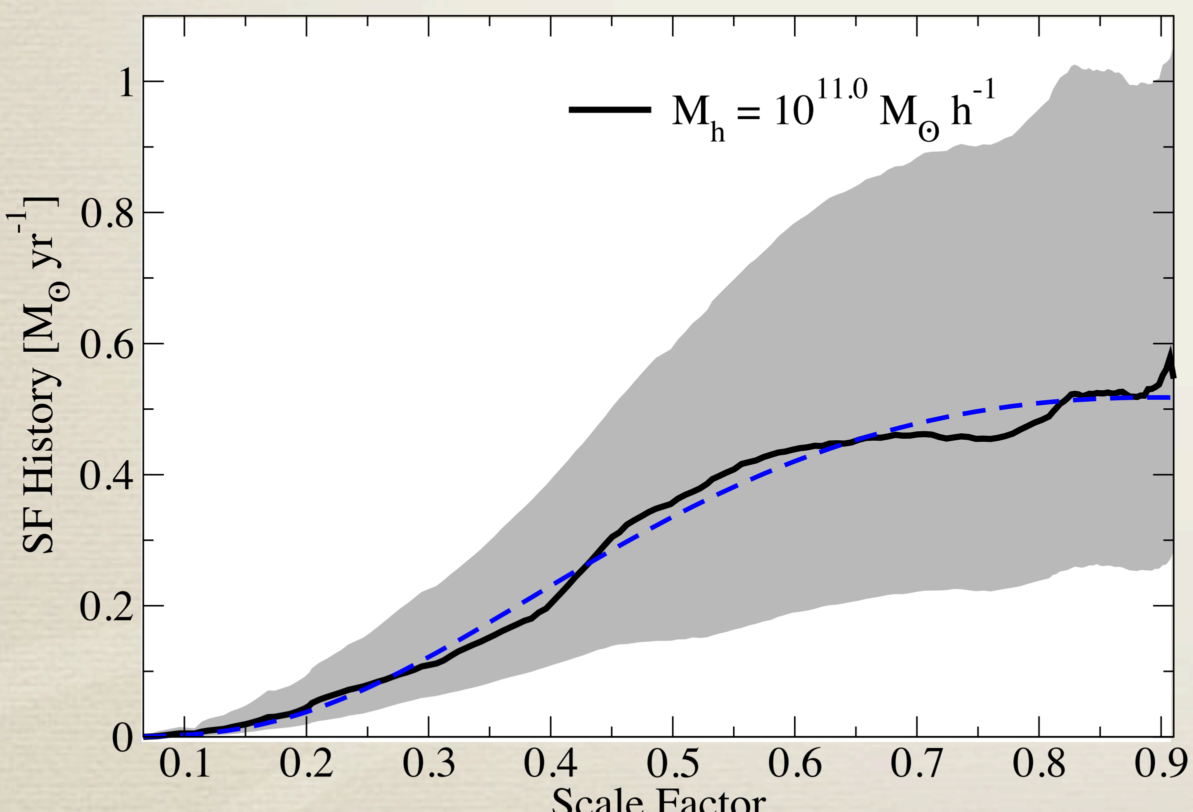
# Star Formation Histories

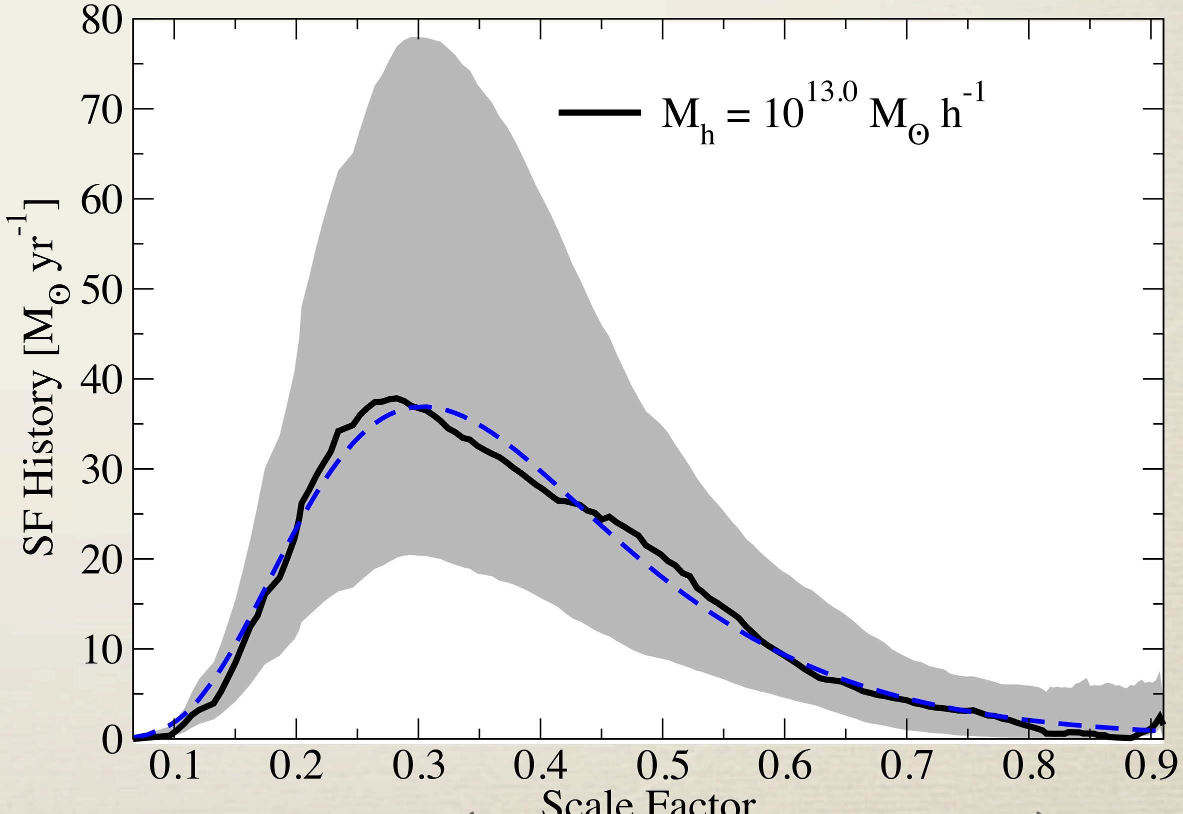
Best-fit model:

$$SFH(a) = Aa^B \exp[C(1-a)]$$

Even better in detail:

$$SFH(a) = Aa^B \exp[C(1-\sqrt[3]{a})]$$




Valid across a wide range of redshifts (0<z<4 at least).

# Final Words

Still preliminary work, but:

Our approach combines constraints from the observed stellar mass function at all times, as well as the observed clustering of galaxies (through the galaxy-halo connection), as well as the cosmic SFR and specific SFRs.

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Our approach combines constraints from the observed stellar mass function at all times, as well as the observed clustering of galaxies (through the galaxy-halo connection), as well as the cosmic SFR and specific SFRs.

We include full treatment and propagation of uncertainties. Unsatisfyingly, systematic uncertainties outweigh statistical ones at almost all redshifts!

# Final Words

Still preliminary work, but:

We no longer see any strong discrepancy between the cosmic star formation rate and the cosmic stellar mass density.

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Still preliminary work, but:

We no longer see any strong discrepancy between the cosmic star formation rate and the cosmic stellar mass density.

We clearly see changes in the redshift evolution of the stellar mass / halo mass relation at $z=2$, corresponding to the shutoff of cold gas streams.

# Final Words

Still preliminary work, but:

We find that the standard picture of exponentially declining star formation rates only works for massive galaxies at low redshifts.

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Still preliminary work, but:

We find that the standard picture of exponentially declining star formation rates only works for massive galaxies at low redshifts.

We provide a simple rise-and-fall model with the same number of parameters as the declining tau model which gives a substantially better fit.

$$SFH(a) = Aa^B \exp[C(1-a)]$$

# Final Words

Still preliminary work, but:

We can better understand
the physics of star formation and the allowable
star formation histories of galaxies
through self-consistently connecting
as many observations as we can.

# Future Work

This model is the first step in an exciting program of research:

By self-consistently combining stellar masses and star formation rates, we already have constraints on an important source of systematic uncertainties (stellar population histories).

# Future Work

This model is the first step in an exciting program of research:

There's no reason why we have to stop there, however!

We can add functionality to generate any observable, such as galaxy colors, metallicities, X-ray luminosity, etc.

# Future Work

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There's no reason why we have to stop there, however!

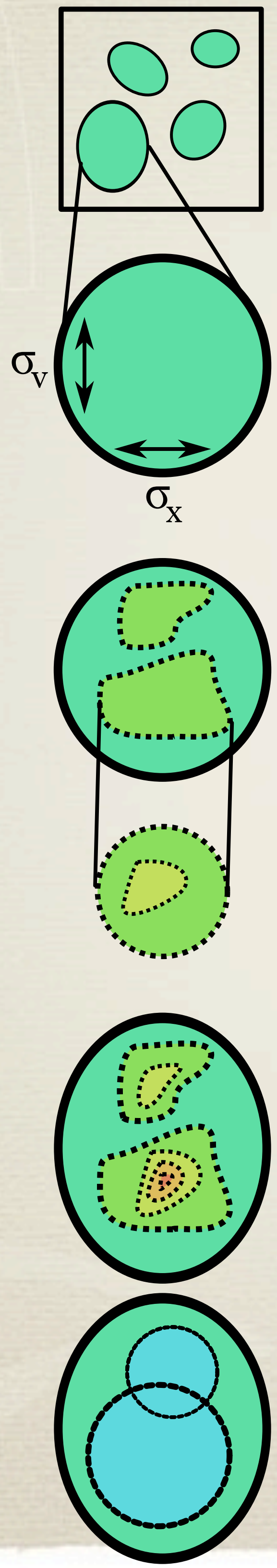
We can add functionality to generate any observable, such as galaxy colors, metallicities, X-ray luminosity, etc.

With a large enough sample of constraining data, we can then vastly improve the current uncertainties in stellar models: meaning, we can extract information on the IMF, on stellar tracks, on dust, and on galaxy metallicities as well!

# Thank you!

Comments / Questions to behroozi@stanford.edu

# The Rockstar Halo Finder




The simulation volume is divided into 3D Friends-of-Friends groups for easy parallelization.

For each group, particle positions and velocities are divided (normalized) by the group position and velocity dispersions, giving a natural phase-space metric.

A phase-space linking length is adaptively chosen such that 70% of the group's particles are linked together in subgroups.

The process repeats for each subgroup: renormalization, a new linking-length, and a new level of substructure calculated.

Once all levels of substructure are found, seed halos are placed at the lowest substructure levels and particles are assigned hierarchically to the closest seed halo center in phase space. (see Knebe et al. 2011 for specific details).

Once particles have been assigned to halos, unbound particles are removed and halo properties (positions, velocities, spherical masses, radii, spins, etc.) are calculated.

Behroozi et al. in prep.

# The Rockstar Halo Finder

In practice, how does it *work*?

That is, how well does it recover halo properties?

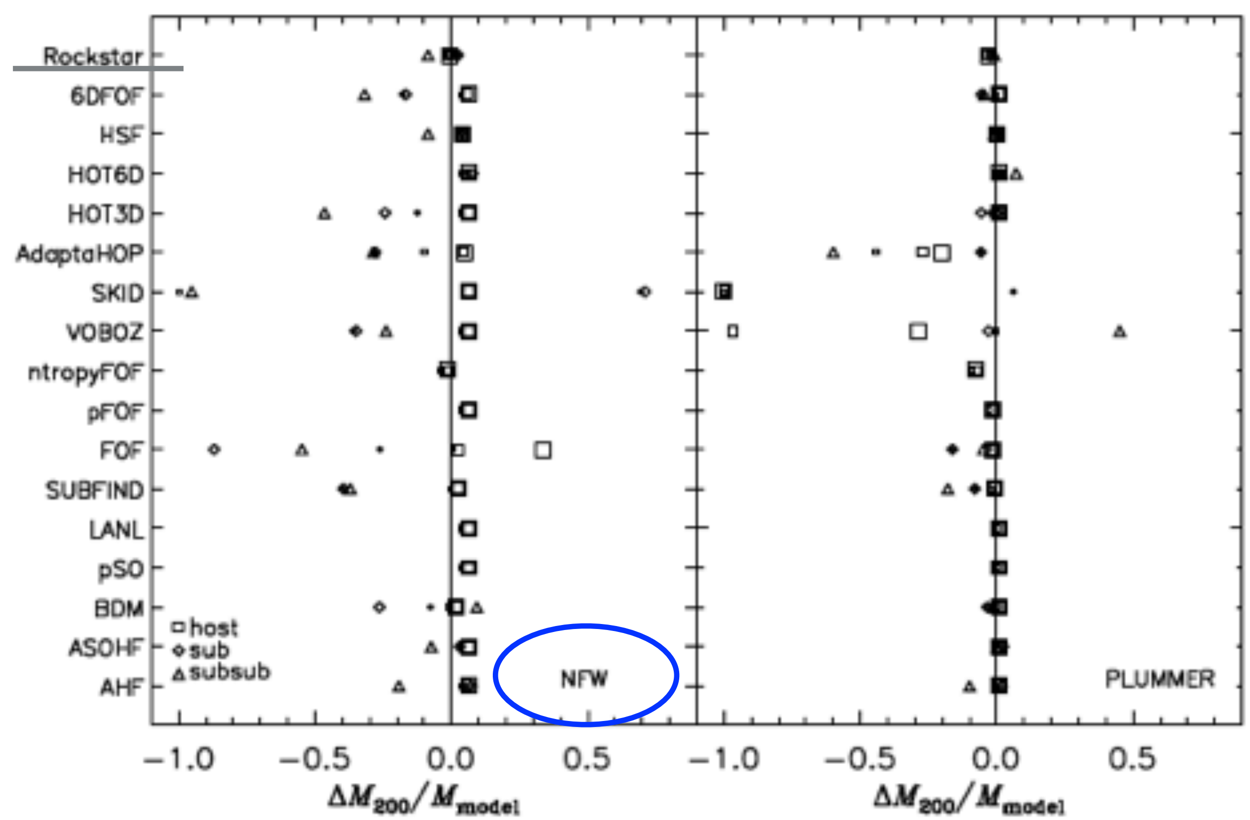



**Figure 5.** $M_{200}$ mass (as determined from the supplied particle lists) measured according to the mean enclosed density being $200 \times \rho_{crit}$ criterion for the NFW (left) and Plummer (right) density mock haloes extracted from each finder's list of gravitationally bound particles. The symbols have the same meaning as in Fig. 2

Knebe et al. 2011

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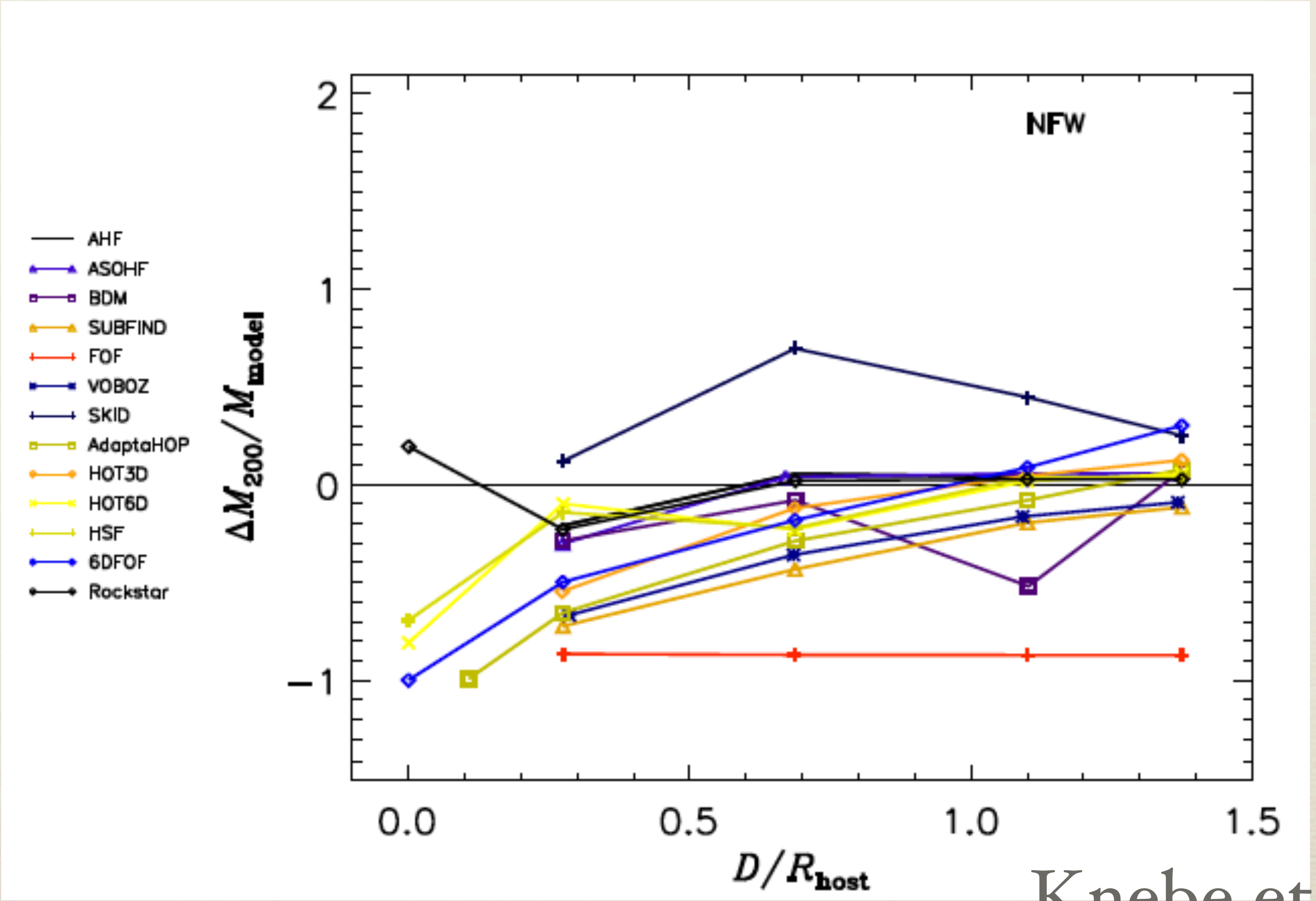


Knebe et al. 2011

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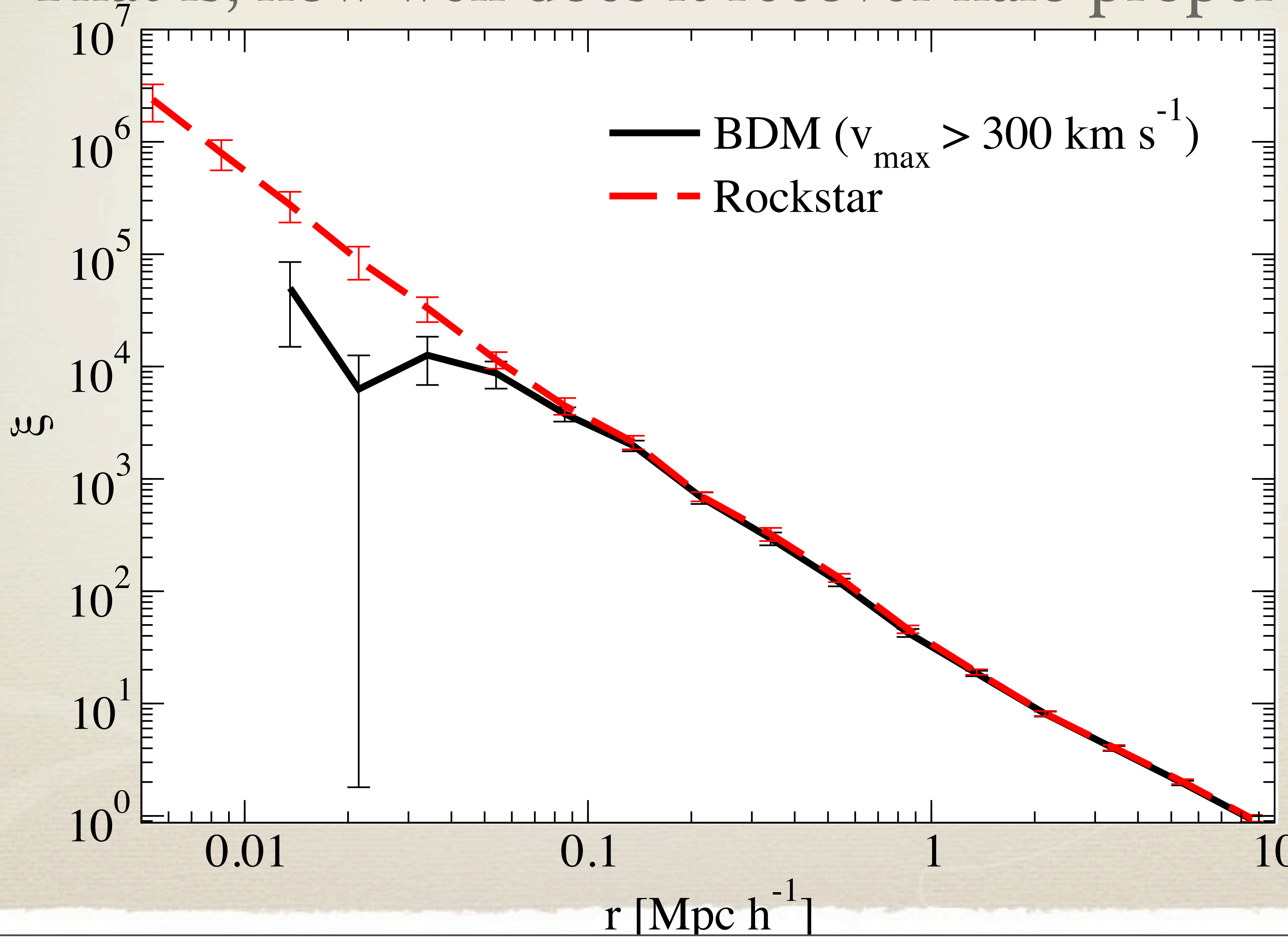


# Consistent Merger Trees

Requirements for accurate identification of halo progenitors:

Do the haloes identified by the halo finder move consistently with the laws of physics?

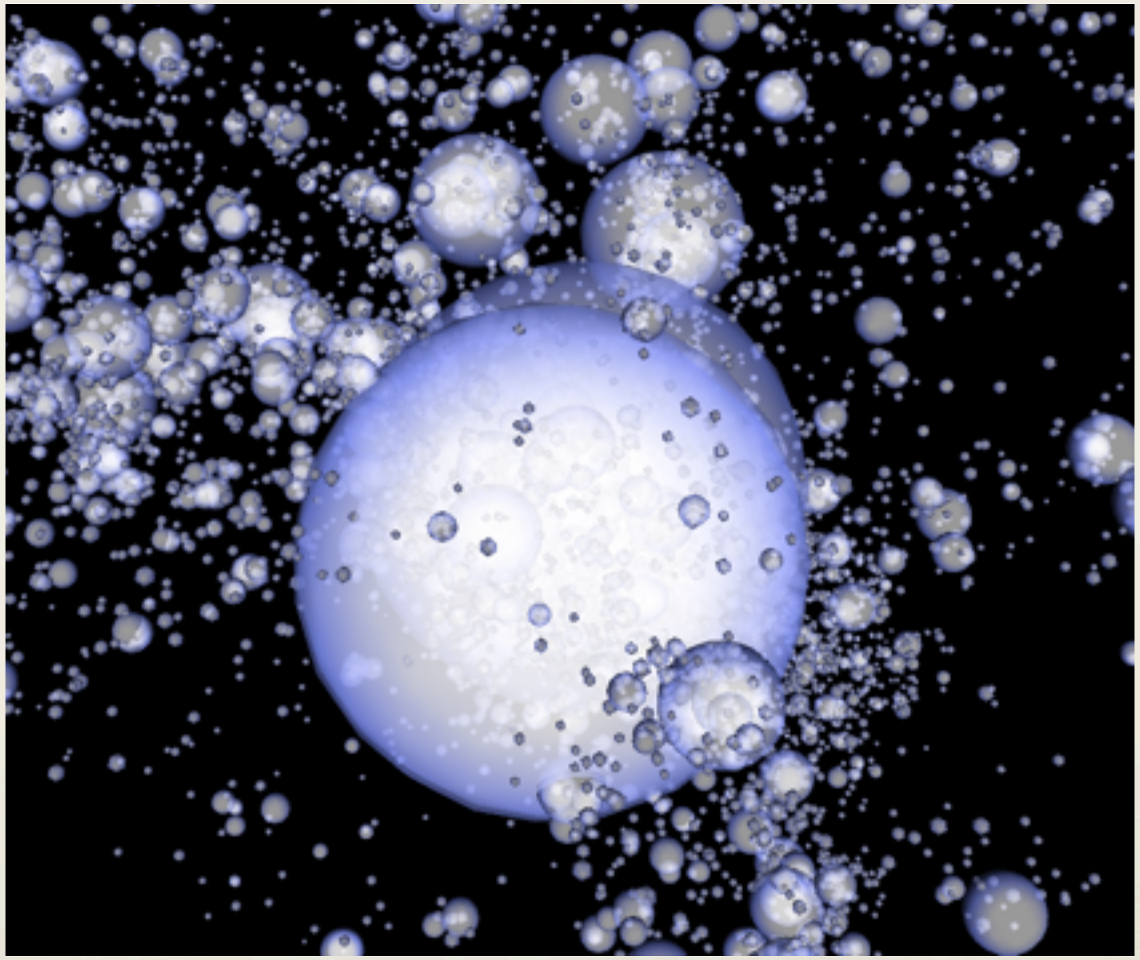
Are halo properties (mass, radius, vmax) stable across timesteps?

Are halos identified consistently across timesteps in the first place?

Especially subhalos?

# Consistent Merger Trees

What do halo catalogs *actually* look like as a function of time?



(Interactive Video)

# Consistent Merger Trees

How do we fix the problems that we see?

We can build explicit modeling of
the gravitational evolution of halos
into the merger tree code.

$$F = \frac{GM_1M_2}{r^2 + r_{vir}^2}$$

Gravitational Acceleration

$$\frac{dF}{dr} = \frac{2GM_1M_2}{r^3} > T_{min}$$

Tidal Merger Criterion

Behroozi et al. in prep.

# Consistent Merger Trees

How do we fix the problems that we see?

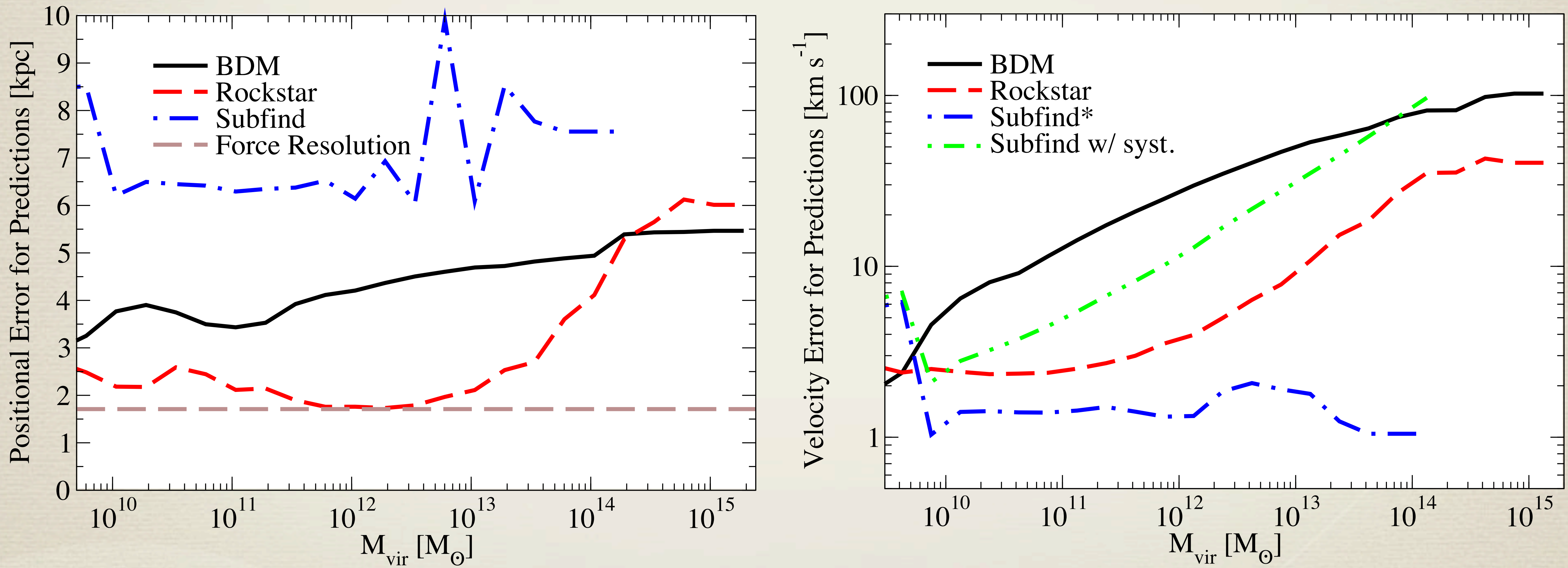
We can build explicit modeling of the gravitational evolution of halos into the merger tree code.

We can then test explicitly for how well individual halo finders do.

Even better, we can interpolate between gaps in the merger tree and repair inconsistent links.

# Consistent Merger Trees

## Tests of Halo Finders on the Bolshoi Simulation

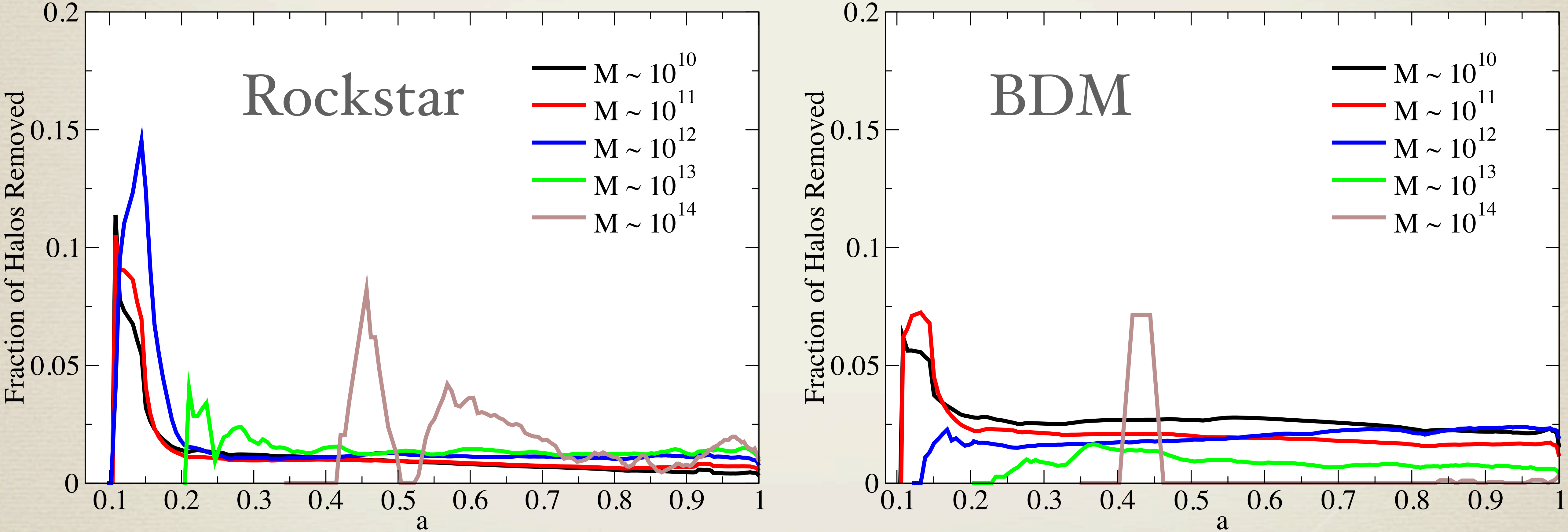



Behroozi et al. in prep.

# Consistent Merger Trees

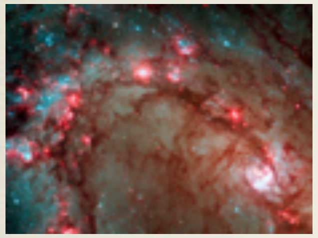
Tests of Halo Finders on the Bolshoi Simulation

Self-consistency as a function of halo mass:




Behroozi et al. in prep.

# Image Sources:



http://spacefellowship.com/news/art15504/picture-of-the-day-the-birth-of-stars.html