

THE STORY OF ALL THE STARS IN THE UNIVERSE

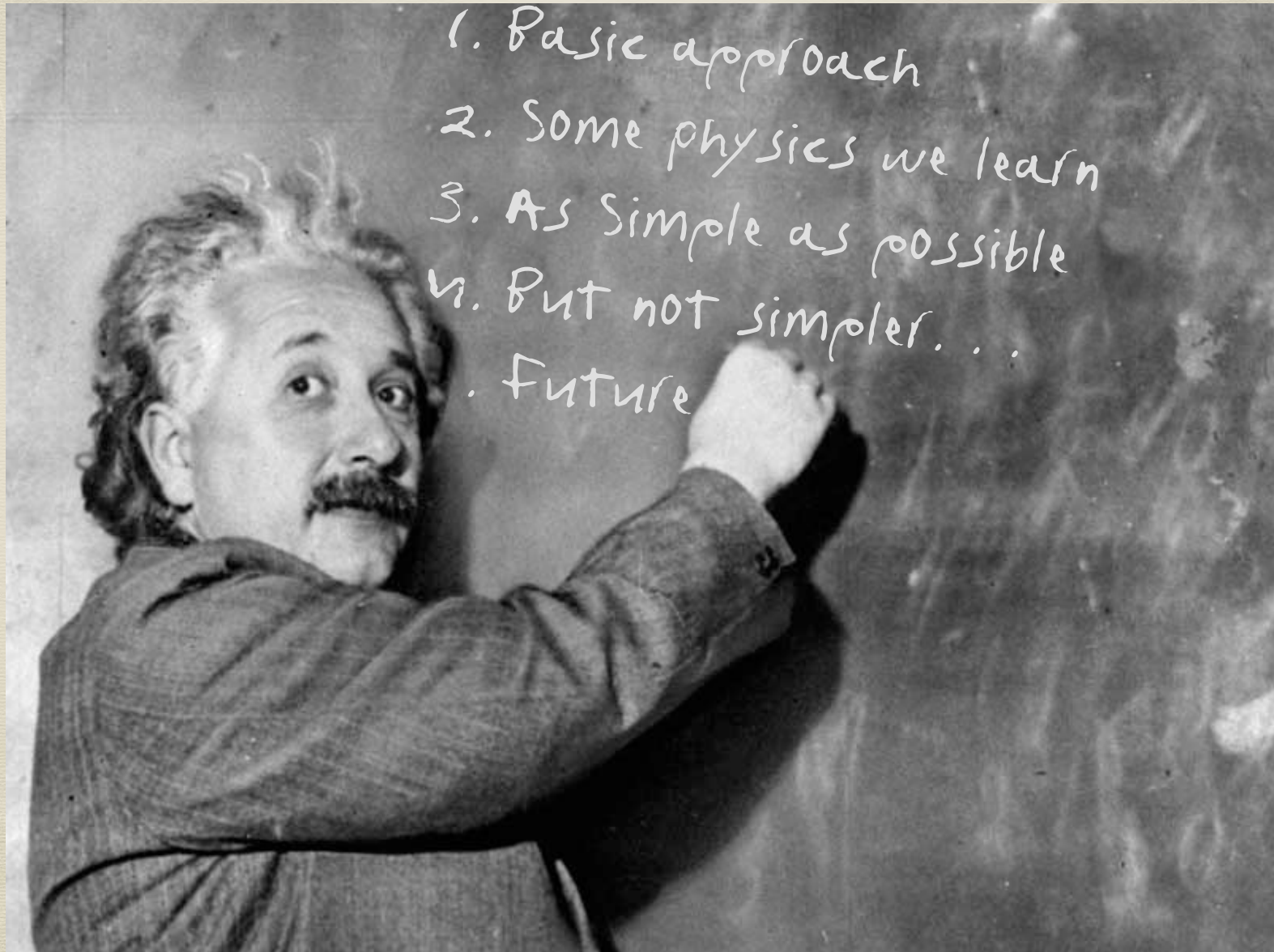
a.k.a. “Galaxy Formation in Dark Matter Halos from $z=15$ to $z=0$ ”



Credit: M31, NASA

Peter Behroozi, STScI; IPMU, 12/3/15

Outline



1. Basic approach
2. Some physics we learn
3. As Simple as possible
4. But not simpler. . .
5. Future

Basic Approach

We can observe galaxies at many different redshifts



Credit: Hubble UDF; NASA, ESA, S. Beckwith (STScI)
and the HUDF Team



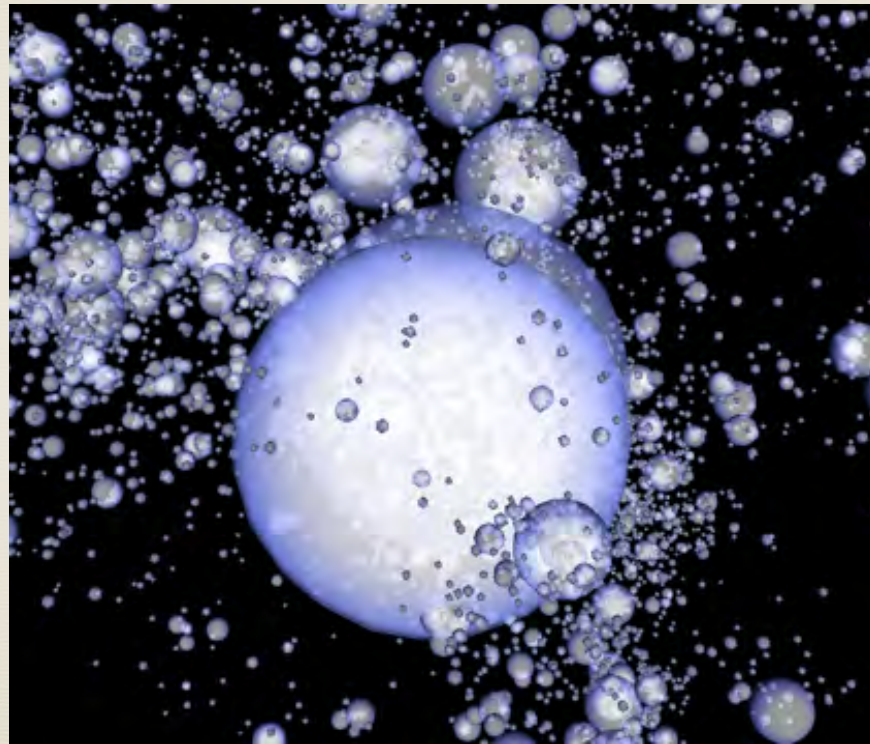
Credit: M101; Adam Block

What we cannot see, nor ever hope to, is a movie of how
a real galaxy evolves with time.

(Real galaxies take hundreds of millions of years to change)

Basic Approach

Yet, this is a basic feature of simulations

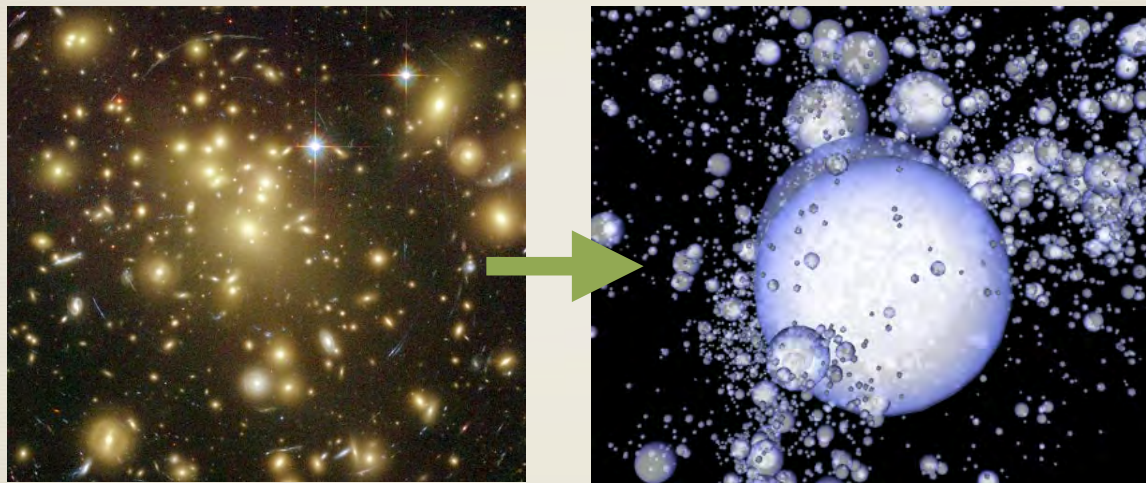


But currently, the only precise results of simulations are the clustering and motion of matter on large scales.

Basic Approach

So, we combine the two:

Observations tell us how many galaxies there are;



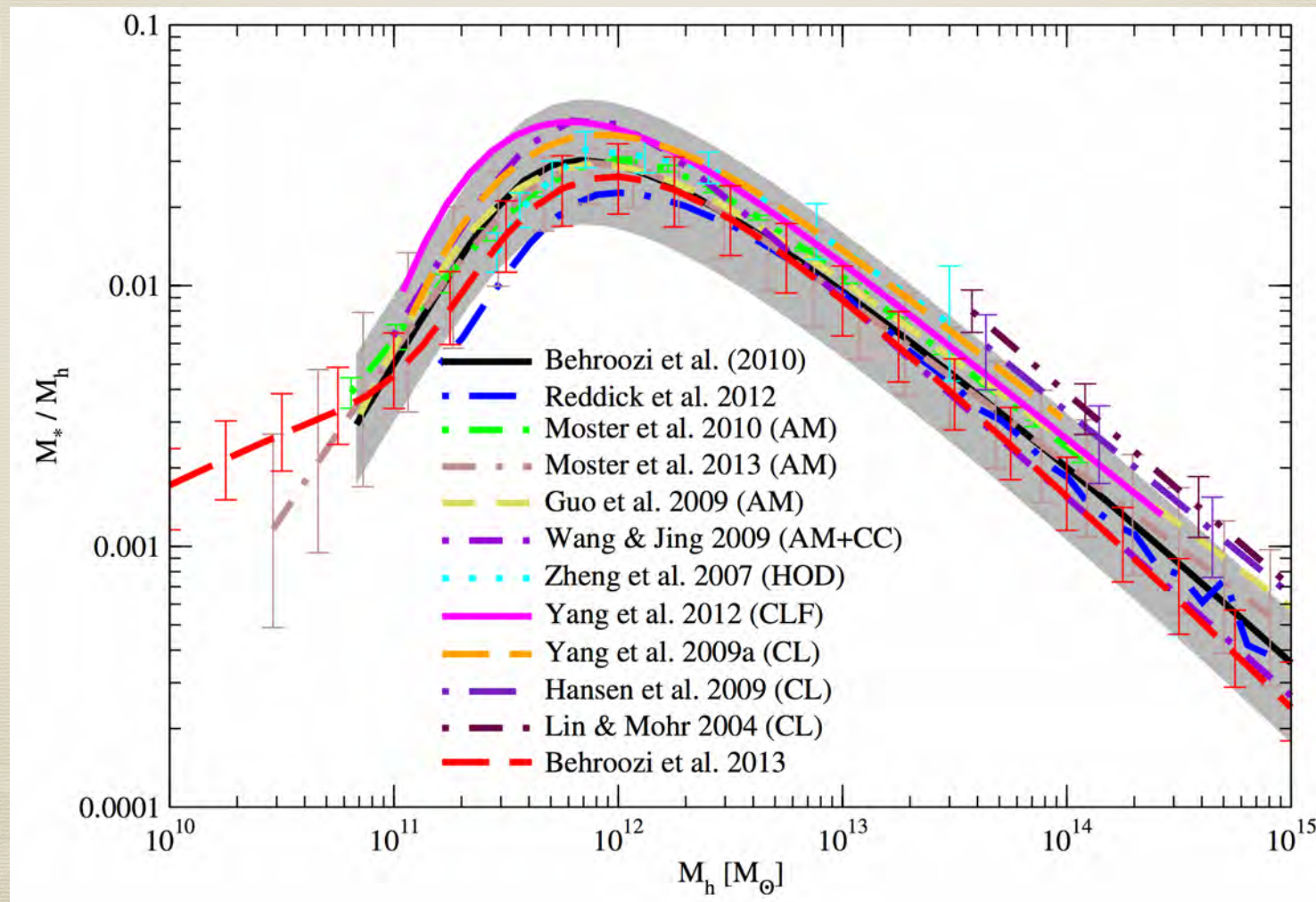
Credit: Abell 1689; N. Benitez et al.

Simulations tell us how often they merge together and what happens when they do---as well as how to *connect* galaxies observed at different times.

So, we ought to be able to reconstruct what happens to stars (on average) in individual galaxies.

Basic Approach

How do we match observed galaxies to halos in simulations?



Behroozi, Wechsler, Conroy (2013)

Basic Approach

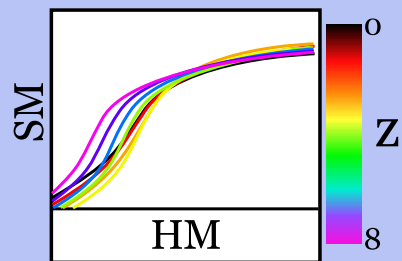
What about higher redshifts?

No-one knows ahead of time.

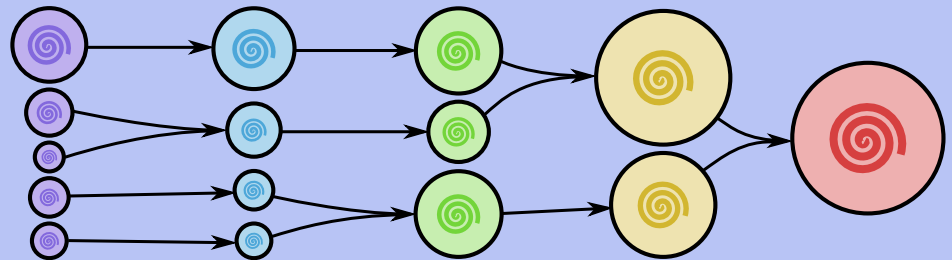
So, we adopt a very flexible parametrization of the matching and let computers search for the answer.

Basic Approach

1. Choose a stellar mass - halo mass (SMHM) relation from parameter space.

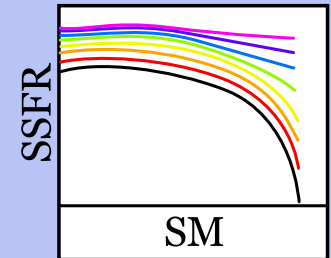
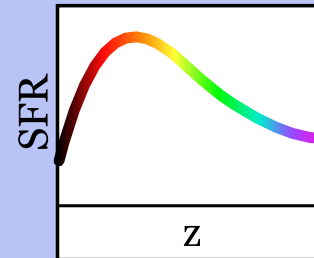
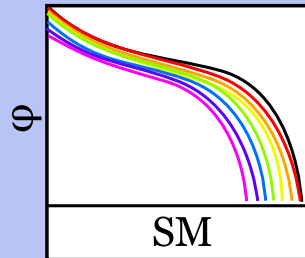


2. Find galaxy growth histories by applying the SMHM relation to dark matter merger trees.

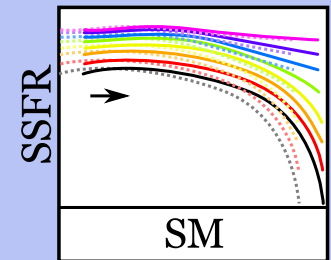
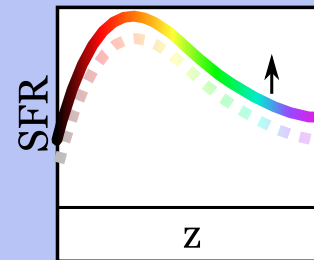
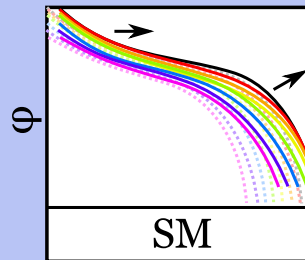


Basic Approach

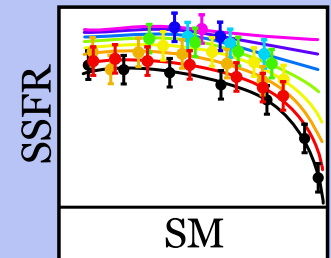
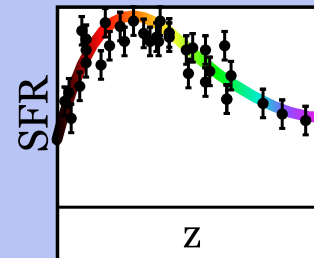
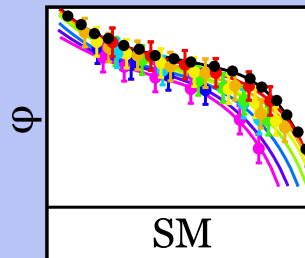
3. Derive the inferred stellar mass functions and star formation rates.



4. Apply effects to simulate observational errors and biases.

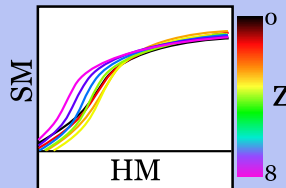


5. Compare to data and calculate likelihood of the chosen SMHM relation.

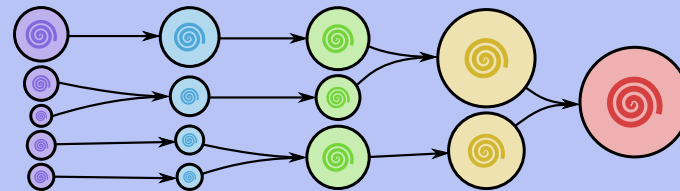


Basic Approach

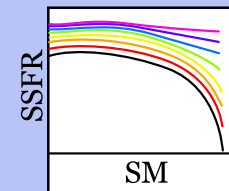
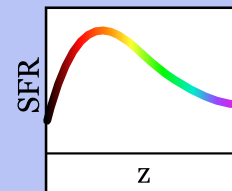
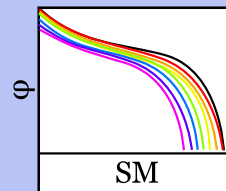
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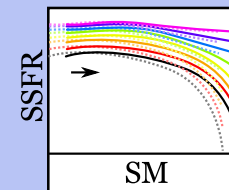
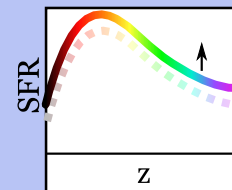
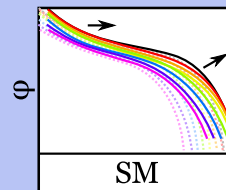
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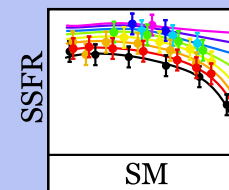
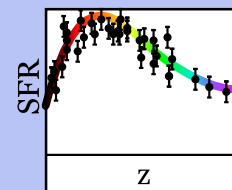
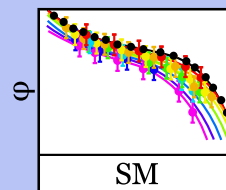
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4. Apply effects to simulate observational errors and biases.



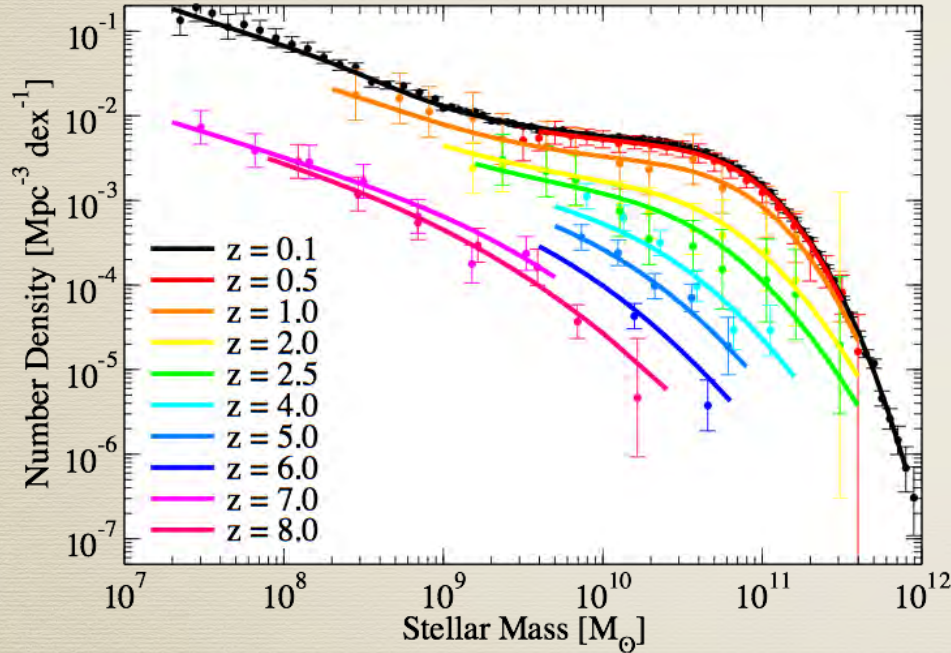
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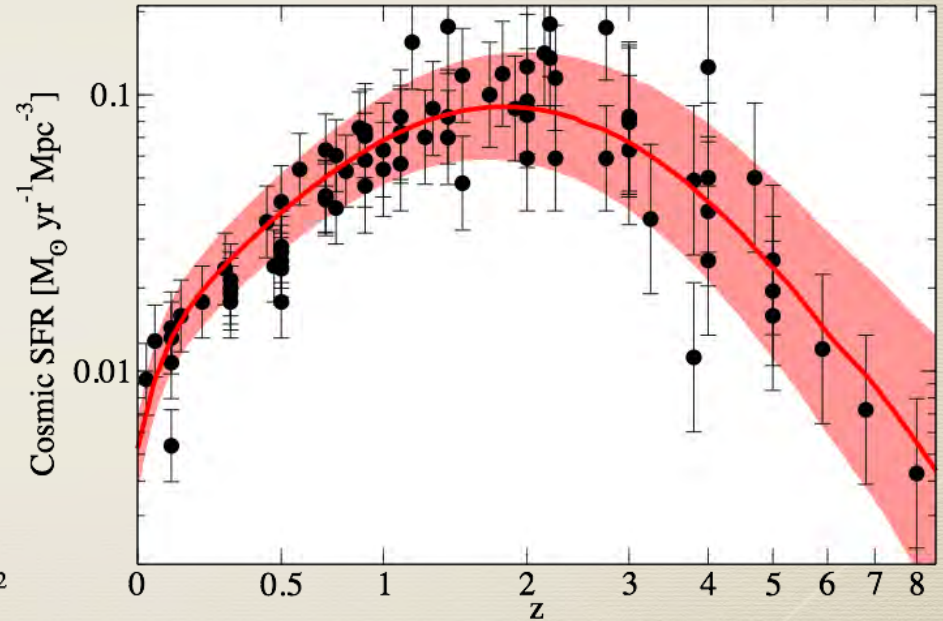
Repeat as often as necessary to explore allowable solutions.

Basic Approach

Data Sets:



Stellar Mass Functions
from PRIMUS, others up to $z=8$

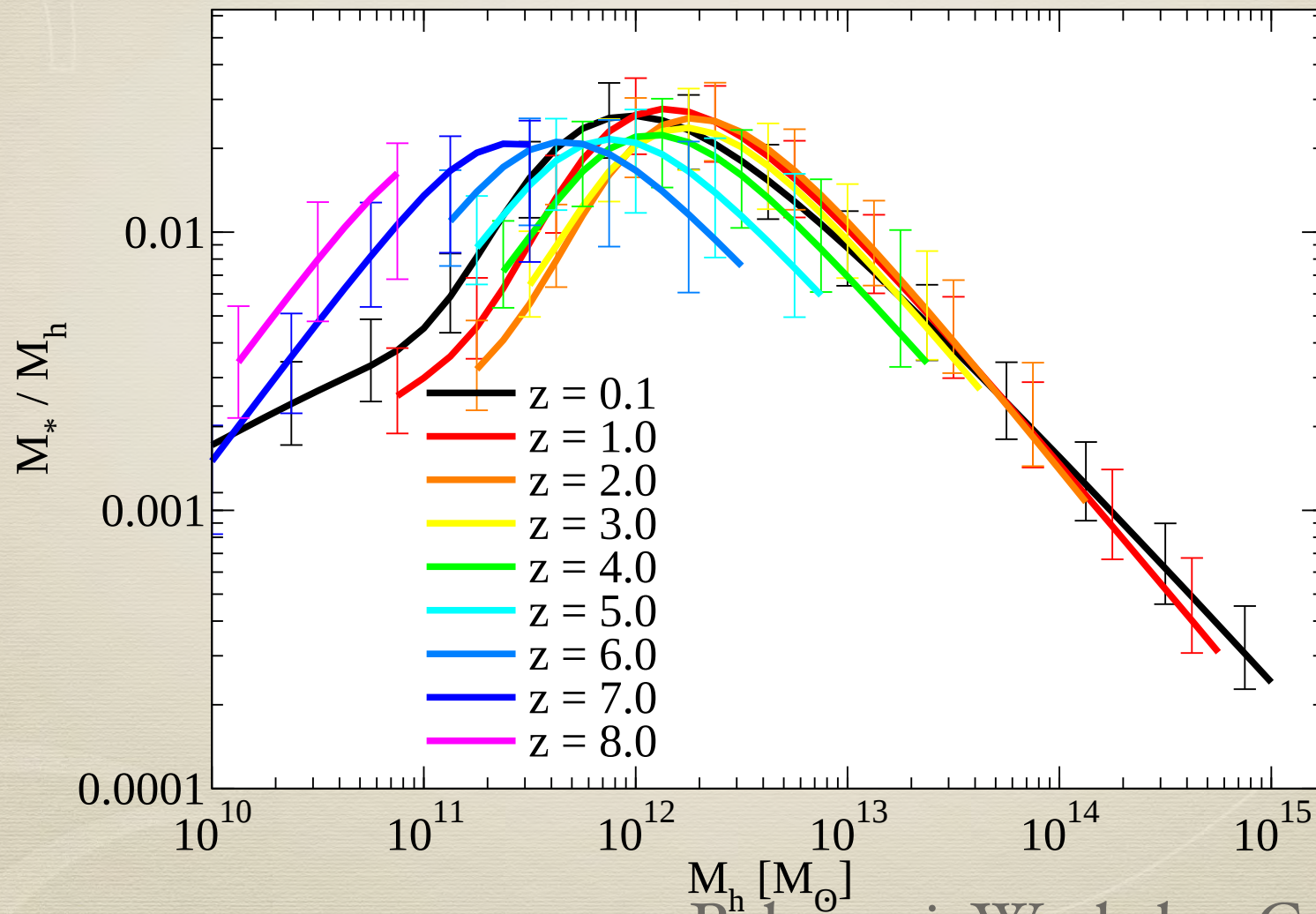


Compilation of cSFRs
to $z=8$

Behroozi, Wechsler, Conroy (2013)

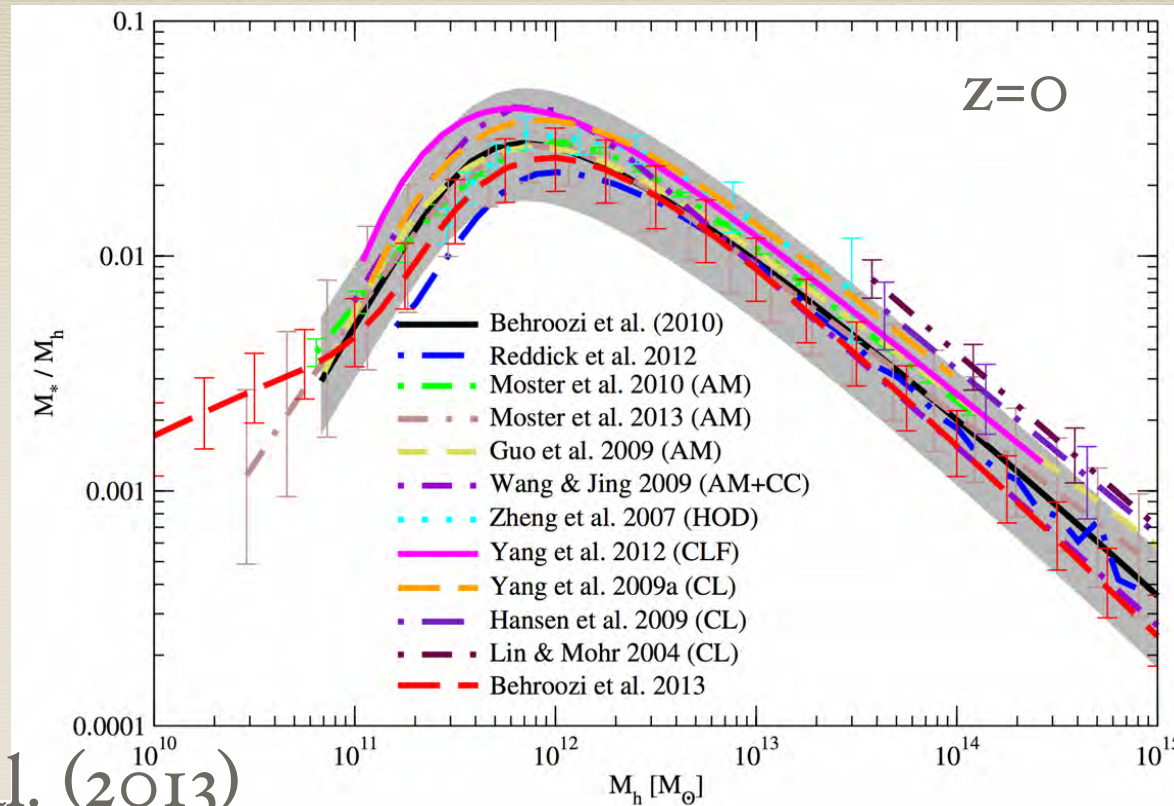
Results

Constraints on the M^*/M_h ratio, useful for SAMs and hydro:

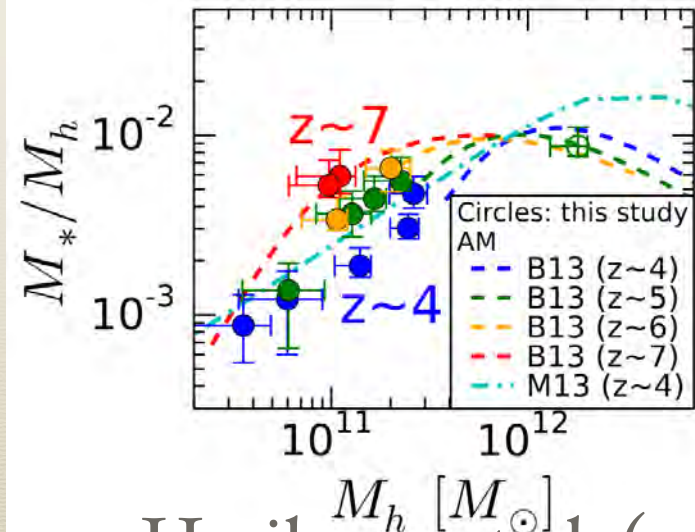
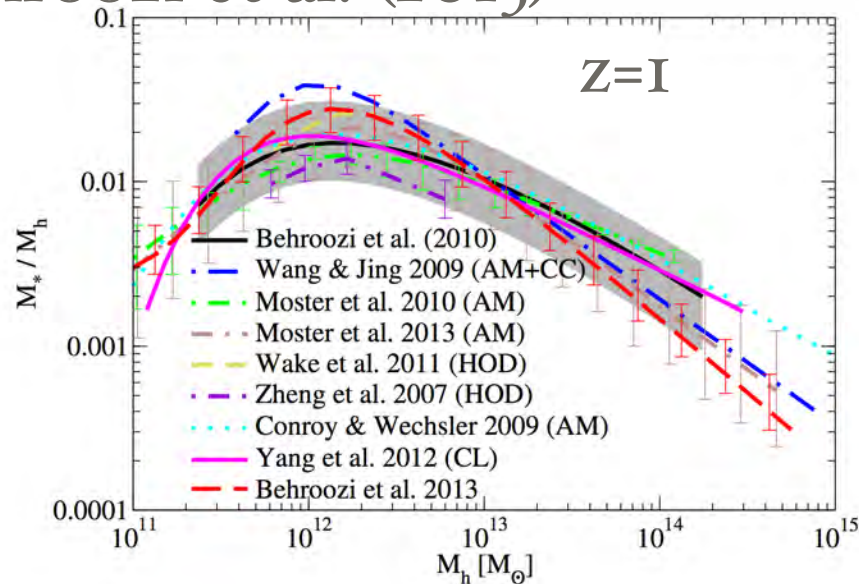


Behroozi, Wechsler, Conroy (2013)

Confirmation from other studies



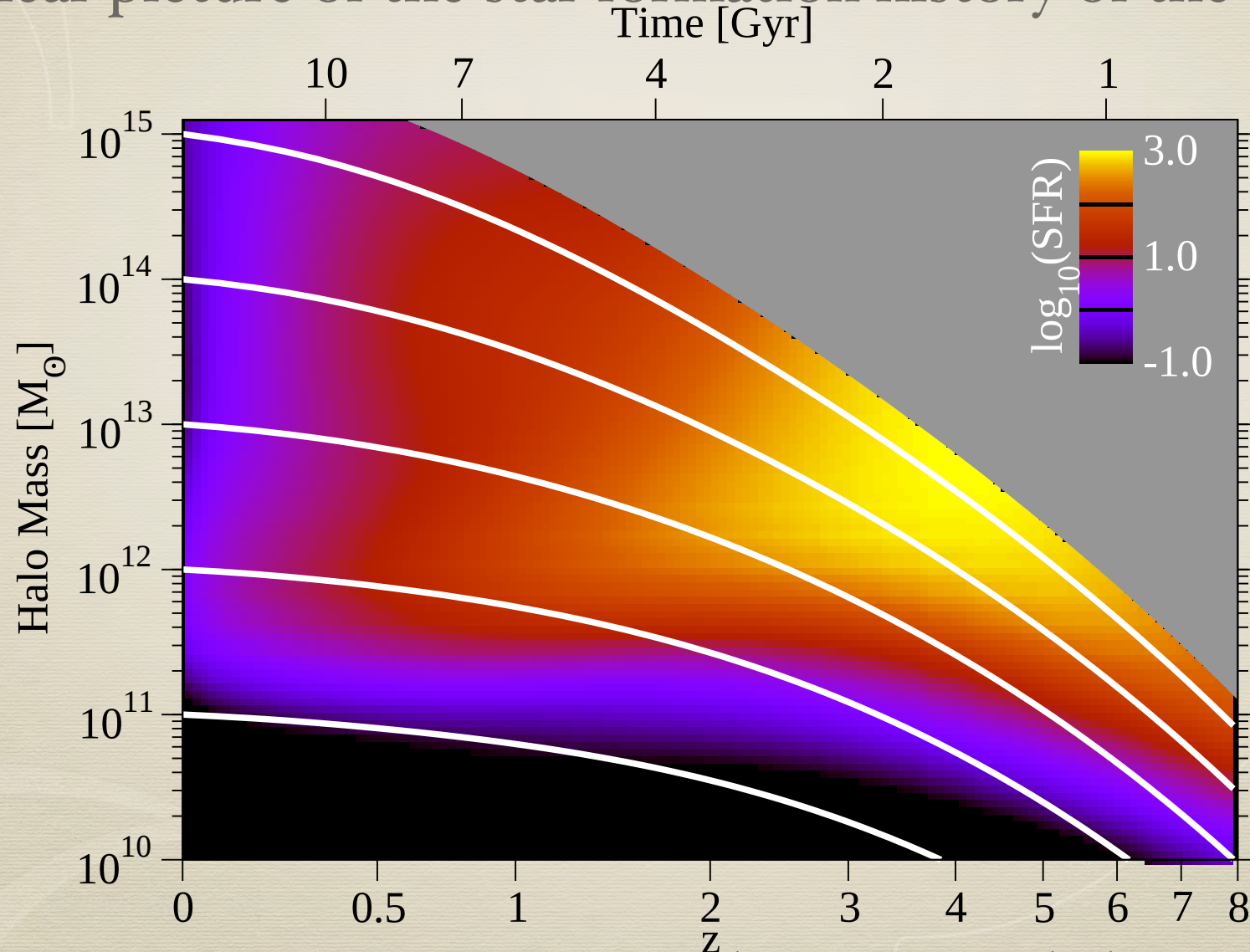
Behroozi et al. (2013)



Harikane et al. (2015)

Results

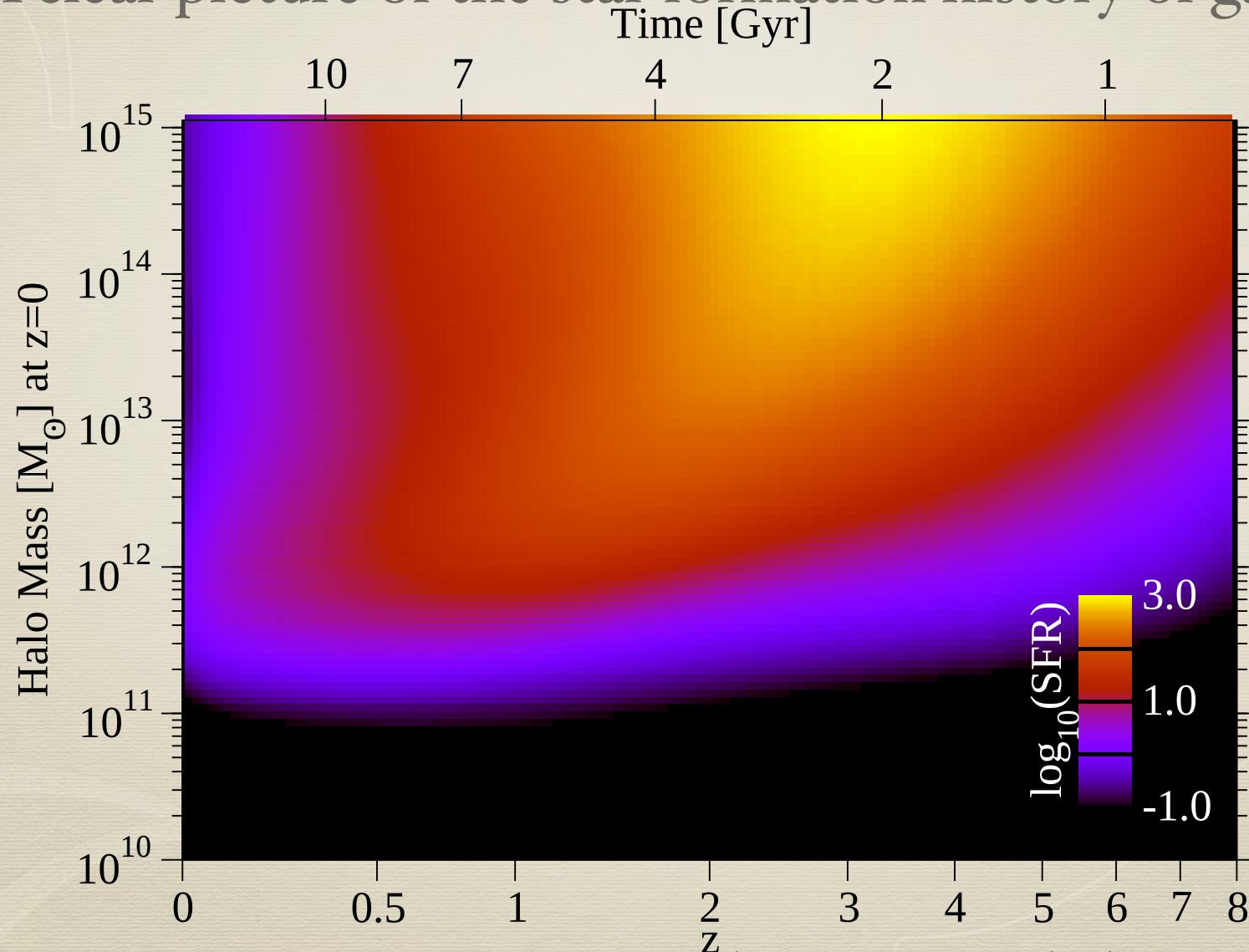
A clear picture of the star formation history of the Universe:



Behroozi, Wechsler, Conroy (2013)

Results

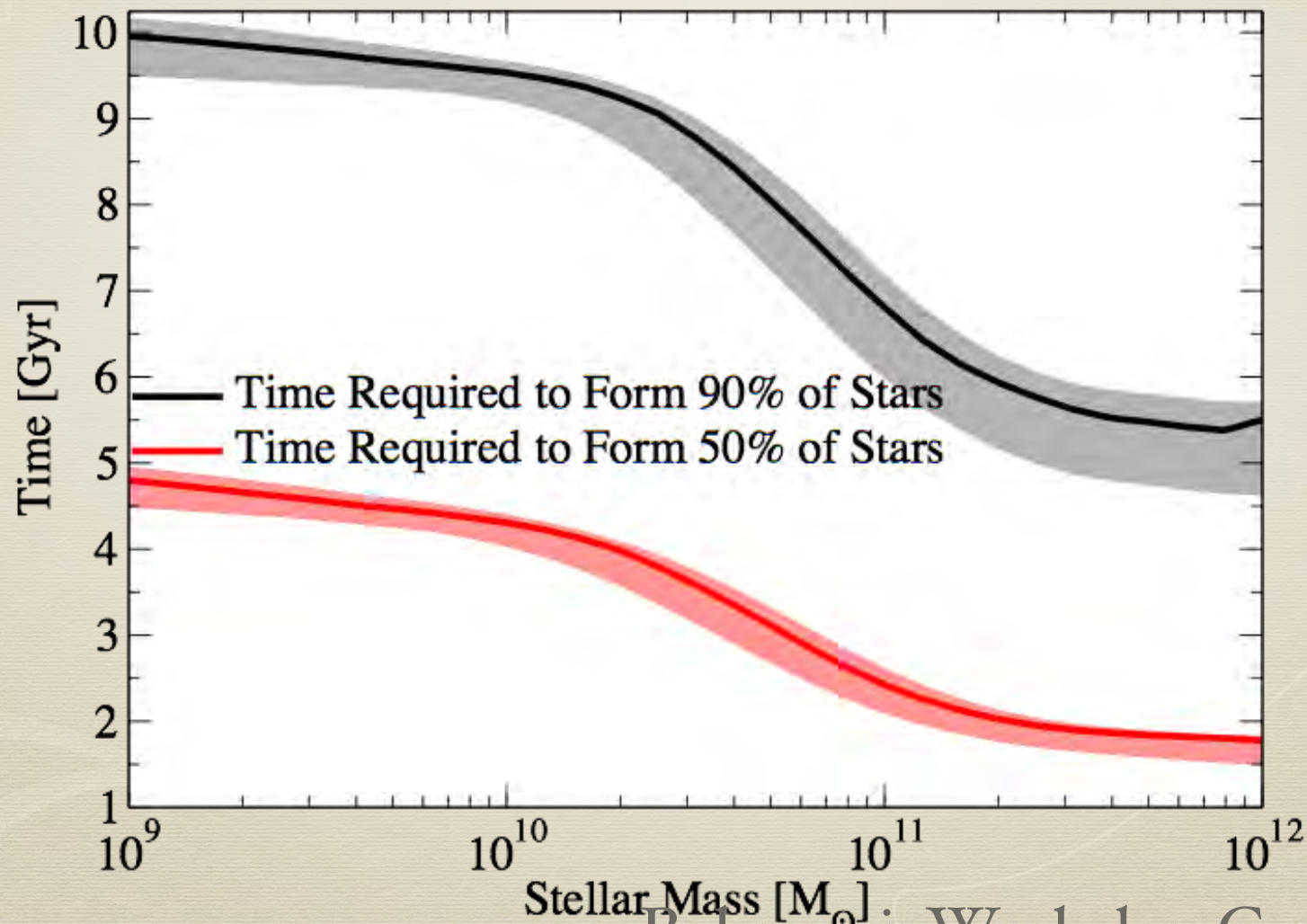
A clear picture of the star formation history of galaxies:



Behroozi, Wechsler, Conroy (2013)

Results

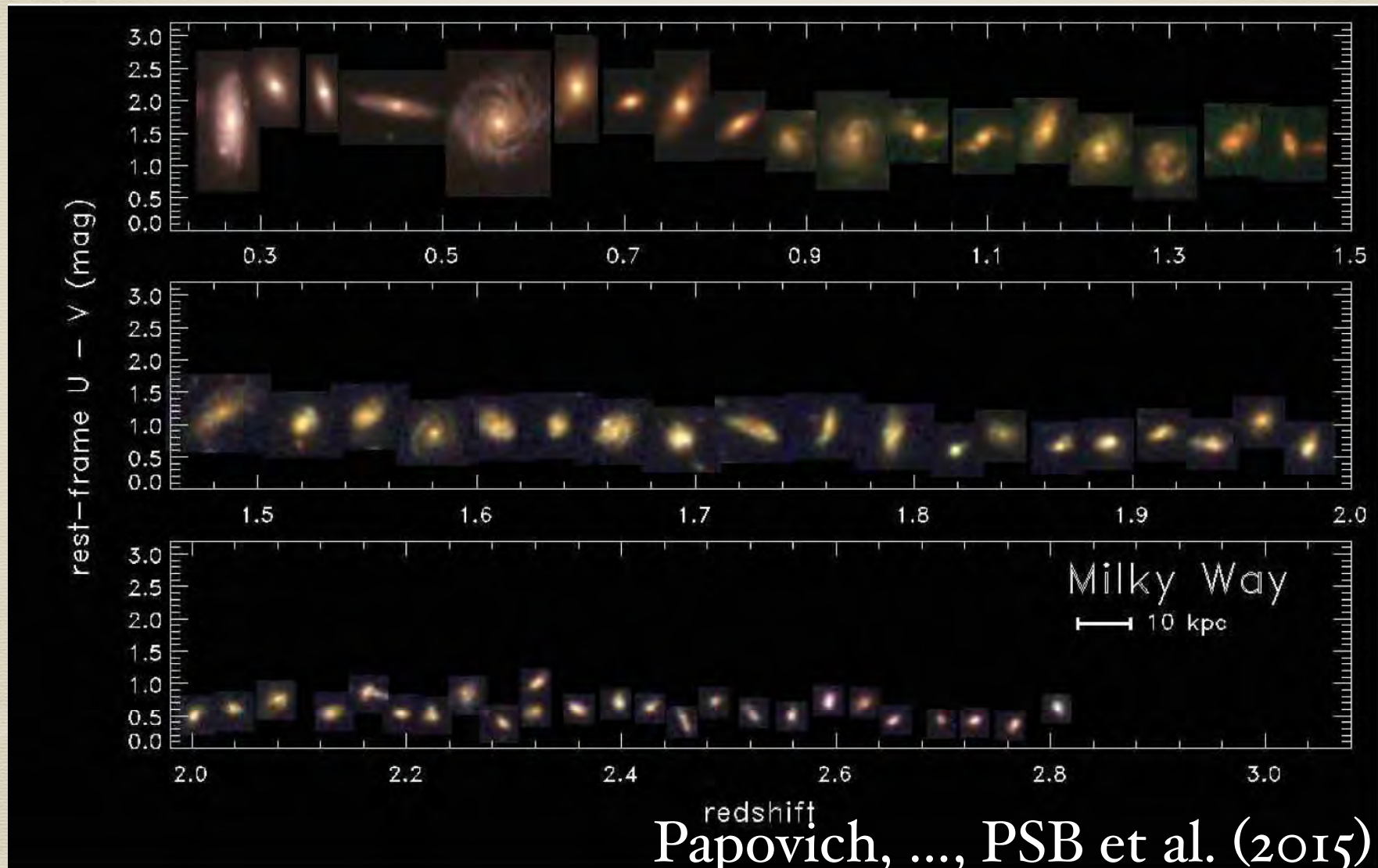
A clear picture of the star formation history of galaxies:



Behroozi, Wechsler, Conroy (2013)

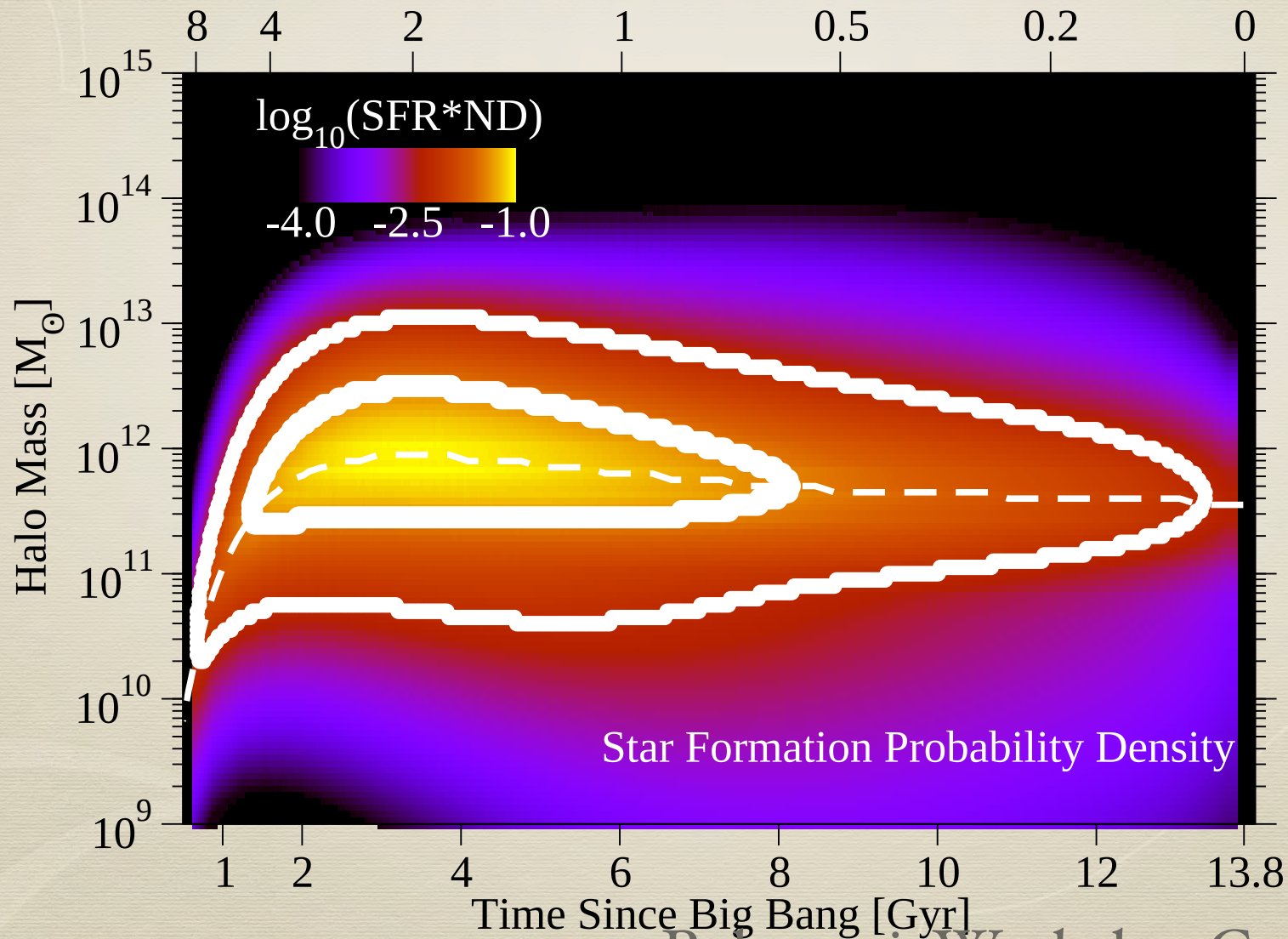
Results

A clear picture of the star formation history of galaxies:

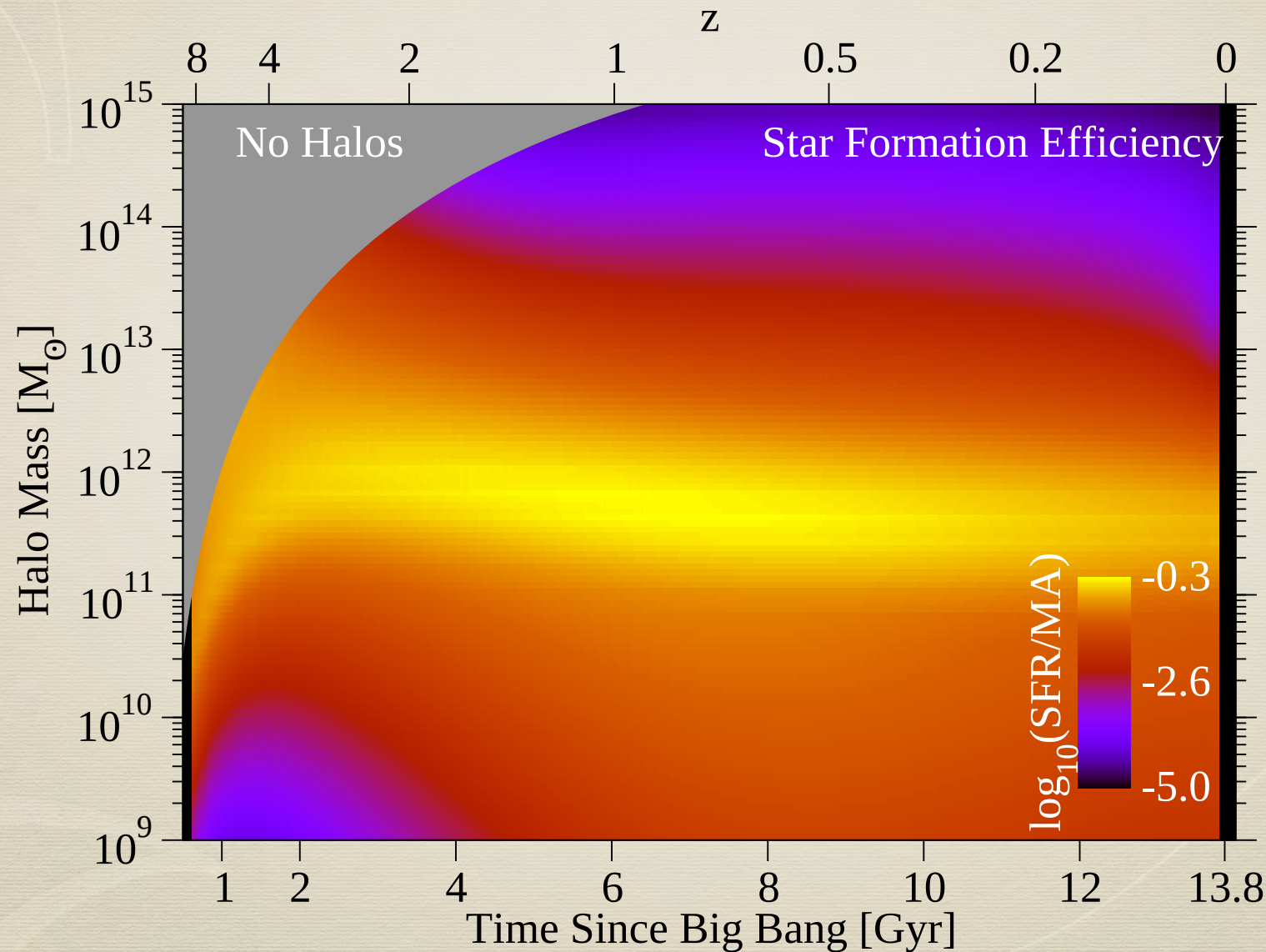


Results

We can also constrain when and where all stars were formed:

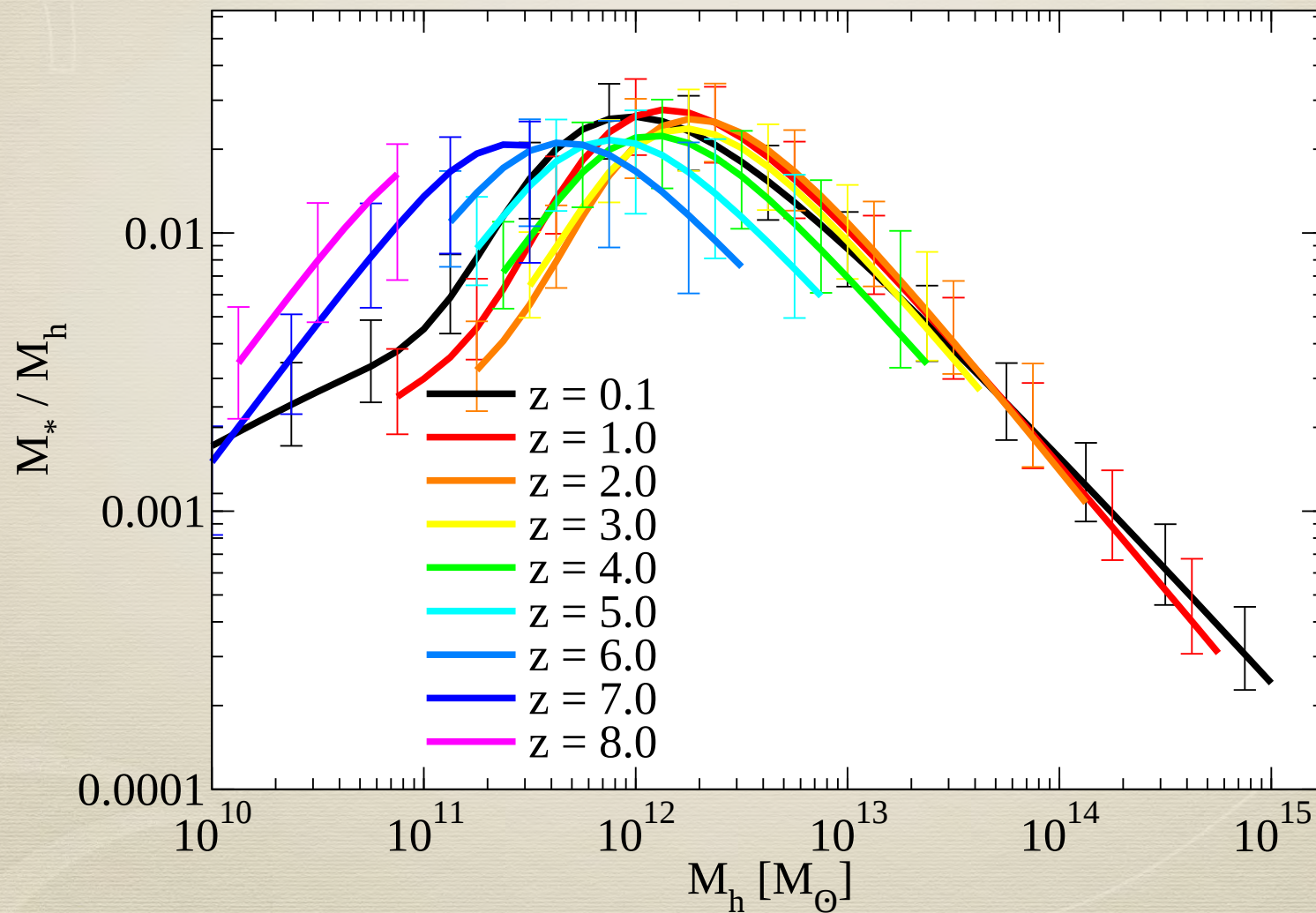


As Simple As Possible



Behroozi, Wechsler, Conroy (2013b)

But Not Simpler...



Behroozi, Wechsler, Conroy (2013)

Context



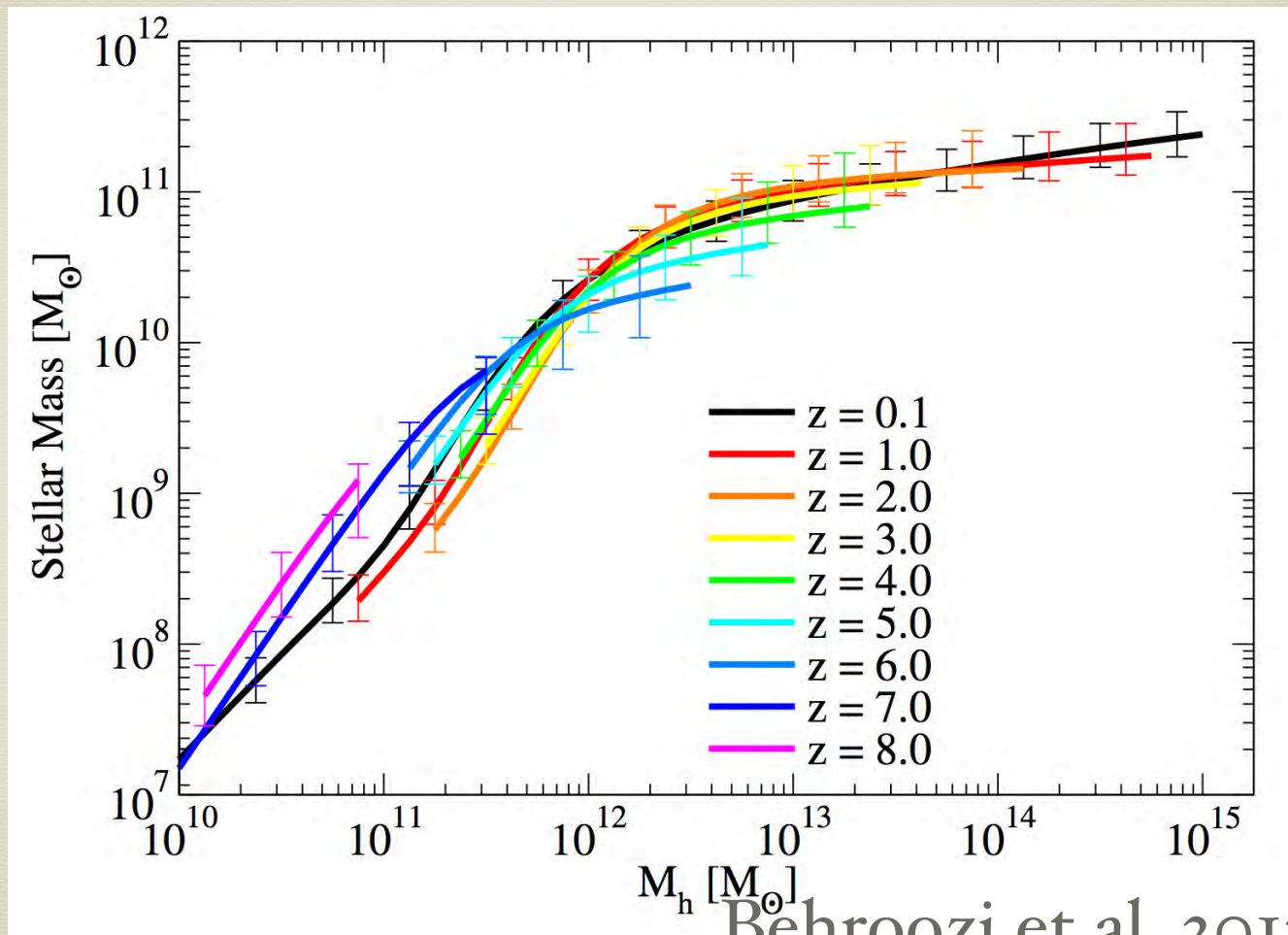
NASA/MSFC/David Higginbotham

Unwinding the Clock



NGC 5033, Adam Block, Mt. Lemmon SkyCenter, University of Arizona

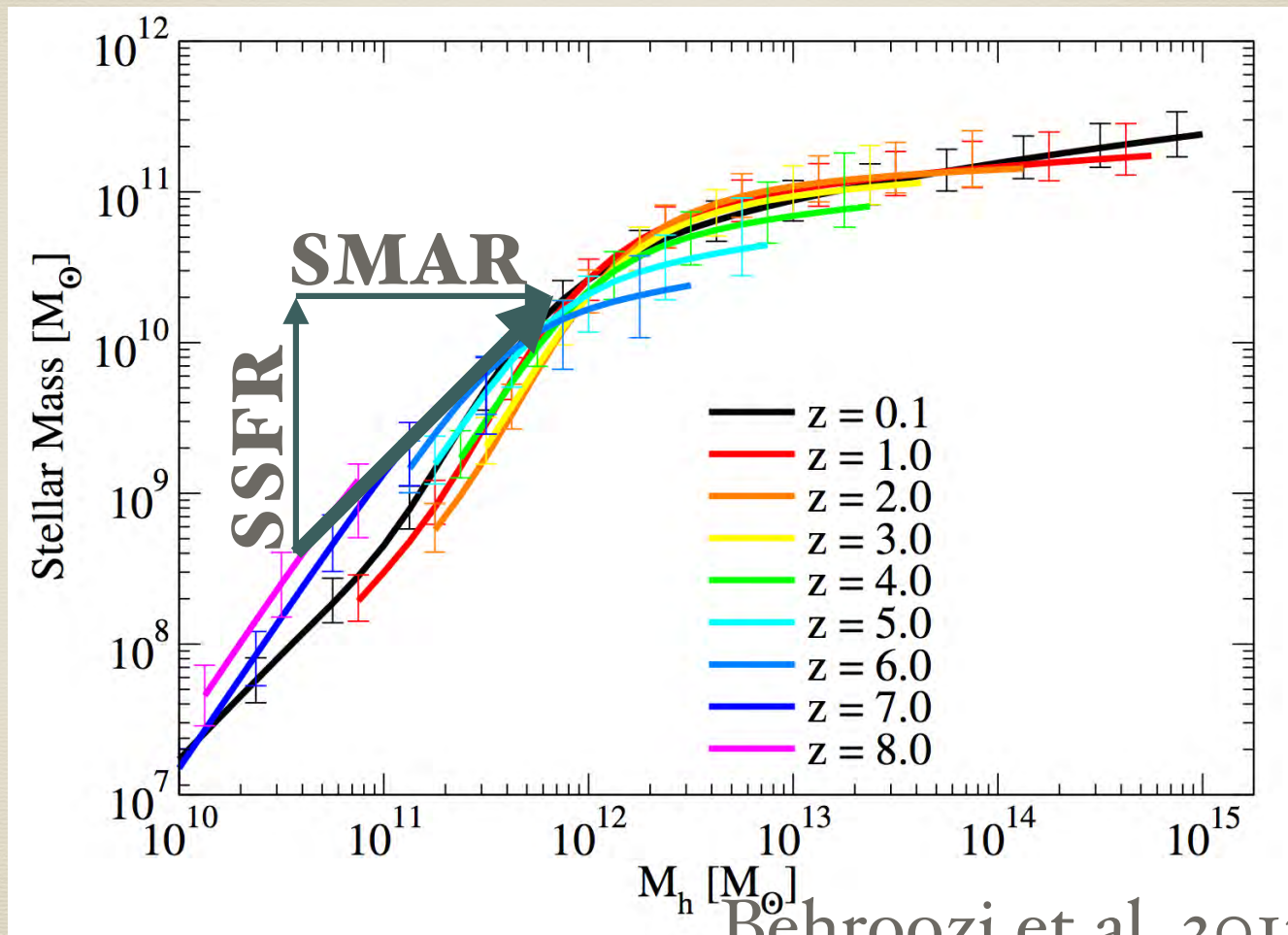
Using Physical Motivations



Behroozi et al. 2013

Connect Galaxies to the Growth of Halos

Using Physical Motivations



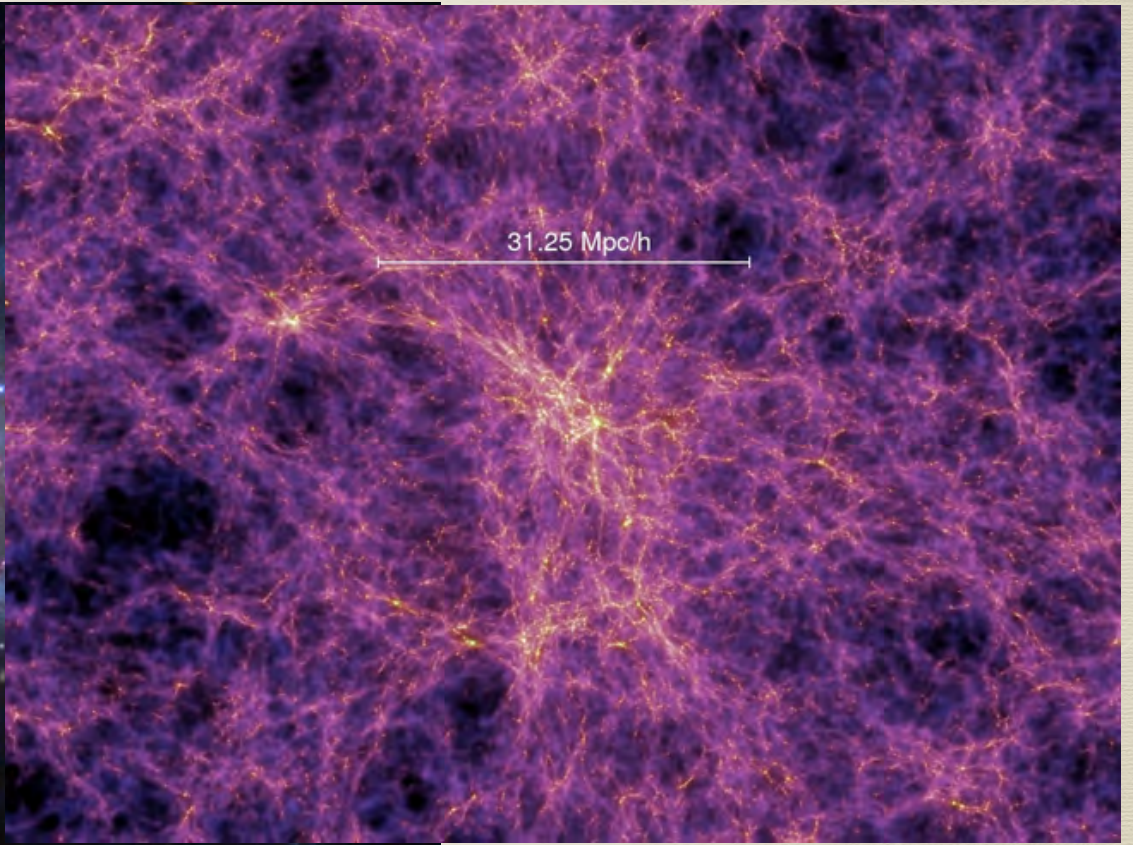
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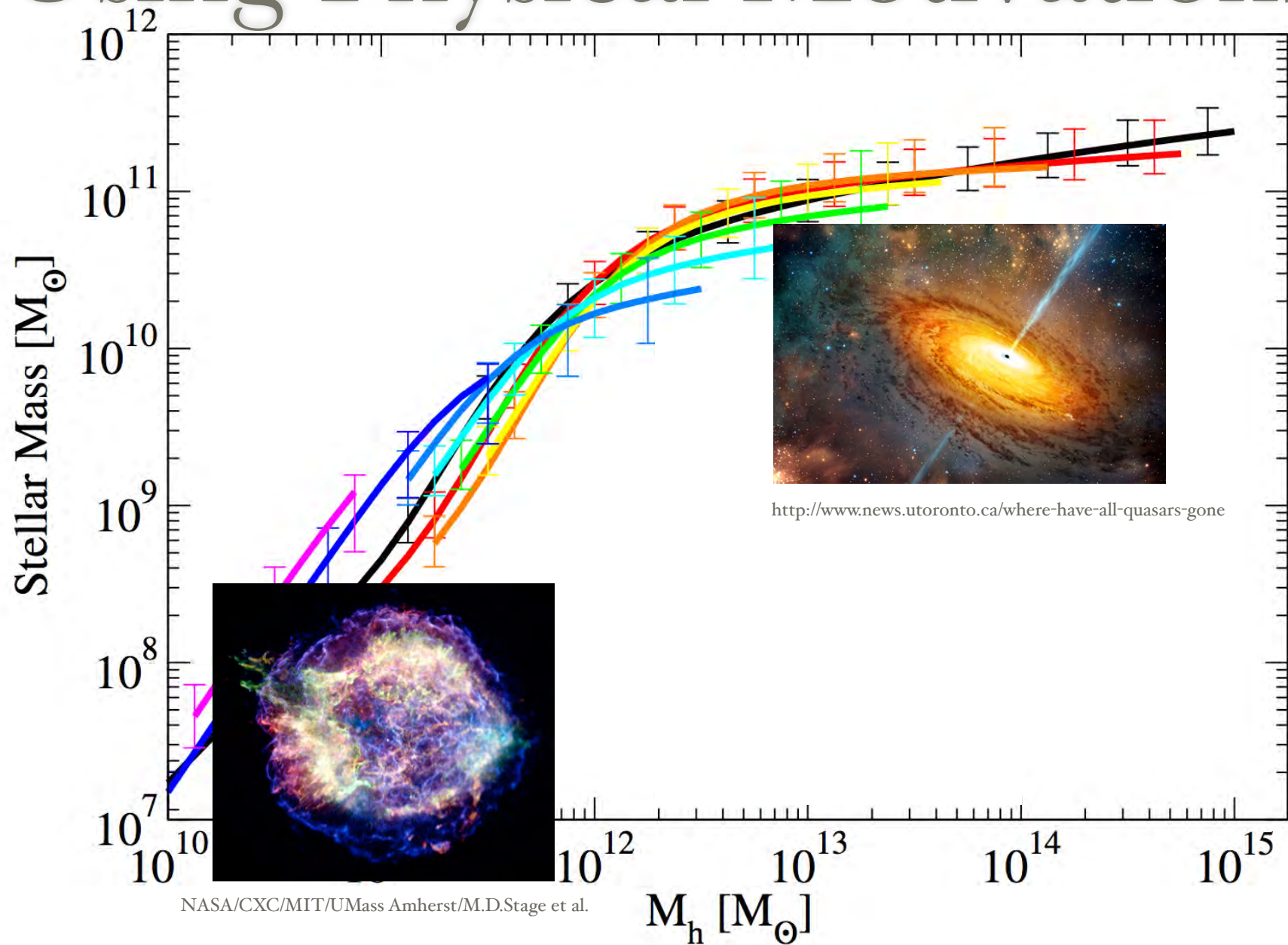
SSFR



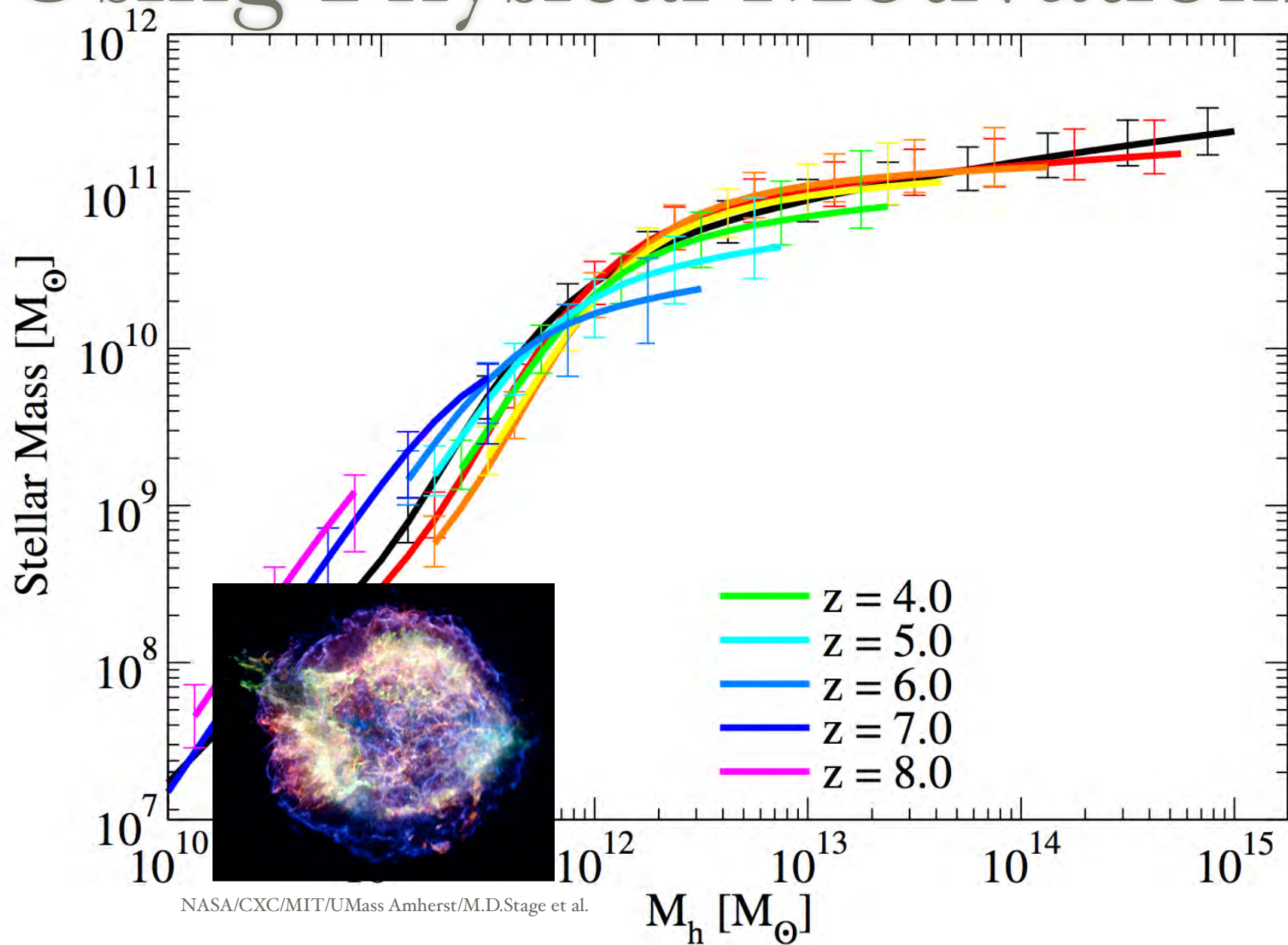
Millennium Simulation, Volker Springel

SMAR

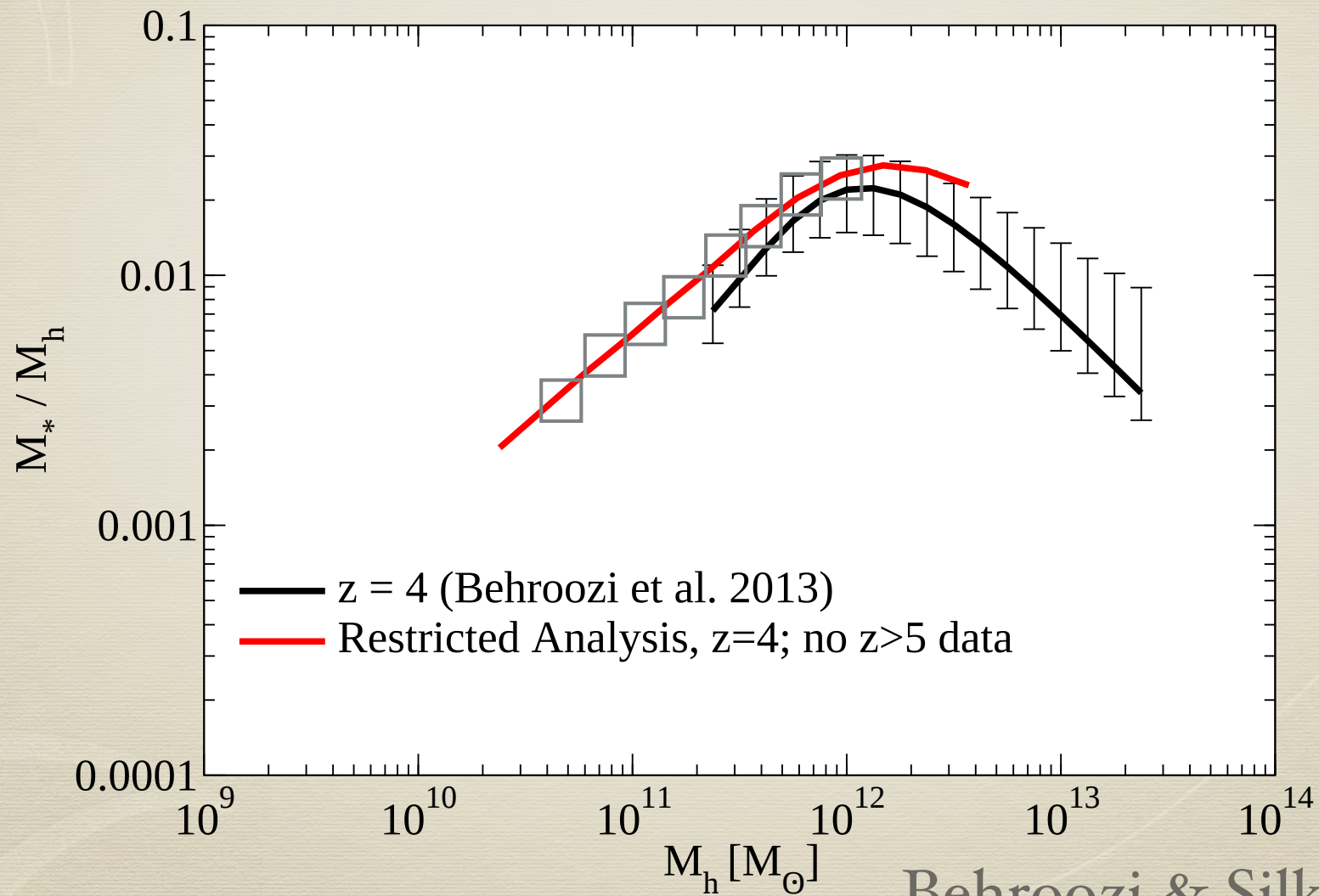
Using Physical Motivations



Using Physical Motivations

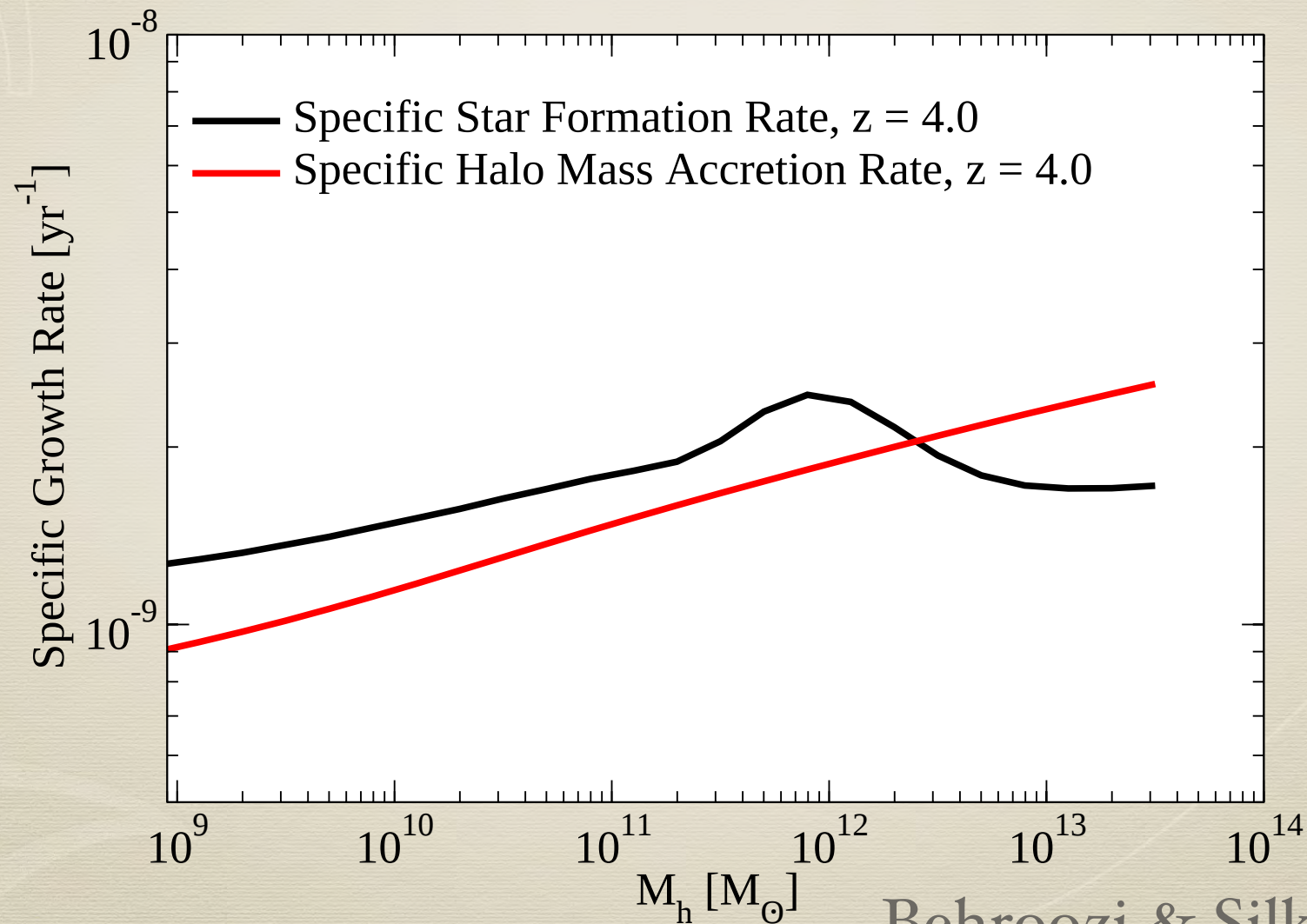


Some Tests



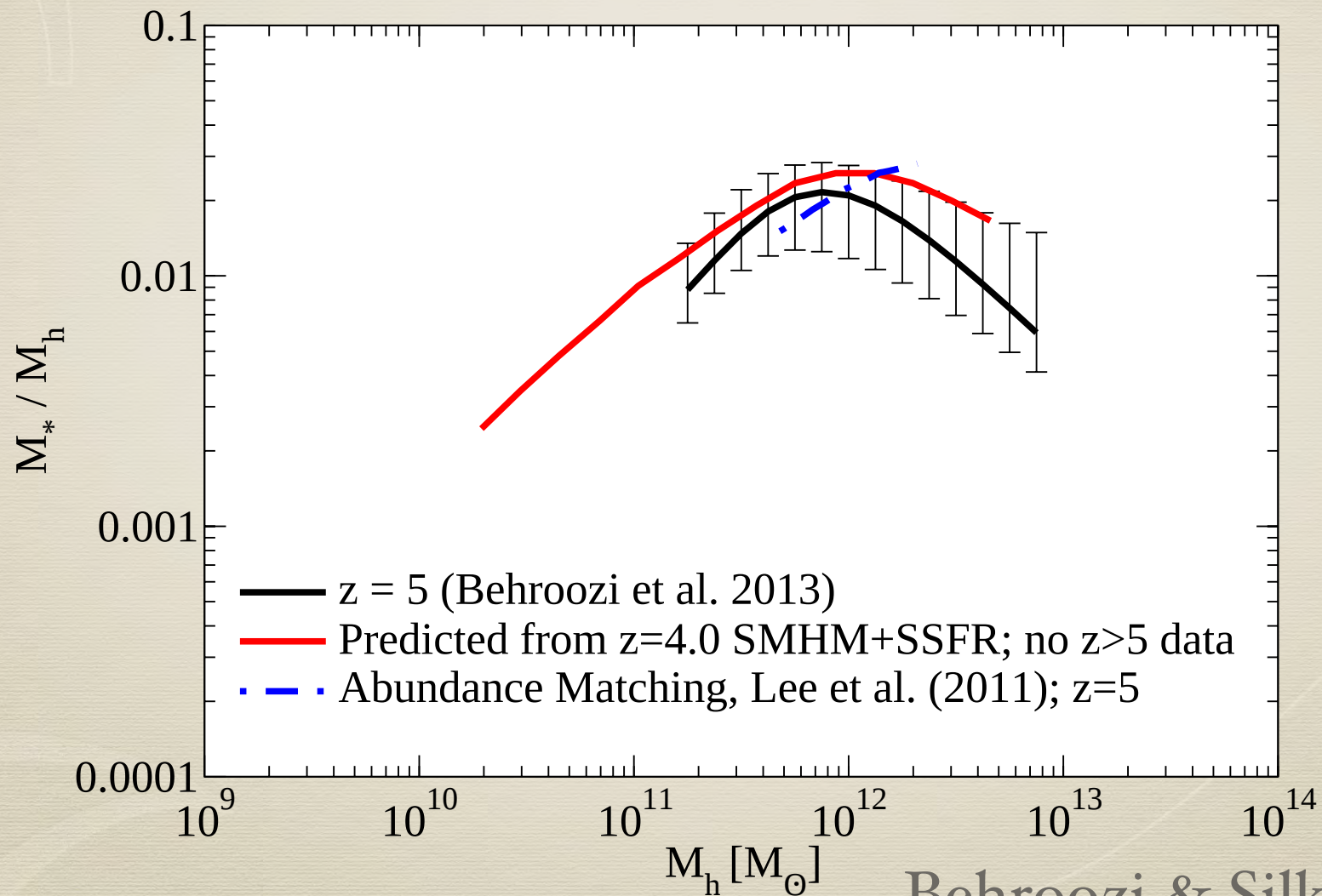
Behroozi & Silk (2015)

Some Tests



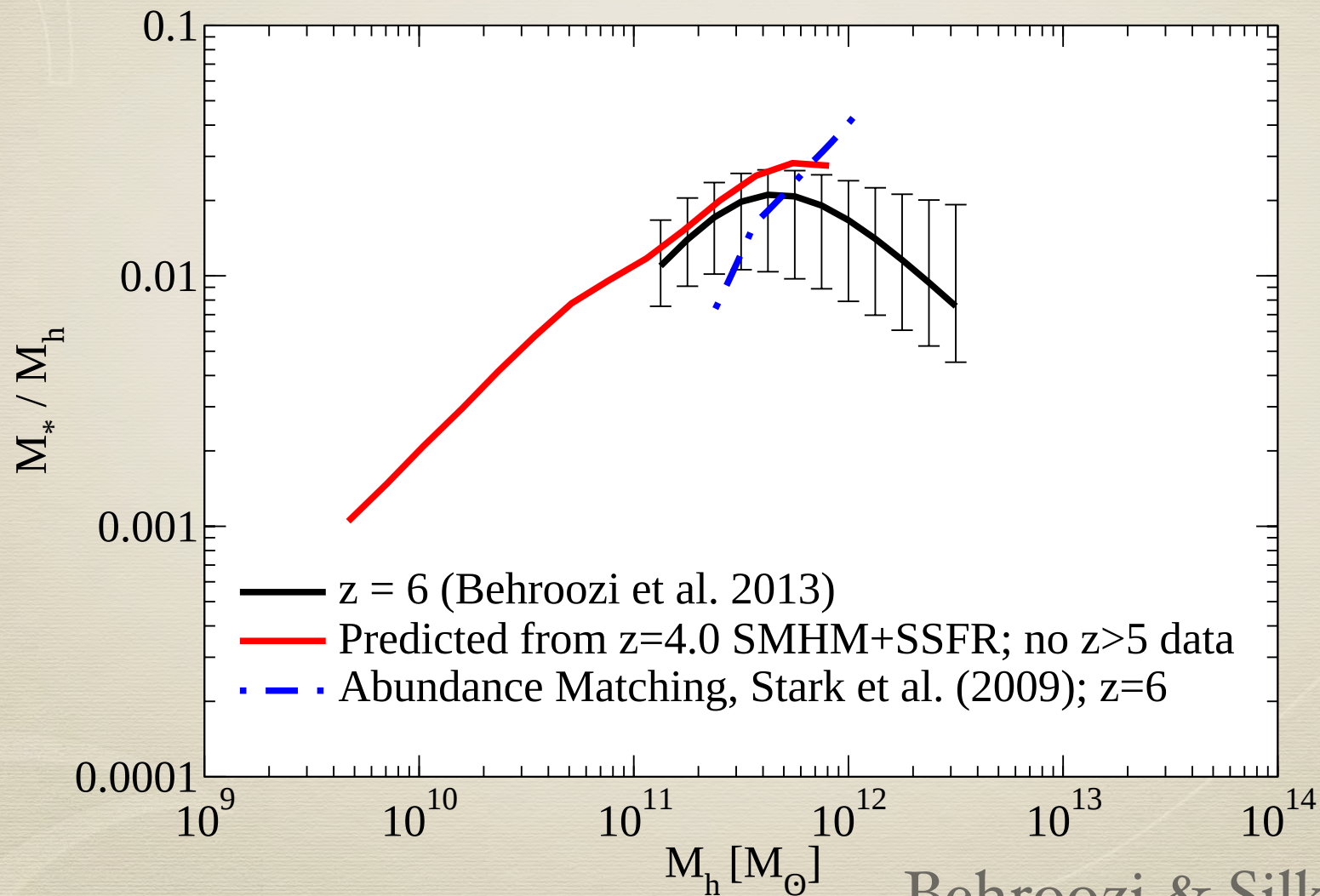
Behroozi & Silk (2015)

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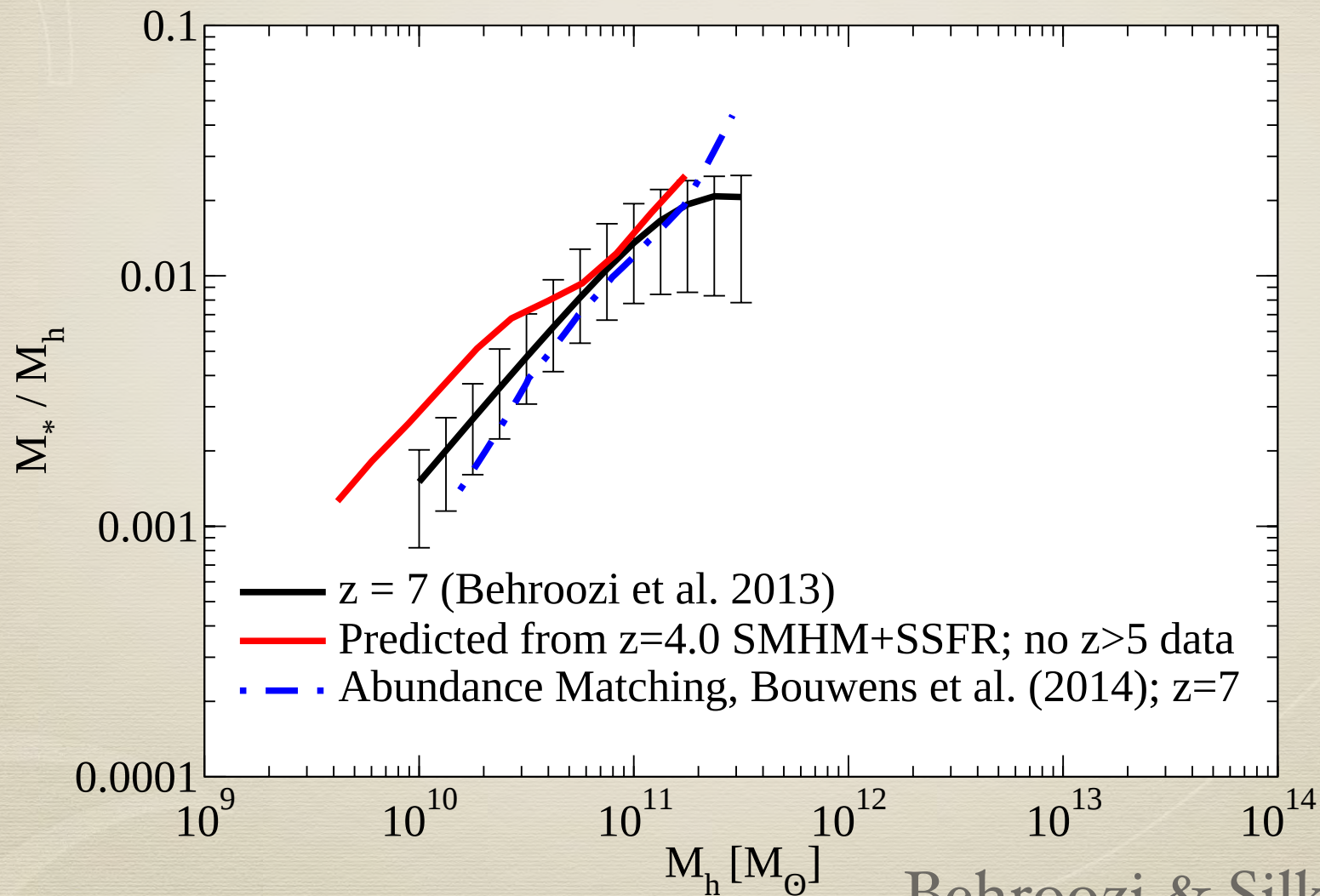
Behroozi & Silk (2015)

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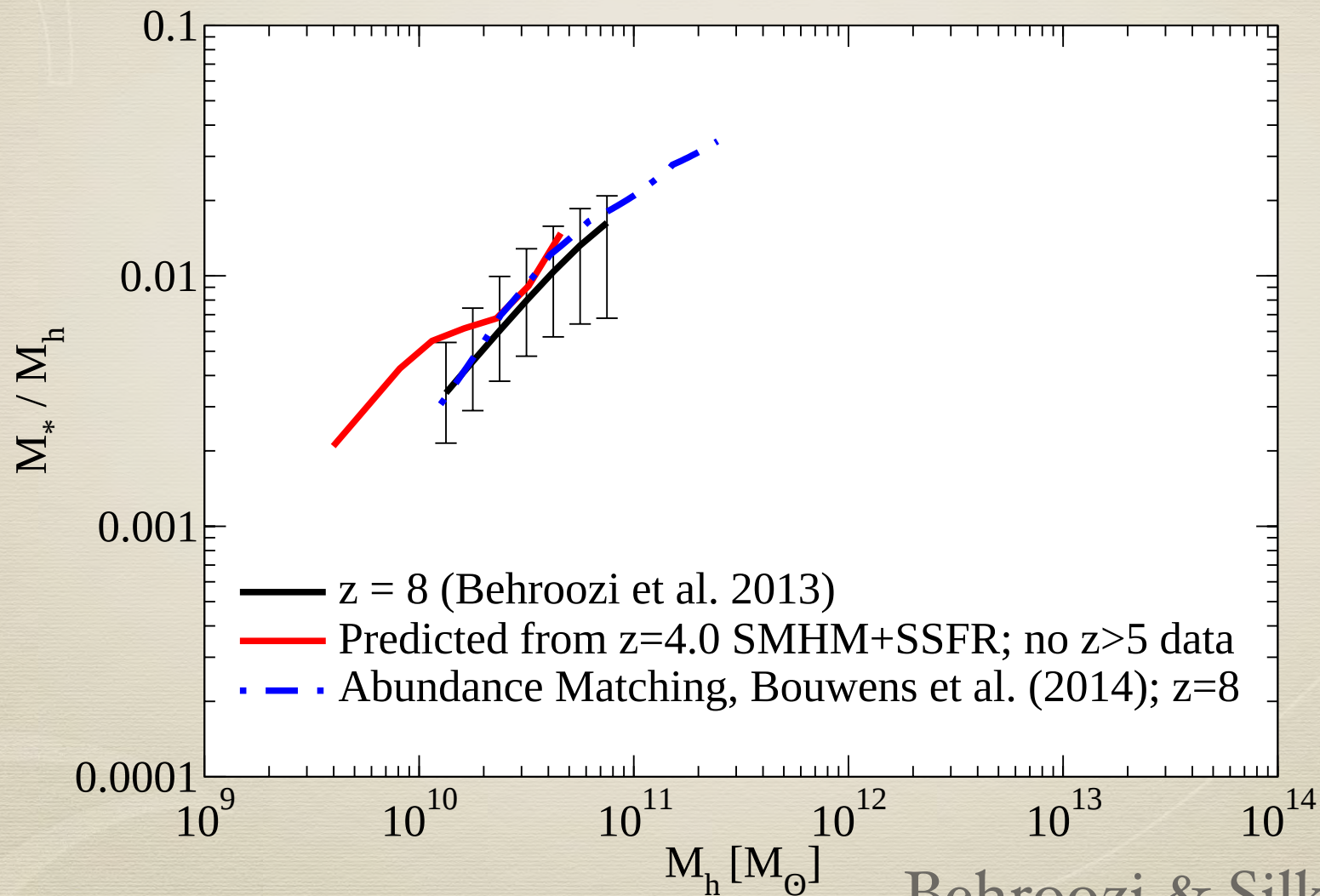
Behroozi & Silk (2015)

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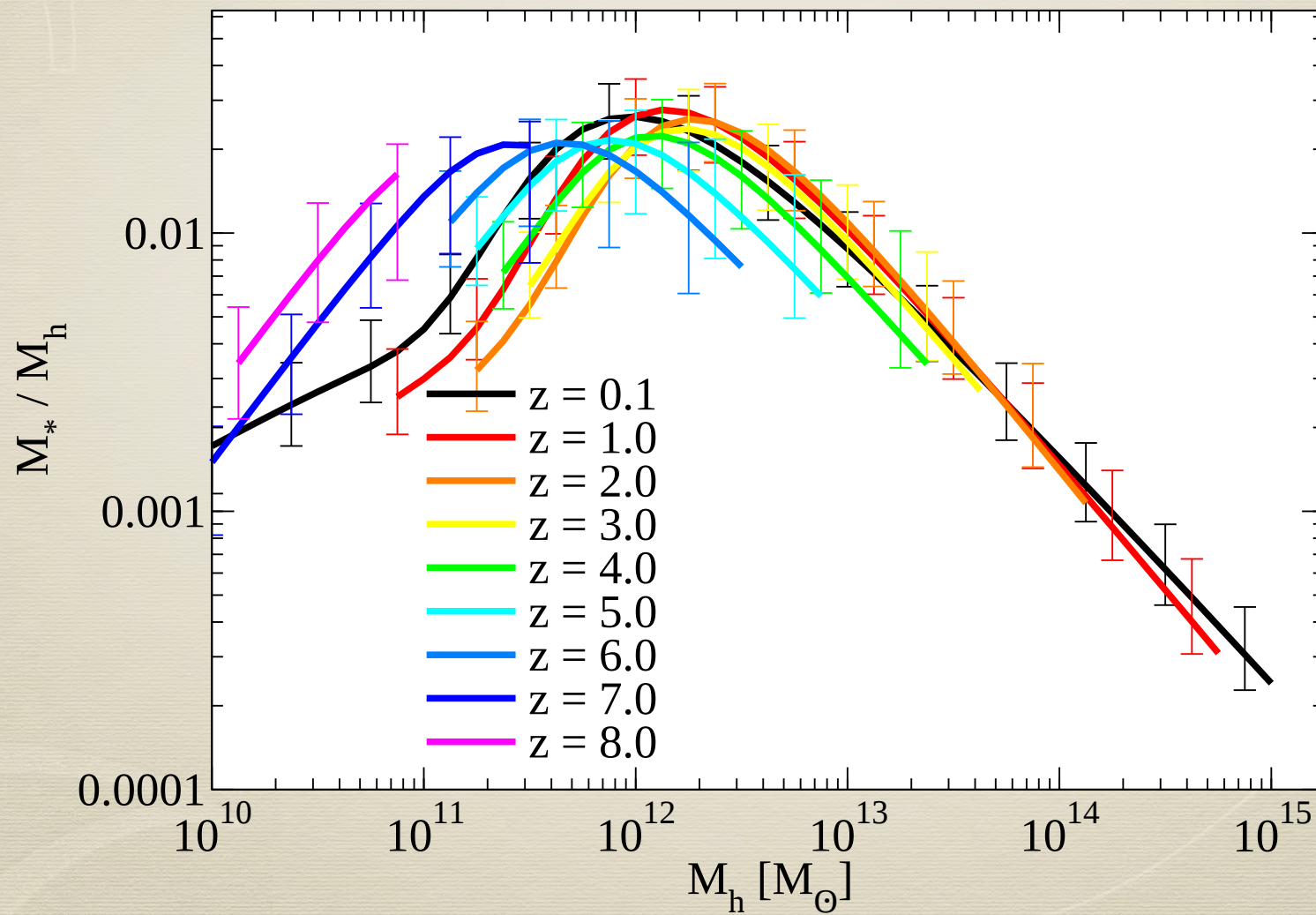
Behroozi & Silk (2015)

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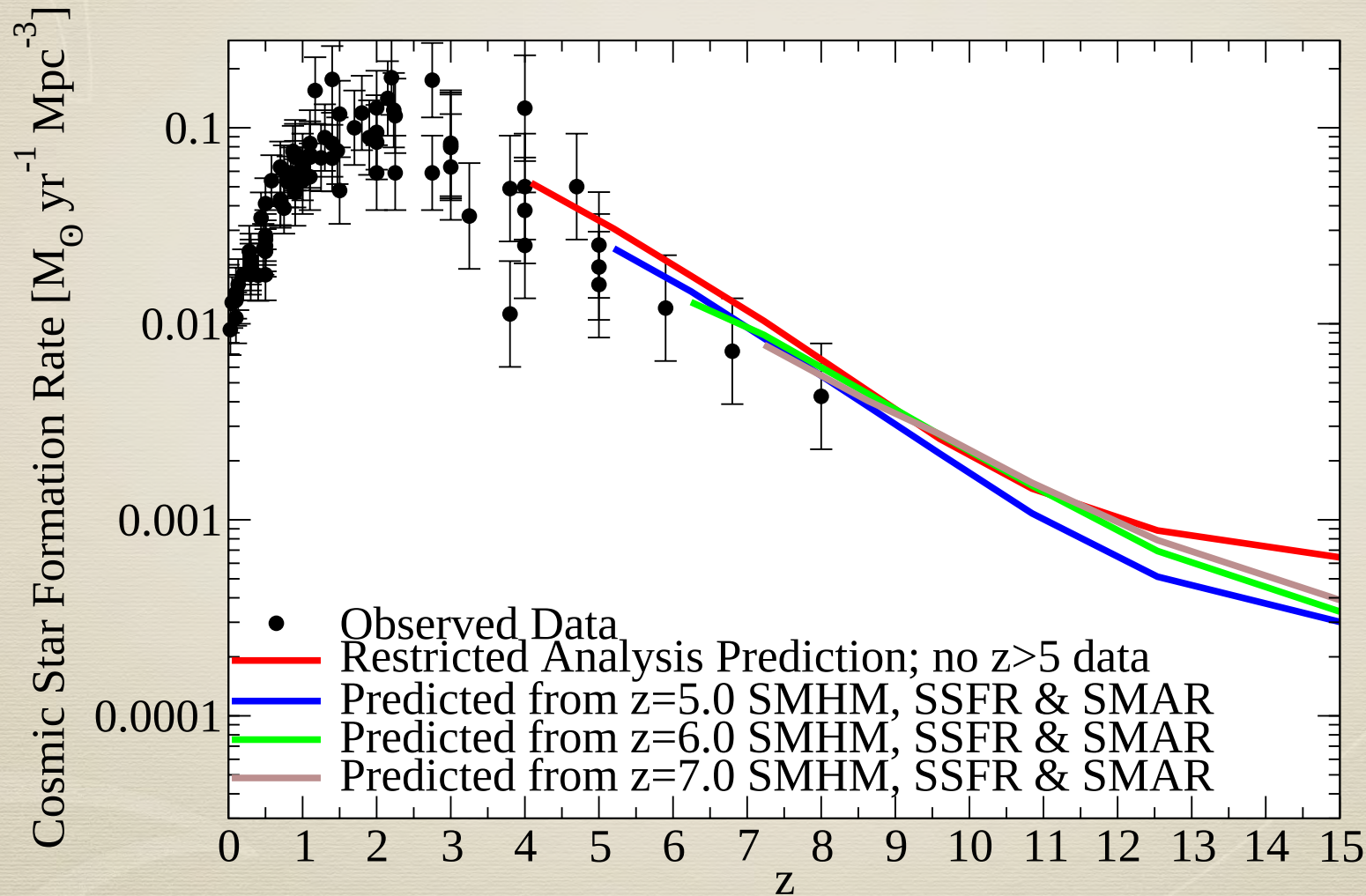


Behroozi & Silk (2015)

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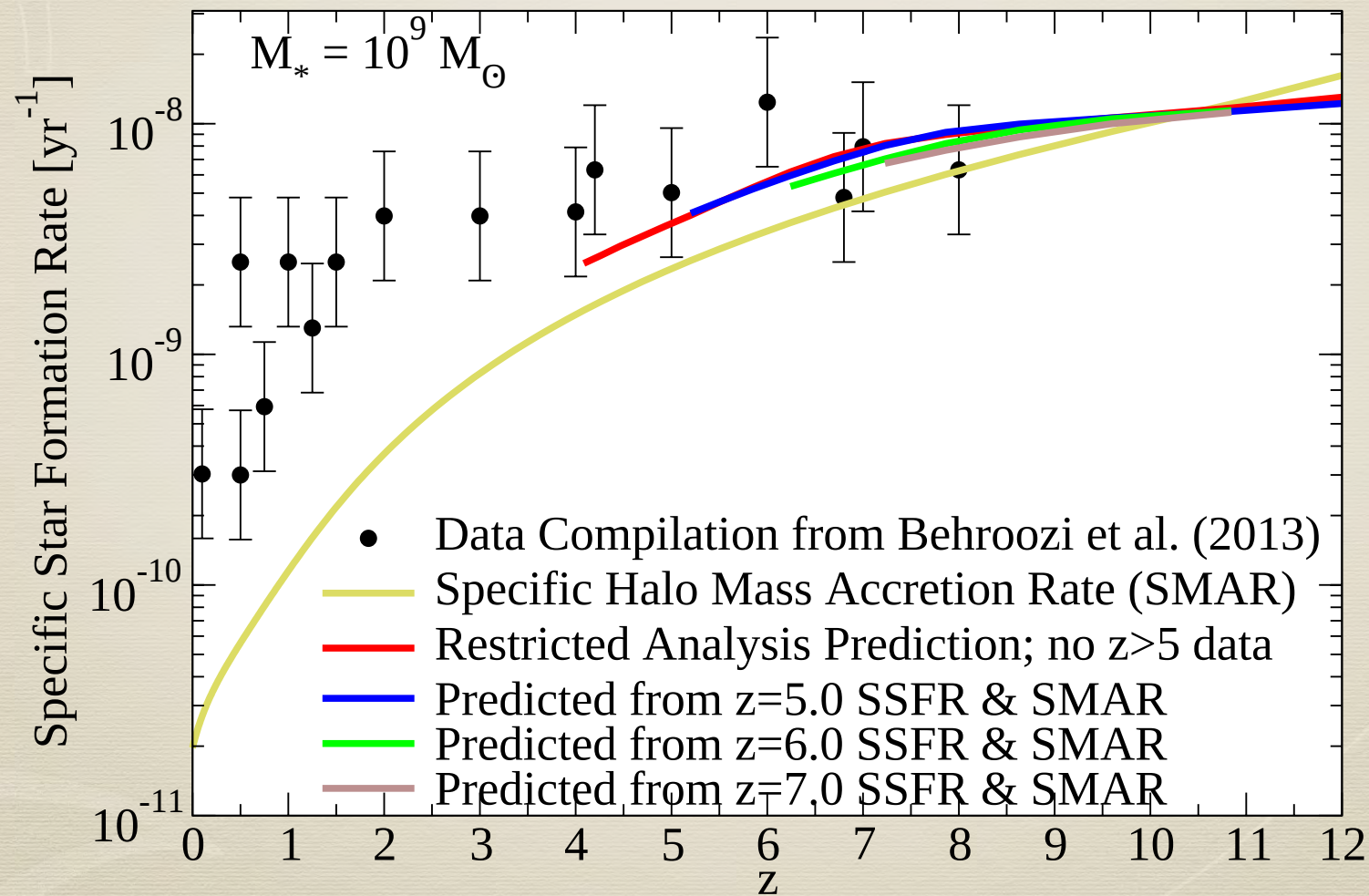


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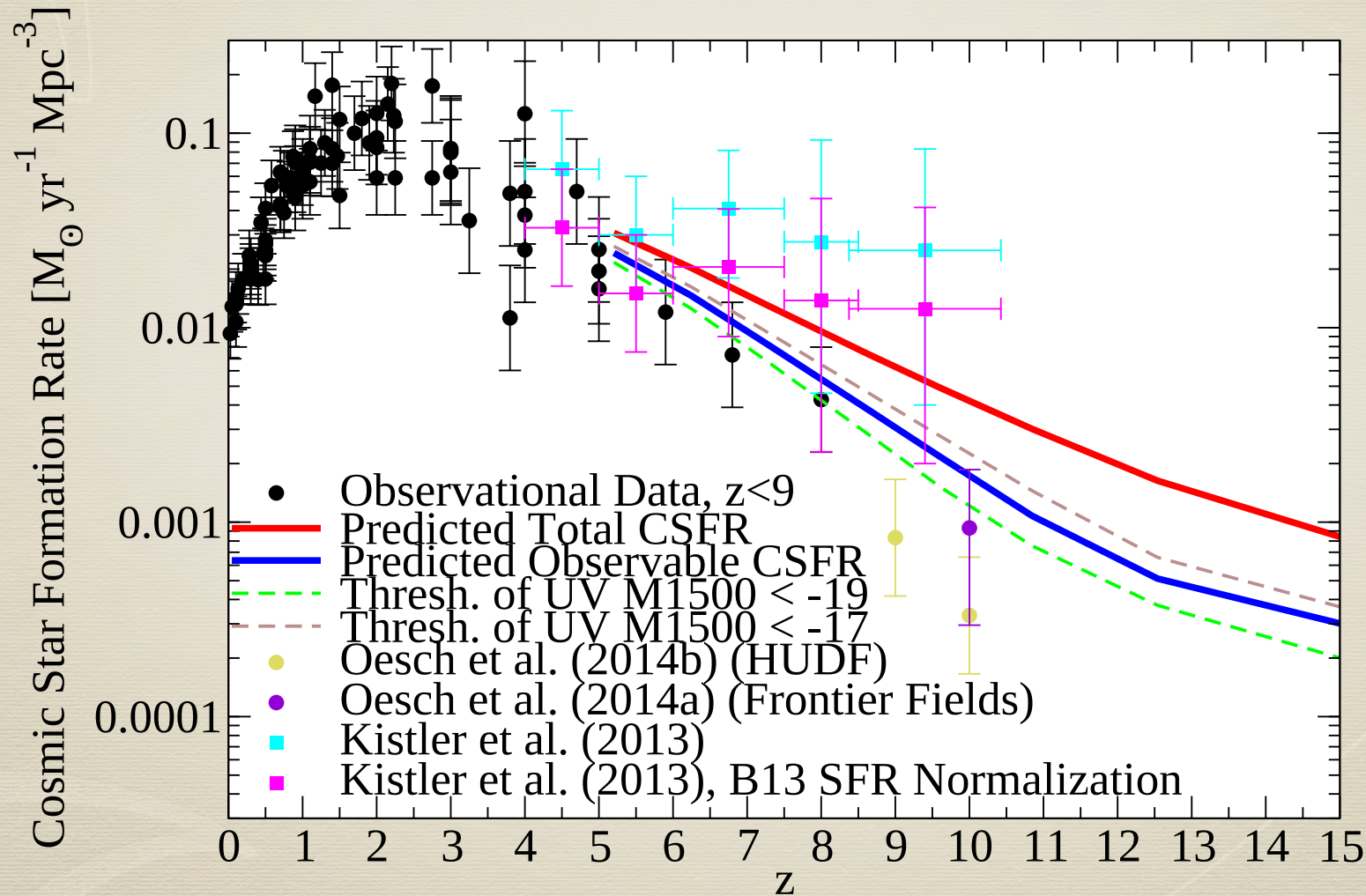
Behroozi & Silk (2015)

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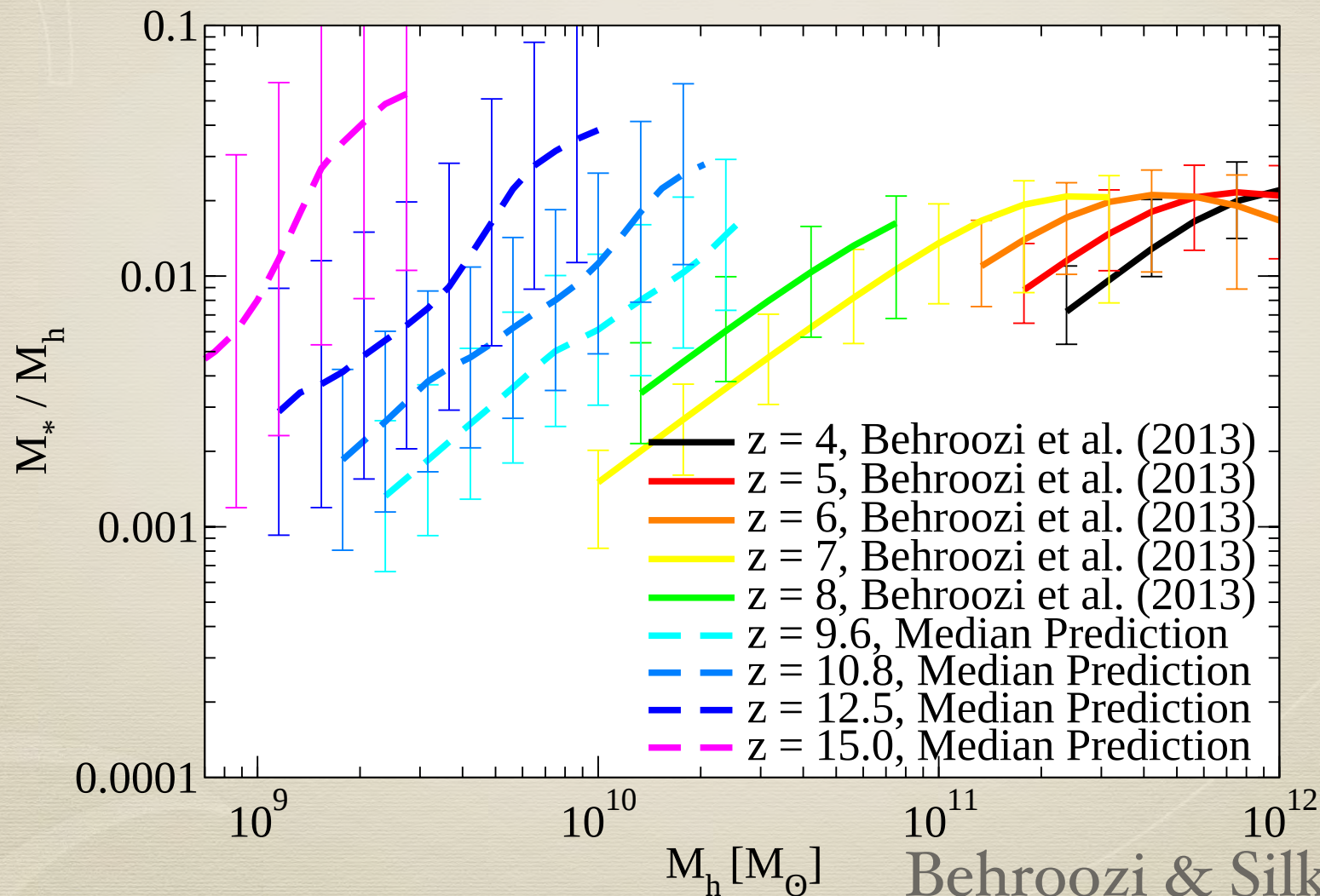
Behroozi & Silk (2015)

Predictions



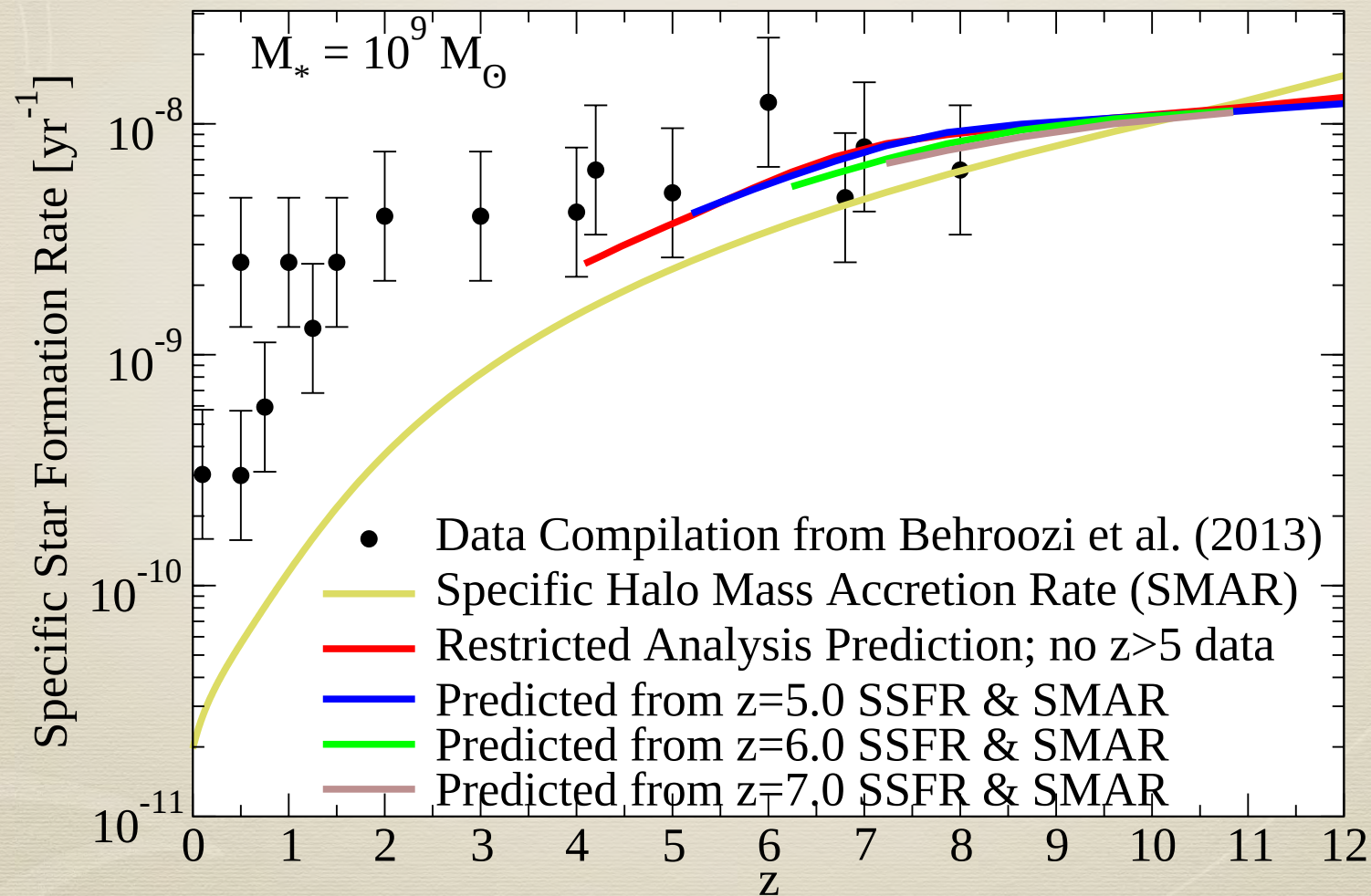
Behroozi & Silk (2015)

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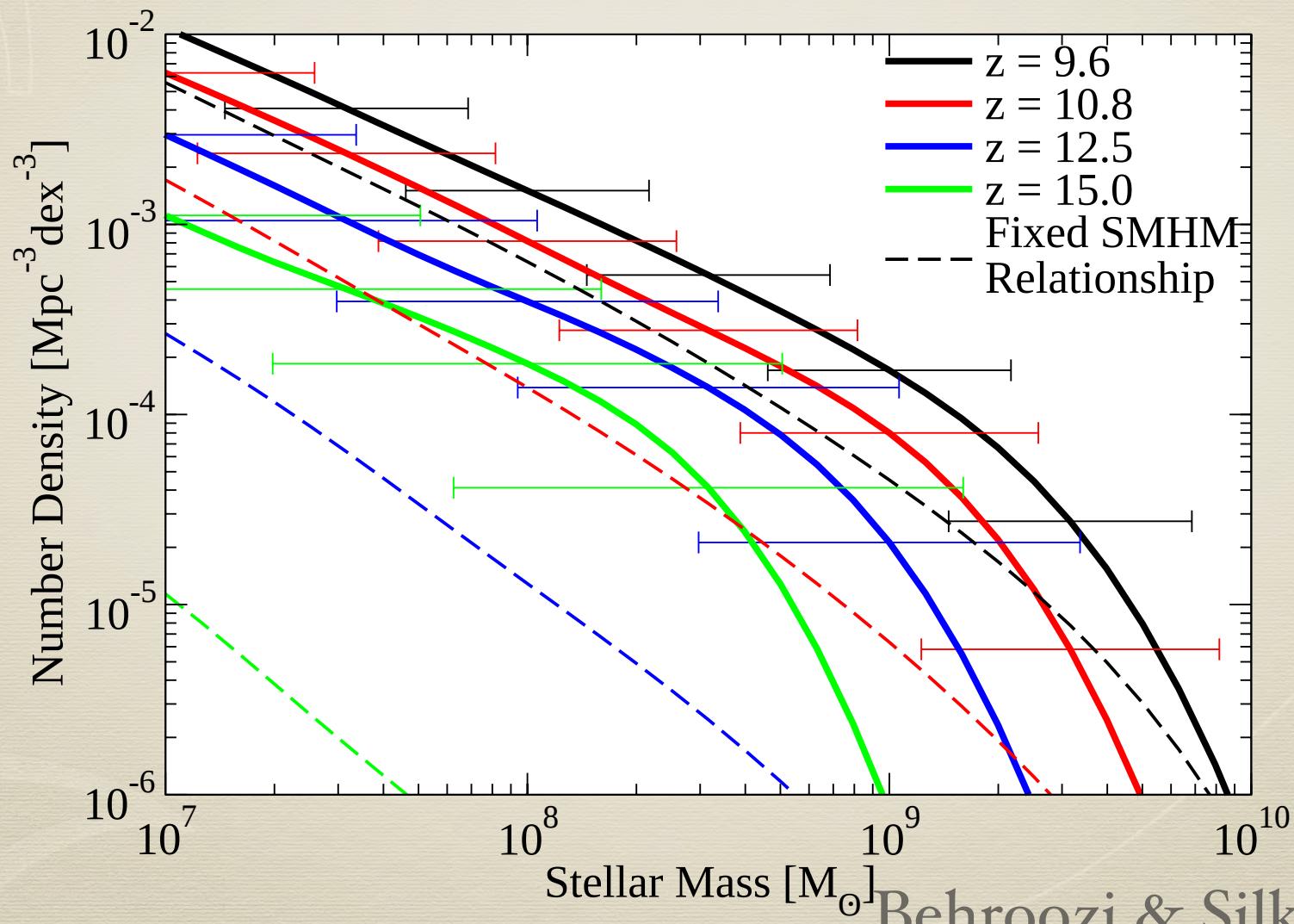
Behroozi & Silk (2015)
See also Finkelstein, Song, Behroozi et al. (2015)

Predictions



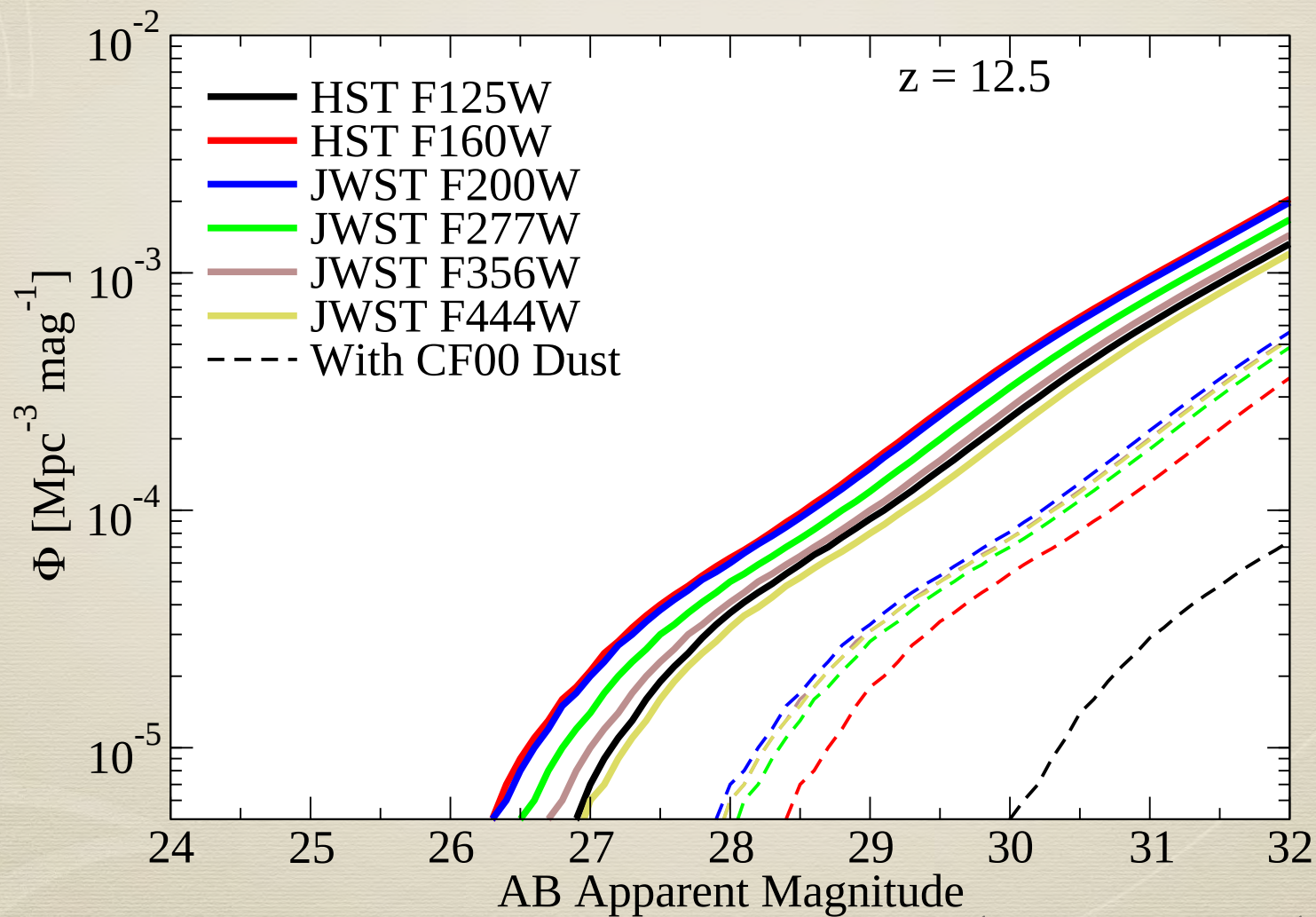
Behroozi & Silk (2015)

Predictions



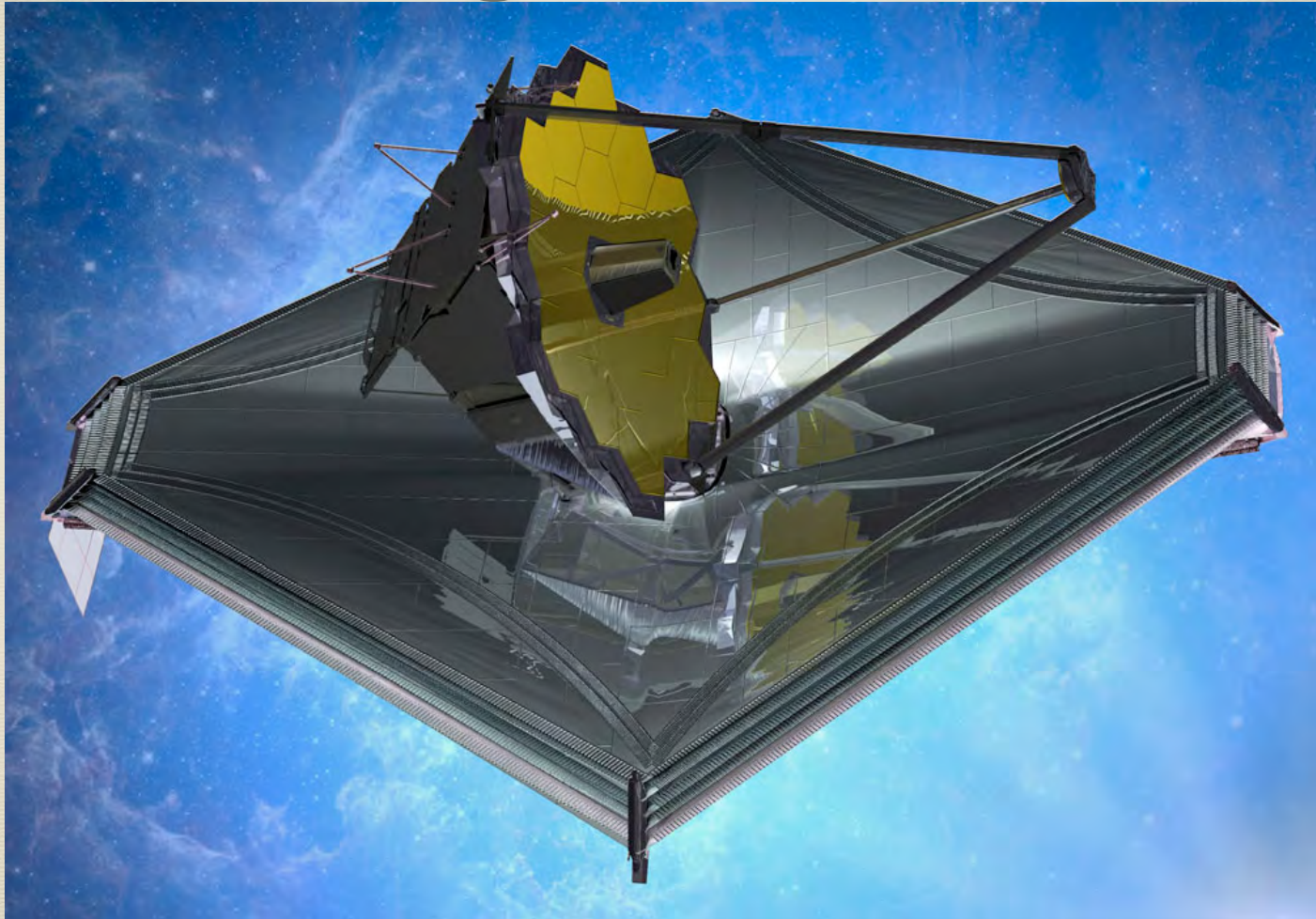
Behroozi & Silk (2015)

Predictions



Behroozi & Silk (2015)

Big Picture

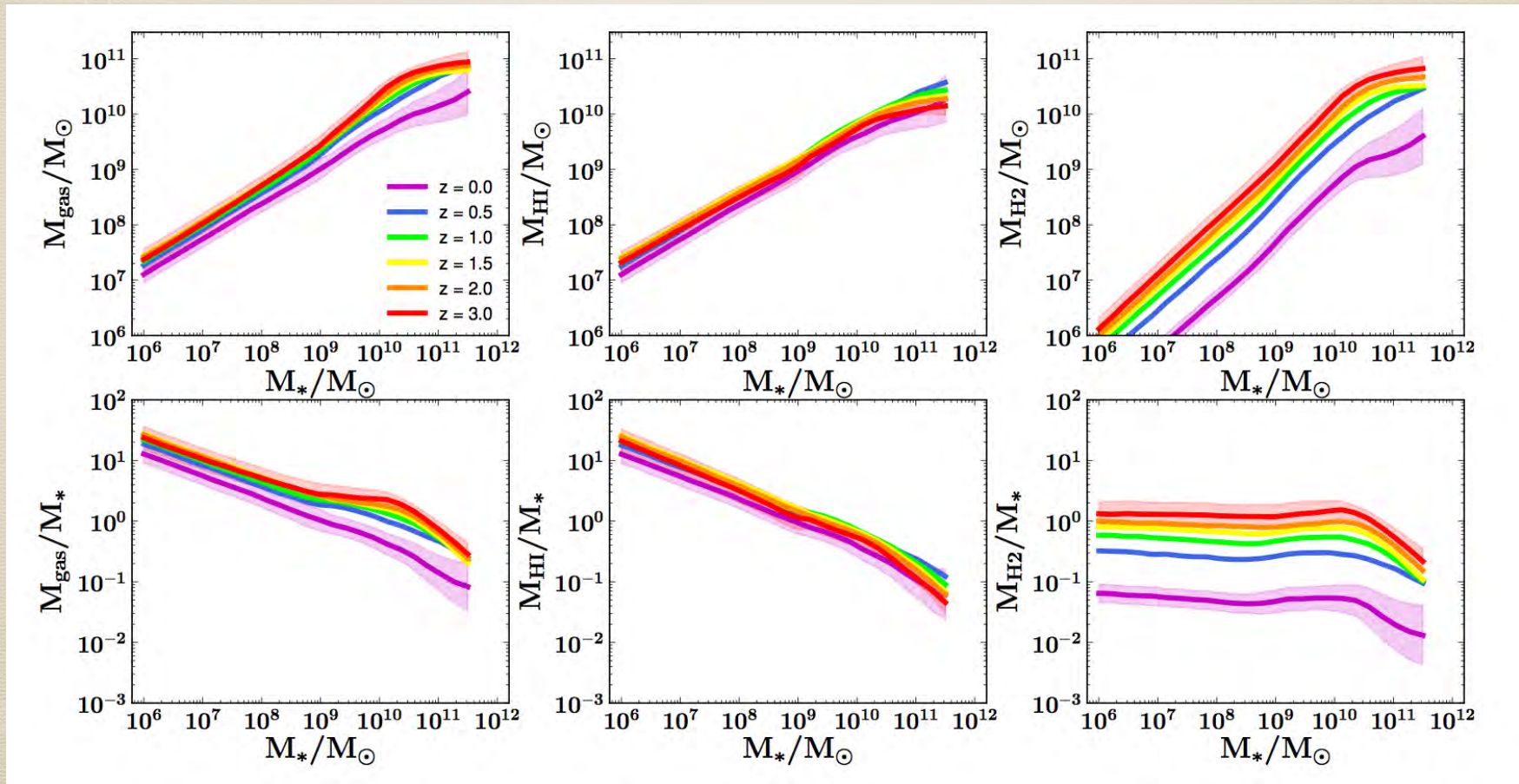


Credit: Northrop Grumman

JWST will be an amazing constraint on early galaxy formation

What's Next?

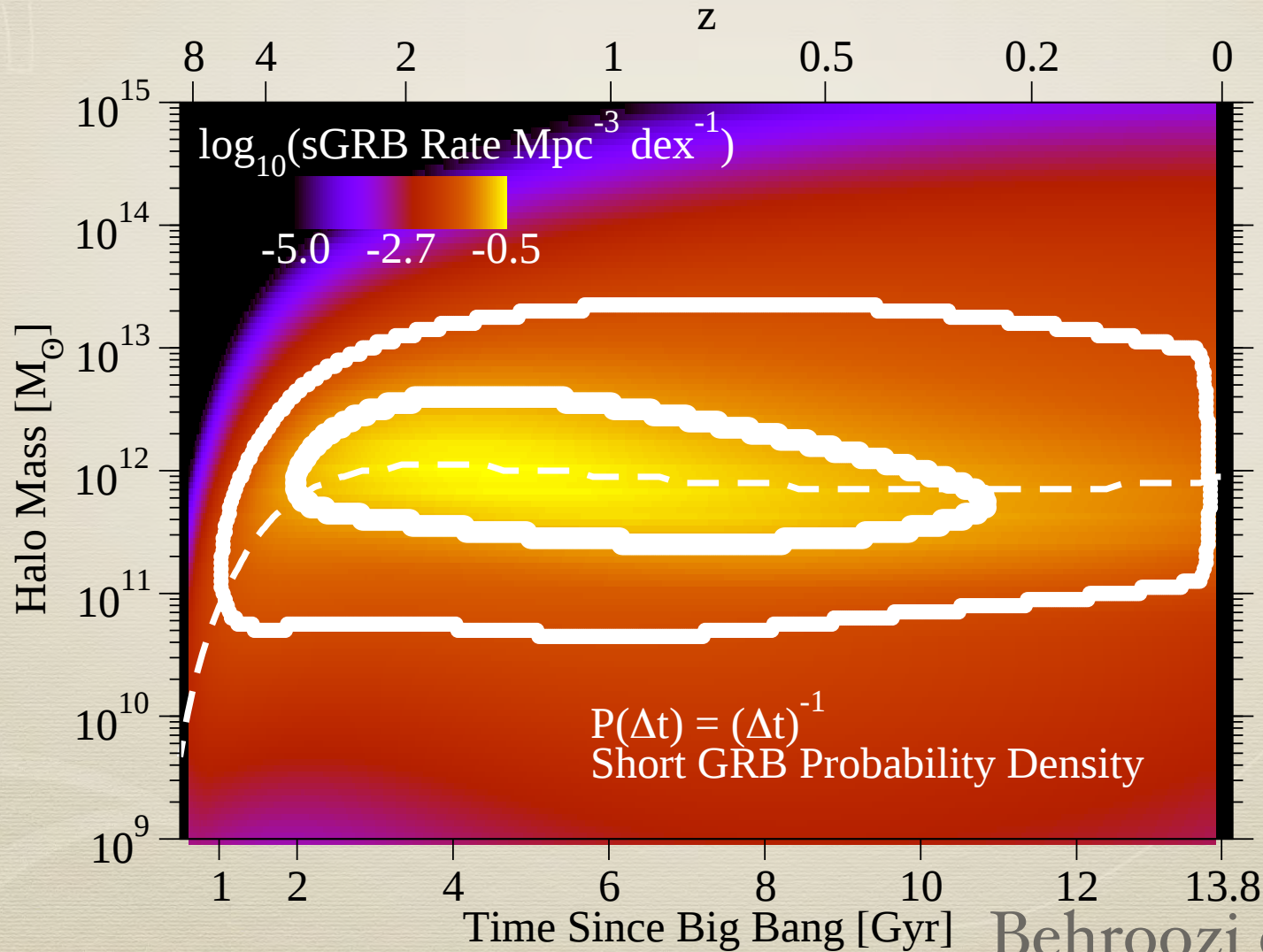
Model Building



Popping, Behroozi & Peeples (2015)

What's Next?

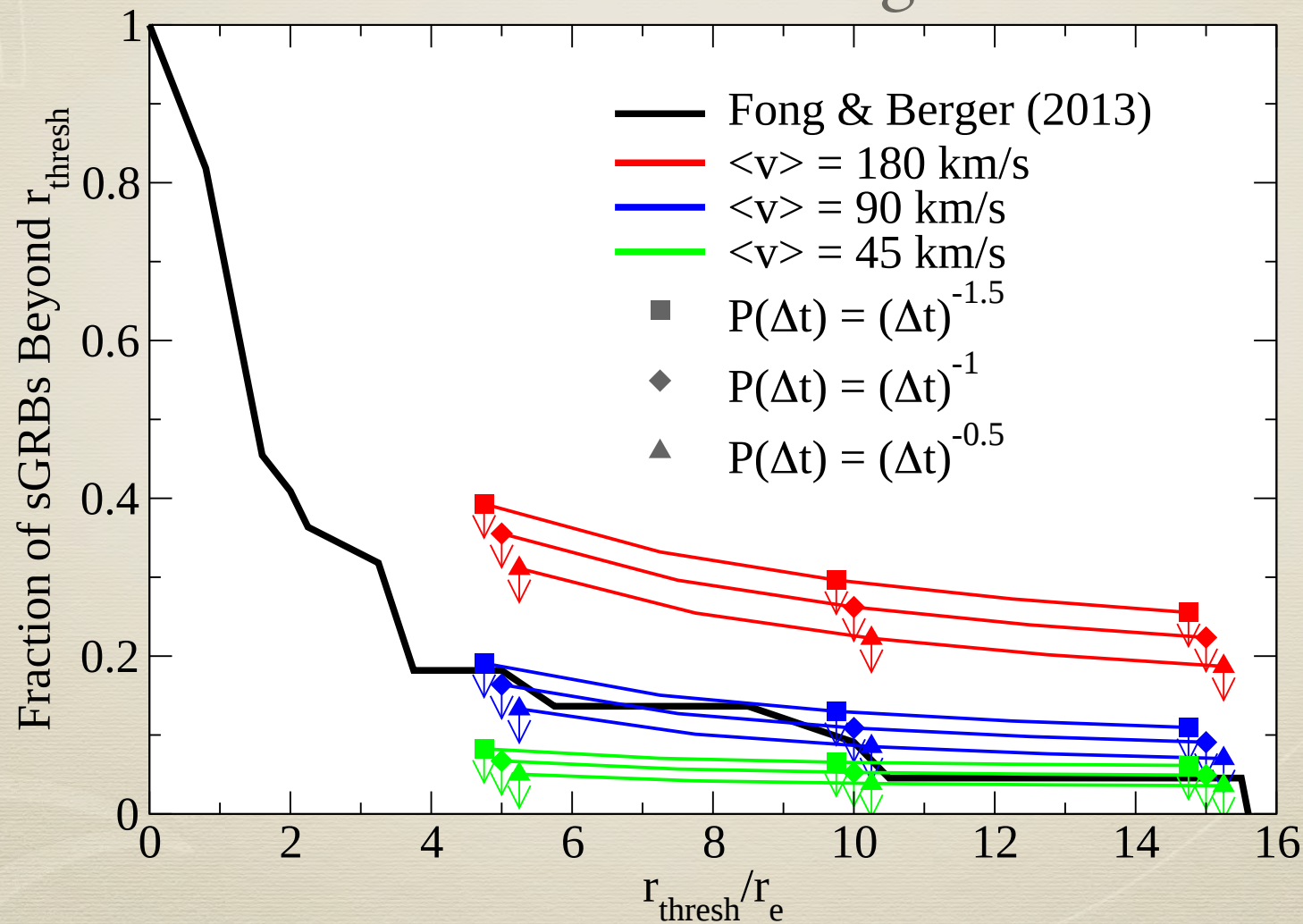
Model Building



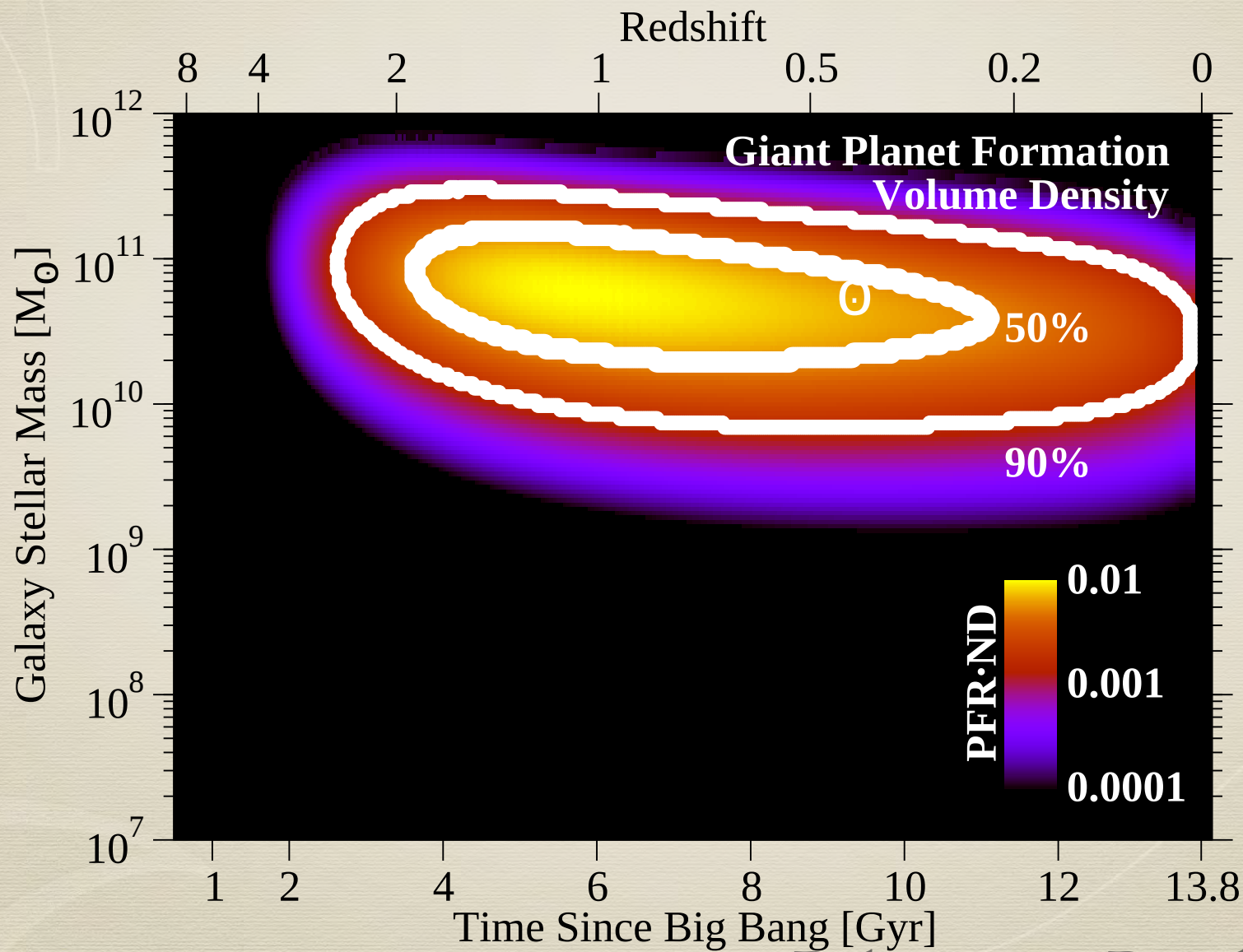
Behroozi et al. (2014)

What's Next?

Model Building



What's Next?



Behroozi & Peebles (2015)

What's Next?

(And much, much more)

Individual galaxy star formation histories

Behroozi, Wechsler, Hearin in prep.

Constraints on galaxy sizes / spins

Lee, Primack, Behroozi et al., in prep.

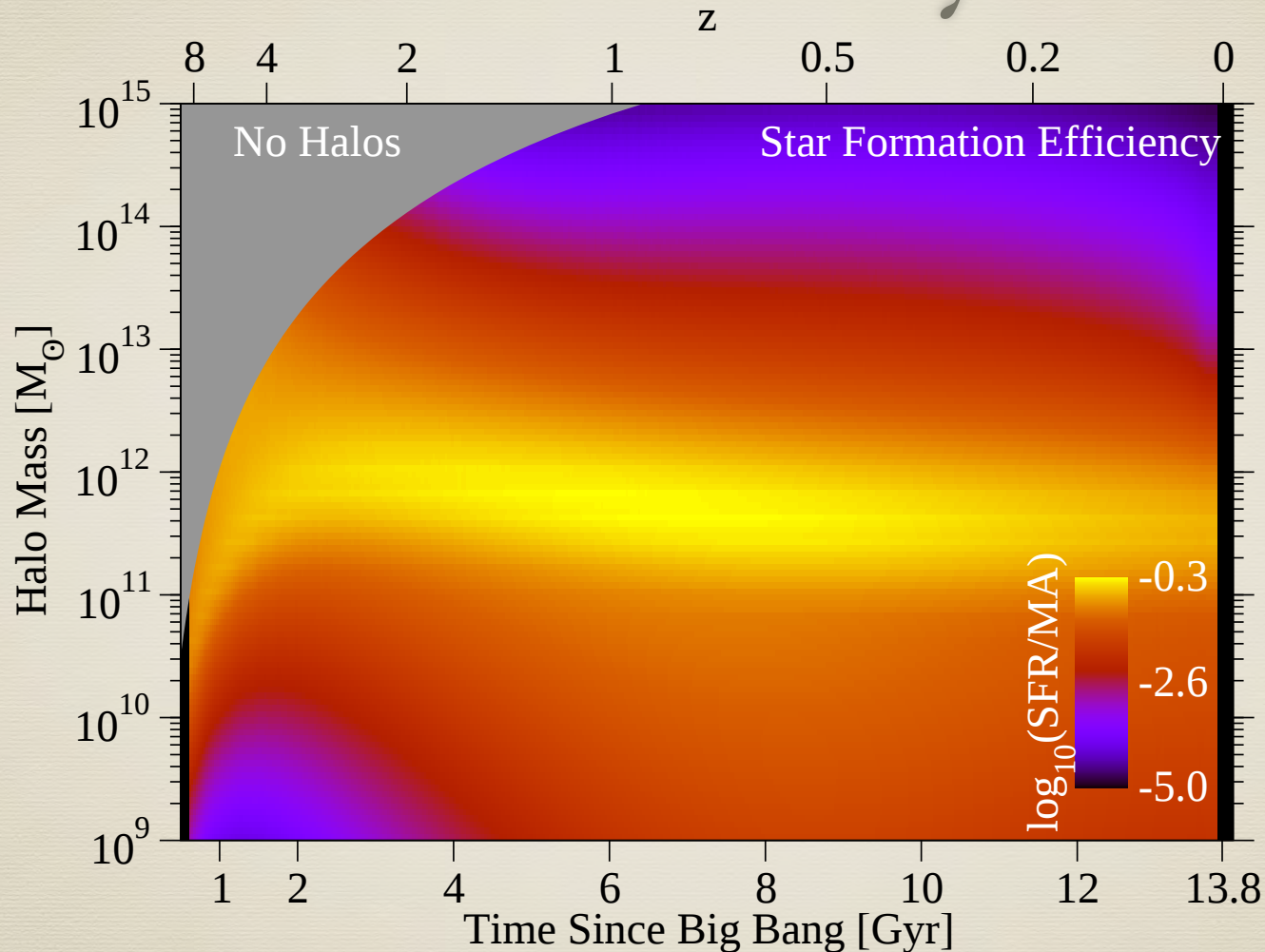
Supermassive black hole growth histories

Behroozi, Hopkins, Silk, Quataert, White in prep.

Constraints on gas flows from metallicity evolution

Peebles, Behroozi, Popping in prep.

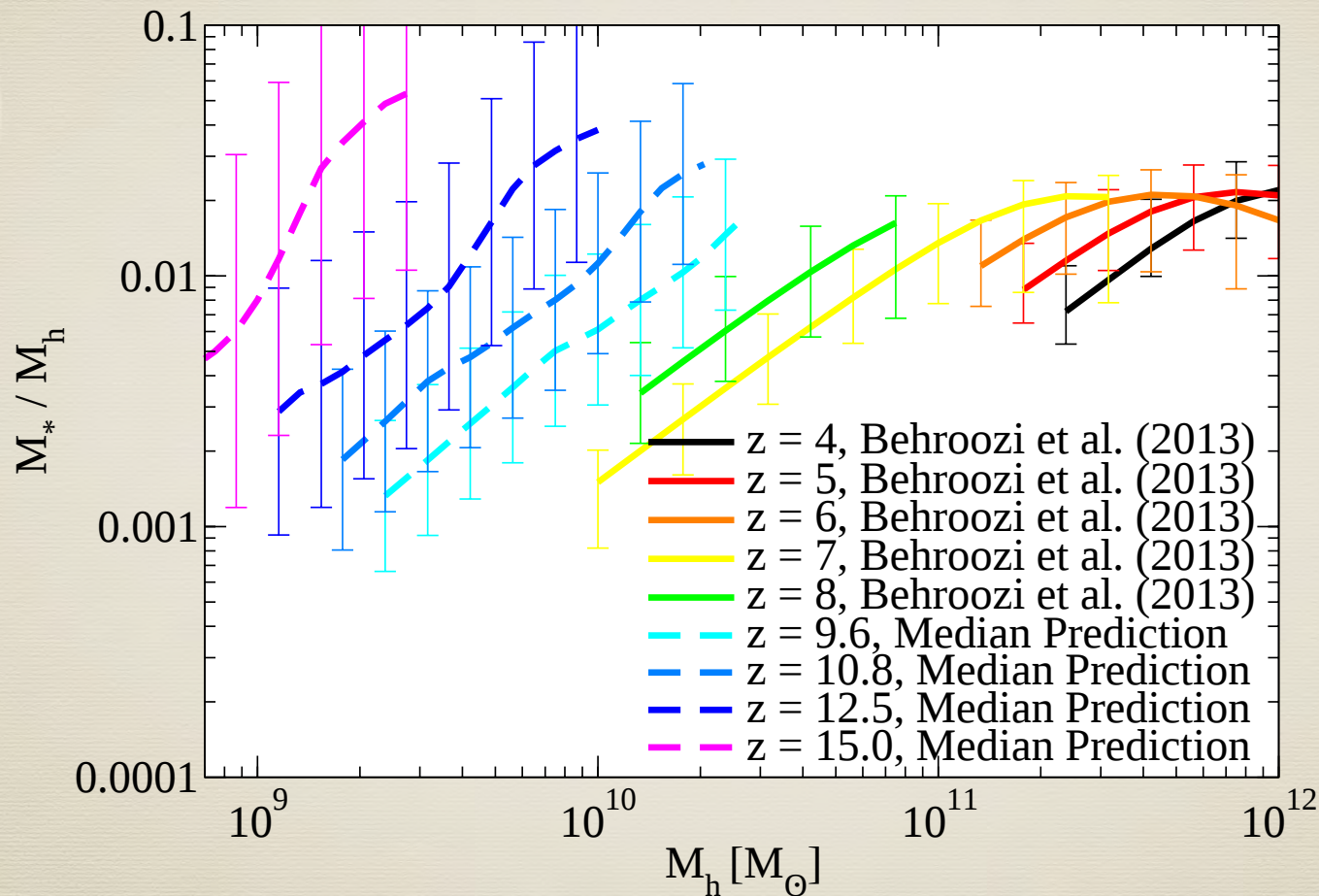
Summary



Galaxy formation at $z < 4$ is mostly a function of halo mass.

Behroozi, Wechsler, Conroy (2013b)

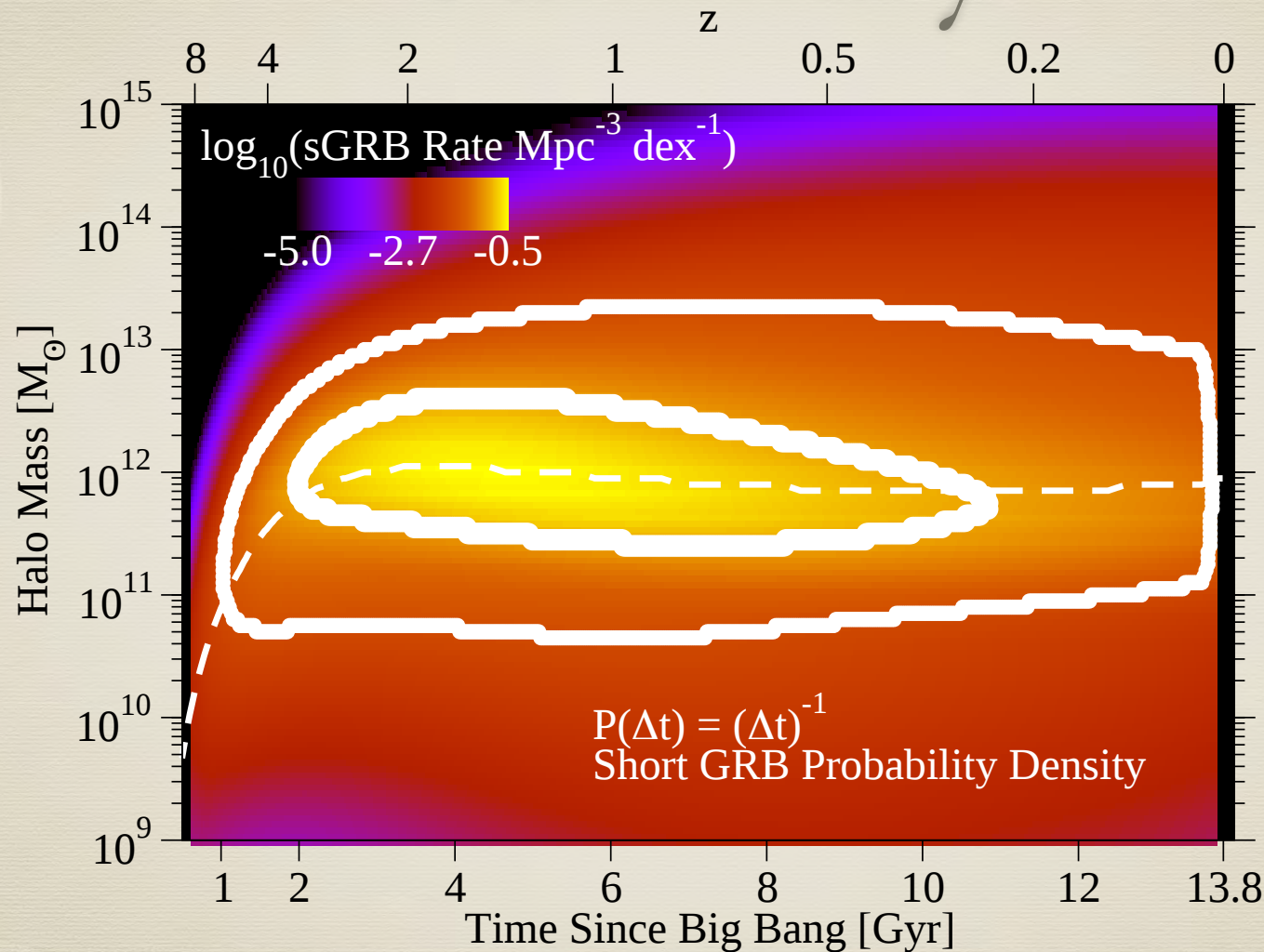
Summary



Not so at $z > 4$! Dwarf galaxies must become more efficient.

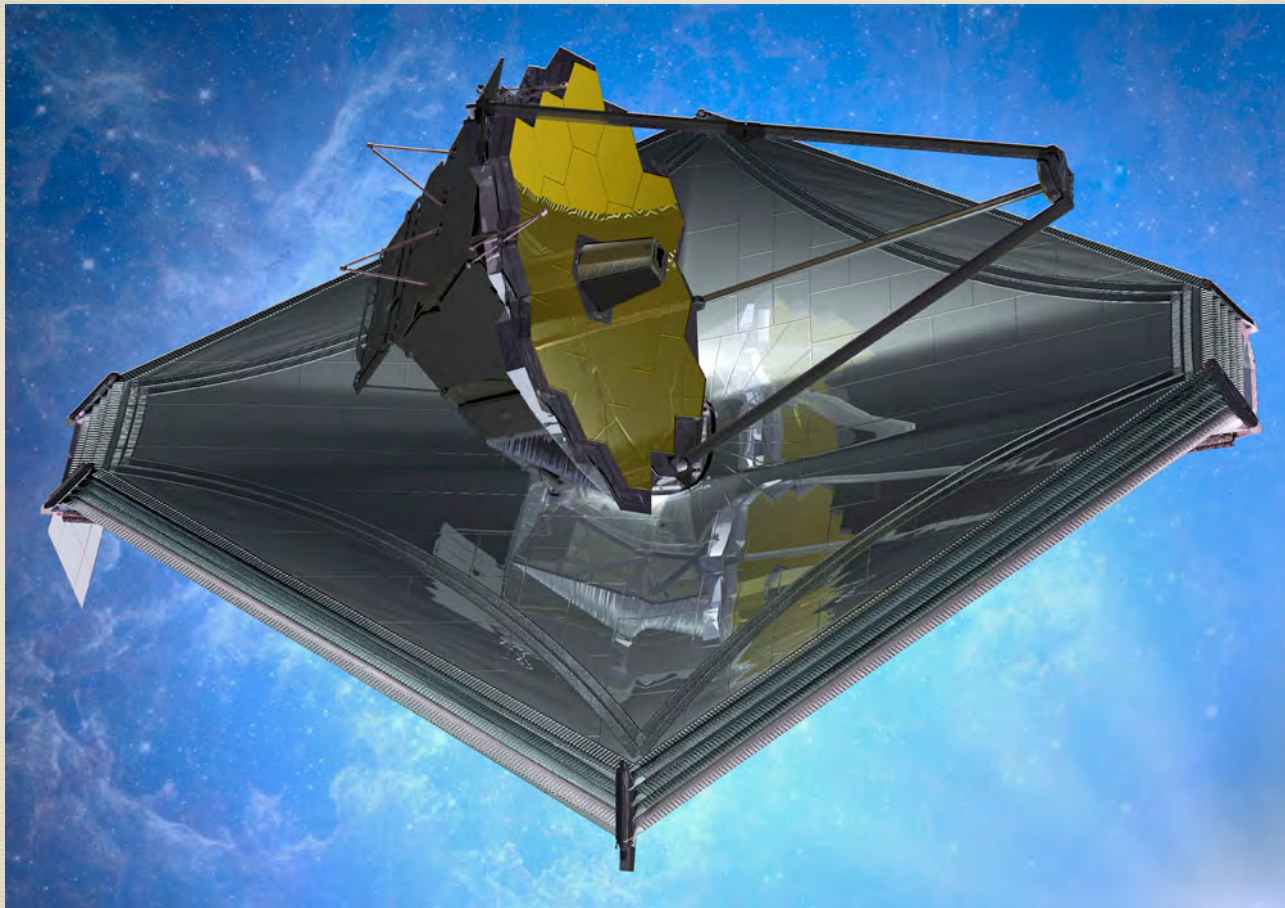
Behroozi & Silk (2015)

Summary



A solid foundation for star formation can only help when modeling gas, SNaE, GRBs, Black Holes, Planets, etc.

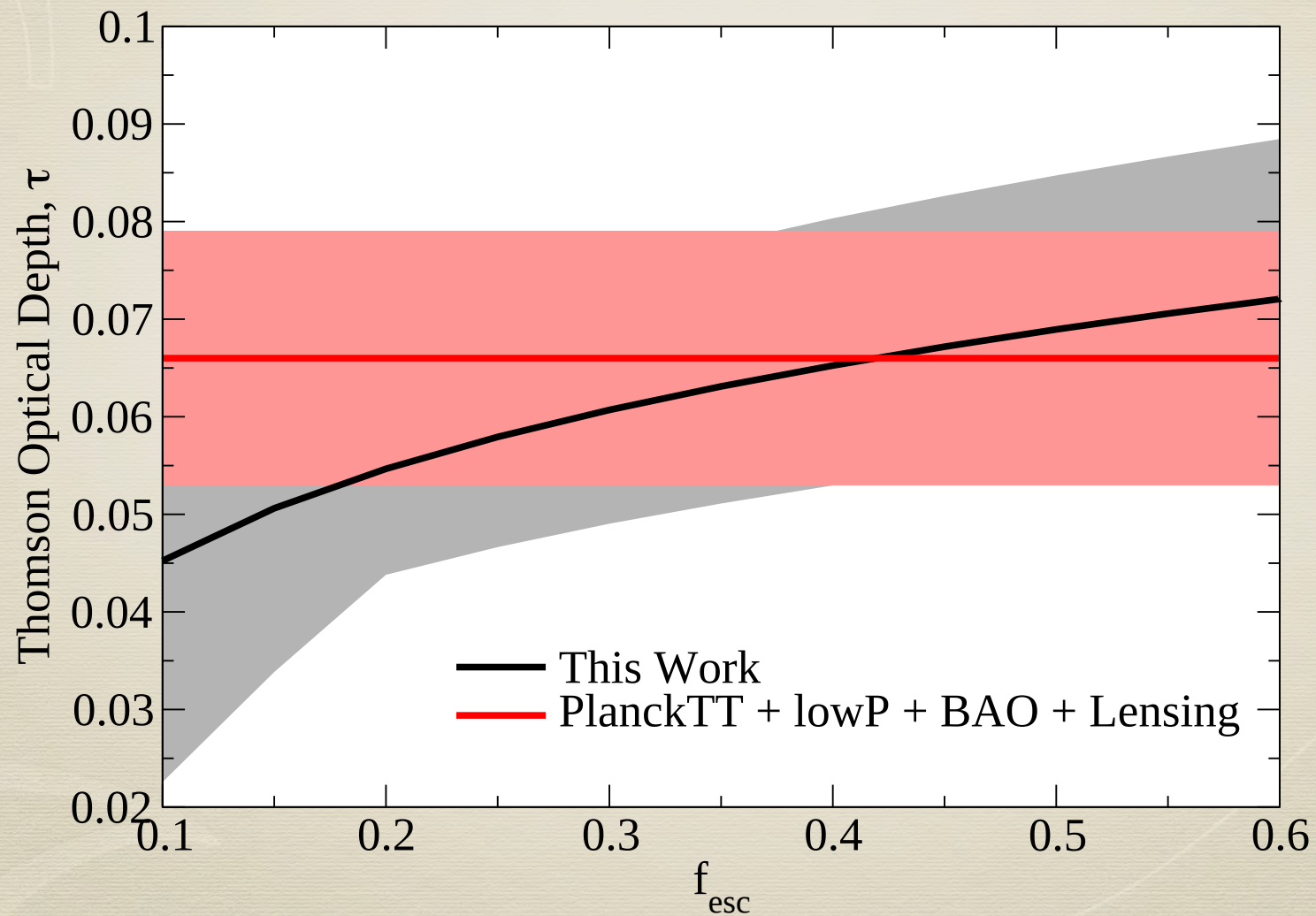
Summary



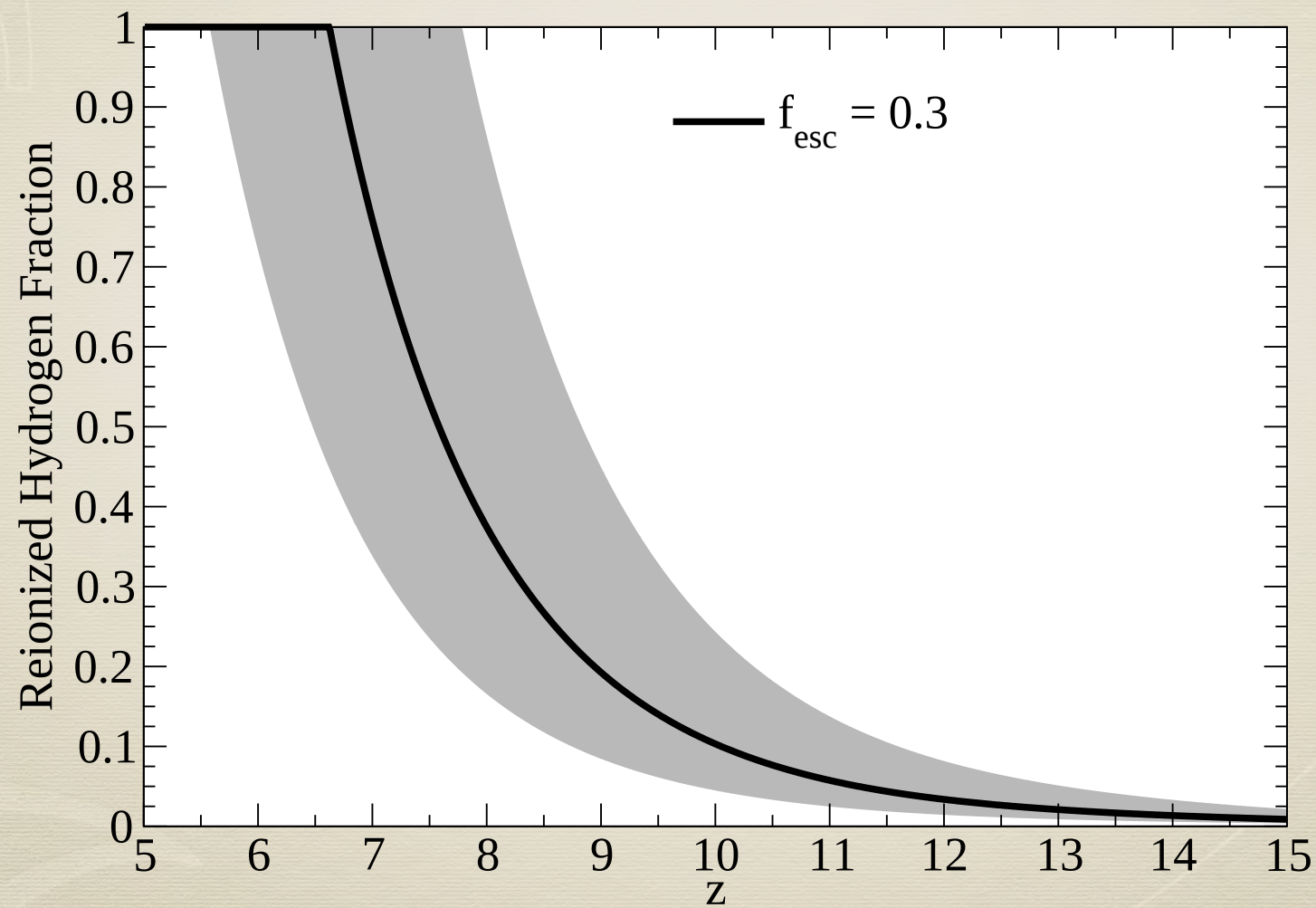
Credit: Northrop Grumman

Lots more to be excited about in the future!

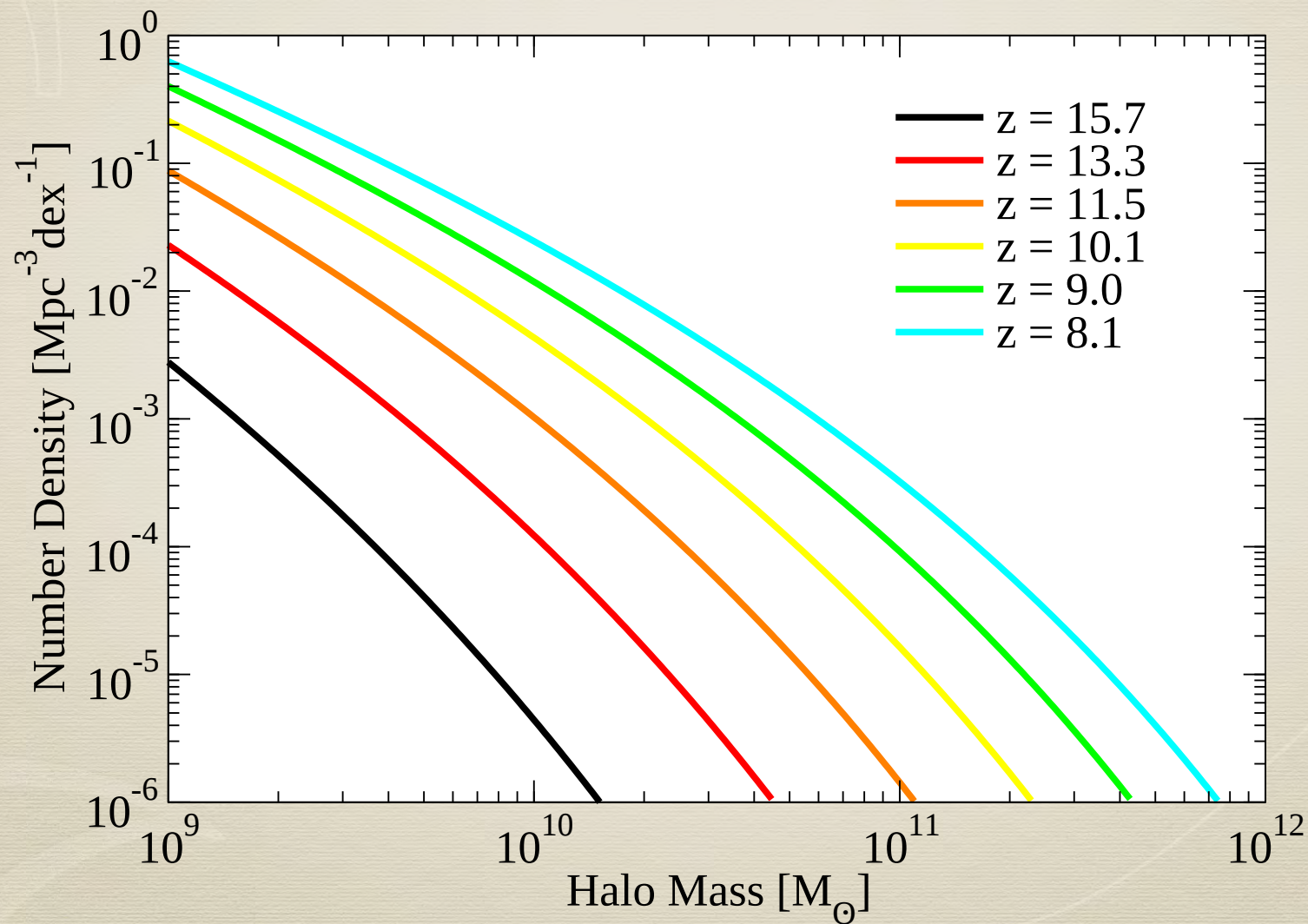
Supplemental



Supplemental



Supplemental



Supplemental

