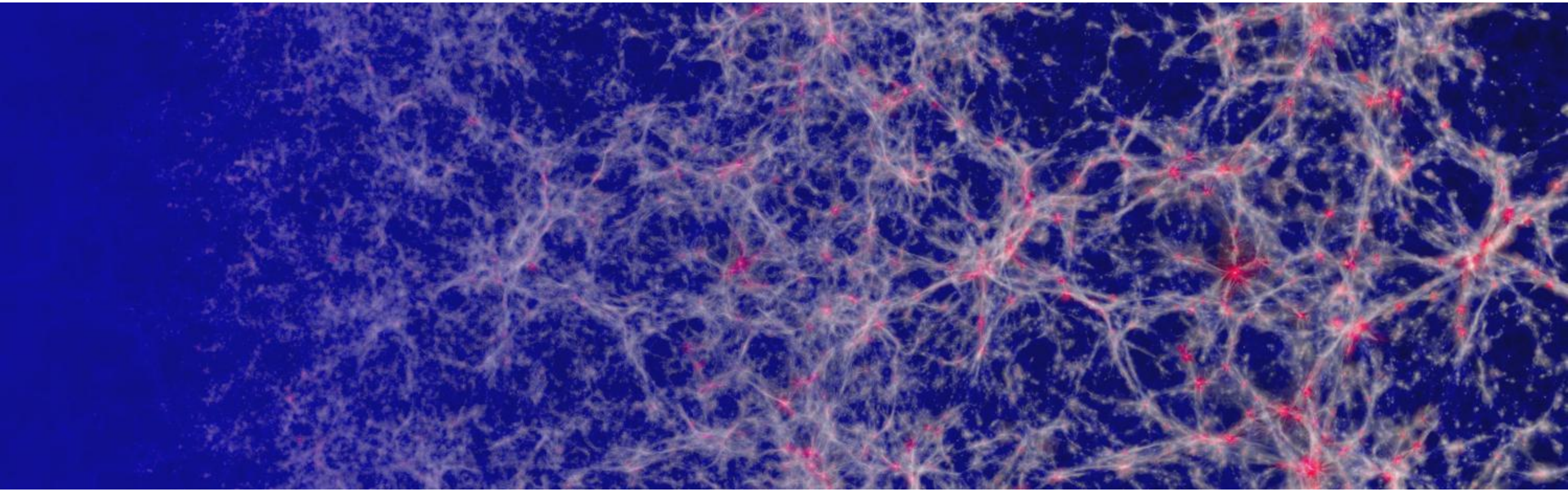
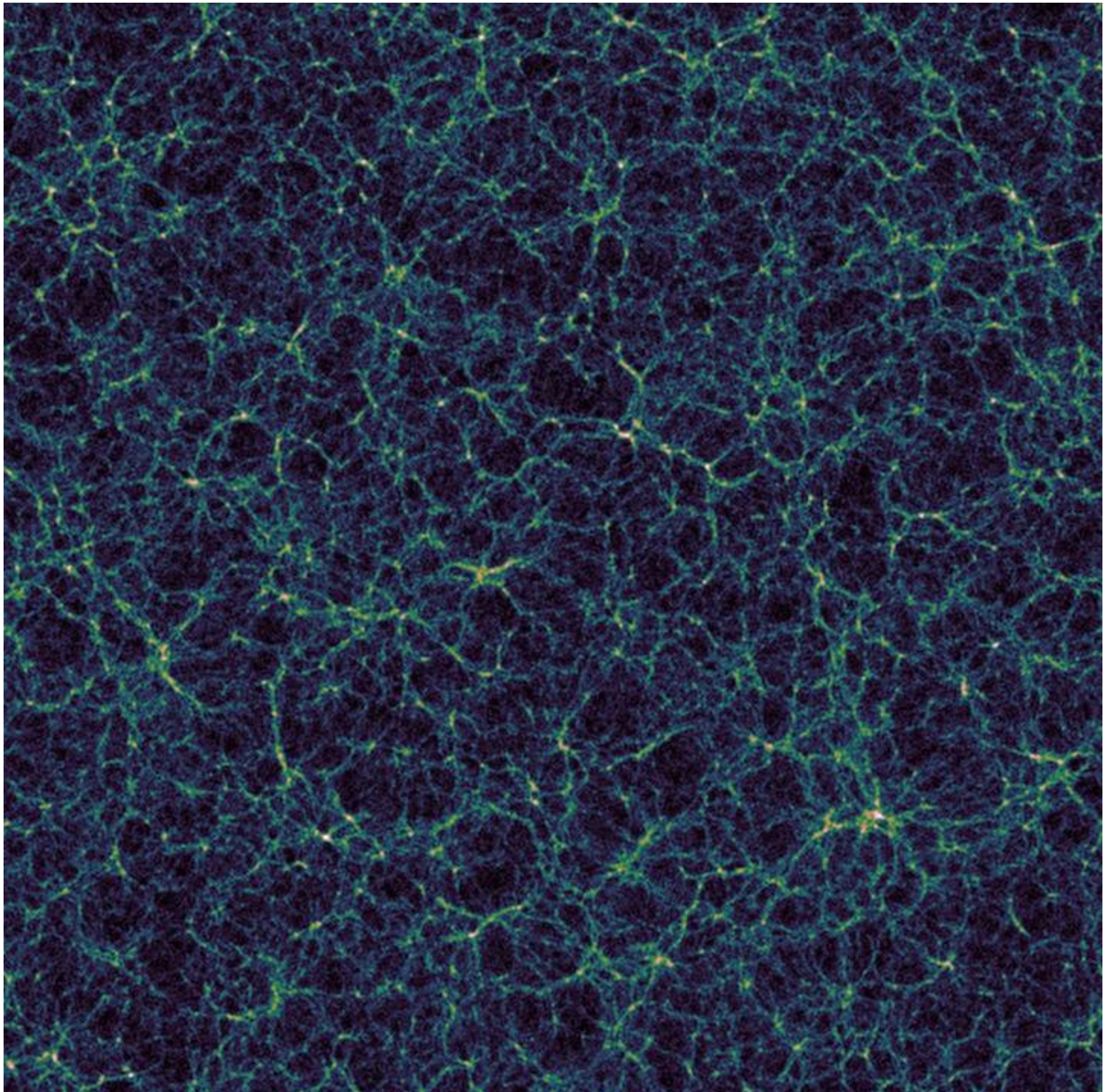
Cosmological Hydro Simulations

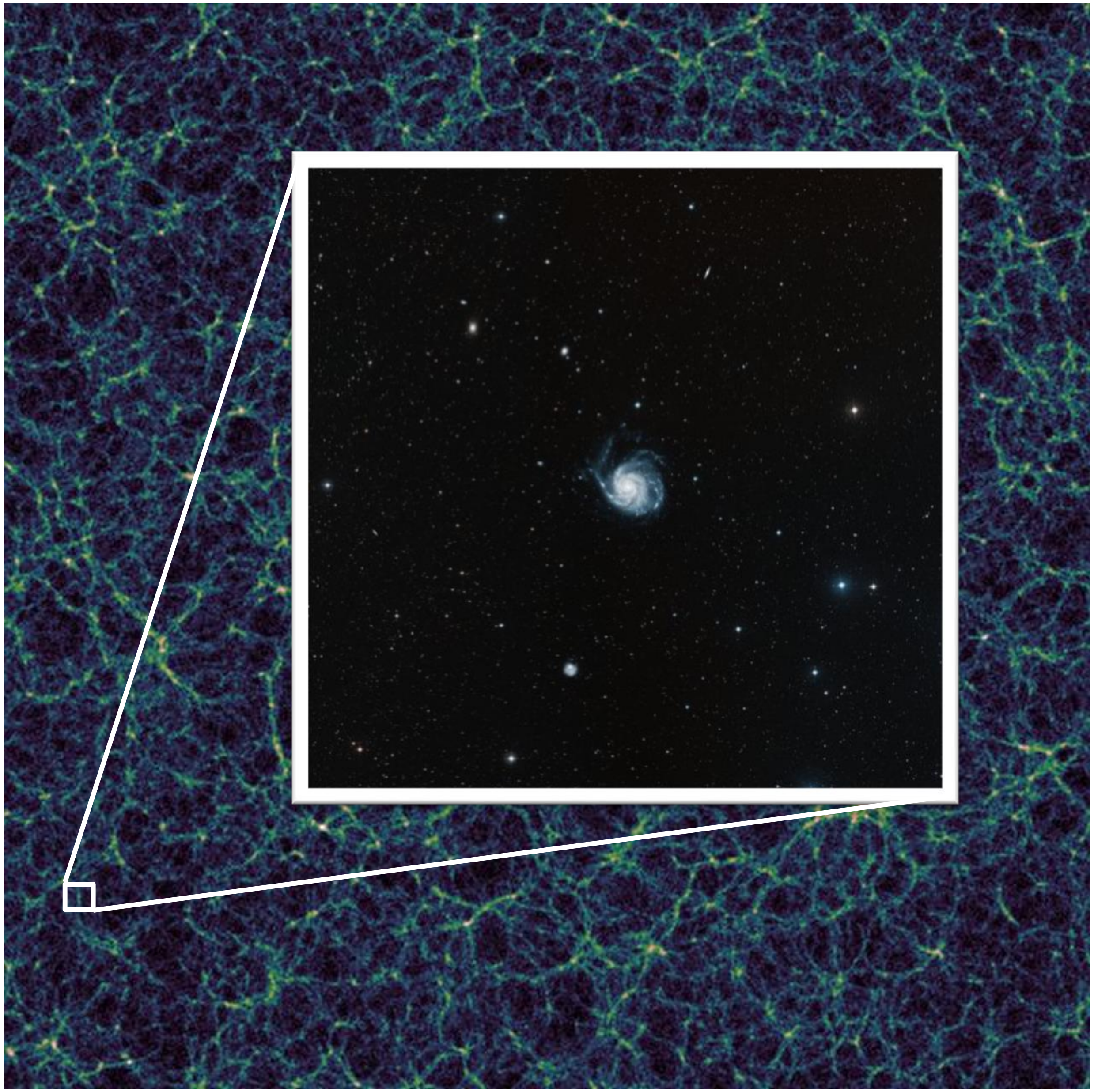
Joop Schaye (Yope Shay), Leiden



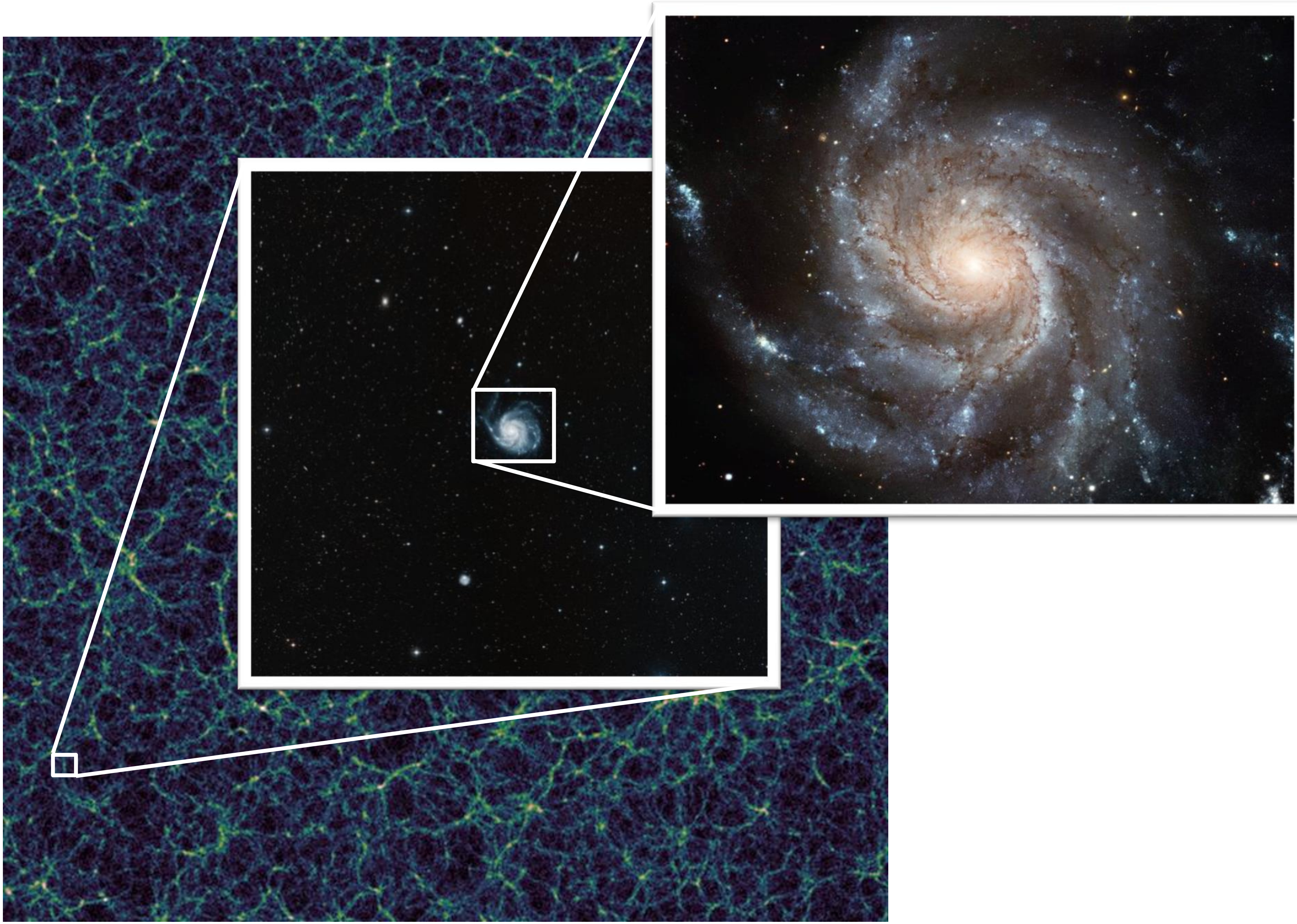
EAGLE 2 Preview



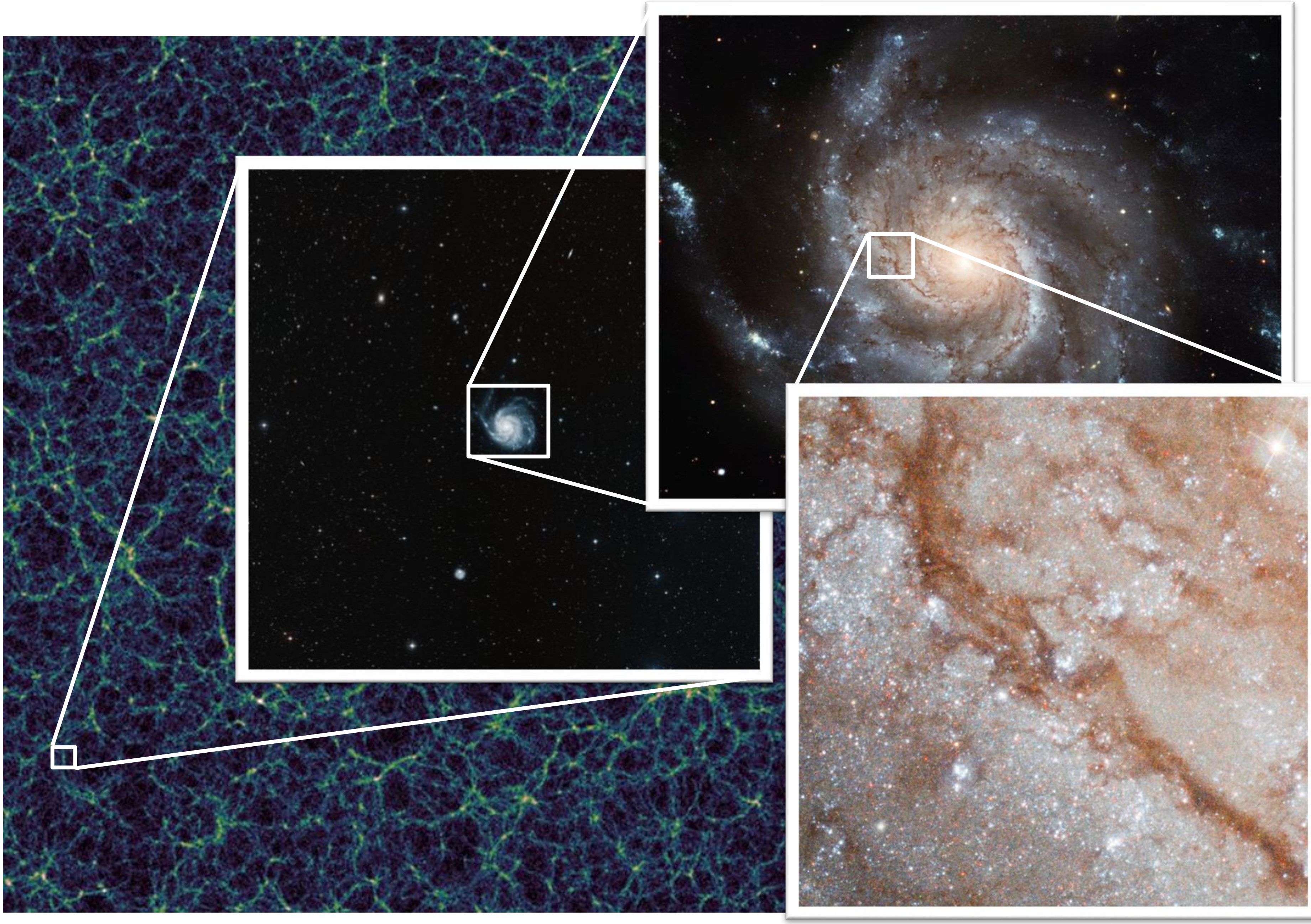
EAGLE 2 Preview



EAGLE 2 Preview



EAGLE 2 Preview



Starting points

- Strong outflows at high redshift are necessary to obtain agreement with a diverse set of observations

- Maximum in stellar fraction – halo mass relation suggests that two types of feedback are needed

- Cosmological simulations cannot resolve the cold ISM.

  → cannot predict the efficiency of feedback
  → cannot predict stellar and black hole masses from first principles

- Calibrated subgrid models required

  → need to compare to relevant observations
  → need to be clear about calibration input

Some implications of the use of (calibrated) subgrid feedback

- Inability to make precise ab initio predictions has consequences for the role of:
  - Accuracy of solvers
  - Numerical convergence
  - Model selection (which simulation should I believe?)
- For our purposes, it is *not* necessarily better to use simulations that:
  - Include more physics
  - Have higher resolution
  - Agree better with *some* observations
- Don’t ask what solver/resolution/physics was used, ask first to see a comparison with the *relevant* observations!

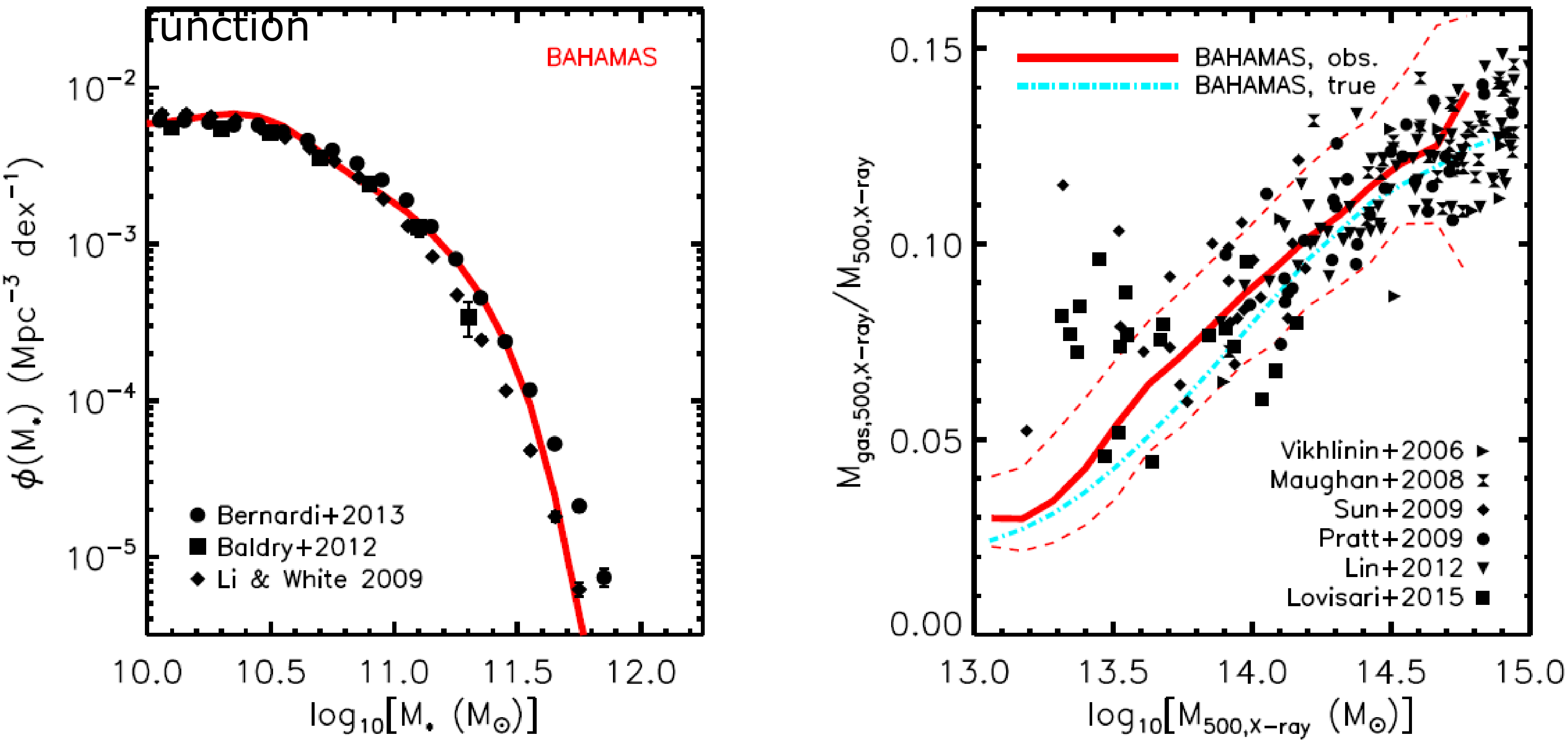
Calibration choices. Examples:

- EAGLE (25-100 Mpc) & BAHAMAS (400 Mpc/h)
  - Kennicut-Schmidt star formation law
  - Evolution of the cosmic SNIa rate density
  - (Stellar mass – black hole mass relation)
  - Galaxy stellar mass function
- EAGLE
  - Galaxy size – mass relation
- BAHAMAS
  - Cluster baryon fraction
- Other groups' choices, particularly 2nd generation simulations, less clear to me

BAHAMAS

Optical:
Galaxy stellar mass function

X-ray:
Cluster gas fraction



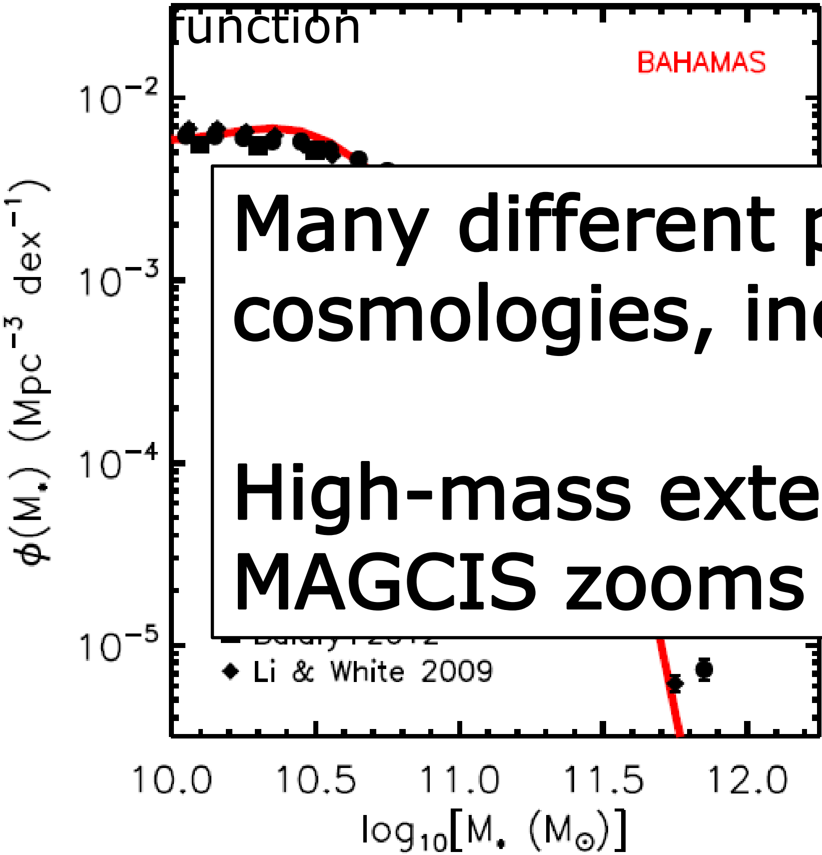
Calibration:
Constant velocity of (fully coupled) kinetic stellar feedback

Calibration:
Temperature jump of AGN thermal feedback events

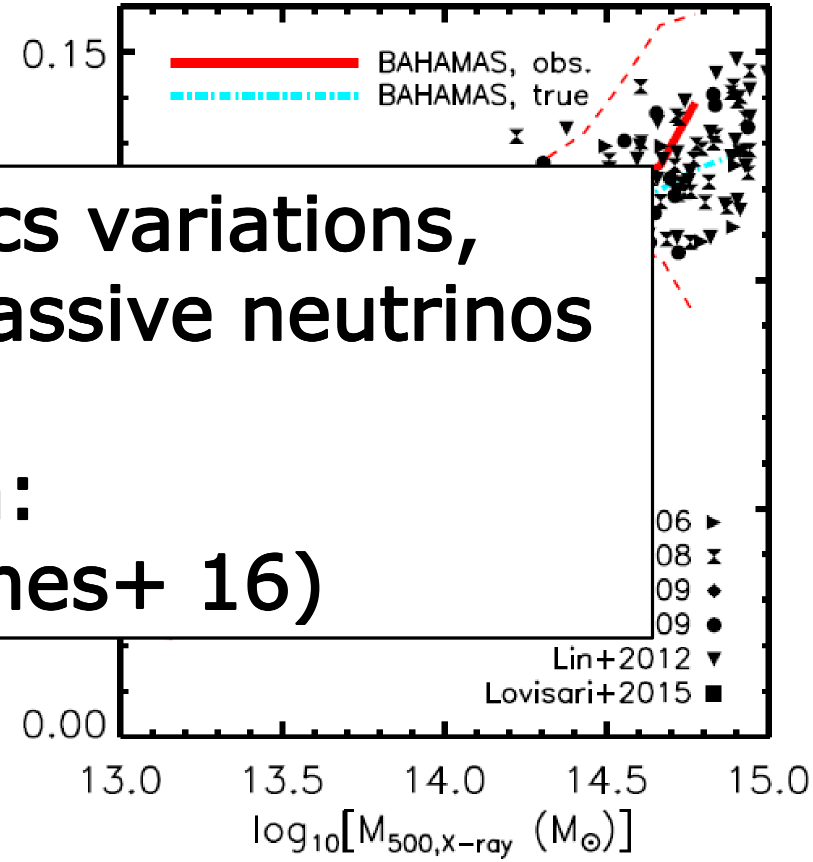
McCarthy, JS, Bird, Le Brun (2016)

BAHAMAS

Optical:
Galaxy stellar mass function



X-ray:
Cluster gas fraction



Many different physics variations, cosmologies, incl. massive neutrinos

High-mass extension:
MAGCIS zooms (Barnes+ 16)

Calibration:
Constant velocity of (fully coupled) kinetic stellar feedback

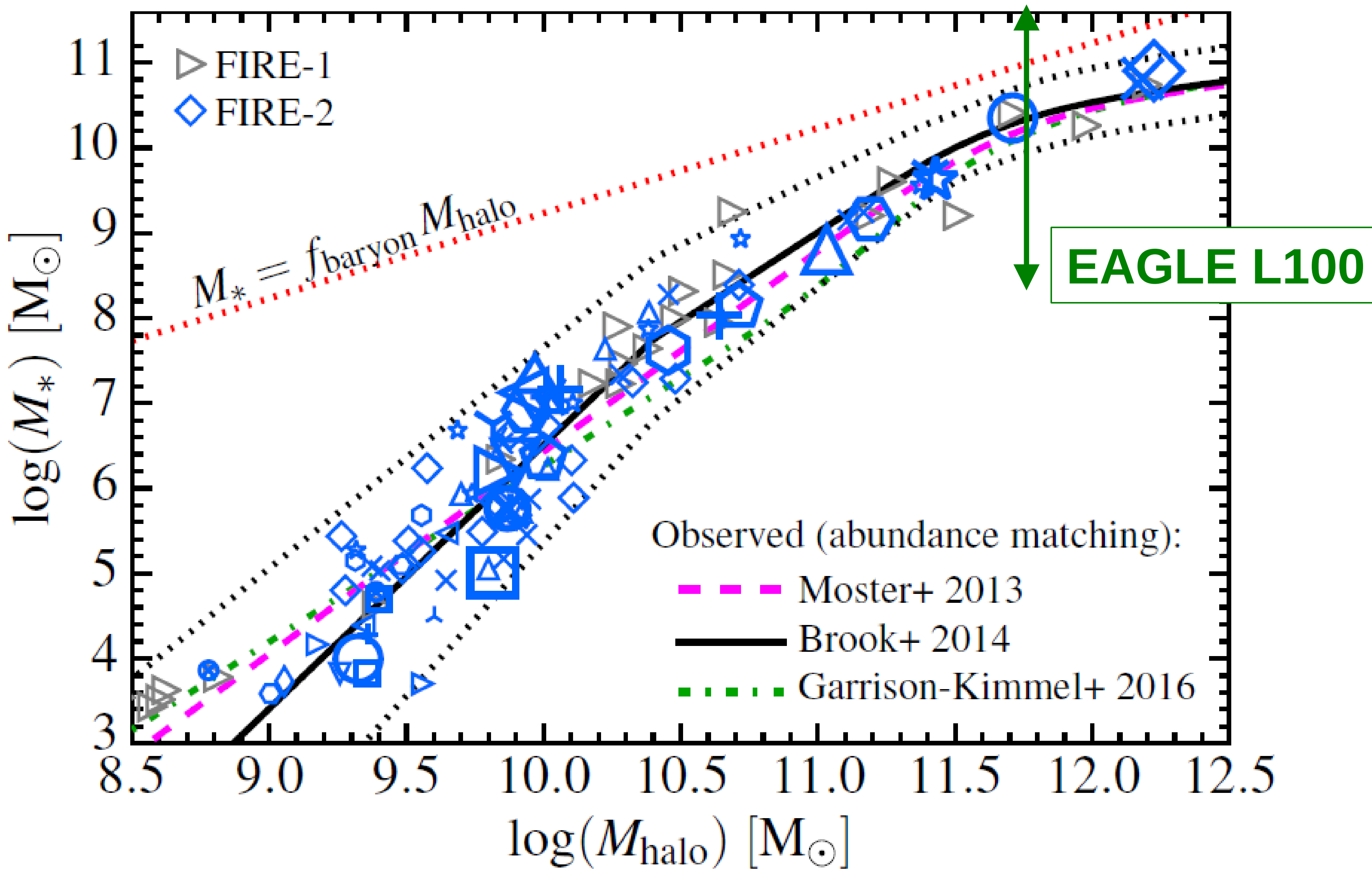
Calibration:
Temperature jump of AGN thermal feedback events

McCarthy, JS, Bird, Le Brun (2016)

Complementary approaches

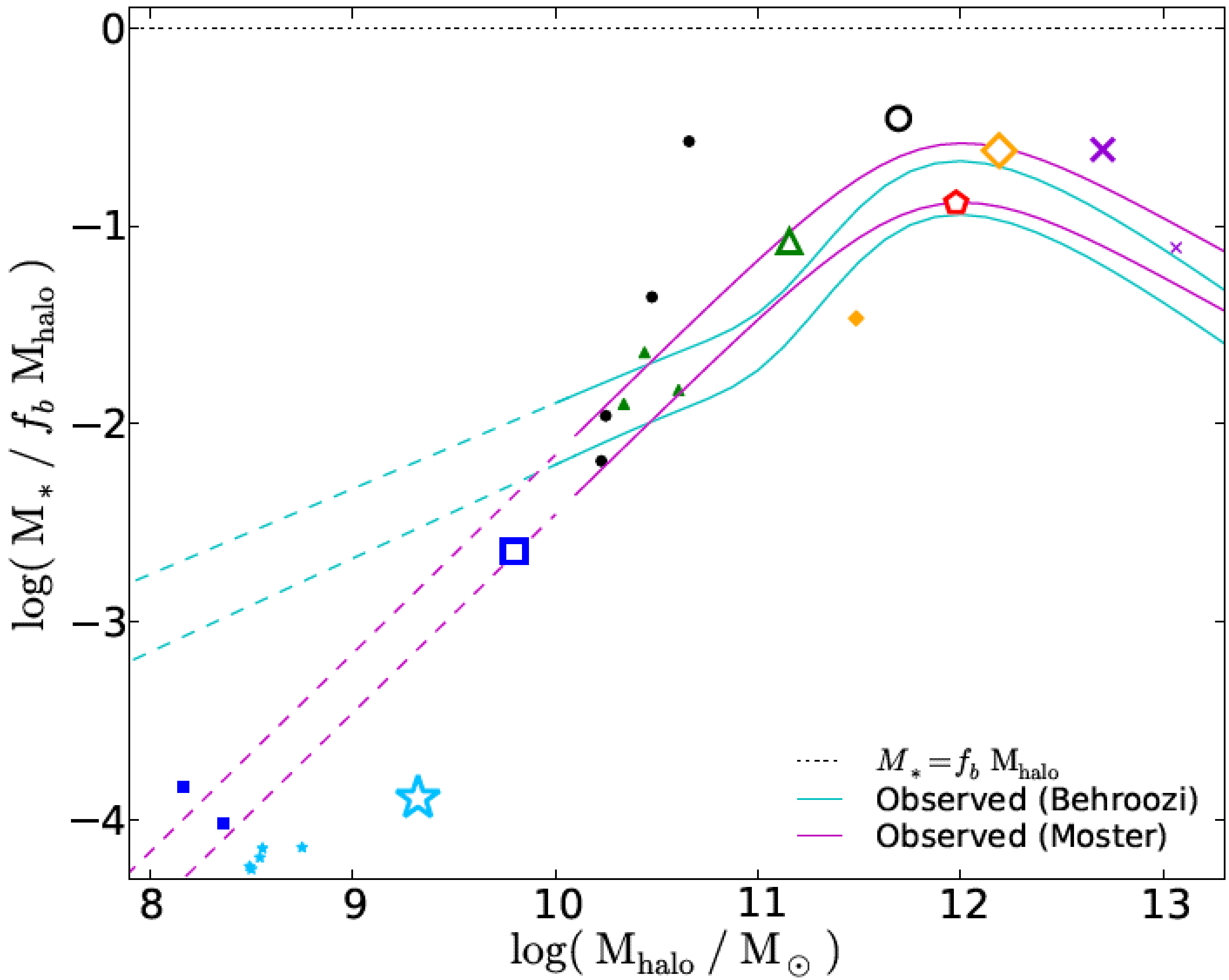
- Sets of zooms of haloes where resolution decreases with halo mass (e.g. FIRE, NIHAO)
  - Maximizes the range of halo masses
  - Maximizes the resolution at each mass scale
- Volumes of ~ 10^2 Mpc at a fixed maximum resolution (e.g. Illustris, EAGLE, Horizon, Massiveblack, Mufasa)
  - No confusion between trends due to resolution and mass scale
  - Large numbers of objects
  - Representative range of environments
  - Easy to compare with observations
  - Intergalactic medium also included

The efficiency of galaxy formation



FIRE-2 (Hopkins et al. 2017)

The efficiency of galaxy formation



FIRE (Hopkins et al. 2014)

Caricature of the differences

- Sets of zooms of haloes where resolution decreases with halo mass
  - Resolved feedback
  - No free parameters
  - High predictive power
- Volumes of ~ 10^2 Mpc at a fixed maximum resolution
  - Unresolved feedback
  - Fine-tuned subgrid parameters
  - Low predictive power

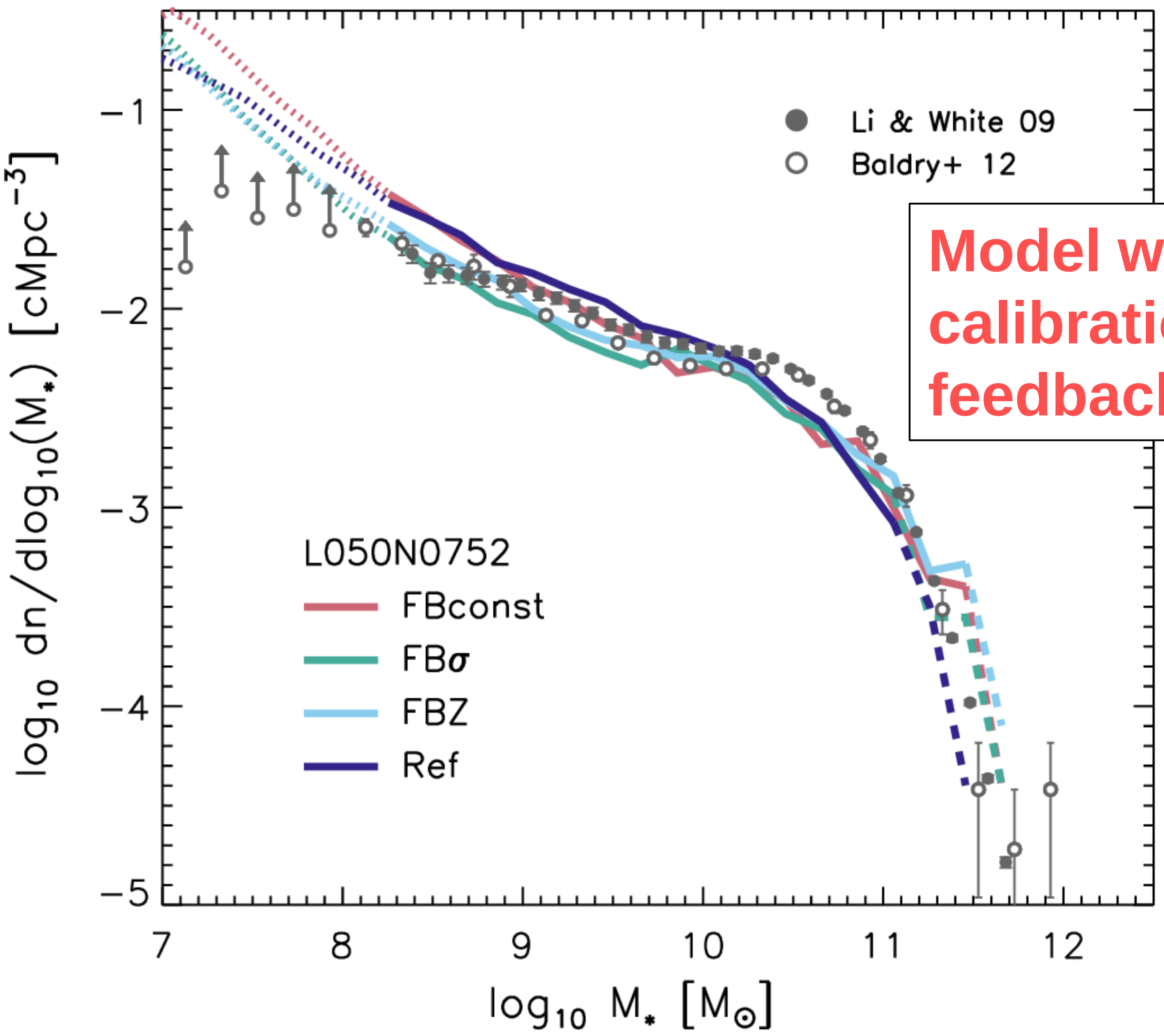
Resolved feedback?

- State-of-the-art zooms can resolve the *onset* of the cold ISM for $M_{200} < 10^{10}\ M_\odot$, i.e. $M_* < 10^7\ M_\odot$
- Cannot *accurately* predict efficiency of feedback w/o resolving at least the onset of the cold ISM
- Subgrid prescriptions for winds remain required
  - Implementation typically at least as important as resolution
  - Overcooling not necessarily solved by large increases in resolution
- Important physics still not included (e.g. RT)
- Predictive power requires numerical convergence, but this has not been demonstrated (a factor of 2 is not okay)

My two cents

- Resolved feedback w/o free parameters is obviously the goal, but we are not there yet
- Success of higher-resolution dwarf galaxies (e.g. star formation law) does not imply lower-resolution intermediate-mass galaxies use correct small-scale physics
- Different resolution simulations cannot be considered to be the same model
- Modifying the subgrid physics (as opposed to parameters) between simulation generations constitutes calibration
- Large-volume simulations can be more thoroughly tested against observations
- Large-volume runs require only modest calibration and only when we require a good match to population statistics

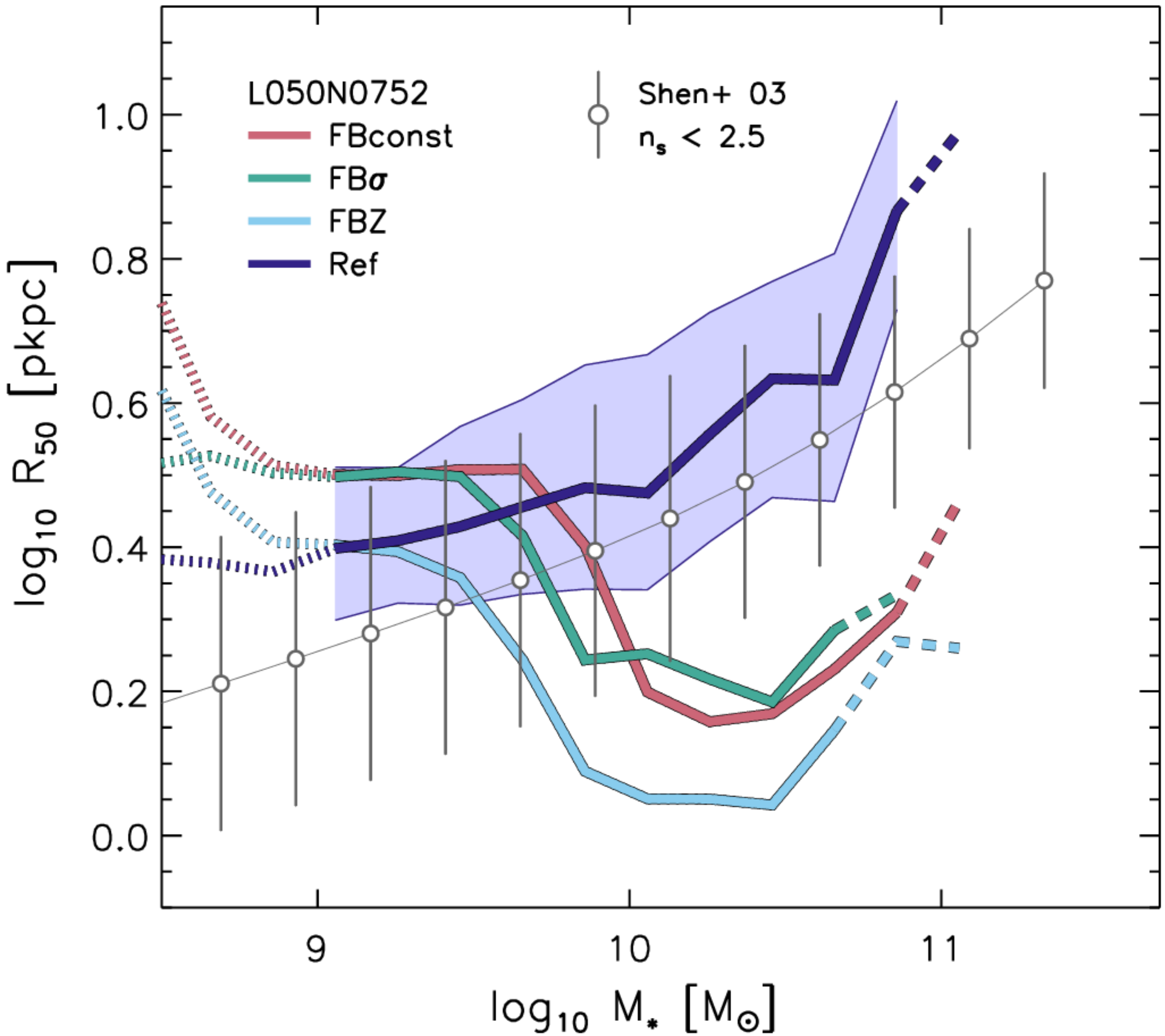
Many ways to fit the mass function



Model without calibration of stellar feedback

Crain, JS et al. (2015)

Sizes

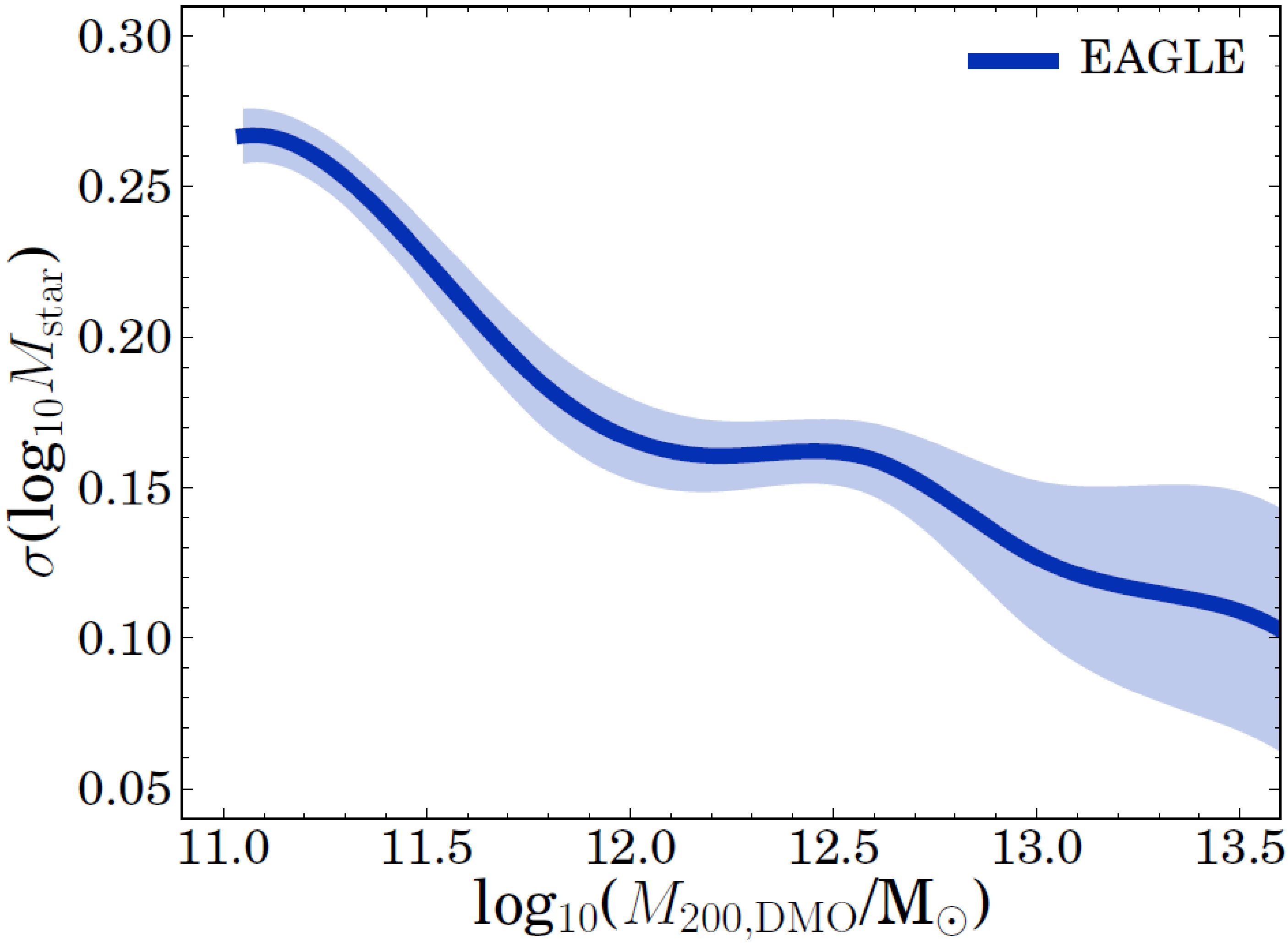


Crain, JS et al. (2015)

Will DM only simulations remain useful?

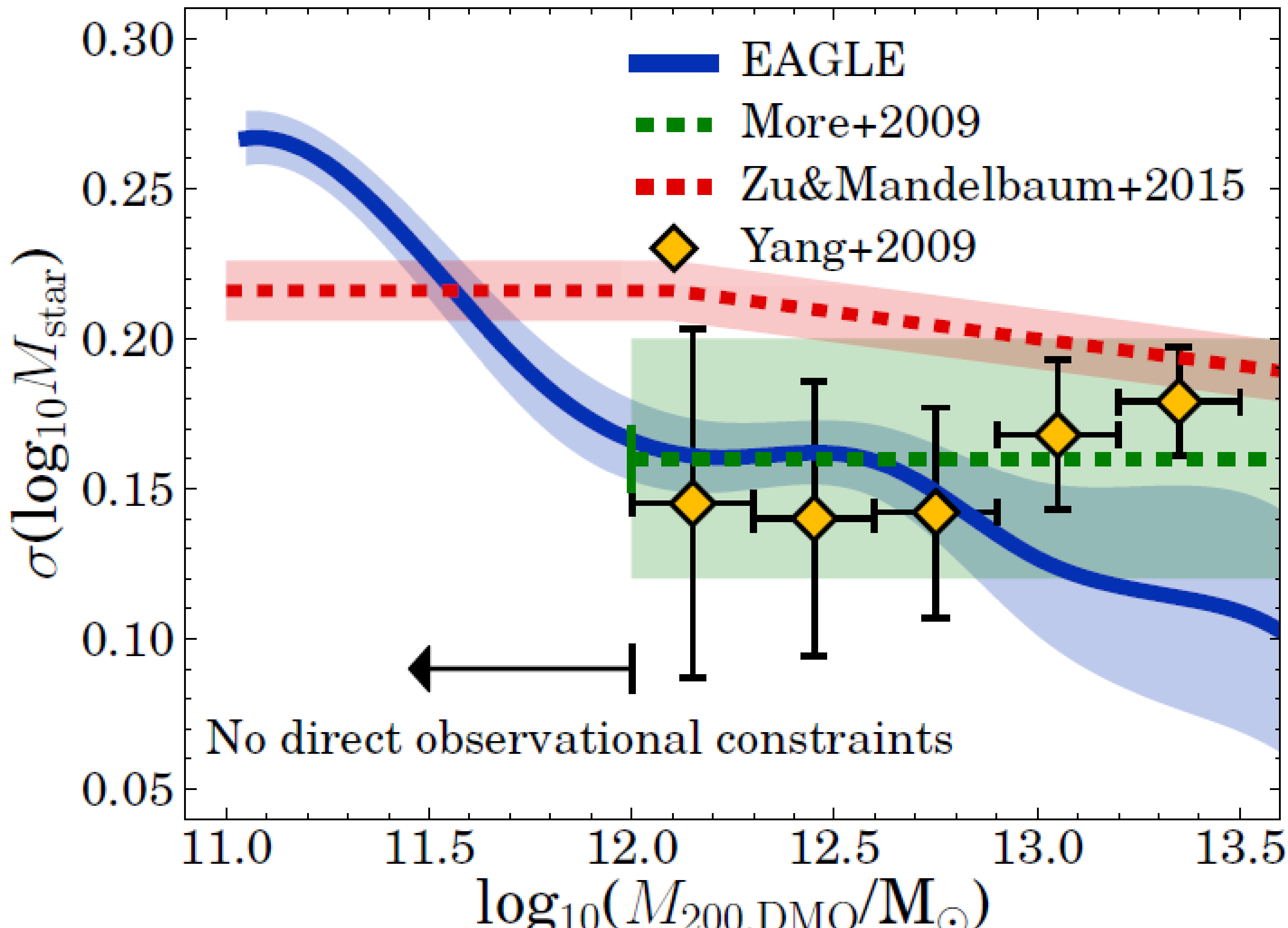
- Cons:
  - Baryonic effects exceed the uncertainties on many DMO, empirical, semi-analytic predictions
  - Even the back reaction on the DM is significant
- Pros:
  - Inner DM haloes correlate better with galaxy properties (e.g. shapes, spins, alignments)
  - Halo number densities unaffected (but masses and satellite number densities are)
  - Large-scale (>> R_{vir}) clustering of subhalos as a function of number density unaffected (but large-scale matter correlations are)
  - ICs captured. Differences in galaxy properties should be traceable to differences in DMO properties unless galaxy formation is truly stochastic

Scatter in $M_*(M_{halo,DMO})$



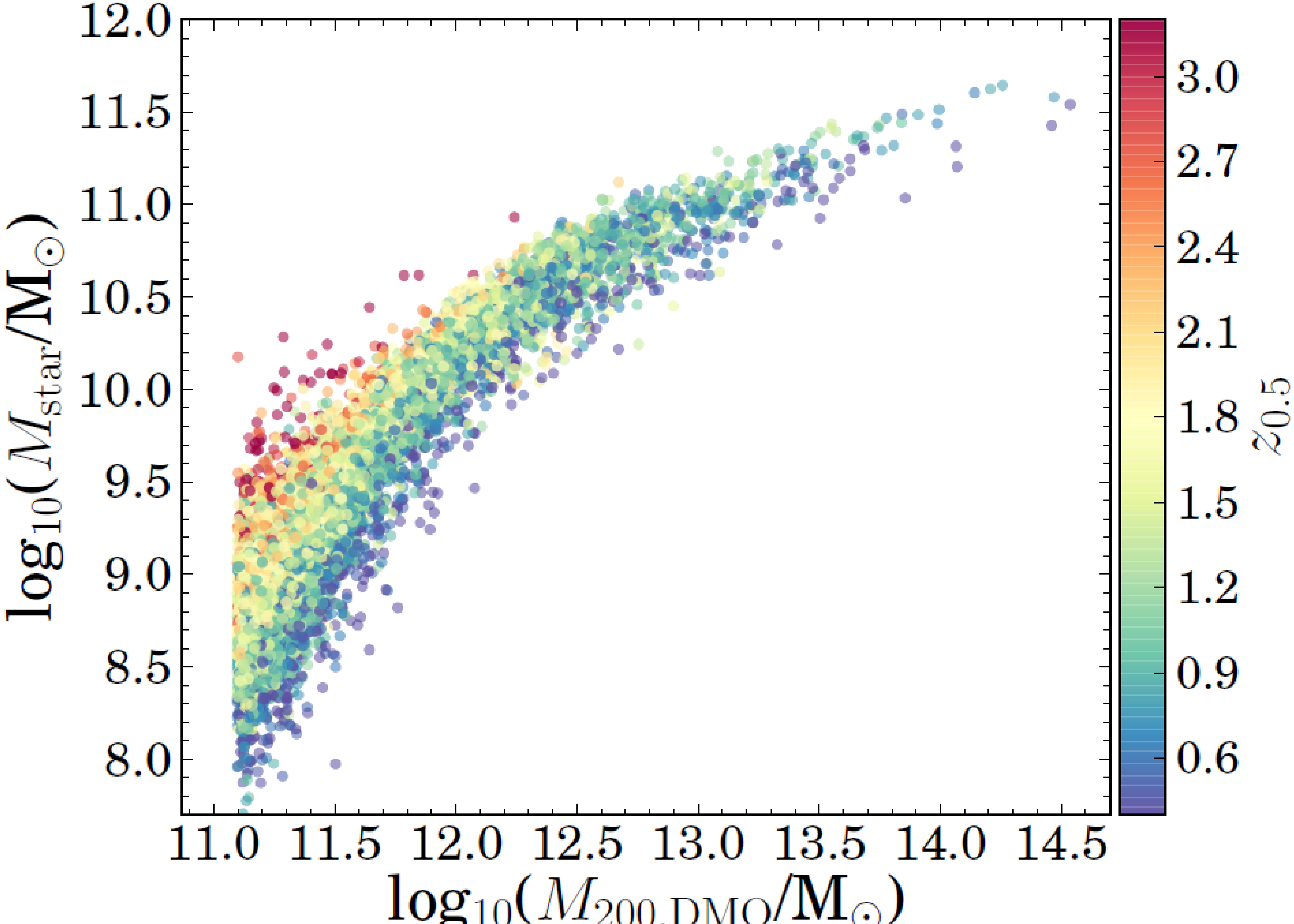
Matthee, JS+ (2016)

Scatter in $M_*(M_{halo,DMO})$



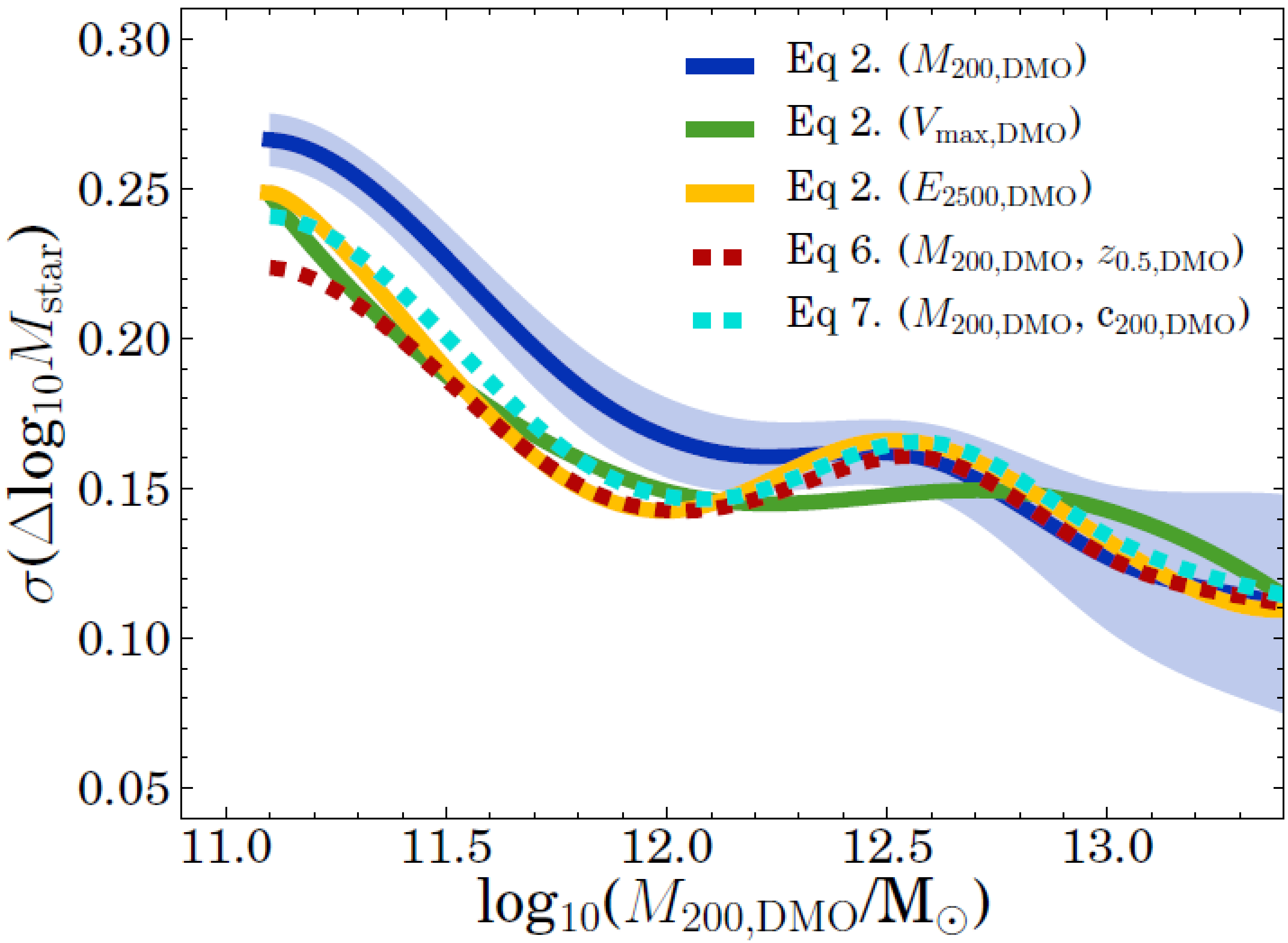
Matthee, JS+ (2016)

Scatter in $M_*(M_{halo,DMO})$: Effect of formation time



Matthee, JS+ (2016)

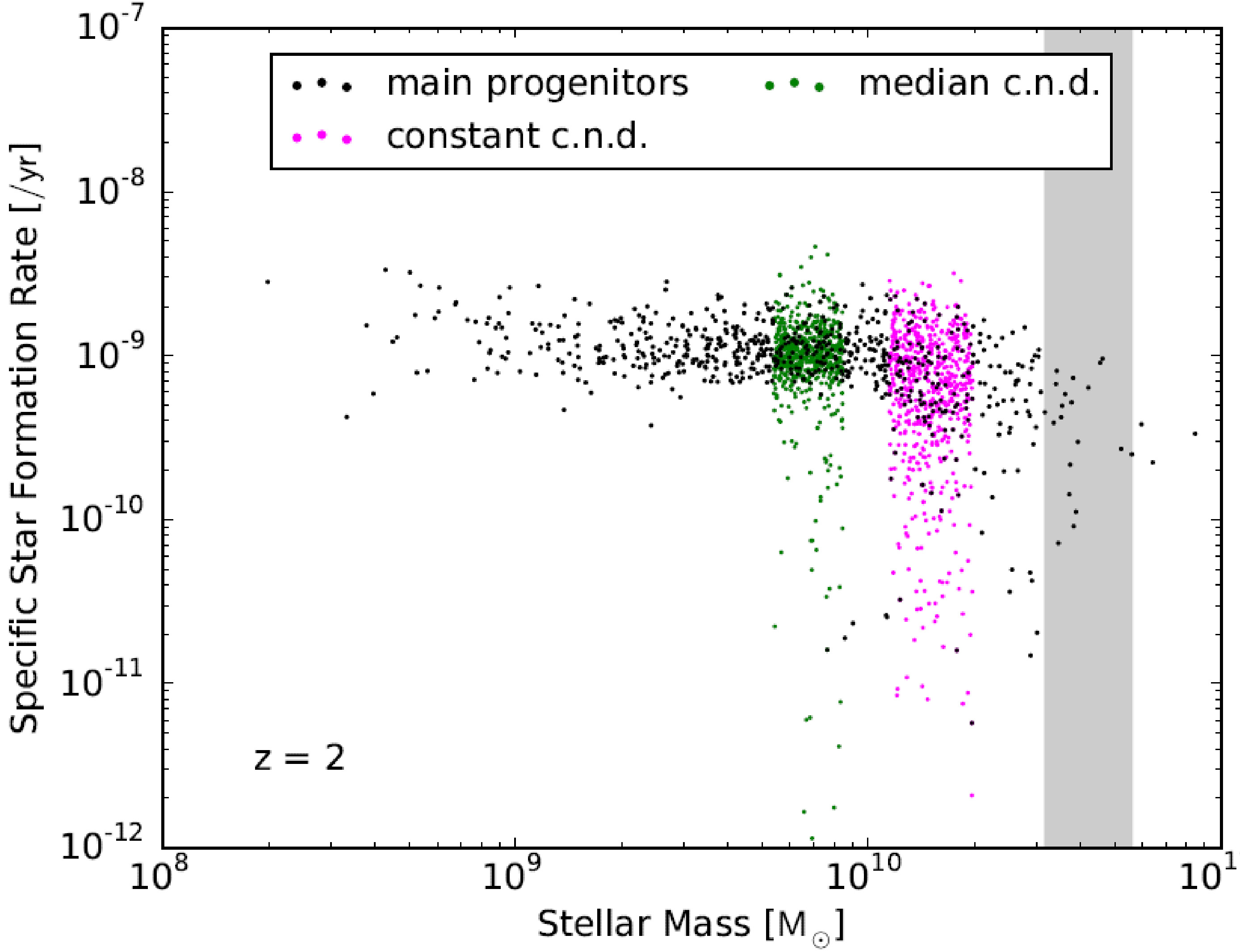
Scatter in $M_*(M_{halo,DMO})$



Most of the scatter still unaccounted for by DM only simulations

Matthee, JS+ (2016)

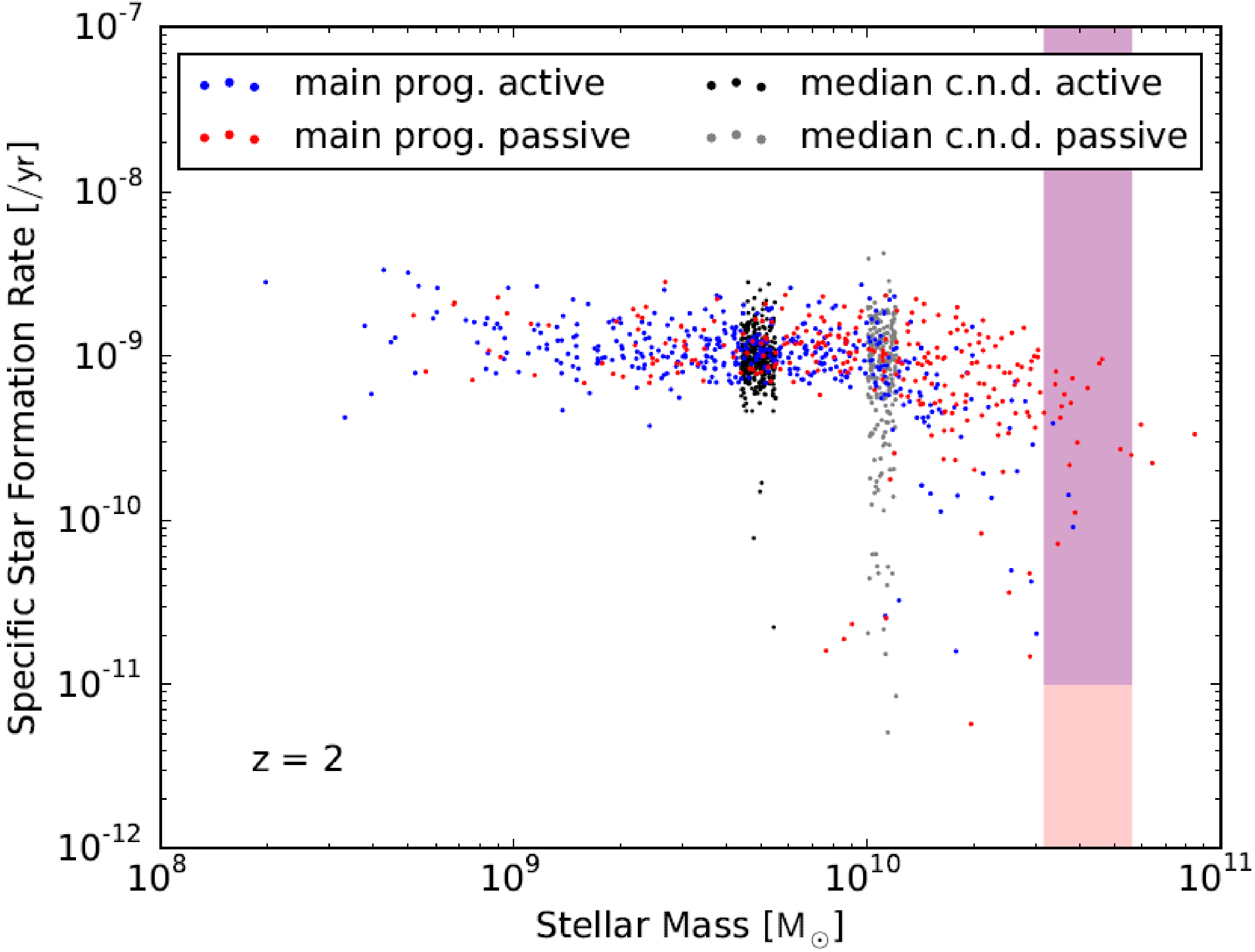
Linking to z=2 progenitors through cumulative number density matching



Scatter is large

Clauwens, JS & Franx (2016b)
(see also Wellons & Torrey 17)

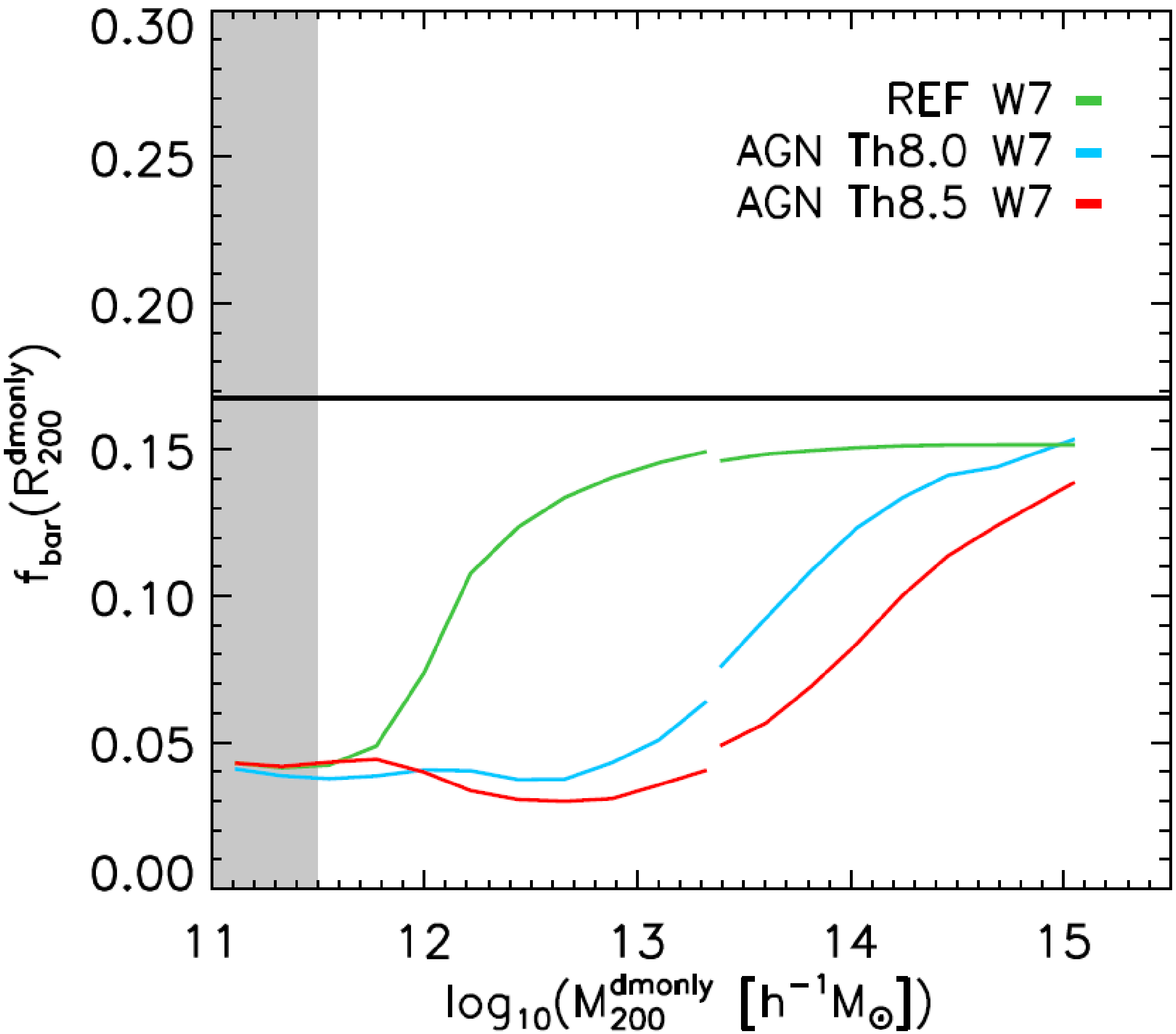
Linking to z=2 progenitors through cumulative number density matching



Systematic dependence on secondary parameters (sSFR)

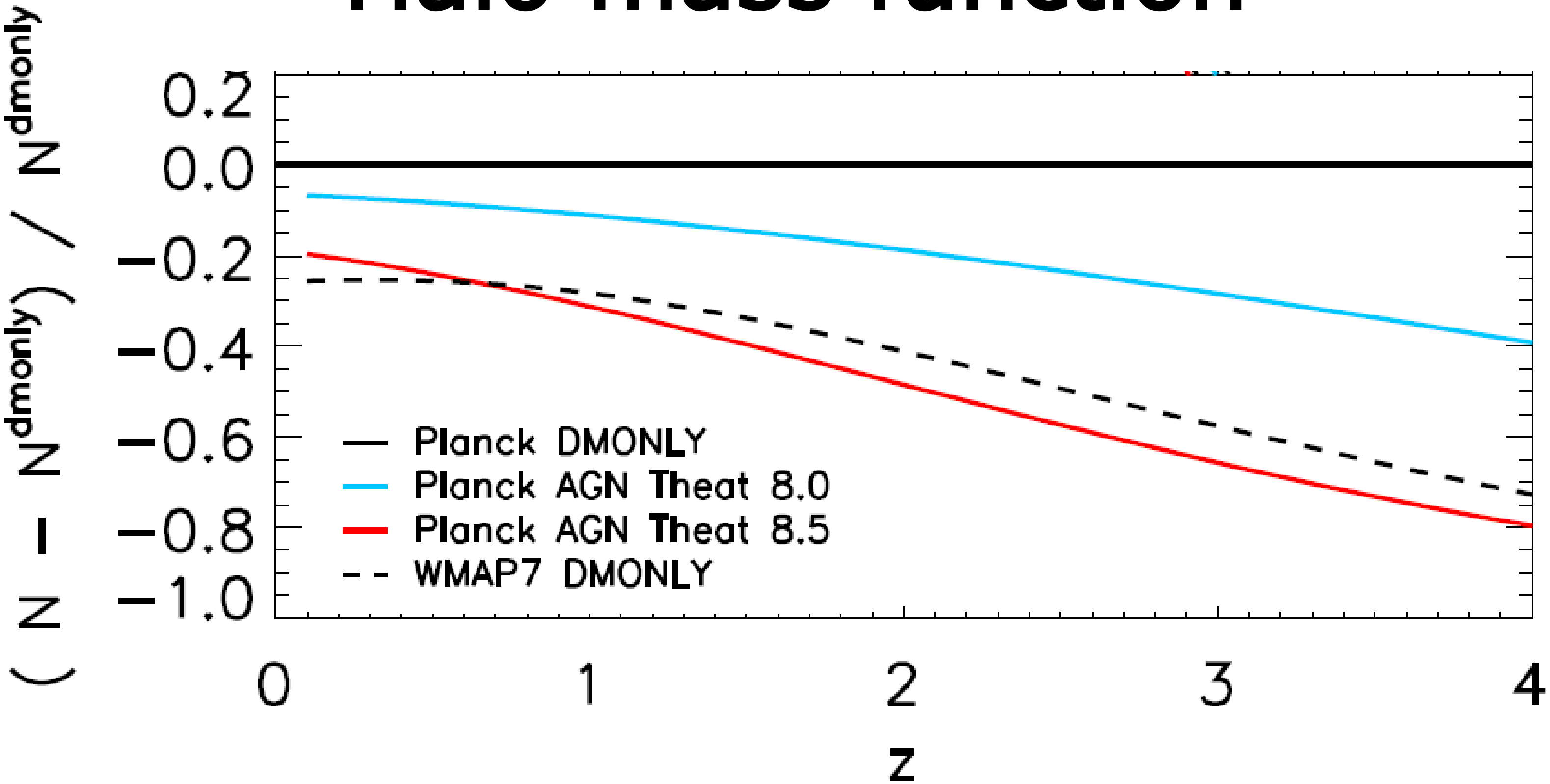
Clauwens, JS & Franx (2016b)

Halo baryon fractions: Cosmo-OWLS



Velliscig, van Daalen, JS+ (2014)

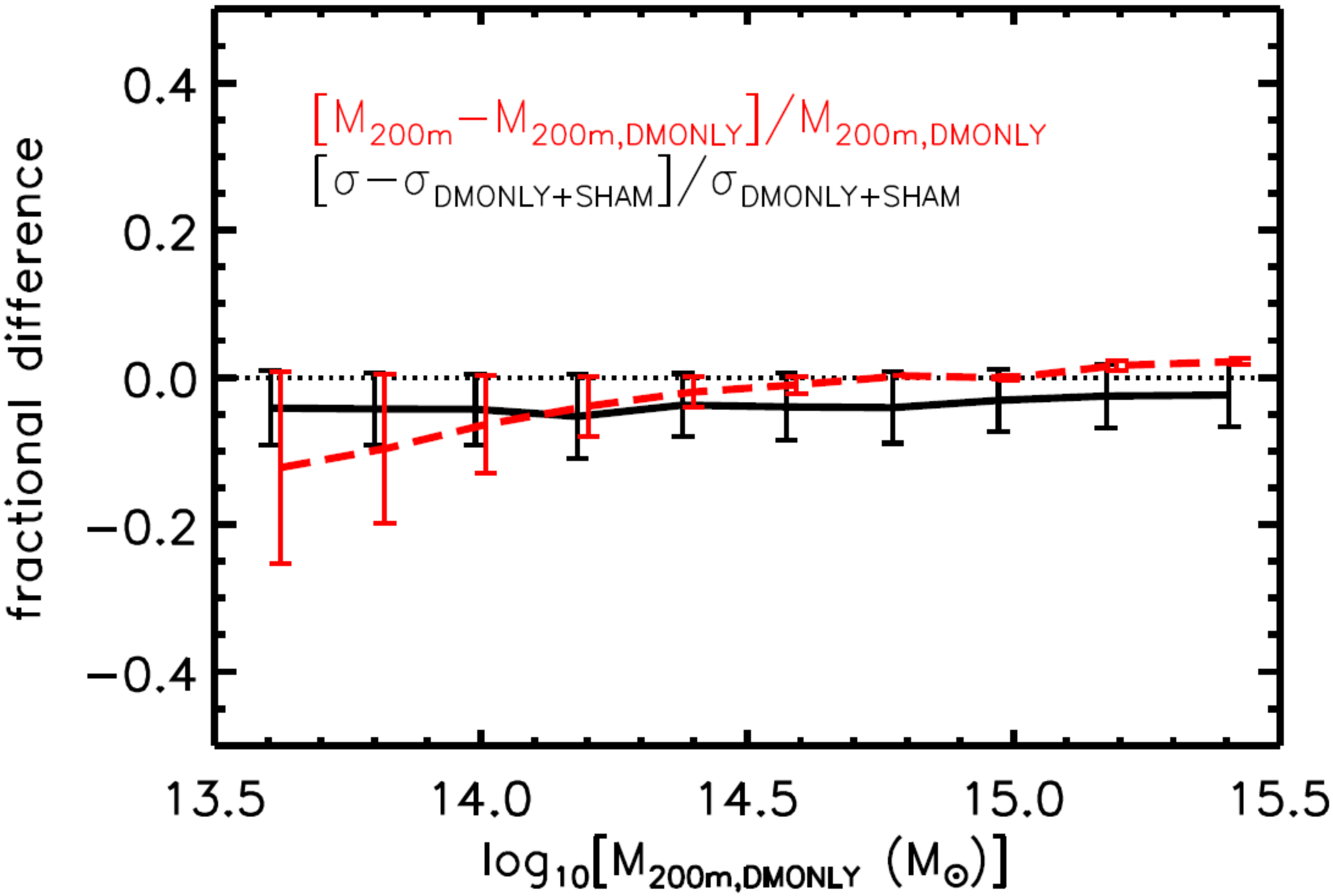
Halo mass function



Feedback changes total halo masses.
Problem cannot be solved by calibrating on true (e.g. lensing) masses.

Velliscig, van Daalen, JS+ (2014)
See e.g. also Cui+ 12; Cusworth+ 14; Martizzi+ 14

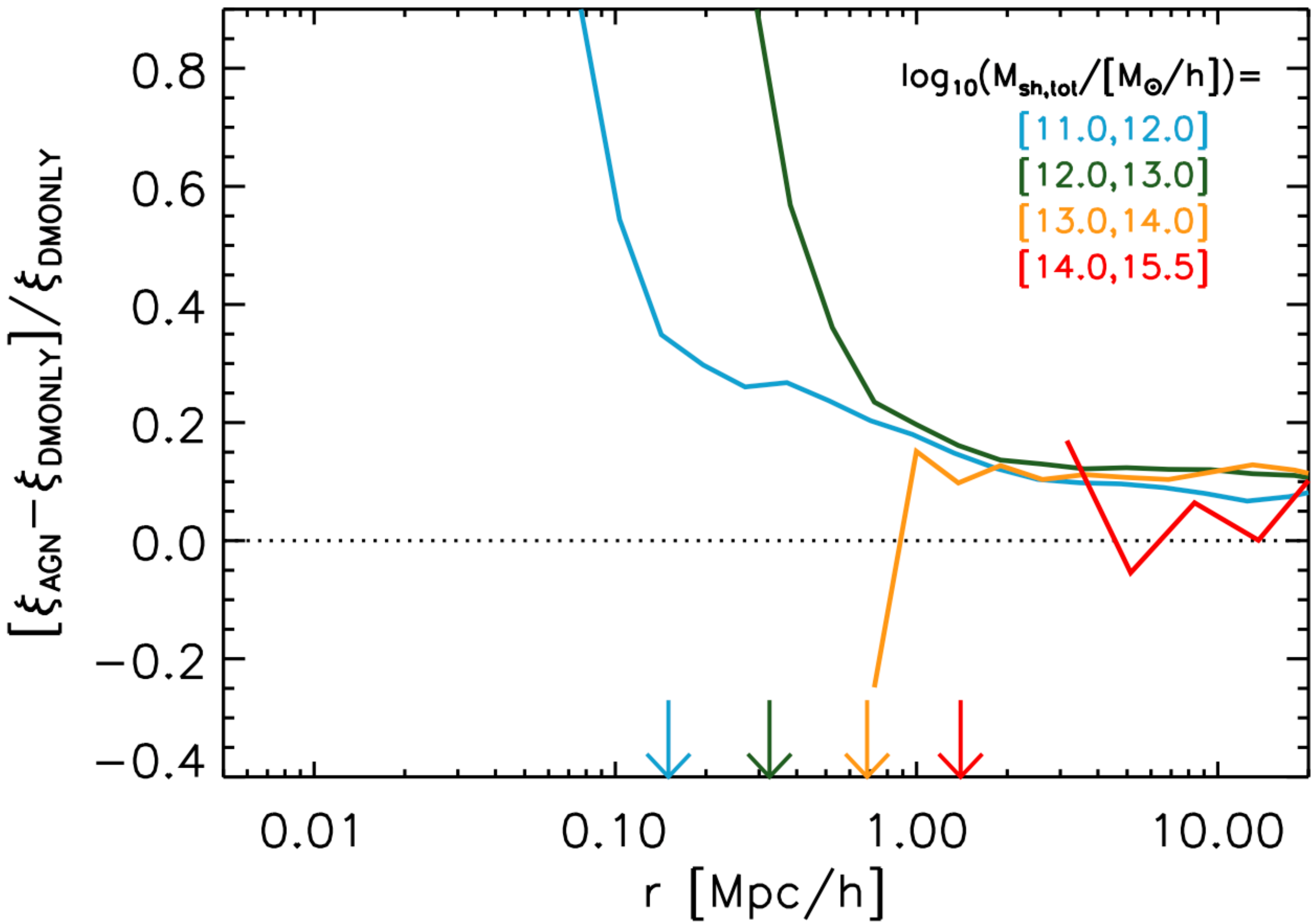
Halo velocity dispersion function



Galaxy velocity dispersion biased low

Caldwell+ 16

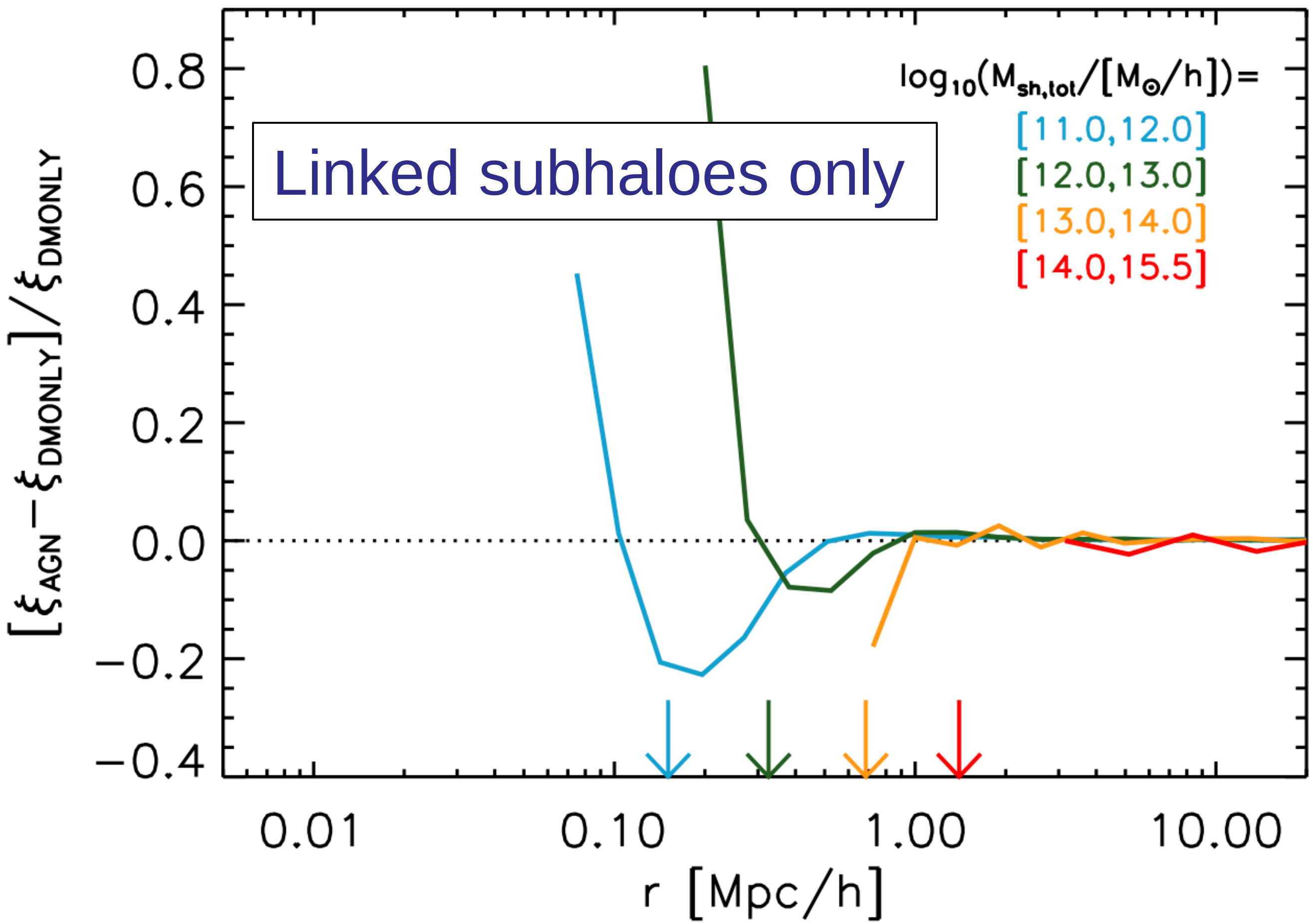
Subhalo autocorrelation: AGN vs DMONLY



Feedback changes large-scale clustering at fixed subhalo mass

Van Daalen, JS+ (2014)

Subhalo autocorrelation: AGN vs DMONLY

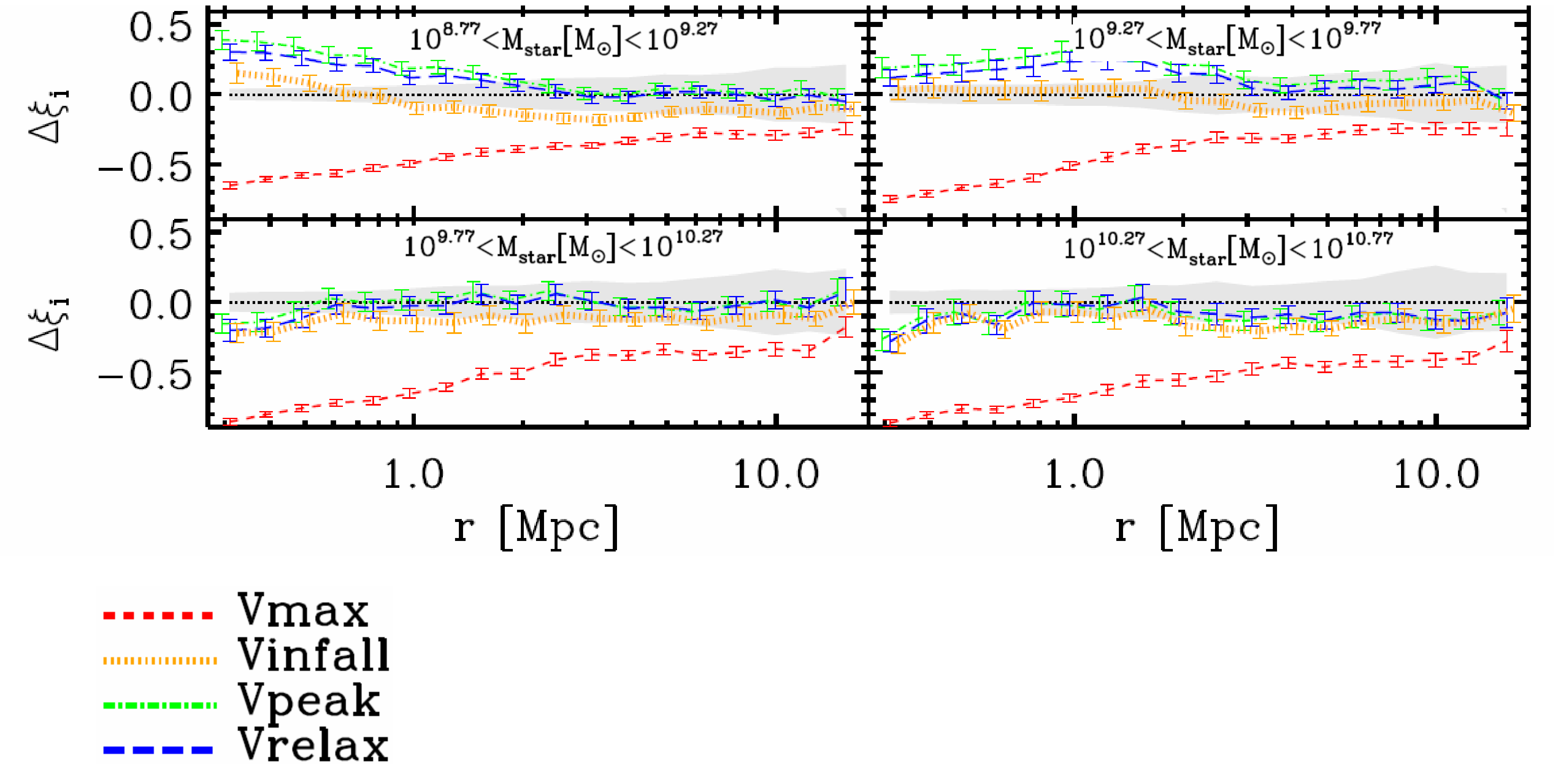


Feedback does not change *large-scale* clustering of a fixed set of subhalos

Scales < 1 Mpc/h are affected

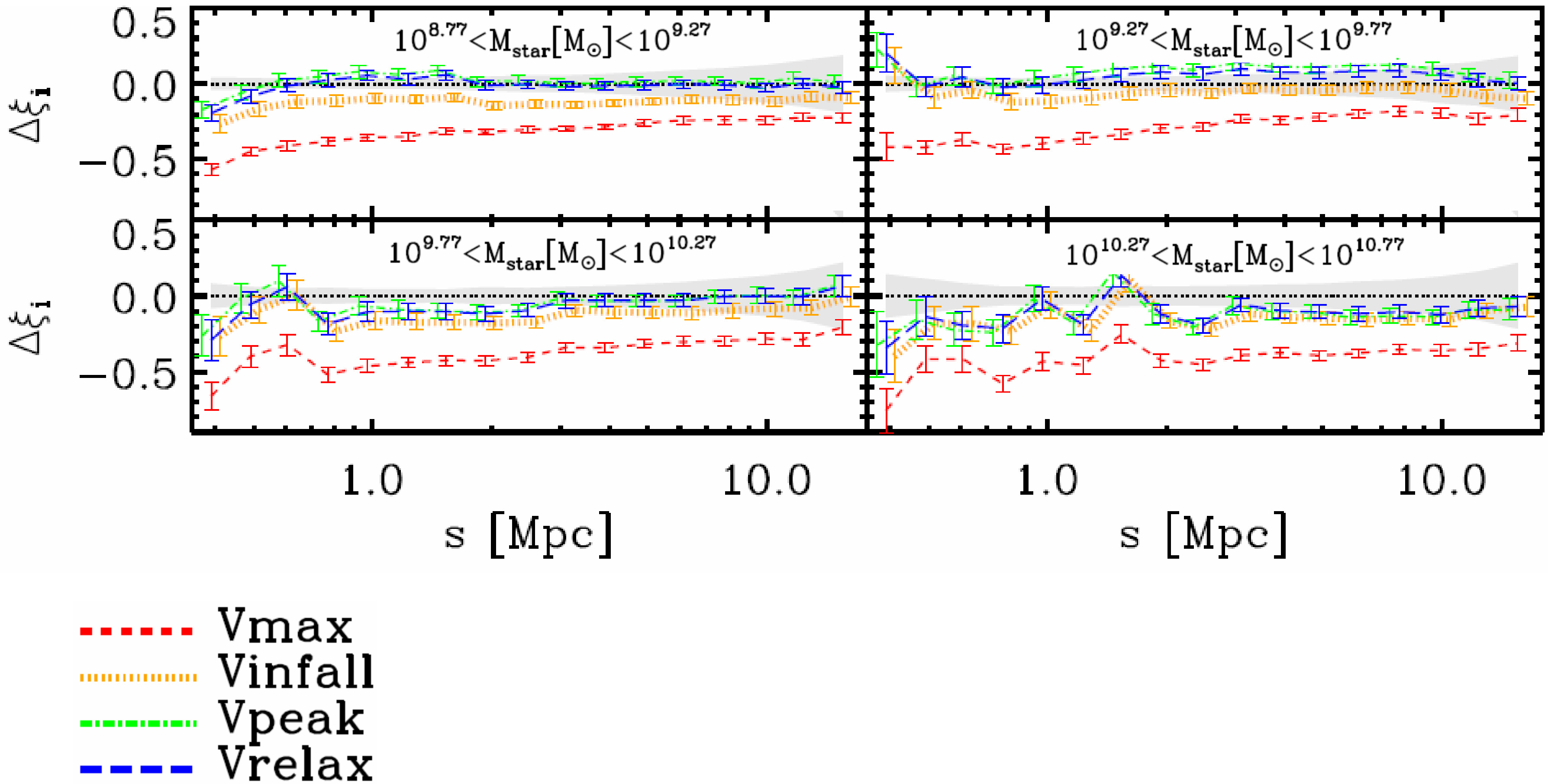
Van Daalen, JS+ (2014)

Real space clustering using SHAM: relative error



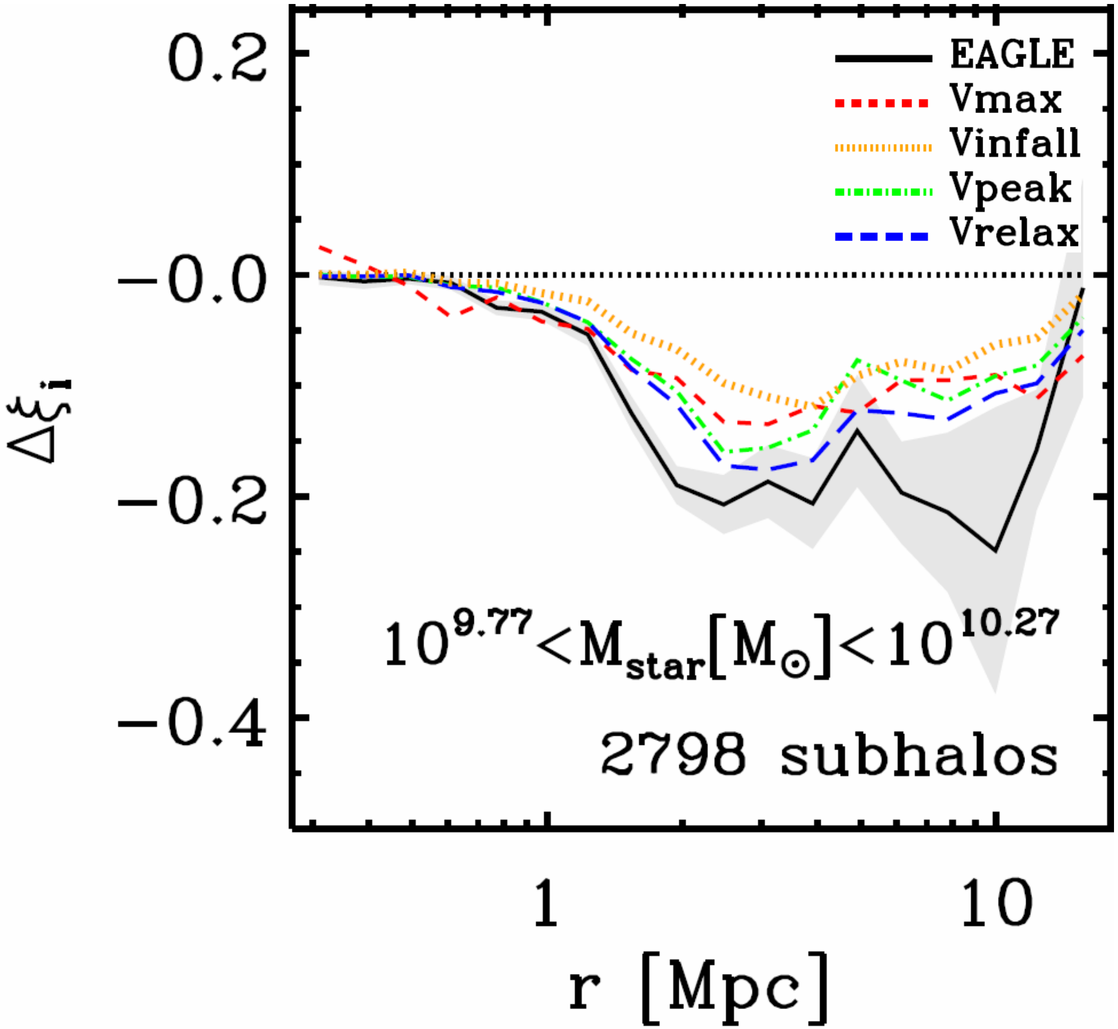
Chavez-Montero, Angulo, JS+ (2015)

Redshift space clustering using SHAM: relative error



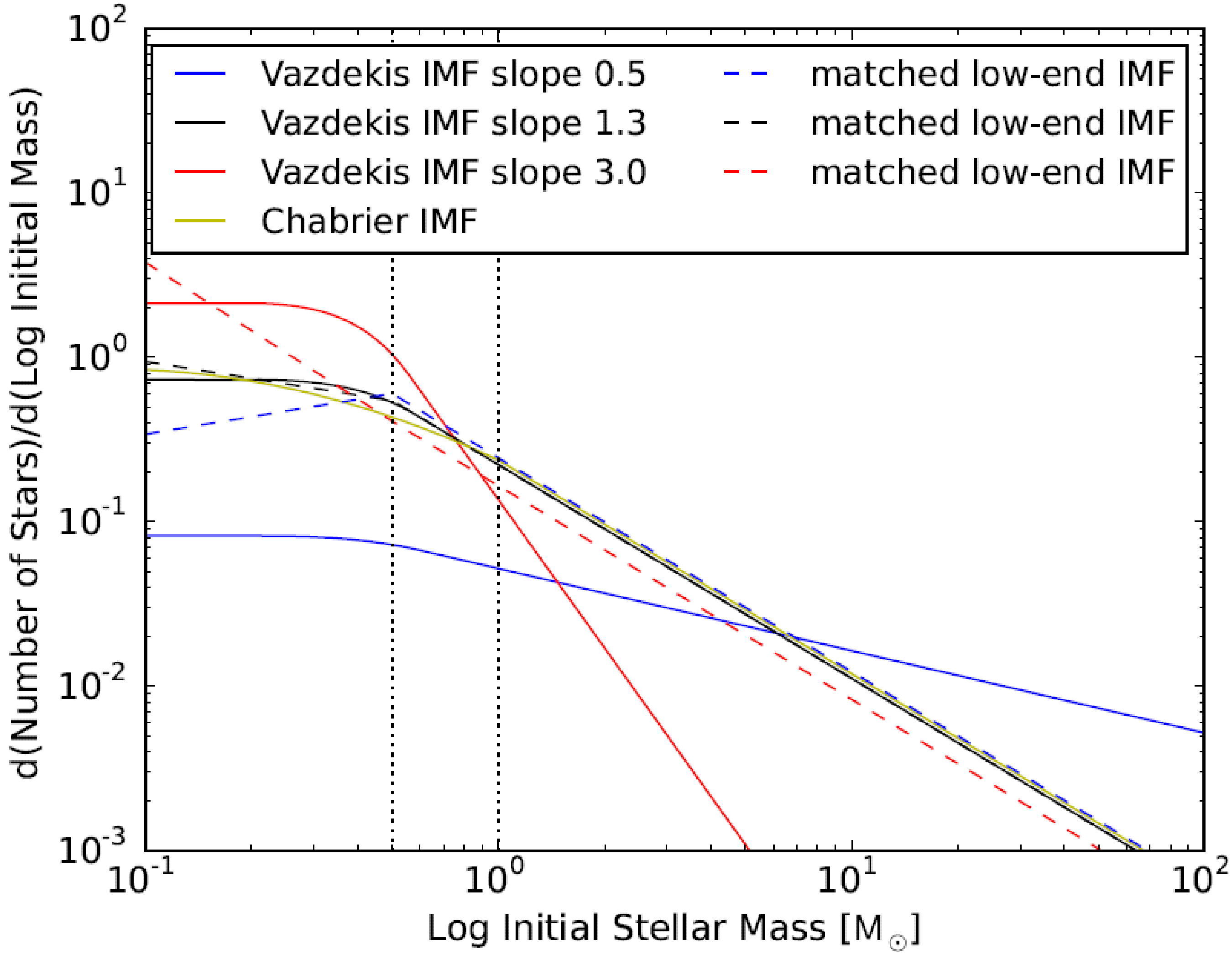
Chavez-Montero, Angulo, JS+ (2015)

Assembly bias: Effect of reshuffling haloes



Chavez-Montero, Angulo, JS+ (2015)

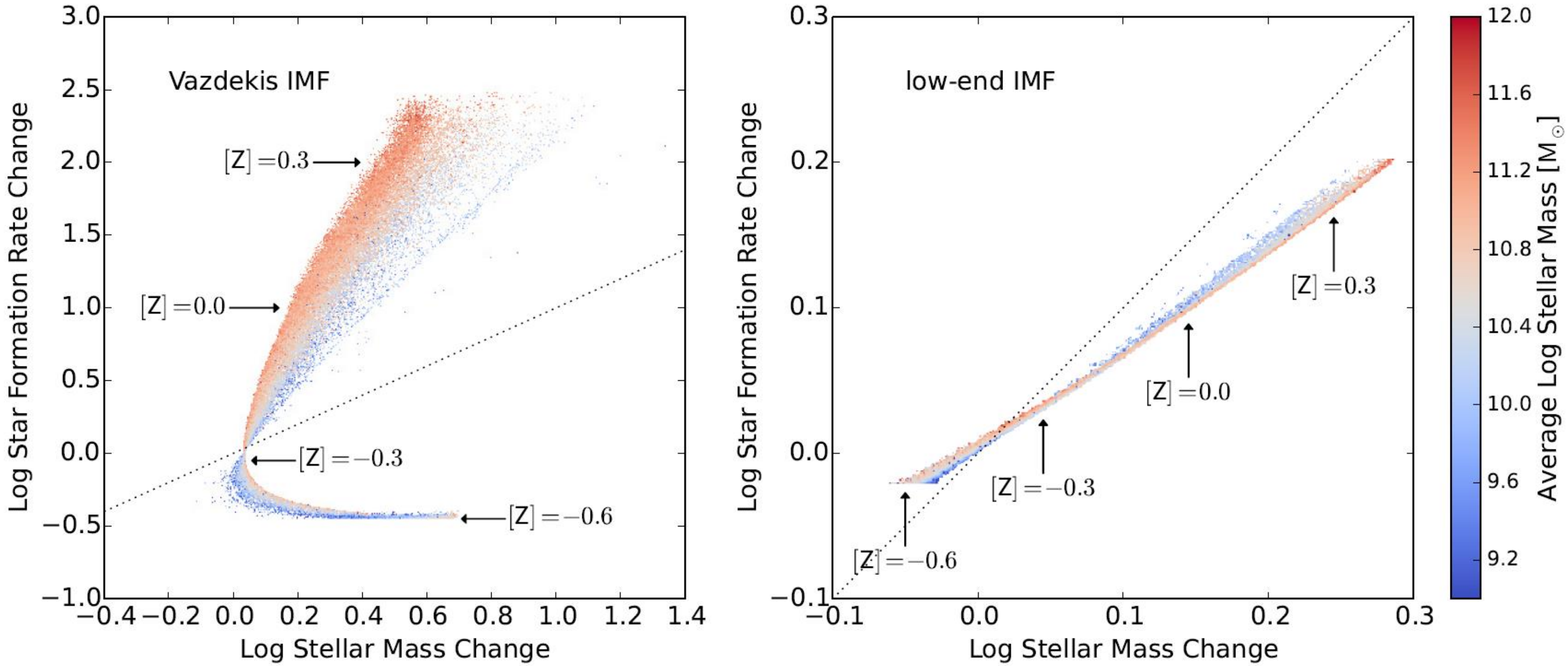
A metallicity-dependent IMF (Martin-Navarro+ 15)



[Z/H] = -0.55, -0.29, +0.26

Clauwens, JS & Franx (2016a)

A metallicity-dependent IMF (Martin-Navarro+ 15)



Observations indicate the IMF is variable.
This could profoundly change the galaxy-halo connection.

Clauwens, JS & Franx (2016a)