Simulating the formation of galaxies

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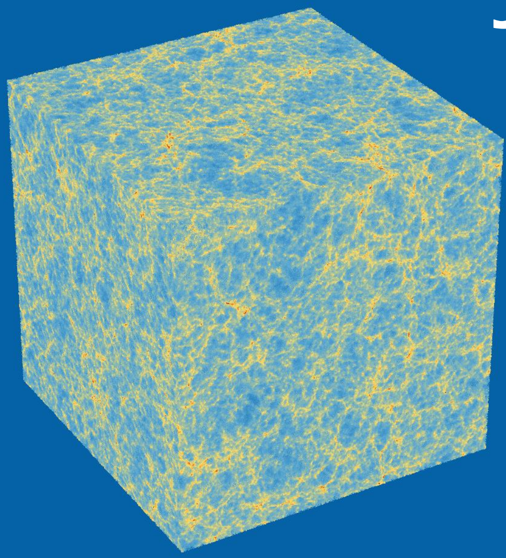
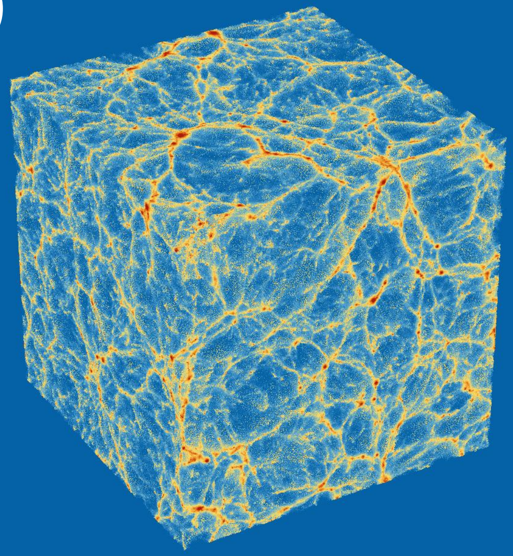
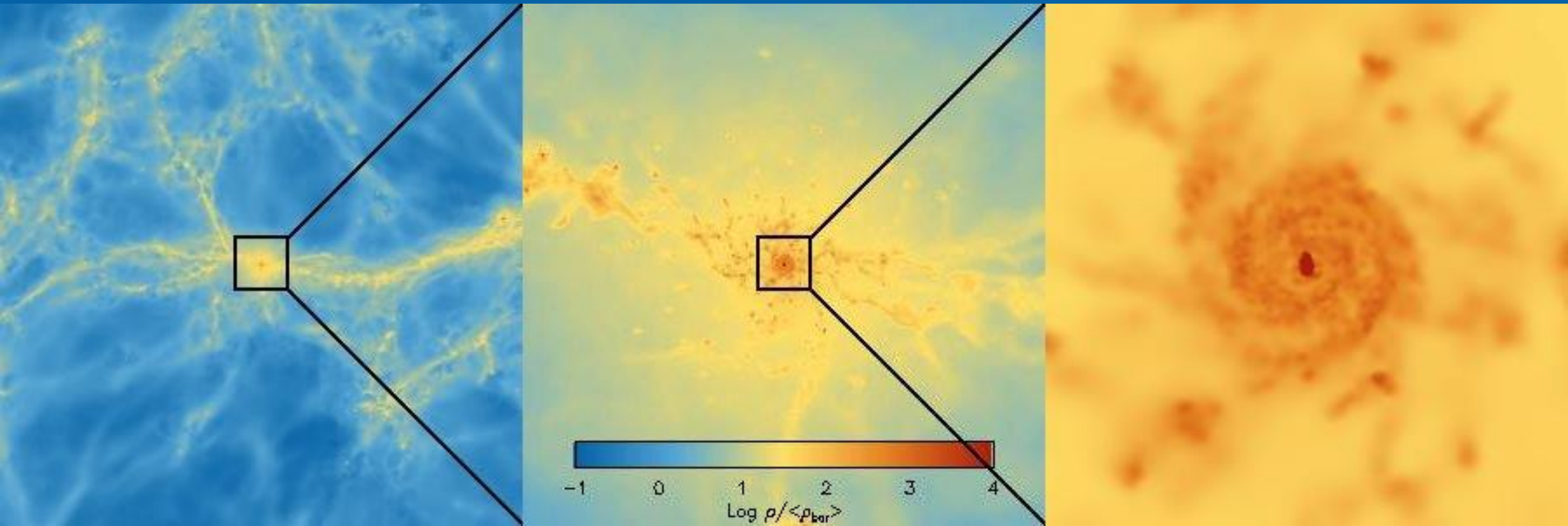


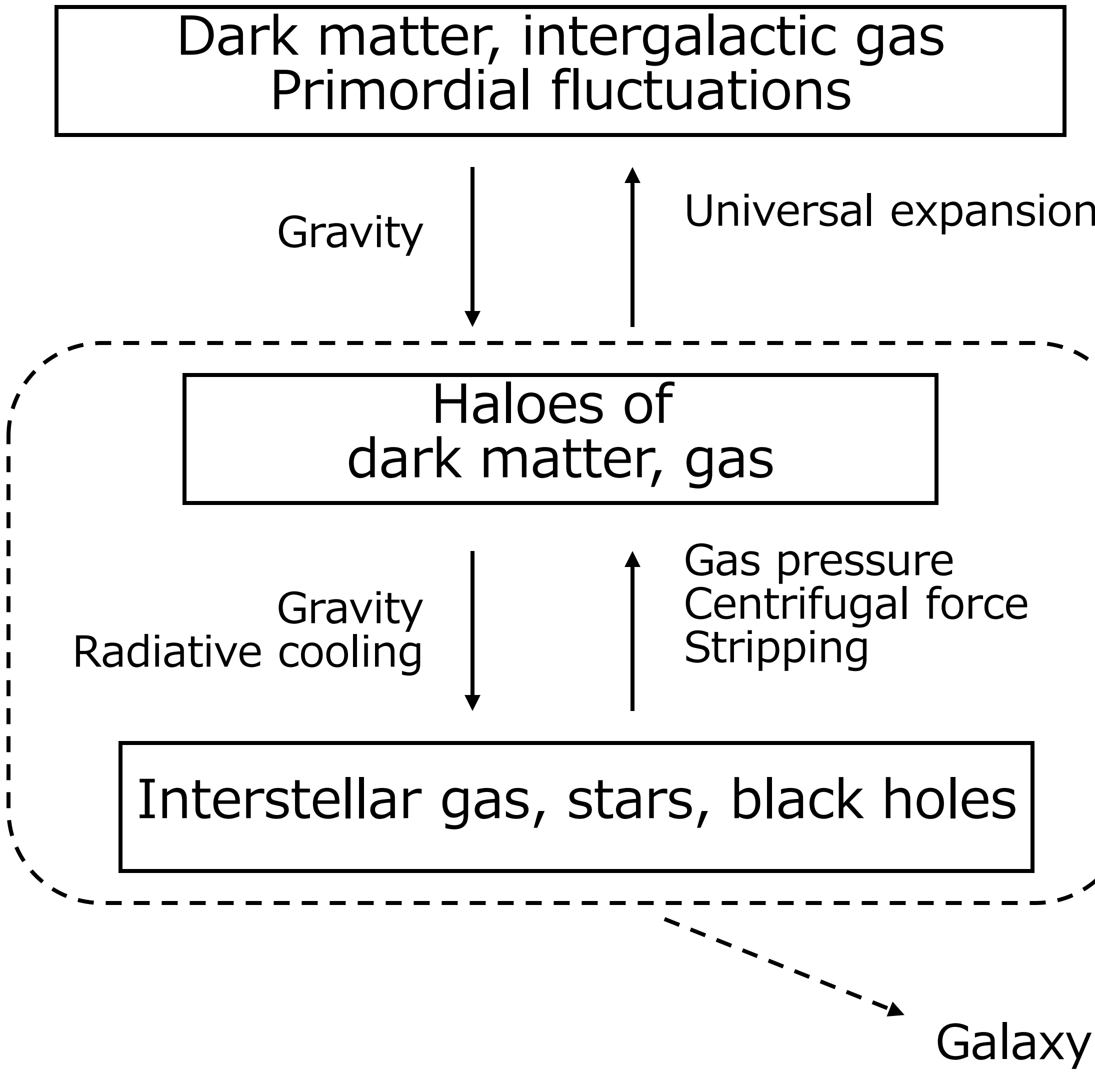




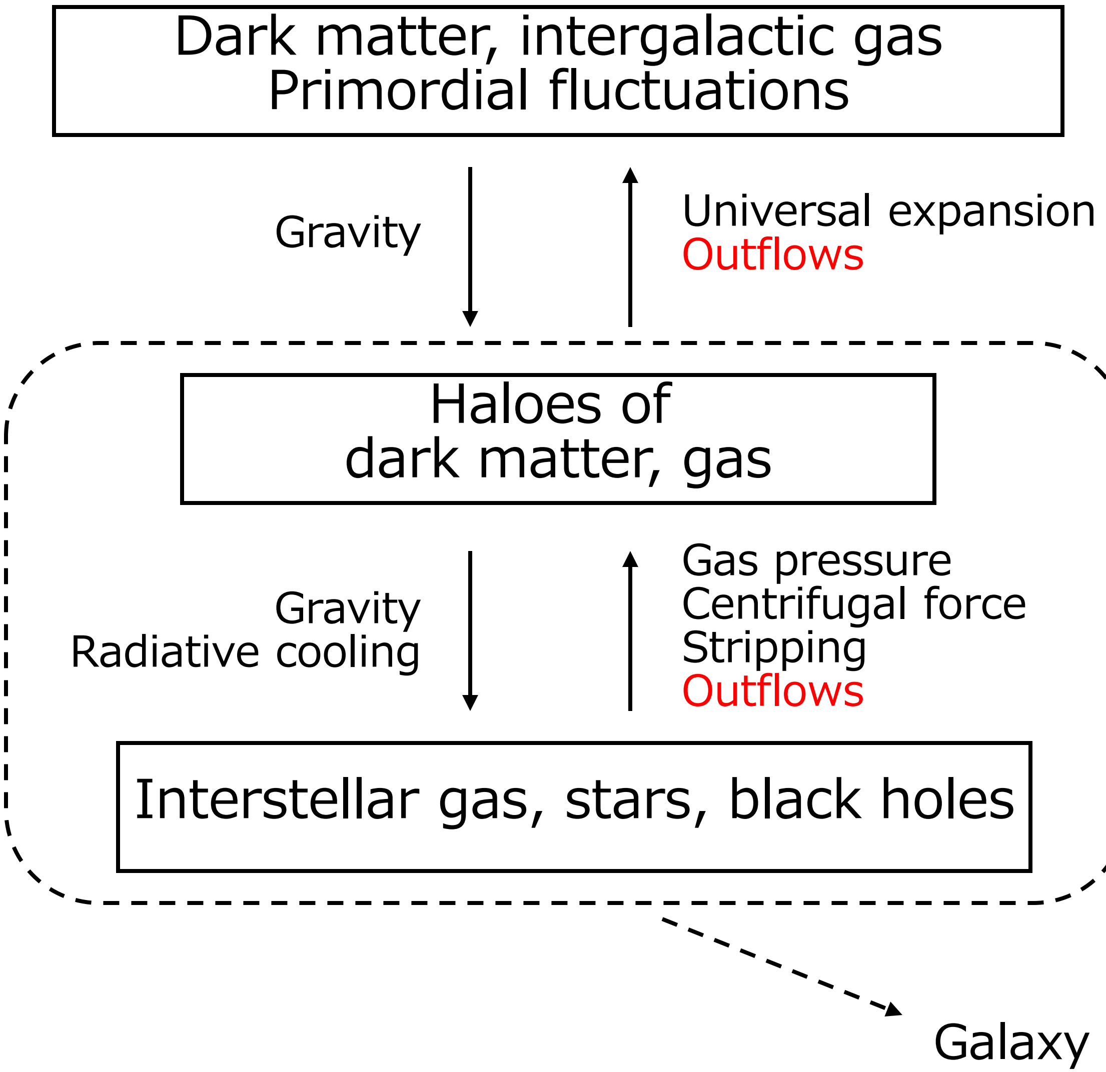
Outline

1. Self-regulated galaxy evolution
2. Cosmological hydrodynamical simulations
3. The EAGLE project
    a) What is it?
    b) What do the simulations look like?
    c) Some examples of things we learnt.

The formation of galaxies



The formation of galaxies



Self-regulated galaxy formation

- Feedback too weak compared to accretion
  - Gas density increases
  - Star formation /BH growth rate increases
  - Feedback increases
- Feedback too strong compared to accretion
  - Gas density decreases
  - Star formation/BH growth rate decreases
  - Feedback decreases

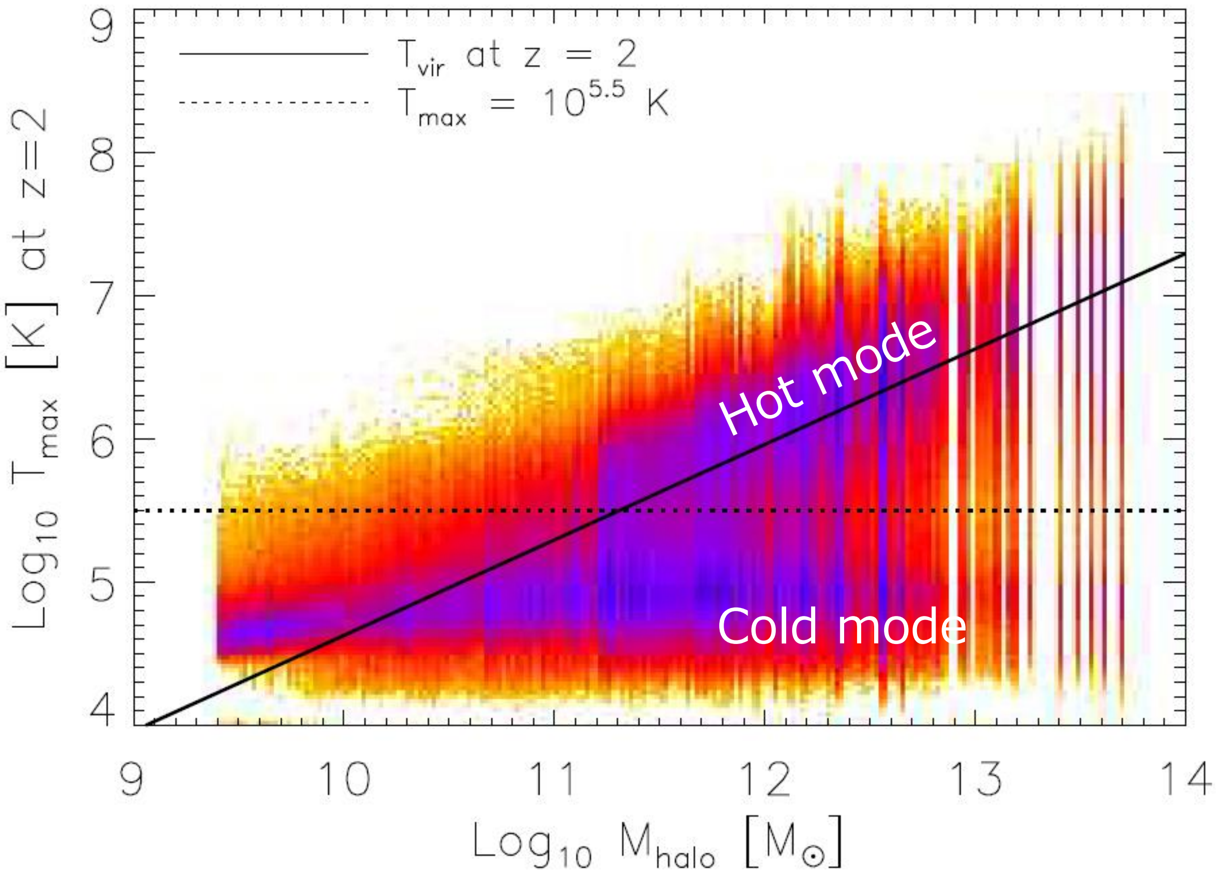
Consequences of self-regulated GF

- Galaxies tend to a state of quasi-equilibrium (outflow ~ inflow), when averaged over suitable length and time scales
  - ➢ Existence of simple scaling relations
- Outflow reacts to inflow
  - ➢ Gas accretion drives galaxy evolution

Consequences of accretion-driven GF

- Gas accretion rate is mainly "smooth"
  - ➢ small scatter in scaling relations
- Gas accretion rates and hence galaxy properties are a function of
  - Halo mass
  - Redshift
  - Environment (e.g. centrals vs. satellites)
- Nature of (halo) gas accretion changes at $M_{halo} \sim 10^{12}\ M_{\odot}$ (cold-mode → hot-mode)
  - ➢ May expect bi-modality in dominant feedback channel and hence in galaxy properties

Two modes of gas accretion



- Bimodal temperature distribution (e.g. Keres+, Dekel+)
- Hot accretion more important in massive haloes (> 10^{12} $M_{\odot}$)

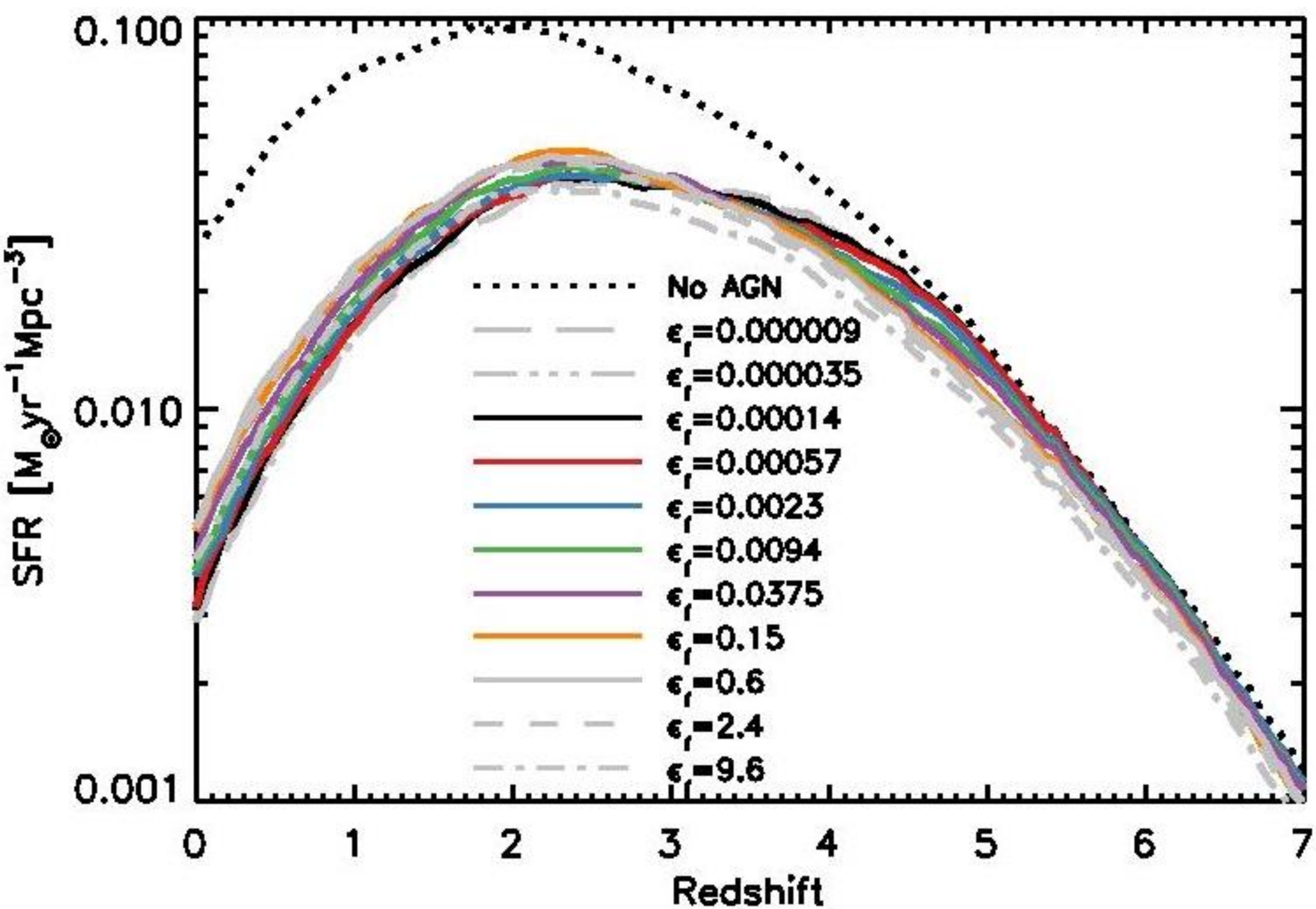
Van de Voort, JS+ (2011a)

Consequences of self-regulated GF

Outflow rate rate is determined by inflow rate. Hence, it is independent of:

- SF feedback efficiency
  - ➢ SFR, and hence M_*, inversely proportional to efficiency of SF feedback (in order to generate the same outflow rate)
  - ➢ M_*-M_{halo} relation cannot be predicted unless the radiative losses in the ISM can be predicted
- AGN feedback efficiency
  - ➢ BH accretion rate, and hence M_{BH}, inversely proportional to efficiency of AGN feedback
  - ➢ M_{BH}-M_* relation difficult to predict from first principles
  - ➢ SFR (and other galaxy properties except M_{BH}) independent of AGN feedback efficiency

Varying the efficiency of AGN feedback



Booth & JS (2009, 2010)

Cosmological hydro simulations

- Evolution from z>~100 to z ~< 10 of a representative part of the universe
- Expansion solved analytically and scaled out
- Initial conditions from the CMB & LSS
- Boundary conditions: periodic
- Components: cold dark matter, gas, stars, radiation (optically thin)
- Discretizaton: time, mass (SPH) or length (AMR)
- Gravity and hydro solvers (and MHD, RT, ⋯)
- Sub-grid modules are a crucial part of the game

Length Scales (cm)

Subgrid models

Directly simulated

10^{-8}	interparticle distance in stars
10^{0}	interparticle distance in ISM
10^{2}	interparticle distance in IGM
10^{11}	stellar radii
10^{18}	interstar distance
10^{20}	star clusters
10^{22}	galaxies
10^{24}	clusters of galaxies
10^{28}	observable universe

Basic resolution requirements

- Convergence requires resolving the Jeans scales:

$$M_{\rm J} \approx 1\times10^7\, h^{-1}\, {\rm M}_\odot\, f_{\rm g}^{3/2} \left(\frac{n_{\rm H}}{10^{-1}\,{\rm cm}^{-3}}\right)^{-1/2} \left(\frac{T}{10^4\,{\rm K}}\right)^{3/2}$$

$$L_{\rm J} \approx 1.5\, h^{-1}\,{\rm kpc}\, f_{\rm g}^{1/2} \left(\frac{n_{\rm H}}{10^{-1}\,{\rm cm}^{-3}}\right)^{-1/2} \left(\frac{T}{10^4\,{\rm K}}\right)^{1/2}$$

- Resolving the warm phase requires:
  - Particle mass << 10^7 $M_\odot$
  - Spatial resolution << 1 kpc
- Resolving gas with $n_H \sim 10$ cm^{-3} and $T \sim 10^2$ K requires:
  - particle mass << 10^3 $M_\odot$
  - spatial resolution << 10 pc
  - Radiative transfer
  - Complex chemistry

Galaxies in hydro simulations

- For many years galaxies in hydro simulations were:
  - Too massive
  - Too compact
  - Too old
  - Too bulgy/elliptical
- This changed thanks mainly to
  - More efficient subgrid implementations of feedback from star formation
  - Inclusion of AGN feedback

The challenge for feedback prescriptions

- *Reality:* Supernovae and accreting black holes inject lots of energy in very little mass
  - → High temperatures
  - → Long cooling times
  - → Efficient feedback
- *Simulations:* Energy injected in lots of mass
  - → Low heating temperatures
  - → Short cooling times
  - → Inefficient feedback

Driving winds: subgrid recipes

- Multiphase particles

  (e.g. Scannapieco, Murante, Aumer/White)
- Suppress cooling by hand

  (e.g. Thacker, Stinson/Brook/Gibson/Governato/Maccio/Mayer/Wadsley)
- Inject momentum (i.e. kinetic feedback) and suppress hydrodynamical interactions by hand

  (e.g. Springel/Hernquist, Davé/Oppenheimer, Dubois/Teyssier, Viel, Vogelsberger)
- Inject sufficient energy per event

  (e.g. Booth & JS ‘09, Dalla Vecchia & JS ‘12, JS+ ’15, Keller/Wadsley)

Implementing thermal FB: requirements

- FB only efficient if heated resolution elements expand faster than they cool radiatively:
  $t_c >> t_s = h/c_s$
  where h is the spatial resolution
- Required T depends on density and resolution

$$\frac{t_{\rm c}}{t_{\rm s}} \simeq 98 \left(\frac{n_{\rm H}}{1\ {\rm cm}^{-3}}\right)^{-2/3} \left(\frac{T}{10^{7.5}\ {\rm K}}\right) \left(\frac{\langle m \rangle}{7 \times 10^4\ {\rm M}_\odot}\right)^{-1/3}$$

- Stochastic implementation: Fix ΔT, heating probability determined by overall efficiency parameter that requires calibration

Dalla Vecchia & JS (2012)

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The EAGLE project: simulating the evolution and assembly of galaxies and their environments

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VIRGO

EAGLE Starting points

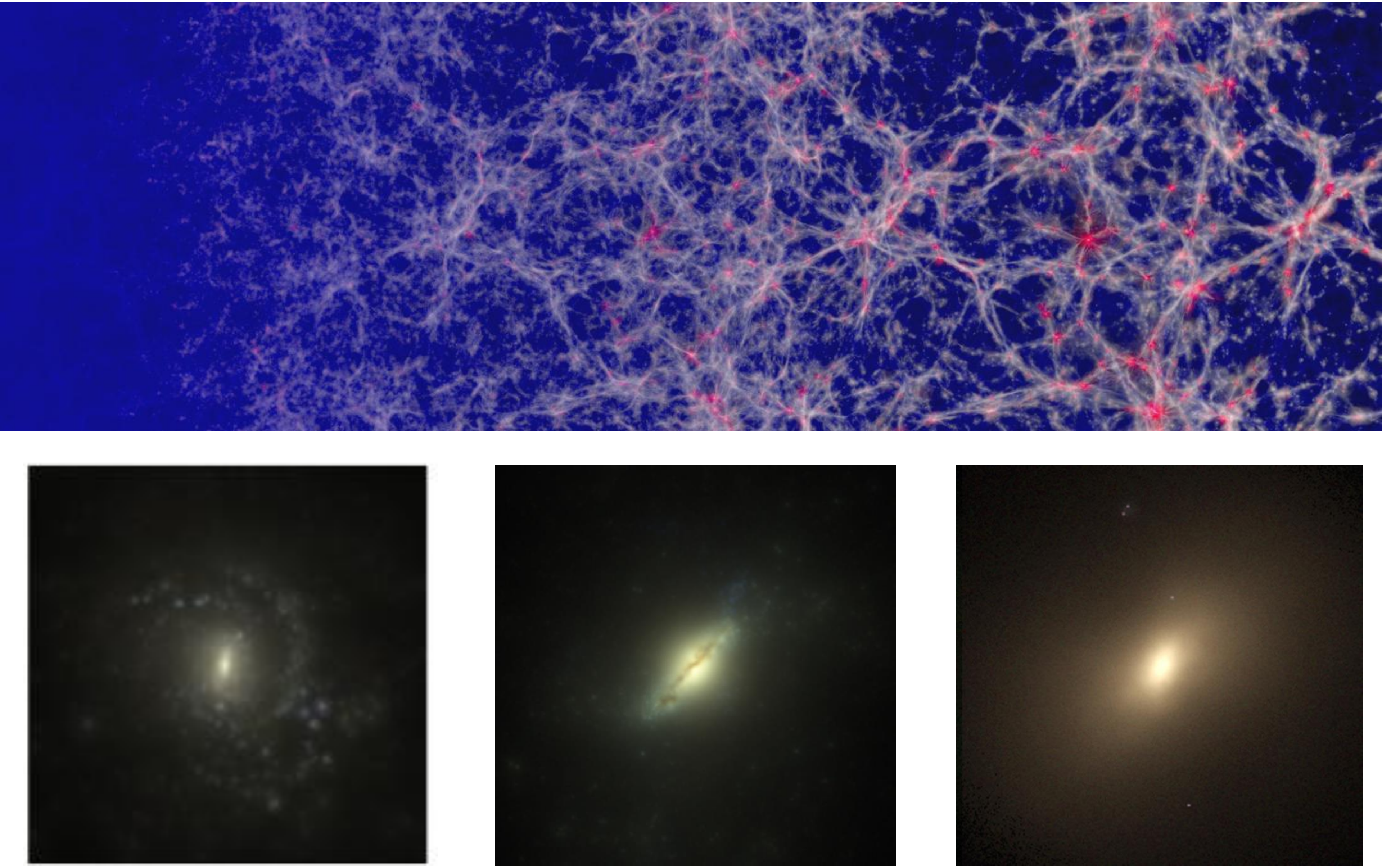
- Strong outflows are necessary to obtain agreement with a diverse set of observations
- Maximum in stellar fraction – halo mass relation suggests that two types of feedback are needed
- Cosmological simulations cannot resolve the cold ISM and hence cannot predict stellar and black hole masses from first principles
- Calibration necessary

  → require subgrid feedback that avoids numerical overcooling but whose efficiency can be controlled
  → need to compare to relevant observations
  → need to be clear about calibration input
  → need to keep it simple

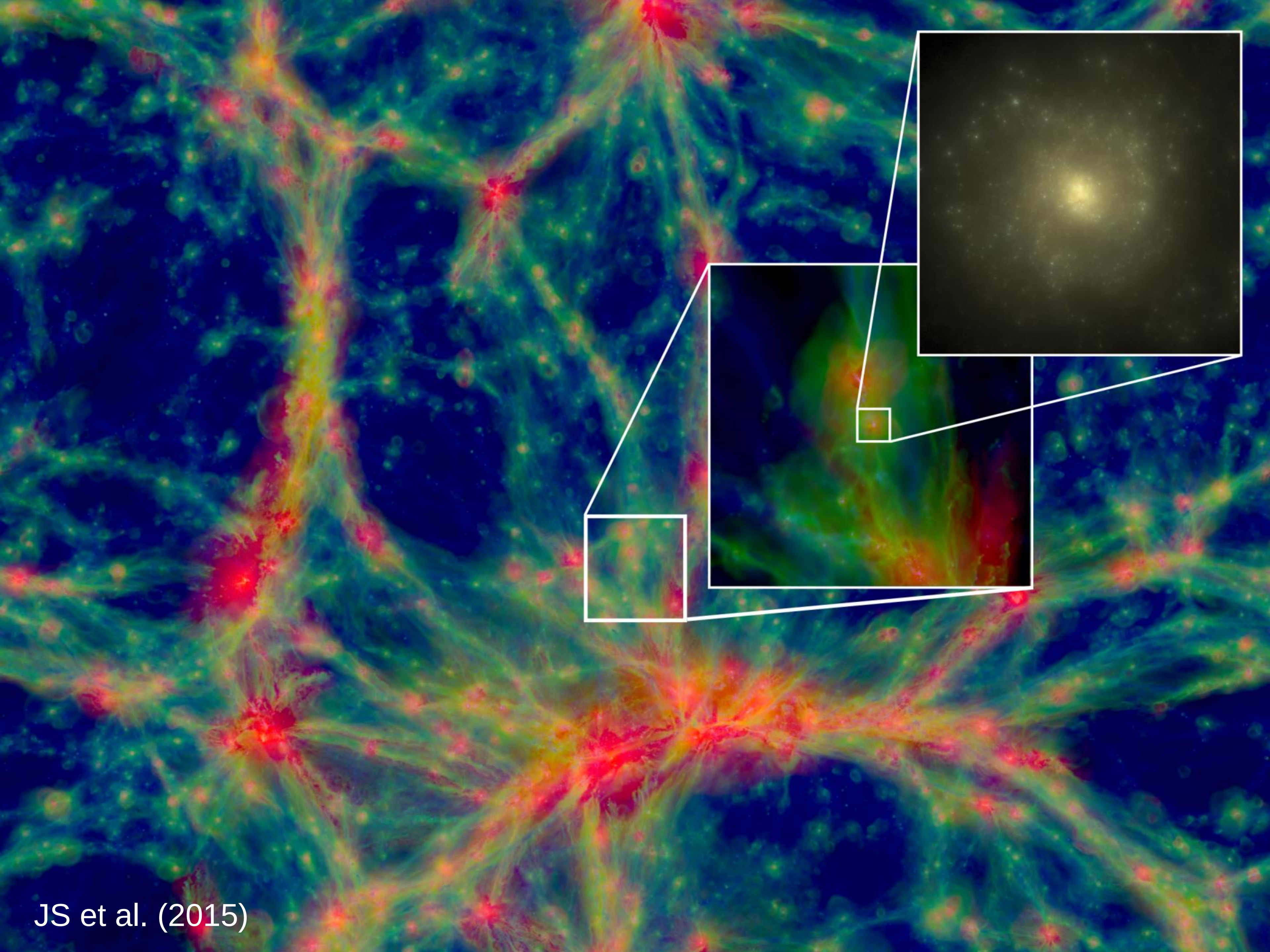
EAGLE:

Evolution and Assembly of GaLaxies and their Environments

- Volumes of 25 - 100 Mpc and zooms
- Particle mass 10^5 – 10^6 $M_\odot$ (smaller for zooms), resolves warm ISM
- Modern SPH
- Includes feedback from stars and AGN (1 type each)
- Subgrid recipes depend only on local gas properties
- Hydro and cooling never turned off
- Winds develop without predetermined mass loading or velocity
- Stellar feedback efficiency calibrated to $z = 0$ mass function and galaxy sizes
- AGN feedback efficiency calibrated to $z = 0$ BH mass – stellar mass relation
- Many different models, spin offs

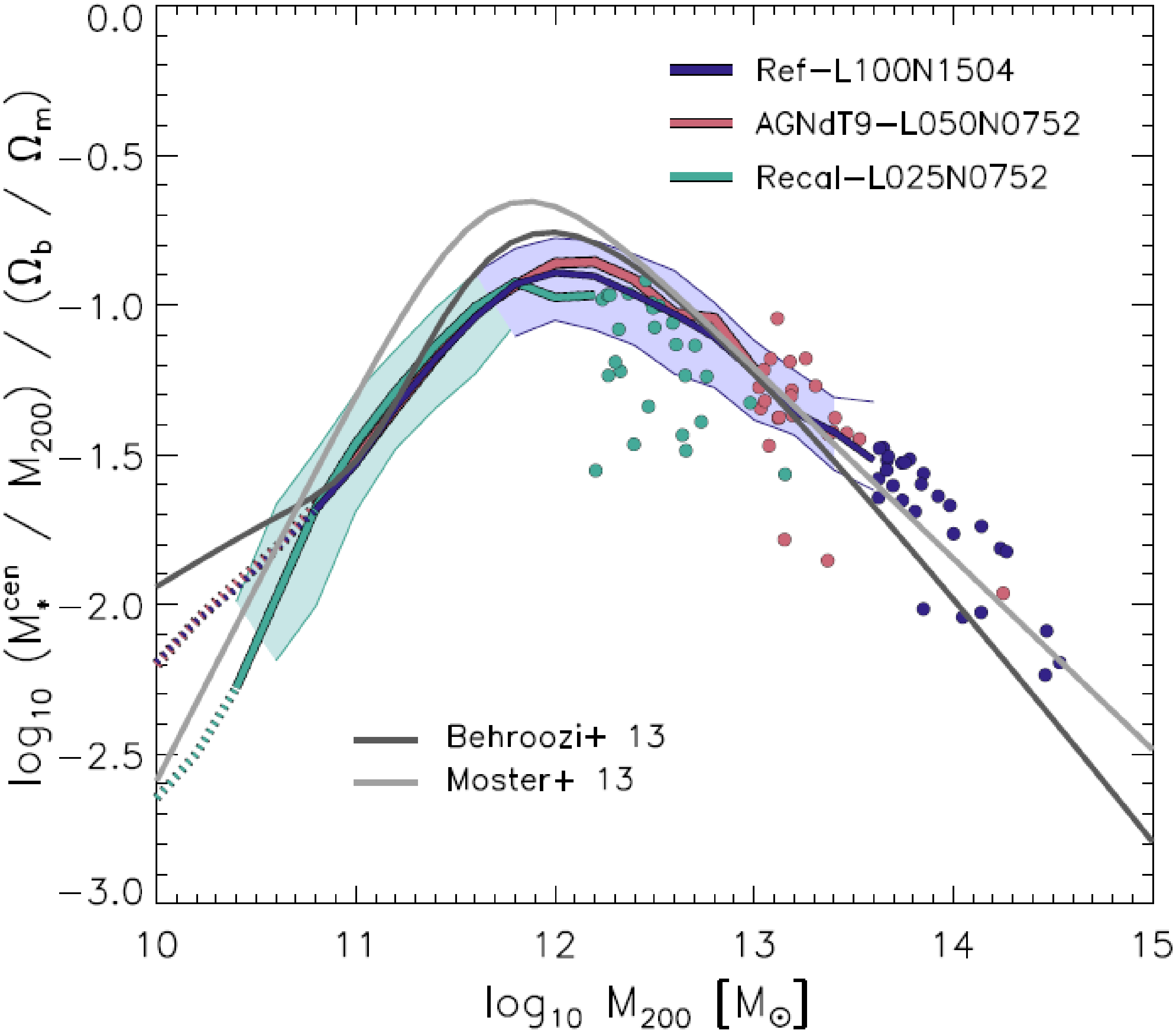


Images by Trayford/McAlpine


JS et al. (2015)

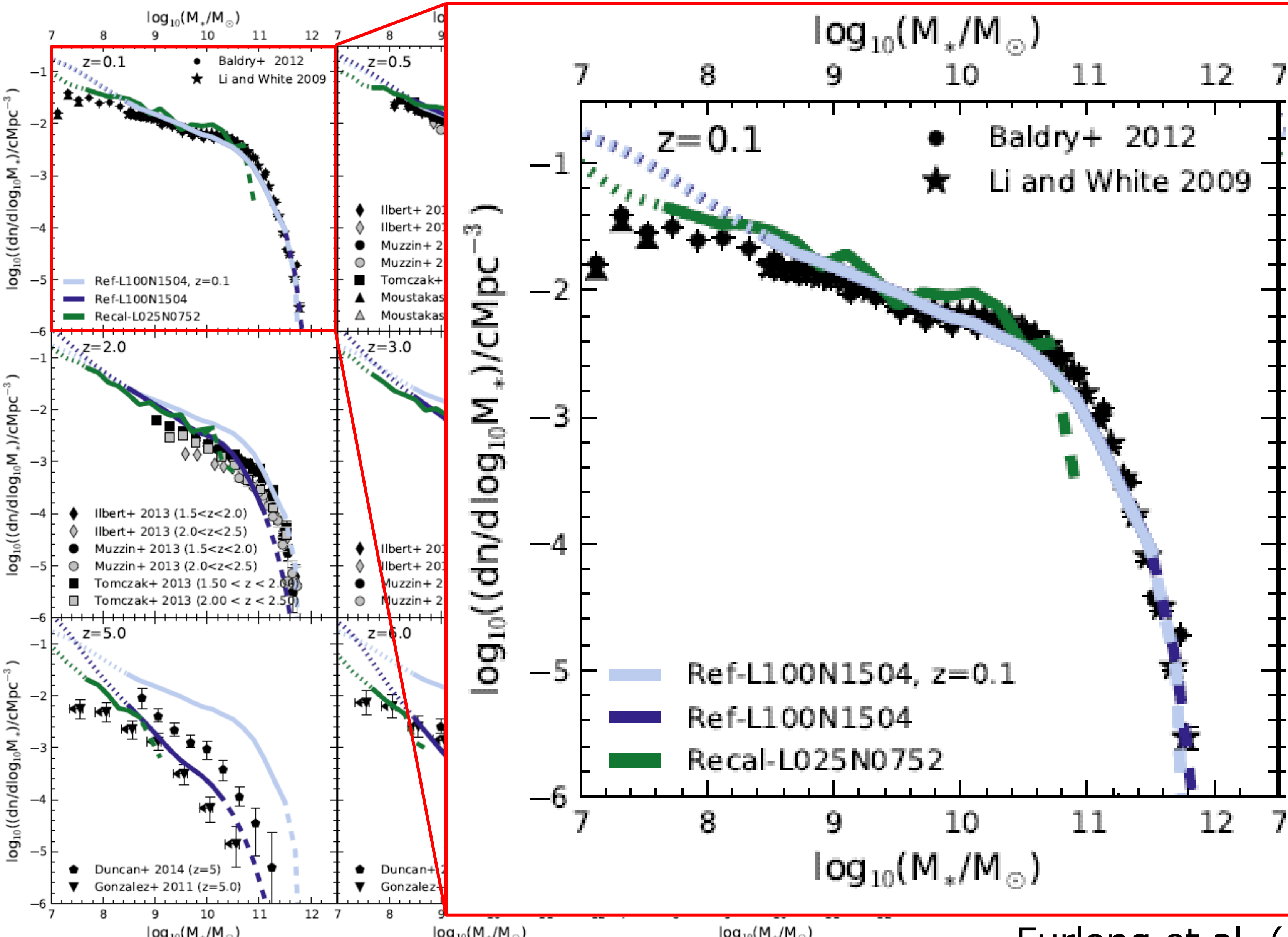
A movie of cosmic evolution

Galaxy formation efficiency



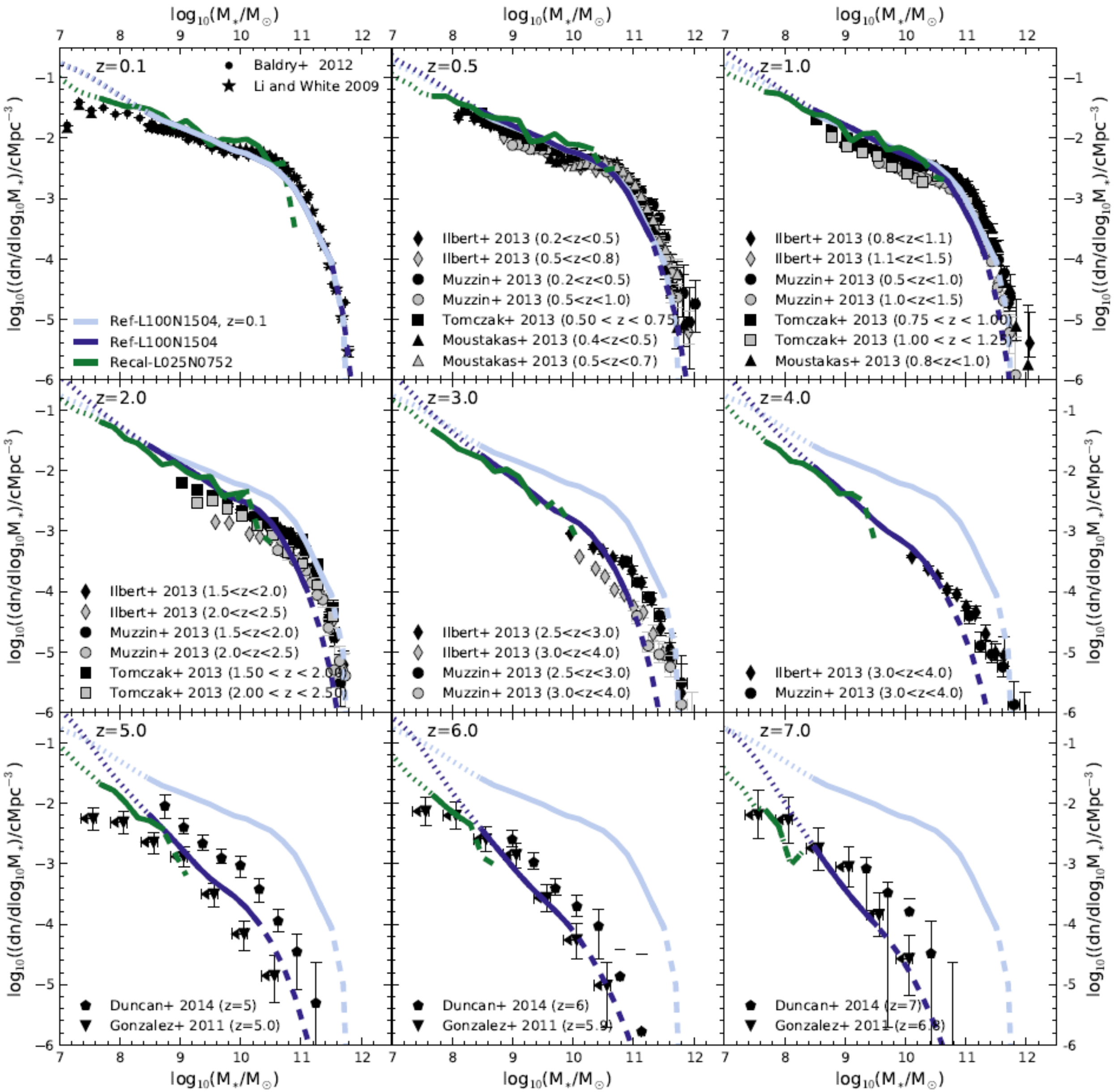
JS et al. (2015)

Evolution of the mass function

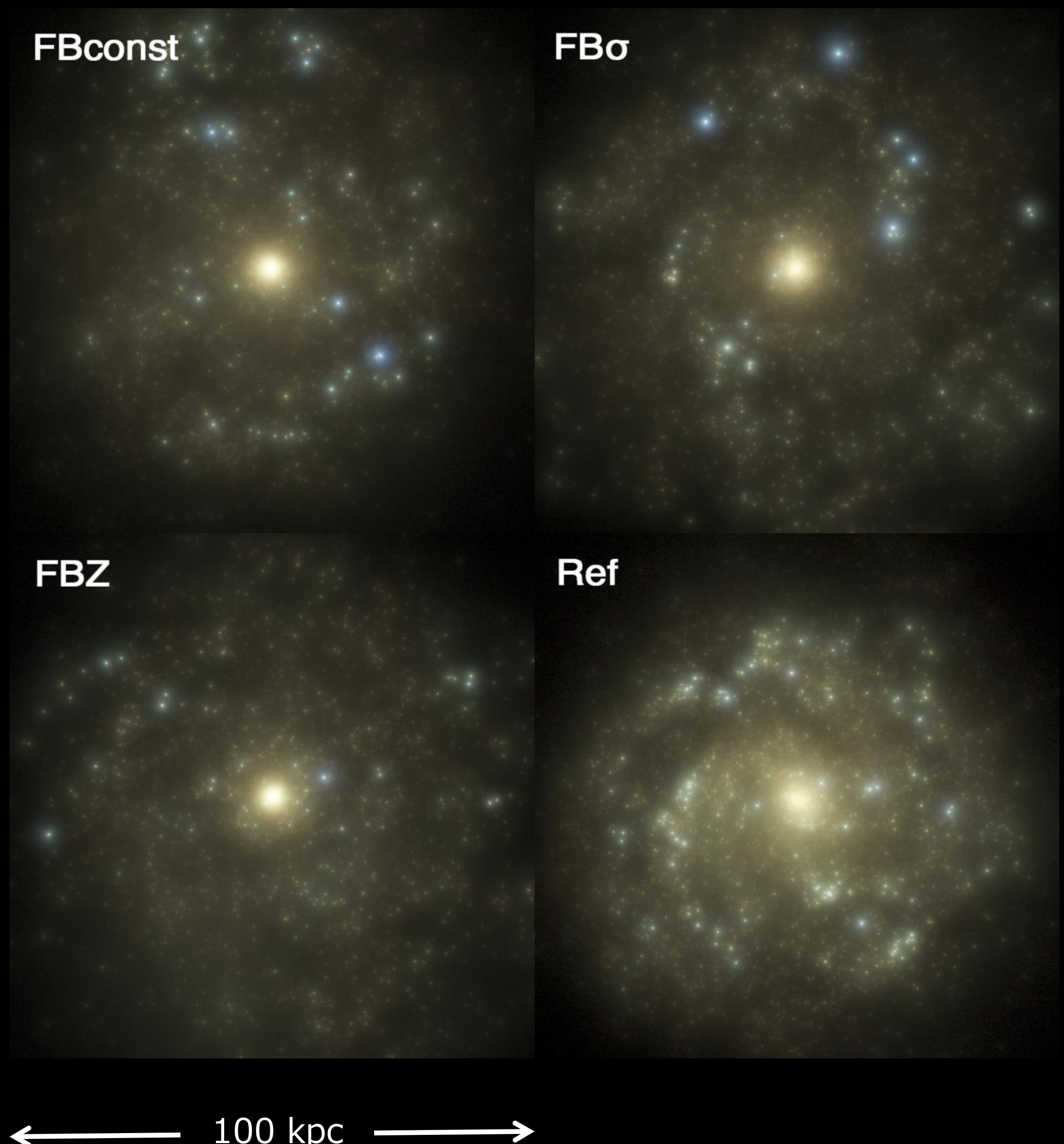


Furlong et al. (2015a)

Evolution of the mass function



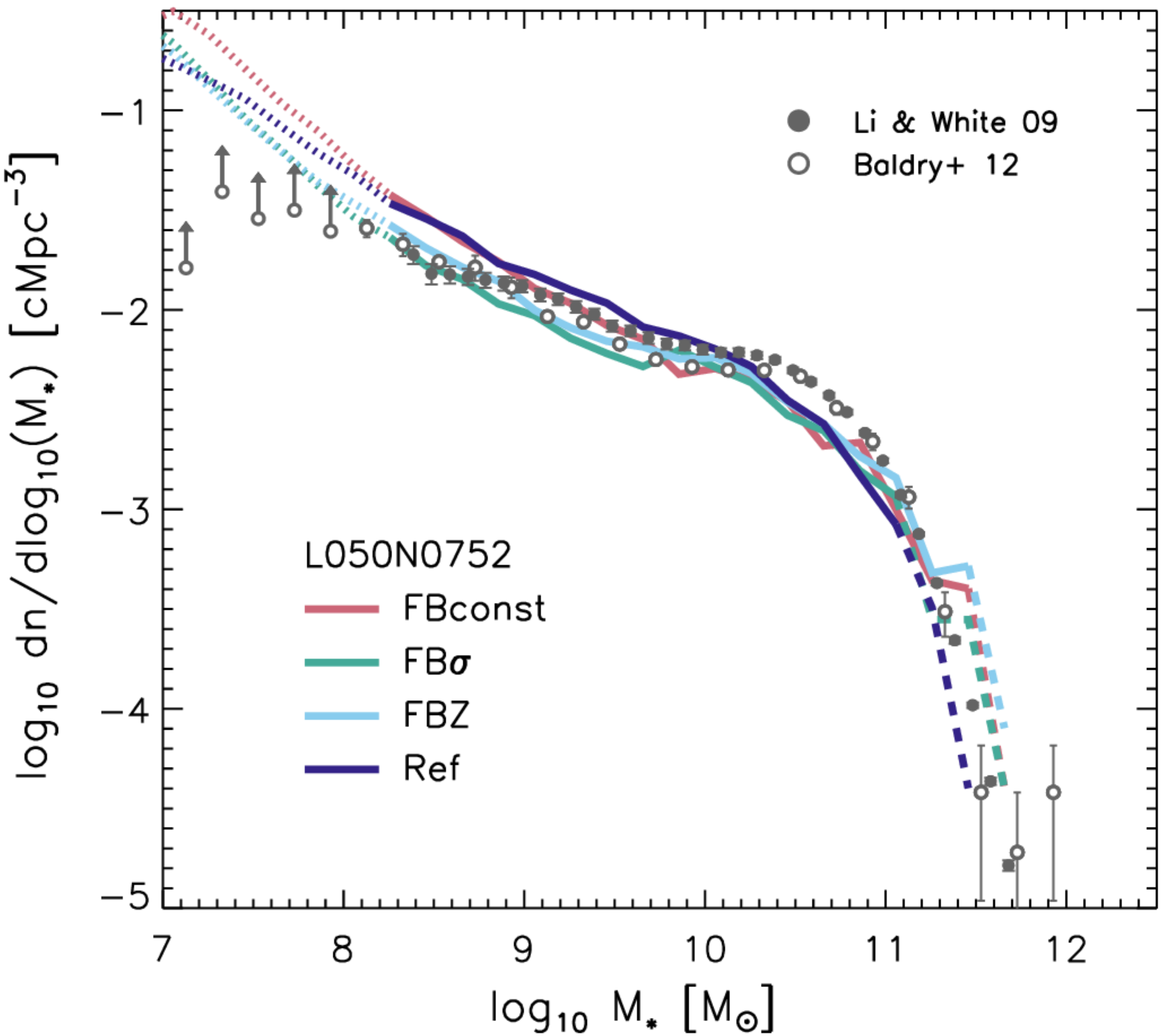
Furlong et al. (2015a)



$M_{200} = 10^{12}\ M_{\odot}$

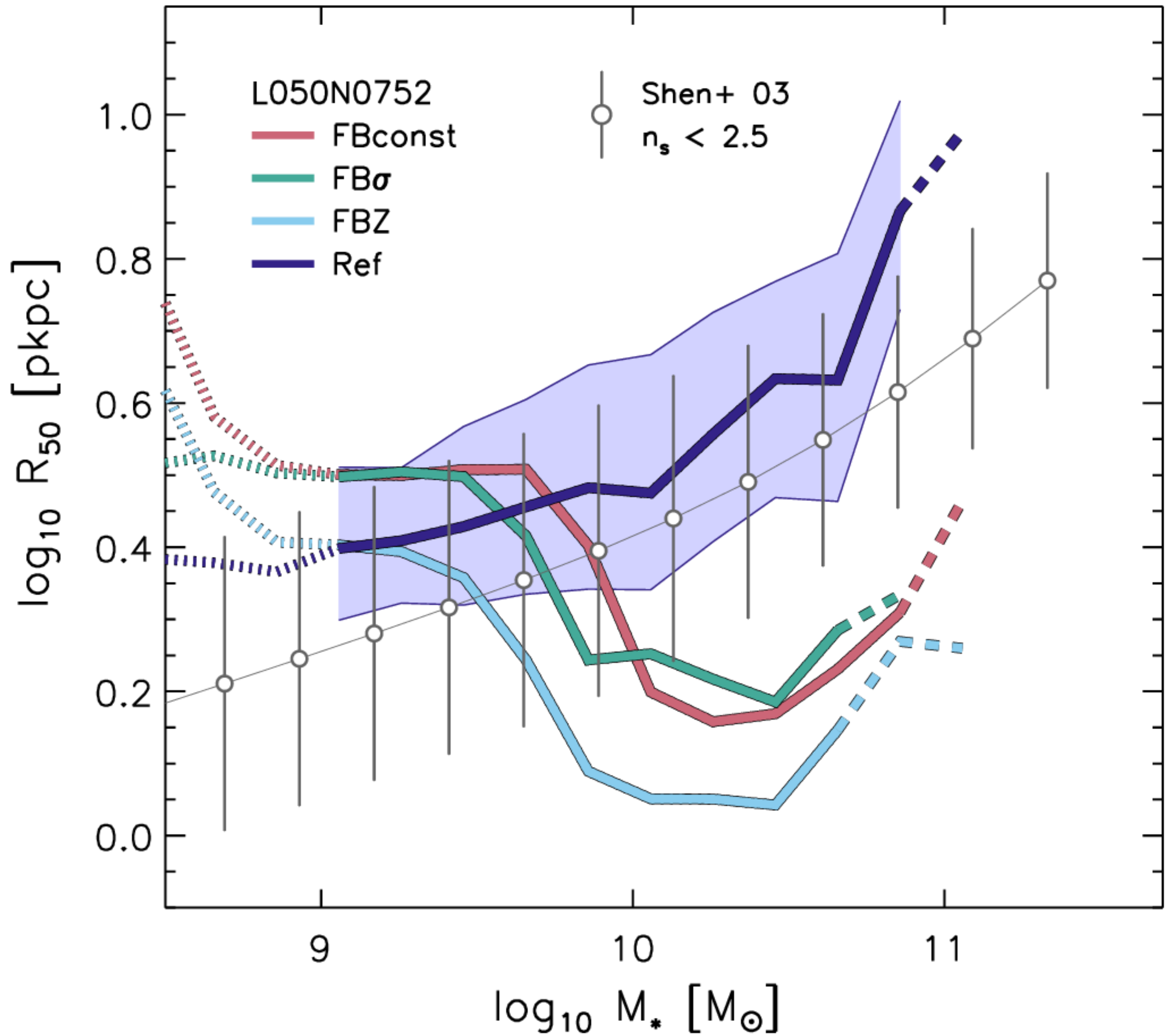
Crain, JS et al. (2015)

Many ways to fit the mass function



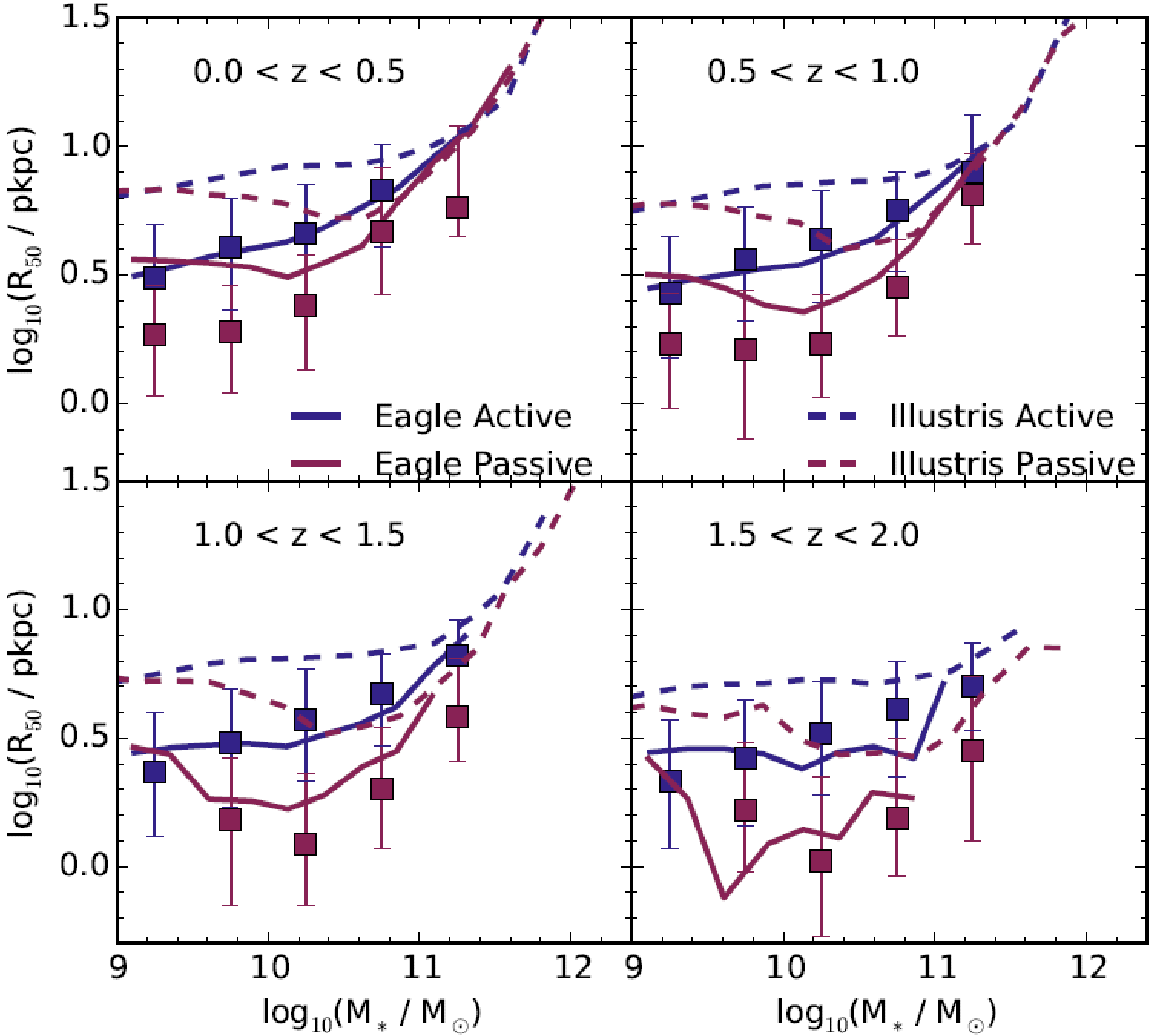
Crain, JS et al. (2015)

Sizes



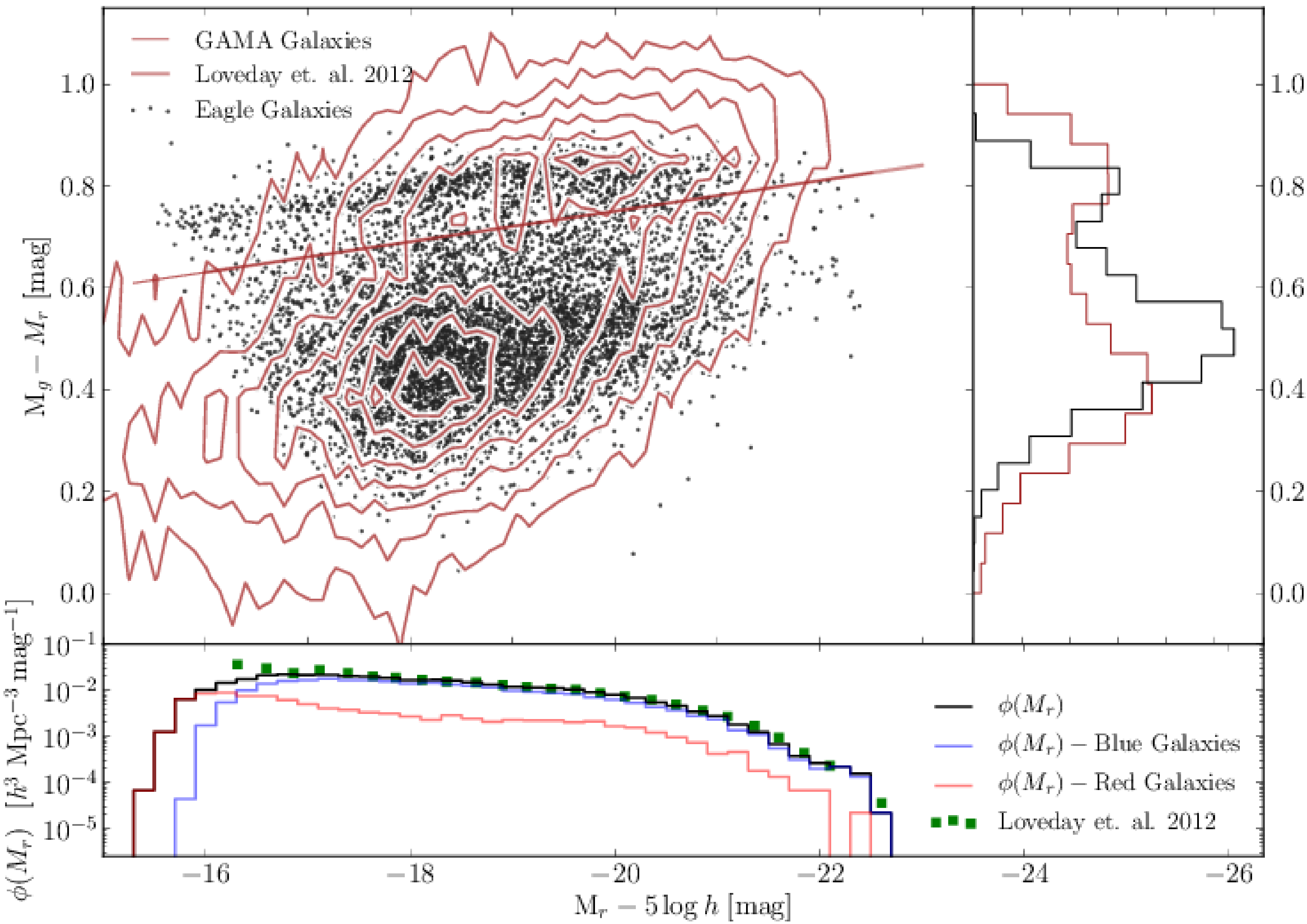
Crain, JS et al. (2015)

Sizes: Evolution



Furlong et al. (2016)

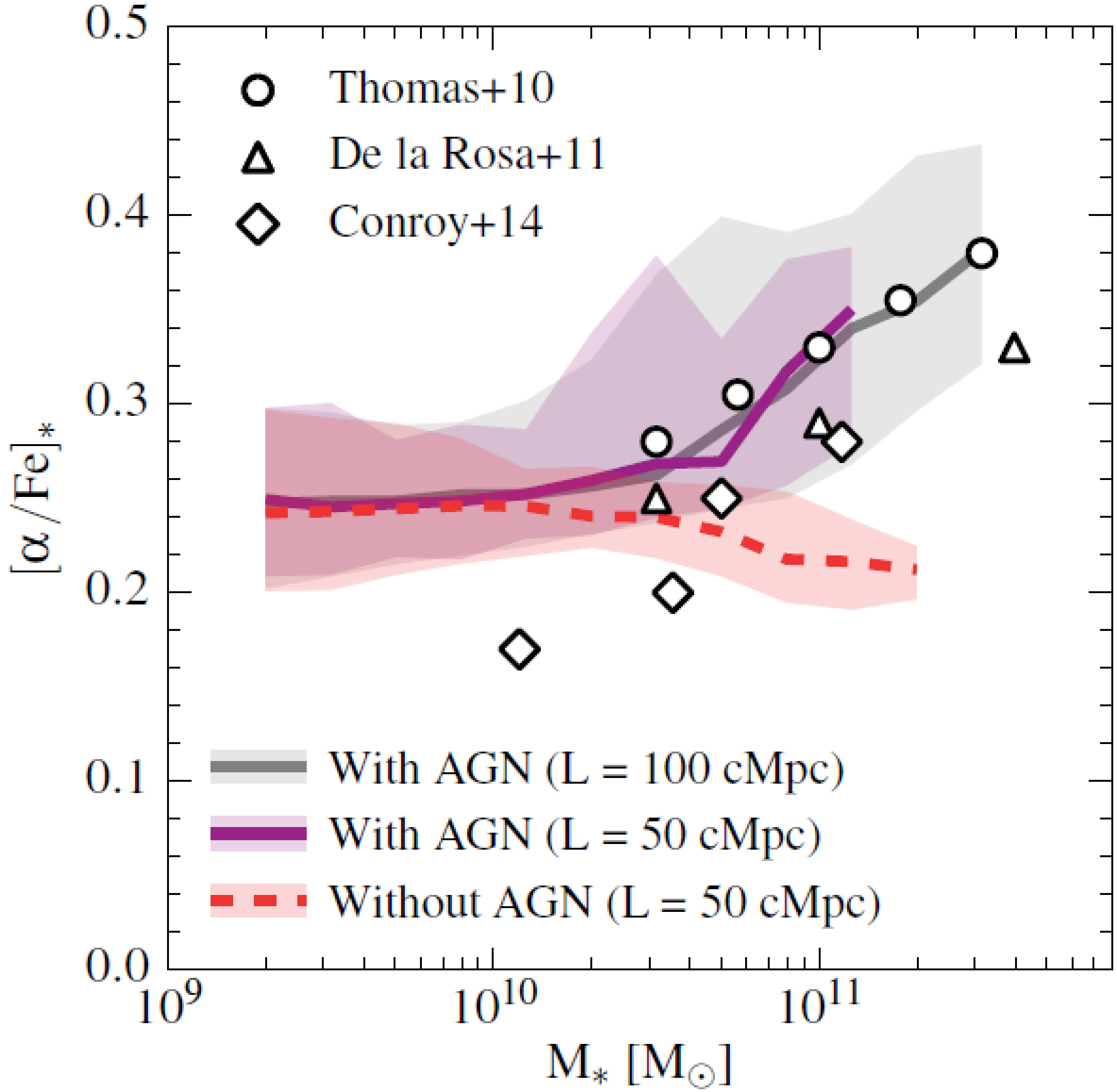
Colour-magnitude diagram: EAGLE vs GAMA



SPSS: Bruzual & Charlot '93
Extinction: Charlot & Fall
Flux limit: GAMA

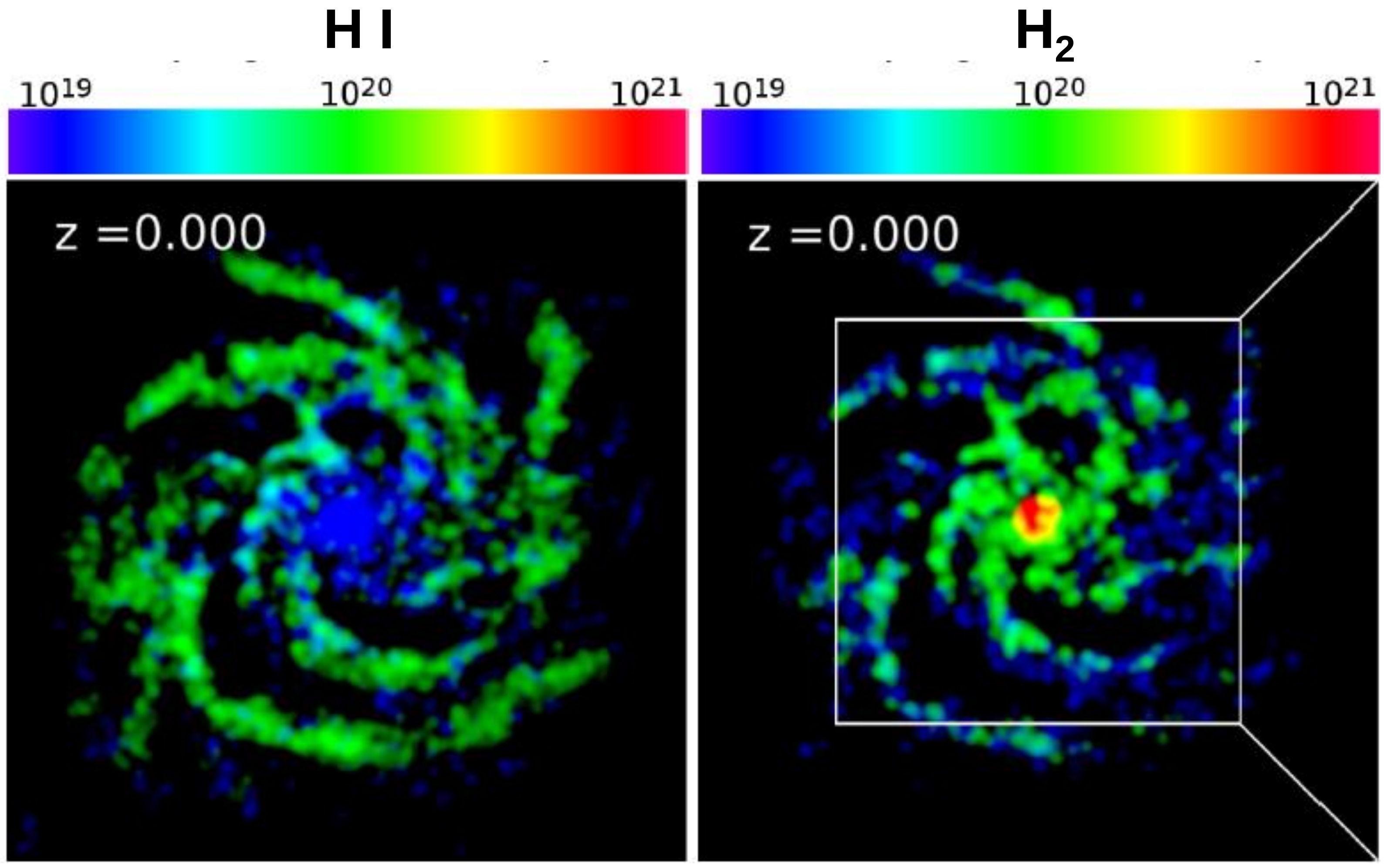
Trayford et al. (2015)

Alpha enhancement of early types



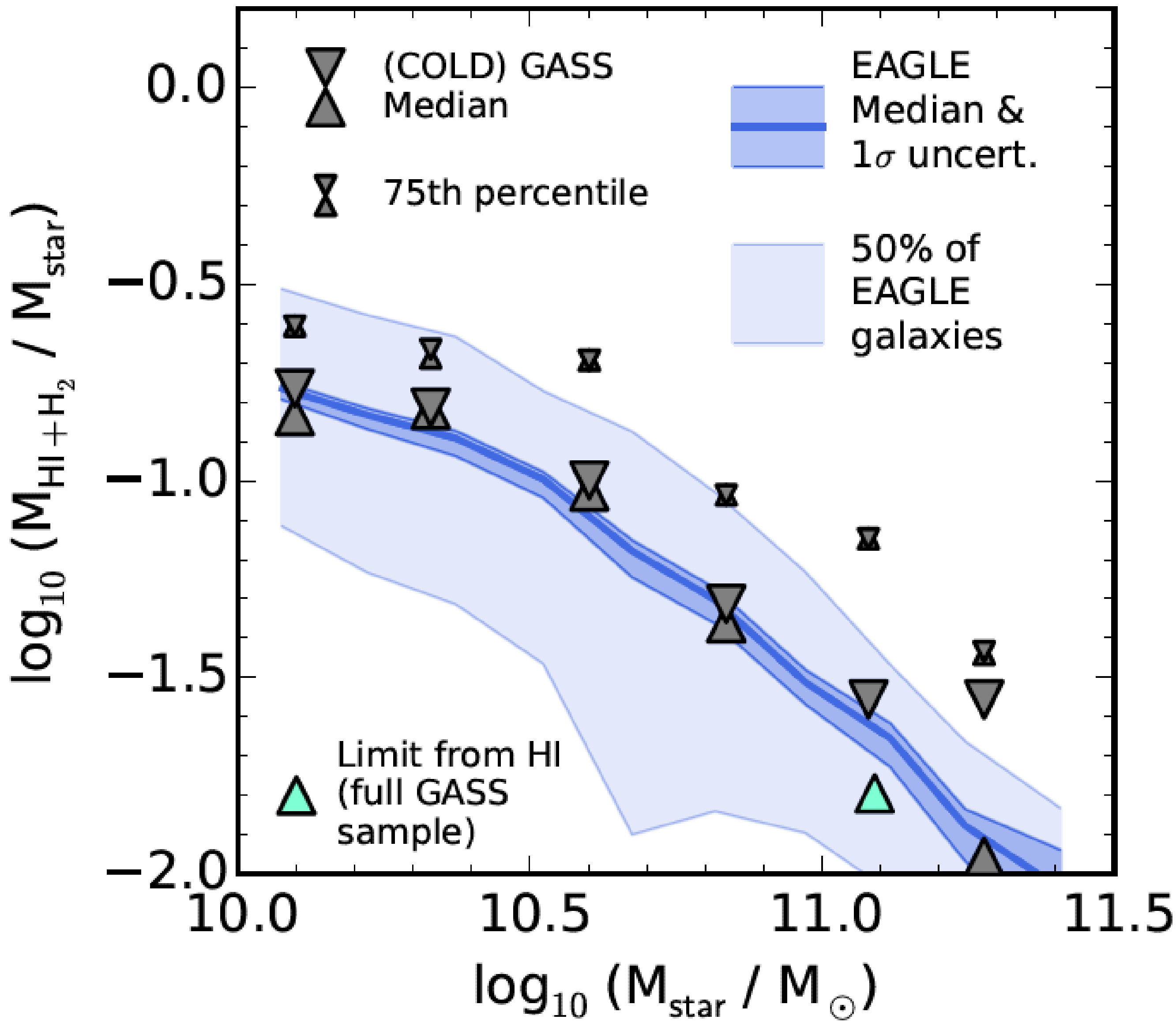
Segers, JS, et al. (2016)

ISM phases



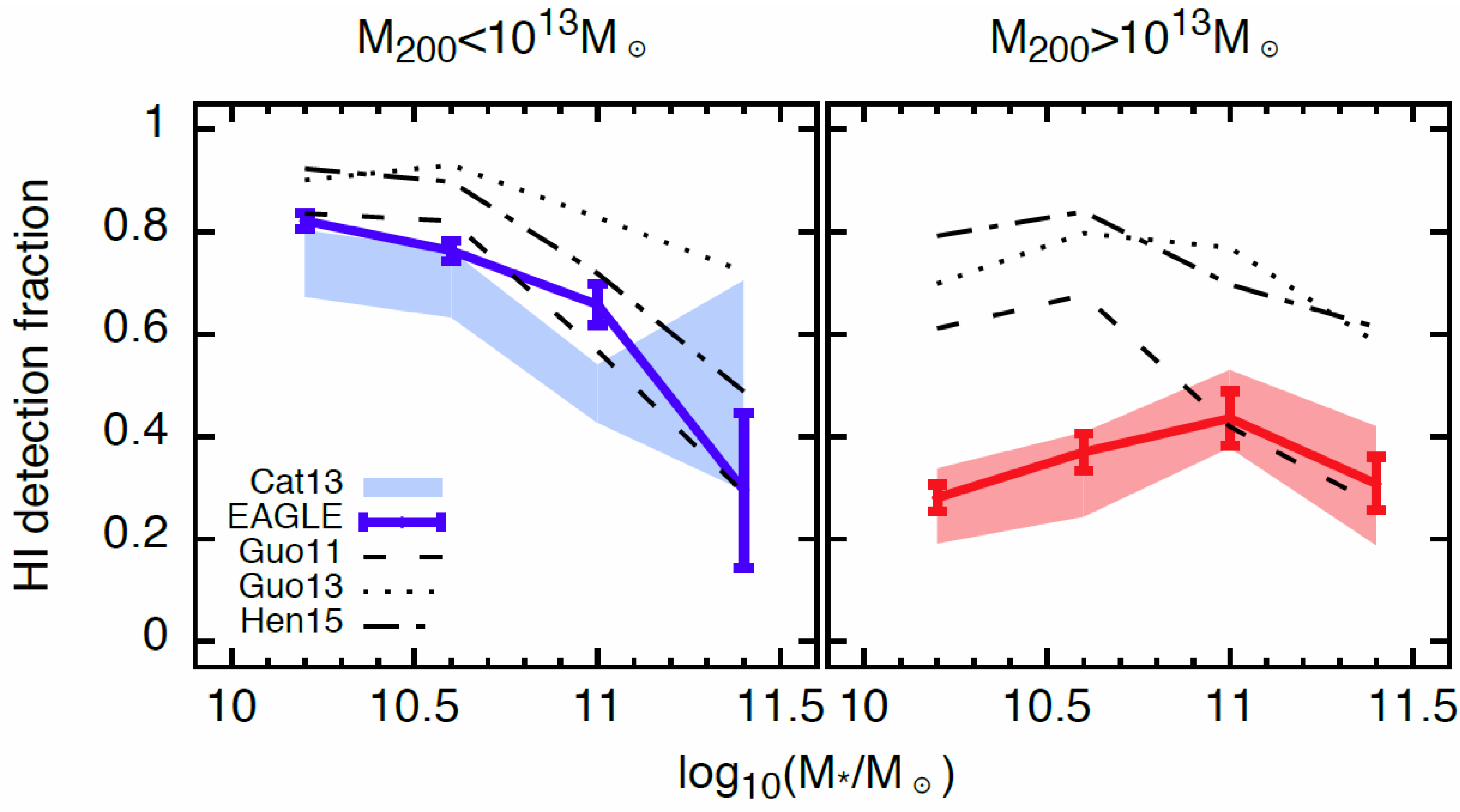
Lagos, Theuns, JS et al. (2015b)

Neutral gas fraction



Bahe et al. (2015)

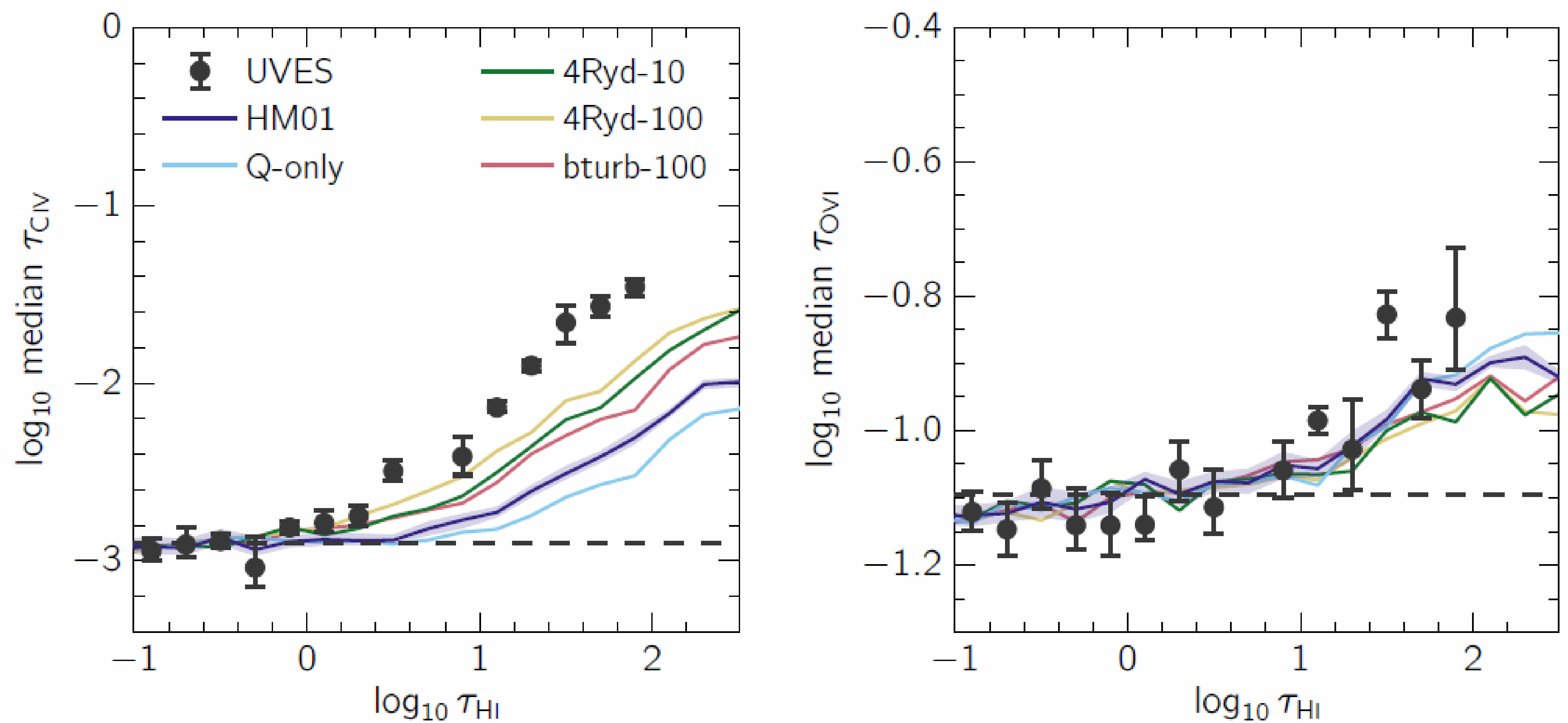
HI: Environmental dependence



Cat13: GASS survey with SDSS group catalog (Catinella+ 2013)

Marasco, Crain, JS et al. (2016)

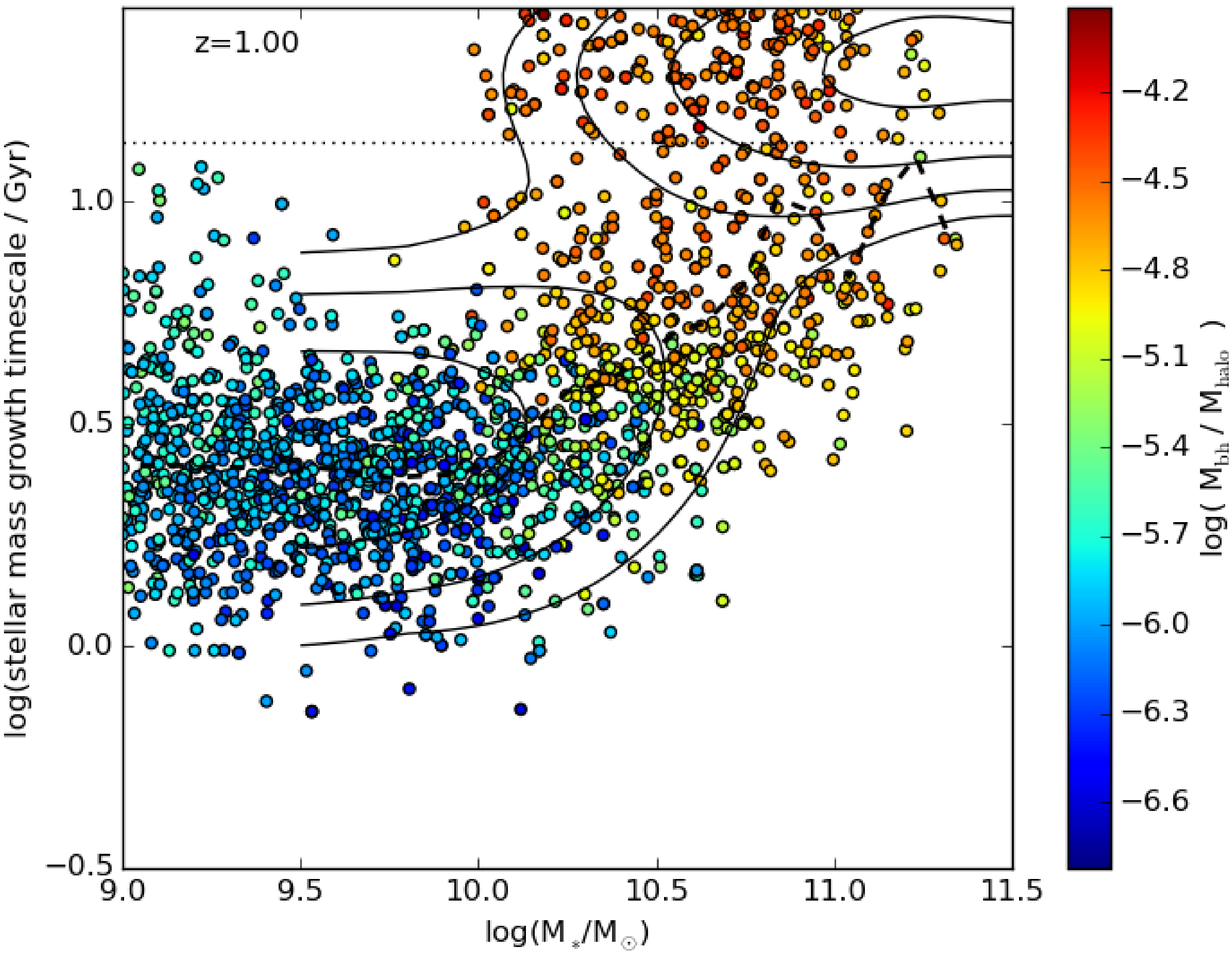
Intergalactic metals at z~3.5: A like-for-like comparison



EAGLE winds may not entrain enough cold gas

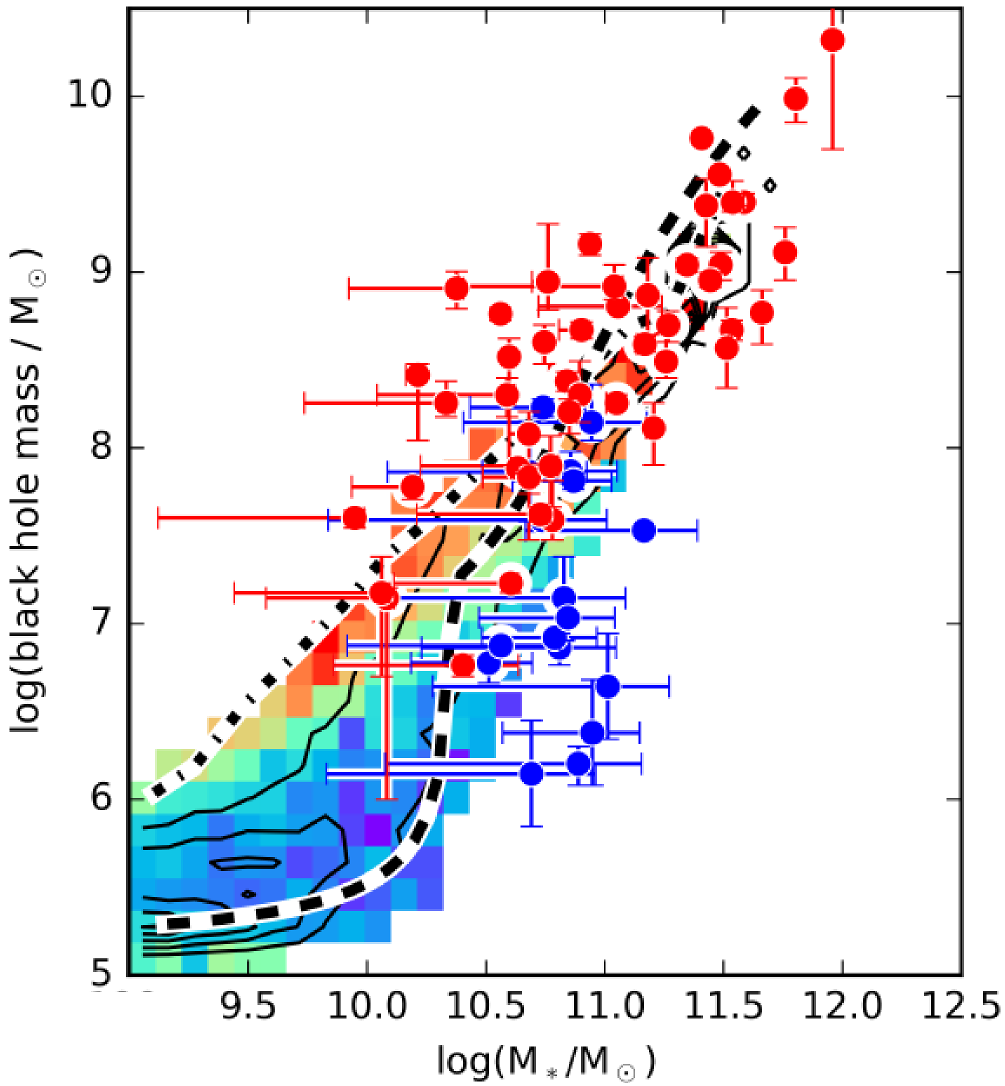
Turner, JS et al. (2016)

Galaxy bimodality and BH mass



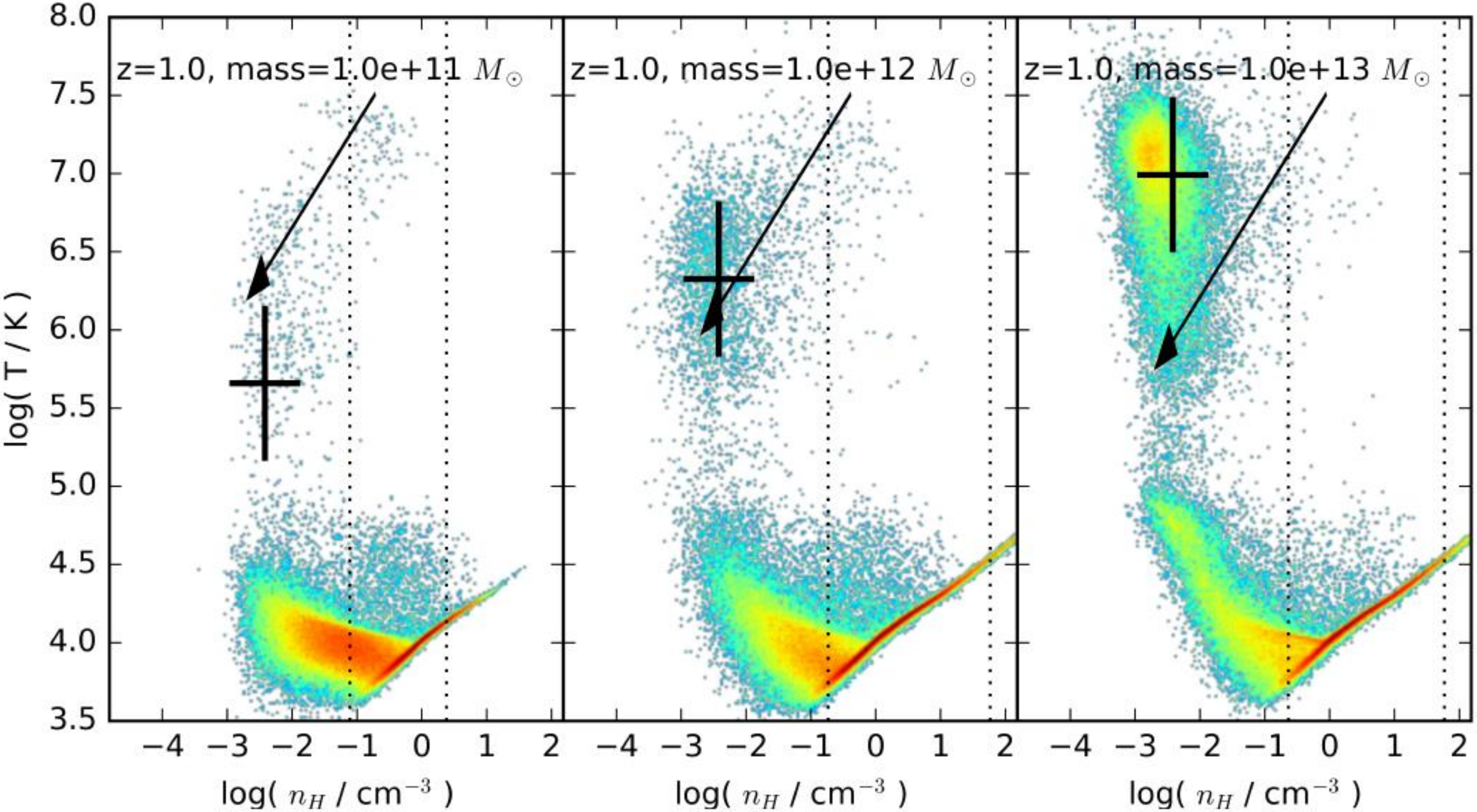
Bower, JS et al. (in prep)

BH – Stellar mass relation



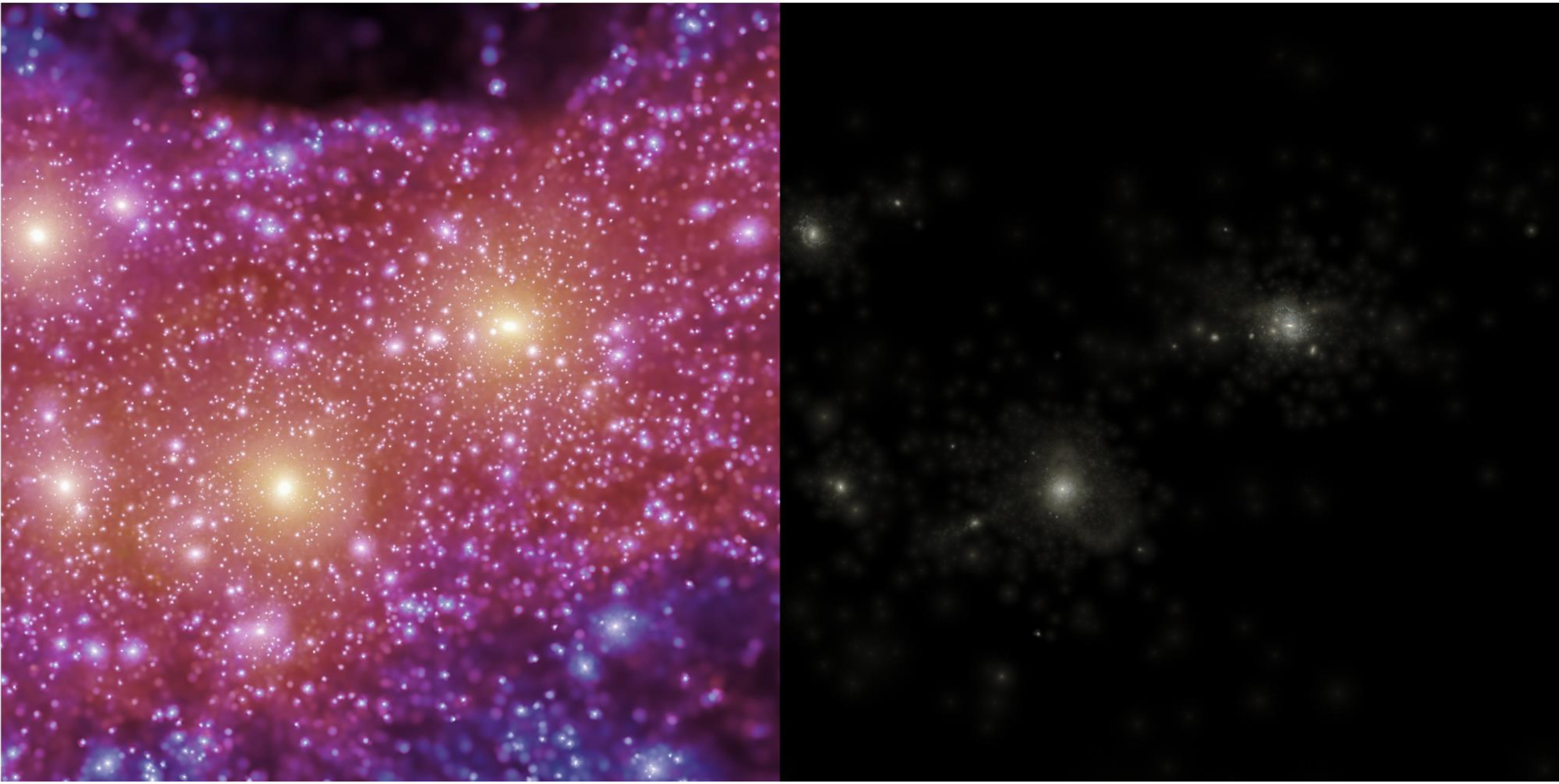
Bower, JS et al. (in prep)

Are the winds buoyant?



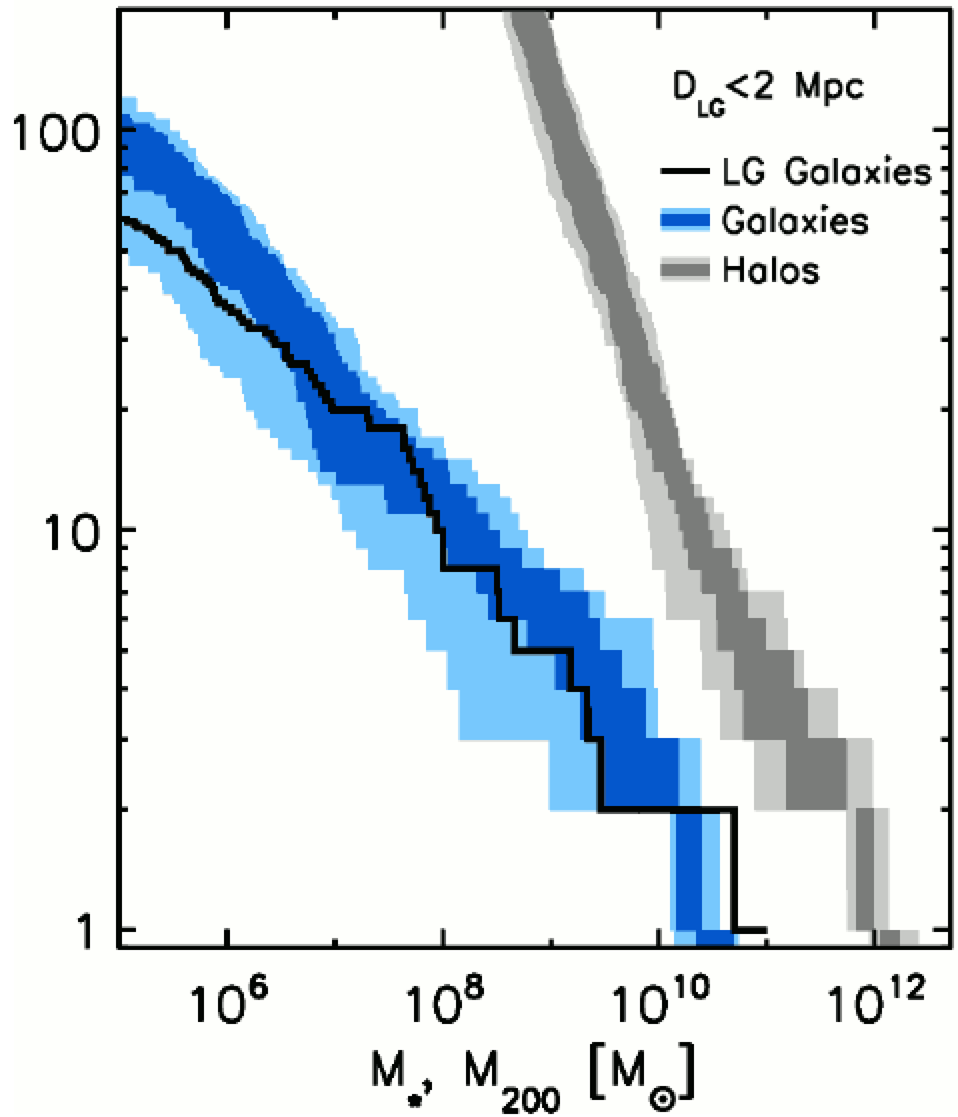
Bower, JS et al. (in prep)

EAGLE Zooms: The APOSTLE project



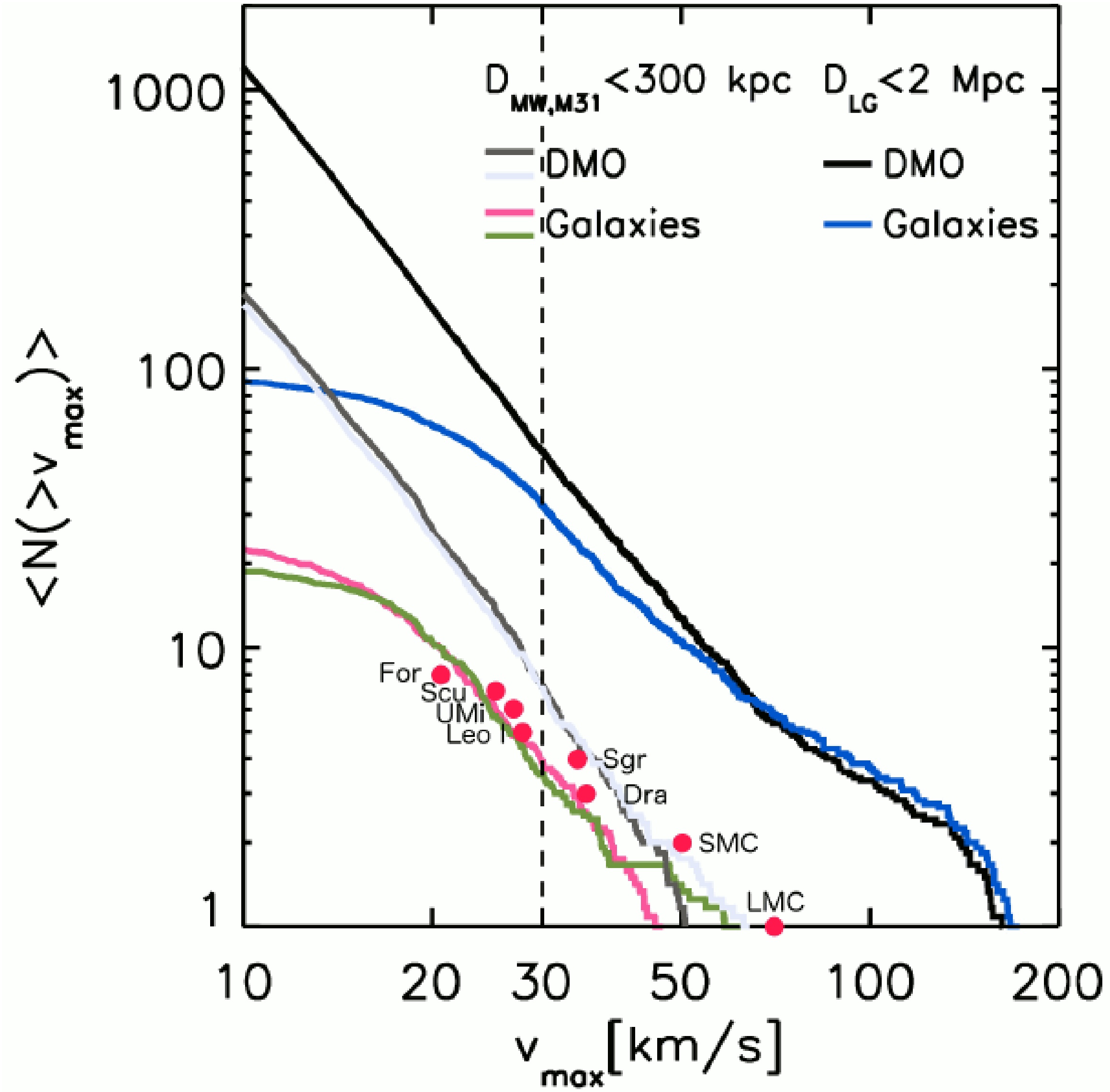
Sawala et al. (2016)

APOSTLE: No missing satellites



Sawala et al. (2016)

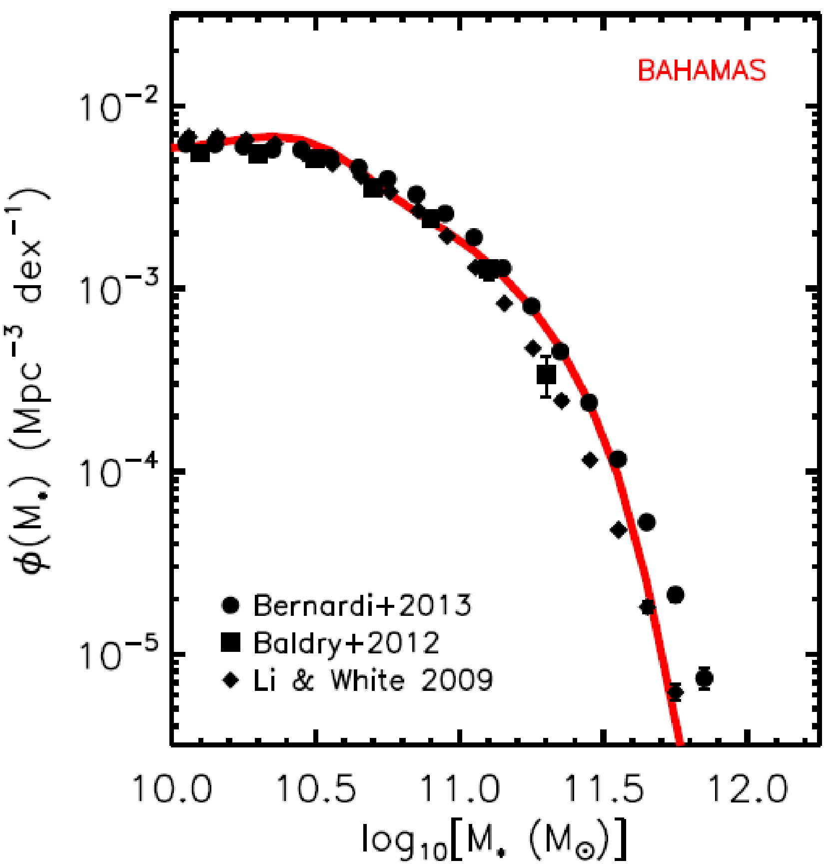
APOSTLE: Not too big to fail



Sawala et al. (2016)

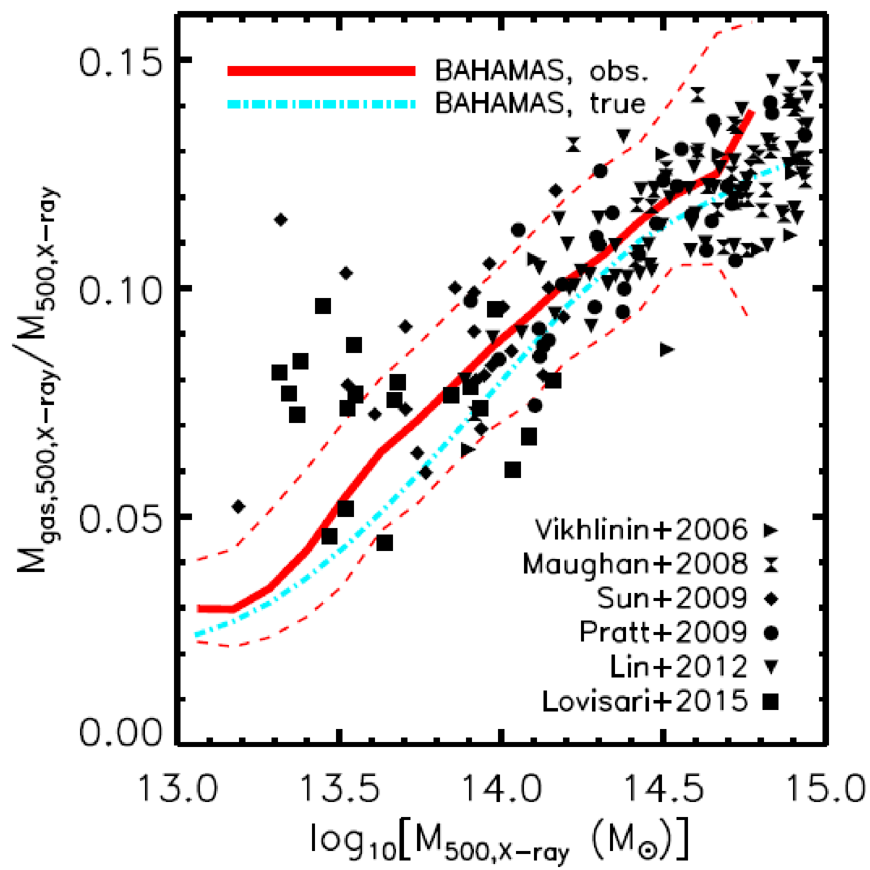
BAHAMAS project

Optical:
Galaxy stellar mass function



Calibration:
Constant velocity of fully coupled kinetic stellar feedback

X-ray:
Cluster gas fraction



Calibration:
Temperature jump of AGN thermal feedback events

McCarthy, JS, Bird, Le Brun (2016)

Conclusions: 1/2

- Galaxy formation is self-regulated. Feedback is critical.
- Cannot predict stellar and black hole masses precisely, feedback needs to be calibrated.
- Unrealistic models can match the relation between stellar and halo mass.
- A large and diverse set of observations are reproduced once the z=0 mass function and sizes match the data (but not everything works!)
- Simple, natural feedback recipes suffice.

Conclusions: 2/2

- Alpha enhancement due to quenching of star formation by AGN
- Lack of buoyancy of wind fluid quenches stellar feedback in hot, hydrostatic haloes.
- Black hole growth and galaxy bimodality are triggered by stellar feedback becoming inefficient.
- Feedback from reionization and star formation solves the “missing satellite” and the “too big to fail” problems.

What is next?

- Higher-resolution enables simulating a colder interstellar gas phase
- Enables formation of thinner disc galaxies
- Subgrid models kick in at smaller scales
- Feedback prescriptions can capture more physics
- Can start to ask key questions like:

  What drives outflows?
- Already possible in zooms of individual galaxies