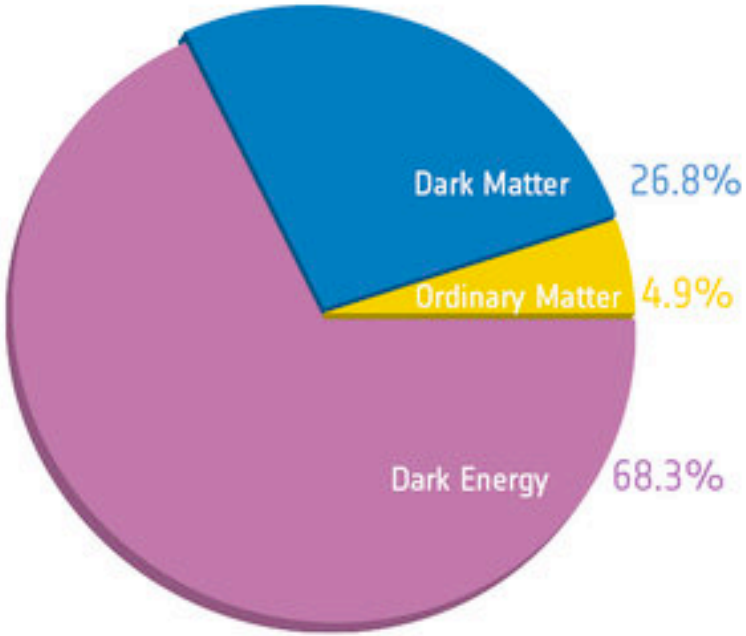
Simulations of Galaxy Formation: the State of the Art

Julio F. Navarro

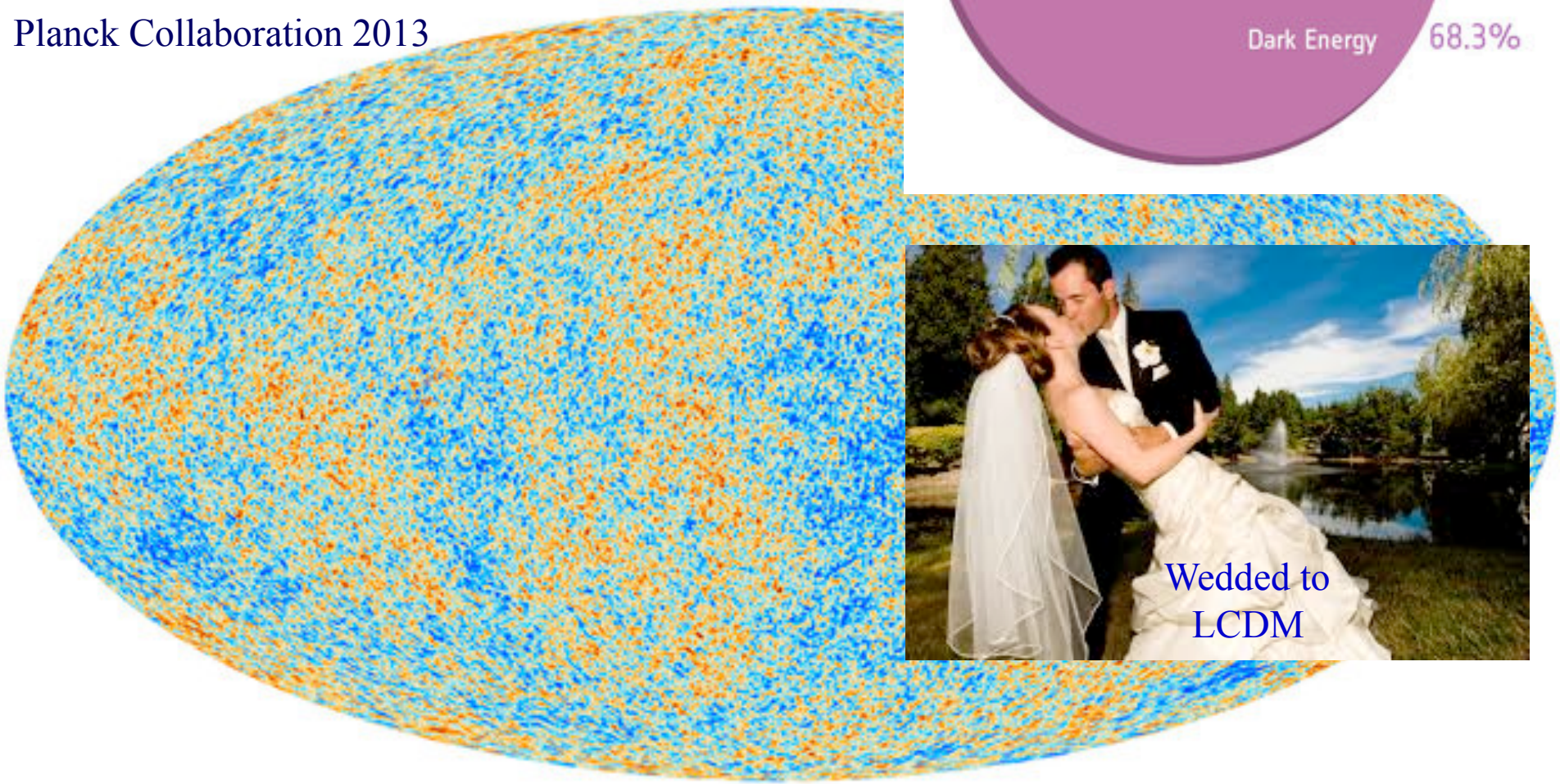
Themes

- The Cosmology
  - Hierarchical clustering and its problems
  - Dark matter halos and galaxies
  - The importance of feedback
- Subgrid physics and numerical methods
- Recent results
- Outstanding problems and outlook

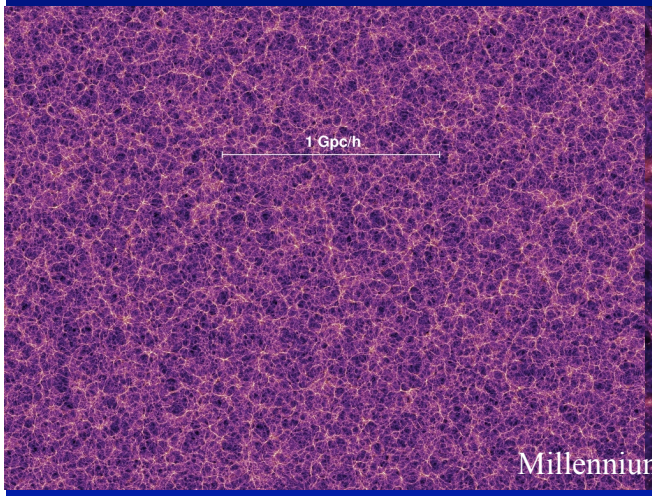
The Standard Model of Cosmology

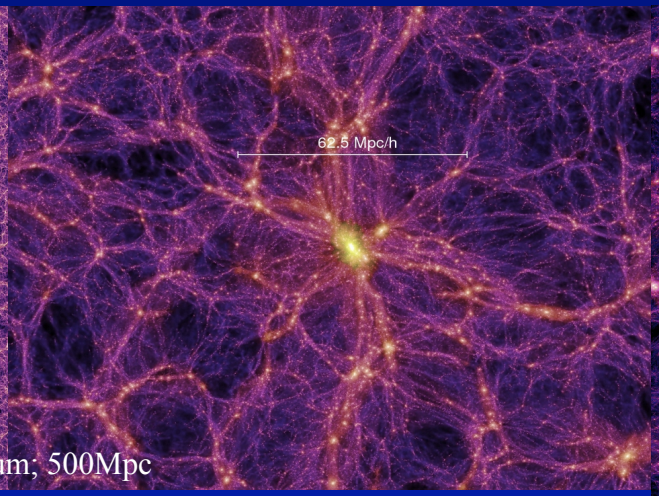


Planck Collaboration 2013

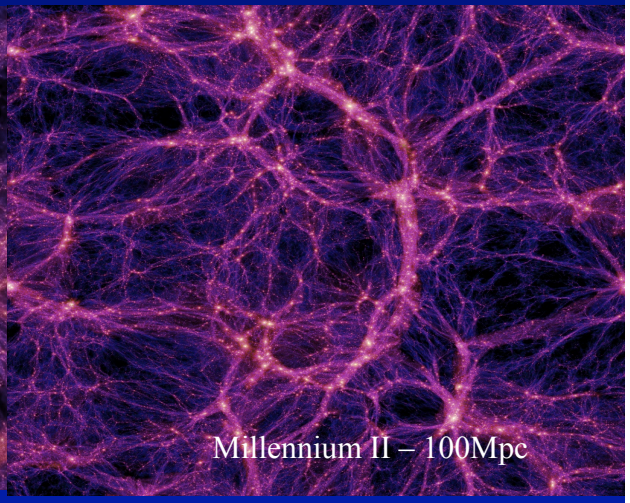


The Clustering of Dark Matter



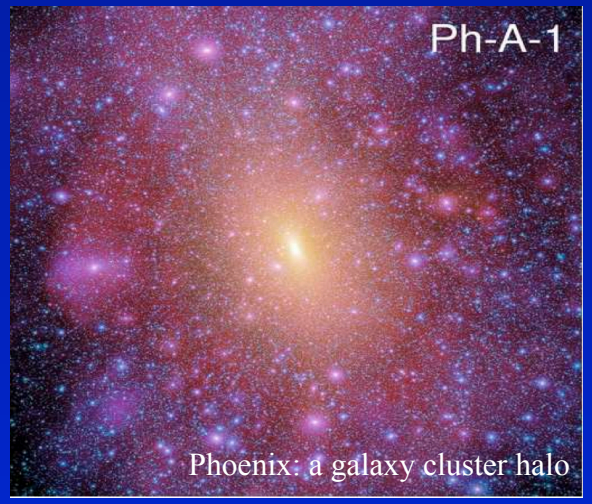


Millennium; 500Mpc



Millennium II – 100Mpc

Aquarius: a galaxy halo



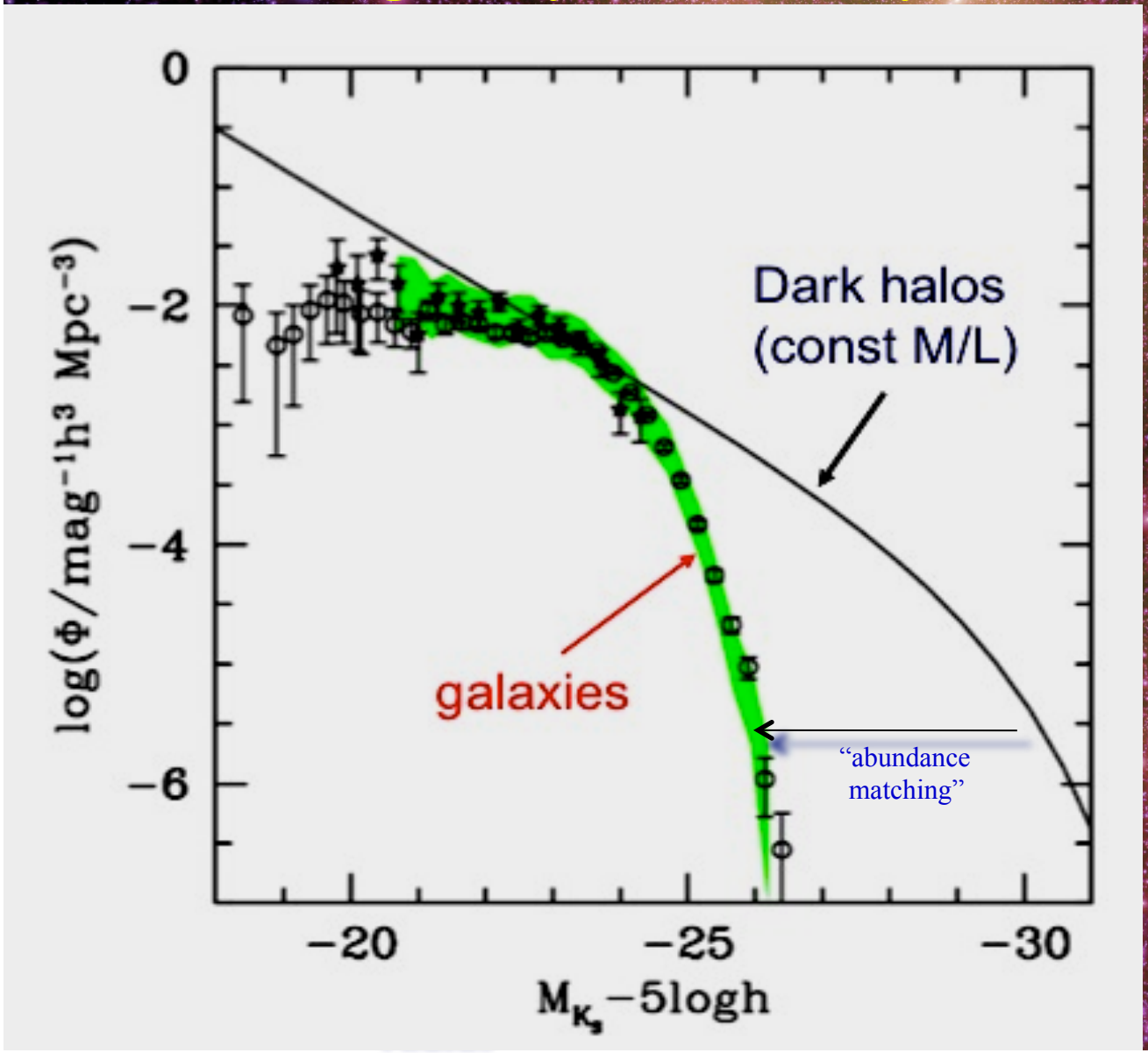
Phoenix: a galaxy cluster halo

Simulations have enabled a full characterization of the clustering of cold dark matter on essentially all astrophysically-relevant scales.

THE PROBLEMS

- Hierarchical assembly
  - Small scales assemble first, unlike galaxies?
- Inventory
  - Many more halos than galaxies
- Early assembly
  - Gas becomes available for star formation at high z
- Baryon budget
  - Most baryons can be accreted into galaxies—but few are
- Mergers
  - Loss of angular momentum
  - Stellar disk survival/ bulgeless galaxies?

CDM halo mass function vs galaxy luminosity function

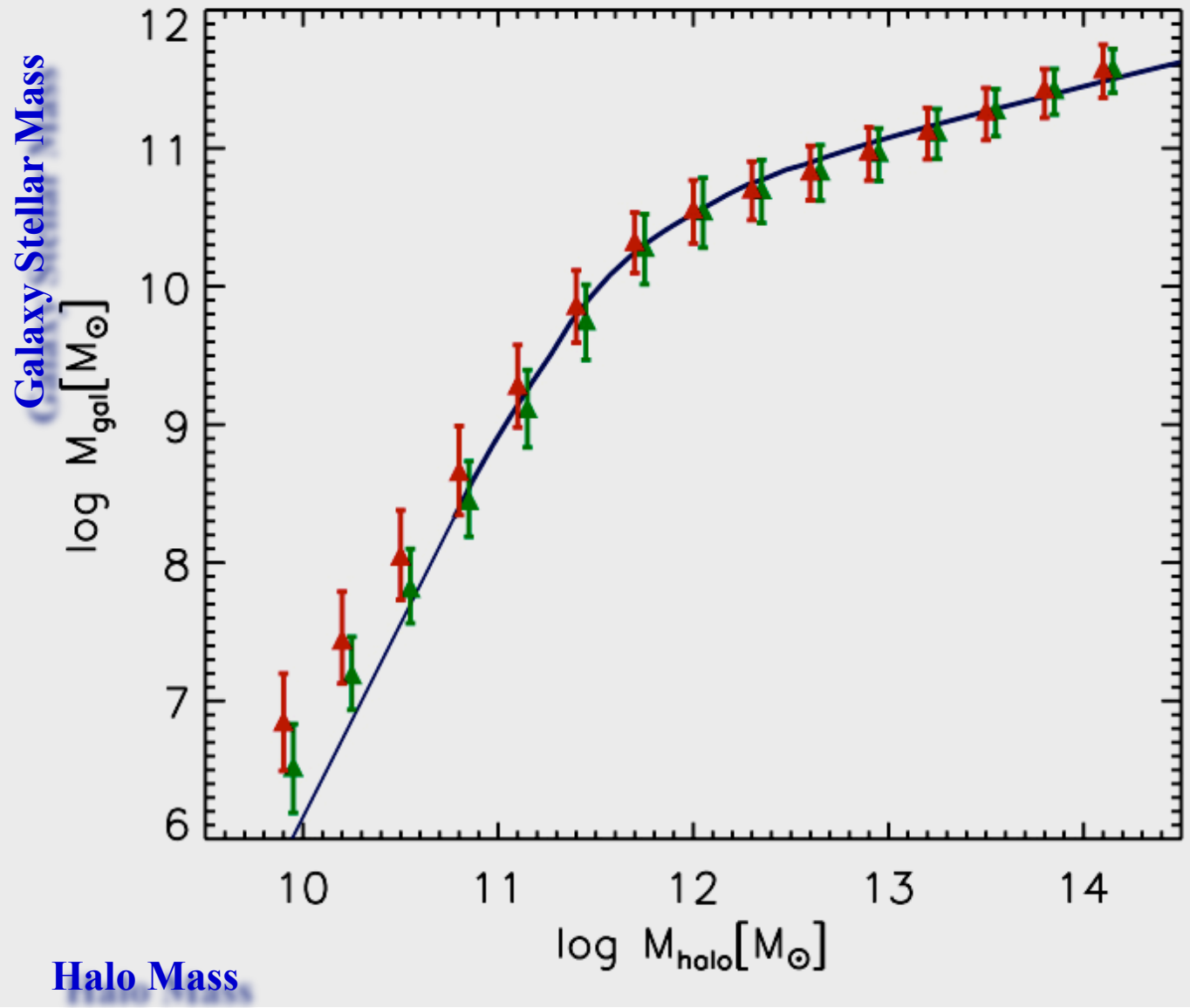


•CDM halo mass function is very well determined from cosmological simulations

• It is *much steeper* than the galaxy luminosity function at the faint end and much shallower at the bright end

•Reconciling the two requires a highly non-linear dependence between galaxy and halo mass.

Galaxy Stellar Mass vs Halo Mass

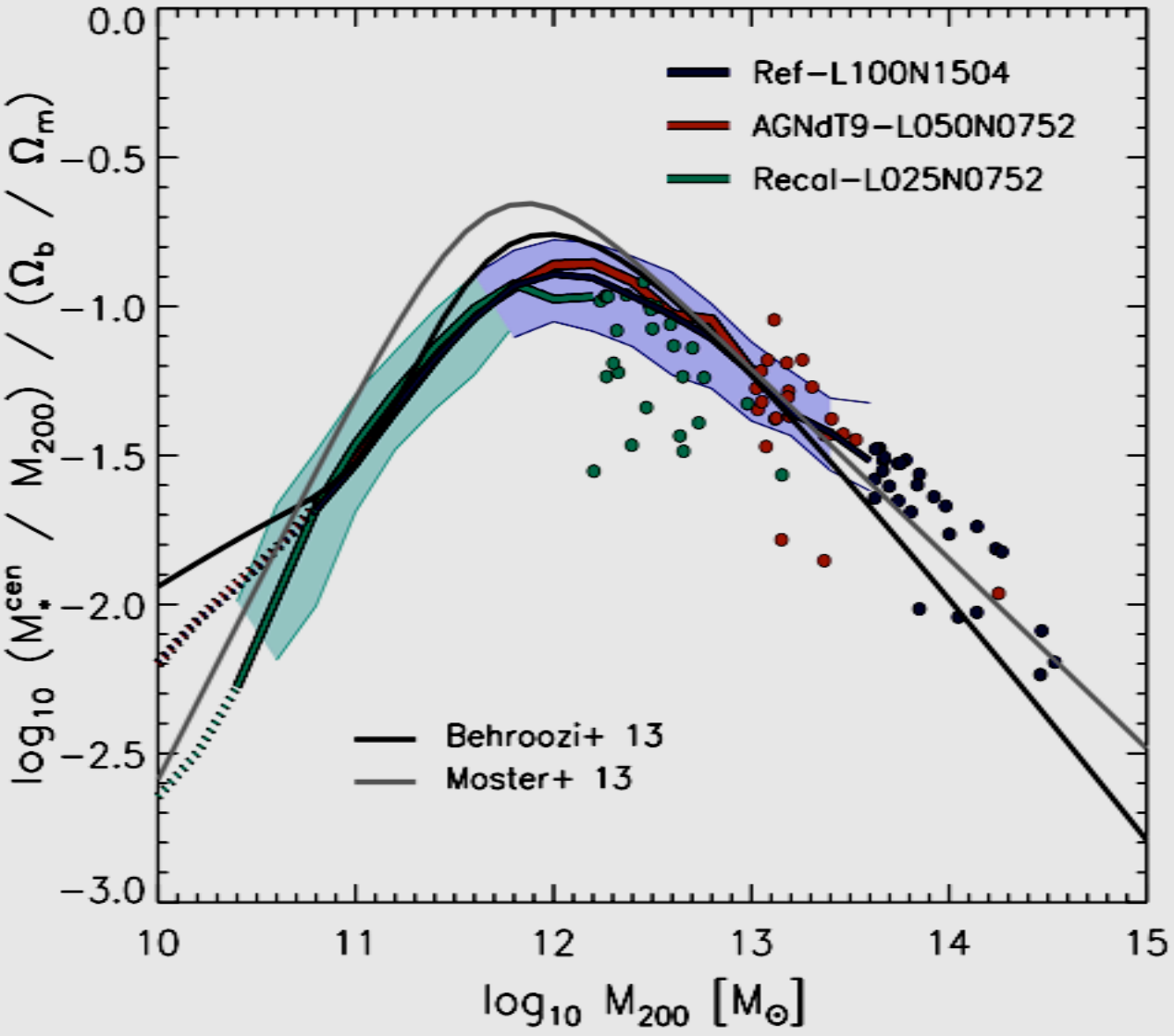


- Steep dependence at low halo mass---implies that most dwarfs live in similar-mass halos

- Yet dwarf galaxies show great diversity in their properties. What is the origin of such diversity?

Guo et al 2011

Galaxy formation efficiency



- Fewer than ~10% of the baryons of each halo make it into galaxies---halo assembly and galaxy assembly may differ substantially

- Halo mass accretion rates ≠ SFR.

- Halo merger rates may be only indirectly related to galaxy merger rates and hence to galaxy morphology

- Angular momentum of baryons may have little relation with the angular momentum of halos.

The importance of feedback

- Main idea:
  - Energy released by evolving stars and massive black holes ("feedback") is responsible for most galaxy properties
  - This is energetically possible---for most galaxies, the energy released is comparable to the its binding energy
  - But difficult---most feedback energy could in principle be radiated away
- Main forms of feedback:
  - Cosmic reionization
  - "Winds" driven by evolving stars/supernovae
  - AGN-driven feedback

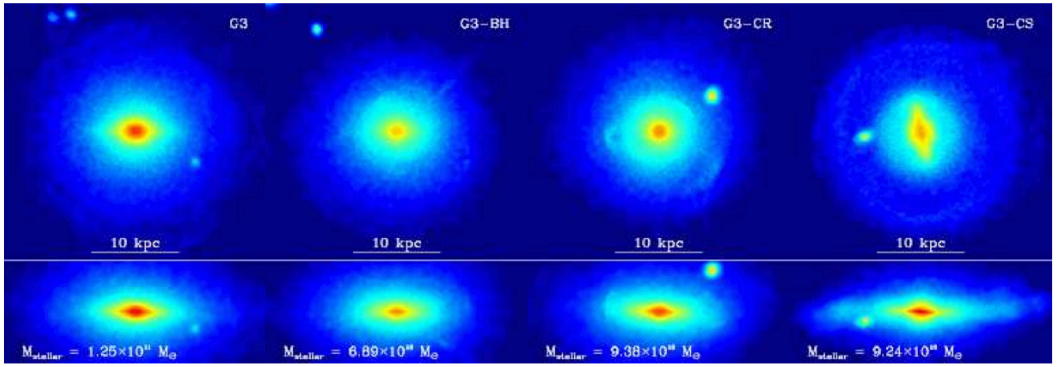
Feedback

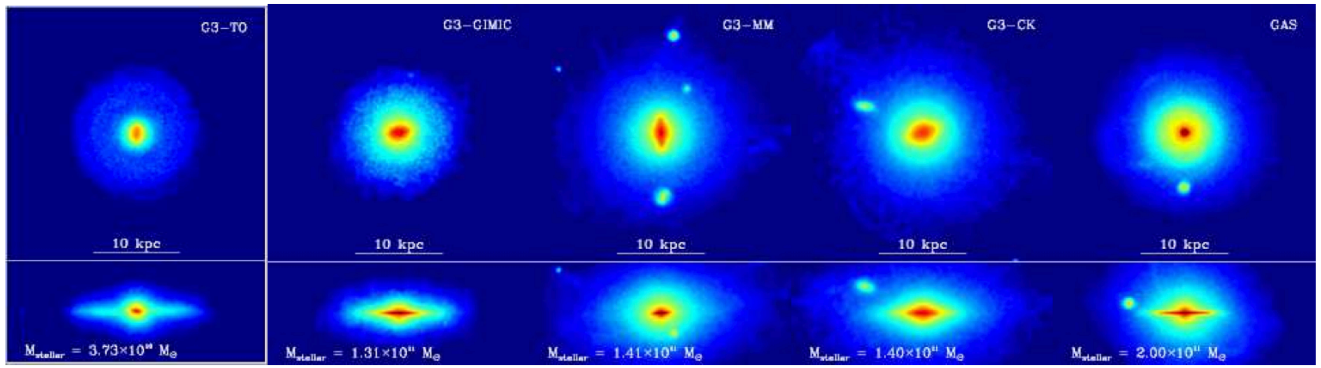
- Feedback physics is complex and ill understood
- Numerical resolution is limited
  - even the most recent simulations resolve a galaxy with at best a few million mass elements
- All galaxy formation simulations rely on "subgrid physics"---numerical modules that are *nearly arbitrarily* calibrated to fit predetermined outcomes
  - This hides many "sins" ("turning off" cooling, "decoupling" winds, etc)
- Simulations are not predictive tools, but rather sophisticated interpretive aides to observation

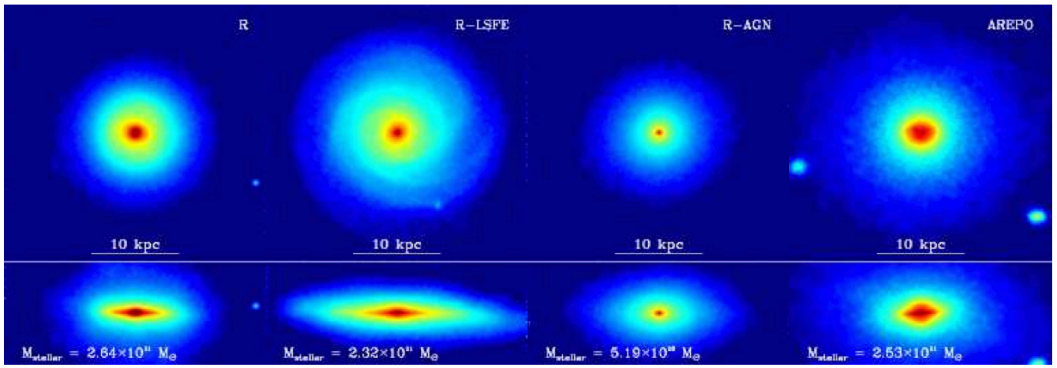
Simulations

- Numerical Methods
  - Smoothed Particle Hydrodynamics
  - Adaptive Mesh Refinement
  - Adaptive Mesh
- Volumes
  - Cosmologically representative volumes (~100 Mpc box)
    - Calibrated to reproduce the galaxy luminosity or mass function
  - "Zoomed-in" runs (typically one halo at a time)
    - Calibrated to reproduce either galaxy morphology (a disk?) or the efficiency of galaxy formation

The Aquila Project



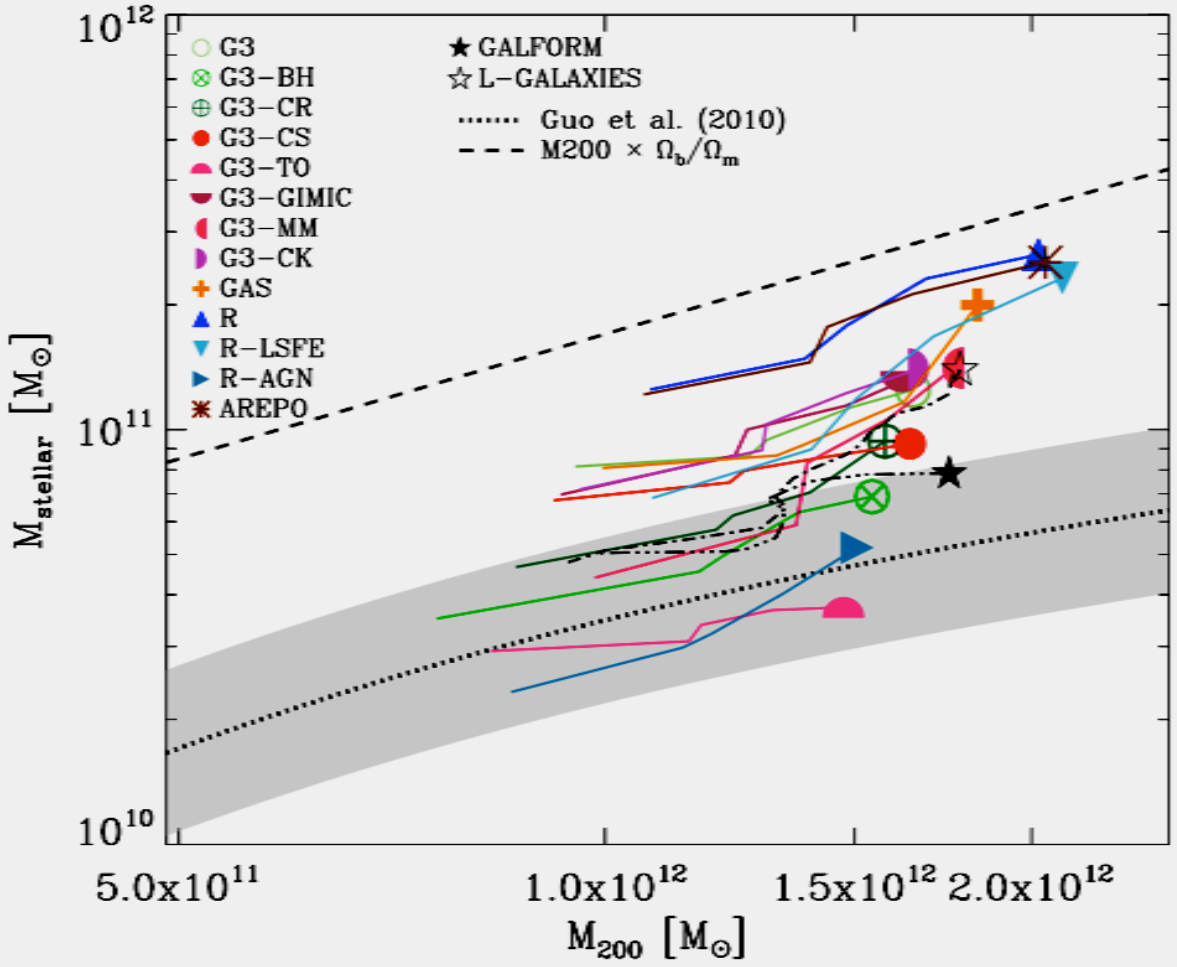




- Many codes were applied to the same initial conditions for a single Milky Way-sized halo
- Simulators were allowed to choose the feedback scheme of their choice
- Results illustrate the wide variety of morphologies, stellar and gaseous masses, and formation histories.
- Most (all?) simulated galaxies failed to match observed disks

Scannapieco et al 2012

The Aquila Project: M_*-M_{halo}

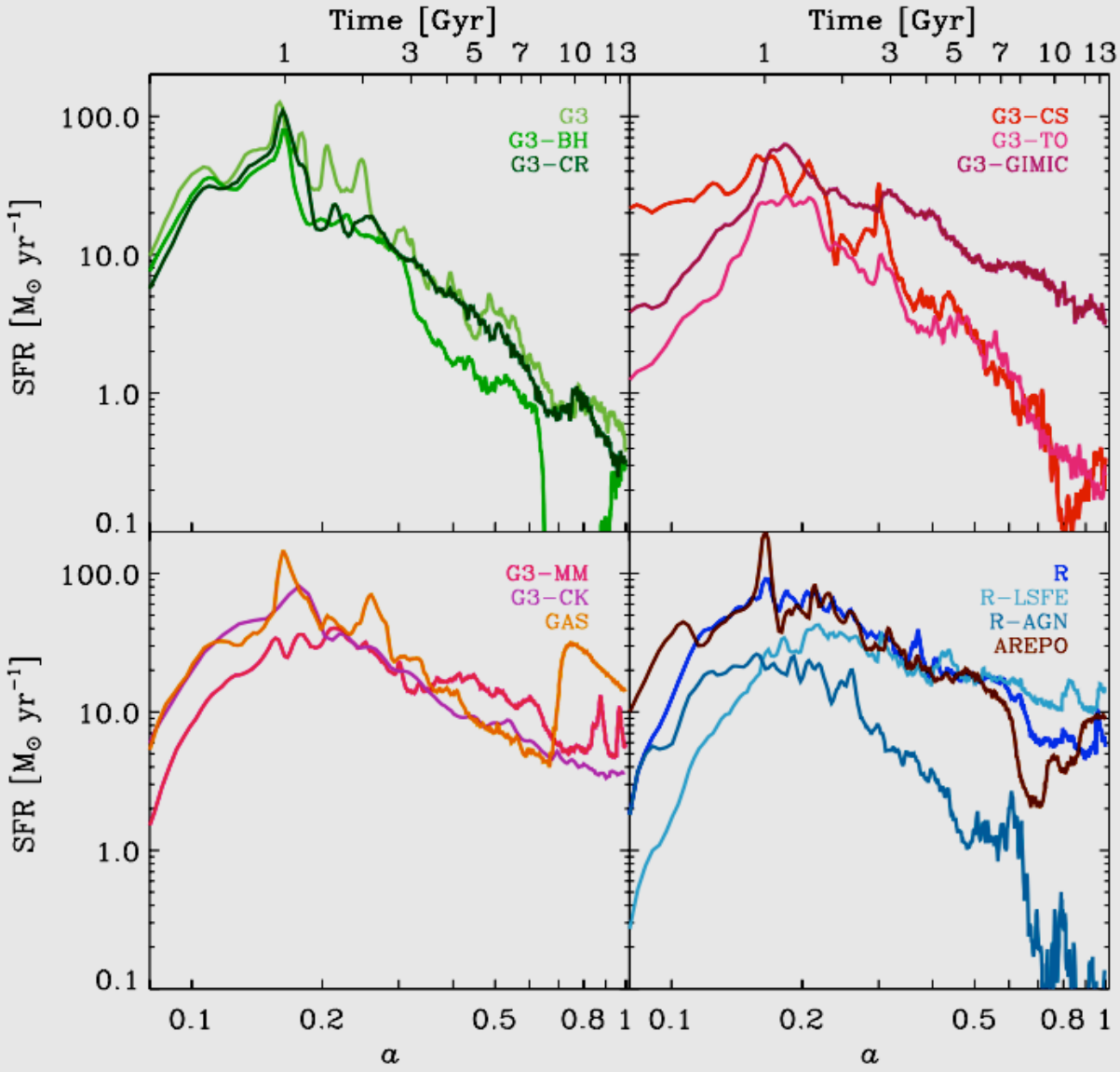


- Aquila galaxies are typically too massive, too concentrated, and form stars much earlier than expected for a "Milky Way-like" galaxy.

- Simulated galaxies that curtailed the early onset of star formation did best.

Scannapieco et al 2012

The Aquila Project: Star Formation Rates

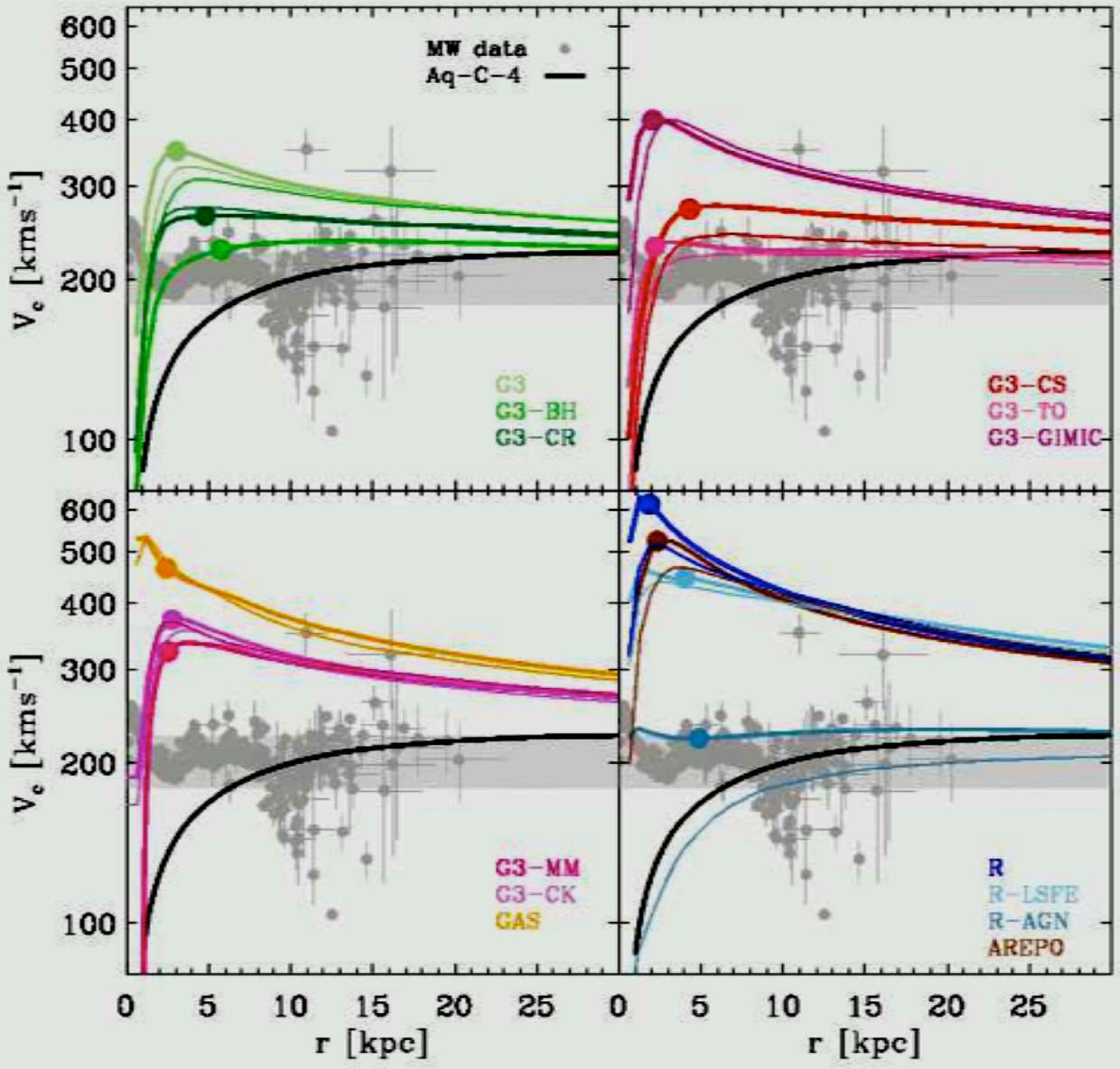


- Aquila galaxies are typically too massive, too concentrated, and form stars much earlier than expected for a "Milky Way-like" galaxy.

- Simulated galaxies that curtailed the early onset of star formation did best.

Scannapieco et al 2012

The Aquila Project: Rotation curves

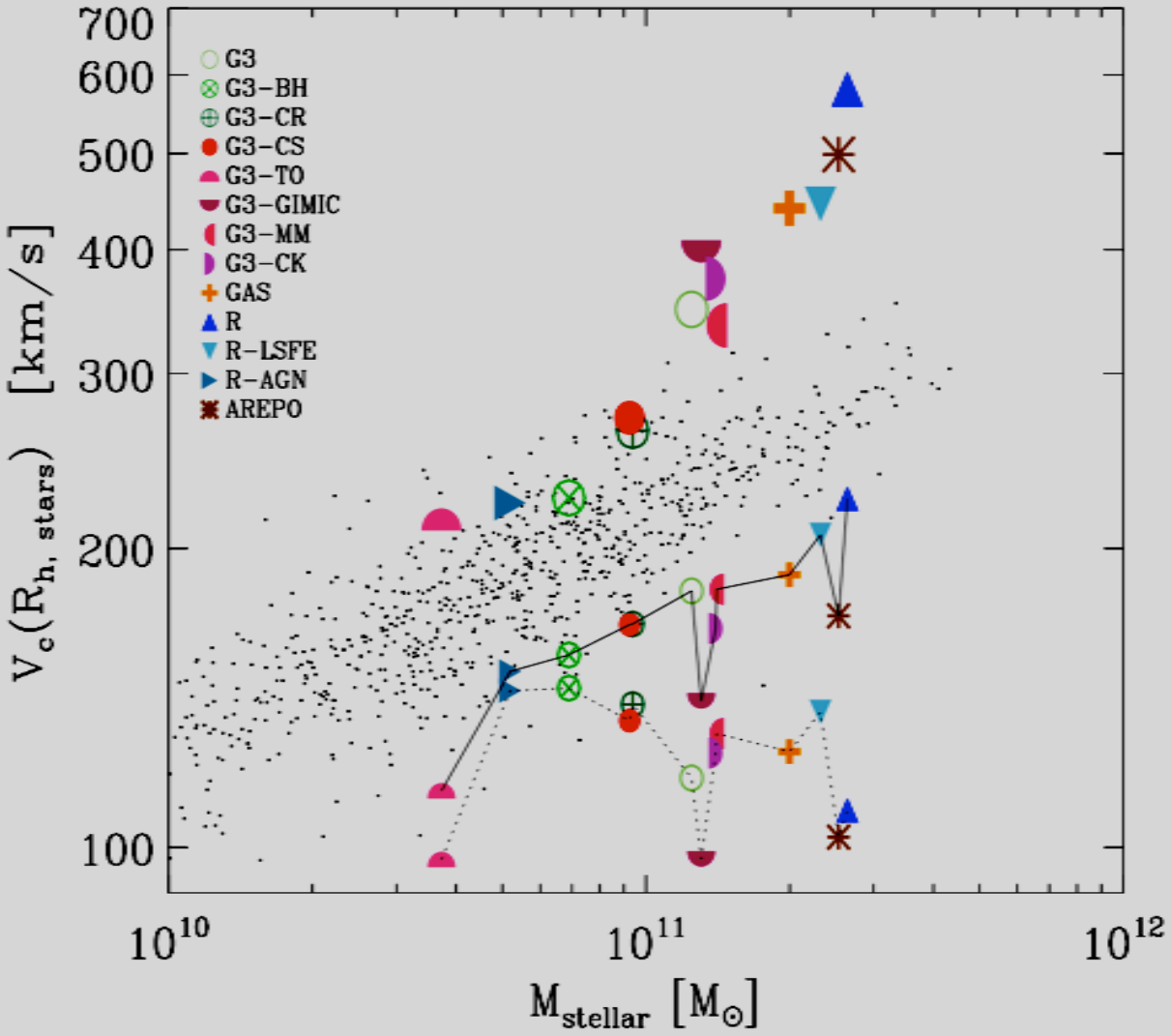


- Aquila galaxies are typically too massive, too concentrated, and form stars much earlier than expected for a "Milky Way-like" galaxy.

- Simulated galaxies that curtailed the early onset of star formation did best.

Scannapieco et al 2012

The Aquila Project: Tully-Fisher relation

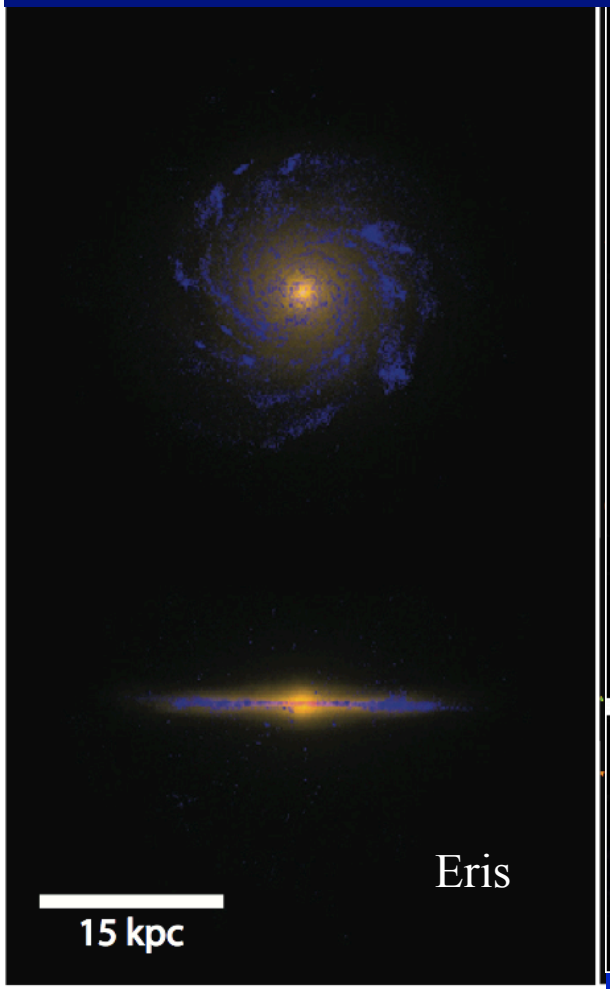


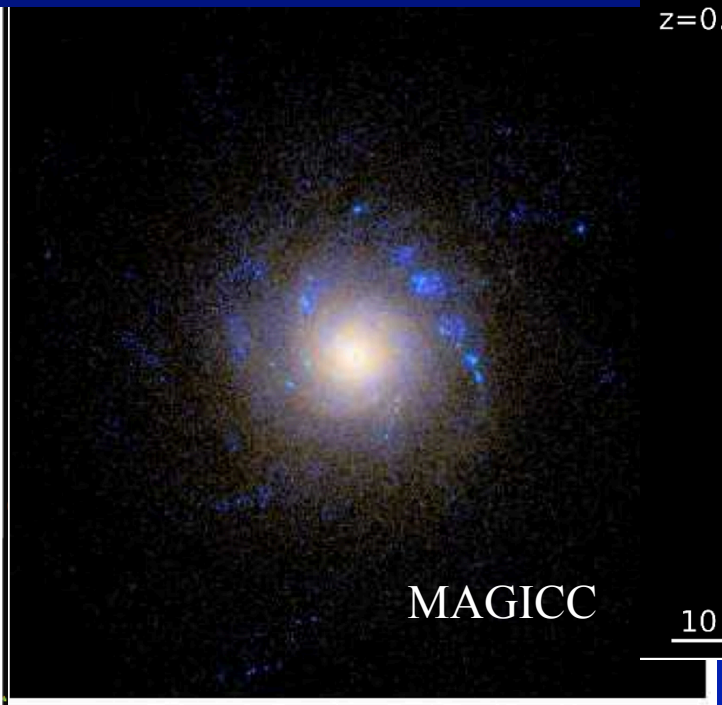
- Aquila galaxies are typically too massive, too concentrated, and form stars much earlier than expected for a "Milky Way-like" galaxy.

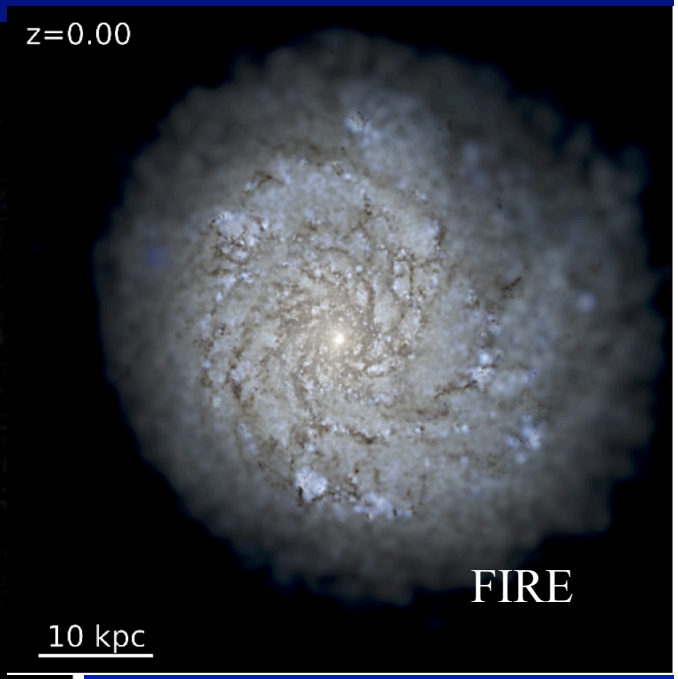
- Simulated galaxies that curtailed the early onset of star formation did best.

Scannapieco et al 2012

Individual galaxy simulations: state of the art



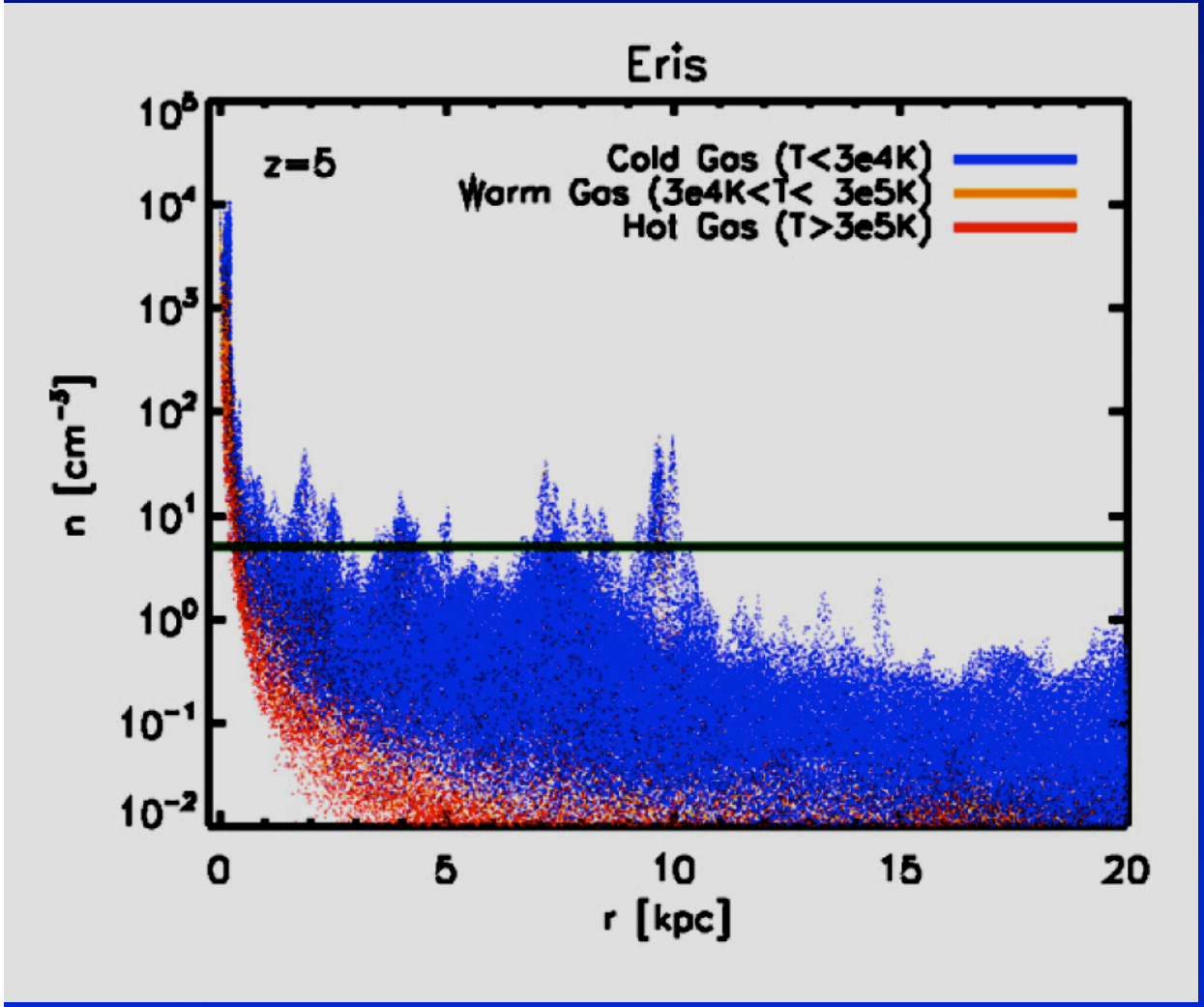




Hopkins ‘13,’14
Governato ‘10,’12, ‘14
Guedes ’11
Stinson’13
Aumer ’13,’14
Agertz’13

- These failures led most groups to update their feedback modules, and the results are now more encouraging.

Individual galaxy simulations: state of the art

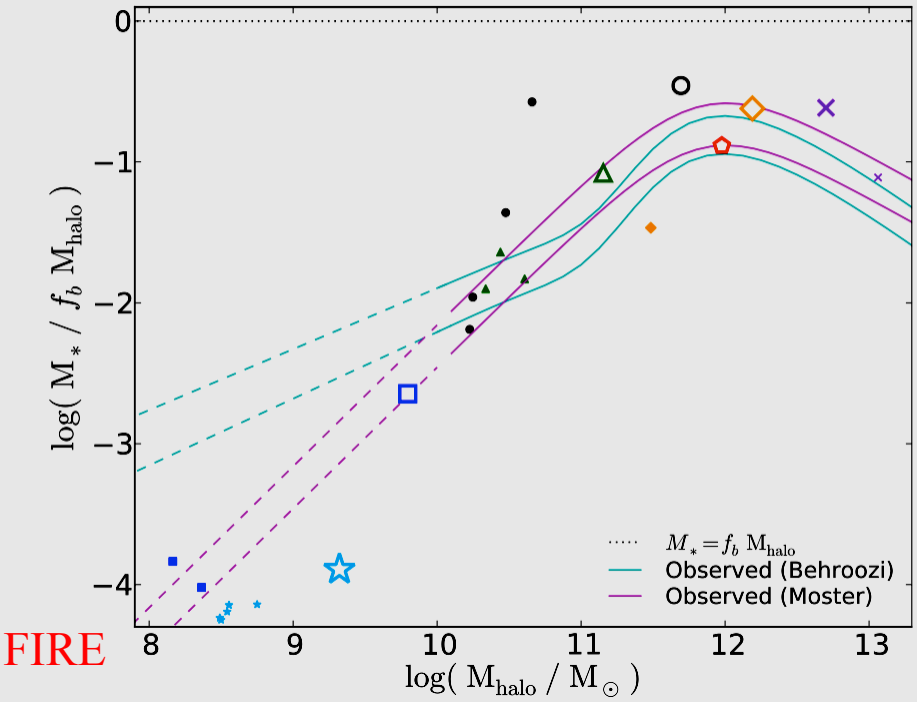


- The improvement has been attributed to
  - higher numerical resolution
  - the adoption of high thresholds for star formation
- n_H=5 cm^{-3} (Guedes'11);
- 7 cm^{-3} (Stinson'13);
- 100 cm^{-3}(Governato'10);
- 1000 cm^{-3} (Hopkins'14)

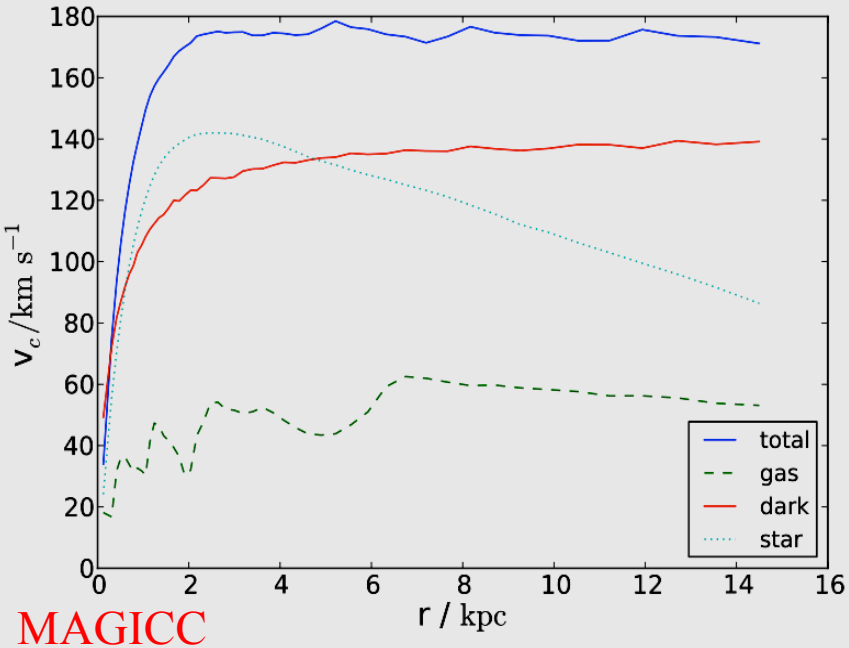
- All argue for good agreement with observation

Guedes et al 2011

Individual galaxy formation simulations



FIRE

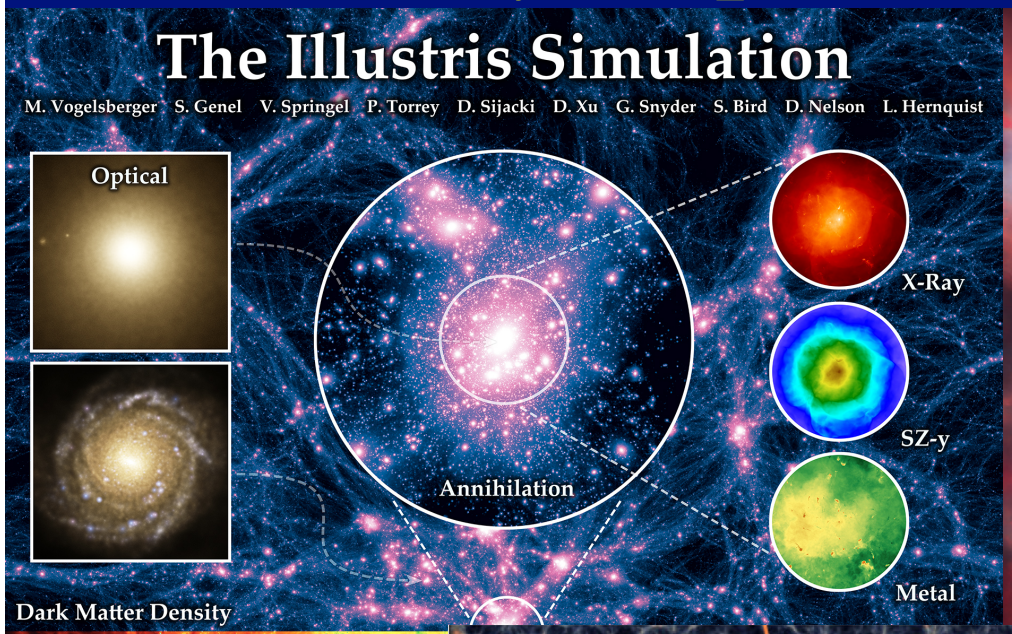


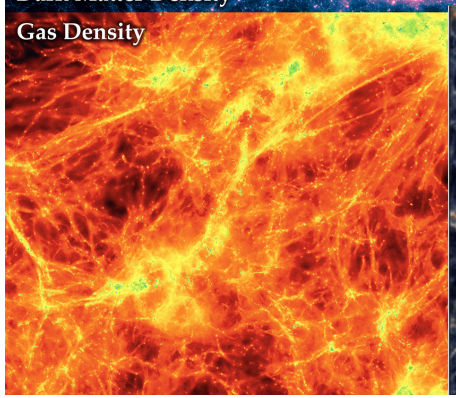
MAGICC

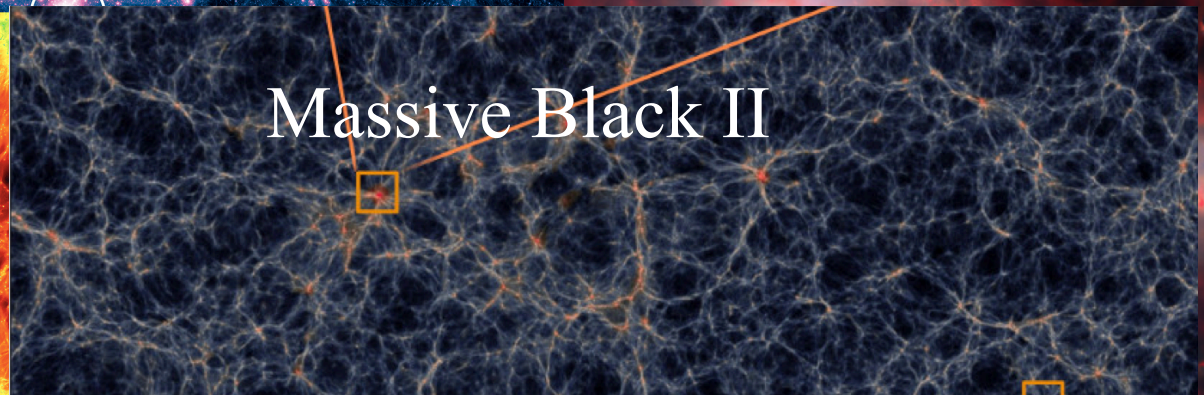
- "Success" is judged on the basis of galaxy morphology (exponential stellar disk); rotation curve shape (flat); and galaxy formation efficiency (low).
- This is progress, but.….simulations have little predictive power, and there is no hard proof that any of these halos should harbor disk galaxies.

- "We might not know what kind of galaxy inhabits an individual halo, but we do know what the population of galaxies looks like." (Scannapieco'12)

Galaxy Population Simulations

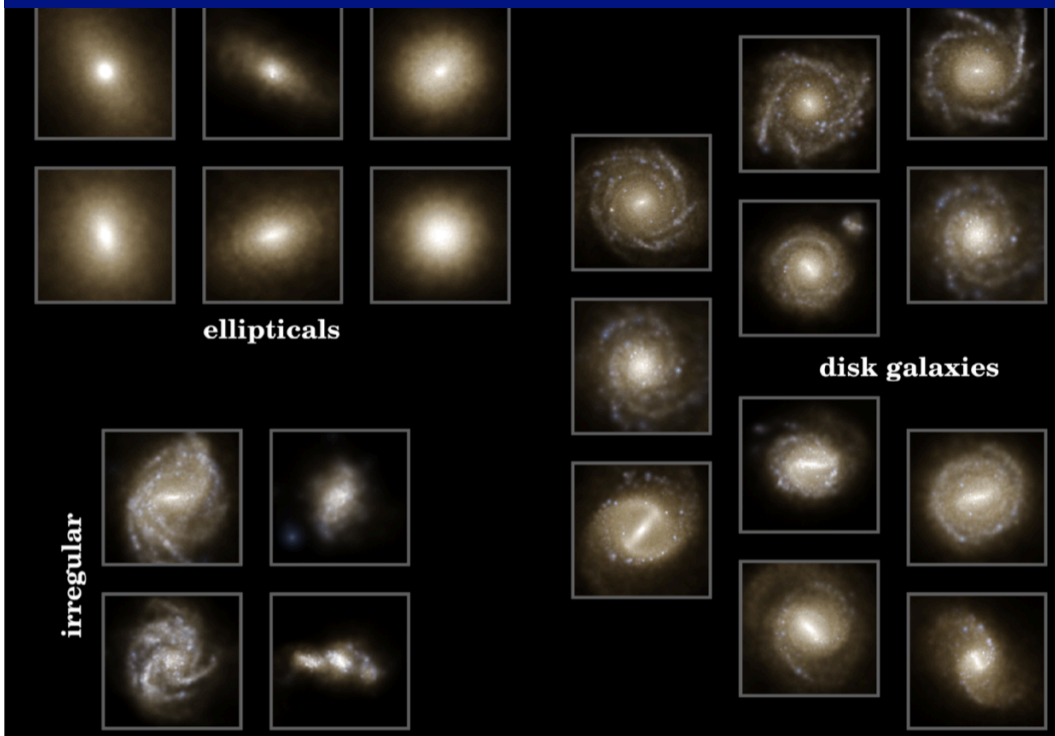


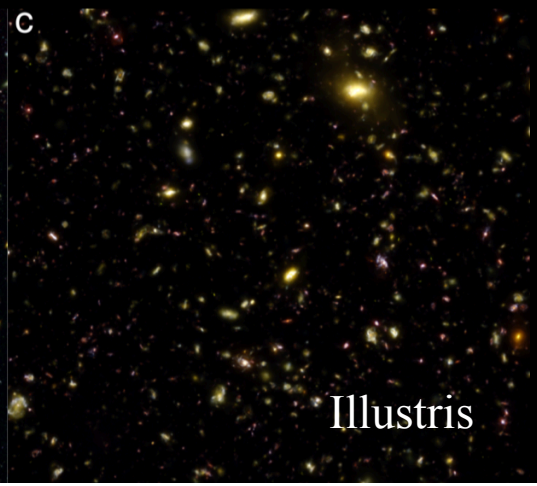




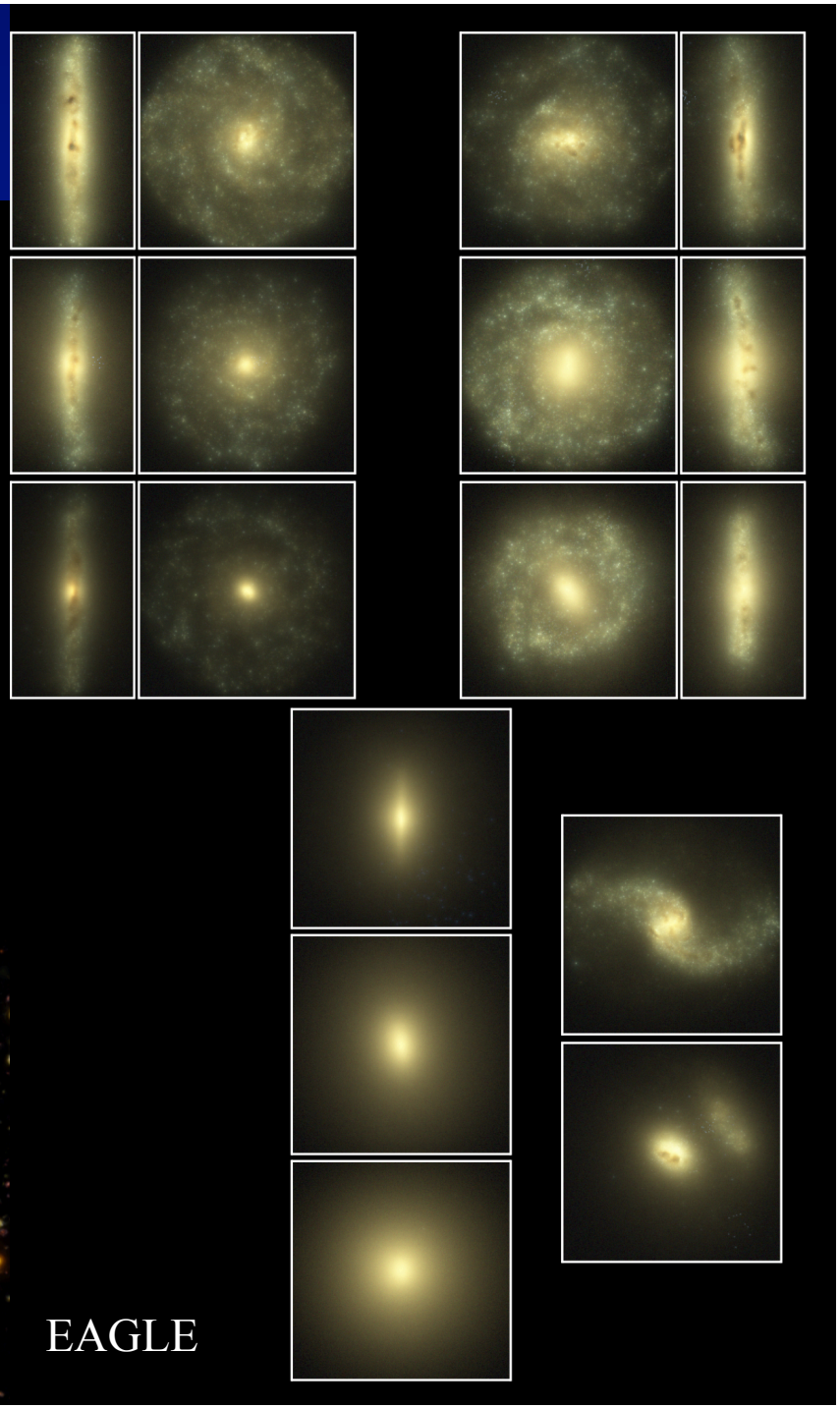
- Three large simulation suites of cosmologically representative volumes (~100 Mpc box) have recently been completed
- Resolution (per galaxy) is worse than individual galaxy simulations, but agreement with observation is quite good

Galaxy gallery



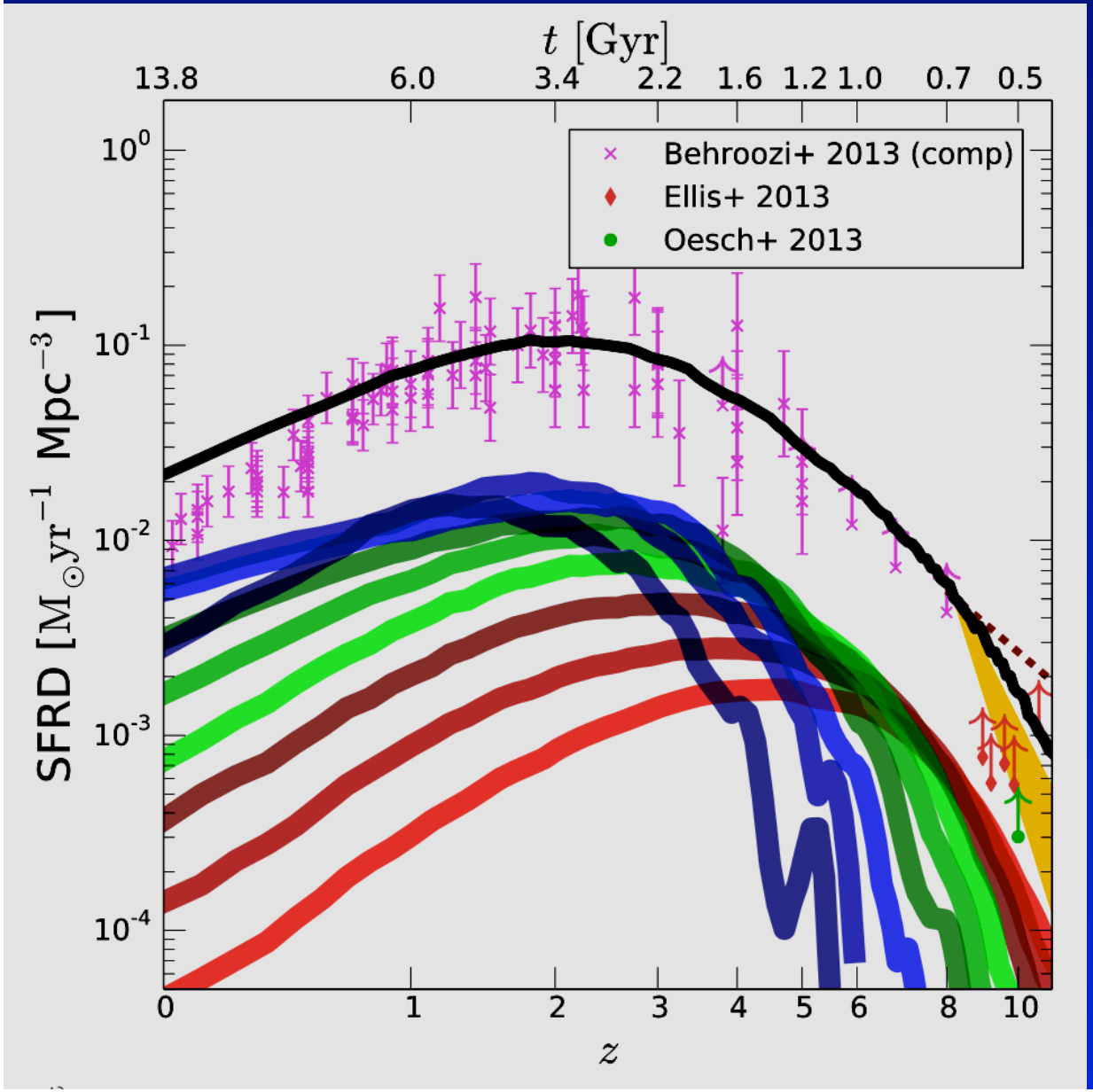


Illustris



EAGLE

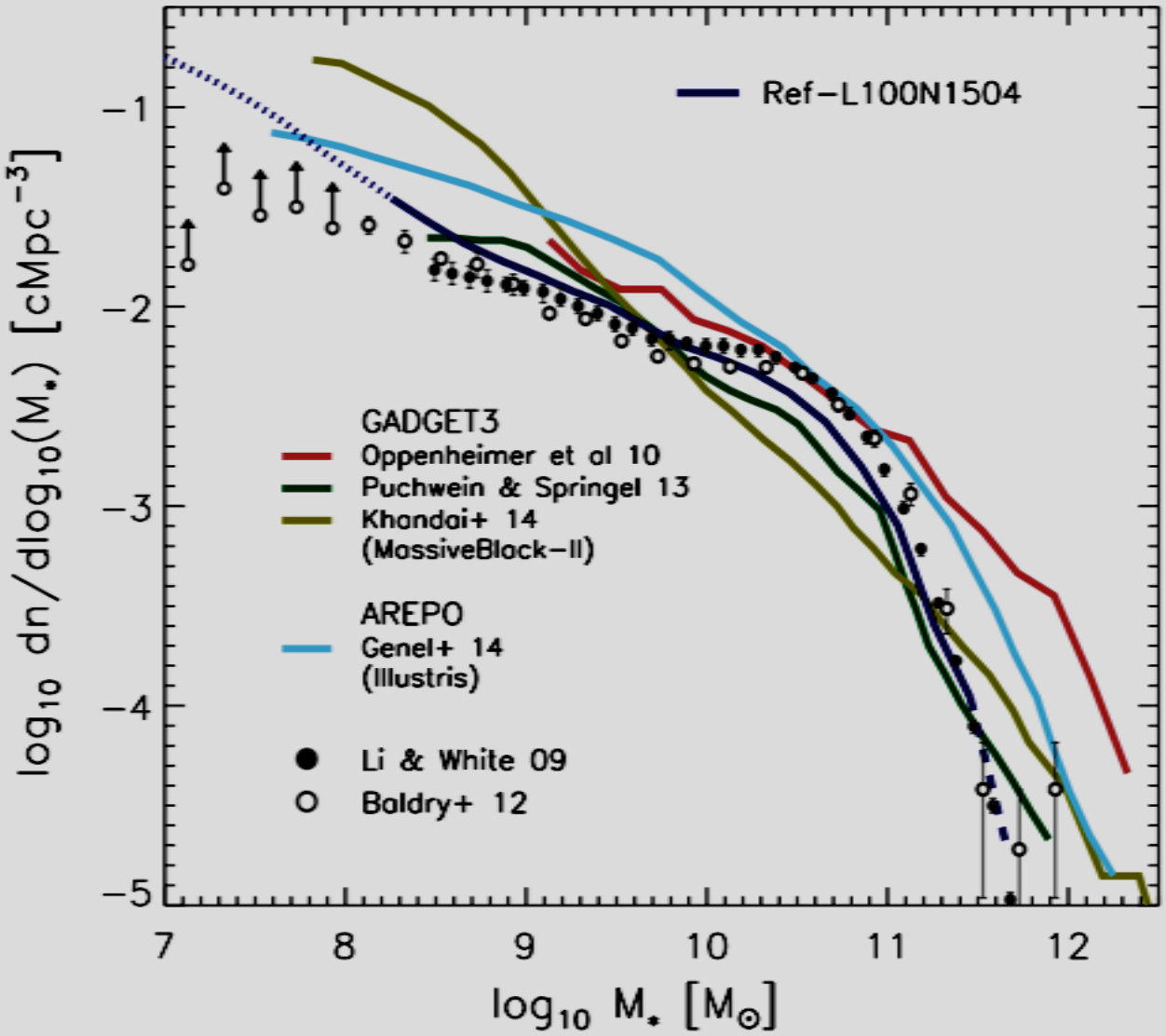
Cosmic Star Formation History



- The time evolution of cosmic star formation is reasonably well reproduced.
- There is a hint that simulations still form too many stars

Vogelsberger et al 2014

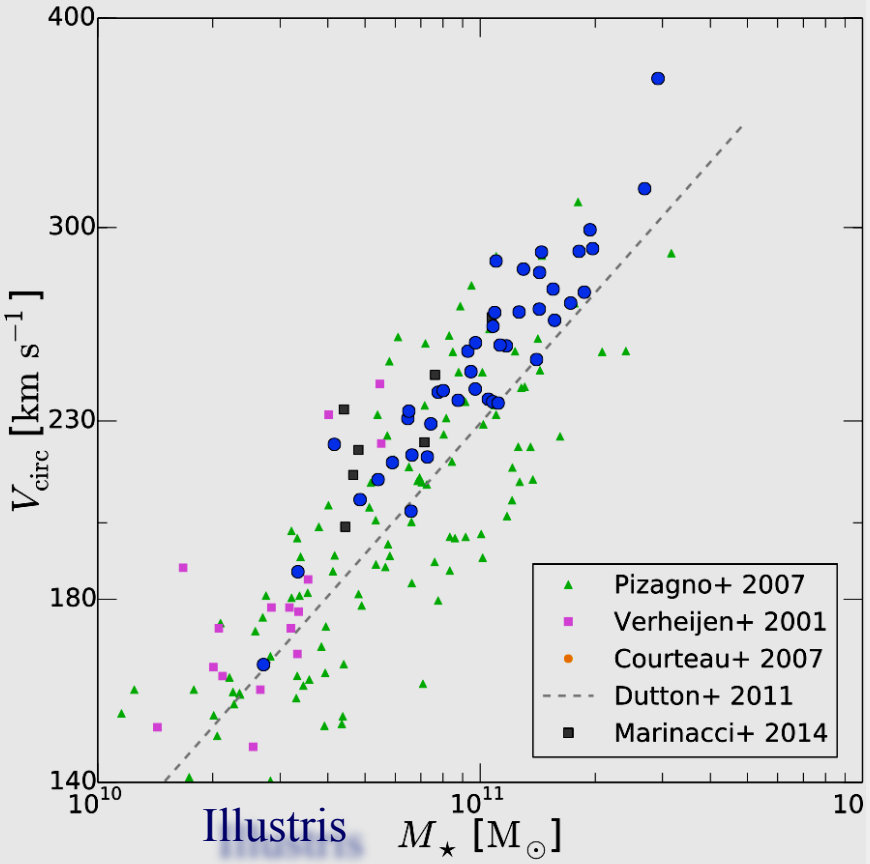
Galaxy Stellar Mass Function

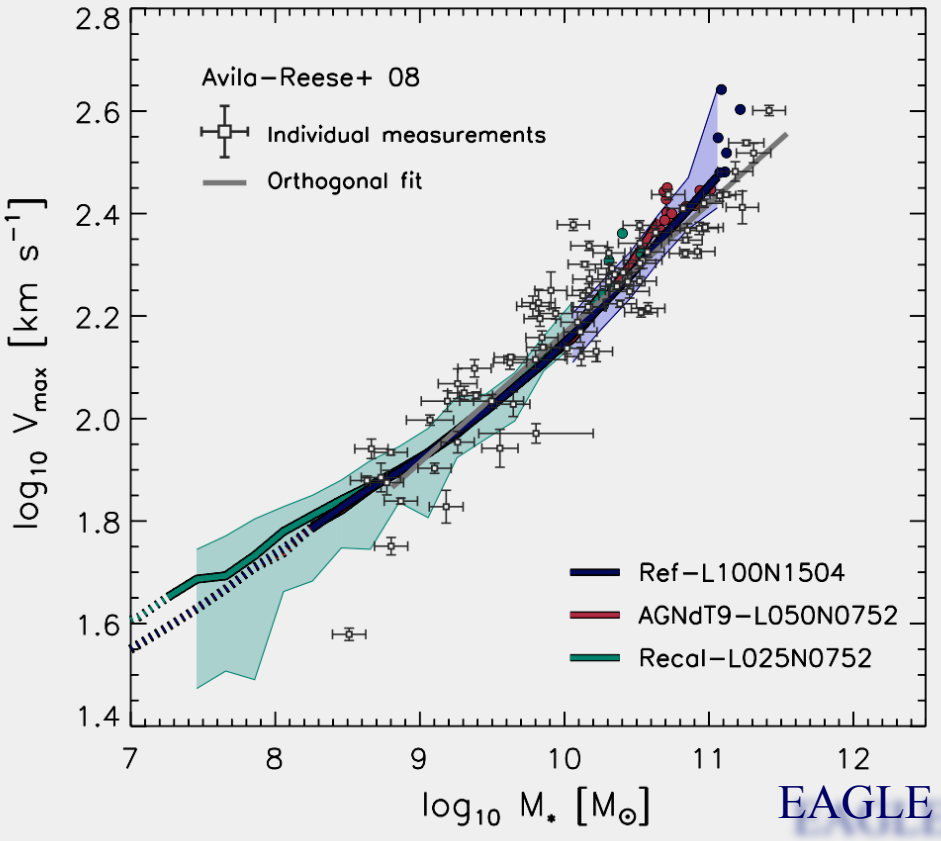


- Feedback is able to reproduce the shape of the galaxy luminosity/ stellar mass function
- Some simulations match it more closely than others, but one shouldn't perhaps read too much into that.

Schaye et al 2014

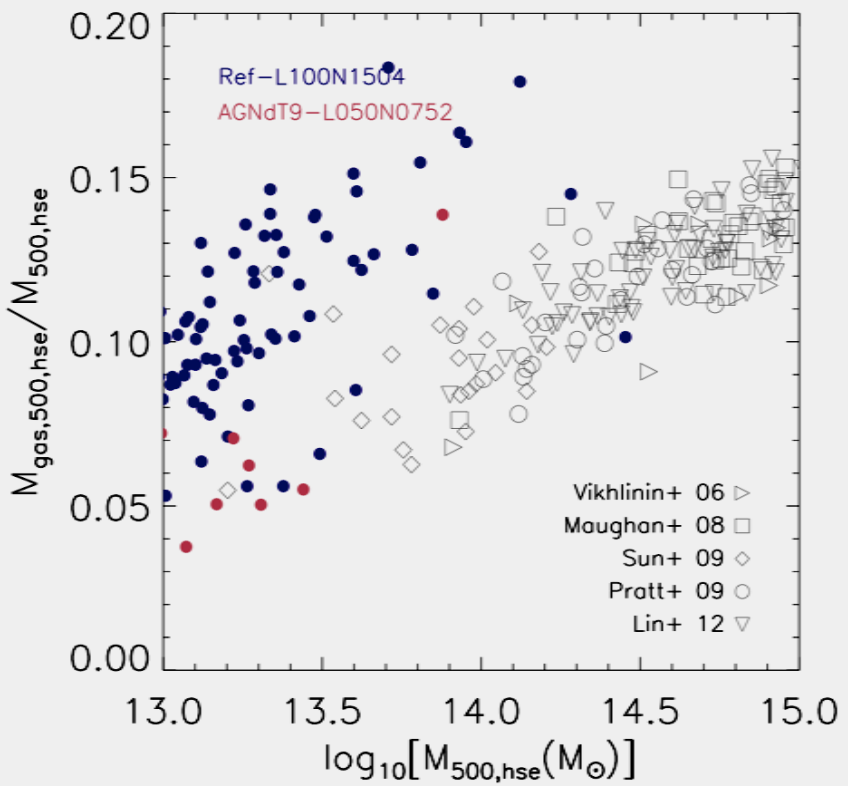
Tully-Fisher relation



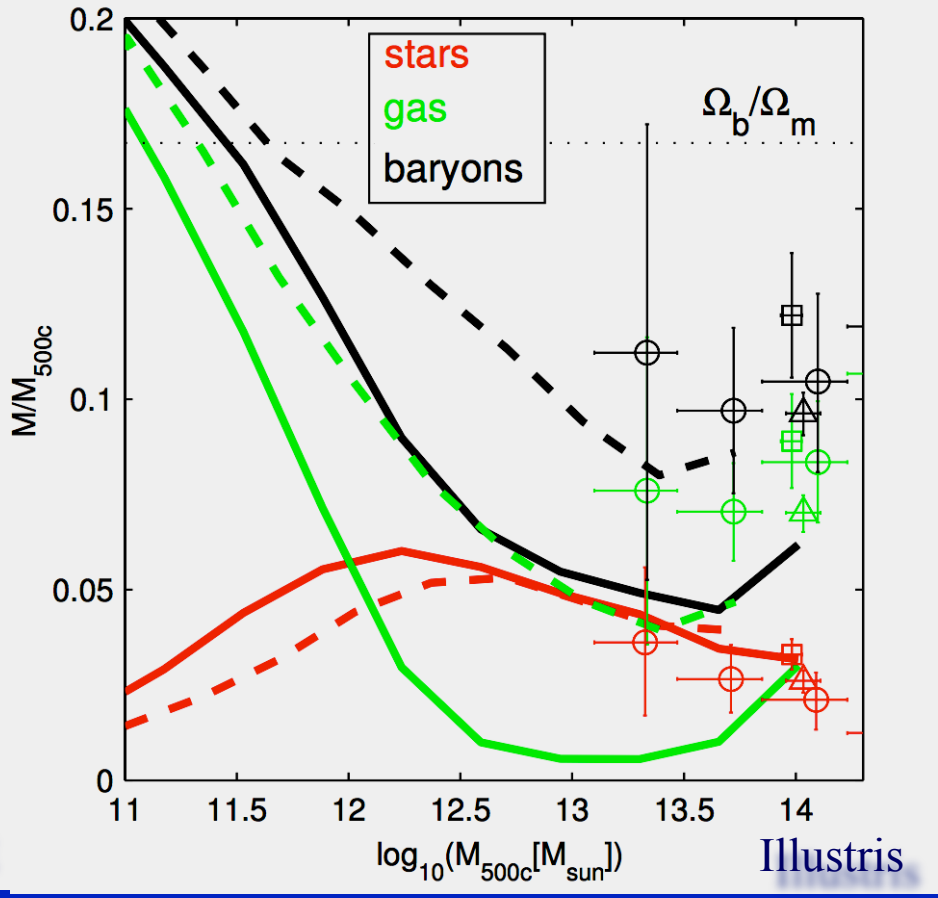


•Galaxies *identified morphologically as disks* seem to trace the observed Tully-Fisher relation.

The gas content of groups and clusters



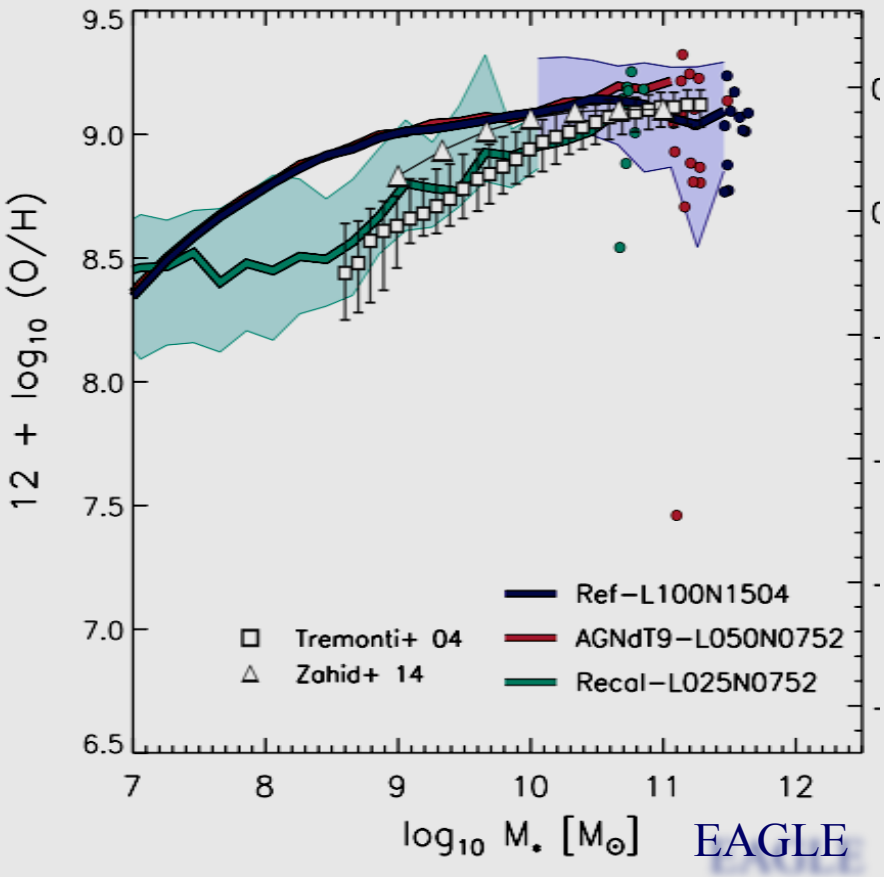
EAGLE



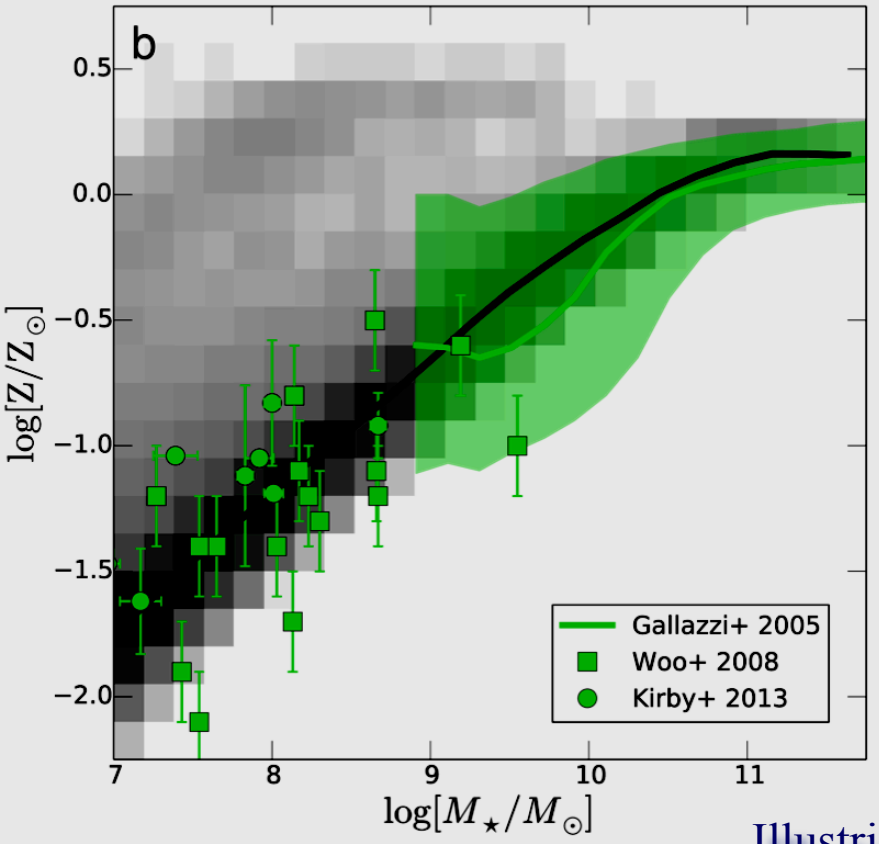
Illustris

- Not everything works out.
- Illustris and EAGLE fail to account for the observed gas content of galaxy groups and clusters.
- Illustris has too little gas, EAGLE has too much!

Mass-metallicity relation



EAGLE

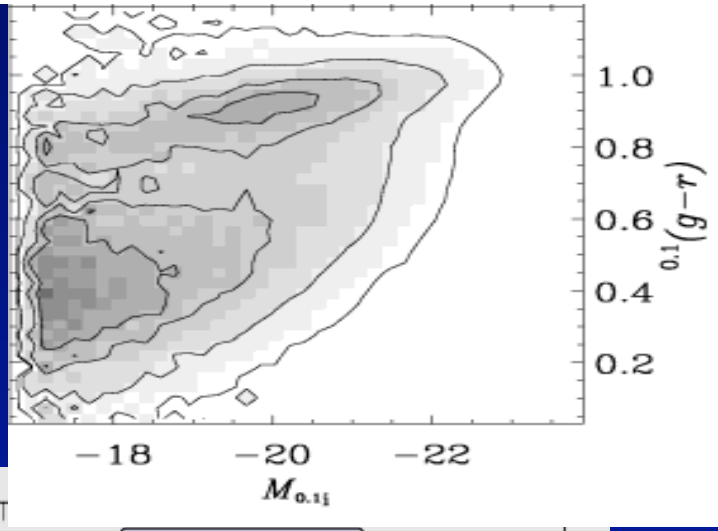


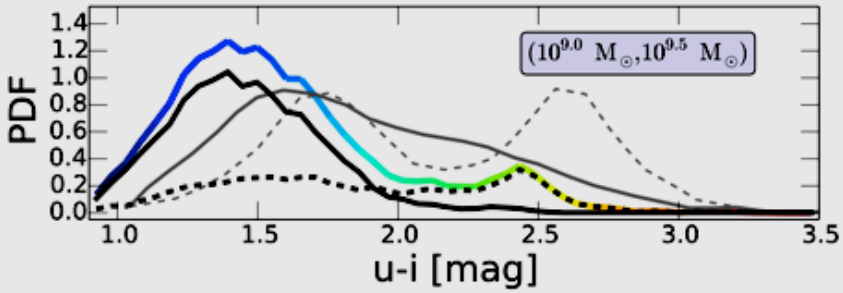
Illustris

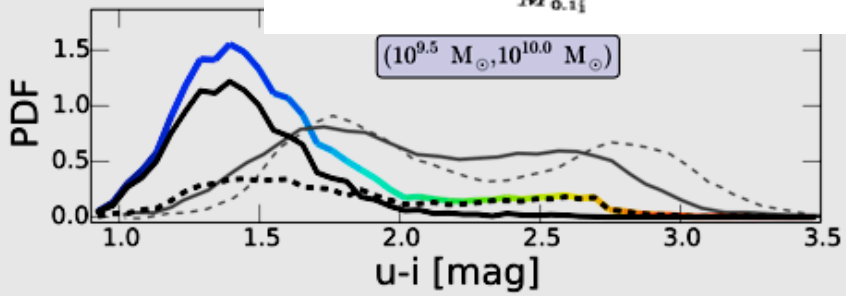
•The mass-metallicity relation is also not very well reproduced. Too many dwarf galaxies have too high metallicities, suggesting that feedback is not as efficient as it should be at ejecting metals.

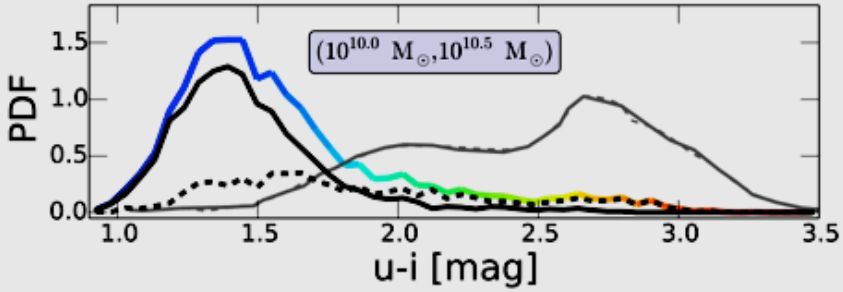
The galaxy color bimodality

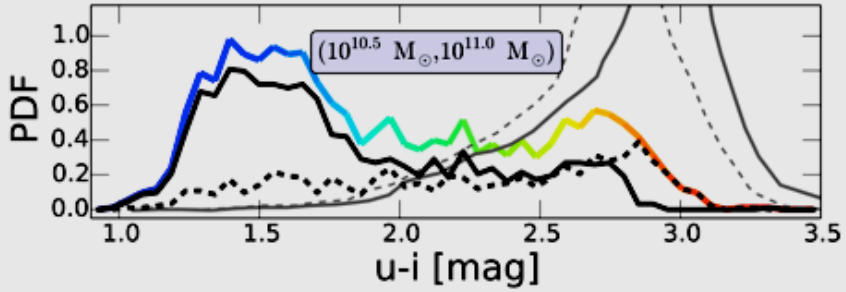
- Not well reproduced in simulations

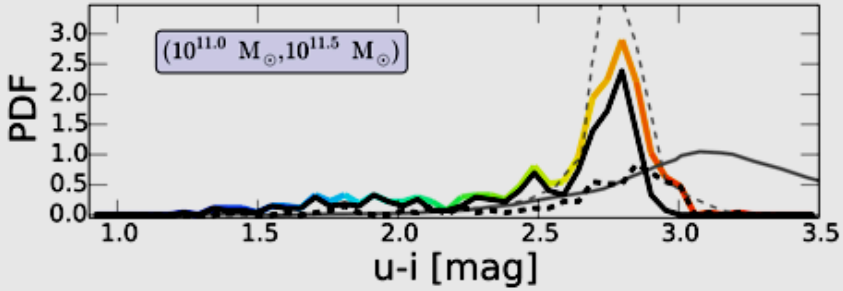


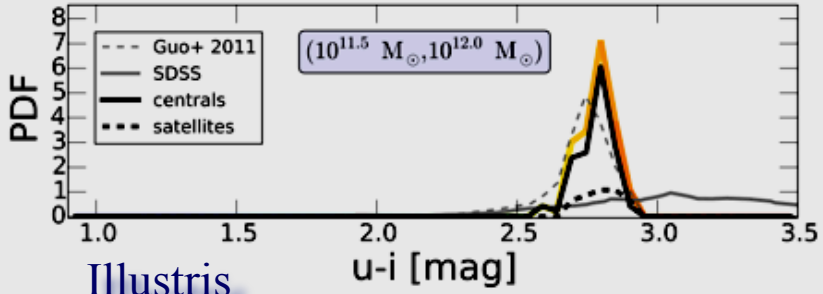






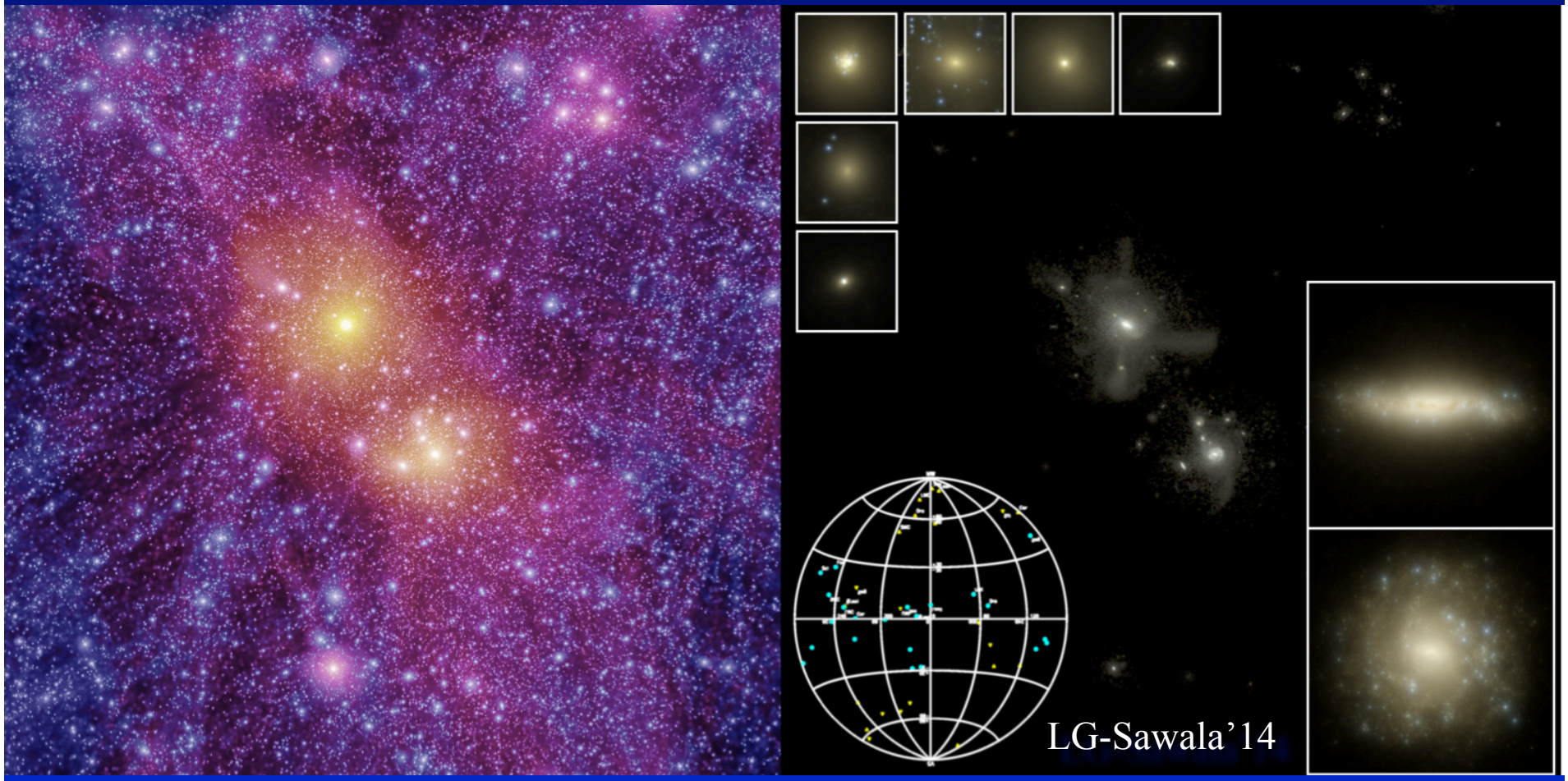






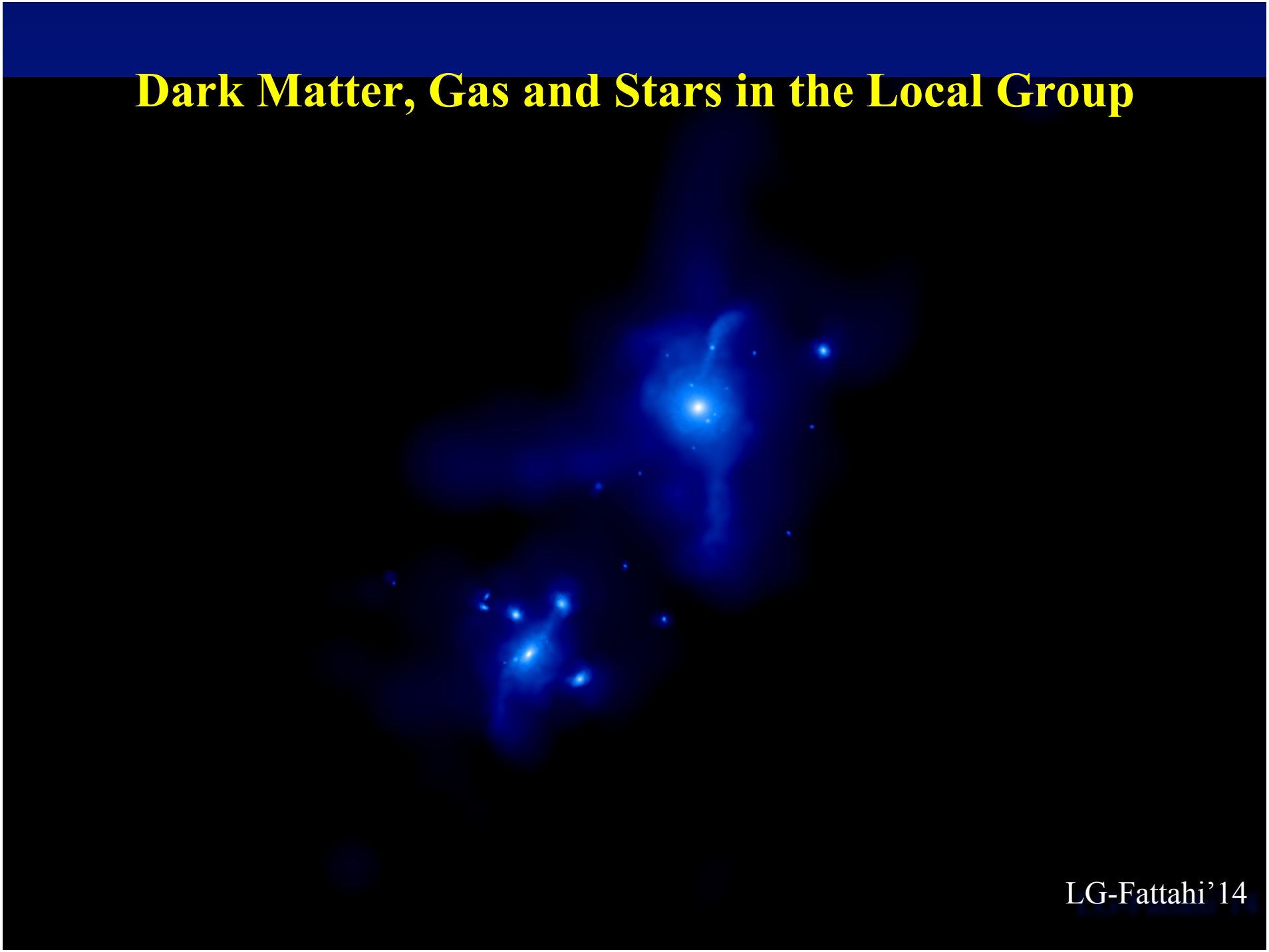
Illustris

Where next?
Think Locally: Local Group and Dwarfs



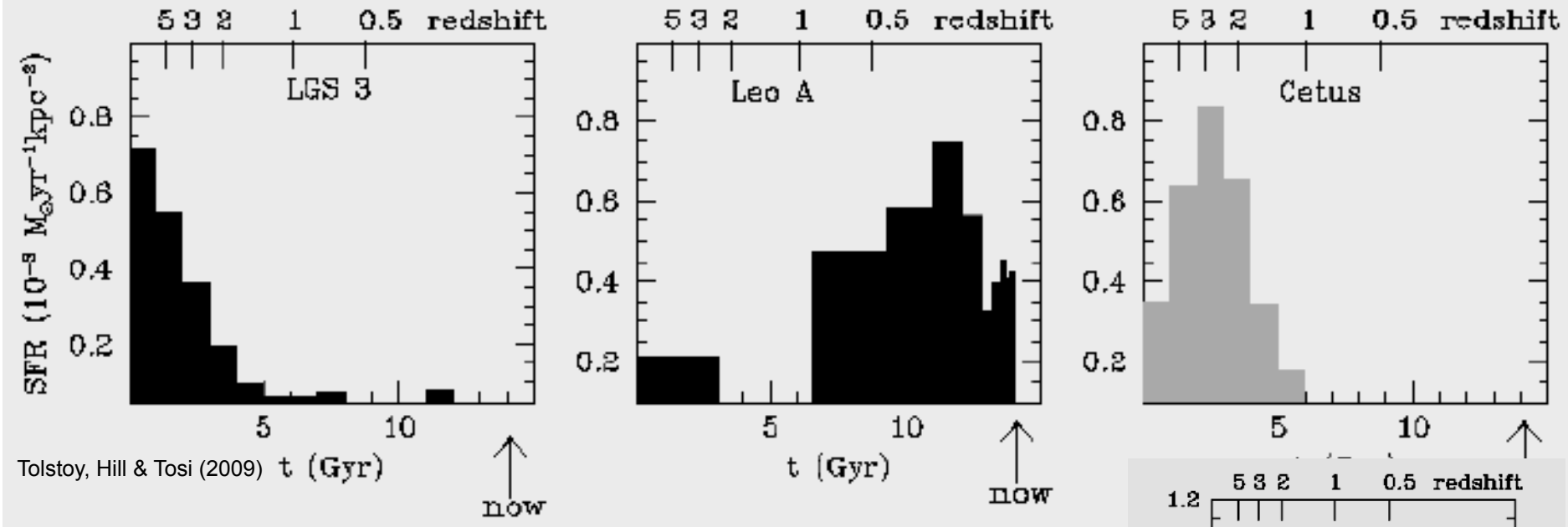
•Local Group simulations can help to exploit the abundance of data being gathered on very faint galaxies, and to address the potential biases that may arise from our particular environment

Dark Matter, Gas and Stars in the Local Group

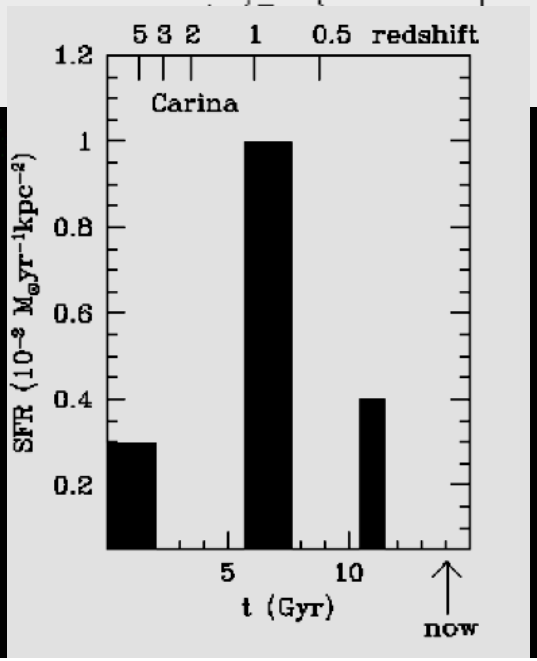


LG-Fattahi'14

Dwarf Galaxy Star Formation Histories

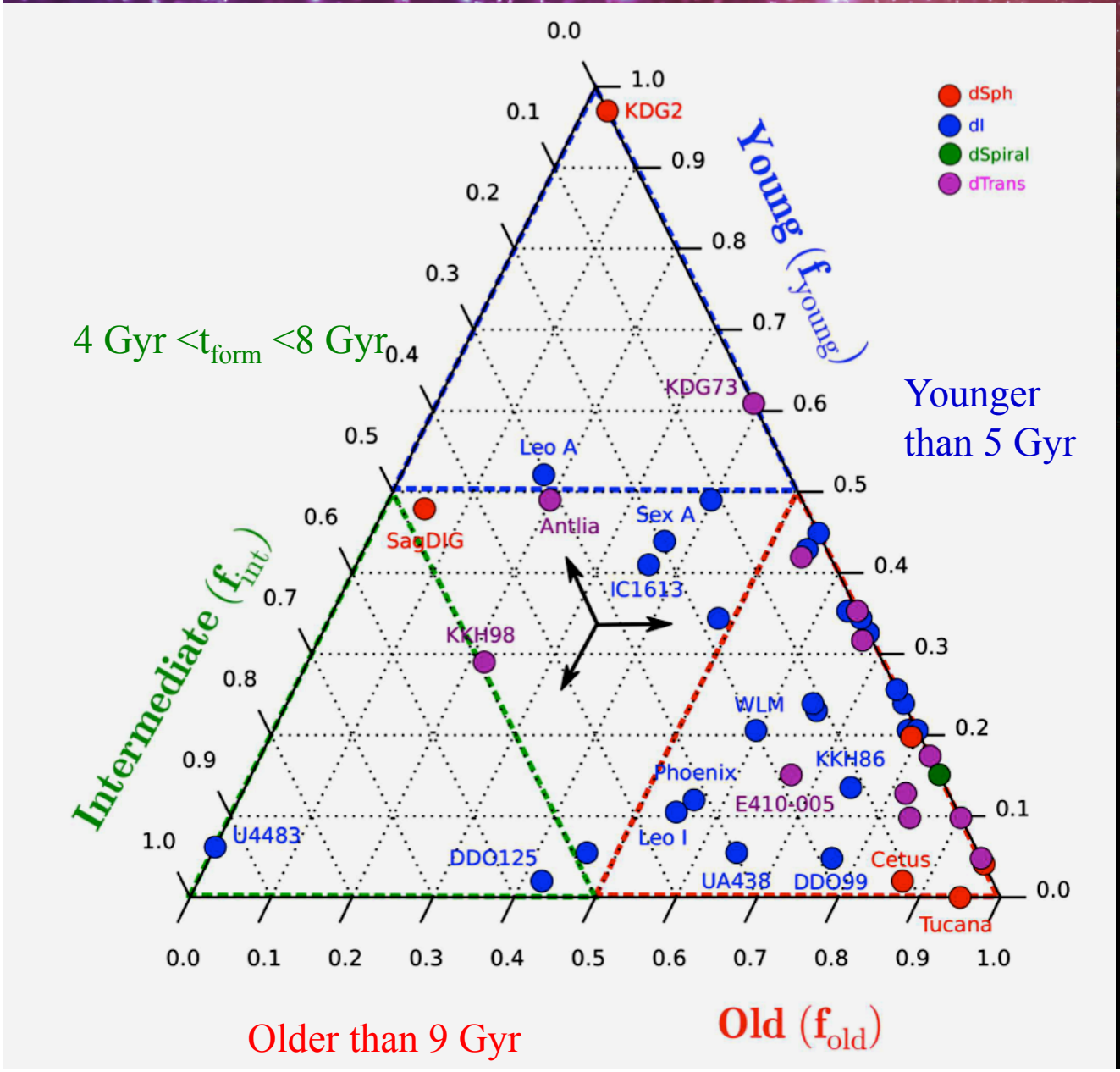


Tolstoy, Hill & Tosi (2009)



If most dwarf galaxies live in halos of similar mass, then what is the *origin of the diversity* in star formation histories of dwarf galaxies in the Local Group?

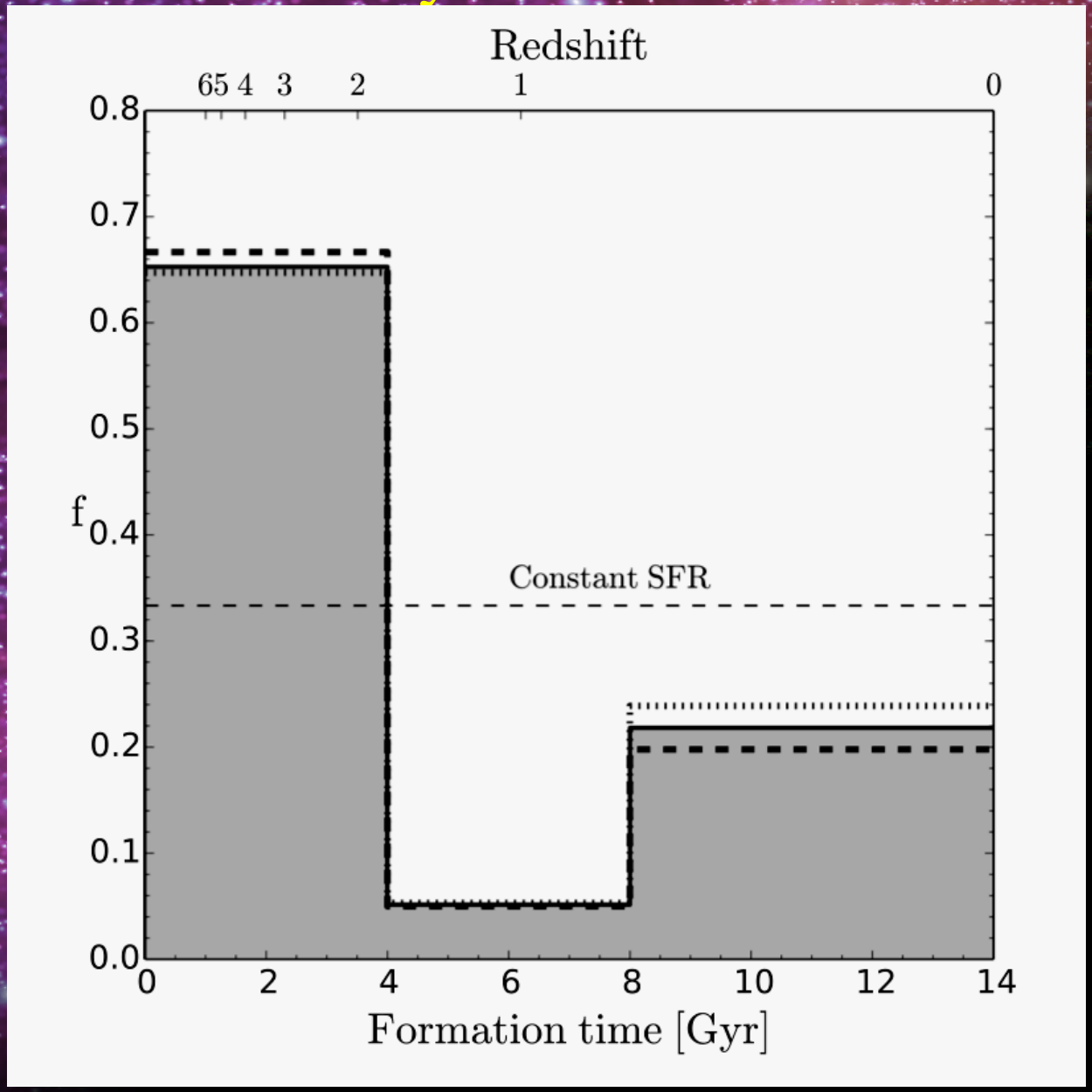
The Diversity of Dwarf Star Formation Histories



Field dwarfs (i.e, not satellites of M31 or MW; -16<MB<-7; 10^5<M_*<10^9) within ~4 Mpc with measured star formation histories (Weisz'14)

Benítez-Llambay et al 2014

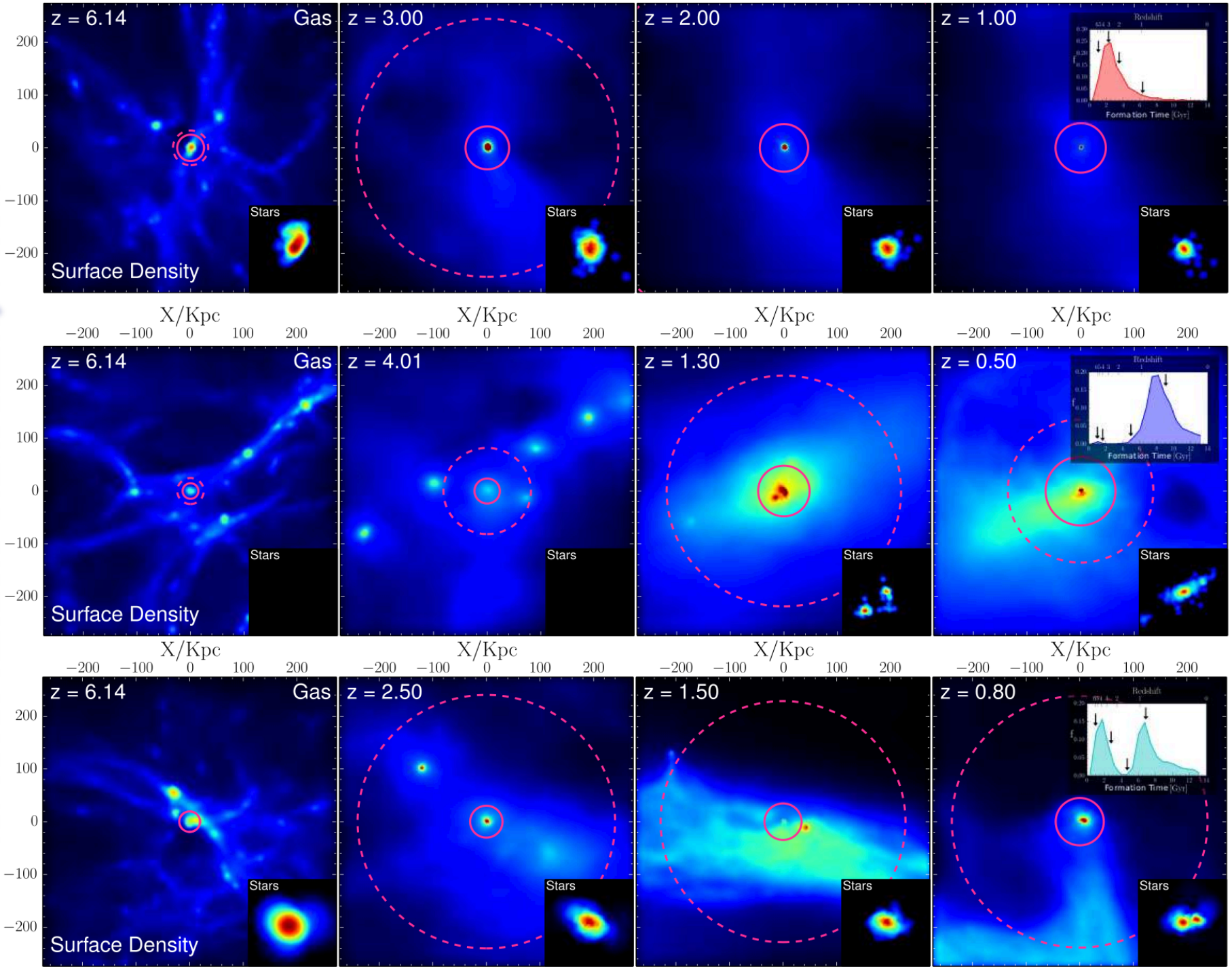
The Diversity of Dwarf Star Formation Histories



Star formation at intermediate times seems disfavoured.

Evidence for reionization?

Benítez-Llambay et al 2014


The CLUES Simulation: Benítez-Llambay et al 2014
z = 6.14
Gas
Surface Density
Stars
z = 3.00
z = 2.00
z = 1.00
Redshift
Formation Time [Gyr]
z = 4.01
z = 1.30
z = 0.50
z = 2.50
z = 1.50
z = 0.80
X/Kpc
Y/Kpc
−200
−100
0
100
200

SUMMARY

Julio F. Navarro

- Numerical simulations of galaxy formation have only recently been able to reproduce the stellar mass, gas content, morphology (disks and spheroids), and kinematics of observed galaxies.
  - Success is a result of improved stellar and AGN feedback algorithms
- No fundamental problem reproducing the main properties of galaxies in the standard LCDM cosmology has been identified
- One challenge is to reproduce the properties of dwarf galaxies in the local Universe
  - Origin of diversity
  - Role of reionization
  - Halo masses of dwarfs
  - Rotation curve problems?