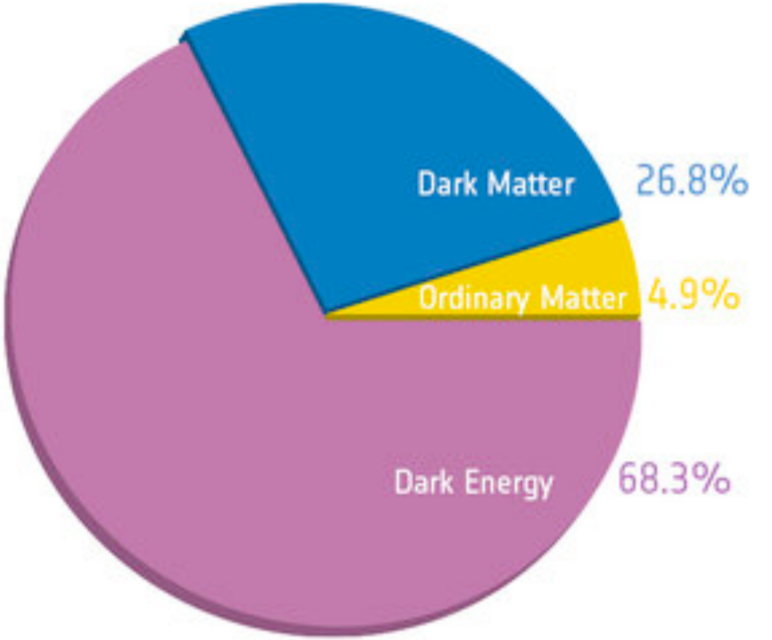
Simulations of Galaxy Formation: the State of the Art

Julio F. Navarro

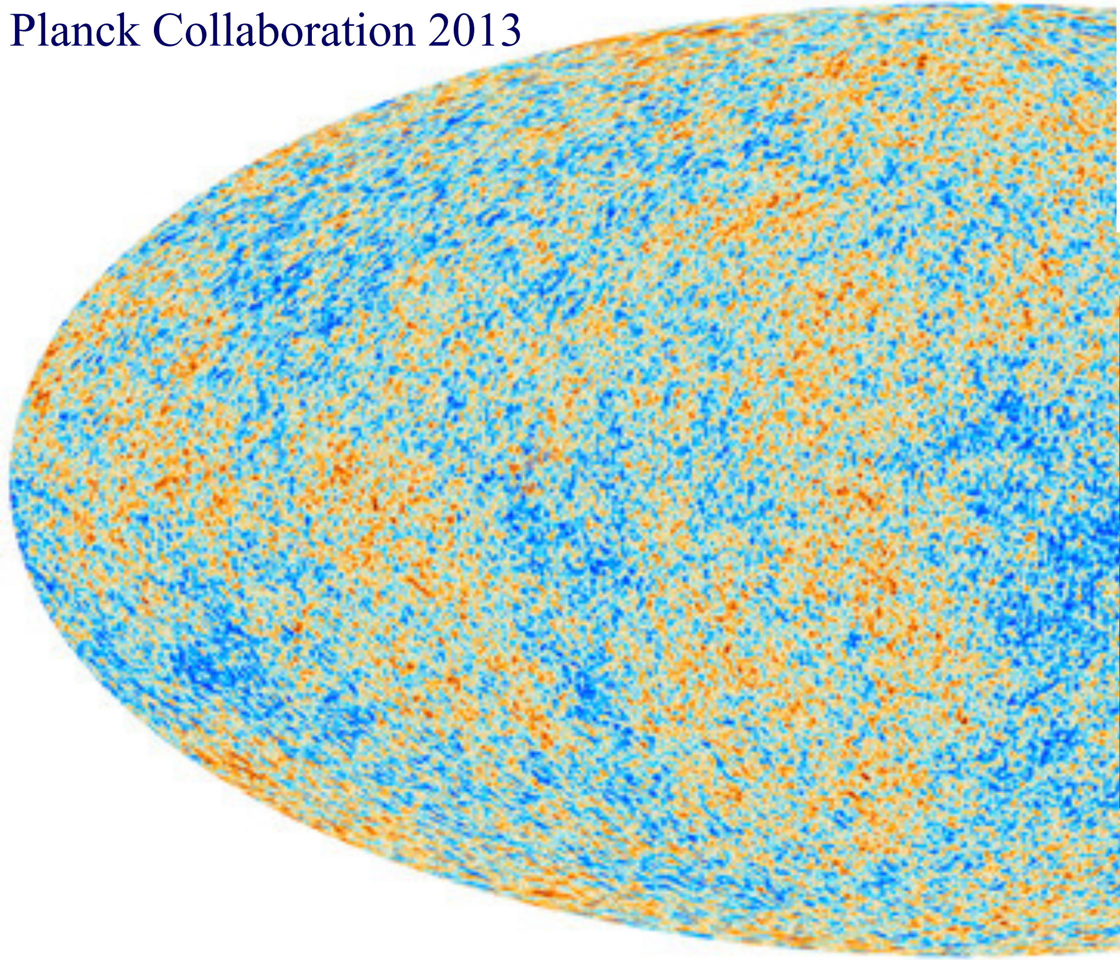
Themes

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

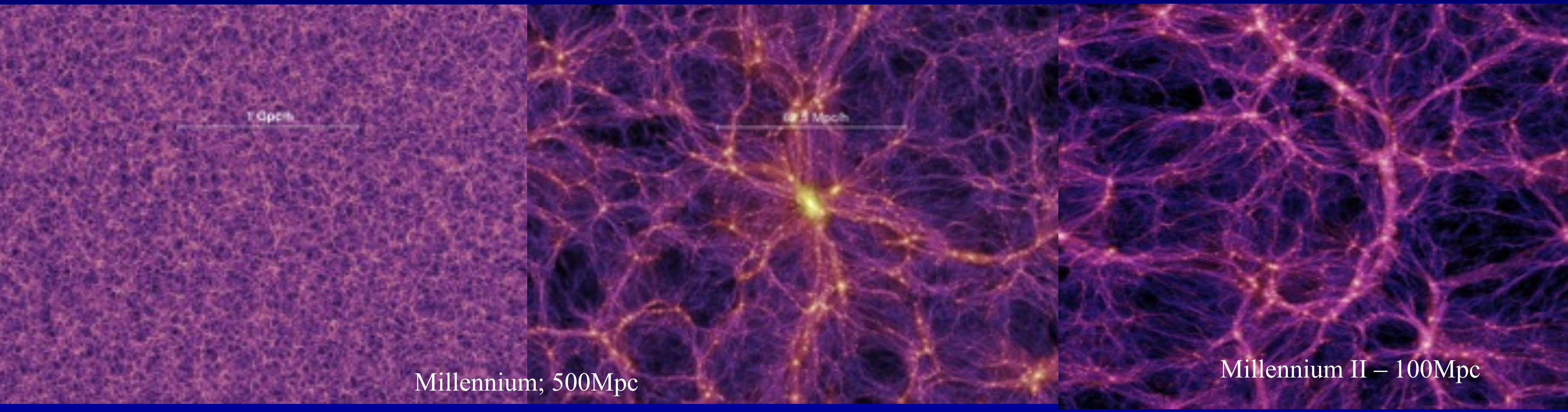
The Standard Model of Cosmology



Planck Collaboration 2013



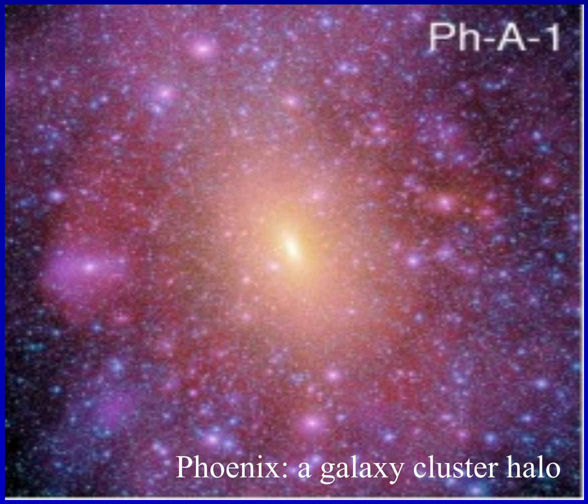
The Clustering of Dark Matter



Millennium; 500Mpc

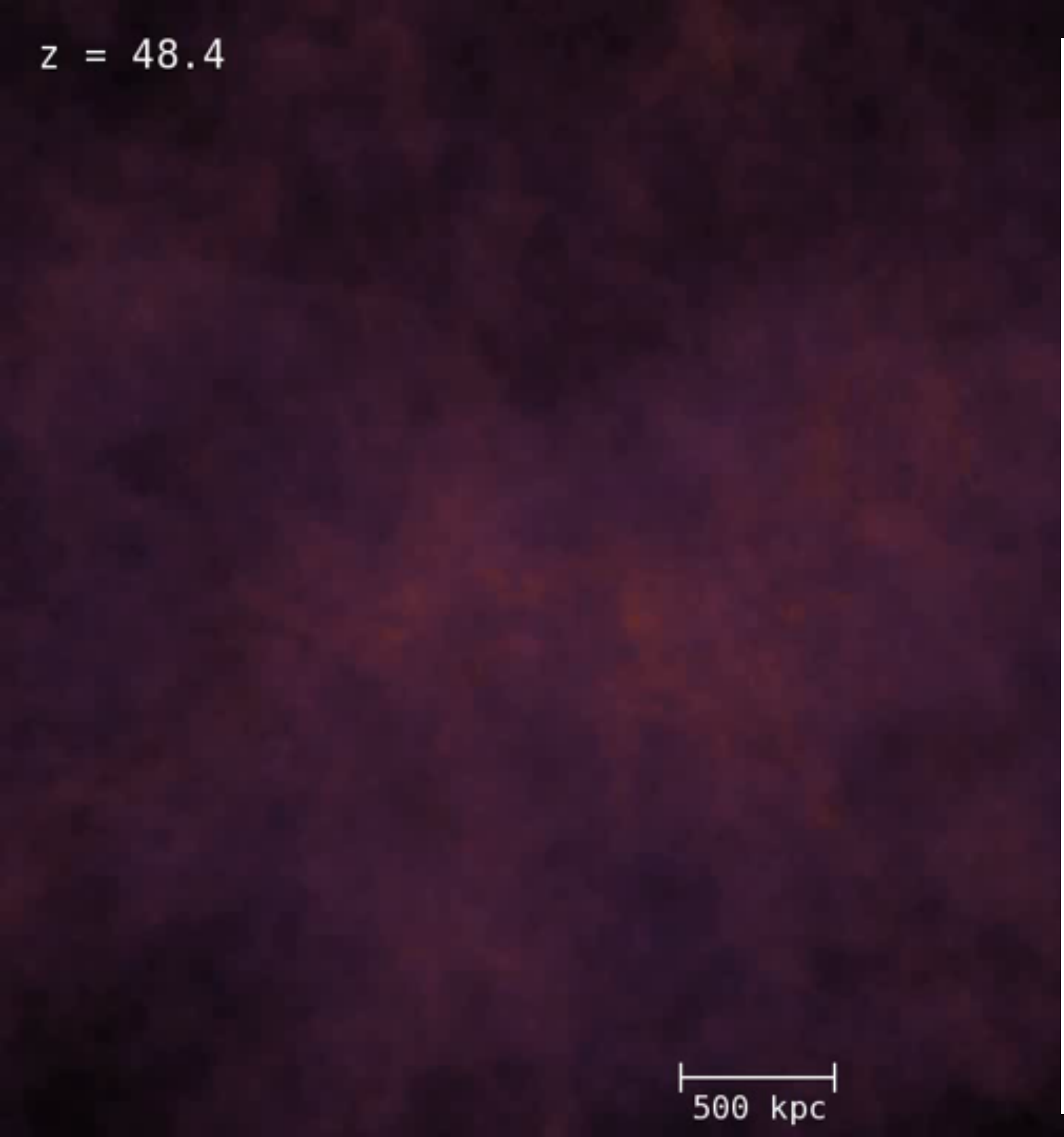
Millennium II – 100Mpc

Aquarius: a galaxy halo



Phoenix: a galaxy cluster halo

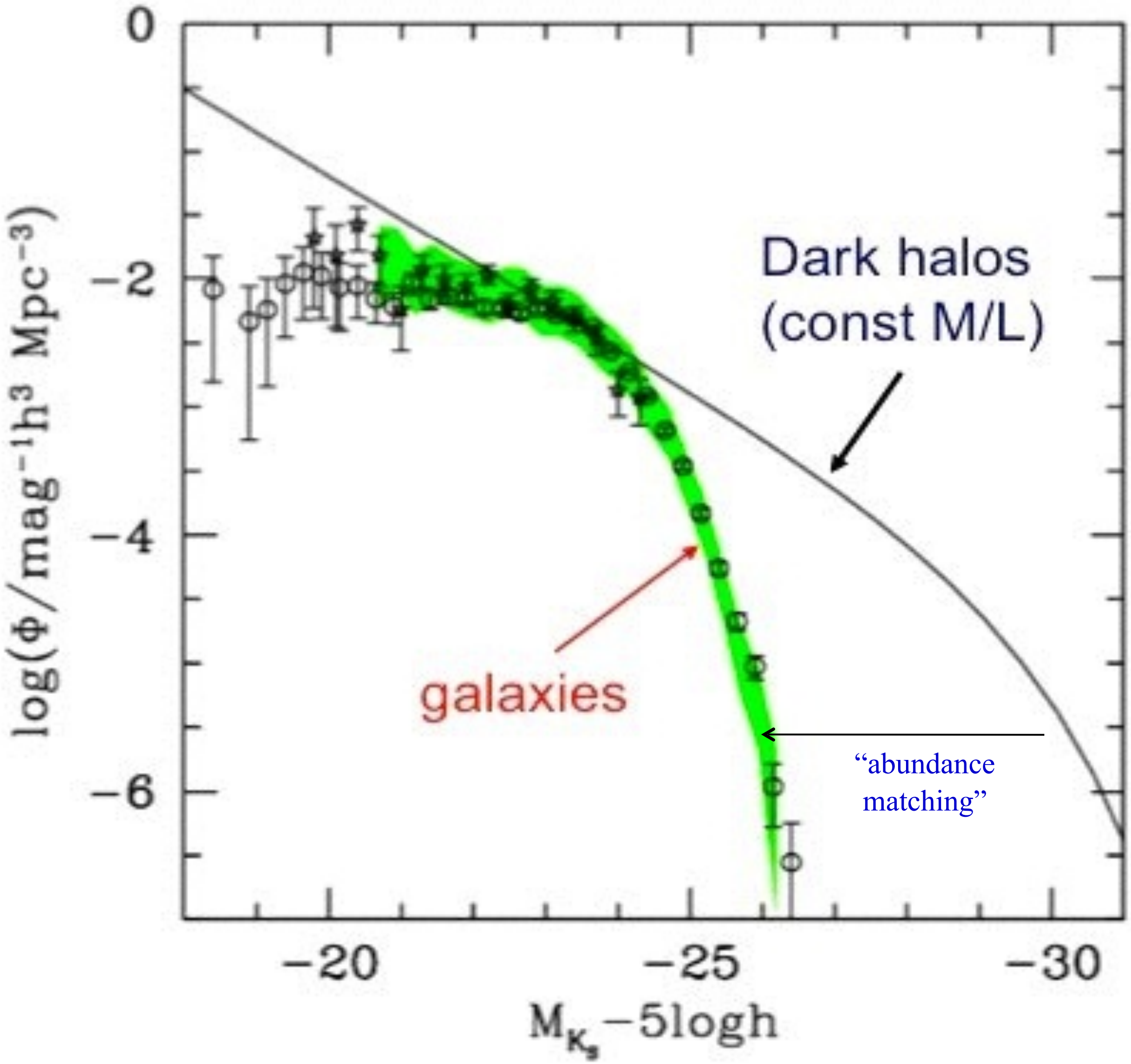
Simulations have enabled a full characterization of the clustering of cold dark matter on essentially all astrophysically-relevant scales.



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?

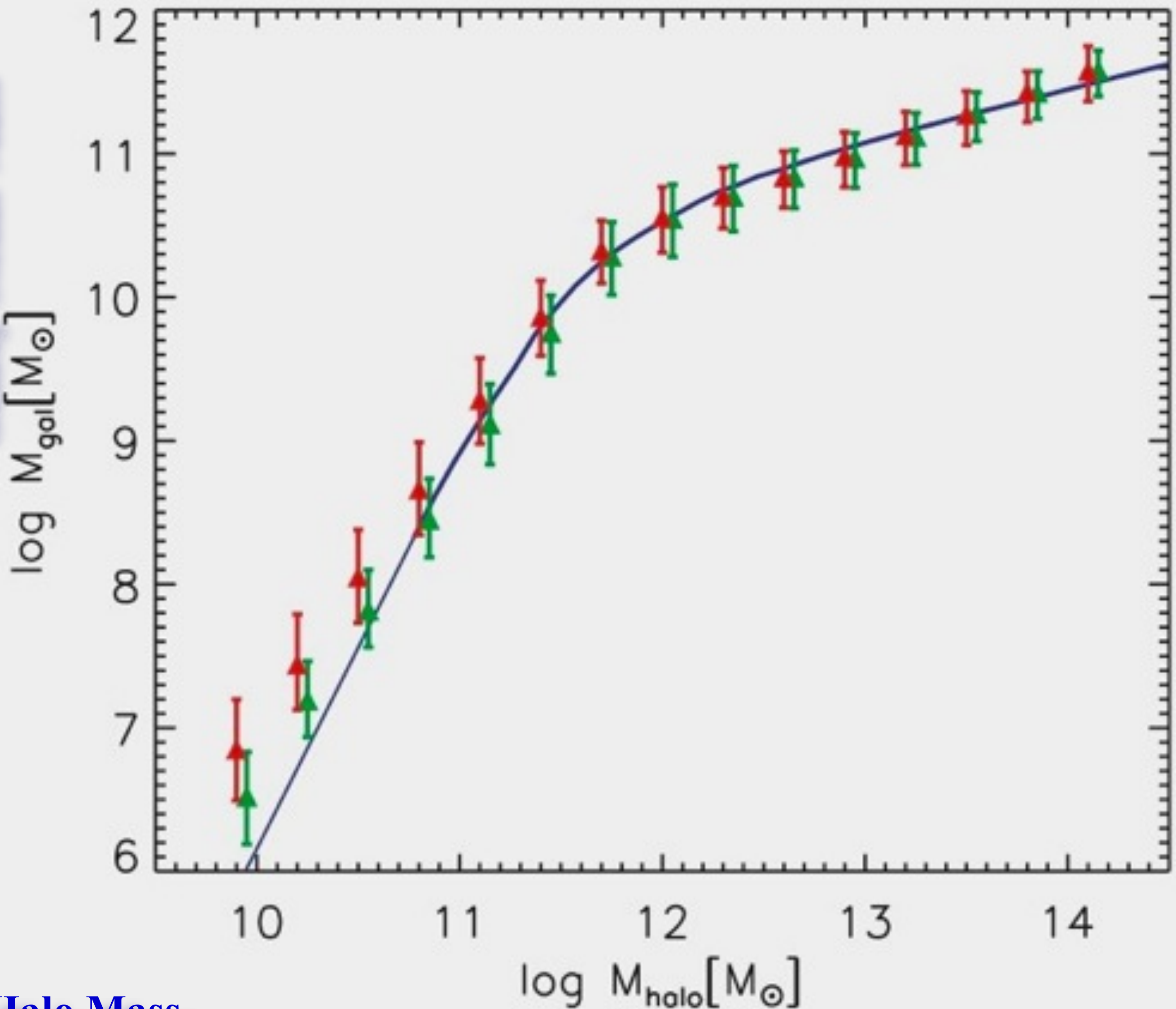
CDM halo mass function vs galaxy luminosity function



- 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

Galaxy Stellar Mass

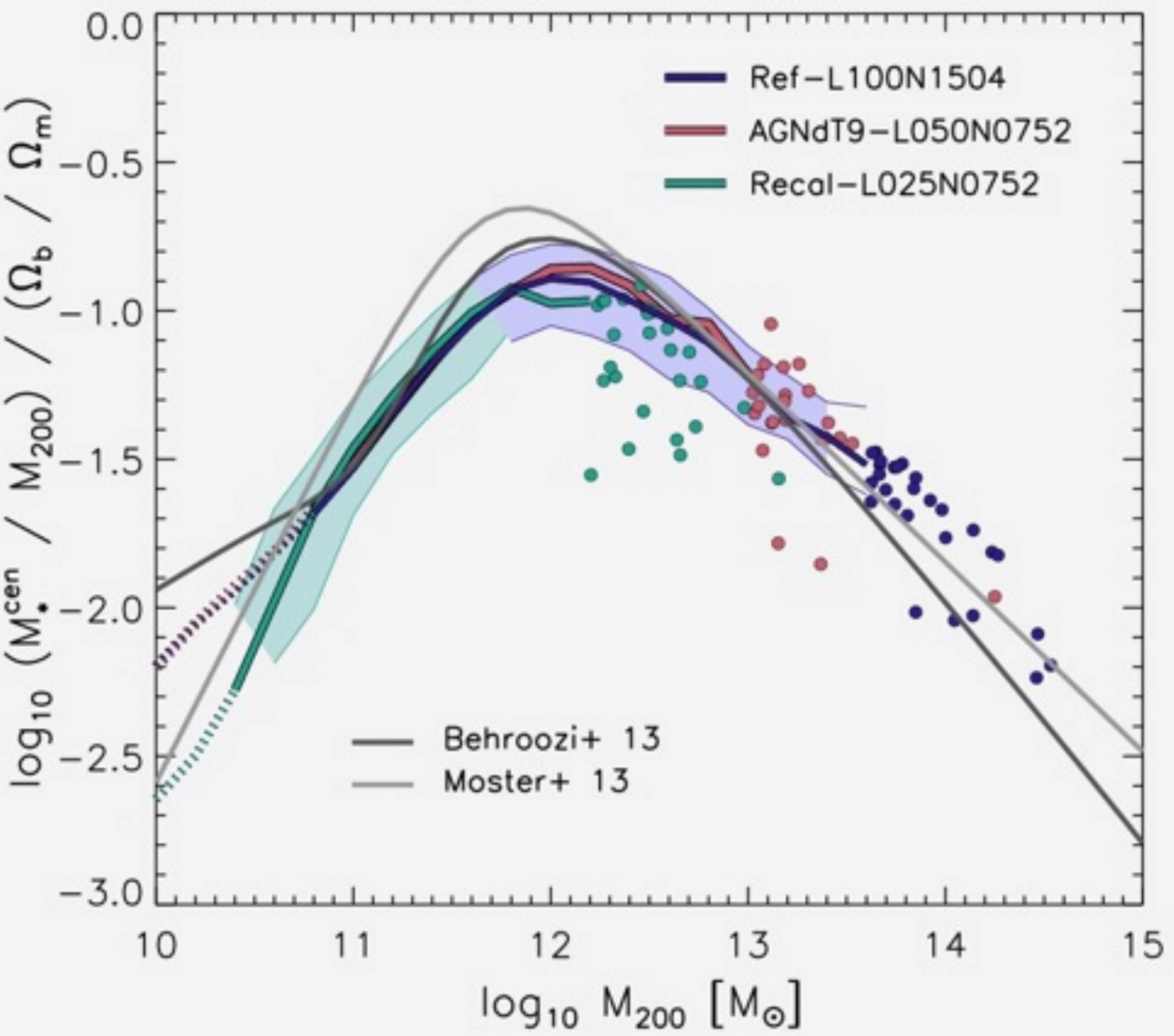


Halo Mass

- 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

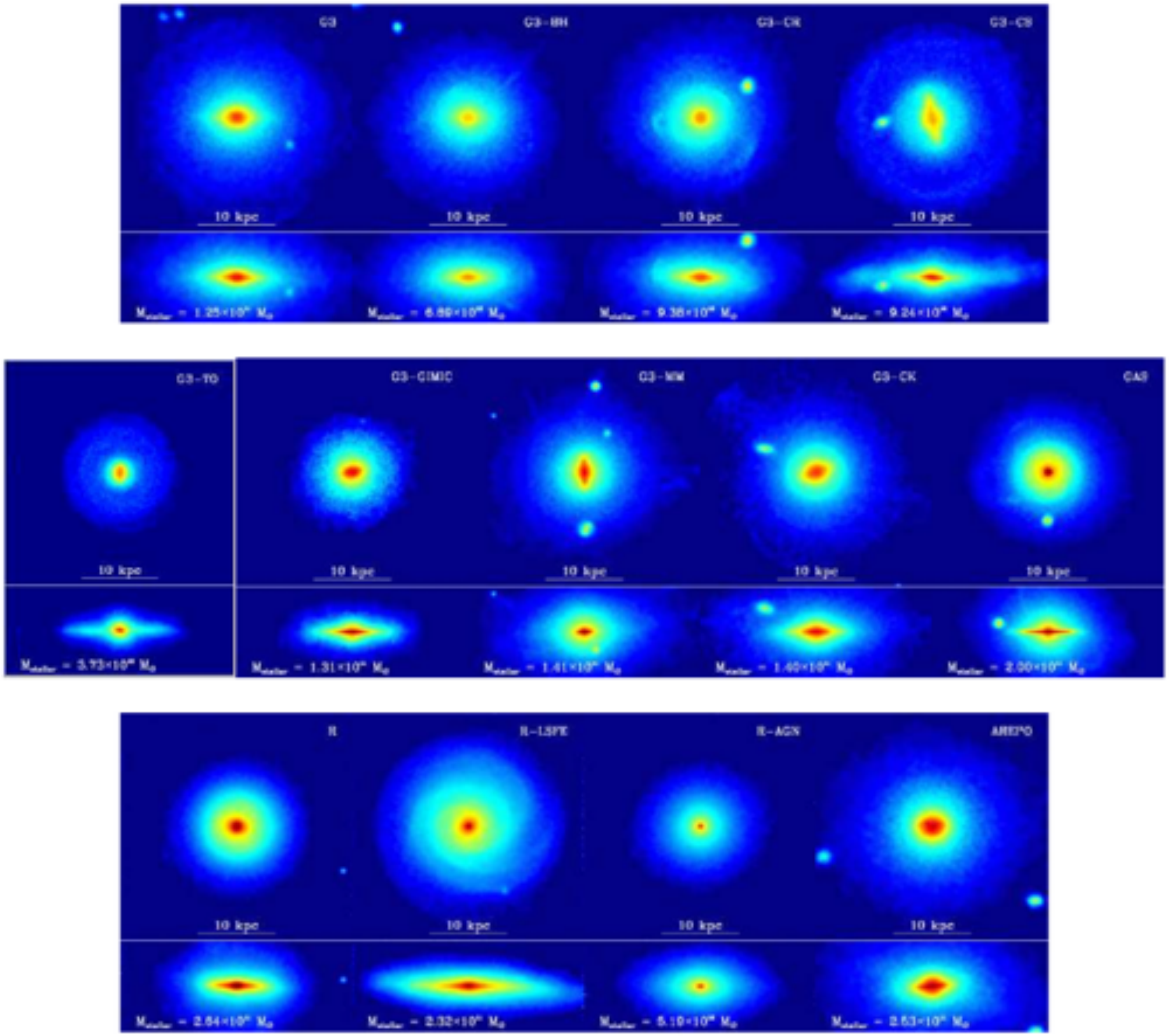
Feedback

- •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 observations

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

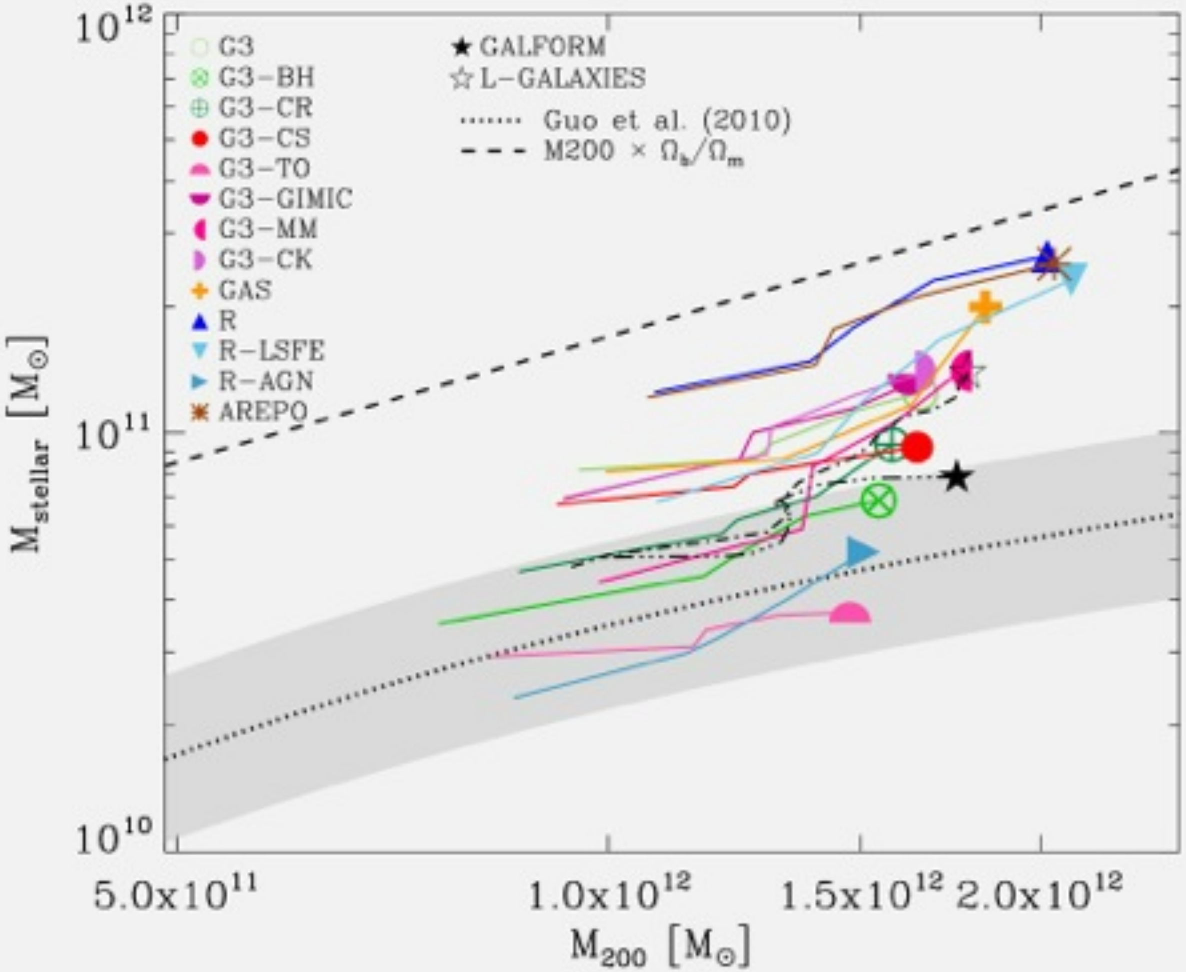
The Aquila Project



- 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}

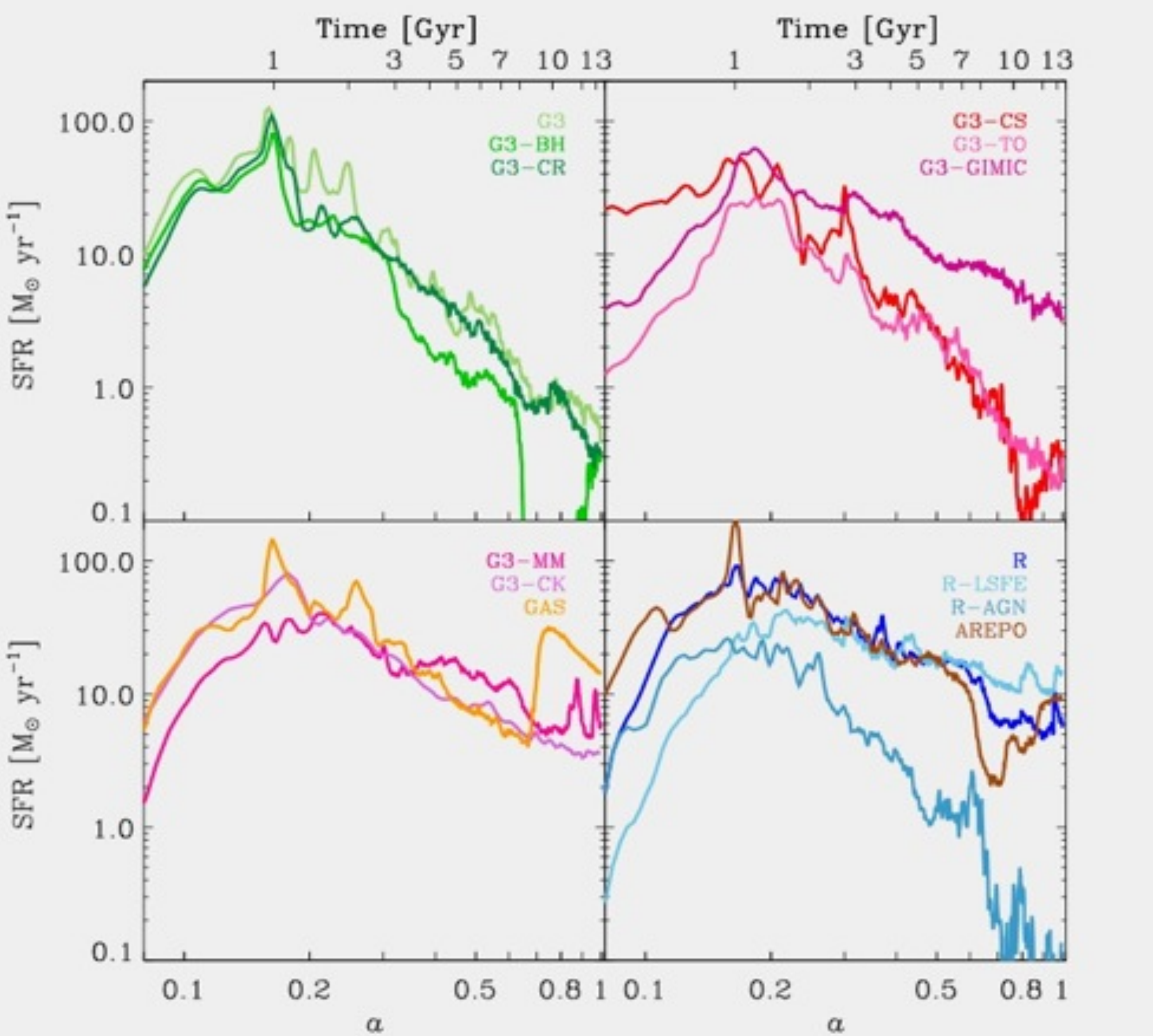


- Aquila galaxies are typically too massive, too concentrated, and form stars much earlier than expected for a "Milky Way-like" galaxy.

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

Scannapieco et al 2012

The Aquila Project: Star Formation Rates



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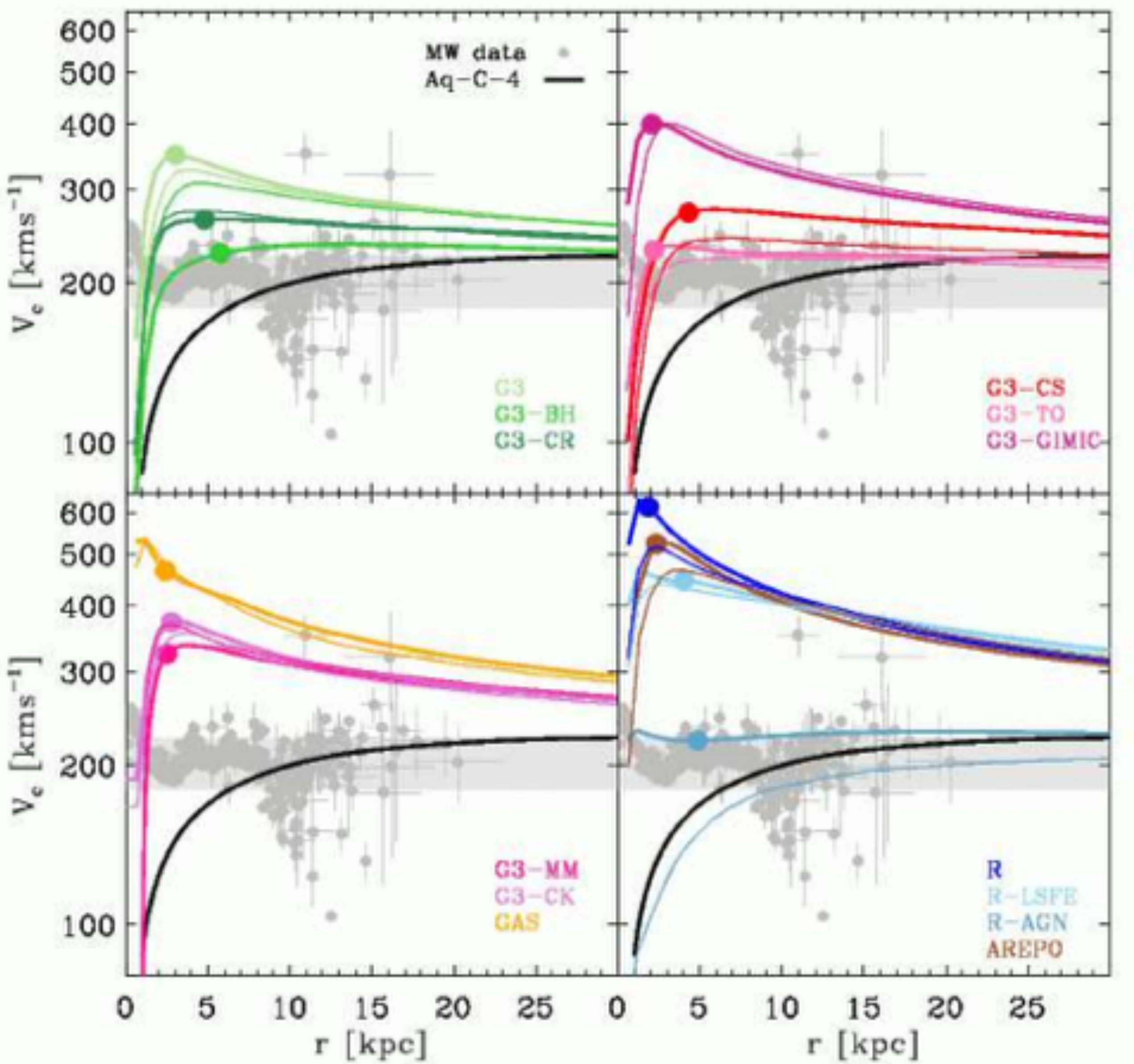
Scannapieco et al 2012

The Aquila Project: Rotation curves



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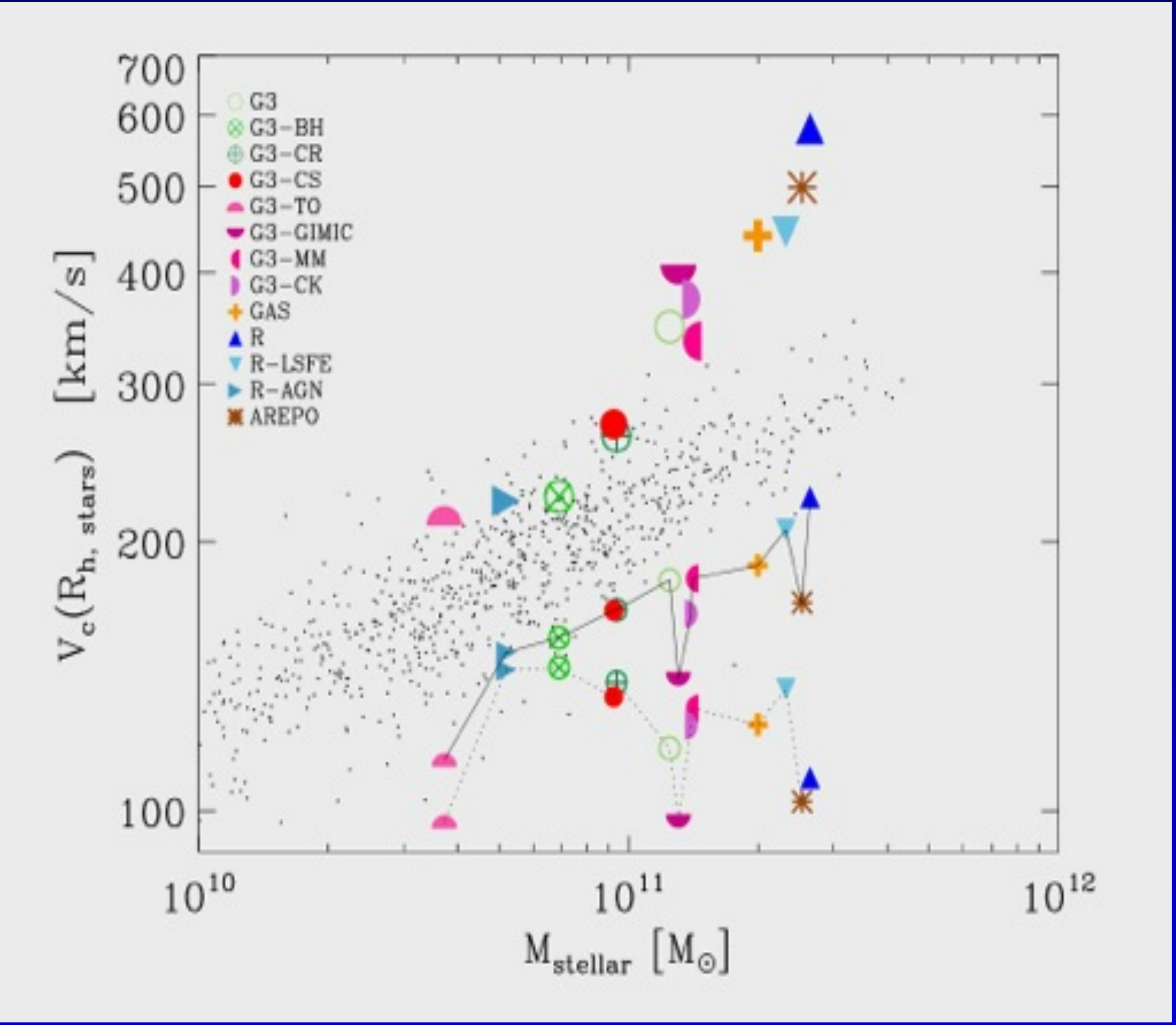
Scannapieco et al 2012

The Aquila Project: Tully-Fisher relation



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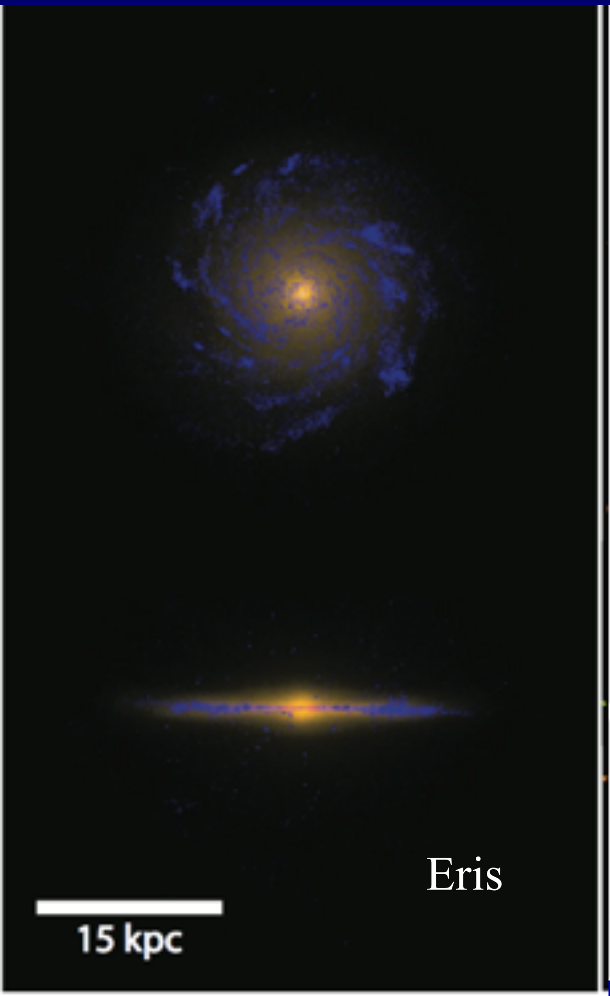
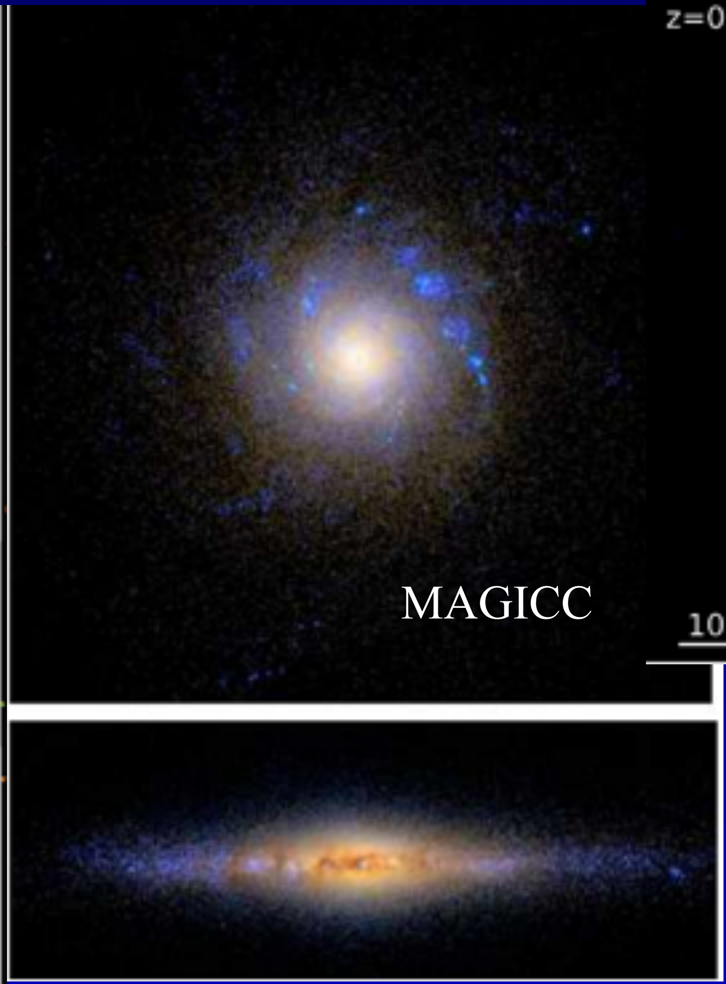
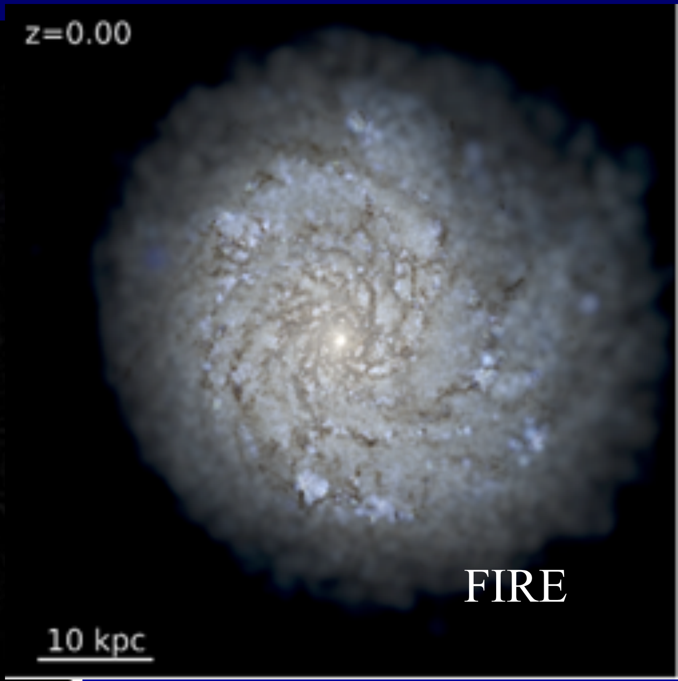
Scannapieco et al 2012

Individual galaxy simulations: state of the art



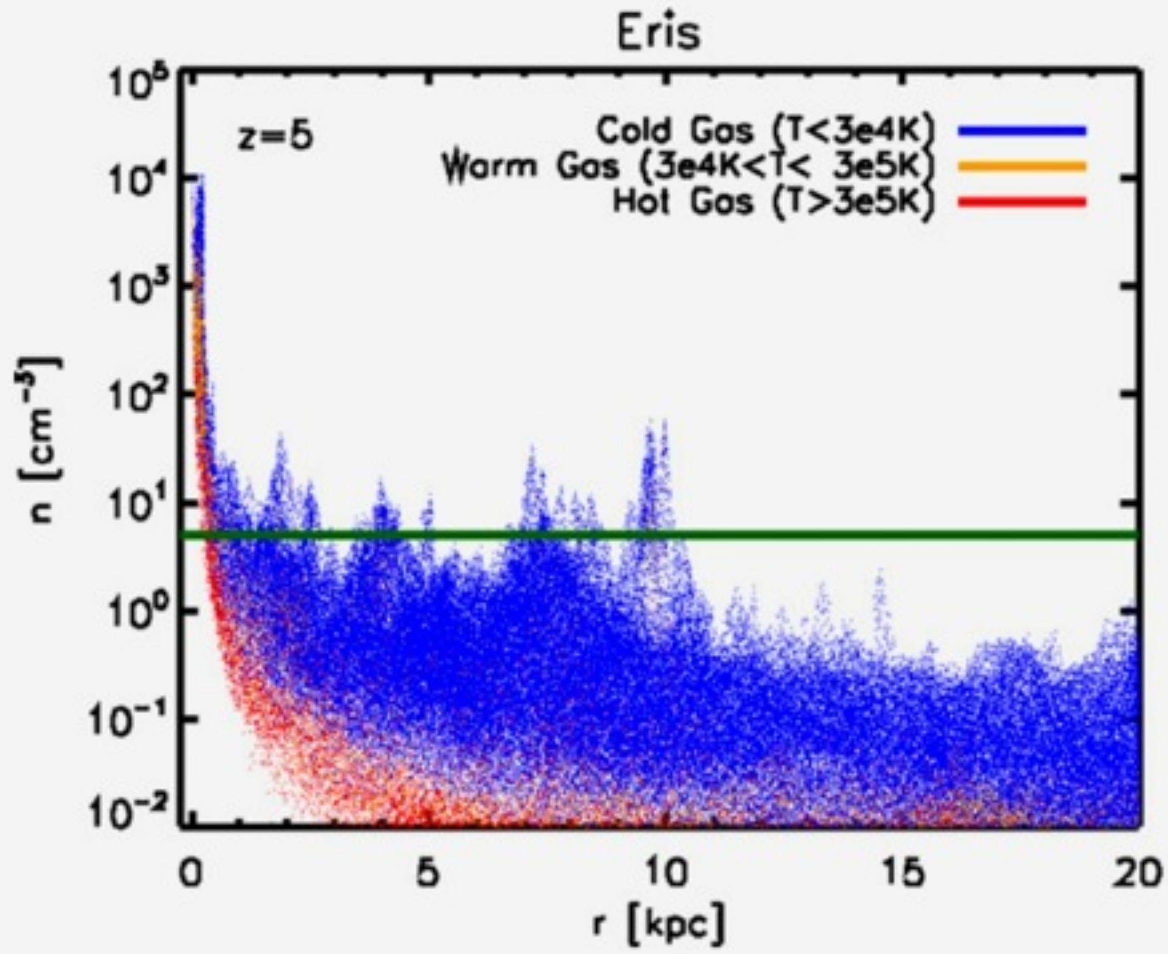




Hopkins '13,'14
Governato '10,'12, '14
Guedes '11
Stinson'13
Aumer '13,'14
Agertz'13

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

Individual galaxy simulations: state of the art

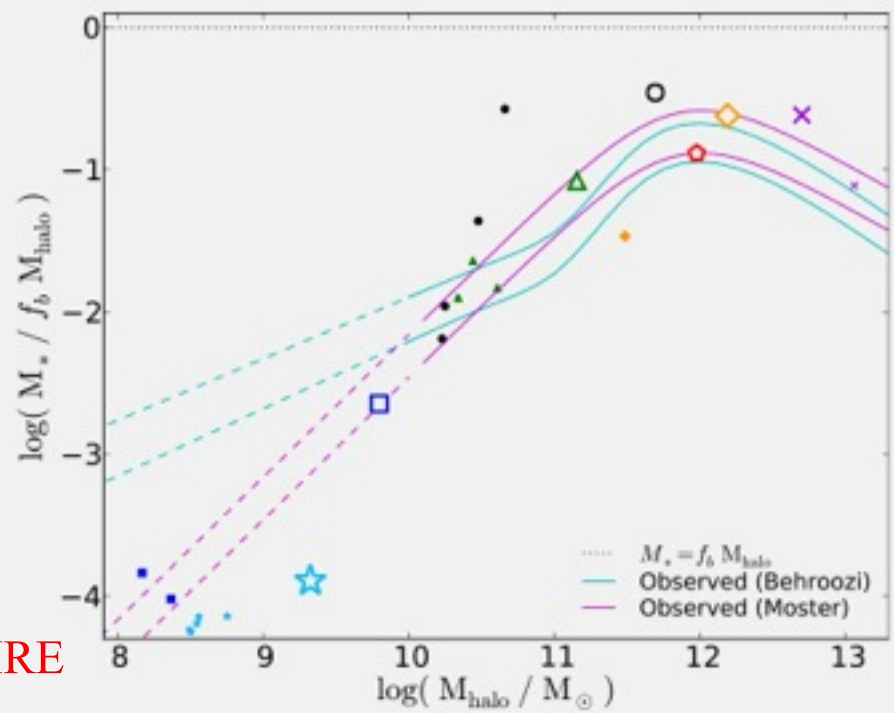


Guedes et al 2011

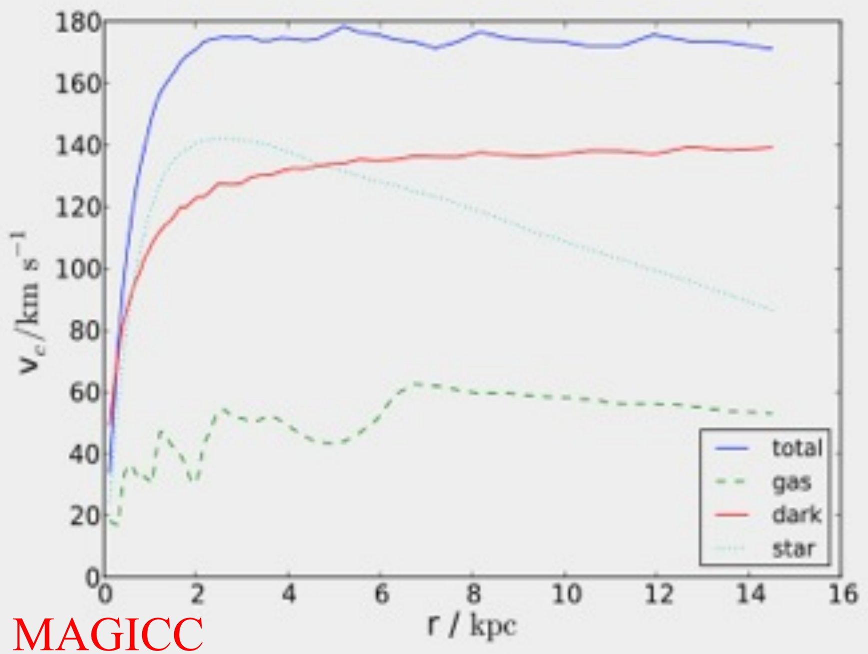
- The improvement has been attributed to
  - higher numerical resolution
  - the adoption of high thresholds for star formation
- n_H=5 cm^{-3} (Guedes'11);
- 7 cm^{-3} (Stinson'13);
- 100 cm^{-3}(Governato'10);
- 1000 cm^{-3} (Hopkins'14)

- All argue for good agreement with observation

Individual galaxy formation simulations



FIRE



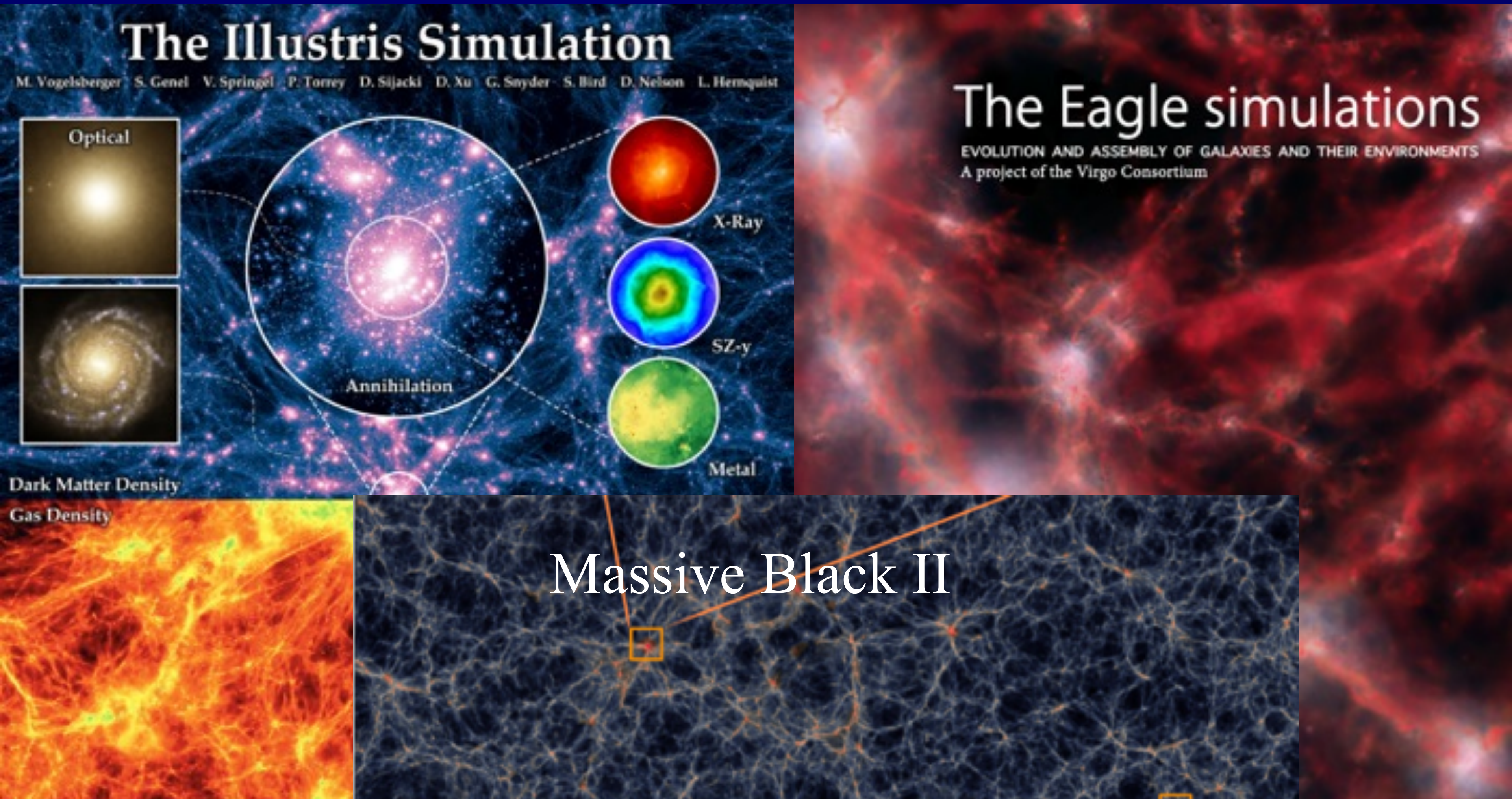
MAGICC

•"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.

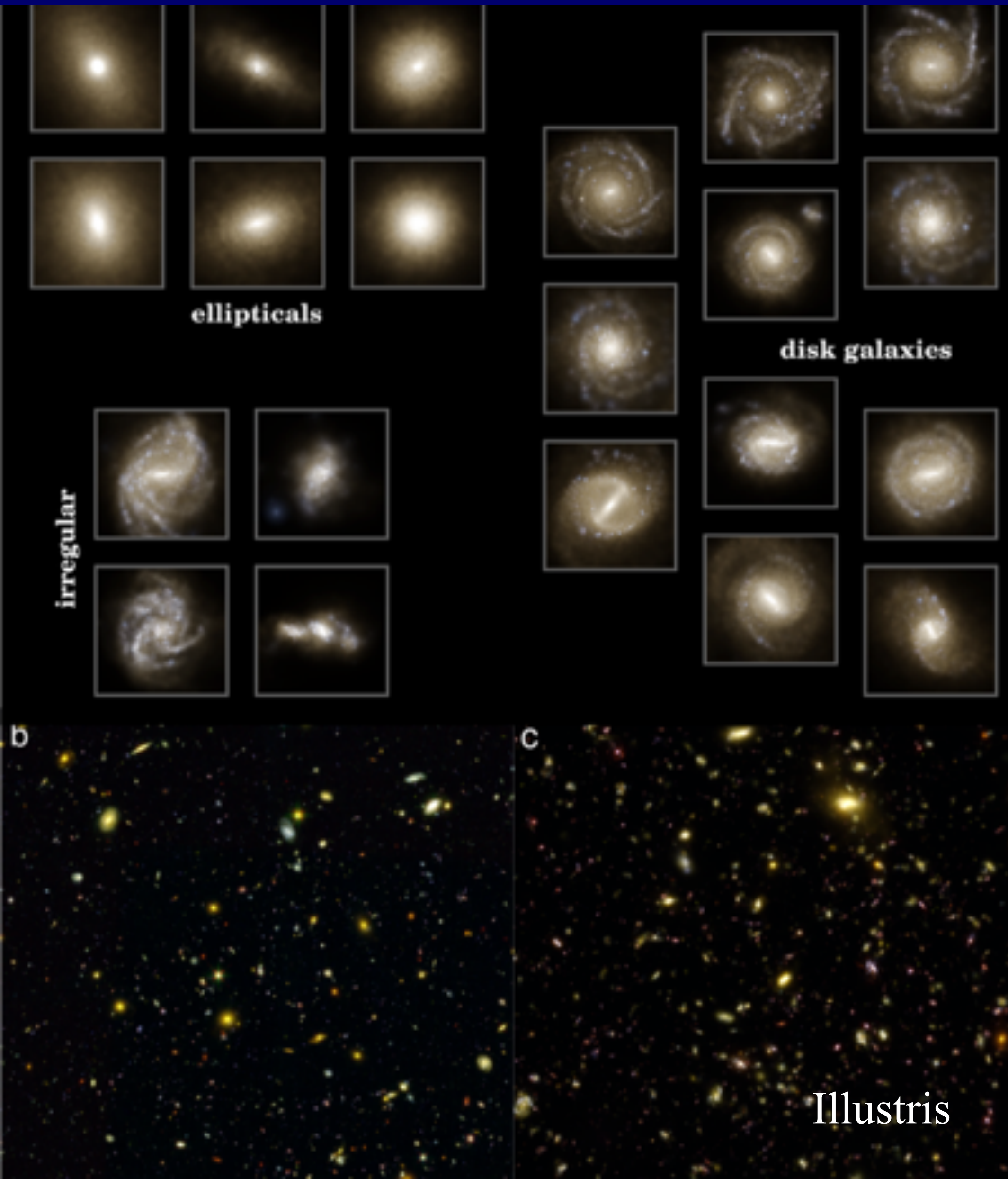
•"We might not know what kind of galaxy inhabits an individual halo, but we do know what the population of galaxies looks like." (Scannapieco'12)

Galaxy Population Simulations

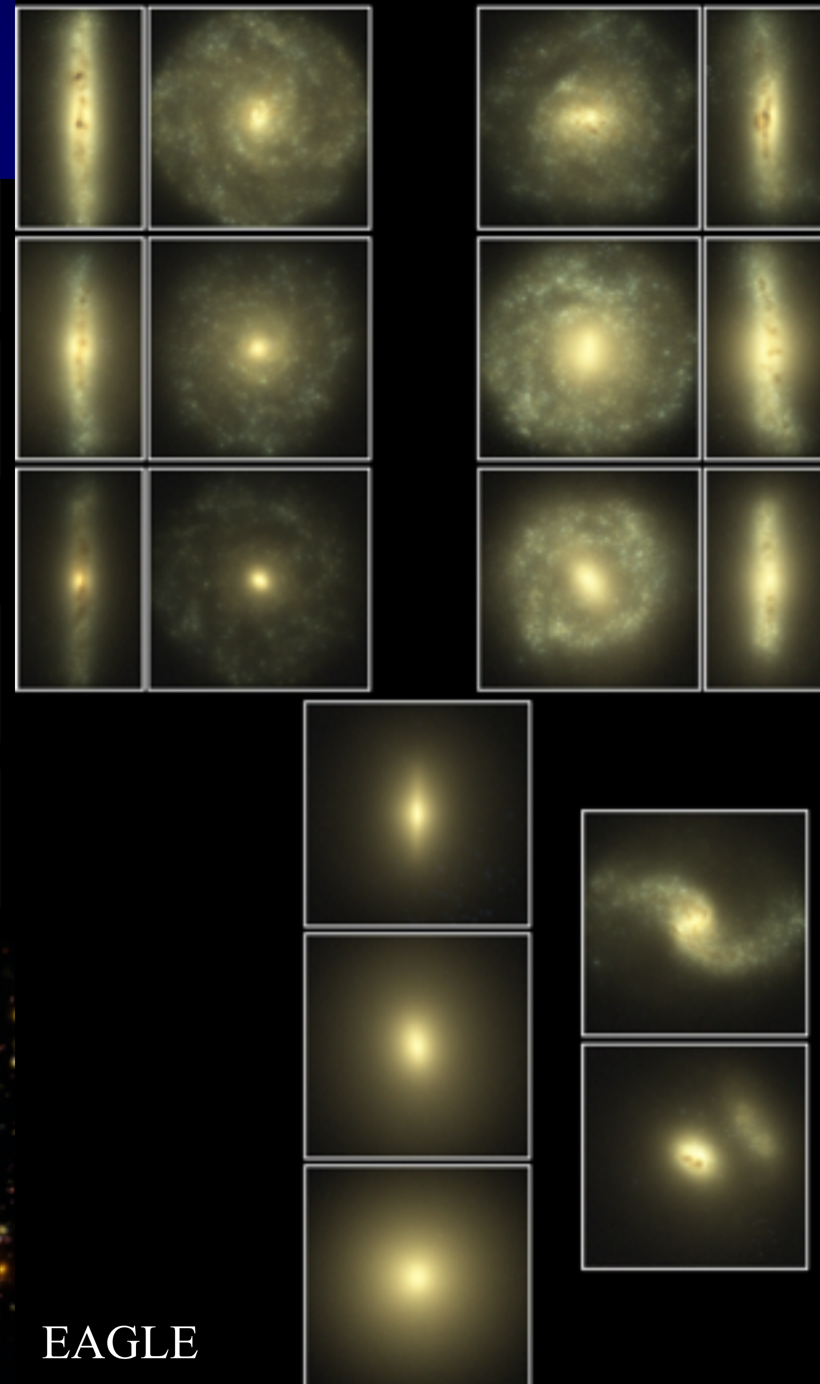


- Three large simulation suites of cosmologically representative volumes (~100 Mpc box) have recently been completed
- Resolution (per galaxy) is worse than individual galaxy simulations, but agreement with observation is quite good

Galaxy gallery

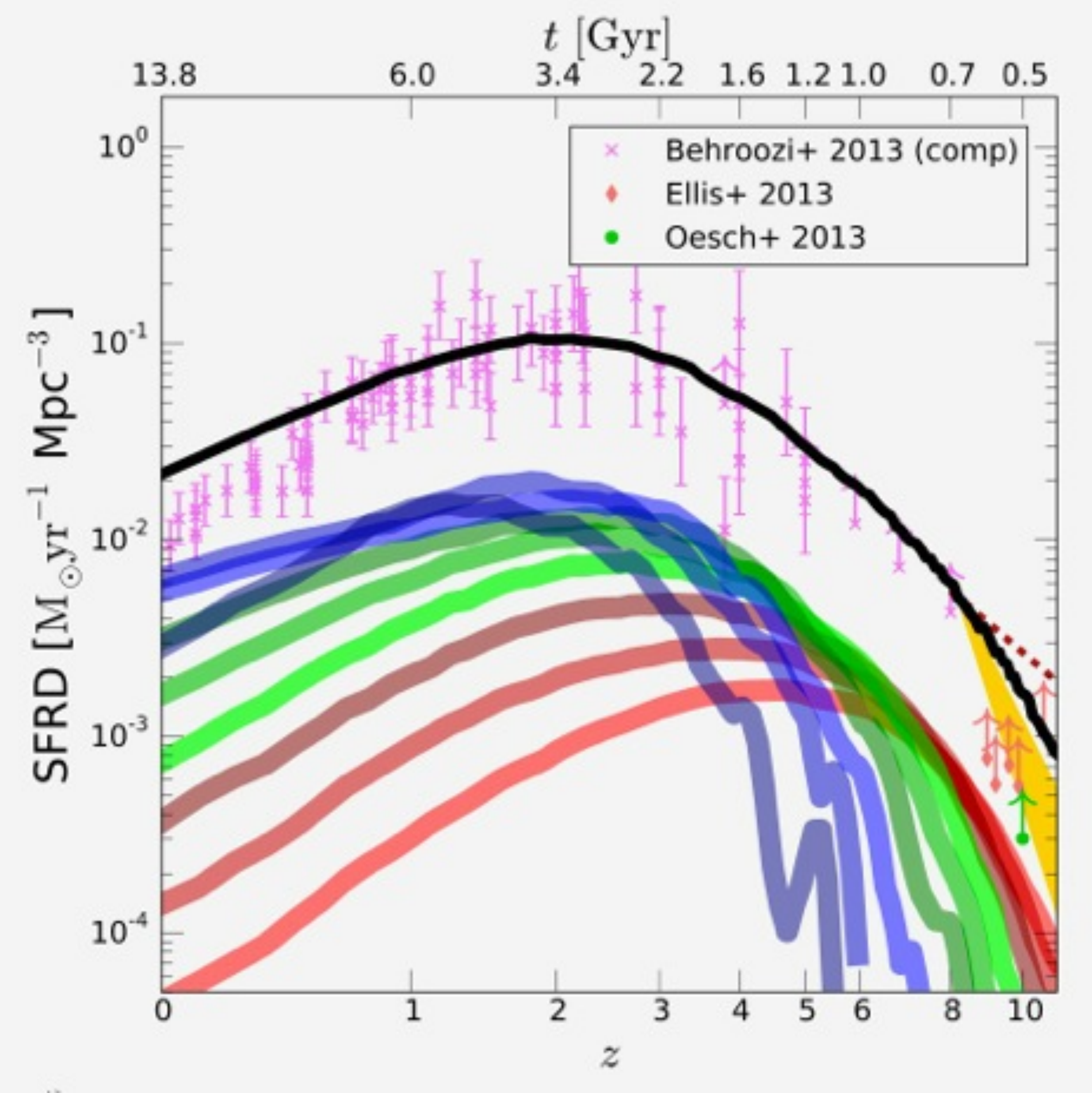


Illustris



EAGLE

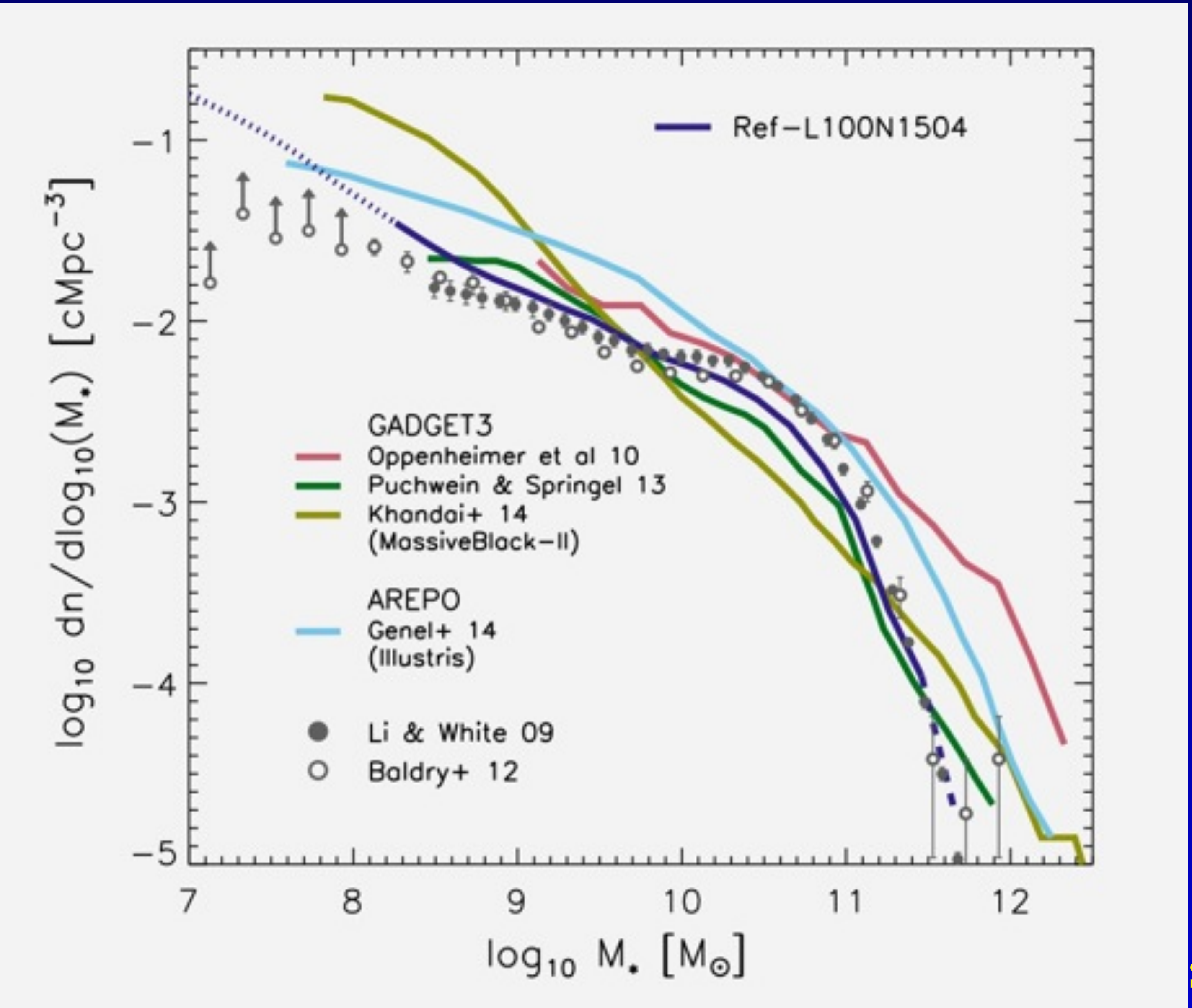
Cosmic Star Formation History



- 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

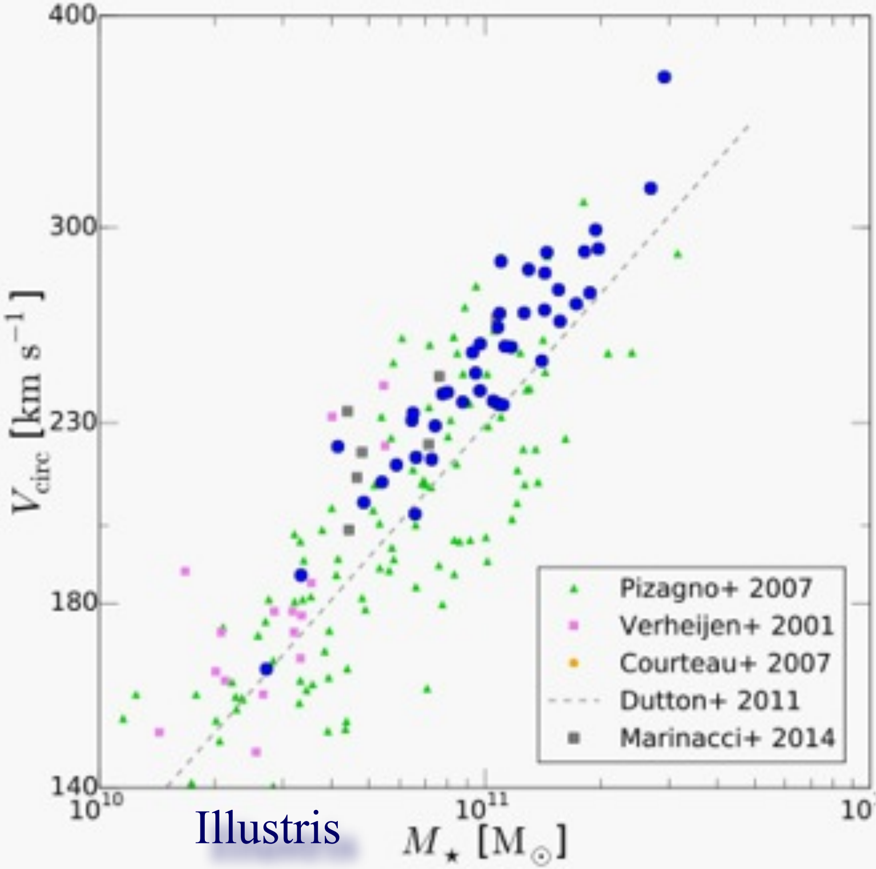
Galaxy Stellar Mass Function



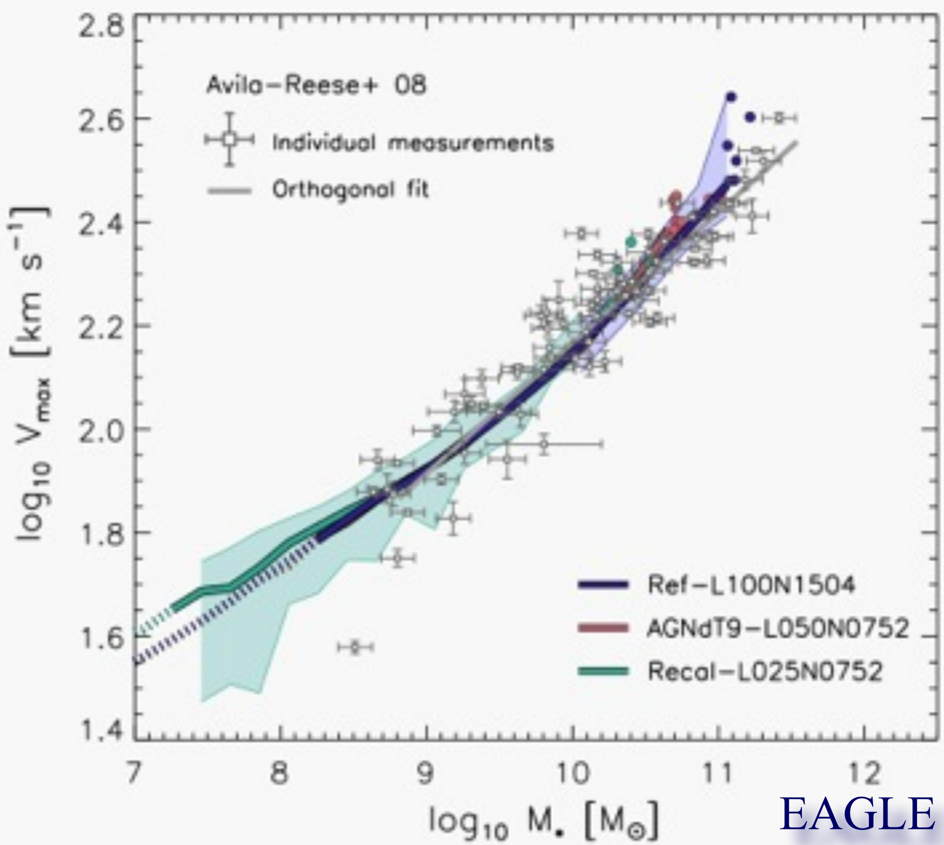
- Feedback is able to reproduce the shape of the galaxy luminosity/ stellar mass function
- Some simulations match it more closely than others, but one shouldn't perhaps read too much into that.

Schaye et al 2014

Tully-Fisher relation



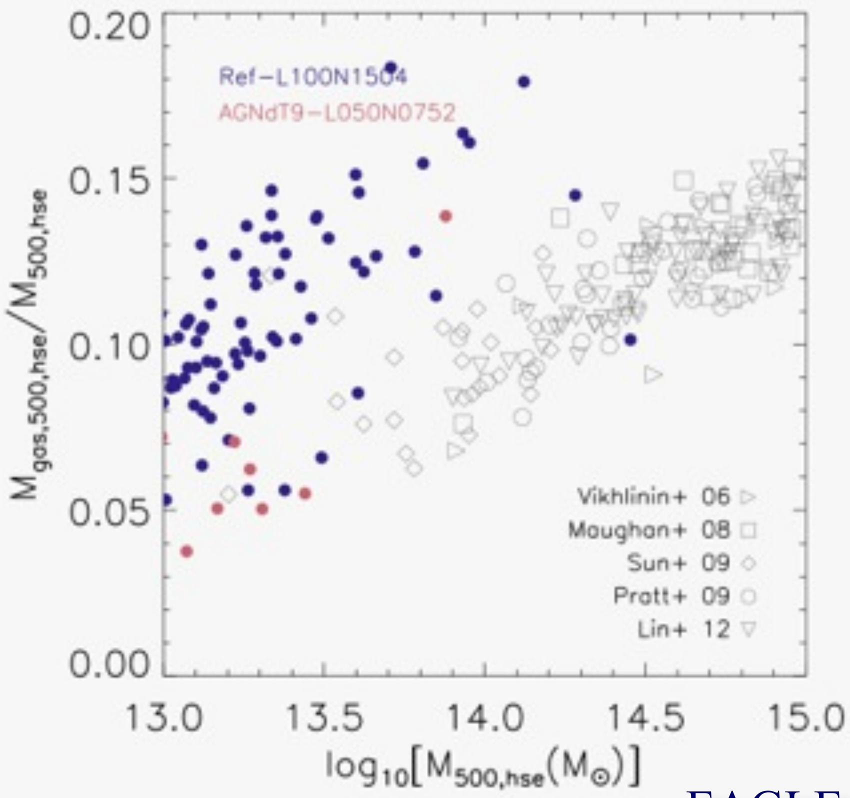
Illustris

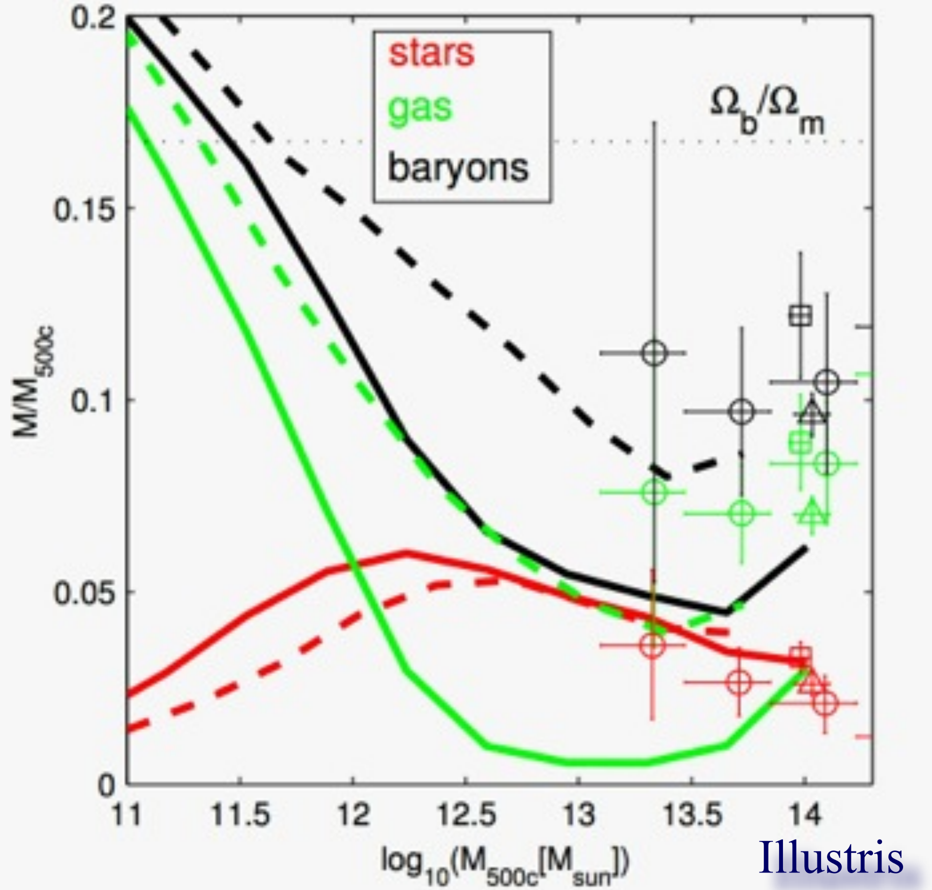


EAGLE

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

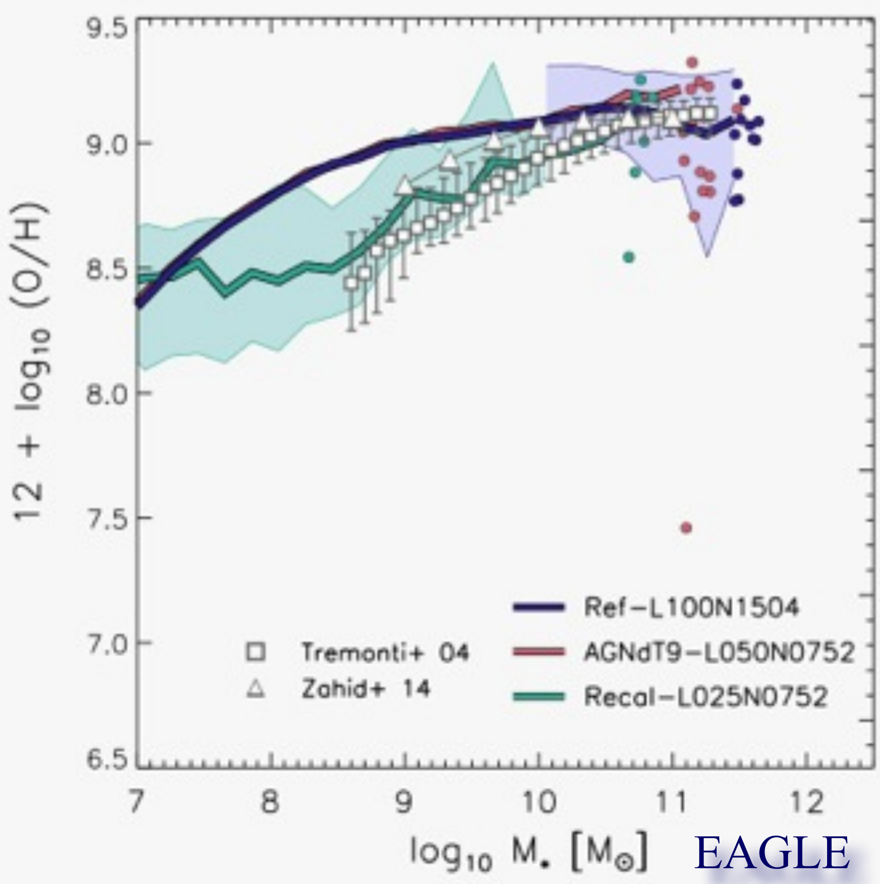
The gas content of groups and clusters

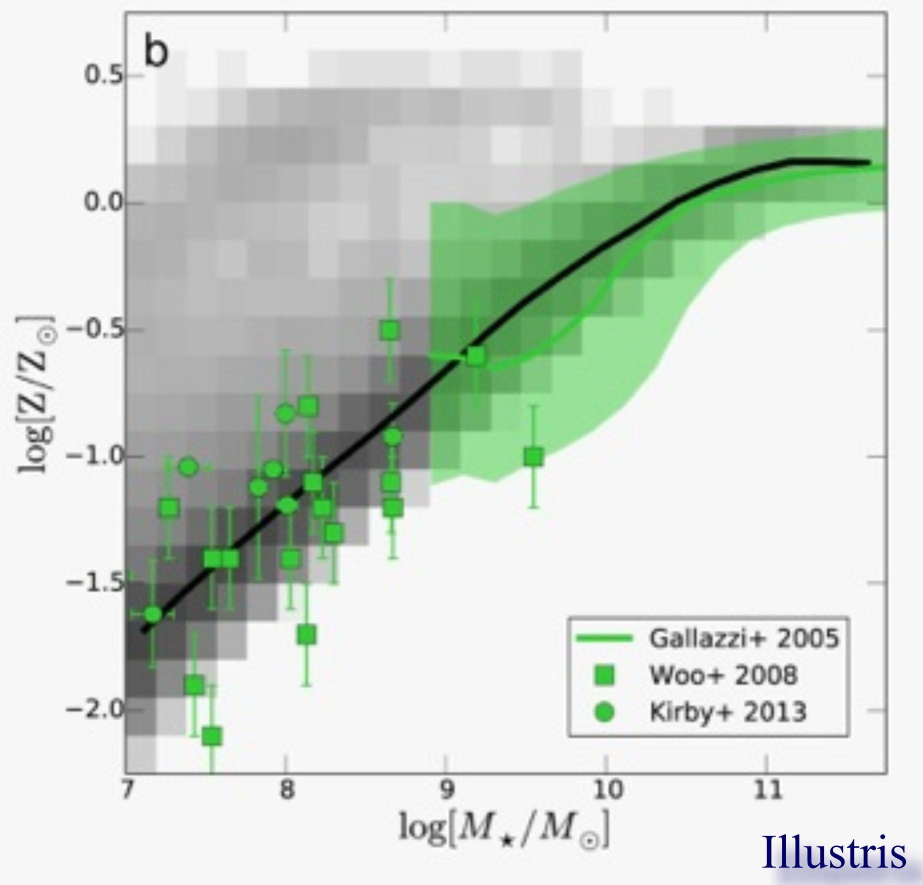




- Not everything works out.
- Illustris and EAGLE fail to account for the observed gas content of galaxy groups and clusters.
- Illustris has too little gas, EAGLE has too much!

Mass-metallicity relation

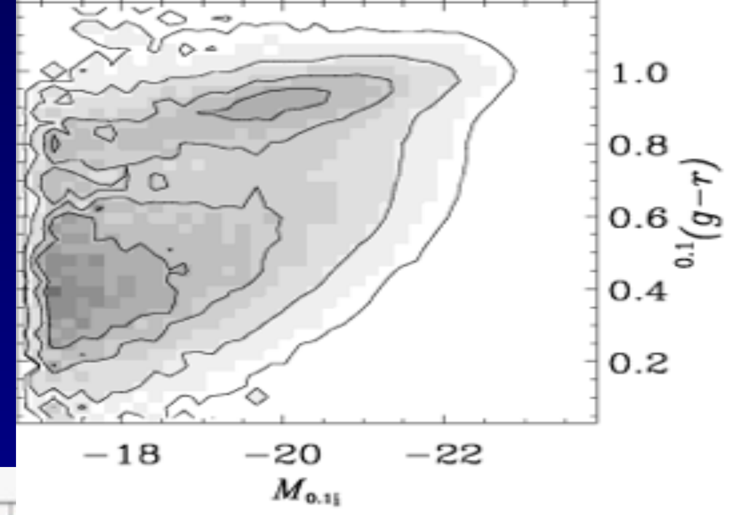


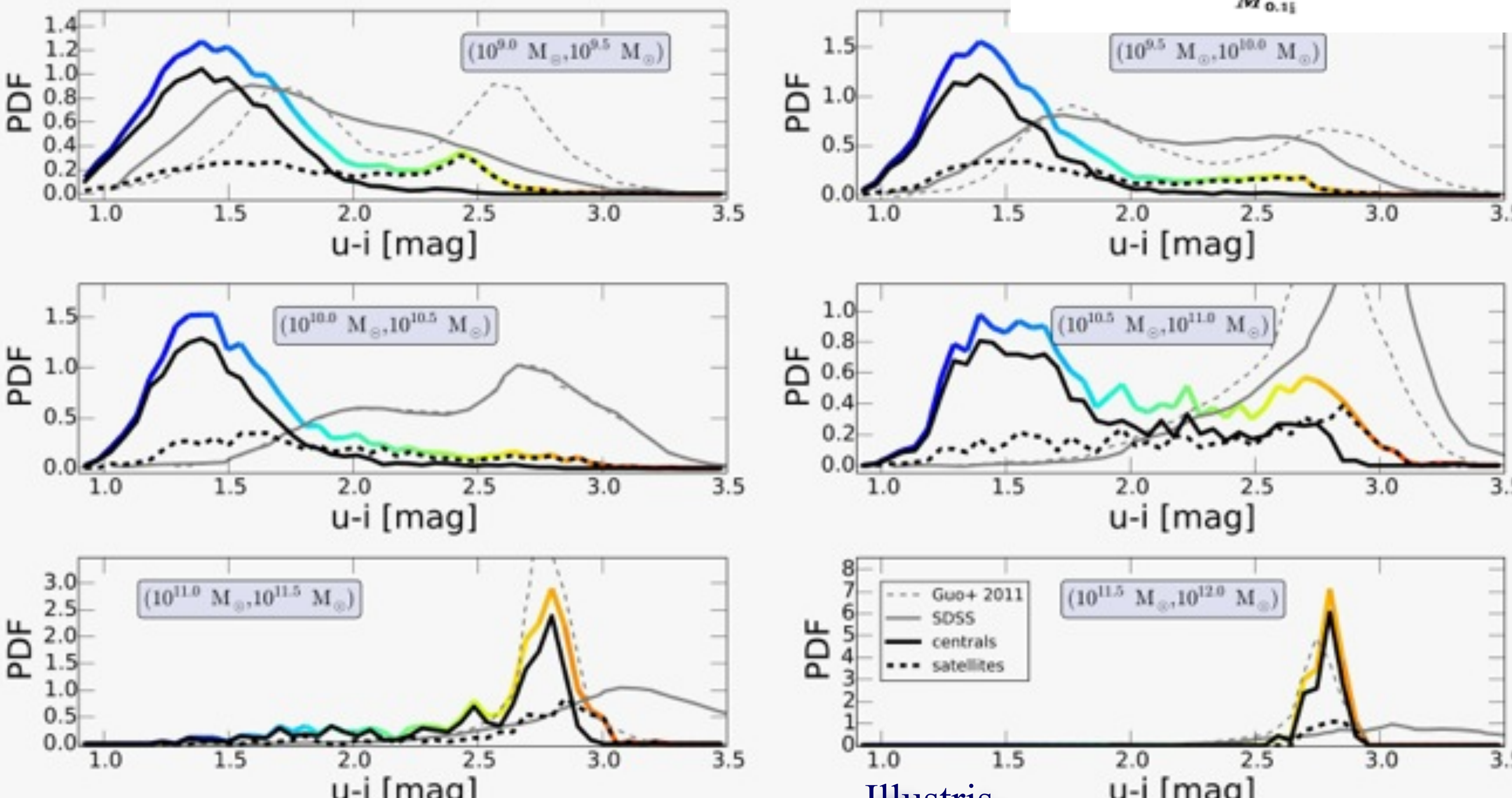


•The mass-metallicity relation is also not very well reproduced. Too many dwarf galaxies have too high metallicities, suggesting that feedback is not as efficient as it should be at ejecting metals.

The galaxy color bimodality

- Not well reproduced in simulations





Illustris

SUMMARY

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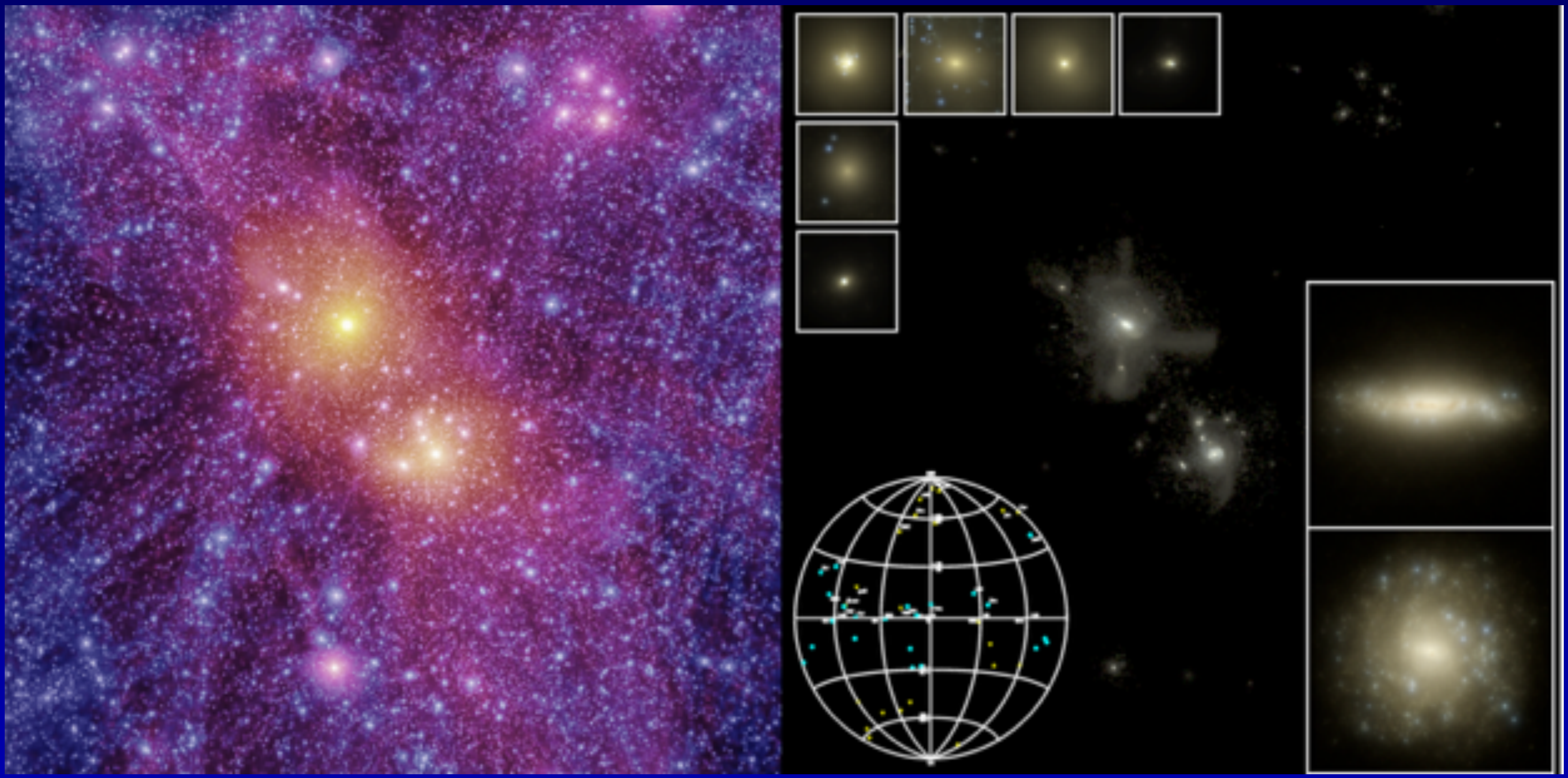
- Numerical simulations of galaxy formation have only recently been able to reproduce the stellar mass, gas content, morphology (disks and spheroids), and kinematics of observed galaxies.
    - Success is a result of improved stellar and AGN feedback algorithms

- No fundamental problem reproducing the main properties of galaxies in the standard LCDM cosmology has been identified on large scales

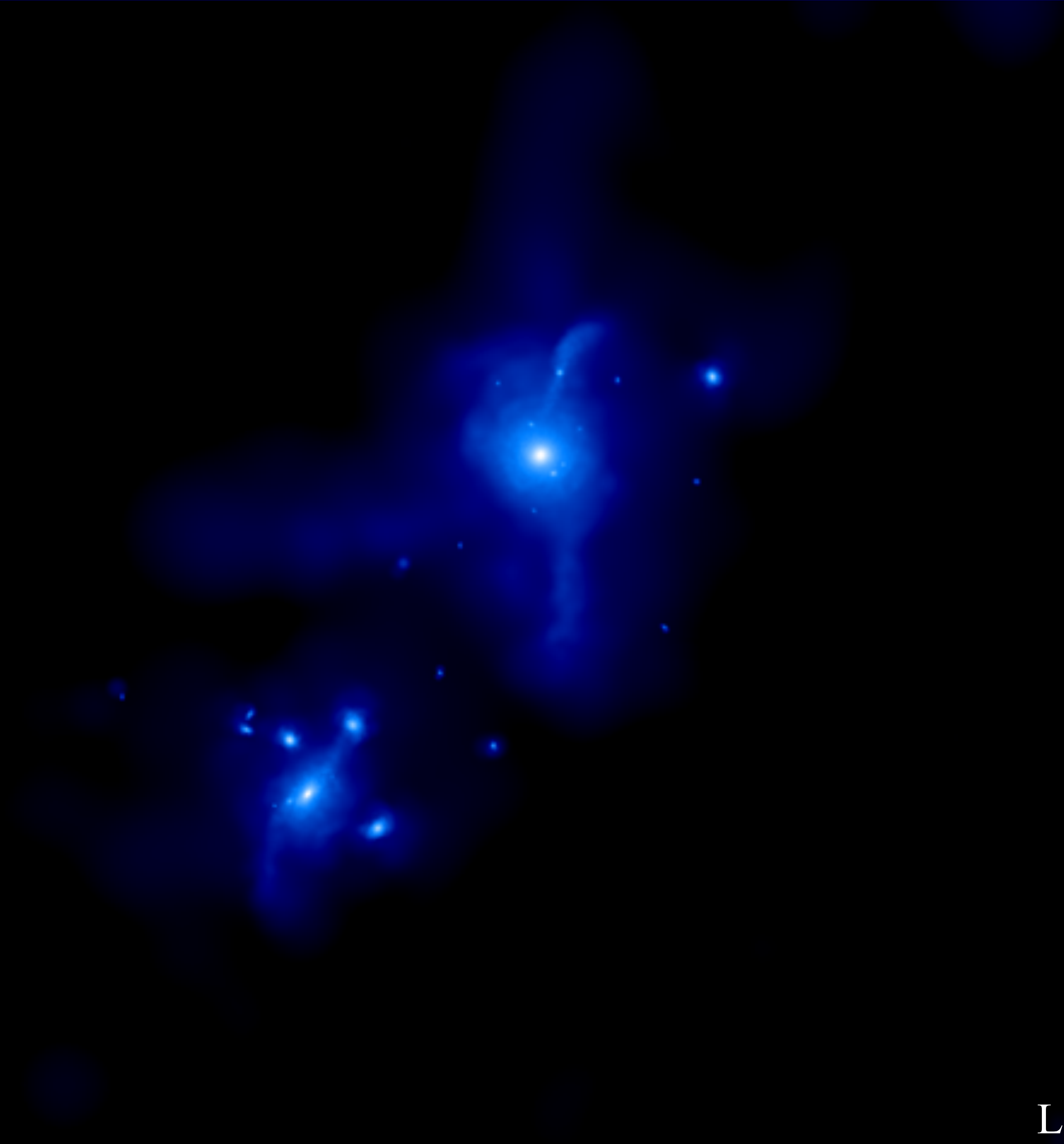
- Some challenges arise from the properties of dwarf galaxies
    - ”Missing satellites” problem
    - “Too-big-to-fail” problem
    - “Alignment” problem
    - “Cusp vs core” problem
    - Origin of diversity
    - Role of reionization

Where next?
Think Locally: Local Group and Dwarfs



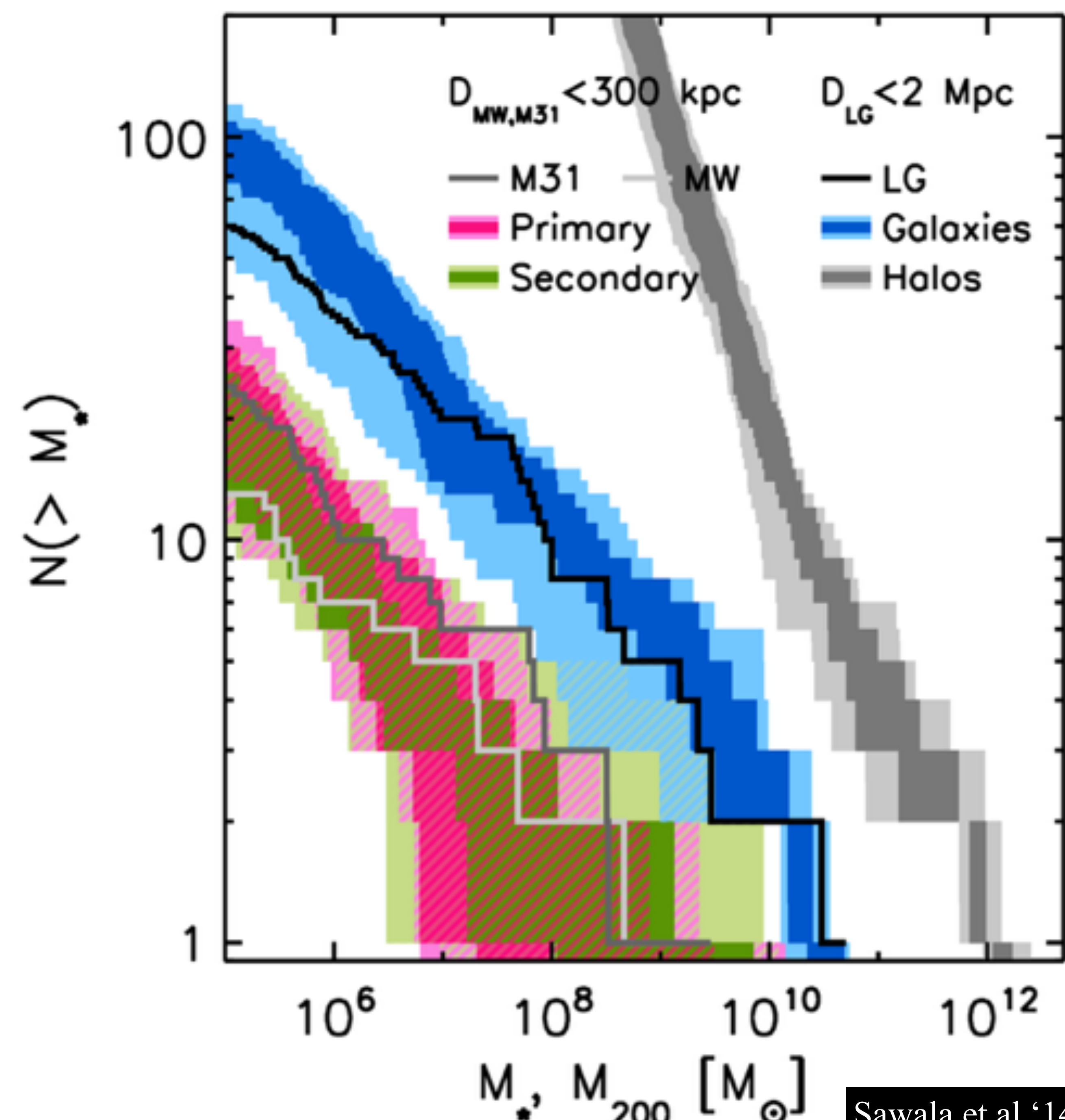
- Local Group simulations can help to exploit the abundance of data being gathered on very faint galaxies, and to address the potential biases that may arise from our particular environment
- Twelve LG candidates have been re-simulated using the *same* code used for the EAGLE project
- Any success on LG scales does not come at the expense of failures on large scales

Dark Matter, Gas and Stars in the Local Group



LG-Fattahi'14

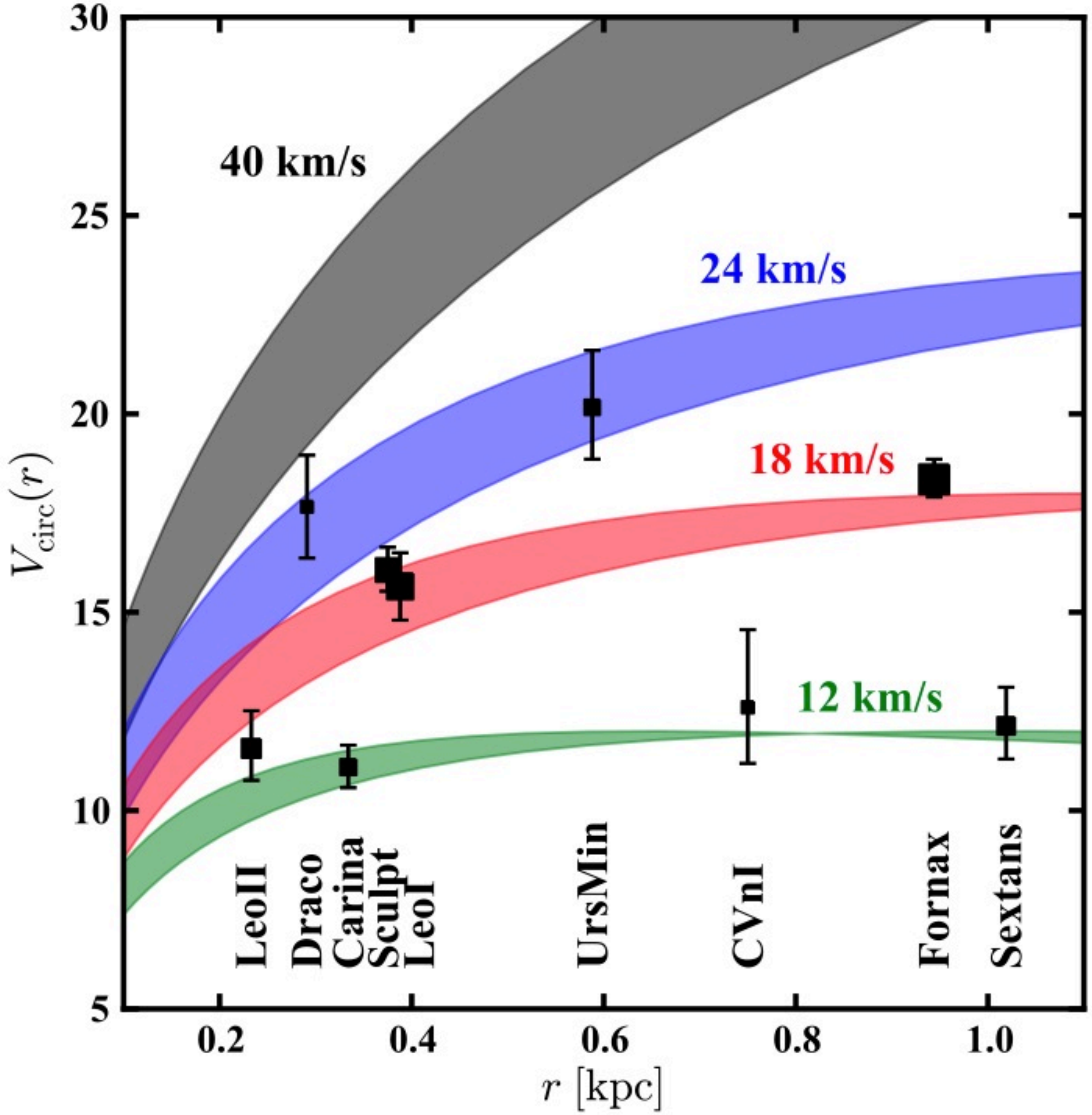
The "missing satellites" problem



Sawala et al '14

- The Local Group re-simulations match quite well the observed number of satellites of each primary and the number of dwarfs within ~2 Mpc from the LG barycentre, down to stellar masses of order ~10^5 M_{sun}

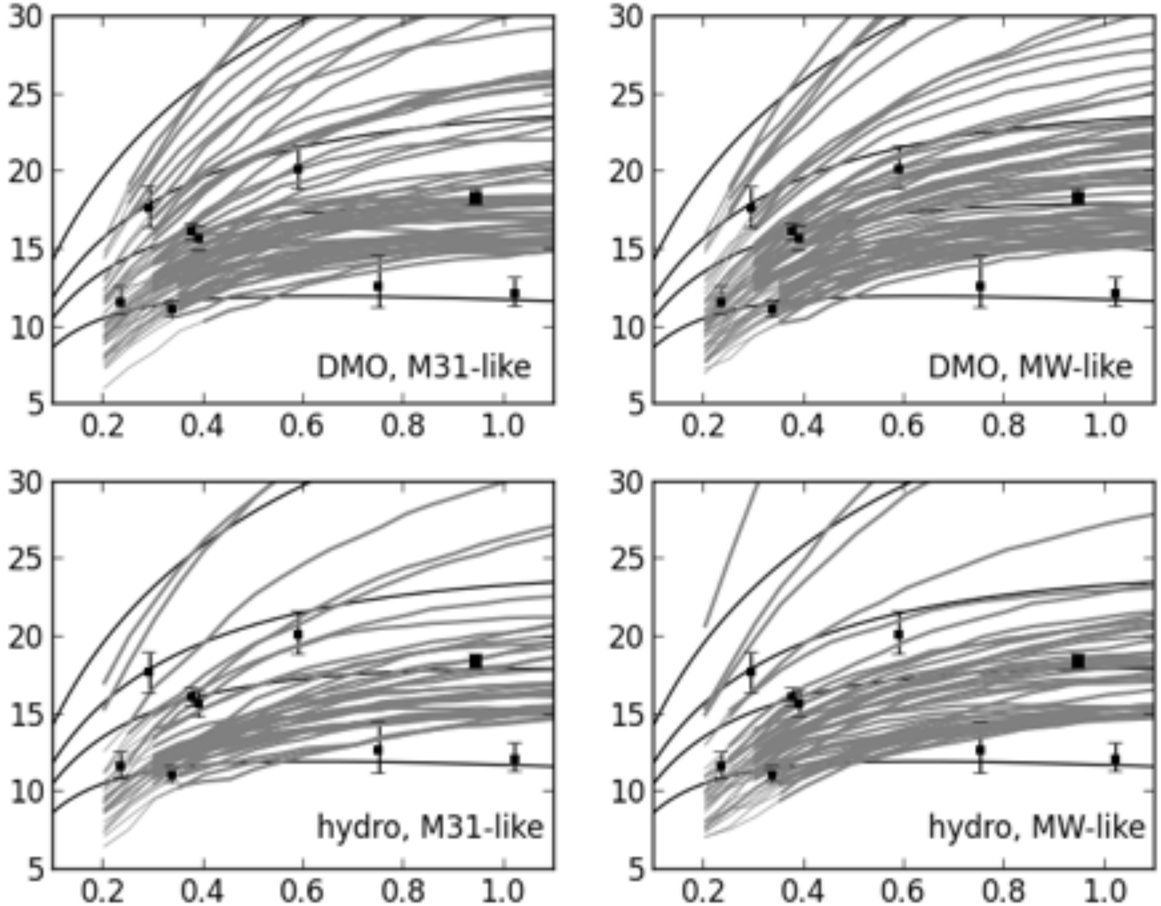
The "too big to fail" problem



- Too big to fail?
- Only 3 Milky Way satellites appear to inhabit halos more massive than V_{max}~30 km/s
- On average, 10 subhalos more massive than this are present in Aquarius halos

Boylan-Kolchin et al '11

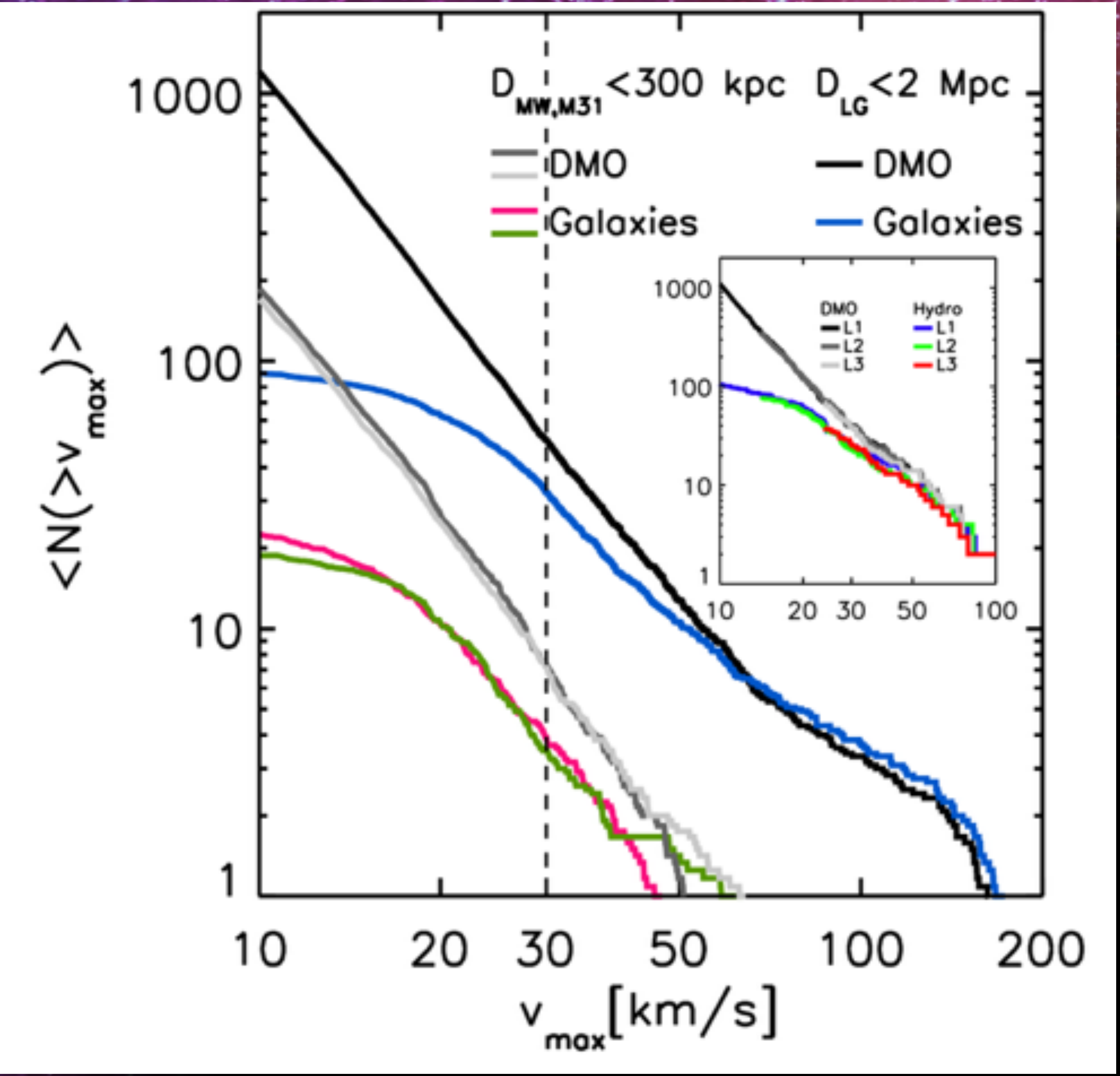
The "too big to fail" problem



- The number of sub halos is greatly reduced, at given V_{max}, in hydrodynamical simulations compared with dark-matter-only runs
- No cores!

Sawala et al 2014

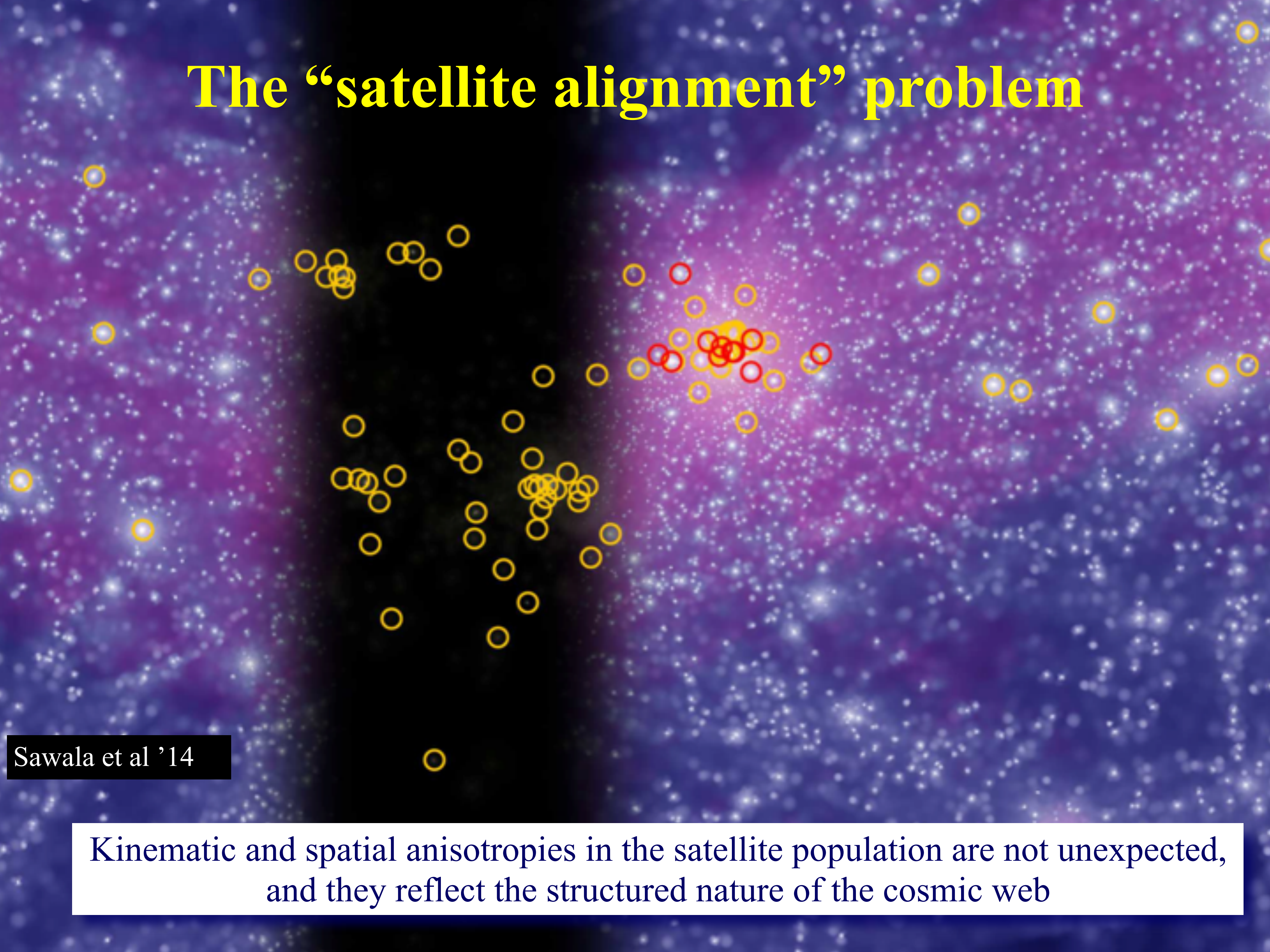
The "too big to fail" problem



- Low-mass subhalos experience a reduction in V_{max} of order 15-20% because of the loss of the baryonic mass.
- This reduces by a factor of ~2 the number of sub halos with V_{max} > 30 km/s, resolving the "too big to fail" problem

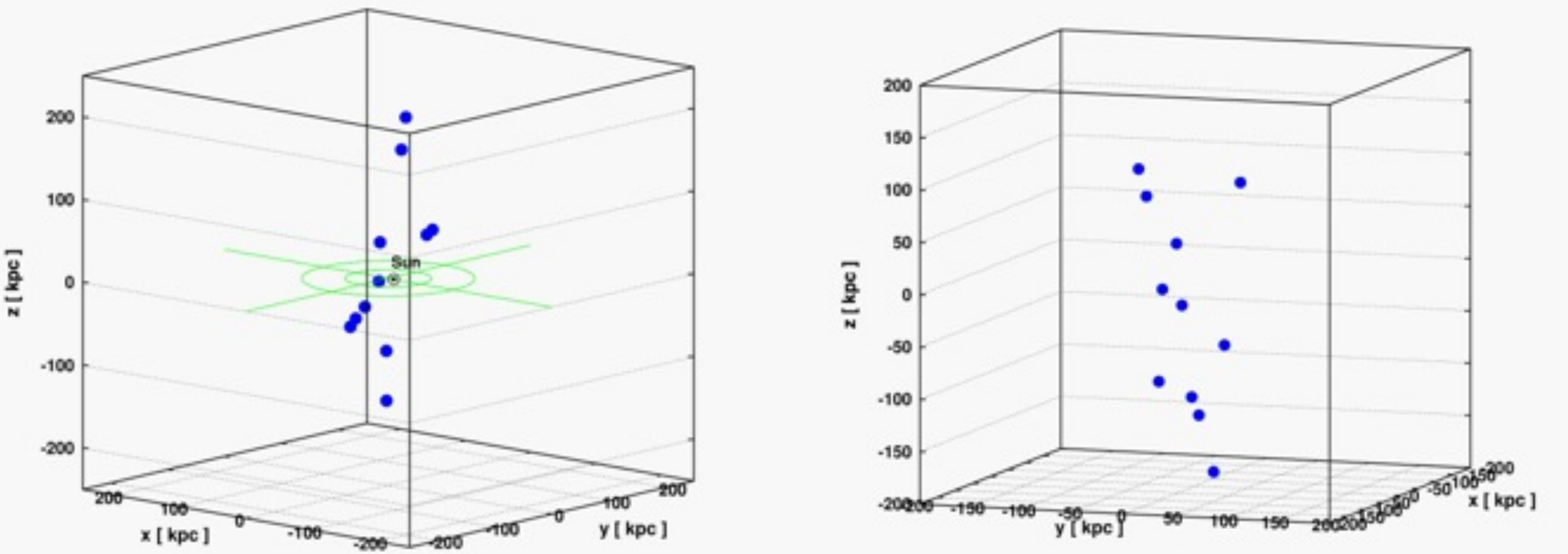
Sawala et al '14

The “satellite alignment” problem



Kinematic and spatial anisotropies in the satellite population are not unexpected, and they reflect the structured nature of the cosmic web

The "satellite alignment" problem

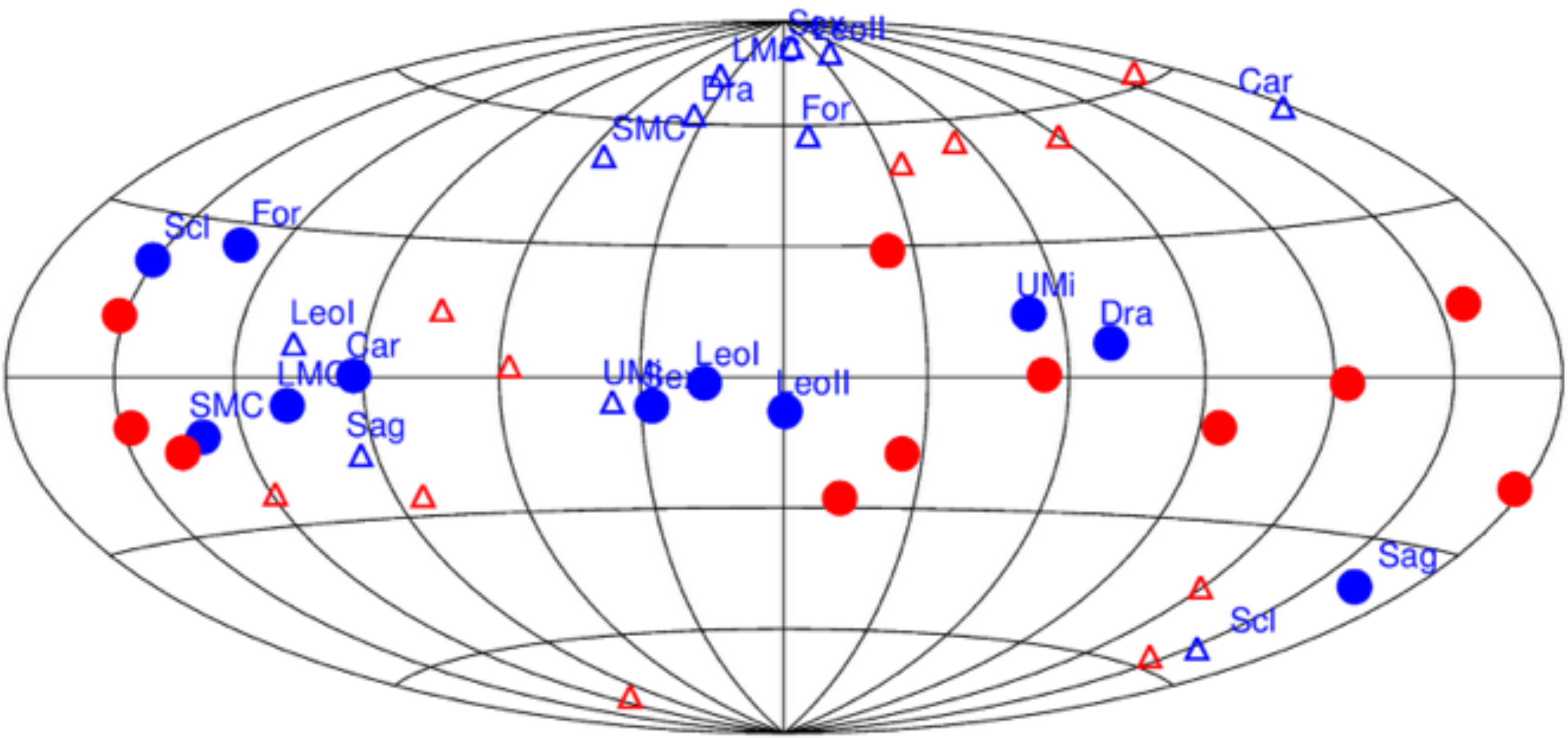


Milky Way LG-5

- Kinematic and spatial anisotropies in the satellite population are not unexpected, and they reflect the structured nature of the cosmic web
- The satellite population of one of our resimulated LG candidates is as "flat" as that of the Milky Way

Sawala et al '14

The “satellite alignment” problem



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Sawala et al ’14

SUMMARY

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- Numerical simulations that include the effects of baryons seem to **resolve three cosmological puzzles** brought about by observations of satellites in the Local Group.
    - The "missing satellites" problem
    - The "satellite alignment" problem
    - The "too big to fail alignment" problem

- Rotation curves of dwarf galaxies, taken at face value, present a problem for LCDM
    - The problem is one of **diversity** at given velocity/mass scale: some galaxies show cores, others do not
    - This **precludes a solution that involves modifying the nature of dark matter**
    - Astrophysical solutions are possible, although they may be difficult to reconcile with the large core sizes observed and with the lack of correlation with other galaxy properties