Dwarf Galaxies as Cosmological Probes

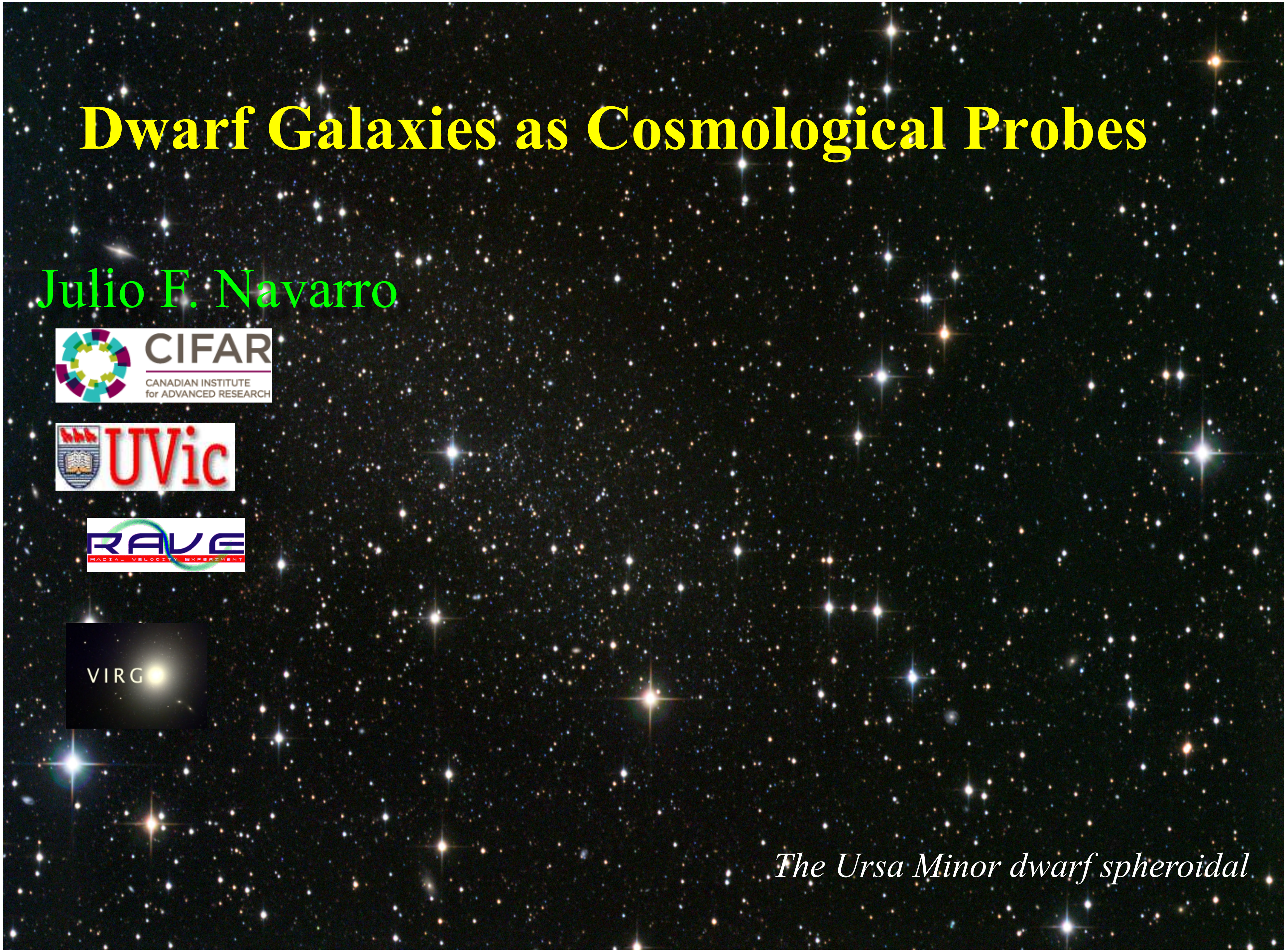
Julio F. Navarro

CIFAR
CANADIAN INSTITUTE for ADVANCED RESEARCH

UVic

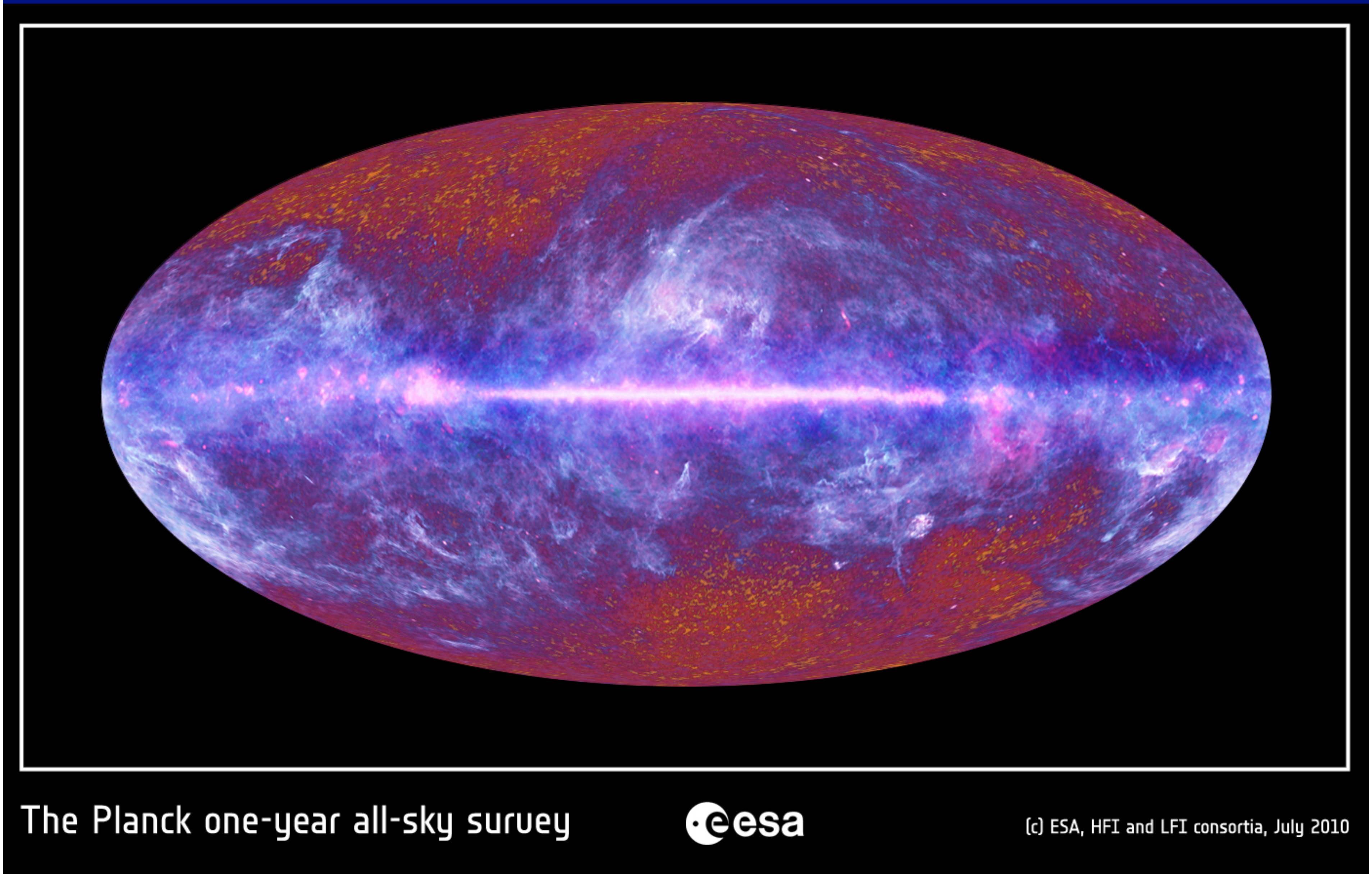
RAVE
RADIAL VELOCITY EXPERIMENT

VIRGO

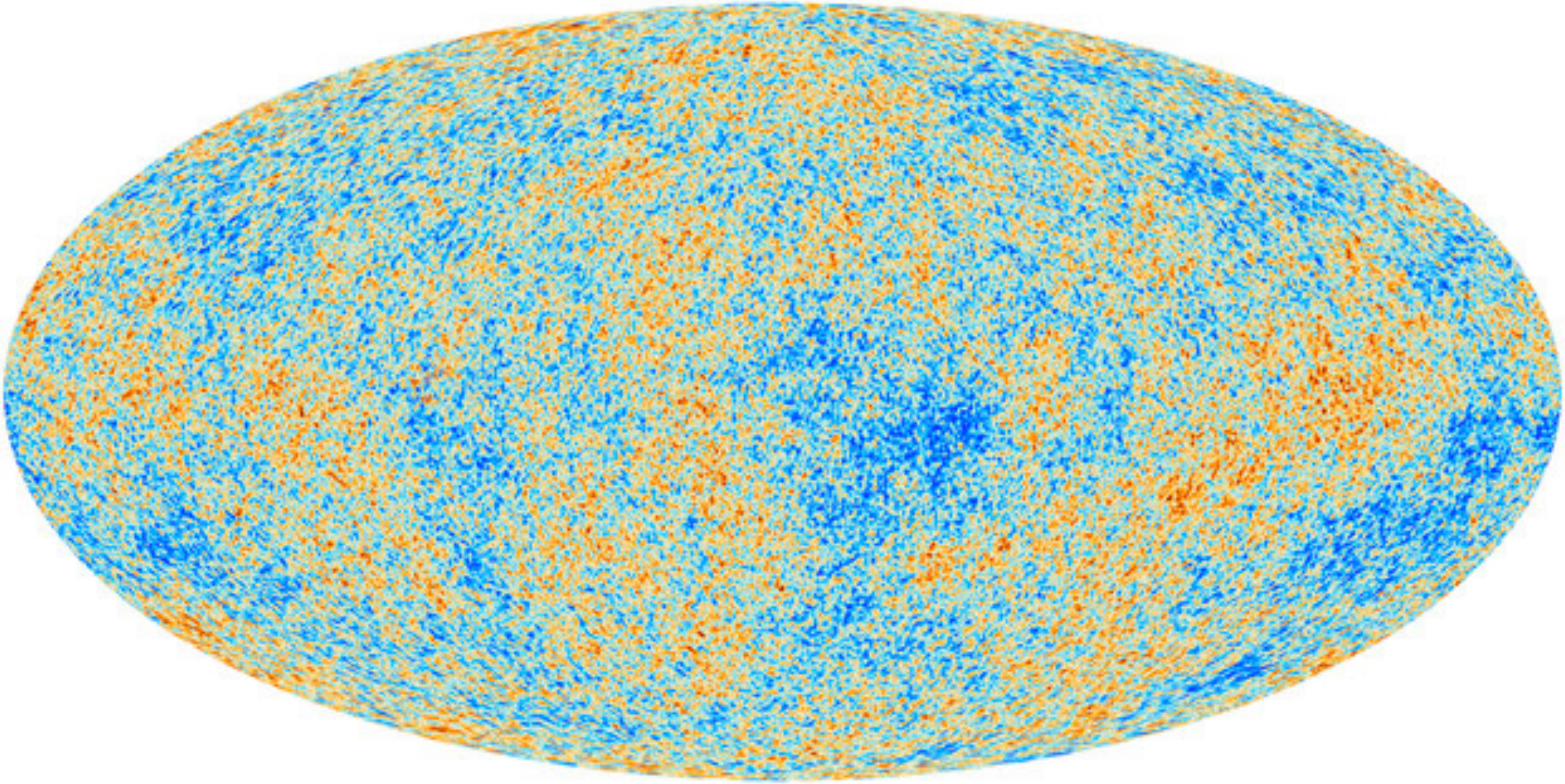


The Ursa Minor dwarf spheroidal

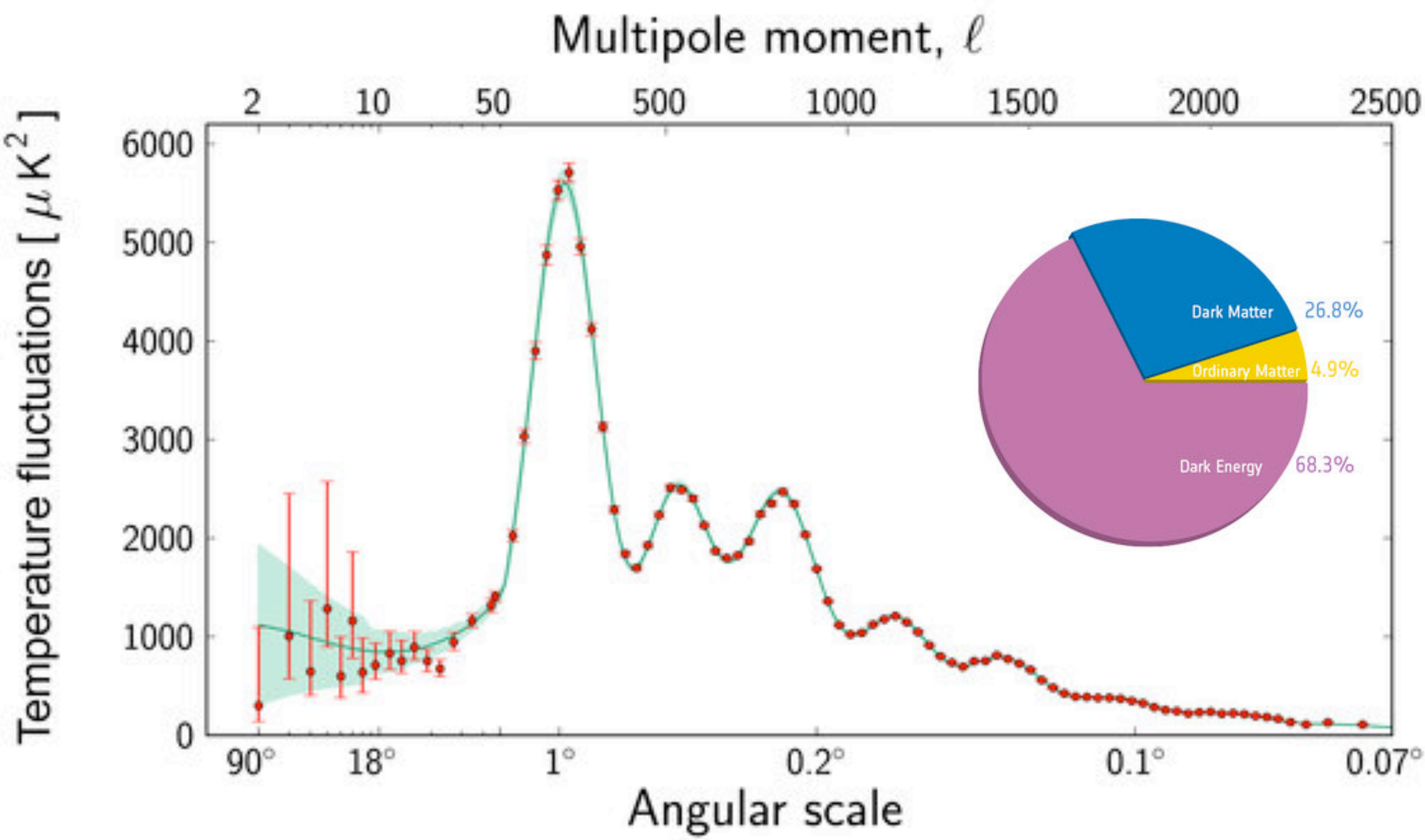
The Cosmological Revolution



First Light

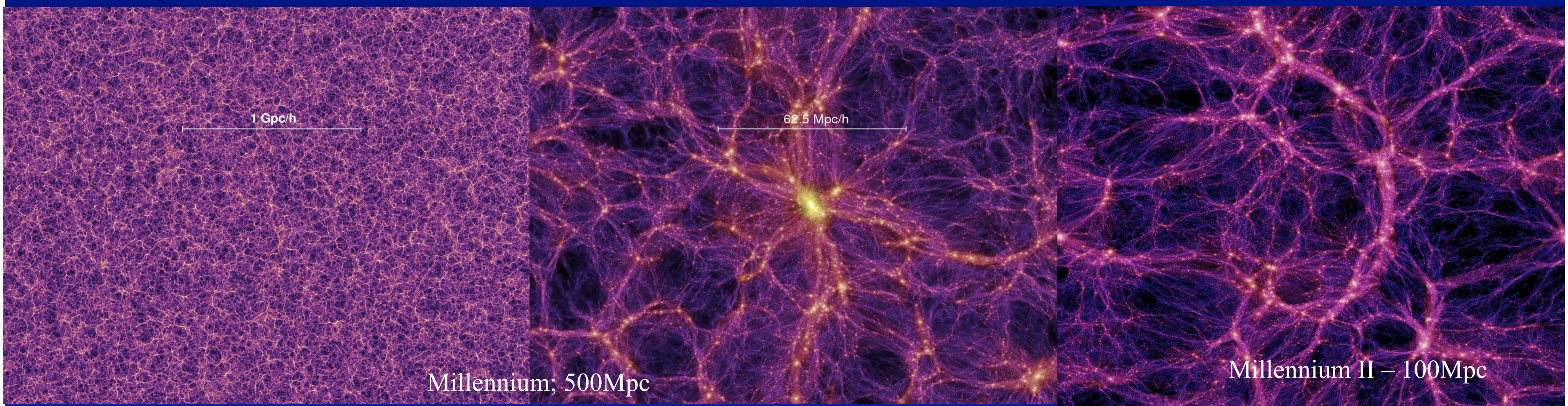


The Cosmological Paradigm



The Clustering of Dark Matter

The Millennium Simulation Series



Millennium; 500Mpc

Millennium II – 100Mpc

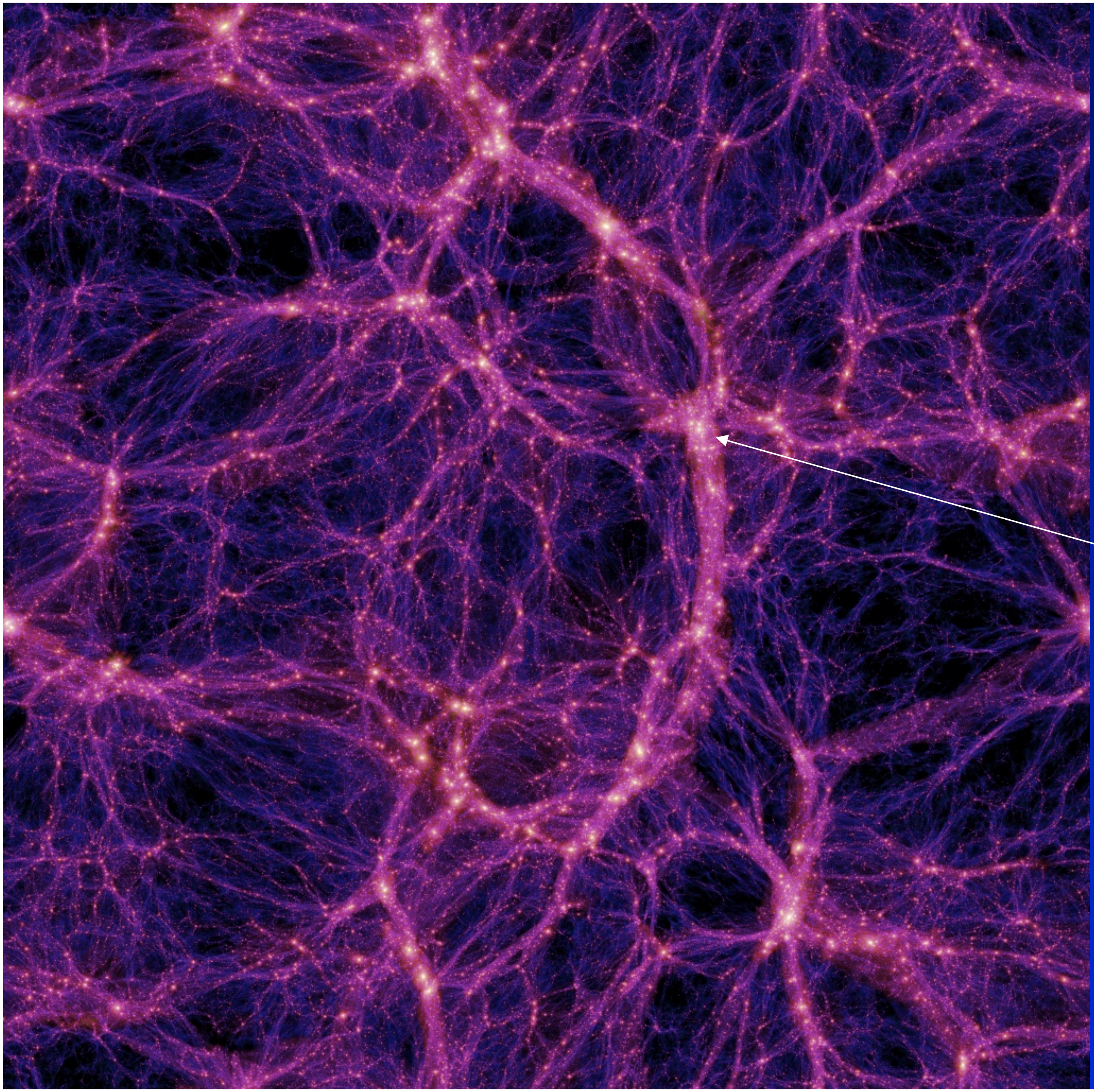

Aquarius: a galaxy halo

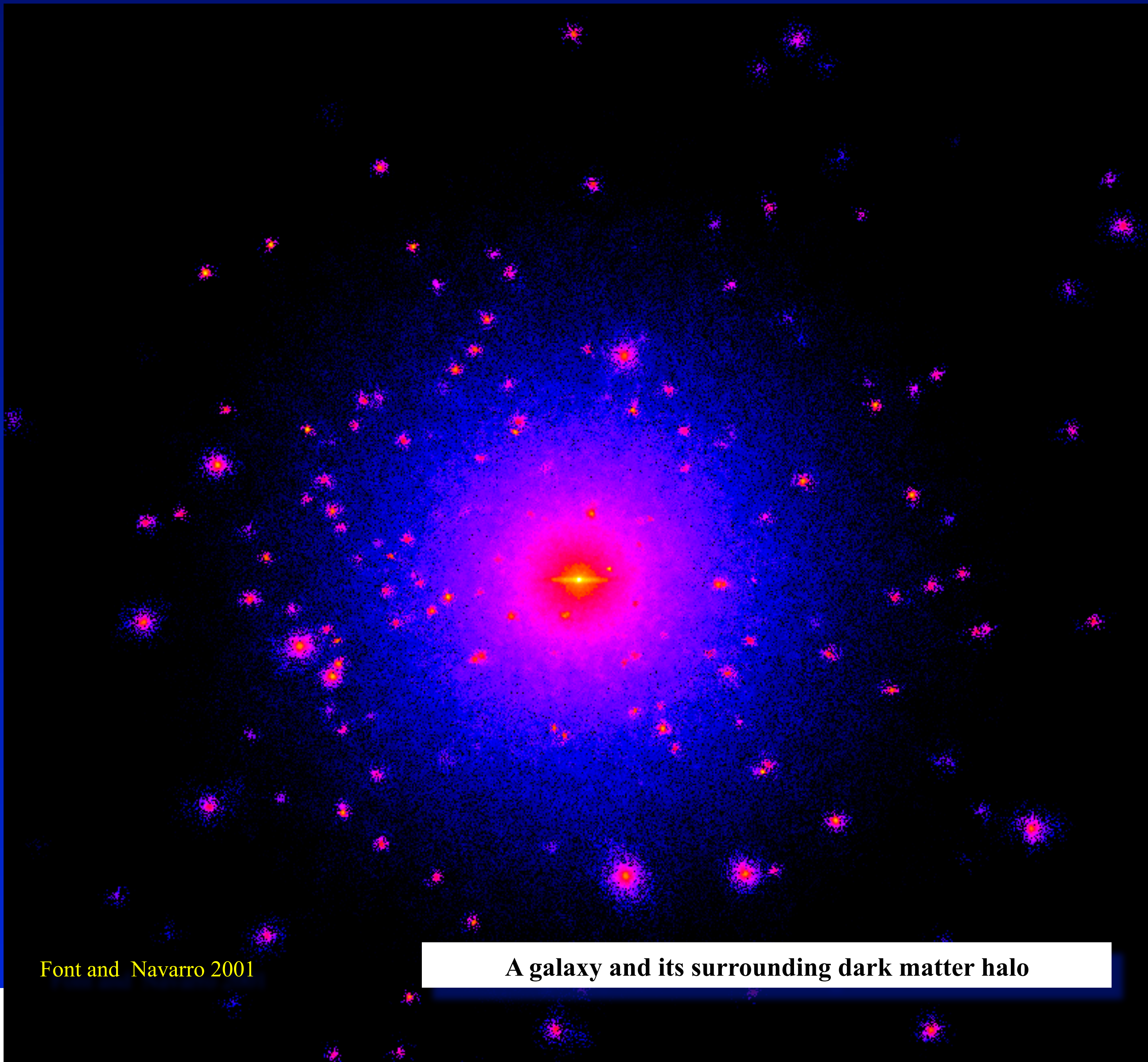
Phoenix: a galaxy cluster halo

Simulations have enabled a full characterization of the clustering of cold dark matter on large and small scales.

VIRGO

Halos: the building blocks of the Cosmic Web

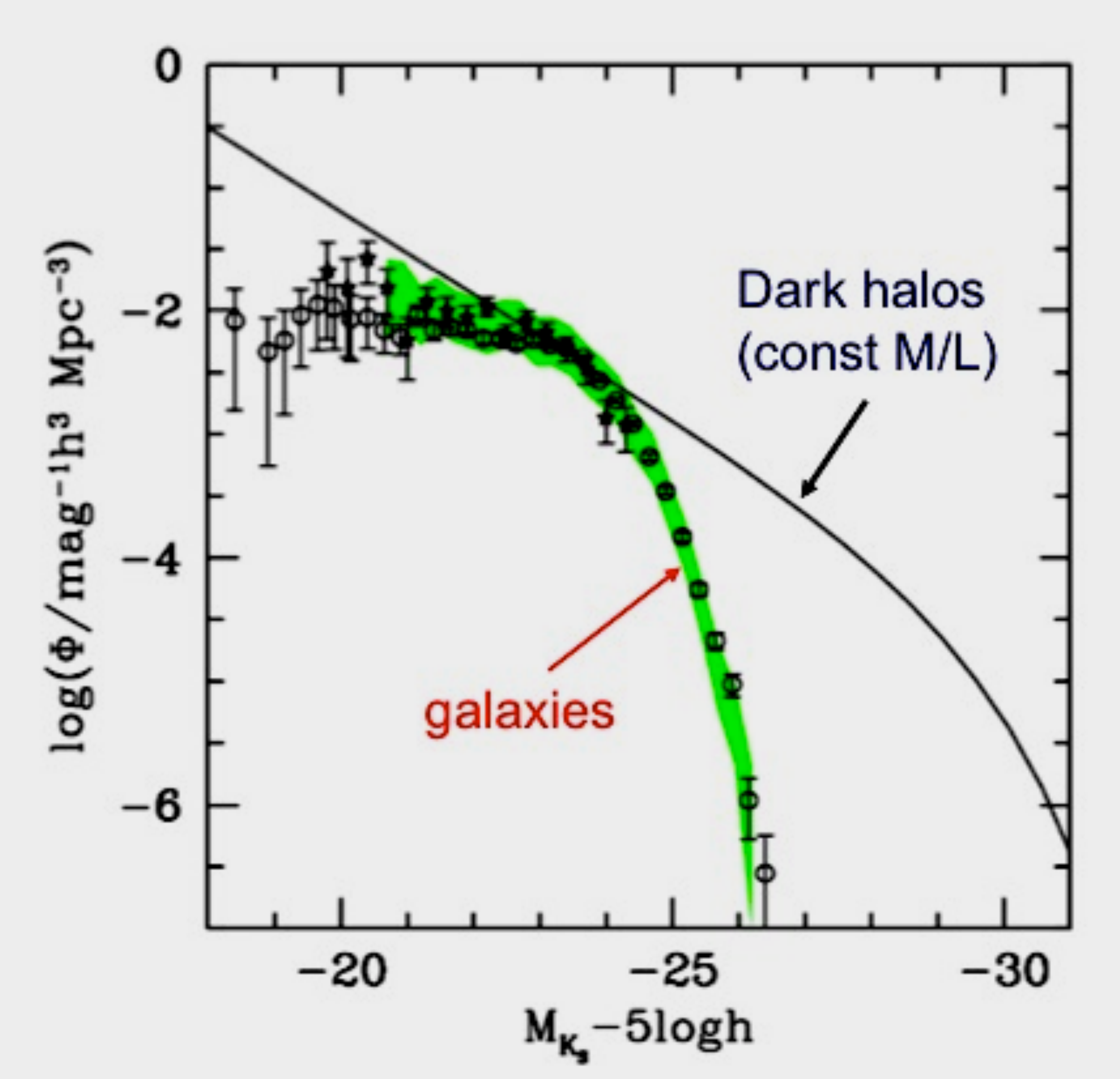




A galaxy and its surrounding dark matter halo


z = 48.4
T = 0.05 Gyr
500 kpc

CDM halo mass function vs galaxy luminosity function

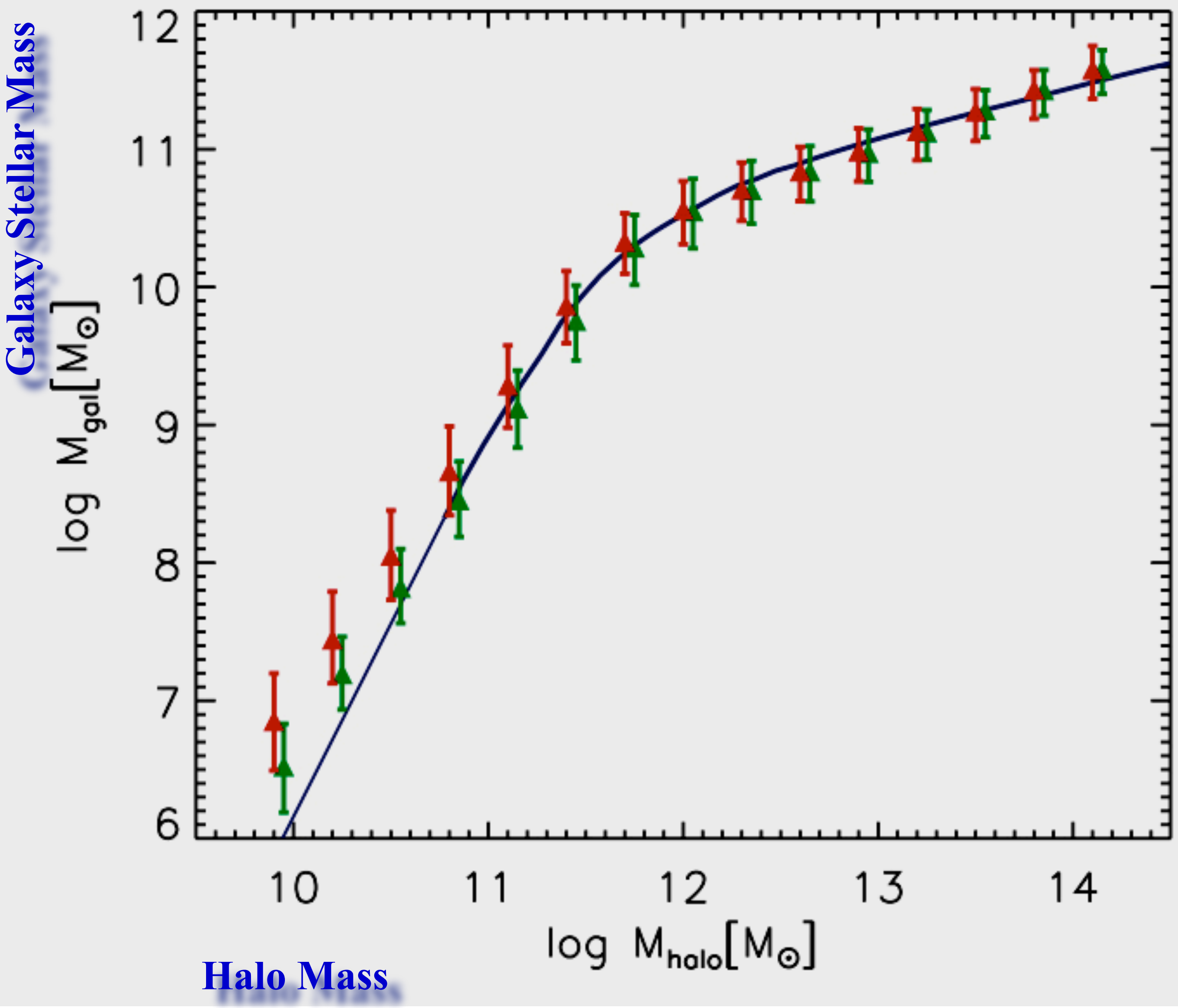


•CDM halo mass function *much steeper* than the galaxy luminosity function at the faint end

•This is a robust prediction of the CDM scenario

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

Galaxy Stellar Mass vs Halo Mass



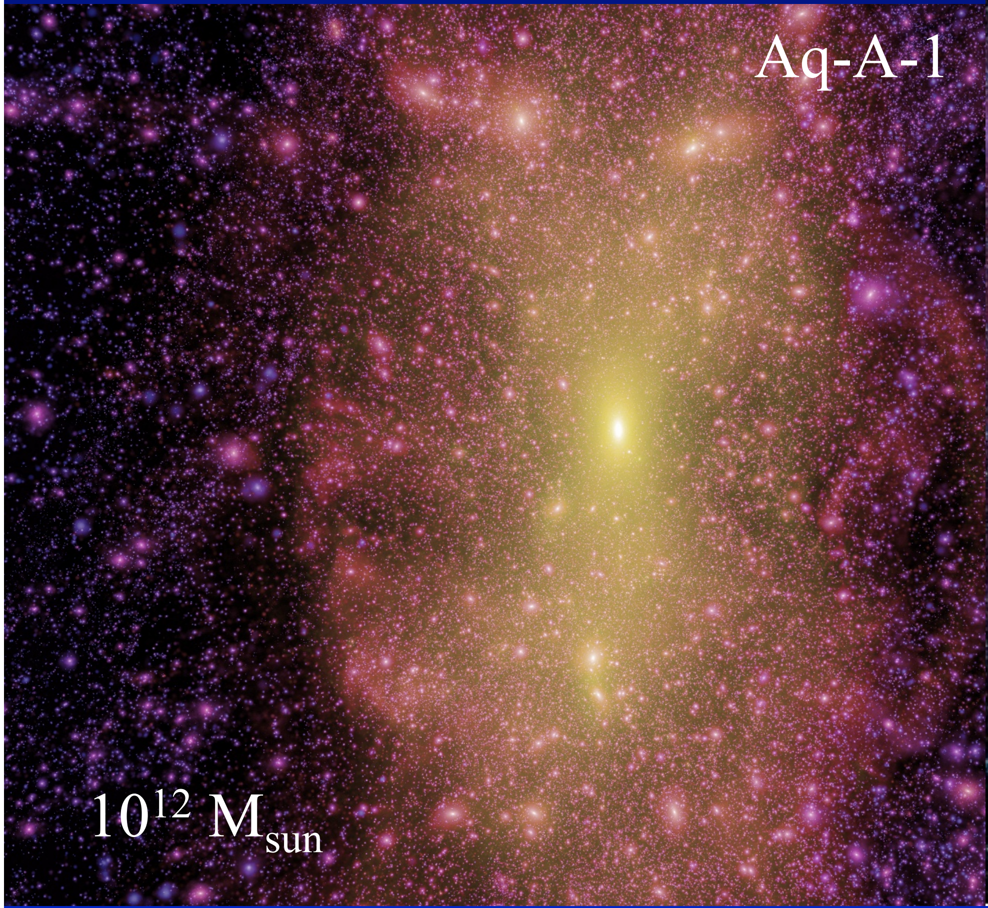
•Steep dependence at low halo mass--a fundamental result of galaxy formation models.

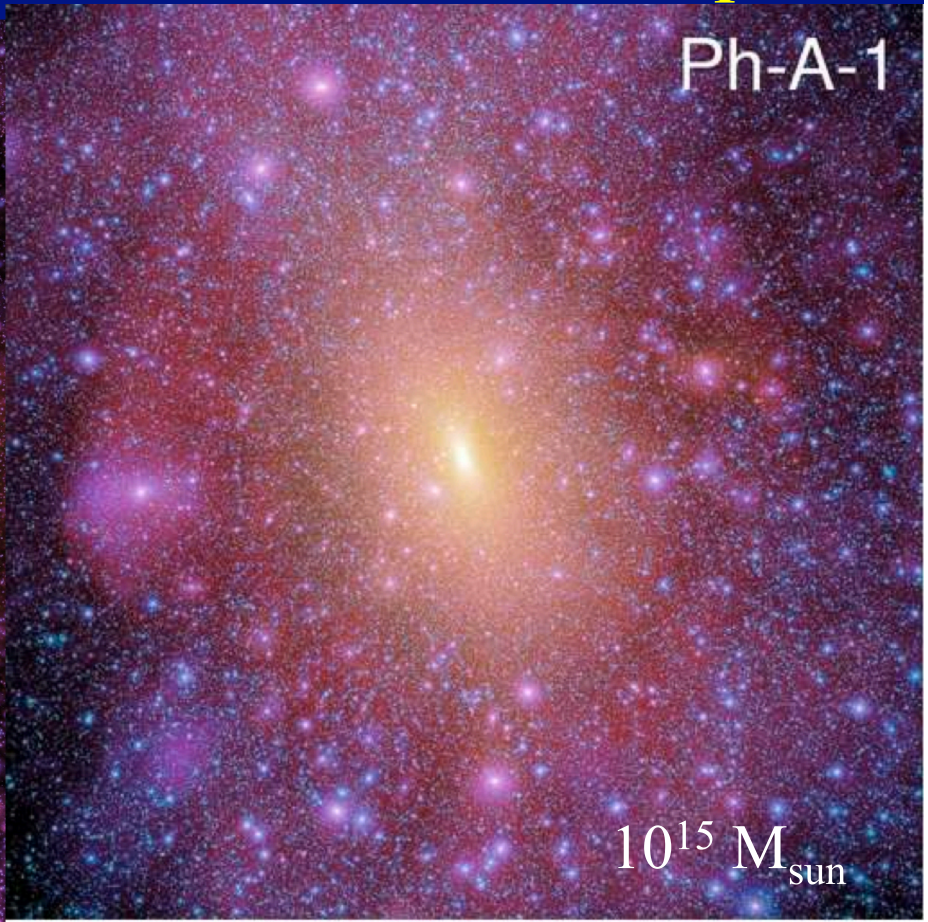
•Power-law behaviour on dwarf-galaxy scales

•Essentially no luminous galaxies should form in halos with mass below a "threshold" of 10^{10} M_{sun}

Guo et al 2011

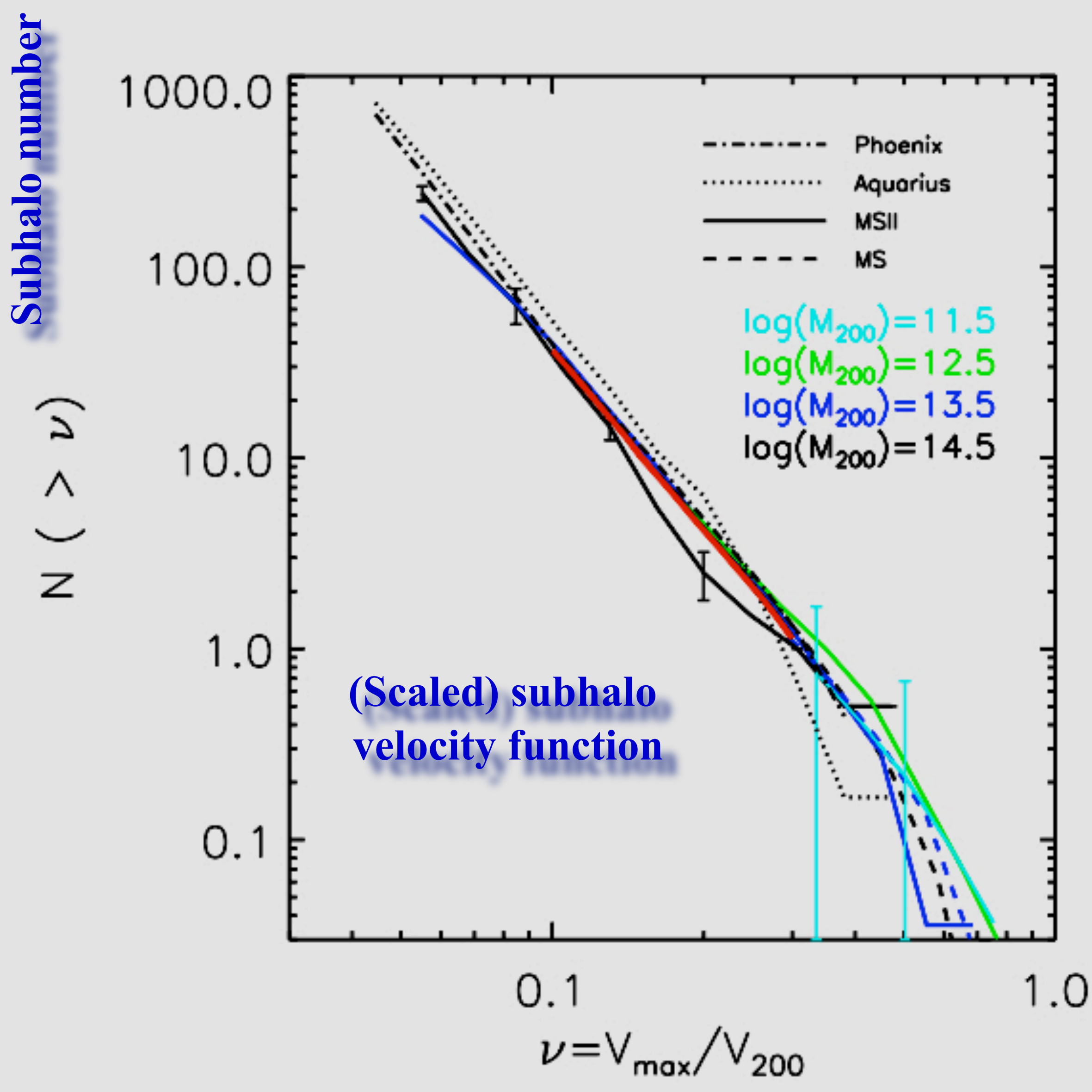
Aquarius and Phoenix : Cold Dark Matter under a numerical microscope





The structure and substructure of CDM halos are approximately self-similar

The invariance of CDM substructure



•CDM halo structure and substructure are self-similar

•The (scaled) subhalo mass function is independent of host halo mass

•Typically, halos have only one subhalo more massive than ~3% of the host halo virial mass

Wang et al 2012

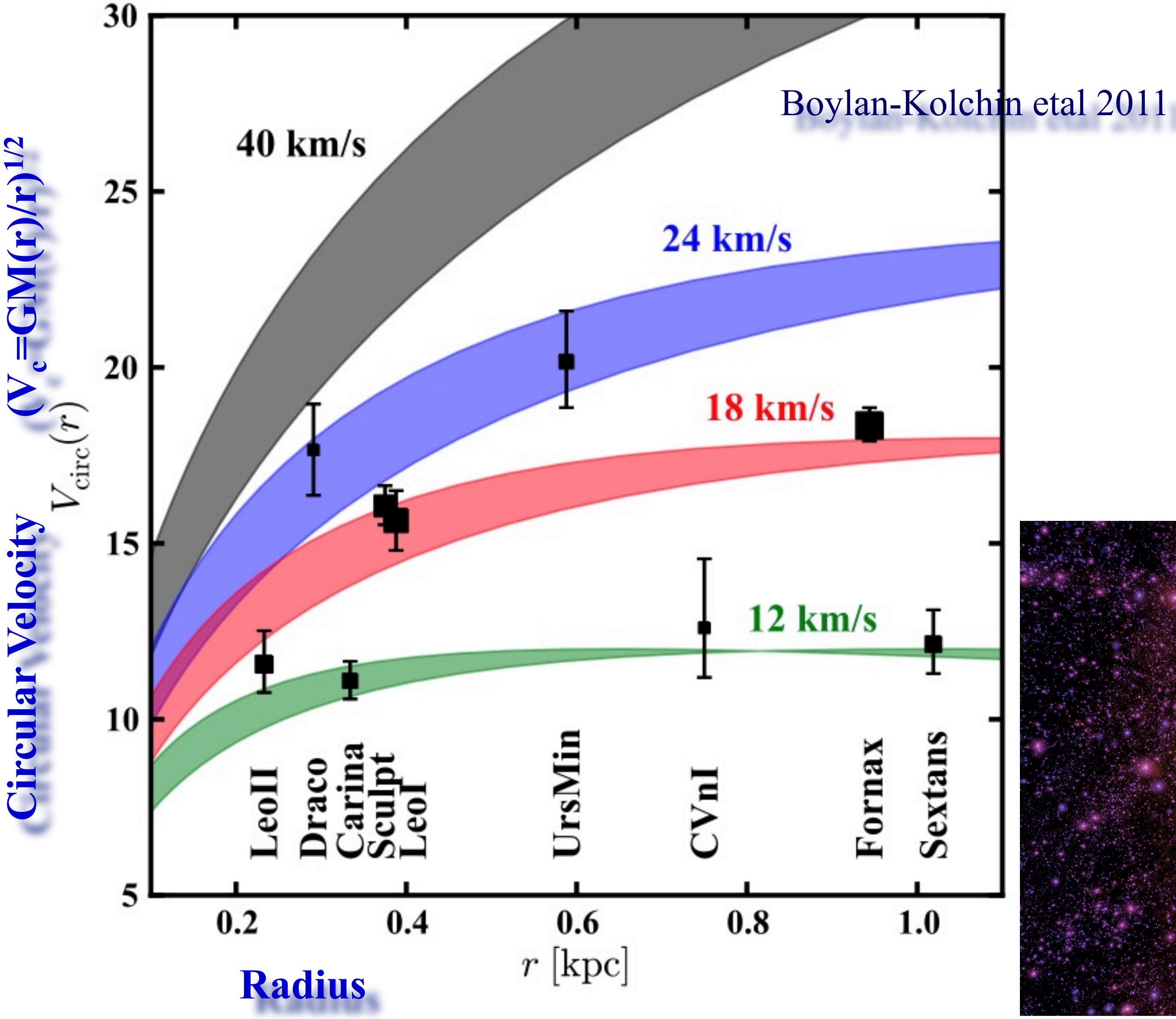
Corollaries for dwarf galaxies

•The steep M_{gal}-M_{halo} relation implies that most dwarfs should populate halos of similar mass (why are then dwarf galaxies so diverse?)

•There is an effective "threshold" in halo mass for galaxy formation

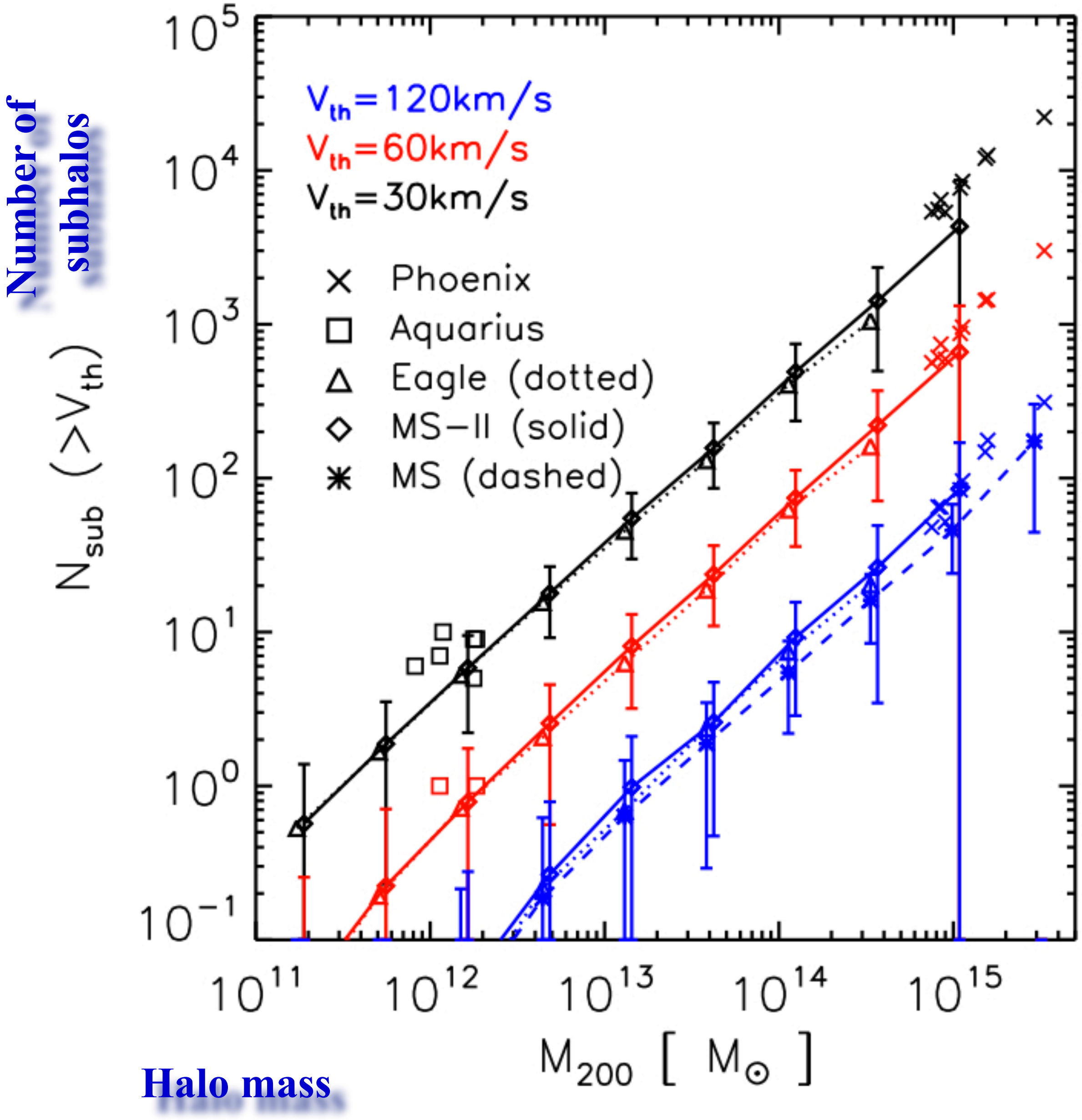
•Subhalos are typically much less massive than the main halo. Given the steep M_{gal}-M_{halo} relation, virialized "groups" of dwarfs should be rare

Dwarf galaxy satellites of the Milky Way



- 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

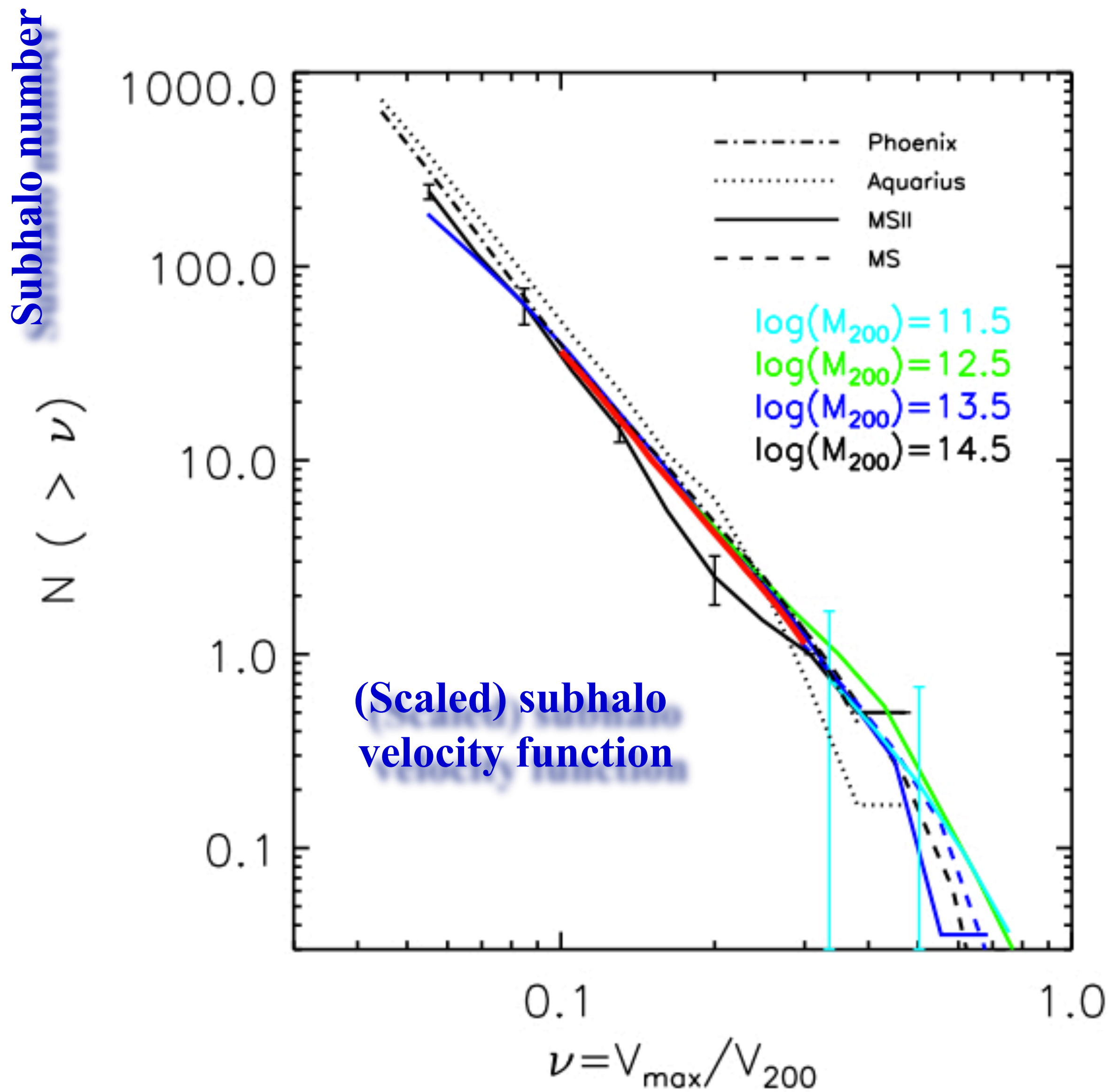
Host halo mass dependence of subhalos



•The number of massive subhalos depends strongly on the host halo mass, and their scarcity means that estimates from a small set of simulations, like Aquarius, might be unreliable

Wang et al 2012

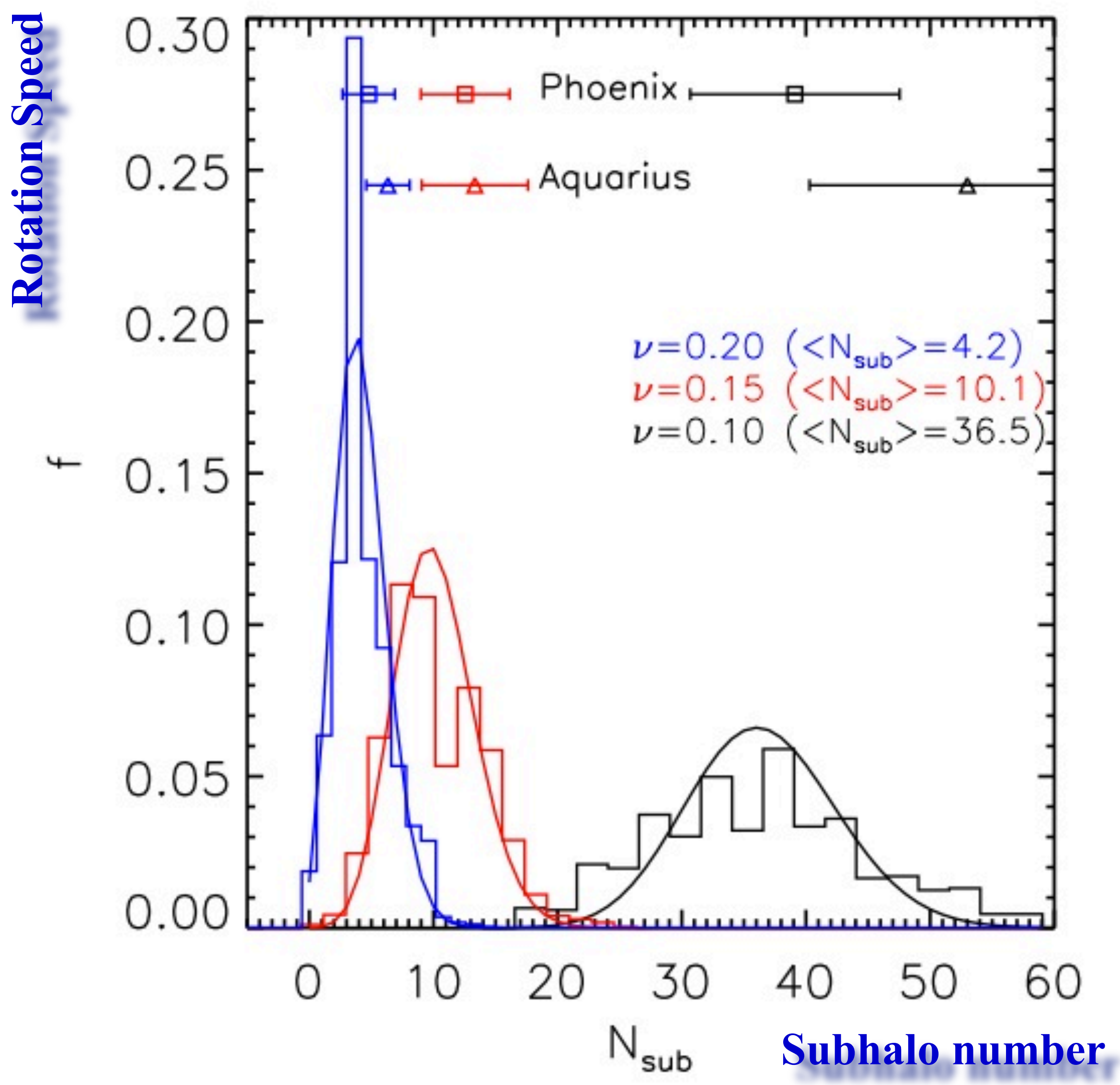
The invariance of the subhalo mass function



- The (scaled) subhalo mass function is independent of host halo mass
- Large sets of halos can be assembled from different simulations to explore the statistics of rare massive subhalos.
- Typically, halos have only one subhalo more massive than ~3% of the host halo virial mass

Wang et al 2012

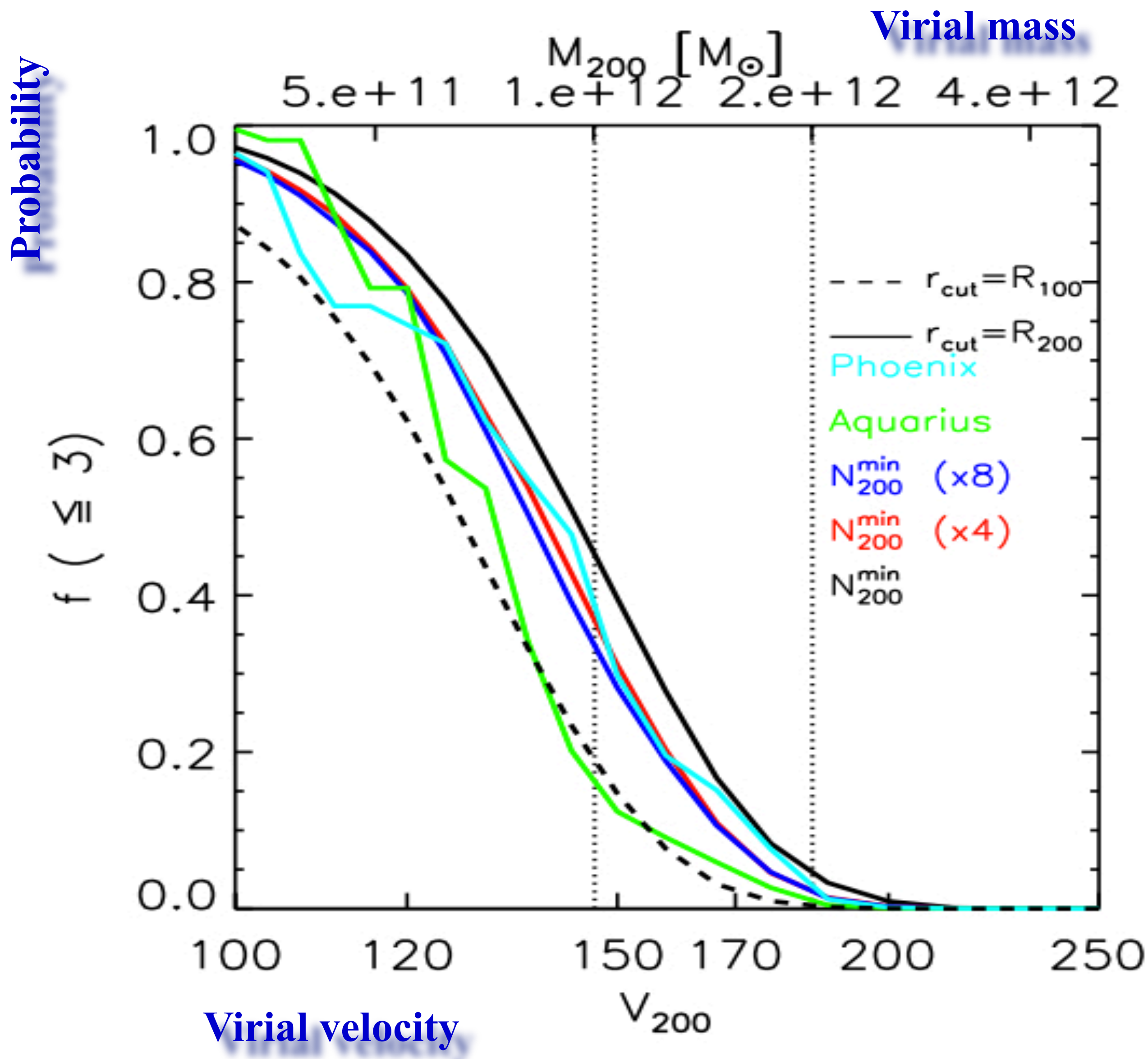
The statistics of massive subhalos



- Rare, massive subhalos are Poisson distributed around a well defined mean that may be computed from simulations.
- This allows us to compute the probability that a Milky Way-like halo has only 3 massive satellites (i.e., V_{max}> 30 km/s).

Wang et al 2012

The mass of the Milky Way halo



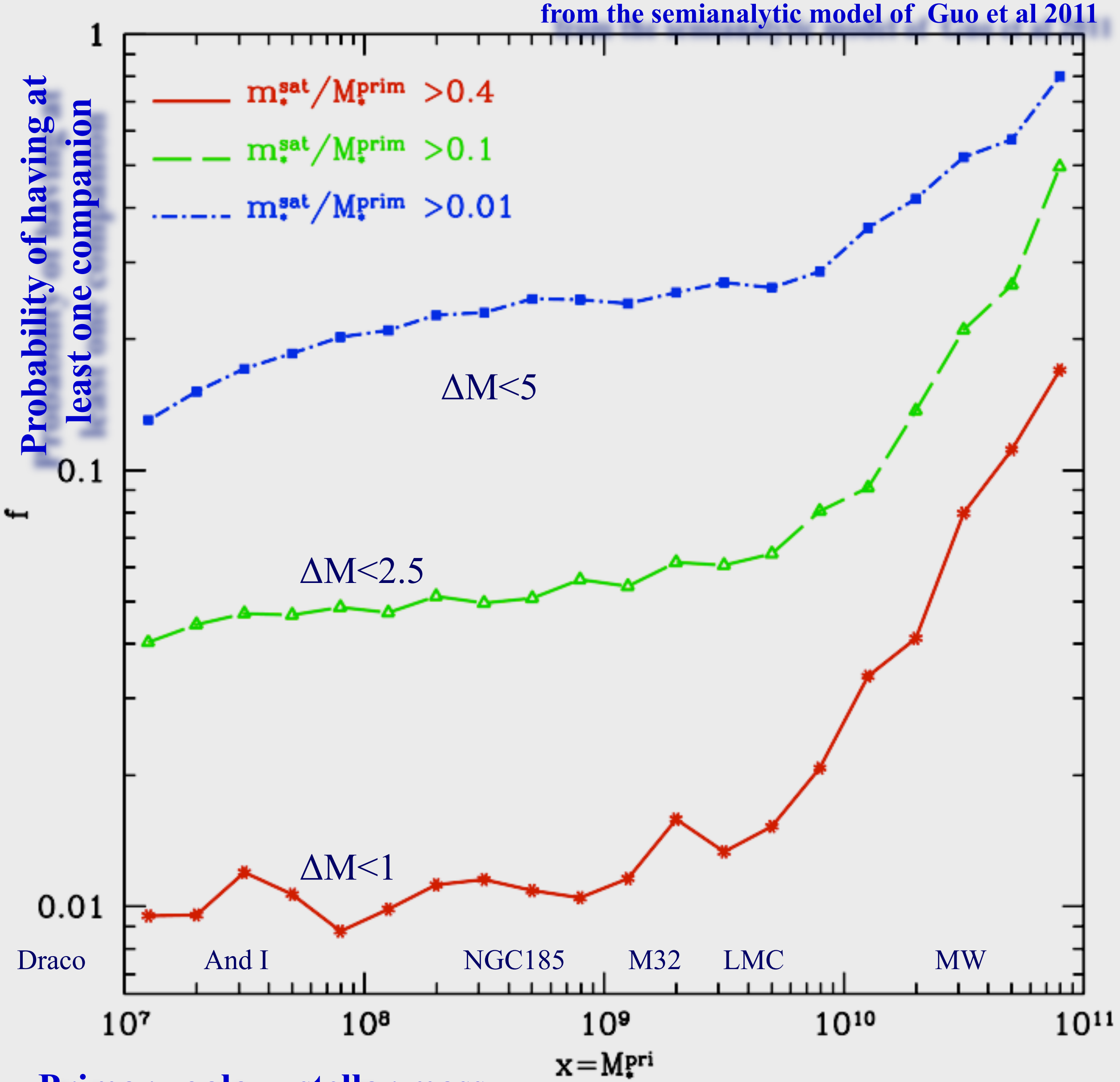
- The number of massive subhalos implies a well defined upper limit on the mass of the Milky Way halo.

- The results are on the low end of, but not inconsistent with, other mass estimates (velocity dispersion of satellites/halo stars, timing argument, etc)

Wang et al 2012

The multiplicity of isolated dwarf galaxies

from the semianalytic model of Guo et al 2011

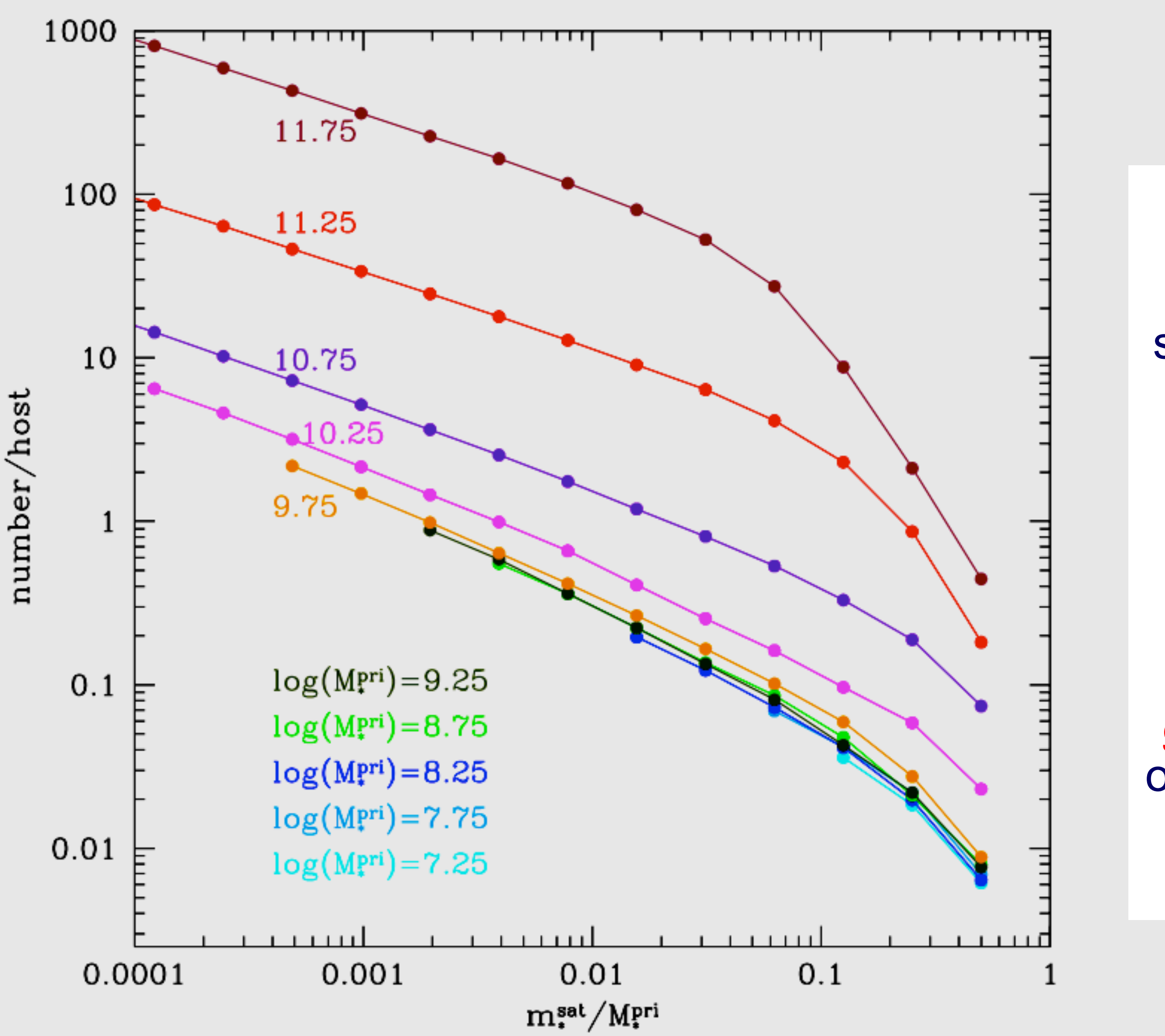


Primary galaxy stellar mass

- The probability that a galaxy is in a virialized group with companions of similar luminosity decreases strongly with galaxy stellar mass

Sales et al 2012

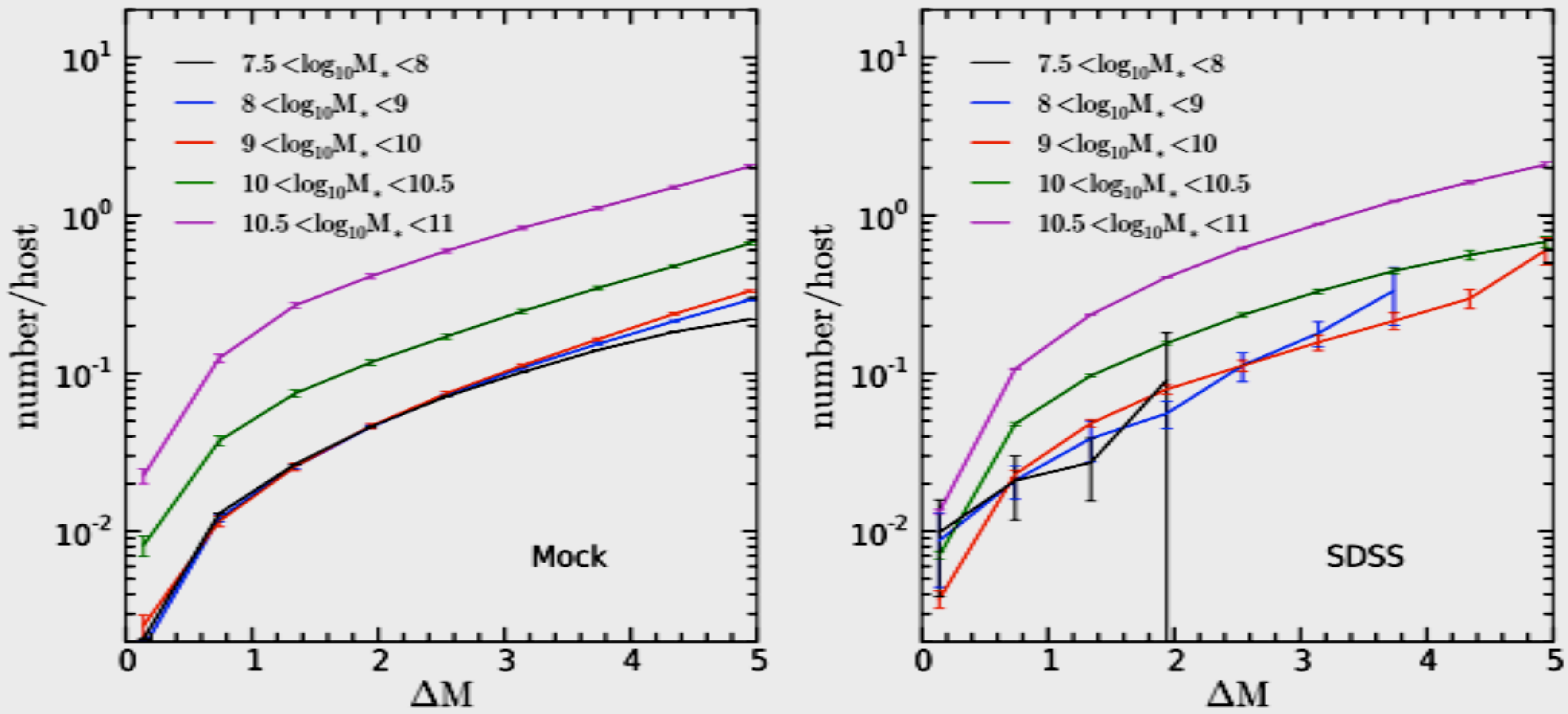
The relative abundance of satellite galaxies



•Because the M_{gal}-M_{200} relation is a *power-law* on the scale of dwarfs, and the substructure mass function is *independent* of mass, then the relative abundance of satellites is *independent of galaxy stellar mass* on the scale of dwarf galaxies.

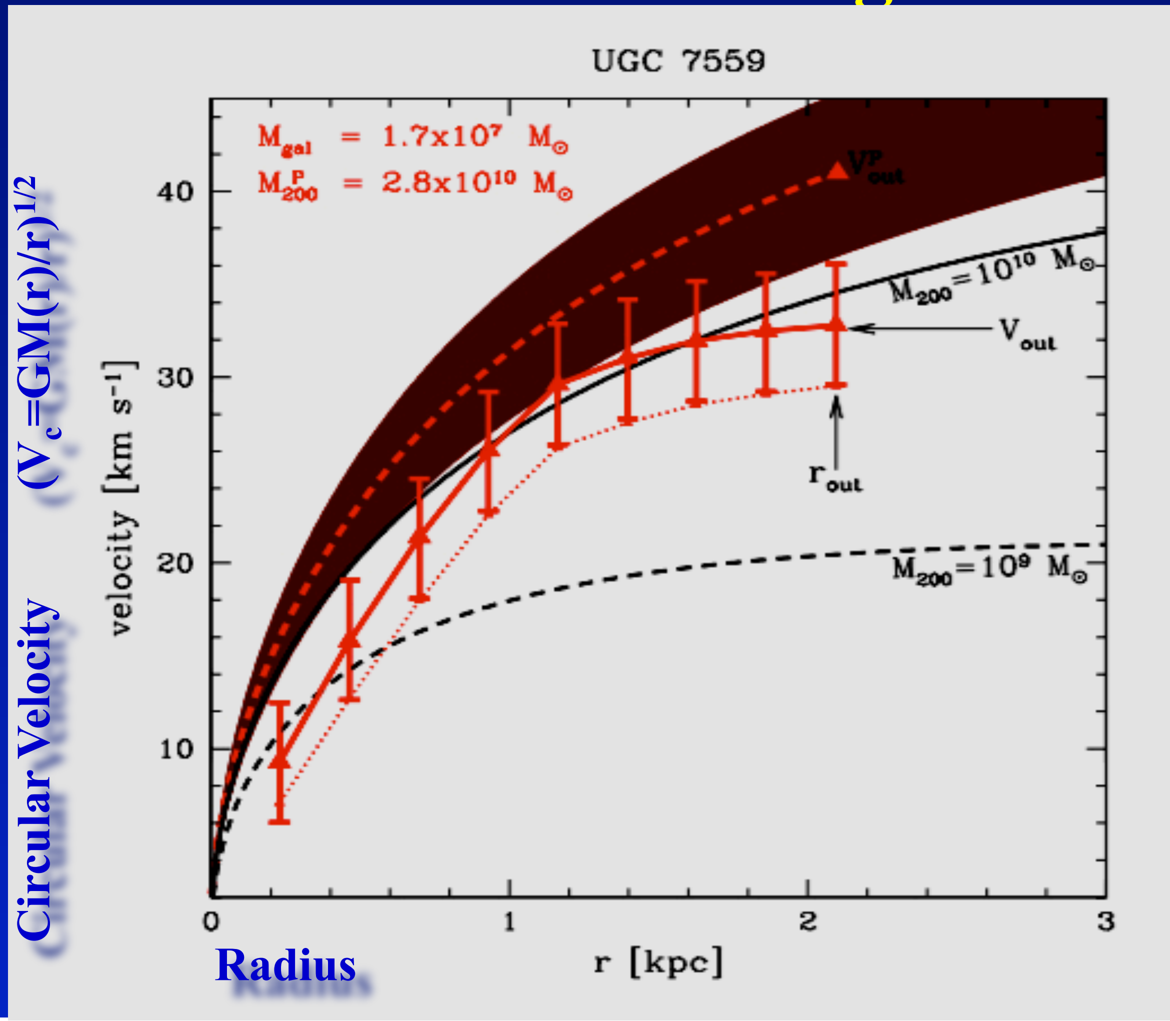
Sales et al 2012

Observed vs model satellite abundance



•There is good agreement between the relative abundance of dwarf galaxies in observational surveys and in semianalytic models. We can interpret this as providing strong support for a steep M_{gal}-M_{200} dependence on dwarf galaxy scales.

The halo mass of dwarf galaxies

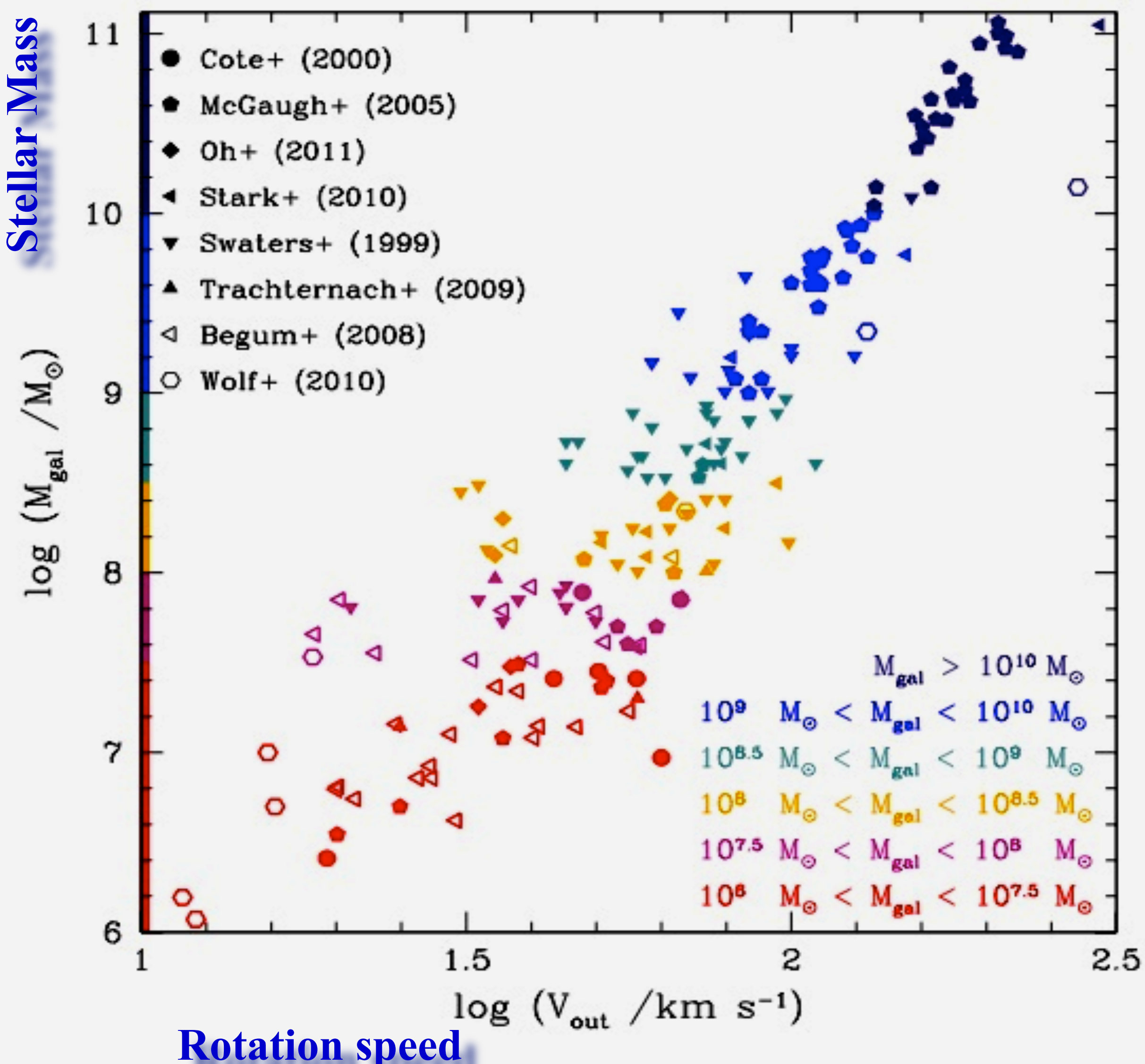


•NFW-like halos of different mass have circular velocity curves that do not cross

•If the mass inside any radius sufficiently far from the center can be measured, then the total halo mass may be estimated

Ferrero et al 2012

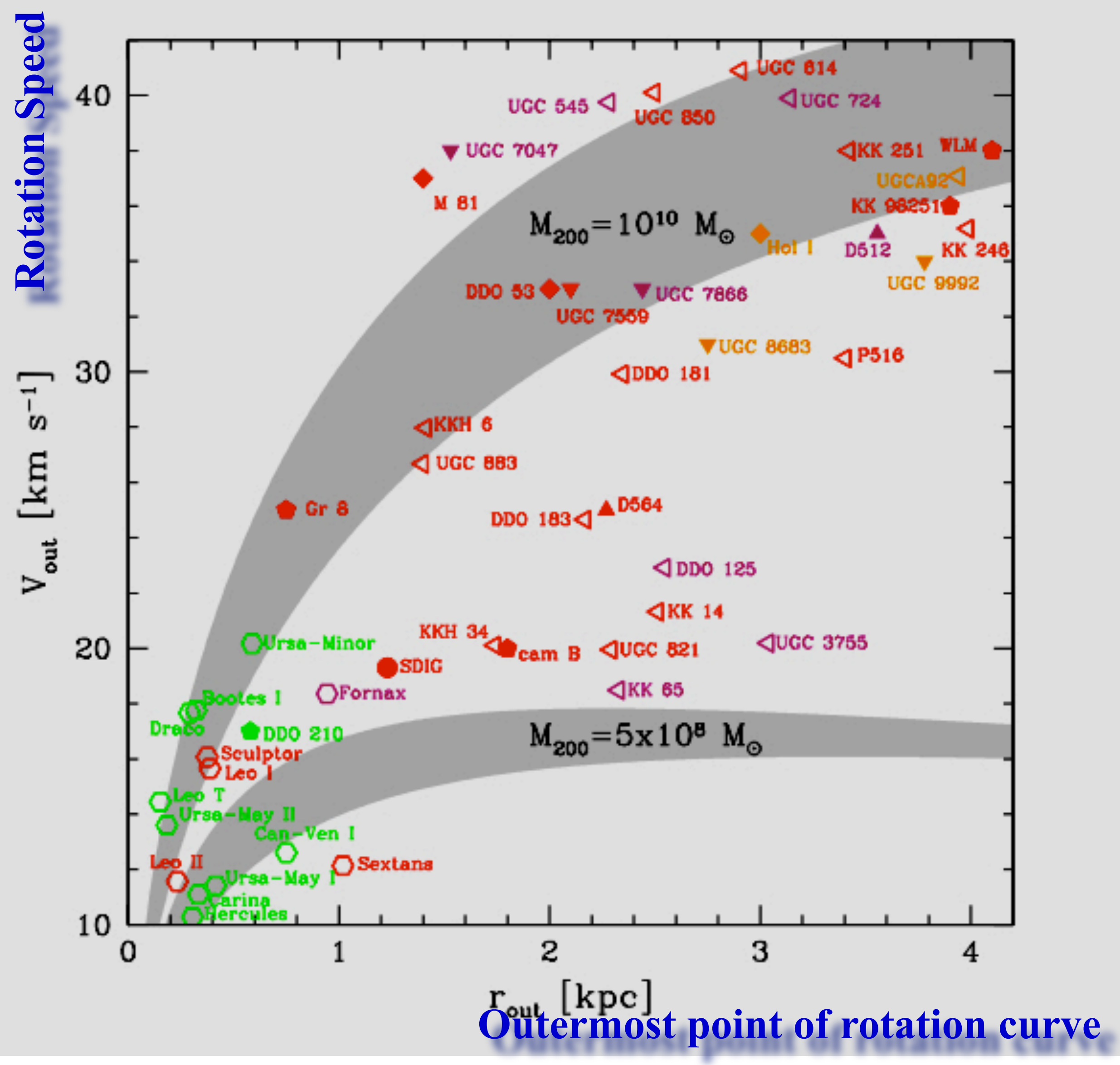
Rotation curves of nearby galaxies



- Rotation velocities have been measured for a number of dwarf galaxies, down to luminosities comparable to globular clusters.

Ferrero et al 2012

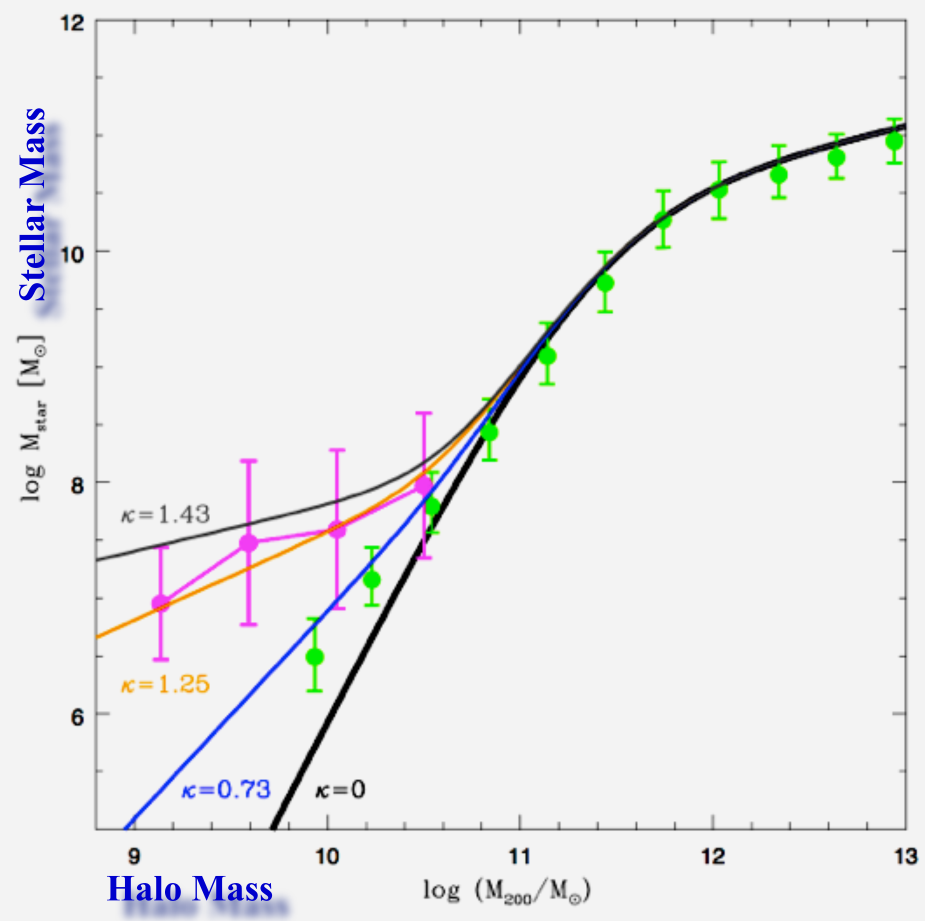
The halo mass of dwarf galaxies

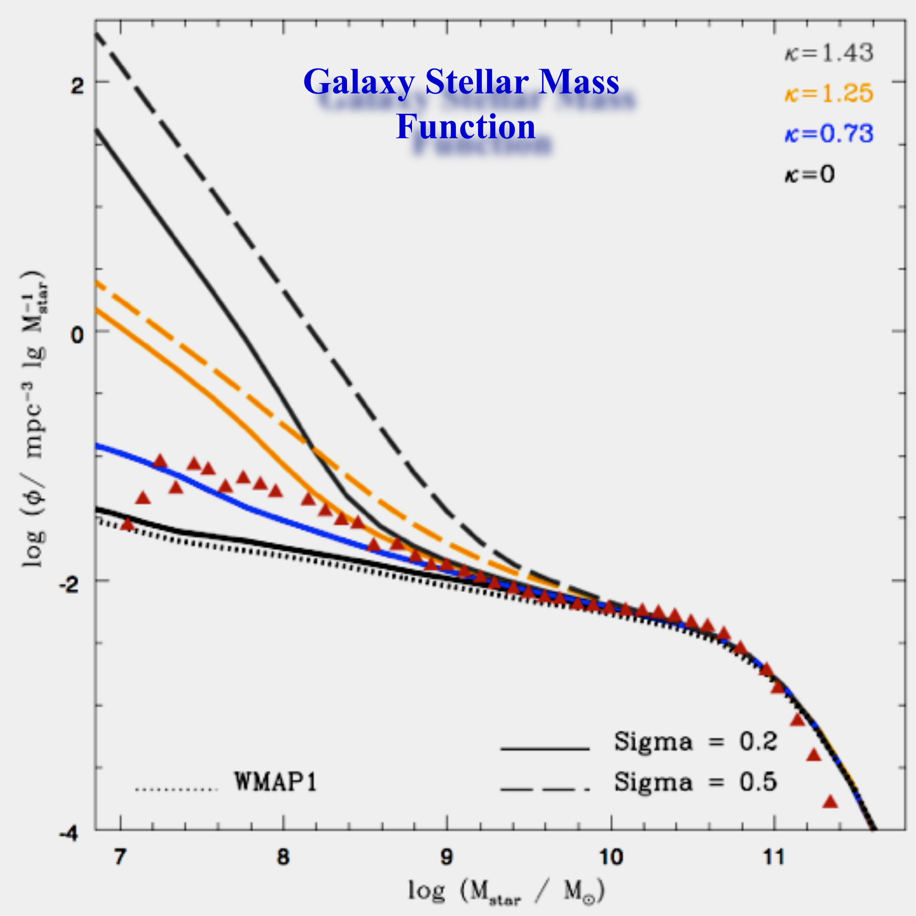


•Rotation curves typically extend far enough to allow meaningful estimates of the total mass of the halos

Ferrero et al 2012

The galaxy stellar mass function

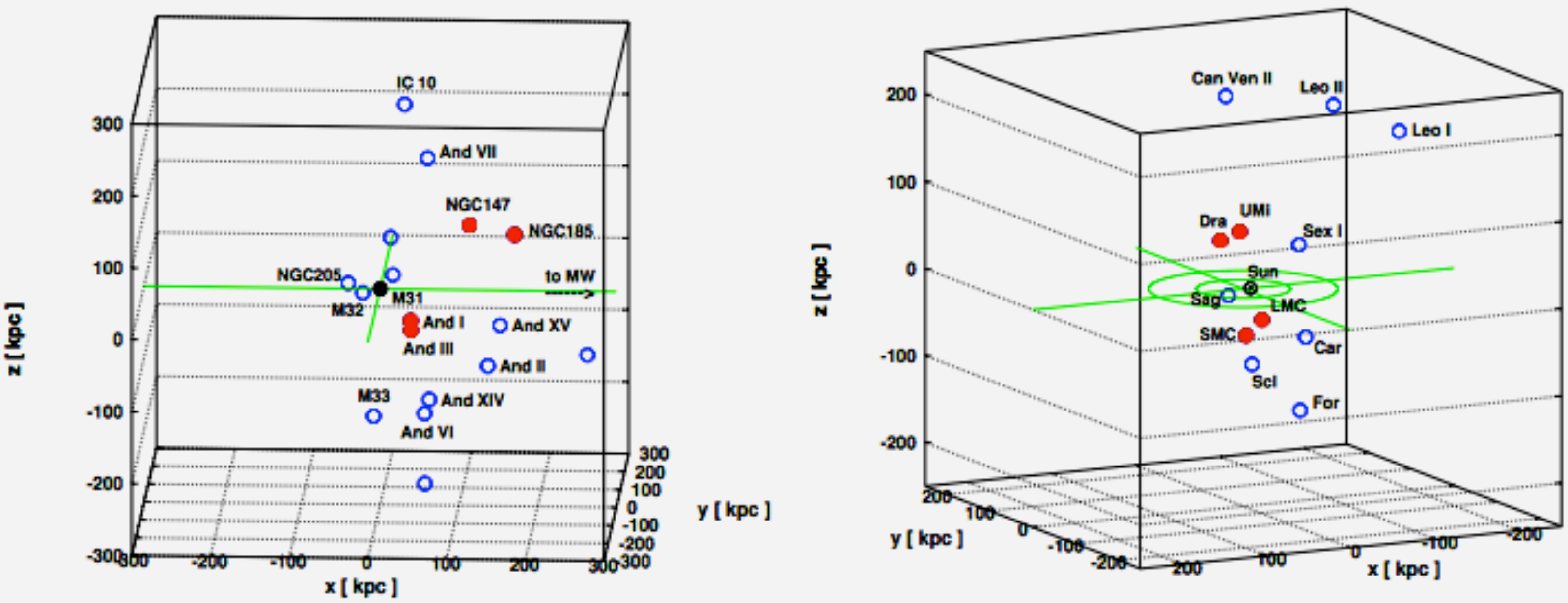




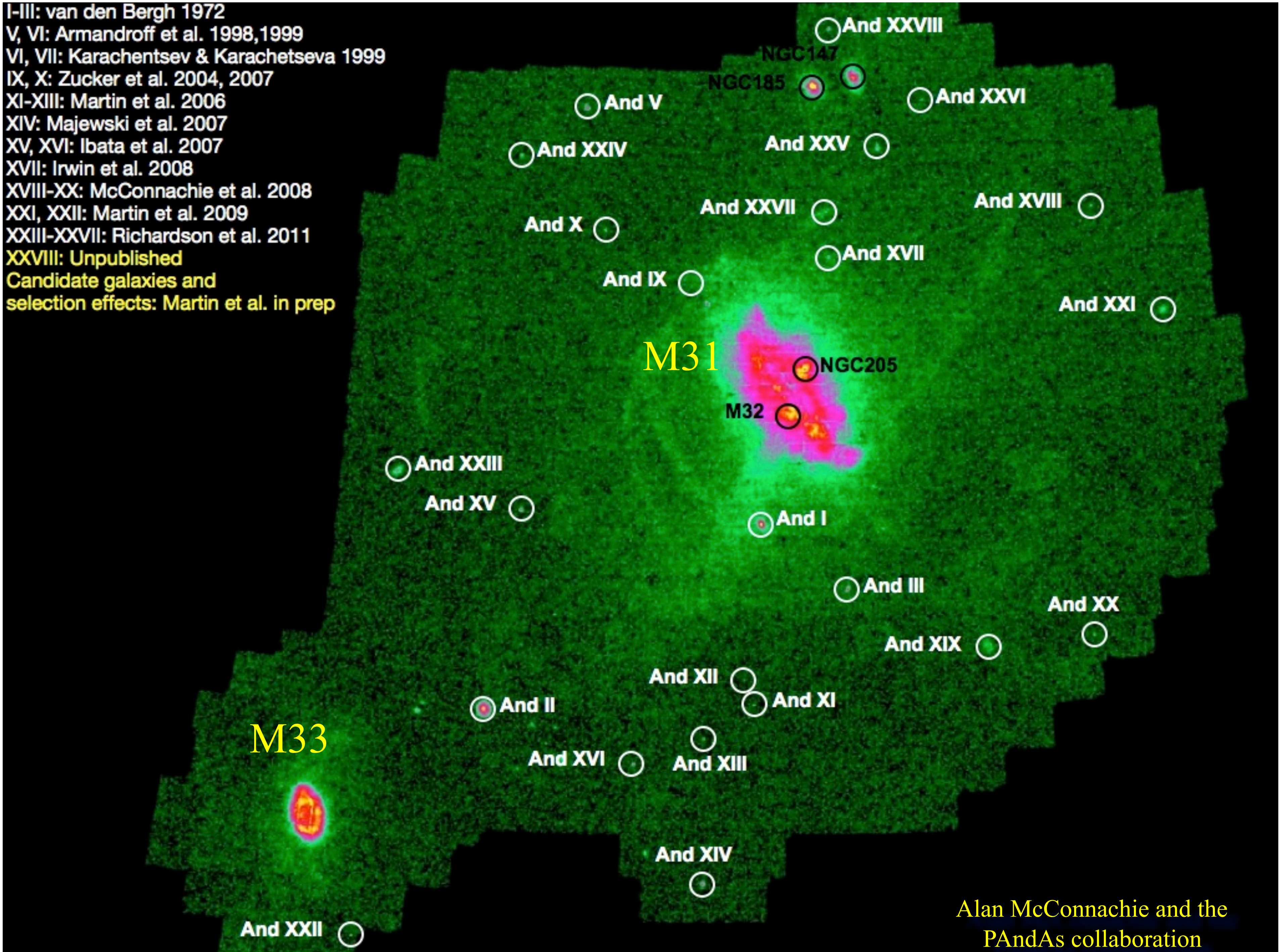
•Taken at face value, these results would imply severe departures from the measured galaxy stellar mass function at the faint end.

Ferrero et al 2012

Local Group Dwarf Satellites

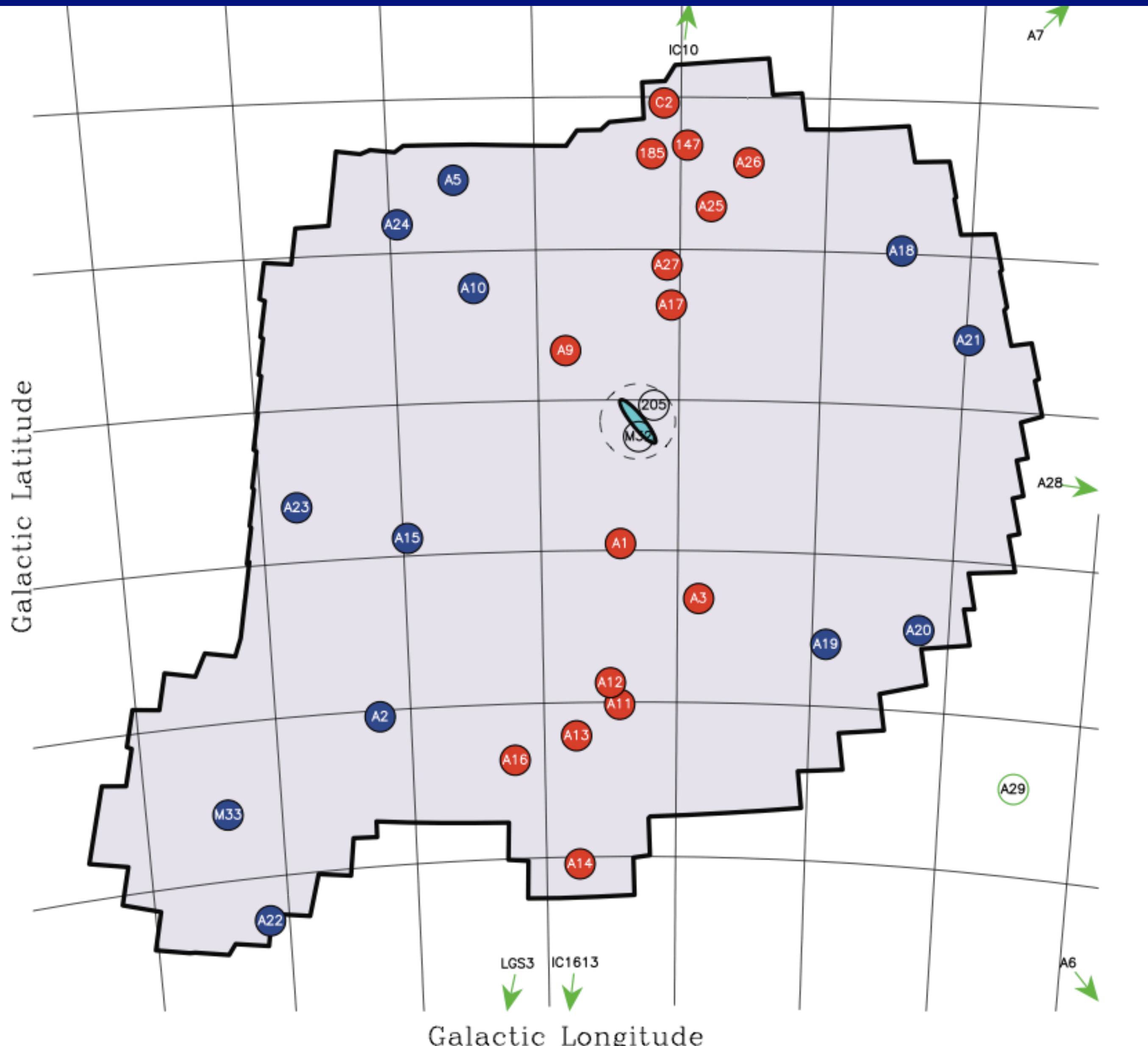


•The distribution of “classical” (M_V<-8) satellite galaxies around the Milky Way and Andromeda is quite anisotropic, with hints of possible physical associations.



I-III: van den Bergh 1972
V, VI: Armandroff et al. 1998,1999
VI, VII: Karachentsev & Karachetseva 1999
IX, X: Zucker et al. 2004, 2007
XI-XIII: Martin et al. 2006
XIV: Majewski et al. 2007
XV, XVI: Ibata et al. 2007
XVII: Irwin et al. 2008
XVIII-XX: McConnachie et al. 2008
XXI, XXII: Martin et al. 2009
XXIII-XXVII: Richardson et al. 2011
XXVIII: Unpublished
Candidate galaxies and
selection effects: Martin et al. in prep
And XXVIII
NGC147
NGC185
And V
And XXVI
And XXIV
And XXV
And XXVII
And XVIII
And X
And XVII
And IX
And XXI
M31
NGC205
M32
And XXIII
And XV
And I
And III
And XX
And XIX
And XII
And XI
And II
M33
And XVI
And XIII
And XIV
And XXII
Alan McConnachie and the
PAndAs collaboration

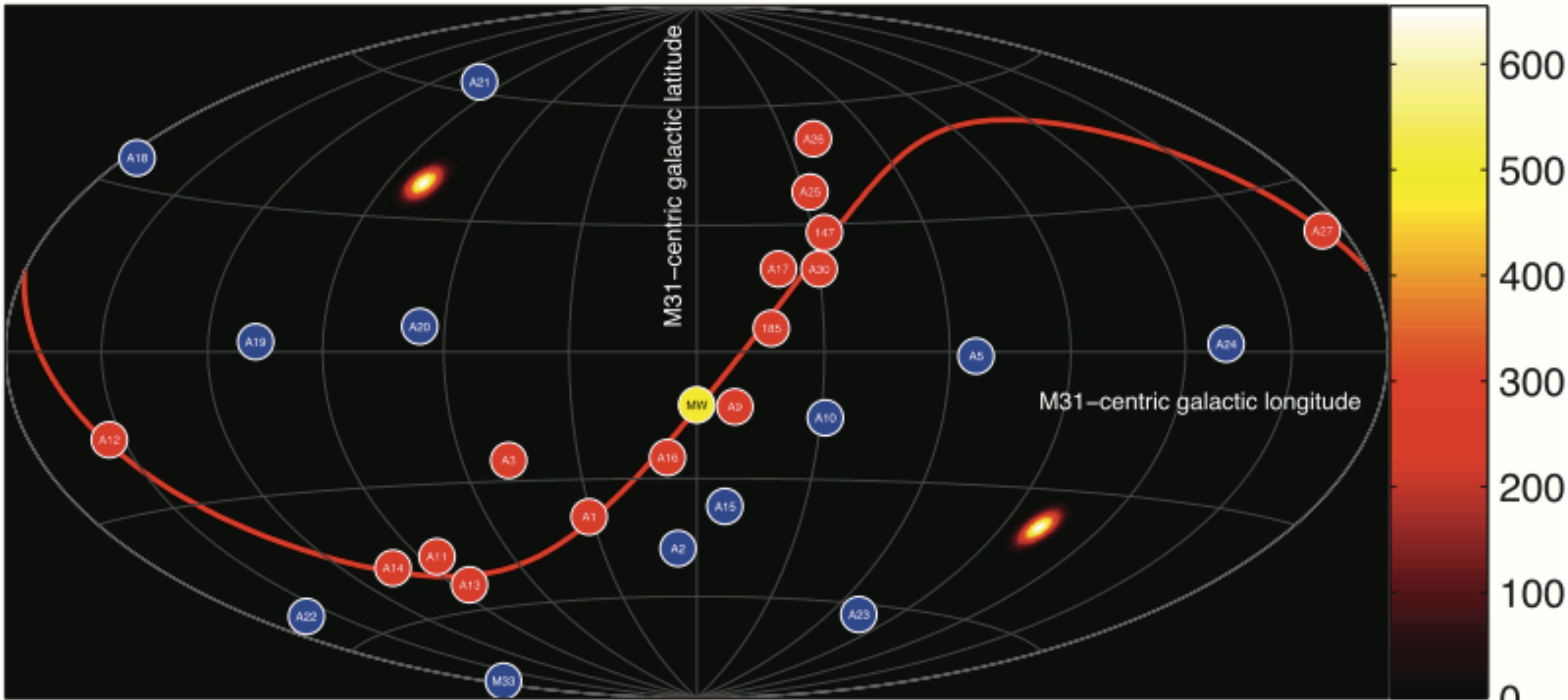
Anisotropies in the satellite population of M31



•Half of all known M31 satellites are in a vast, thin structure (rms vertical height ~14 kpc) that extends out to 400 kpc from M31.

Ibata et al, Nature 2013

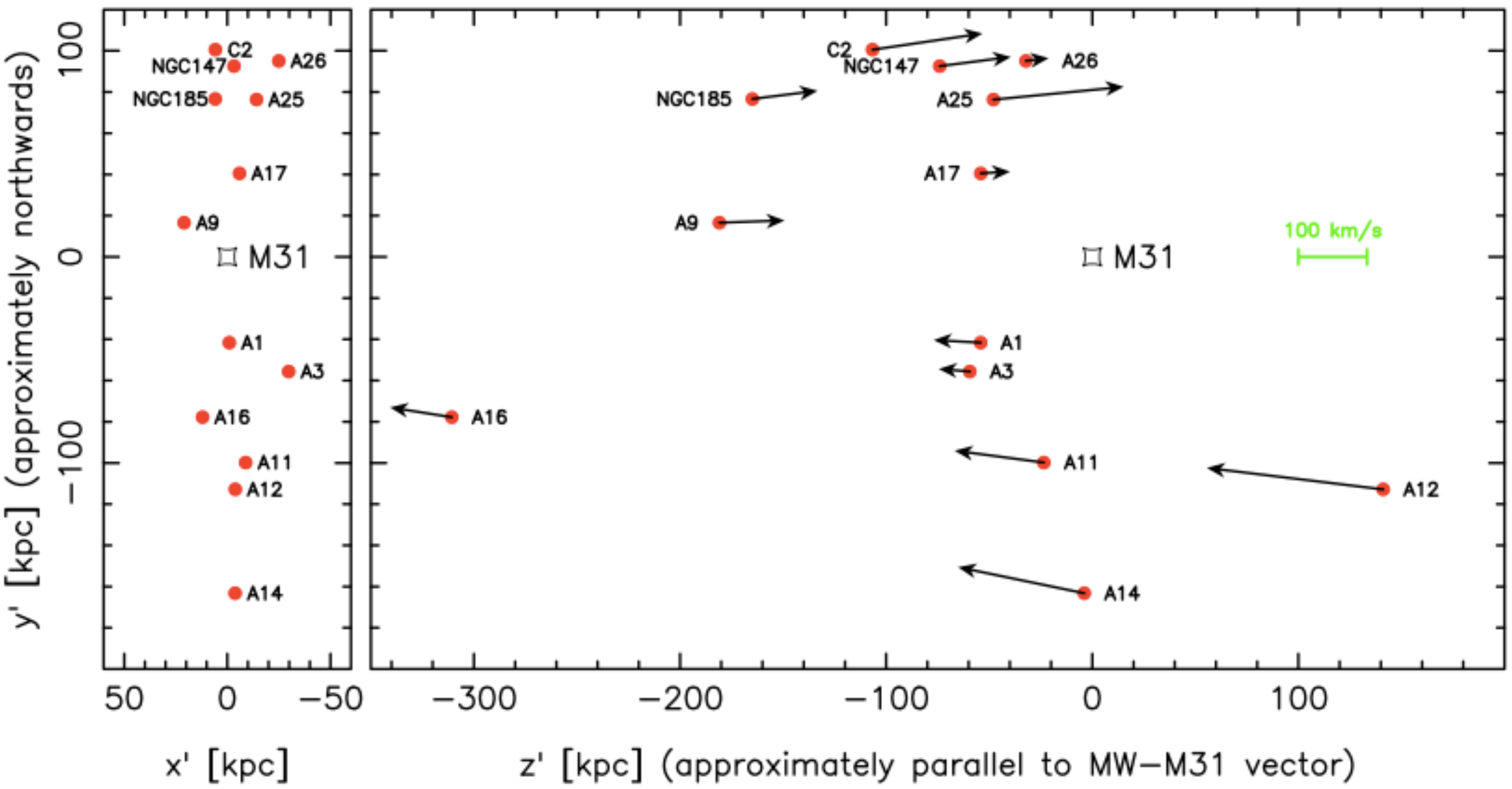
Anisotropies in the satellite population of M31



•Satellite distribution as seen from M31's center.

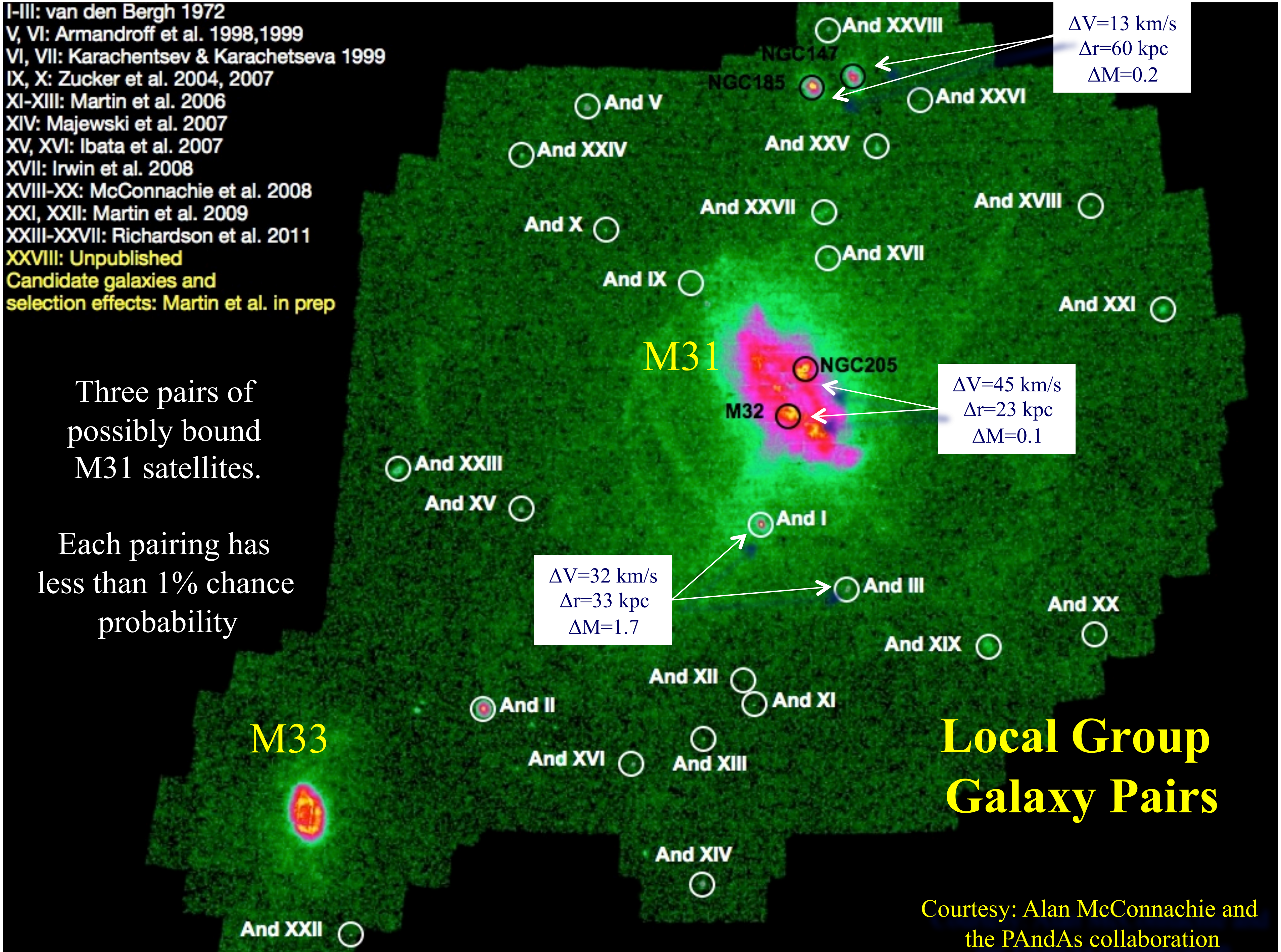
Ibata et al, Nature 2013

Anisotropies in the satellite population of M31



•The velocity distribution of satellites around M31 shows a large degree of coherence.

Ibata et al, Nature 2013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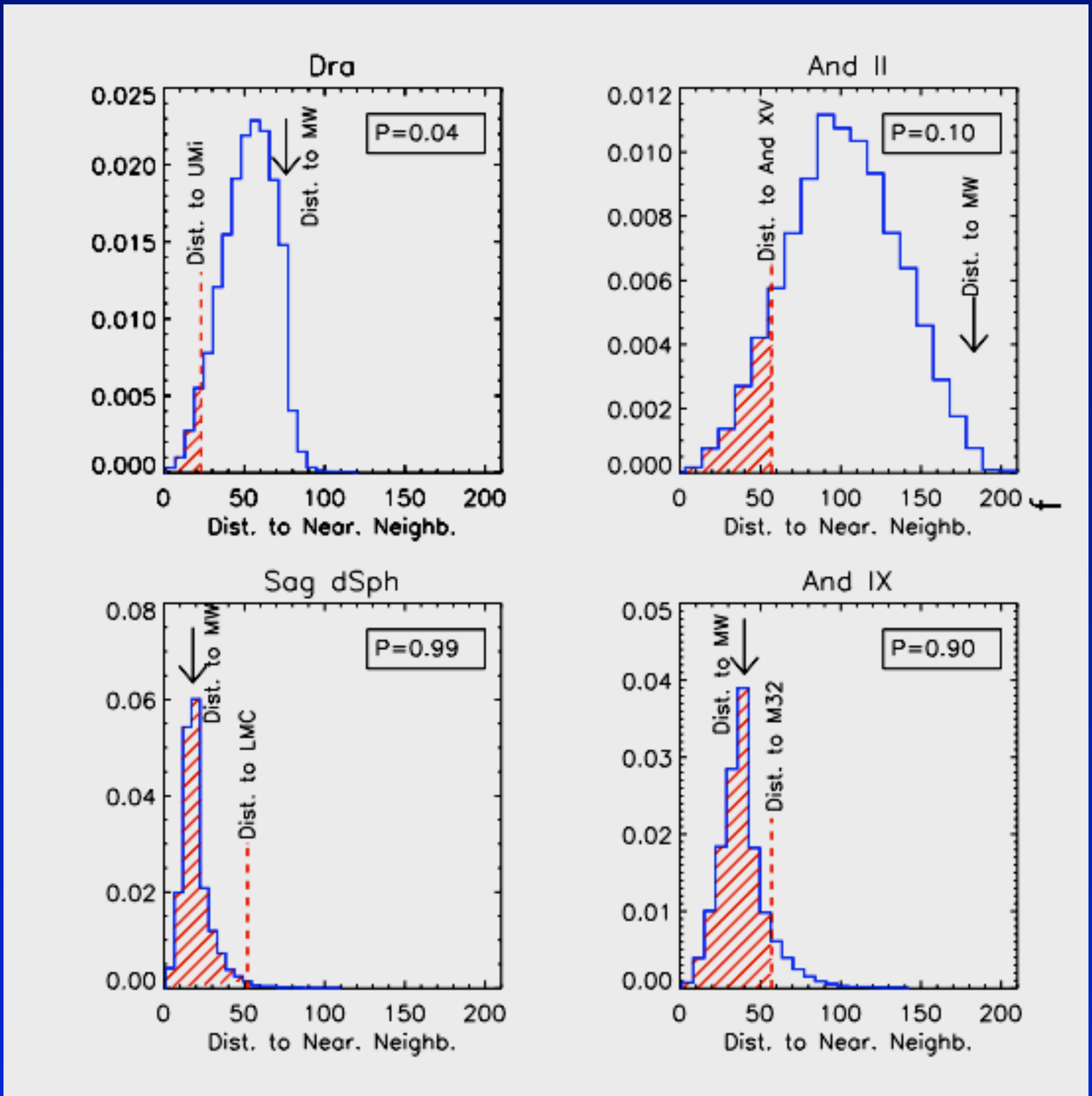
XXI, XXII: Martin et al. 2009
XXIII-XXVII: Richardson et al. 2011
XXVIII: Unpublished
Candidate galaxies and selection effects: Martin et al. in prep
Three pairs of possibly bound M31 satellites.
Each pairing has less than 1% chance probability
ΔV=13 km/s
Δr=60 kpc
ΔM=0.2
ΔV=45 km/s
Δr=23 kpc
ΔM=0.1
ΔV=32 km/s
Δr=33 kpc
ΔM=1.7
And XXVIII
NGC147
NGC185
And XXVI
And V
And XXIV
And XXV
And XXVII
And XVIII
And X
And XVII
And IX
And XXI
M31
NGC205
M32
And XXIII
And XV
And I
And III
And XX
And XIX
And XII
And XI
And II
M33
And XVI
And XIII
And XIV
And XXII
Local Group Galaxy Pairs
Courtesy: Alan McConnachie and the PAndAs collaboration

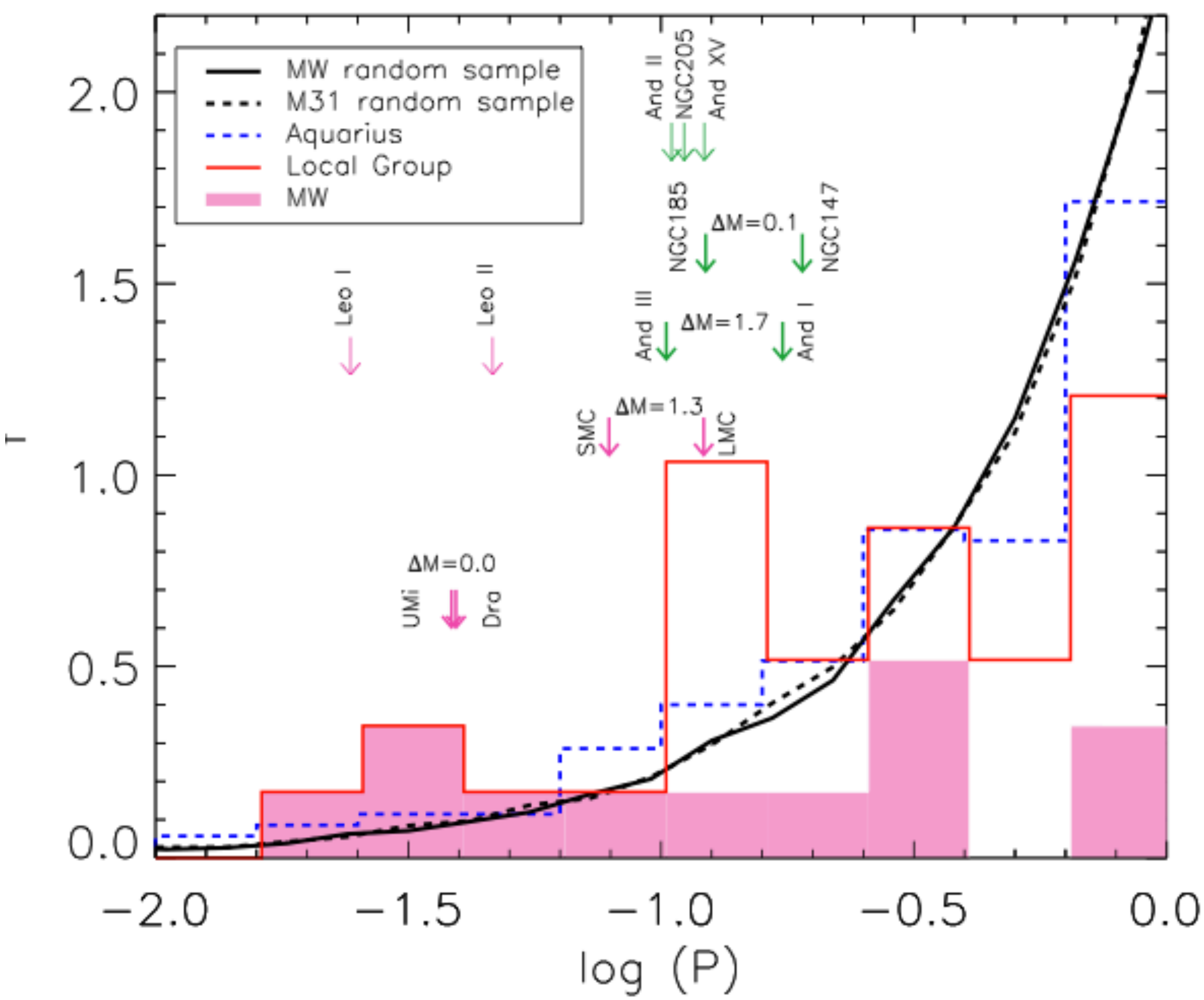
Nearest-Neighbour Probability



- The distribution of nearest-neighbour distances assuming an isotropic distribution compared with the observed one.
- Likely physical pairs show up as highly unlikely nearest neighbours.

Fattahi et al 2012

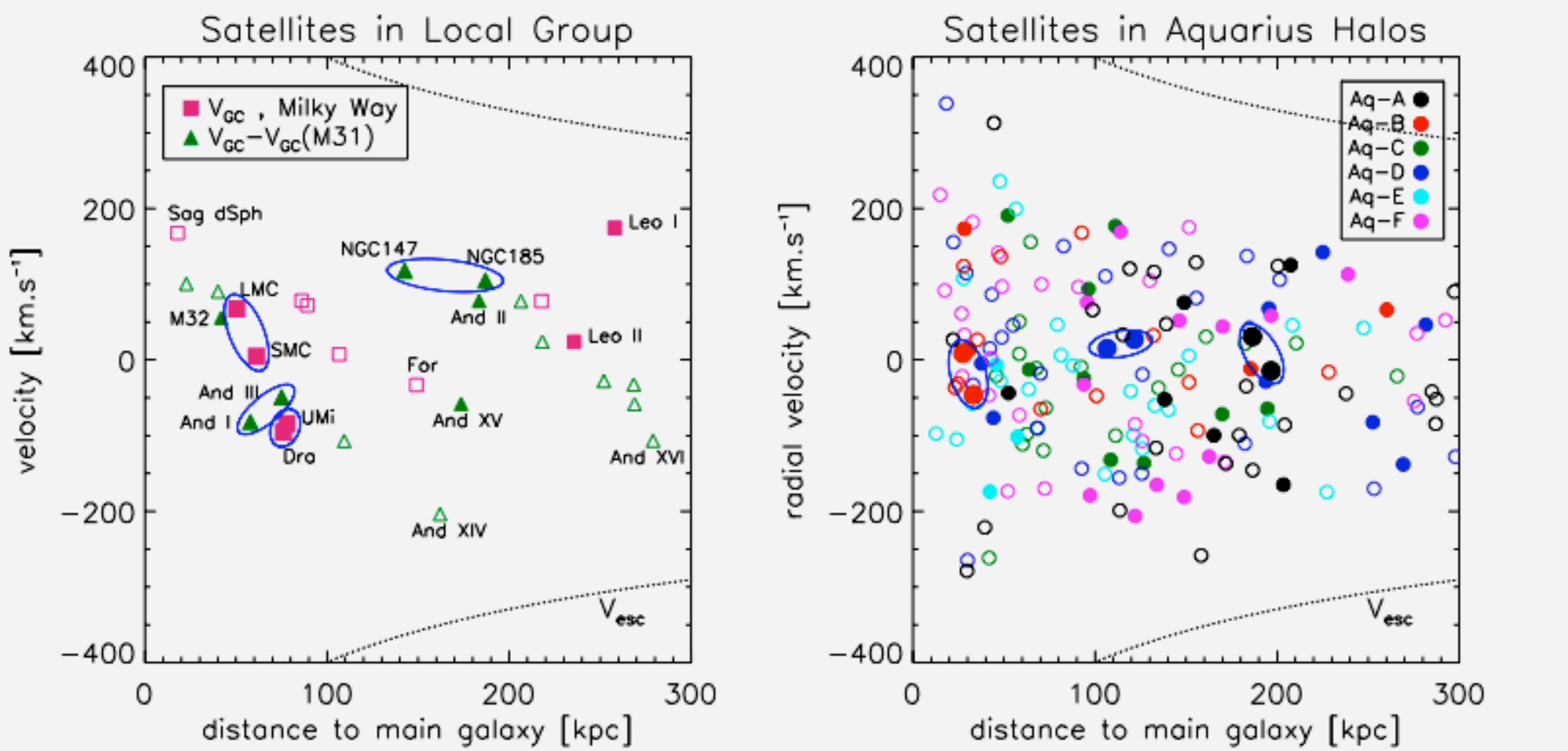
Nearest-Neighbour Probability Distribution



- Distribution of nearest-neighbour probabilities compared with random samples and with Aquarius satellites.
- Note that the Local Group has a much higher fraction of likely pairs, indicated by the low probability of random association.

Fattahi et al 2012

Relative velocity/spatial separation of dwarf pairs

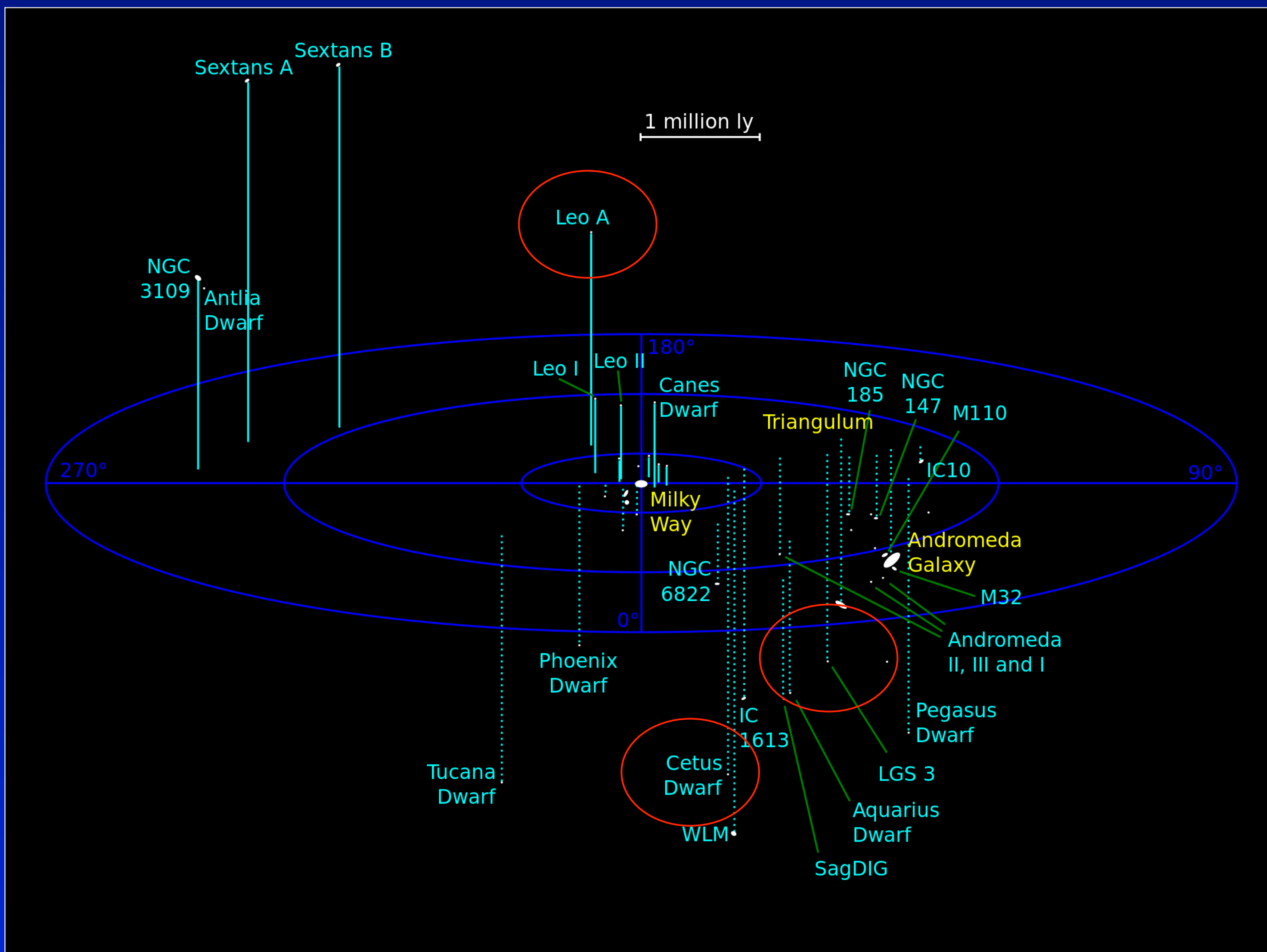


•Some of the likely pairs identified in position have low velocity differences, and similar luminosities.

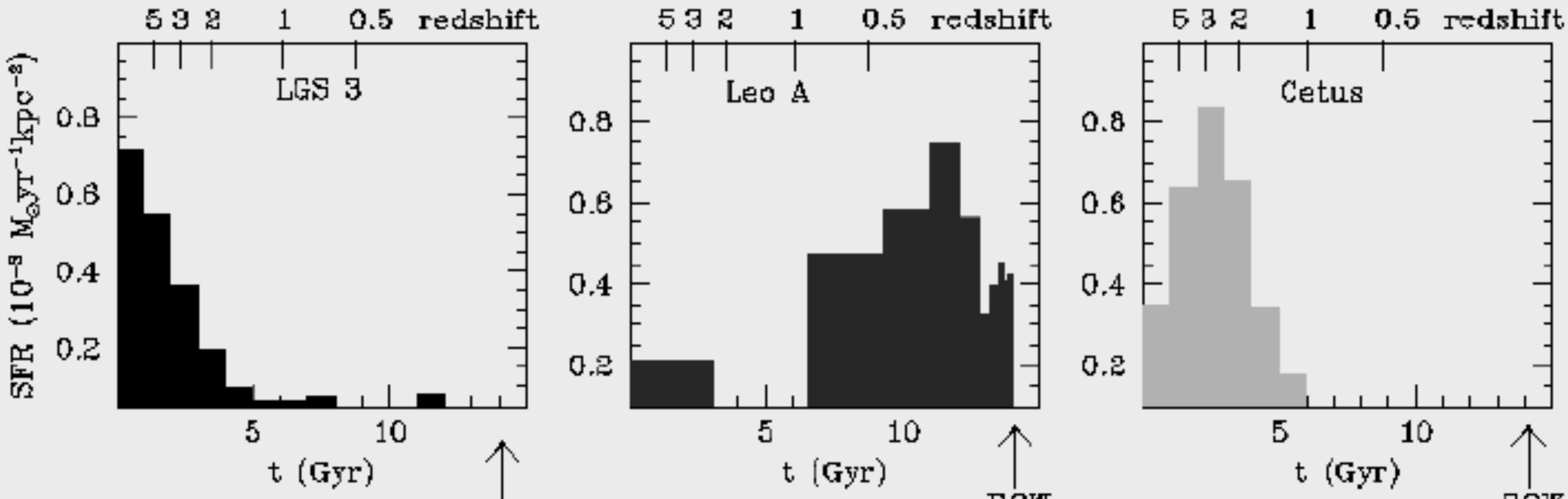
•30% of Local Group “classical” satellites are in likely pairs, compared with fewer than 4% in Aquarius satellites.

Fattahi et al 2012

The Local Group of Galaxies

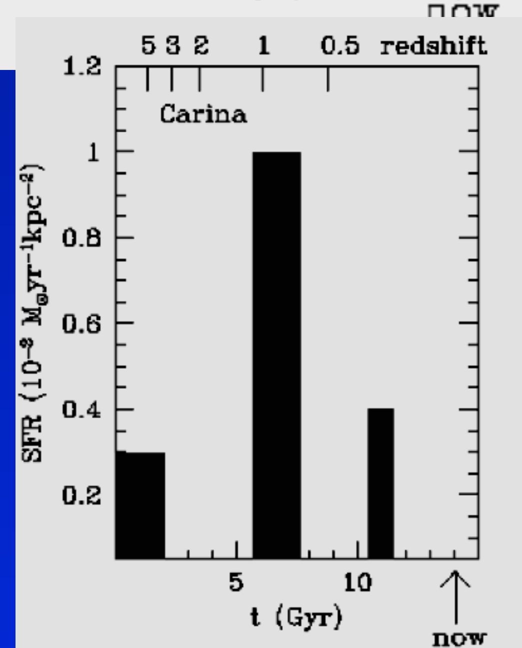


Star Formation Histories

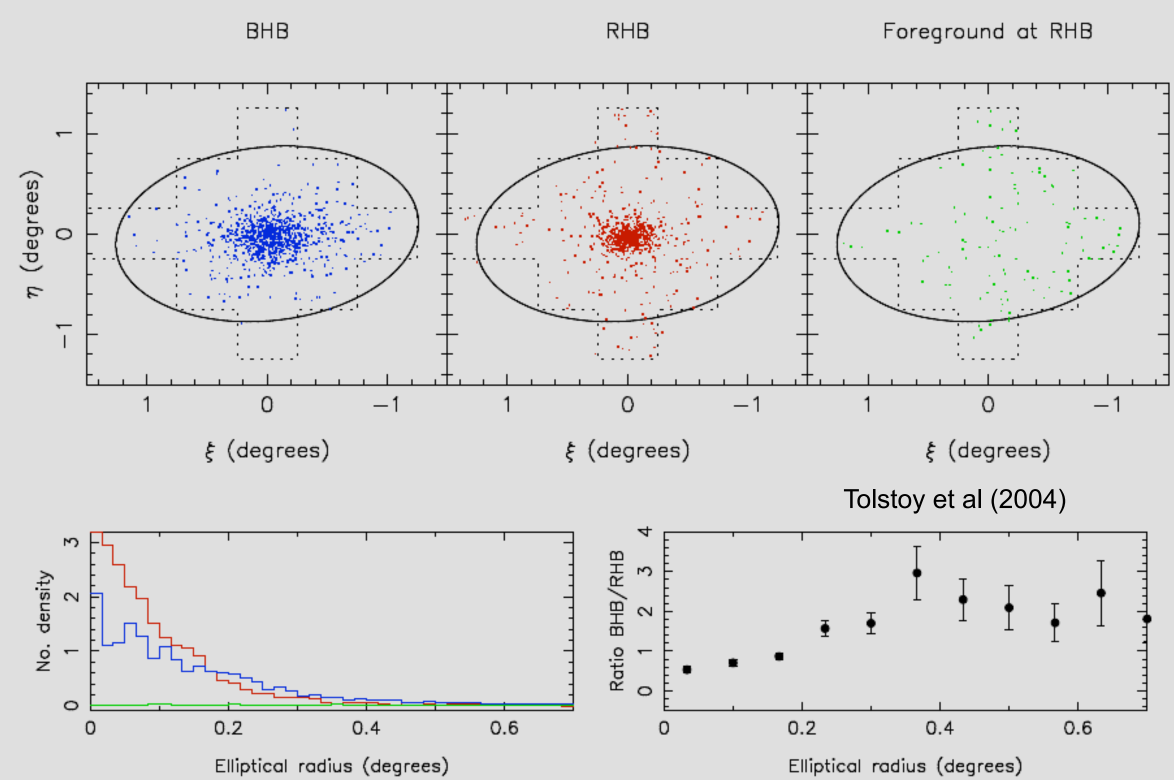


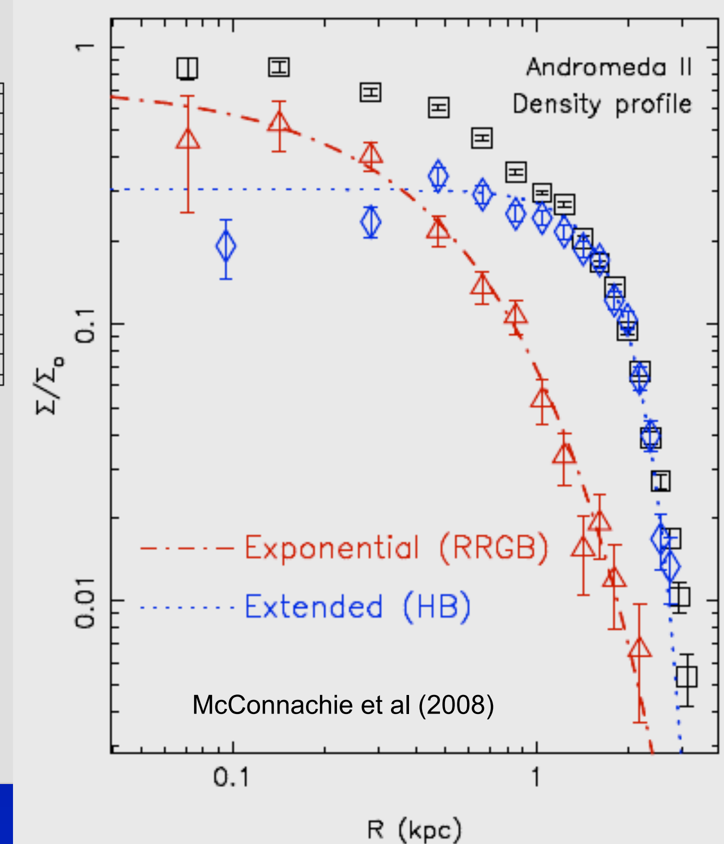
Tolstoy, Hill & Tosi (2009)

What is the origin of the diversity in star formation histories of dwarf galaxies in the Local Group?



Multiple Stellar Components



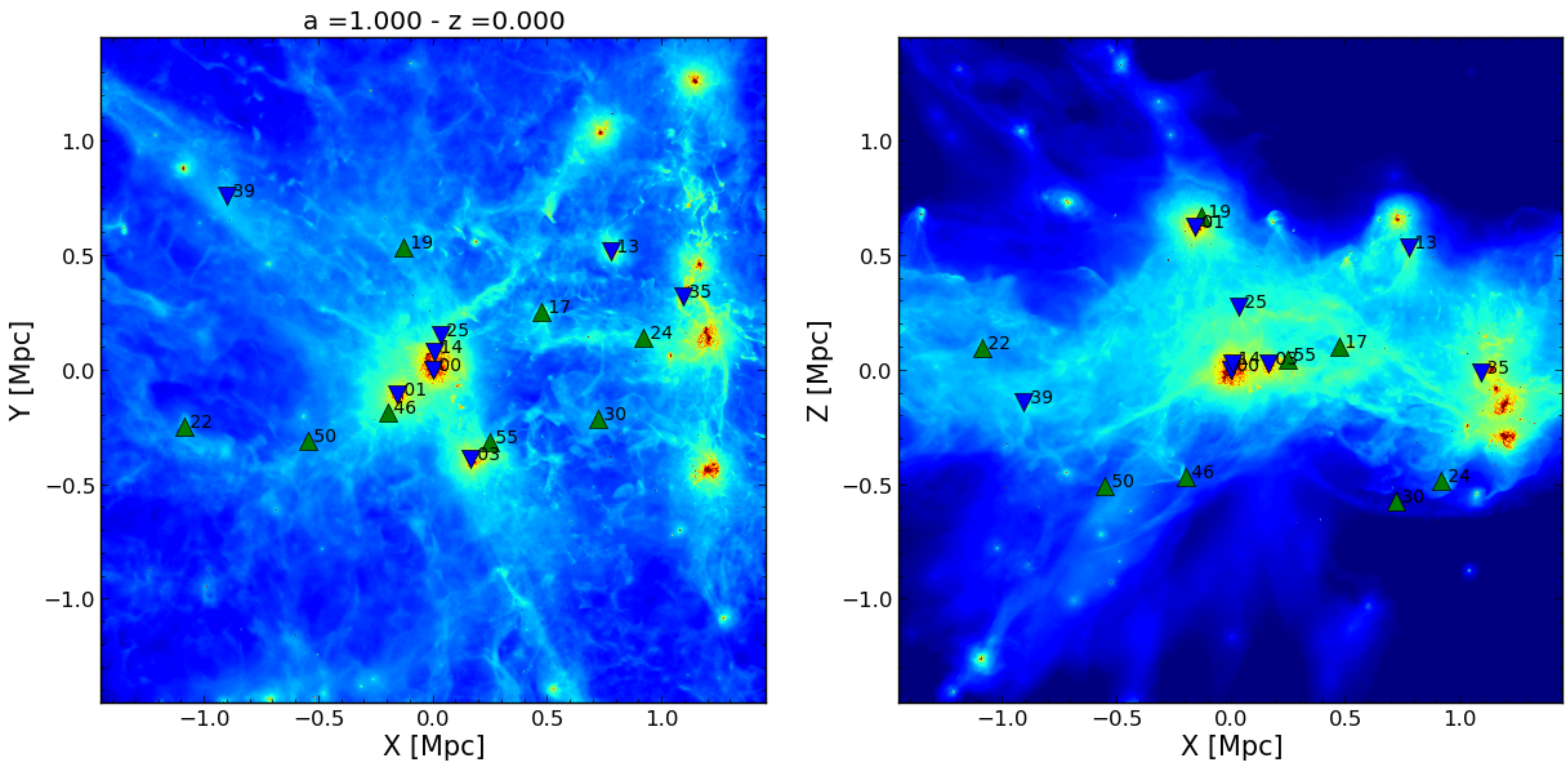


What is the origin of the distinct multiple stellar components in Local Group dwarfs?

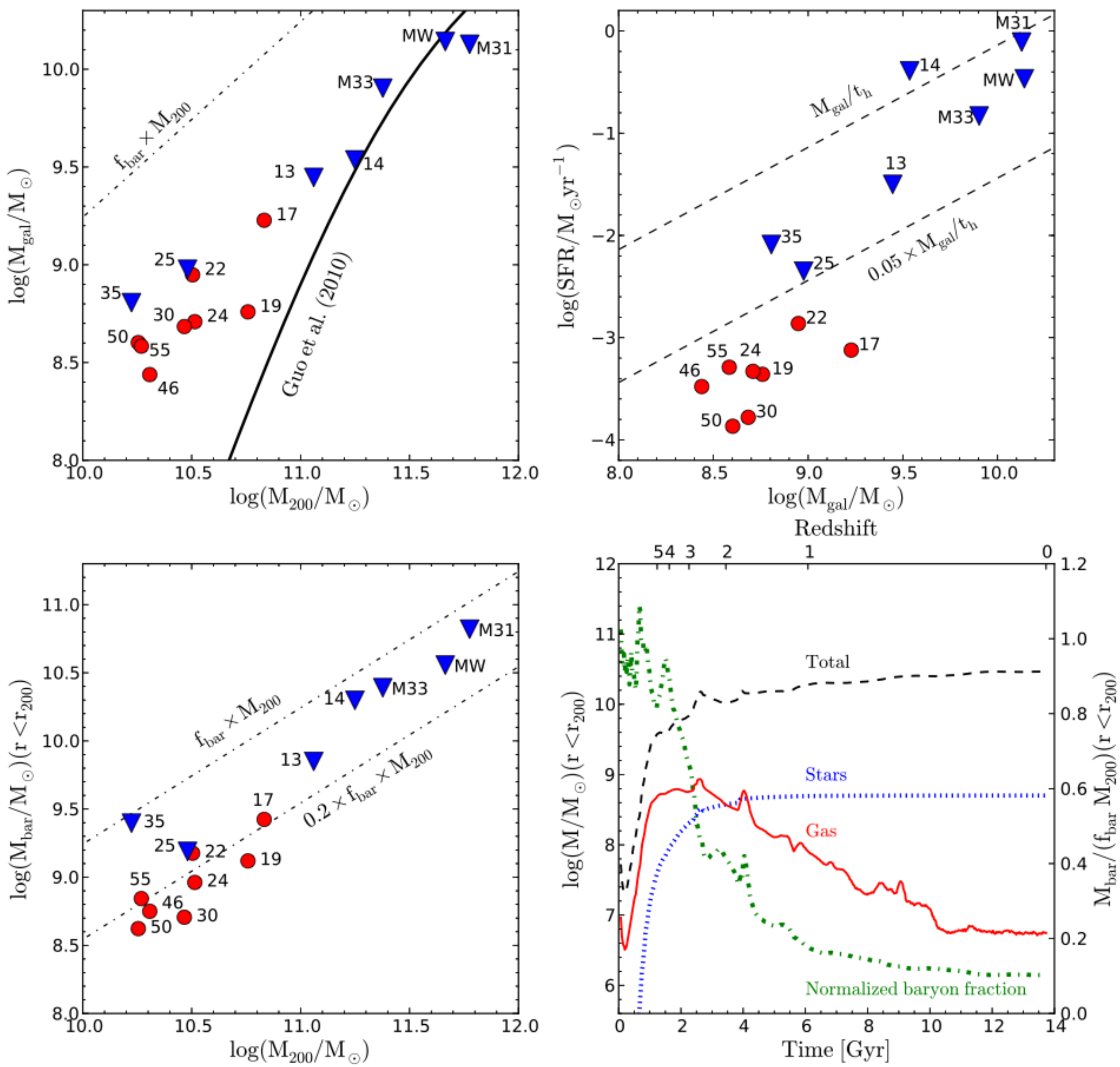
•The Constrained Local UniversE Simulations (CLUES) evolve a region akin to the Local Group of Galaxies in the WMAP3 cosmology.

•SPH-Gadget2, with reionization, star formation, and feedback-driven winds.

•Note aspherical shape of LG region



Galaxy Properties



- CLUES Local Group galaxies exhibit a wide variety of properties. In particular, there is a class of galaxies that have few stars and are almost devoid of gas.

Benítez-Llambay et al 2013

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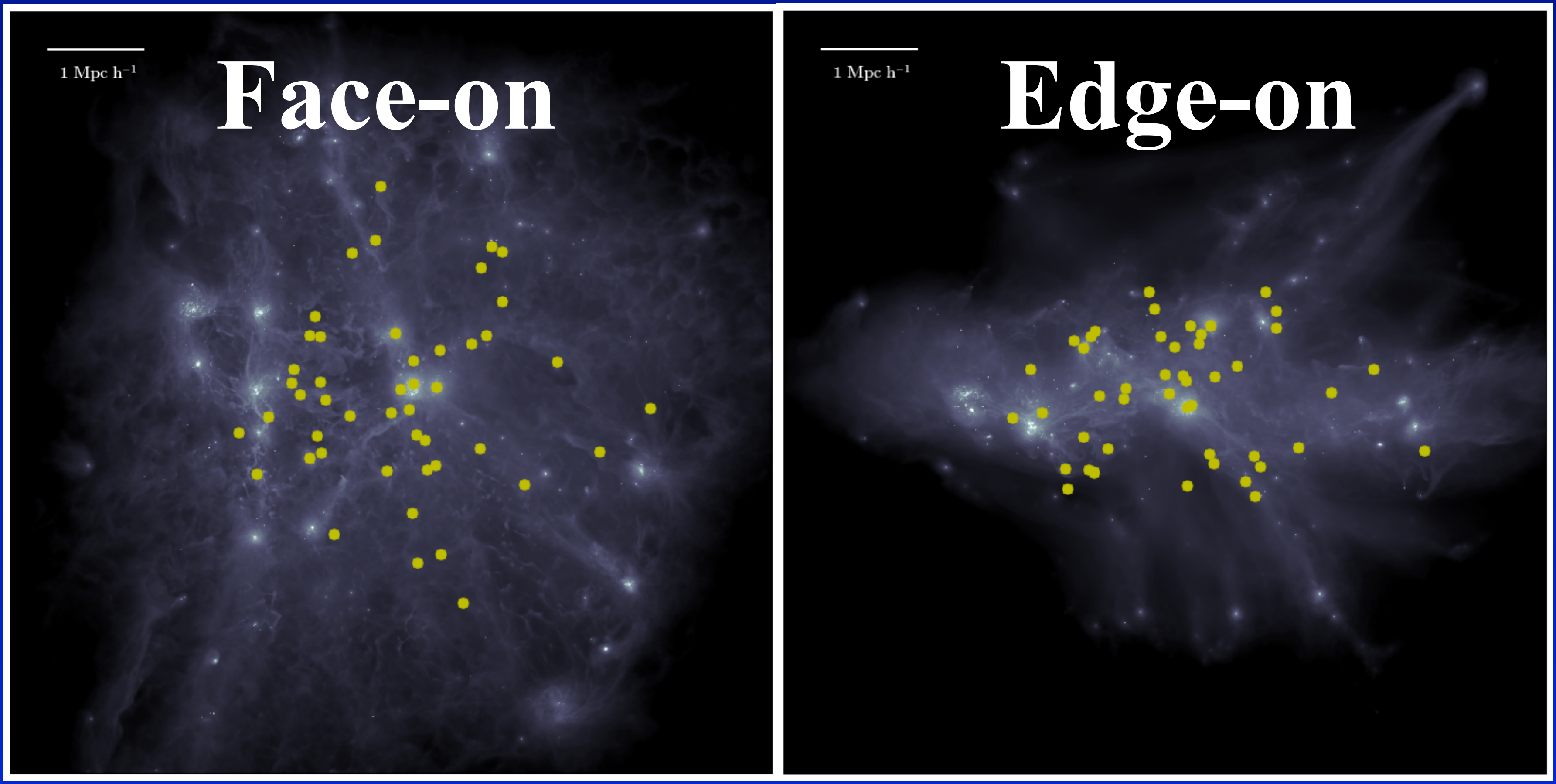

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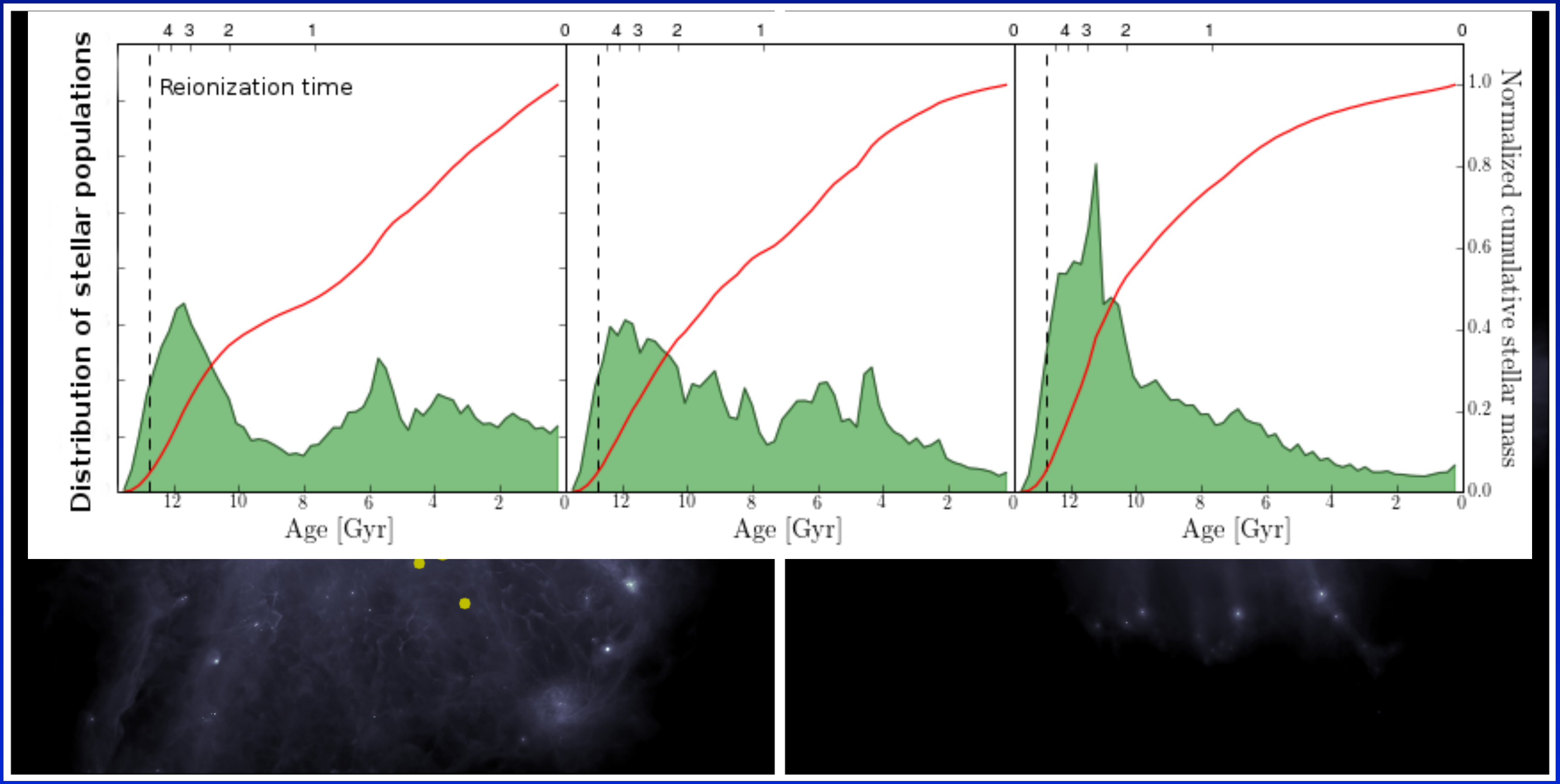

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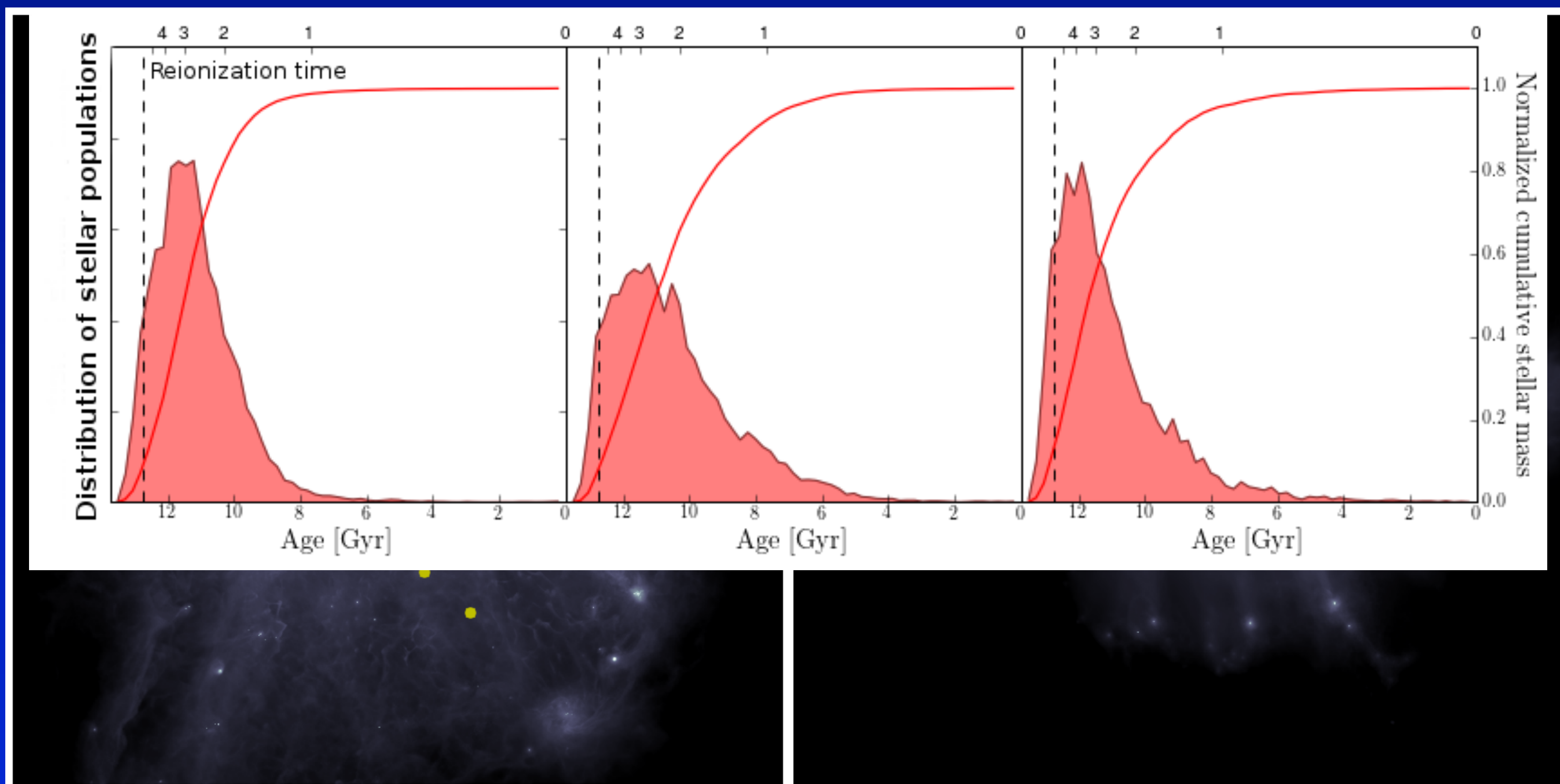

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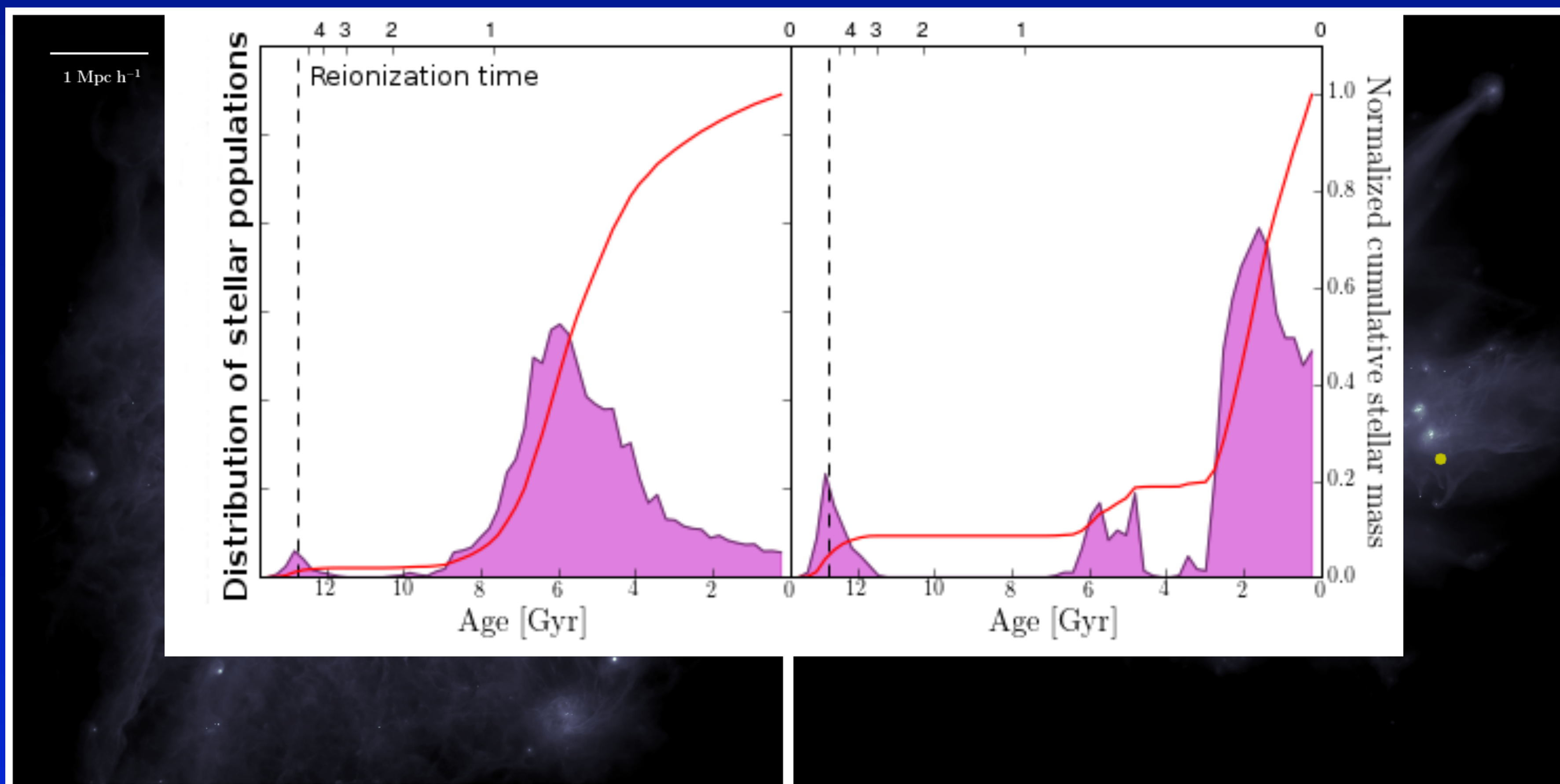

CLUES
Constrained Local UniversE Simulations

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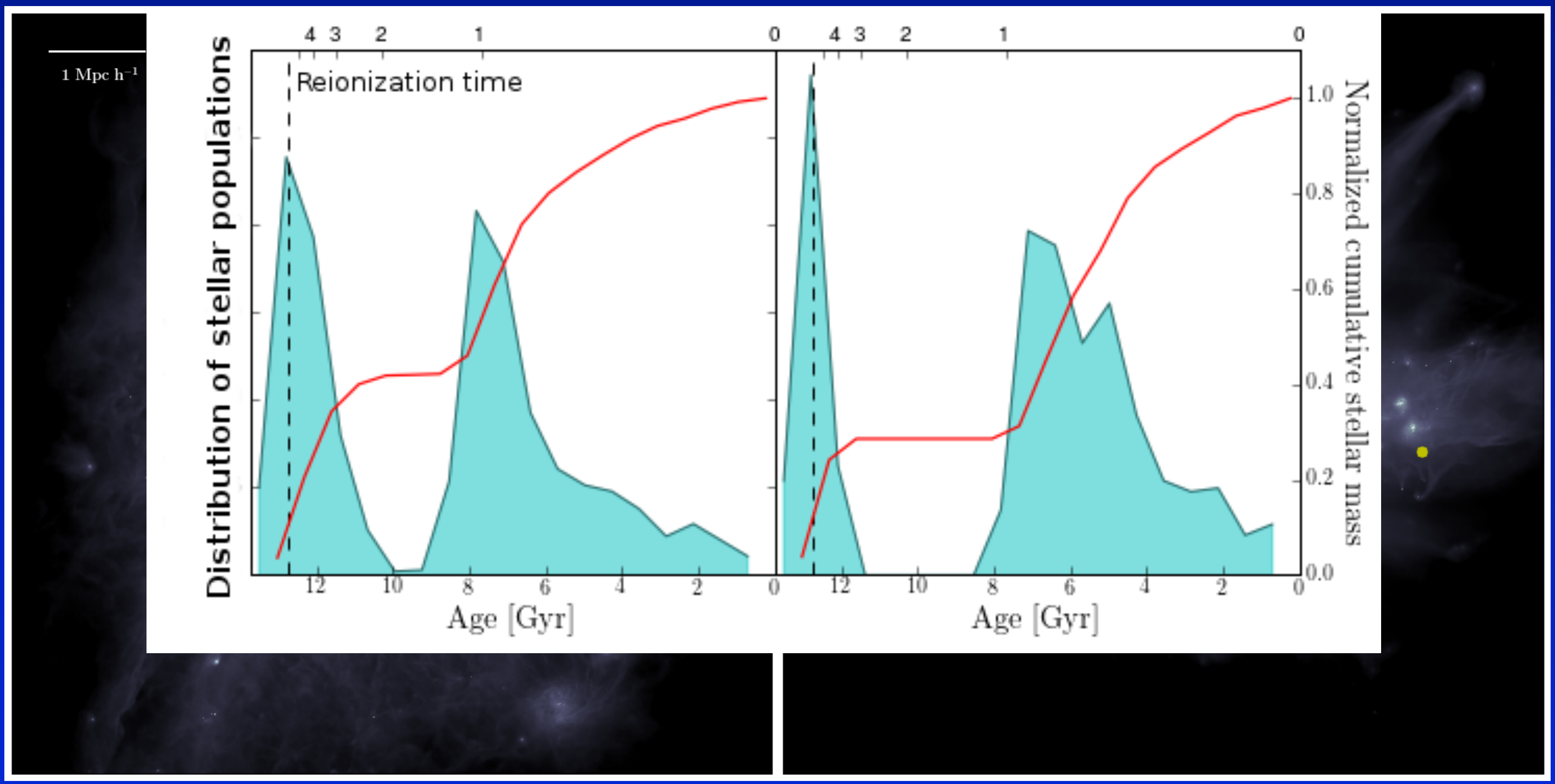

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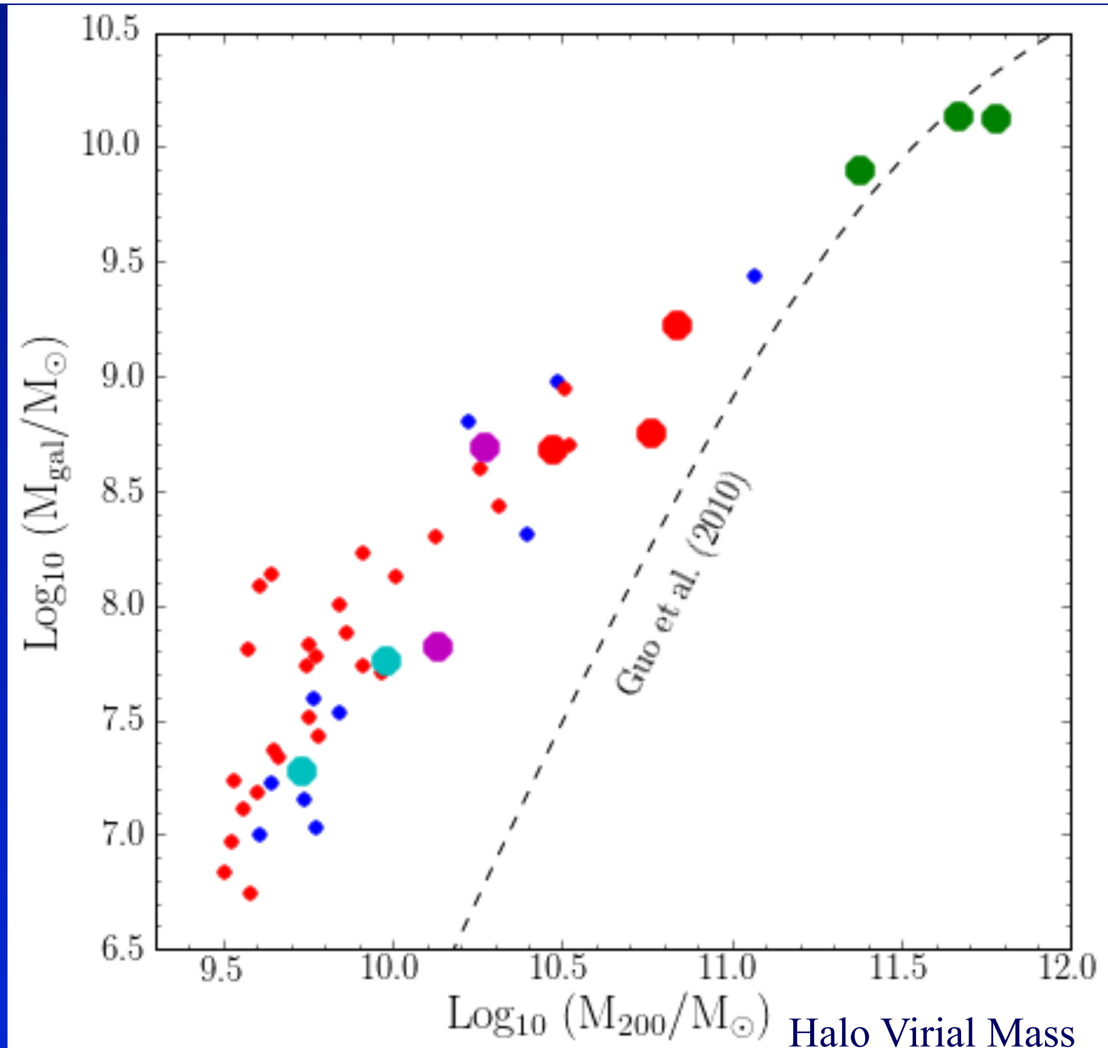
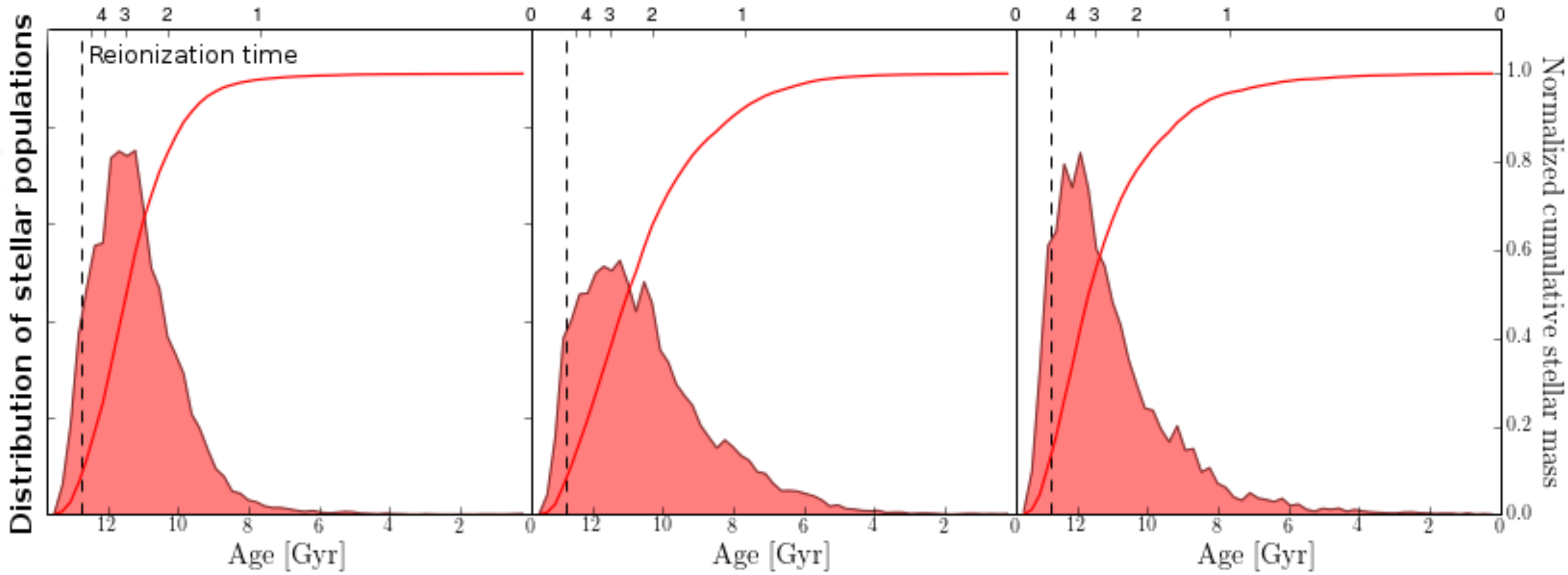
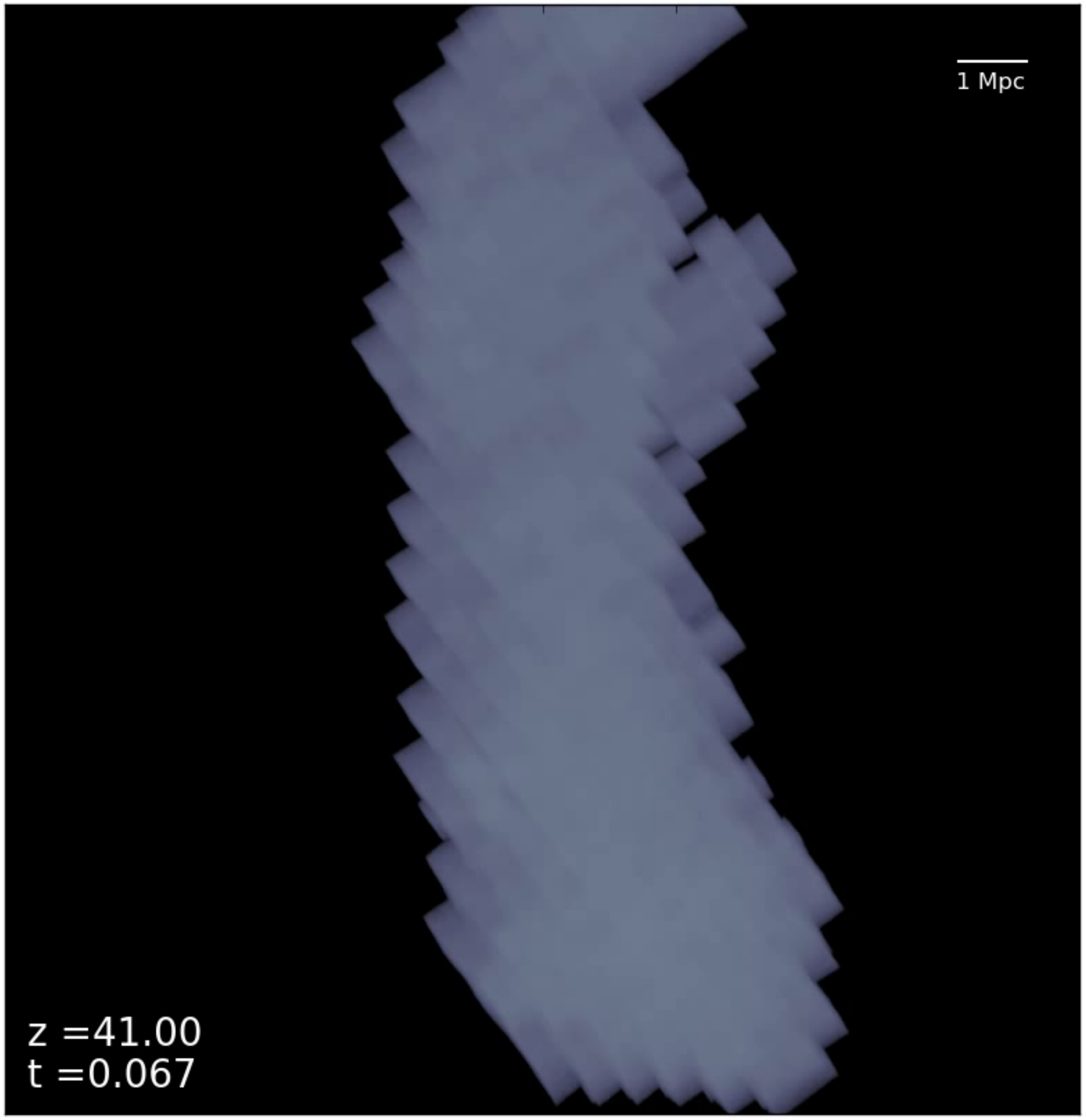
Galaxy Stellar Mass



Dwarf galaxies with a single early star formation episode





Benítez-Llambay et al 2013

CLUES

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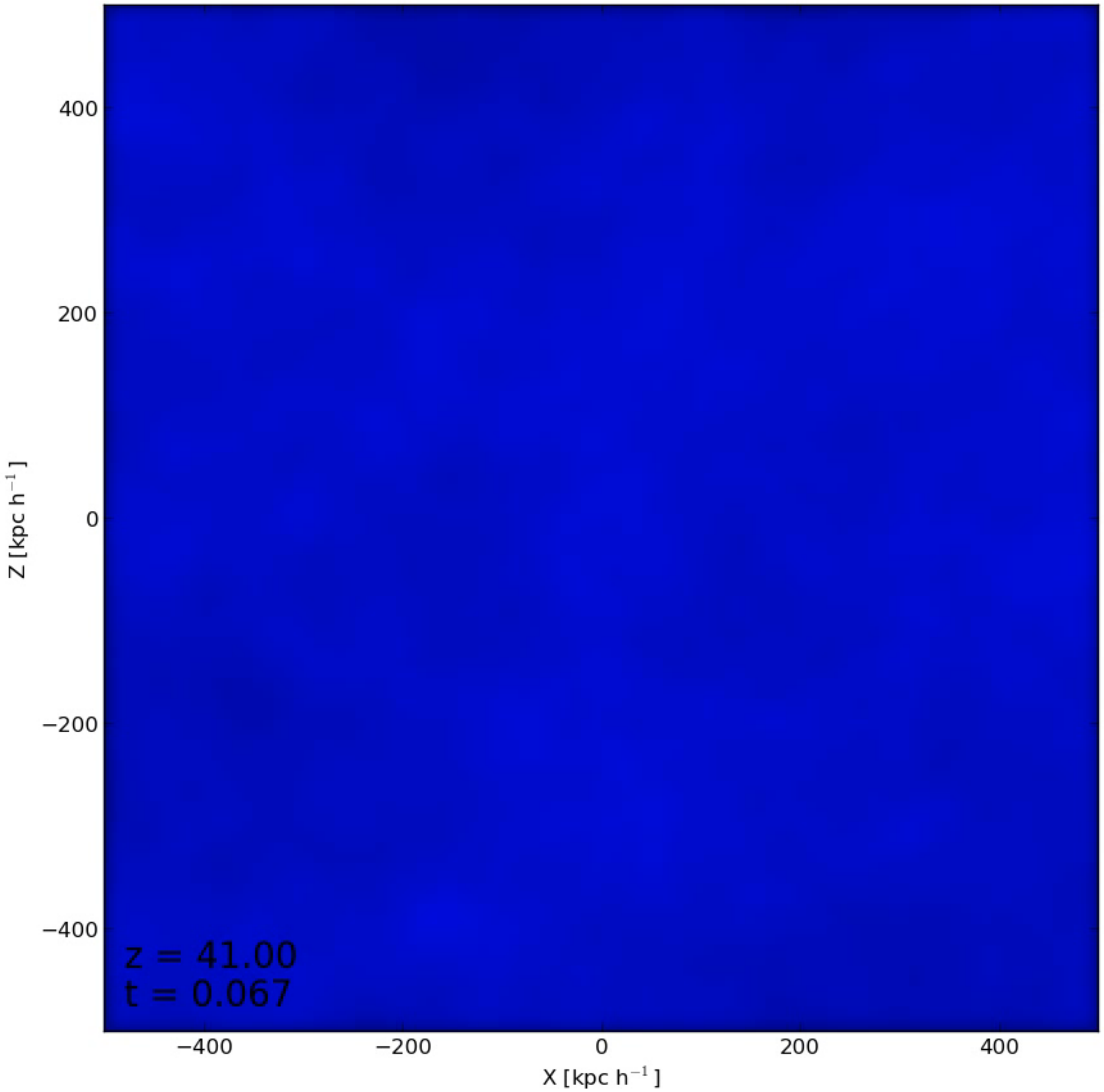
•SPH-Gadget2, with reionization, star formation, and feedback-driven winds.

•~53M dark matter particles, same number of gas particles.

•m_{gas}=4.4 10^4 M_{sun}/h
•m_{DM}=2.5 10^5 M_{sun}/h



Cosmic Web Stripping

- Dwarf galaxies are stripped of gas by the ram pressure that results from interaction with the pancake.
- This process is especially effective in dwarf galaxies, since ram pressure scales like $\rho_p V_p^2$ whereas the pressure that holds gas in a halo scales like $\rho_{gal} V_{vir}^2$

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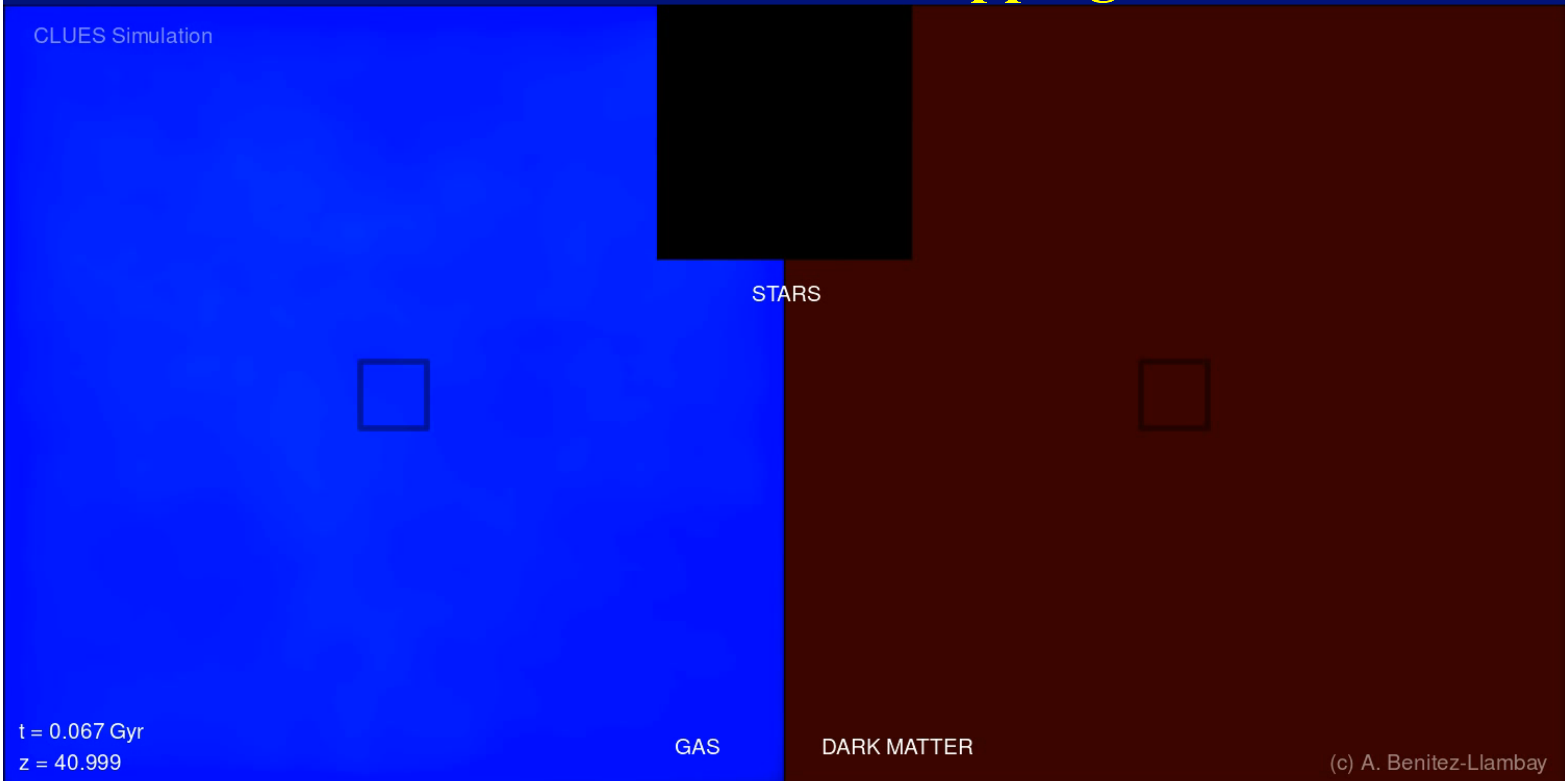
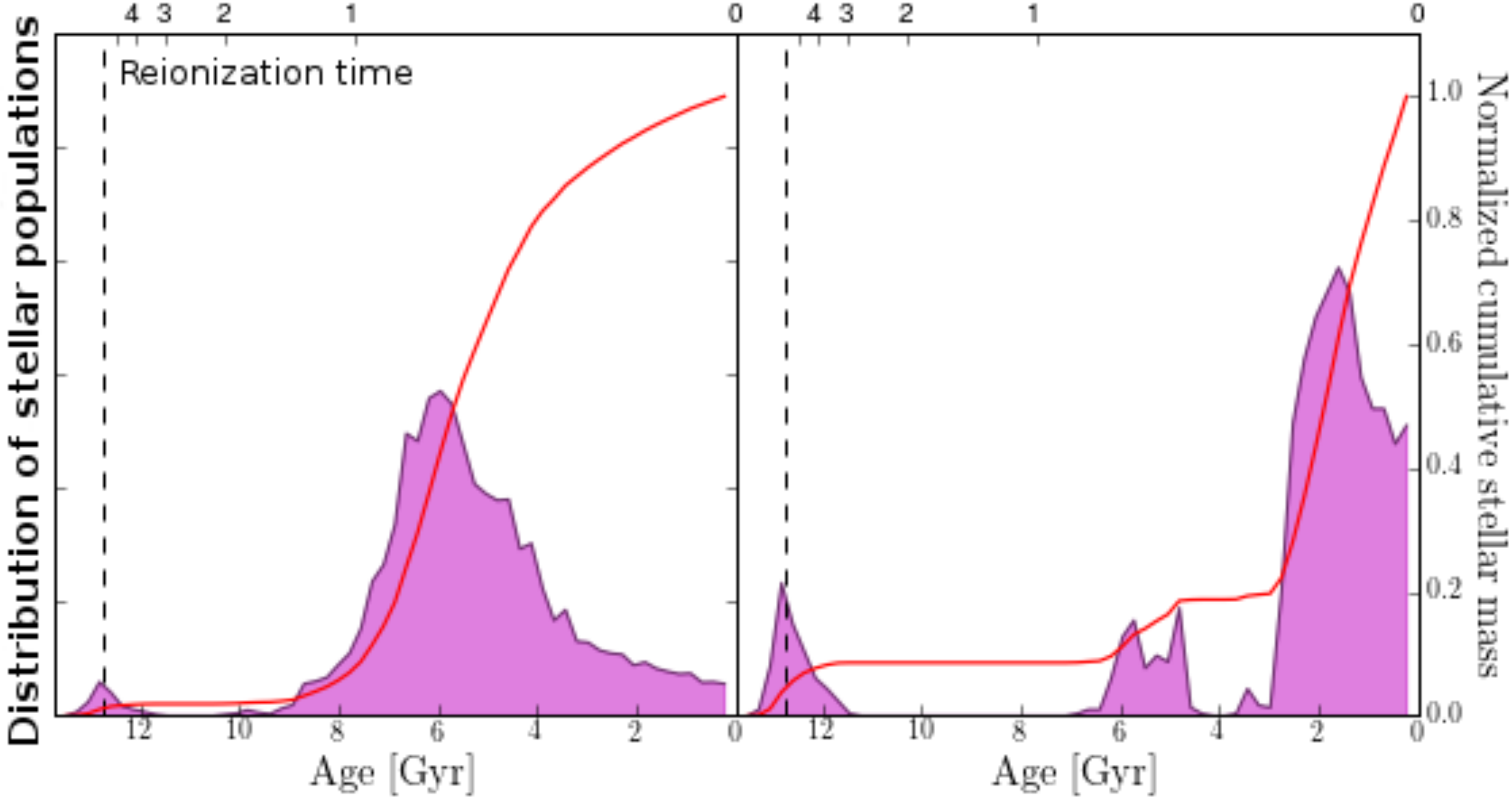
Cosmic Web Stripping



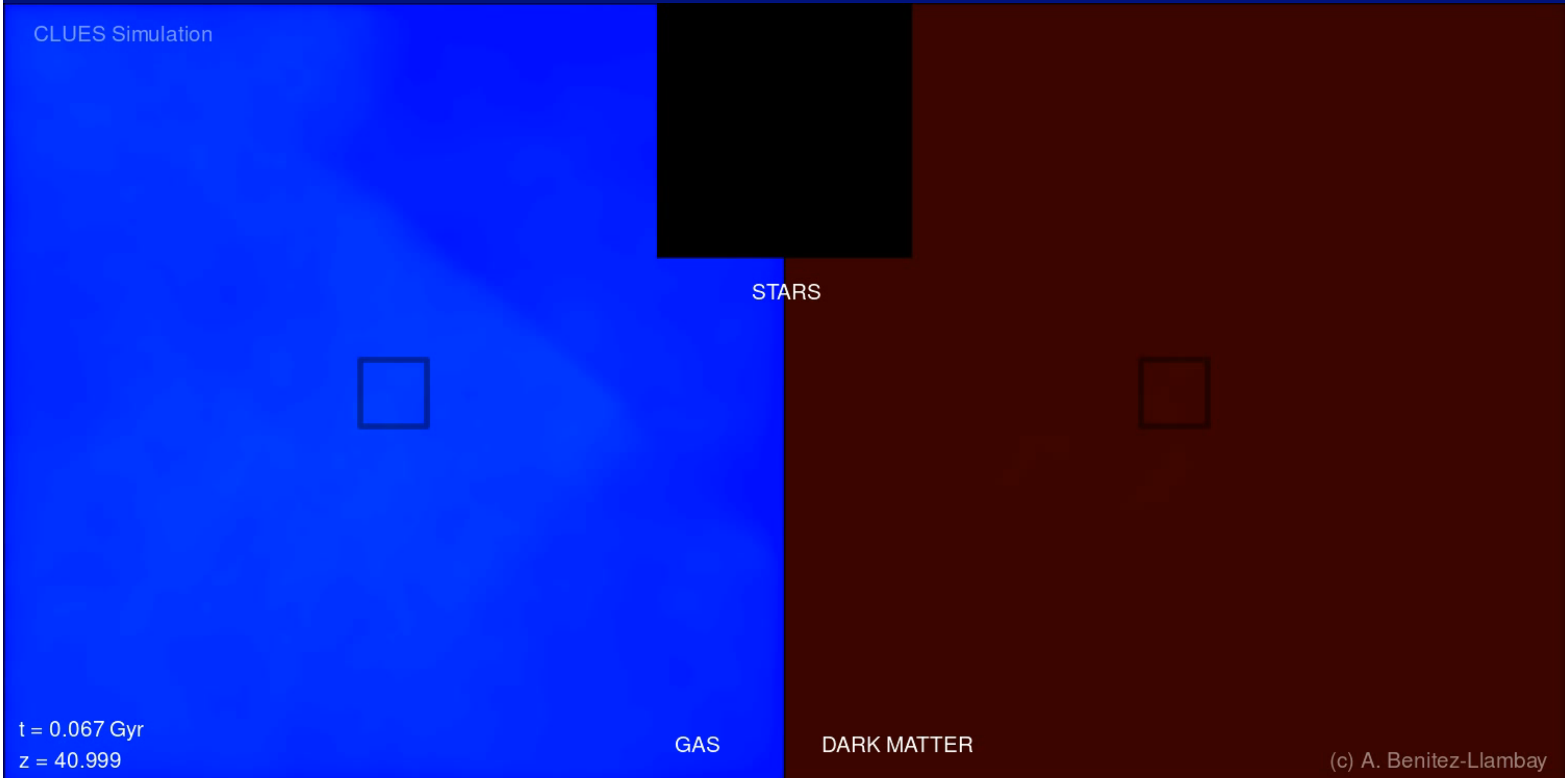
•Cosmic web stripping does not affect the dark matter, because of its collisionless nature.

•Cosmic web stripping offers a natural mechanism to prevent or reduce the galaxy formation efficiency in low-mass halos without appealing to feedback.

Dwarf galaxies with delayed star formation

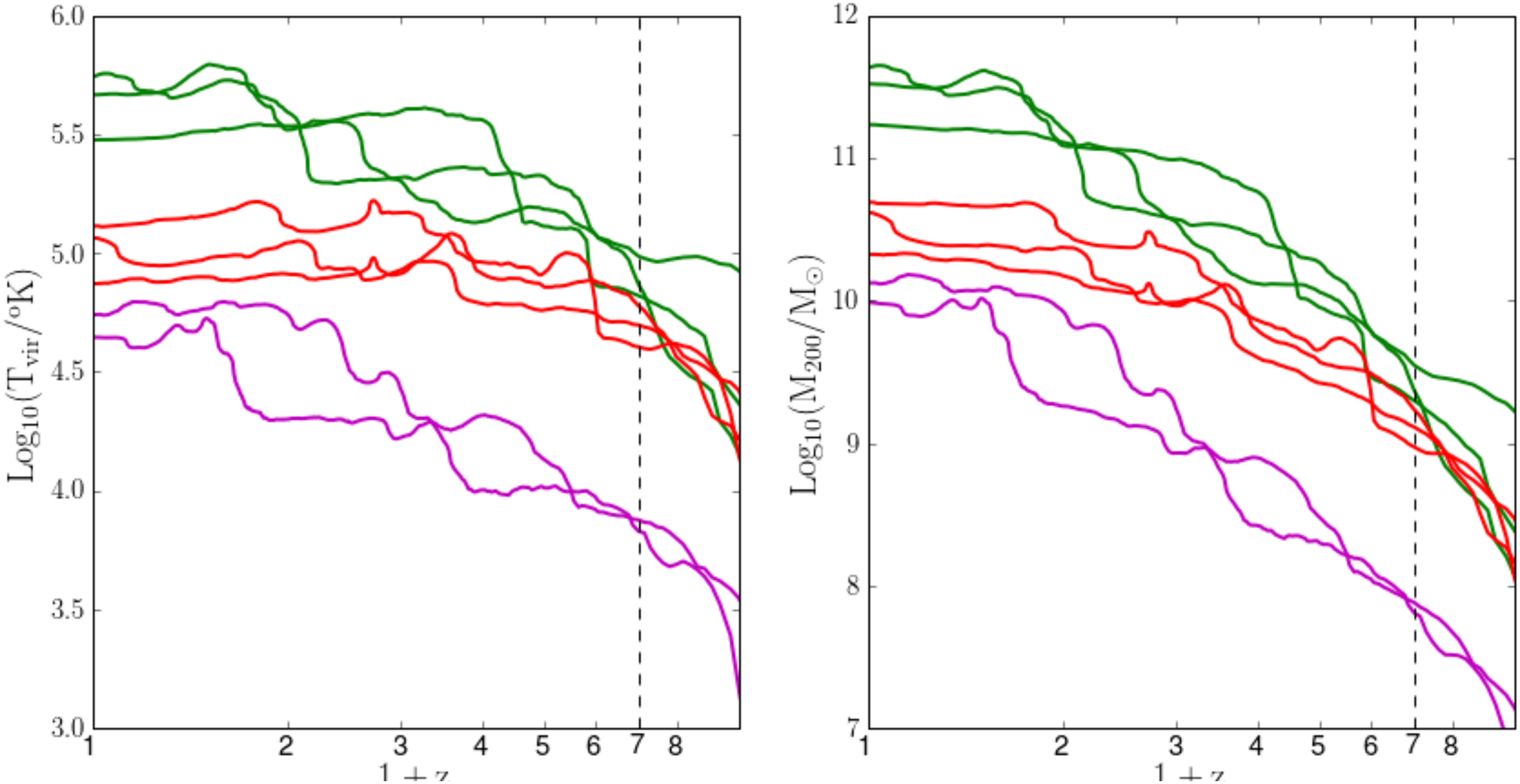


The Impact of Reionization



- Halos whose virial temperature at the epoch of reionization is below 10^4 K have their gas supply evaporated by reionization.
- Only as they become more massive later on they are able to transform gas into stars.

Mass and virial temperature evolution



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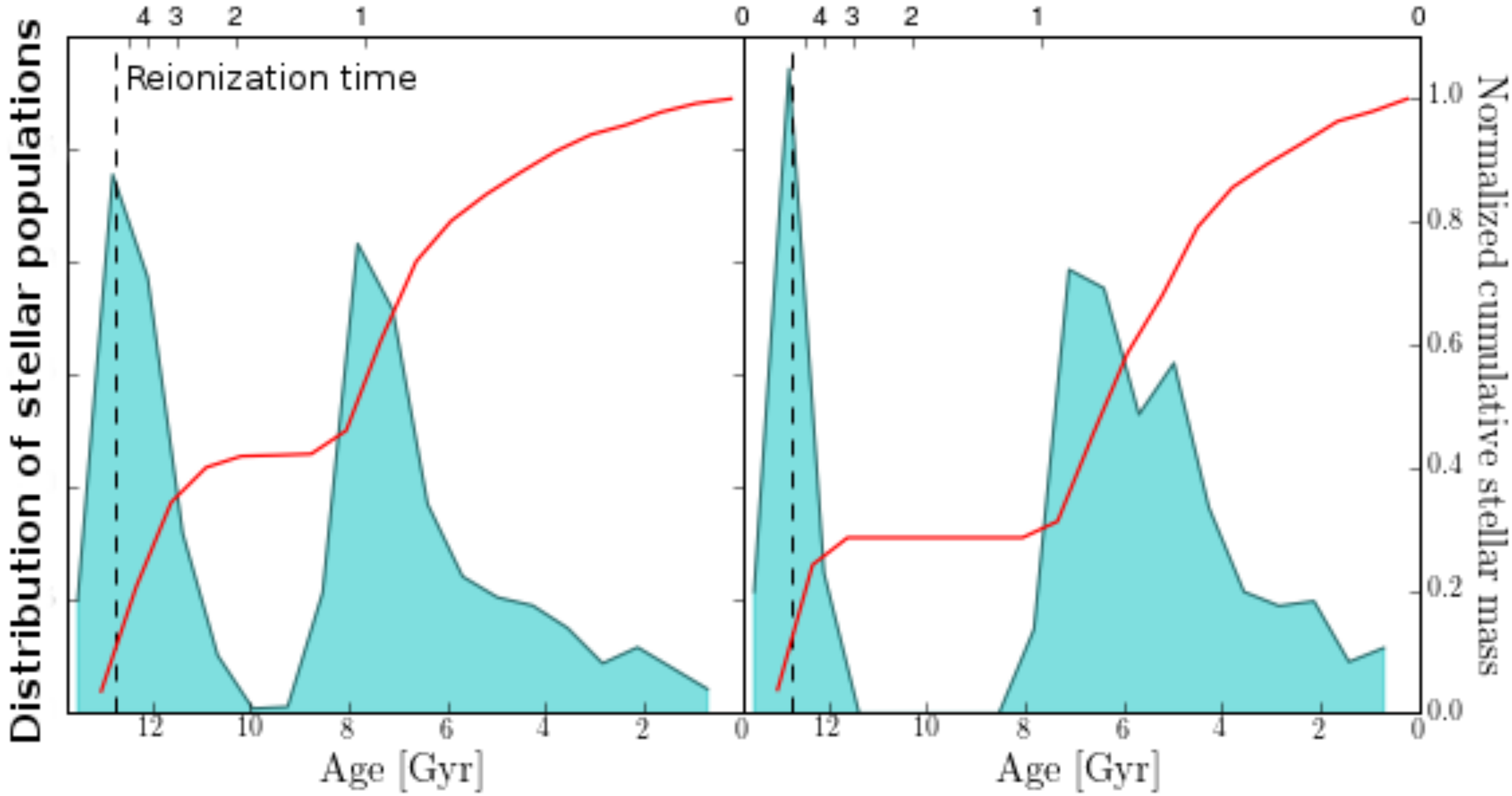
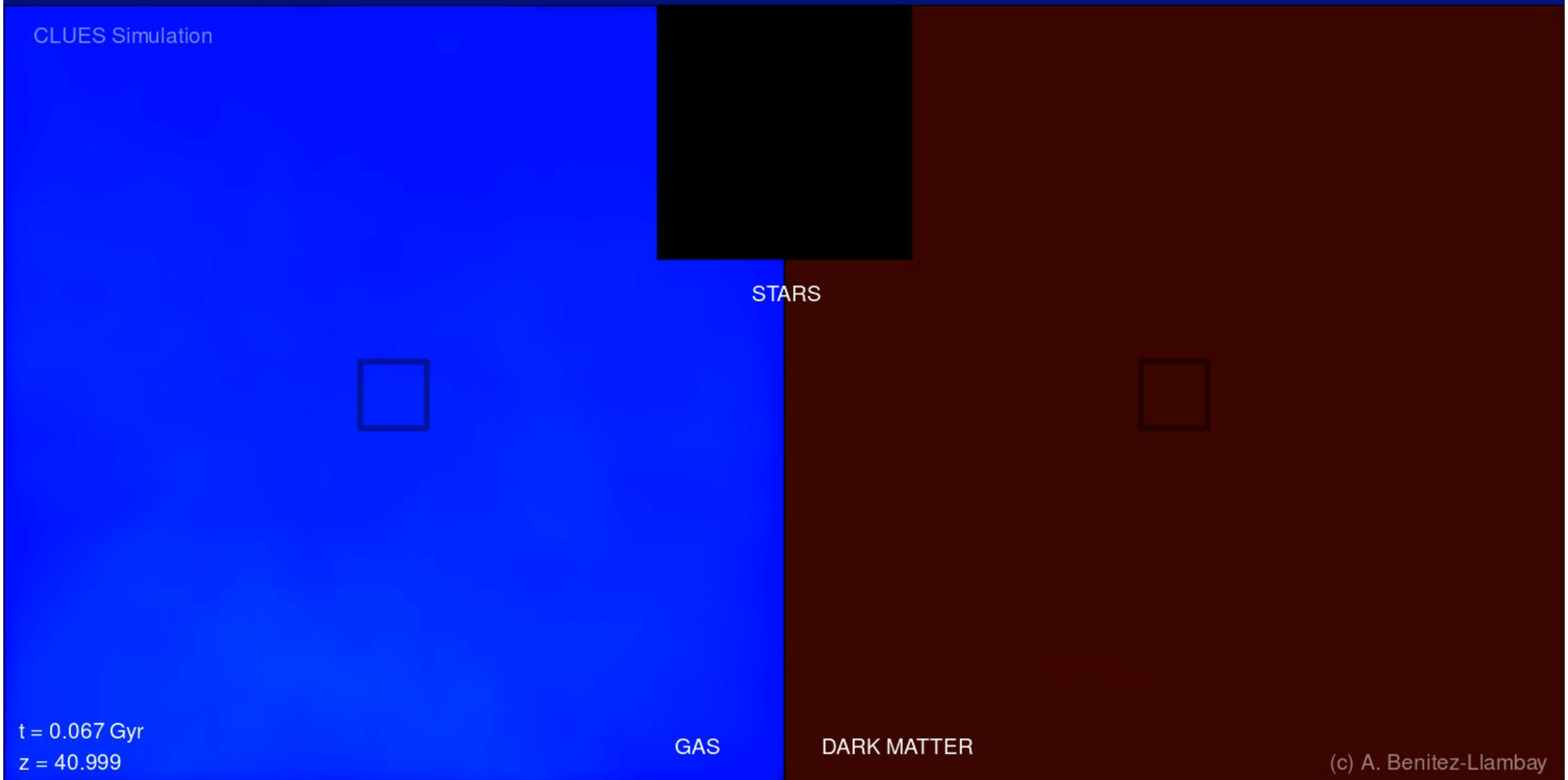
Dwarf galaxies with two distinct stellar populations

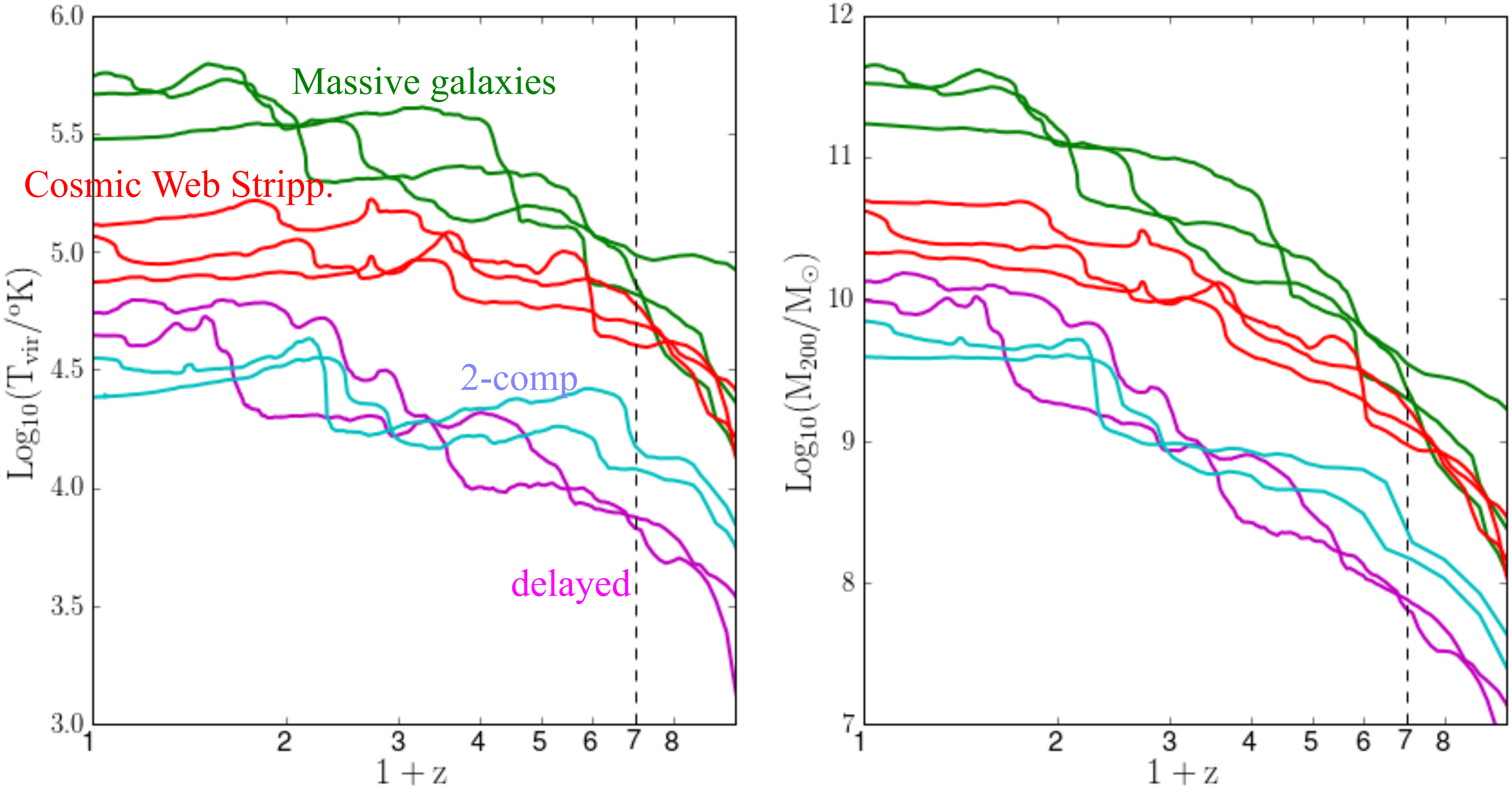


The Impact of Reionization



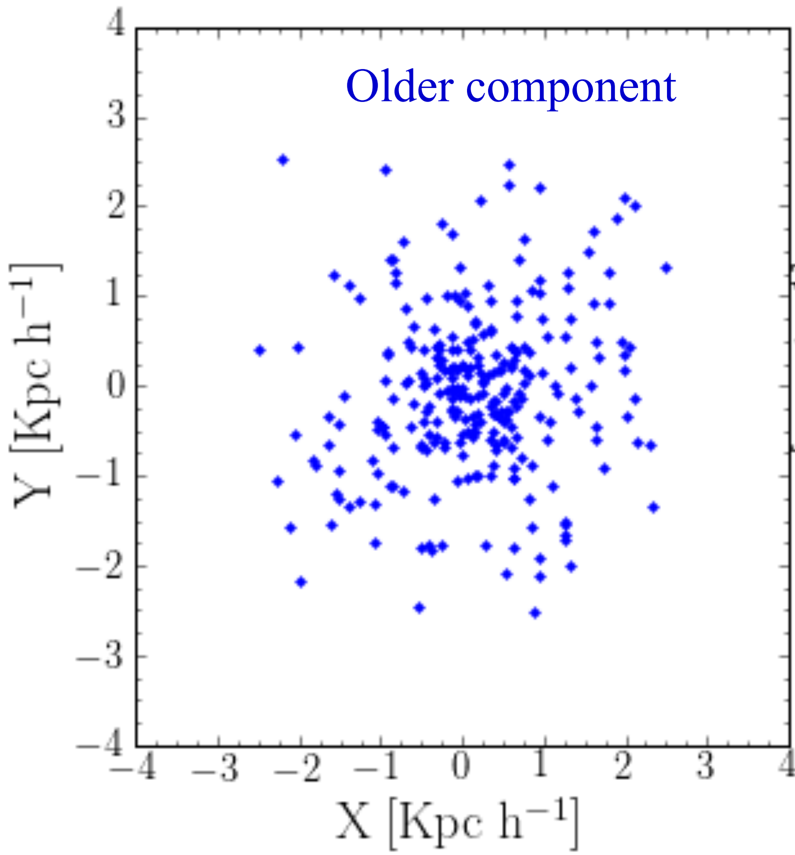
•Galaxies with two stellar components form as a result of a merger of two low-mass systems: one that forms stars early (and loses its gas through winds) and another whose star formation is delayed.

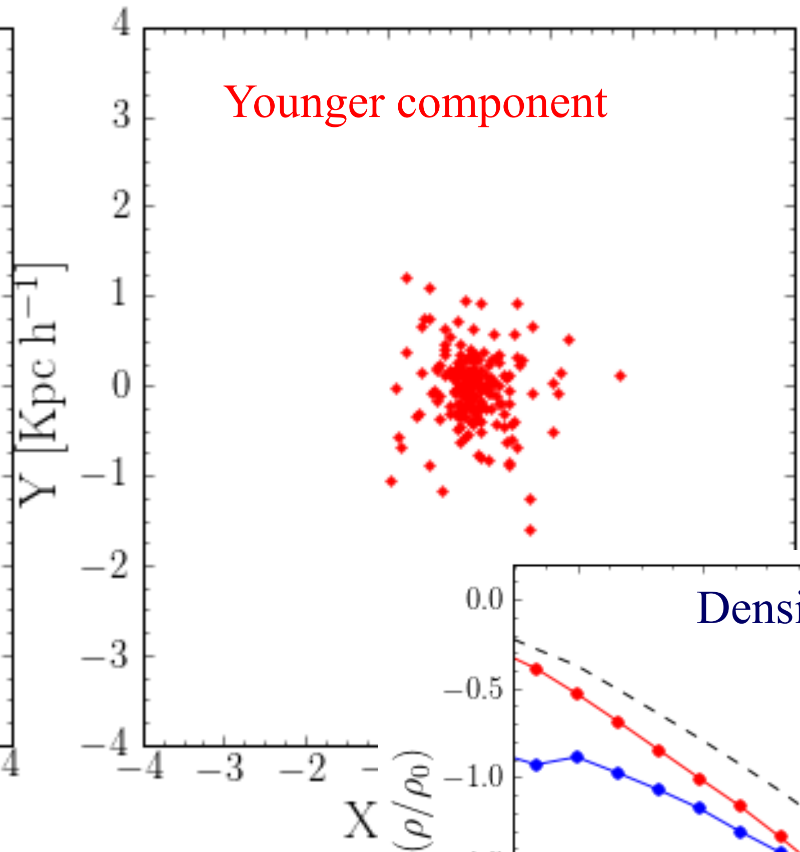
Mass and virial temperature evolution

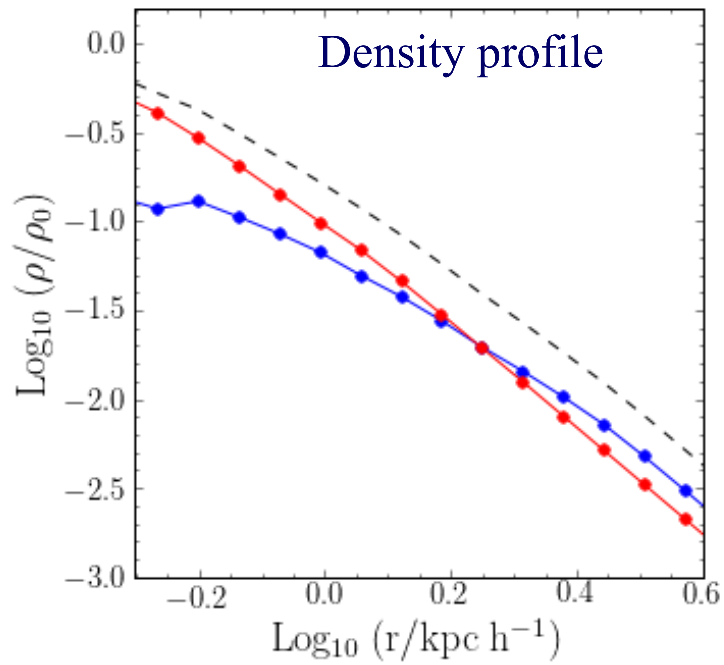


•Reionization, interaction with the cosmic web, and the halo mass accretion history all combine to determine the star formation history of a dwarf galaxy.

Two-component galaxies

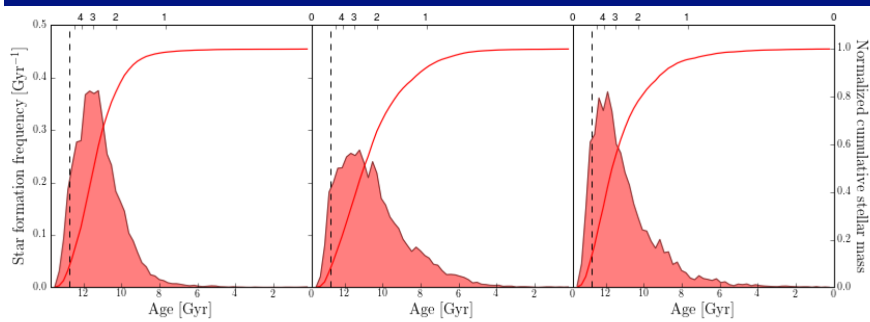




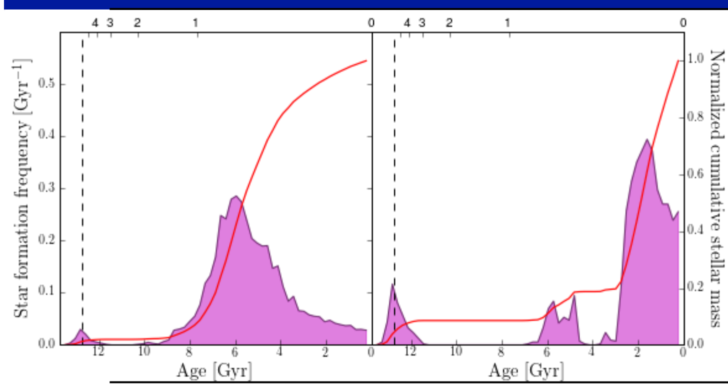


- Dwarfs with two stellar components distinct in age are also distinct in their spatial distribution.
- The older component is more extended radially

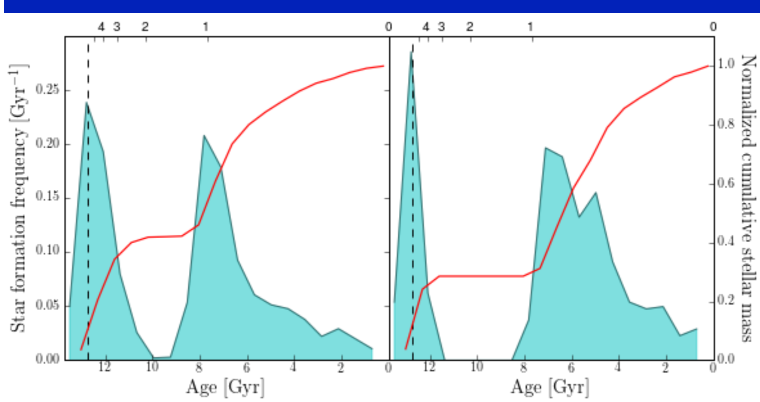
Conclusions



•Relatively massive halos: stellar winds and cosmic web stripping can efficiently remove gas from low mass halos and truncate star formation.



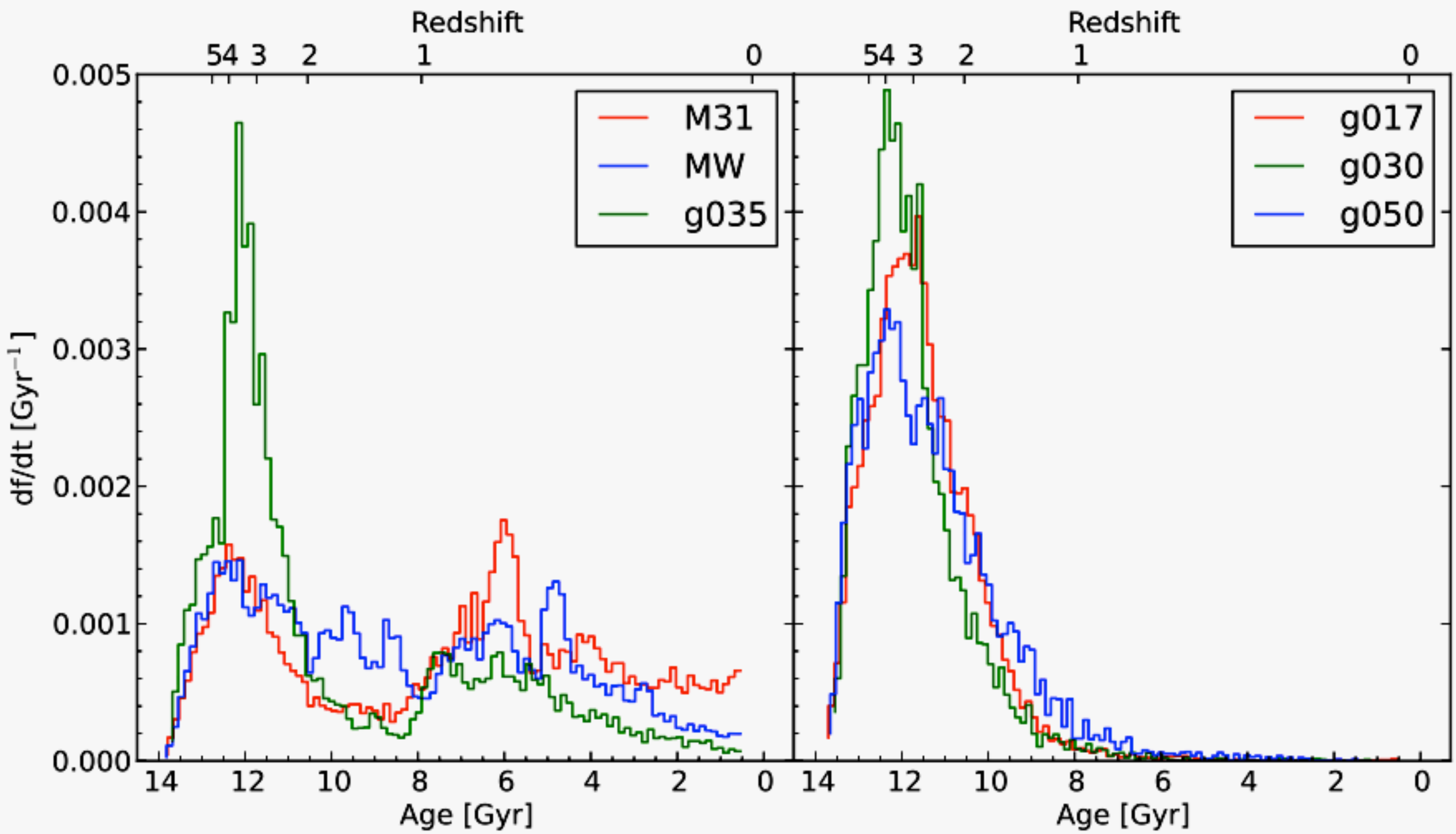
•- Reionization can prevent stars from forming in halos that have low virial temperatures at early times. The gas does not escape the system and can be reaccreted later and form stars as the system grows.



•Systems with two episodes of star formation are a combination of the above scenarios: an early star formation episode that is truncated by either winds or web stripping is followed by accretion of gas supplied by a low-mass halo that retained gas during reionization.

- This may explain the origin of multiple

Star formation histories of CLUES LG galaxies



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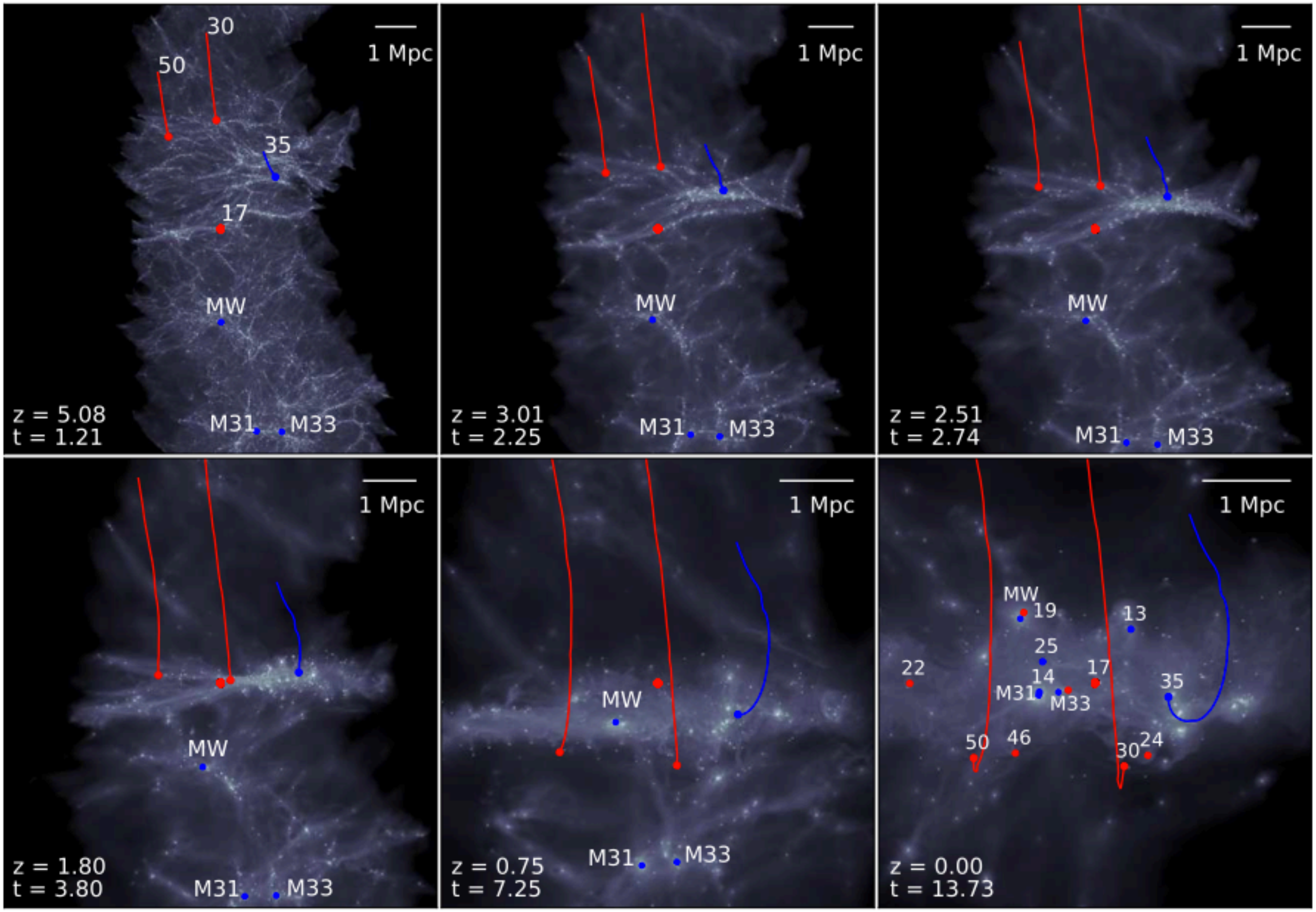
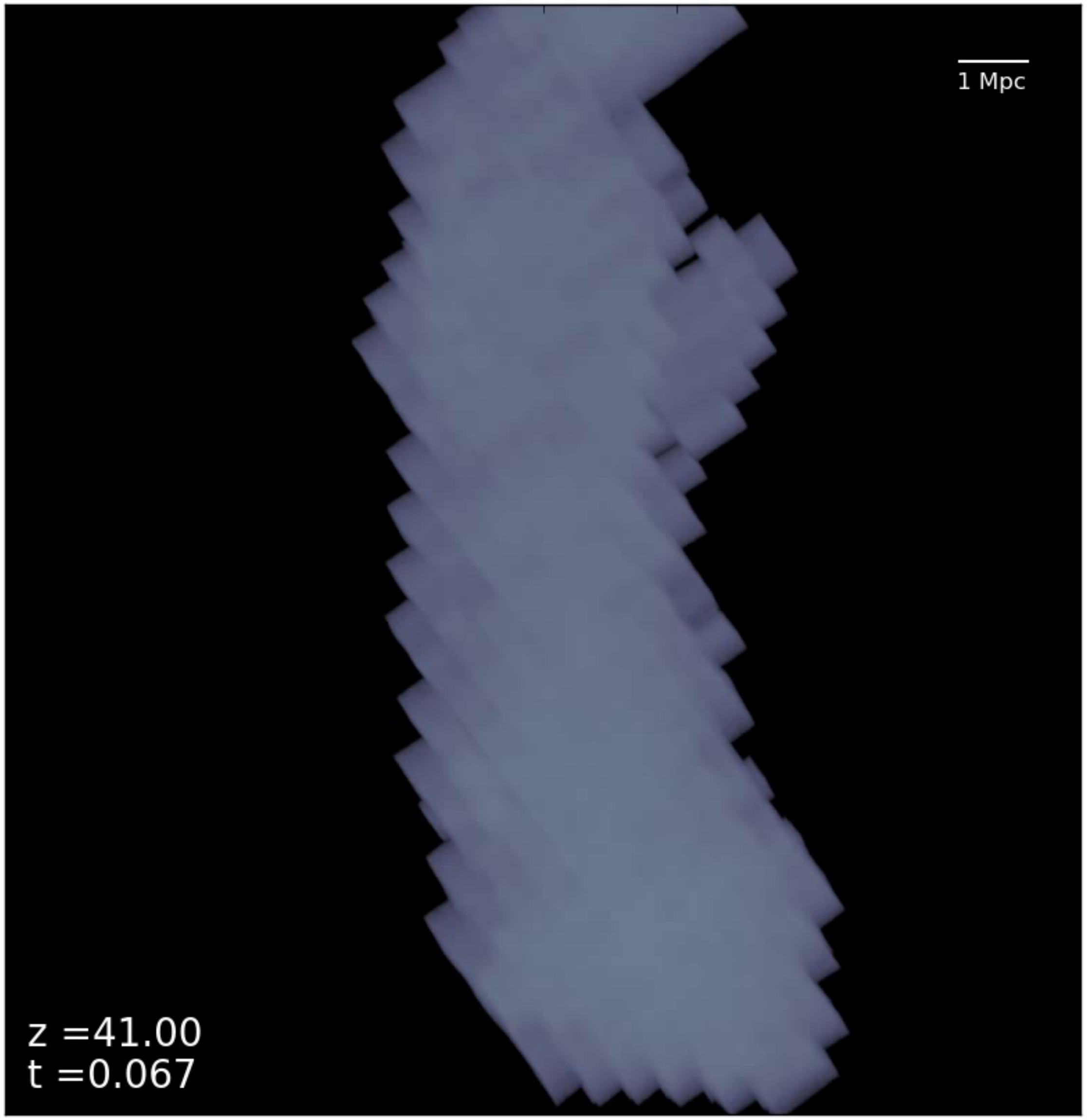
The trajectories of dwarf galaxies through the cosmic web





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CLUES

- The Constrained Local UniversE Simulations evolve a region akin to the Local Group of Galaxies in the WMAP3 cosmology.
- SPH-Gadget2, with reionization, star formation, and feedback-driven winds.
- ~53M dark matter particles, same number of gas particles.
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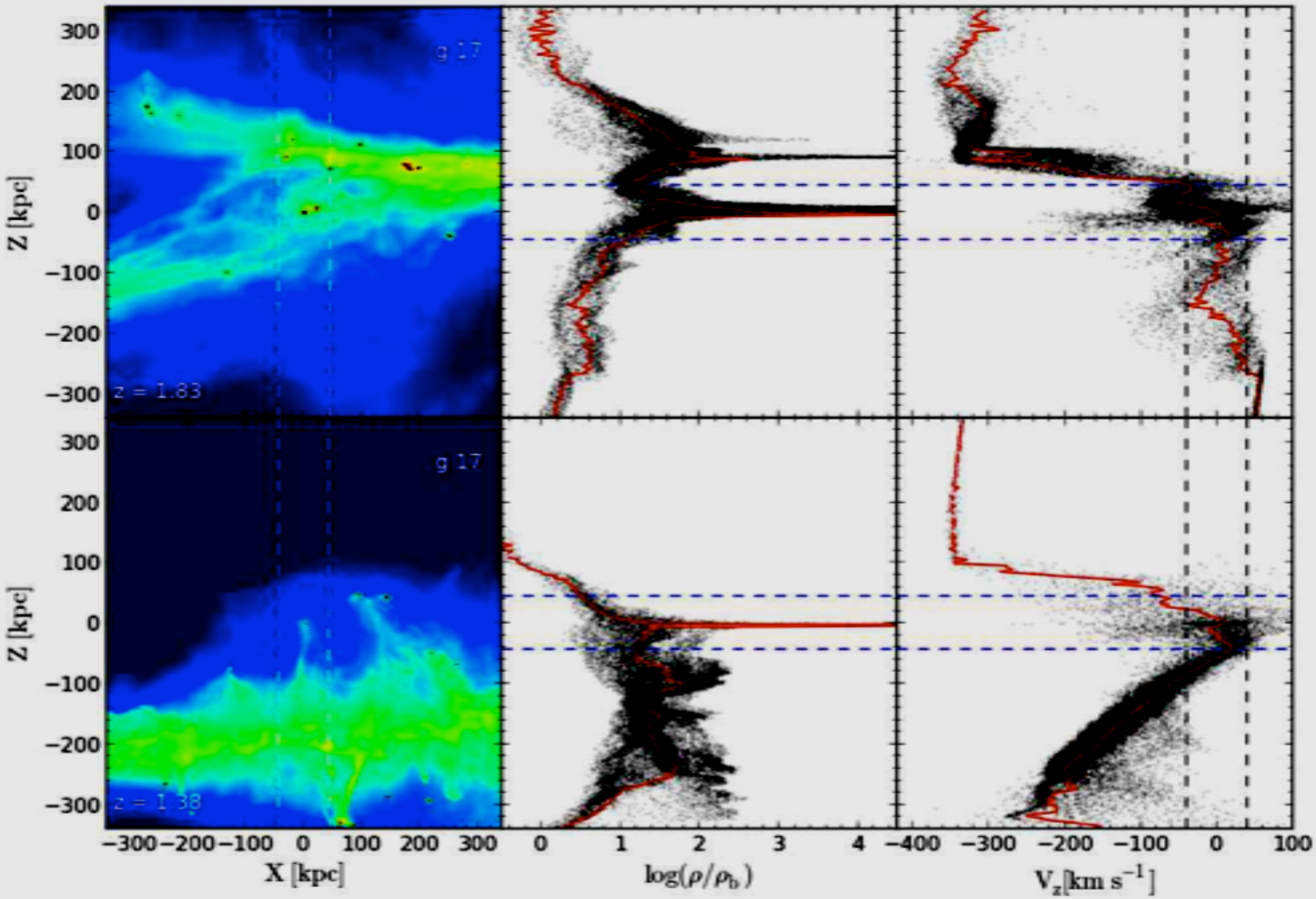
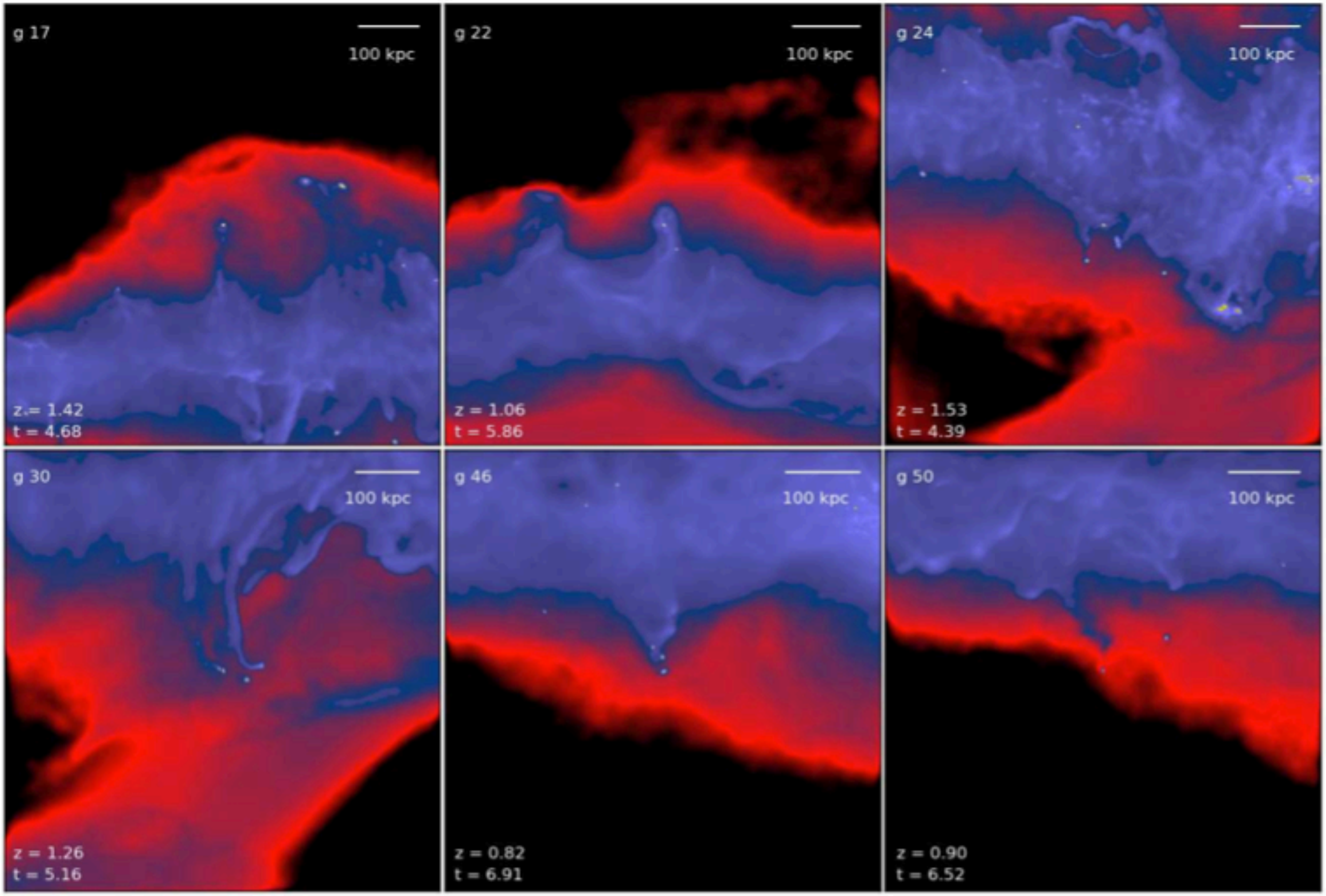
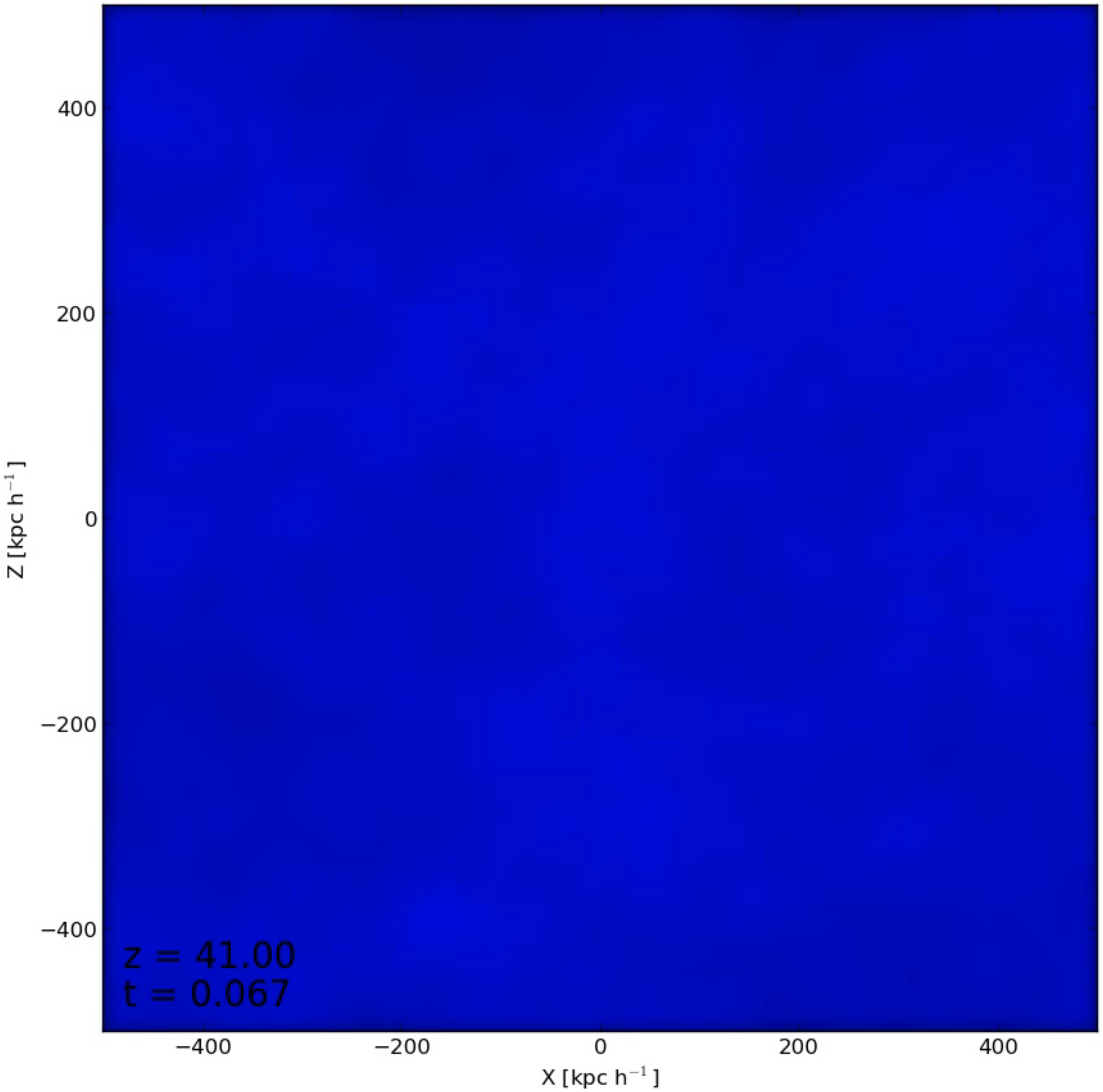
Pancake-galaxy interaction for galaxy 17



Pancake-galaxy interaction for other galaxies





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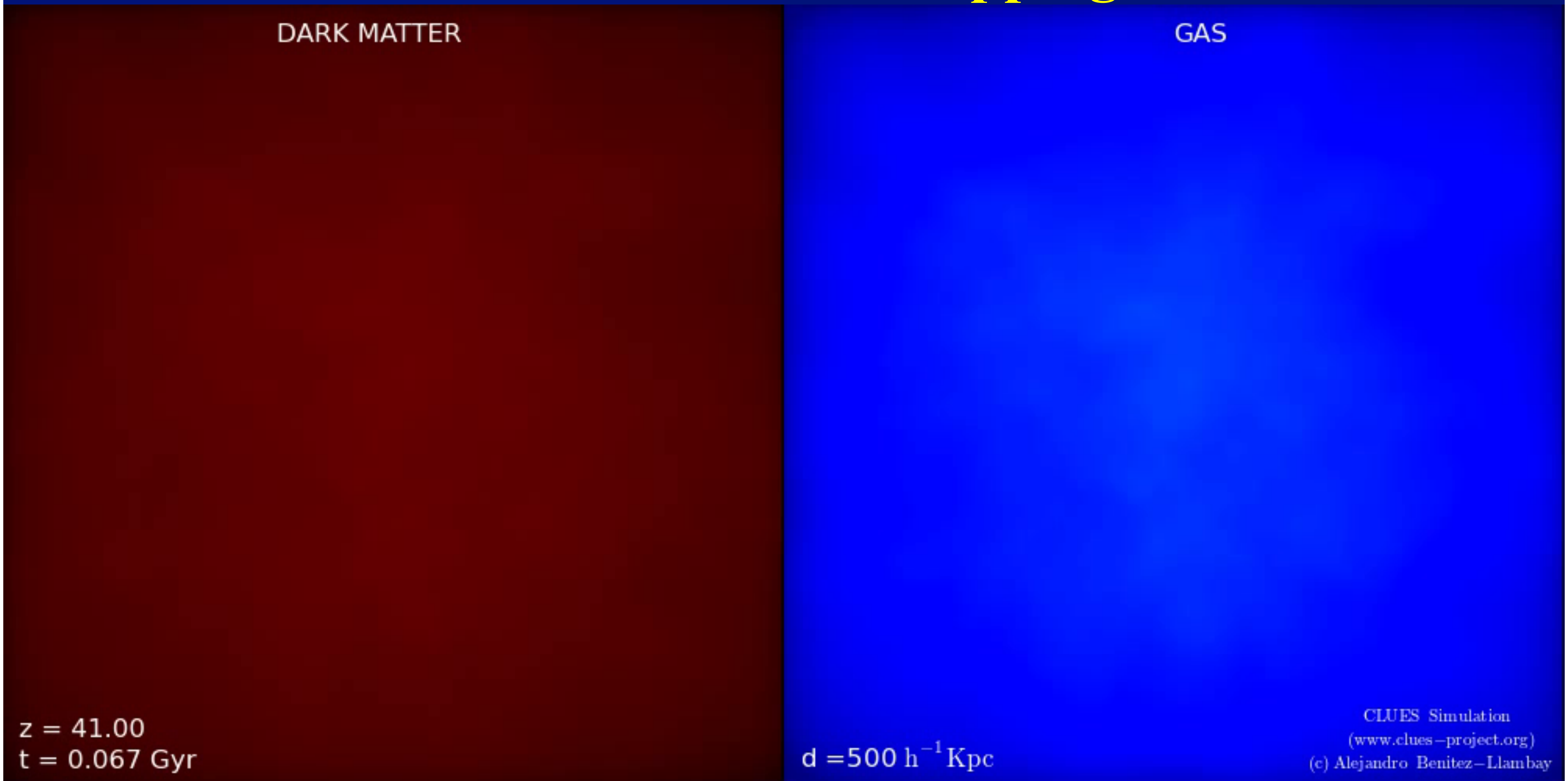
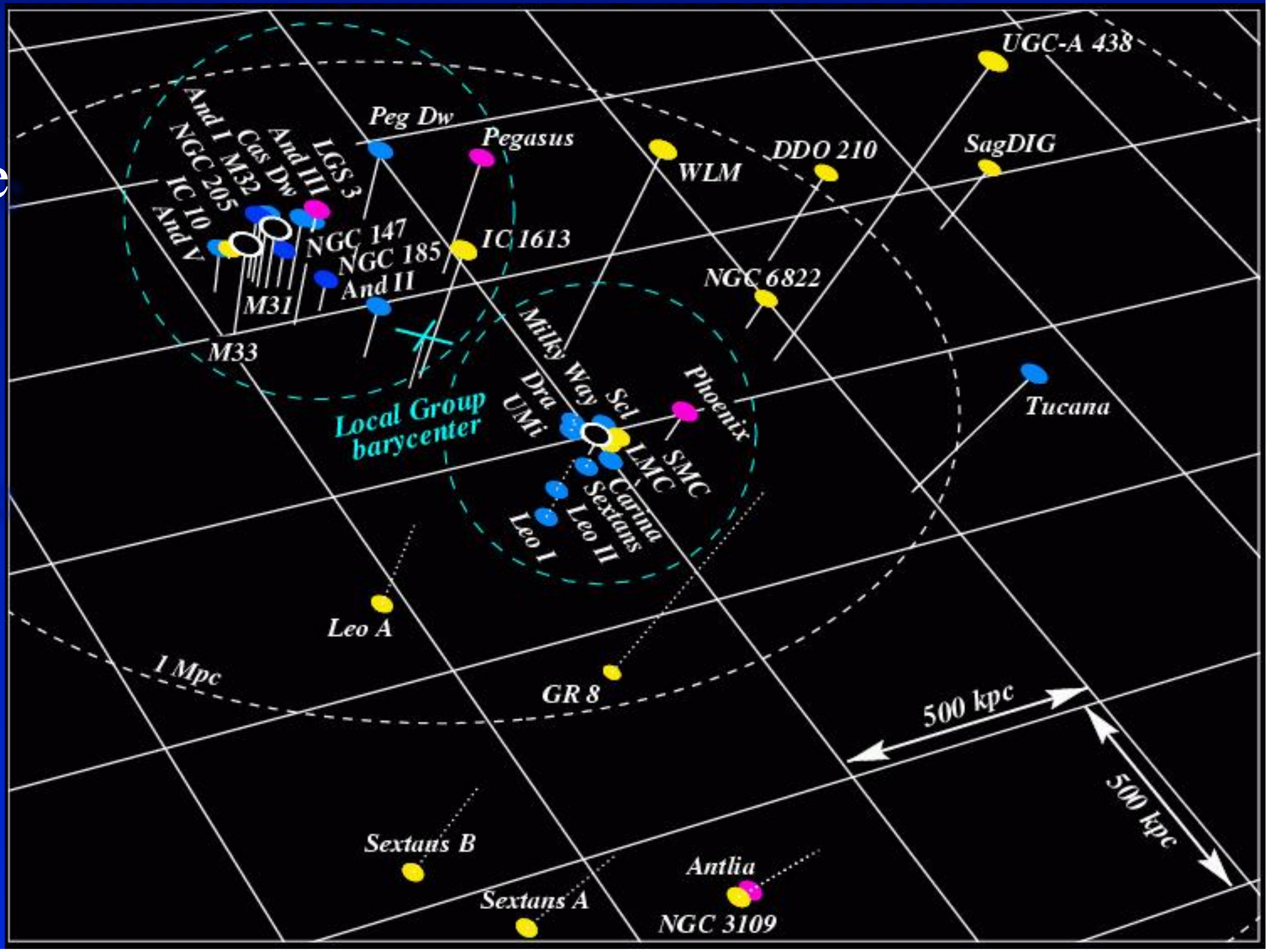


- Cosmic web stripping does not affect the dark matter, because of its collisionless nature.
- Cosmic web stripping offers a natural mechanism to prevent or reduce the galaxy formation efficiency in low-mass halos without appealing to feedback.

Observational implications

Difficult to disentangle the effects of cosmic web stripping from those of reionization and feedback

The existence of isolated dwarf spheroidal galaxies, like Cetus and Tucana



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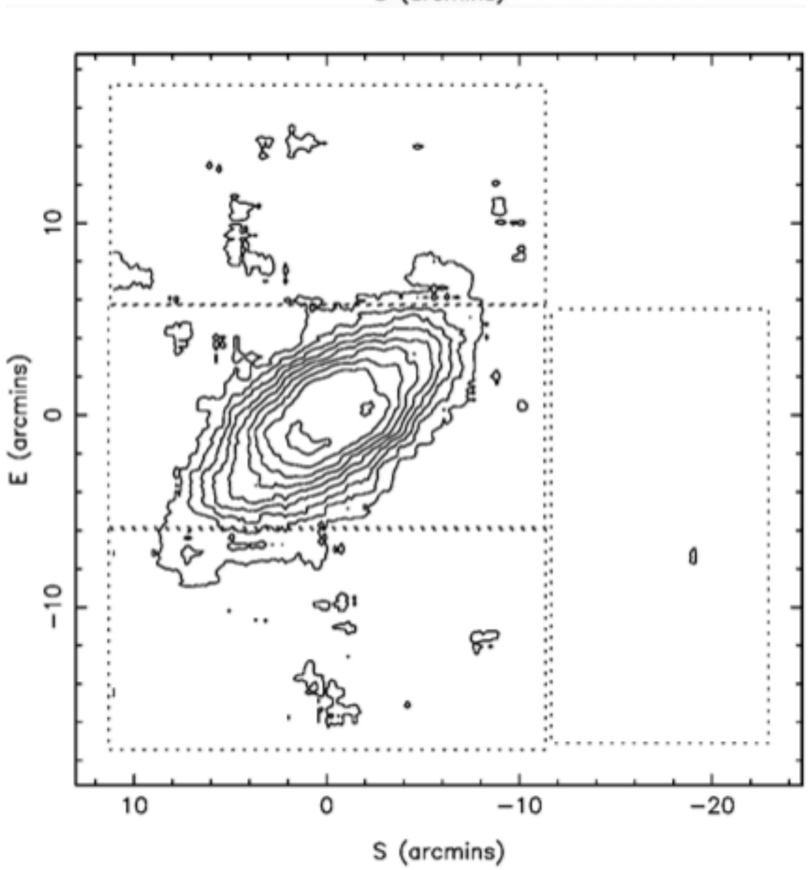

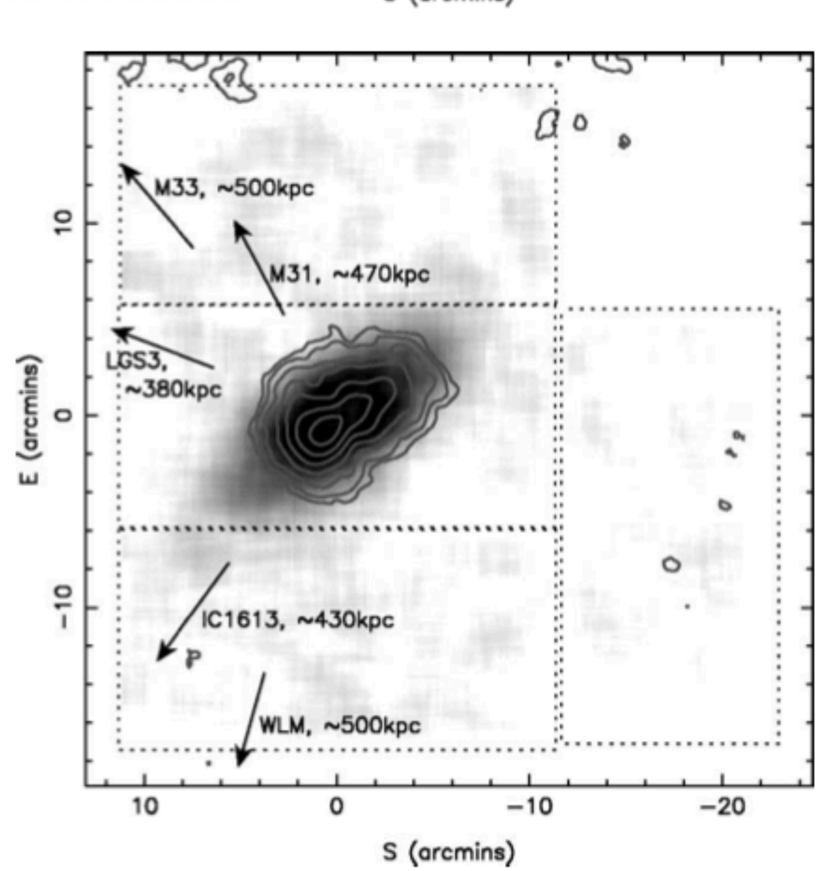

Some isolated galaxies in the Local Group, like Pegasus, show signs of ram pressure stripping (McConnachie et al 2007)