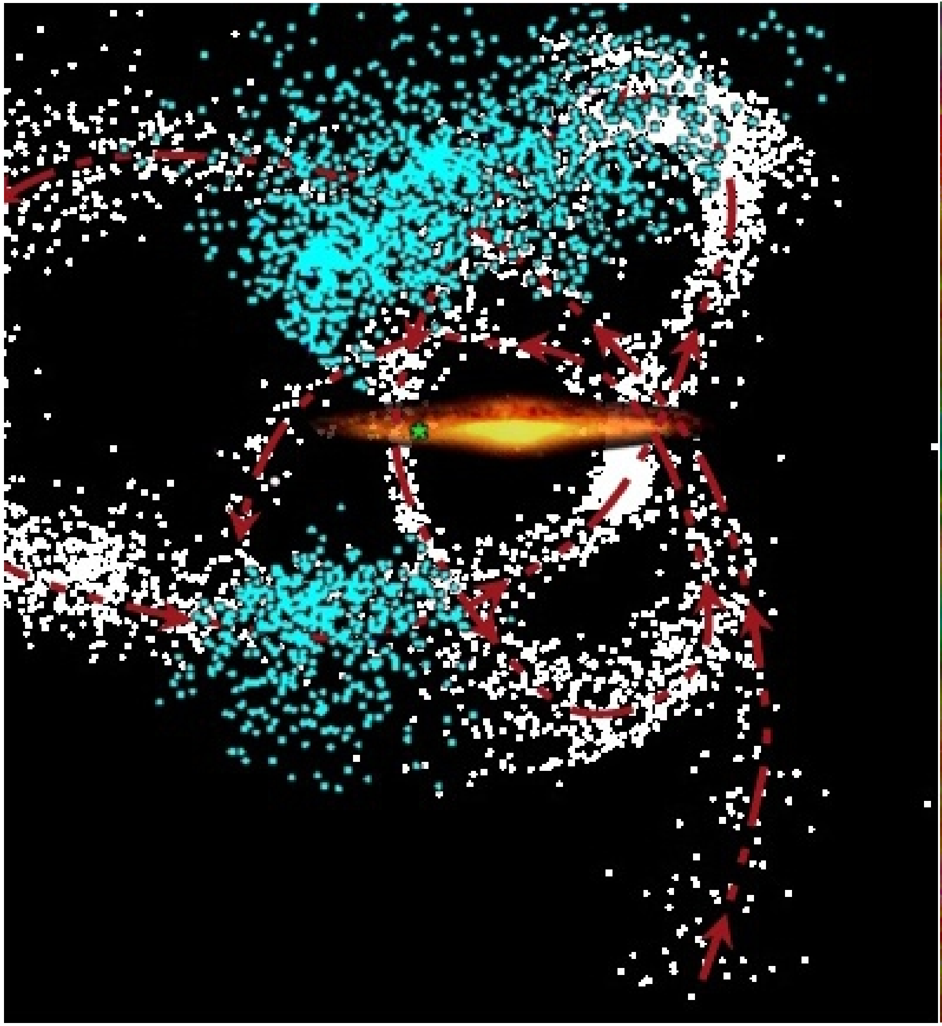
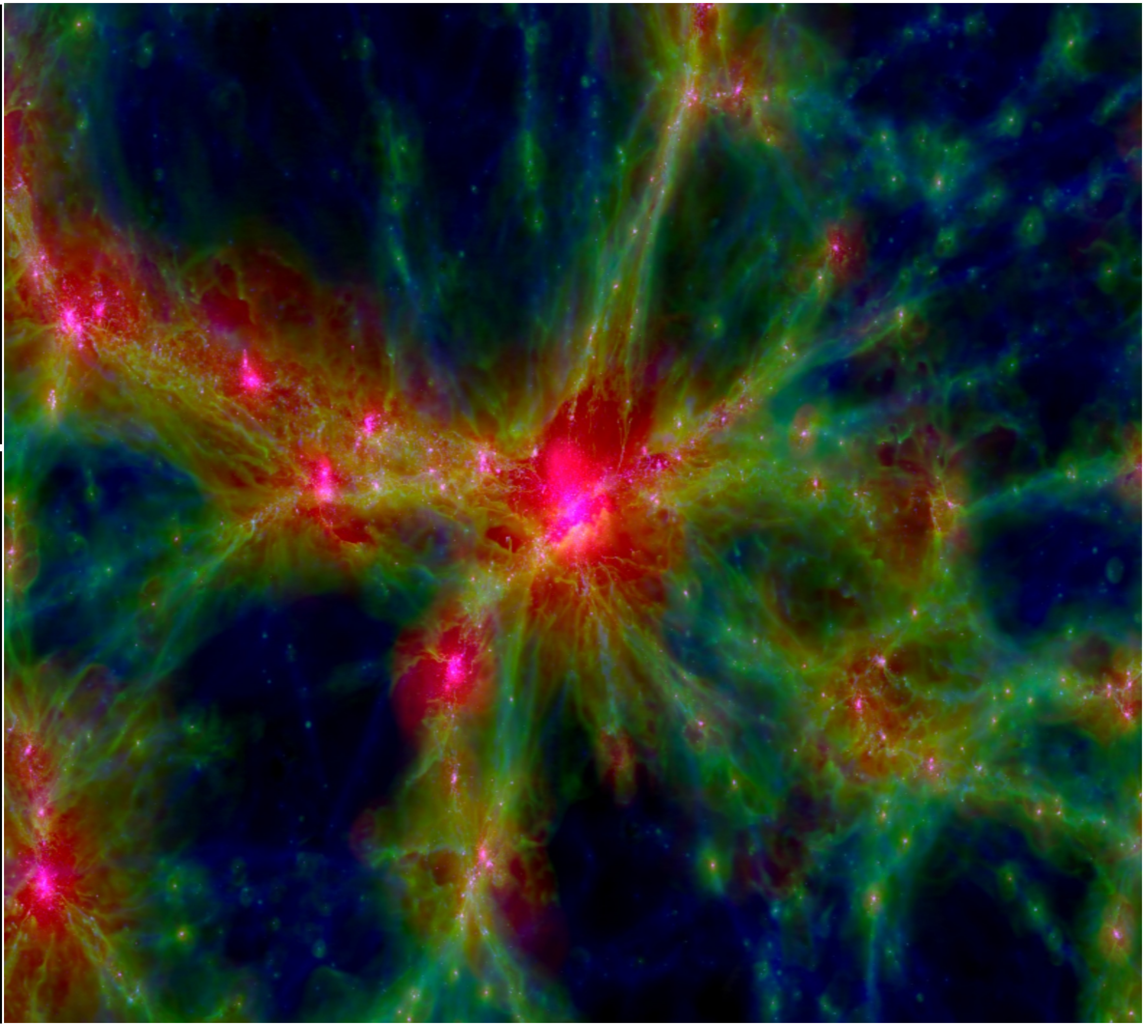
FORMATION AND PROPERTIES OF THE STELLAR HALOS OF GALAXIES IN A LCDM UNIVERSE

Two main techniques

Hybrid methods



Full Hydrodynamical simulations



TRACING GALAXY FORMATION WITH STELLAR HALOS. I. METHODS

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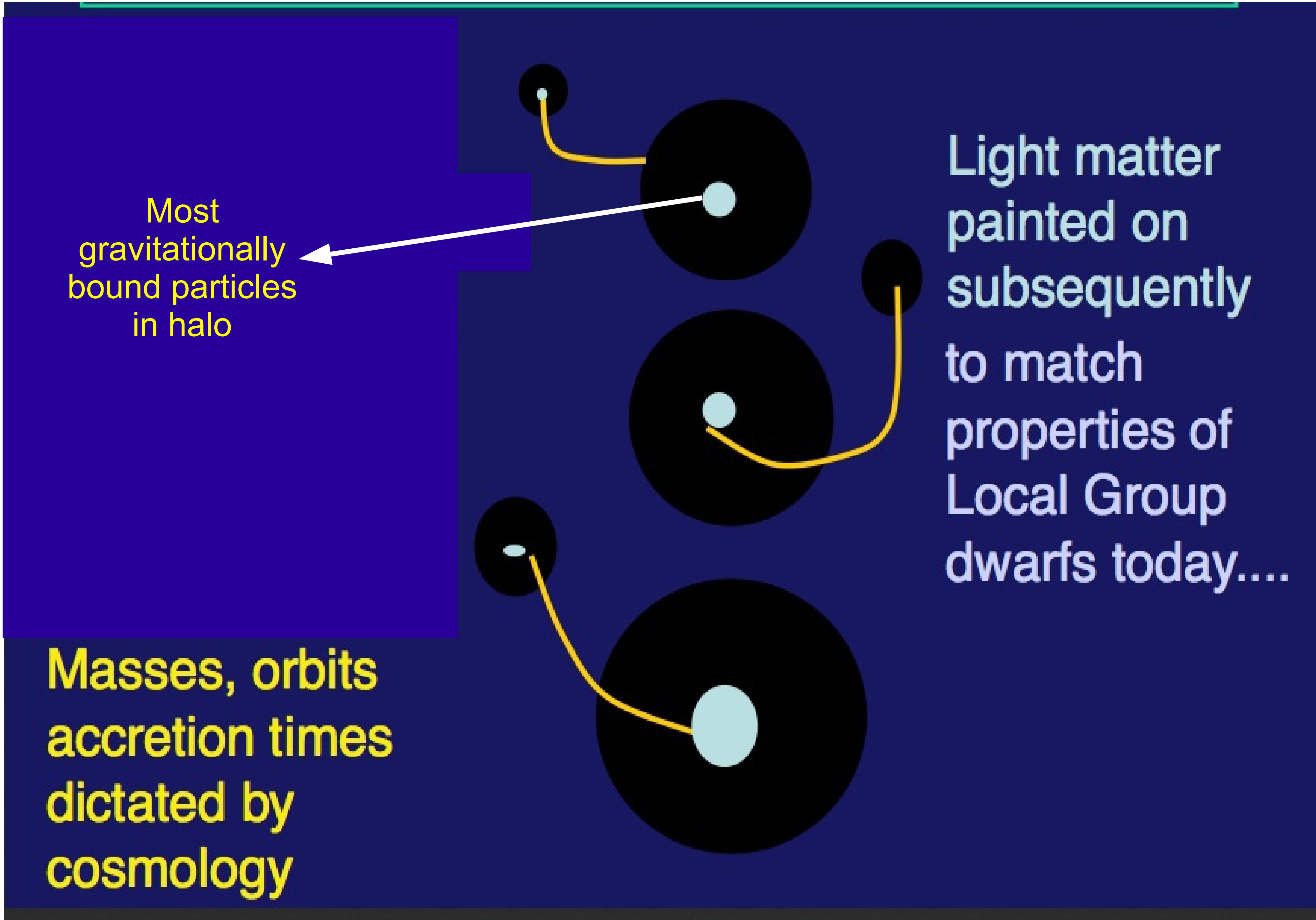
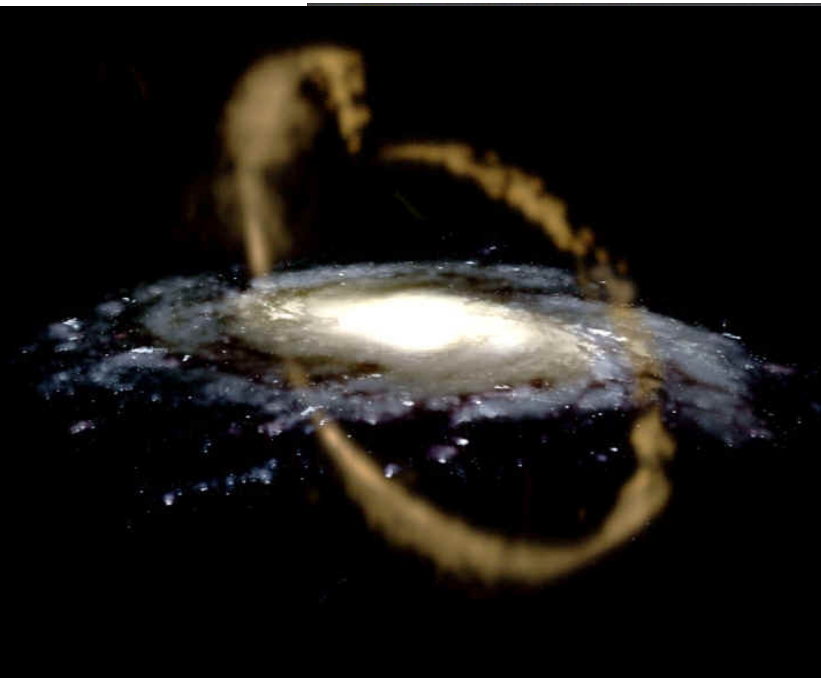
ABSTRACT

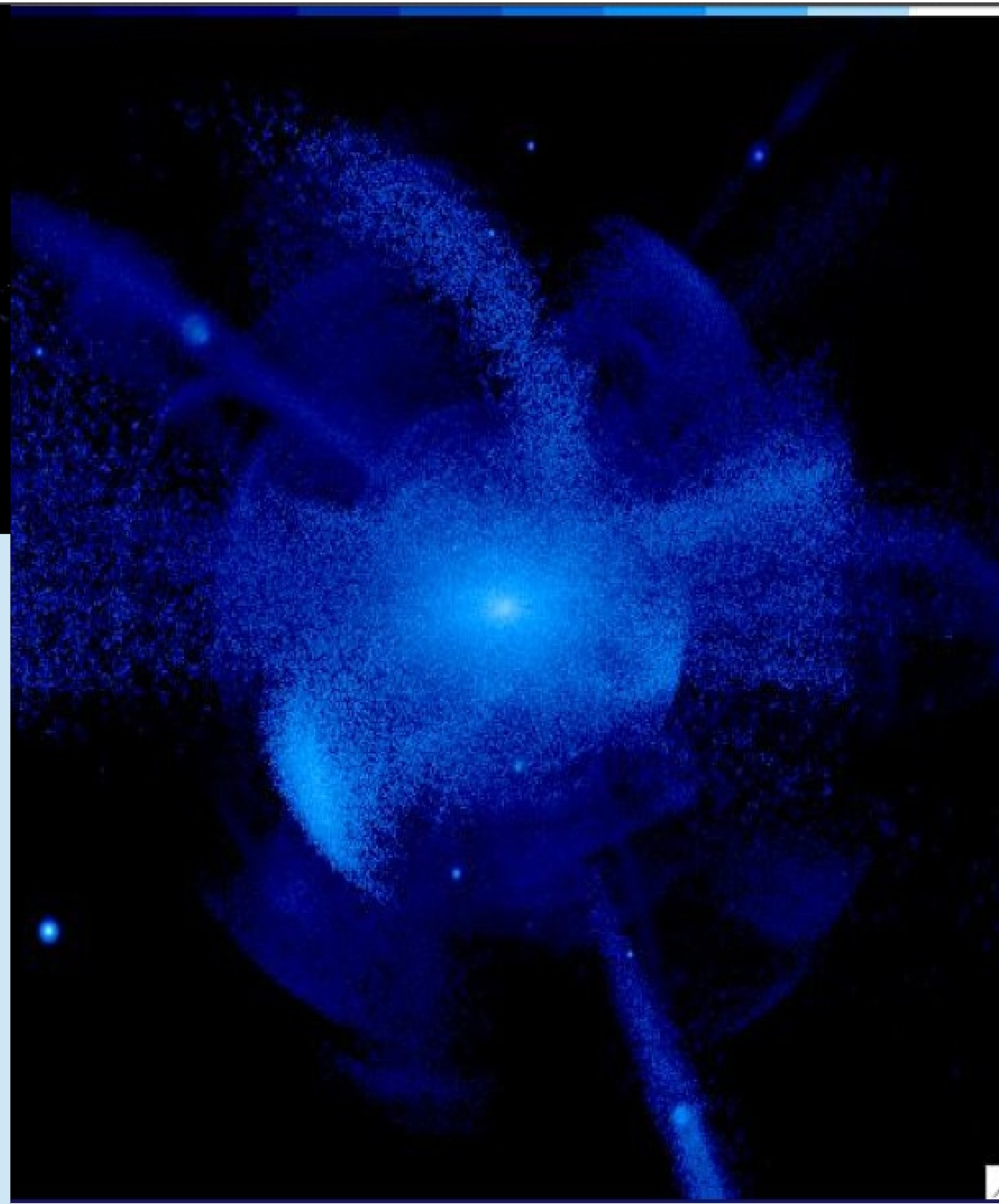
If the favored hierarchical cosmological model is correct, then the Milky Way system should have accreted ~100–200 luminous satellite galaxies in the past ~12 Gyr. We model this process using a hybrid semianalytic plus *N*-body approach that distinguishes explicitly between the evolution of light and dark matter in accreted satellites. This distinction is essential to our ability to produce a realistic stellar halo, with mass and density profile much like that of our own Galaxy, and a surviving satellite population that matches the observed number counts and structural parameter distributions of the satellite galaxies of the Milky Way. Our accreted stellar halos have density profiles that typically drop off with radius faster than the dark matter and follow power laws at $r \gtrsim 30$ kpc with $\rho \propto r^{-\alpha}$, $\alpha \simeq 3$–4. They are well fit by Hernquist profiles over the full radial range. We find that stellar halos are assembled from the inside out, with the majority of mass (~80%) coming from the ~15 most massive accretion events. The satellites that contribute to the stellar halo have median accretion times of ~9 Gyr in the past, while surviving satellite systems have median accretion times of ~5 Gyr in the past. This implies that stars associated with the inner halo should be quite different chemically from stars in surviving satellites and also from stars in the outer halo or those liberated in recent disruption events. We briefly discuss the expected spatial structure and phase-space structure for halos formed in this manner. Searches for this type of structure offer a direct test of whether cosmology is indeed hierarchical on small scales.


Most gravitationally bound particles in halo
Light matter painted on subsequently to match properties of Local Group dwarfs today....
Masses, orbits accretion times dictated by cosmology

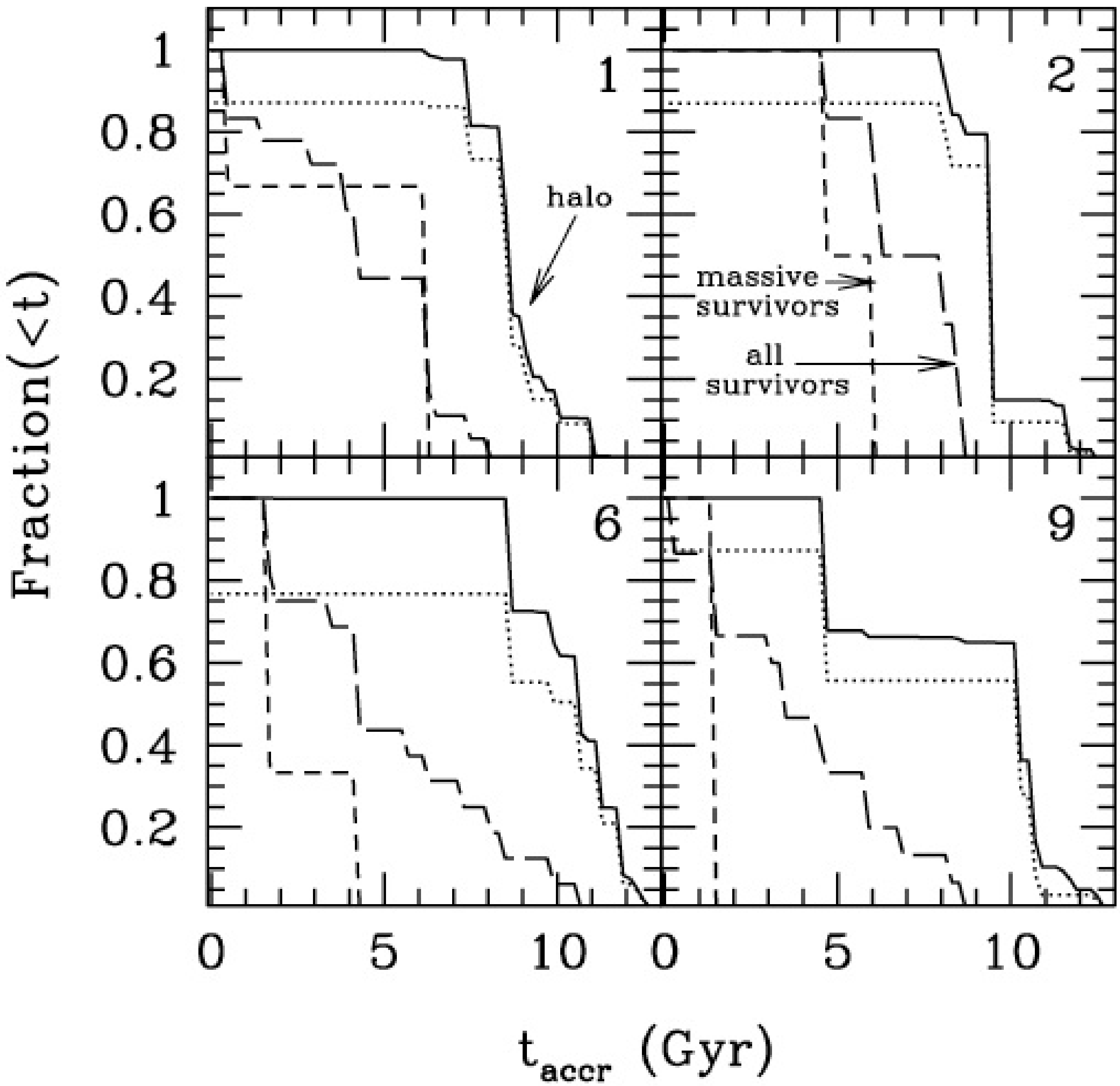


Tidal disruption of multiple accreting satellites forms the halo. Brightest features are from larger, more recent accretion events.

MAJOR SIMPLIFICATION: Idealized disk+bulge+halo potential (evolves with time)



When and how is the halo of the Milky Way built?

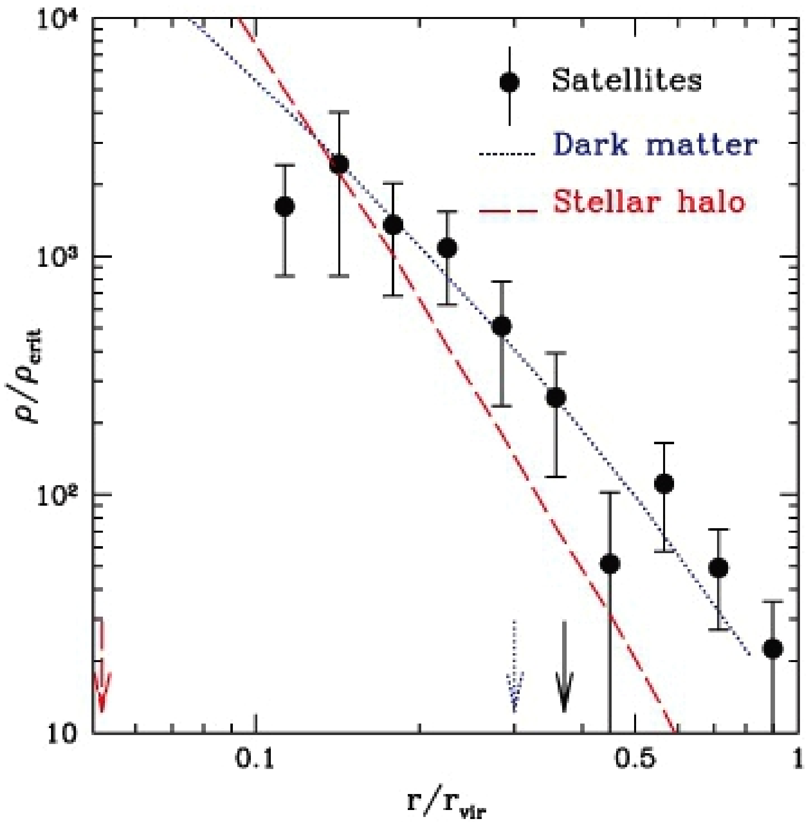


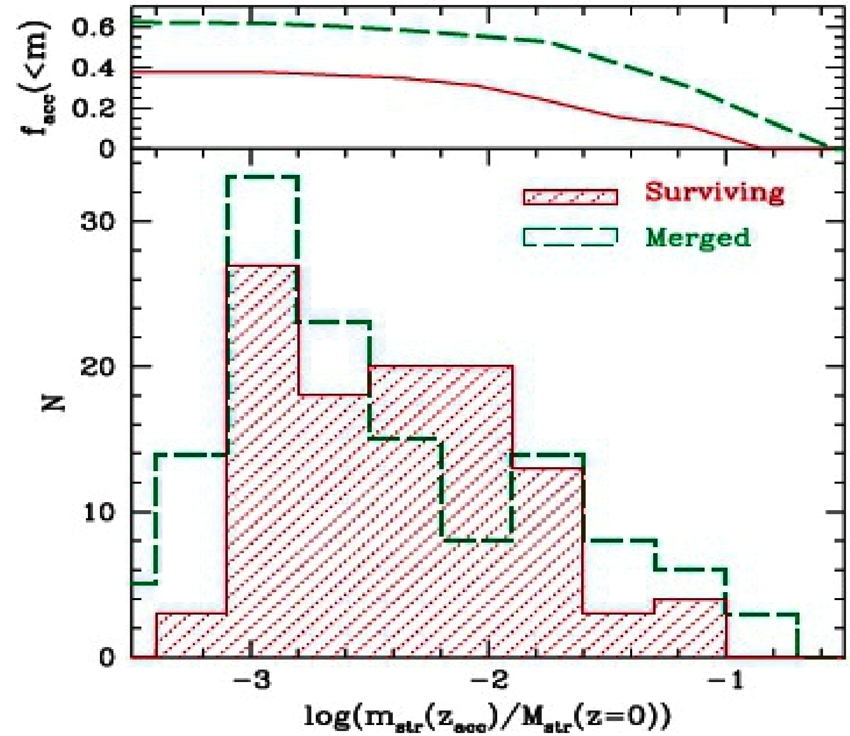
1) Halo built at early epochs, lookback times of 9-10 Gyr

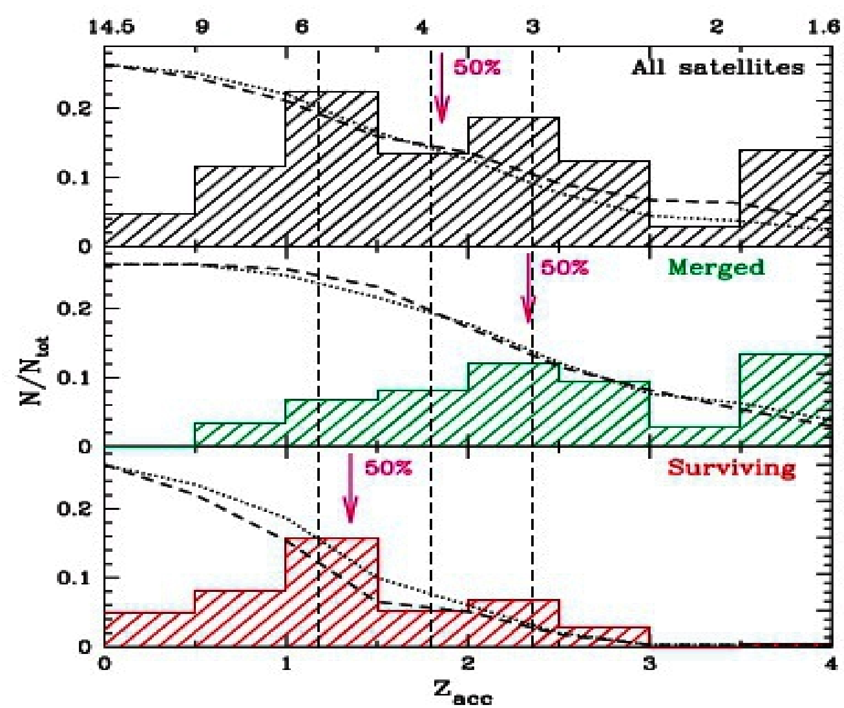
2) Most of halo mass comes from the disruption of a more massive satellite

3) Surviving satellites are accreted late (4-5 Gyr ago)

Sales et al 2007: Statistics of disrupted and surviving satellites in the halo

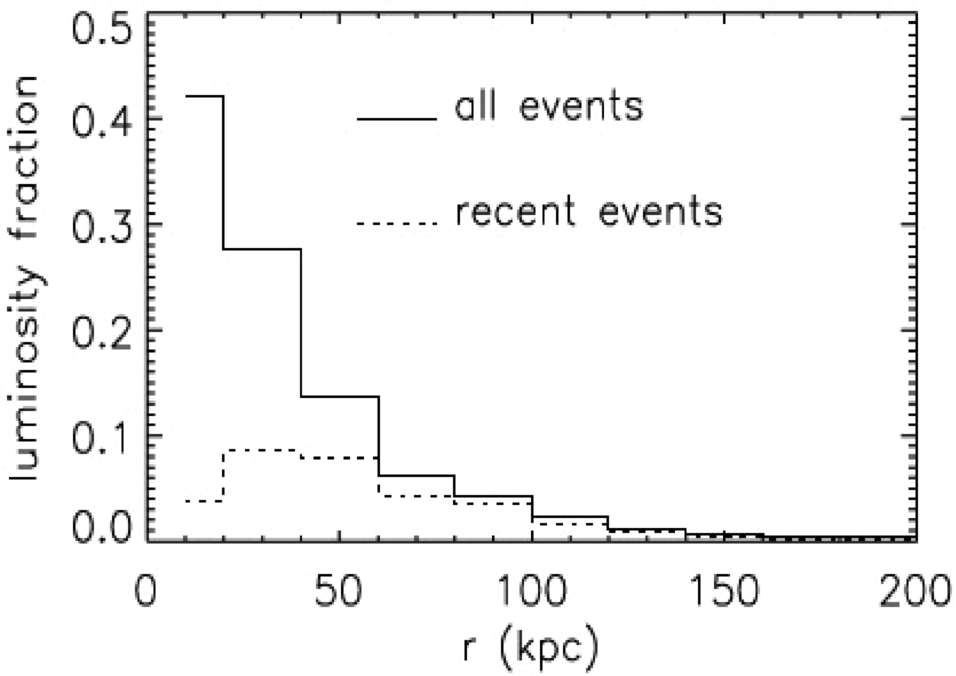


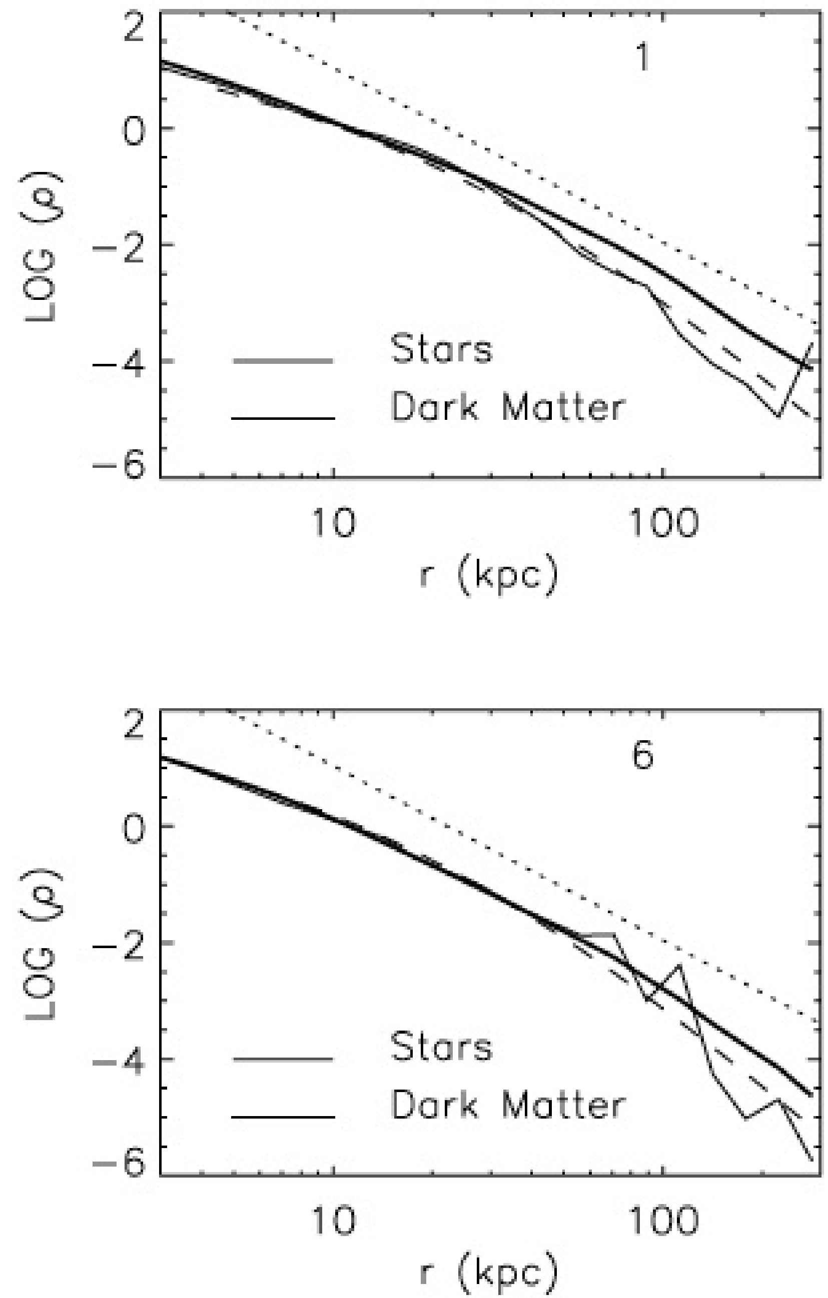




Predicted stellar density profiles well-fit by a Hernquist profile: slope -3 to -4.

Outer halo built more recently than inner halo





Complex phase-space structure, particularly in outer halo, where the signatures of more recent accretion events clearly visible as streams

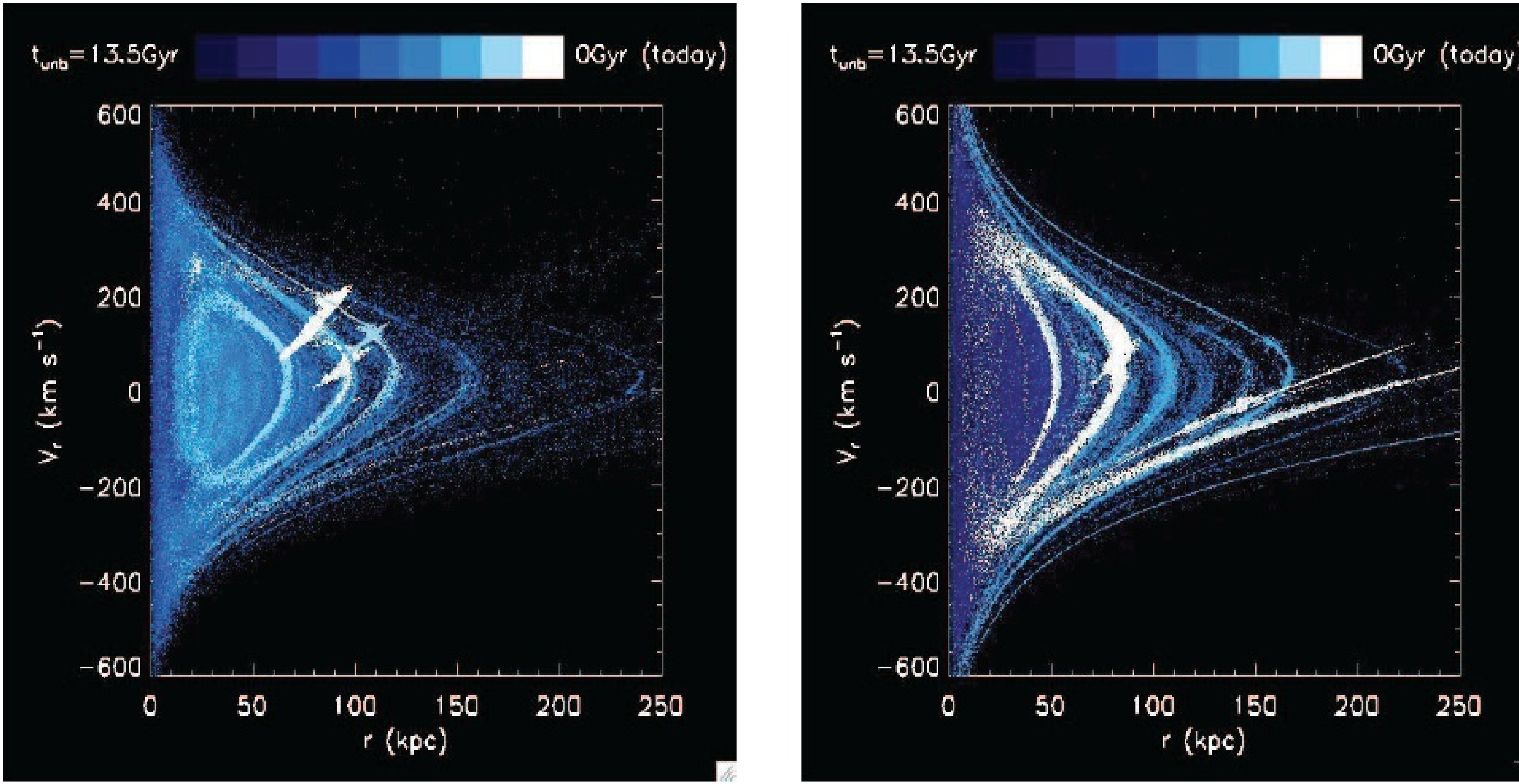
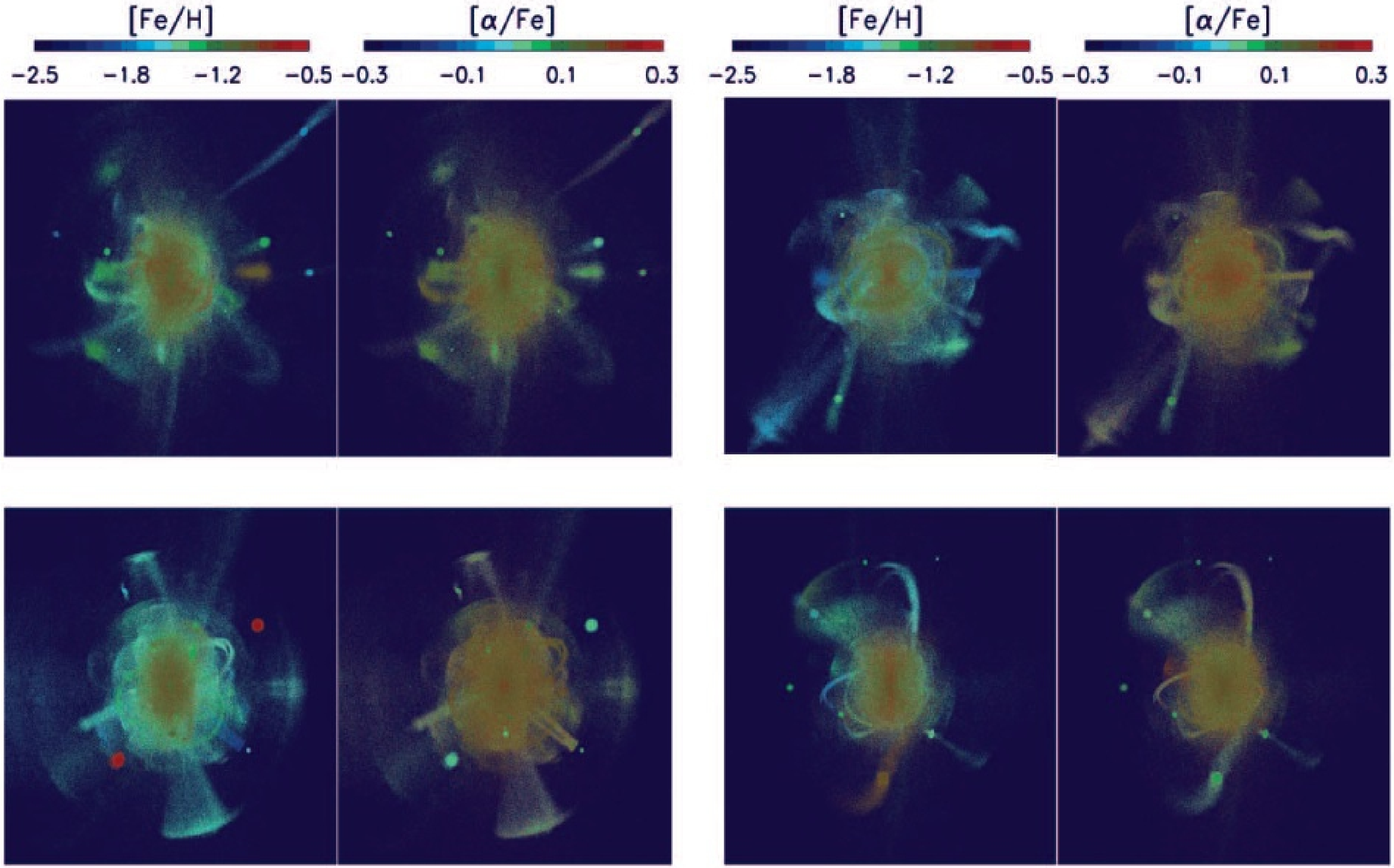


FIG. 15.—Radial phase-space diagrams (V_r vs. r relative to the host halo center) for halos 1 (*left*) and 9 (*right*). Each point represents 1000 solar luminosities. The color code reflects the time each particle became unbound to its parent satellite. White points are either bound or became unbound in the last 1.5 Gyr, while dark blue points became unbound more than 12 Gyr ago. The radial color gradient reflects the tendency for inner halo stars to be accreted (and stripped) early in the Galaxy's history. The white feature at $r \sim 80$ kpc in halo 9 represents a very recent disruption event—the most recent massive disruption seen in our ensemble of 11 halo realizations.

Metallicity and element abundance ratios studied in detail in two follow-on papers by Font et al 2006



Models predict flat metallicity and element abundance ratio gradients for most systems

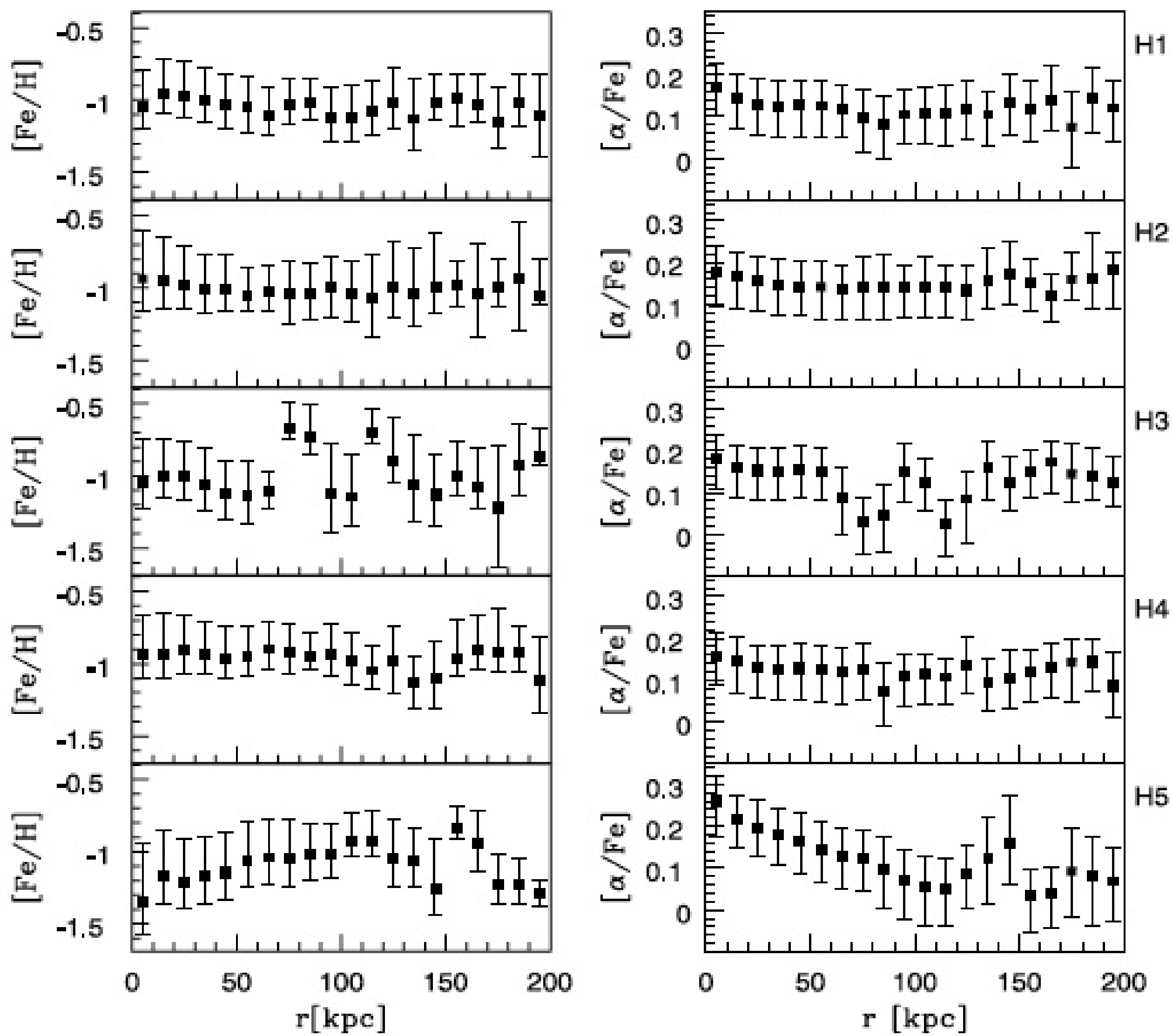
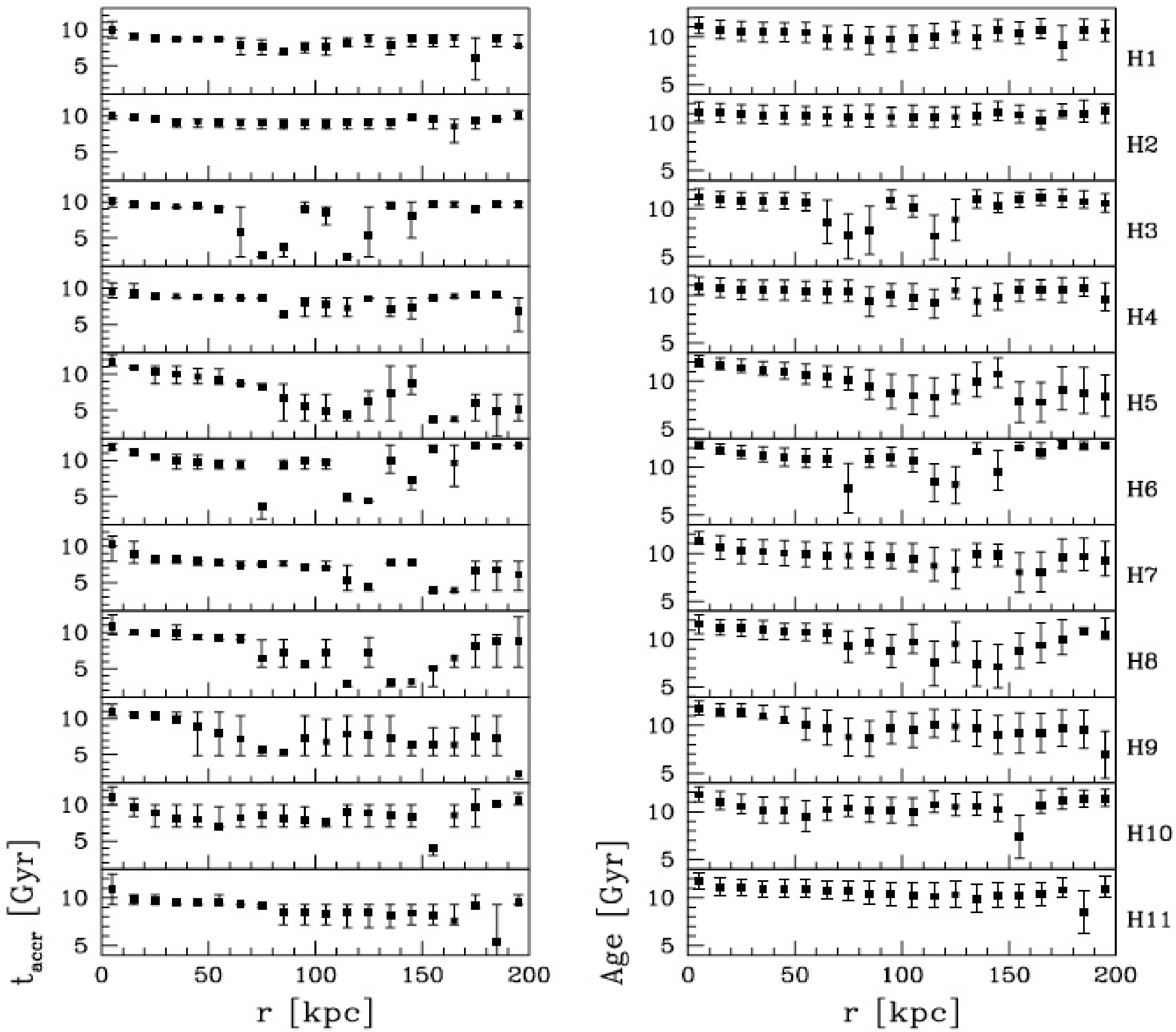


FIG. 5.—Radial distributions of [Fe/H] (*left*) and [α/Fe] (*right*) for halos H1–H5 (*top to bottom*). The chemical abundances are weighted averages in radial shells of width $dr = 10$ kpc. Error bars represent weight-averaged 25% and 75% values of the absolute spread in abundance ratios within each radial bin.



This is because most of the halo stars are predicted to have been accreted at early times.

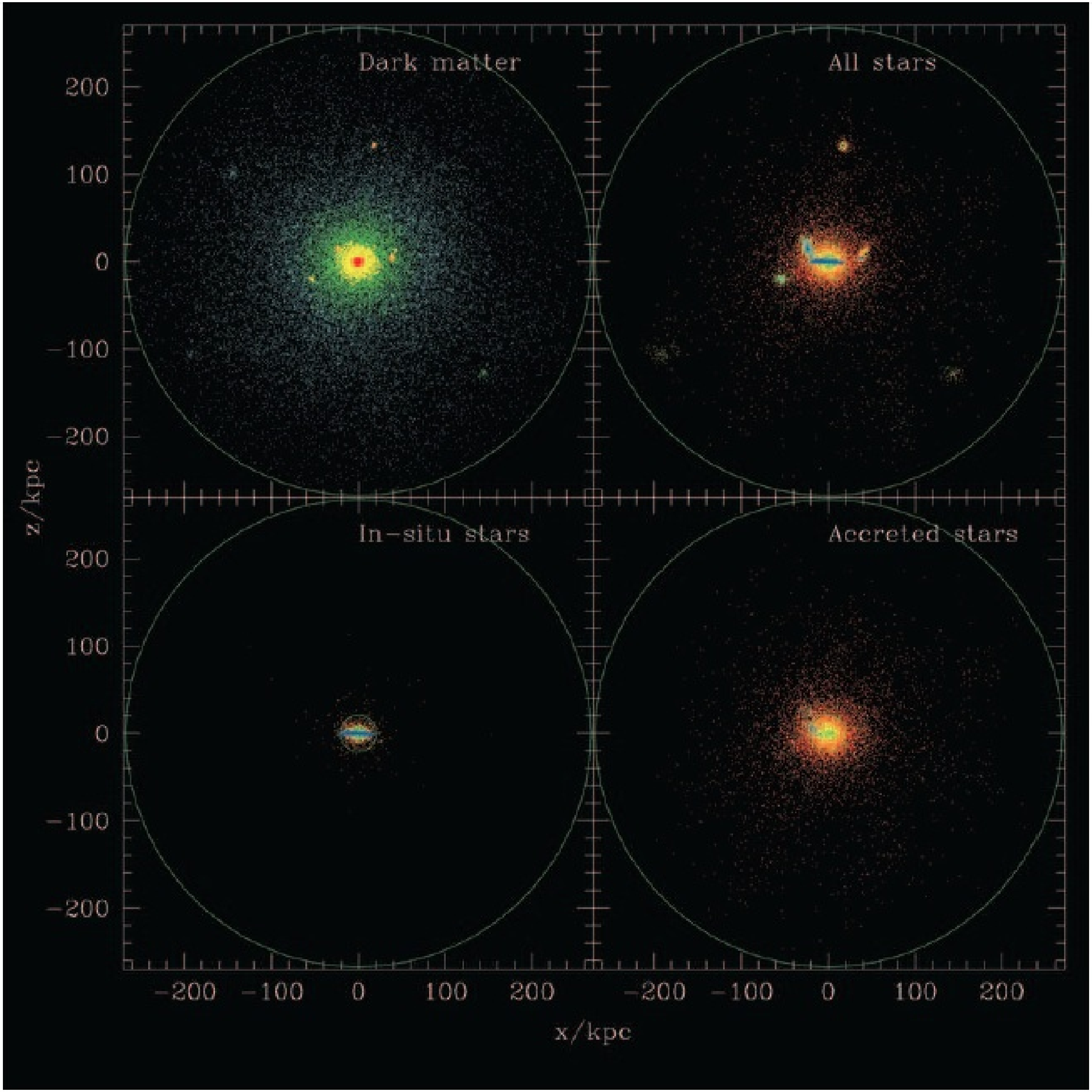
(similar results obtained by De Lucia & Helmi 2008; Cooper at al 2010 using self-consistent N-body+SAMS)

Stars beyond galaxies: the origin of extended luminous haloes around galaxies (2006)

Mario G. Abadi,[1★†] Julio F. Navarro,[1,2‡] and Matthias Steinmetz[3]

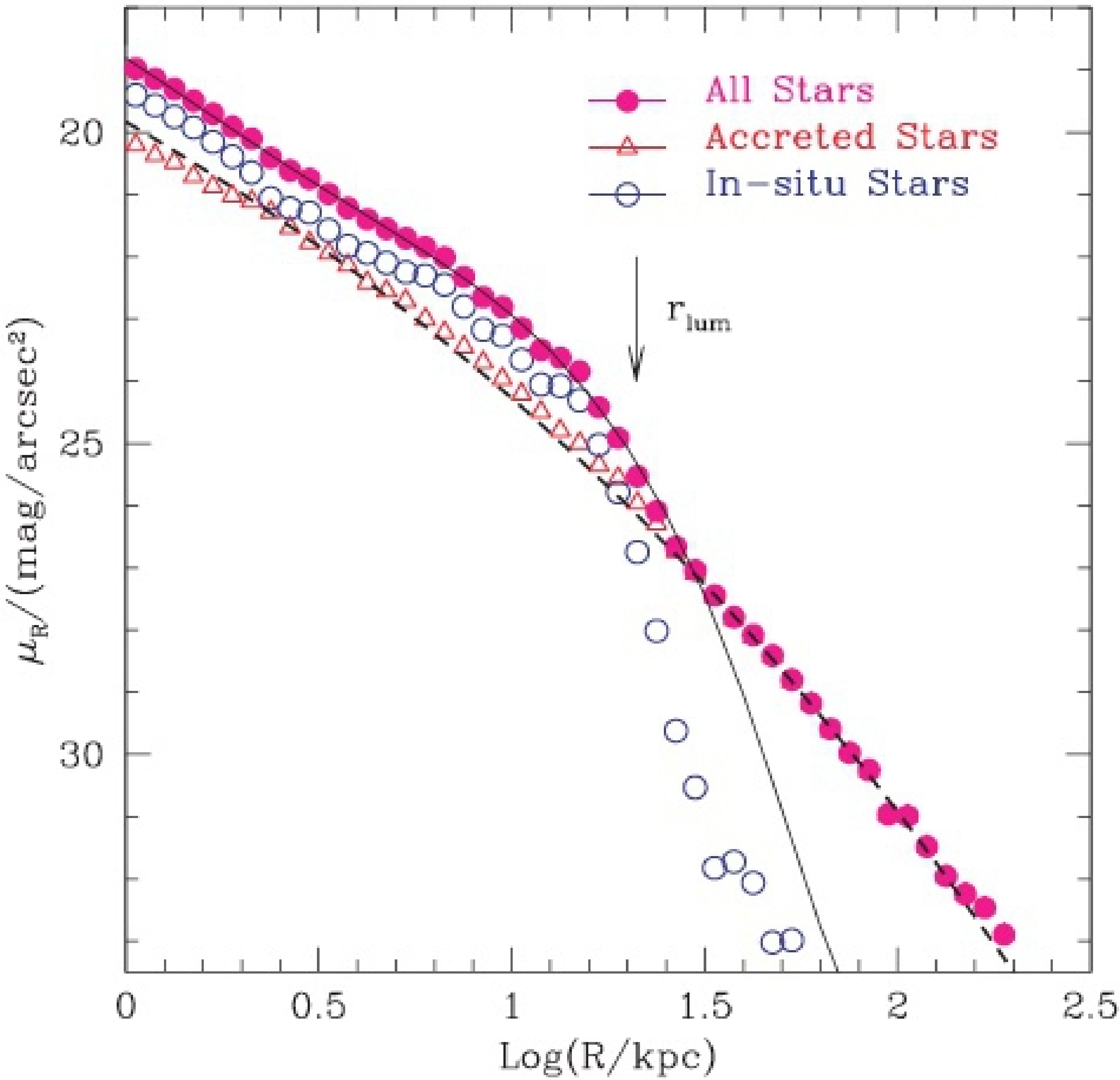
ABSTRACT

We use numerical simulations to investigate the origin and structure of the luminous haloes that surround isolated galaxies. These stellar structures extend out to several hundred kpc away from a galaxy, and consist of stars shed by merging subunits during the many accretion events that characterize the hierarchical assembly of galaxies. Such an origin suggests that outer luminous haloes are ubiquitous and that they should appear as an excess of light over extrapolations of the galaxy's inner profile beyond its traditional luminous radius. The mass profile of the accreted stellar component is well approximated by a model where the logarithmic slope steepens monotonically with radius; from $\rho \propto r^{-3}$ at the luminous edge of the galaxy to r^{-4} or steeper near the virial radius of the system. Such spatial distribution is consistent with that of Galactic and M31 globular clusters, suggesting that many of the globulars were brought in by accretion events, in a manner akin to the classic Searle–Zinn scenario. Luminous haloes are similar in shape to their dark matter counterparts, which are only mildly triaxial and much rounder than dark haloes formed in simulations that do not include a dissipative luminous component. The outer stellar spheroid is supported by a velocity dispersion tensor with a substantial and radially increasing radial anisotropy: from $\sigma_r^2/\sigma_t^2 \sim 2$ at the edge of the central galaxy to $\sim$5 at the virial radius. These properties distinguish the stellar halo from the dark matter component, which is more isotropic in velocity space, as well as from some tracers of the outer spheroid such as satellite galaxies.



Introduced the concept of the "in situ" stellar halo

1. In situ stars dominate over accreted stars at R < 30 kpc
2. Two mode halo leads to break in surface brightness profile
3. Fitted double Sersic laws to profile



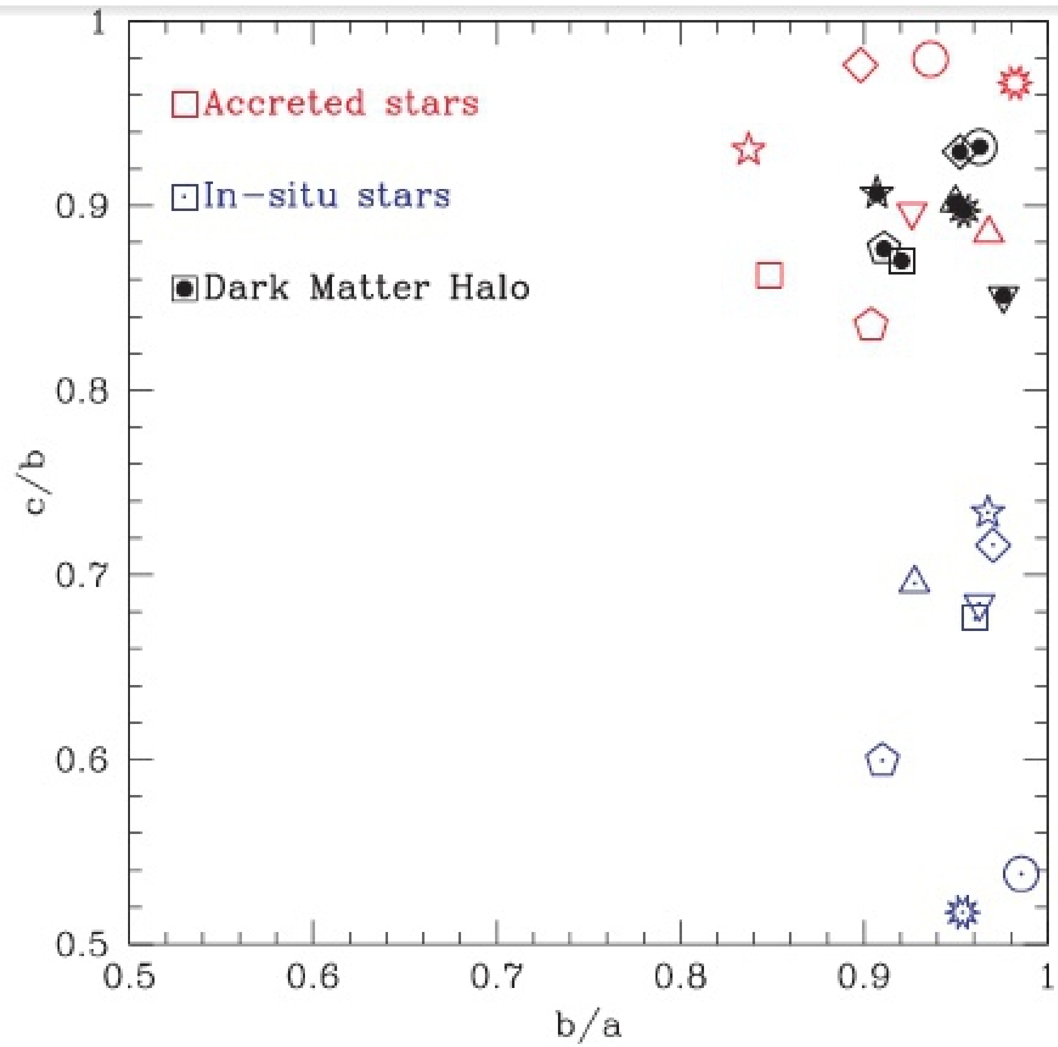
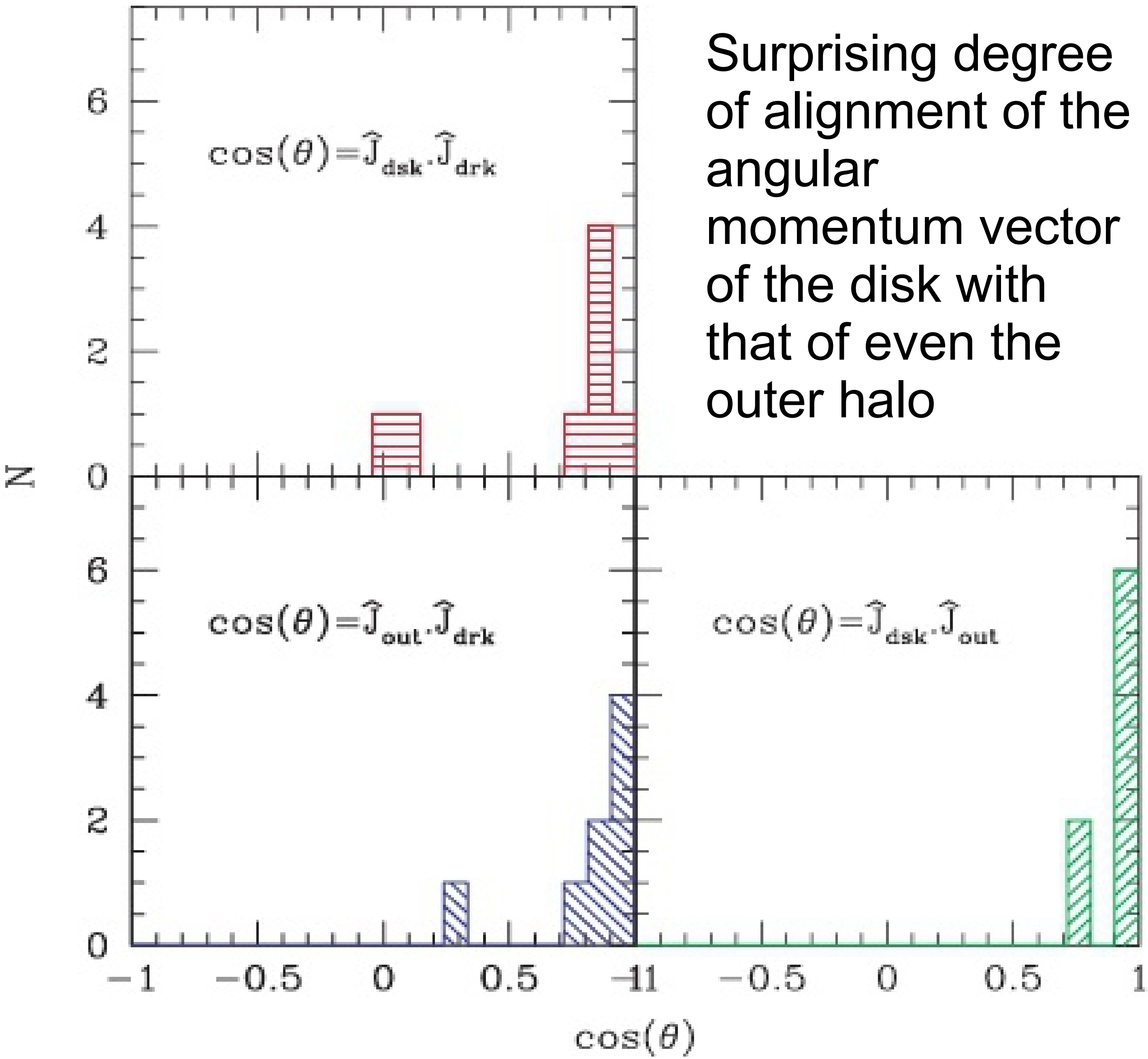


Figure 7. Inertia axial ratios of the dark matter halo, as well as of the accreted and *in situ* stellar components. Axial ratios are computed by diagonalizing the inertia tensor $I_{ij} = \sum m_i x_i x_j$ for all particles of each component within the virial radius of the system. Note that the shapes of the dark matter and accreted components are similar and only mildly triaxial, but that the *in situ* stars are predominantly oblate. This reflects the fact that *in situ* stars have a higher proportion of newly formed stars, which tend to arrange themselves in a disc-like structure (see Fig. 1).

Accreted stars and dark matter halo have axis ratios consistent with PROLATE ellipsoids.

In situ stars in halo are OBLATE



Surprising degree of alignment of the angular momentum vector of the disk with that of even the outer halo

McCarthy et al 2012 study of halo structure and kinematics using GIMIC hydrodynamic simulations

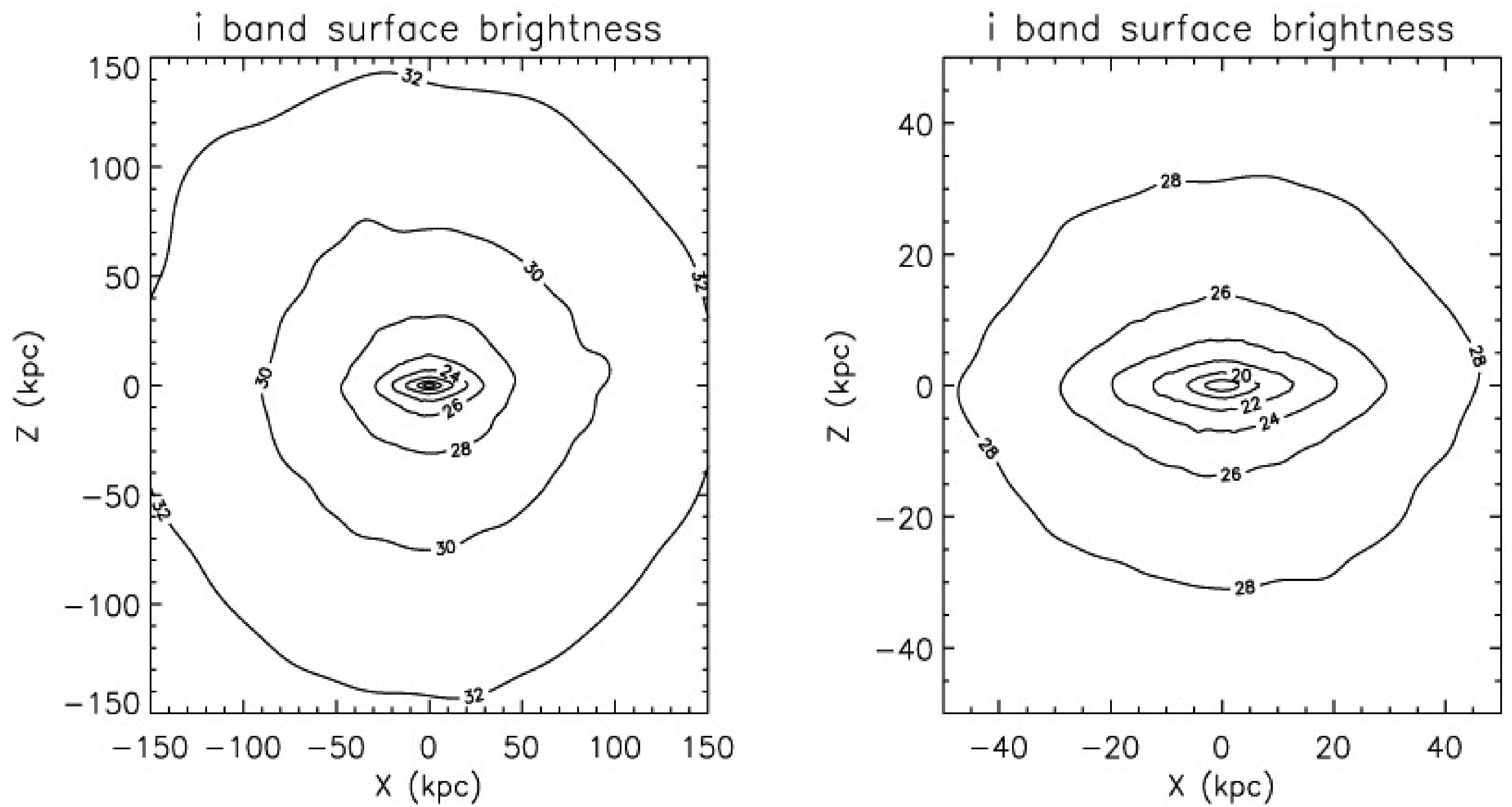


Figure 5. Stacked SDSS *i*-band surface brightness contour maps of the simulated galaxies. The galaxies are rotated to an edge-on configuration before stacking. Self-gravitating substructures (satellites) have been excised and the map has been heavily smoothed using an SPH kernel (see text for details). The numbers associated with the contours give the mean surface brightness in mag arcsec^{-2}. Left: large-scale view. Right: zoom-in on the central regions. Note the stellar disc is generally confined to $|Z| < 2$ kpc. It is readily apparent that the spheroid shows a significant degree of flattening, particularly in the inner regions ($r \lesssim 40$ kpc).

Clear rotation signatures are seen out to R> 50 kpc (McCarthy et al 2012)

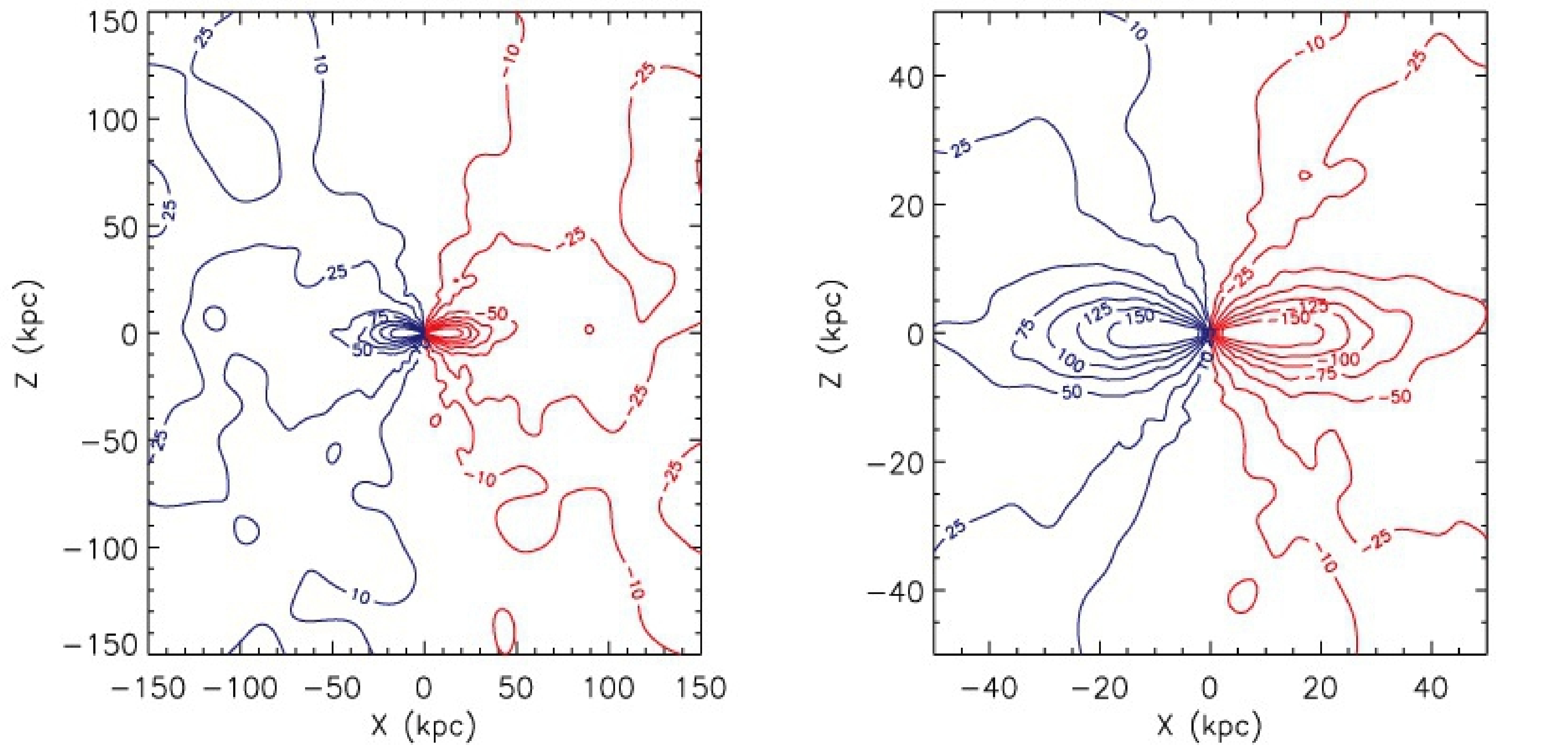


Figure 9. A stacked line-of-sight (v_y) velocity contour map. All 412 simulated galaxies have been rotated to an edge-on configuration before stacking. Red contours indicate motion away from the observer, whereas blue contours indicate motion towards the observer. The numbers associated with the contours give the line-of-sight velocity in km s^{-1}. Left: large-scale view. Right: zoom-in on the central regions. Note that the stellar disc is generally confined to $|Z| < 2$ kpc.

Font et al 2011: GIMIC simulations show clear metallicity gradient in better agreement with M31 observations. Break occurs at transition between in situ and accreted component.

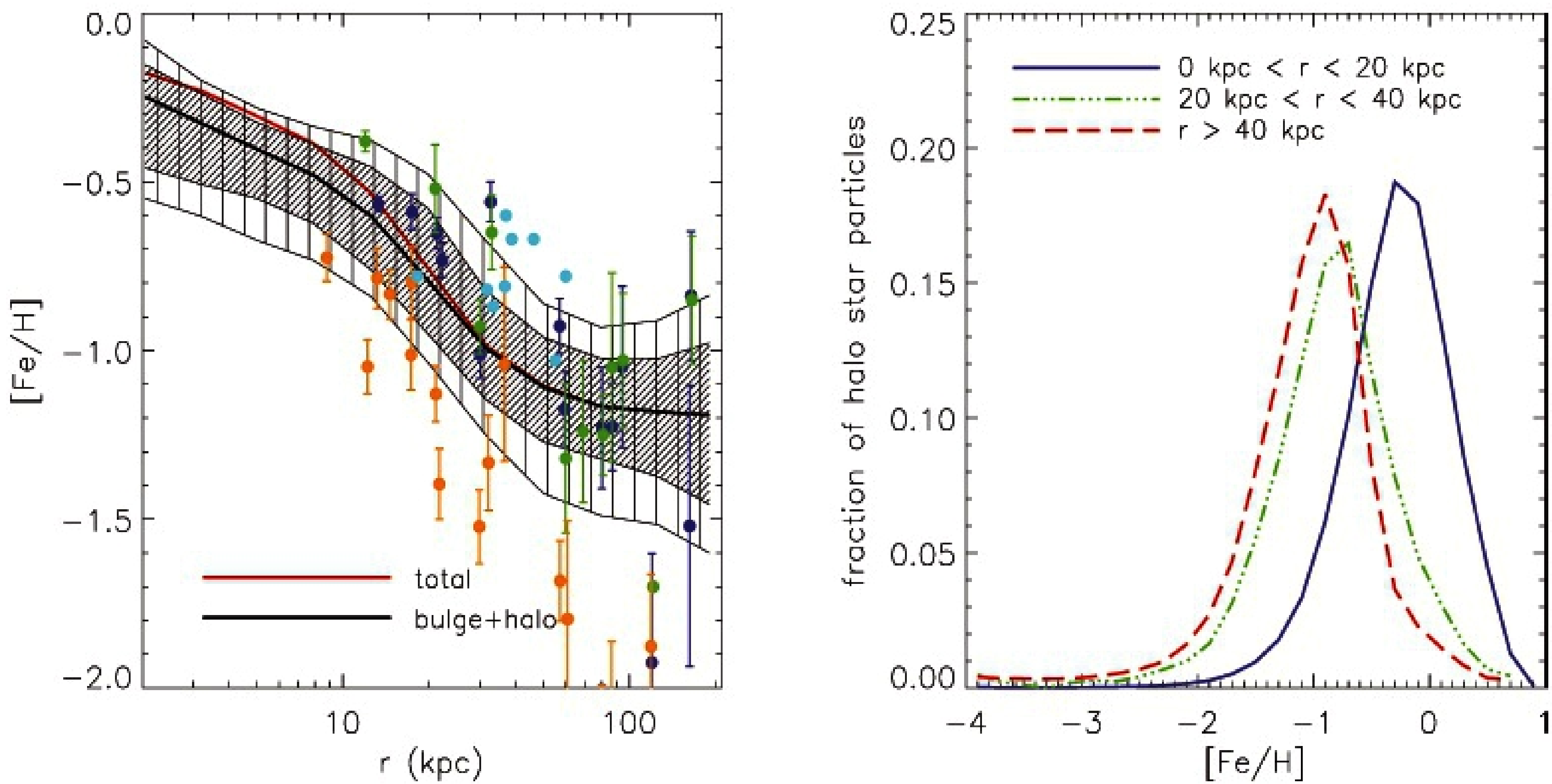


Figure 5. Left-hand panel: median spherically averaged stellar metallicity profiles. The solid red curve is the median stellar metallicity profile for all stars, whereas the solid black curve is the median stellar metallicity profile for just the bulge+halo component. The finely (sparsely) hatched region encloses the 14th and 86th (5th and 95th) percentiles of the stellar halo metallicity profile. The solid blue, green, cyan and orange circles represent M31 metallicity measurements of Gilbert et al. (2009a), Kalirai et al. (2006), Richardson et al. (2009) and Koch et al. (2008), respectively. The observational data have been scaled to the same set of solar abundances. Right-hand panel: median MDF in three radial bins. Significant negative metallicity gradients are a ubiquitous feature of the simulated galaxy populations.

What is the origin of the "in situ" halo?

Purcell & Bullock 2010 proposed that the disk was heated by accretion events based on idealized N-body experiments.

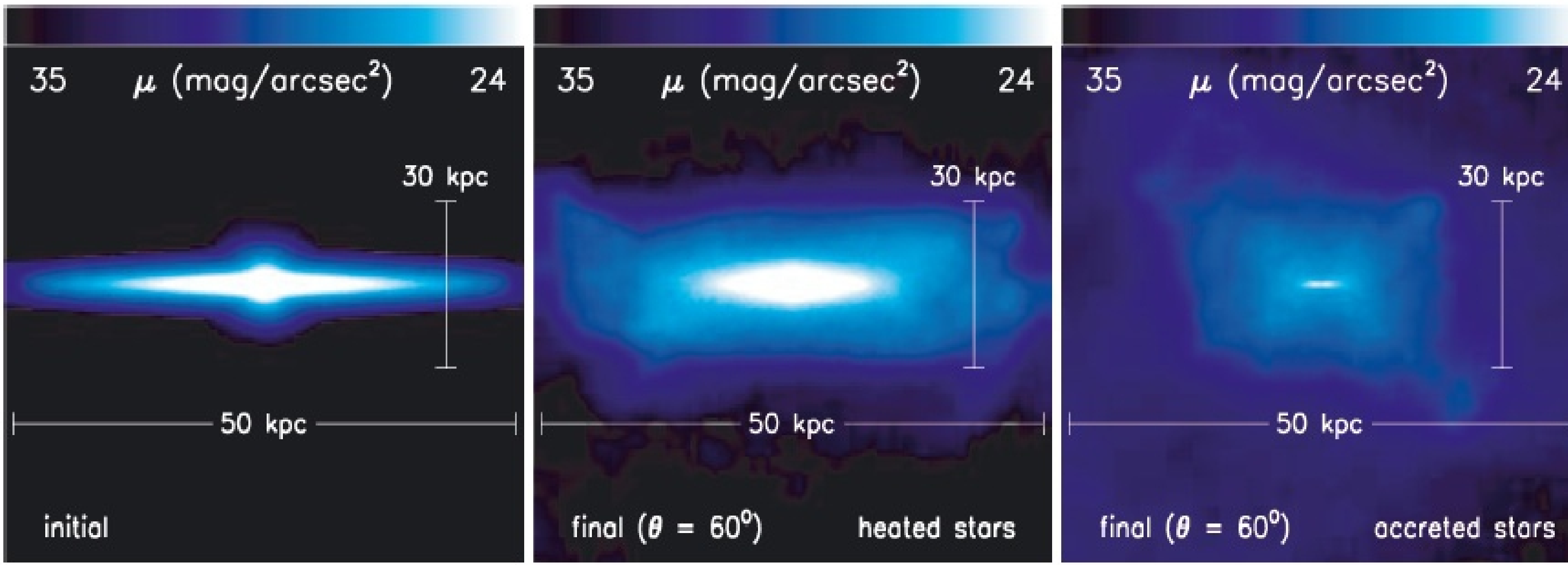
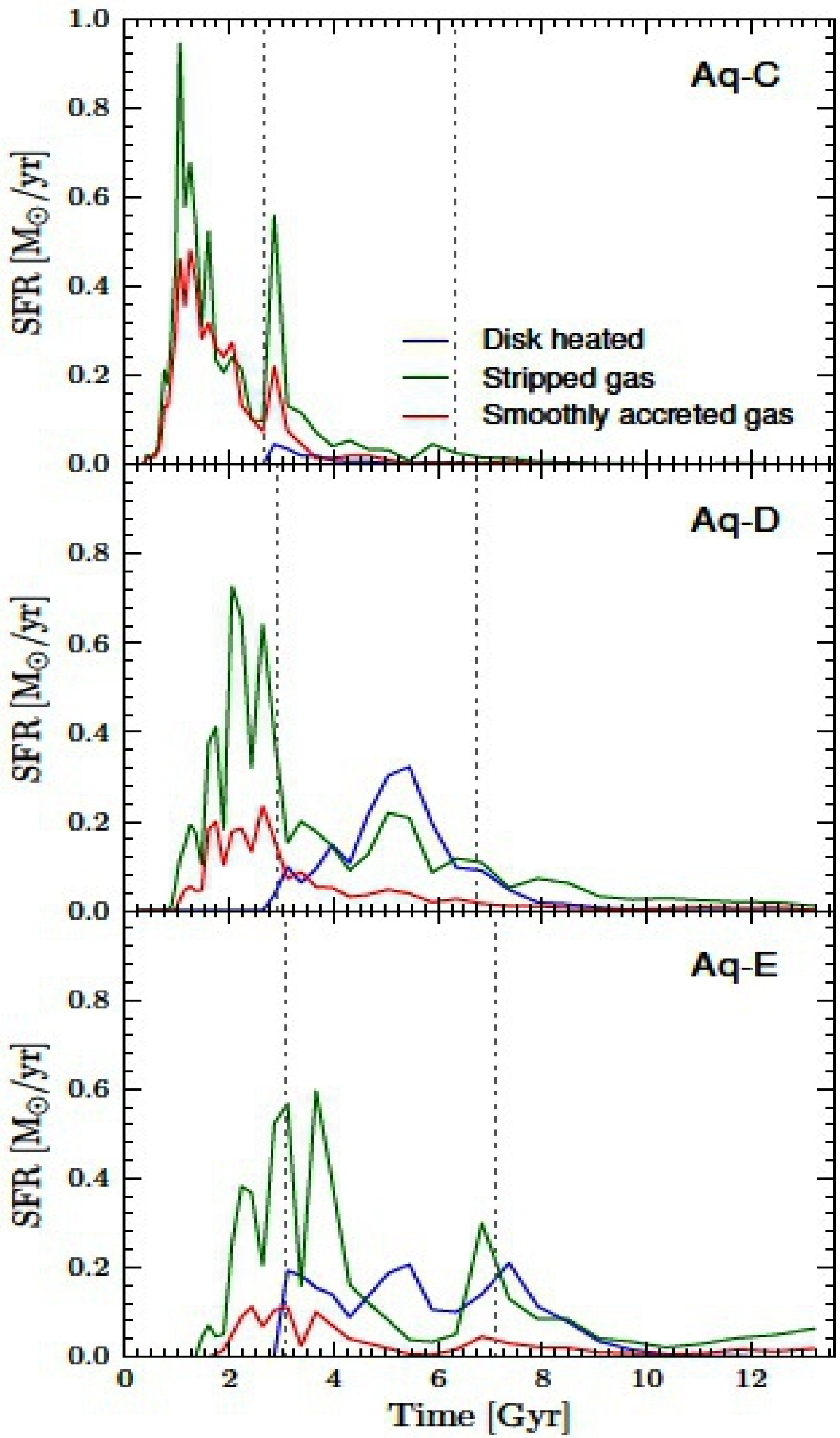


Figure 1. Surface brightness maps of our primary system, viewed edge-on: the initial model is visualized in the left-hand panel, while the centre panel shows only stars belonging to the primary galaxy following the prograde infall with an orbital inclination of 60° and the right-hand panel subsamples the accreted stars only. In all cases, surface densities have been converted into surface brightnesses using a stellar-mass-to-light ratio $M_{\star}/L = 3$; note that the brightness limits have been chosen in order to accentuate stellar halo substructure at the expense of saturating the galactic disc region.



Recent careful study by Cooper et al 2015 divides “in situ” halo into 3 categories of origin:

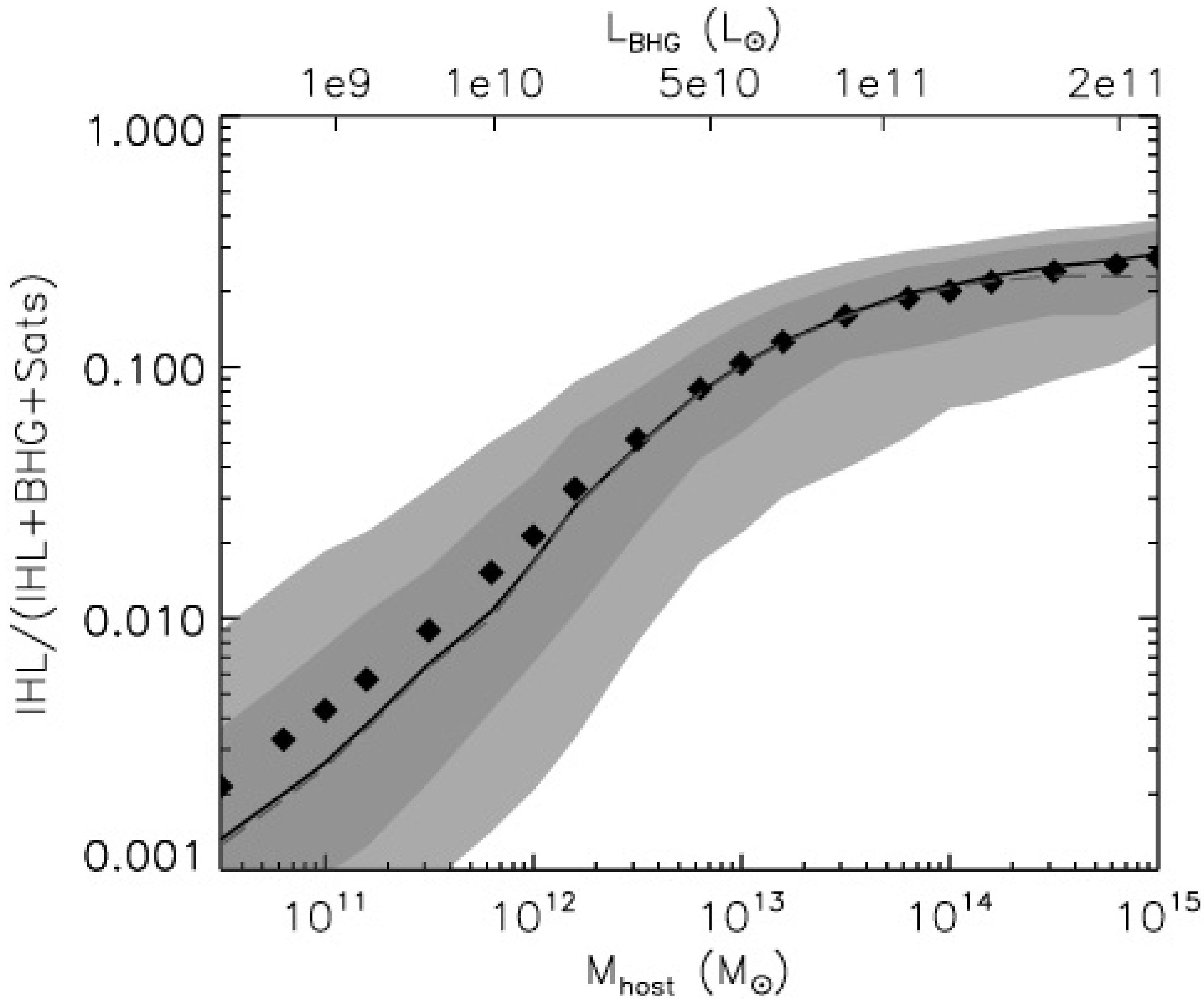
(i) ‘heated disc’ stars, which met the thin disc circularity criterion when they were formed, but are not in the disc at $z = 0$;

(ii) stars formed from ‘stripped gas’, brought into the main dark matter halo bound to a subhalo and subsequently stripped by tidal forces or ram pressure;

(iii) stars from ‘smoothly acccreted gas’, which enters the main dark matter halo through direct (smooth) accretion.

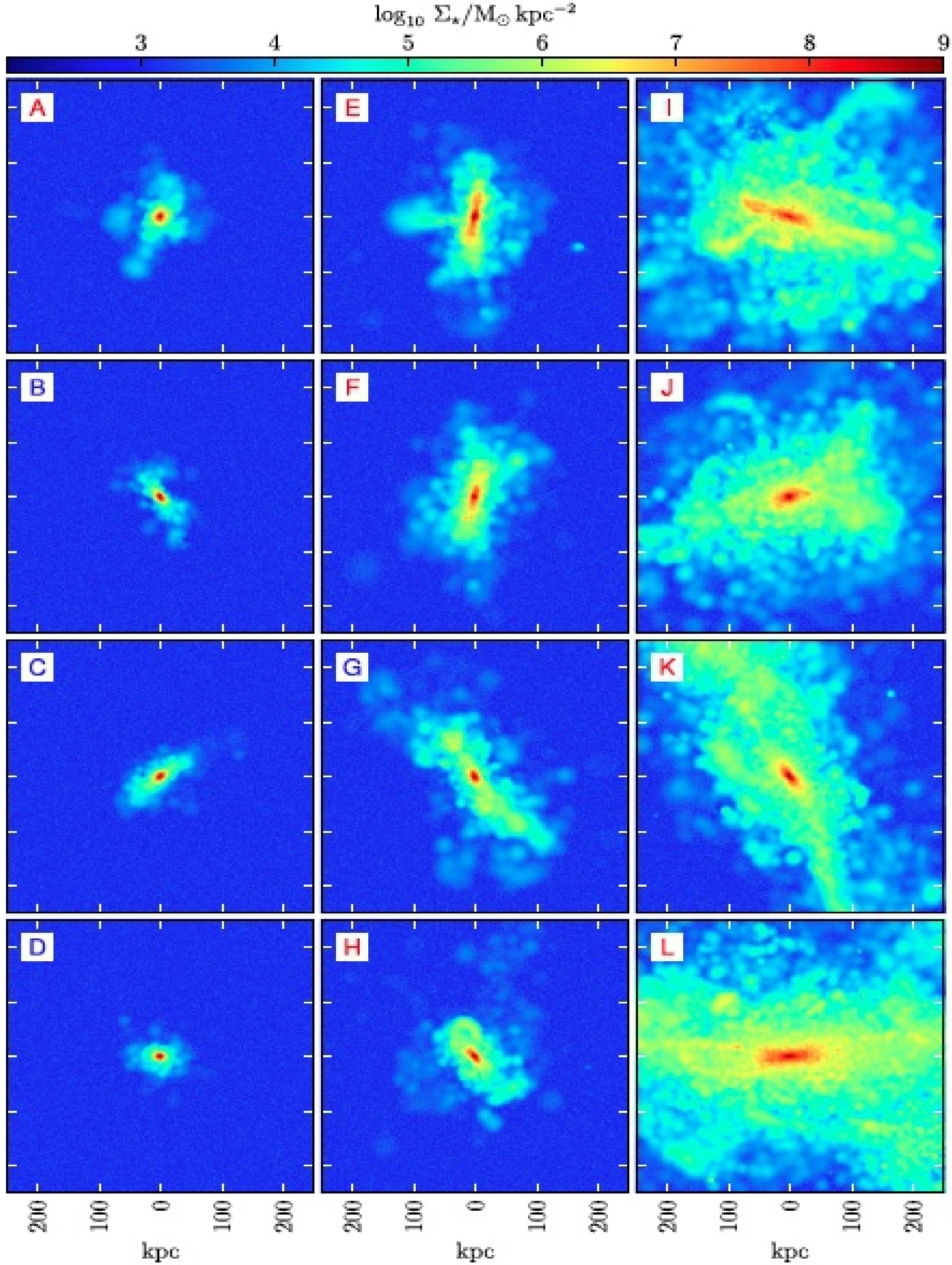
“Heated disk” stars in the minority

Beyond the Milky Way: Halo properties of galaxies across a wide mass range



Purcell et al 2007:

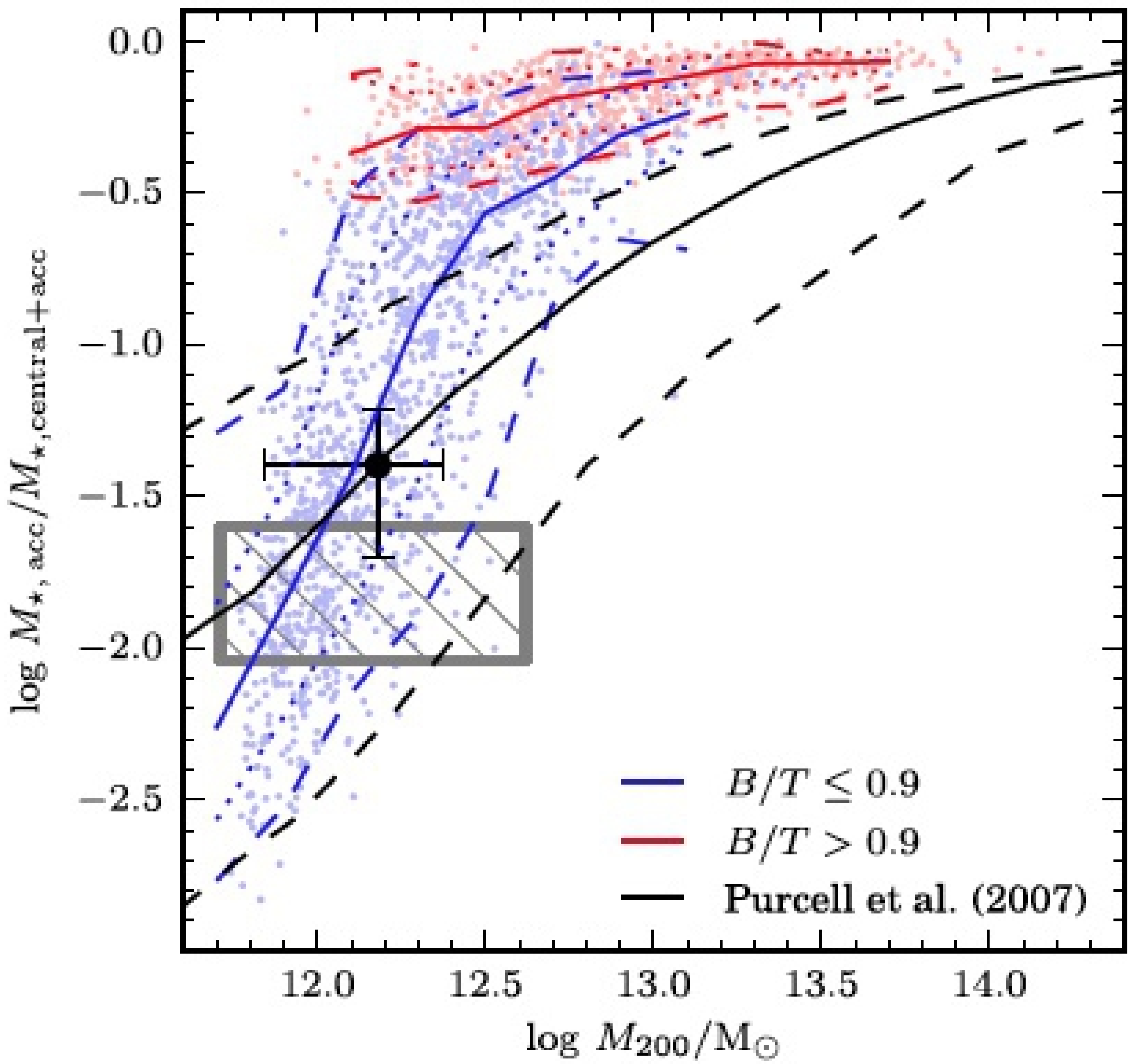
Fraction of mass in accreted component expected to increase strongly with halo mass.



Results from hybrid N-body + SAMS modelling of Cooper et al 2013, applied to Millennium II simulations

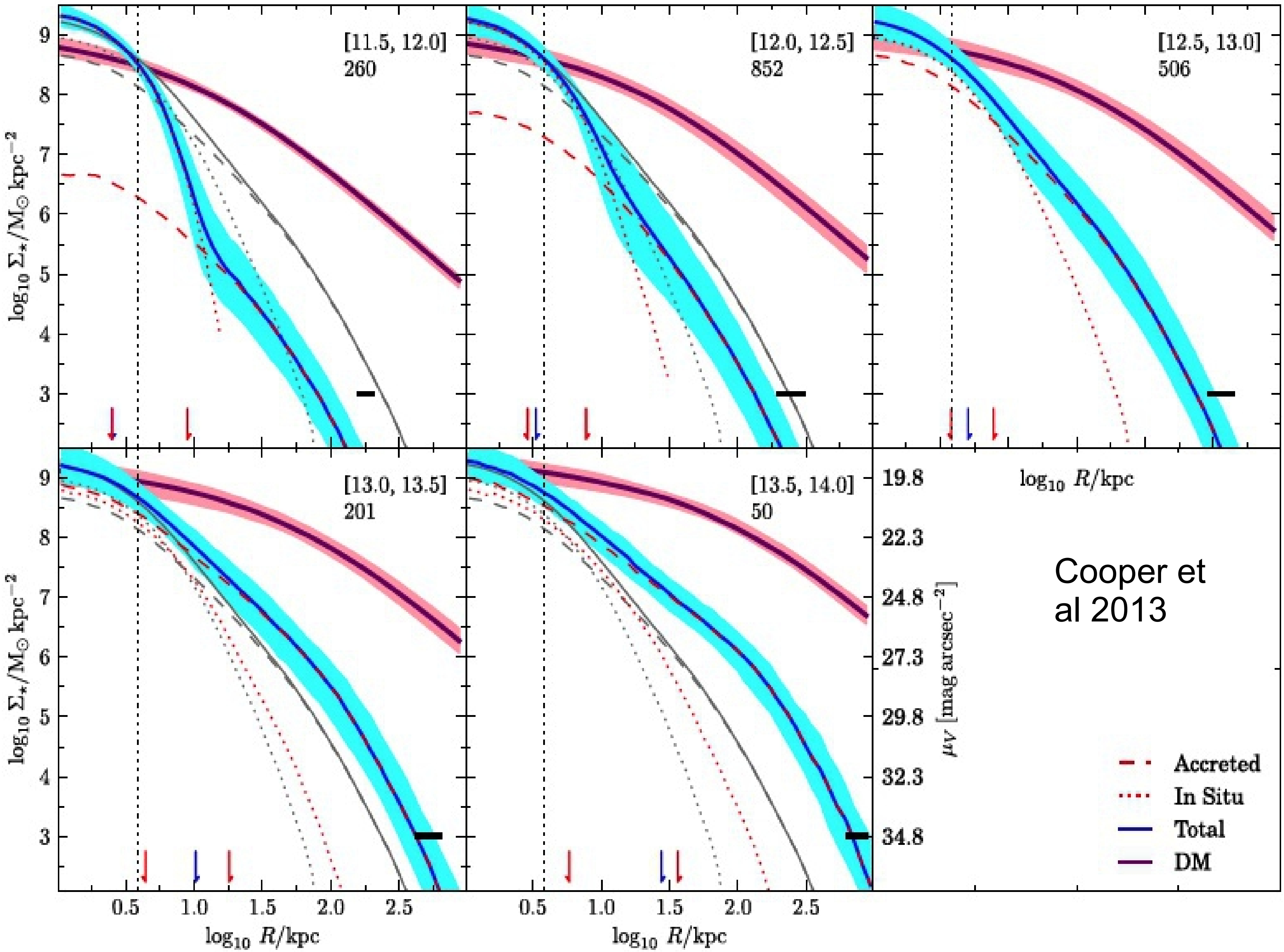
Models are tied to the Guo et al 2011 SAMS, which produce excellent fits to z=0 stellar mass function, colour/luminosity relation, clustering properties.

Cooper et al 2013

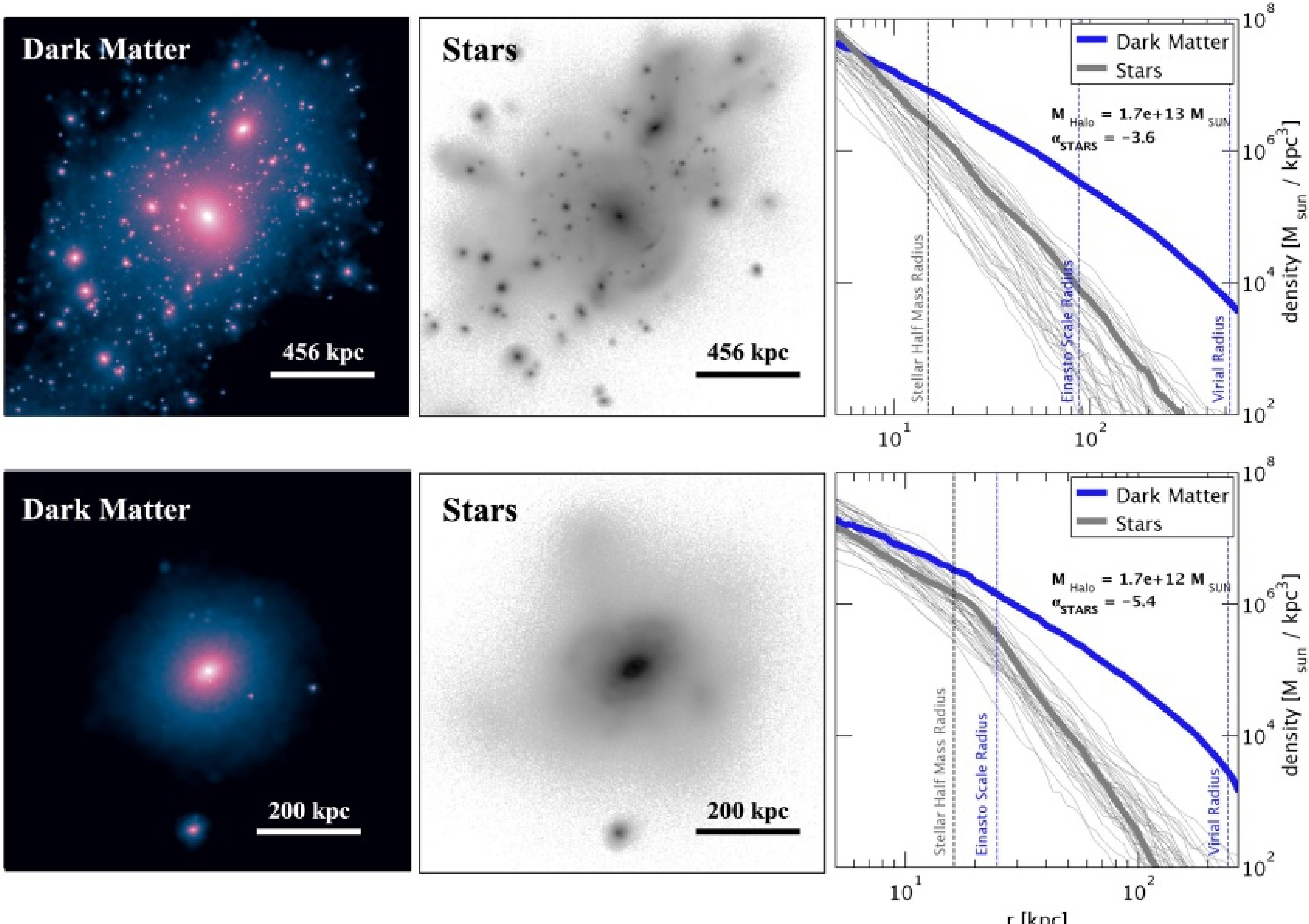


Qualitatively similar results to Purcell et al 2007; quantitative differences in the predictions.

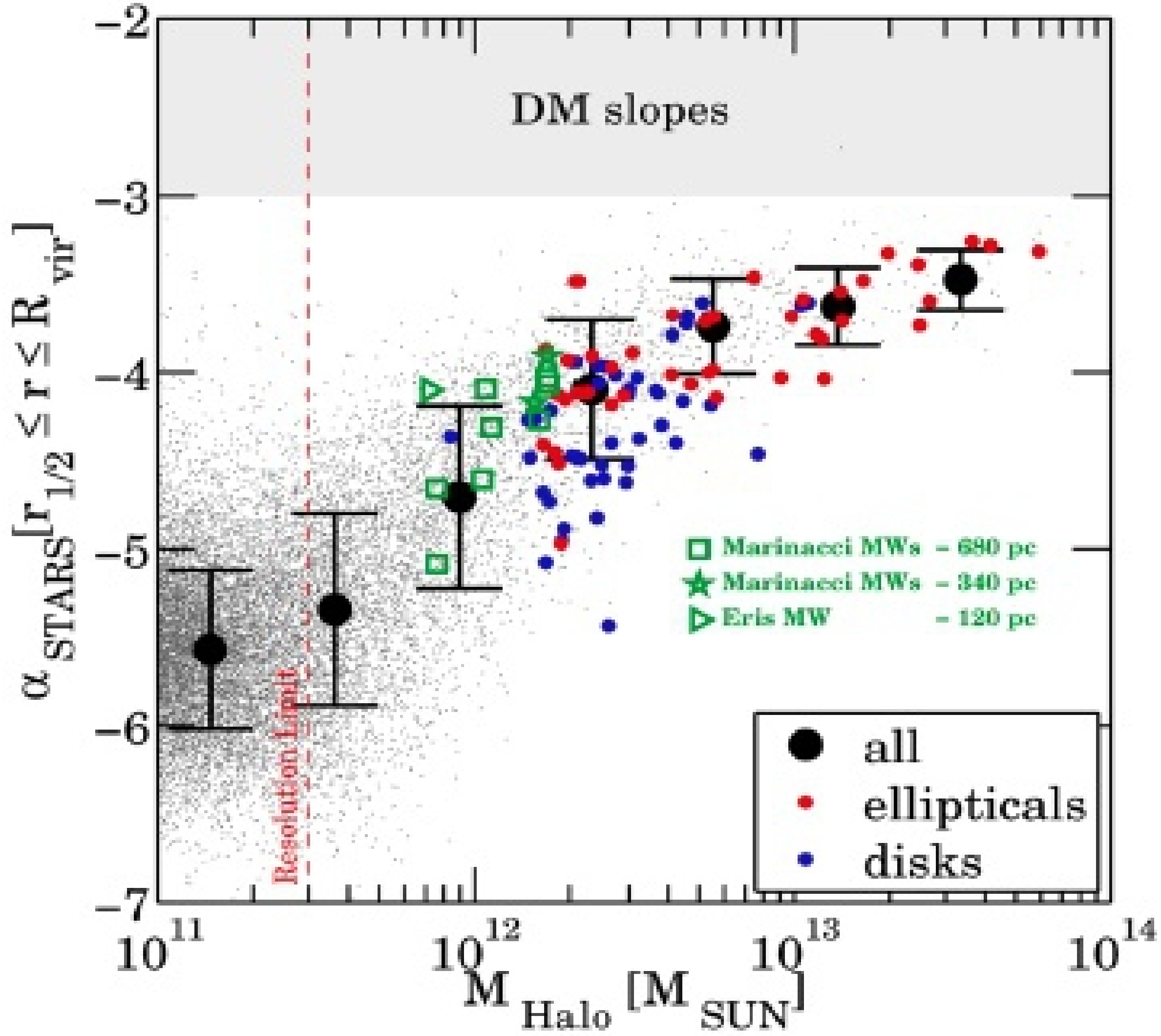
Systematic change in predicted stellar density profiles as a function of halo mass – caused by increasing dominance of accreted component.



Confirmed by Pillepich et al 2014 study using ILLUSTRIS simulations



Slope of outer accreted component as a function of halo mass (Pillepich et al 2014)



What about dwarf galaxies?

Accreted component is tiny, but halos could be formed from heated stars....(Maxwell et al 2012)

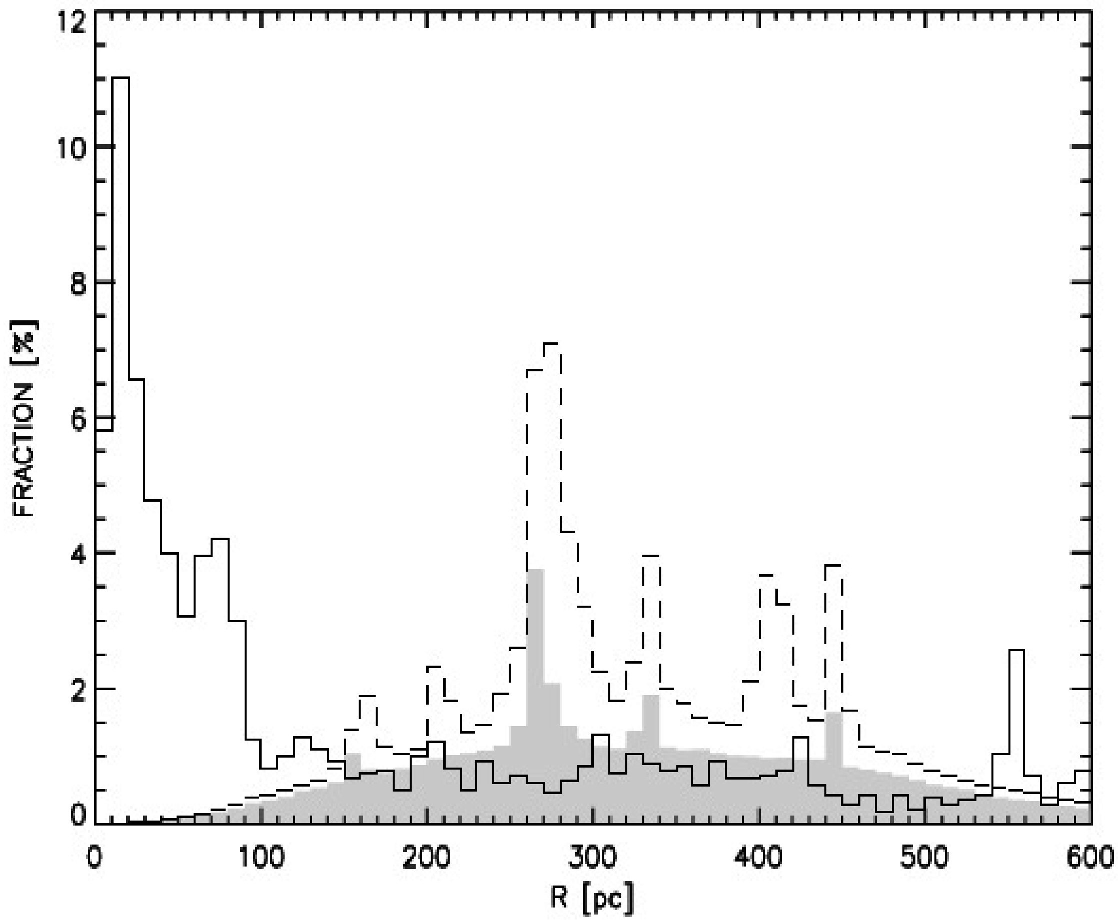
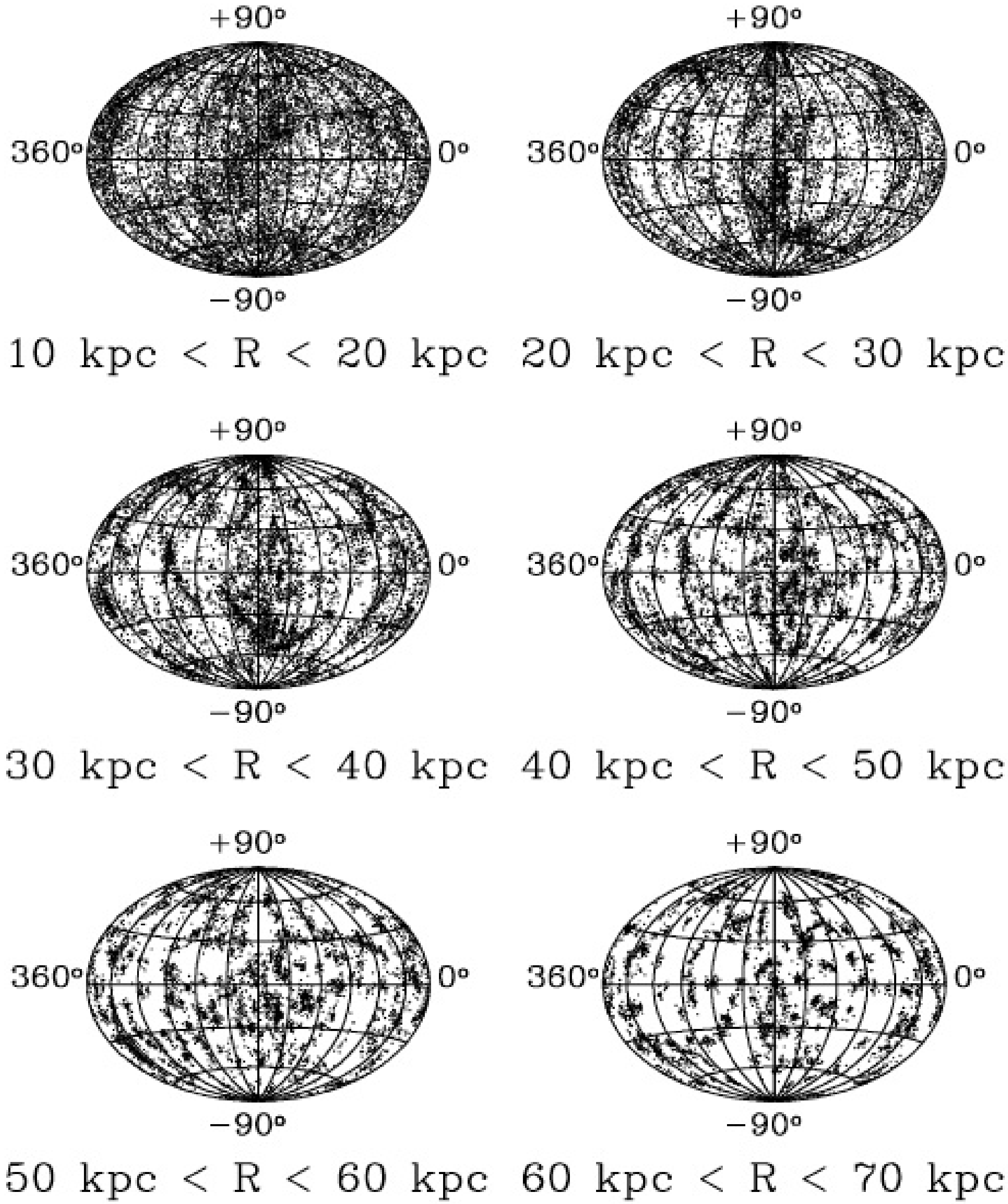
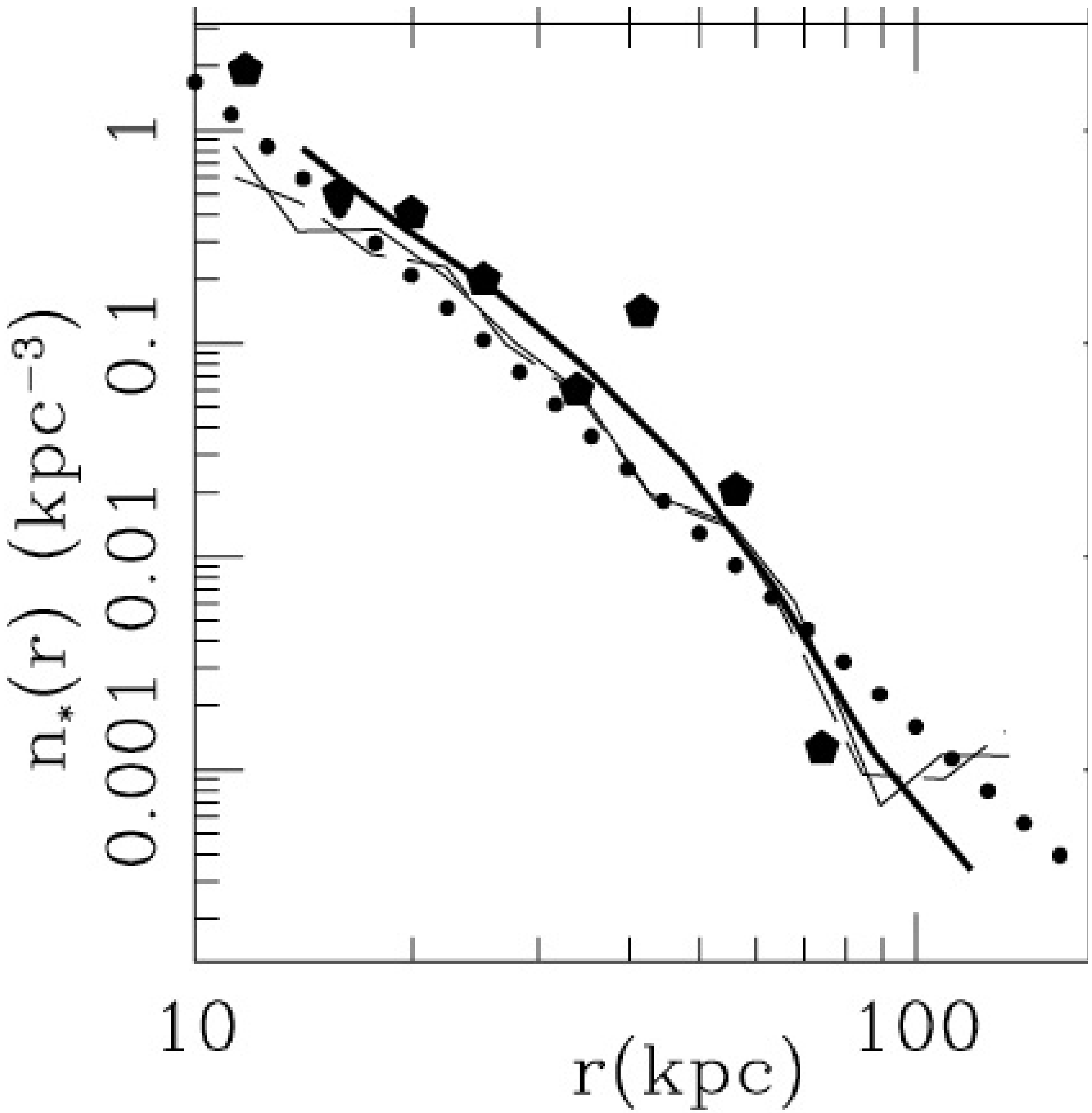


Figure 2. Normalized distribution of the stellar formation radius (solid) and the final stellar radius (dashed). The shaded region corresponds to the distribution of final radii for the stars that formed within 100 pc.

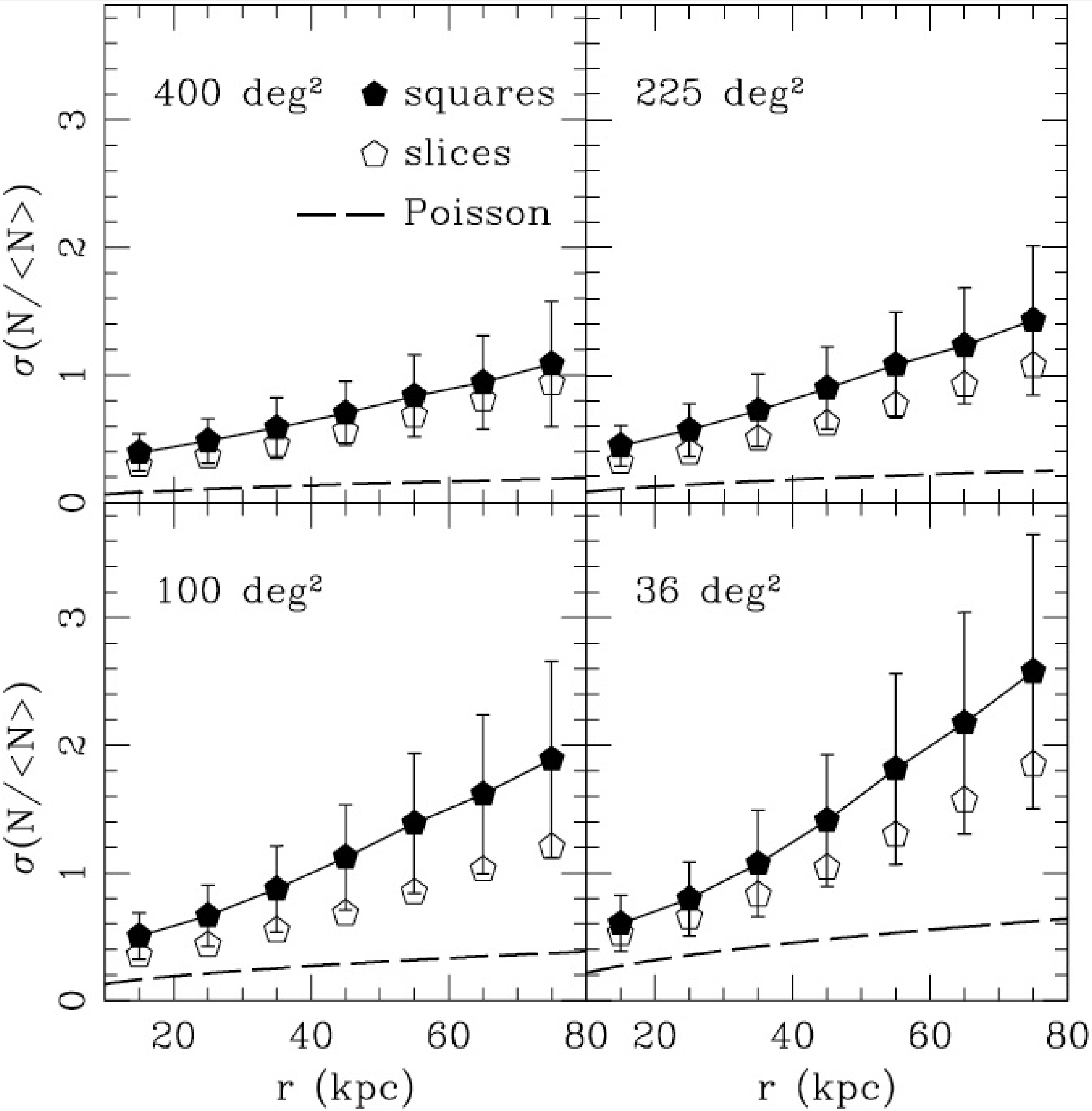
HALO SUBSTRUCTURE



In 2001, Bullock et al made mock maps of RR Lyrae stars from the galactic halo for comparison with available SDSS data



Demonstrated model could reproduce star count density as a function of distance.



Predictions for rms fluctuation in counts as function of scale and distance

FUTURE ROUTES FOR MODELS

1) More systematic analysis of galaxy halos as a function of mass, galaxy type, environment using large simulations : Shapes, kinematics, stellar populations

2) Quantification of substructure –methodology depends on type of data to be compared with.

3) The effect of gas dynamics – what the key observational signatures of processes like dynamical disk heating and supernovae feedback for the in situ halo?

4) Growing evidence for AGN feedback in early Universe – is there a fossil record embedded in the stellar populations, structure, kinematics of early-type galaxies?