On the Dynamical Behavior of Brightest Halo Galaxies

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Important Questions

How does galaxy formation depend on environment? Can we relate this to the environmental dependence of dark matter halo formation in cosmological models?

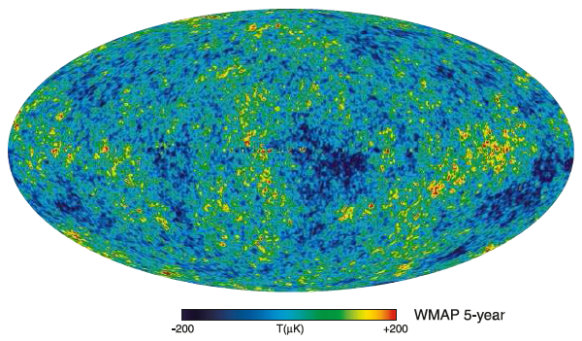
How are galaxies affected by their host halos? What aspects of galaxy formation and evolution can be explained by halo formation and evolution?

How do central galaxies in halos and satellite galaxies in halo substructures evolve differently? Can we explain their dynamical behavior?

Outline

- introduction
  - formation of halos from dark matter
  - growth of large-scale structure
- connecting halos and galaxies, theory and observations
  - analytic and semi-analytic models
  - constraints from abundance and clustering of halos/galaxies
  - complementary tools: group catalogs, mark statistics
- dynamical behavior of 'central' and 'satellite' galaxies
  - are brightest halo galaxies central galaxies?
  - are brightest halo galaxies always at the halo center?

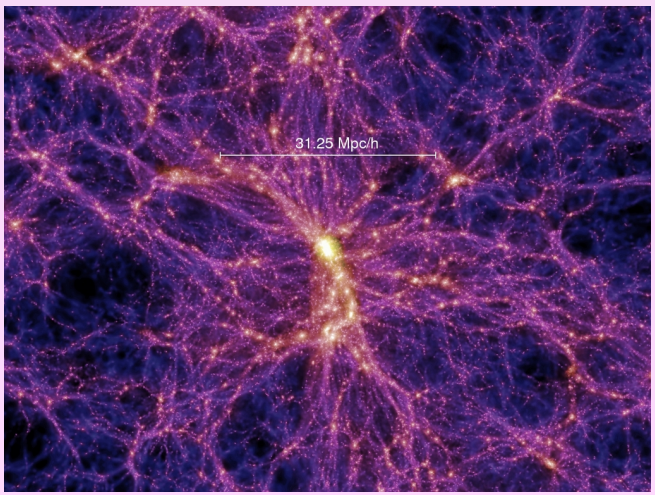
Introduction: Hierarchical Structure Formation



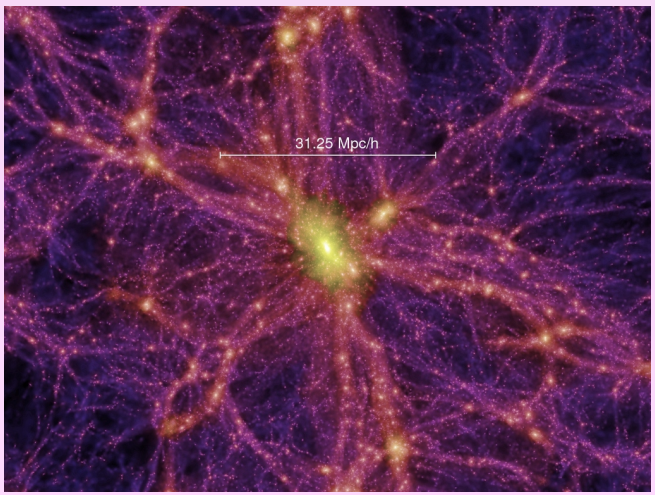
WMAP,
Hinshaw et al. (2008)

- matter gravitates towards initial density peaks, collapses to form structure
- dark matter halo formation determined by gravity & cosmology → matter in dense regions collapse to form spherical "halos"
- hierarchical merging → most massive halos today originated in denser environments

z=1.4



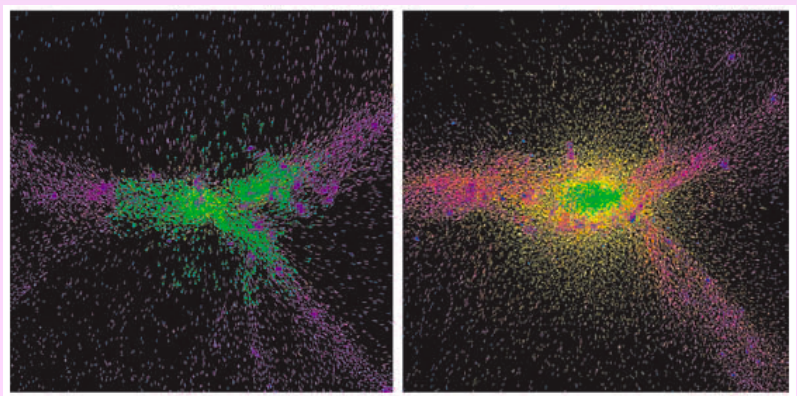
z=0



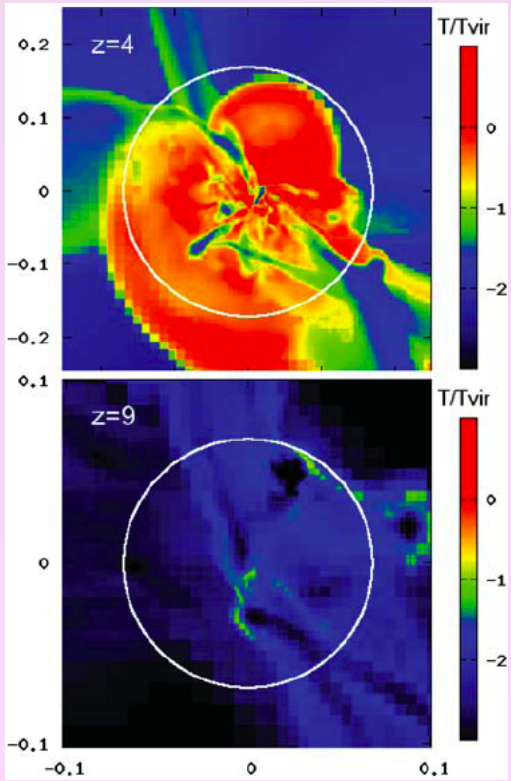
Millennium Simulation, Springel et al. (2005)

Introduction: Gas Cooling & Galaxy Formation in Halos

- galaxies form from cooling dense gas, in same overdense regions as halos
- 'cold mode' of gas accretion is filamentary, and dominates at early times, in low-mass halos
  - star formation regulated by supernovae feedback
- *vs.* 'hot mode', dominates at late times in massive halos

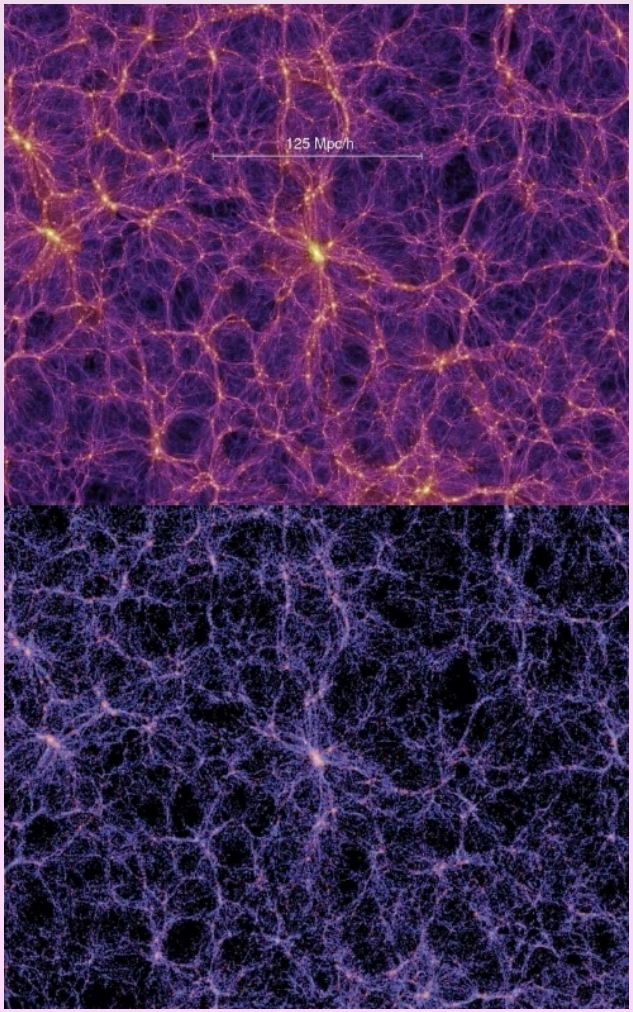


Kereš et al. (2005)



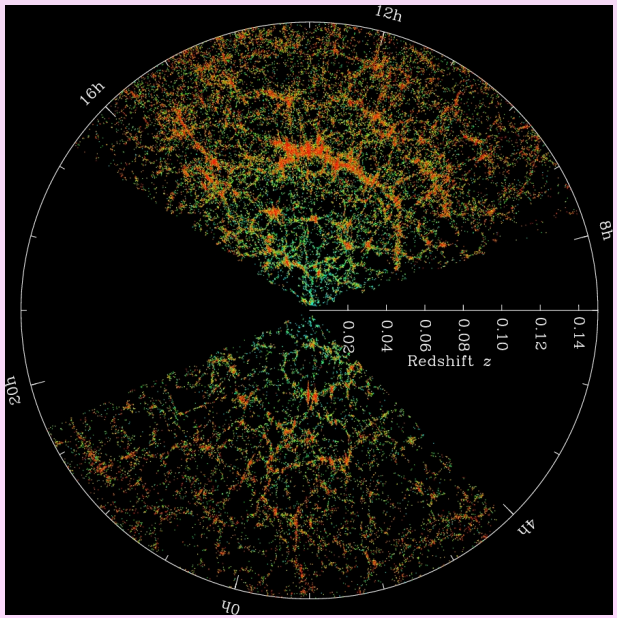
Dekel & Birnboim (2006)

Introduction: Structure from Dark + Luminous Matter



Millennium Simulation,
Croton et al. (2006)

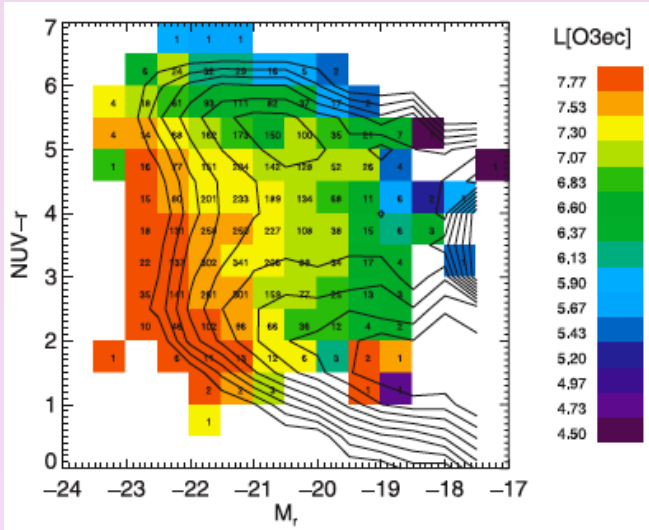
- galaxy attributes correlated with halo mass (*e.g.* luminosity, color, stellar mass, SFR) are correlated with environment
- we can study the environmental dependence of halo/galaxy formation through their clustering properties



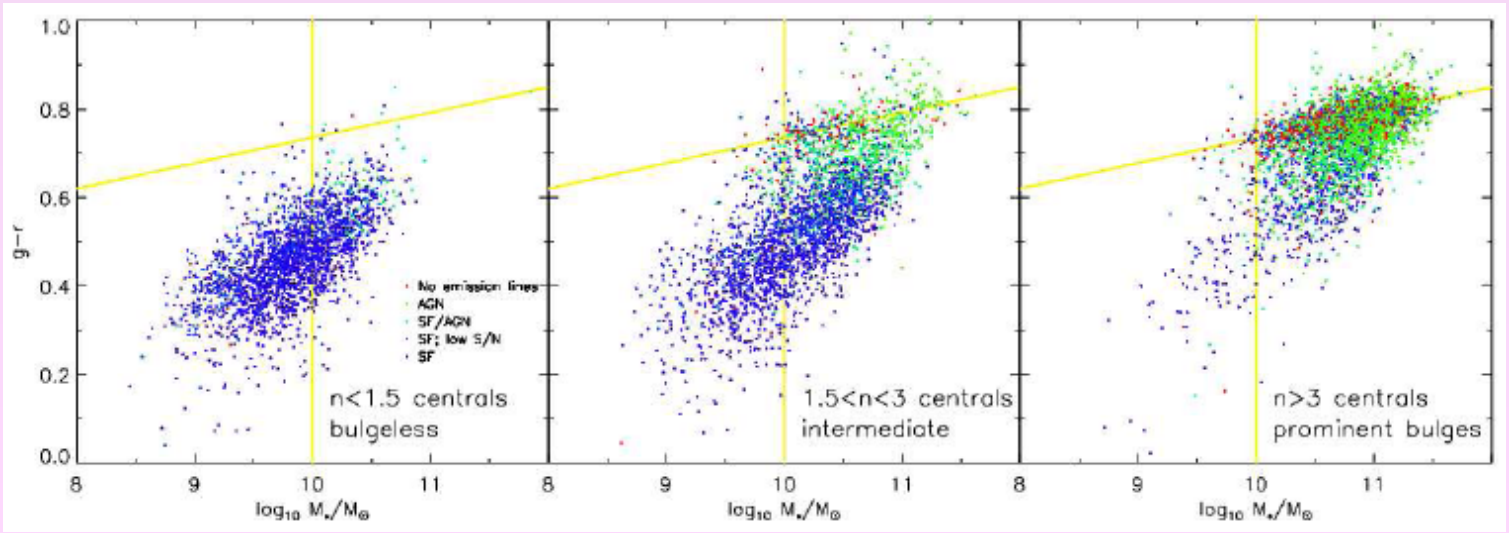
SDSS, Blanton (2008)

Introduction: Galaxy Evolution, Star Formation Quenching

- 'central' galaxies in halos experience mergers, become massive, form large bulge component
- active galactic nuclei grow in bulge, and feedback eventually quenches star formation



Martin et al. (2008)



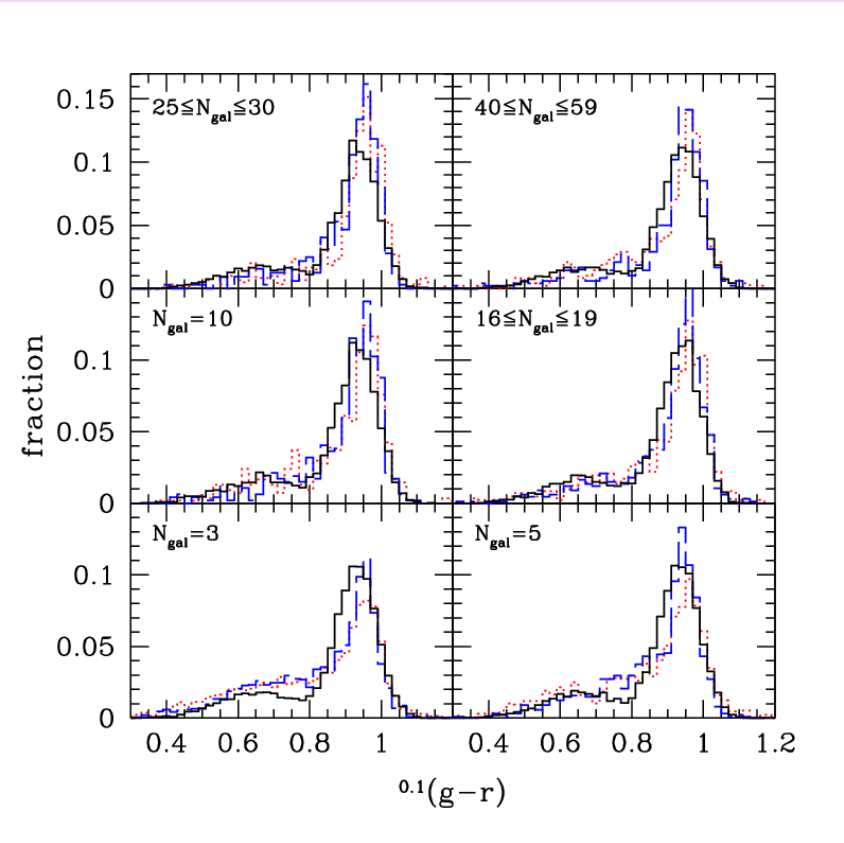
Bell (2008)

Introduction: Galaxy Evolution, Star Formation Quenching

Satellite galaxy properties are nearly independent of halo mass...

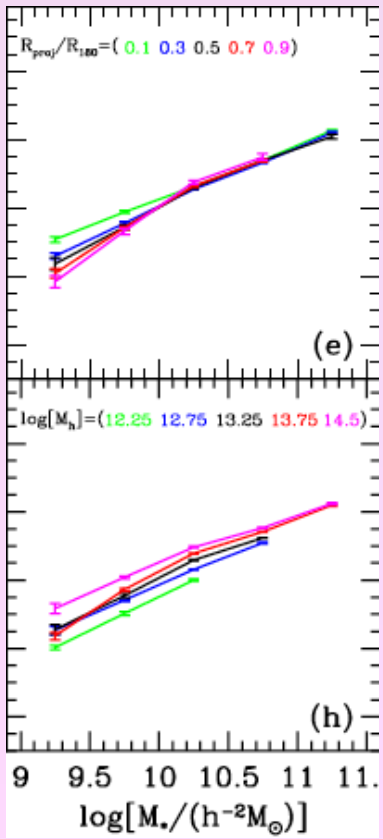
...therefore, the process through which satellites' star formation is quenched must occur in halos of all masses (e.g. 'strangulation')

satellite colors indep. of $N_{\rm gal}$



Skibba (2009)

more dependent on stellar mass



van den Bosch et al. (2008)

Connecting Halos and Galaxies

OR... Connecting Theory and Observations

Halo occupation models: linking halos to observed galaxies using global statistics (such as number densities and clustering as a function of luminosity)

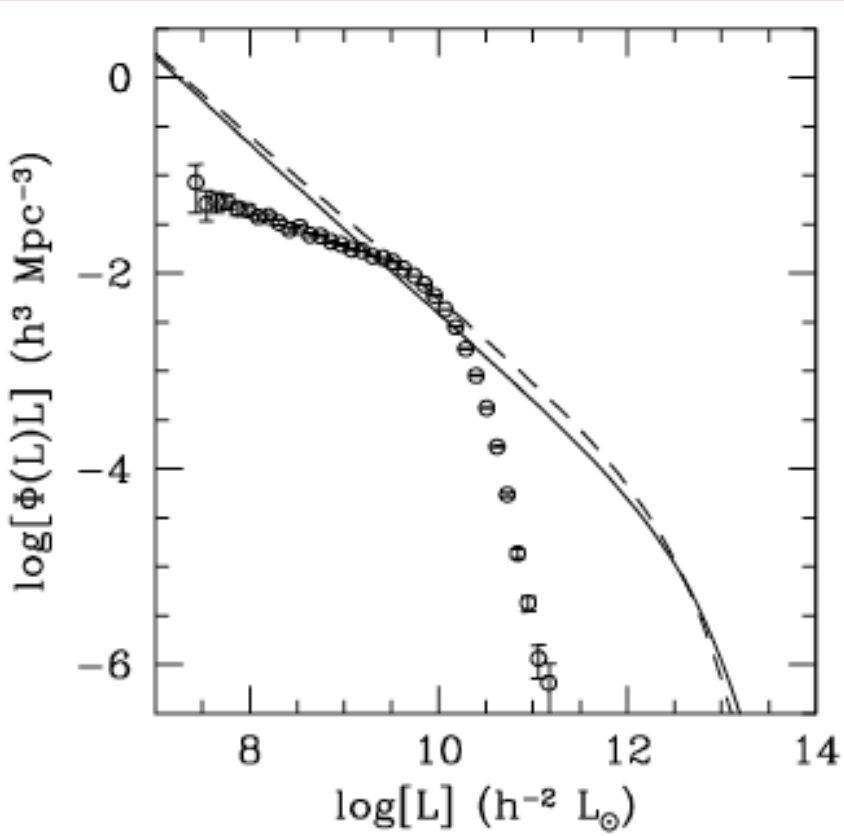
- 'halo occupation distribution' models (Sheth, Weinberg, and collaborators)
- 'conditional luminosity function' models (van den Bosch, Cooray, and collaborators)
- 'sub-halo abundance matching' models (Kravtsov, Wechsler, and collaborators)

complementary to semi-analytic models and hydrodynamic simulations

Abundances and Clustering of Galaxies and Halos

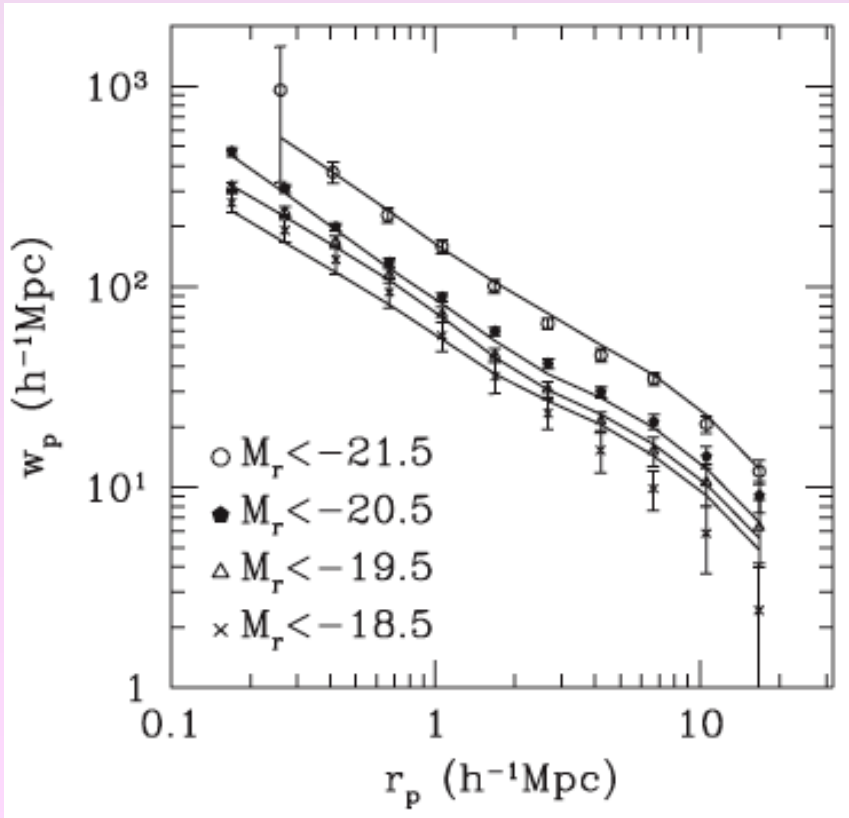
halo occupation models constrained by galaxy abundance and clustering as a function of luminosity:

luminosity & mass functions



Yang et al. (2003)

luminosity-dependent clustering



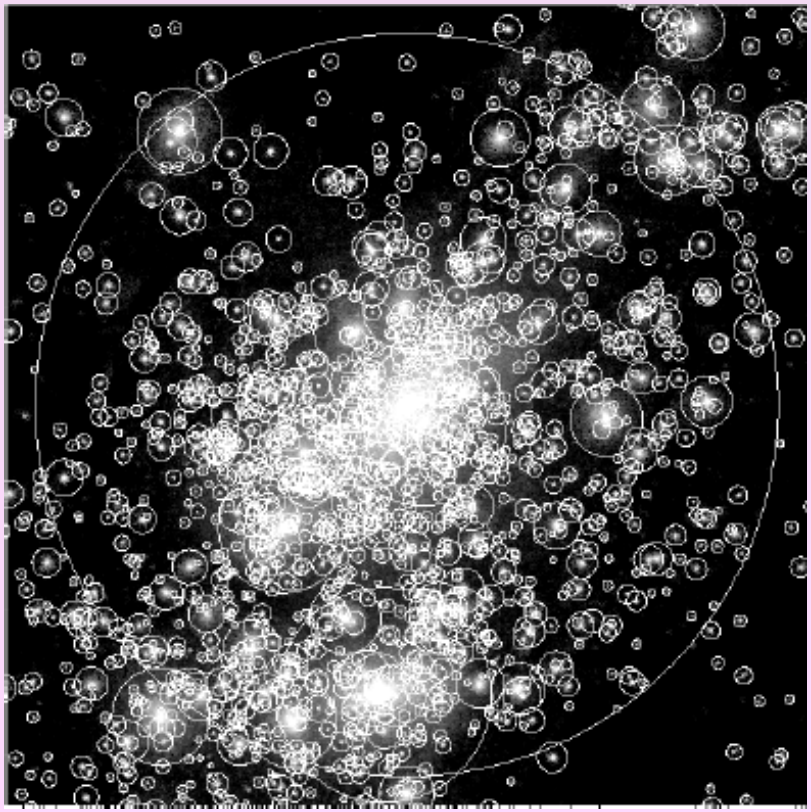
Zehavi et al. (2005)

Galaxies Occupying Dark Matter Halos

Models associate brightest galaxy in a group or cluster with the 'central' galaxy, assumed to be at center of the halo

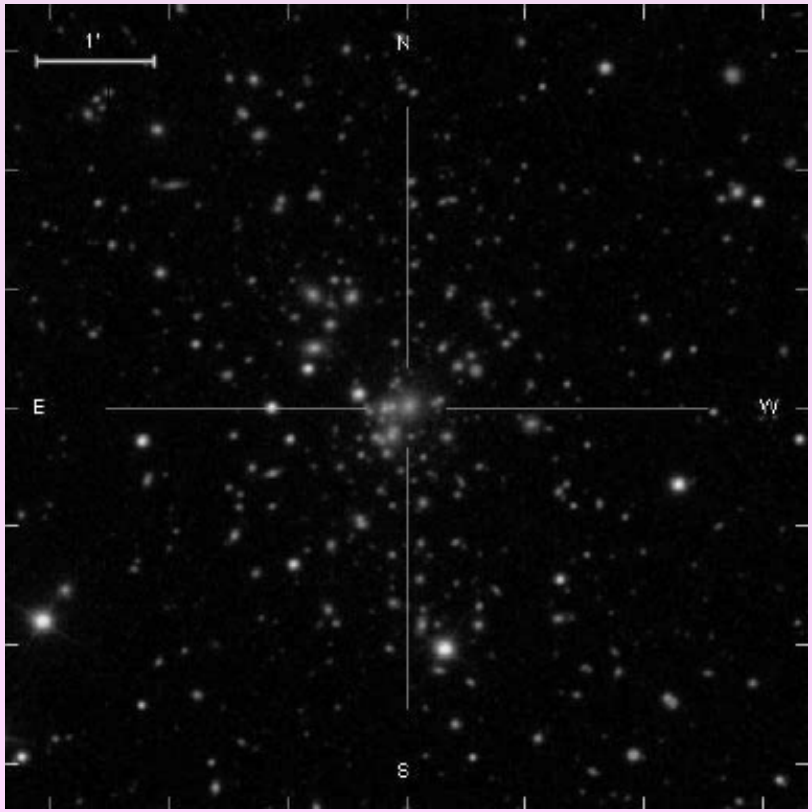
Additional 'satellite' galaxies associated with halo substructures

halo with many subhalos



Kravtsov et al. (2004)

cluster with many galaxies



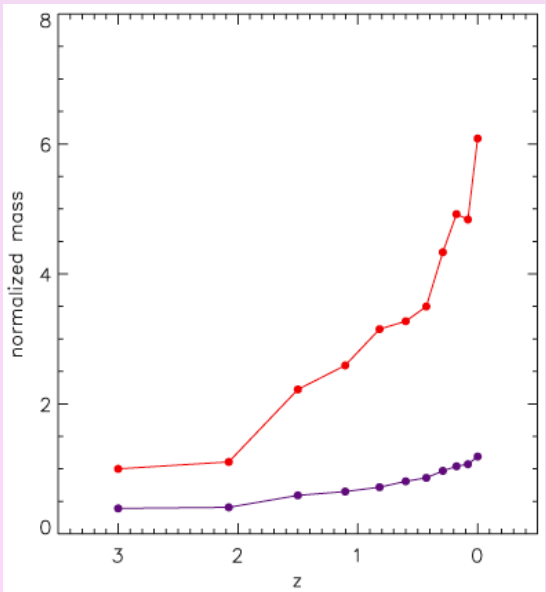
Koester et al. (2007)

Formation of Brightest Halo Galaxies

As subhalos are accreted onto the host halo, satellites will also eventually merge with the central galaxy, increasing its mass (left)

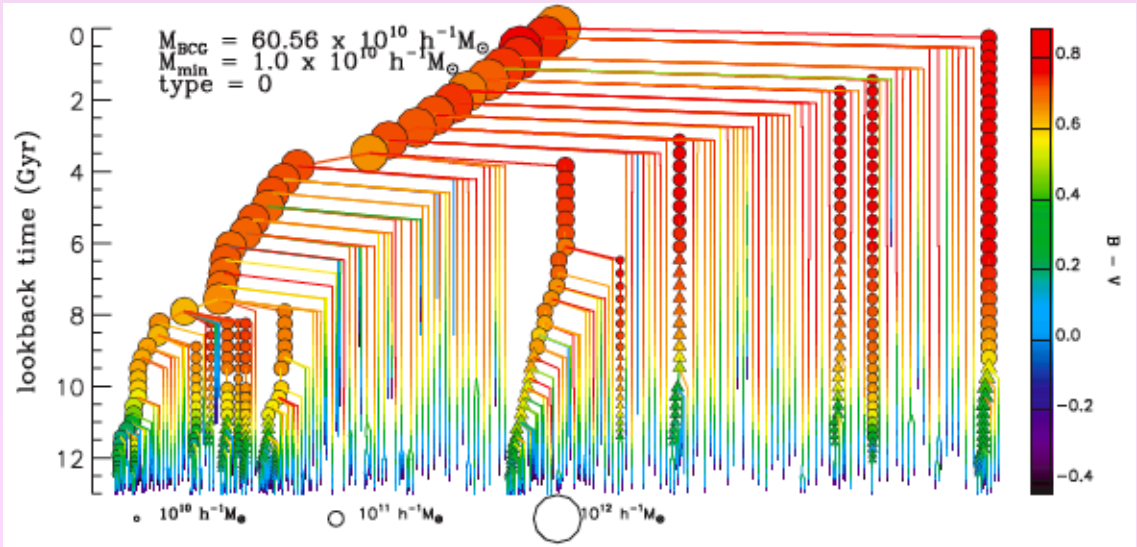
BCGs assemble the bulk of their mass through mergers, and are expected to dominate the satellite galaxies, in terms of mass (right)

mass assembly



Ruszkowski & Springel (2009)

merger tree



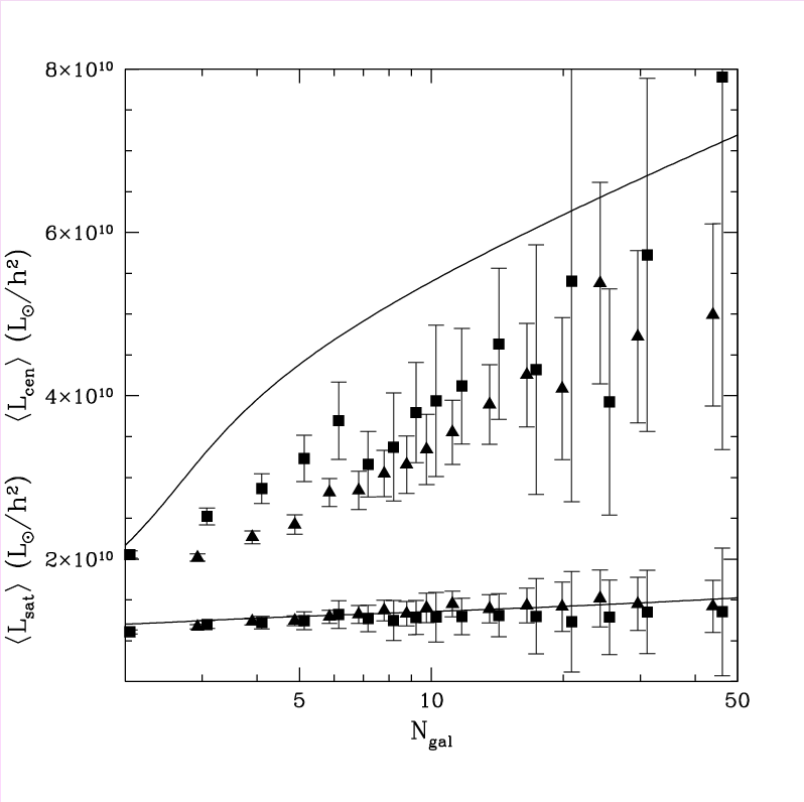
De Lucia & Blaizot (2007)

Central and Satellite Galaxy Luminosities

Brightest halo galaxy is much more luminous than the *typical* satellite galaxy in the halo

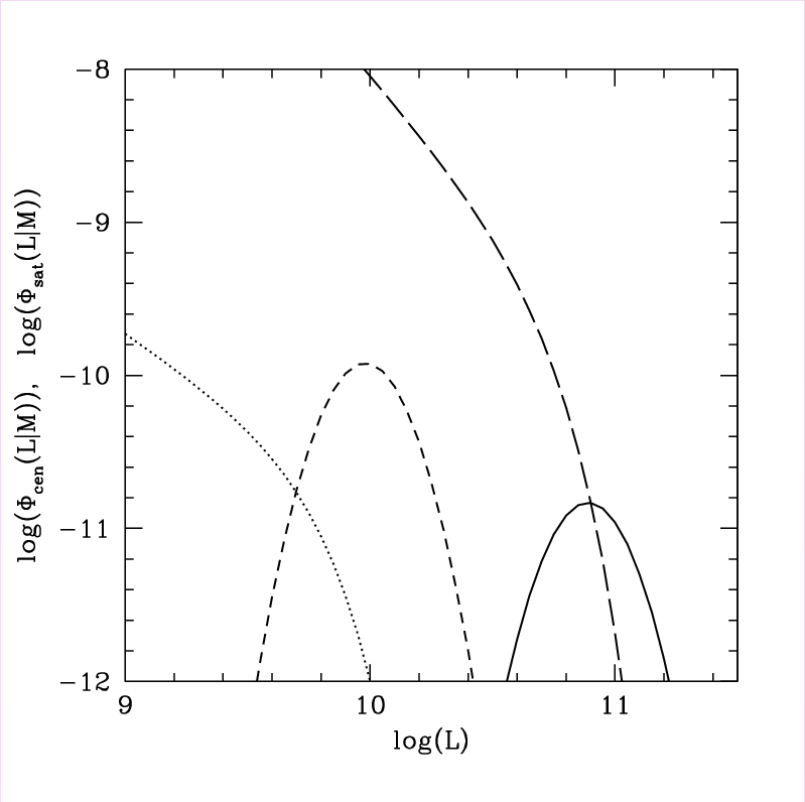
but there can be multiple bright galaxies, especially in massive halos

mean central & satellite luminosities



Skibba et al. (2007)

central and satellite CLFs

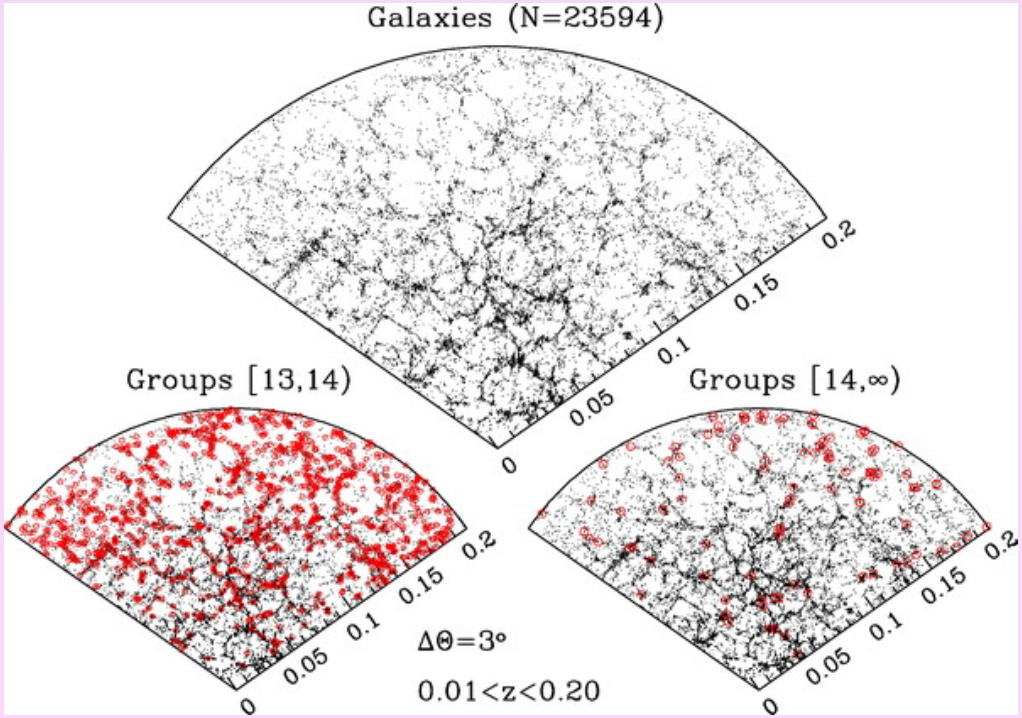


Skibba et al. (in prep.)

Galaxy Group Catalog

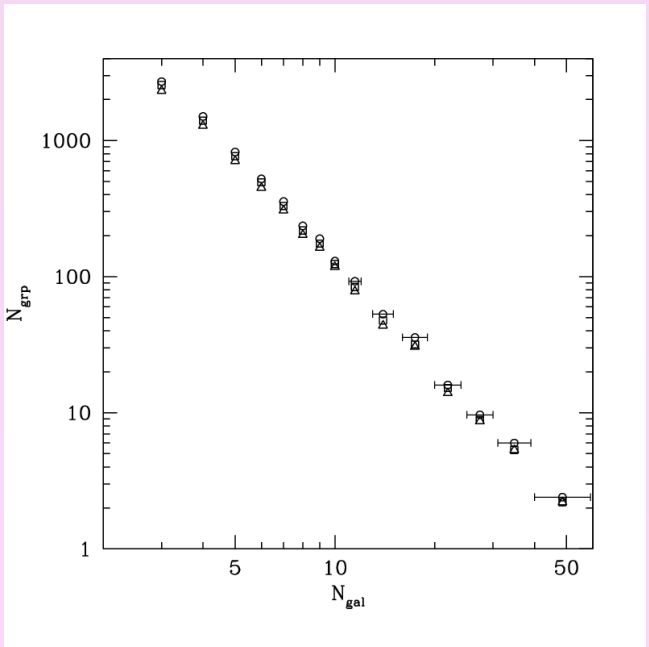
Algorithm finds galaxy groups in the SDSS, using constraints from conditional luminosity function

SDSS galaxy groups



Yang et al. (2007)

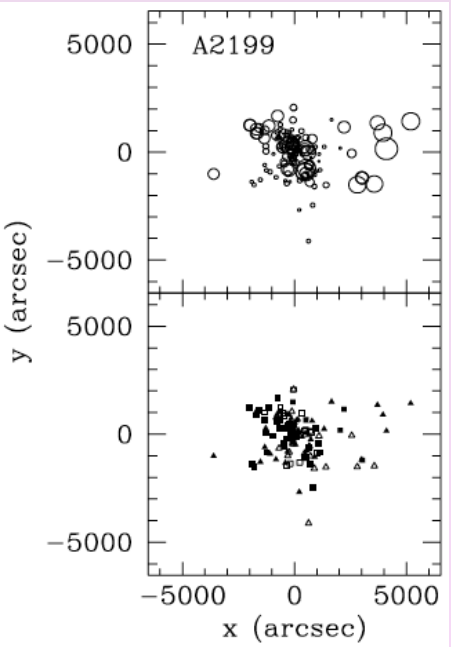
abundance of groups & clusters

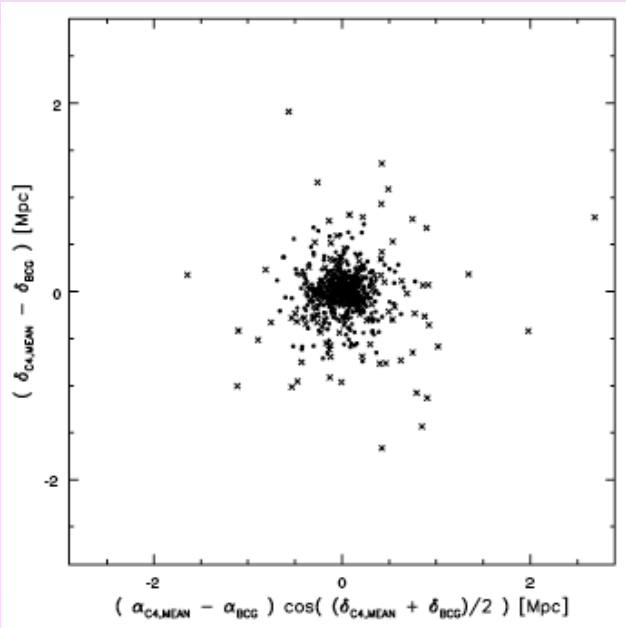


Skibba et al. (in prep.)

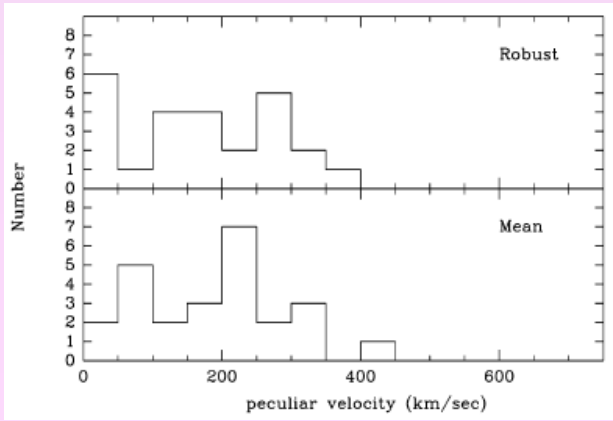
Examples of central galaxies offset from cluster center

- some central galaxies have significant offsets in their line-of-sight velocities (right) and projected positions (below)
- wide distribution of offsets—is this expected?





von der Linden et al. (2007)
C4 cluster catalog



Oegerle & Hill (2001)
25 Abell clusters

Quantifying the offsets of brightest halo galaxies

We are improving and extending analysis of van den Bosch et al. (2005), using SDSS galaxy group catalog (Yang et al. 2007) based on conditional luminosity function modeling (Cacciato et al. 2008).

Using line-of-sight velocities from redshifts, we quantify offset between brightest halo galaxy and $N_{\rm sat}$ satellite galaxies:

BHG velocity offset parameter

$$\mathcal{R} = \frac{\sqrt{N_{\rm sat}}(\bar{v}_{\rm sat} - v_{\rm BHG})}{\hat{\sigma}_{\rm sat}}$$

Using projected separations, we also quantify the spatial offset:

BHG spatial offset parameter

$$\mathcal{S} = \frac{\sqrt{N_{\rm sat}}(\bar{r}_{p,\rm sat} - r_{p,\rm BHG})}{\sigma_{r_{p,\rm sat}}}$$

Quantifying the offsets of brightest halo galaxies

SDSS group catalog affected by interlopers and incompleteness, so we compare distribution of velocity offsets to mock group catalogs (based on CLF, using same group finder, survey geometry, etc.) with either nonzero $b_{\rm vel}$ or $f_{\rm BHGsat}$

Two explanations as to why brightest halo galaxies (BHGs) are offset and moving with respect to the halo center:

$\Rightarrow$ **Hypothesis #1**: central galaxies are the BHGs, but have some amount of 'velocity bias' ($b_{\rm vel}$), resulting in a particular distribution of offsets

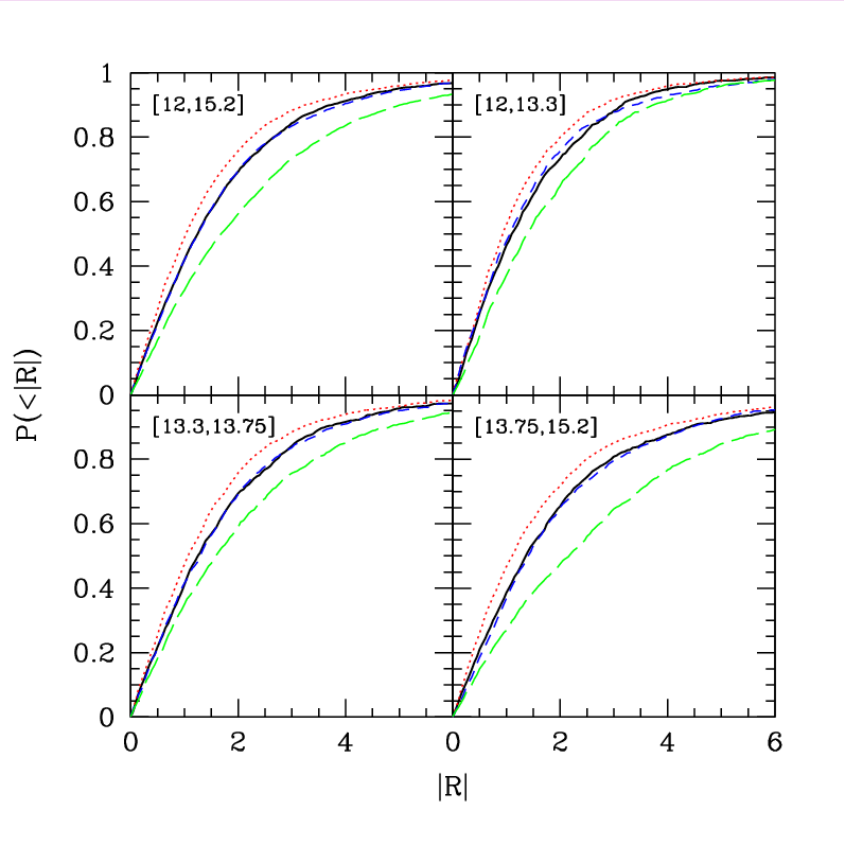
$\Rightarrow$ **Hypothesis #2**: BHGs are actually satellite galaxies in some fraction of halos ($f_{\rm BHGsat}$), and are therefore offset and moving relative to the halo center

Hypothesis #1: Central galaxies with velocity bias

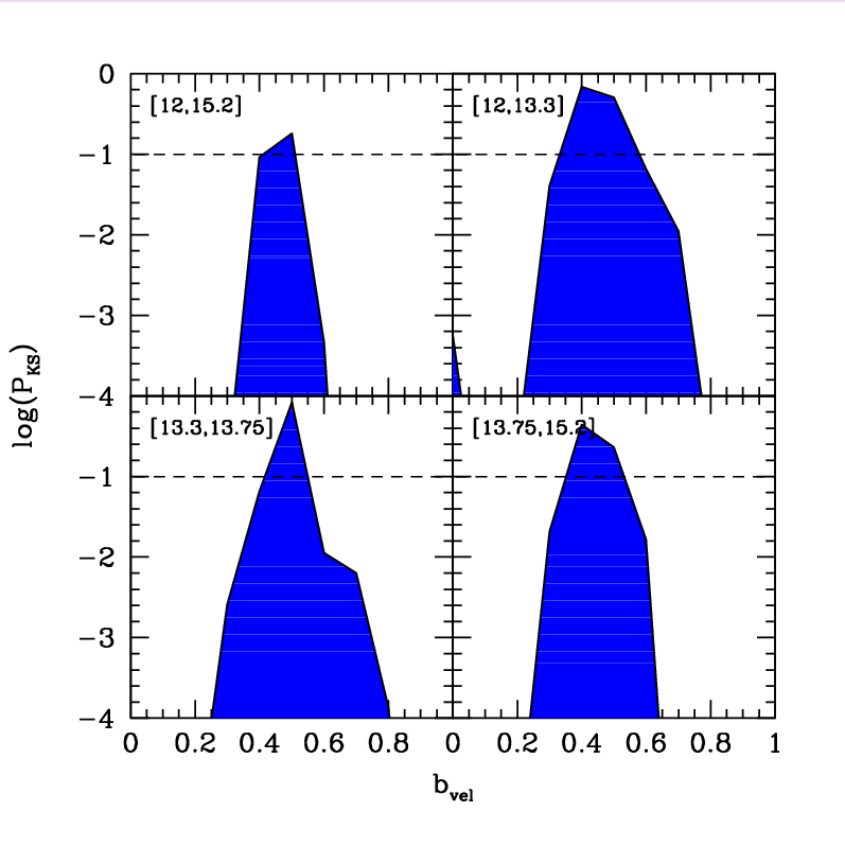
comparing $P(<\mathcal{R})$ of SDSS data *vs* mock group catalogs: constrains amount of velocity bias

velocity bias is large ($b_{\rm vel} \approx 0.5$), and approx indep of $M_{\rm halo}$

cumulative $\mathcal{R}$ distributions



KS probabilities



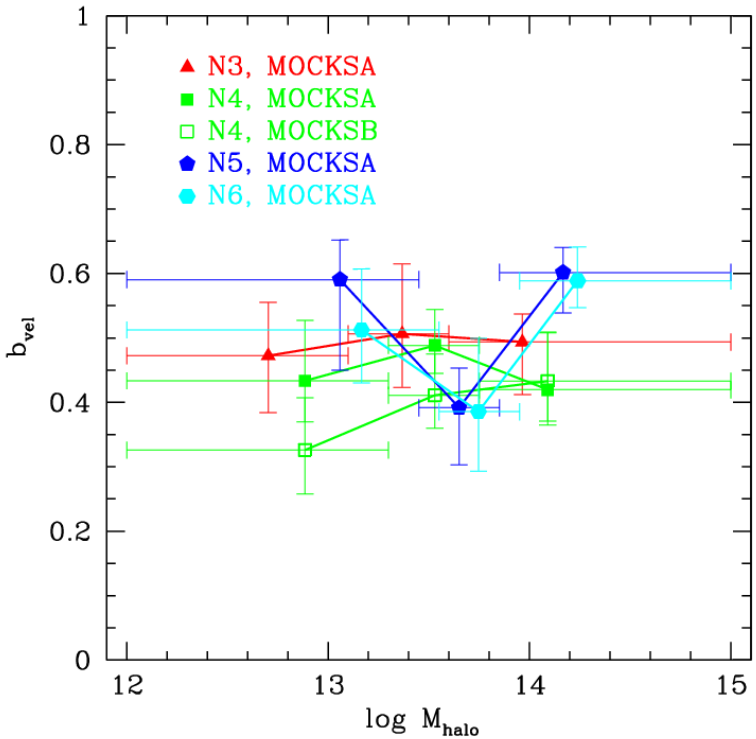
Hypothesis #1: Central galaxies with velocity bias

summary of results for halo mass dependence, for groups with $N_{\rm gal} \geq 3$ (red), 4 (green), 5 (blue), 6 (cyan)

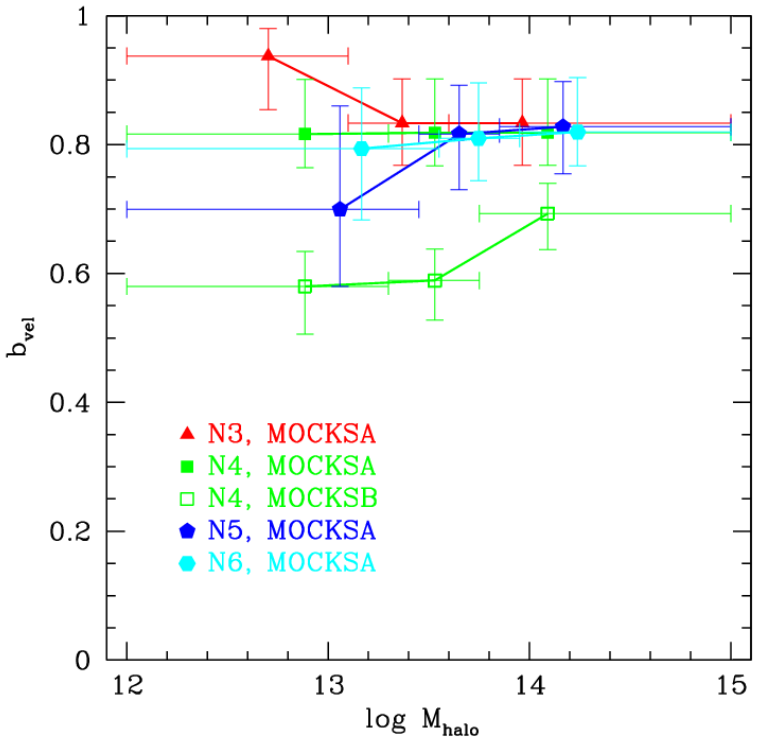
results from dynamics & spatial positions of BHGs ($\mathcal{R}$- & $\mathcal{S}$-distributions) *disagree*

$\Rightarrow$ **BHG offsets cannot be explained by velocity bias!**

dynamical



spatial

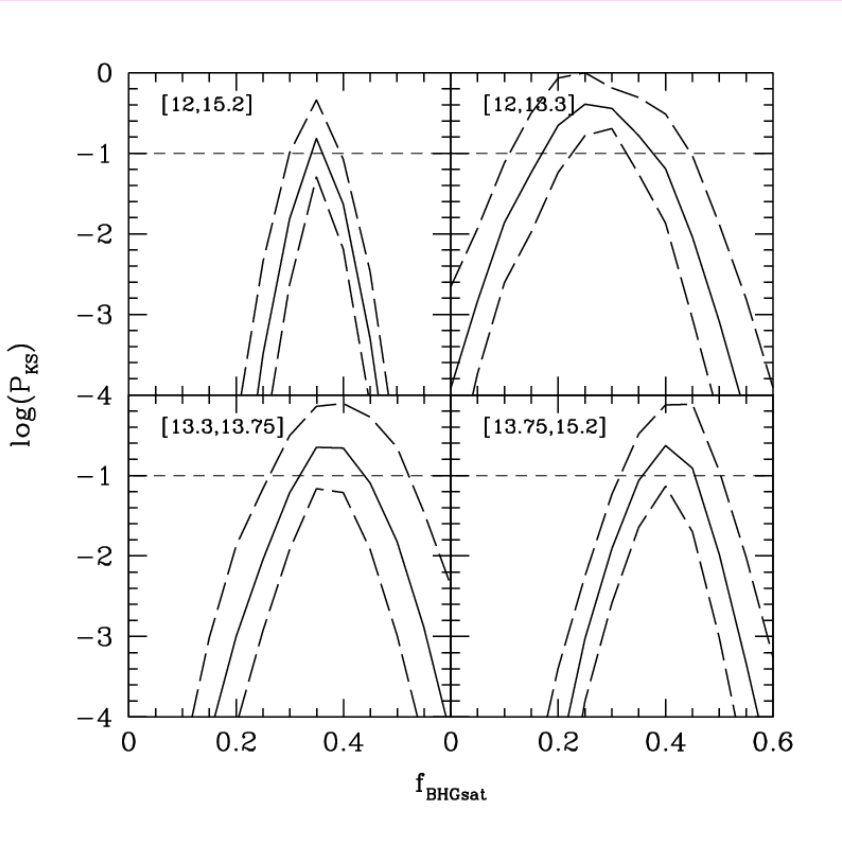


Hypothesis #2: Groups with Satellite BHGs

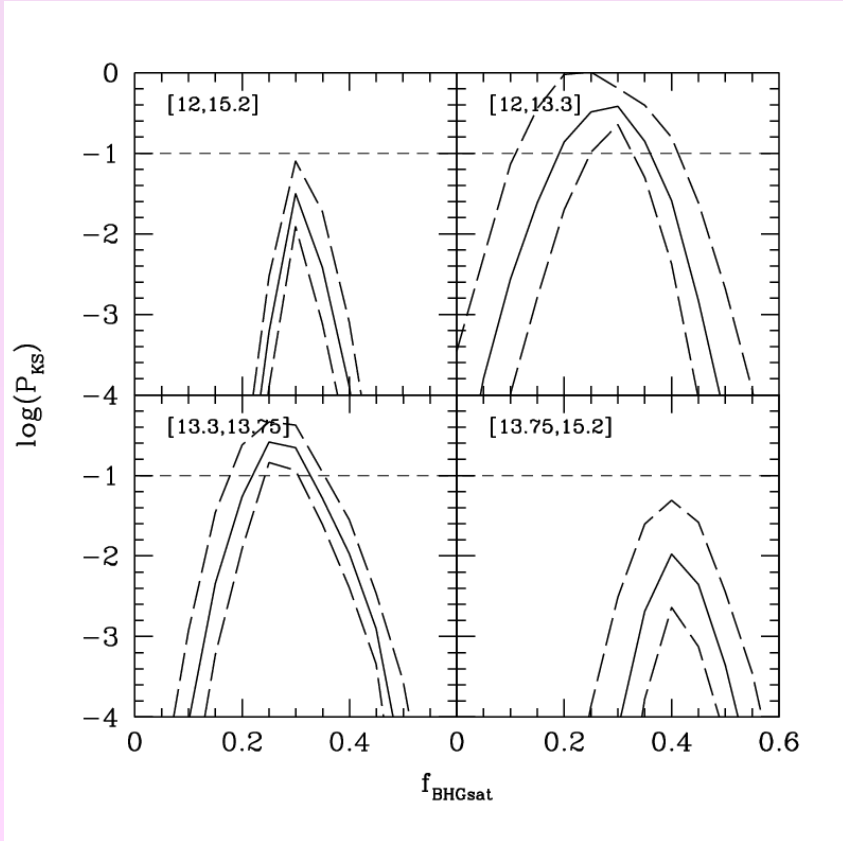
Alternative explanation: in a large fraction of groups, a *satellite* is the brightest member

We perform same analysis of distributions of $\mathcal{R}$ & $\mathcal{S}$ BHG offsets, but comparing to mocks with no velocity bias and some $f_{\rm BHGsat}$

dynamical



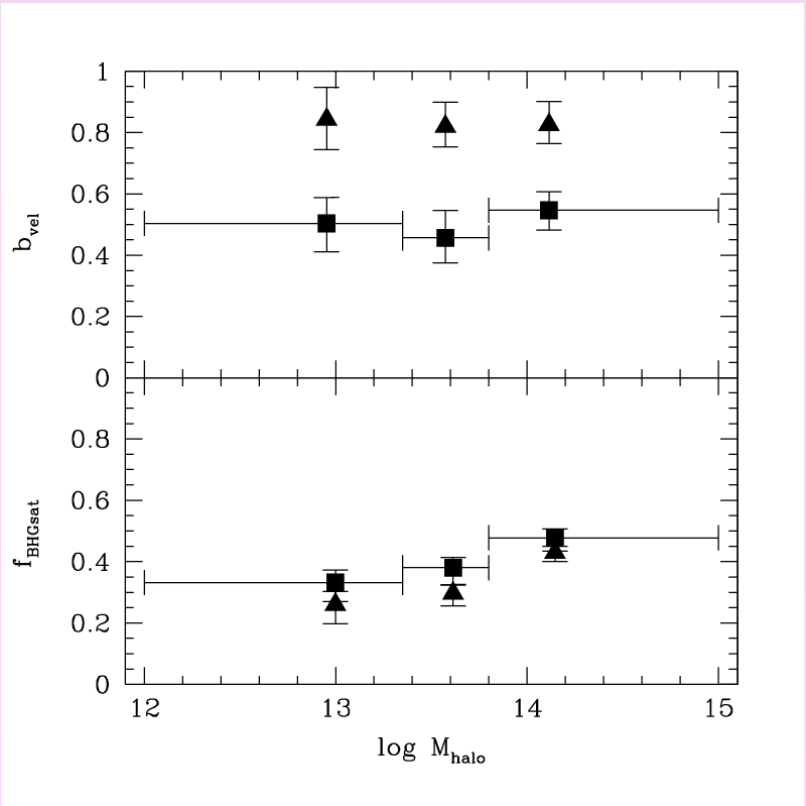
spatial



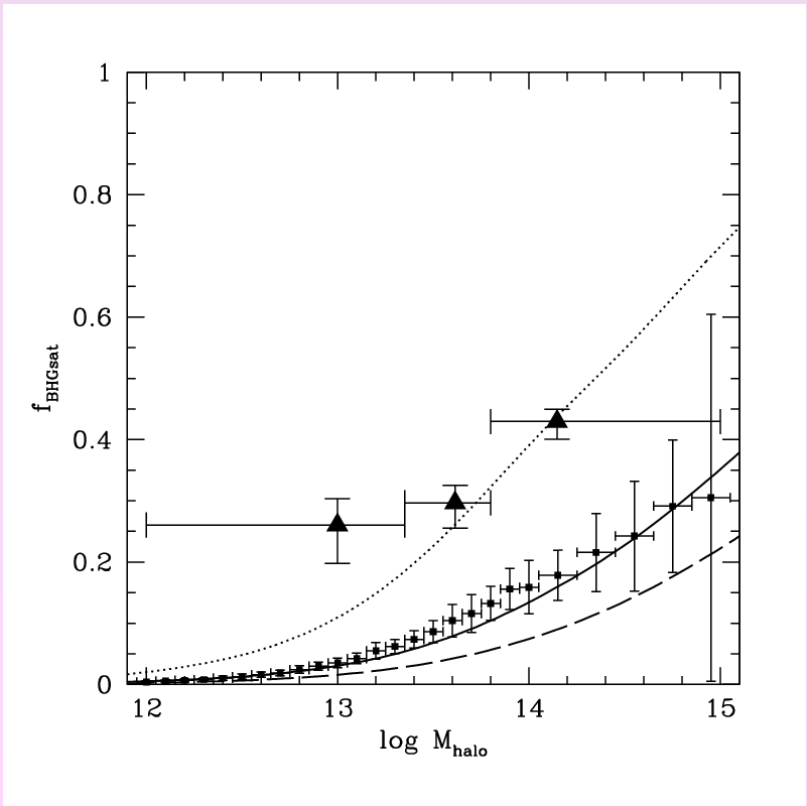
Main Result: High Fraction of Satellite BHGs

relative velocities & positions of BHGs mostly explained by groups with satellite BHGs, plus small amount of velocity bias

DOMINANT EFFECT: SATELLITE BHGS



consistent with CLF



Skibba, van den Bosch, et al. (in prep.)

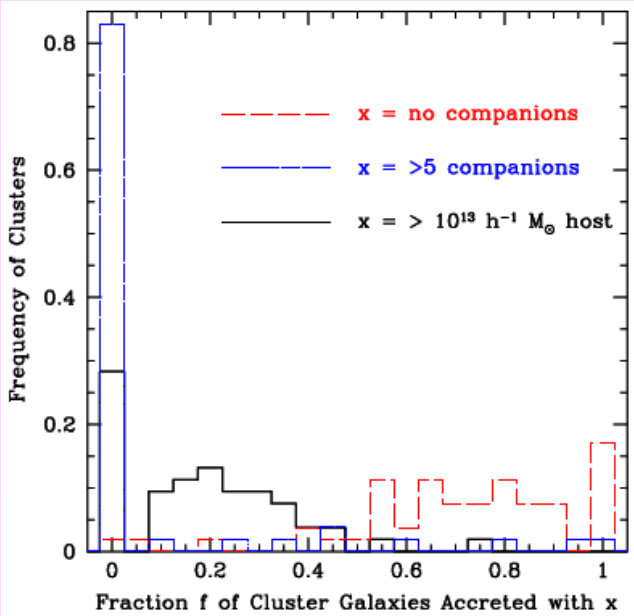
Why?

Why in so many halos is the brightest galaxy a satellite? Could they be unrelaxed systems, with recently accreted massive satellites?

some clusters do accrete satellites from groups (left); these satellites could be massive

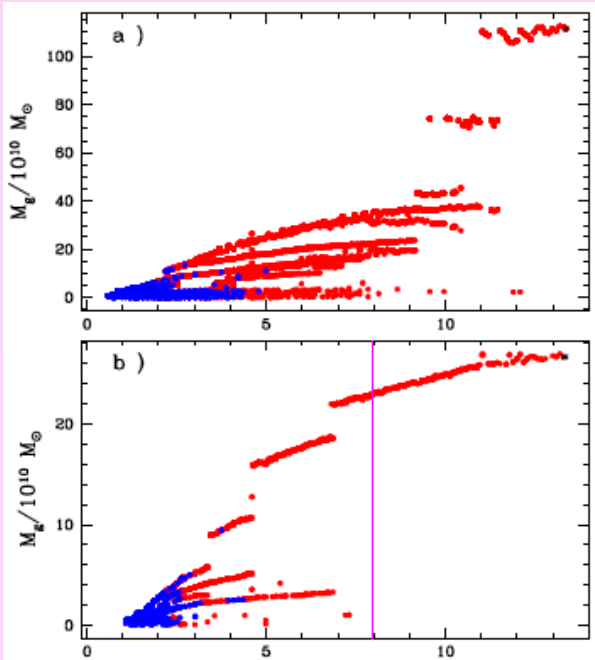
accreted satellites may continue forming stars (right); this could increase their mass relative to central galaxy

assembly of clusters



Berrier et al. (2009)

cen (top) & sat (bottom) mass assembly



Simha et al. (2008)

Conclusions

- Analytic & semi-analytic models assume central galaxies and BHGs are the same objects, and that central galaxies are at rest at the center of the potential well. *Both assumptions are false.*
- **The spatial and velocity offsets of brightest halo galaxies are mostly explained by a large fraction of groups and clusters in which a satellite is the brightest (or most massive) galaxy**
- **This fraction increases with halo mass**, from $\approx 25\%$ to $\approx 40\%$ in massive halos, consistent with CLF with scatter in central galaxy luminosity and satellite LF with shallow slope
- What is the physical explanation? Many halos hosting groups and clusters may be unrelaxed systems, with relatively recently accreted massive satellites. Galaxies can continue to grow even after they are accreted as satellites.