Are Brightest Halo Galaxies 'Central' Galaxies?

Ramin Skibba (University of Arizona)

collaborators: Frank van den Bosch, Ravi Sheth, Xiaohu Yang, Andrea Macciò, Surhud More, Idit Zehavi, Fabio Fontanot, Darren Croton, Andrew Benson

UC Berkeley

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Important Questions to Explore

How do galaxy formation and evolution depend on the galaxy's environment?

How are galaxies affected by the dark matter halos that host them? What aspects of galaxy formation 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?

Conclusions about Brightest Halo Galaxies

- Analytic & semi-analytic models assume central galaxies and brightest halo galaxies (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 BHGs are mostly explained by a fraction of groups and clusters in which a satellite is the brightest (or most massive) galaxy.**

- **This fraction is large and increases with halo mass**, from $\approx 25\%$ to $\approx 40\%$ in massive halos, with important implications for various areas in astronomy.

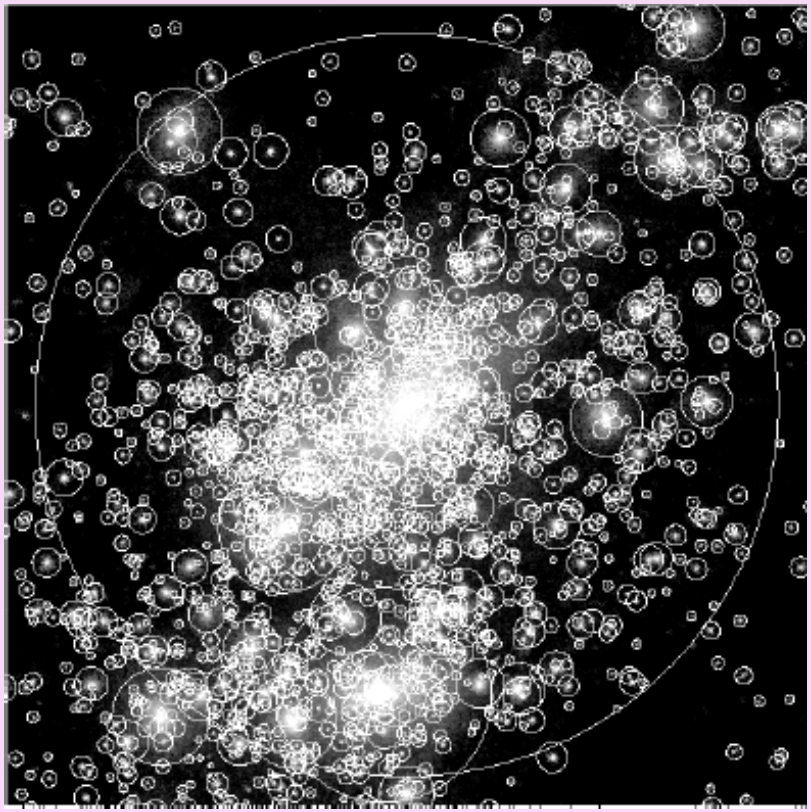
Skibba et al. (2011, MNRAS, 410, 417)

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

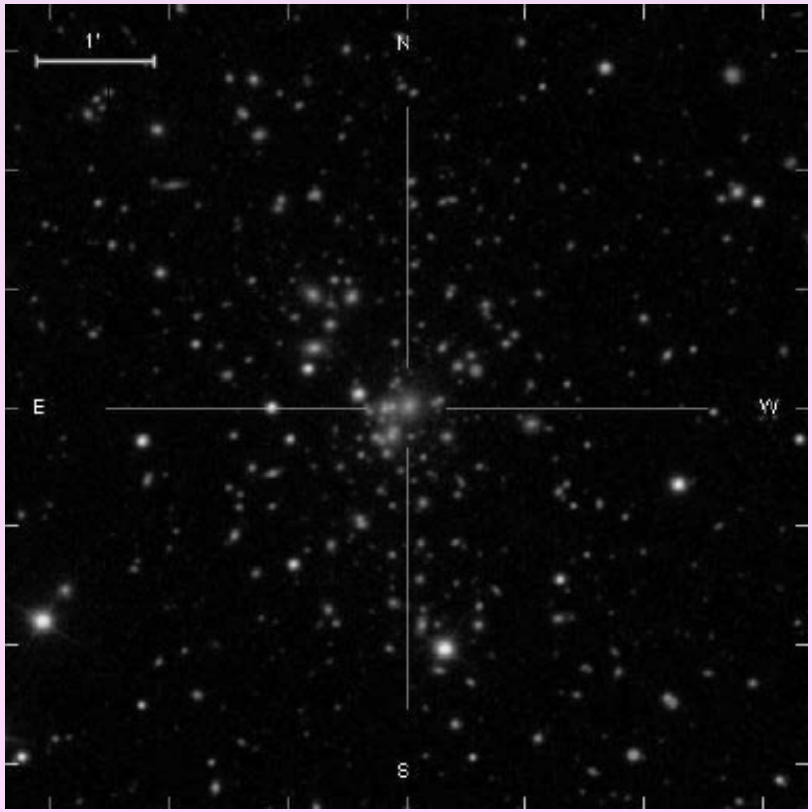
Additional 'satellite' galaxies associated with halo substructures

halo with many subhalos



Kravtsov et al. (2004)

cluster with many galaxies



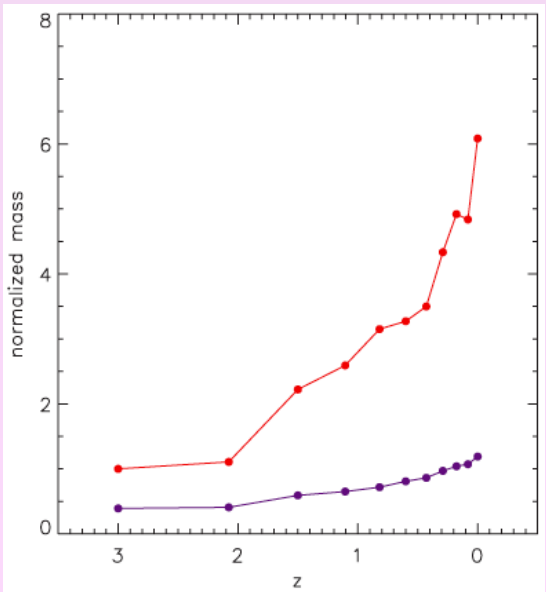
Koester et al. (2007)

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)

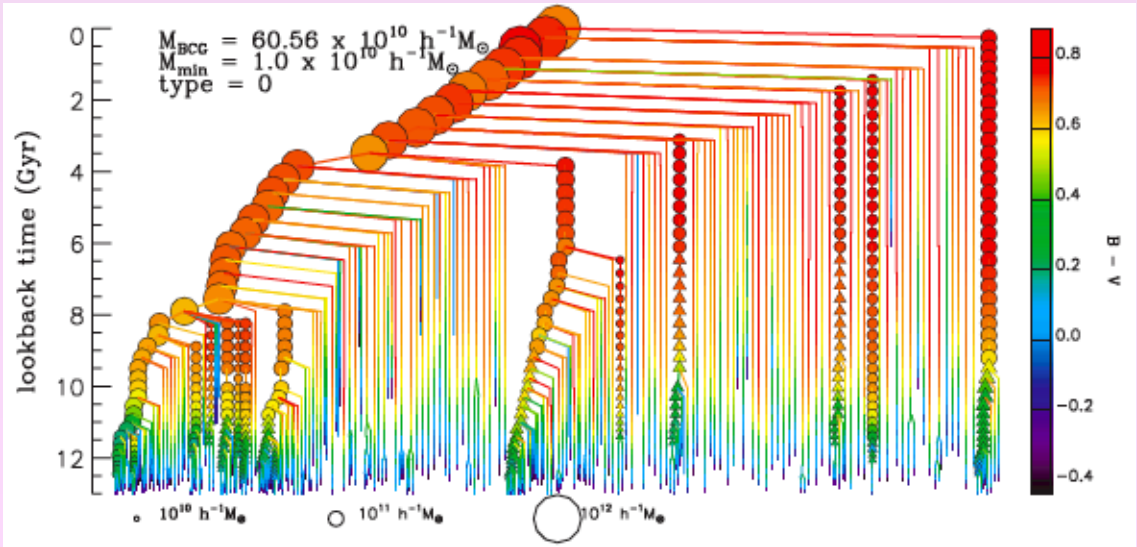
BCGs assemble the bulk of their mass through mergers, and are expected to dominate the satellite galaxies, in terms of mass (right)

mass assembly



Ruszkowski & Springel (2009)

merger tree



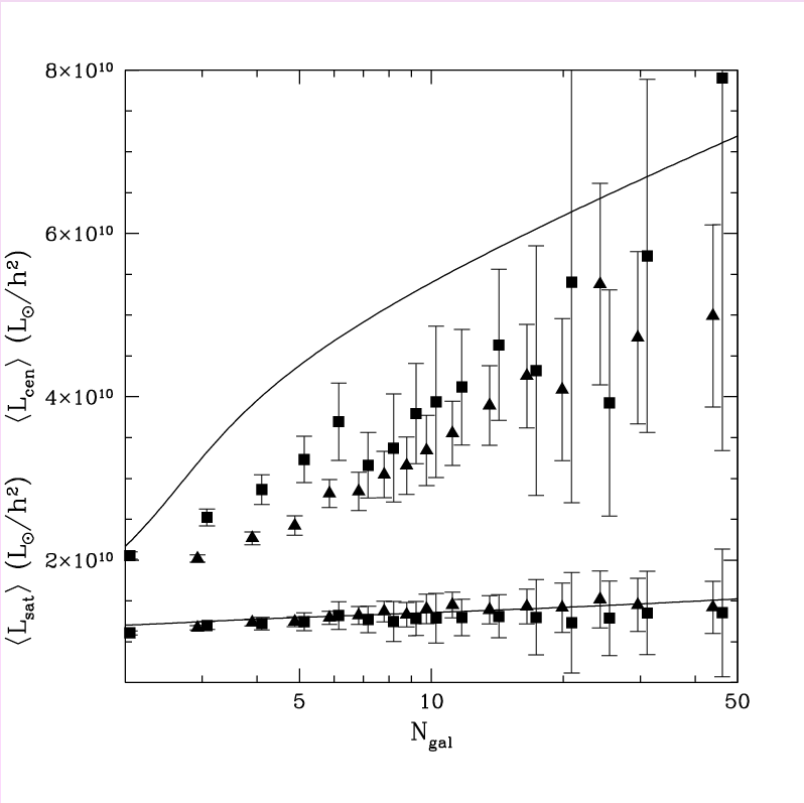
De Lucia & Blaizot (2007)

Central and Satellite Galaxy Luminosities

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

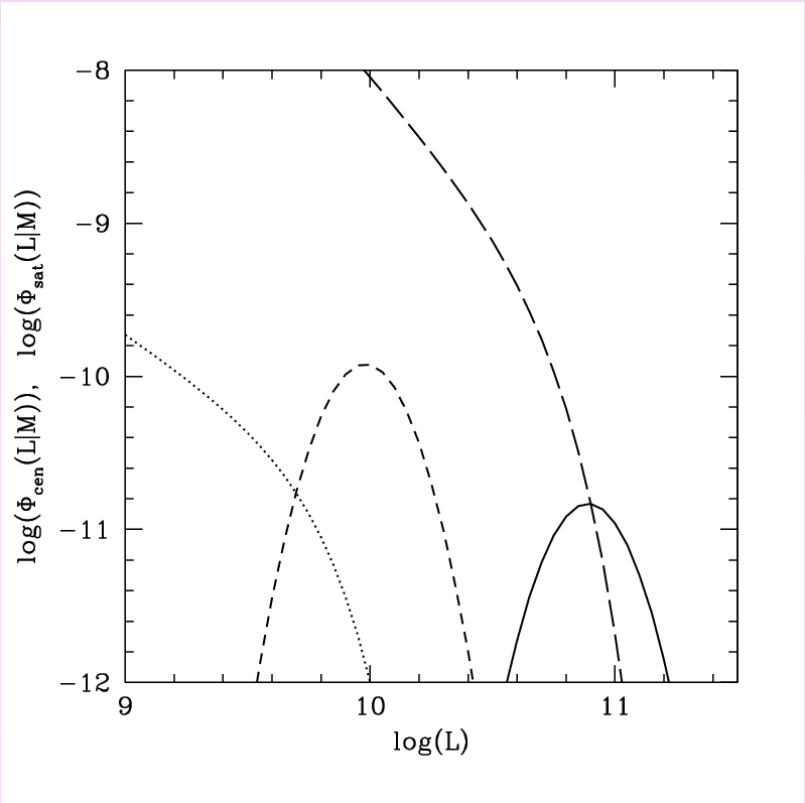
but there can be multiple bright galaxies, especially in massive halos

mean central & satellite luminosities



Skibba et al. (2007)

central and satellite CLFs

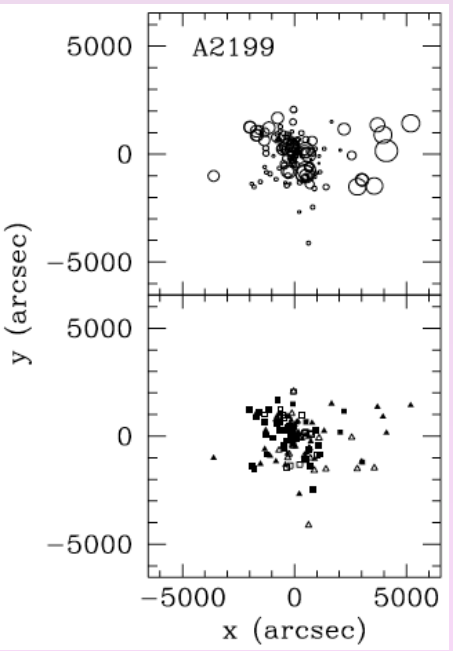


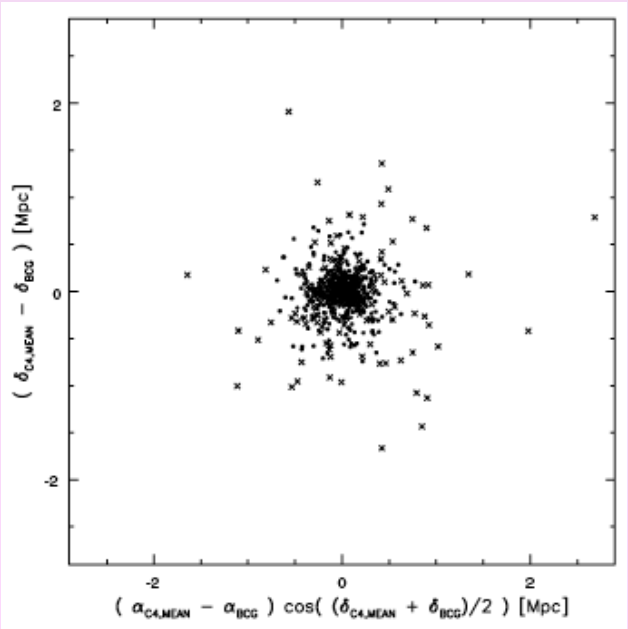
van den Bosch et al. (2007)

but see Paranjape & Sheth (2011)

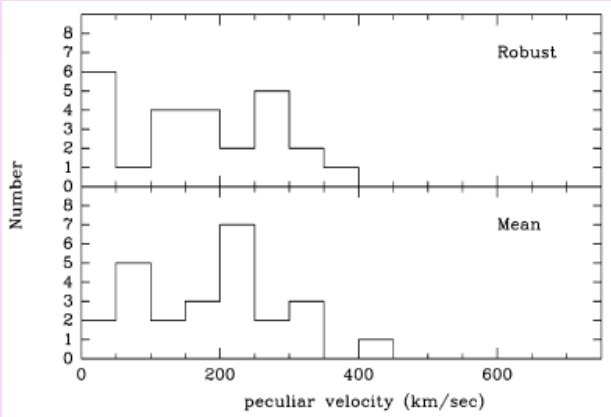
Examples of central galaxies offset from cluster center

- 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) and 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 $f_{\rm BNC}$.

Three 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**

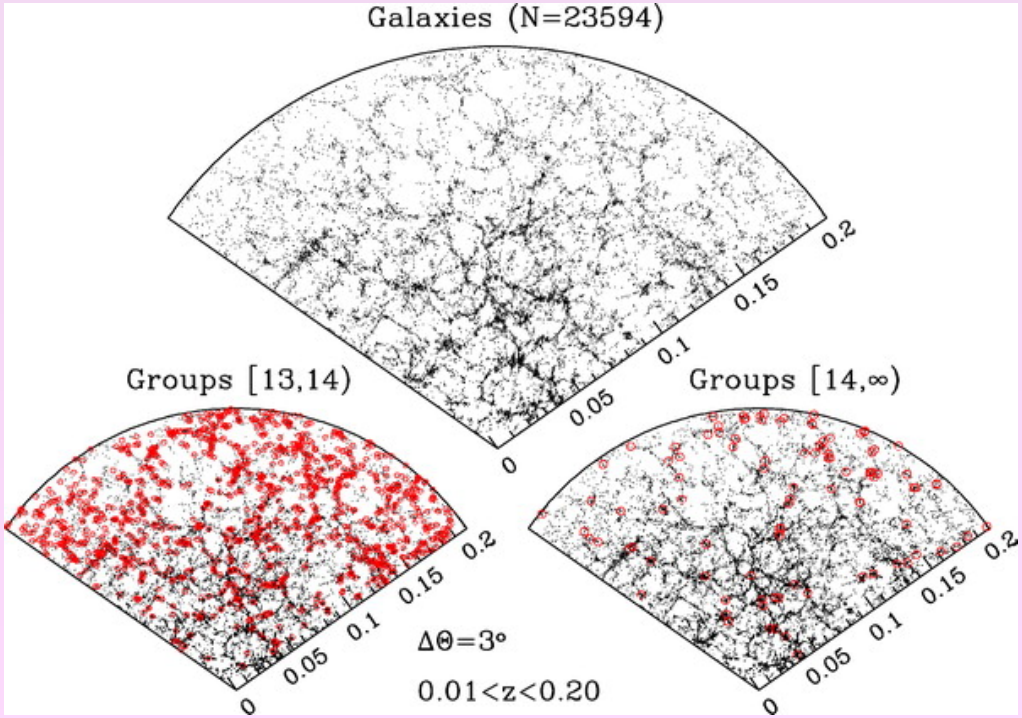
$\Rightarrow$ **Hypothesis #2: BHGs are actually satellite galaxies in some fraction of halos ($f_{\rm BNC}$), and are therefore offset and moving relative to the halo center**

$\Rightarrow$ **Hypothesis #3:** We also test the effect of a fraction of satellites clumped in a substructure ($f_{\rm sub}$), which would make the BHG appear to be offset from the other halo galaxies.

Galaxy Group Catalog

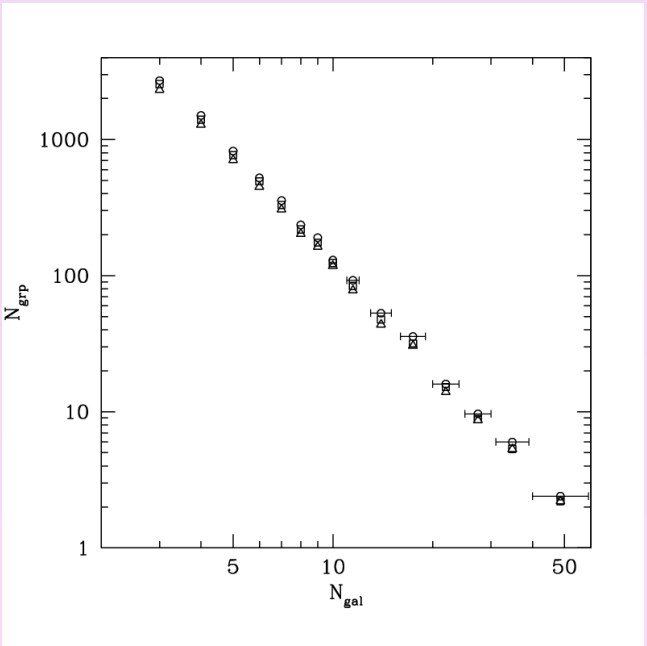
Algorithm finds galaxy groups in the SDSS, using constraints from conditional luminosity function

SDSS galaxy groups



Yang et al. (2007)

abundance of groups & clusters

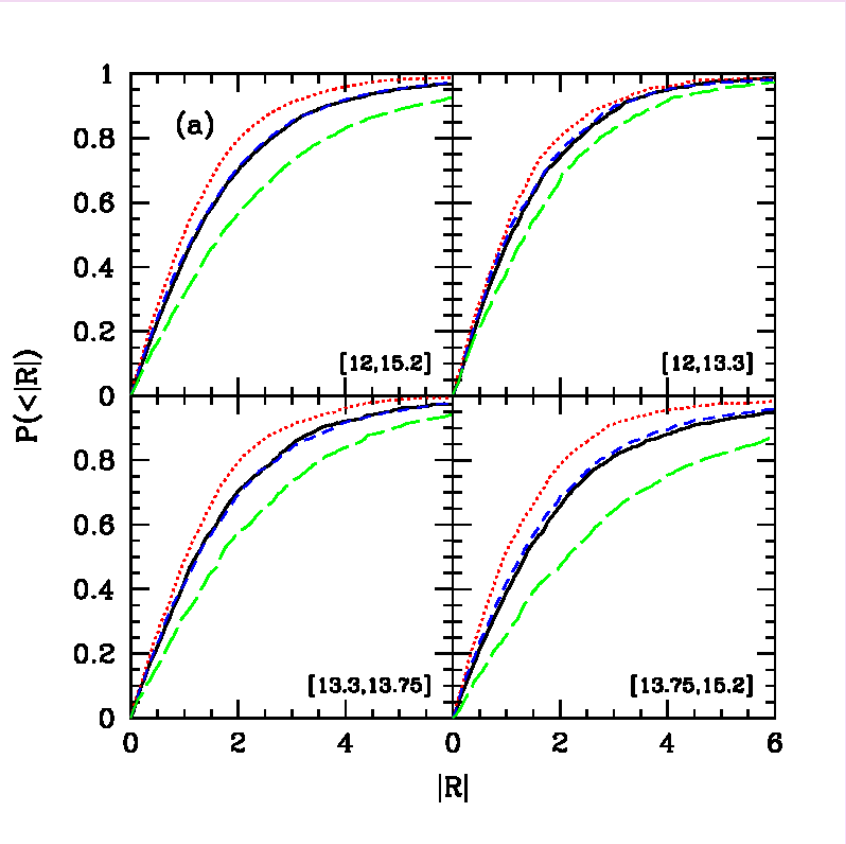


Skibba et al. (2011)

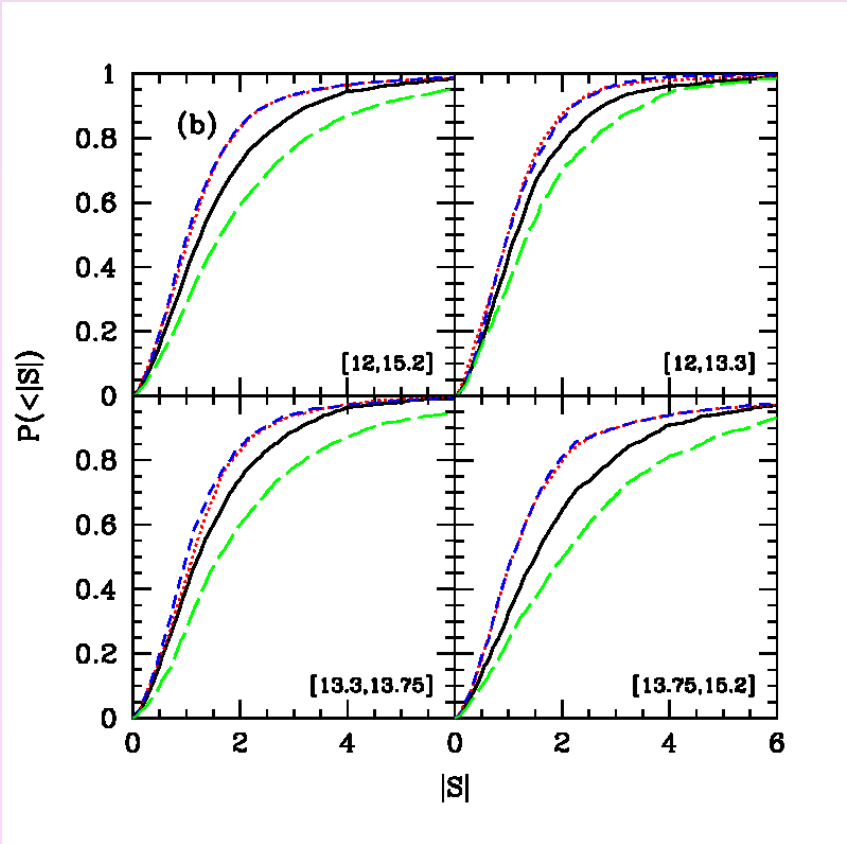
Hypothesis #1: Central galaxies with velocity bias

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

cumulative $\mathcal{R}$ distributions



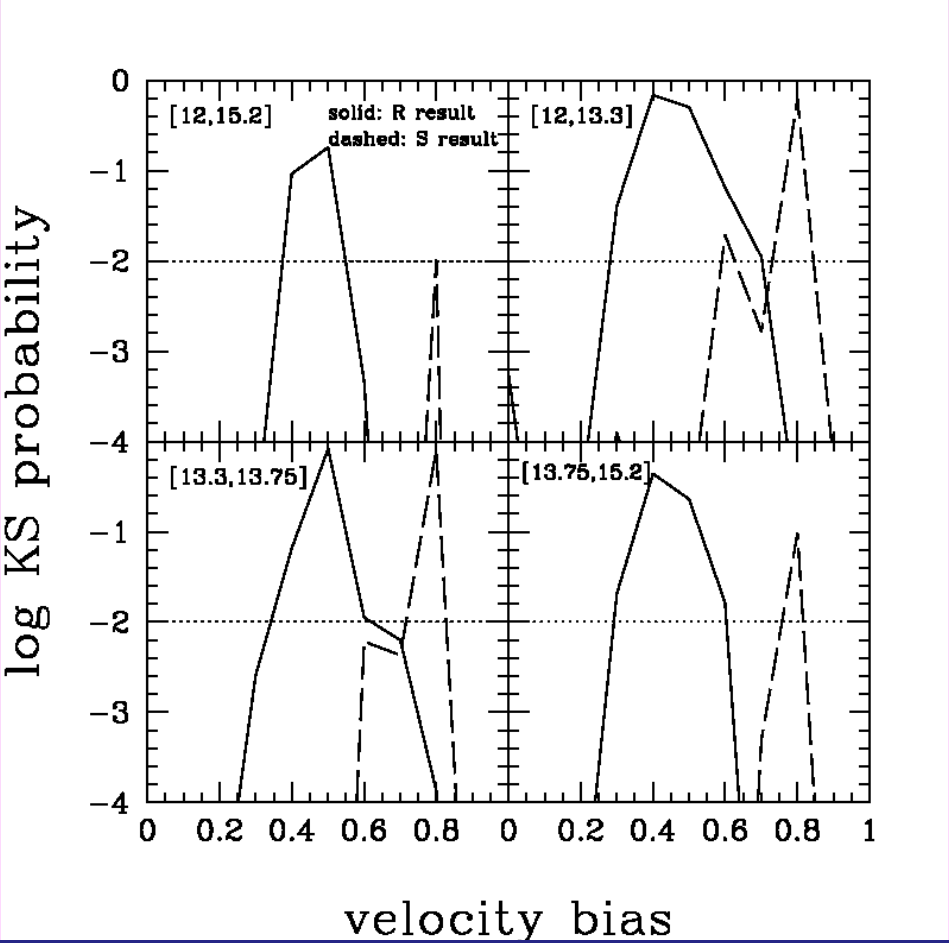
cumulative $\mathcal{S}$ distributions



Hypothesis #1: Central galaxies with velocity bias

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

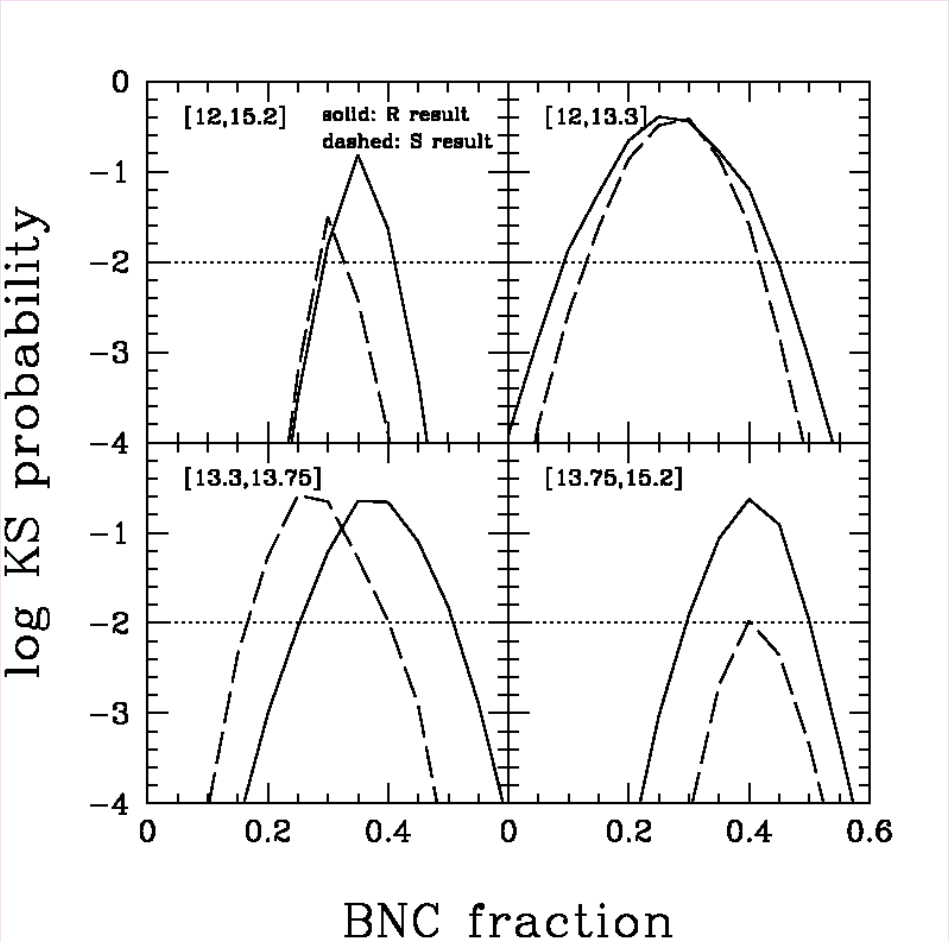
$\Rightarrow$ **BHG offsets cannot be consistently explained by velocity bias!**



Hypothesis #2: Groups with Satellite BHGs

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

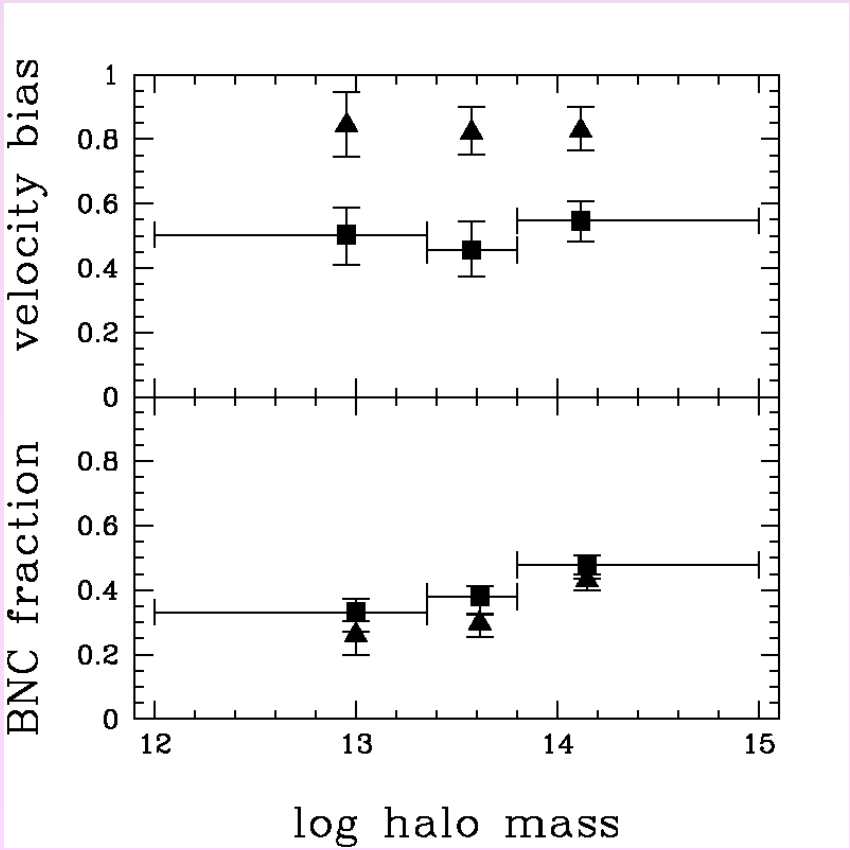
We perform same analysis of distributions of $\mathcal{R}$ & $\mathcal{S}$ BHG offsets, but comparing to mocks with no velocity bias and non-zero $f_{\rm BNC}$



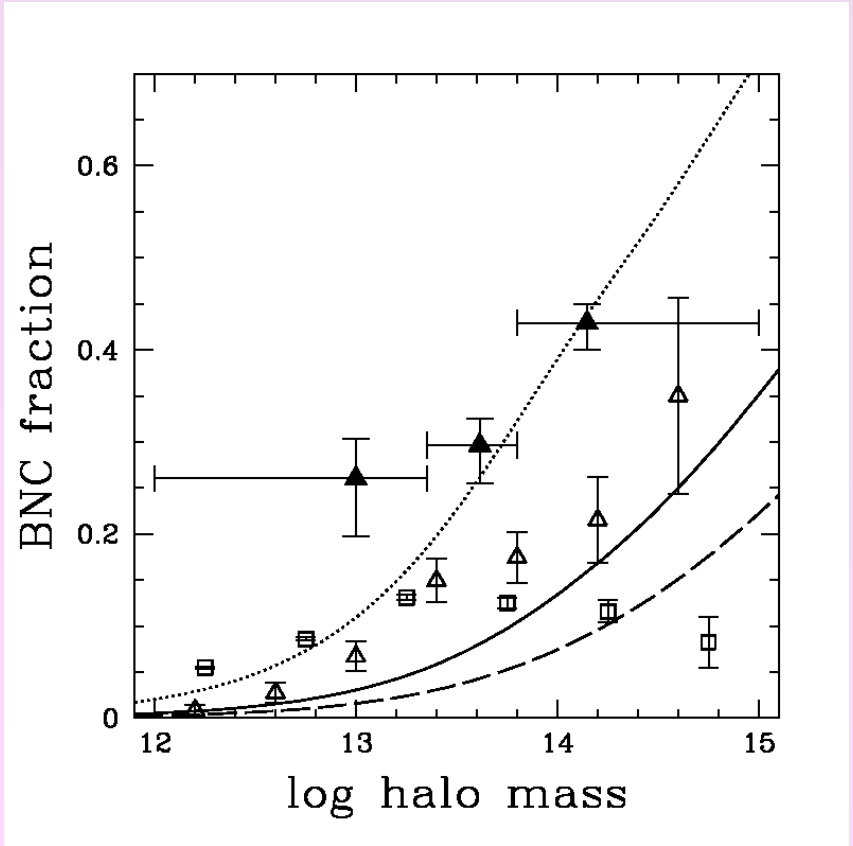
Main Result: High Fraction of Satellite BHGs

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

DOMINANT EFFECT: SATELLITE BHGS



larger fraction than expected

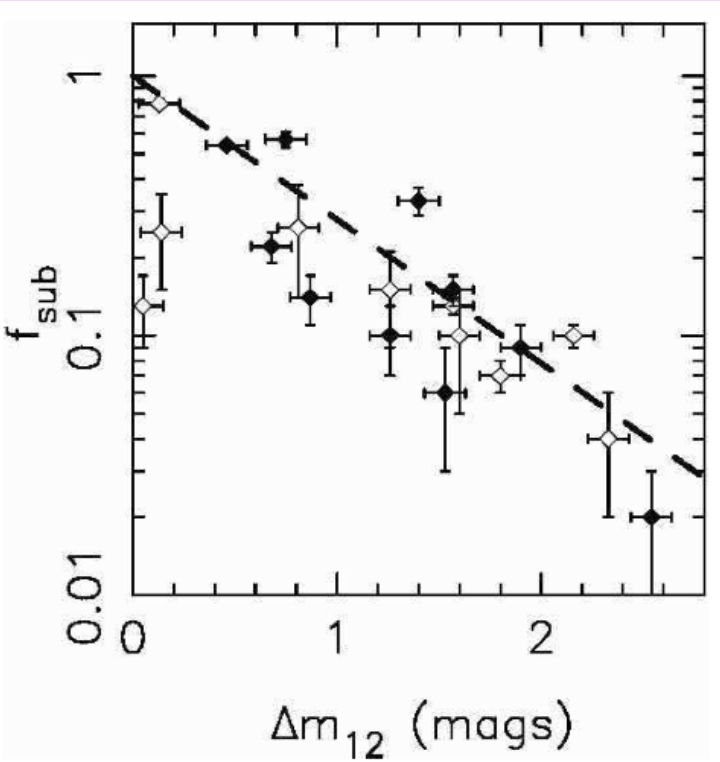


One More Test: Substructures

In principle, apparently offset BHGs could be due to substructures (not included in the mock group catalogs).

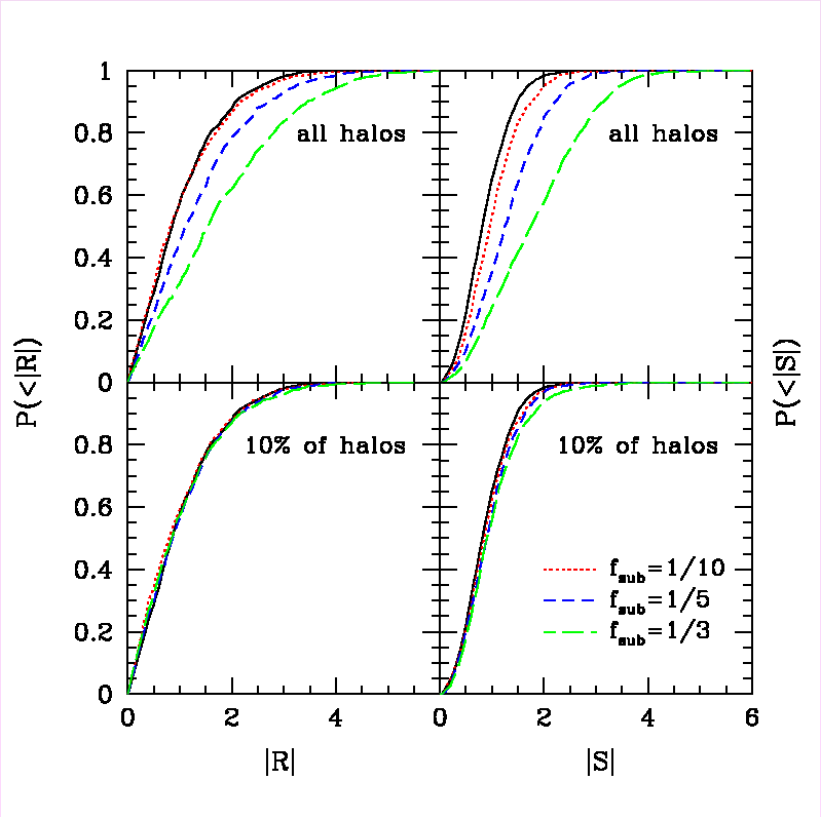
We estimate $\sim 8\%$ of systems have massive substructures, and this is not enough to significantly affect the distributions of $\mathcal{R}$ & $\mathcal{S}$ offsets

substructures $\rightarrow$ less dominant BHGs?



Richard et al. (2010)

overall, substructures have small effect



Skibba et al. (2011)

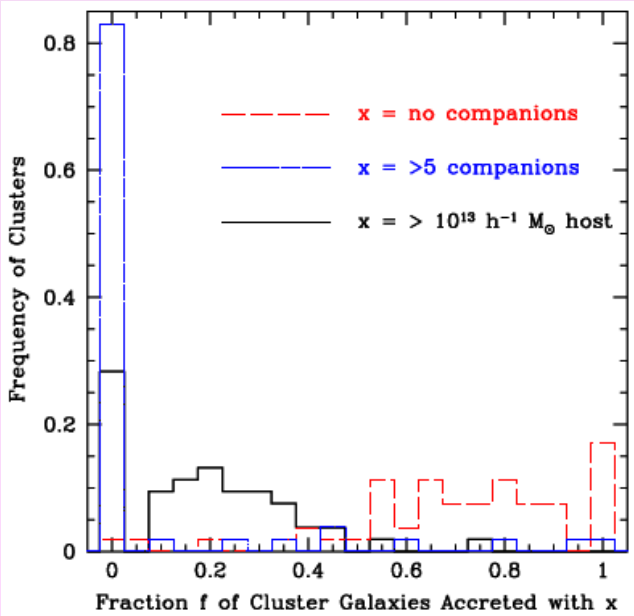
Why?

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

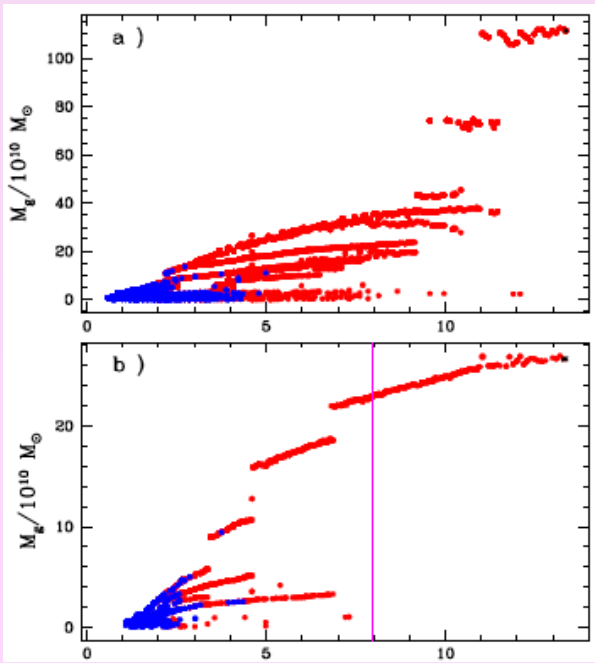
accreted satellites may continue forming stars (right); this could increase their mass relative to central galaxy

assembly of clusters



Berrier et al. (2009); Cohn (2011)

cen (top) & sat (bottom) mass assembly



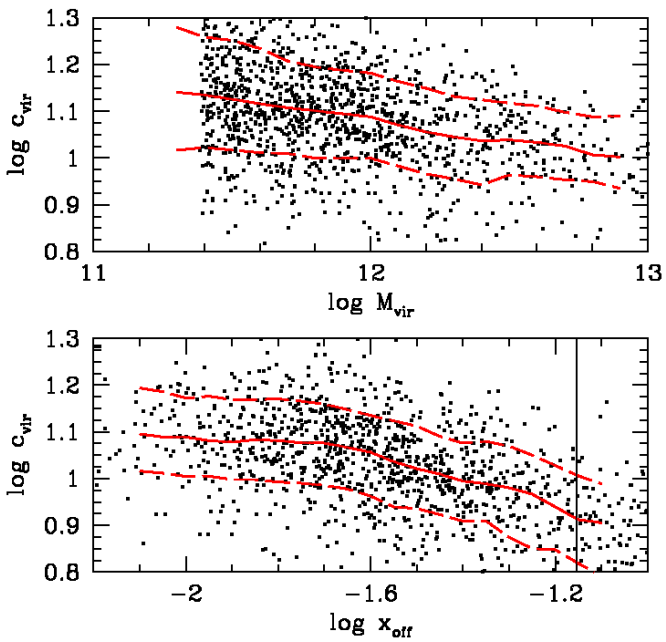
Simha et al. (2008)

A Related Issue: Unrelaxed Halos

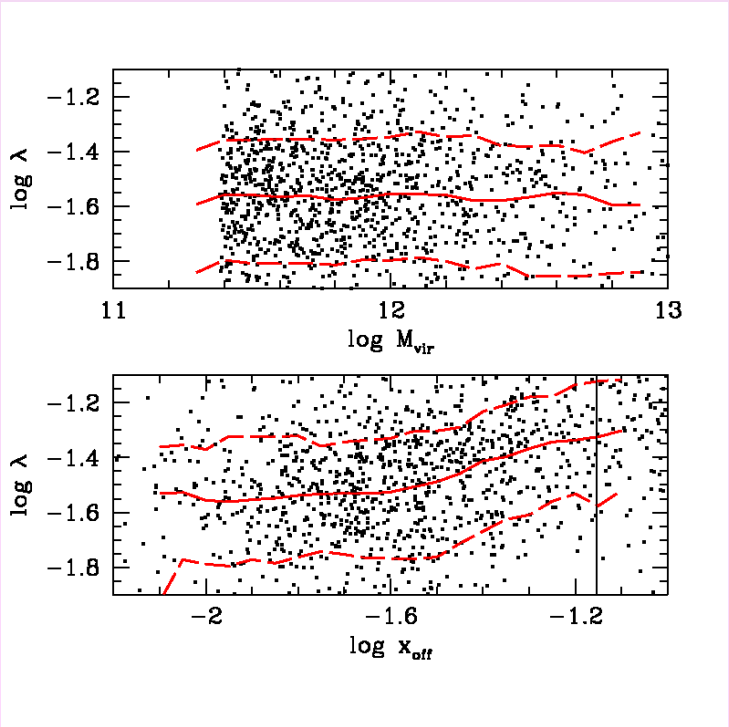
Results from Principal Component Analysis of halo properties:

- **halo mass is not a dominant halo property!** Mass appears on $1^{\rm st}$ PC only for relaxed halos (in dynamical equilibrium)
- **halo relaxedness is as important as halo mass**

correlation with concentration



and spin parameter



Skibba & Macciò (2011, MNRAS, 416, 2388)

Implications of Our Result

implications for different fields:

- large fraction of systems without dominant central galaxy
- studies of galaxy clustering and weak lensing should account for large $f_{\rm BNC}$ (see e.g., Reid et al. 2010)
- cluster mass estimates (e.g., from satellite kinematics; More et al. 2011) could be biased; mass-richness relation could be affected (e.g., Rozo et al. 2011)
- studies of BCGs as 'standard candles', or association of BCGs with central galaxies, for cosmological constraints
- comparisons of 'central' and 'satellite' galaxies in groups & clusters (e.g. Neistein et al. 2011)
- also specific applications: e.g., Milky Way and LMC, SMC (Busha et al. 2010b); or galaxies in Coma cluster

More Implications

constraints on galaxy formation models:

- dynamical friction time-scales may be too short (Boylan-Kolchin et al. 2008)
- related issue: may need to revise assumptions about merger rates (Hopkins et al. 2010)
- star formation in infalling satellites is not immediately suppressed (e.g. Weinmann et al. 2009); uncertainty of star formation after mergers (Cox et al. 2008)
- fate of disrupted satellites: mergers versus contribution to ICL

Conclusions

- Analytic & semi-analytic models assume central galaxies and brightest halo galaxies (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 BHGs are mostly explained by a non-zero fraction of groups and clusters in which a satellite is the brightest (or most massive) galaxy.

- This fraction is **surprising large** and **increases with halo mass**, from $\approx 25\%$ to $\approx 40\%$ in massive halos, with important implications for various areas in astronomy.

Extensions

extensions of this project...

- focused studies of galaxy formation models (with Benson, Fontanot): constraints on merger rates and star formation physics
- relation between galaxy kinematics, infalling subhaloes, alignment with large-scale structure, (Cohn, White)
- more comparisons with statistics of halos and substructures
- apply these results to construct more realistic mock catalogs