Are Brightest Halo Galaxies ‘Central’ Galaxies?

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1. Overview

According to the current paradigm of galaxy formation, all galaxies form as a result of gas cooling at the center of the potential well of dark matter halos. When a halo and its ‘central’ galaxy is accreted by a larger halo, it becomes a subhalo and its galaxy becomes a ‘satellite’ galaxy. By analyzing the positions and velocities of brightest halo galaxies (BHGs) relative to the other galaxies occupying the halos, we show that two related assumptions in this paradigm are false. *We argue that: (i) the central galaxy in a halo is not always the most luminous (or most massive) galaxy; and (ii) the brightest galaxy is not always at rest at the center of a virialized halo's potential well.*

We use a galaxy group catalog extracted from the Sloan Digital Sky Survey, and we compare it to mock group catalogs. We analyze the distributions of two parameters, quantifying the (projected) spatial offsets and (line-of-sight) velocity offsets of BHGs, relative to the other galaxies in the halos. We test three hypotheses that could explain the spatial and dynamical offsets of BHGs:

- Central galaxies are the BHGs, but have some amount of ‘velocity bias’ (b_{vel}), resulting in a particular distribution of offsets.
- **In some fraction of halos (f_{BNC}) the brightest galaxy is not the central one, and is therefore offset (and moving) to the halo center.**
- Halos may have a fraction of their satellites (f_{sub}) clumped in a substructure, so that the BHG appears to be offset from the other halo galaxies.

We argue that, although all three effects occur, the second hypothesis is by far the dominant effect. We quantify the fraction fBNC and find that it increases from 0.25 in low-mass haloes to 0.40 in massive haloes. This fraction is surprisingly large, and is at odds with predictions from semi-analytic models of galaxy formation. We suggest that dynamical friction time-scales in the models are too short, or the mass growth of satellite galaxies is suppressed too efficiently.

2. SDSS Group Catalog *vs.* Mock Catalogs

We use the Yang et al. (2007) galaxy group catalog, which is constructed by applying a dark matter halo-based group-finding algorithm to the SDSS, Data Release Four (Adelman-McCarthy et al. 2006). We include galaxies with an extinction-corrected apparent magnitude brighter than m_r=–18 and with redshifts in the range $0.01 < z < 0.20$. We have 7234 groups with three or more galaxies that satisfy our selection criteria. We exclude groups in which the most massive galaxy is not still the most massive member of the group when fiber-collided galaxies are included, yielding a sample of 6260 groups.

We construct mock galaxy redshift surveys (MGRSs) by populating dark matter halos in numerical simulations with galaxies of different luminosities, using the conditional luminosity function (CLF) model described in Cacciato et al. (2009). The CLF describes the halo occupation statistics of SDSS galaxies, and it is constrained to match the SDSS *r*-band luminosity function and clustering strength of SDSS galaxies as a function of luminosity.

A brightest halo galaxy (BHG) may be separated from the center of the dark matter halo for one of two reasons: (*i*) **it may be a satellite galaxy, rather than the central galaxy of the halo**; (*ii*) **or it may be a central galaxy that is offset and moving with respect to the center of the potential well**. We attempt to explain the relative positions and velocities of BHGs with models in which either the BHGs are satellites in some fraction of halos, or the BHGs have peculiar velocities with a particular distribution.

3. Galaxy Positions and Velocities

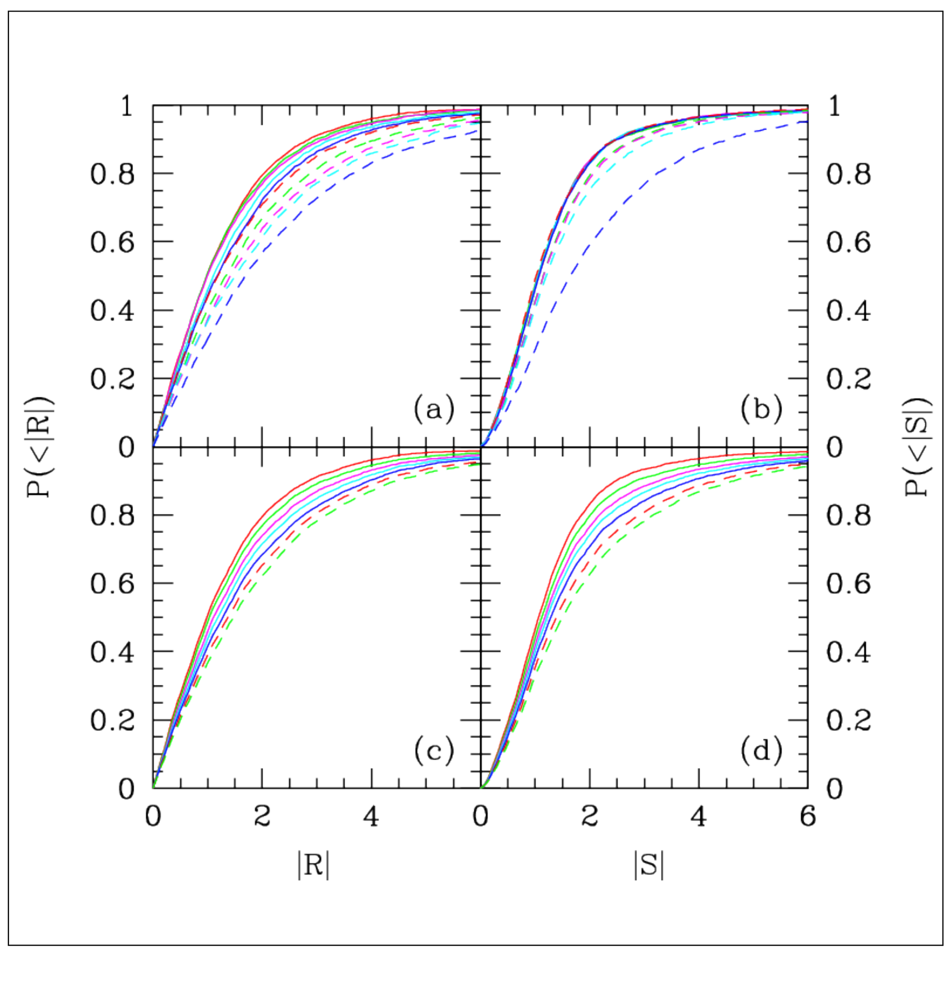
We quantify the relative line-of-sight velocities (from redshifts) and projected separations of brightest halo galaxies using the following parameters.

spatial offset: $$S = \frac{\sqrt{N_{sat}}\left(\bar{r}_{p,sat} - r_{p,BHG}\right)}{\sigma_{r_{p,sat}}}$$

velocity offset: $$R = \frac{\sqrt{N_{sat}}\left(\bar{v}_{sat} - v_{BHG}\right)}{\sigma_{sat}}$$

We compare the cumulative distributions of these *R* and *S* parameters in the SDSS group catalog and mock group catalogs. We construct two sets of mock catalogs: *(i)* mocks in which some fraction of halos the brightest galaxy is not the central galaxy, and *(ii)* mocks in which the BHGs are central galaxies but have a peculiar velocity relative to their host dark matter halos.

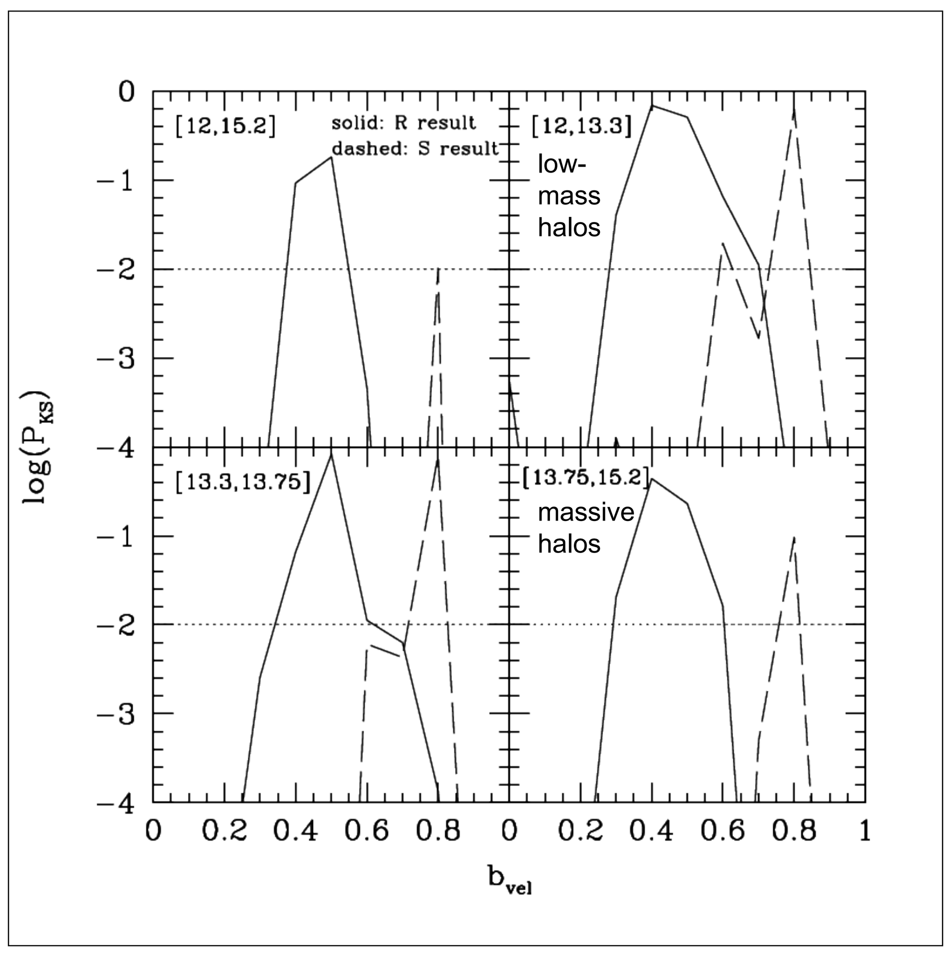
Models in which the brightest halo galaxy is always the central galaxy and is always at the center of the dark matter halo are ruled out by the data. In the mock catalogs, the *R* and *S* distributions vary with f_{BNC} and b_{vel} (right), allowing us to constrain one or both of these parameters with the distributions obtained from the SDSS catalog.



4. Results

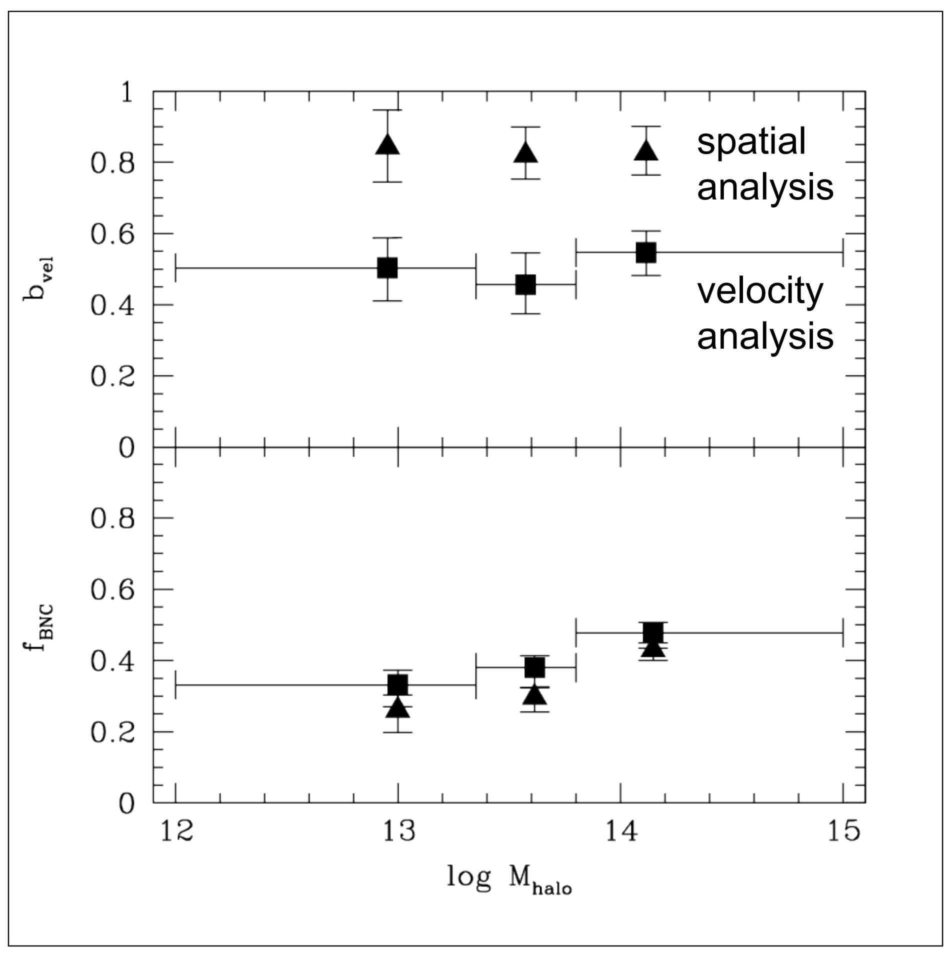
Hypothesis #1: Brightest halo galaxies are offset from the center of their host dark matter halos, and from the other group members, because they have velocity bias.

The velocity analyses with *R* distributions (solid lines) yield lower values of b_{vel} than spatial analyses with *S* distributions (dashed lines). (See also upper panel of figure below.) *Therefore, velocity bias cannot consistently explain the velocity and spatial offsets of BHGs.*



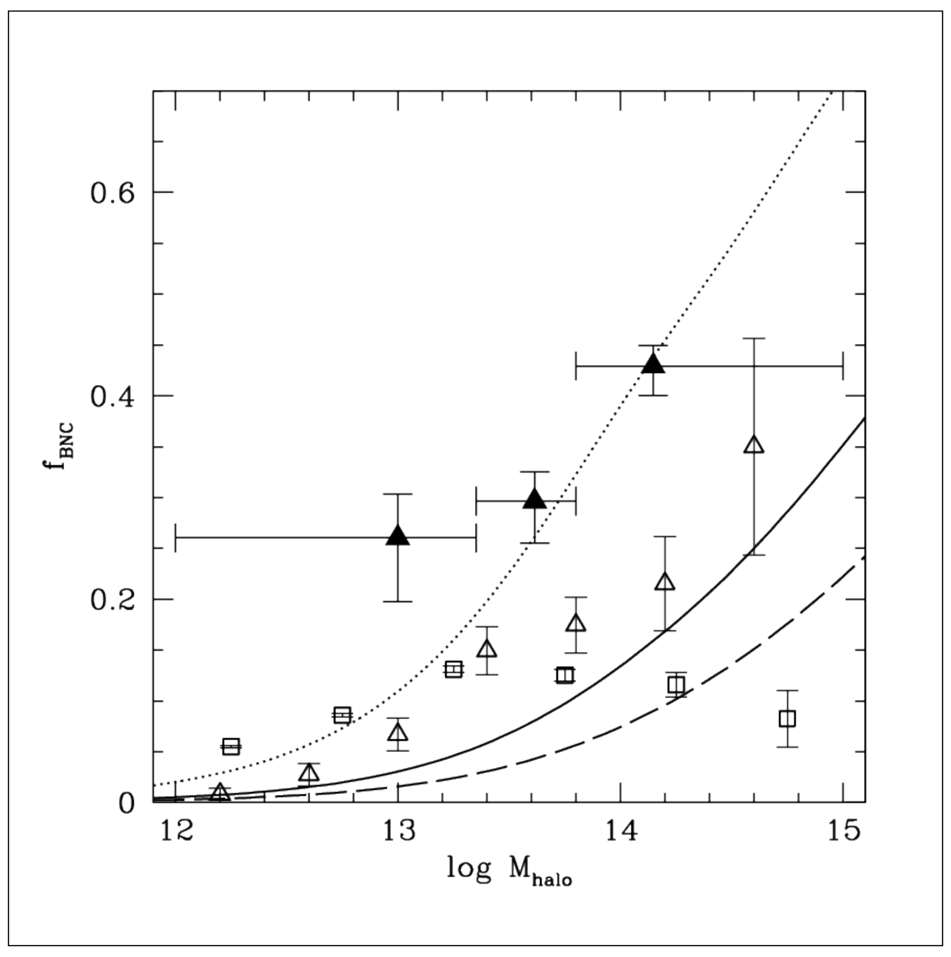
Hypothesis #2: Brightest halo galaxies are offset from the center of their host halos, and from the other group members because they are sometimes satellite galaxies.

The relative line-of-sight velocities and projected separations of BHGs are consistent with a similar fraction f_{BNC} (lower panel). *Therefore, we argue that the velocity and spatial offsets of BHGs are mostly due to the fact that in a large mass-dependent fraction of halos they are* not *central galaxies.*



Statistically, the large fraction of halos with satellite BHGs can be explained by scatter in central galaxy luminosity at fixed halo mass and a satellite luminosity function with a slope shallower than expected (dotted line).

The fraction f_{BNC} is also significantly larger than predicted by two semi-analytic models (open points; Croton et al. 2006; Monaco et al. 2007). Perhaps the dynamical friction time-scales in the models are too short, or star formation in satellites is too efficiently suppressed.



5. Conclusions

Galaxy formation models typically assume that the central galaxy in a halo is the most massive and most luminous galaxy, and that the central galaxy is at rest at the center of the dark matter halo. *Both of these assumptions are false.*

- **The observed velocity and spatial offsets of brightest halo galaxies imply that in a significant fraction of halos, the BHG is *not* the central galaxy.** This fraction is large and increases from **≈25% in low-mass halos** to **≈40% in massive halos**.

We argue that the large fraction of halos with satellite BHGs is due to recently accreted relatively massive satellite galaxies that have not merged and may still be growing. These systems may also be dynamically unrelaxed, which is not unexpected, because many halos themselves are unrelaxed (Skibba & Macciò 2011).