Predictably Missing Satellites: Subhalo Abundance in Milky Way-like Halos

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Abstract

Many solutions have been proposed for the infamous 'missing satellites problem'; however, the impact of the specific properties of the Milky Way (MW) halo relative to the typical halo of its mass have yet to be explored. We investigate how the properties of dark matter halos with mass comparable to our Galaxy's correlate with the abundance of subhalos by building two models of subhalo abundance as functions of host halo properties. We conclude that the MW should be expected to have **22%-44% fewer than average subhalos with low maximum rotation velocities** (95% range) and up to **72% fewer subhalos with high rotation velocities** than a typical halo of the MW's mass. We find that halo spin, shape, and especially concentration provide useful information for predicting subhalo abundance in the MW mass range, and that models tuned to explain missing satellites using mean halo properties may actually overcorrect for the subhalo surplus.

Introduction

Problem:

We investigate here the 'missing satellites problem (MSP), i.e. the over-prediction of the abundance of satellite halos of a particular rotation speed within a CDM model relative to the number of galaxies of similar velocities that have actually been observed in the MW (e.g., Klypin et al. 1999; Moore et al. 1999; Bullock 2010).

We explore any impact the unusual properties of the MW has on the abundance of subhalos in our Galaxy. Halo properties other than mass correlate with the subhalo population; incorporating their effects yields improved predictions of subhalo populations for a halo ***whose properties*** match the MW.

Dark Matter Halo Properties

1. Concentration $(c_{\rm NFW})$

-The concentration parameter characterizes the degree to which the mass of the halo is concentrated toward the halo center (Navarro et el. 1996).

2. Spin $(\lambda_{\rm B})$

-Angular momentum in DM halos is parameterized using a dimensionless quantity called the spin parameter (Peebles 1980, Bullock et al. 2001b).

3. Shape (c/a)

-Dark matter halos are triaxial ellipsoids, commonly described by the ratios of their principal axis lengths (Allgood et al. 2006); we choose the shortest axis to longest axis ratio as our measure of shape.

4. Scale Factor at Last Major Merger $(a_{\rm LMM})$

-The scale factor of the Universe at the time of the most recent major merger (with a mass ratio of 0.3 or greater).

Figure 1 (at the top of the next column) shows the density of dark matter in several of the halos from our simulations, in order of decreasing concentration (Mao et al. 2015). It is evident that host halos with smaller concentrations have larger subhalo abundances (note that concentration is tightly correlated with accretion history).

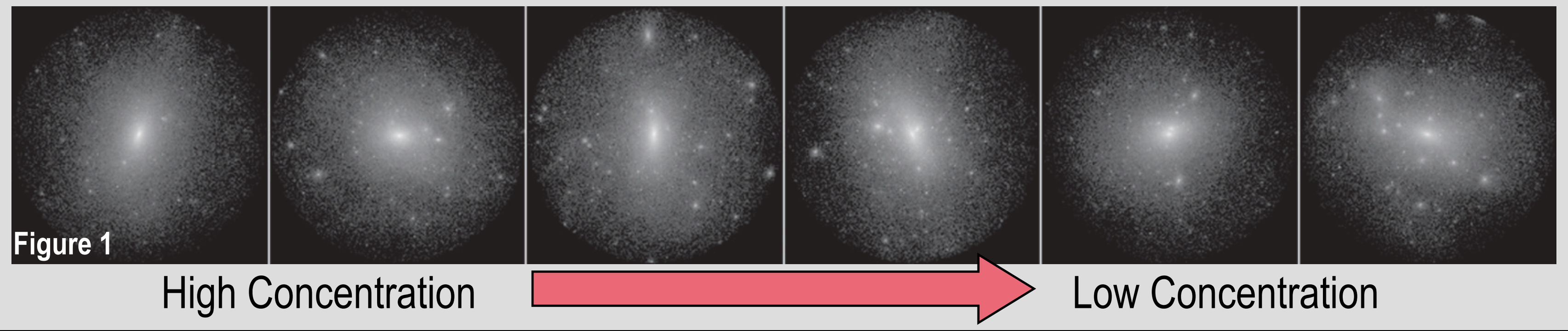

Figure 1

Simulations

- 45 Milky Way-mass ($M_{\rm vir} = 10^{12.1\pm0.03}\,{\rm M}_\odot$) halos from zoom-in cosmological simulations from Mao et al. 2015.
- Simulation resolution limit is ~10 km/s, corresponding to $V^{\rm sat}_{\rm max}/V^{\rm host}_{\rm max} = V^{\rm frac}_{\rm max} = 0.065$
- *ROCKSTAR* halo finder identifies halos, subhalos, and halo properties (Behroozi et al. 2013)

Milky Way vs. Simulated Halos

Figure 2 plots all possible combinations of the host halo parameters:

- Orange dashed region indicates range of estimated values for Sb galaxy host halos (similar to the MW)
- Black points with error bars represent estimated properties for the MW host halo
- Colored points correspond to simulated halos

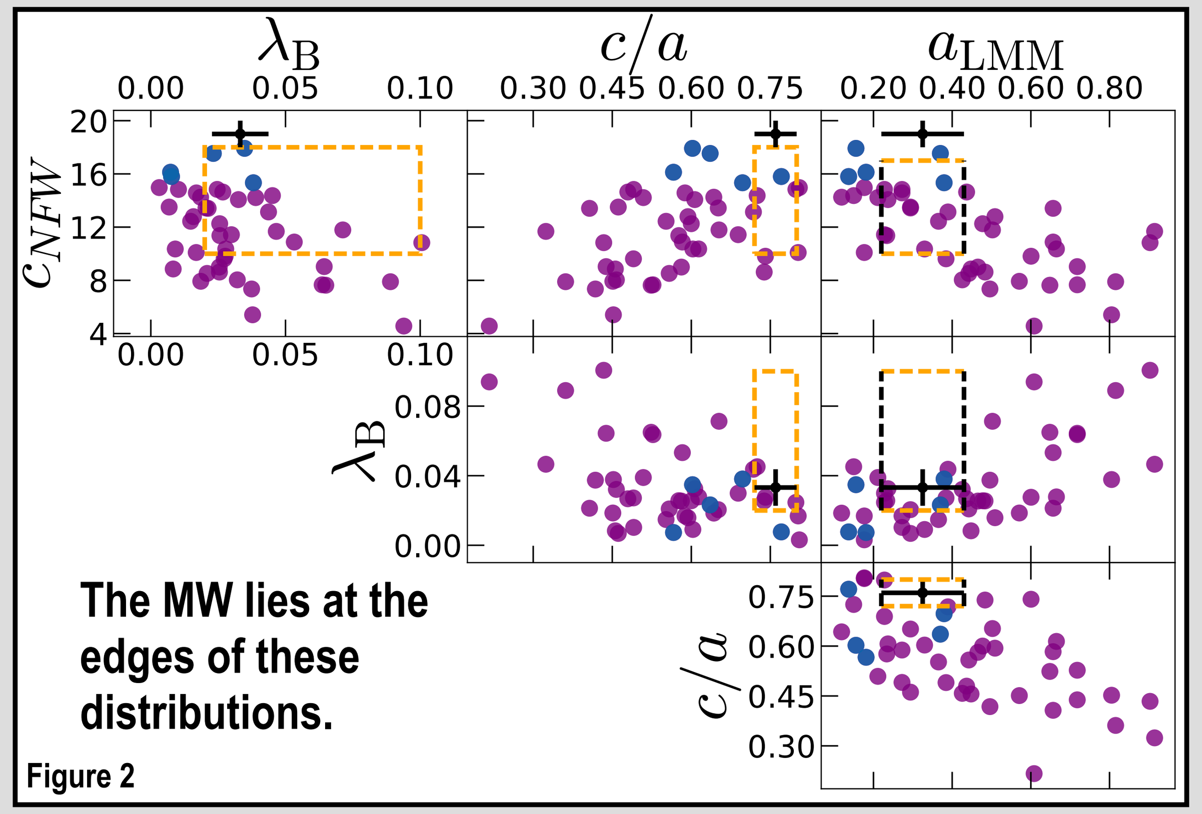

Figure 2

Predicting Milky Way Subhalo Abundance

We have built power-law scaling relation models utilizing ***combinations*** of halo properties as predictors for the number of subhalos above a given velocity to produce more accurate predictions of the subhalo abundance in the MW.

One-parameter model - incorporating only concentration to predict subhalo abundance
Three-parameter model - incorporating concentration, spin, and shape

Results

Incorporating both subhalo abundance fit and MW parameter uncertainties (purple regions), we find the Milky Way halo **is predicted to have fewer subhalos than is typical for its mass**, by:

- **Low velocity:** 22-44% (at 95% confidence)
- **High velocity:** 38-72%

Uncertainties including Poisson scatter (orange regions) are greater, making the presence of satellites as large as the Magellanic Clouds rare but not extraordinary.

Results

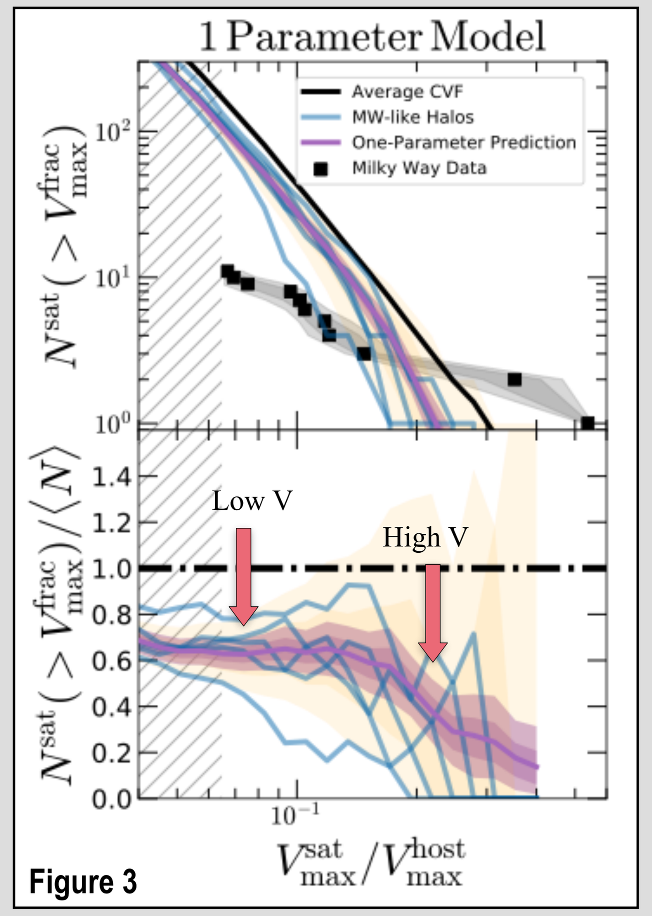

Figure 3

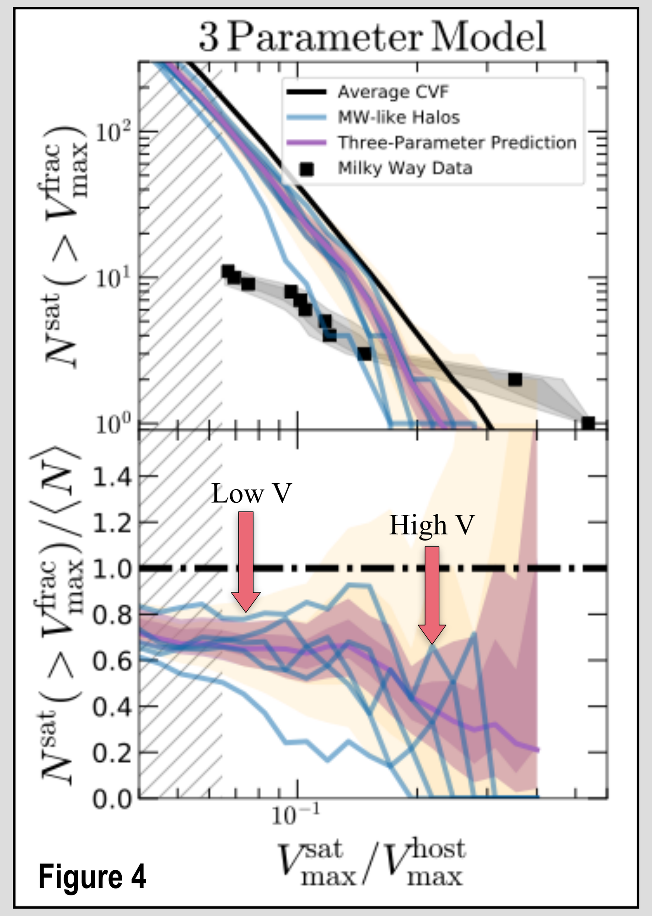

Figure 4

In both models **the predicted CVF for the Milky Way lies well below the average for the Milky Way-mass dark matter halos.**

In Figures 3 & 4 the purple lines show the predicted cumulative velocity functions (CVF) for the MW from the three- and one-parameter models when incorporating the MW host halo properties:

- Upper panel shows average cumulative number of subhalos as a function of subhalo velocity normalized by the maximum velocity of the respective host
- Bottom panel shows the ratio of the fit to the average cumulative velocity function including all host halos

Conclusions

Most information on subhalo abundance is captured with concentration alone.

When exploring factors affecting the MSP & too-big-to-fail and tuning models to match the MW's satellite population, models should predict that a galaxy will have a MW-like satellite population, not for an ***average*** halo of MW host mass, but rather **for one which has MW-like properties across the board.**

Future Work

ROCKSTAR, like previous analysis tools, includes subhalo mass when calculating host halo properties. This can have a substantial effect; for example, including the angular momentum associated with a companion like the LMC can change the inferred halo spin by a factor of two when not including the mass in subhalos (which observational constraints rarely incorporate).

Work is currently underway to explore how the ***meaning*** of halo properties change **when not including the mass in subhalos.** Figure 5 shows how the distribution of halo properties in an N-body simulation changes when subhalo mass is not included.

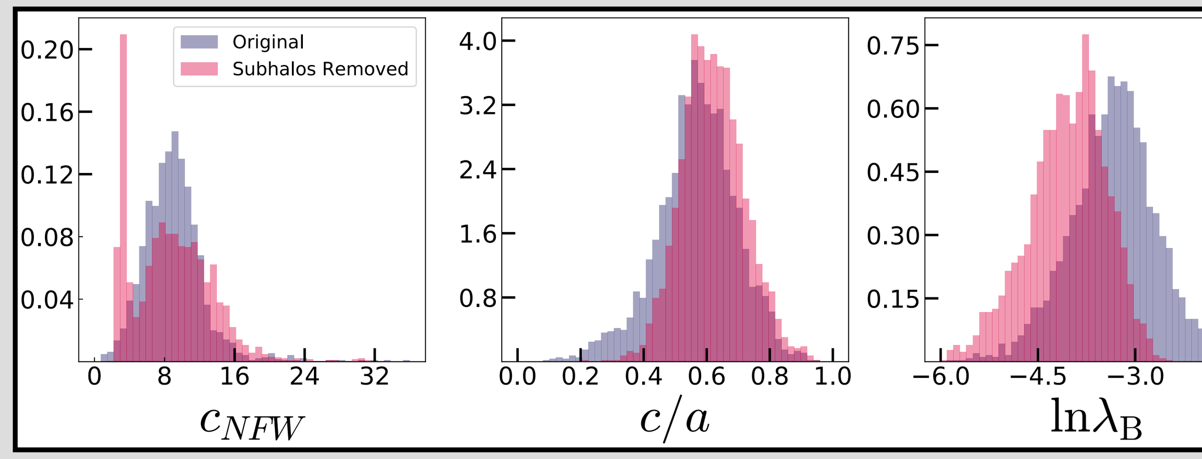

Figure 5

Sources: Allgood B., Flores R. A., Primack J. R., Kravtsov A. V., Wechsler R. H., Faltenbacher A., Bullock J. S., 2006, MNRAS, 367, 1781; Behroozi P. S., Wechsler R. H., Wu H.-Y., 2013, ApJ, 762, 109; Bullock J. S., Dekel A., Kolatt T. S., Kravtsov A. V., Klypin A. A., Porciani C., Primack J. R., 2001b, ApJ, 555, 240; Bullock J. S., 2010, preprint, p. arXiv:1009.4505 (arXiv:1009.4505); Klypin A., Kravtsov A. V., Valenzuela O., Prada F., 1999, ApJ, 522, 82; Licquia T. C., Newman J. A., Brinchmann J., 2015, ApJ, 809, 96; Licquia T. C., Newman J. A., Bershady M. A., 2016, ApJ, 833, 220; Mao Y.-Y., Williamson M., Wechsler R. H., 2015, ApJ, 810, 21, Moore B., Ghigna S., Governato F., Lake G., Quinn T., Stadel J., Tozzi P., 1999, ApJ, 524, L19; Navarro J. F., Frenk C. S., White S. D. M., 1996, ApJ, 462, 563; Peebles P. J. E., 1980, The large-scale structure of the universe