The Large Magellanic Cloud in the SDSS and LCDM: Is There A "Found Satellites Problem"?

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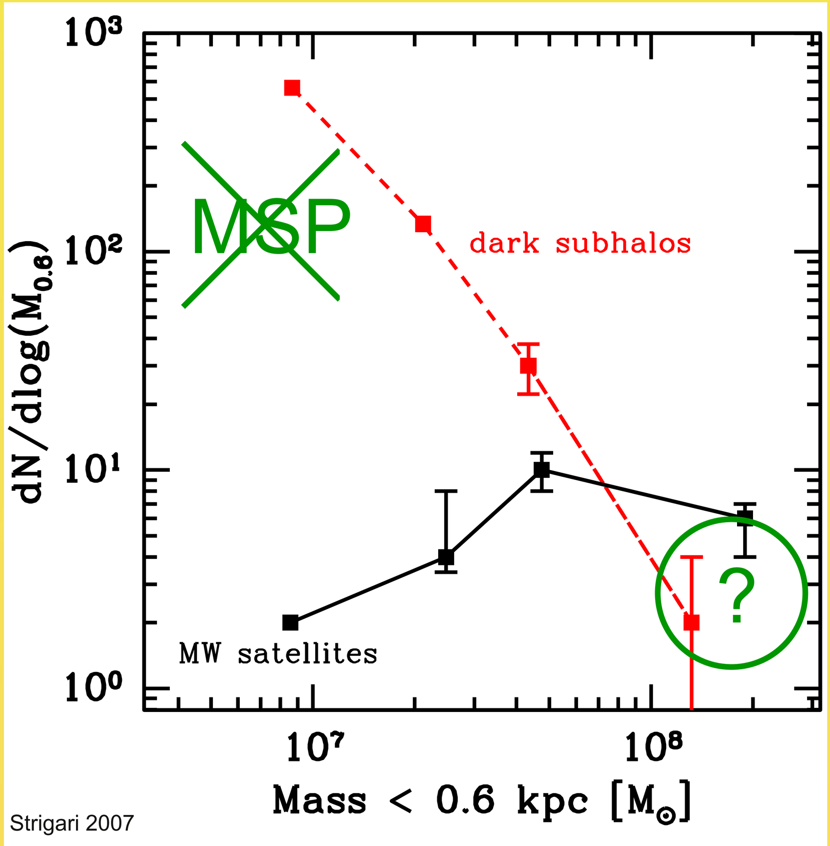
Substructure in ΛCDM provides a number of interesting puzzles. While the missing satellites problem is well-studied, there are suggestions of an opposite problem on the bright end. Subhalos large enough to host luminous satellites are uncommon, so the existence of the Large Magellanic Cloud (LMC) orbiting the Galaxy can potentially be a challange for ΛCDM. Hence, we describe a search for analogs to an isolated galaxy pair like the Milky Way/LMC system in the SDSS and interpret these results with cosmological simulations. We note that while the LMC may not be unusual based on its luminosity, it is remarkably blue for such satellites. Thus, color may have implications for the LMC's orbital history. We discuss use of these methods as general tools for interpreting similar satellites in a cosmological context.

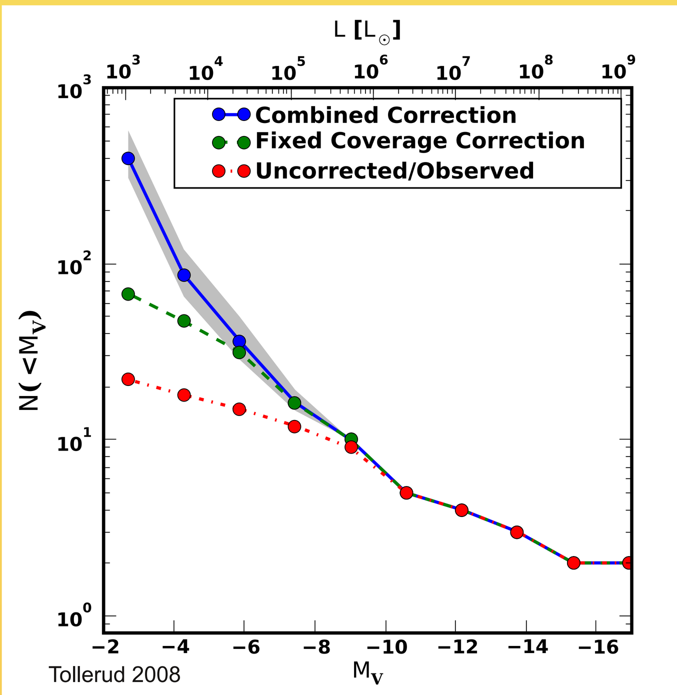
Satellites in ΛCDM: Issues?



Strigari 2007

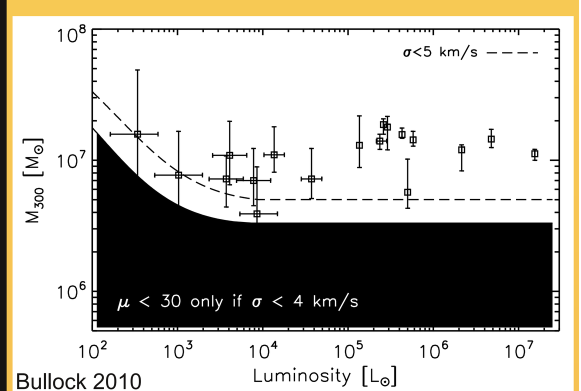
Biases Control Faint Satellite Counts Even For MW

The Missing Satellites Problem (MSP) has concerned LCDM for some time (Klypin 99, Moore 99) - there exist too few satellite galaxies bound to large halos to account for all of the subhalos predicted by simulations. The recent doubling of the number of known Milky Way satellite galaxies due to SDSS suggests an explanation: detection bias.

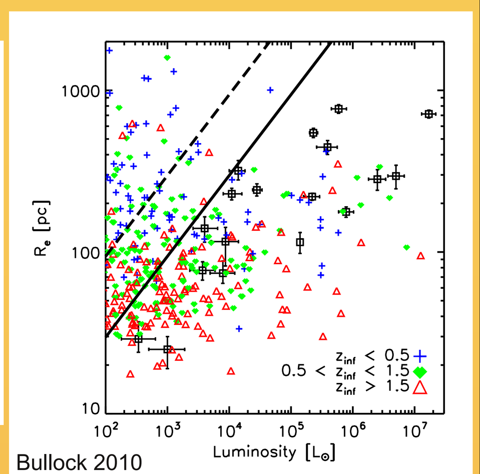


Tollerud 2008

Tollerud et al. 2008 showed how, using detection limits for dSphs from Koposov 2008 and Walsh 2009, large numbers of satellites are undetected due to their intrinsically low luminosities, if the satellites follow LCDM-like subhalo distributions. Correcting for this luminosity bias can result in enough undetected satellites to alleviate the MSP.



Bullock 2010

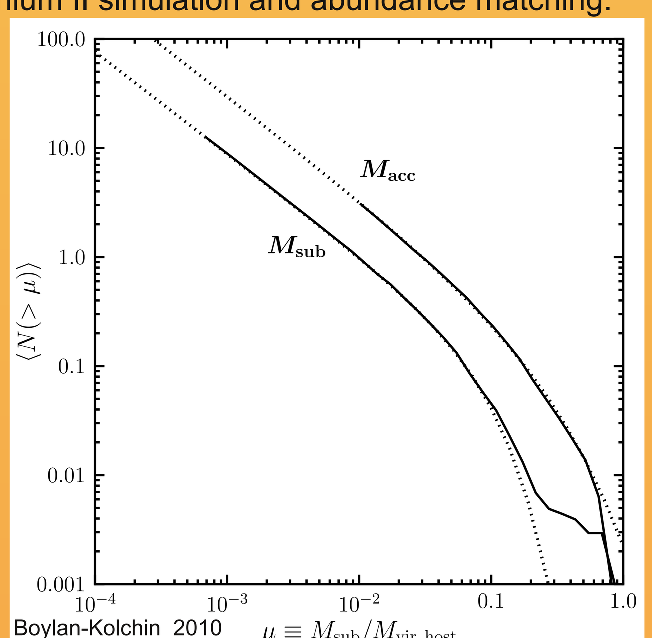


Bullock 2010

Bullock et al. 2010 showed the importance of surface brightness detection bias. Koposov 2008 and Walsh 2009 both find sharp cutoffs in detectability with surface brightness, so physically larger satellites go undetected. This results in another factor of ~ 2 dSphs likely to go undetected in SDSS, as well as rendering only the highest (dark matter) mass satellites detectable.

Bright Satellites (Like LMC) Unusual?

In contrast, the bright Milky Way satellites (the Magellanic Clouds) may be unusual in their presence. As the figure at the top of this panel shows, simulations suggest most Milky Way-like halos should not have an LMC-mass subhalo. Boylan-Kolchin et al. 2010 find ~10% of Milky Way-like halos should have Magellanic Clouds, based on the Millennium II simulation and abundance matching.



Boylan-Kolchin 2010

MW/LMC Analogs

(Tollerud et al. 10, in prep)

Motivated by the observation that subhalos corresponding to the Magellanic Clouds might be unusual for Milky Way-sized halos (see left panels), we search the SDSS for analogs to the MW/LMC system. These systems are then compared to halo/subhalo samples in n-body simulations that are selected to be as similar as possible to the selection performed on the SDSS data.

SDSS DR7/VAGC Sampling

We use the NYU Value Added Galactic Catalog (Blanton et al. 2005) with the SDSS DR7 spectroscopic sample as our source catalog, using the K-corrected absolute magnitudes (with h=1).

- Host must be isolated and MW luminosity.
- Satellite must be LMC luminosity and nearest to Host.
- Sample is Volume-limited.

i.e.:

- Host must have r < -20
- Host must have no bright (r<-20) galaxies within 700 kpc/h or only one 250-700 kpc/h away.
- Host must have z < .035
- Satellite must have -17.5 < r < -20
- Satellite must be closest neighbor of host
- $|v_{host}-v_{sat}|$ < 500 km/s
- d_{proj} < 250 kpc/h

The redshift restriction ensures the sample is volume-limited for satellites down to r < -18. The satellite magnitude range is set to approximate the luminosity of the LMC from RC3 adapted to the SDSS bands: r_{LMC} ~ -18, while still maintaining a volume large enough to have a decent statistical sample.

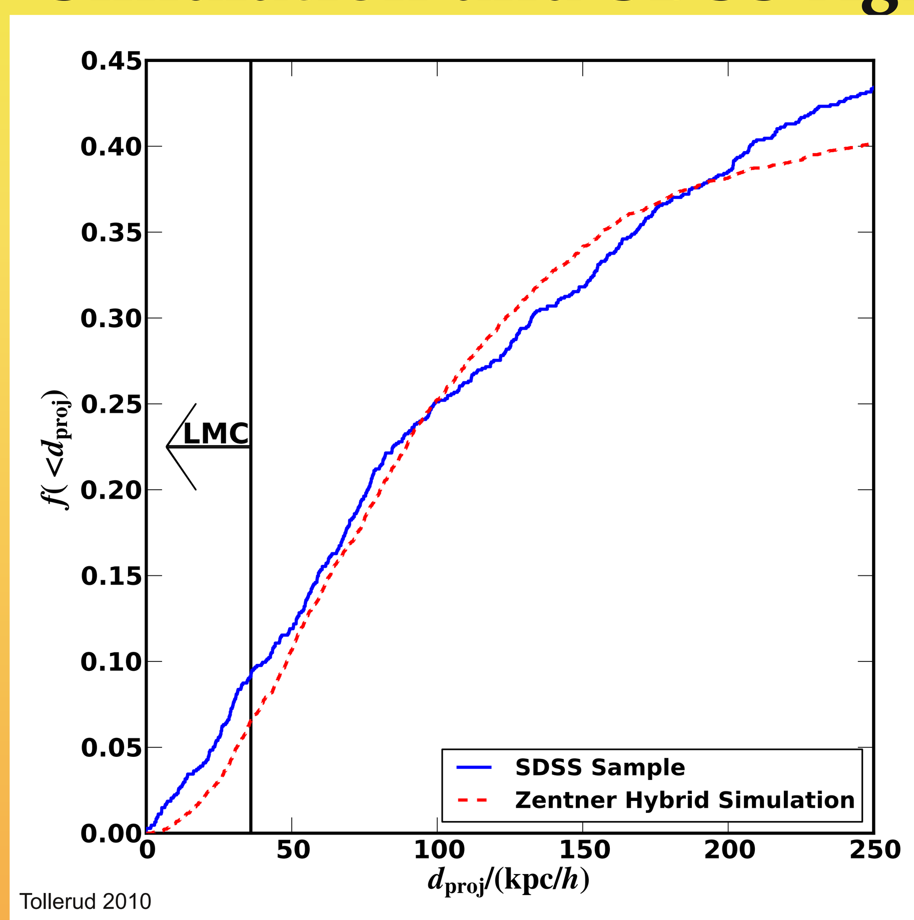
Simulation & Controls

Our primary comparison simulation is that of Zentner et al. 2005. The model is a hybrid n-body model that uses a cosmological n-body simulation for host/main halos, joined to a detailed semi-analytic model for subhalos. Thus it is a better substructure catalog than is possible with n-body alone.

We sample from this simulation using the same seperation and redshift requirements as the SDSS sample, and use abundance matching to determine halo mass ranges for the host and subhalo sample: host v_{max} > 196 km/s , and 114 km/s < v_{max} < 196 km/s for subhalos. As described in Barton et al. 2009, this sample gives > 98% isolated hosts, justifying our isolation criteria.

Due to the size of SDSS fibers, the SDSS spectroscopic sample can be biased against very close pairs. To assess this effect, we also construct a catalog that relaxes the Δv < 500 km/s requirement for both the simulation and the SDSS sample. The simulation reveals less than 99.5% of apparent LMCs within 100 projected kpc/h from their host are true satellites, and even at 250 kpc/h, over 95% are. Within the fiber radius at z=.035, the radial distributions are indistinguishable in the two SDSS samples. Hence, we use the Δv sample, as it has fewer false satellites at intermediate distances.

Simulation and SDSS Agree

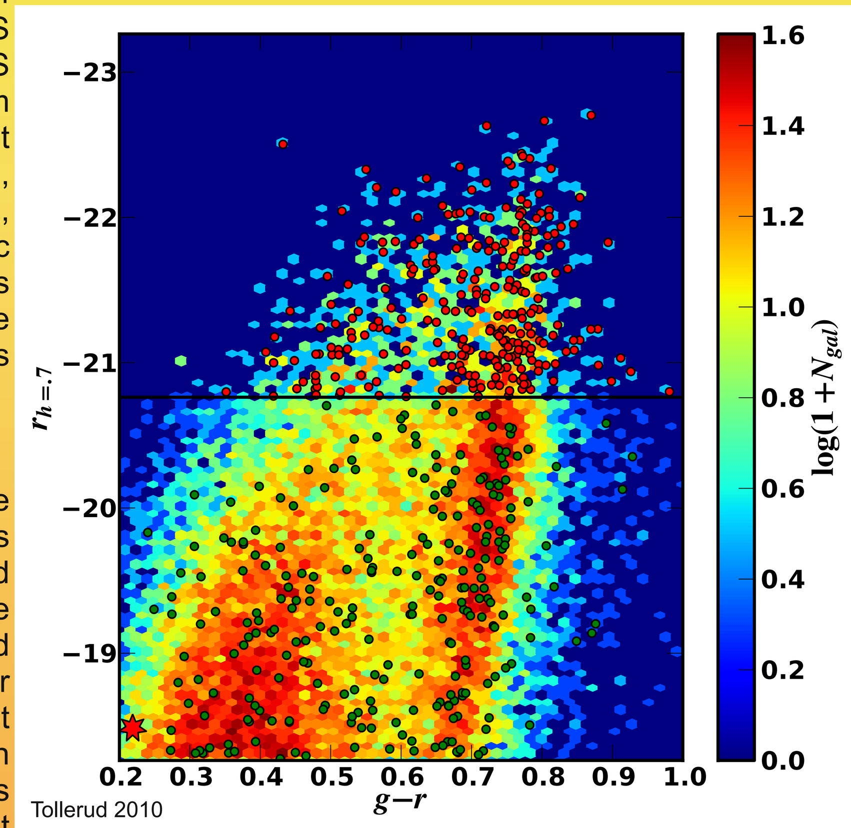


Tollerud 2010

To the left, we show the distribution of host-satellite separations for the SDSS and simulation samples. The main SDSS sample closely tracks the distribution from the simulation. There are deviations at very small separations and >200 kpc/h, but the deviations are surprisingly small, approximately at the level of cosmic variance. Additionally, ~10% of analogs are within the physical distance of the LMC. This implies the LMC/MW pair is not a strikingly improbable combination.

LMC Is Unusually Blue

To the right, we show the color-magnitude diagram of satellites (with d<100 km/s) as green circles, and their hosts as red circles. The color bins underneath are CMD distributions for all objects that could have been hosts (above black line) or satellites (below). It is clear from this plot that the LMC, while not unusual in luminosity for an MW-like satellite, is strikingly blue - in fact, one of the bluest satellites in the sample.



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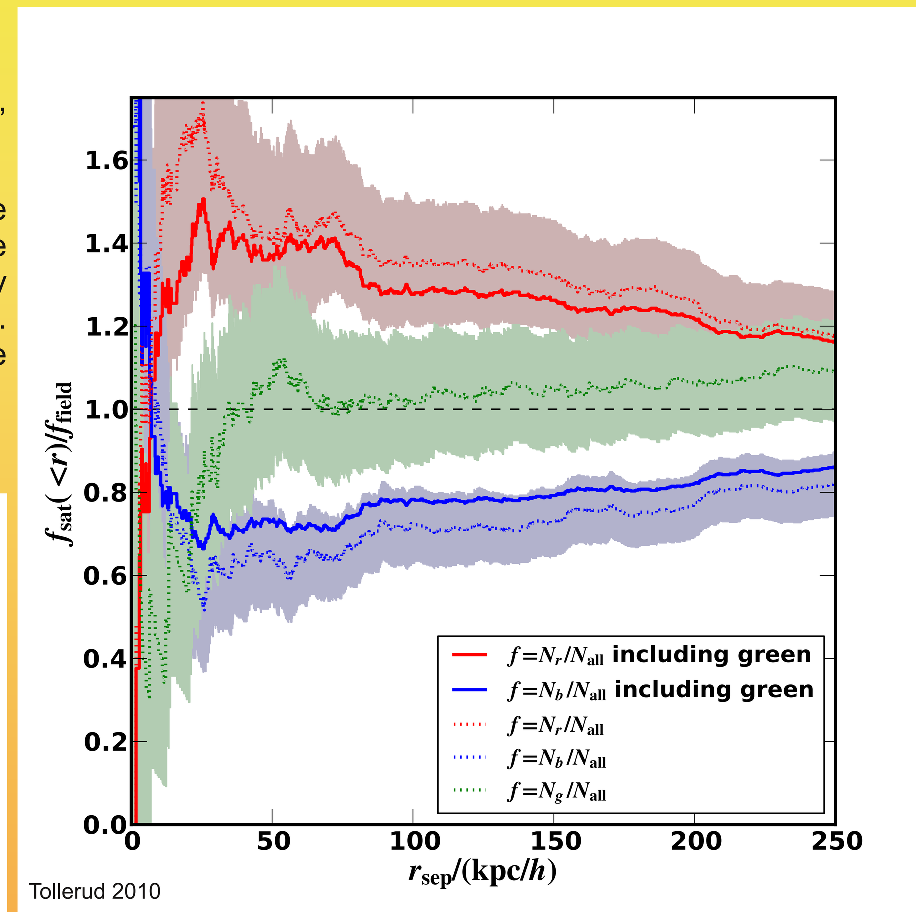
LMC Analogs Are Typically Red

With a sample of SDSS systems that the simulation shows are genuine MW/LMC-like systems, we further consider what this sample can tell us about the population statistics of the satellites.

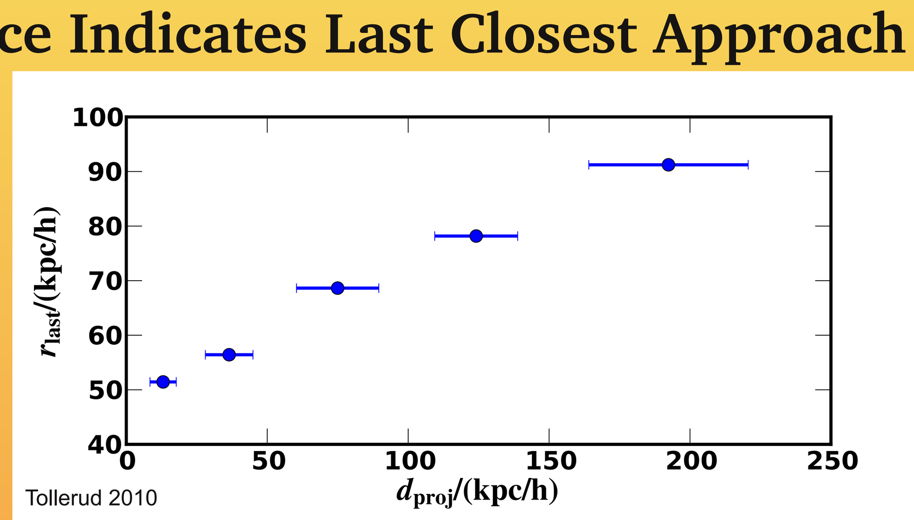
We first bin the satellites into red (0.64<g-r<1), blue(0<g-r<0.5), and green(0.5<g-r<0.64) on the basis of the satellites' observed SDSS color. We then compare the fraction of satellites that are in each bin relative to the fraction in the same color bin for all galaxies in the satellite luminosity range (i.e. primarily a field sample). We show this to the right, along with Poisson error regions. Clearly, the satellites have a tendency to be more red than the field population, except for the very smallest separations.



Tollerud 2010

Projected Distance Indicates Last Closest Approach

The plot on the lower-left of this panel shows the mean distance of last closest approach as a function of projected separation for the Zentner sample. This clearly indicates that nearby satellites are more likely to have had a closer approach to their host, suggesting they may experience triggered star formation.



Tollerud 2010

Conclusions

- In the SDSS, ~ 10% of Milky Way-like galaxies have LMC-like satellites at similar distances, suggesting the LMC is not that strange.
- The radial distribution of LMC-like satellites is consistent with a simulation selected using the same criteria as that used for the SDSS sample, implying n-body simulations correctly reflect the dynamics of LMC/MW systems.
- The LMC is remarkably blue compared to similar satellites. This may imply it is on first infall (as the proper motions of Kallivalyalil et al. 2006 suggest), suggesting that the MW may have had a relatively quiet accretion history (e.g. Hammer et al. 2007, Purcell et al. 2009), until the present epoch.

References

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