How common are the Magellanic Clouds?

Brian Gerke, KIPAC/SLAC

UCSC Galaxy Formation Workshop

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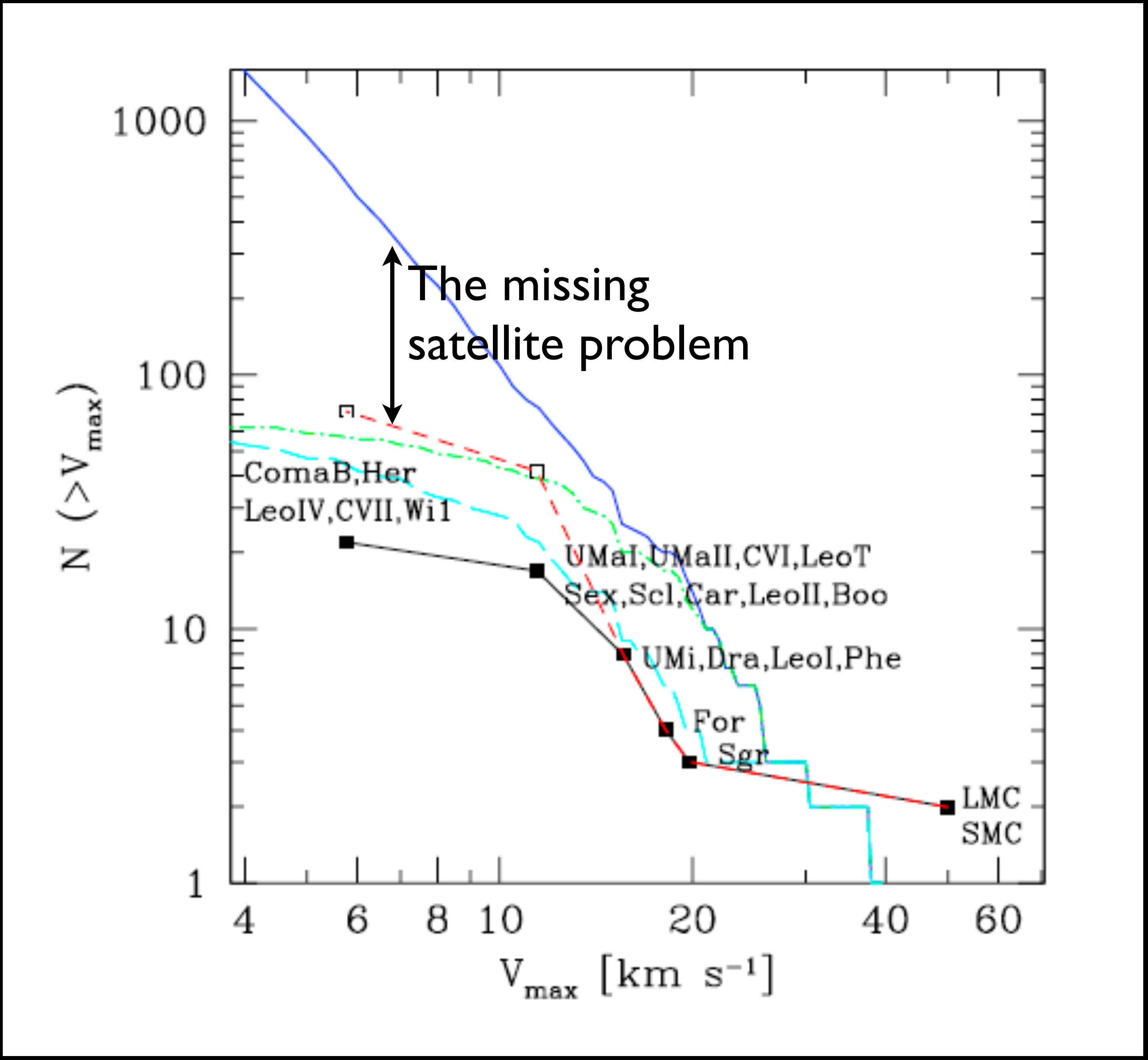
With: Lulu Liu, Risa Wechsler,
Michael Busha, Peter Behroozi



The missing satellite problem
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N (>V_{max})
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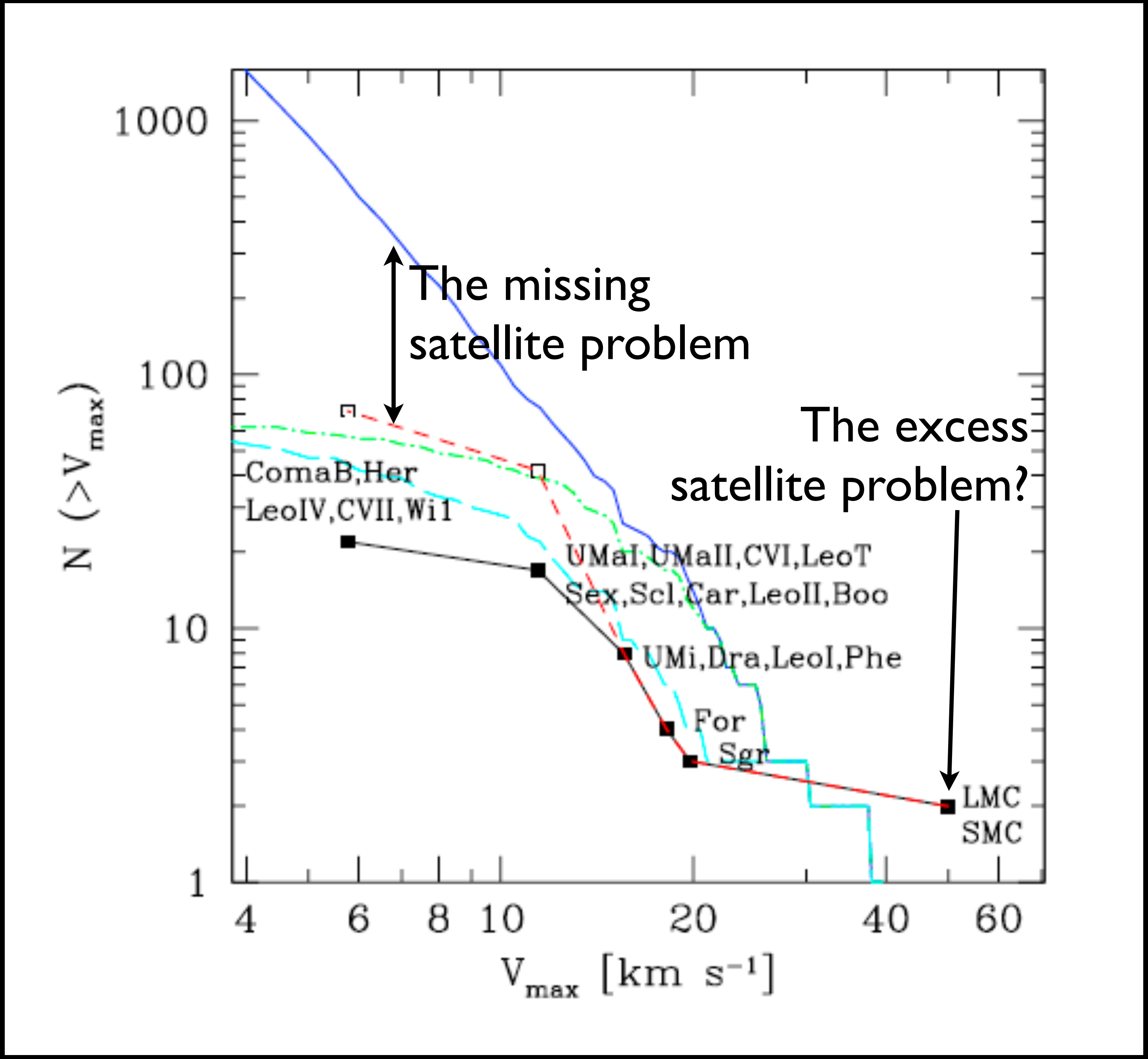
V_{max} [km s^{-1}]
ComaB,Her
LeoIV,CVII,Wi1
UMaI,UMaII,CVI,LeoT
Sex,Scl,Car,LeoII,Boo
UMi,Dra,LeoI,Phe
For
Sgr
LMC
SMC

Madau+ 08



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The excess satellite problem?
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For
Sgr
LMC
SMC

Madau+ 08

There's no place like home? Statistics of Milky Way-mass dark matter halos

Michael Boylan-Kolchin[1*], Volker Springel[1], Simon D. M. White[1], and Adrian Jenkins[2]
[1] *Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Str. 1, 85748 Garching, Germany*
[2] *Institute for Computational Cosmology, Department of Physics, University of Durham, South Road, Durham DH1 3LE, UK*

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ABSTRACT
We present an analysis of the distribution of structural properties for Milky Way-mass halos in the Millennium-II Simulation (MS-II). This simulation of structure formation within the standard ΛCDM cosmology contains thousands of Milky Way-mass halos and has sufficient resolution to properly resolve many subhalos per host. It thus provides a major improvement in the statistical power available to explore the distribution of internal structure for halos of this mass. In addition, the MS-II contains lower resolution versions of the Aquarius Project halos, allowing us to compare our results to simulations of six halos at a much higher resolution. We study the distributions of mass assembly histories, of subhalo mass functions and accretion times, and of merger and stripping histories for subhalos capable of impacting disks at the centers of halos. We show that subhalo abundances are *not* well-described by Poisson statistics at low mass, but rather are dominated by intrinsic scatter. Using the masses of subhalos at infall and the abundance-matching assumption, there is less than a 10% chance that a Milky Way halo with $M_{\rm vir} = 10^{12}\,M_{\odot}$ will host two galaxies as bright as the Magellanic Clouds. This probability rises to $\sim 25\%$ for a halo with $M_{\rm vir} = 2.5 \times 10^{12}\,M_{\odot}$. The statistics relevant for disk heating are very sensitive to the mass range that is considered relevant. Mergers with mass ratio at accretion greater than 1:30 could well impact a central galactic disk and are a near inevitability since $z = 2$, whereas only half of all halos have had a merger with mass ratio at accretion greater than 1:10 over this same period.

The plan:
Identify analogs of the Milky Way in SDSS and see what fraction have an LMC and an SMC.

The Milky Way system

- The Milky Way
  - M_V = -20.9 (corresponds to $M_{0.1,r}$ = -21.2 for the average SDSS galaxy of similar luminosity)
  - Isolated: nearest neighbor of similar luminosity is M31 at 0.7 Mpc
- The LMC
  - M_V = -18.5 (2.4 mags fainter than MW)
  - 50 kpc from MW
- The SMC
  - M_V = -17.1 (3.8 mags fainter than MW)
  - 63 kpc from MW

Sample Selection

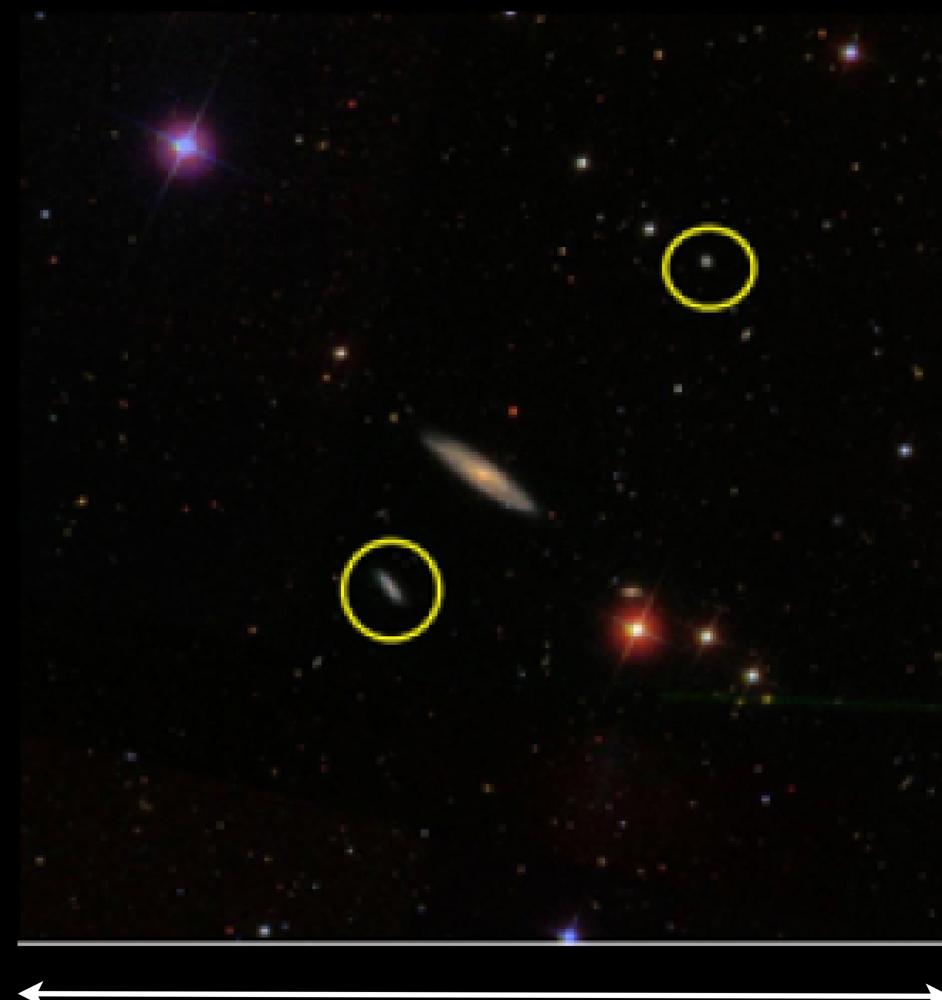
- Milky Way analogs
  - Similar luminosity: M_r = -21.2 +/- 0.2.
  - Isolated: no brighter galaxy within R_{iso} = 0.5 Mpc.
  - Not within R_{iso} of a survey edge (so we limit to NGC).
  - Later, we will also divide by color.
- LMC/SMC analogs
  - Between 2 and 4 magnitudes fainter than their host.
  - Close satellites: within R_{sat} = 150 kpc of their host.

The specific selection criteria are arbitrary; we will vary them to test the robustness of our results.

Spectroscopic Satellites

- SDSS main spectroscopic sample has completeness limit at (conservatively) r ~ 17.6. To get SMCs with spectra, hosts must have r < 13.6.
- There are 199 isolated, MW-like galaxies this bright in SDSS NGC. Of these:
  - 132 (66%) have zero MC analogs.
  - 51 (25.6%) have one.
  - 16 (8%) have two.
  - None have more than two.
- This is consistent with simulation results, but statistically limited. We can get a larger sample with the photometric catalog.

But first...

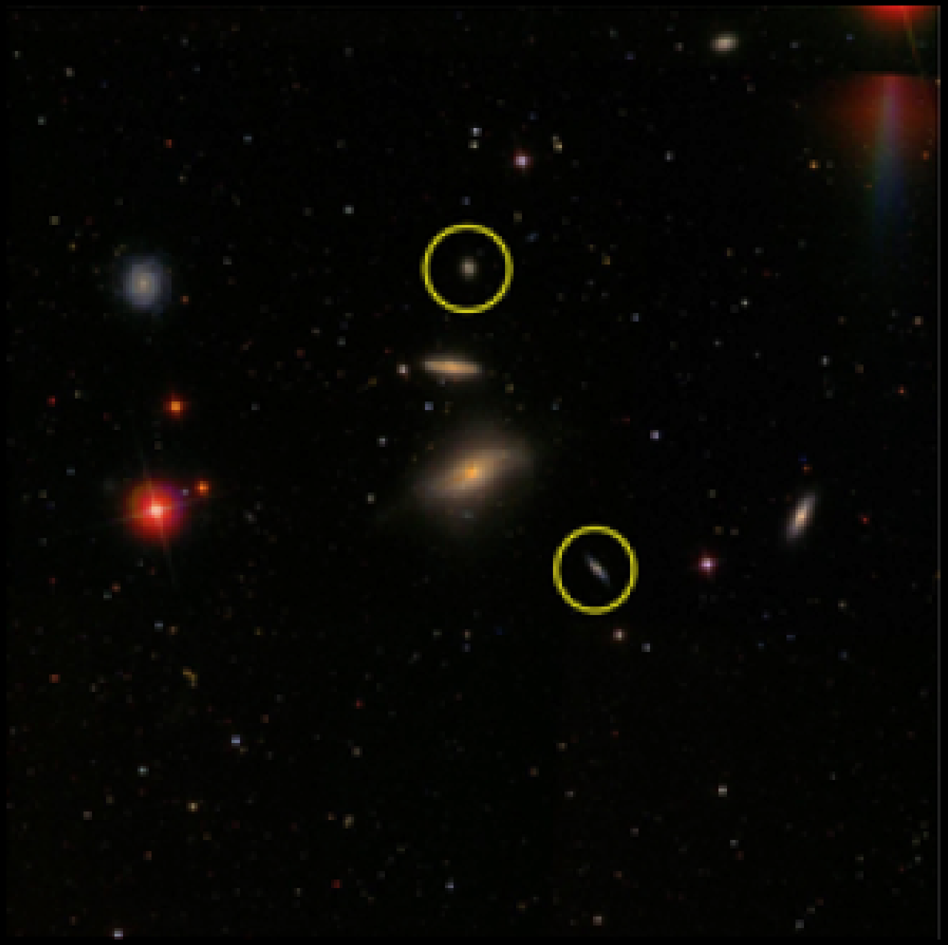


300 kpc

300 kpc


300 kpc

300 kpc



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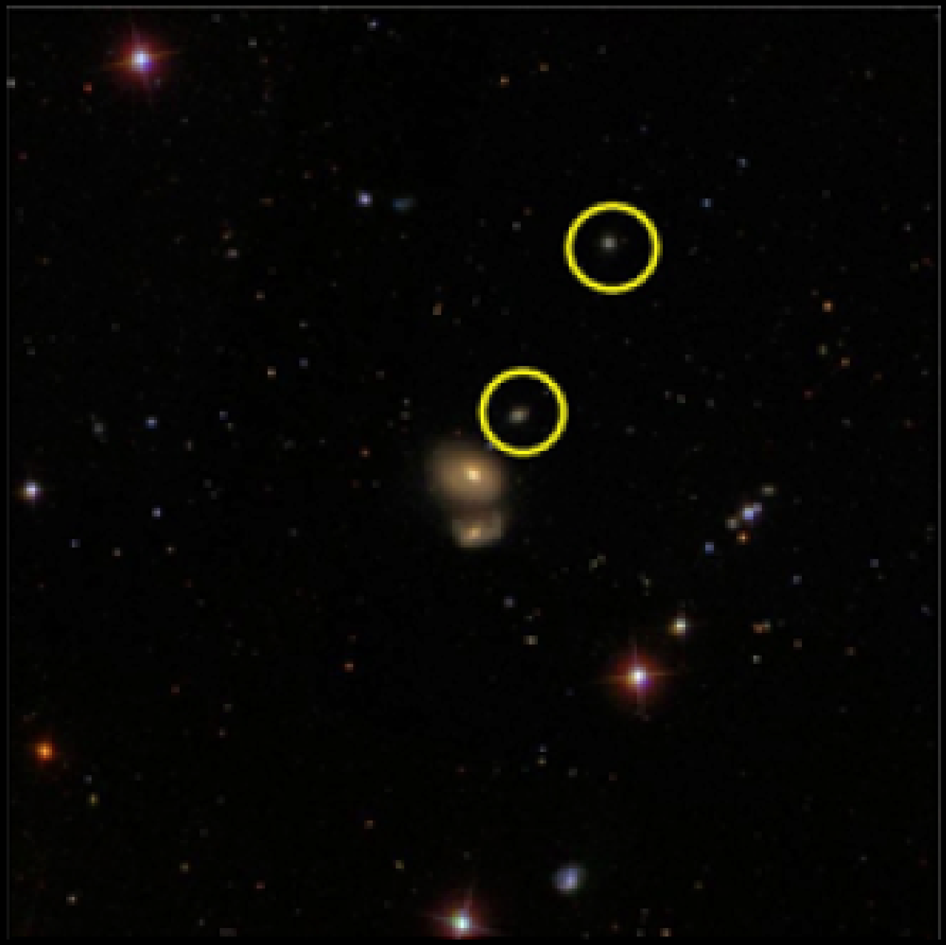
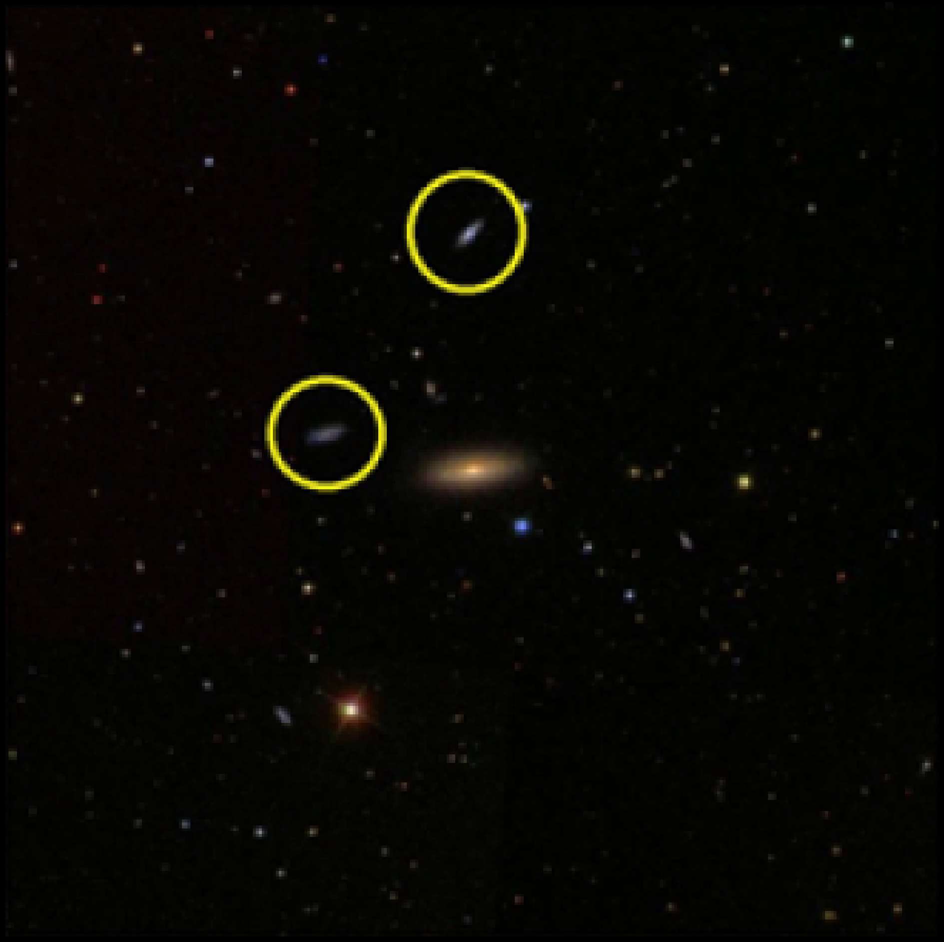
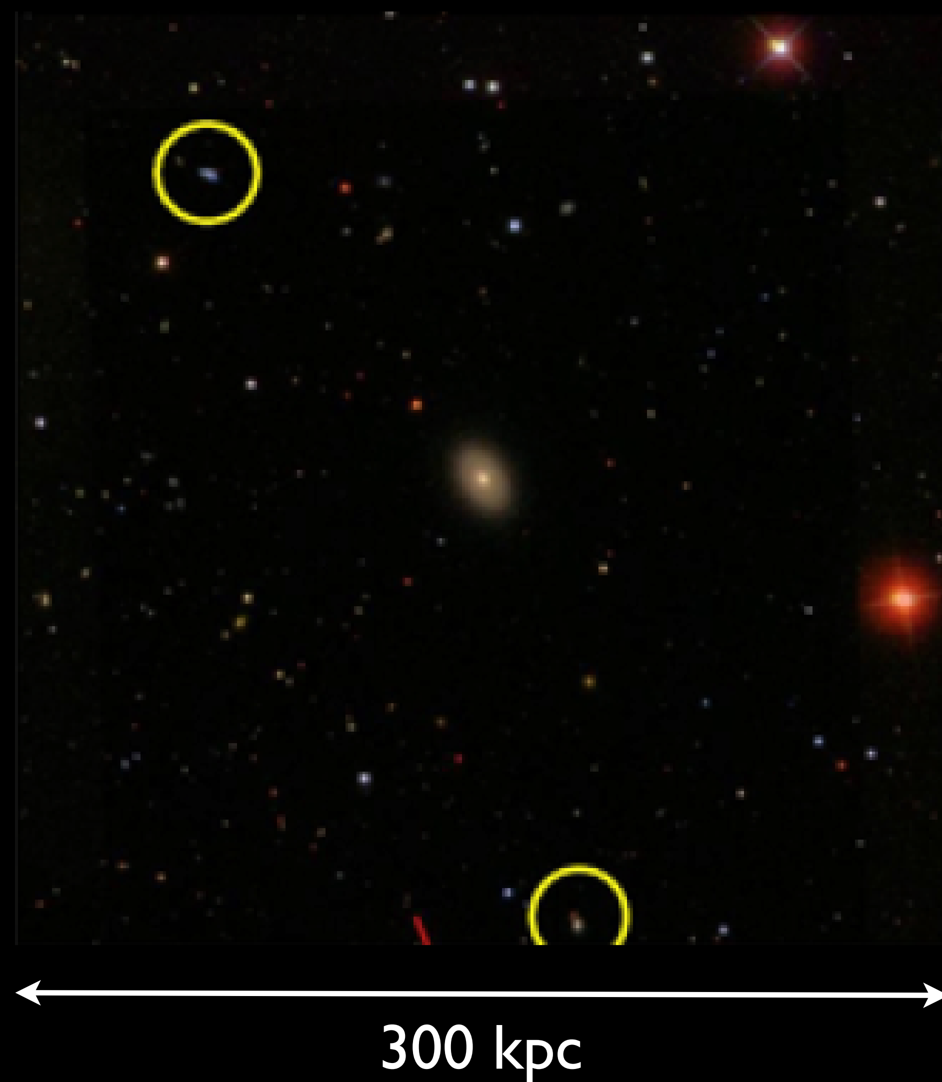
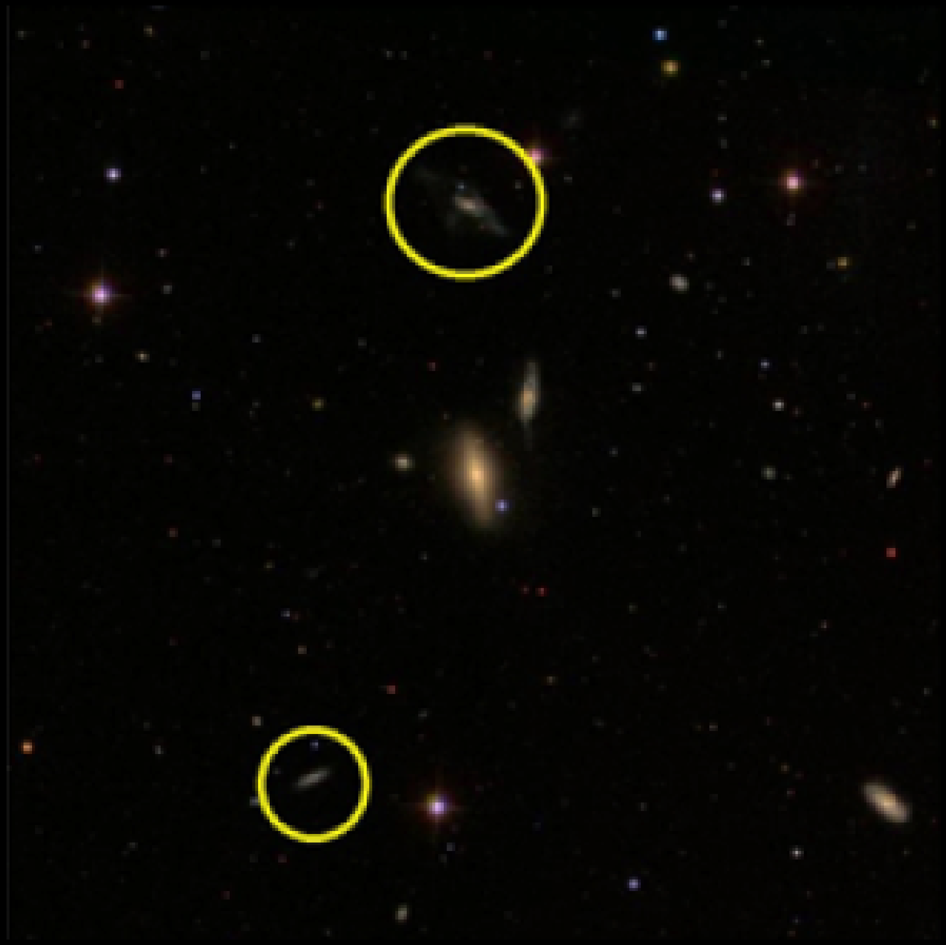


300 kpc



300 kpc


300 kpc

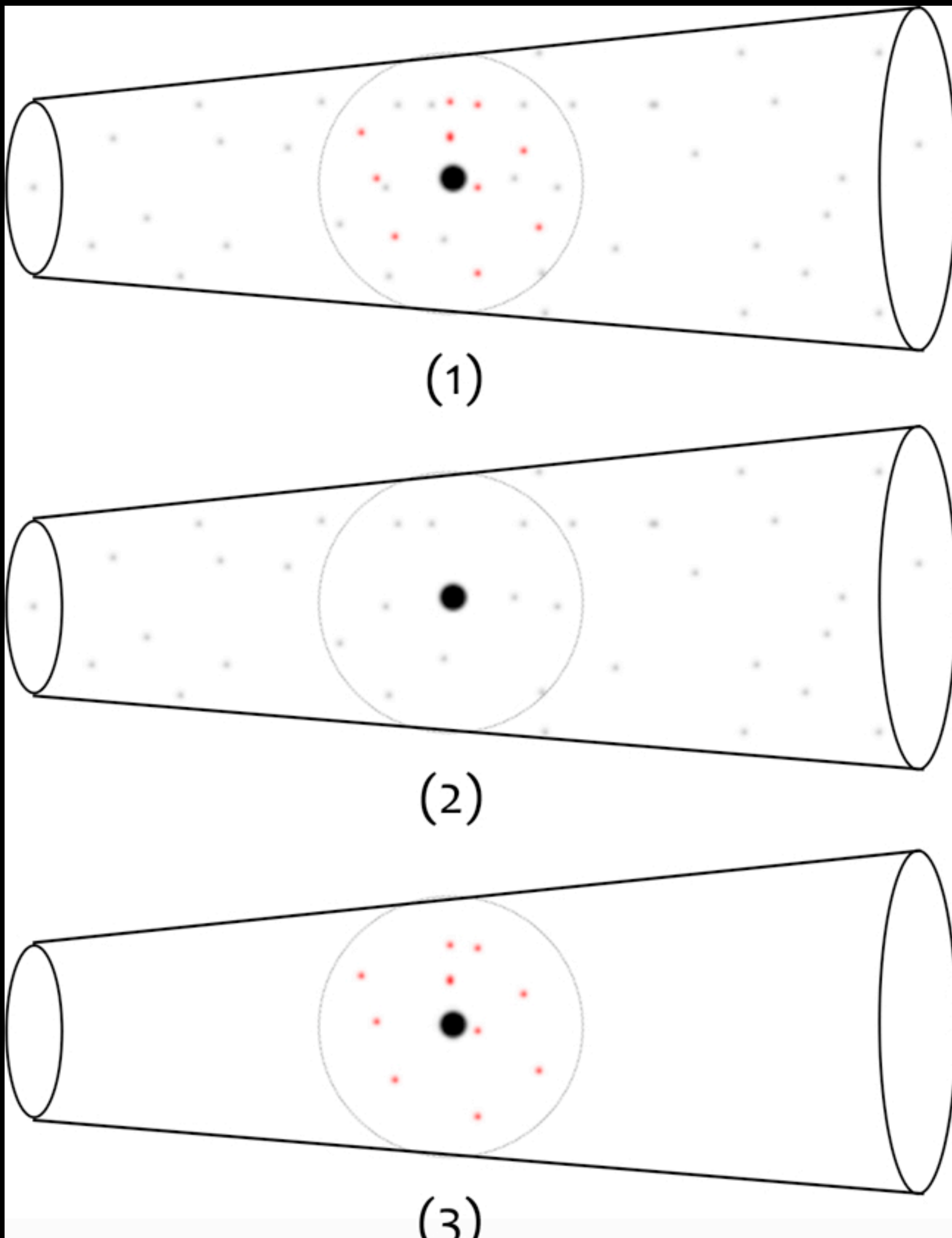


300 kpc

Photometric Satellites

- The basic idea: Identify MW analogs in the spectroscopic sample (22,500 in the NGC) and look for photometric objects 2-4 mags fainter in apparent magnitude.
- Completeness limit for photometry is $r \sim 21$, so hosts must have $r < 17$.
- The photometric set will be dominated by foreground/background objects.
- Photo-z's provide some help in excluding *obvious* background, but they are not nearly sufficient.
- We will need to perform statistical foreground/background subtraction.
- Goal: the PDF for hosting N_{sat} satellites, $P(N_{sat})$

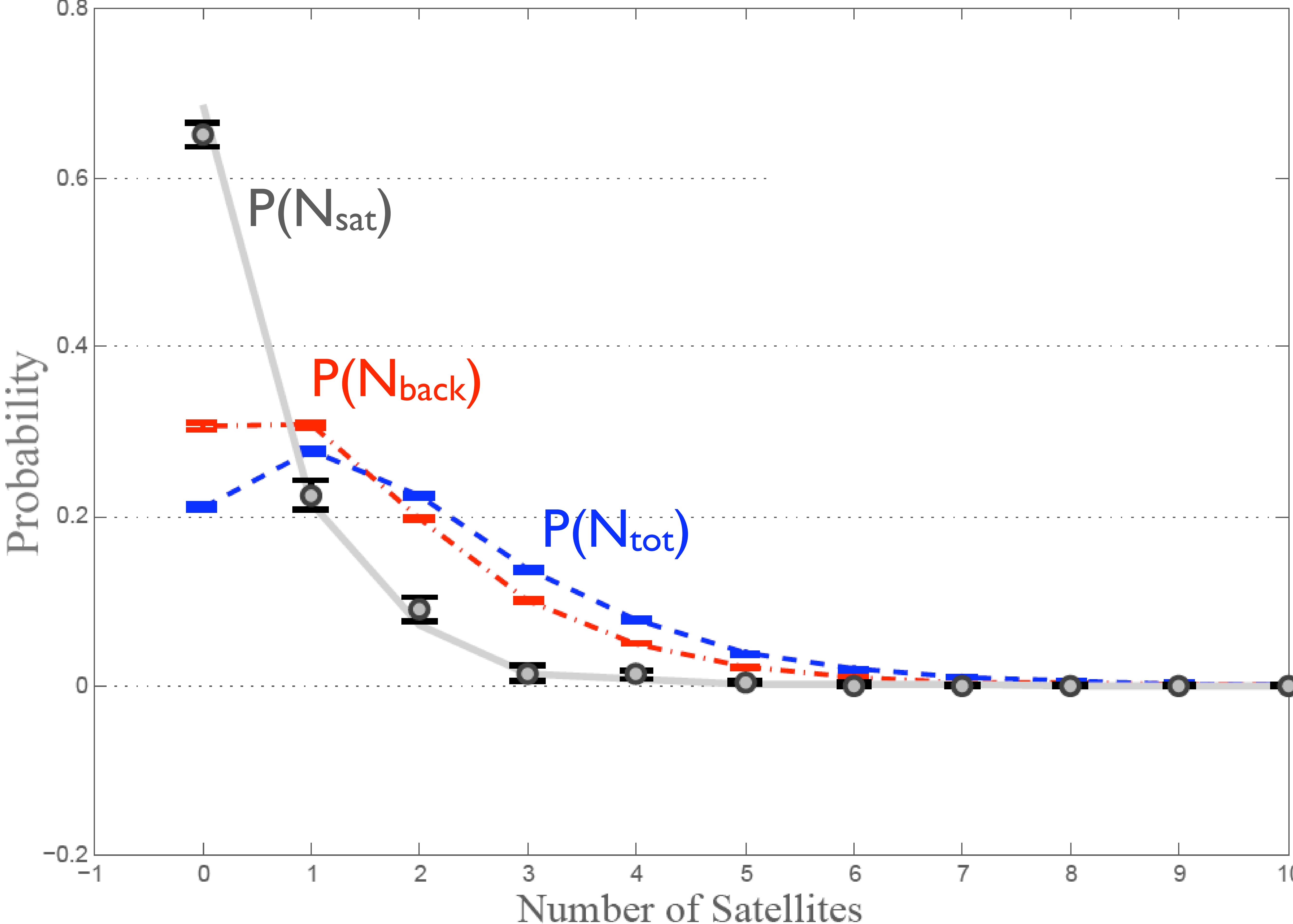
Background subtraction



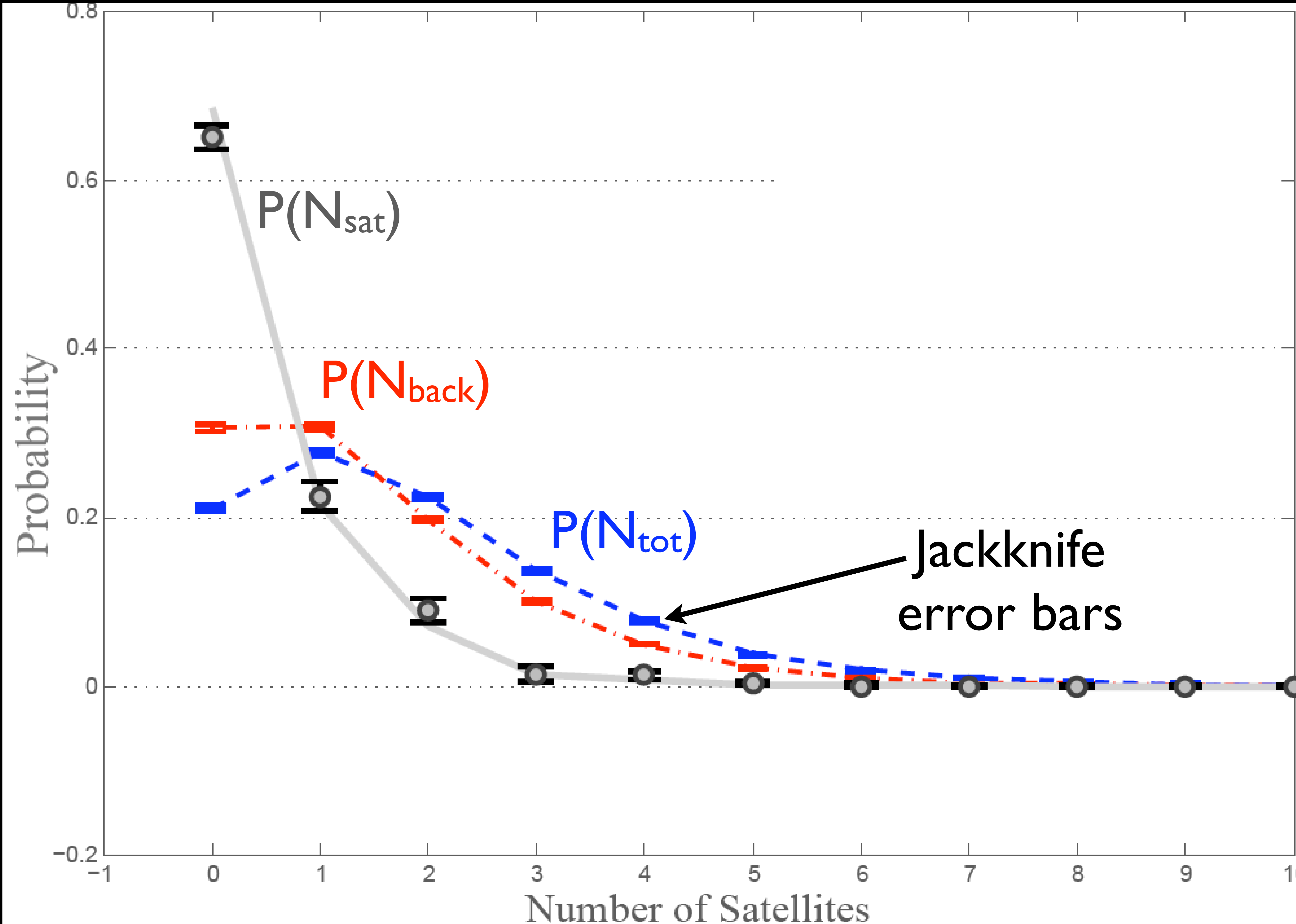
1. Count faint objects near MW analogs to get total PDF $P(N_{tot})$.

2. "Randomize" RA/Dec positions and count satellites to estimate background: $P(N_{back})$.

3. The desired signal appears as part of a convolution: $P(N_{tot}) = P(N_{sat}) * P(N_{back})$. We can deconvolve this using FFTs to get $P(N_{sat})$.



Liu, BFG, Wechsler, Behroozi, Busha, in prep.



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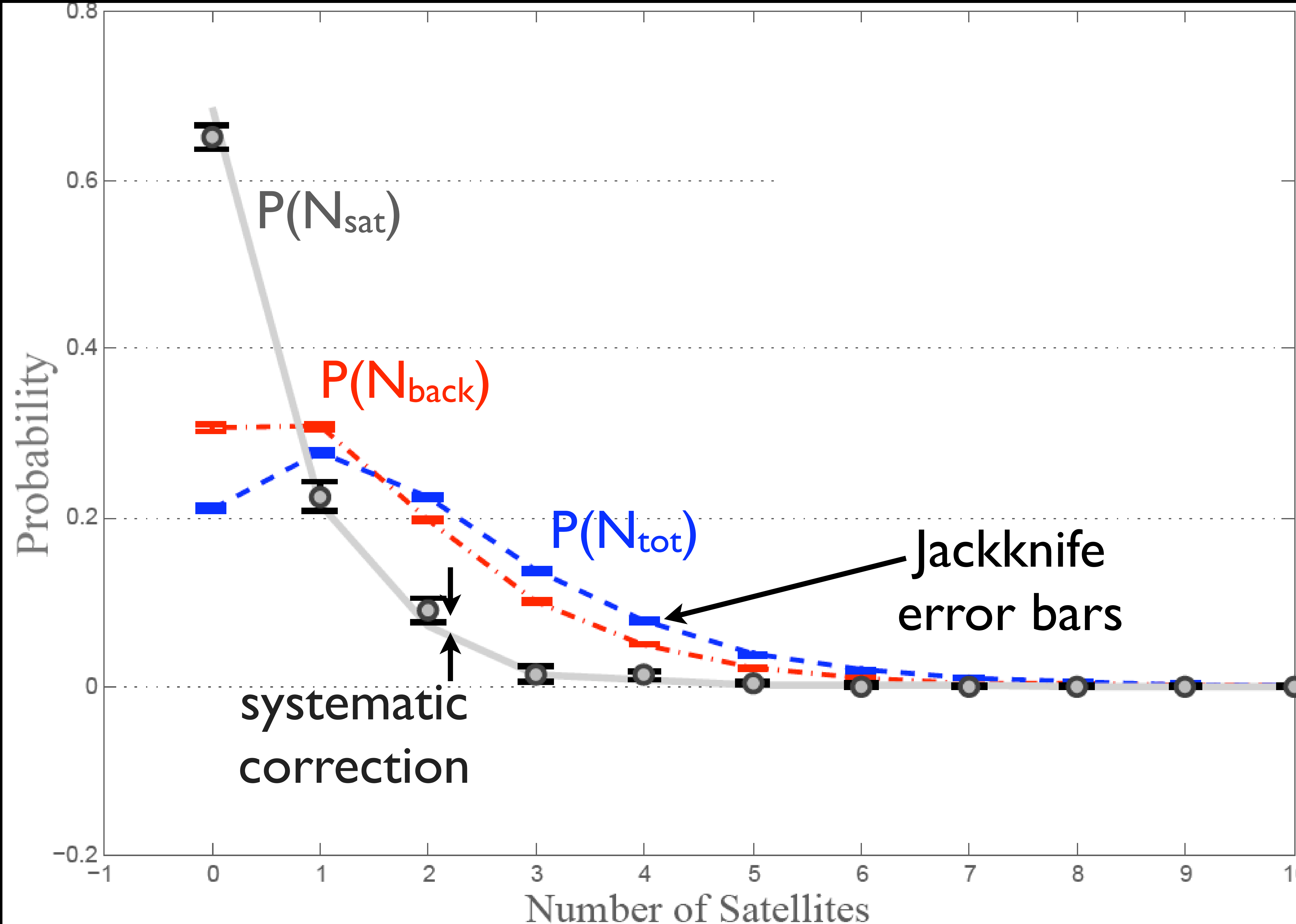

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Systematic Errors

- We use photo-z errors to do a rough background cut. Catastrophic photo-z errors will mean that some true satellites will be eliminated here.
  - We can estimate this from the photo-z validation set or P(z) distribution.
- There will be residual correlations along the line of sight between MW analogs and MC-sized dwarfs, beyond our random background estimates.
  - We can estimate this via integrals of the correlation function (assuming linear bias).
- These are both are 10-20% effects, *in opposite directions*. Correction factors can be computed analytically.

Main results

Number of Satellites	Percentage of MW-sized Galaxies	Systematic Adjustment
Zero	$68.4^{+1.4}_{-1.5}$	-3.3
One	$21.6^{+1.8}_{-1.7}$	+0.9
Two	$7.7^{+1.3}_{-1.4}$	+1.9
Three	$1.3^{+1.0}_{-0.9}$	+0.0
Four	$0.8^{+0.6}_{-0.5}$	+0.3
Five	$0.2^{+0.3}_{-0.2}$	+0.1
Six	$0.2^{+0.2}_{-0.2}$	-0.2

TABLE 1
PROBABILITY OF OCCURRENCE OF N LMC/SMC LUMINOSITY SATELLITES AROUND A MW-LUMINOSITY HOST GALAXY, FOR N=0-6

NB: systematic correction for line-of-sight correlations is not included here. The adjustment numbers will likely shrink (and may change sign).

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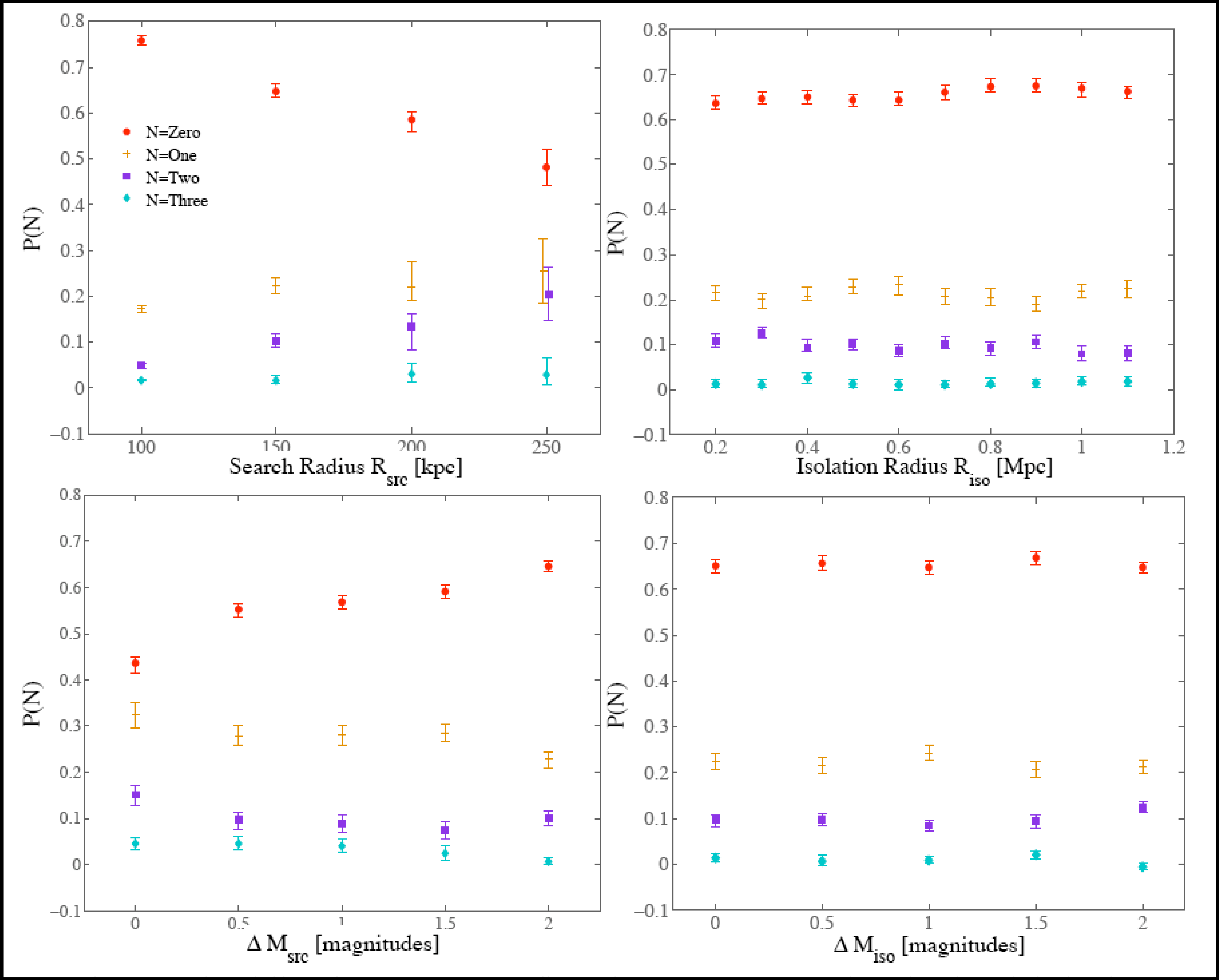
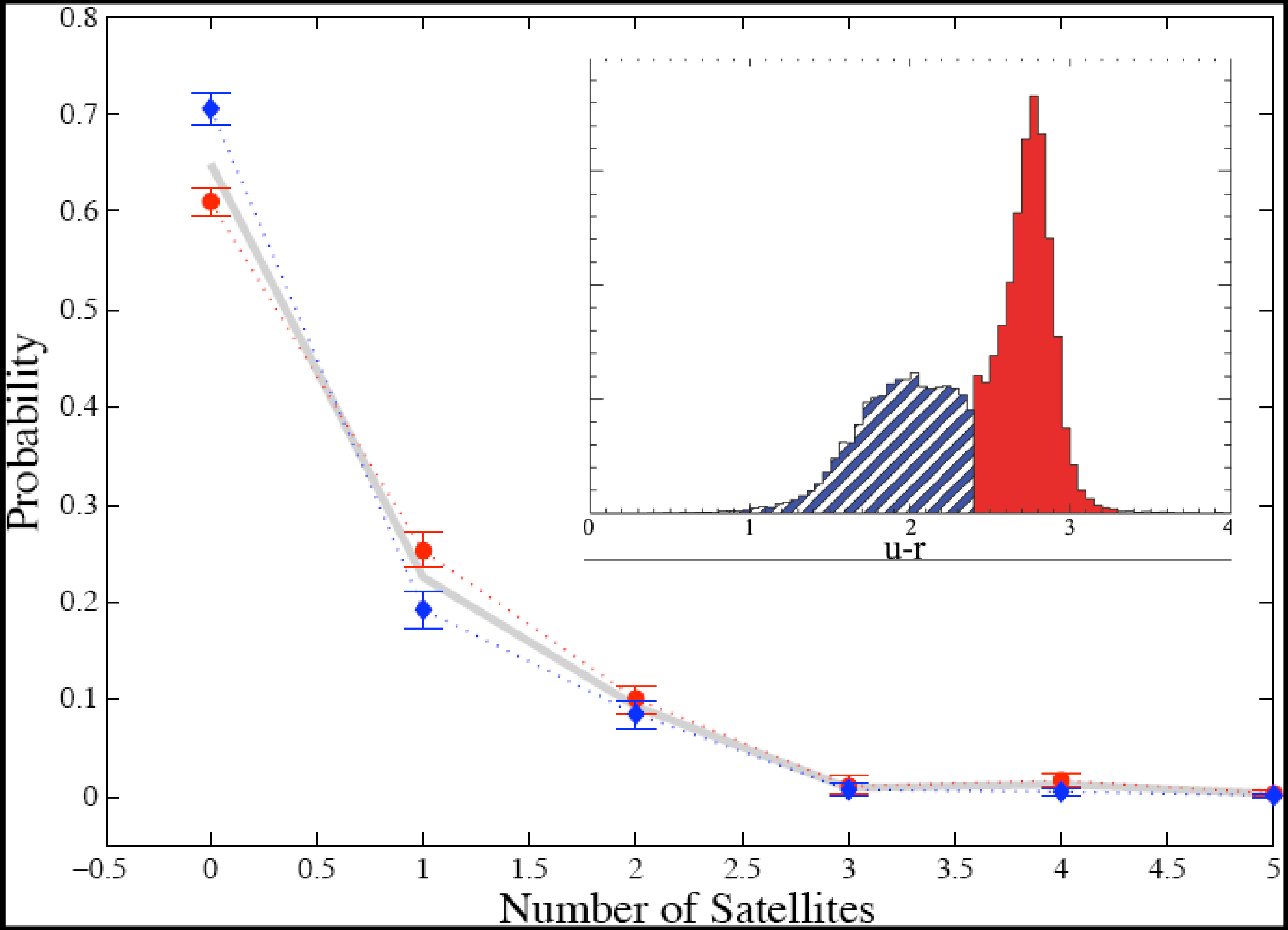
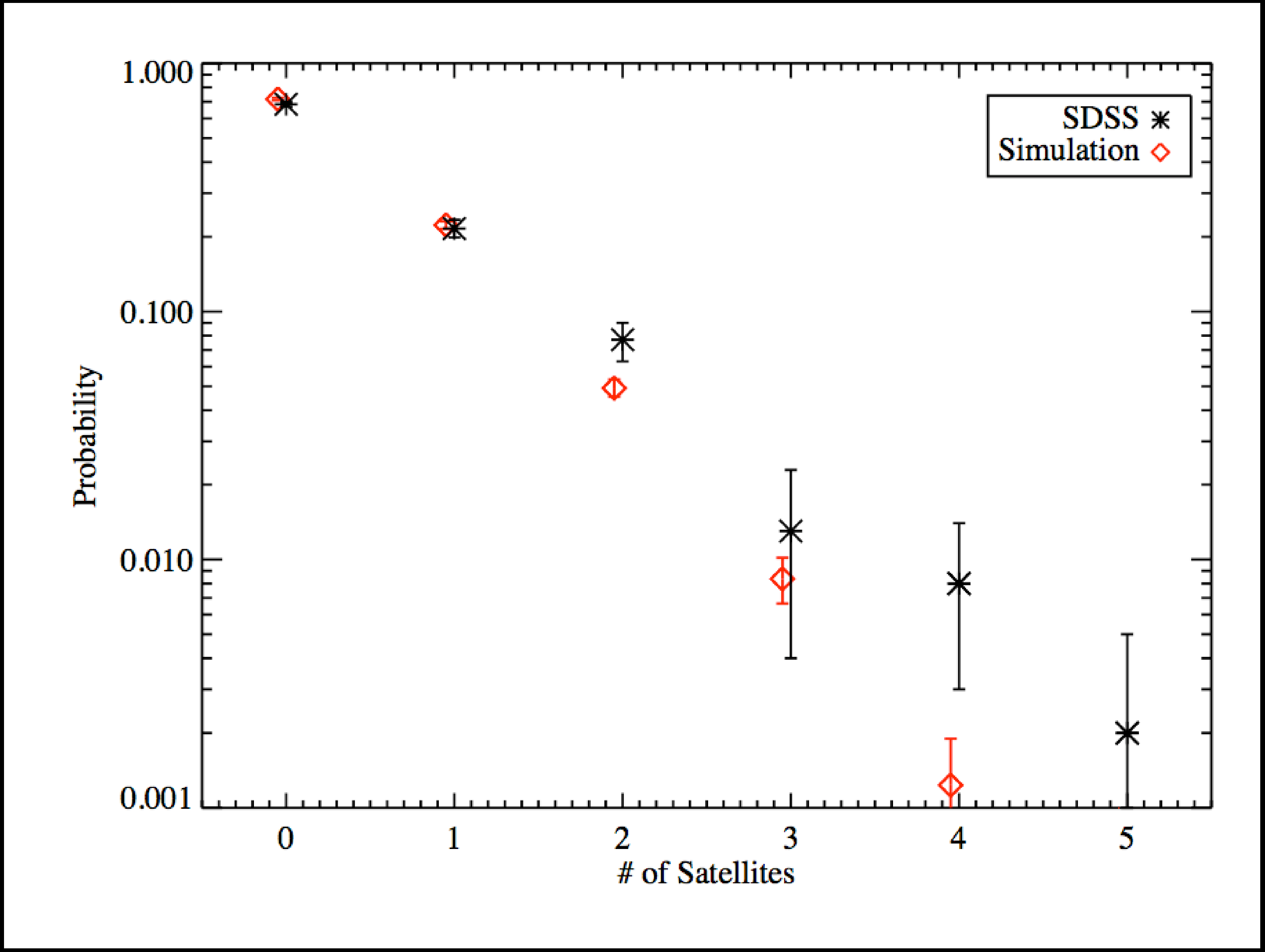
Varying the selection



Red vs. blue hosts



Comparison with Bolshoi simulation



Busha et al. in prep.

Summary and a question

- For isolated galaxies in SDSS with magnitudes similar to the Milky Way:
  - The *majority* have no satellites like the Magellanic Clouds.
  - <10% have two such satellites.
  - LMCs and SMCs are even rarer for blue galaxies.
- This is in broad agreement with N-body models.
- Is this "anti-Copernican"?

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  - LMCs and SMCs are even rarer for blue galaxies.
- This is in broad agreement with N-body models.
- Is this “anti-Copernican”?
  - No. It should not be a surprise if a “randomly chosen” galaxy is a 1-in-10 outlier in at least one property.

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Stripe 82

The coadded photometry in Stripe 82 is significantly deeper, allowing us to consider a disjoint set of hosts extending to slightly higher redshift.

Results are entirely consistent with the NGC.