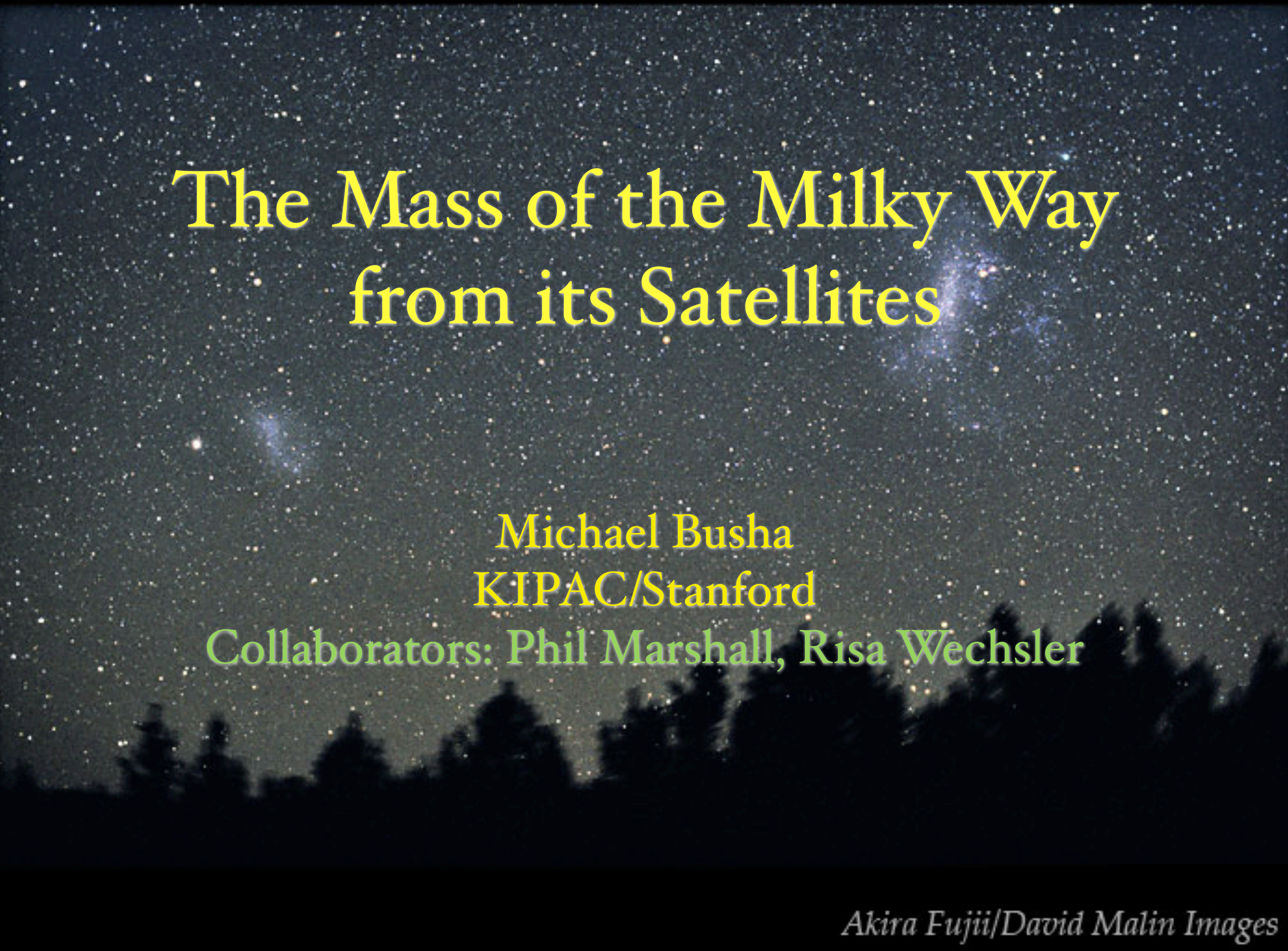
The Mass of the Milky Way
from its Satellites
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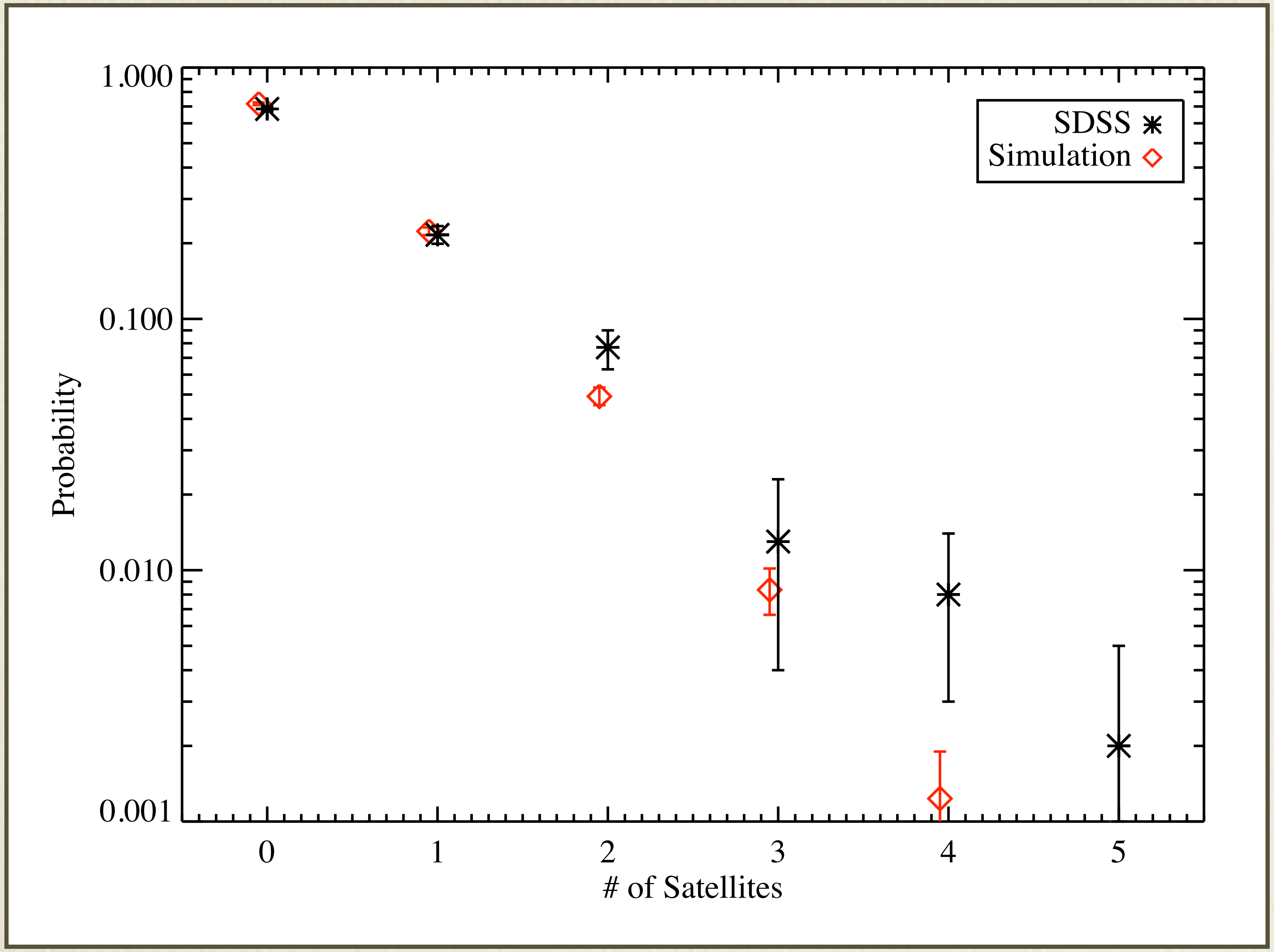
Akira Fujii/David Malin Images

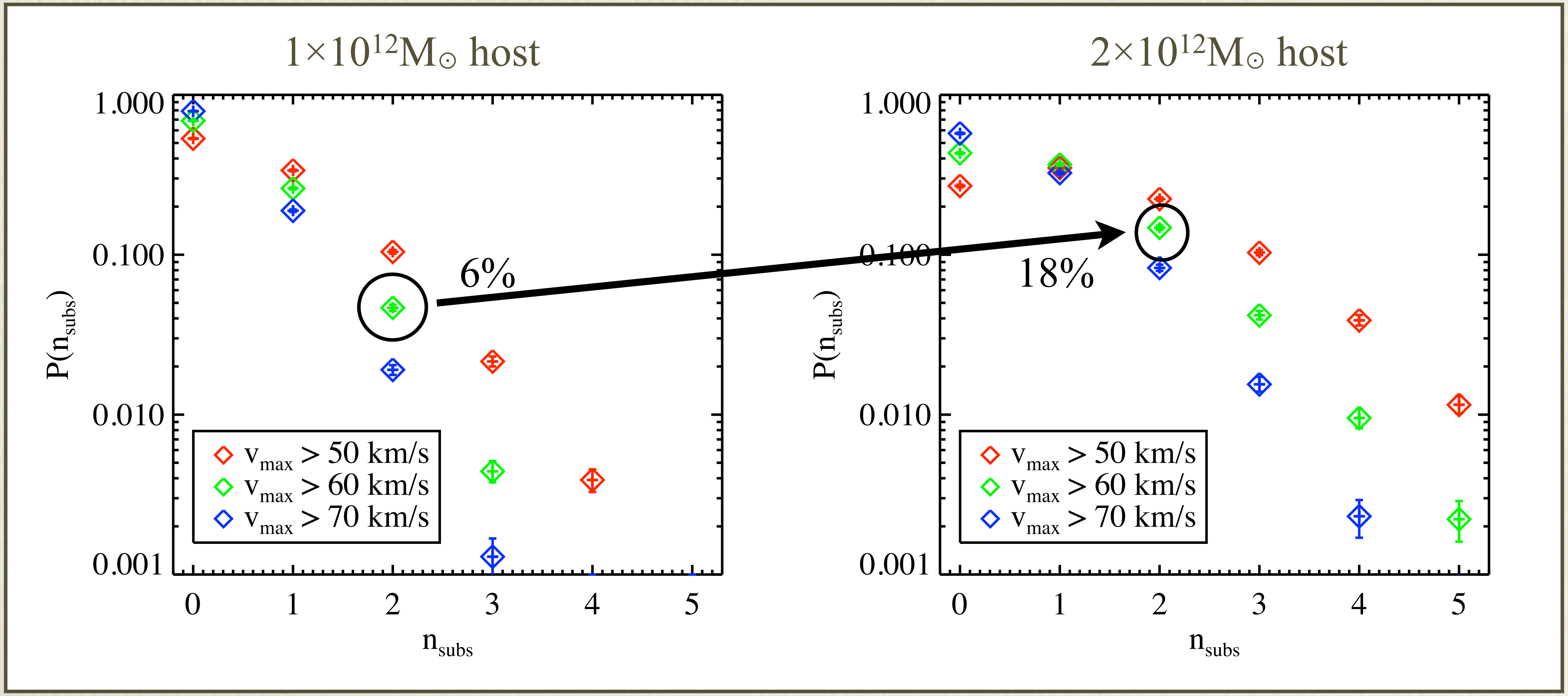
Introduction

- As seen earlier in this conference, the Bolshoi simulation + SHAM does a good job reproducing the distribution of satellite galaxies around Milky Way like hosts.



Introduction

- As seen earlier in this conference, the Bolshoi simulation + SHAM does a good job reproducing the distribution of satellite galaxies around Milky Way like hosts.
- Some “tension” in kinematics arguing for a higher-mass MW.
  - What does this actually imply about the mass of the Milky Way?



Can we use information about the Magellanic Clouds to constrain the mass of the Milky Way?

- Earlier today (Gerke, Tollerud), we heard about the likelihood for a Milky Way-like galaxy (magnitude) to host two Magellanic Cloud-mass satellites.
  - Work mostly in observational space with SDSS, has also been done with simulations (i.e., Boylan-Kolchin).
- Ask the reverse question: Assuming the appropriate substructure population, what is the likelihood distribution for the host population?
  - Work in simulation space using Bolshoi which provides a *very* detailed model of the dark matter distribution in a 250 kpc/*h* box.

Can we use information about the Magellanic Clouds to constrain the mass of the Milky Way?

- Observational Constraints on the Milky Way (some 500 years old!):
  - Not a "satellite" of a larger structure
  - Has exactly two satellites clouds with $v_{max} > 55$ km/s
  - No other substructures within 300 kpc with $v_{max} > 25$km/s

    (Fornax is next brightest with $v_{max} \sim 20$ km/s)

	LMC	**SMC**
v_{max}	~70 km/s	~60 km/s
r_0	49.53 kpc	60 kpc
v_{rad}	89 ± 4 km/s	23 ± 7 km/s
Speed	293 ± 39 km/s	301 ± 52 km/s

Watkins, Evans, & An 2010;
Kallivayalil, van der Marel, & Alcock 06;
Krachentsev et al 04;
van der Marel et al 02

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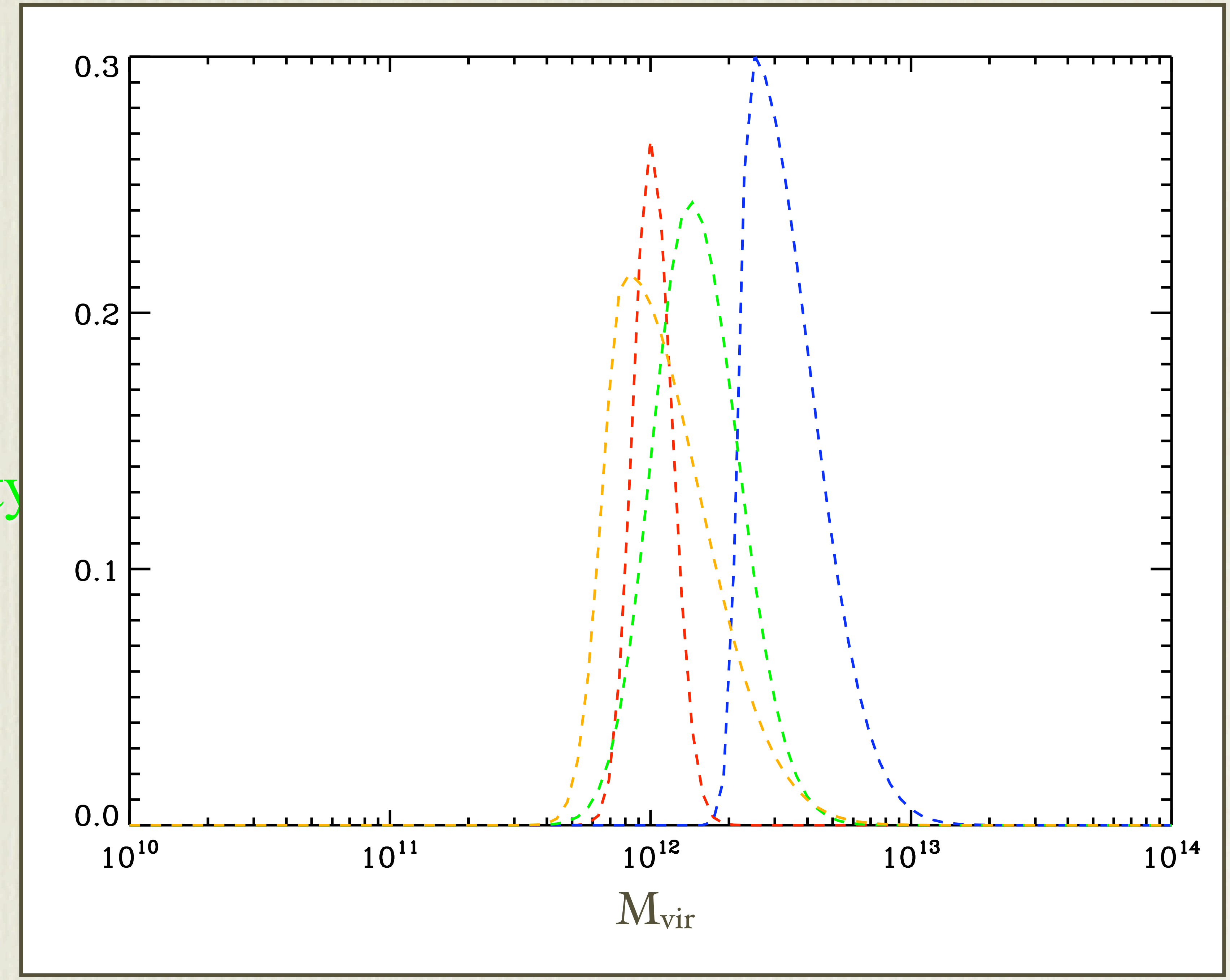
- Our model for interpreting the data:
  - Look for analogs in Bolshoi: a full model of the dark matter distribution in the universe.
  - Complete down to 50 km/s, able to resolve all MC-mass subhalos
  - Make increasingly strict cuts by weighting simulation halos on a range of Magellanic Cloud properties

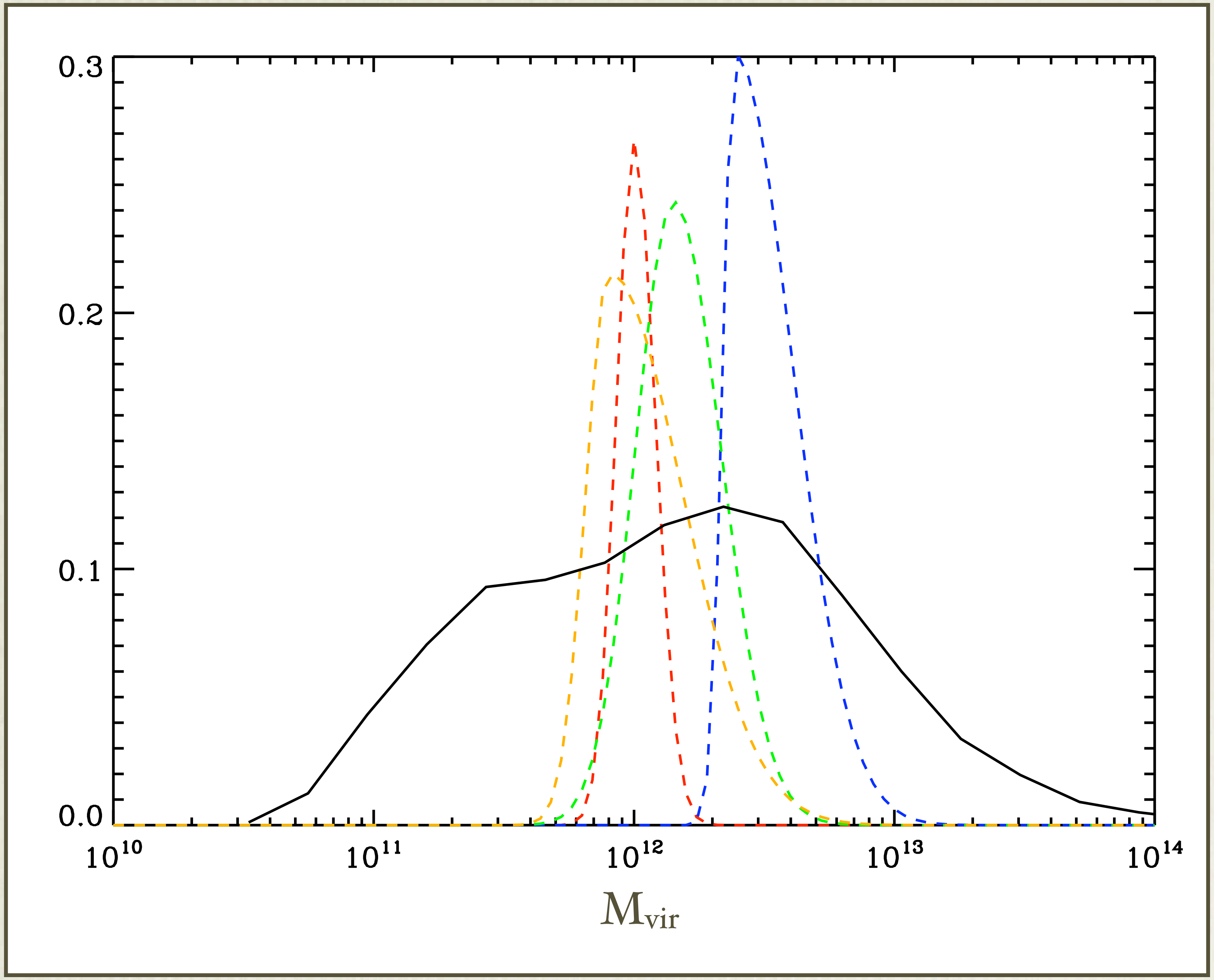
The Mass of the MW: Current Constraints

- Battaglia 05: Radial velocity dispersion profile from globular clusters and satellites
- Smith 07: Escape velocity assuming NFW profile
- Xue 08: Radial velocity dispersion from BHB stars in SDSS
- Li 08: Timing Argument



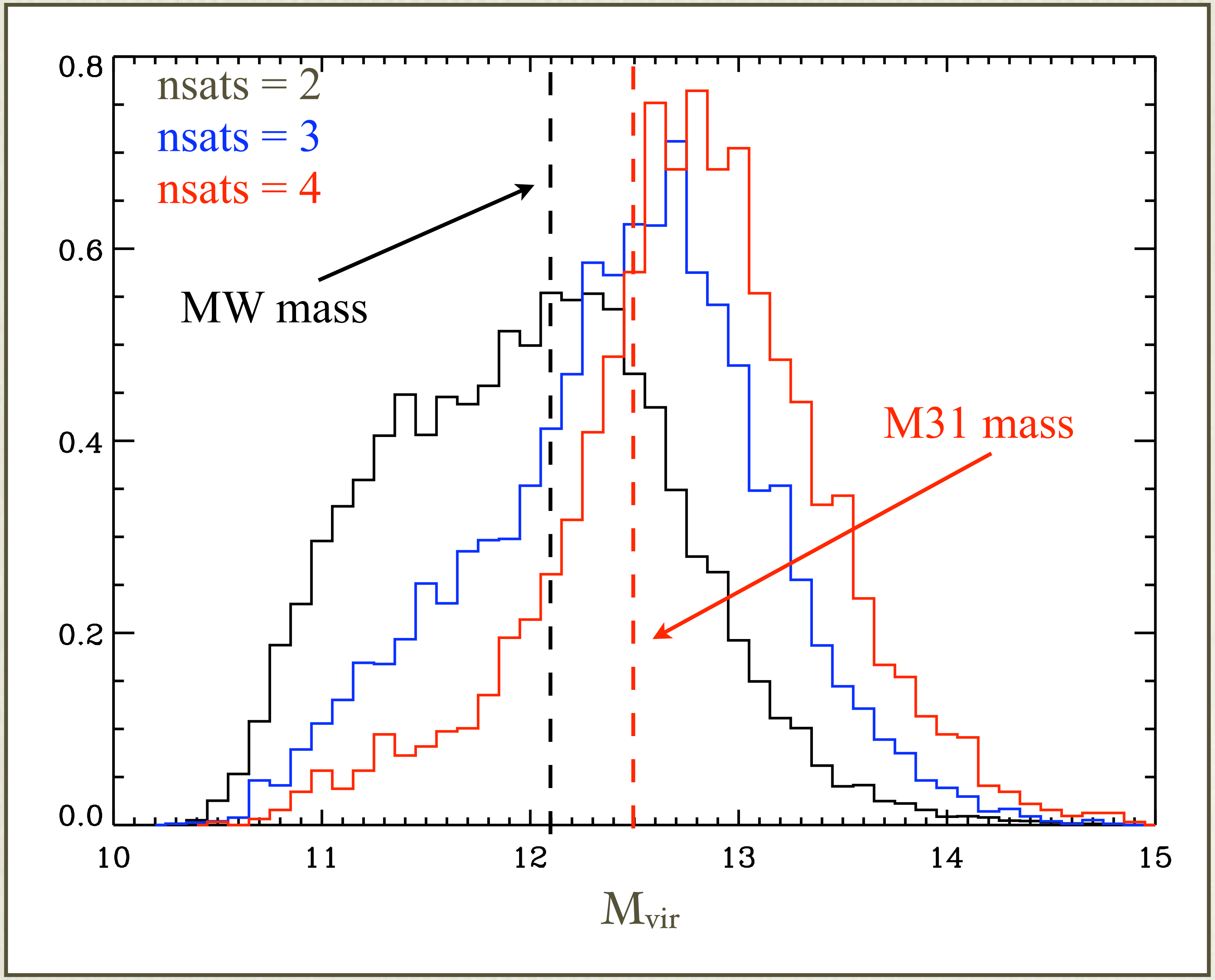
The Effect of the Magellanic Clouds

- Results from demanding that a host halo has exactly two smaller satellites within 300 kpc.
- Find 35,000 objects
- Peak value: $2\times10^{12} M_\odot$
- Very wide spread, but in the ballpark considering this is such a rough measurement.
- Part of the spread is driven by the mass function.



The Effect of More Satellites

- Mass PDF for selecting hosts with increasingly more subhalos within 300 kpc

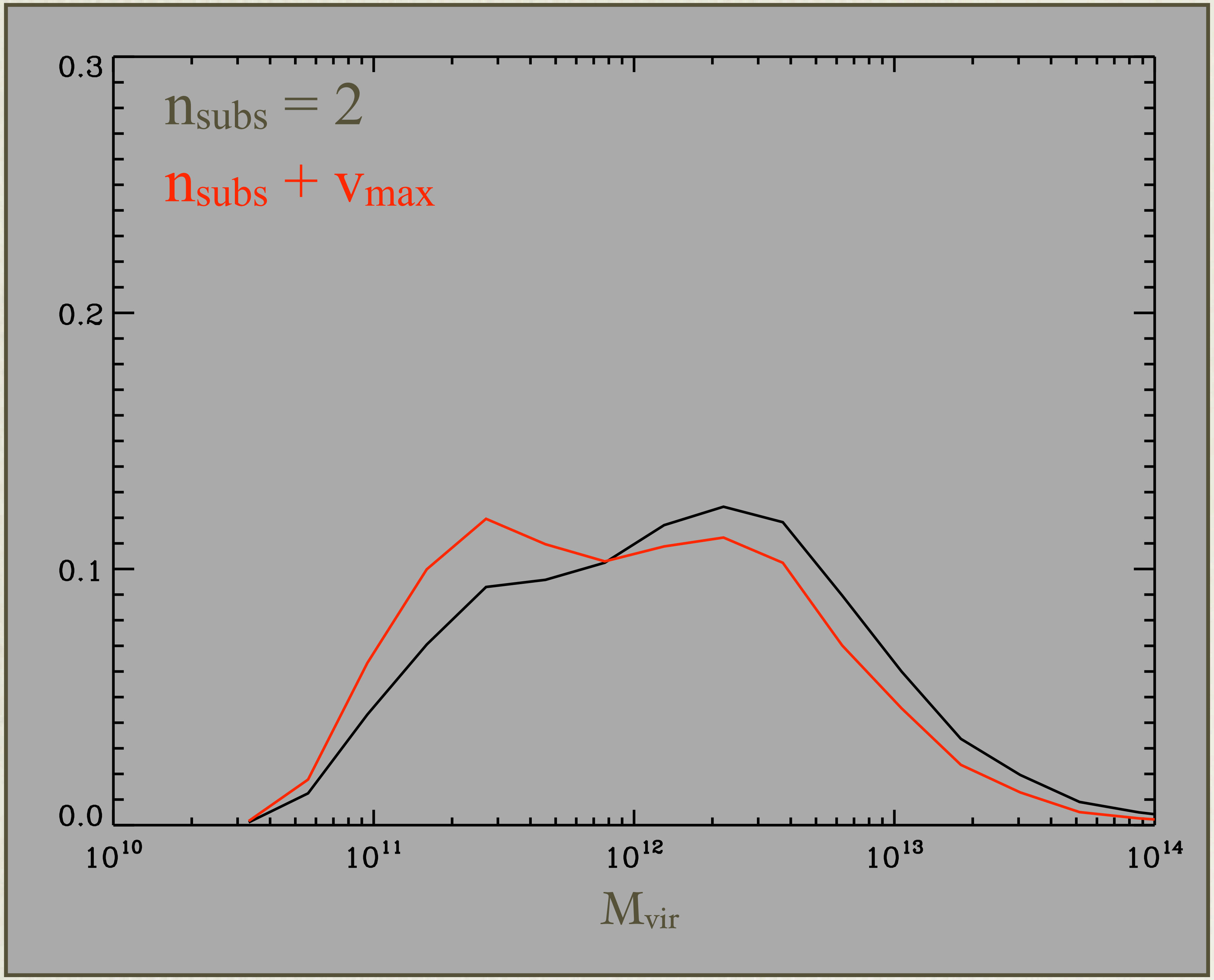


Additional Constraints on the Satellites

- We can refine our constraints by imposing additional criteria on the properties of the satellites,

$$w = e^{-\frac{(\mathcal{O}-\mathcal{M})^2}{2\sigma}}$$

- Imposing v_{max} and radial velocity criteria have the strongest impacts



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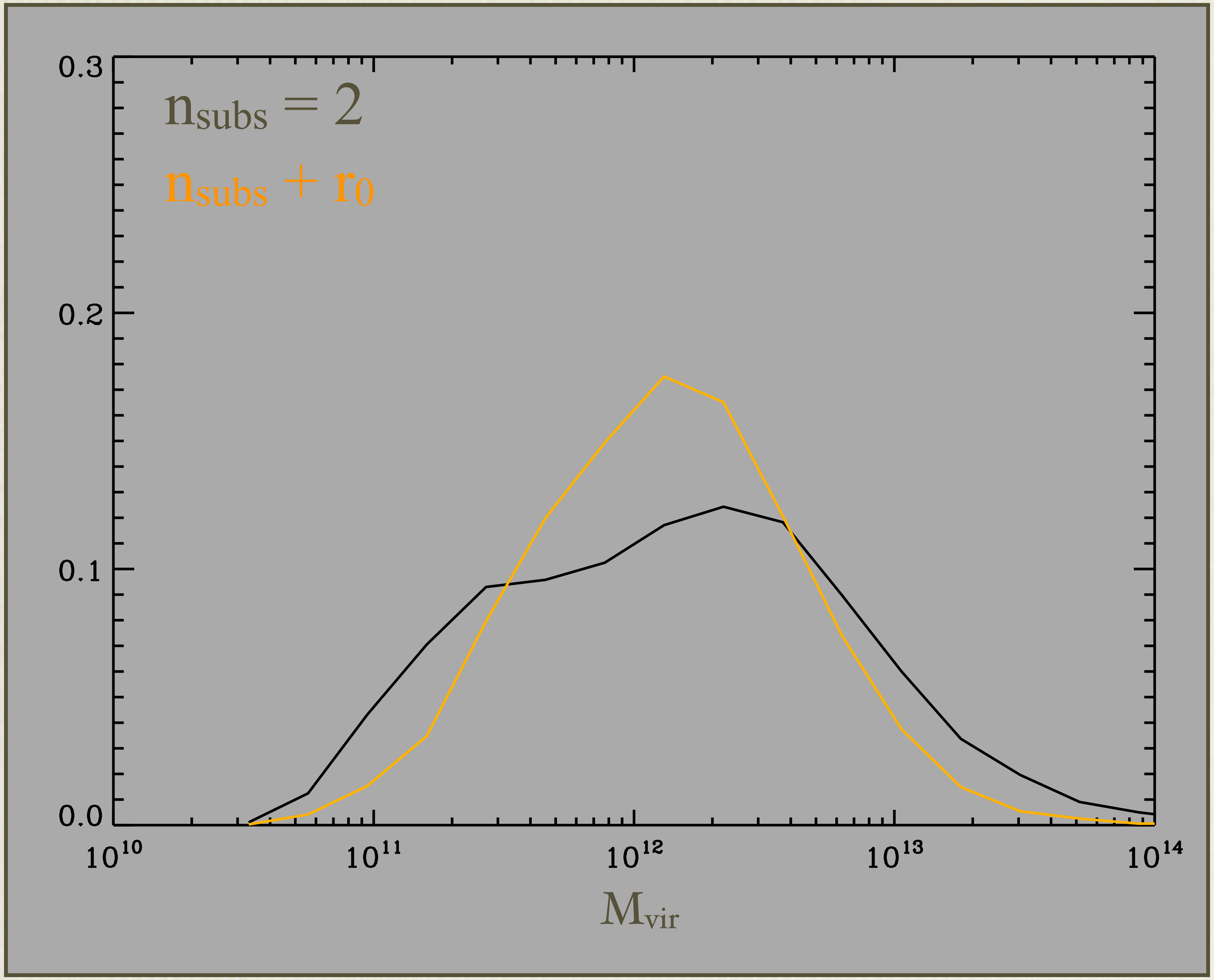

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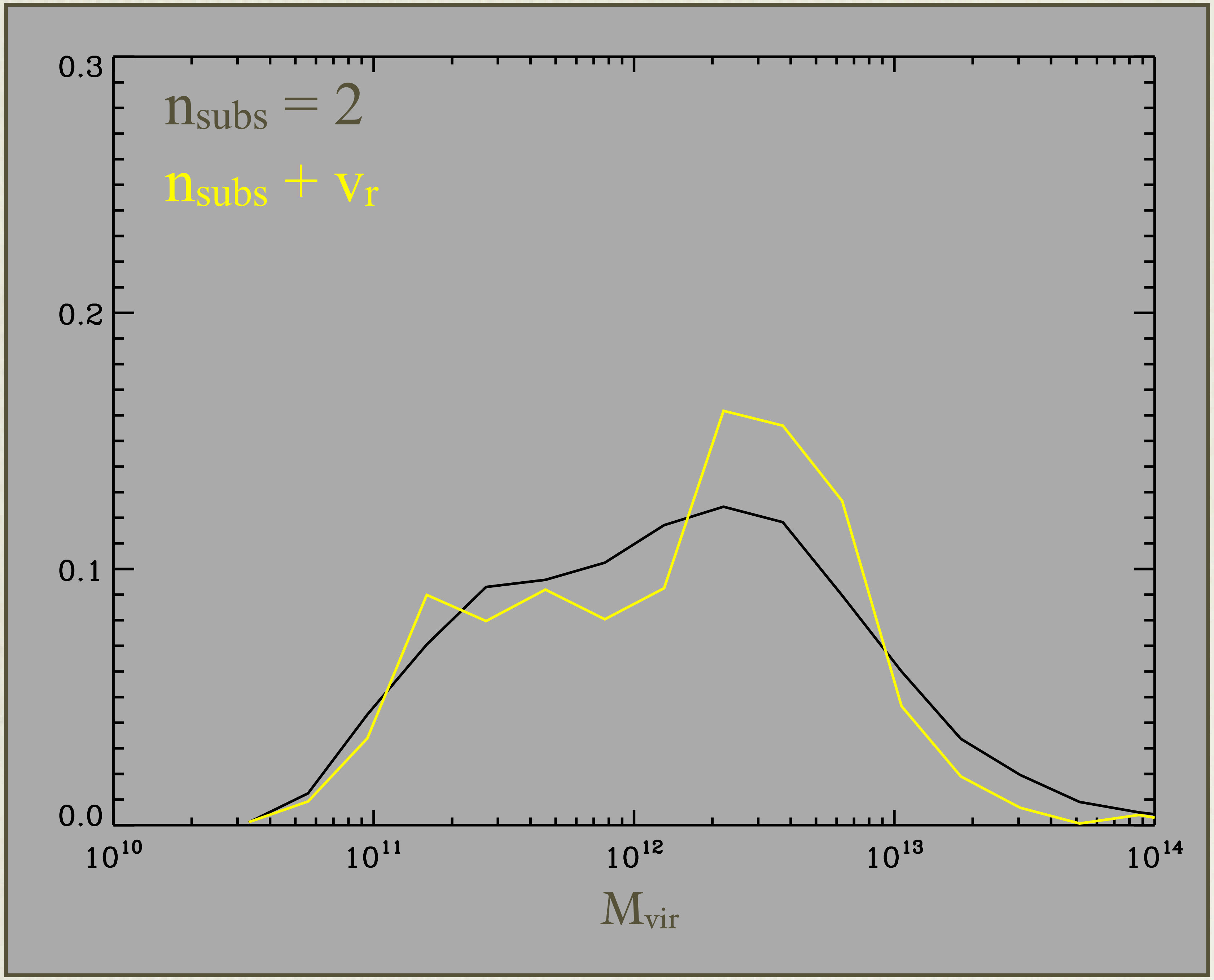

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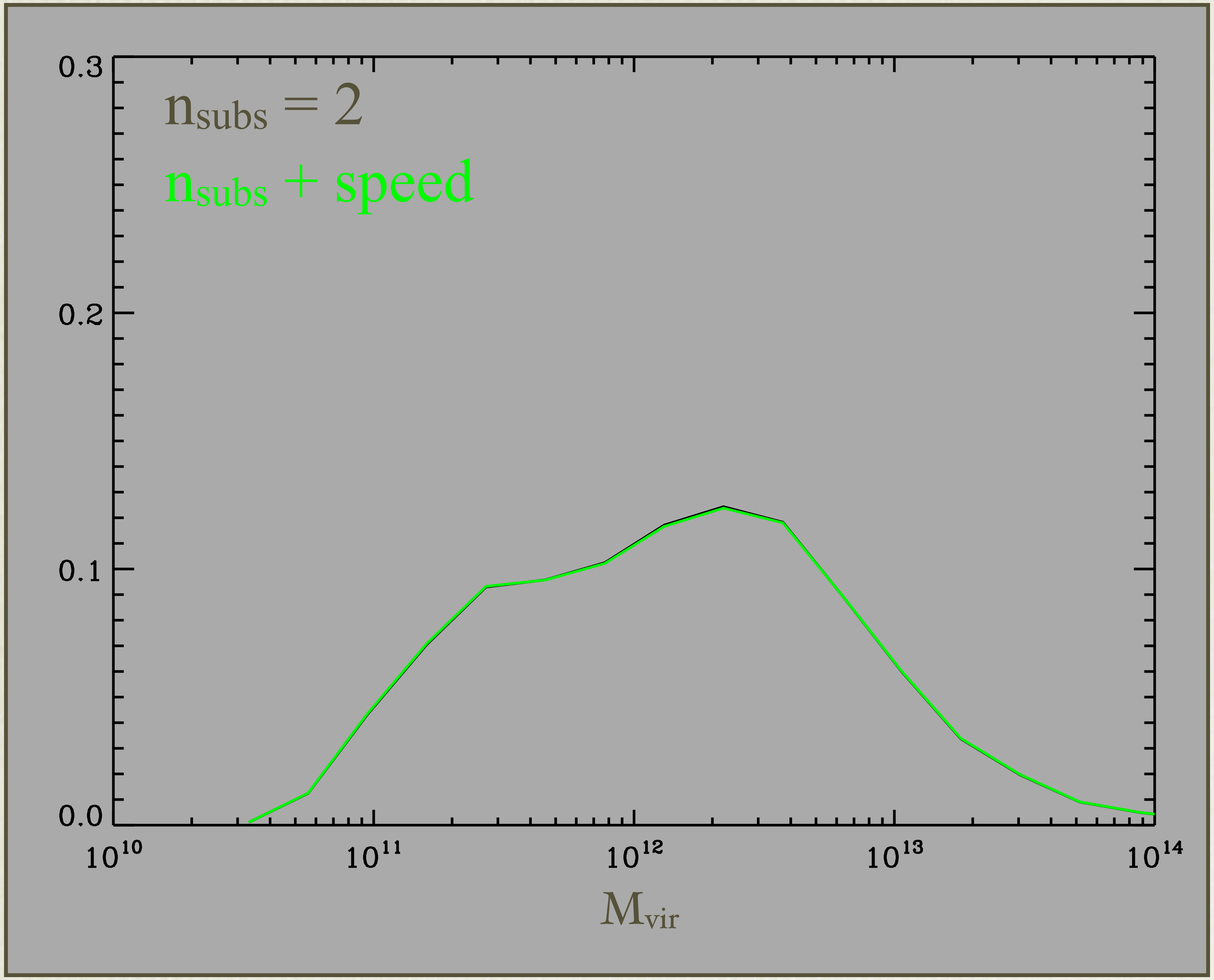

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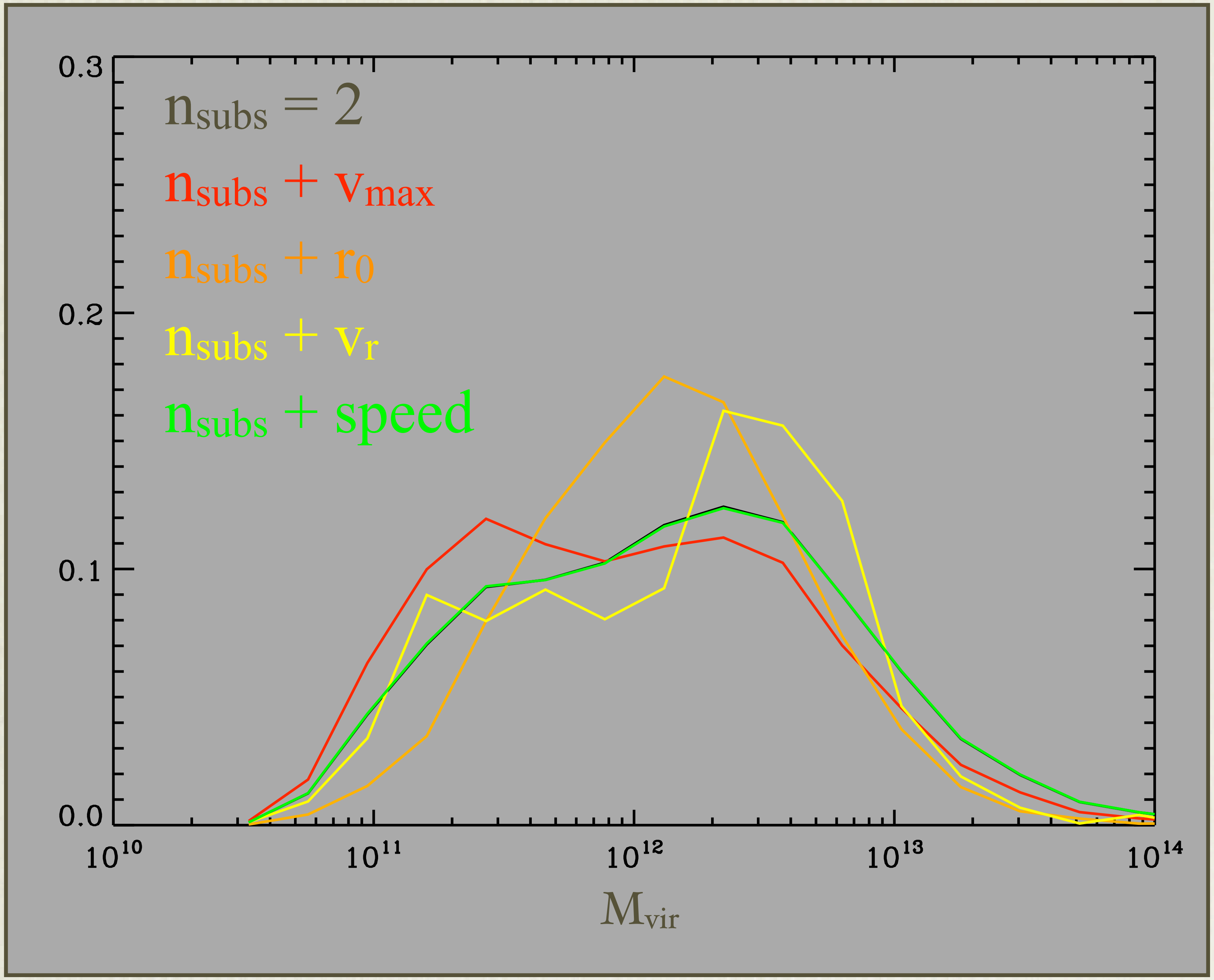
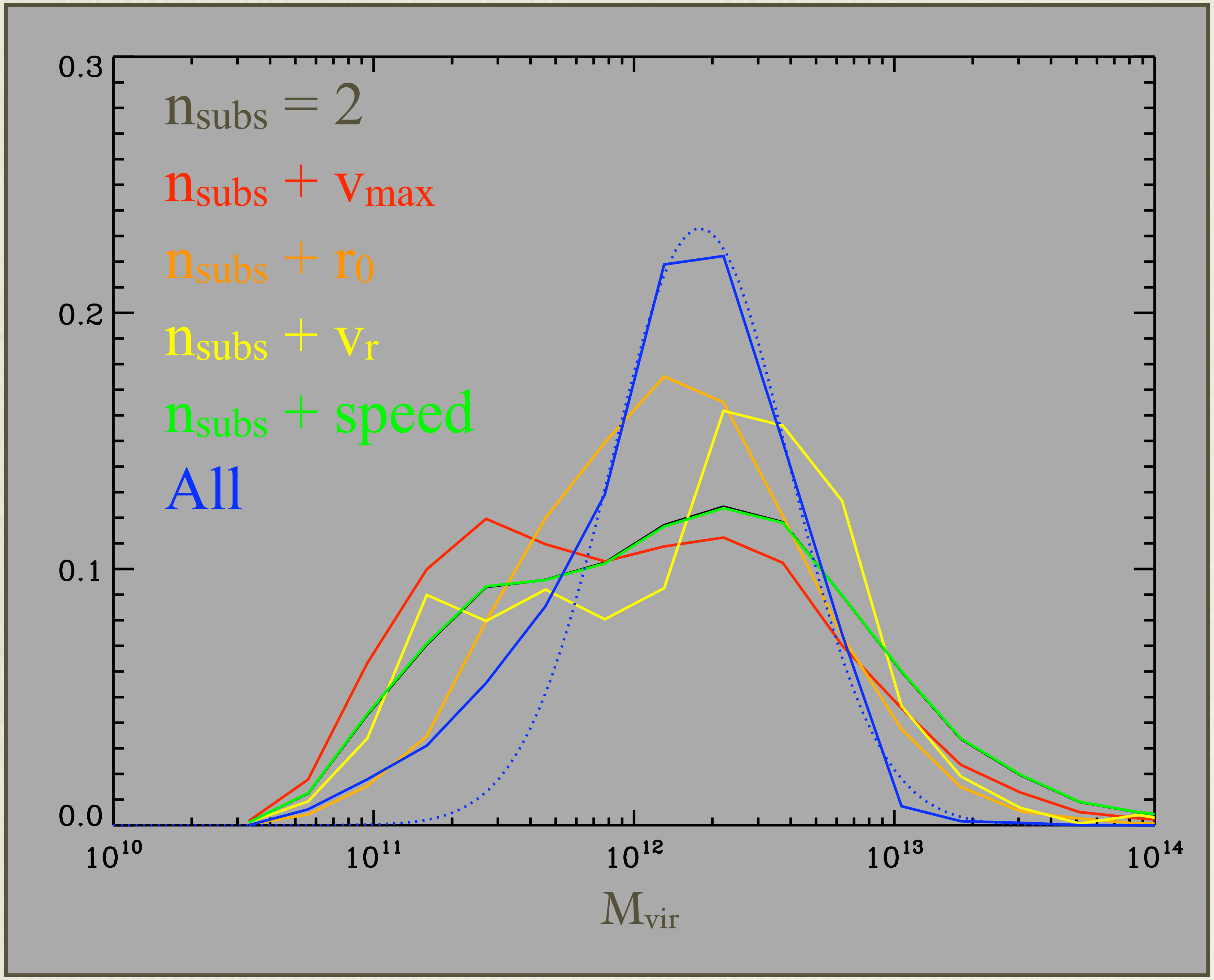


Additional Constraints on the Satellites

- Combining these constraints results in a significantly tighter measurement of the Milky Way Mass:

$\log(M_{vir}) = 12.26 \pm 0.34$

$(n_{subs} + v_{max} + r_0 + v_r)$



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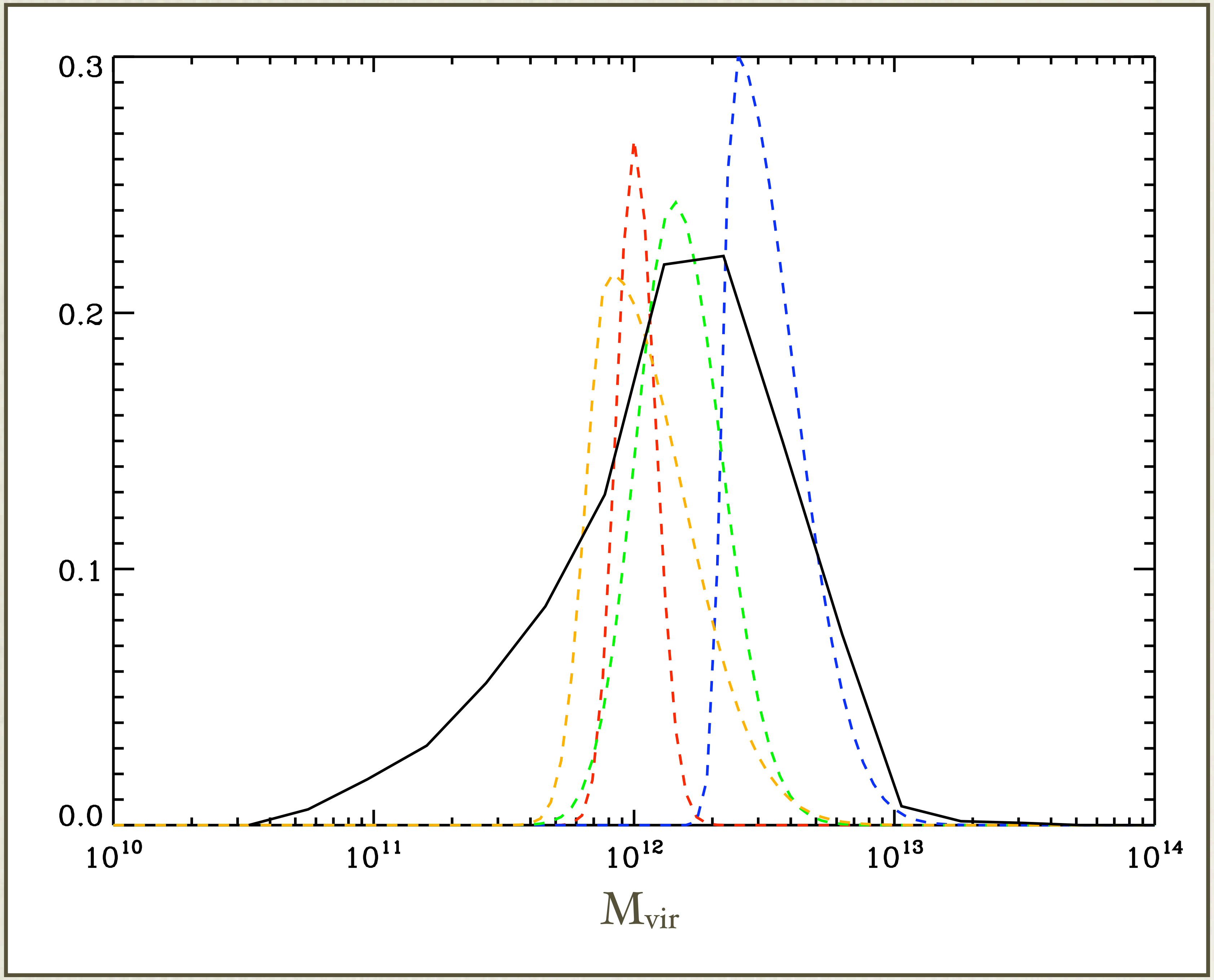
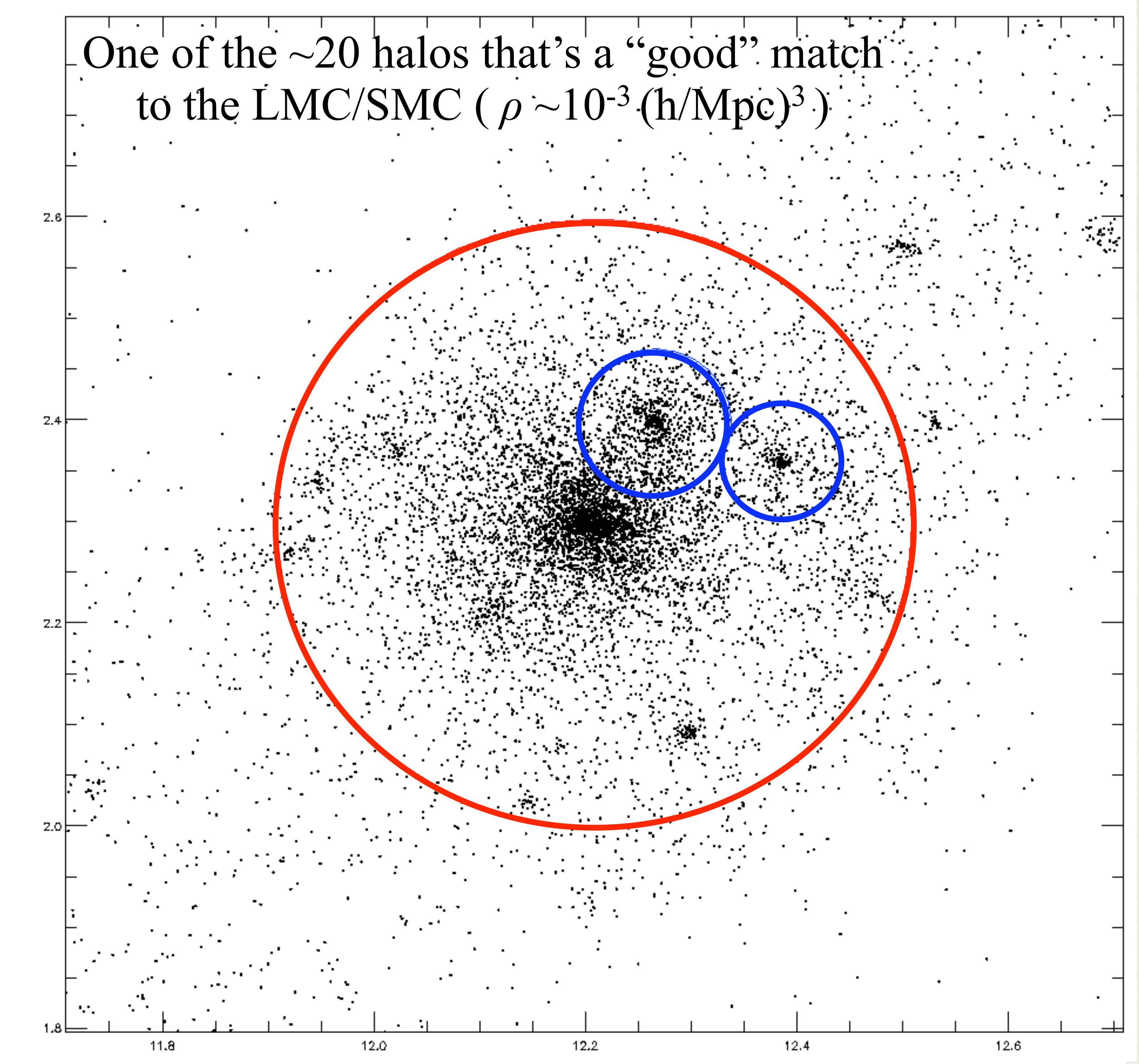
- Can be compared directly with other measurements -- not competitive, but perfectly brackets the range of recent measurements



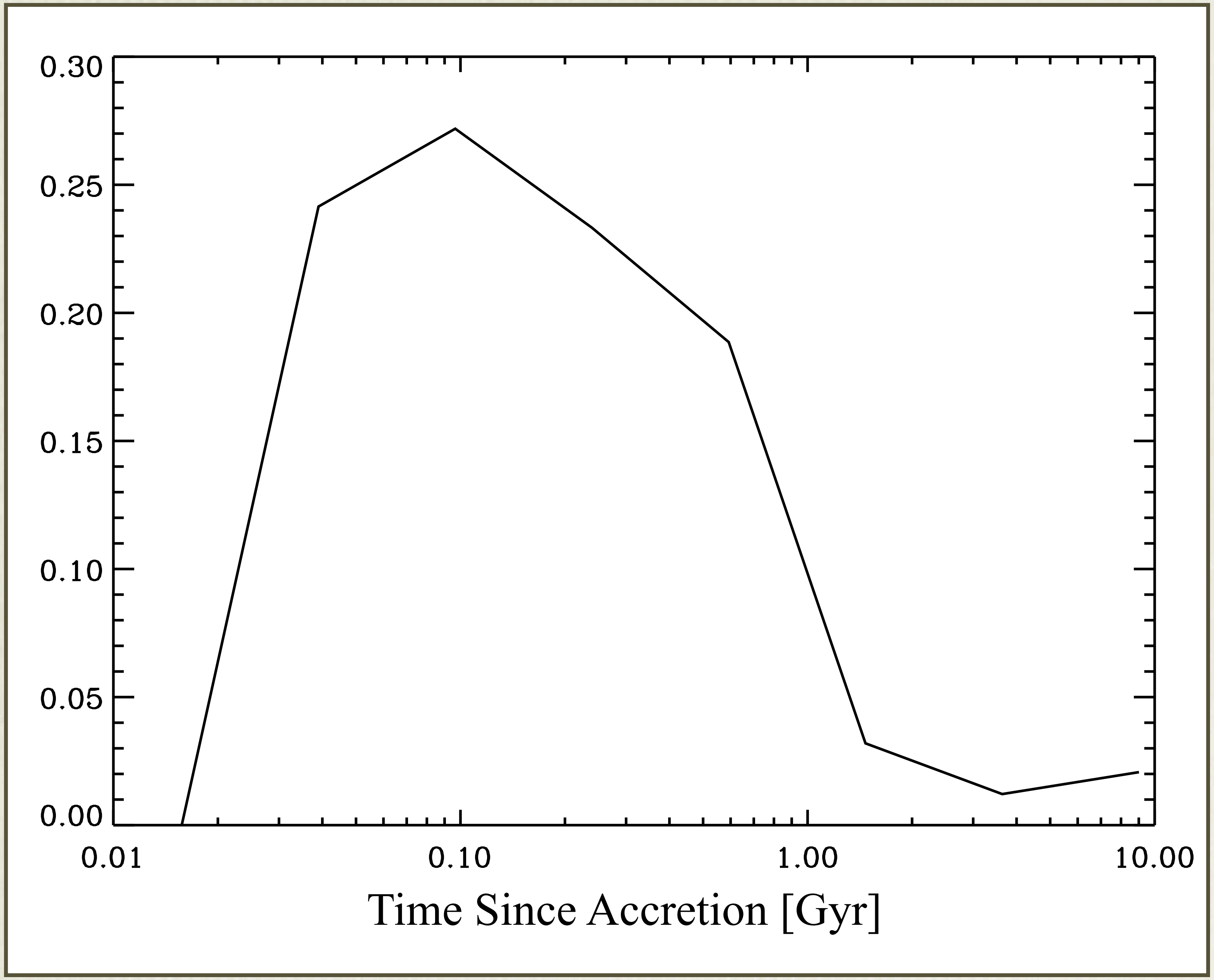
The Resulting Hosts

- Get ~ 20 “close” matches, hundreds of decent ones.
- Can do two things with the resulting catalog:
  - Apply more priors to better constrain the mass (at the expense of statistics).
  - Look at the posterior distribution of other properties and compare with observations, learn more about the MW.



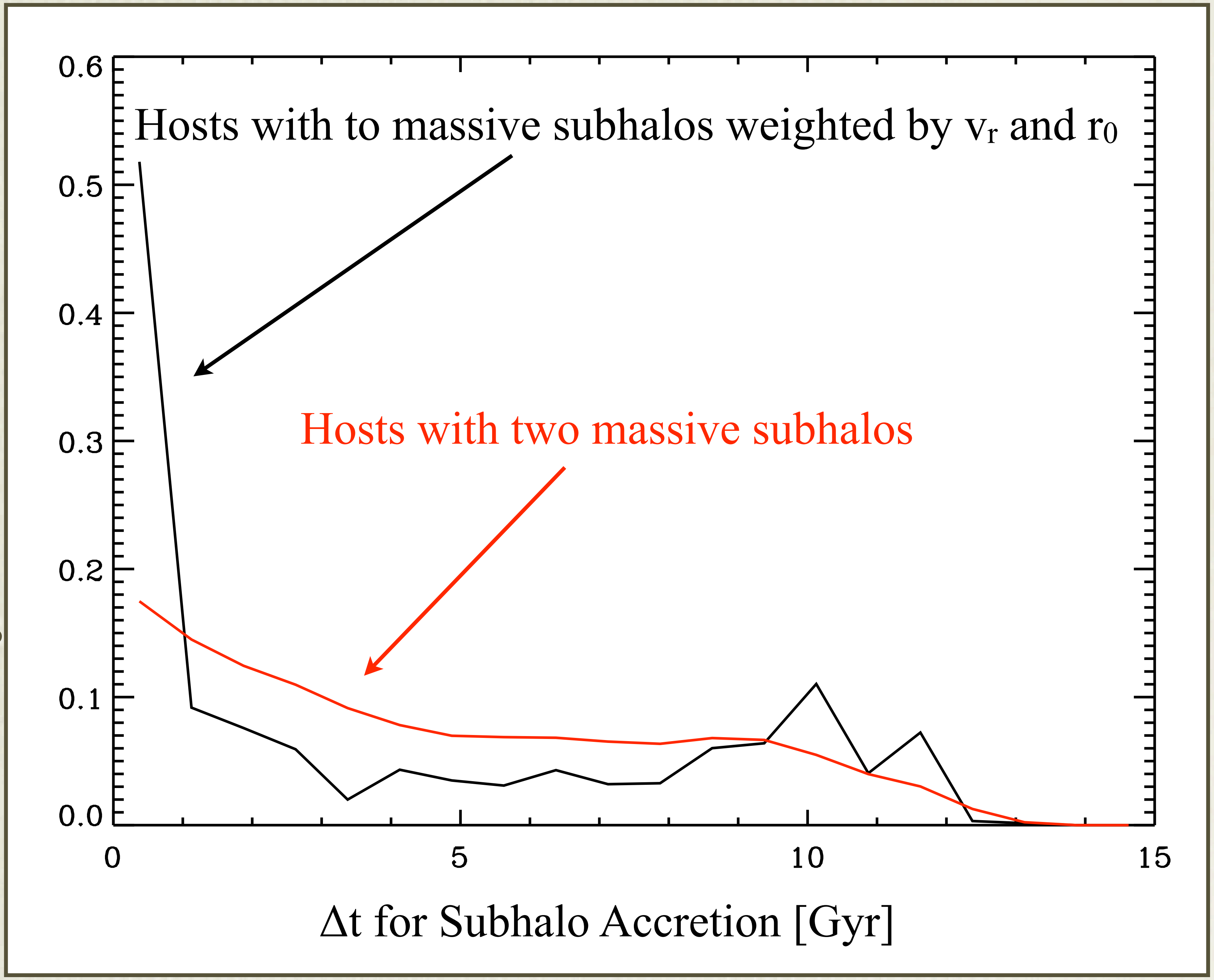
Accretion Time of the Subhalos

- Recent work indicates that the LMC and SMC may be on their first passage through the Milky Way.
- In our selection of Bolshoi objects, over 90% of the objects were accreted in the past Gyr (roughly a crossing time of the MW).



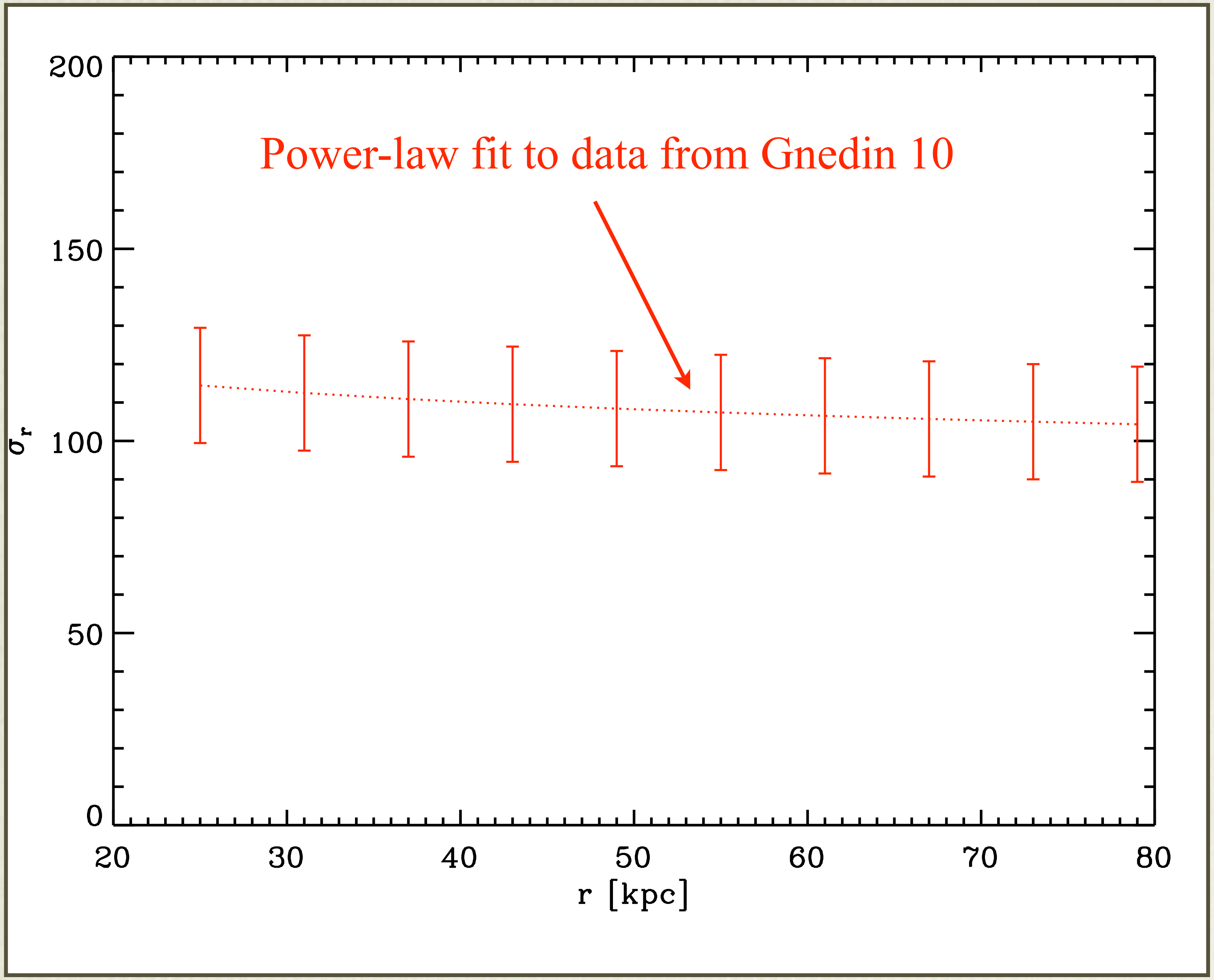
Accretion Time of the Subhalos

- Also speculation that the Magellanic Clouds may have accreted as bound objects.
- The Bolshoi hosts that have similar r_0 and r_v distributions strongly agree with this, halos with just v_{max} selected LMC and SMC analogs don't.



Radial Velocity Dispersion

- Compare measurements of the radial velocity dispersion profile to observations of BHB stars, globular clusters and satellites directly to the Bolshoi dark matter measurements.



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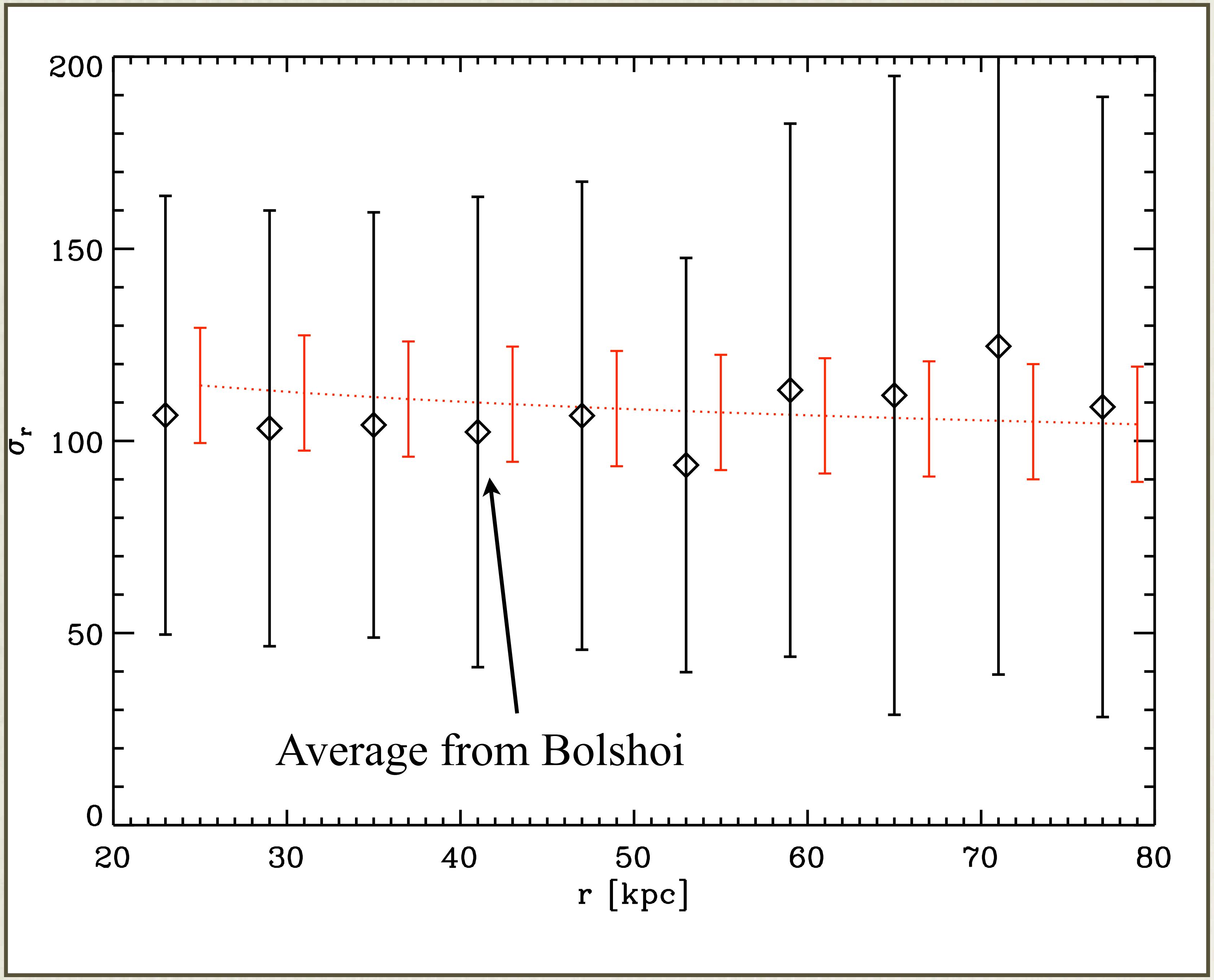

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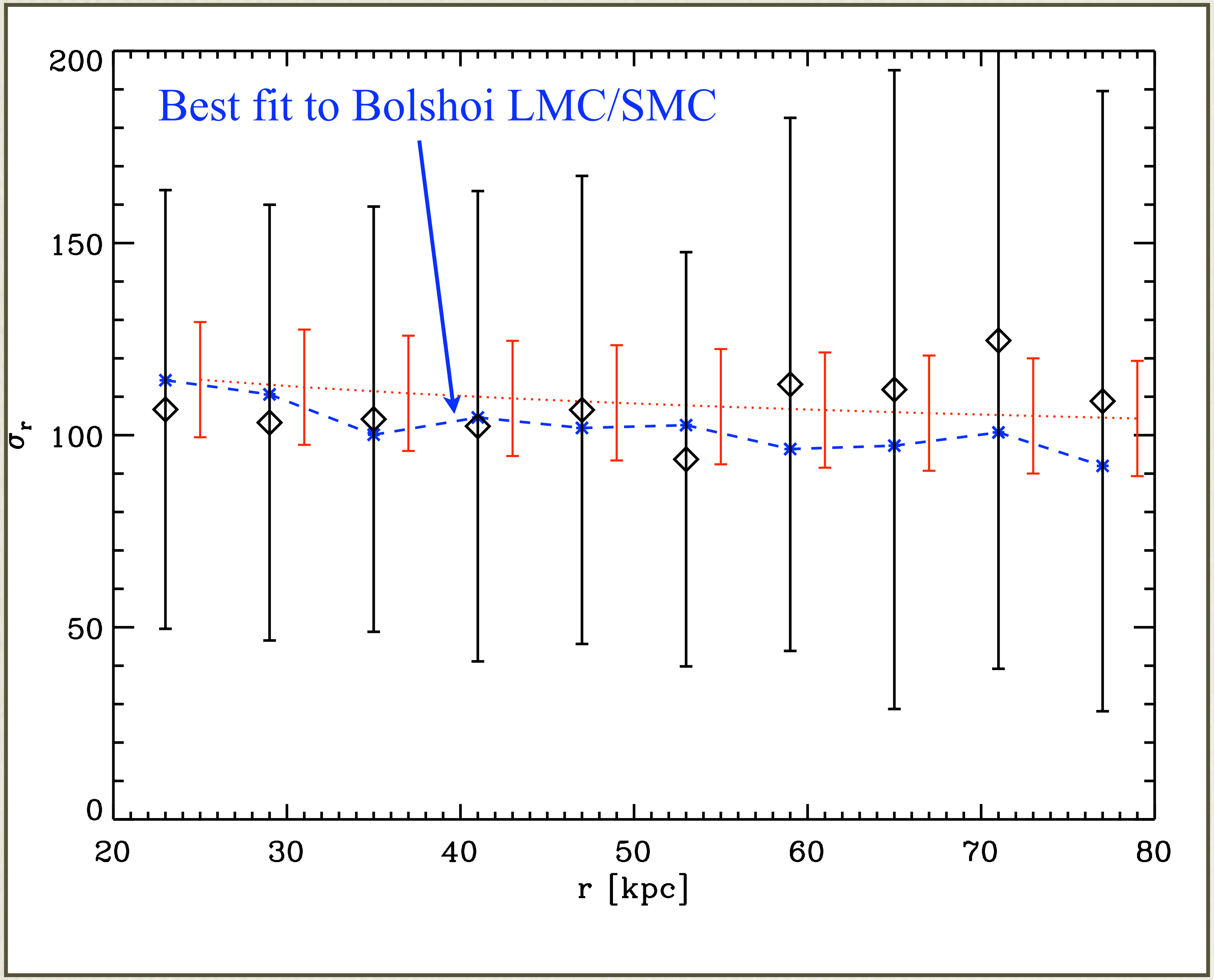
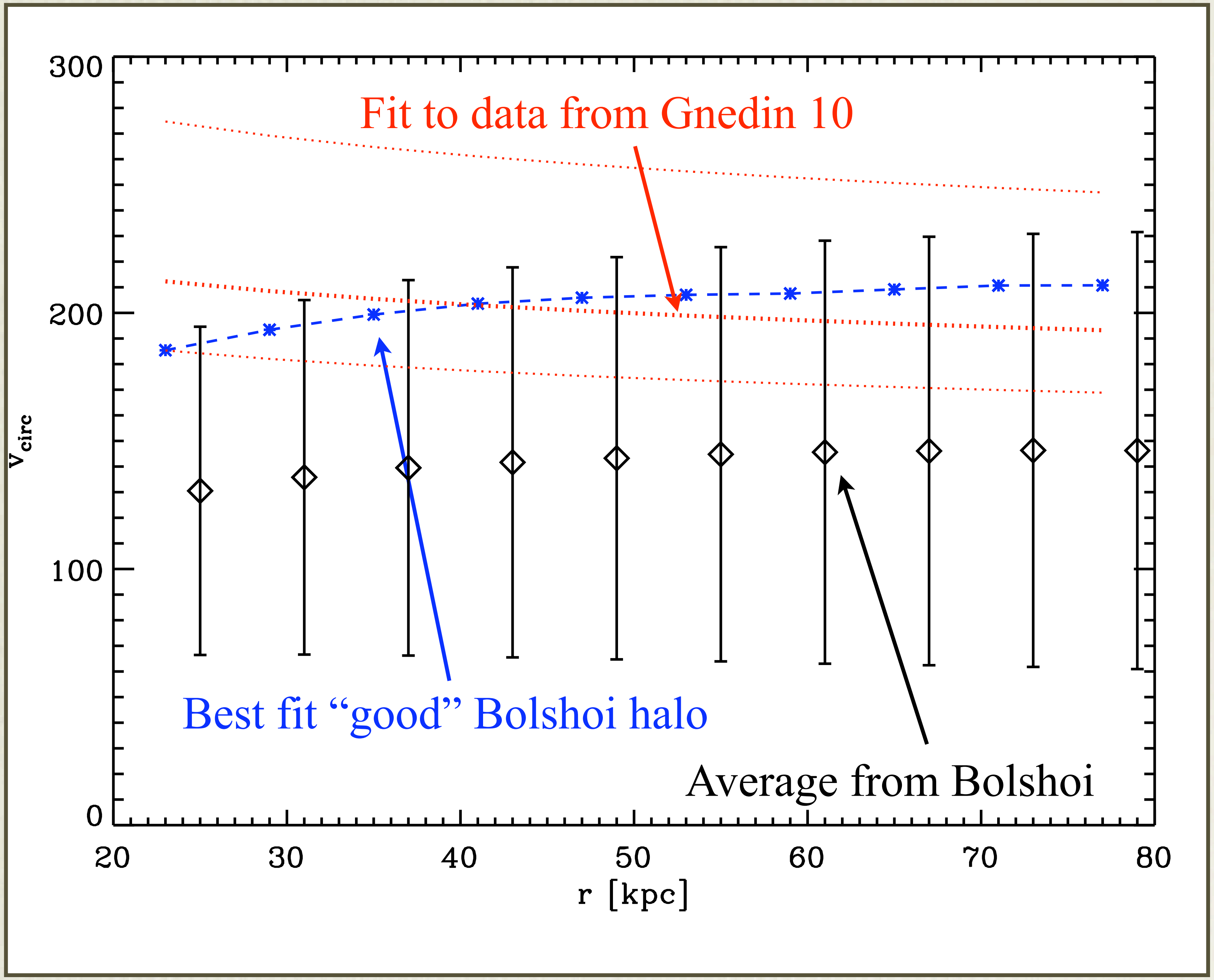


Circular Velocity Profile

- We can play the same game with the circular velocity profile.
- While we still see consistency, the profile for the Milky Way is significantly higher than the mean profile from the Bolshoi halos.



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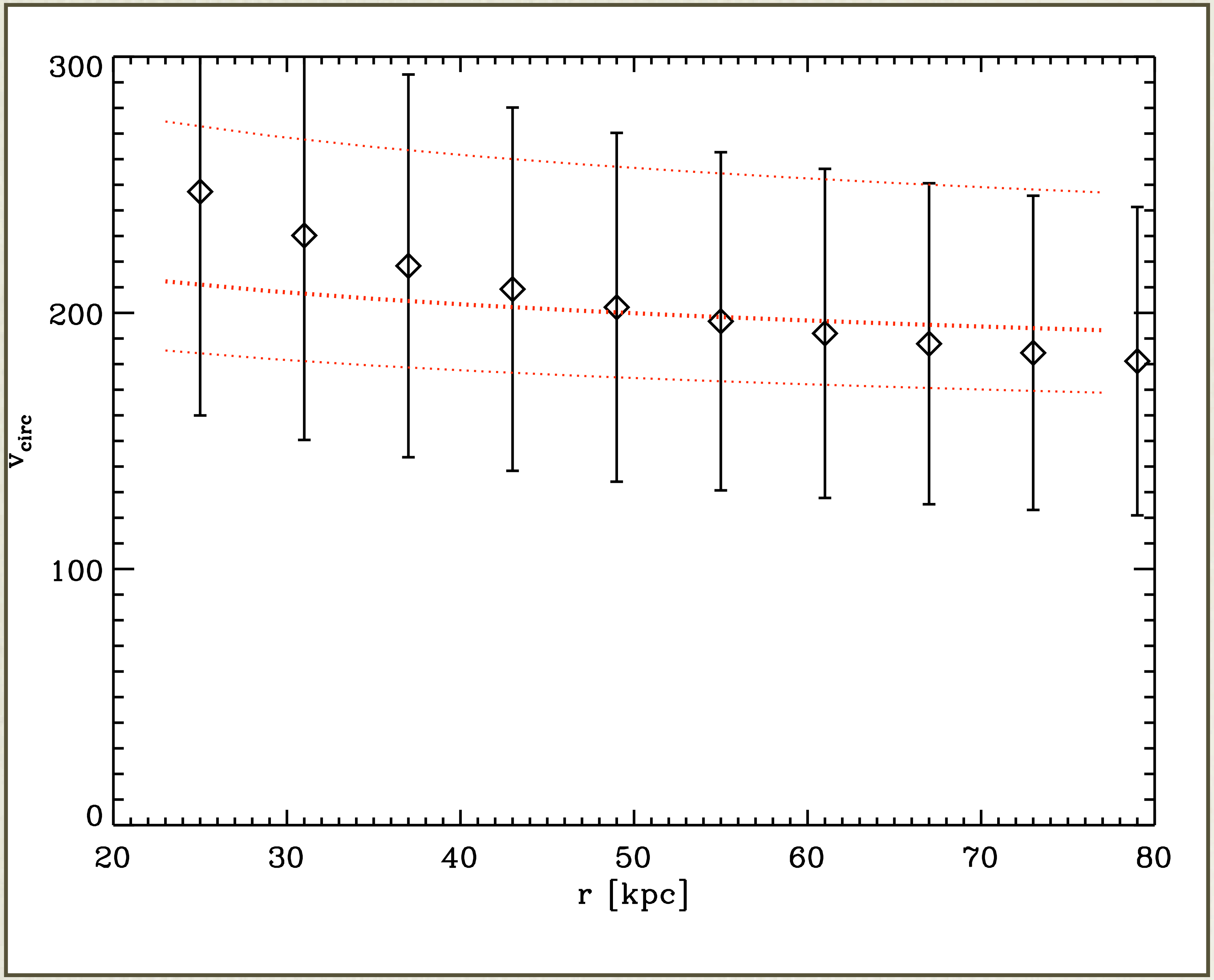
    - Can improve the fit by moving "baryonic mass" to the center.



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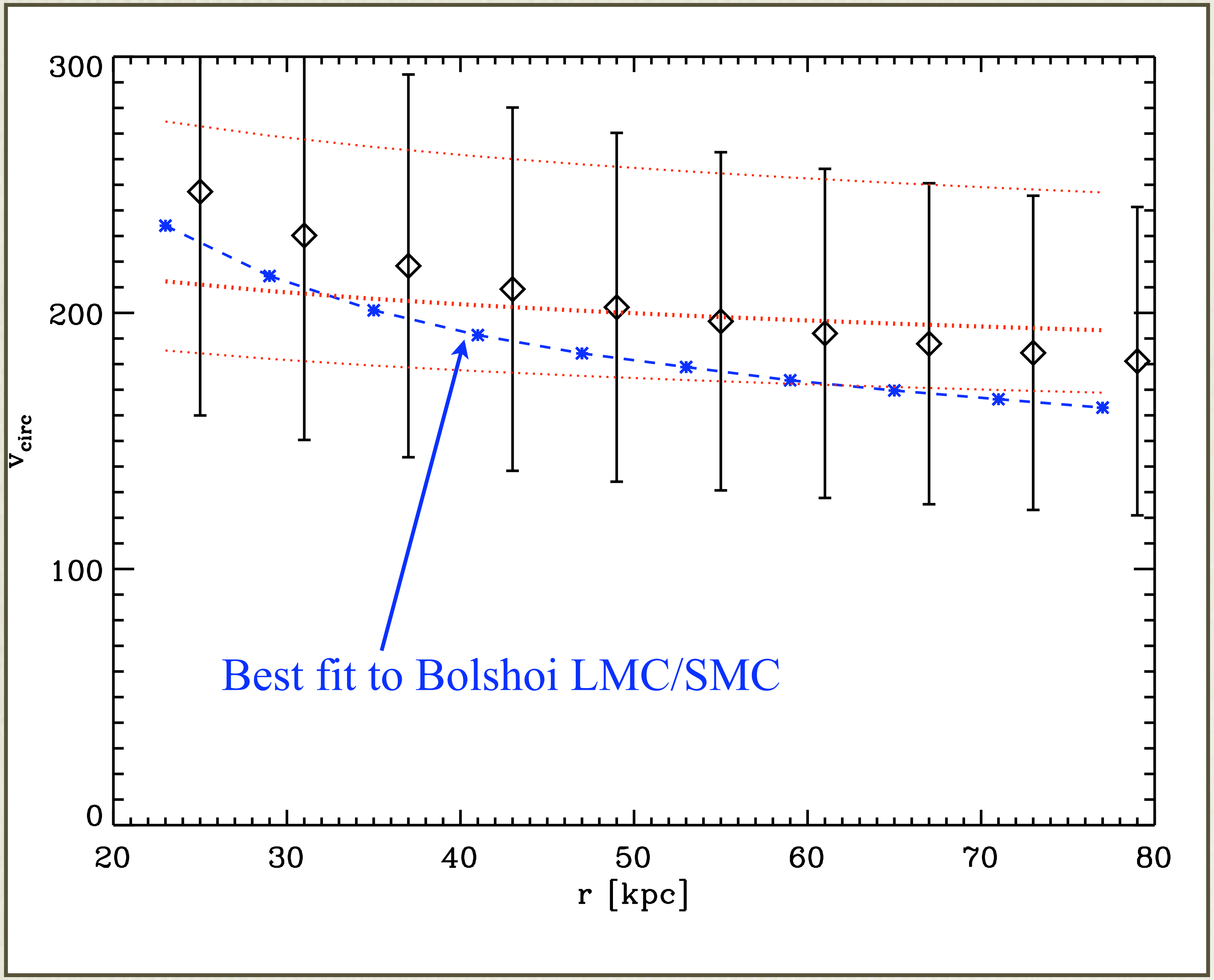

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Conclusions

- Given that we have exactly two Magellanic Clouds, the Bolshoi simulation puts reasonable constraints on the Milky Way in excellent agreement with more "thorough" observations.
  - $M_{MW} = 1.8{\times}10^{12}{\pm}0.8M_{\odot}$

- Properties of MW analogs in the simulation in good agreement with other observational constraints.
  - Predict recent, simultaneous accretion of the LMC and SMC.
  - Good agreement with regards to the radial velocity dispersion.
  - Circular velocity profiles in Bolshoi may be somewhat lower than, but consistent with, measurements from the Milky Way.

- Agree with Erik and Brian: No "found satellites" problem, no violation of the Copernican principle -- if you look at simulated halos with two massive substructures, the Milky Way looks fairly typical!