Modeling Subhalos and Satellites in Milky Way-like Systems

Ethan Nadler (Stanford/KIPAC)

4/24/18

KIPAC

Current & Previous Work

- Milky Way satellite modeling (with R. Wechsler, K. Bechtol, Y.-Y. Mao, G. Green)
- Subhalo disruption (with R.W., Y.-Y.M., S. Garrison-Kimmel, A. Wetzel: 1712.04467)
- Bispectra of Massive Tracers in EFTofLSS (with L. Senatore, A. Perko: 1710.10308)
- Idealized N-body and hydro simulations (with S.P. Oh, S.Ji, T. Abel: 1701.01449)

UC SANTA BARBARA PHYSICS

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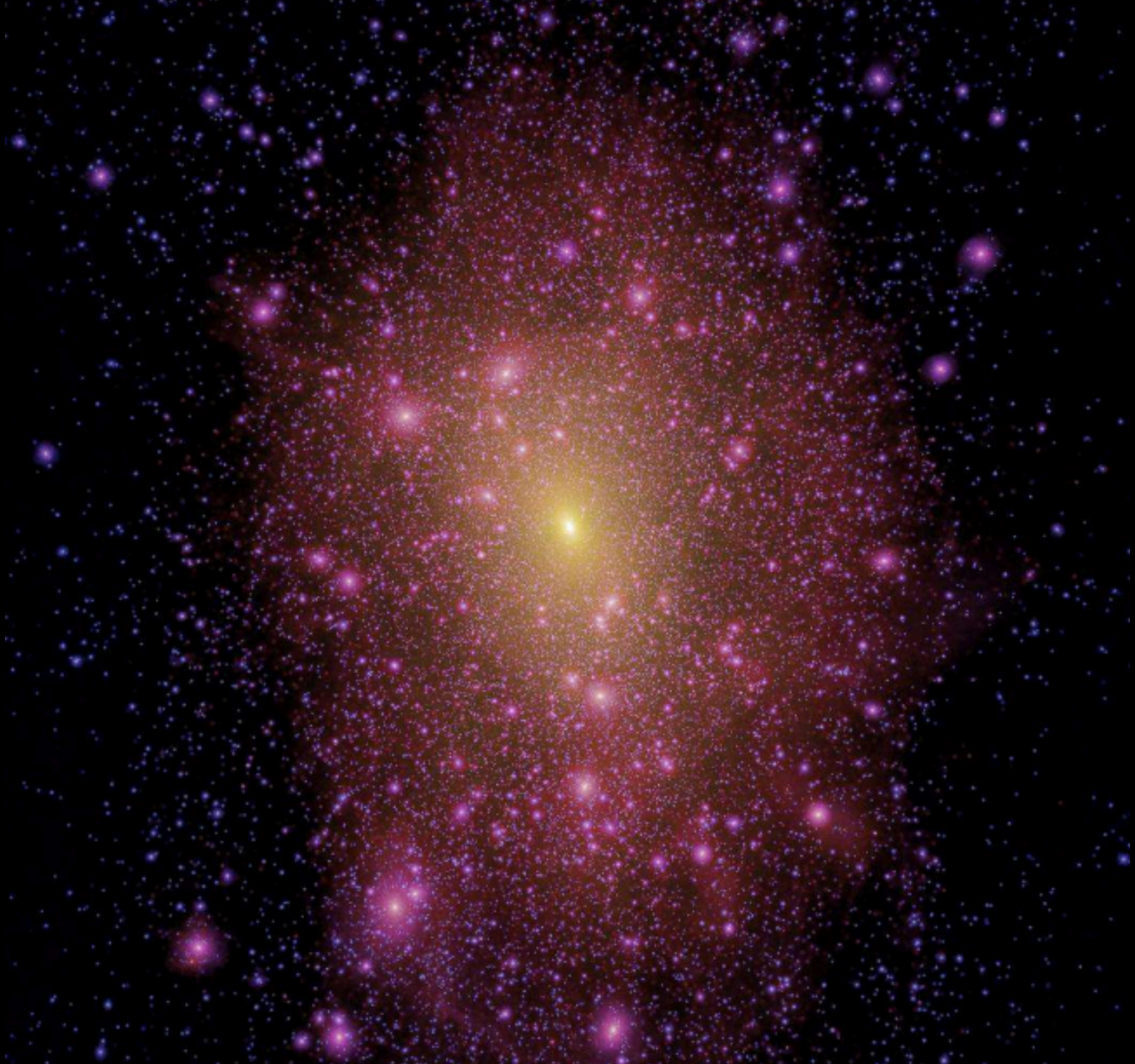
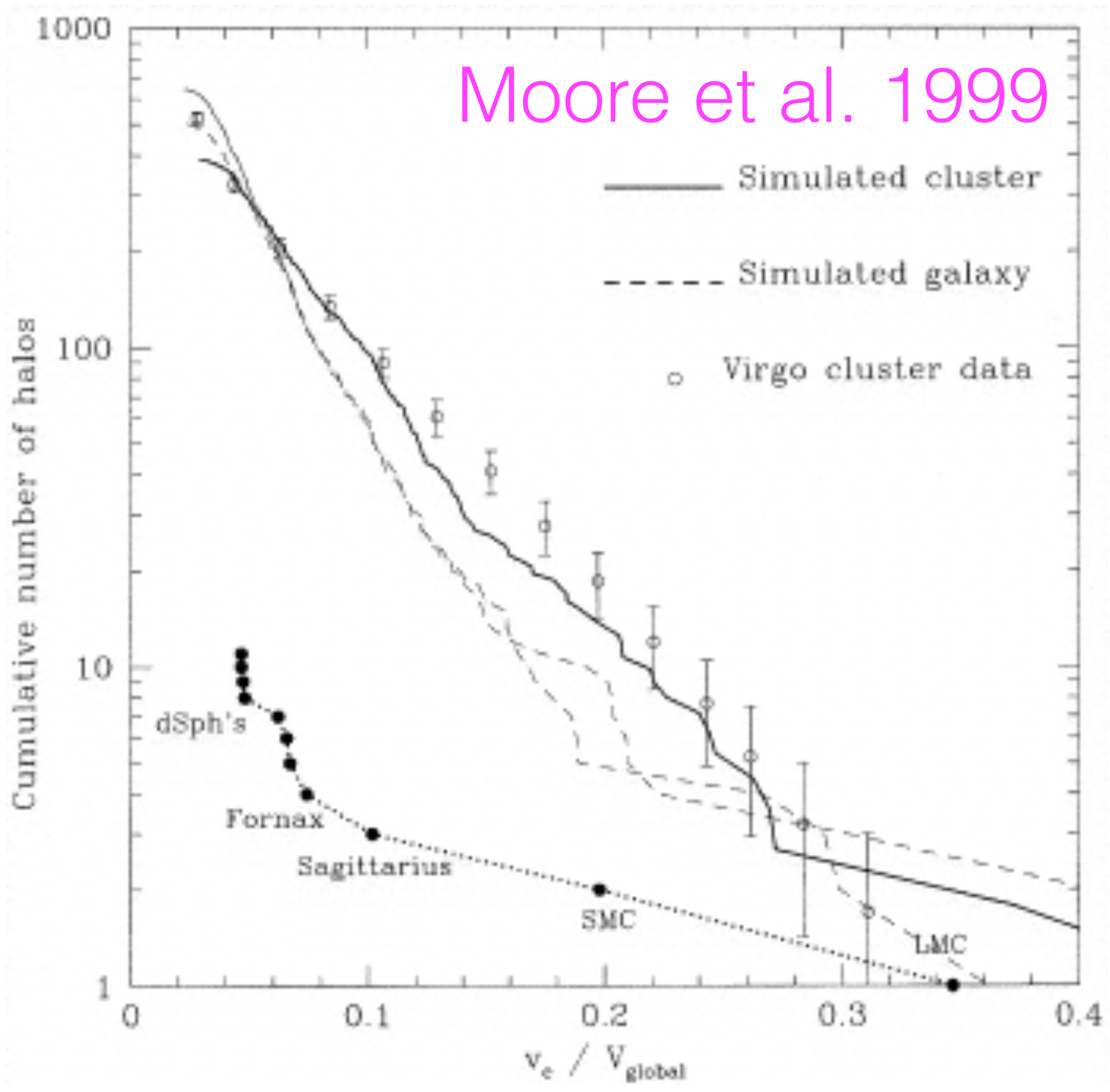


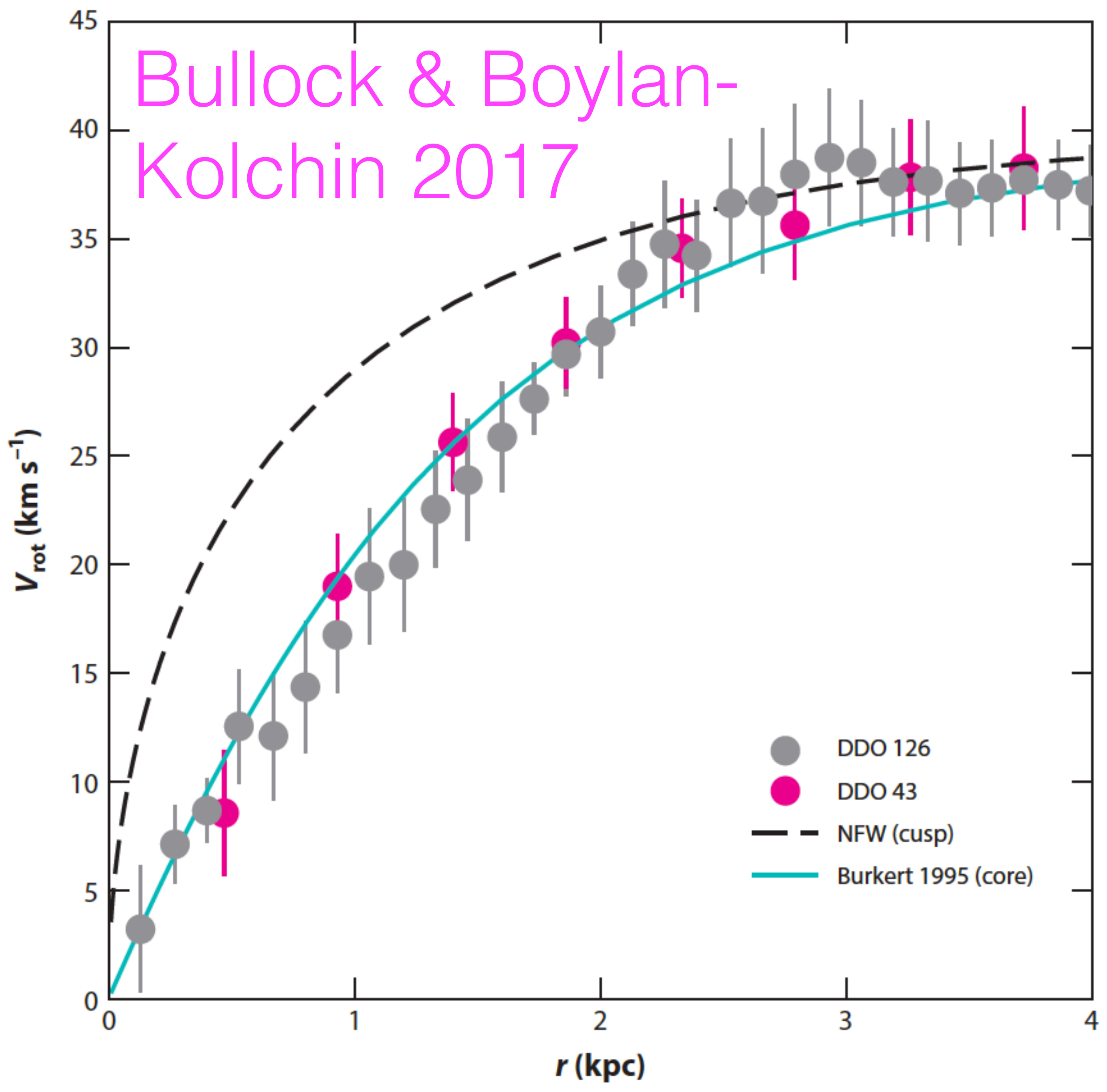
Lovell et al. 2011

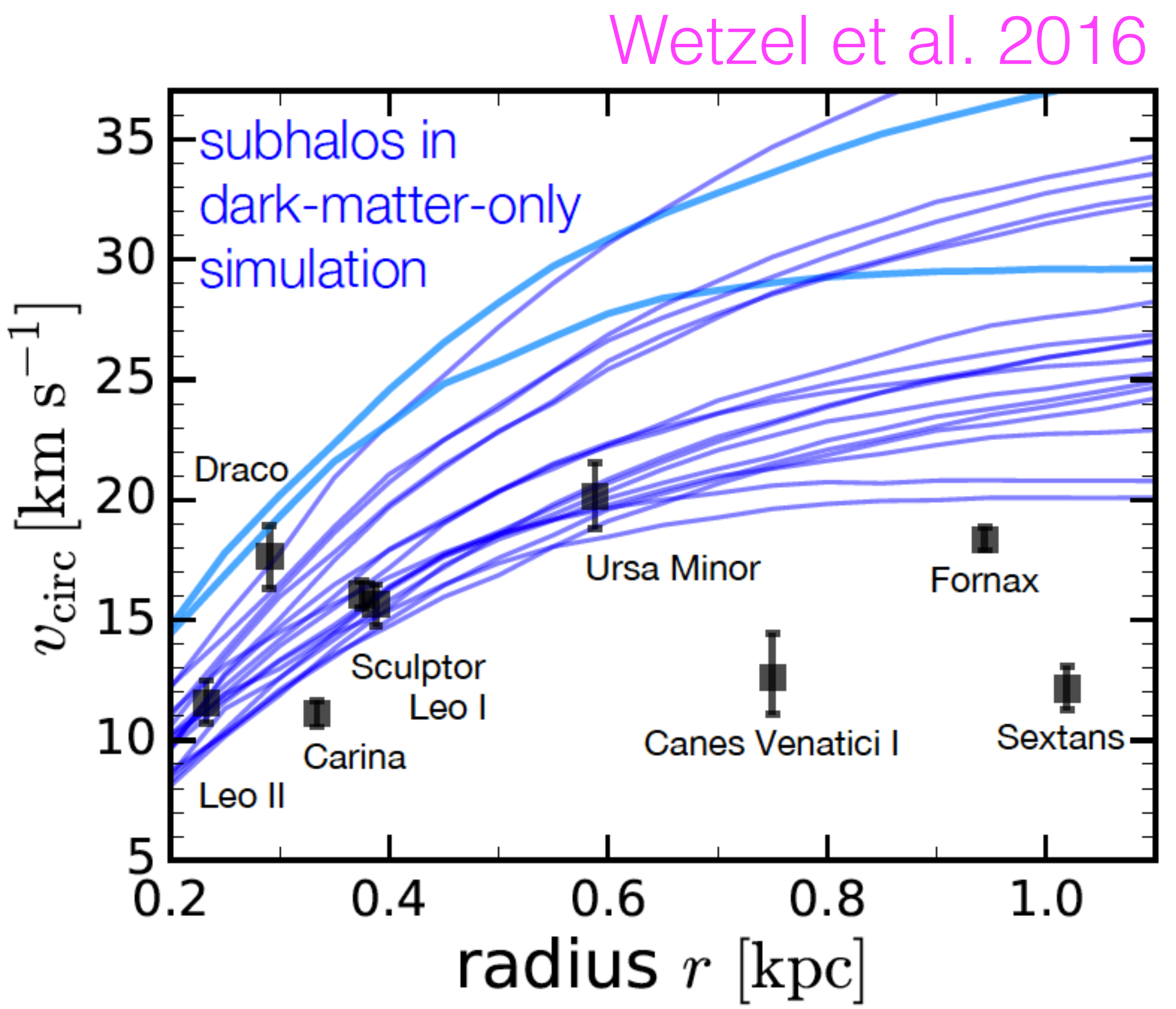
Lovell et al. 2011

Small-Scale Challenges to ΛCDM?

1. Missing Satellites: too few inferred low-mass subhalos
2. Cusp/core: dwarf galaxies tend to have cored inner density profiles
3. Too Big to Fail: circular velocities of MW/M31 subhalos << predicted values







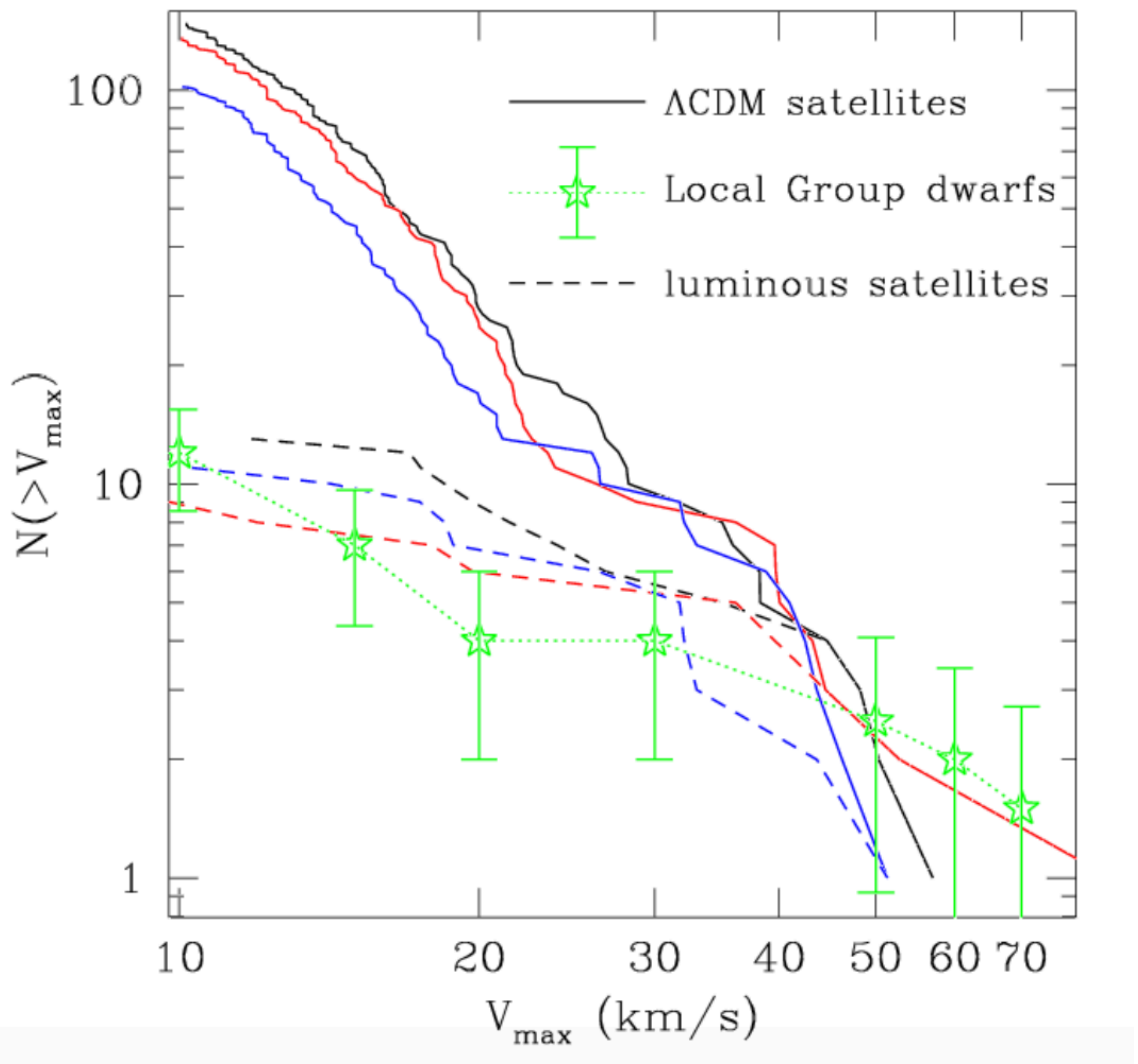
Small-Scale Challenges to ΛCDM?

1. Missing Satellites: reionization, stellar feedback suppress galaxy formation

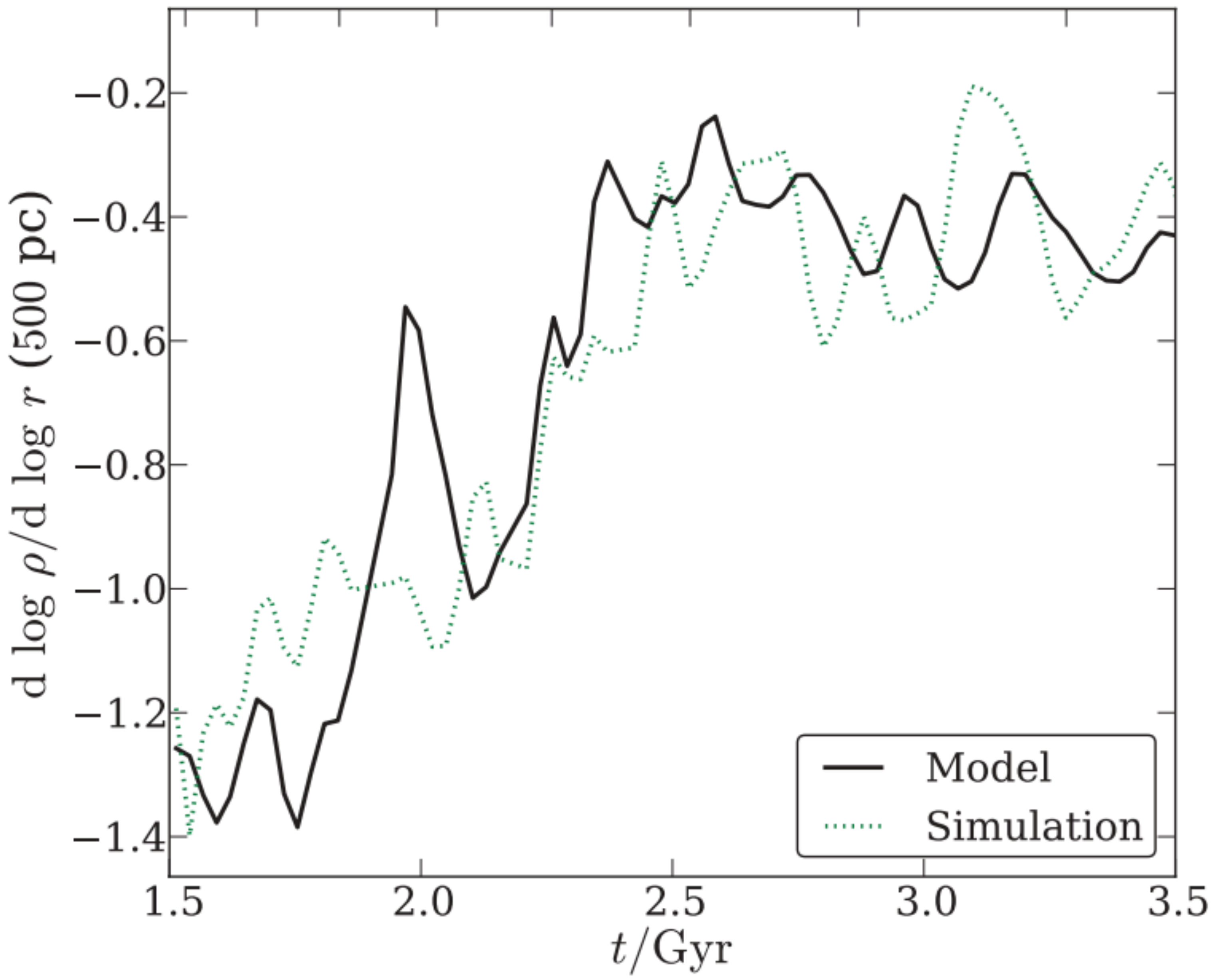
2. Cusp/core: stellar feedback —> rapid gas outflows, softened density cusps

3. Too Big to Fail: tidal subhalo disruption + internal feedback?

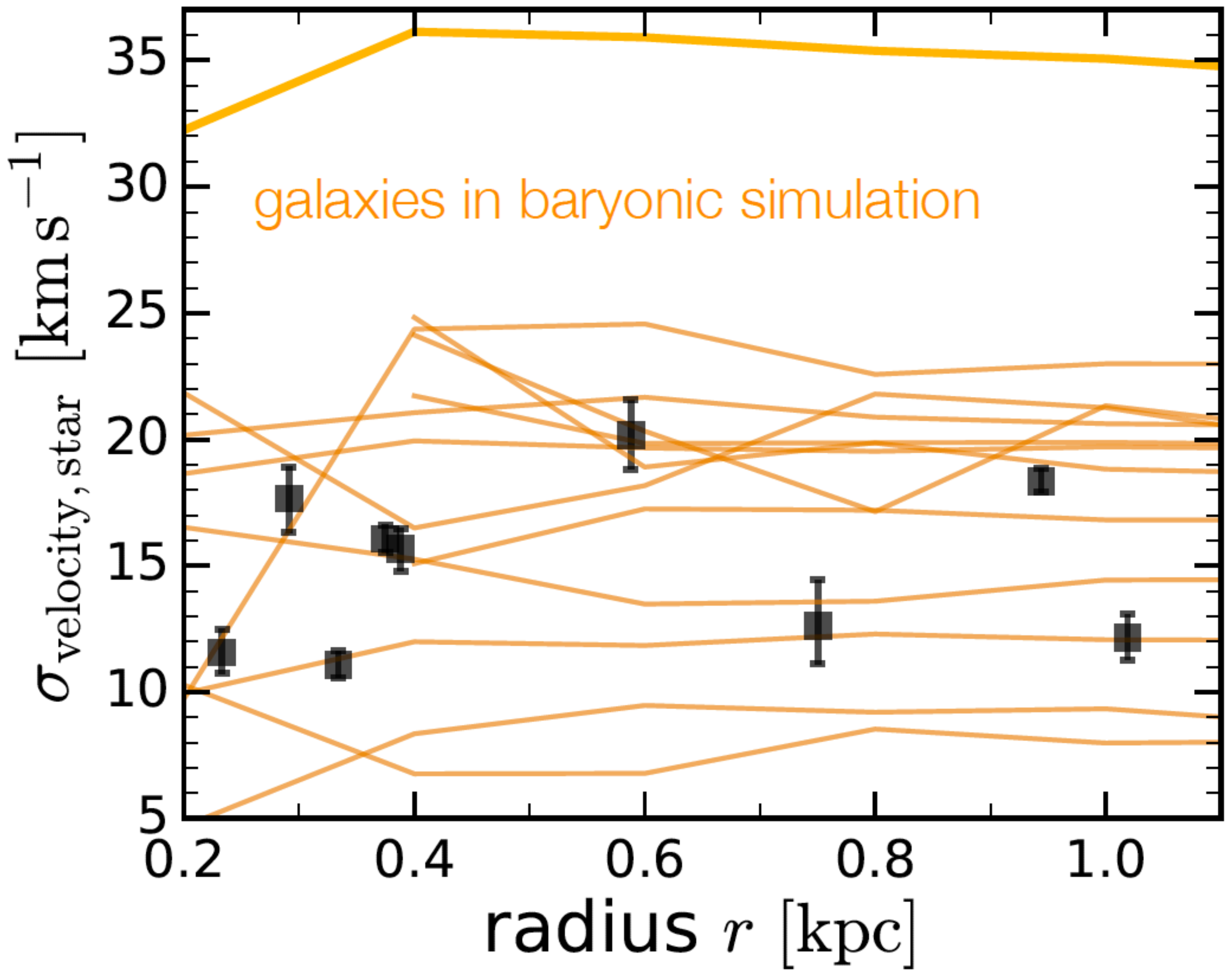
Kravstov et al. 2004



Pontzen & Governato 2012



Wetzel et al. 2016



Small-Scale Challenges to ΛCDM?

Instead of “is X a small-scale problem?”

…

“What can we learn about the physics of subhalos and satellites in Milky Way-like systems from X?”

Outline

1. Simulating Milky Way Analogs

2. Predicting Subhalo Disruption

3. Modeling Milky Way Satellites

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1. Simulating Milky Way Analogs

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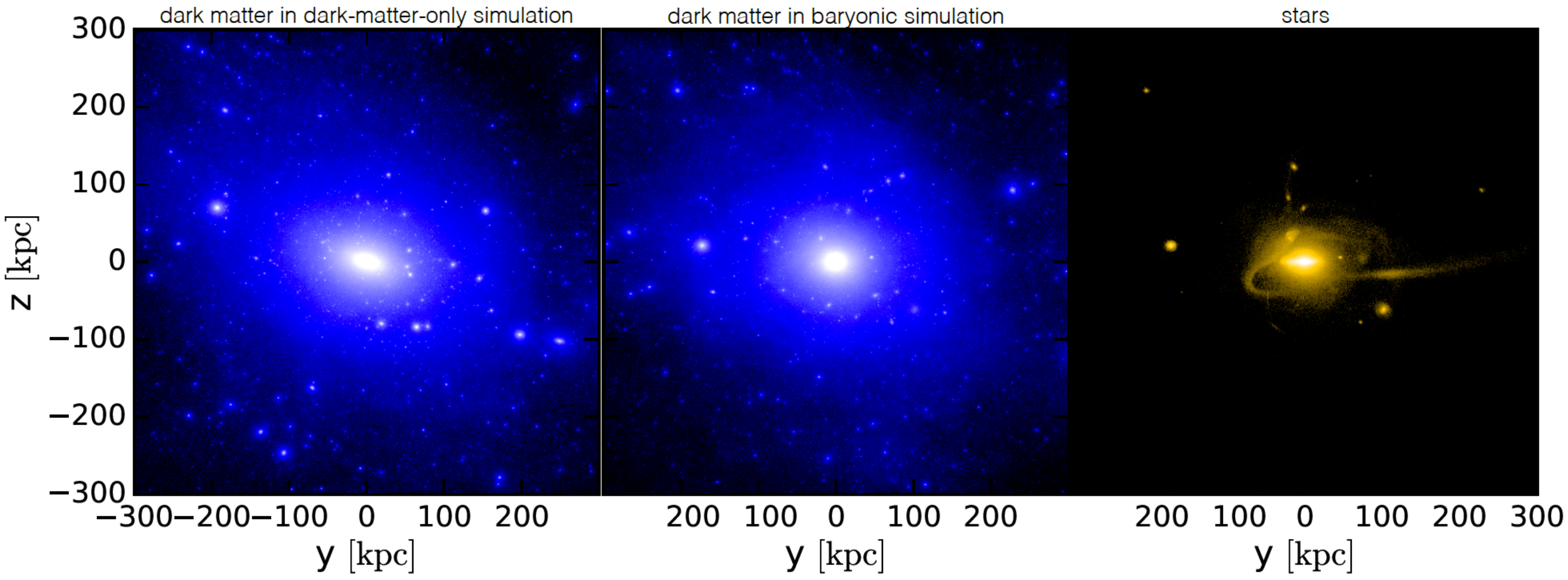
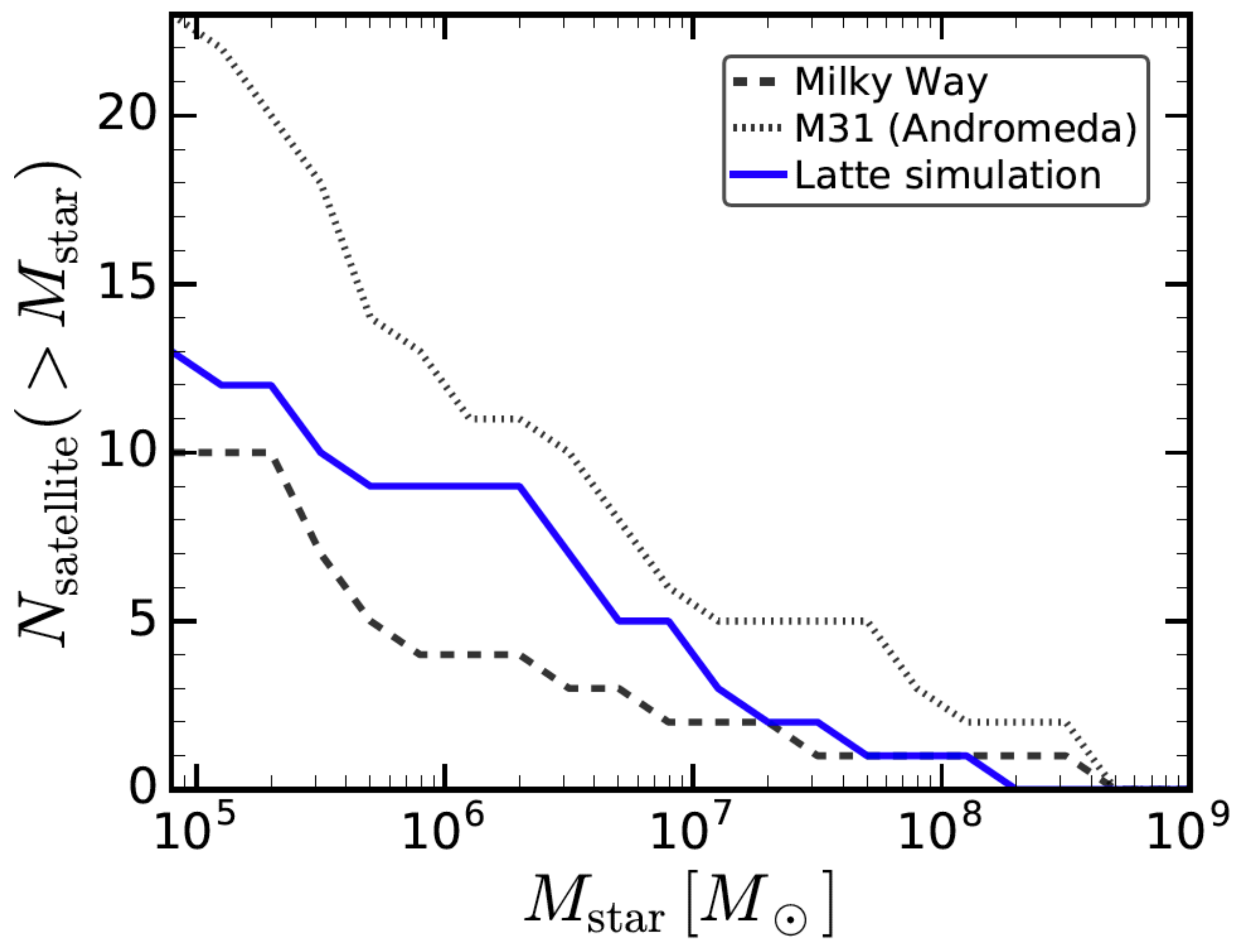
Simulating Milky Way Analogs

- Feedback in Realistic Environments: cosmological simulations of galaxy formation
- Star formation, stellar feedback, photo-ionization models …
- Satellite abundance in two zoom-ins consistent with MW/M31

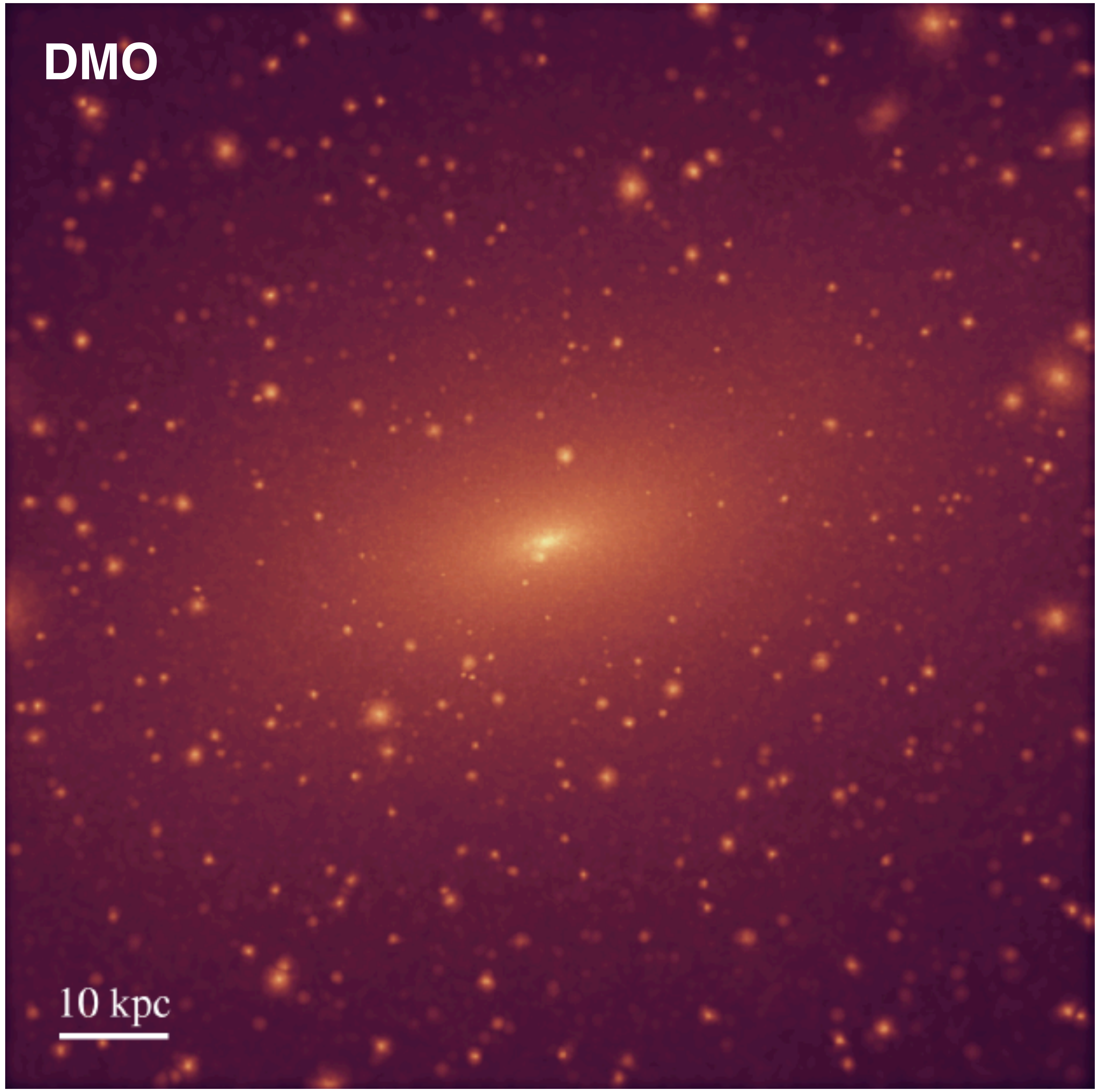
FIRE
Feedback In Realistic Environments

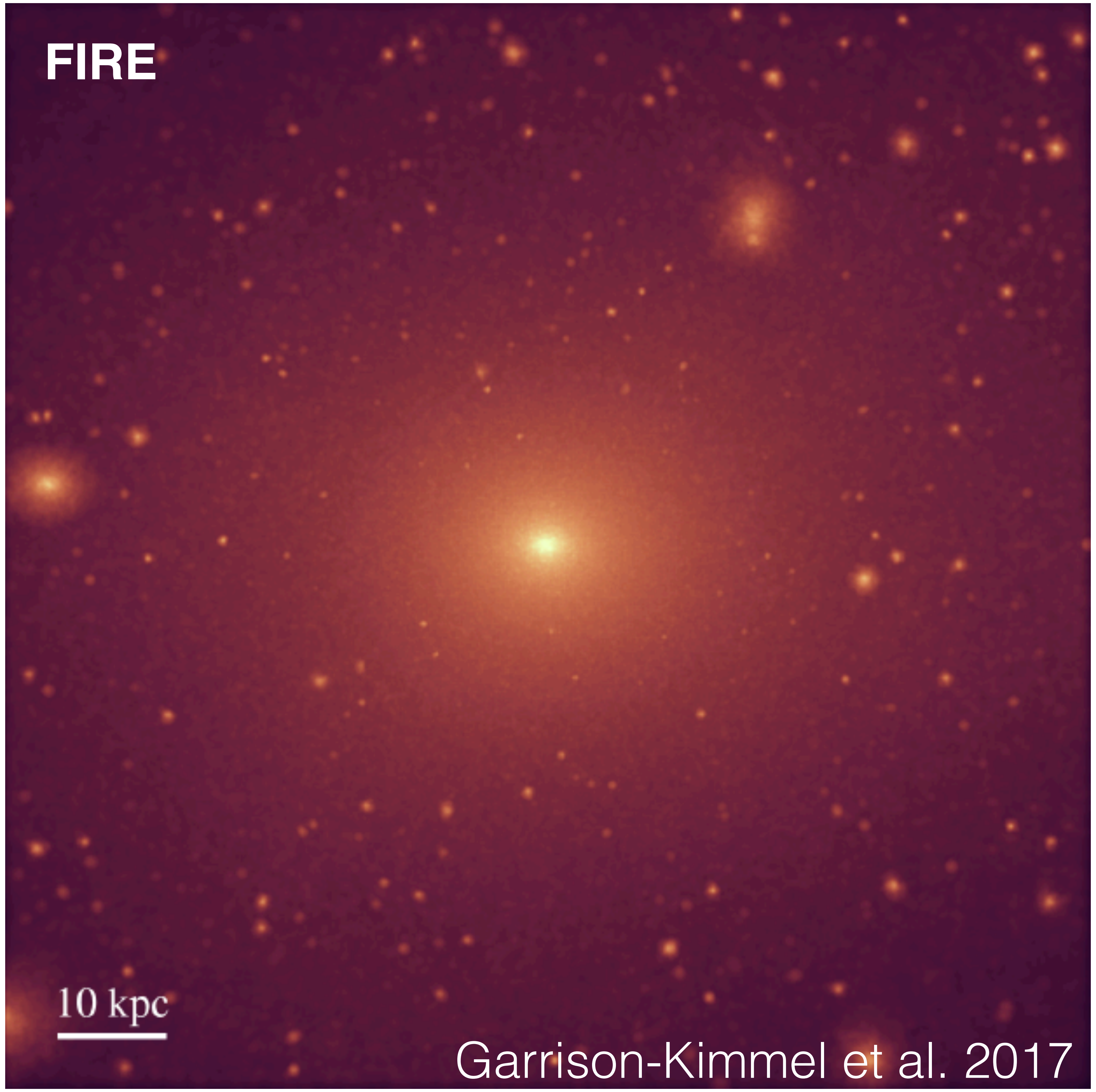


Wetzel et al. 2016



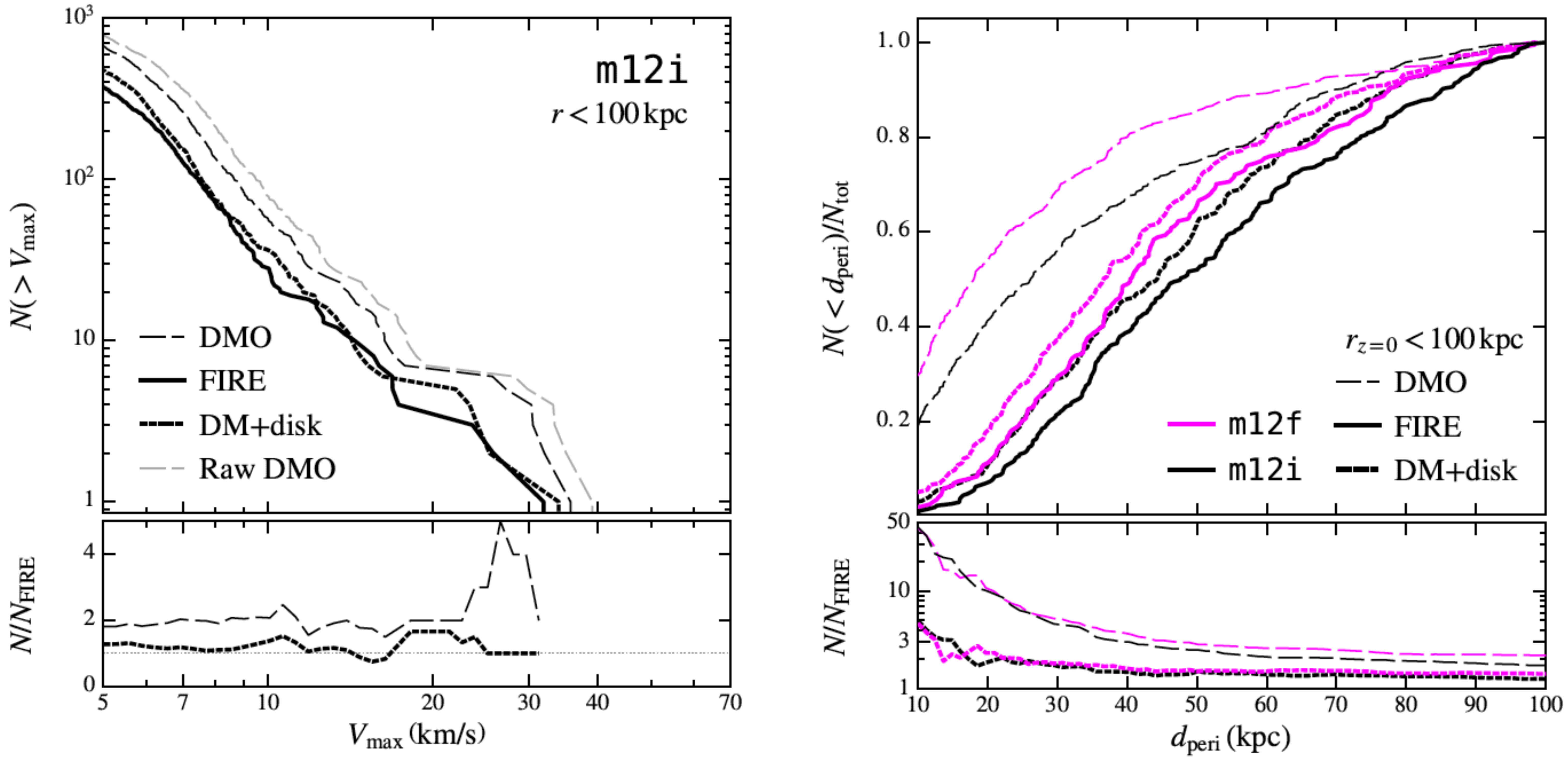
Subhalo Disruption

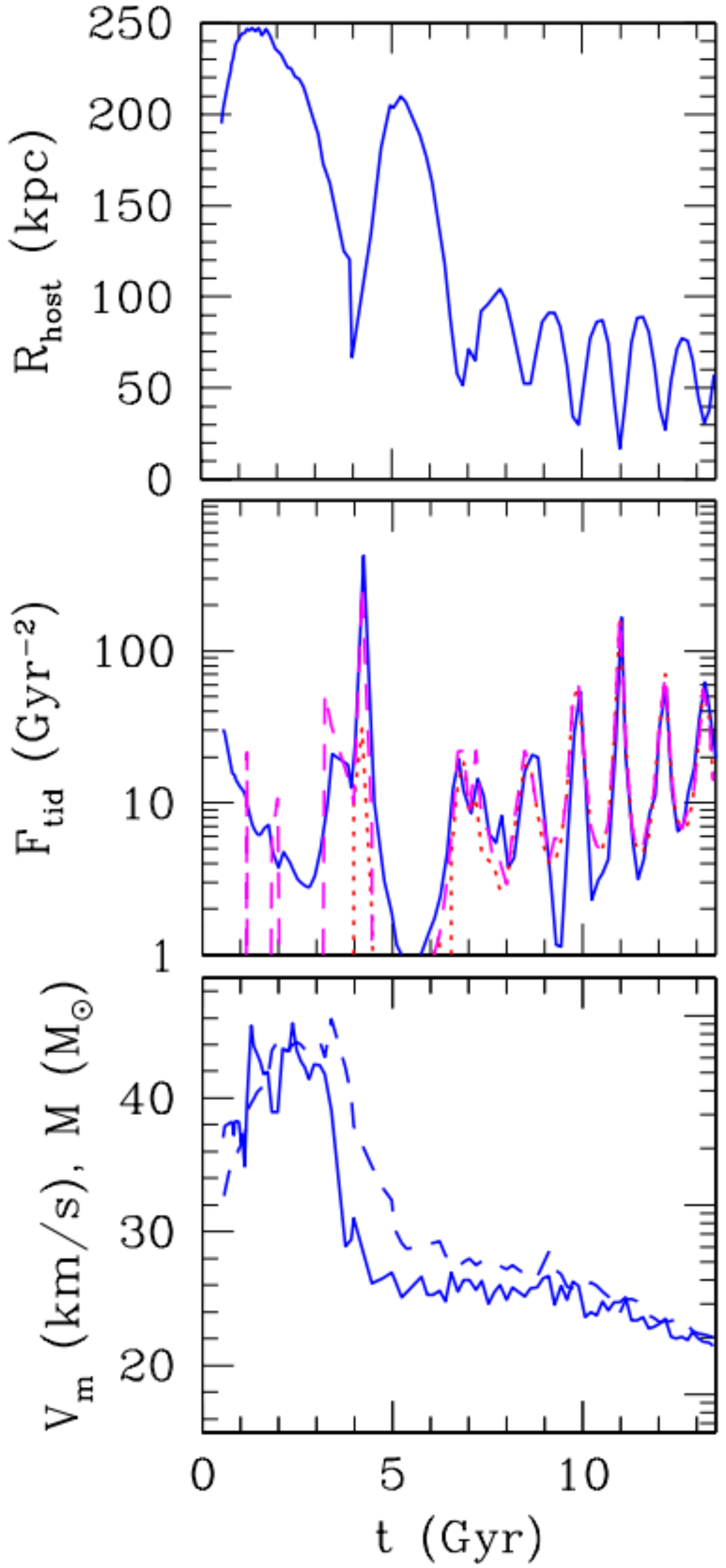




Subhalo Disruption

- Tidal stripping results in significant subhalo mass reduction
- Galactic disk in hydro sims dominates subhalo disruption



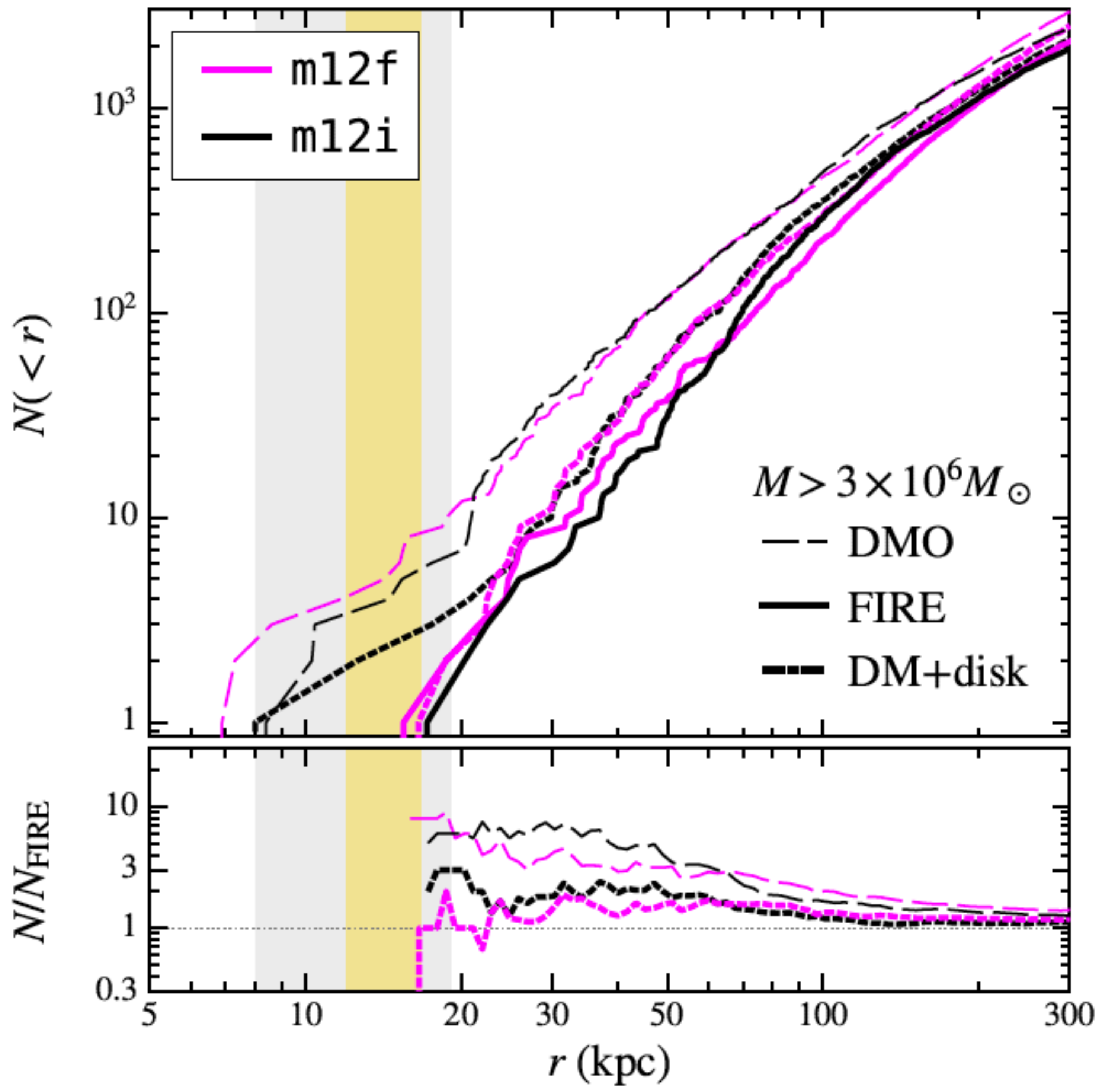


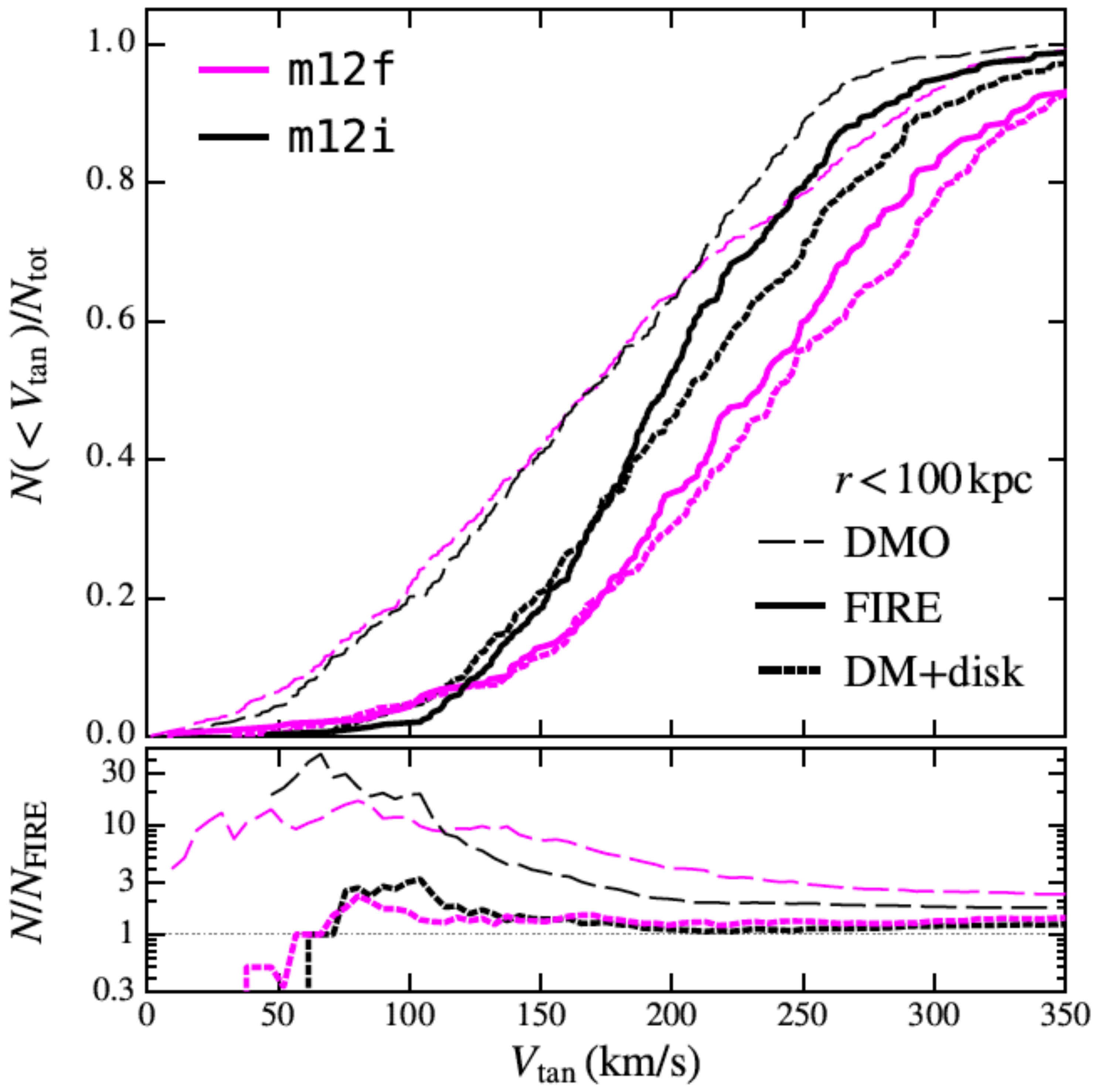
Garrison-Kimmel et al. 2017

Kravstov et al. 2004

Subhalo Disruption: Implications

- Extreme reduction in number of surviving subhalos within ~ 50 kpc of galactic disk
- Implications: stellar streams, lensing anomalies, satellite completeness correction





Garrison-Kimmel et al. 2017

Outline

1. Simulating Milky Way Analogs

2. Predicting Subhalo Disruption

3. Modeling Milky Way Satellites

MODELING THE IMPACT OF BARYONS ON SUBHALO POPULATIONS WITH MACHINE LEARNING

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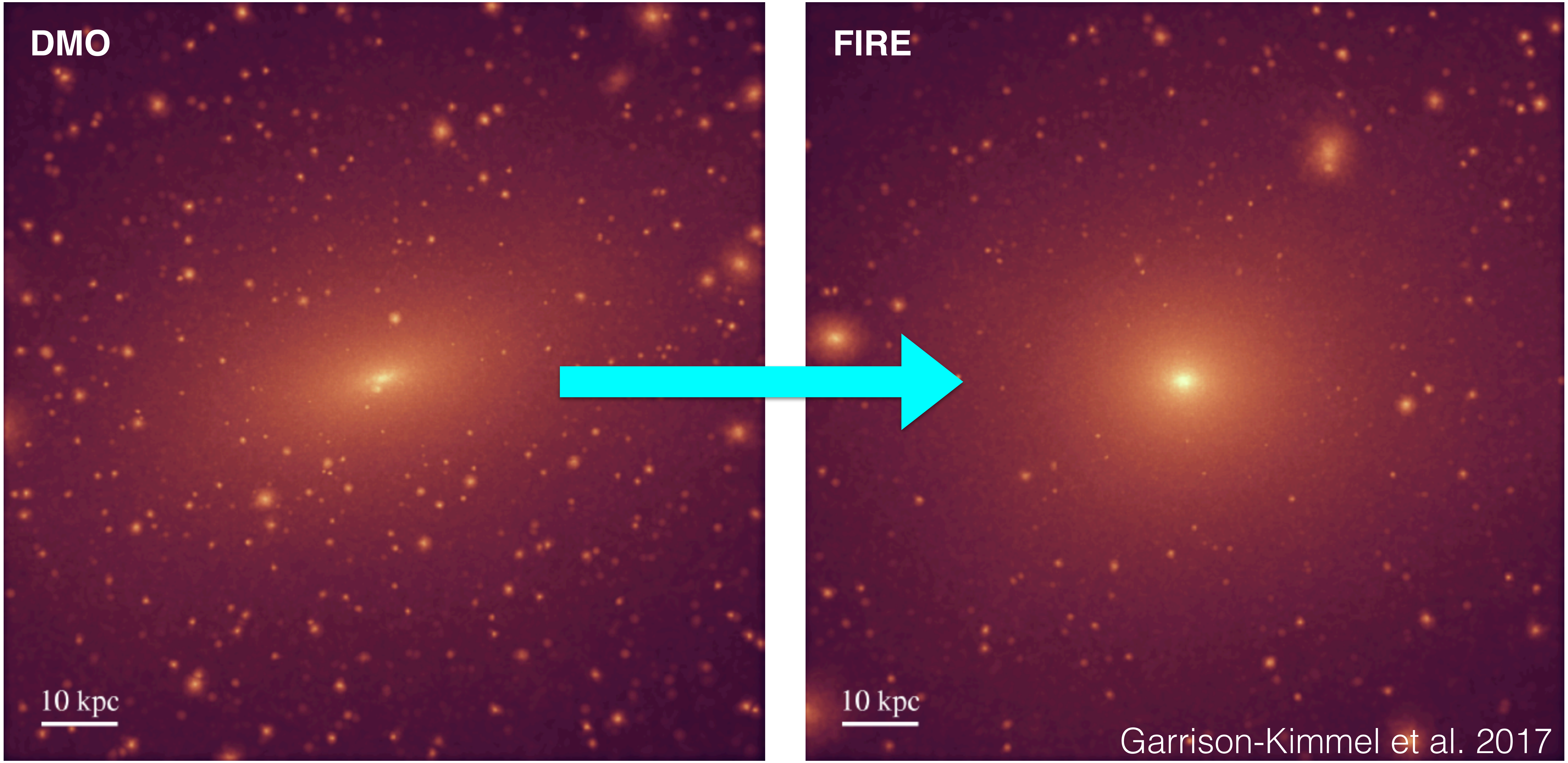
ABSTRACT

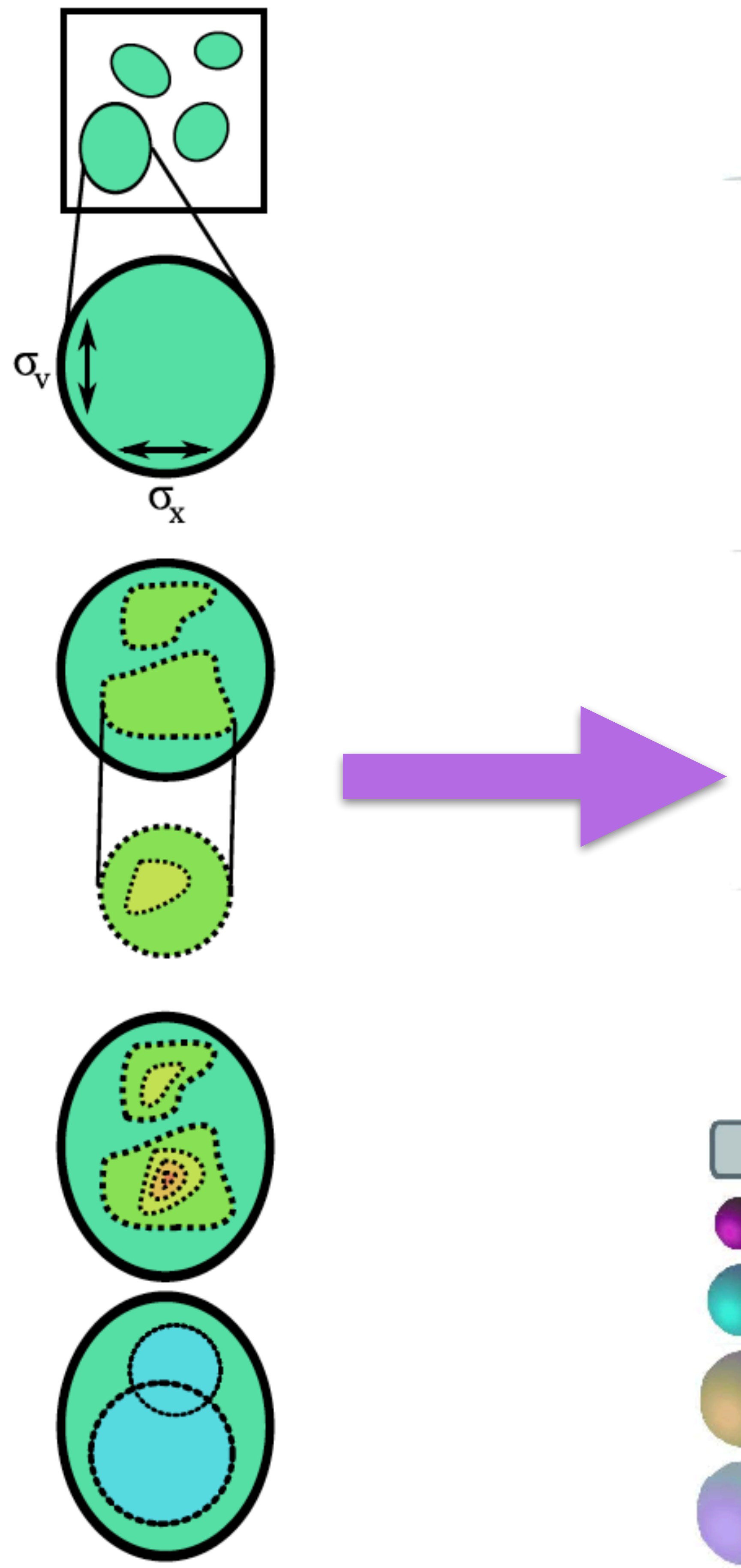
We identify subhalos in dark matter only (DMO) zoom-in simulations that are likely to be disrupted due to baryonic effects by using a random forest classifier trained on two hydrodynamic simulations of Milky Way-mass host halos from the Latte suite of the Feedback in Realistic Environments (FIRE) project. We train our classifier using five properties of each disrupted and surviving subhalo: pericentric distance and scale factor at first pericentric passage after accretion, and scale factor, virial mass, and maximum circular velocity at accretion. Our five-property classifier identifies disrupted subhalos in the FIRE simulations with 95% accuracy. We predict surviving subhalo populations in DMO simulations of the FIRE host halos, finding excellent agreement with the hydrodynamic results; in particular, our classifier outperforms DMO zoom-in simulations that include the gravitational potential of the central galactic disk in each hydrodynamic simulation, indicating that it captures both the dynamical effects of a central disk and additional baryonic physics. We also predict surviving subhalo populations for a suite of DMO zoom-in simulations of MW-mass host halos, finding that baryons impact each system consistently and that the predicted amount of subhalo disruption is larger than the host-to-host scatter among the subhalo populations. Although the small size and specific baryonic physics prescription of our training set limits the generality of our results, our work suggests that machine learning classification algorithms trained on hydrodynamic zoom-in simulations can efficiently predict realistic subhalo populations.

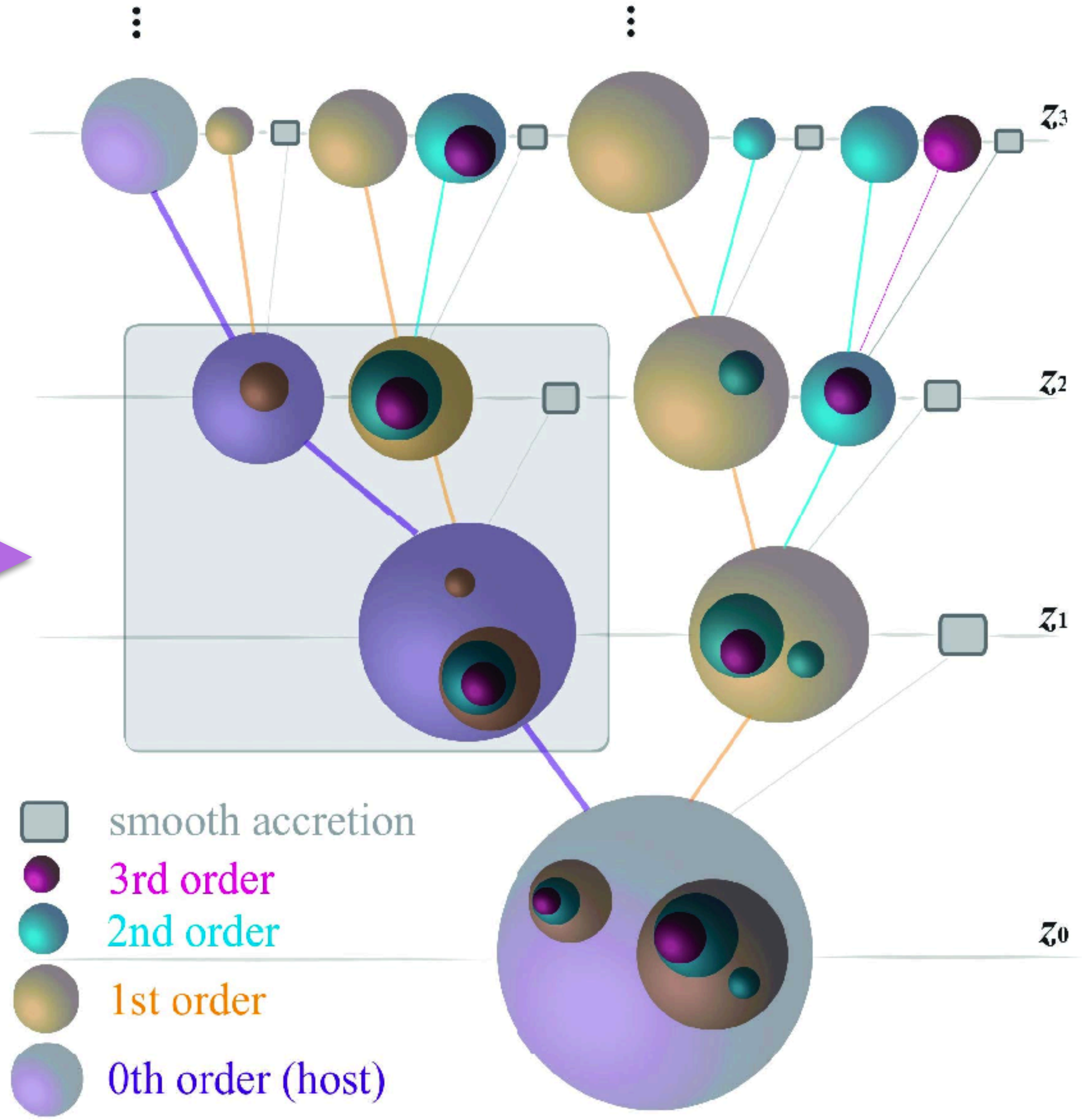
Predicting Subhalo Disruption



Halo Merger Trees

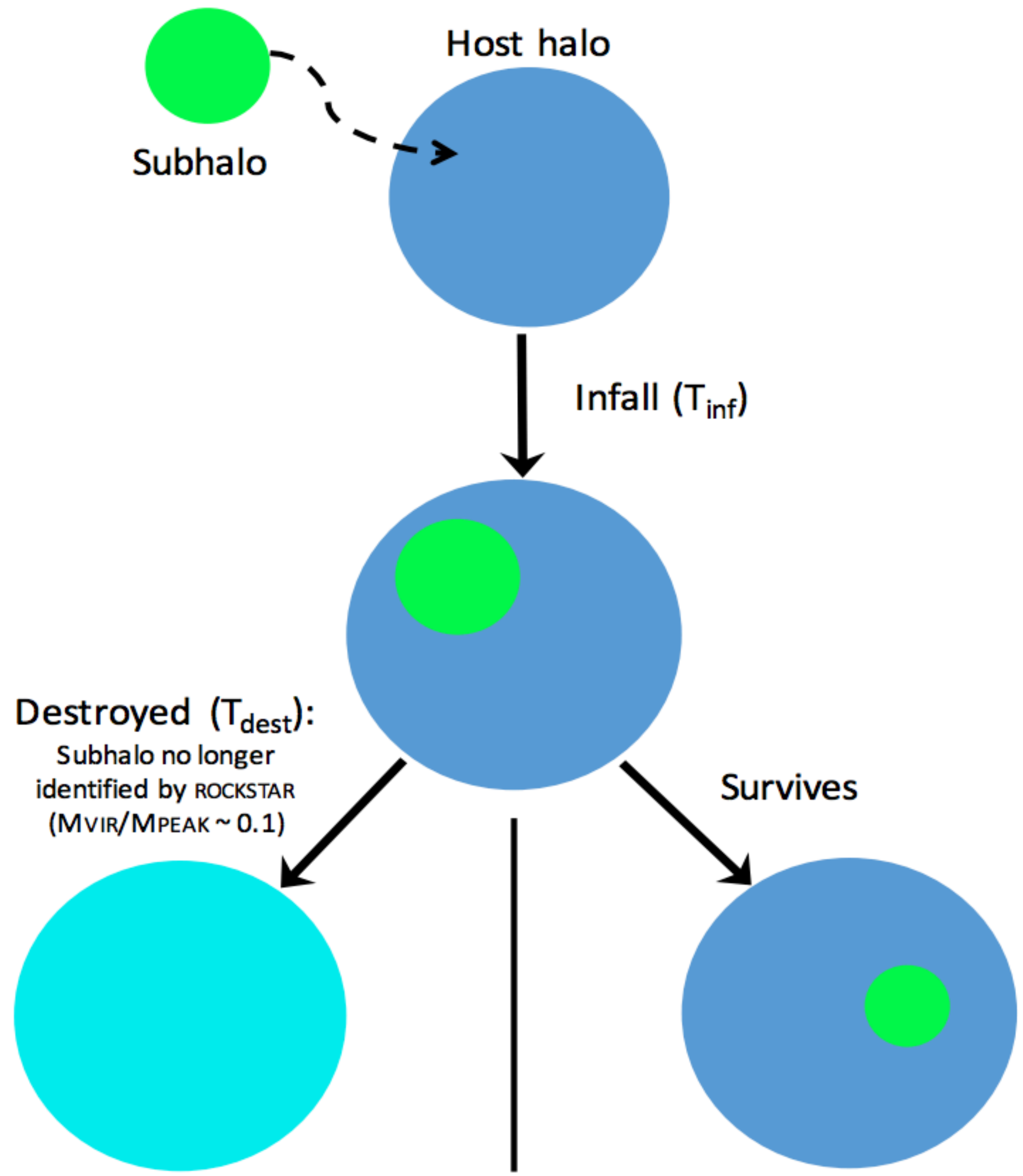
Links between (sub)halos describe evolution:





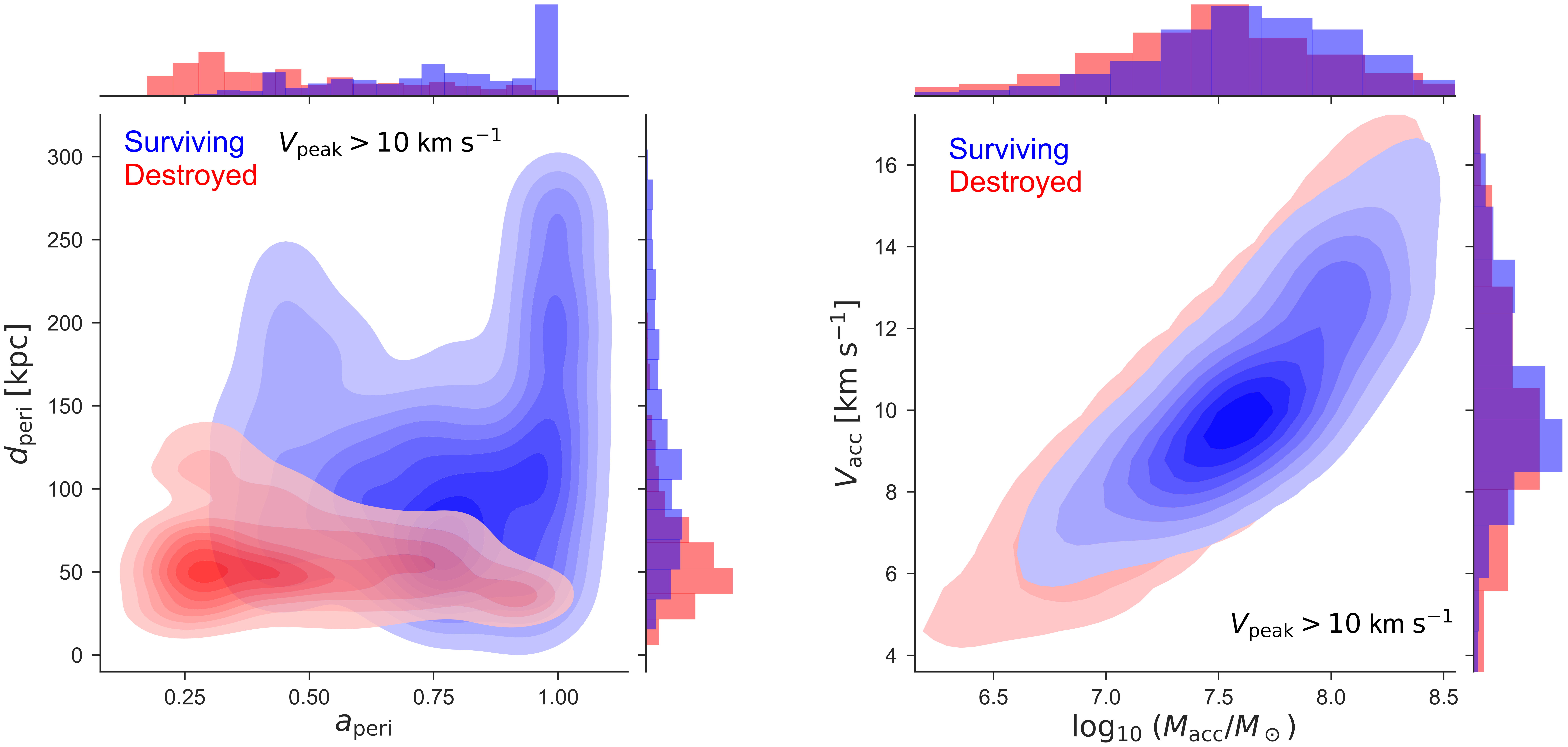
Behroozi et al. 2011

Jiang & van den Bosch 2013



Deason et al. 2015

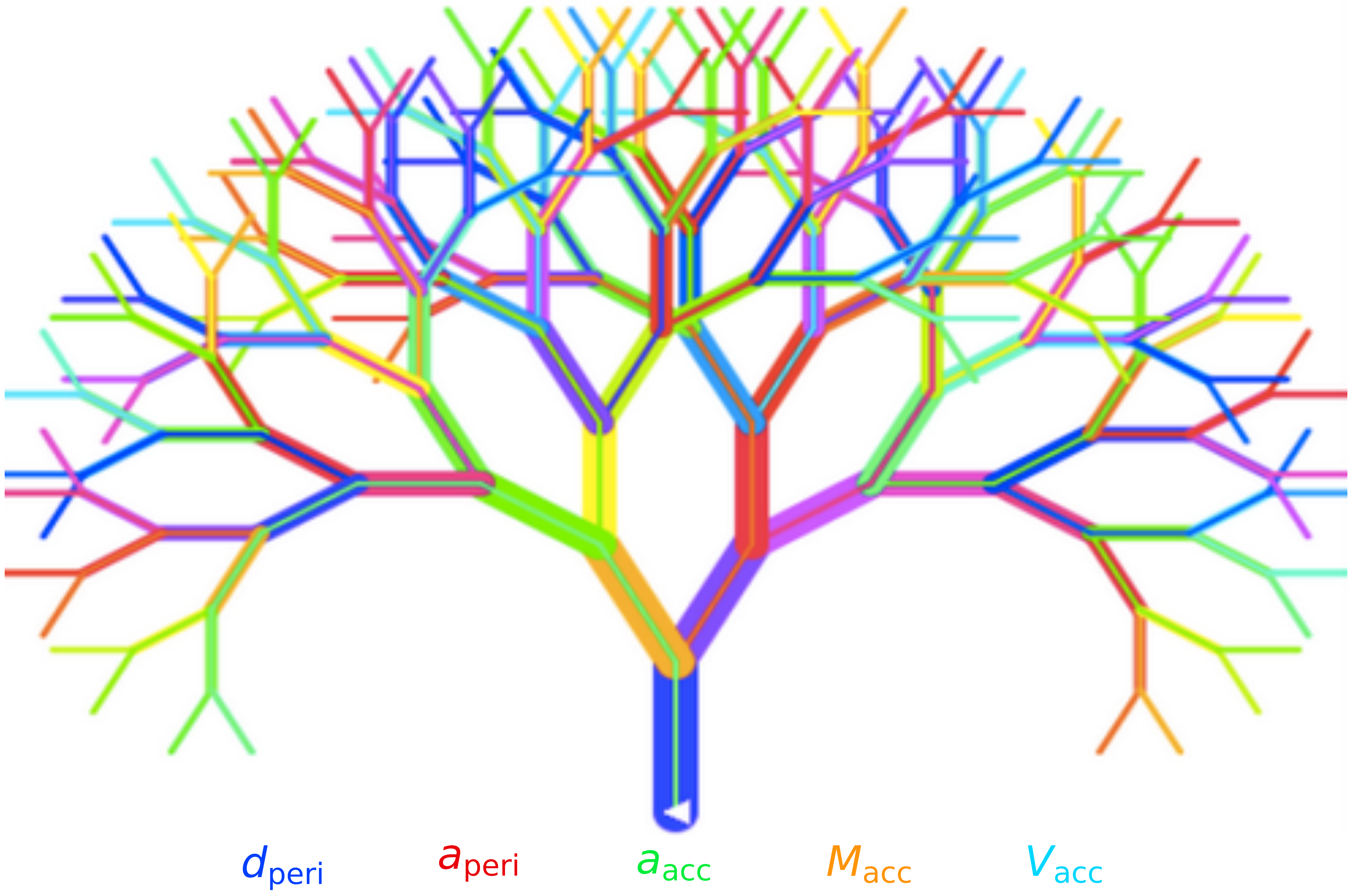
Can identify disrupted subhalos!

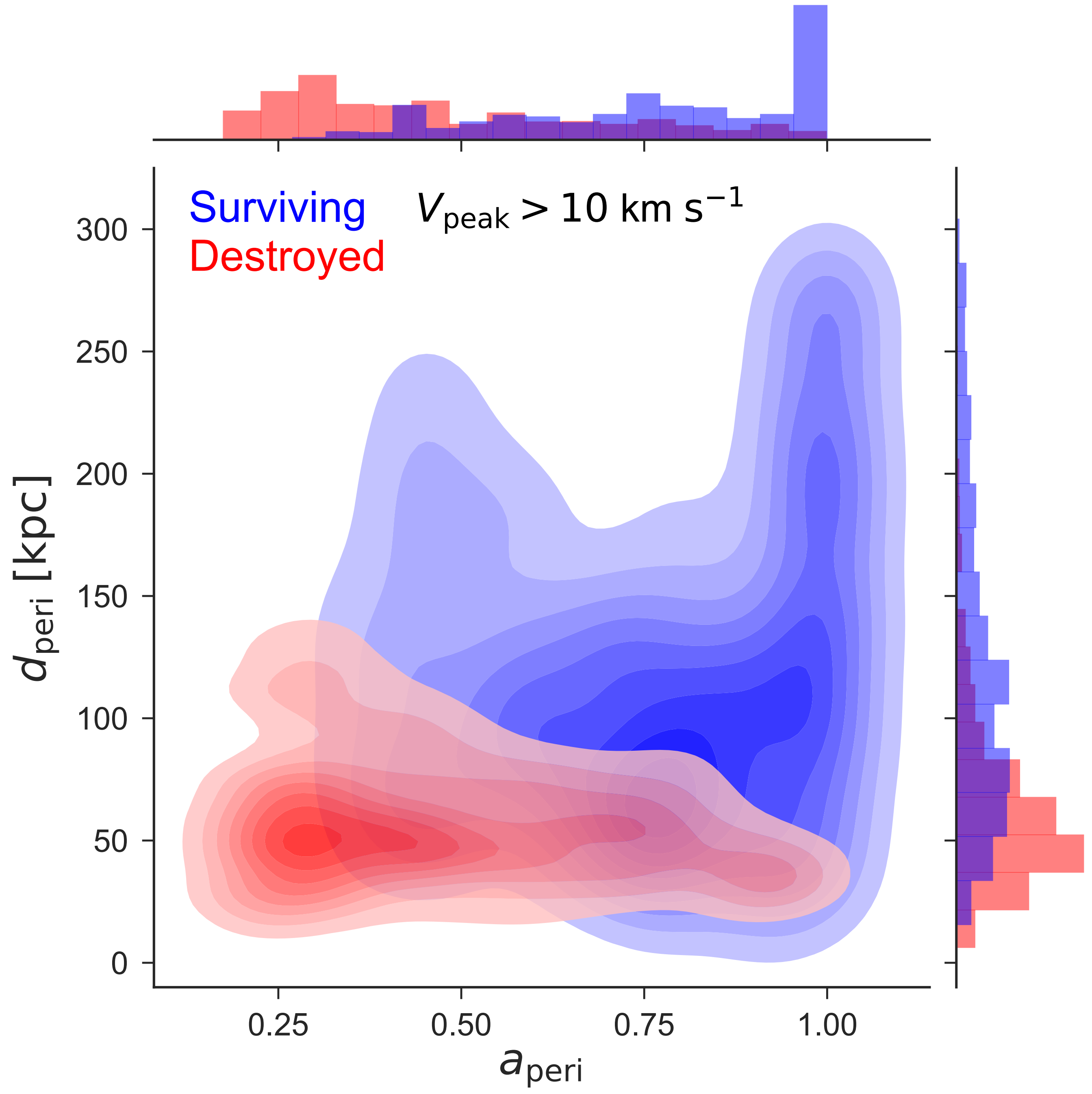


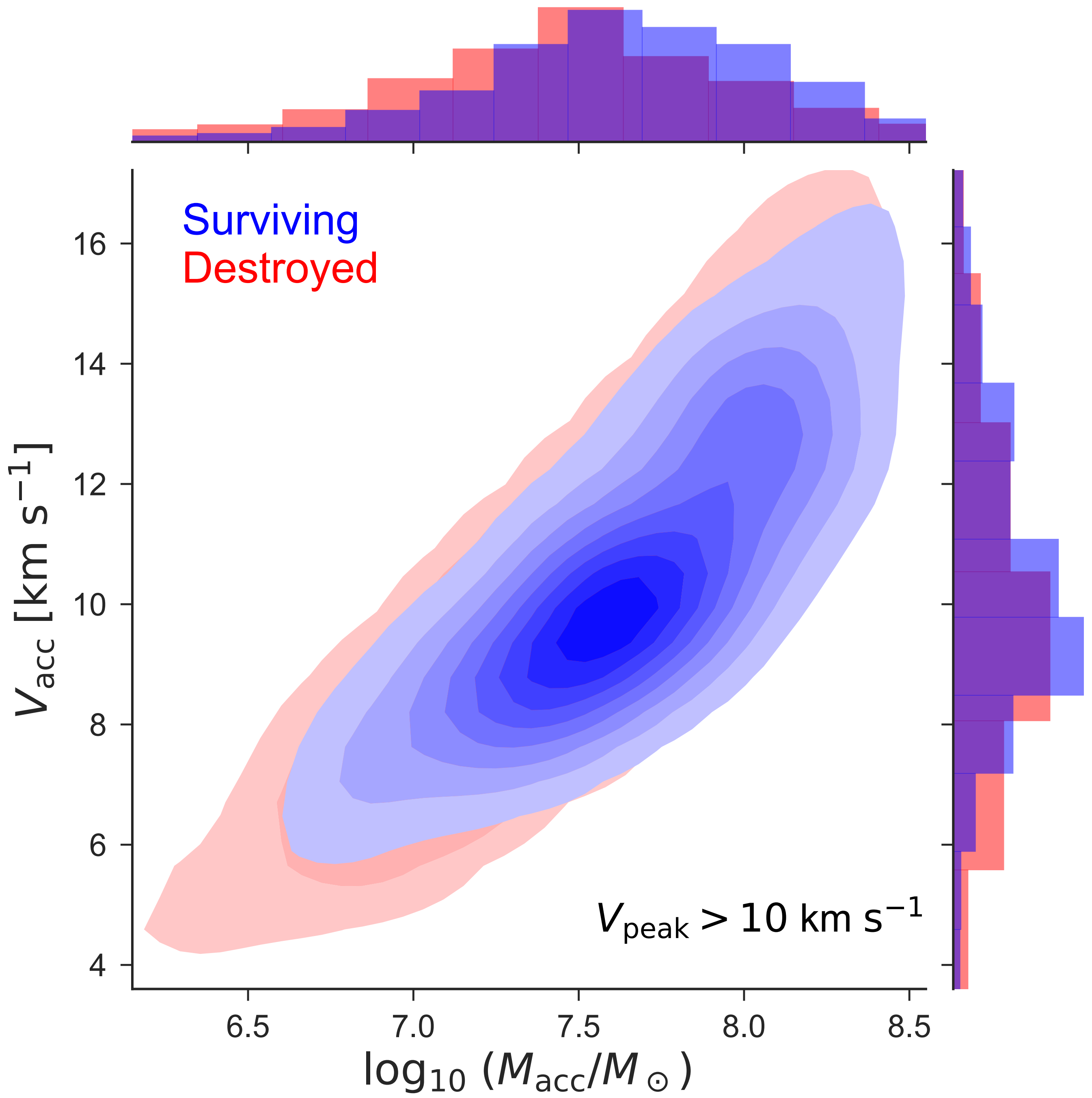
Surviving
Destroyed
$V_{\rm peak} > 10$ km s^{-1}
$d_{\rm peri}$ [kpc]
$a_{\rm peri}$
0
50
100
150
200
250
300
0.25
0.50
0.75
1.00
Surviving
Destroyed
$V_{\rm peak} > 10$ km s^{-1}
$V_{\rm acc}$ [km s^{-1}]
$\log_{10}(M_{\rm acc}/M_\odot)$
4
6
8
10
12
14
16
6.5
7.0
7.5
8.0
8.5

Random Forest Classification

Decision trees classify disrupted/surviving subhalos

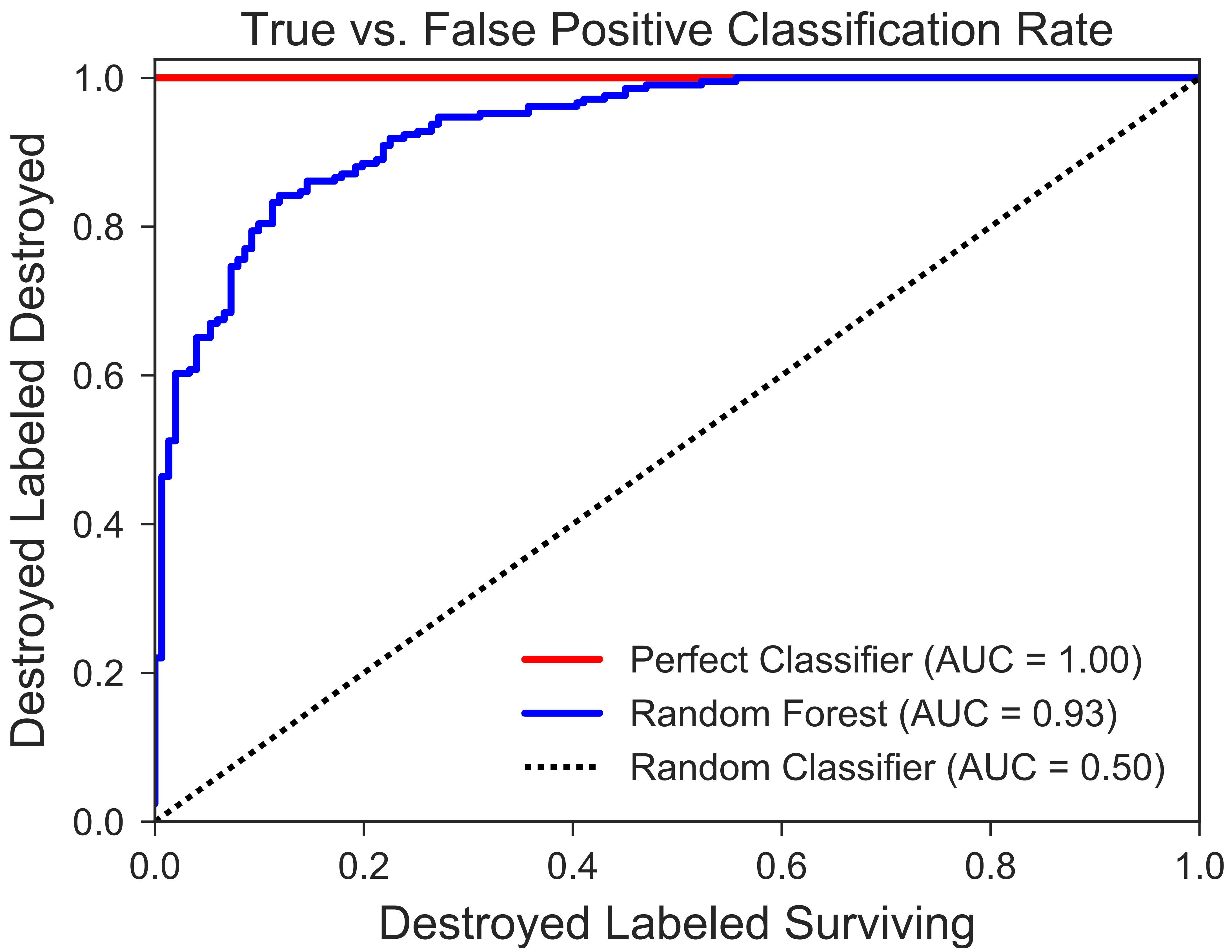


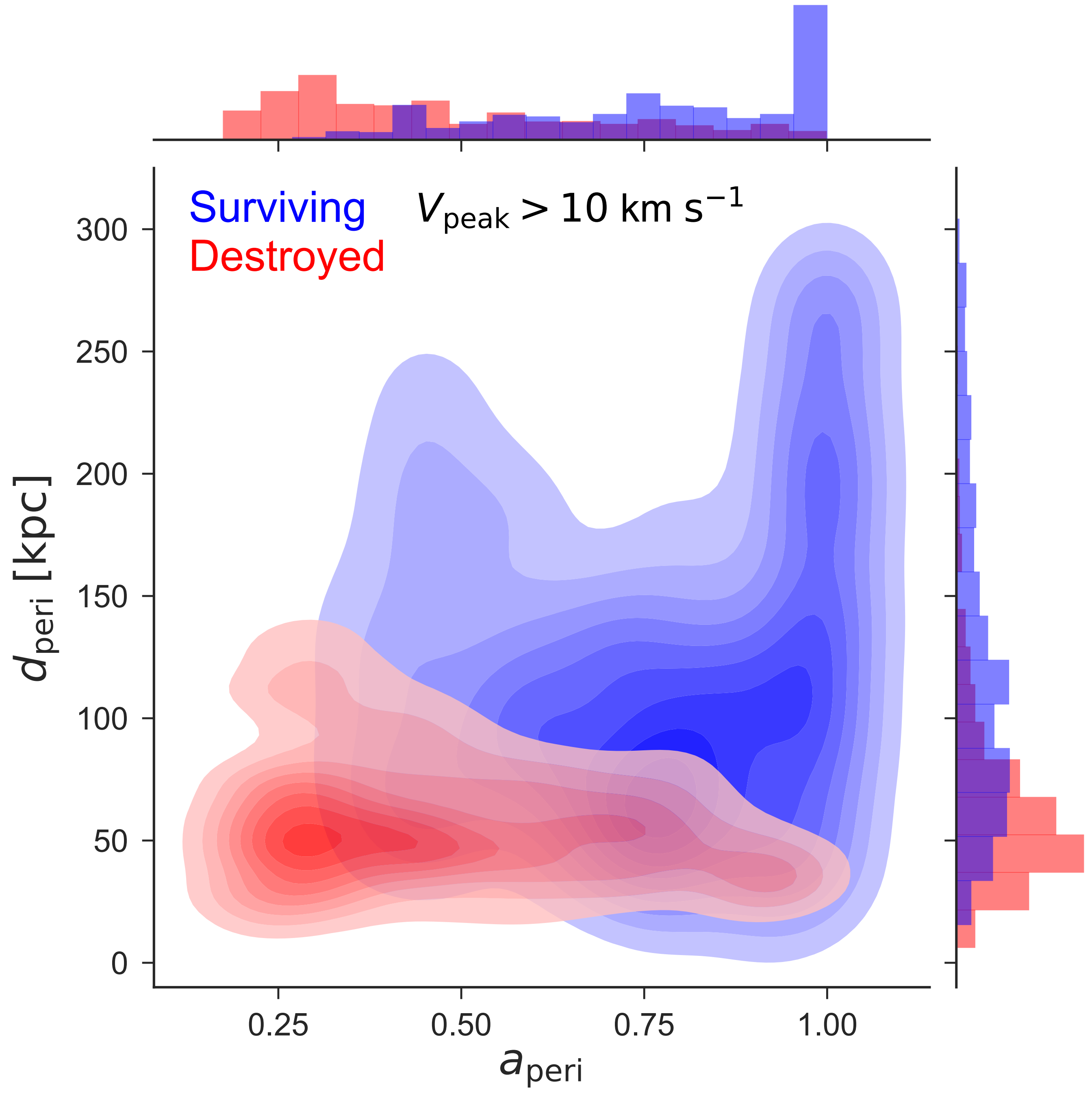


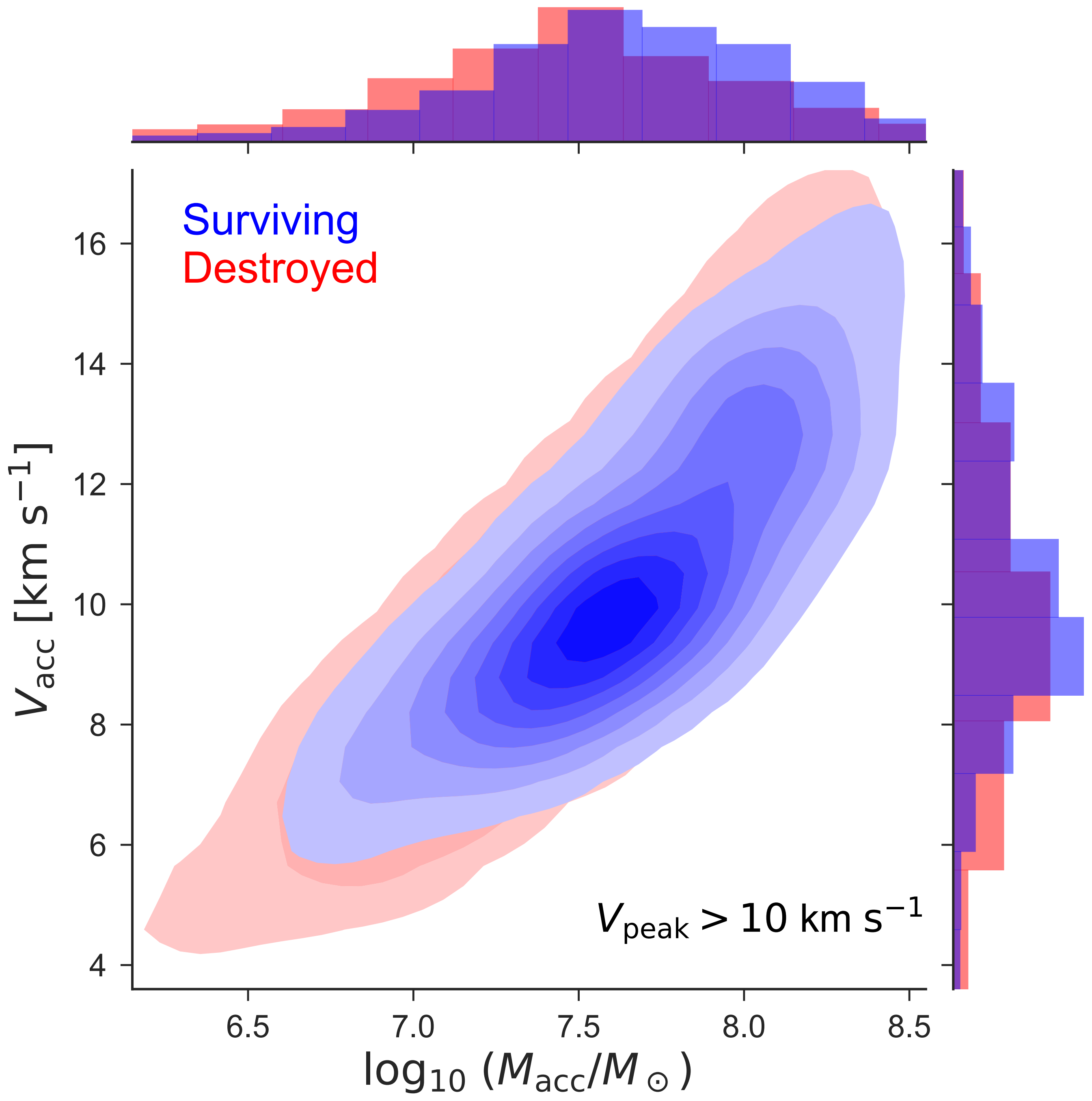


Random Forest Classification

- Five subhalo features encode ~90% of disruption
- Tests: ROC Curve (0.93 AUC), OOB score (85%)

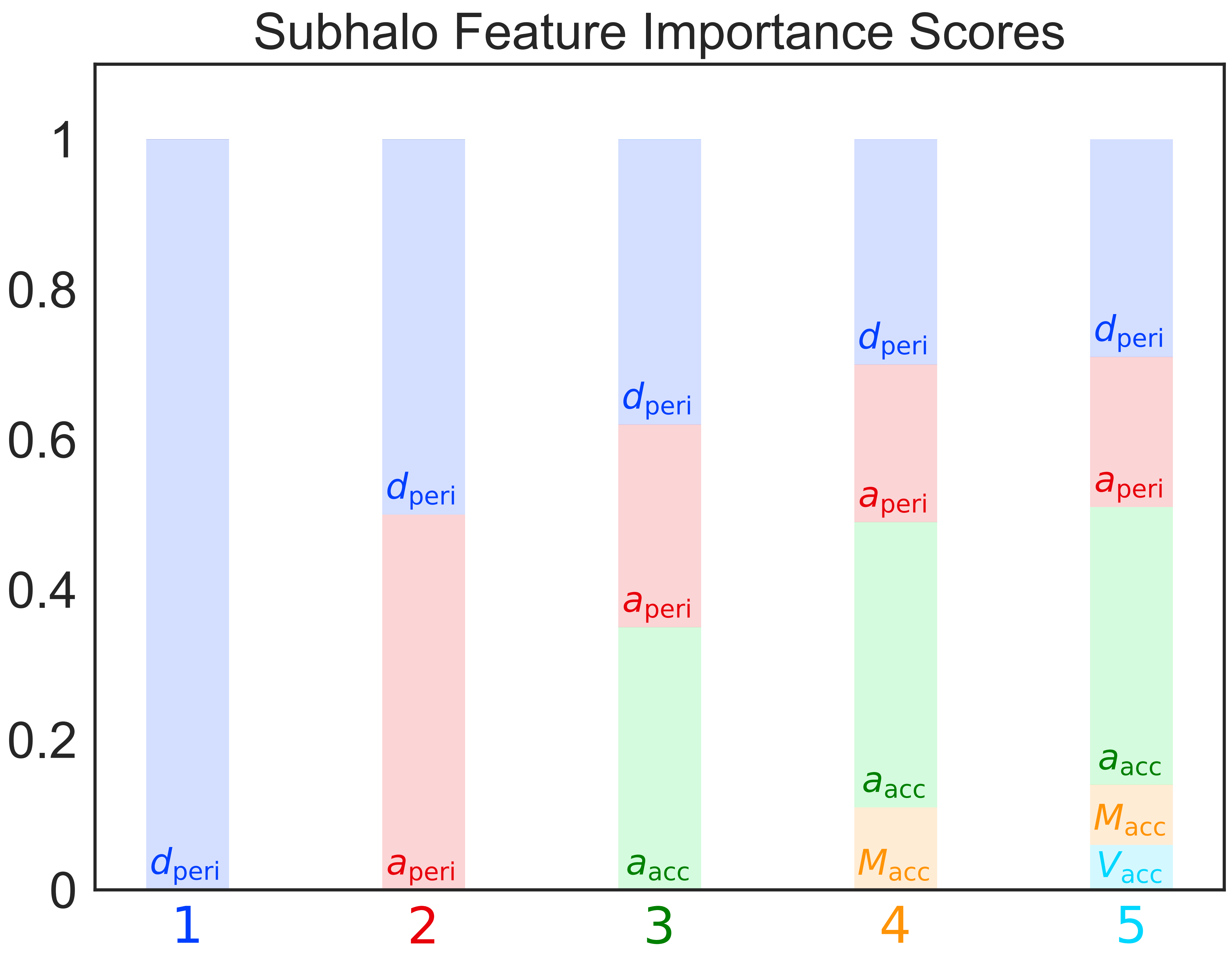


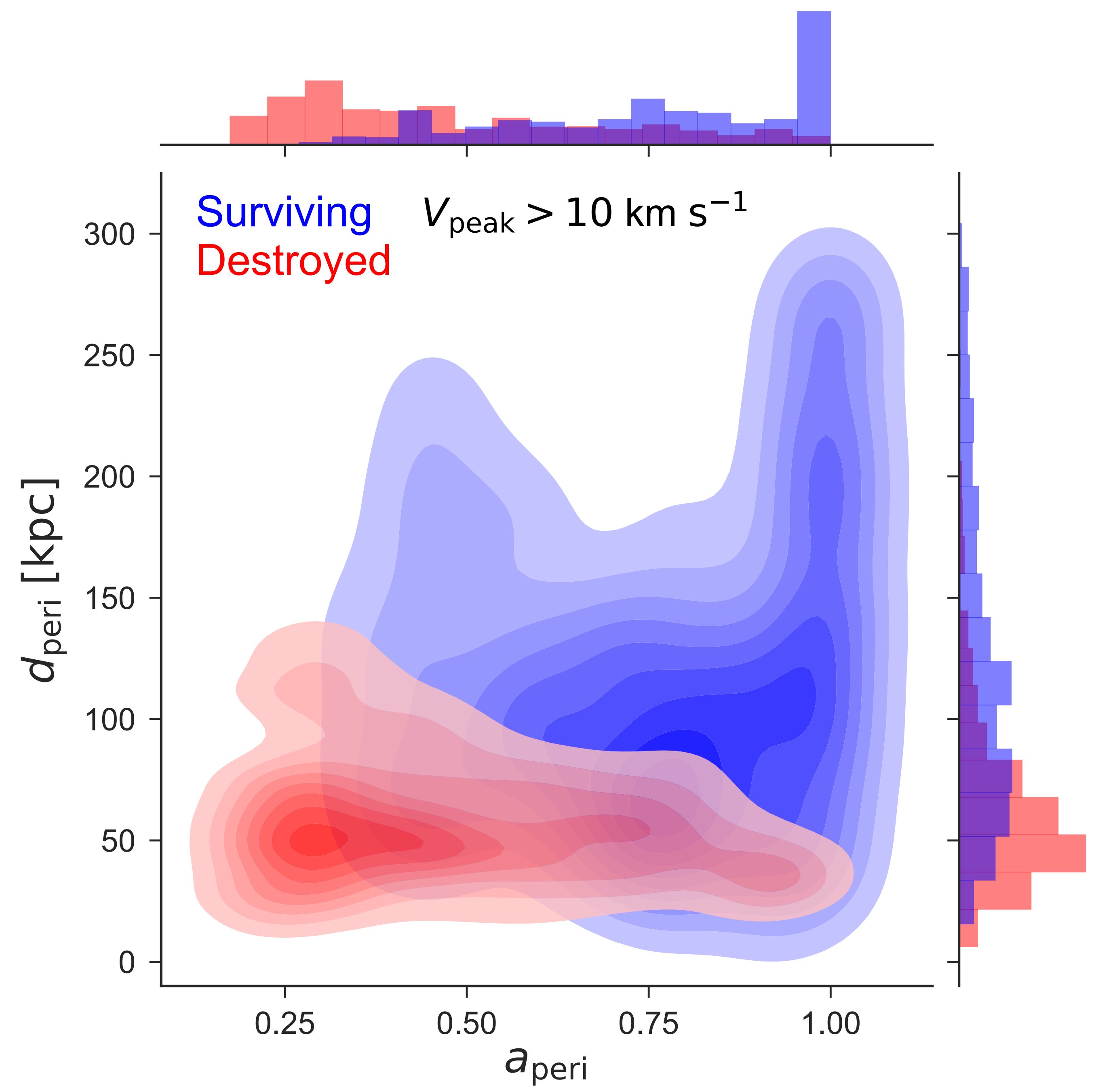


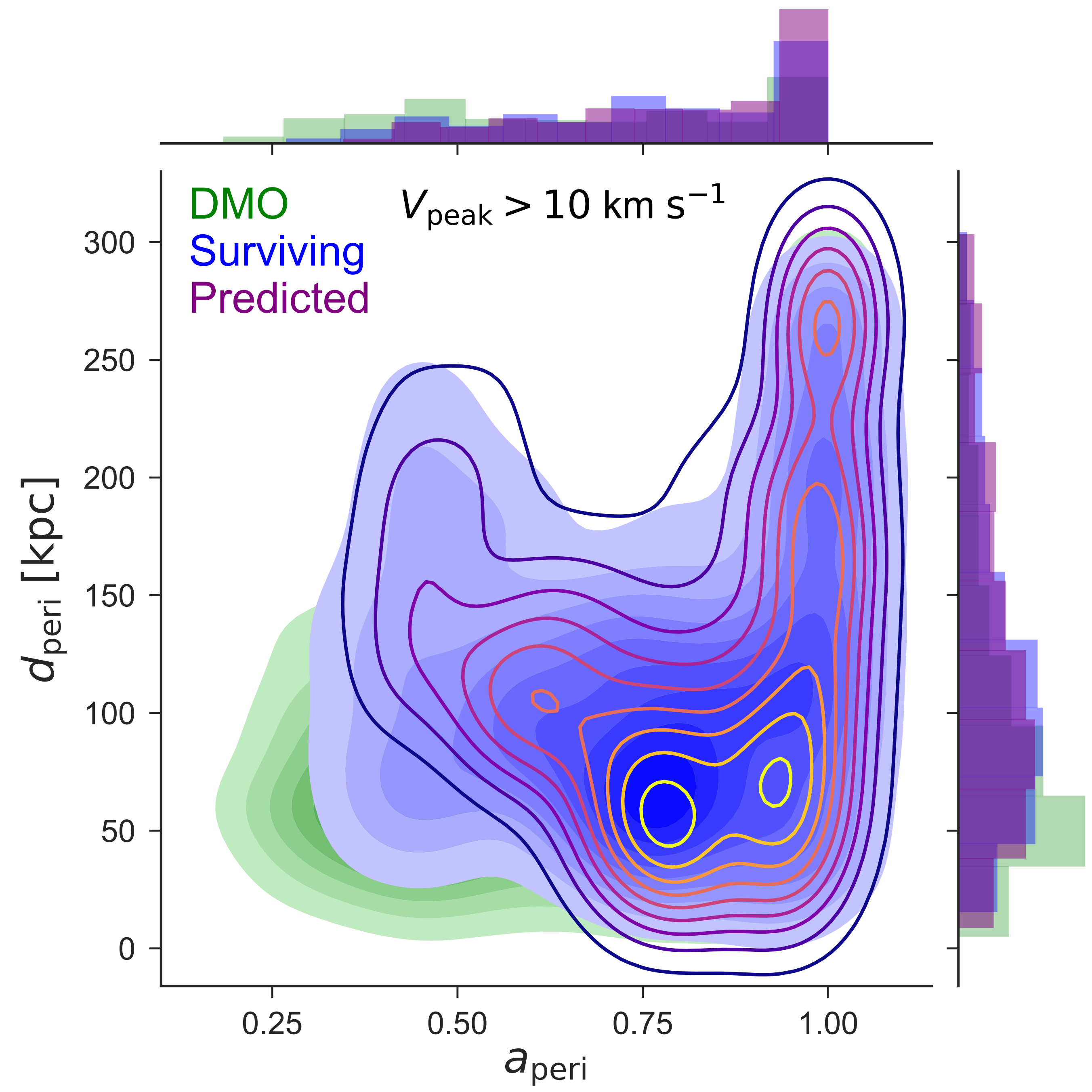


Random Forest Classification

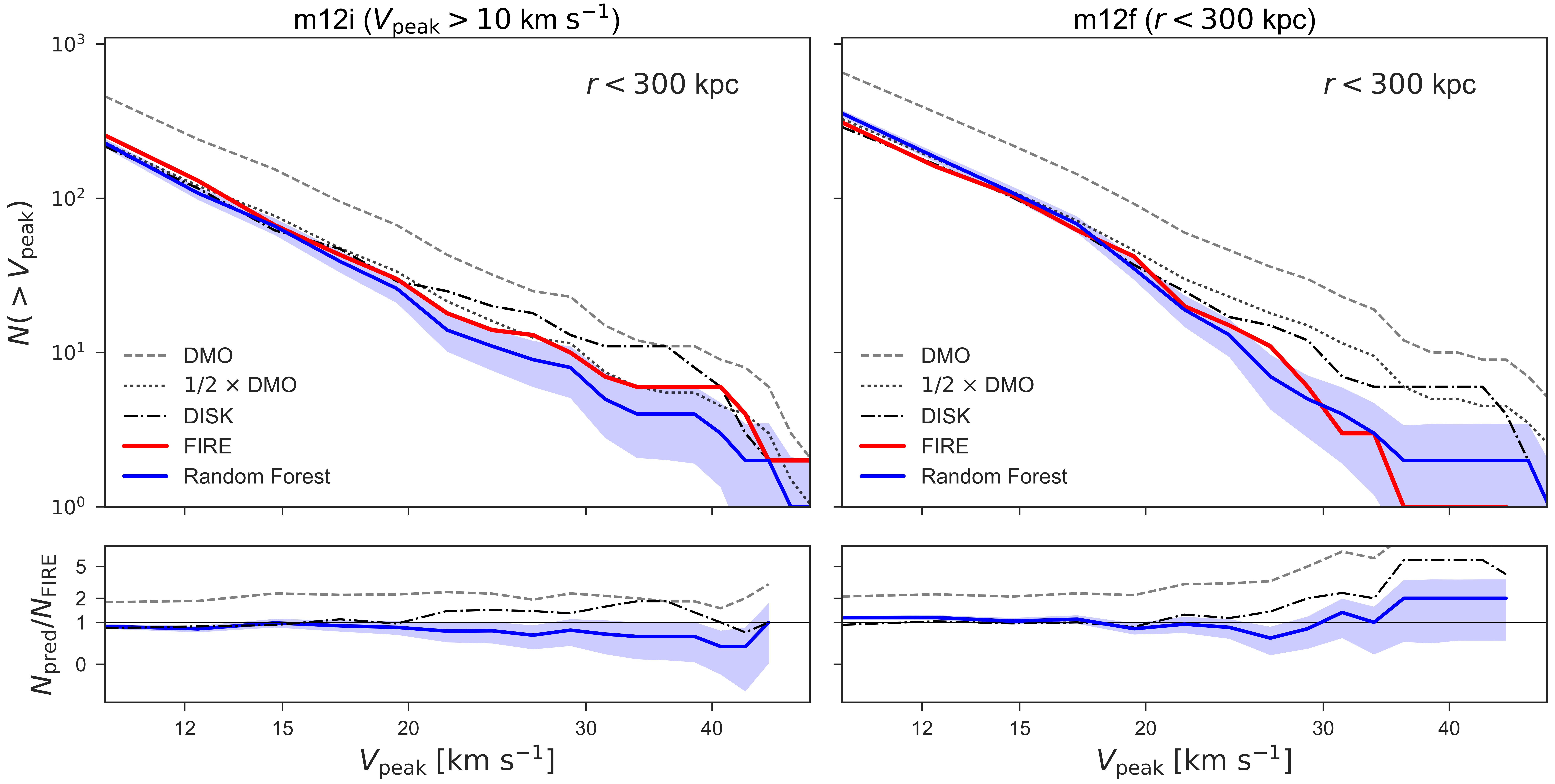
- Pericentric properties and accretion time are key
- Predicted subhalo properties consistent with FIRE



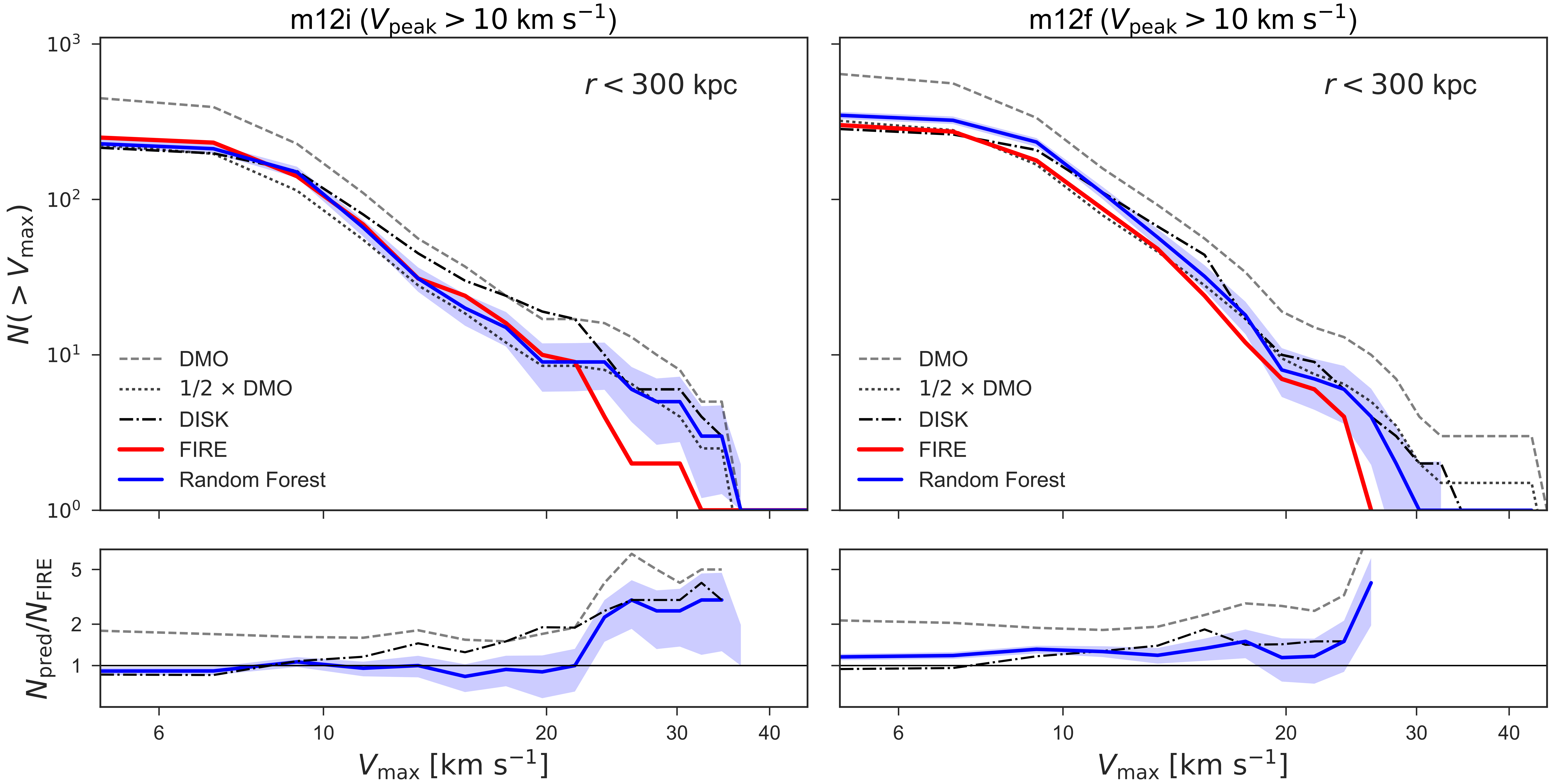




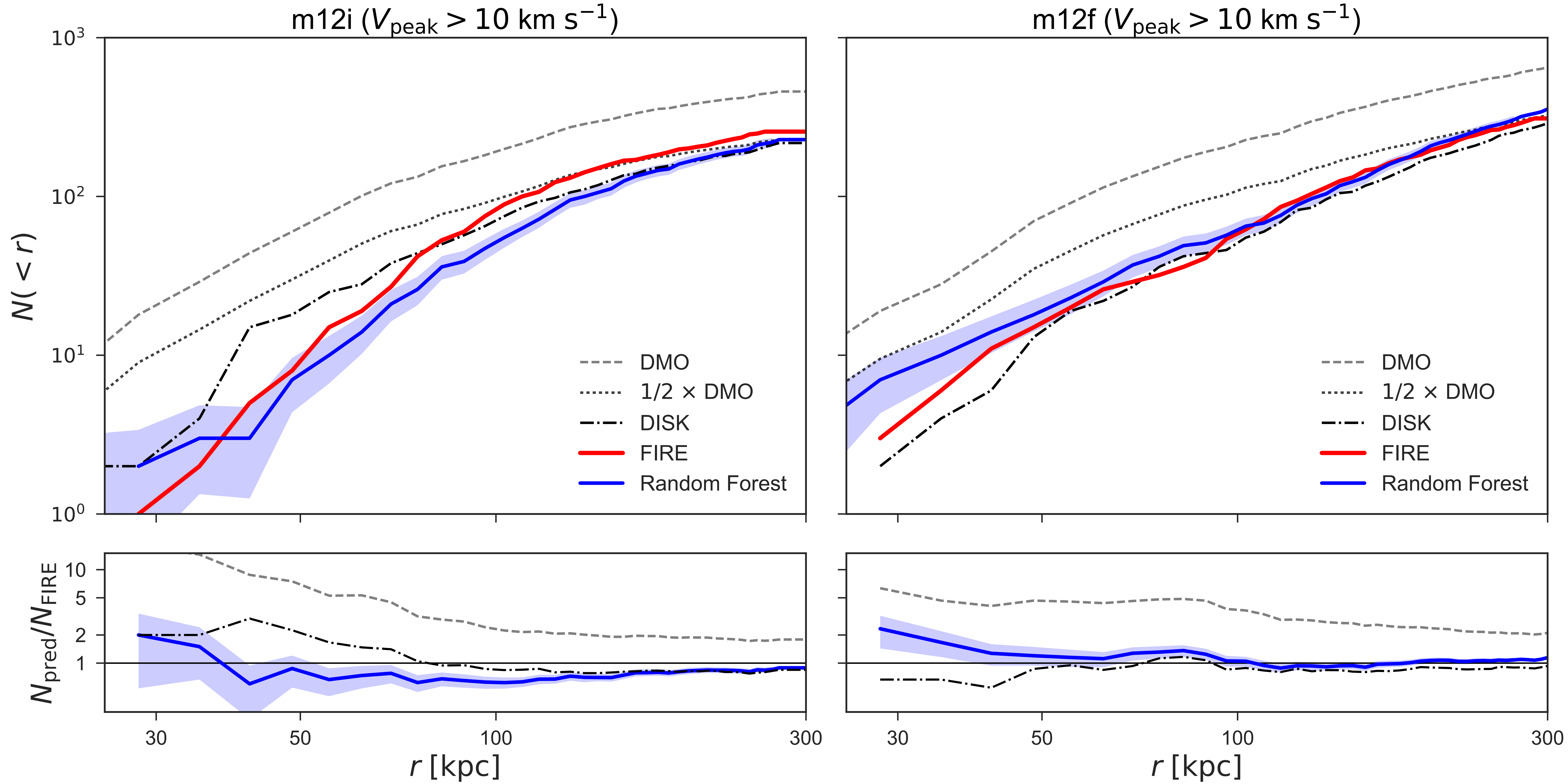
Peak Velocity Functions



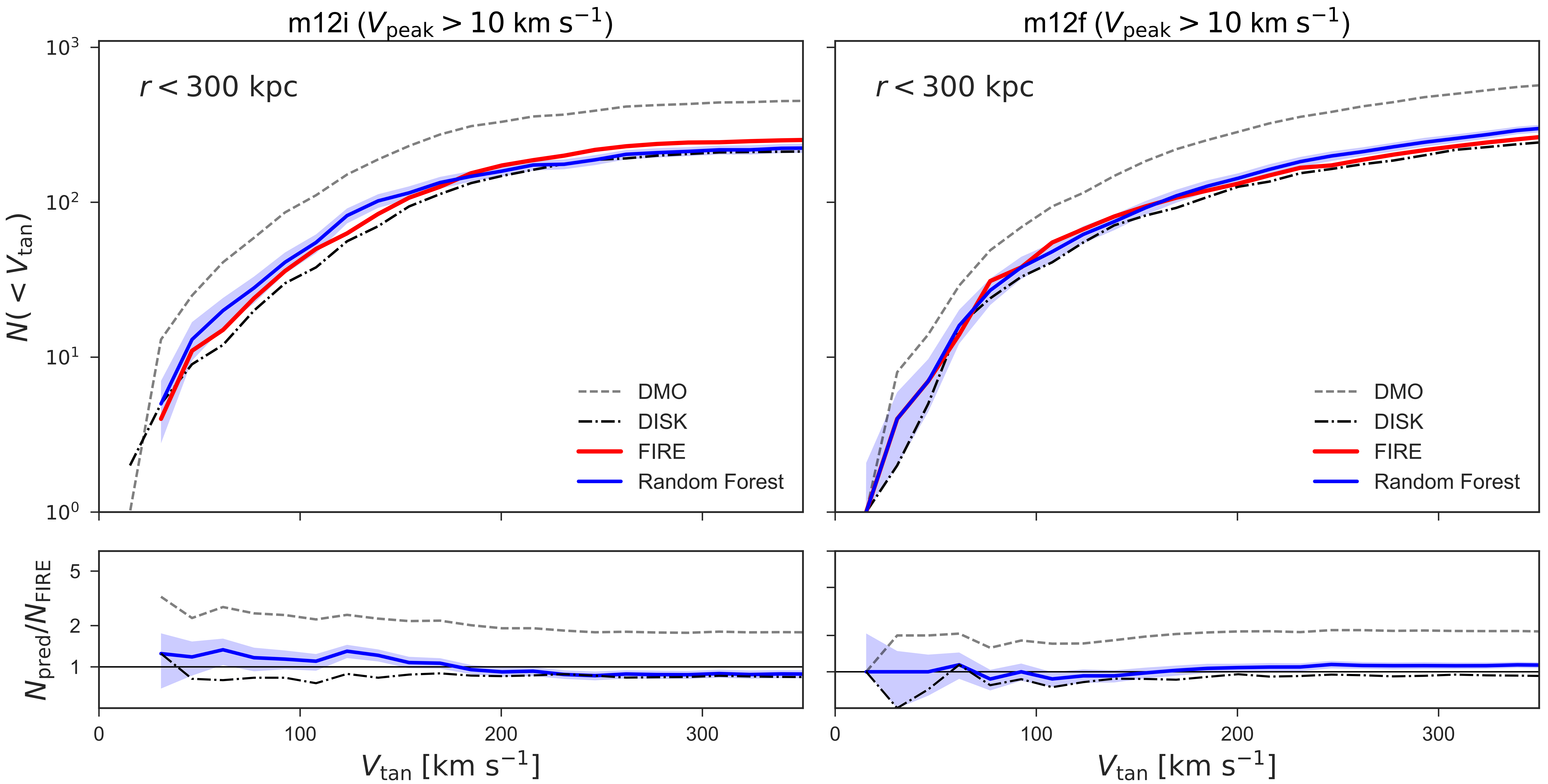
Velocity Functions



Radial Distributions



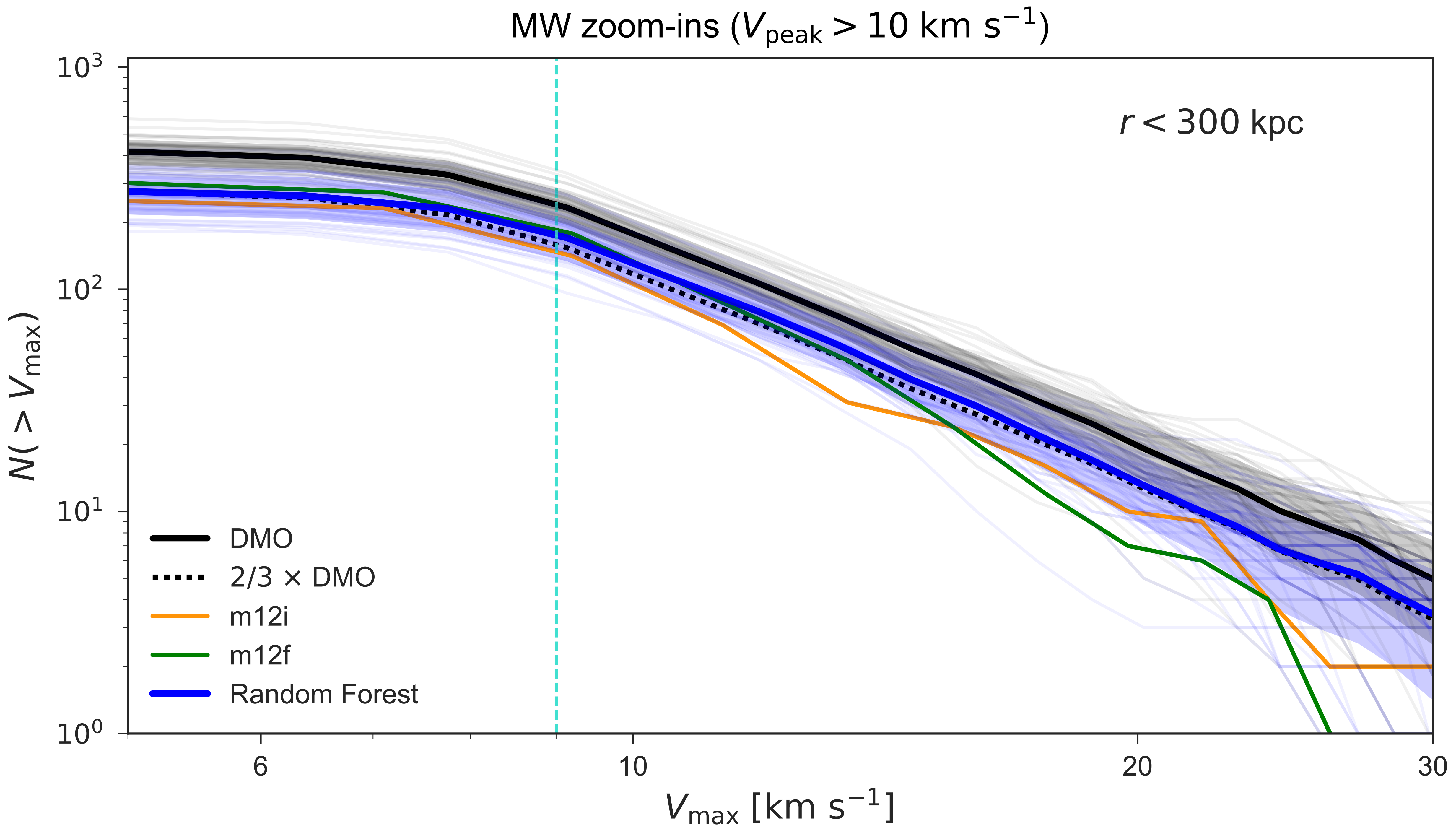
Orbital Velocity Distributions

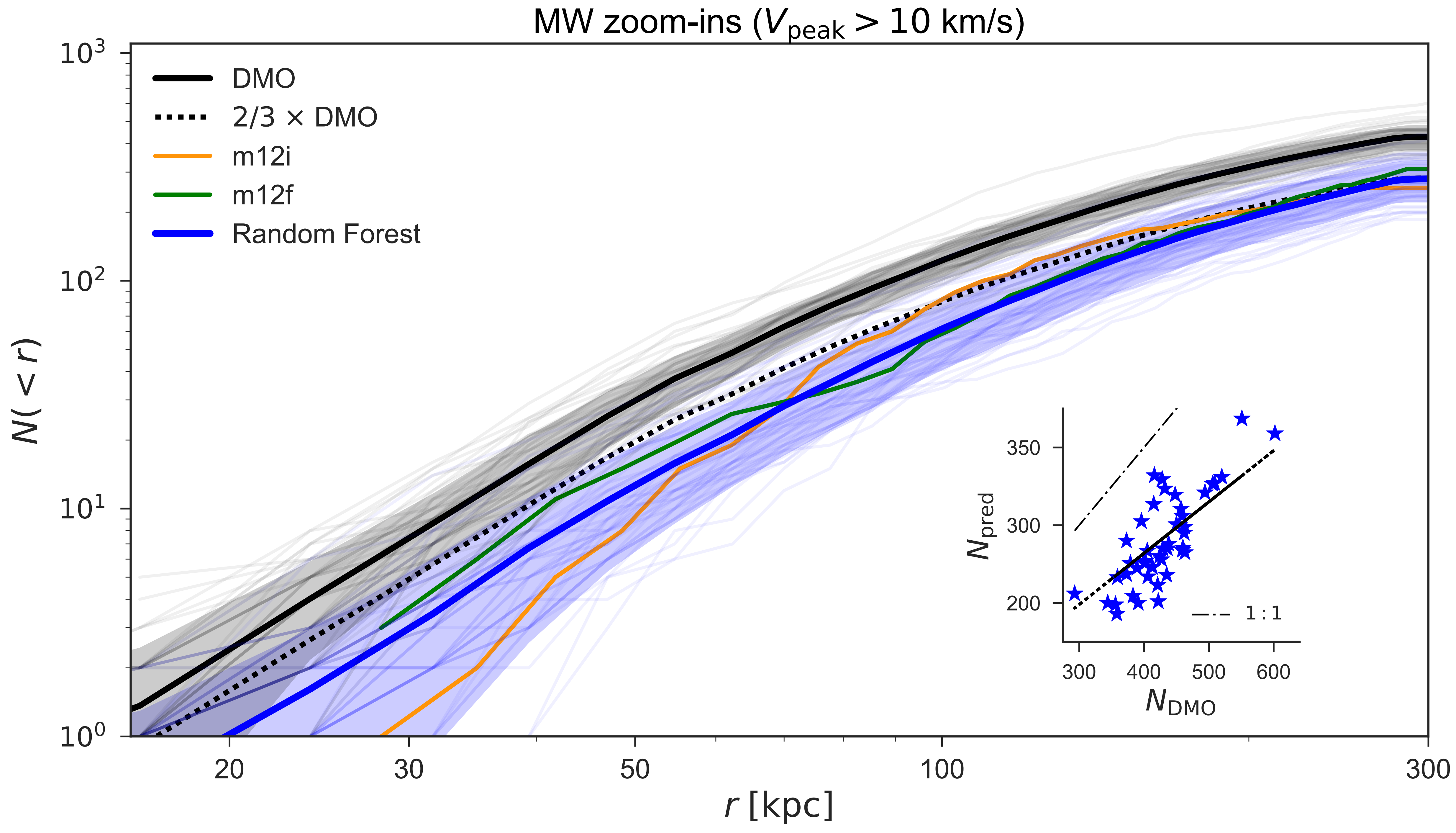


Applications and Extensions

Trained model (github/ollienad) predicts subhalo disruption probabilities

Example: 45 MW zoom-ins with range of formation histories (Mao et al. 2015)

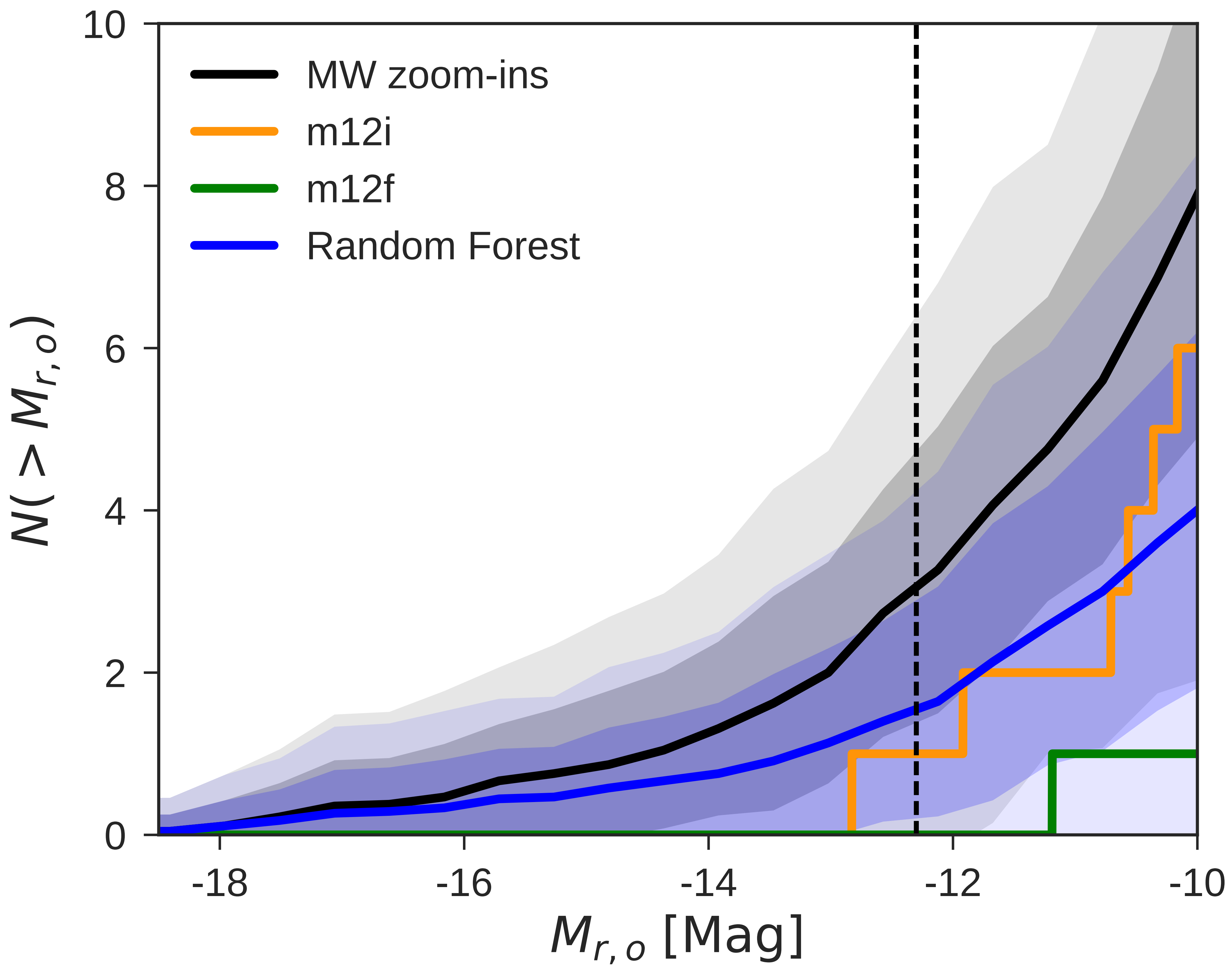


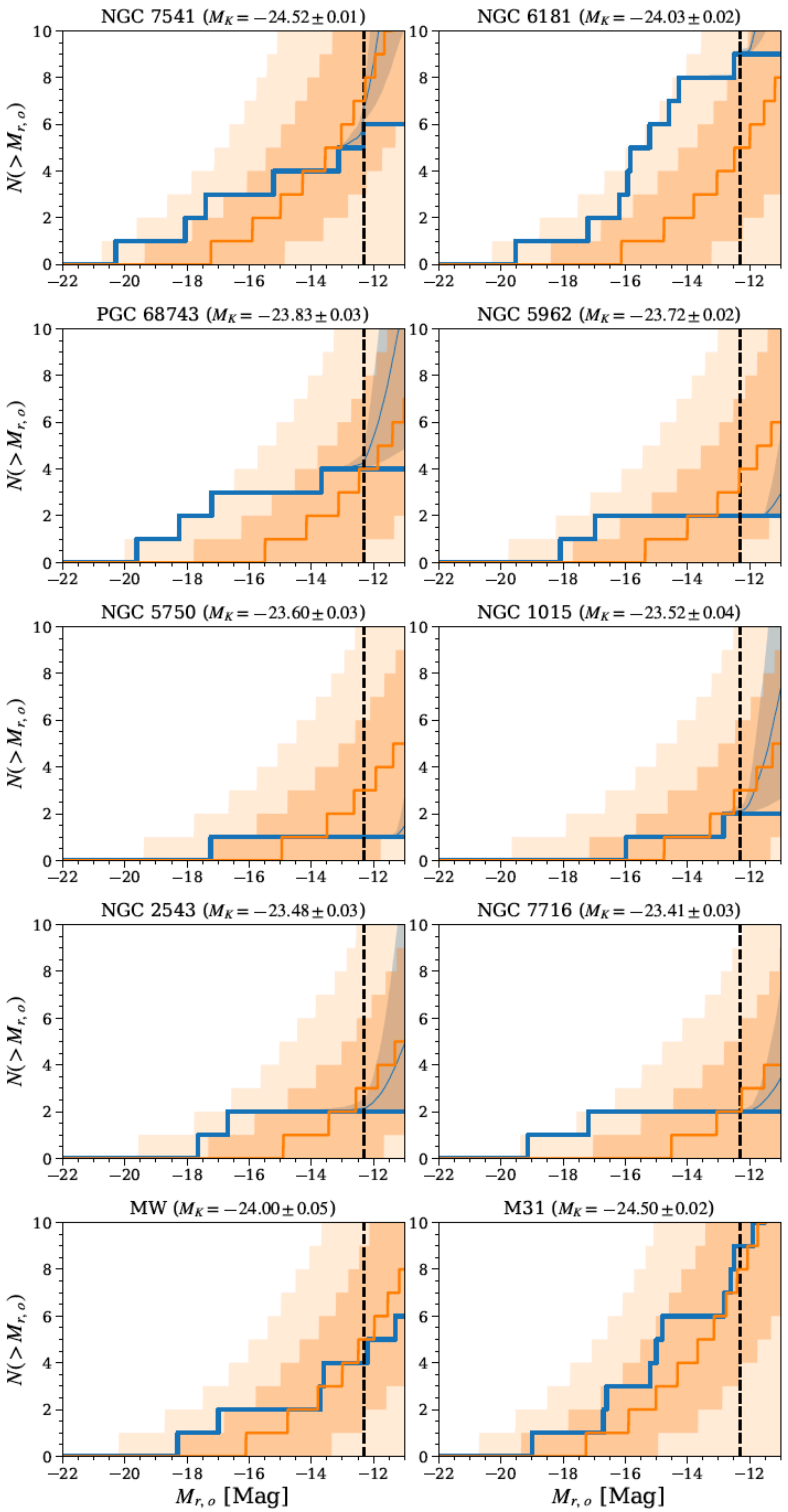


Predicted disruption is larger than halo-to-halo scatter!

Applications and Extensions

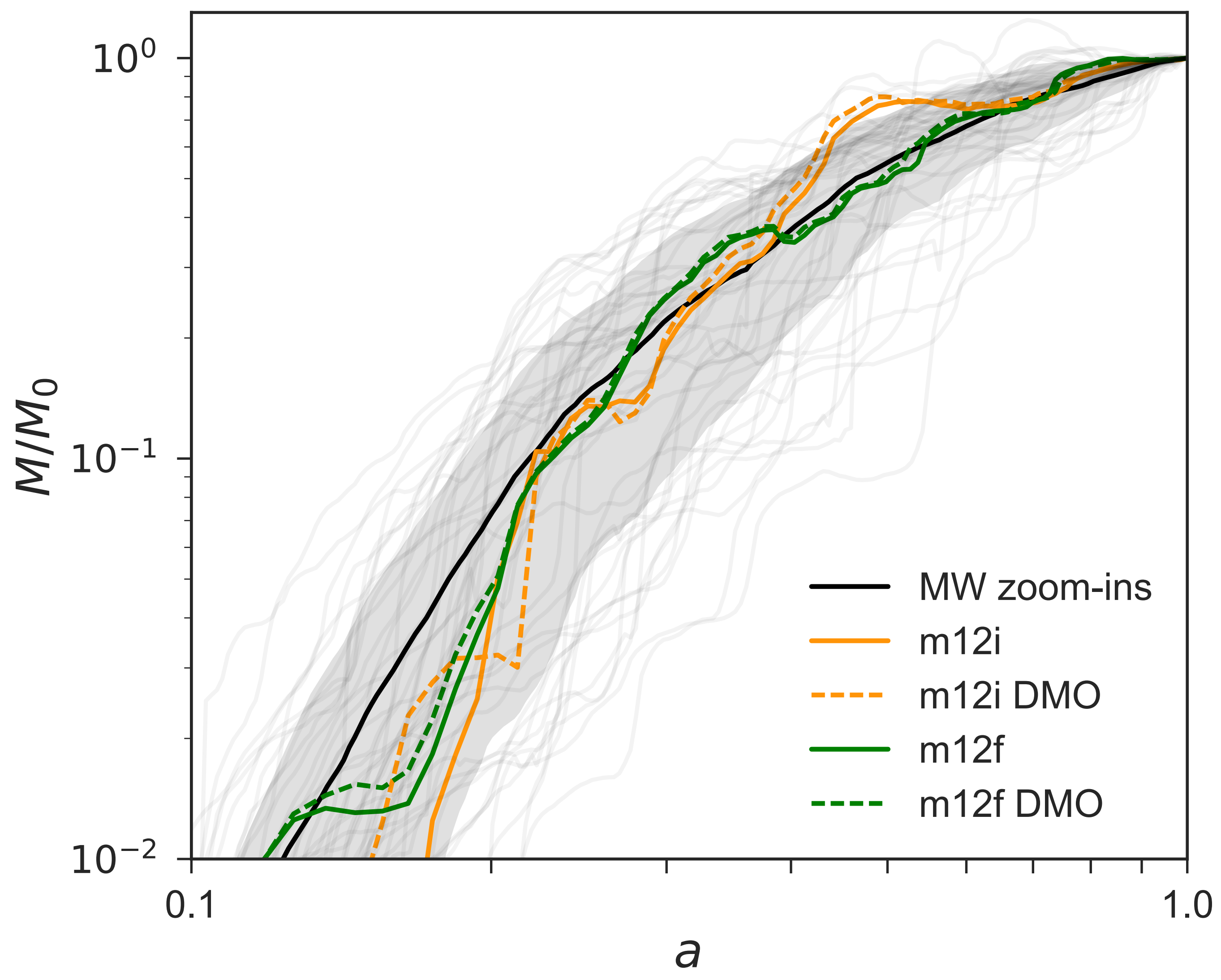
- Predict satellite luminosity functions for MW analogs
- Use to interpret SAGA observations (Geha et al. 2017)





Future Work

- Only trained on two disk-dominated FIRE simulations!
- Generalize for different formation histories, hydro codes
- How does the algorithm perform for different host masses?
- Different feature selection without disk-driven disruption?
- How do these results relate to artificial subhalo disruption?
- How do baryonic processes affect subhalo segregation?



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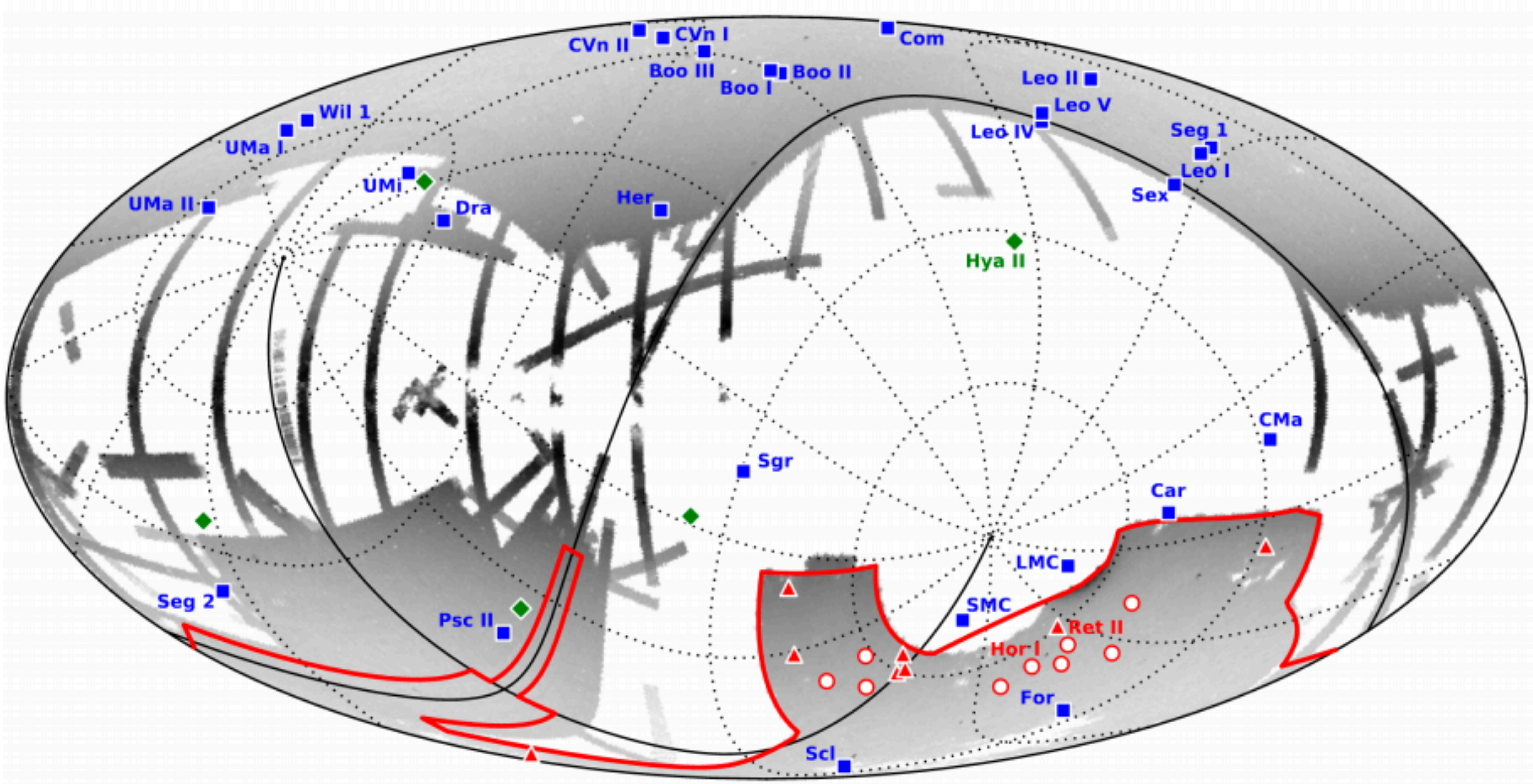
Modeling Milky Way Satellites

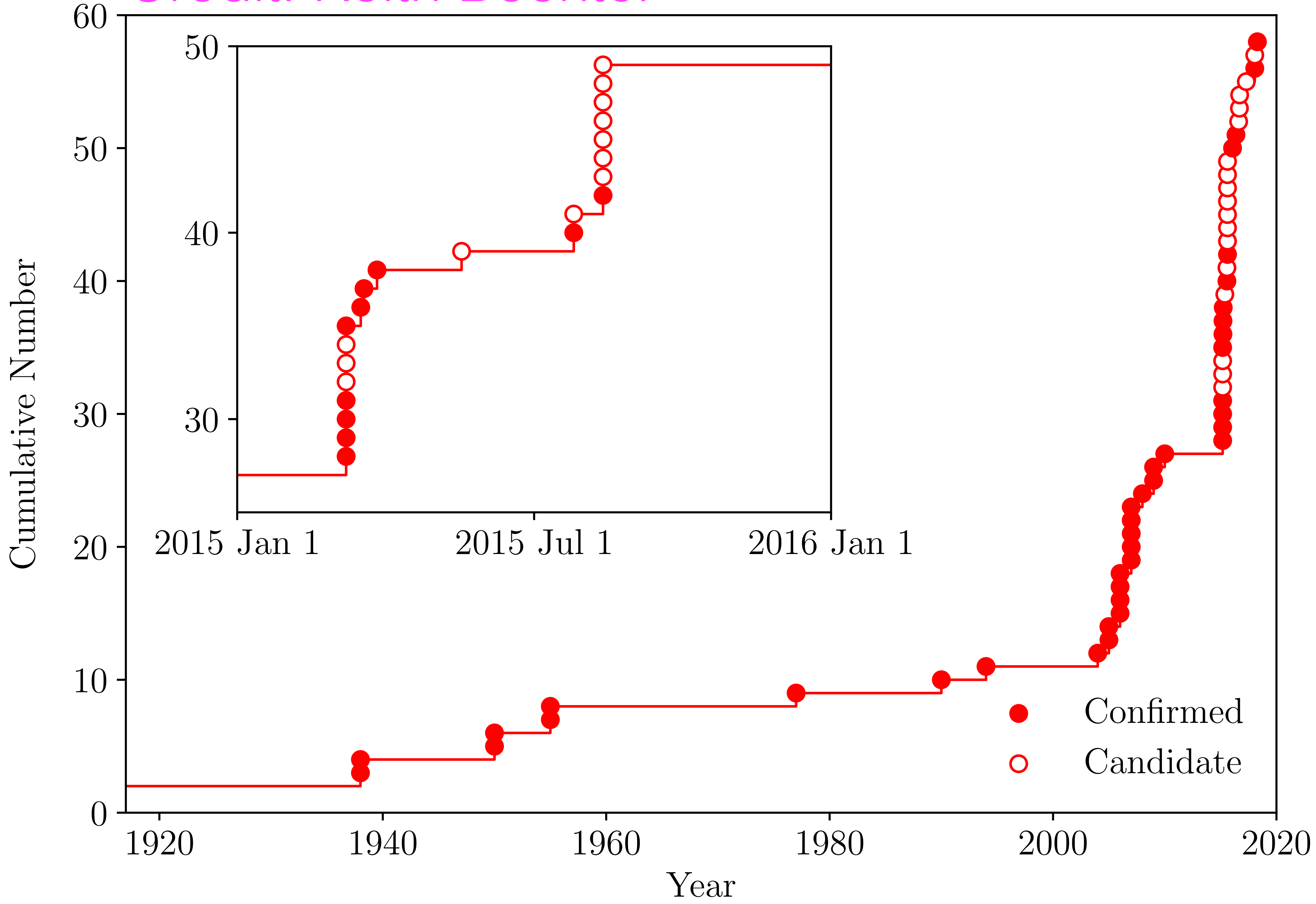


Drlica-Wagner et al. 2015

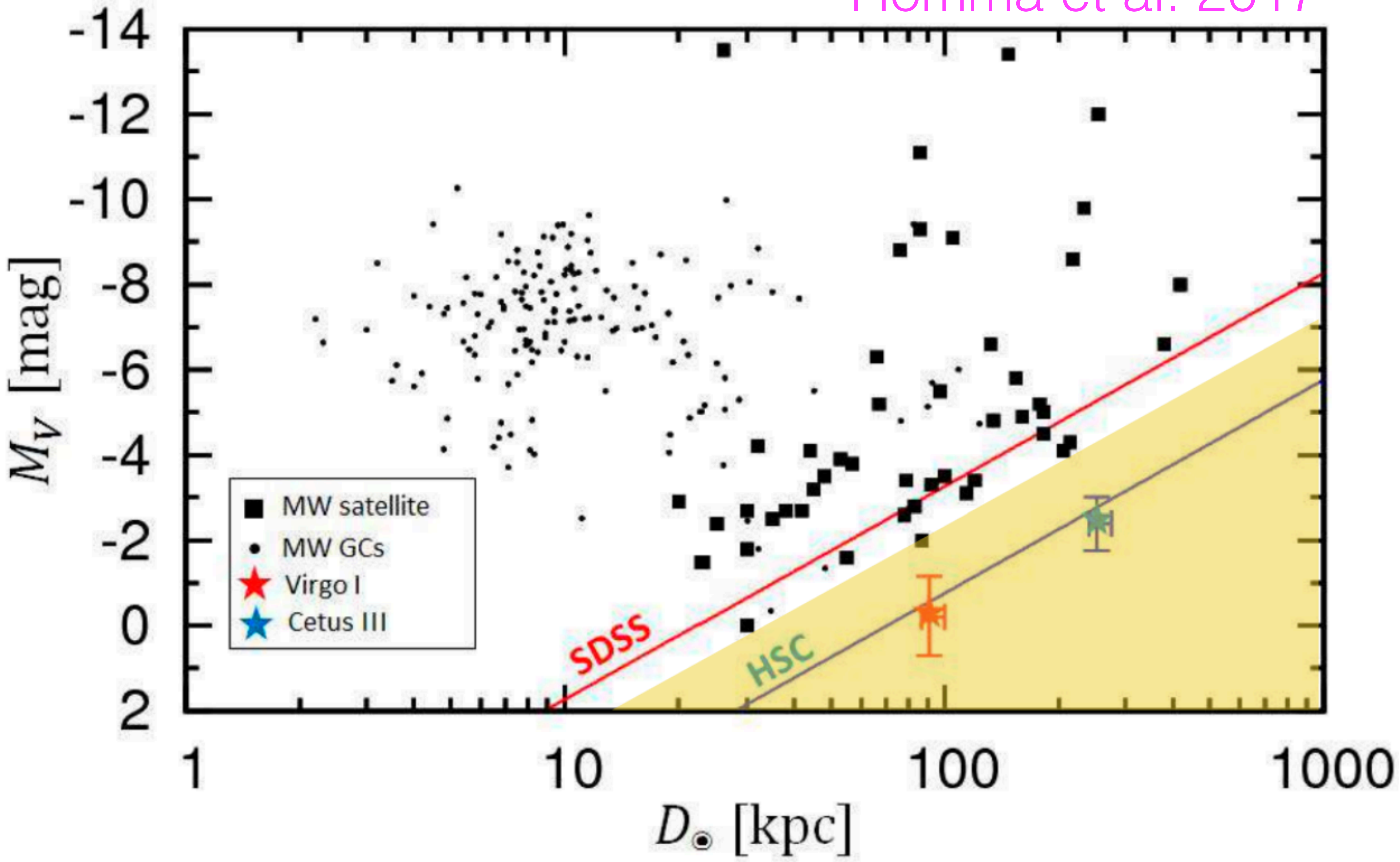
with Risa Wechsler, Keith Bechtol, Yao-Yuan Mao, Greg Green

Modeling Milky Way Satellites

Credit: Keith Bechtol



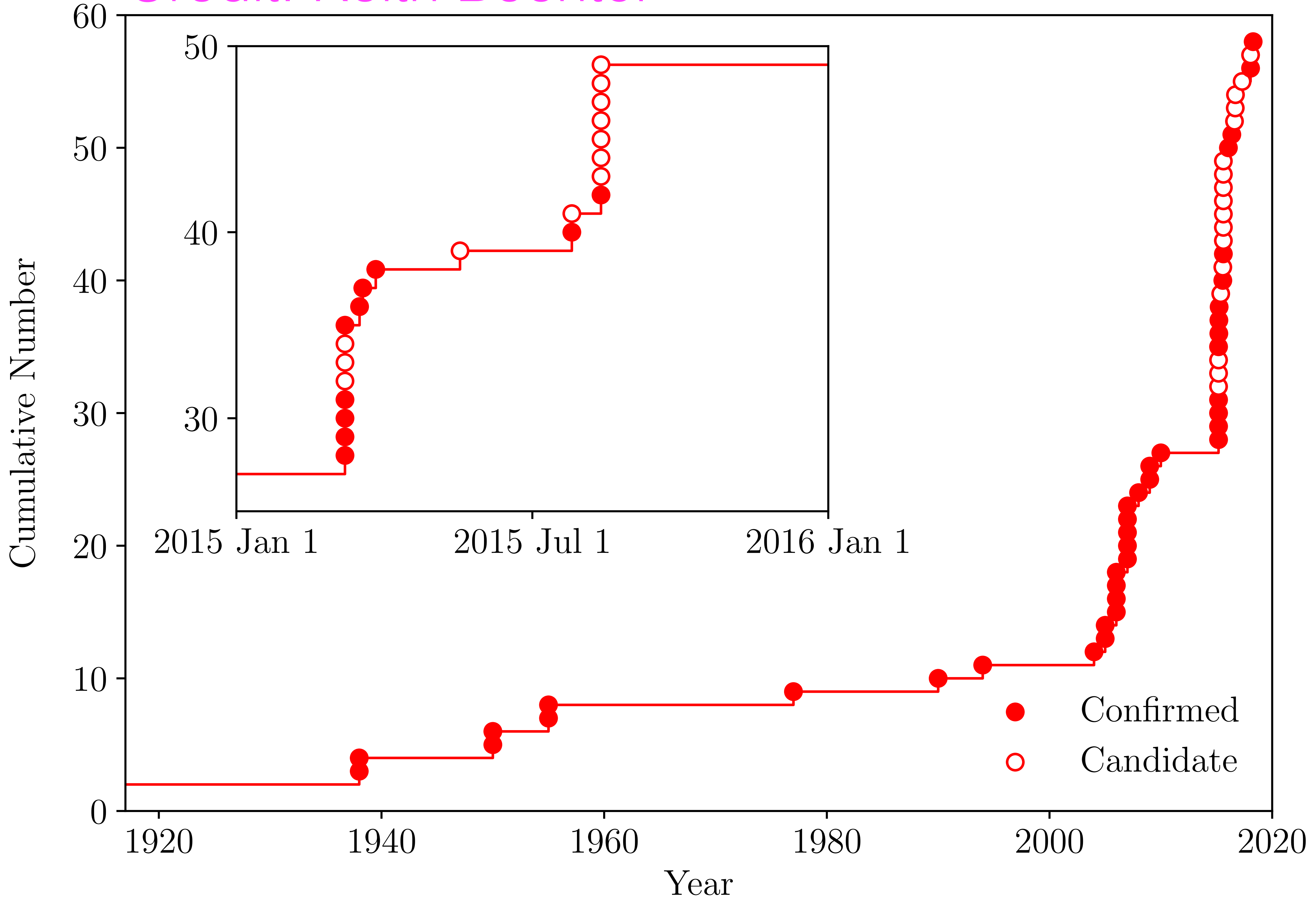
Homma et al. 2017



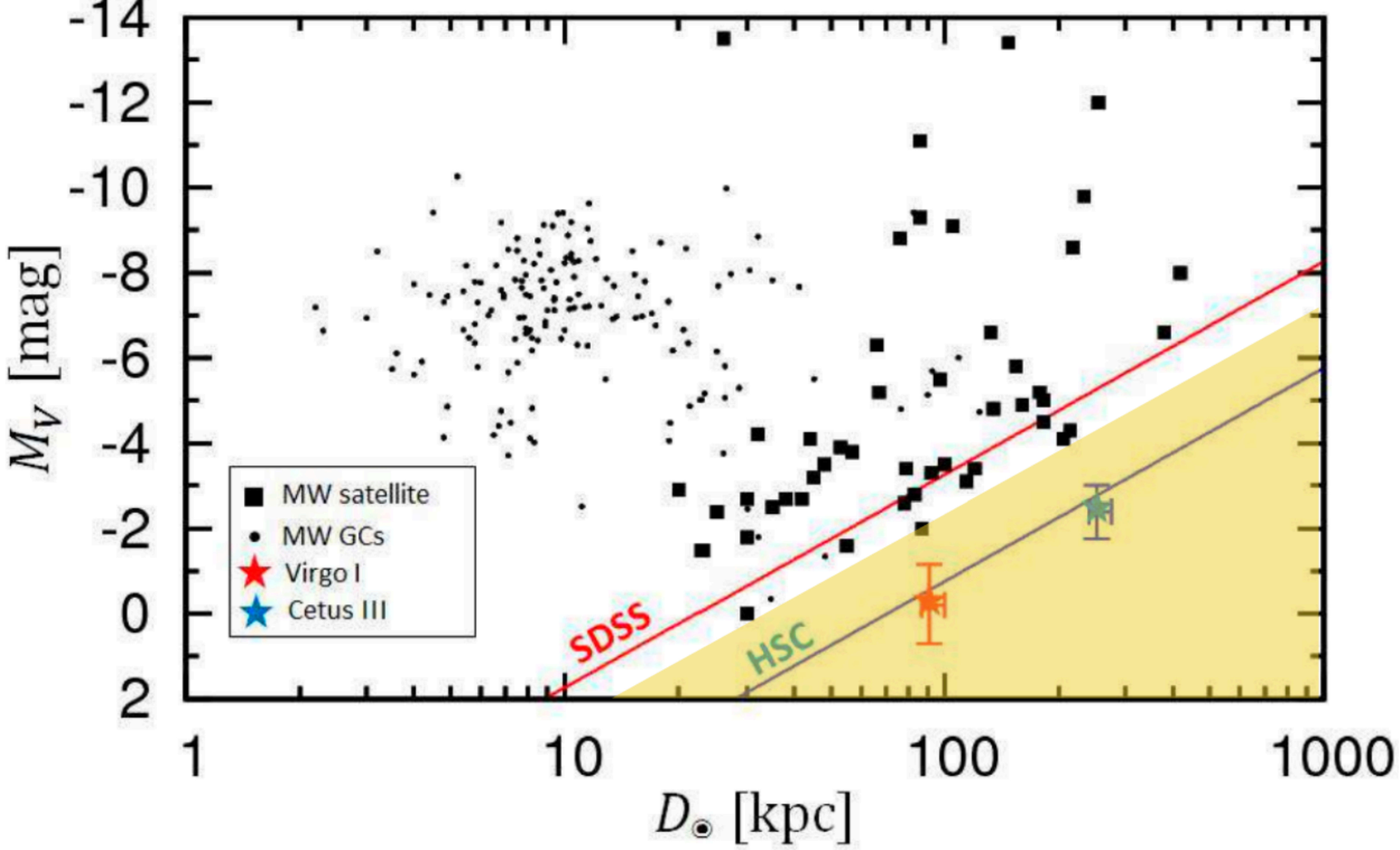
Rapid discovery rate: DES, Pan-STARRS, MagLiteS, …

Modeling Milky Way Satellites

Credit: Keith Bechtol



Homma et al. 2017



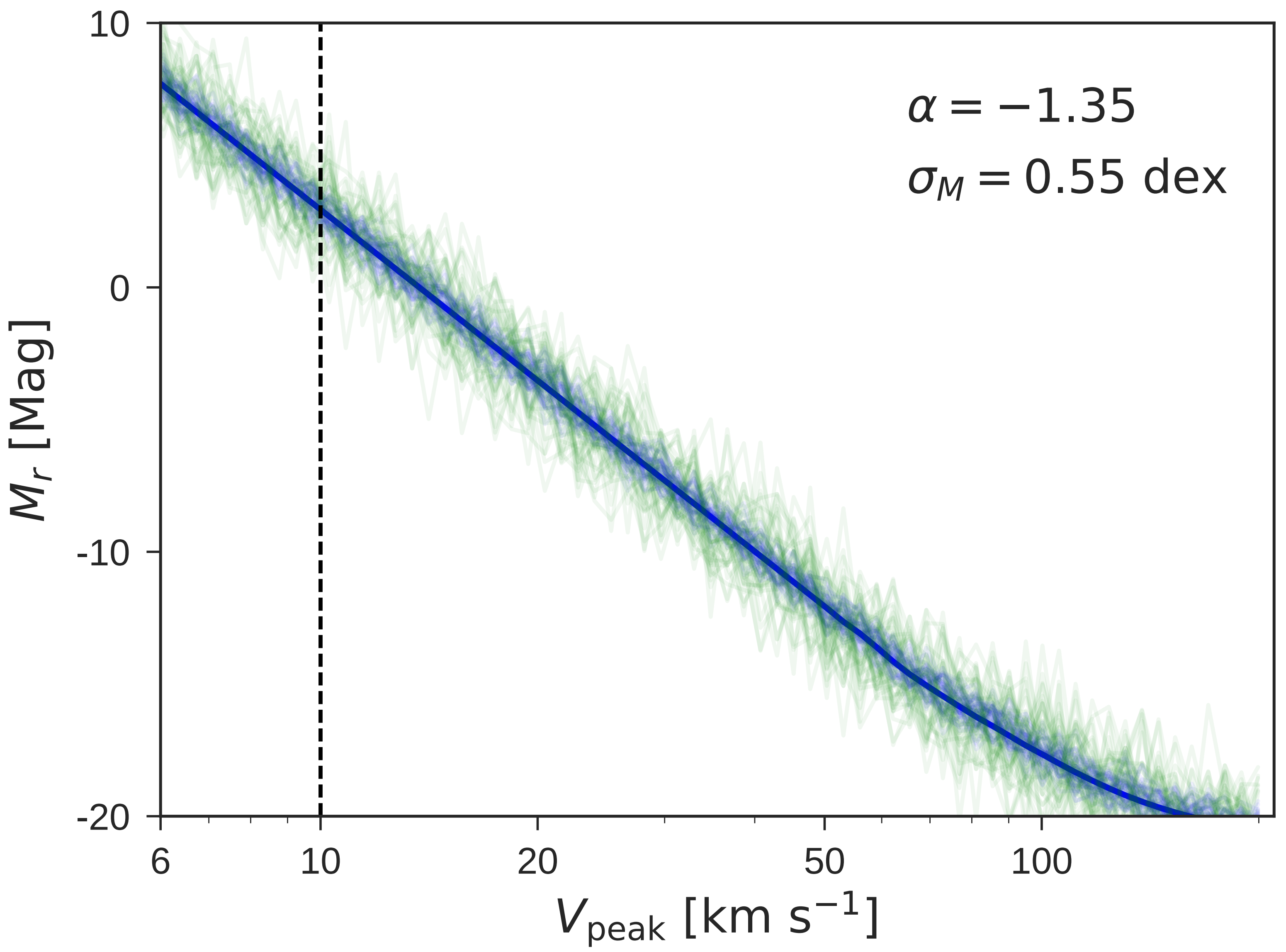
How do the MW satellite luminosity function, radial distribution, and **size** distribution constrain the low-mass galaxy-halo connection?

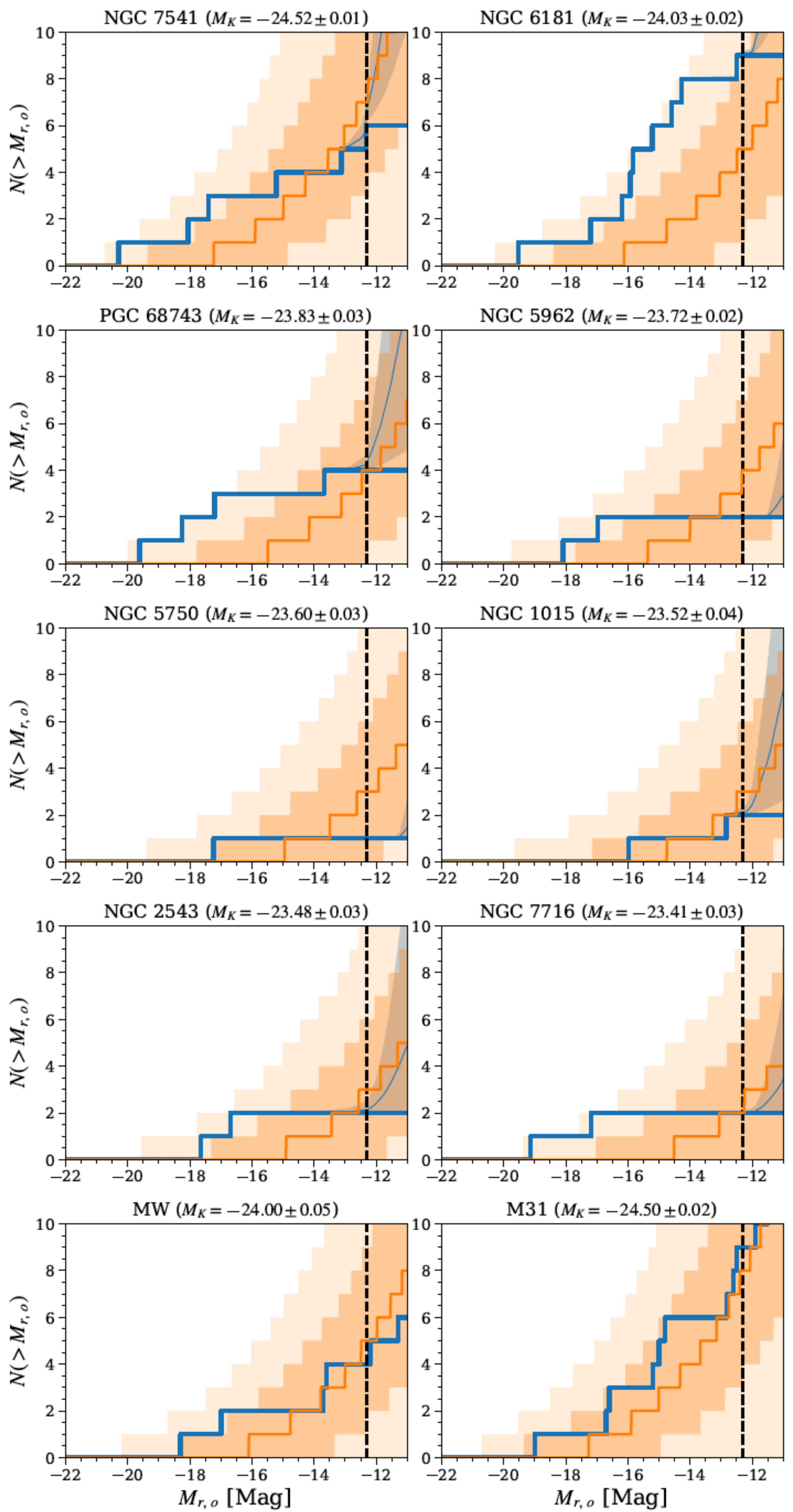
Model Building: Luminosities

- Abundance match to GAMA luminosity function
- Parameters: faint-end luminosity function slope, abundance matching scatter
- SAGA systems suggest a shallower slope?

α : faint-end slope of $\mathrm{d}N/\mathrm{d}L$

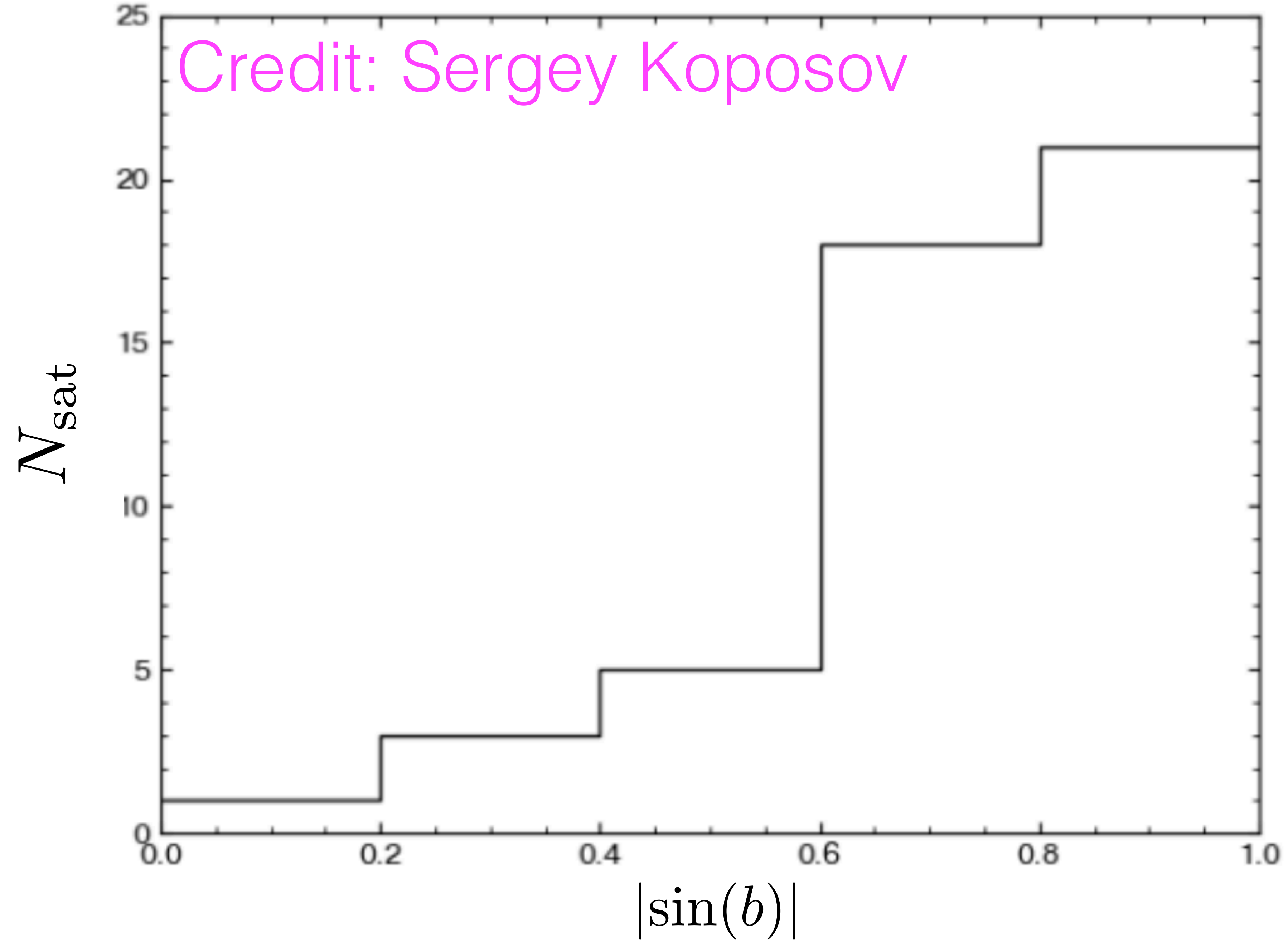
σ_M : M_r–V_{peak} scatter [dex]



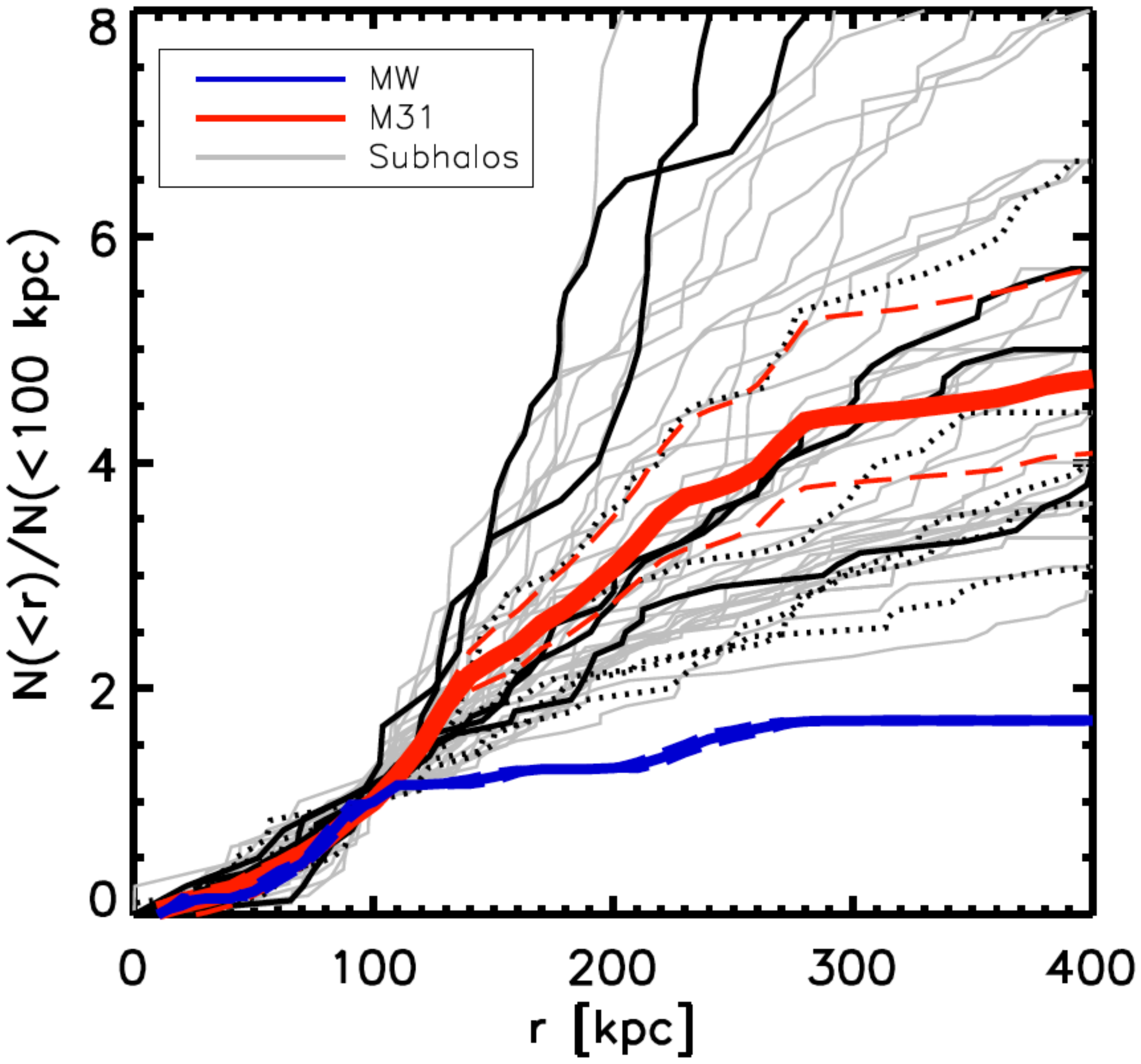


Model Building: Radial Distributions

- Is the radial concentration of MW satellites rare?
- Likely a completeness issue; surface brightness limits, satellites behind disk difficult to detect



Yniguez et al. 2013

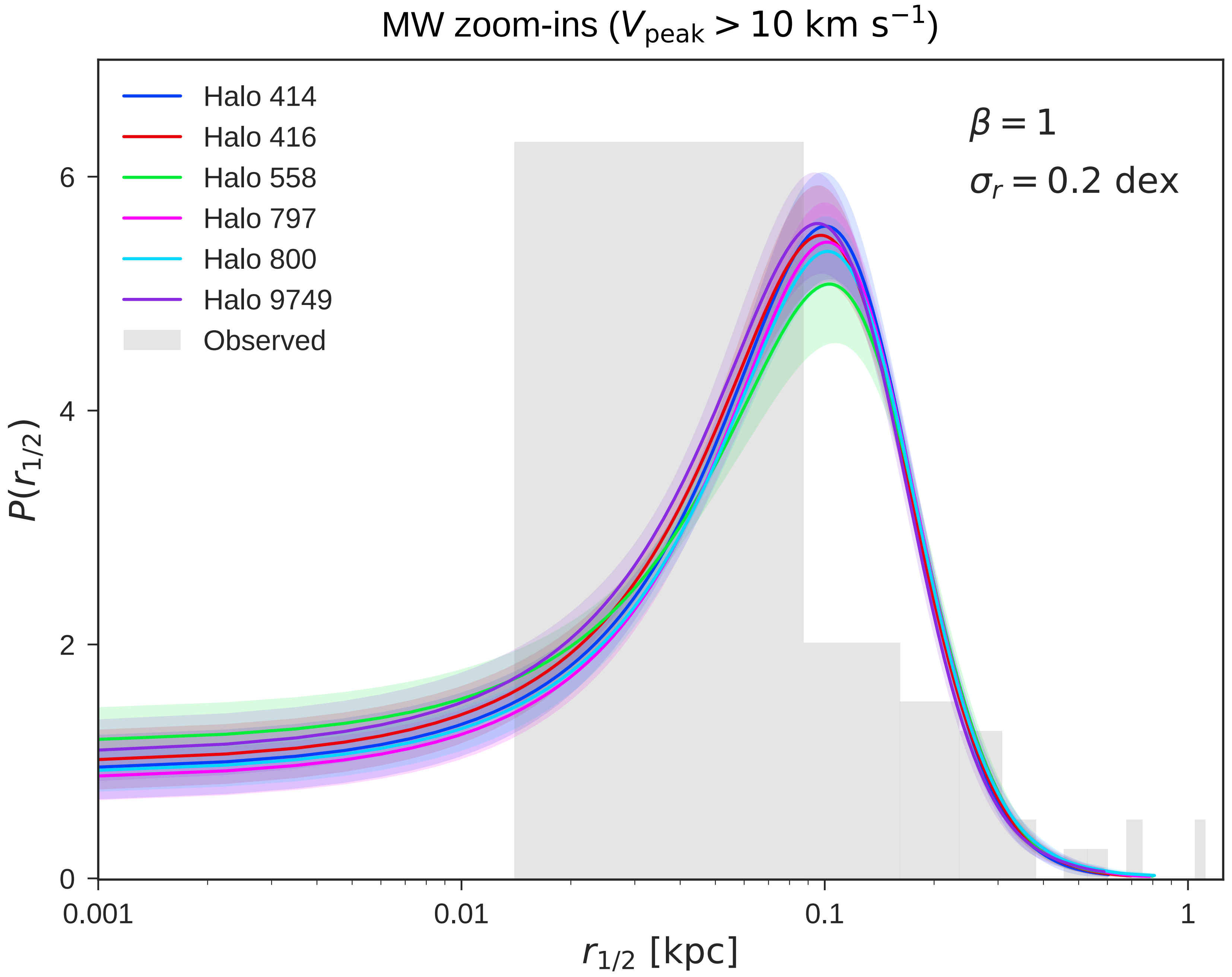


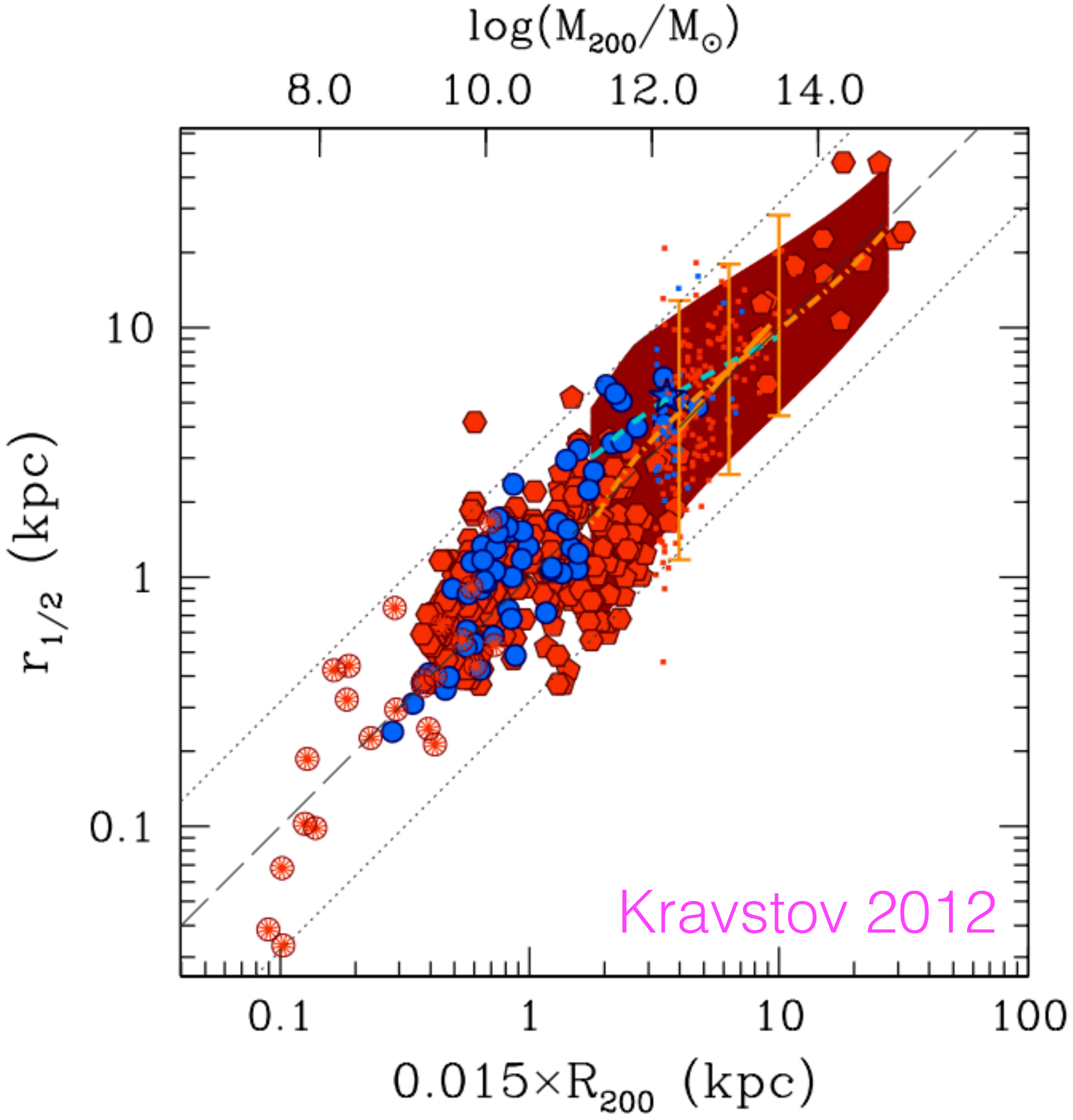
Model Building: Sizes

- Does the tight relationship between halo virial radius and galaxy half-light radius hold for dwarf satellites?
- Parameters: accretion vs. present-day size, scatter

$$\beta : R_{200,\mathrm{acc}} \left(\frac{R_{200,z_0}}{R_{200,\mathrm{acc}}} \right)^{\beta}$$

$$\sigma_r : r_{1/2}\text{–}R_{200} \text{ scatter [dex]}$$



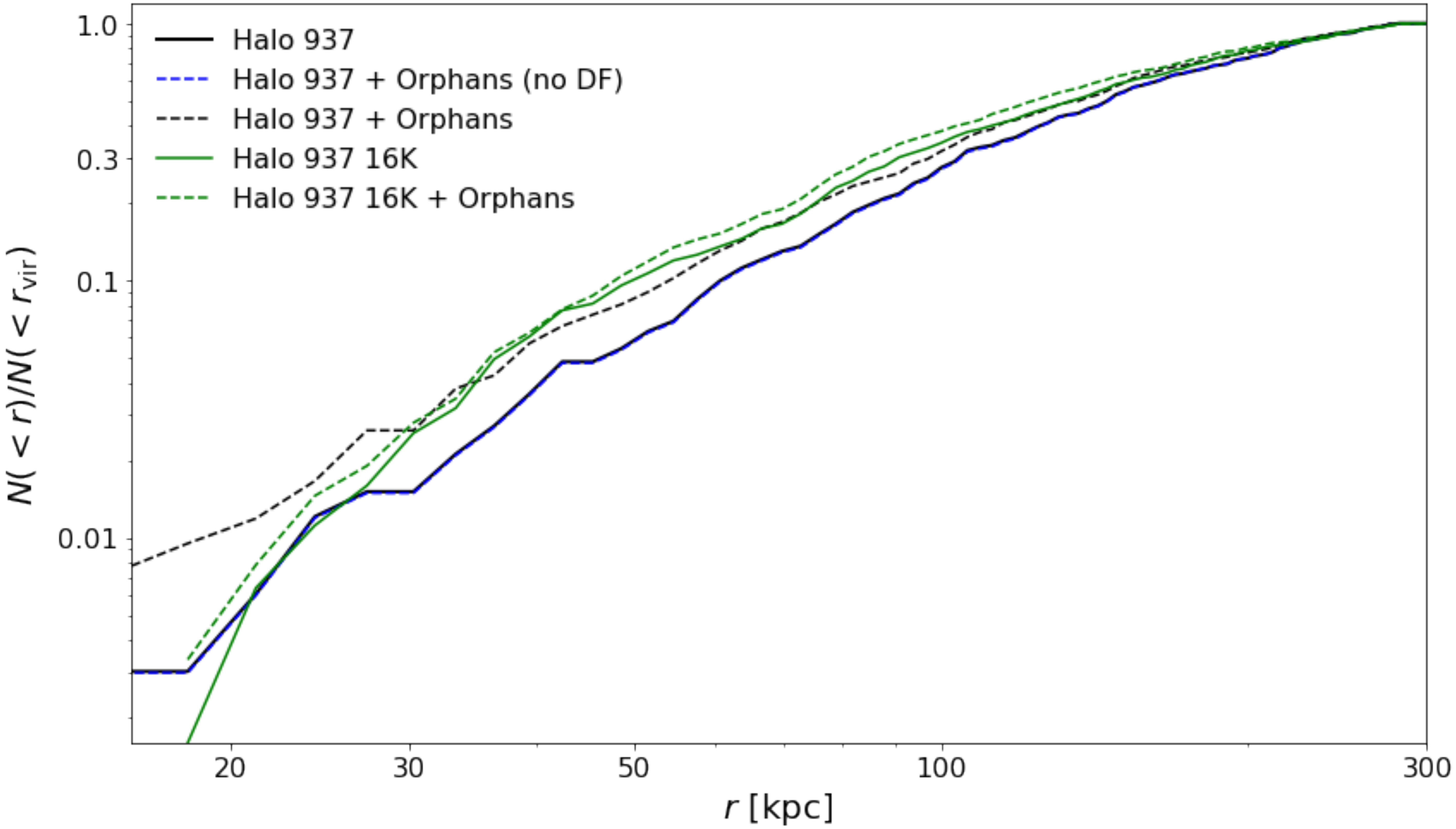


Model Building: Disruption & Orphans

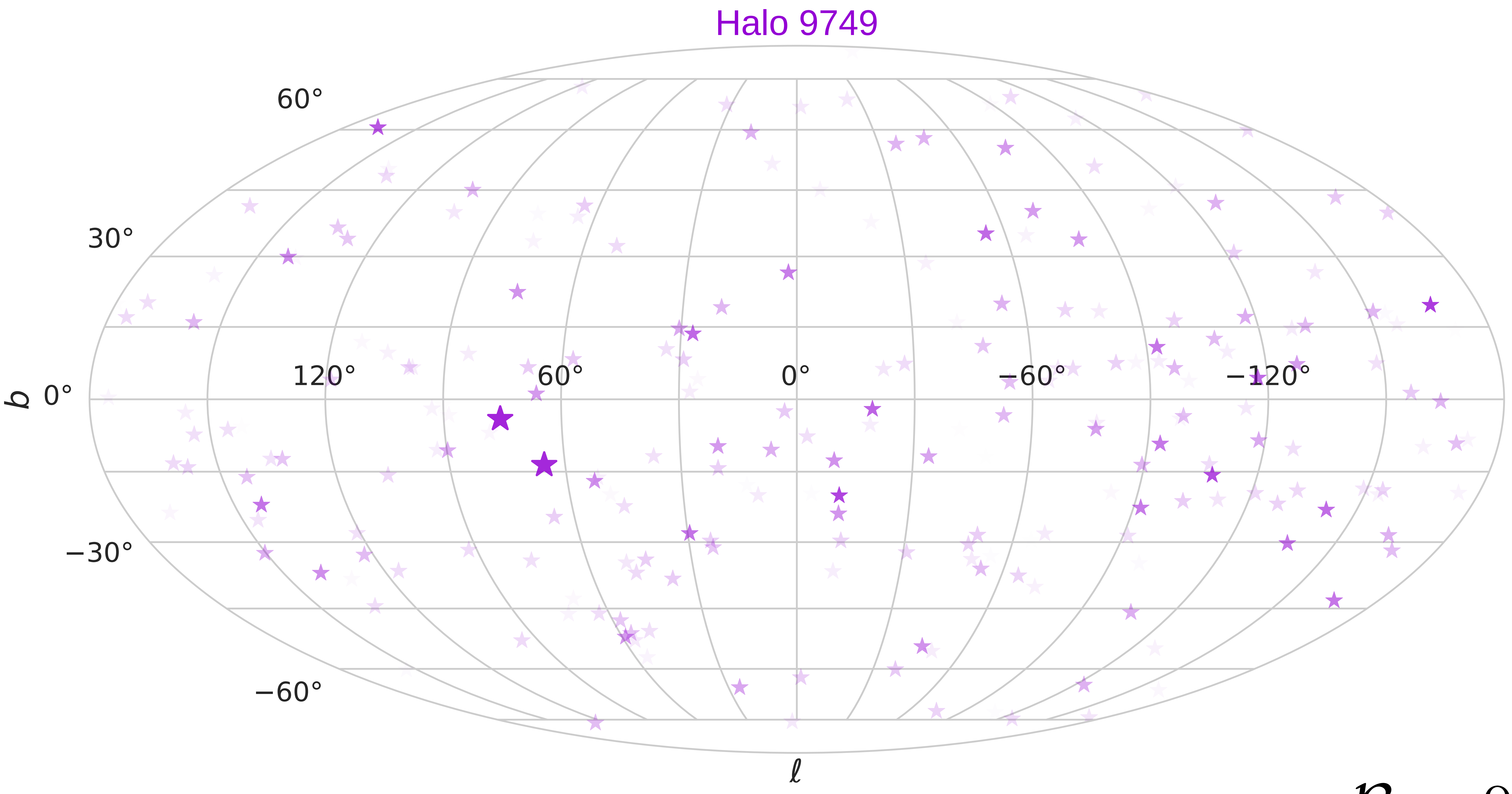
- Baryonic disruption: parameterize strength of random forest disruption probability
- Orphans: track disrupted subhalos with dynamical friction, stripping models

$$\mathcal{B}: \; p_{\text{disrupt}} \rightarrow p_{\text{disrupt}}^{1/\mathcal{B}}$$

$$\mathcal{O}: p_{\text{disrupt}} = (1 - V_{\text{max}}/V_{\text{peak}})^{\mathcal{O}}$$

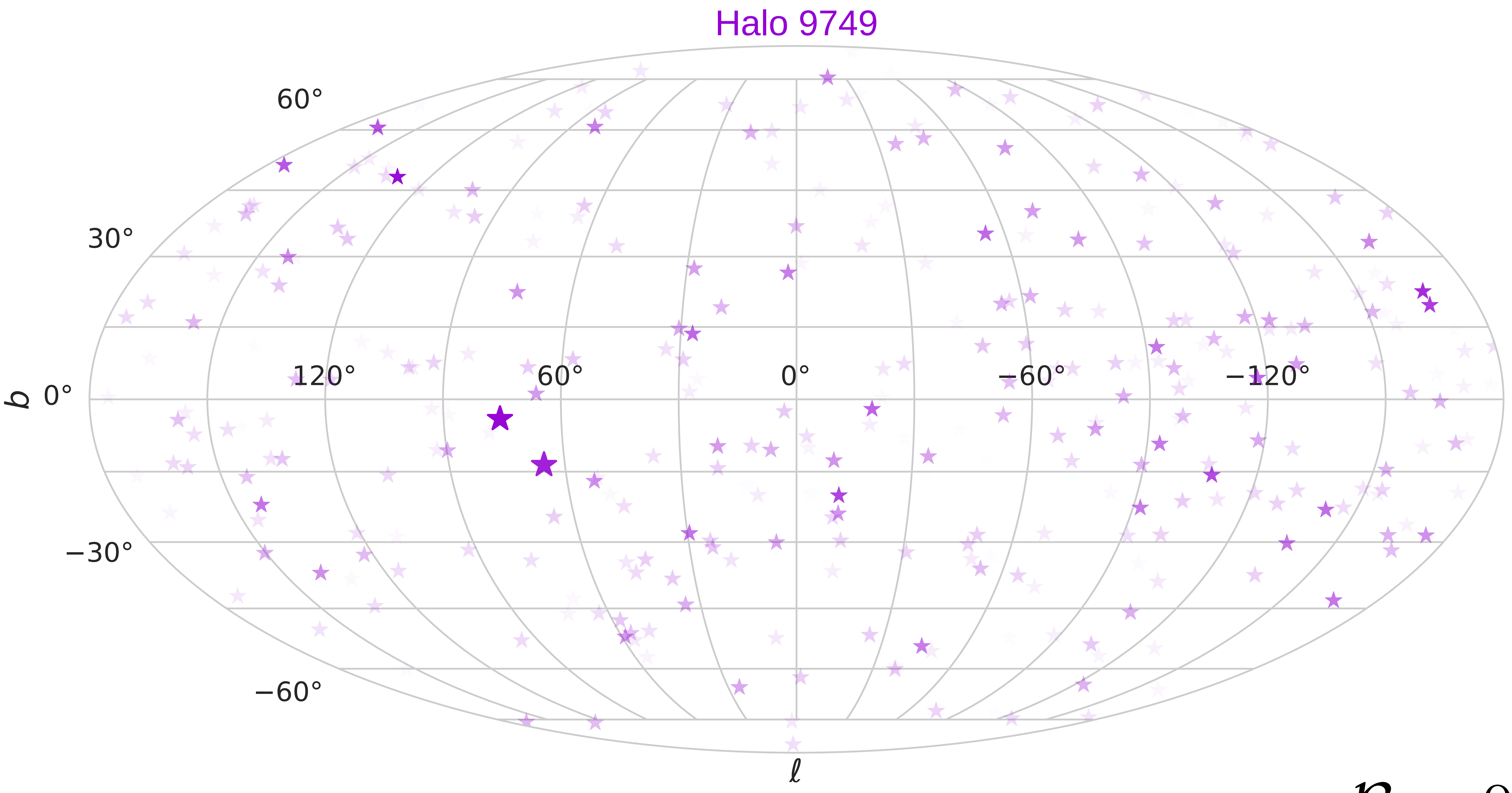


Satellite Distributions



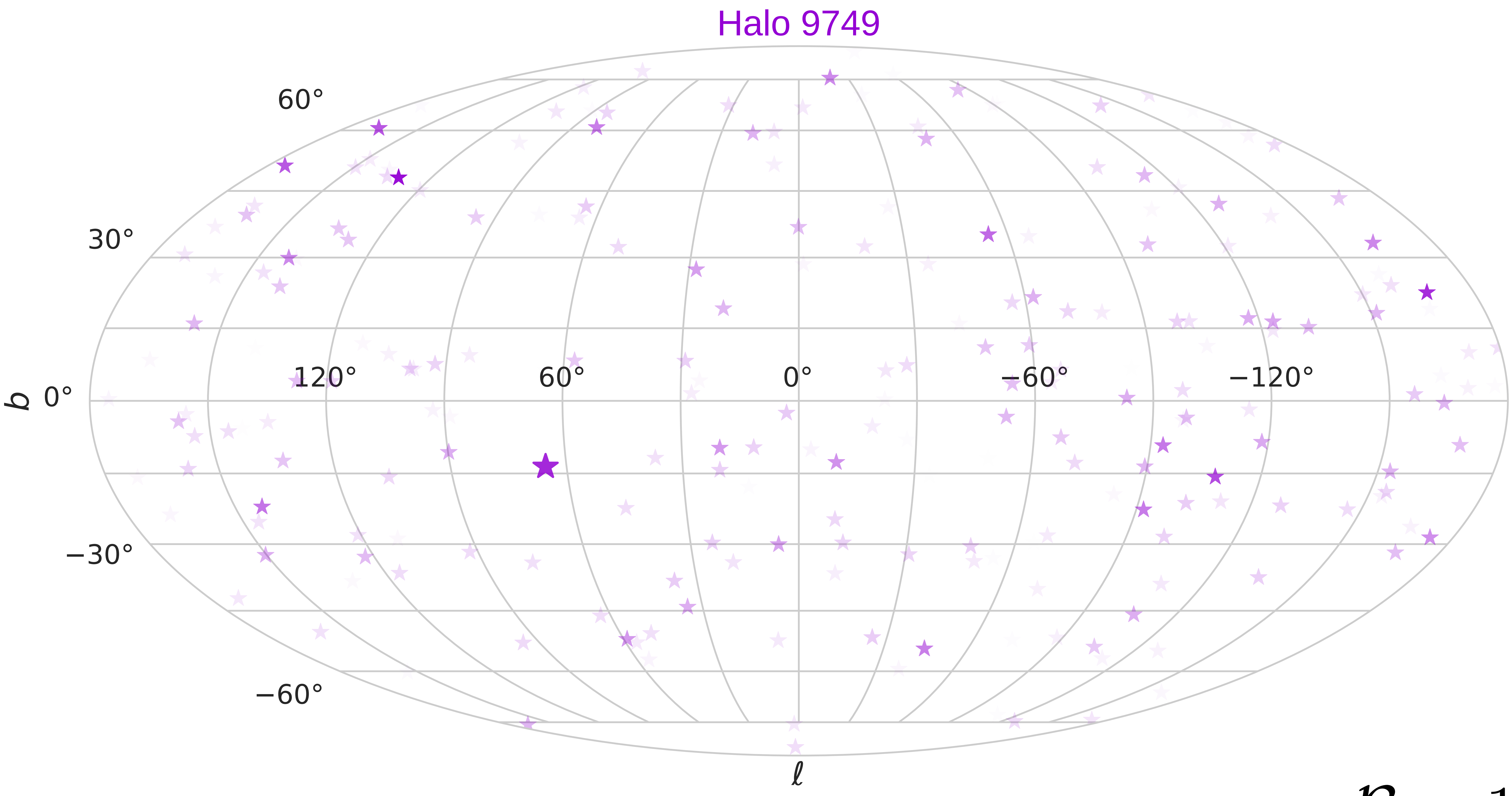
$$\mathcal{B} = 0, \ \mathcal{O} = 0$$

Satellite Distributions



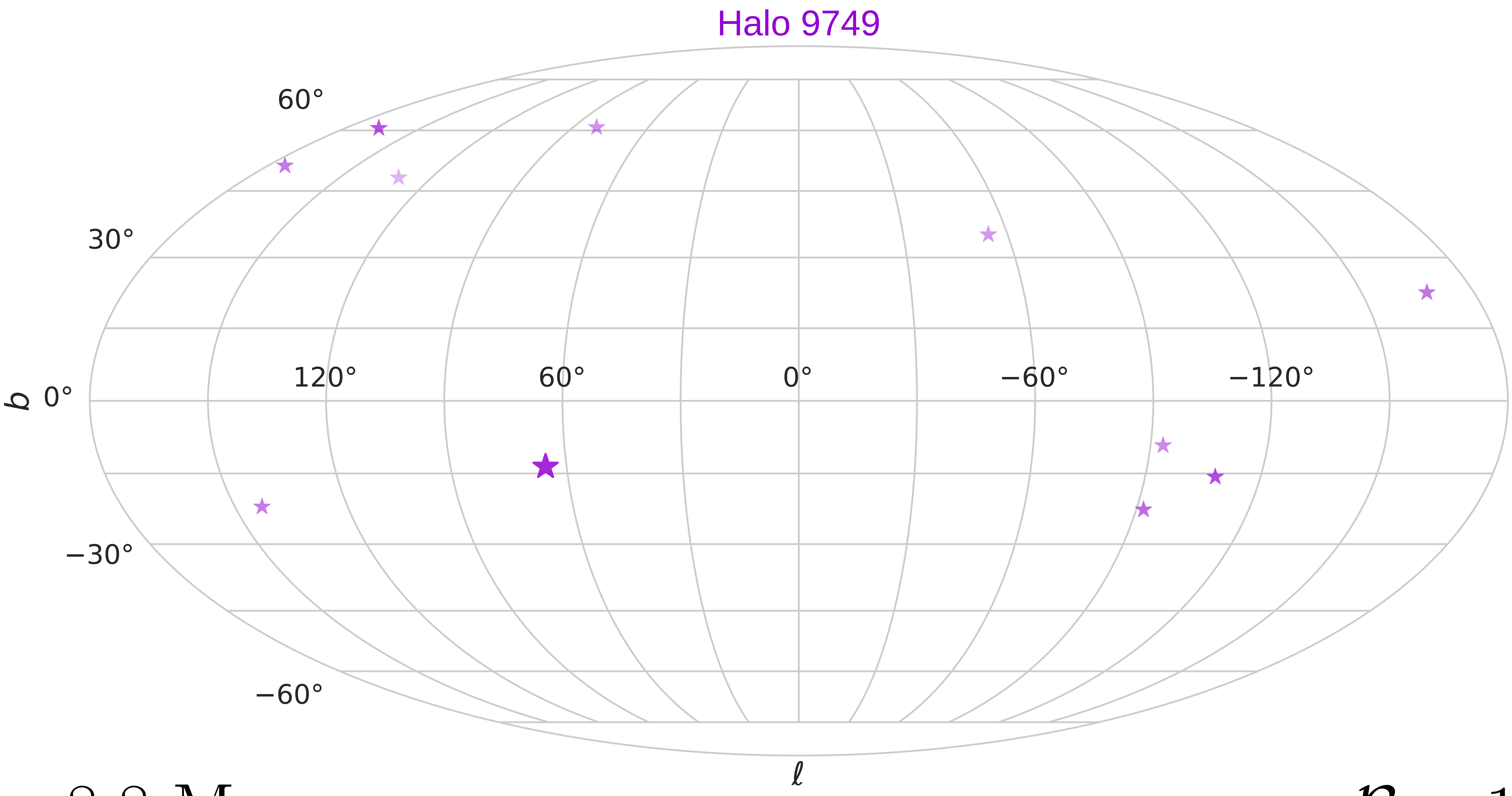
$$\mathcal{B} = 0,\ \mathcal{O} = 1$$

Satellite Distributions



$$\mathcal{B} = 1,\ \mathcal{O} = 1$$

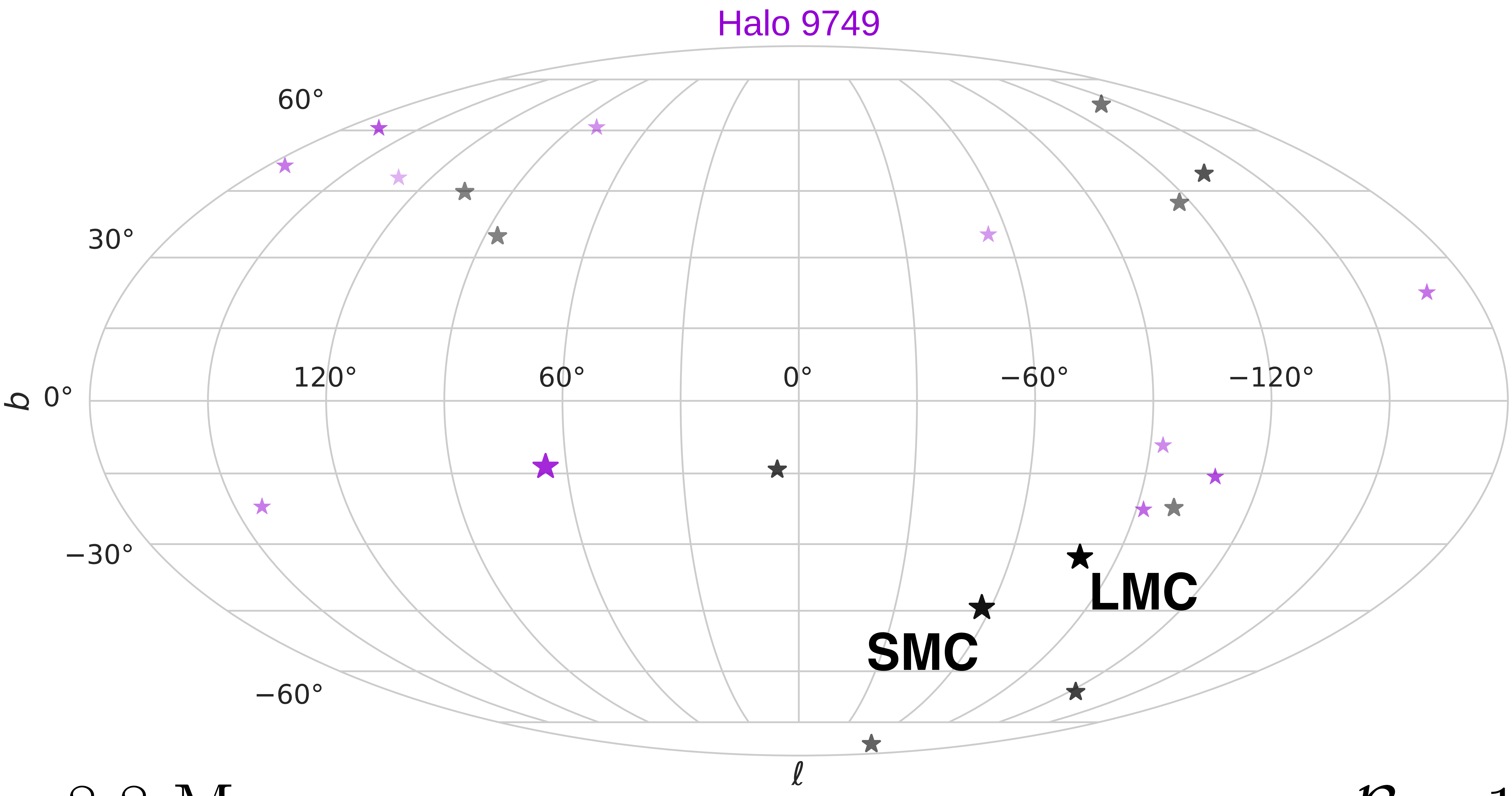
Classical Satellite Distributions



$M_V \leq -8.8$ Mag

$\mathcal{B} = 1,\ \mathcal{O} = 1$

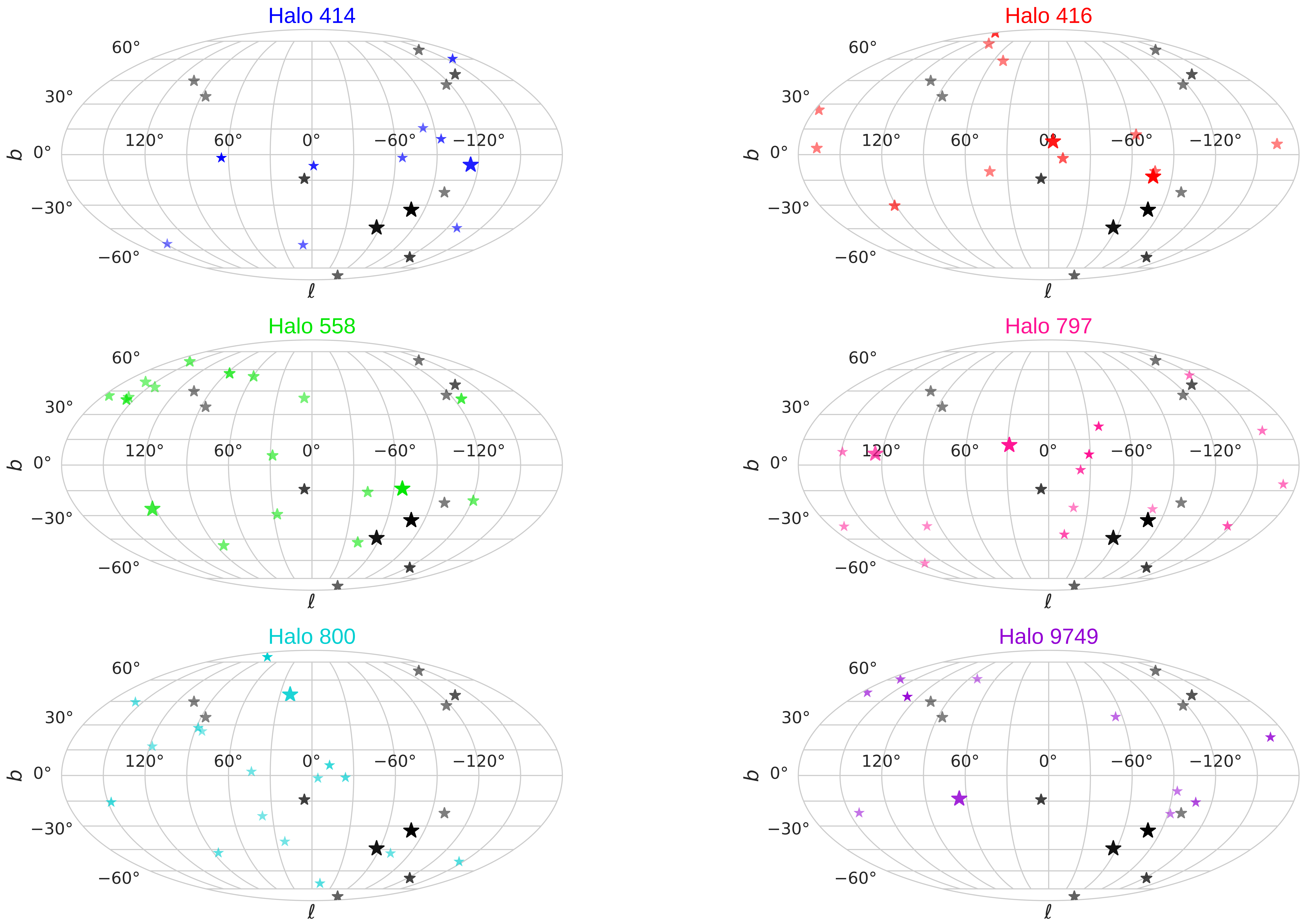
Classical Satellite Distributions



$M_V \leq -8.8$ Mag

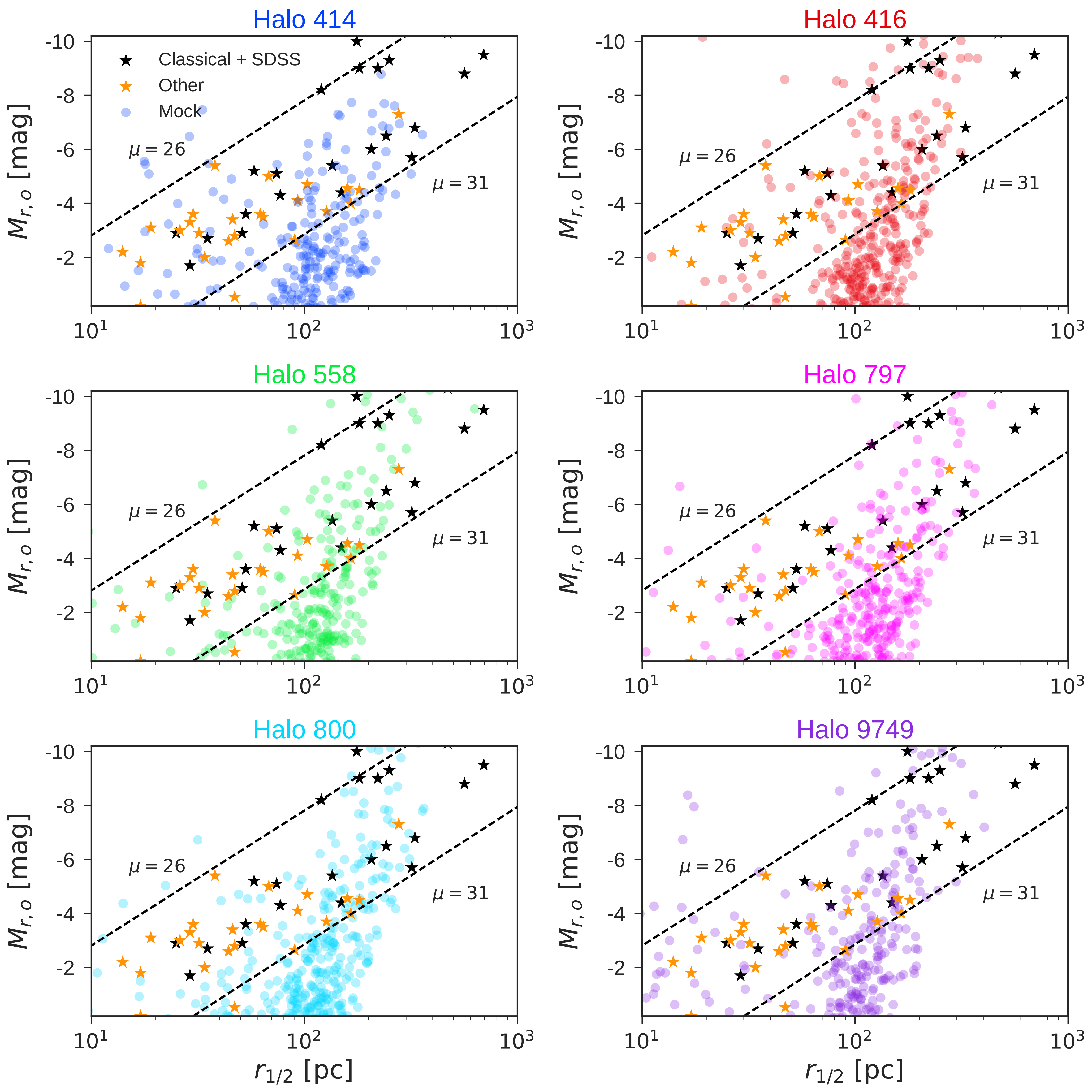
$\mathcal{B} = 1, \ \mathcal{O} = 1$

Classical Satellite Distributions

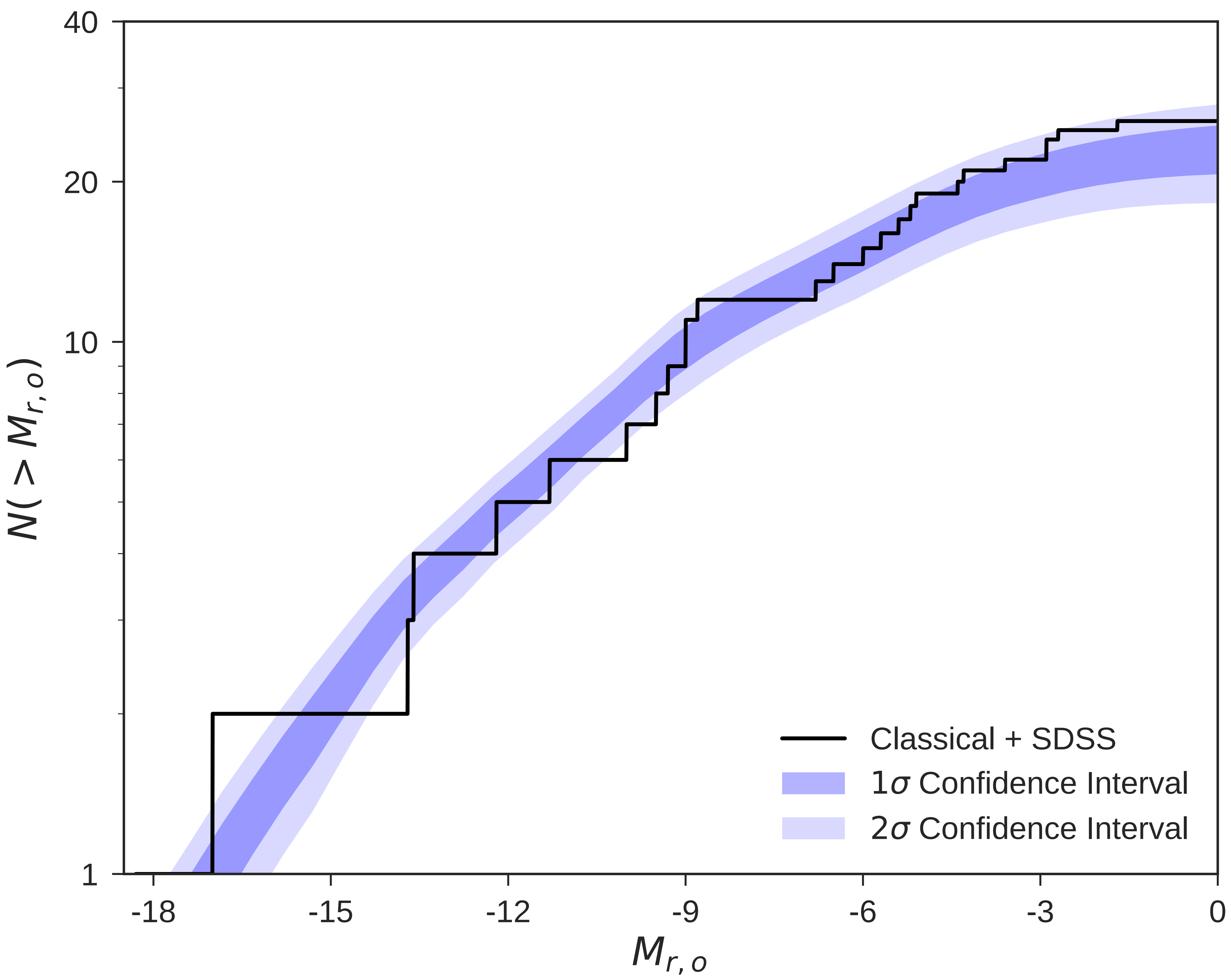


Mock Observations of Milky Way Satellites

Many large satellites below $\mu = 31$?



"Observed" luminosity function



Interpreting Full-Sky Observations

SDSS + DES + Pan-STARRS + MagLiteS + … —> full-sky luminosity function

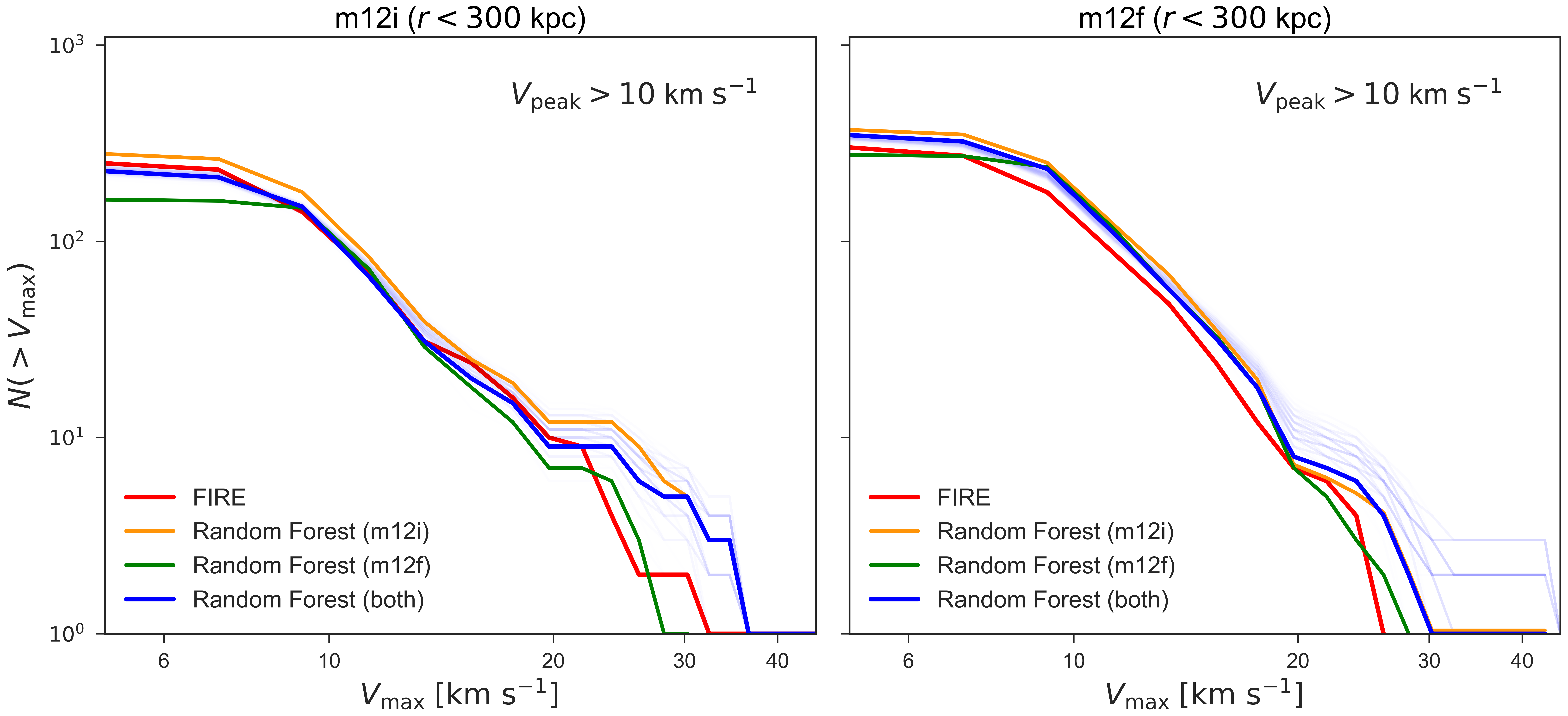
There are significant modeling uncertainties: baryonic impact, orphans, abundance matching/size models, LMC/SMC, …

Some data-driven questions:

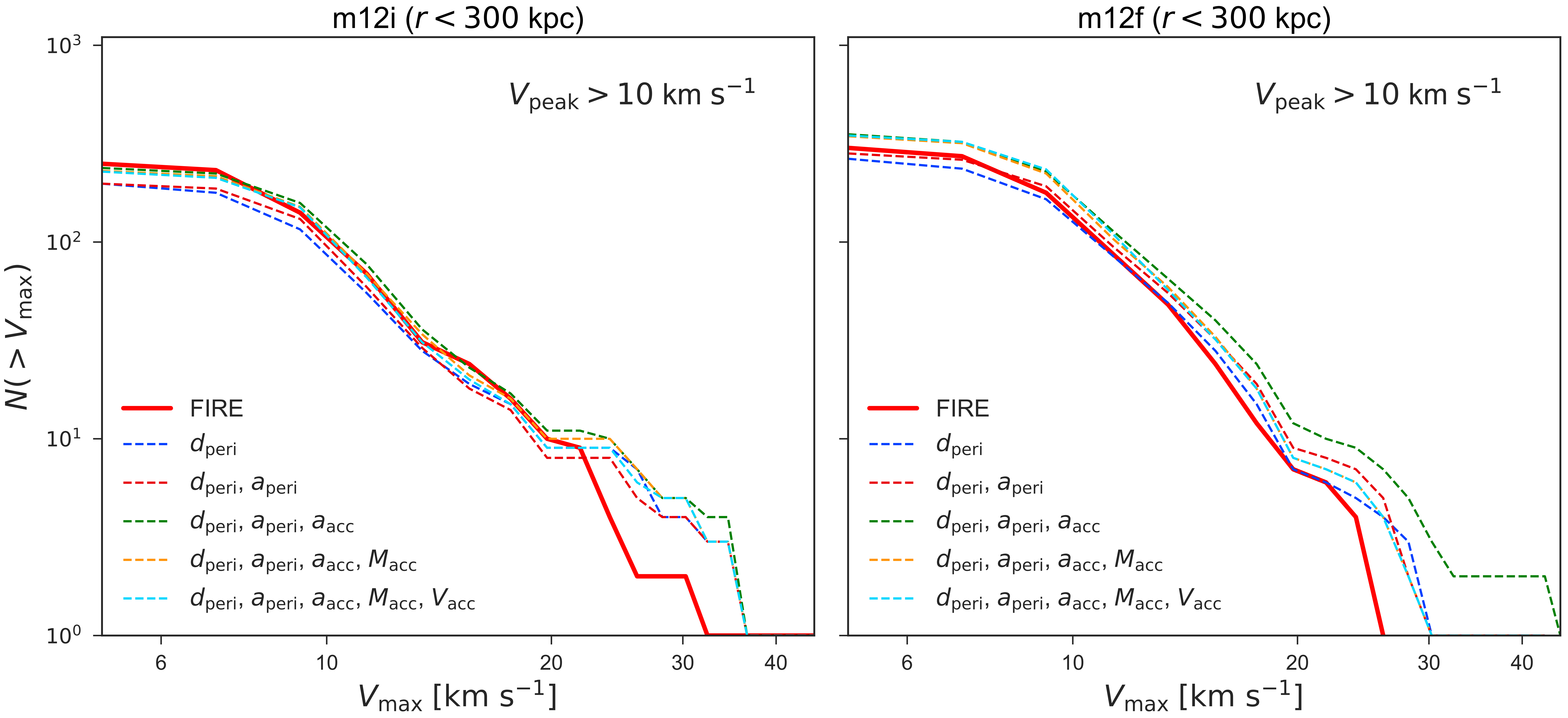
- Are observed/predicted satellite distributions consistent with isotropy?
- Is there evidence for a distinct LMC/SMC satellite population?
- Is there evidence for a faint-end luminosity function cutoff?
- Is there evidence for a plane of satellites, and is this consistent with simulations?

Thanks: Risa Wechsler, Yao-Yuan Mao, Greg Green, Shea Garrison-Kimmel, Andrew Wetzel!

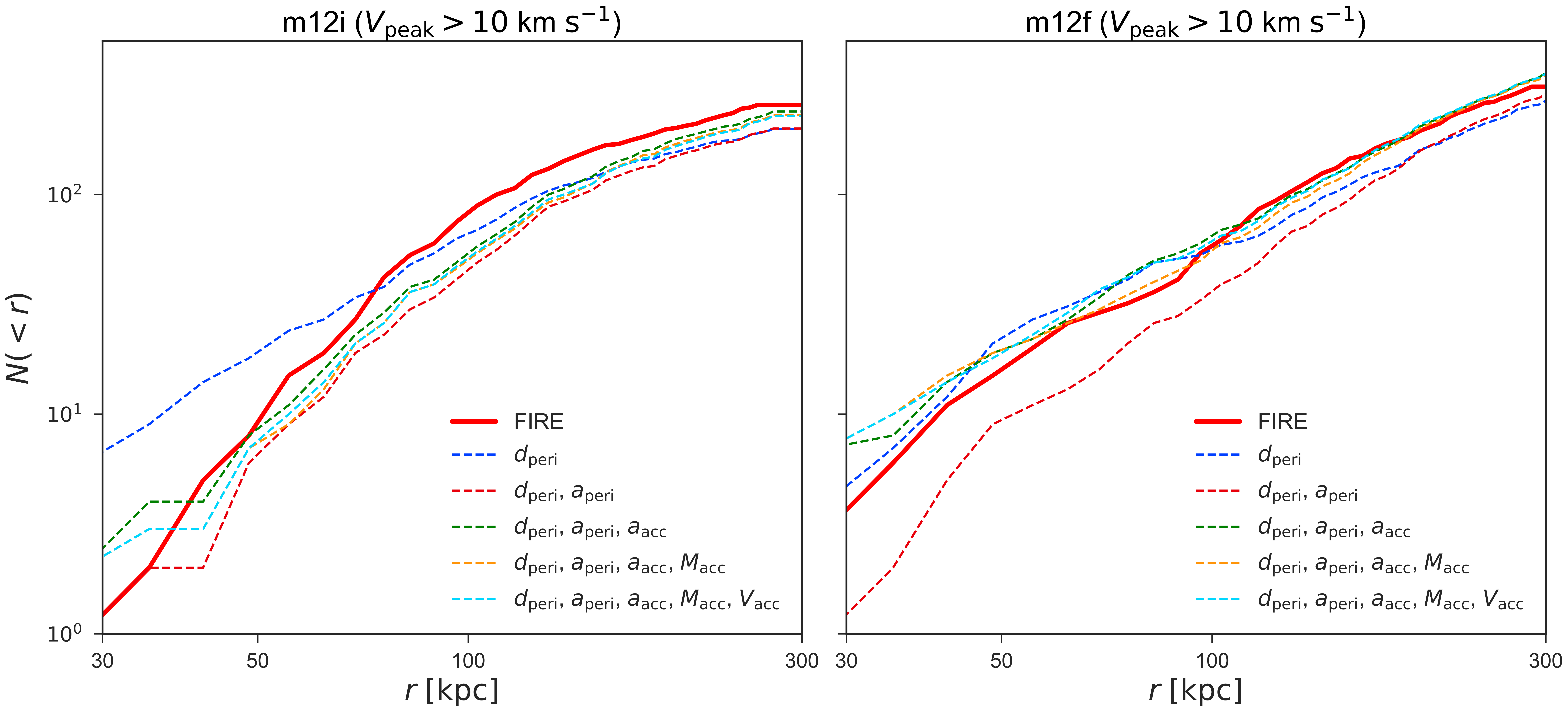
Training Data



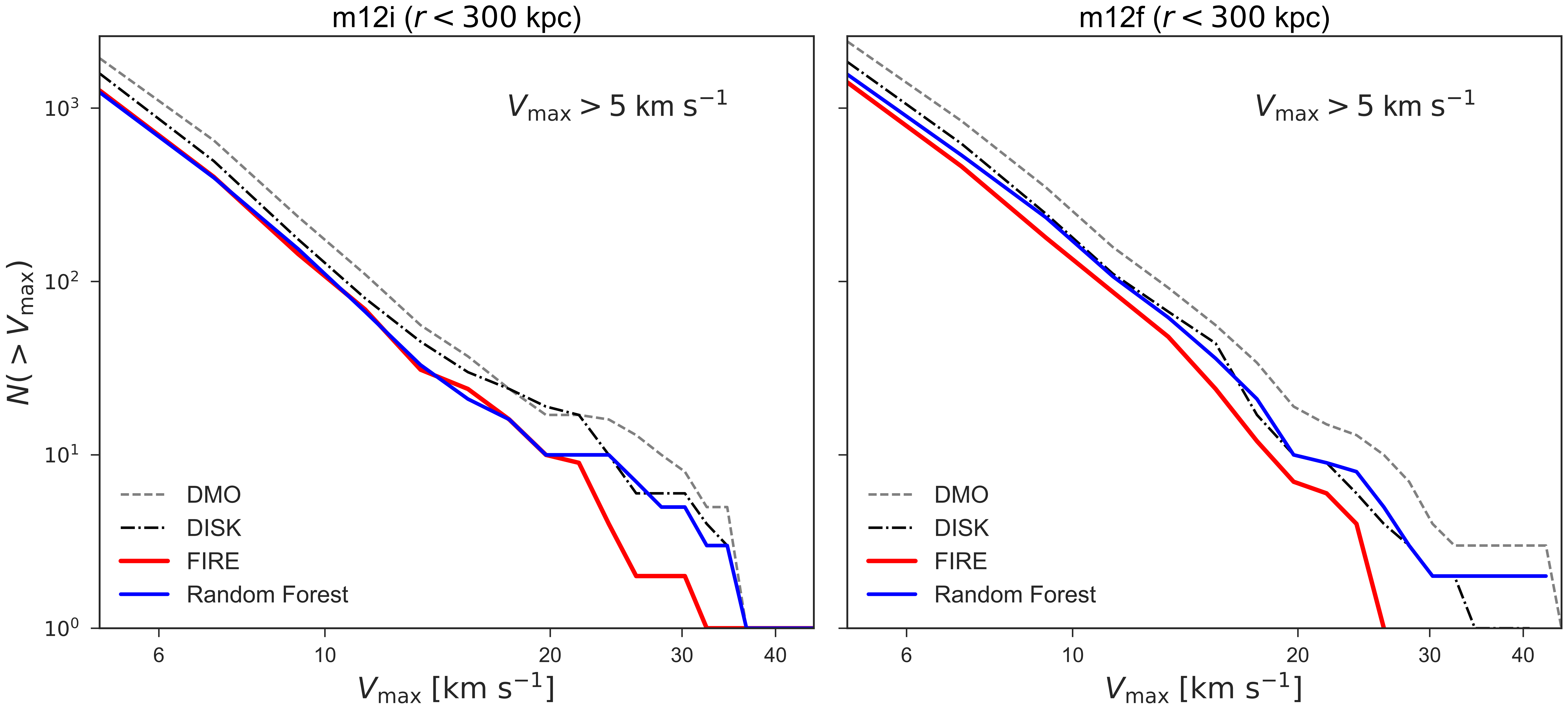
Feature Selection



Feature Selection



Resolution Effects



Radial Velocity Distributions