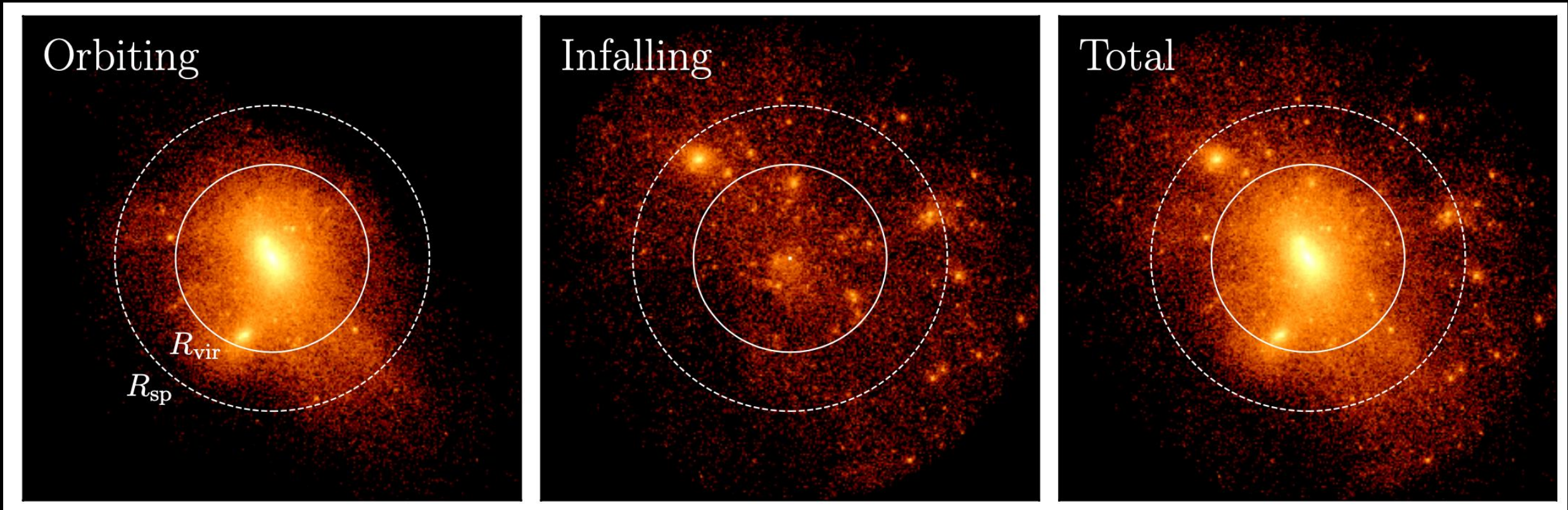
Dynamical Halos are Better!



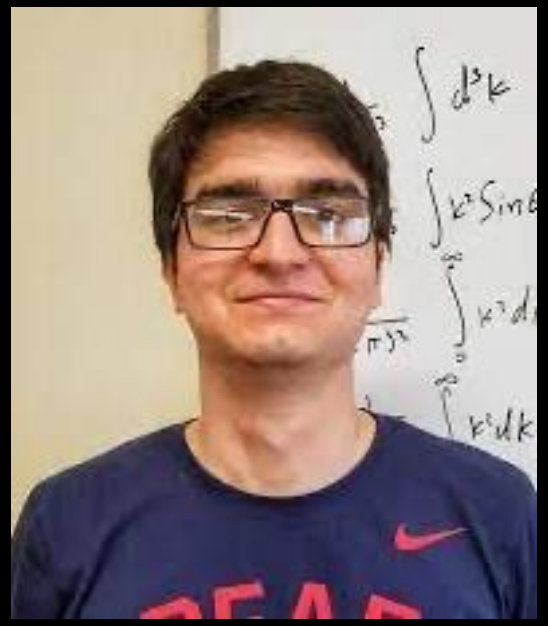
Eduardo Rozo

THE UNIVERSITY OF ARIZONA

Valencia Workshop on the Small-Scale Structure of the Universe and Self-Interacting Dark Matter

Valencia, Spain, July 2025

Bulk of the work shown here was performed by:



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Benedikt Diemer

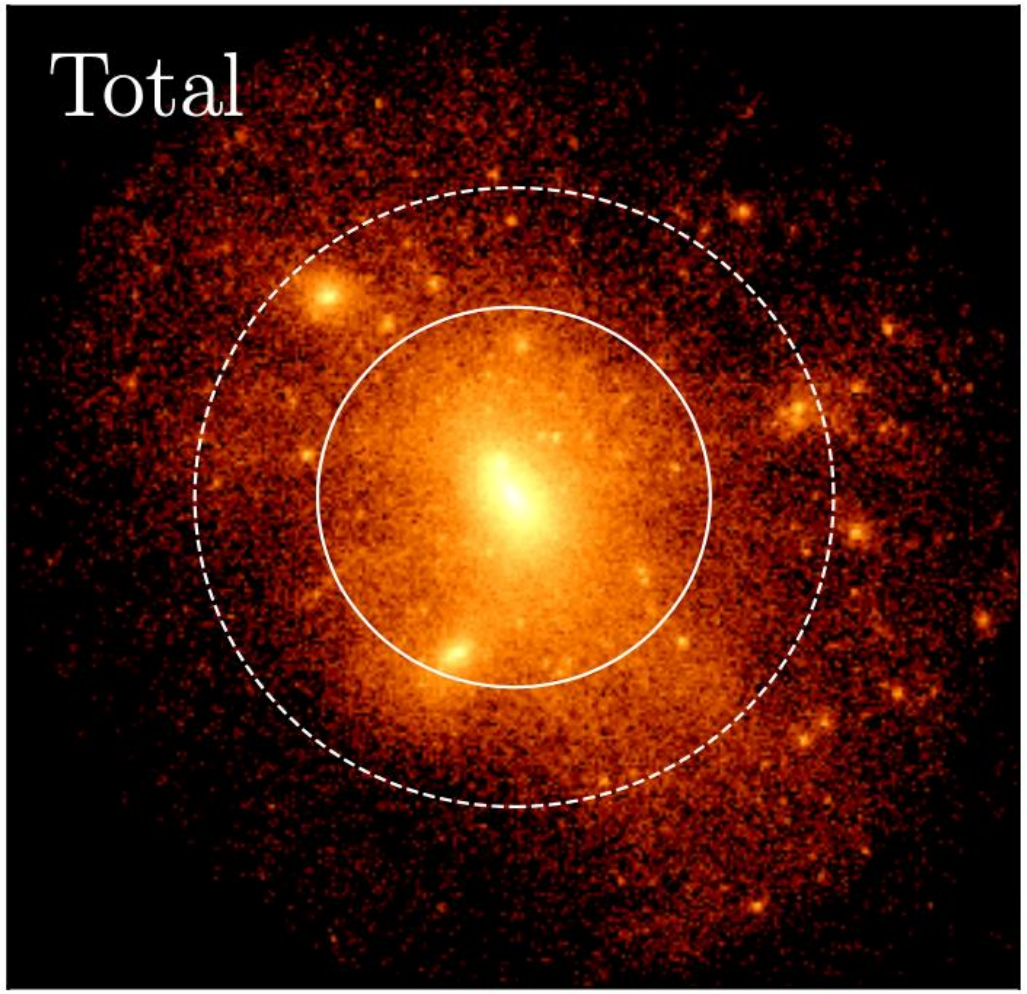
Calvin Onsaga

Vladimir Ze’ev

Susmita Adhikari

What is a halo?

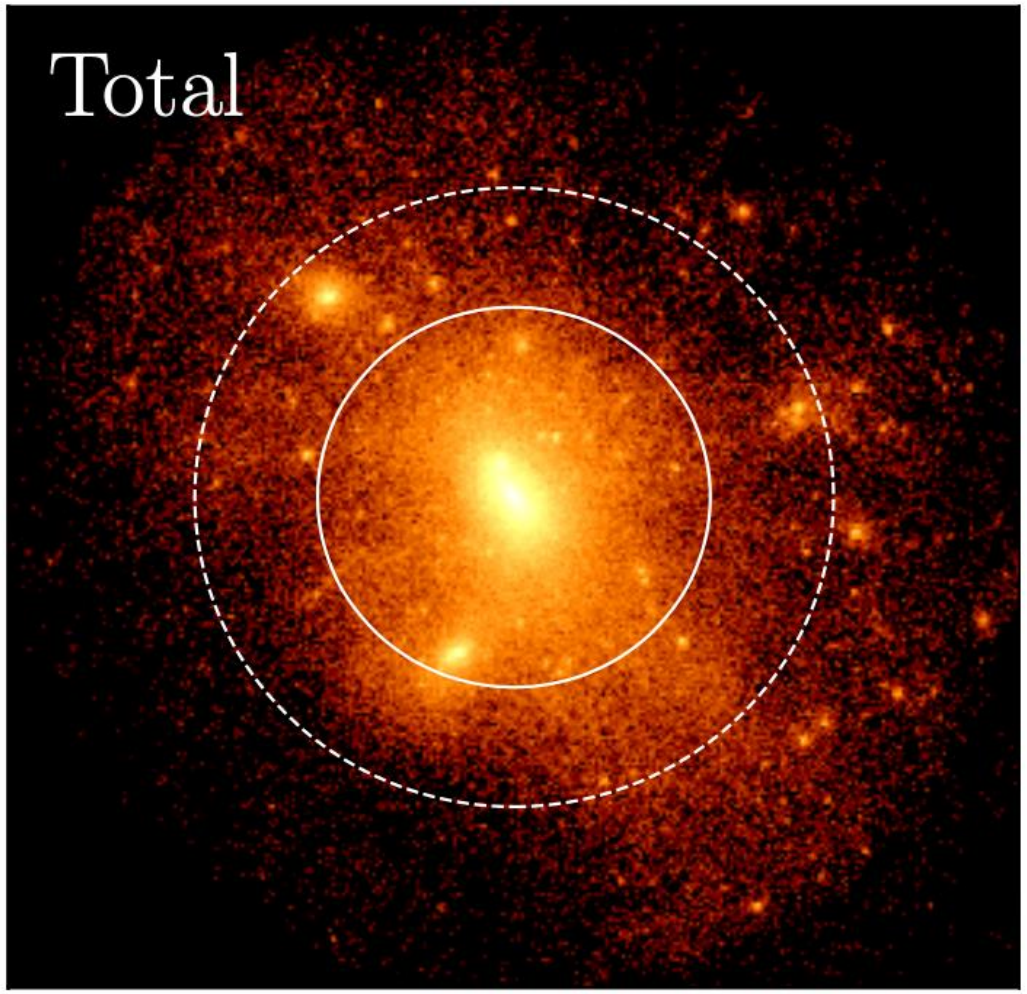
This is a halo.



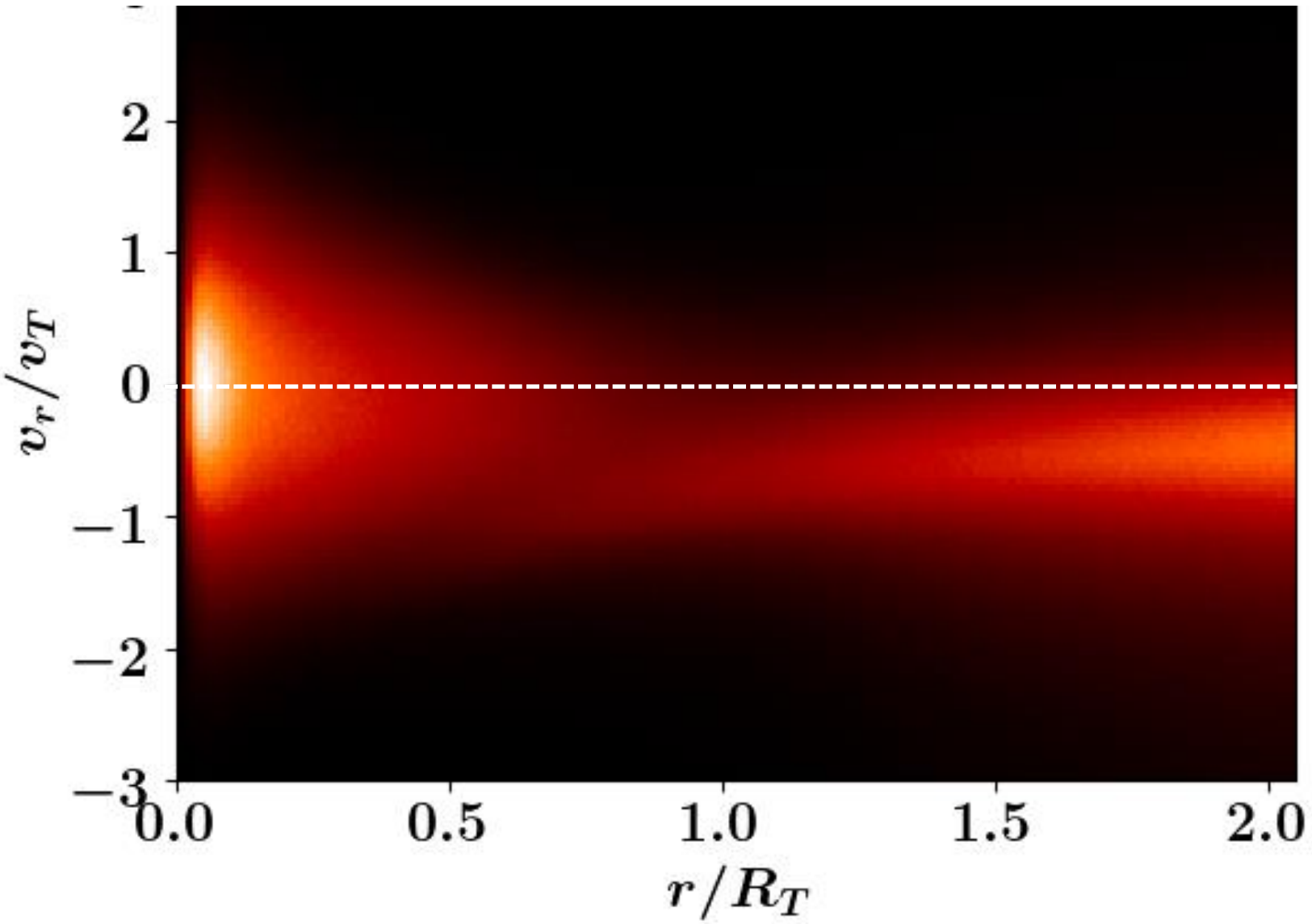
This is a halo.

Question:

Which particles belong to the halo, and which don’t?



The halo is easy to see in phase space!



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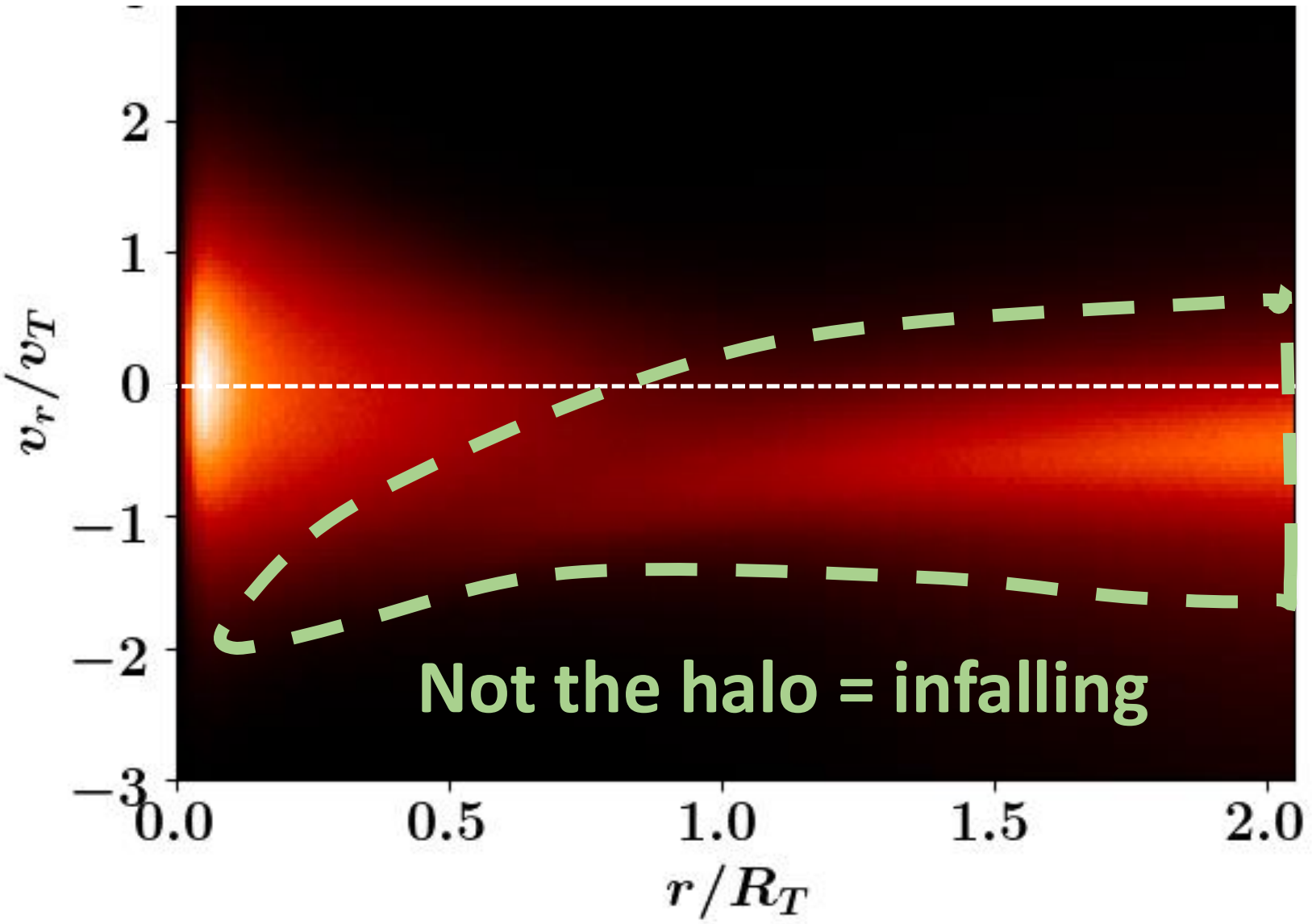

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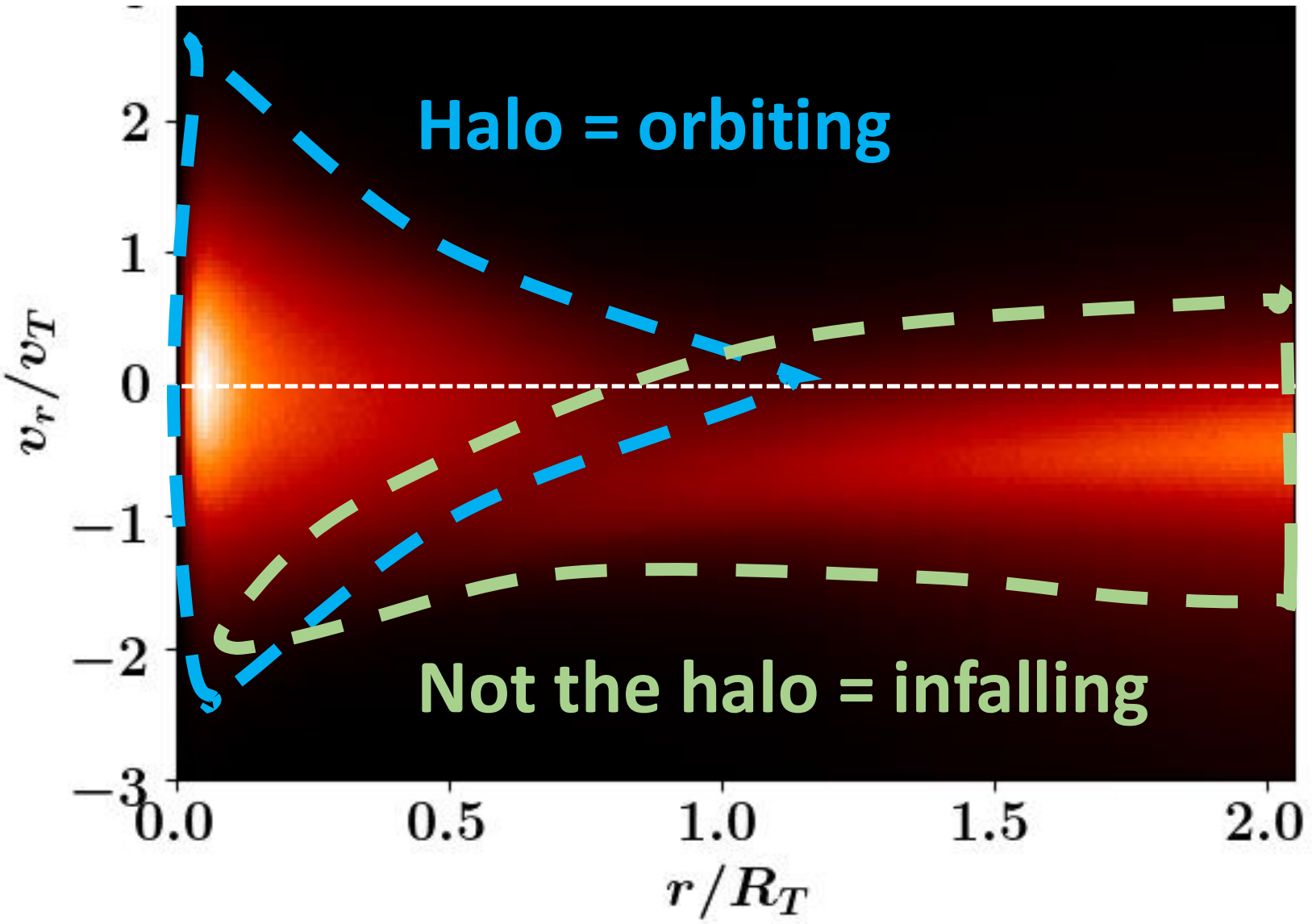
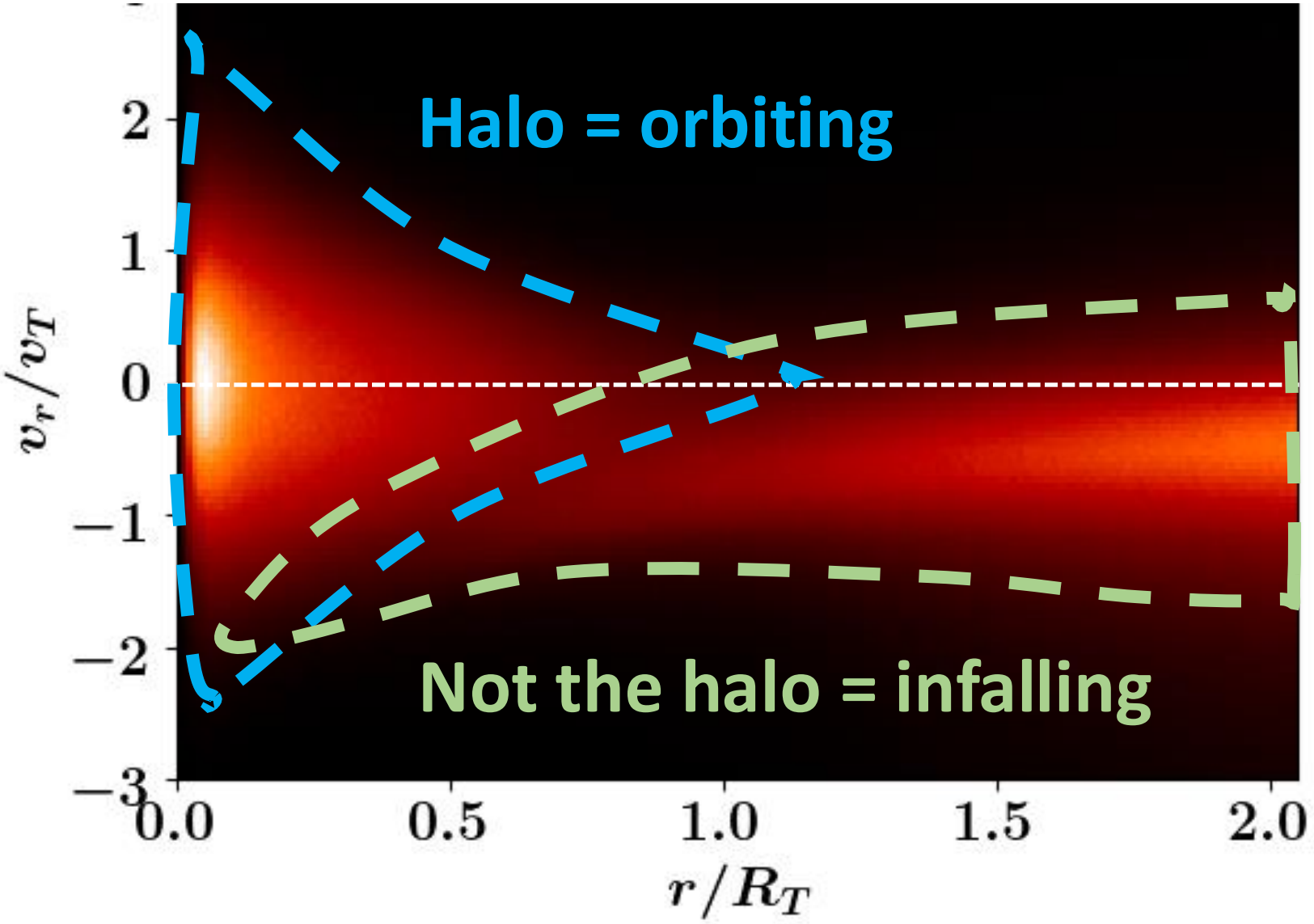


There is no radial boundary that cleanly separates halo from non-halo particles.



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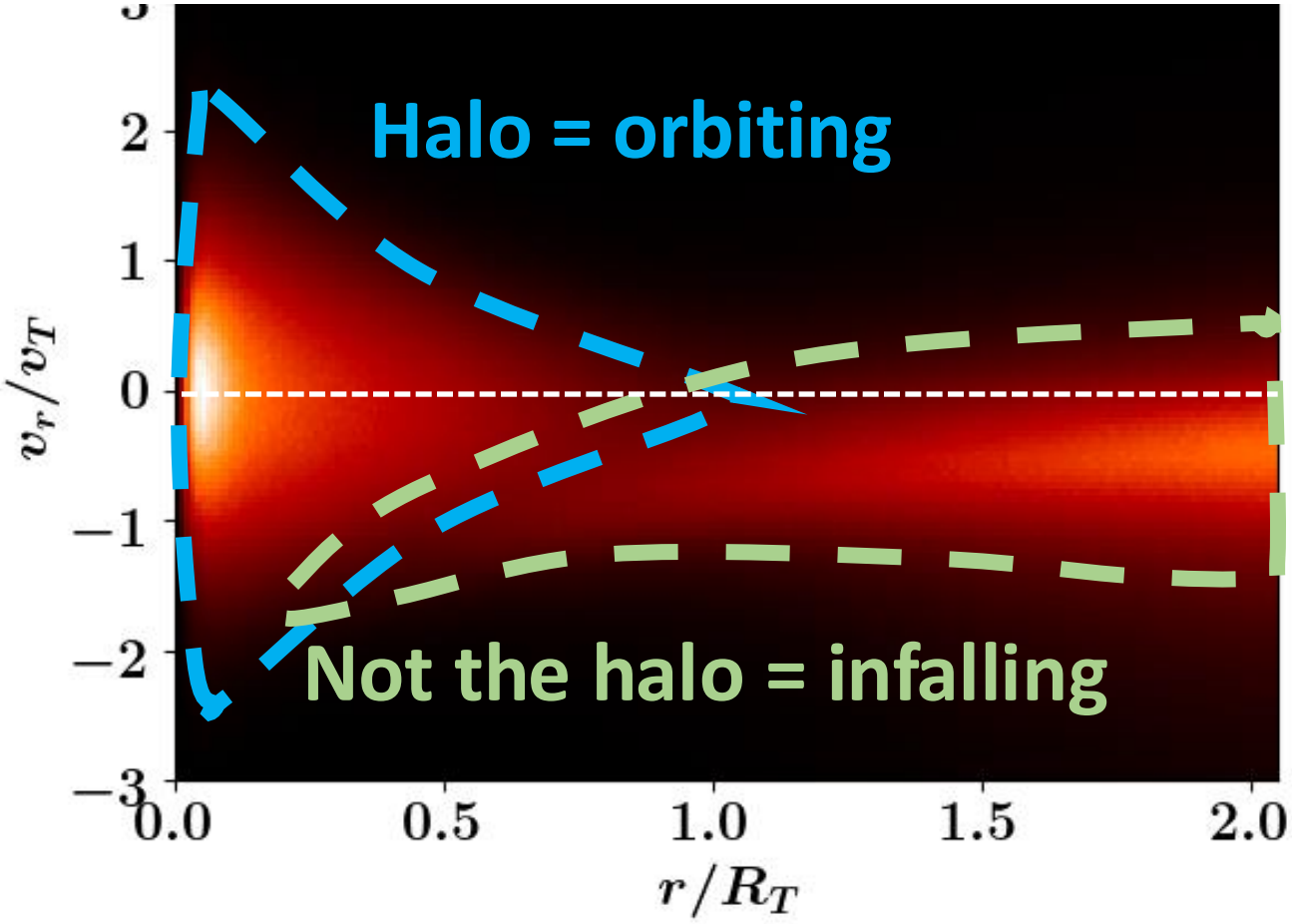

Need a way to selected “orbiting” particles.

Example:

A particle is “orbiting” if it has had a pericentric passage.

- Requires particle tracking: this is resource intensive!

Garcia et al 2022, 2207.11827

Proposed definition: **A dynamical halo is the collection of particles orbiting their self-generated potential.**

This talk:

Are there any advantages to foregoing the idea of a halo boundary?

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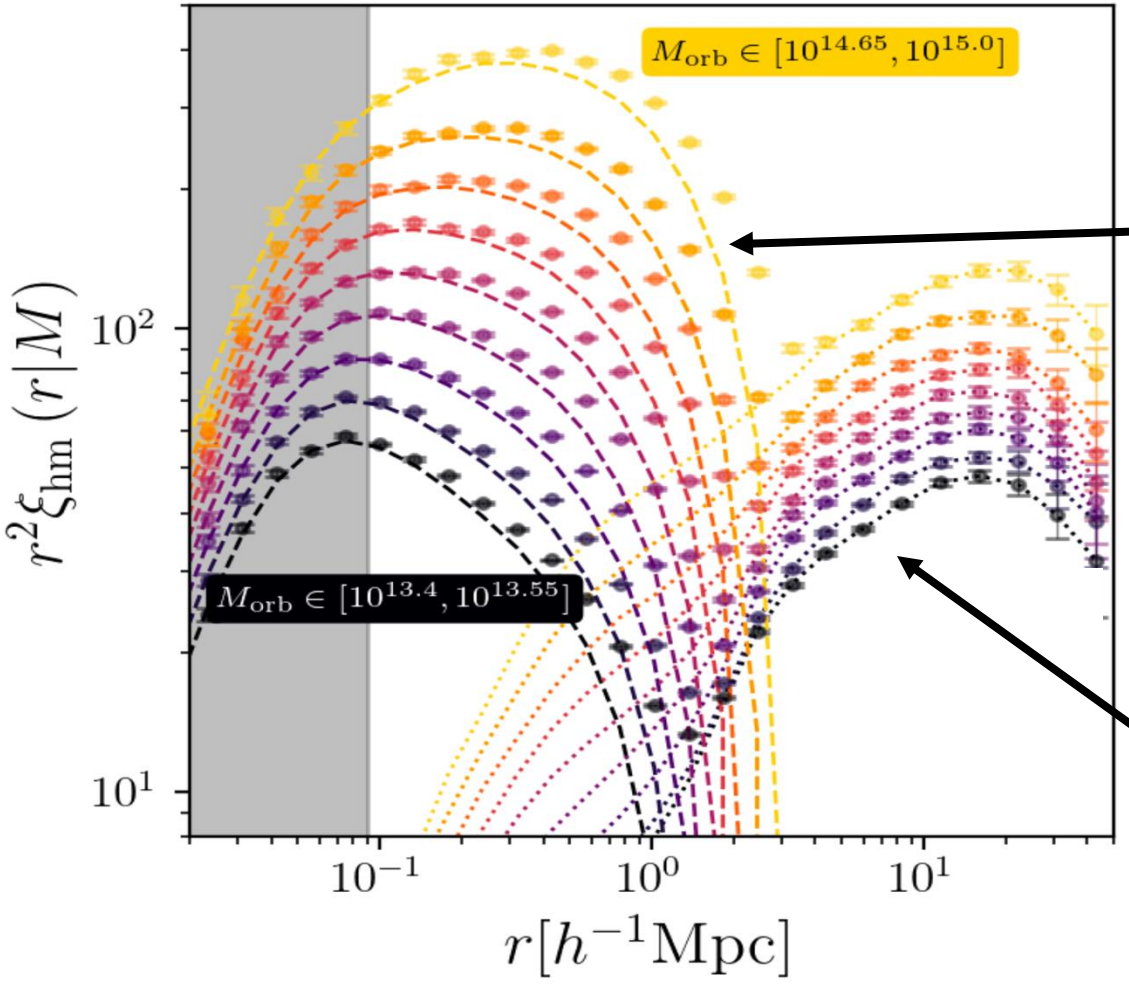
This talk:

Are there any advantages to foregoing the idea of a halo boundary?

Yes.

Advantage no. 1:

Dynamical halos enable us to build a better halo model



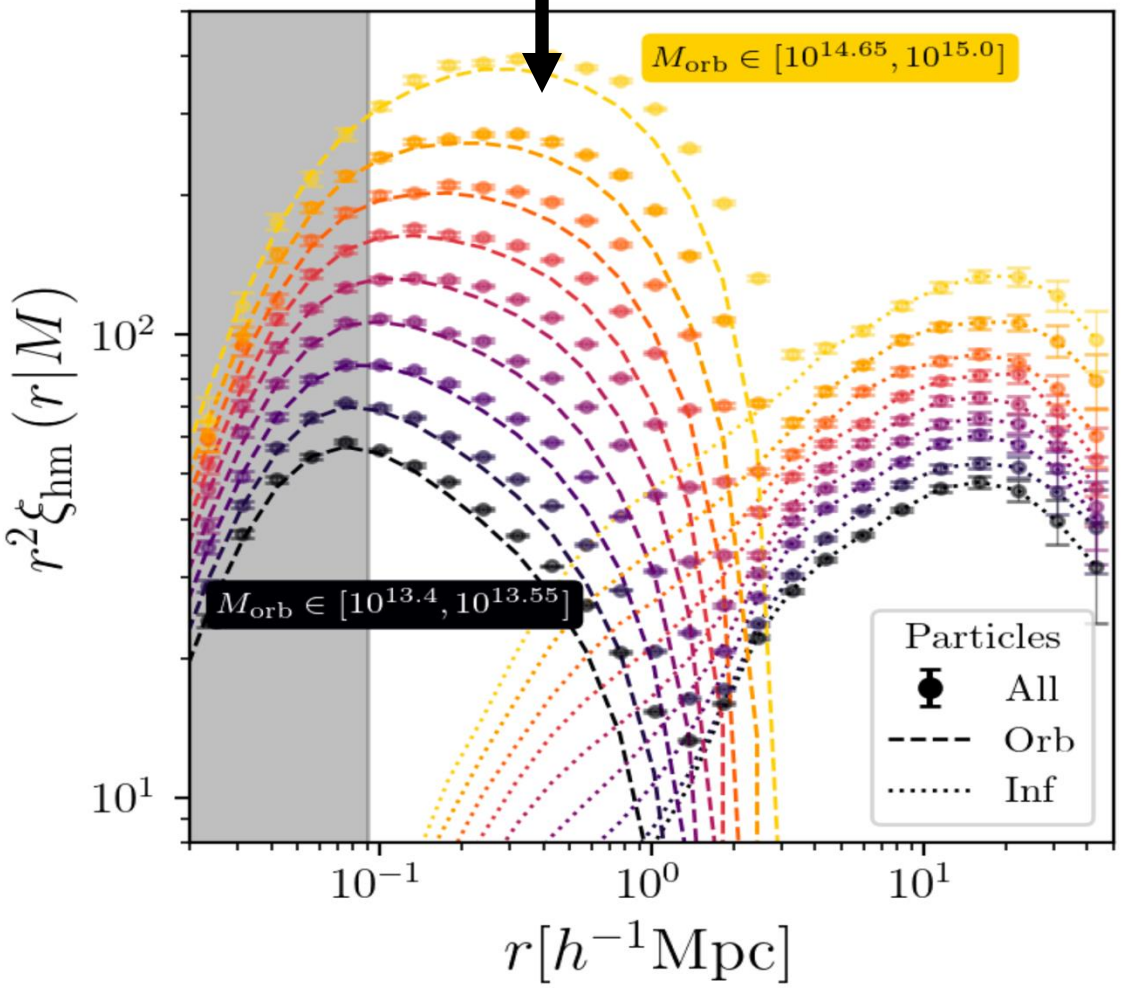
Points w/ error bars: simulation data.

Dashed lines: *orbiting particles.*

Dotted lines: *infalling particles.*

Salazar et al. 2024: arXiv:2406.04054

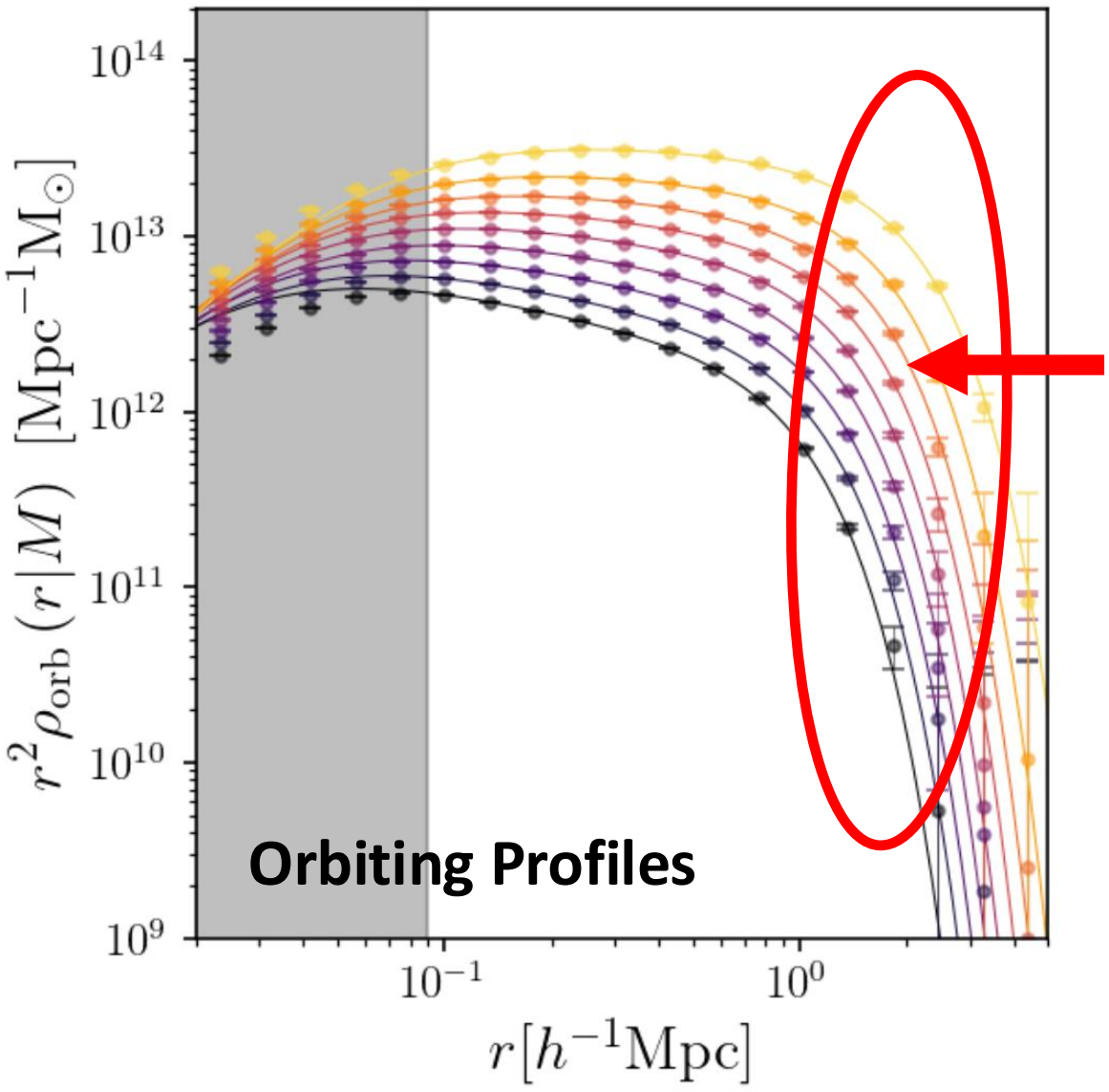
Halos are not NFW!



- Halo concentration is in part due to to *infall* material.
- Infall material has never interacted with the core
- The c-M relation may not be the most useful way of talking about SIDM.

Salazar et al. 2024: arXiv:2406.04054

Orbiting profile has a rich phenomenology that may be relevant for SIDM



Orbiting profiles have two parameters

1. Halo radius
   - Exponential truncation scale

Shields et al., in preparation

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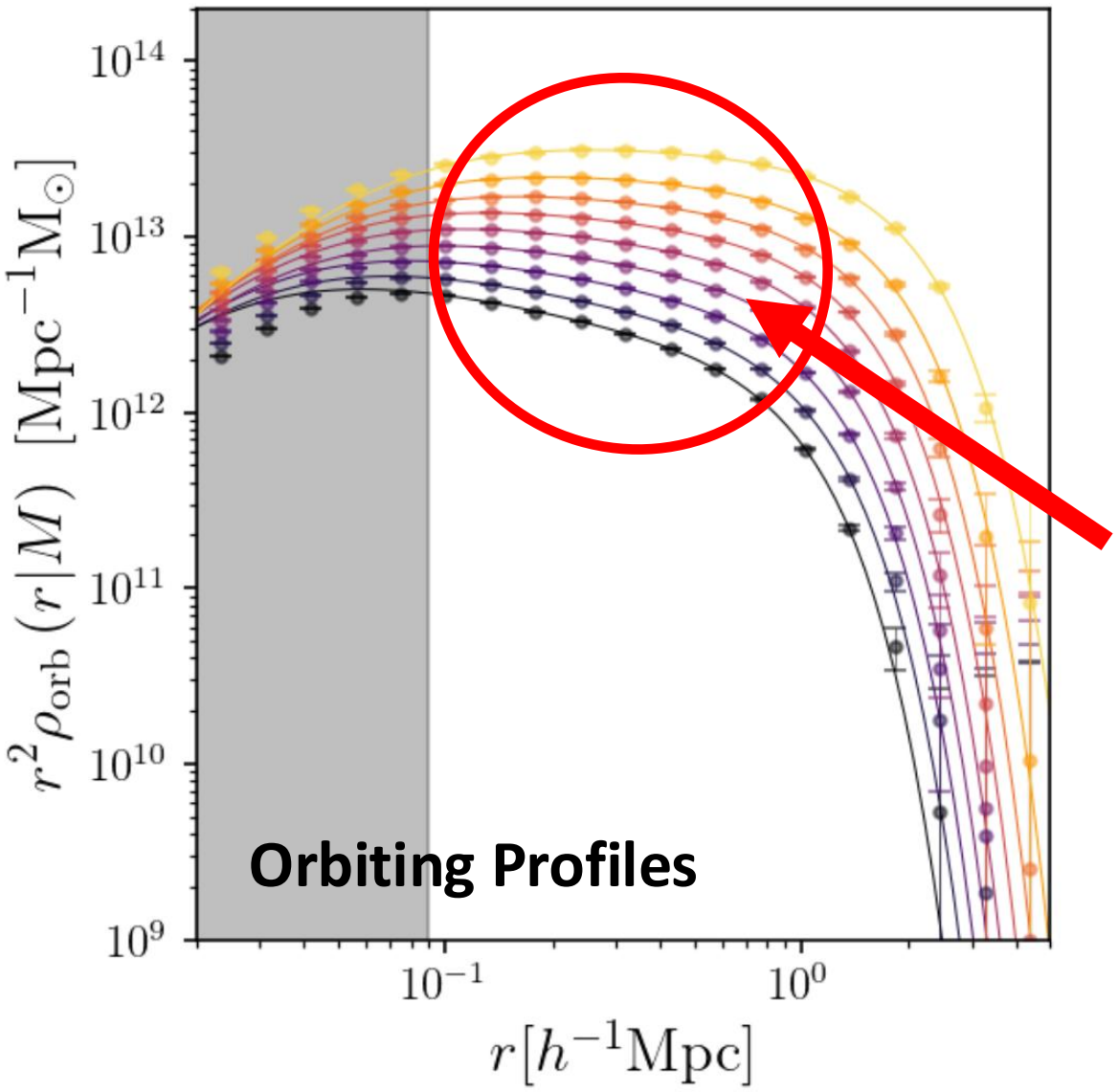


Orbiting profiles have two parameters

1. Halo radius
   - Exponential truncation scale
2. Slope of the inner profile
   - Plays the role of “concentration”
   - Tightly correlated with halo radius at fixed mass!

Shields et al., in preparation

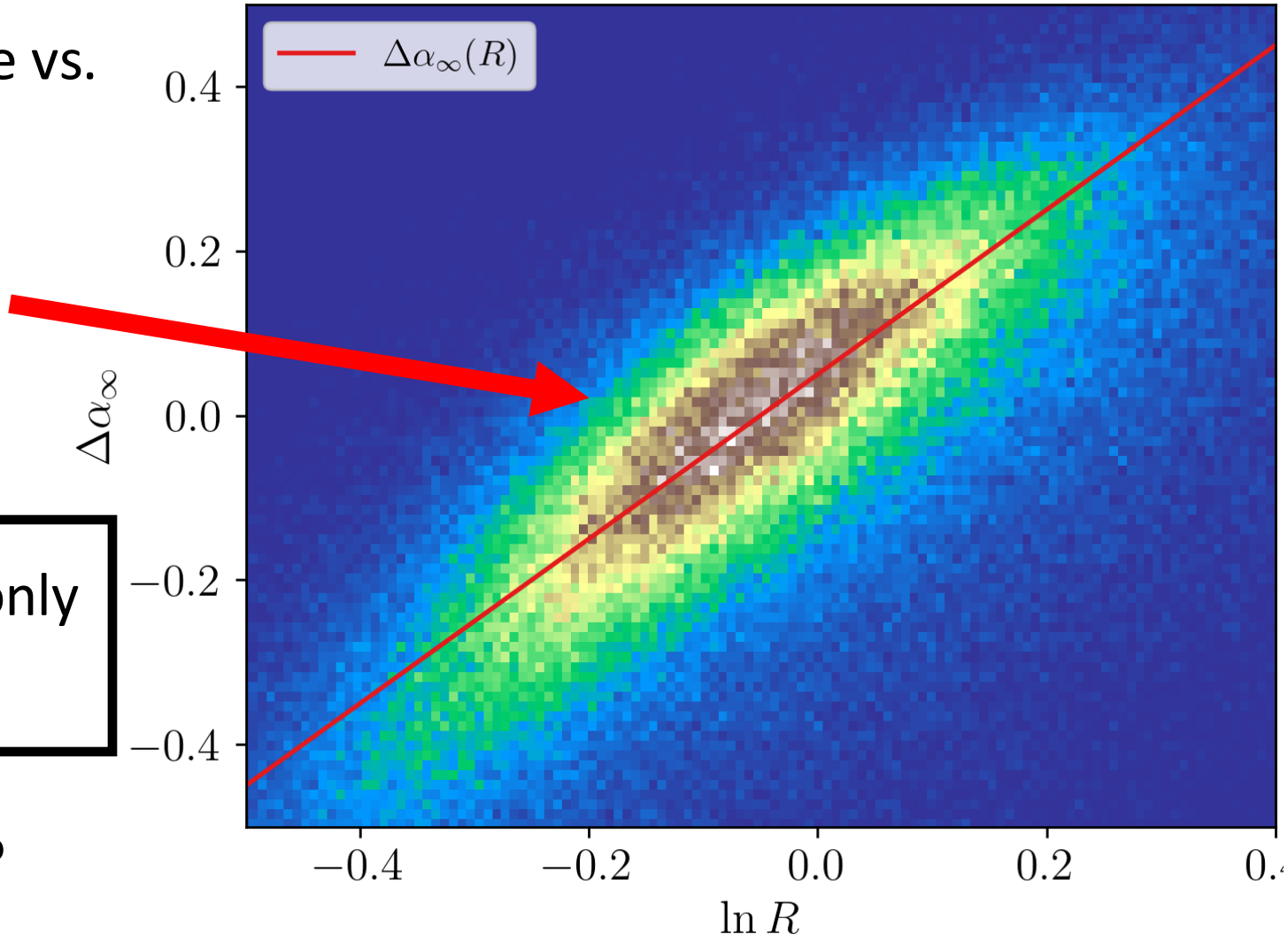
At fixed mass, profiles have *one degree of freedom:* r_{h}.

Fit individual halos, and plot slope vs. halo radius.

- Profile slope is tightly correlated with halo radius.

Profiles can be described using only one degree of freedom: r_{h}.

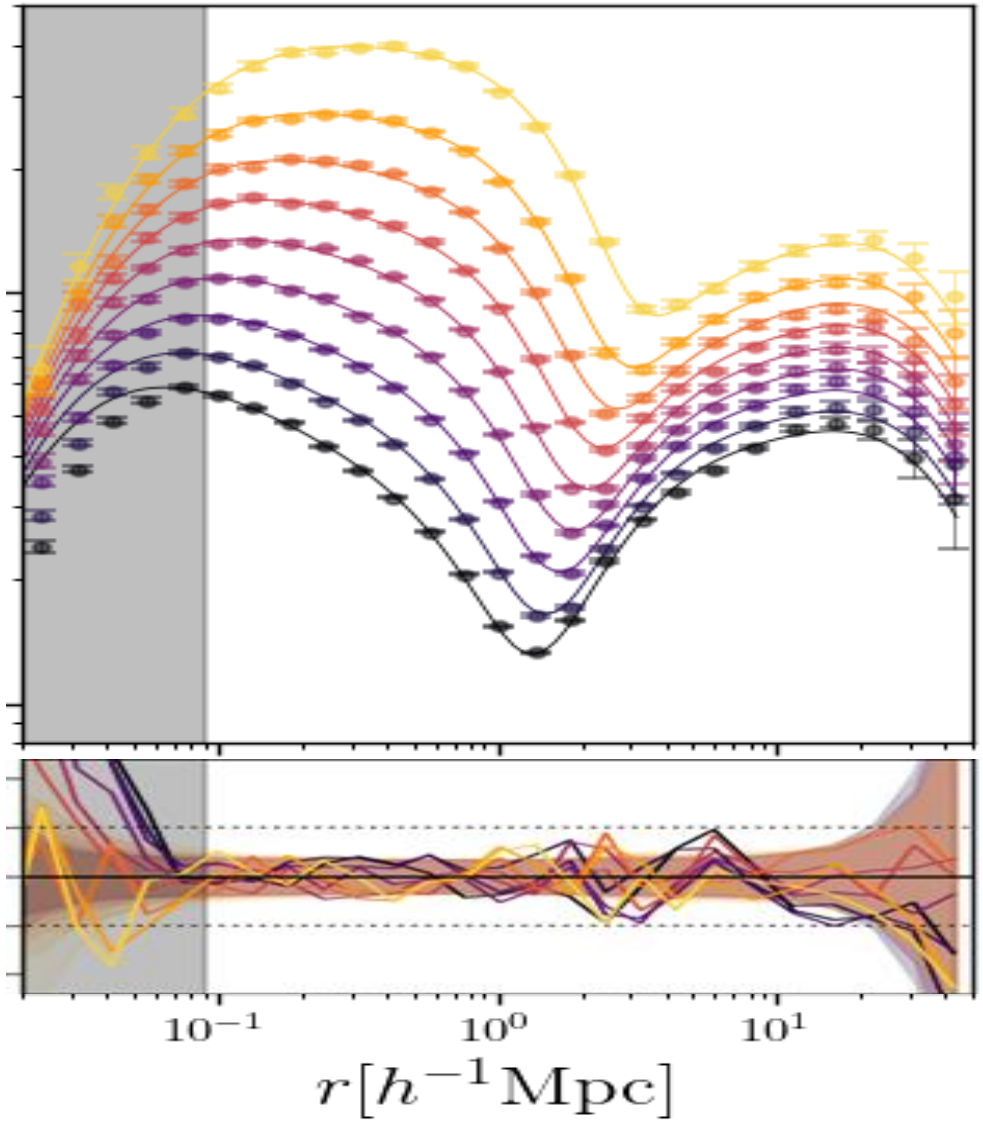
How does this change in SIDM?



Shields et al., in preparation.

Advantage no. 1:

Dynamical halos enable us to build a better halo model



$$\xi_{\rm hm} = \xi_{\rm hm}^{1-{\rm halo}} + \xi_{\rm hm}^{2-{\rm halo}}$$

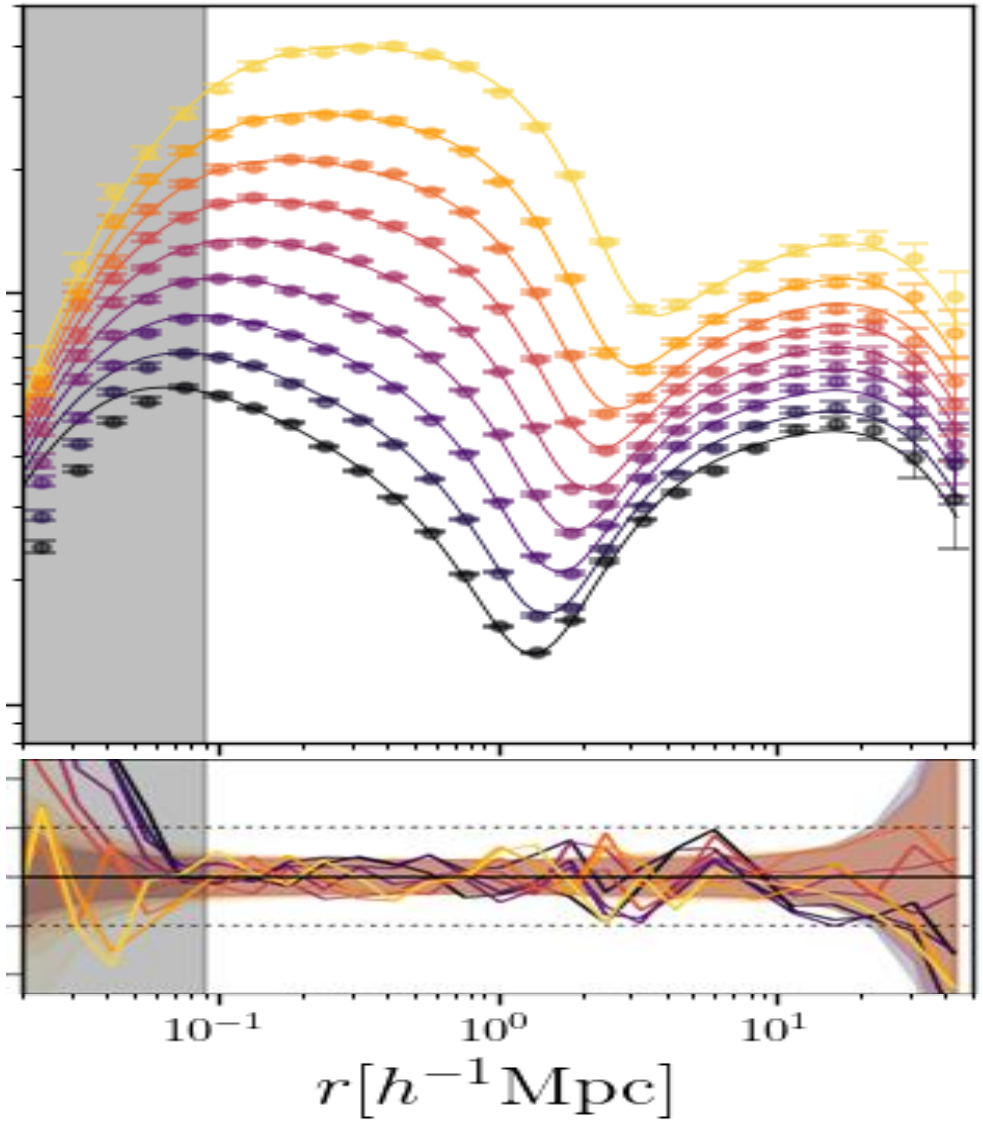
$$\rho = \rho_{\rm orb} + \rho_{\rm inf}$$

- Revised halo model is accurate to $\approx 2\%$ or better.

Salazar et al. 2024: arXiv:2406.04054

Advantage no. 1:

Dynamical halos enable us to build a better halo model



Problem: Non-linear growth is treated in an ad-hoc way.

$$\xi_{\mathrm{inf}} = b(1+\Delta(r))\xi_{\mathrm{LPT-lin}}$$

Power-law: captures non-linger growth

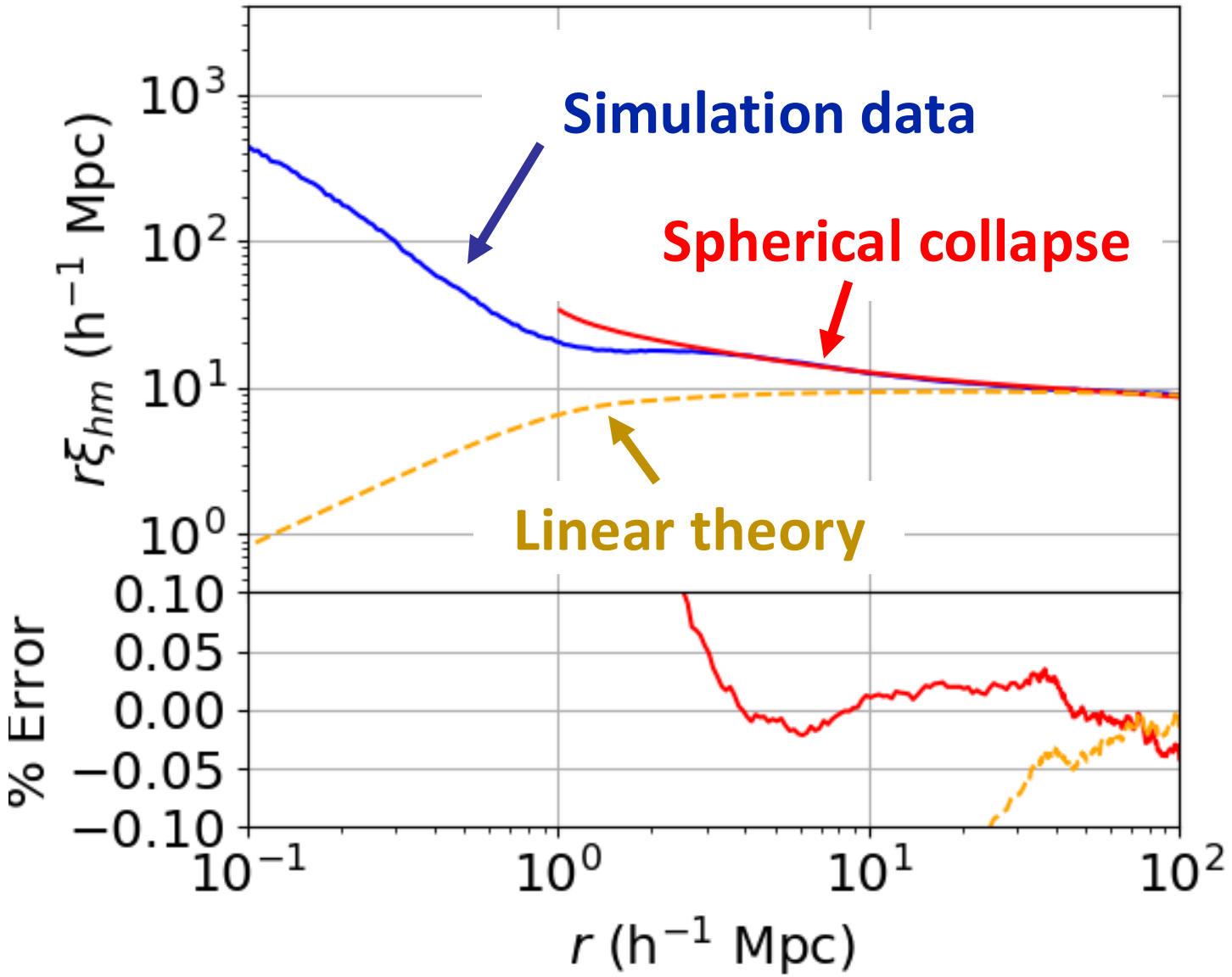
Advantage no. 2: **The dynamical halo framework opens new theoretical avenues.**

Key idea: Non-linear evolution of the density field is due to mass falling in towards the halo.

- We can treat infall analytically using spherical collapse!
- Initial conditions set by linear theory.

Approach trades perturbative limit for spherical symmetry.

$\Omega_m = 1$



Spherical collapse accurately models infall profiles.

Recovers linear theory on large scales.

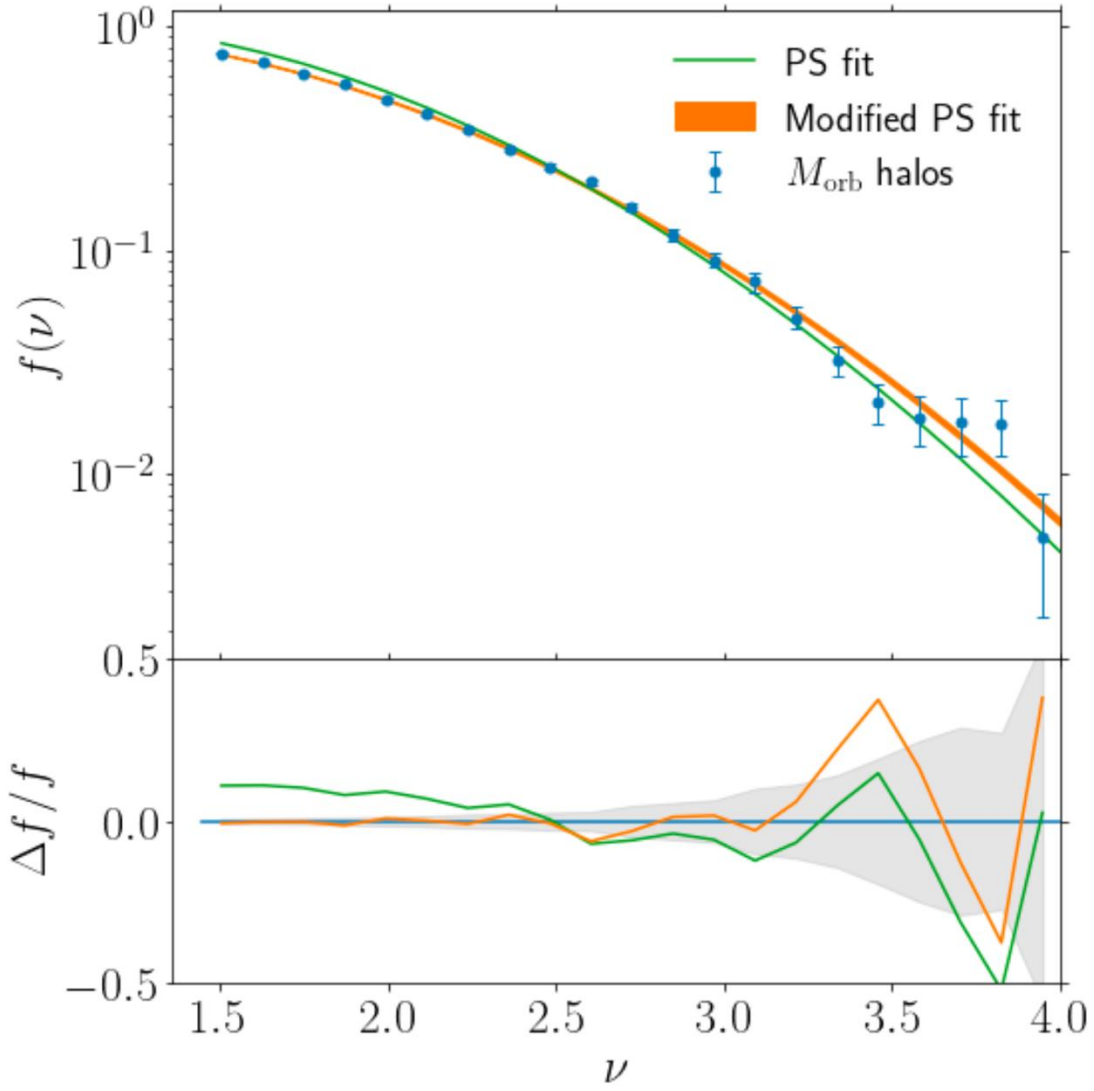
Generalization to ΛCDM in progress.

Advantage no. 3: **The Mass Function + Bias of Dynamical Halos is Easier to Model!**

- Spherical collapse predict a Press-Schechter mass function.
- Traditional approach: Identify collapsed mass with spherical overdensity (virial) mass.
- New approach: Identify collapsed mass with orbiting mass.
  - ➢ This is a very natural identification!

    Formally correct for purely radial orbits!

Advantage no. 3: **The Mass Function + Bias of Dynamical Halos is Easier to Model**



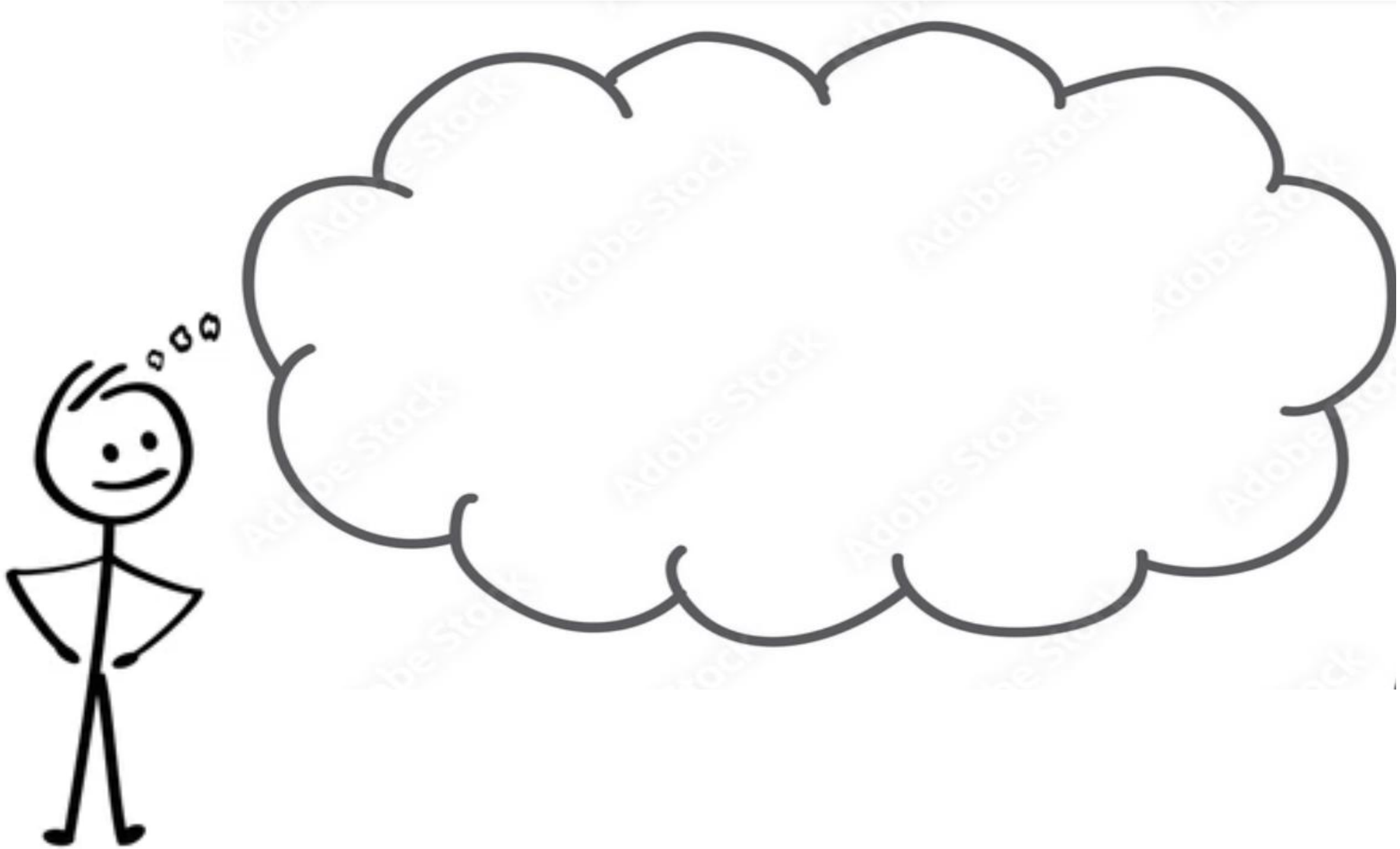
Excellent agreement with a mass-dependent threshold δ_c.

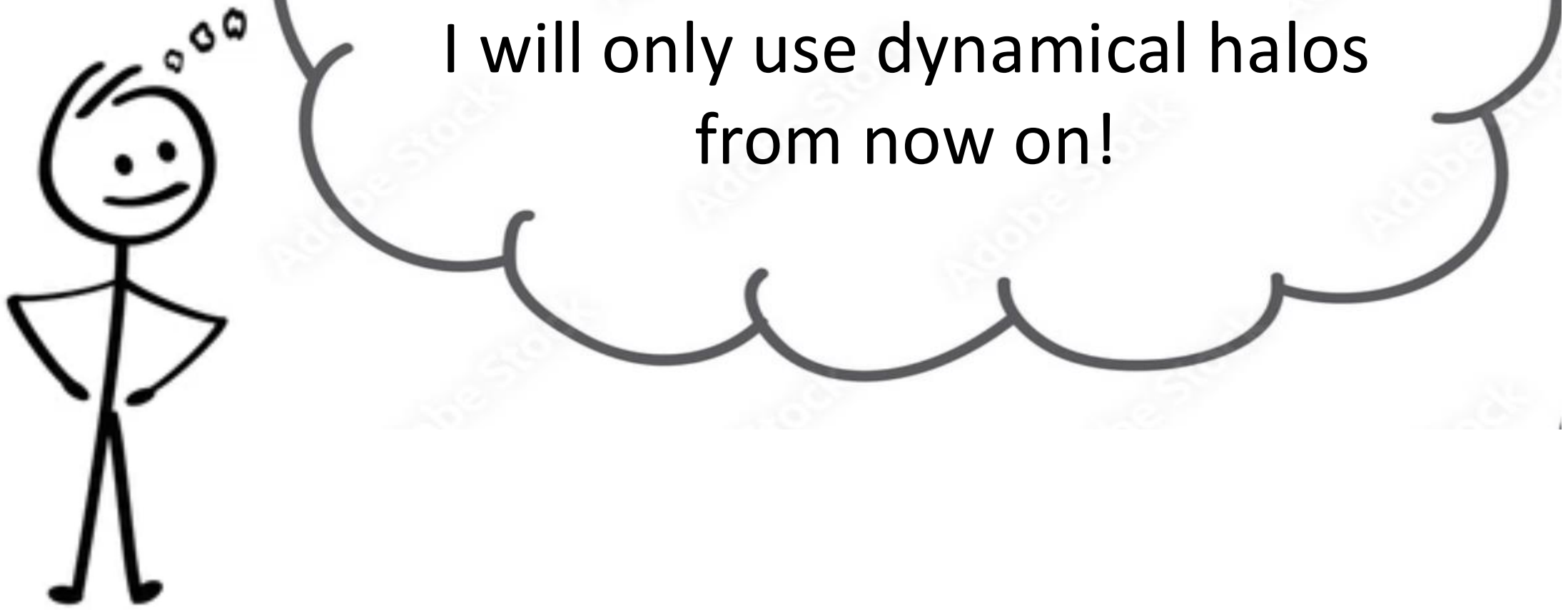
Find: $\delta_c \in [1.52, 1.68]$

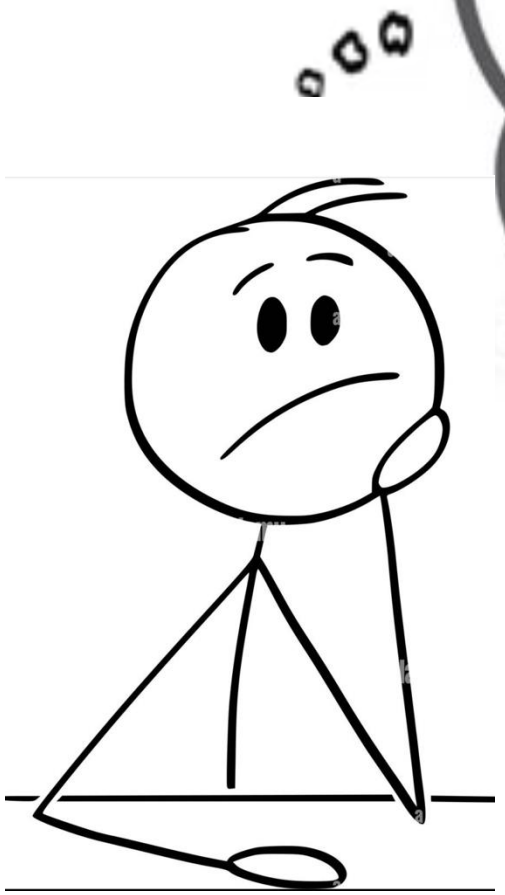
Recovered values of δ_c match expectations (Shapiro et al. 1999).

Halo bias is consistent w/ peak/background split.

Garcia et al. 2023, 2207.11827




Wow! This is great!
I will only use dynamical halos from now on!



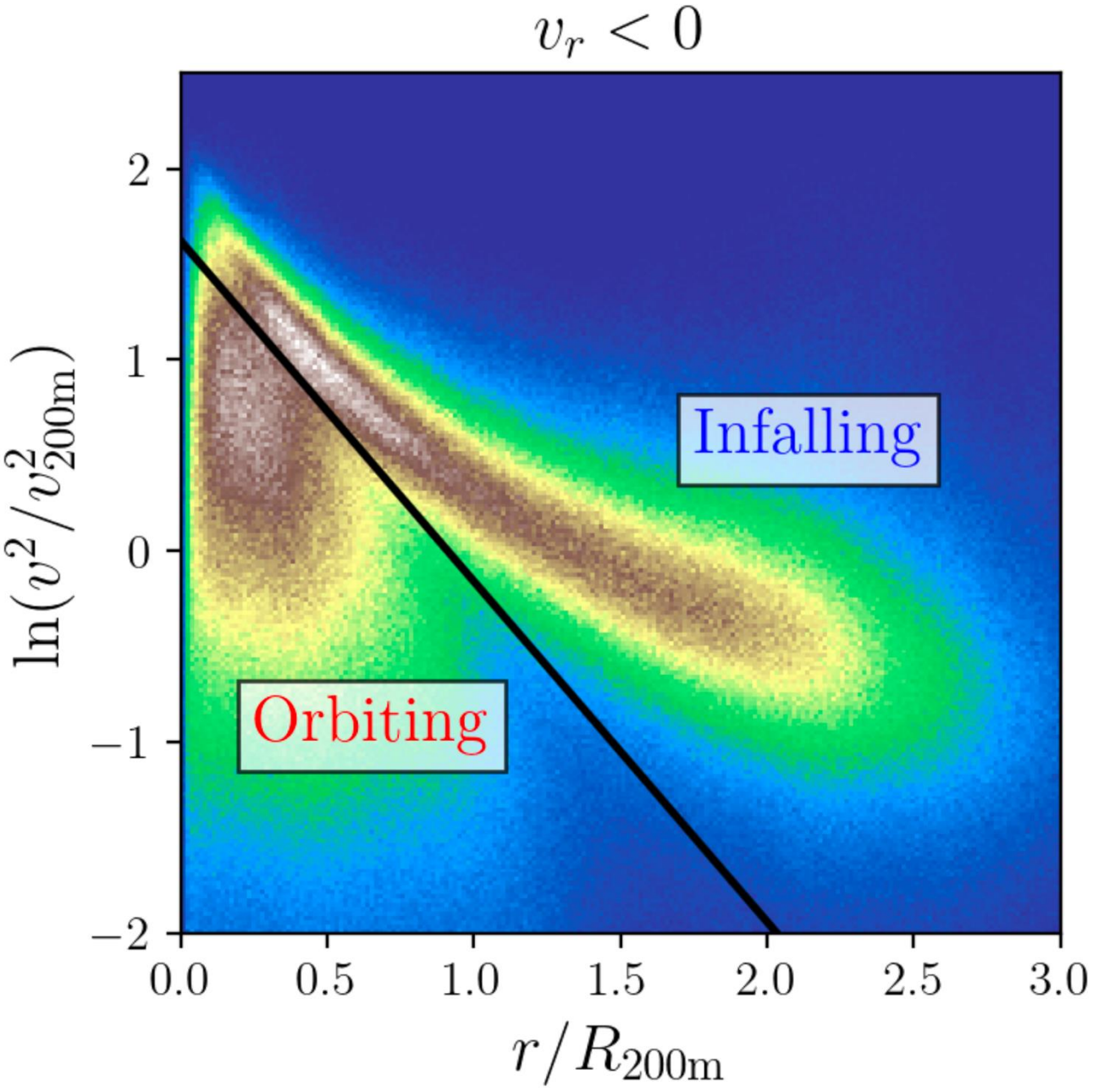
But wait a minute…

This is too much work! I just want someone to give me the halo catalogs!

- Parallelized post-processing of Rockstar catalogs to produce a catalog of dynamical halos.

https://github.com/edgarmsalazar/oasis

Salazar et al., in preparation



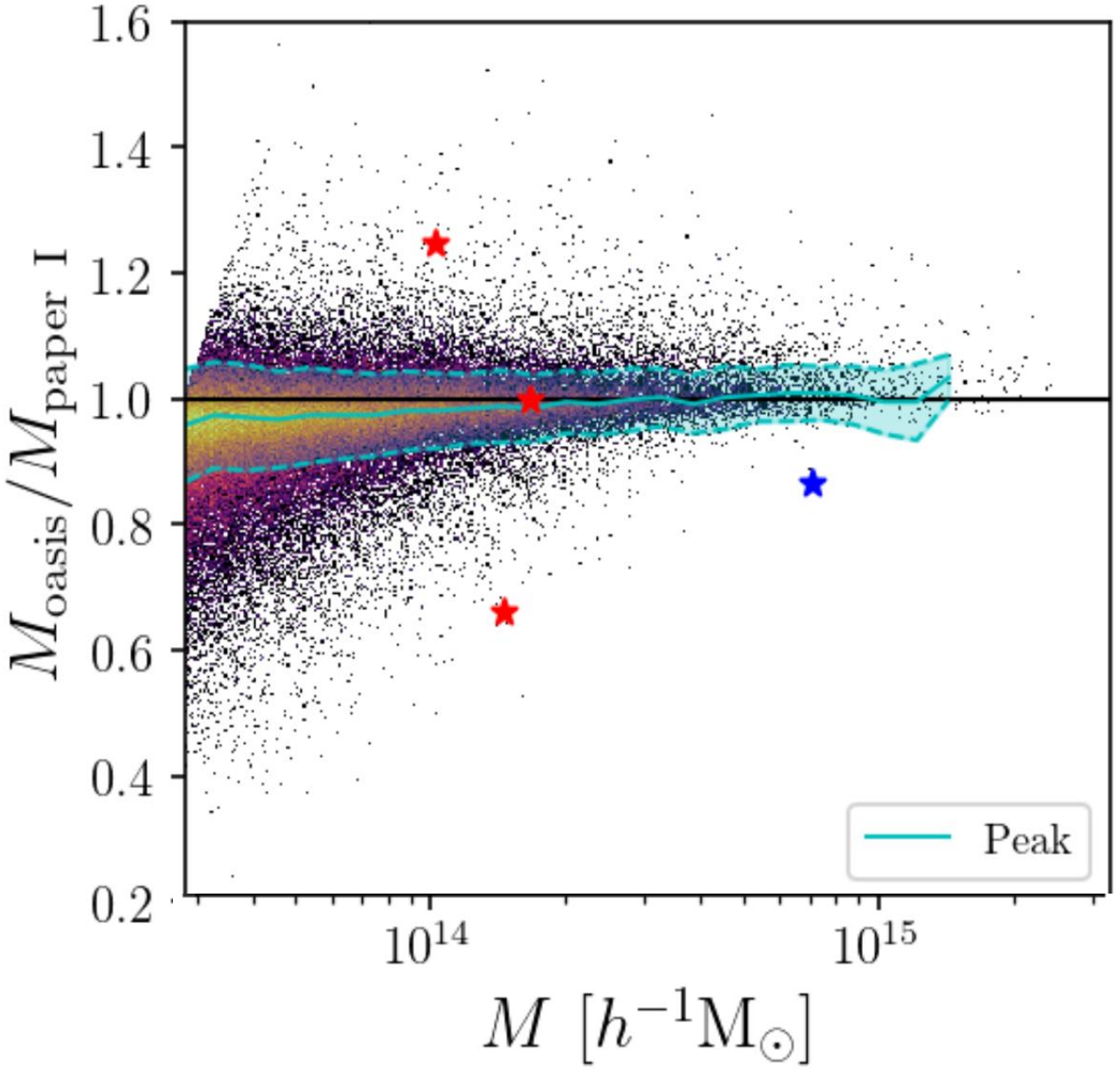
Key idea:

Orbiting particles are (or will be) bound.

- Orbiting particles have less KE than infalling particles!
- Select orbiting particles with a KE energy cut.

KE can be self-calibrated from the simulation.

Salazar et al., in preparation



Oasis Results:

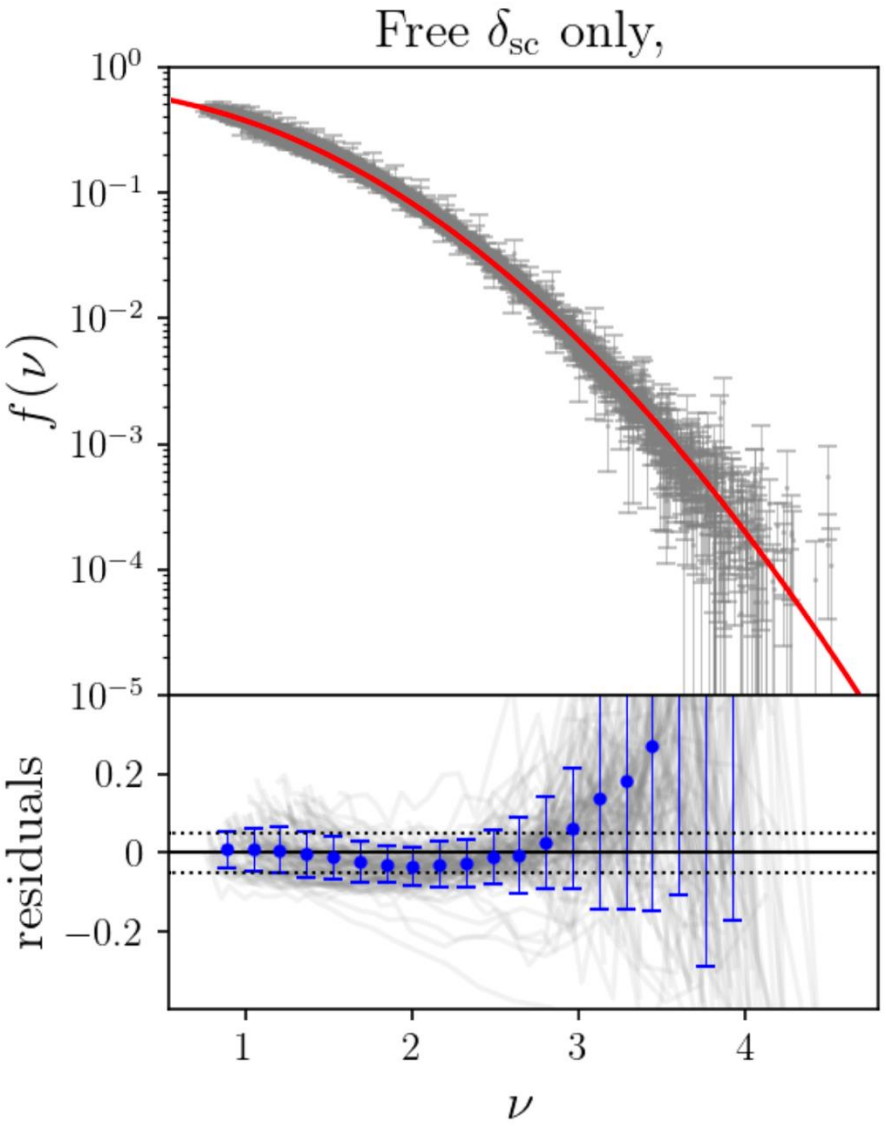
- KE and orbit-based masses are tightly correlated.

  Nearly no offset, and ≈ 4% scatter.

Clearly a step up from spherical overdensity halos!

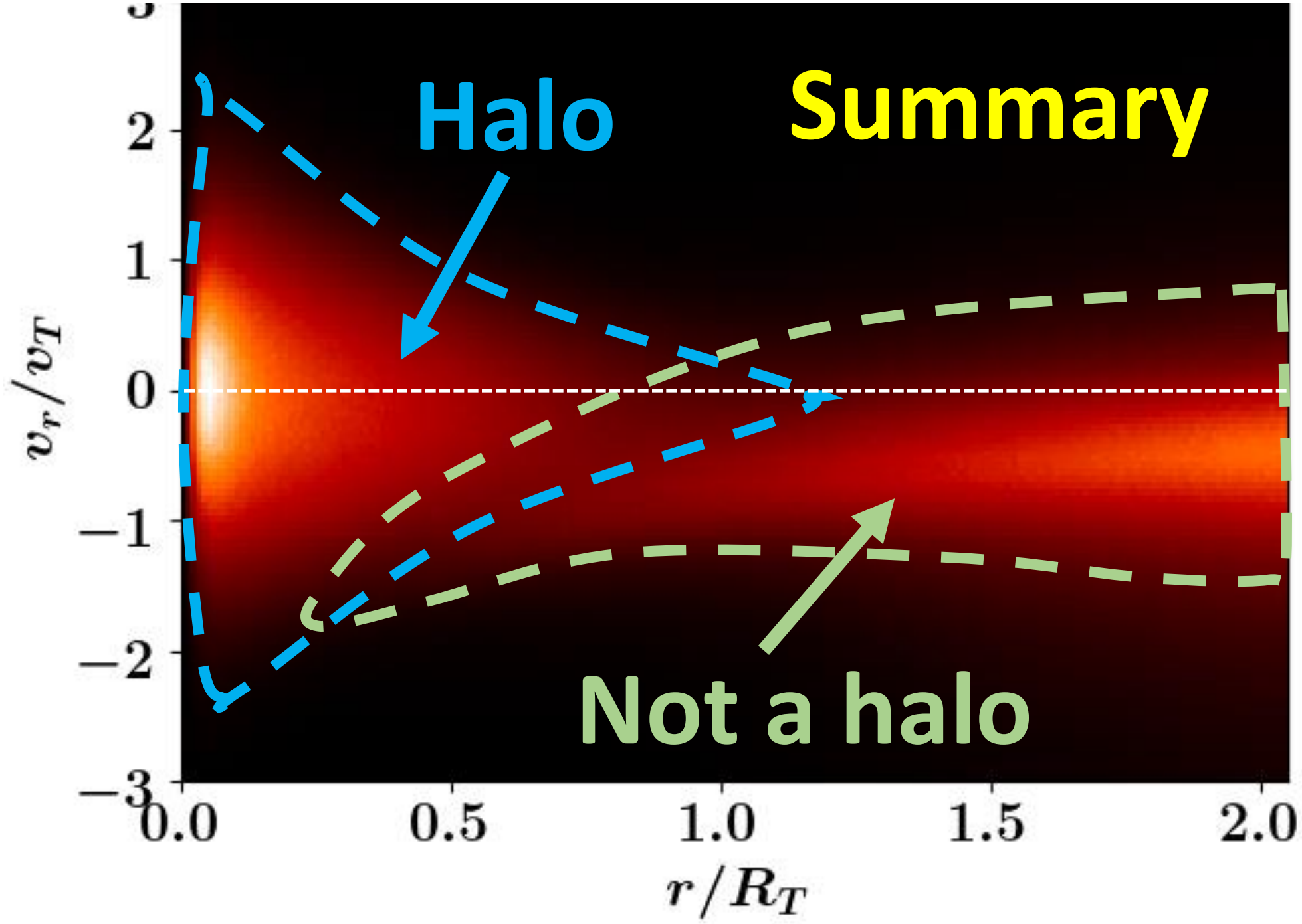
Salazar et al., in preparation

The Dynamical Halo Mass Function from Oasis



- Measured the mass function for 100 Quijote simulations.
- High mass end is universal and Press-Schechter to within $\approx 5\%$.
- Effective threshold for collapse is $\delta_{sc} = 1.52$.

Salazar et al., in preparation


Halo
Summary
Not a halo
2
1
0
−1
−2
−3
v_r/v_T
0.0
0.5
1.0
1.5
2.0
r/R_T

Summary

- Halos do not have radial boundaries: rather, *halos should be defined as the collection of all orbiting particles*.

Dynamical halos have many advantages:

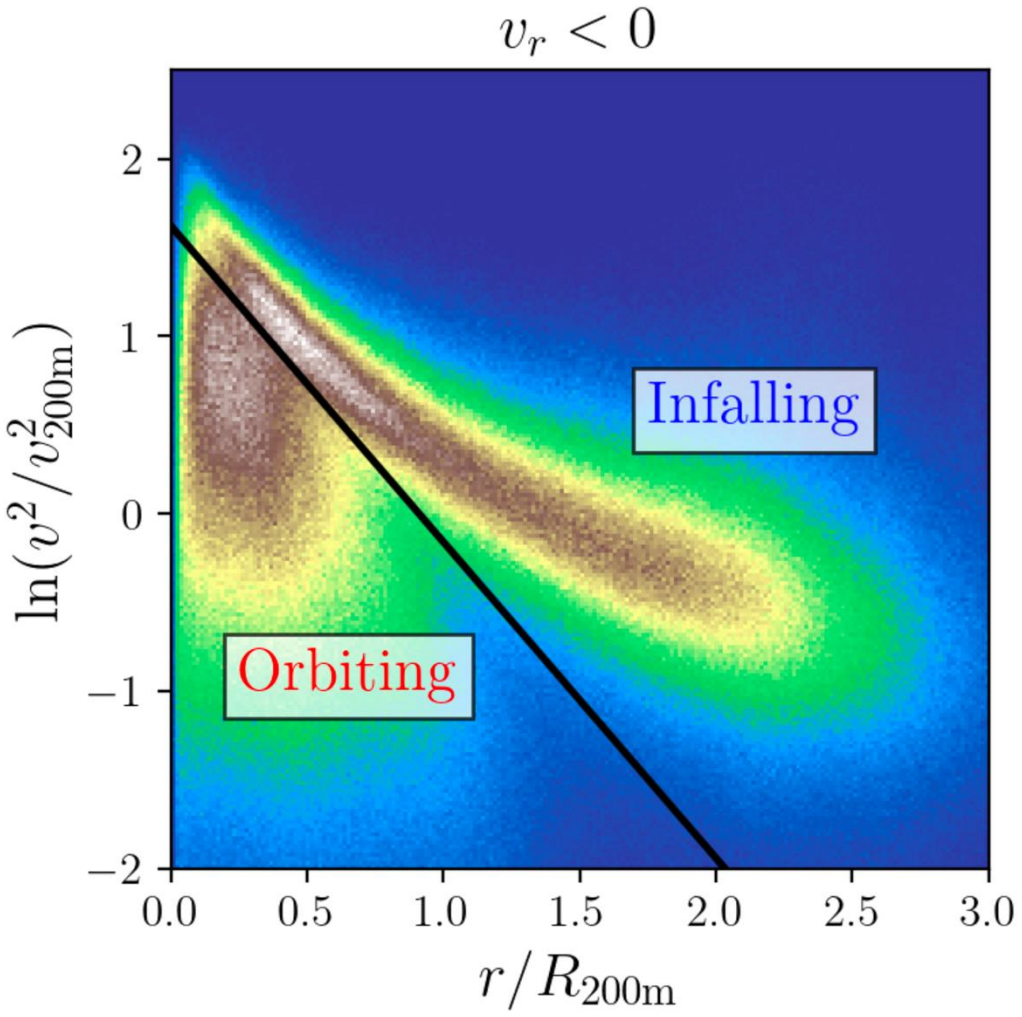
- Naturally gives rise the 1-halo/2-halo structure of the halo model.
- Orbiting profile has a single degree of freedom: *the halo radius.*
- Infall profile can be modelled using spherical collapse (in progress).
- Improves agreement between simulations and Press-Schechter

Developed a fast algorithm to generate dynamical halo catalogs from simulations.

https://github.com/edgarmsalazar/oasis

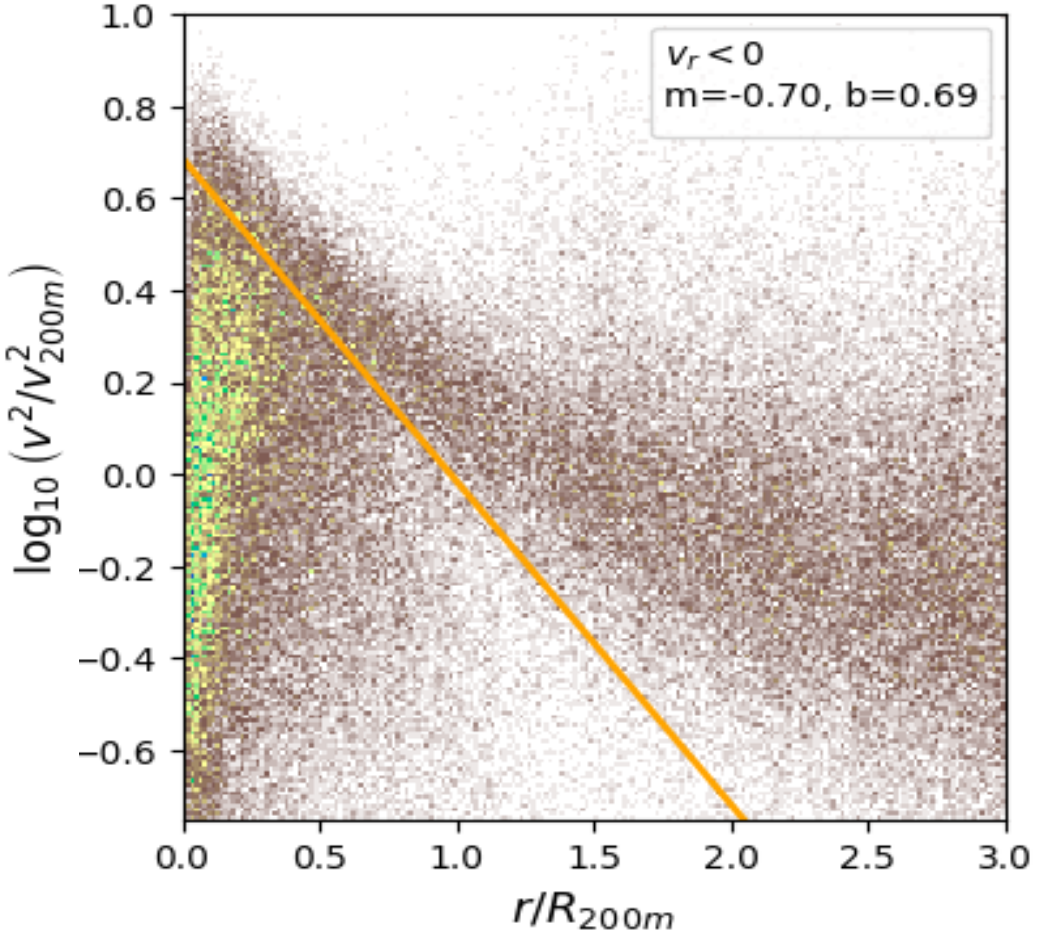
Extra Slides

Will Baryons Mess Everything Up?



- Orbiting/infall split is well motivated for DM particles.
- Does this kind of thinking even make sense for baryons?

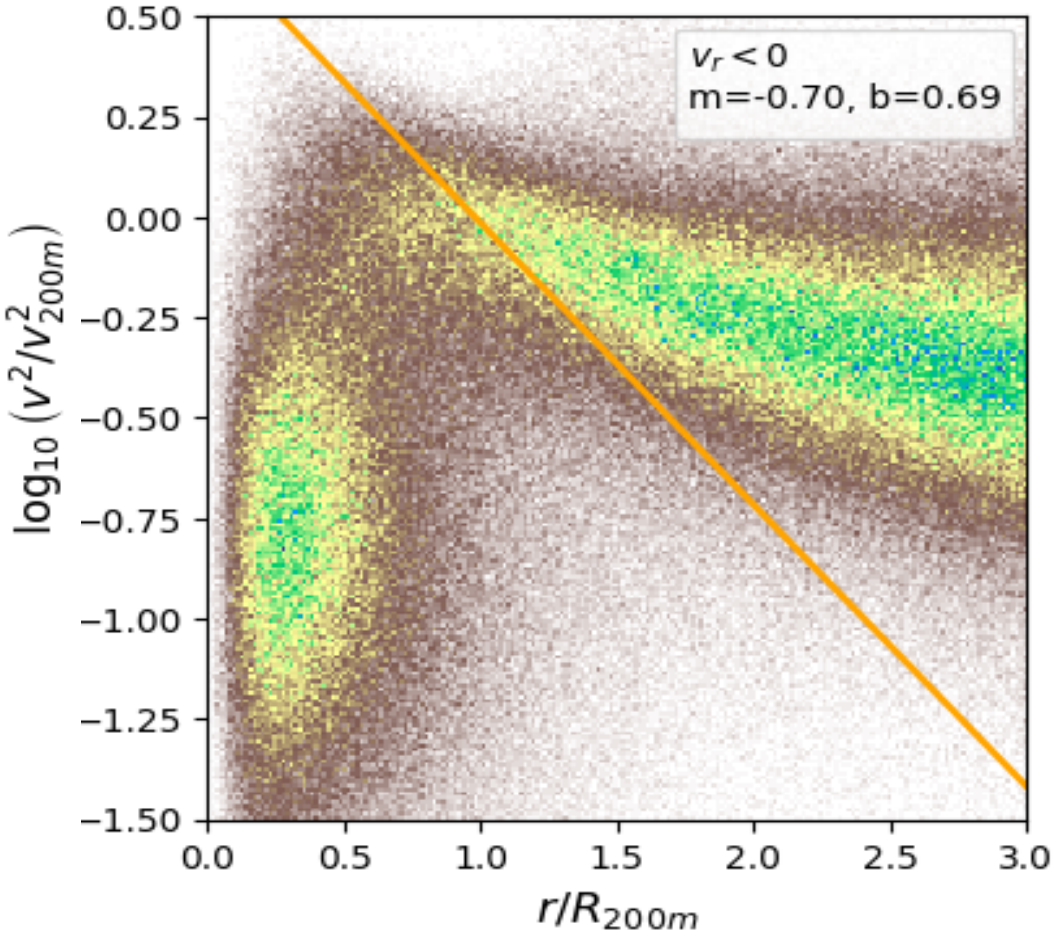
Baryons Can Be Accommodated!



- Stars are collisionless, so they behave similarly to dark matter.

Baryons Can Be Accommodated!

Y-axis scale changed



- Stars are collisionless, so they behave similarly to dark matter.
- Infall gas hits the halo atmosphere and comes to “rest”
  - KE cuts are even *cleaner* with gas particles!

Expect the orbiting/infall framework will generalize to ΛCDMB.