A New Way to Think About Halos and Galaxy Clusters

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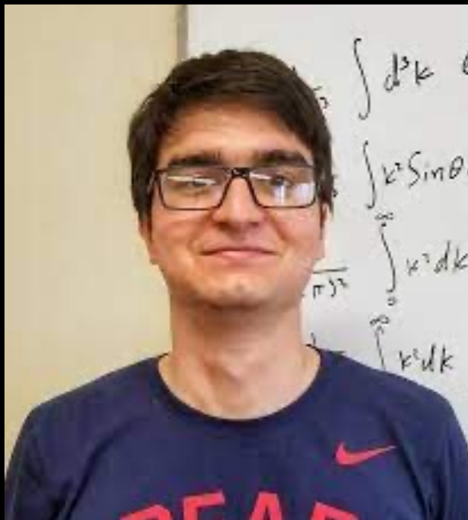


Rafael García

Edgar Salazar

Brandon Wolfe

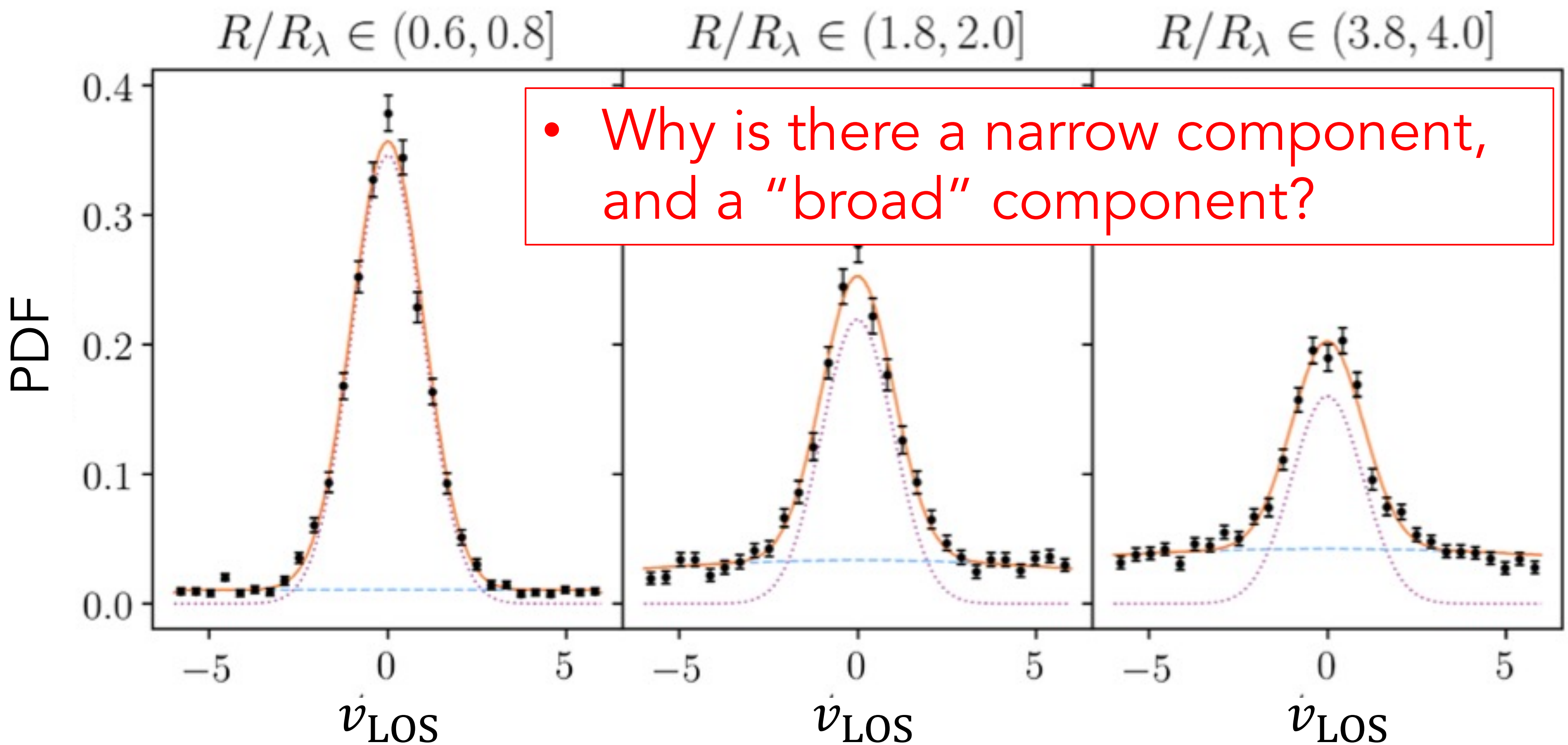
Paxton Tomooka

Susmita Adhikari
Benedikt Diemer
Daisuke Nagai

Han Aung
Connor Sweeney

Quiz Time!

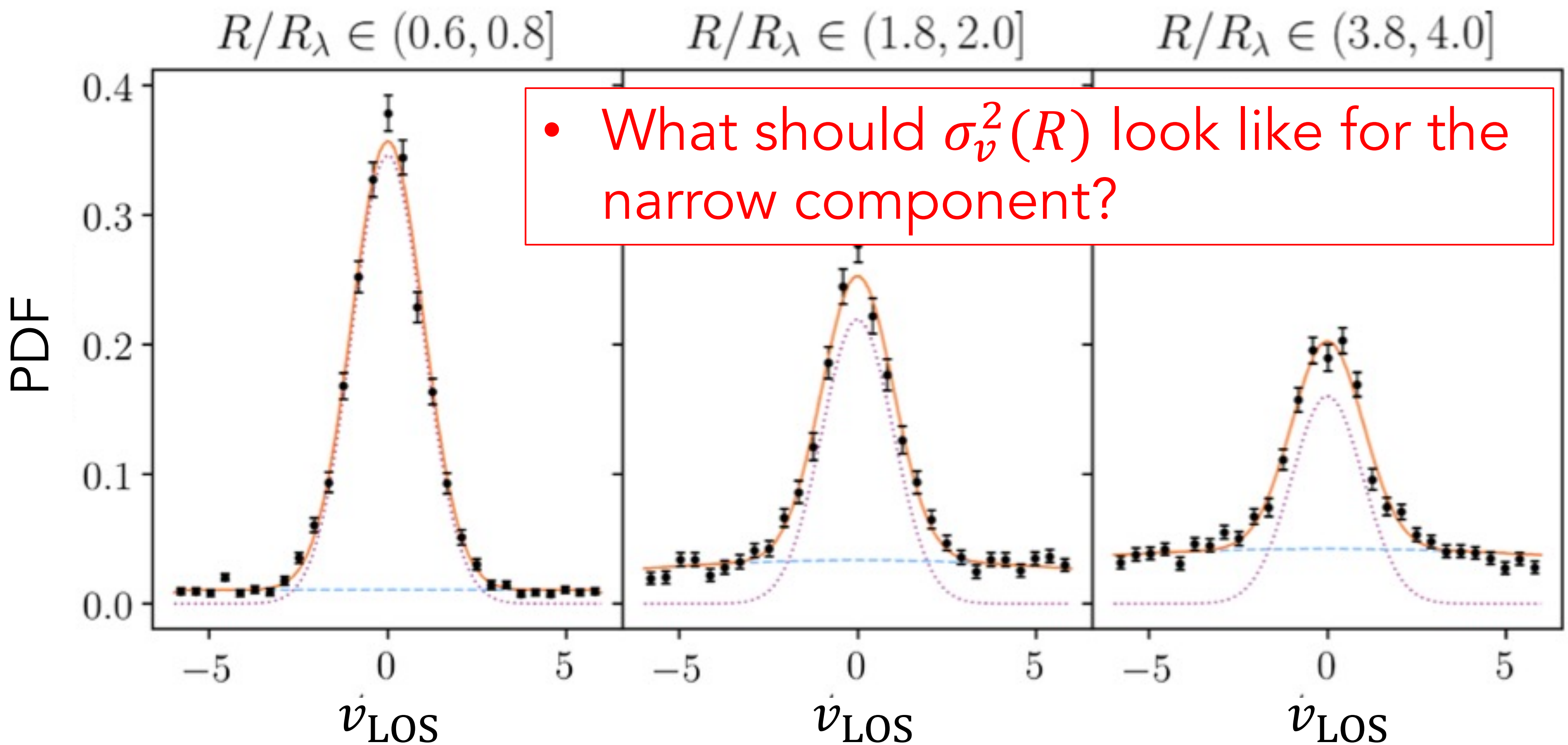
The Distribution of LOS Velocities of Galaxies Around Clusters



- Why is there a narrow component, and a "broad" component?

Tomooka, ER, et al. 2020, 2003.11555

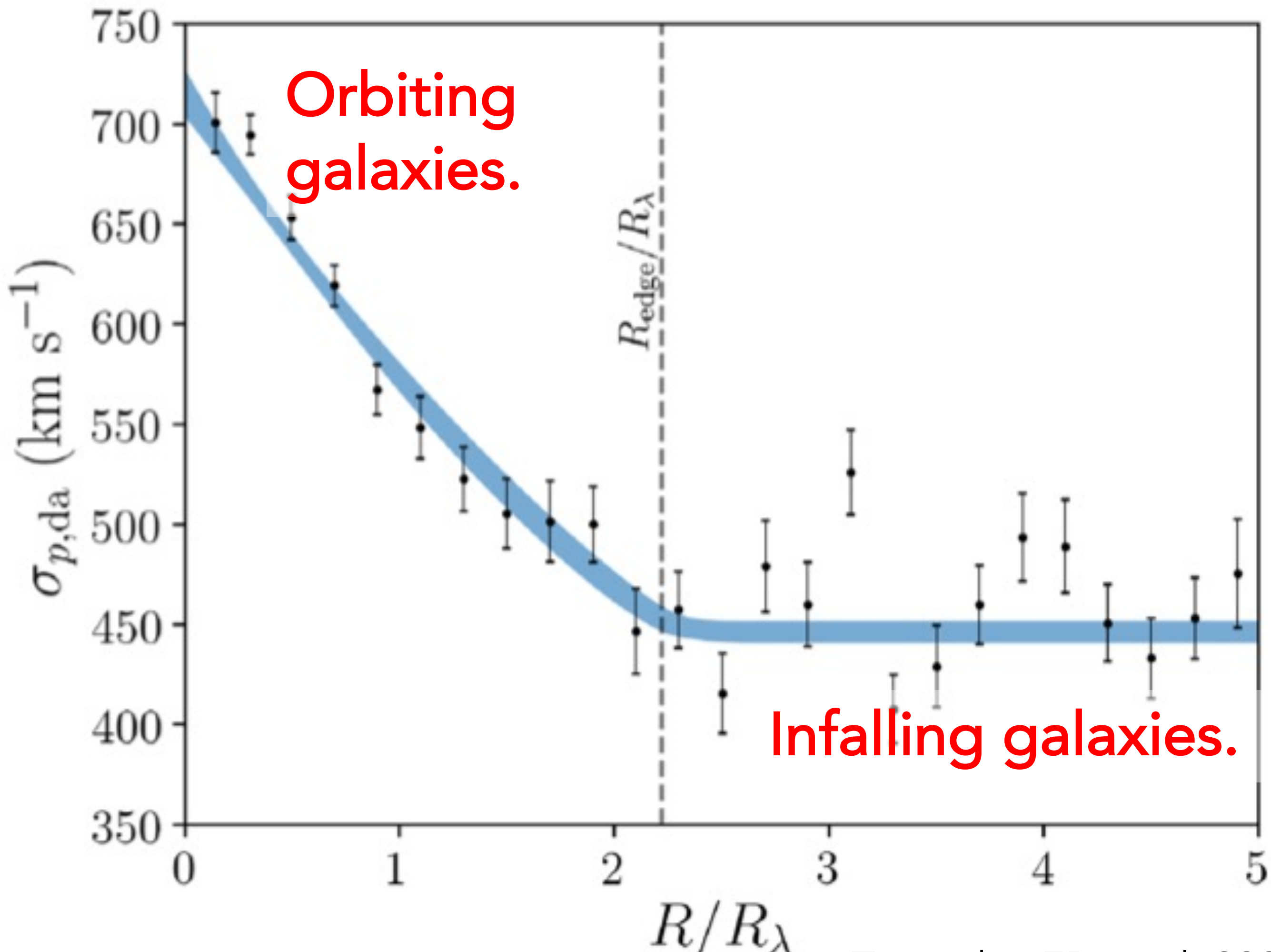
The Distribution of LOS Velocities of Galaxies Around Clusters



- What should $\sigma_v^2(R)$ look like for the narrow component?

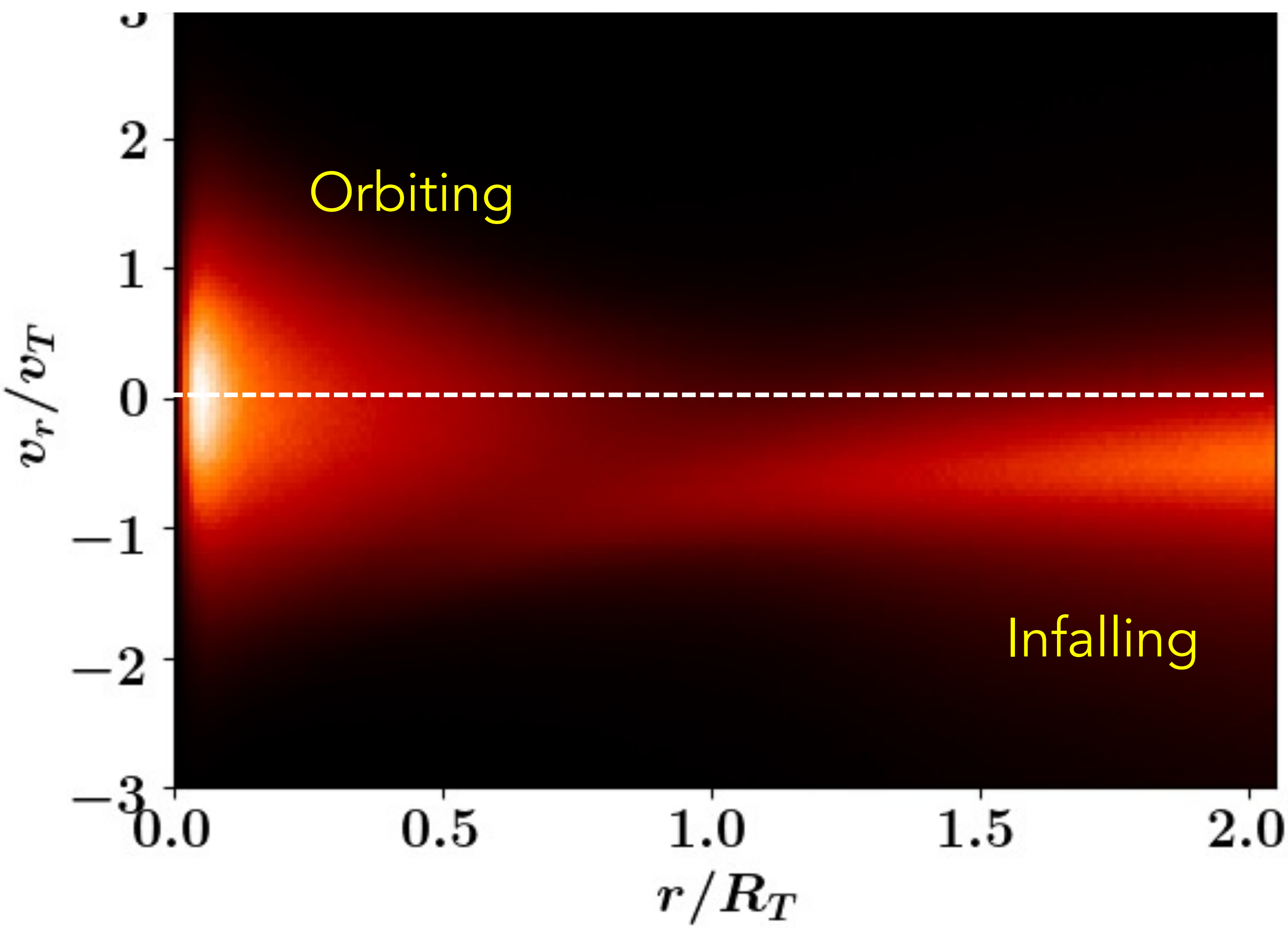
Tomooka, ER, et al. 2020, 2003.11555

The Velocity Dispersion of Galaxy Clusters



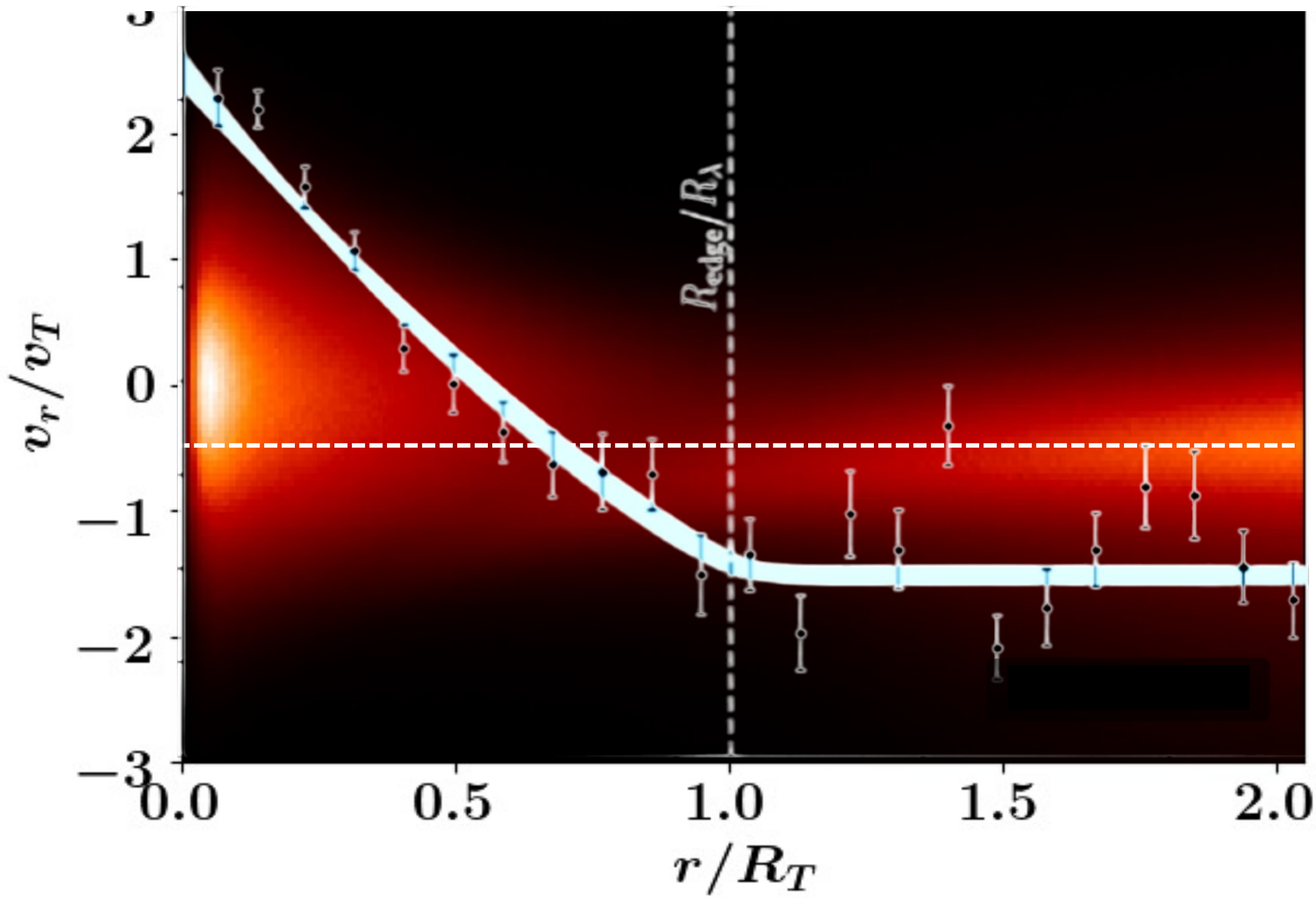
Tomooka, ER, et al. 2020, 2003.11555

The Phase Space of a Halo

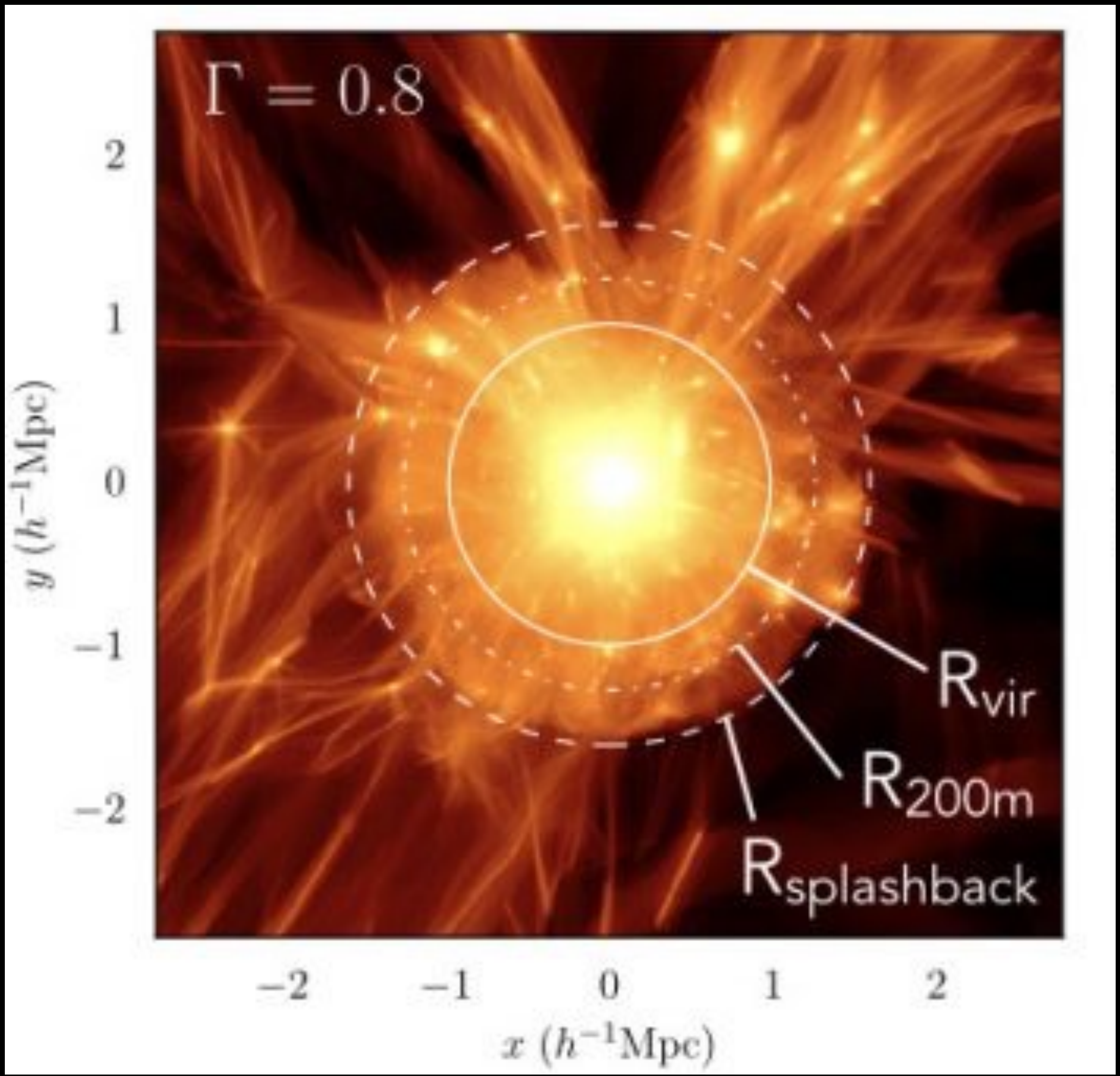


Garcia et al 2022, 2207.11827

- There is an orbiting/infall dichotomy
- This dichotomy has observable implications.

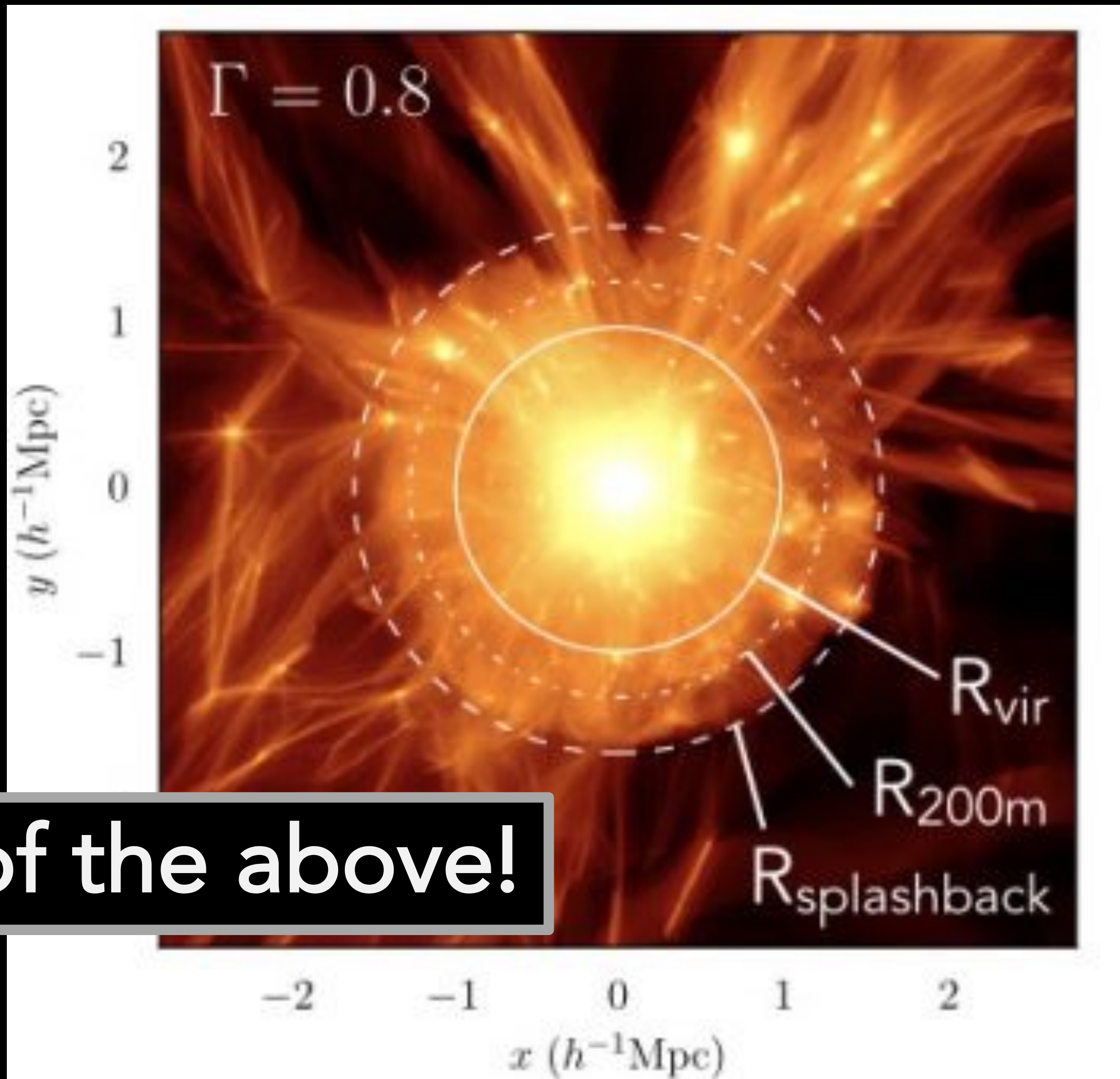


What is the Right Halo Boundary?



Credit: Benedikt Diemer

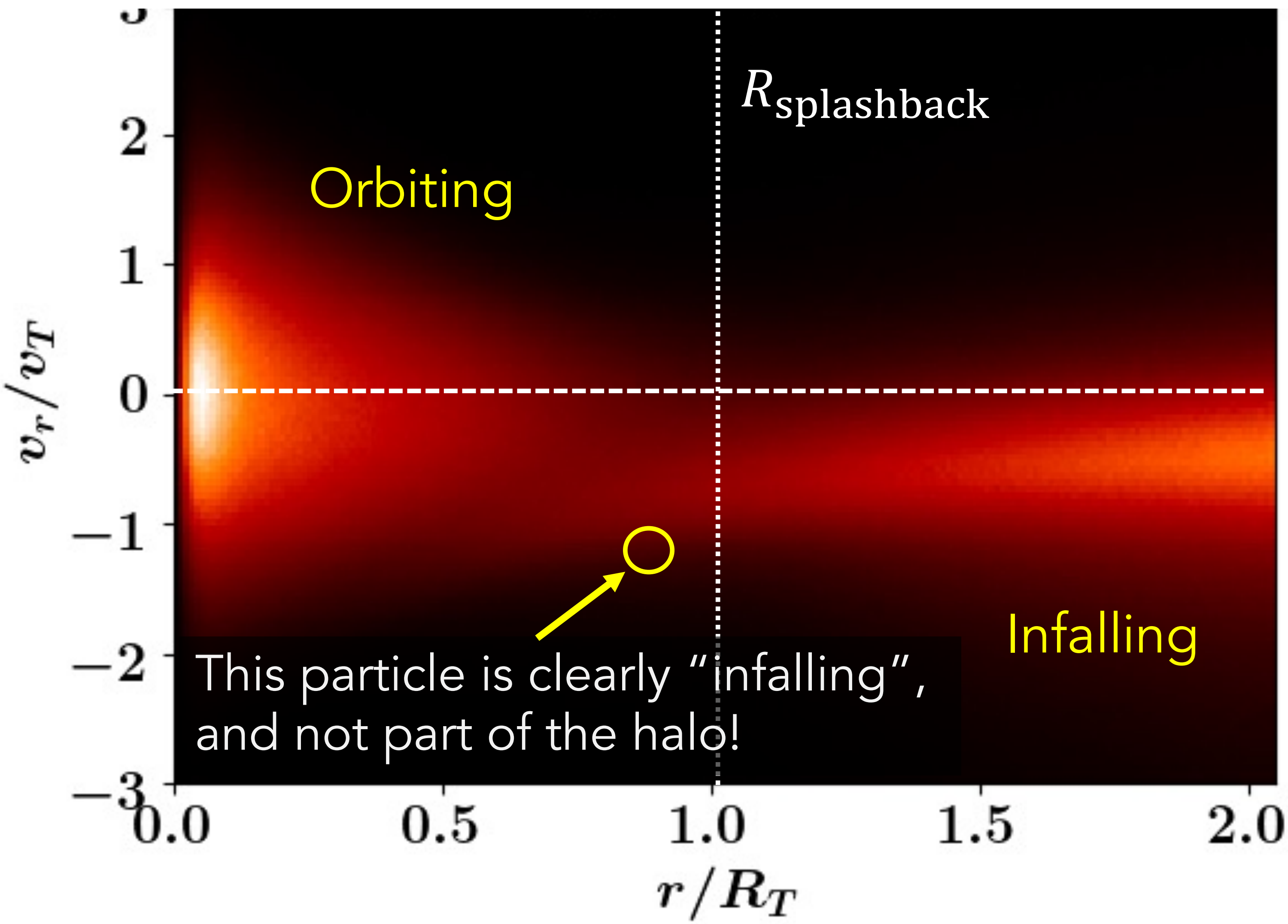
What is the Right Halo Boundary?



None of the above!

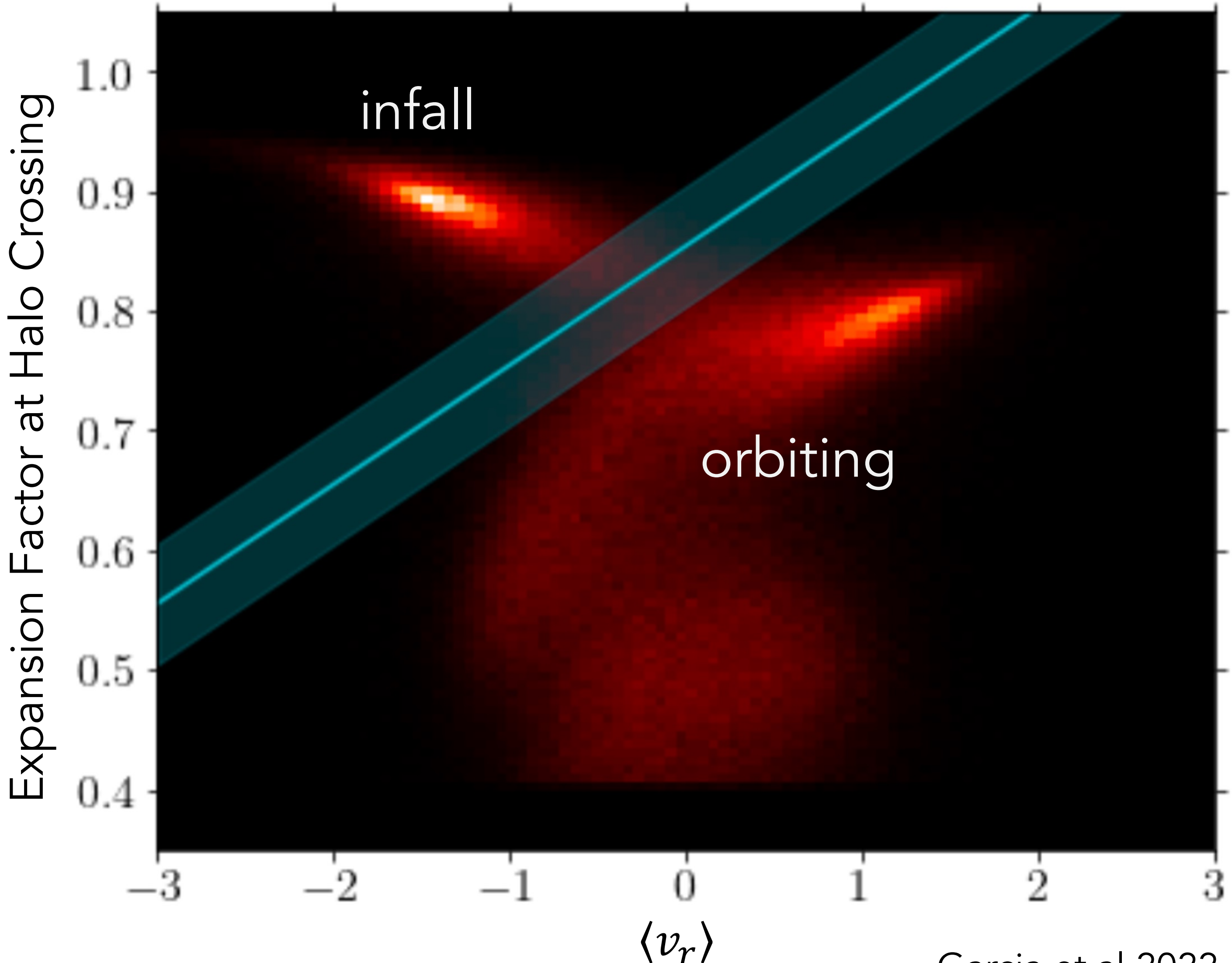
Credit: Benedikt Diemer

The Problem w/ *ANY* Radial Boundary



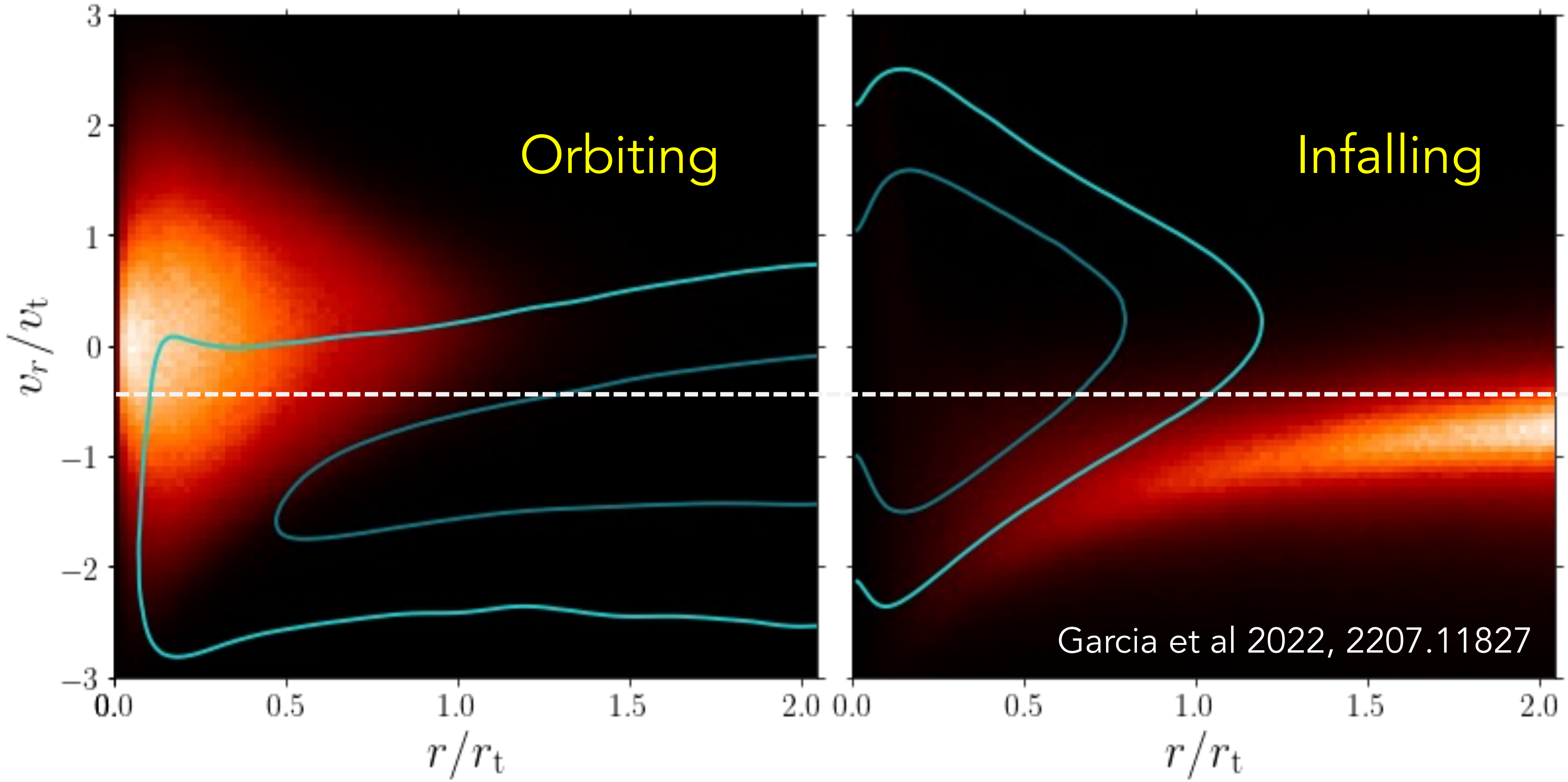
Garcia et al 2022, 2207.11827

- Using particle histories, we can can distinguish between orbiting and infalling at the 1% level.



Garcia et al 2022, 2207.11827

The Orbiting/Infall Dichotomy



- This decomposition is *unique* at the percent level!

A New Halo Definition

A halo is the collection of all orbiting particles in a dark matter structure.

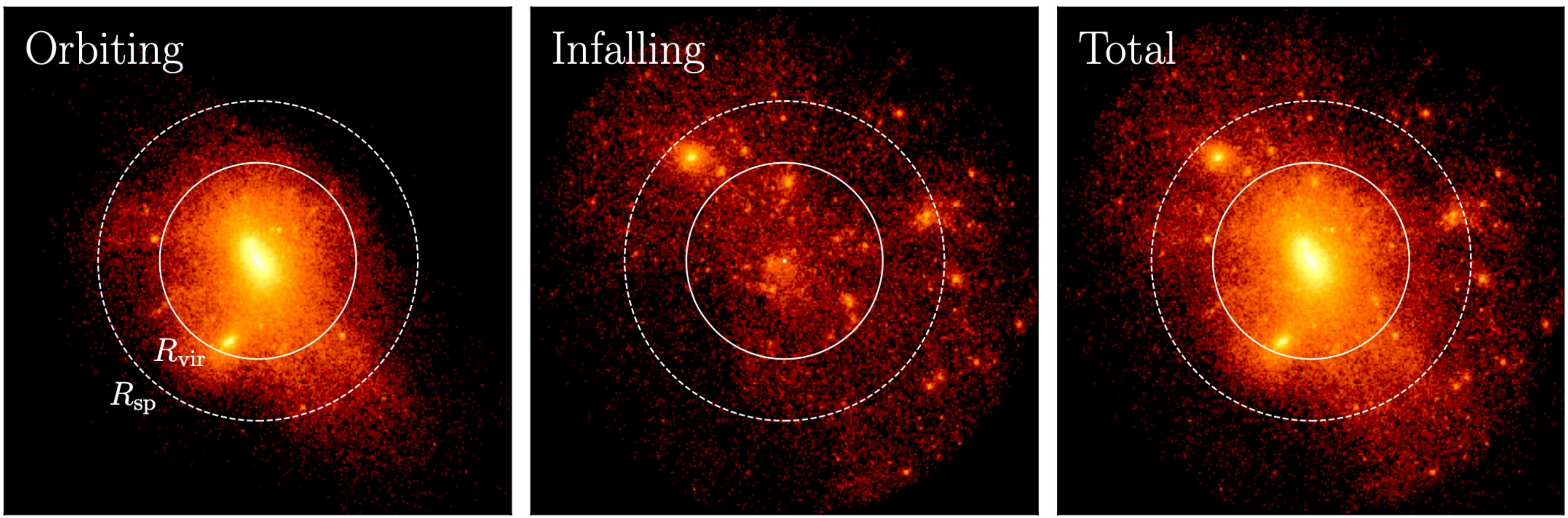
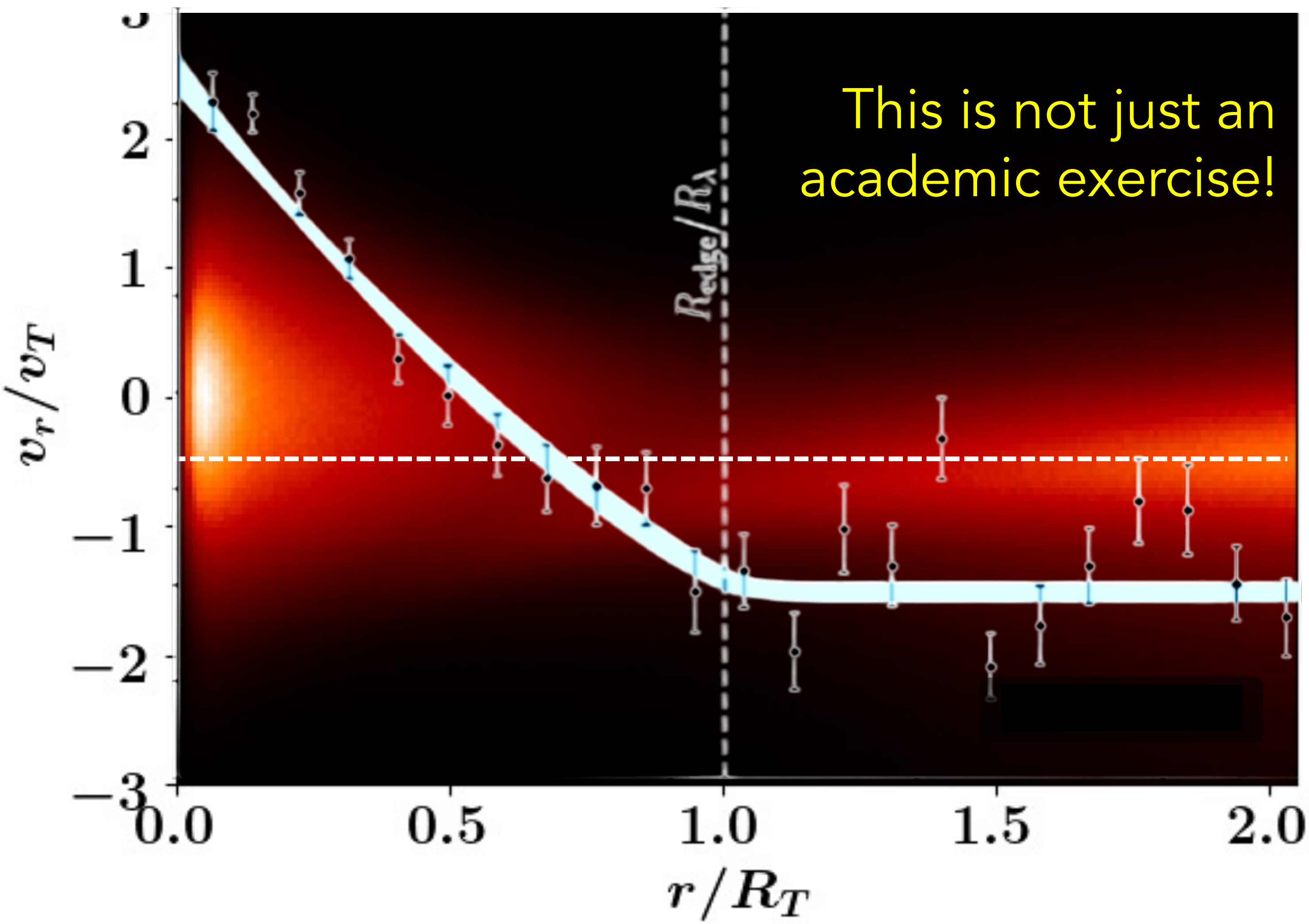


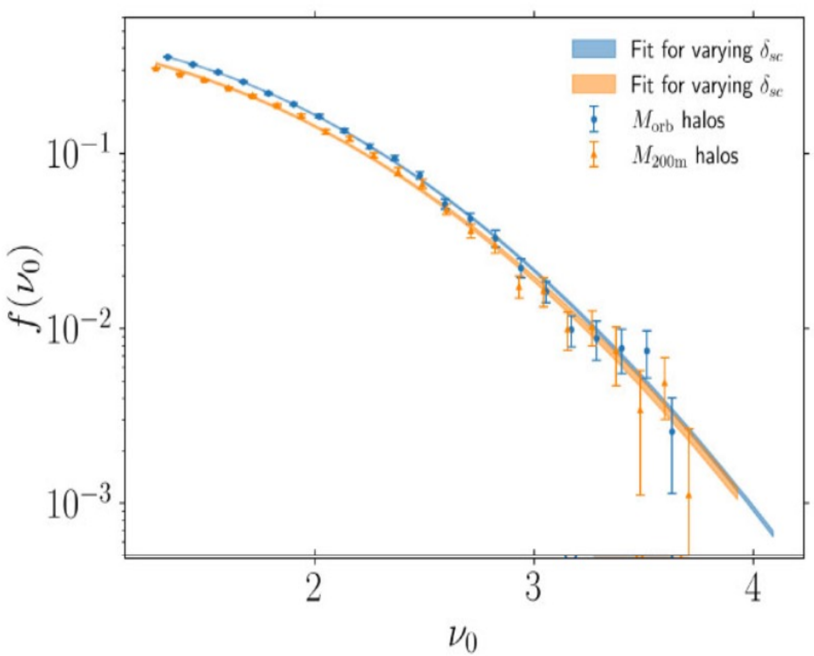
Image credit: Benedikt Diemer

The proposed halo definition is unique, physically motivated, and its salient features are present in the data!



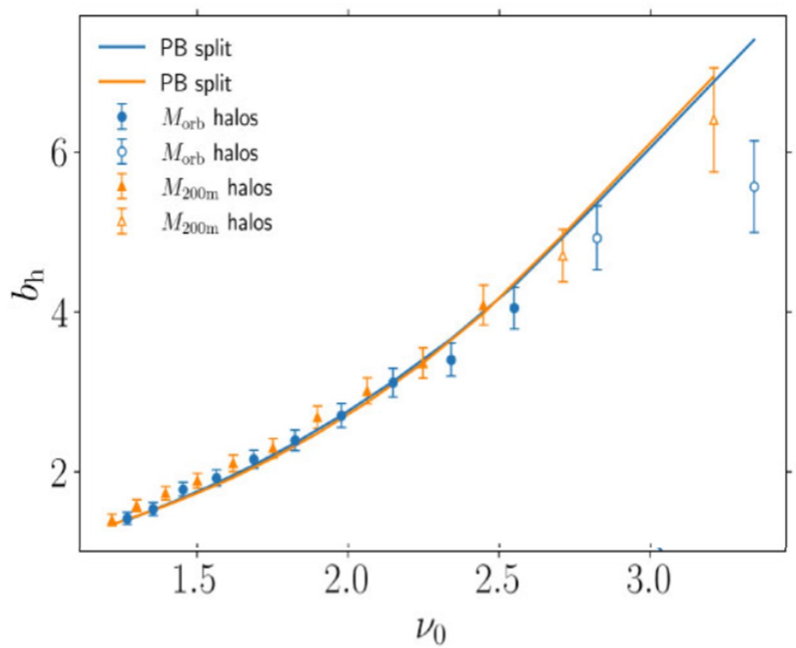
Implication No. 1: Simple Halo Statistics

- Mass function is very nearly Press—Schechter.



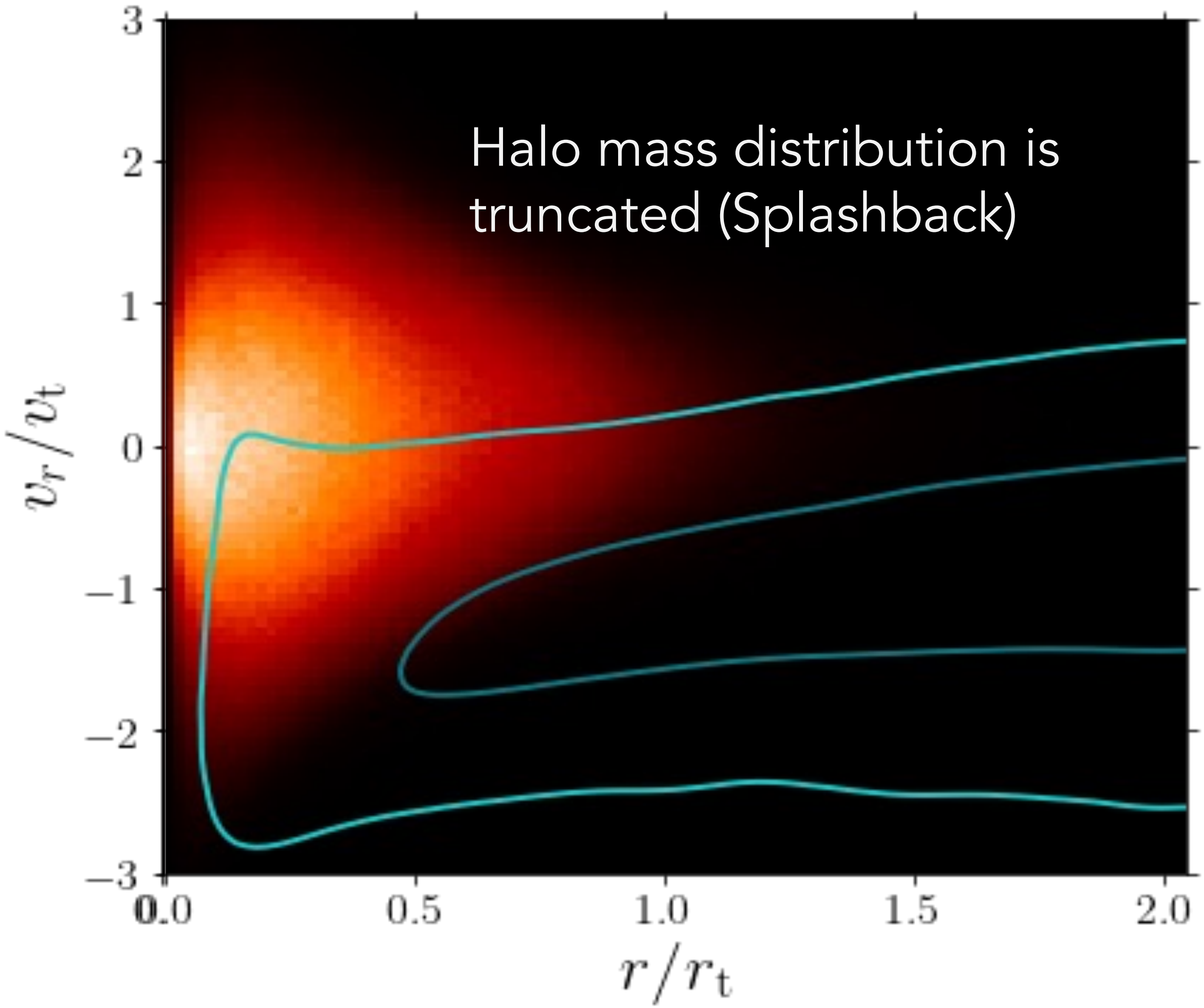
  - PS w/ slowly moving barrier is good to $\approx 1\%$.

- Halo bias is consistent w/ Peak-background split

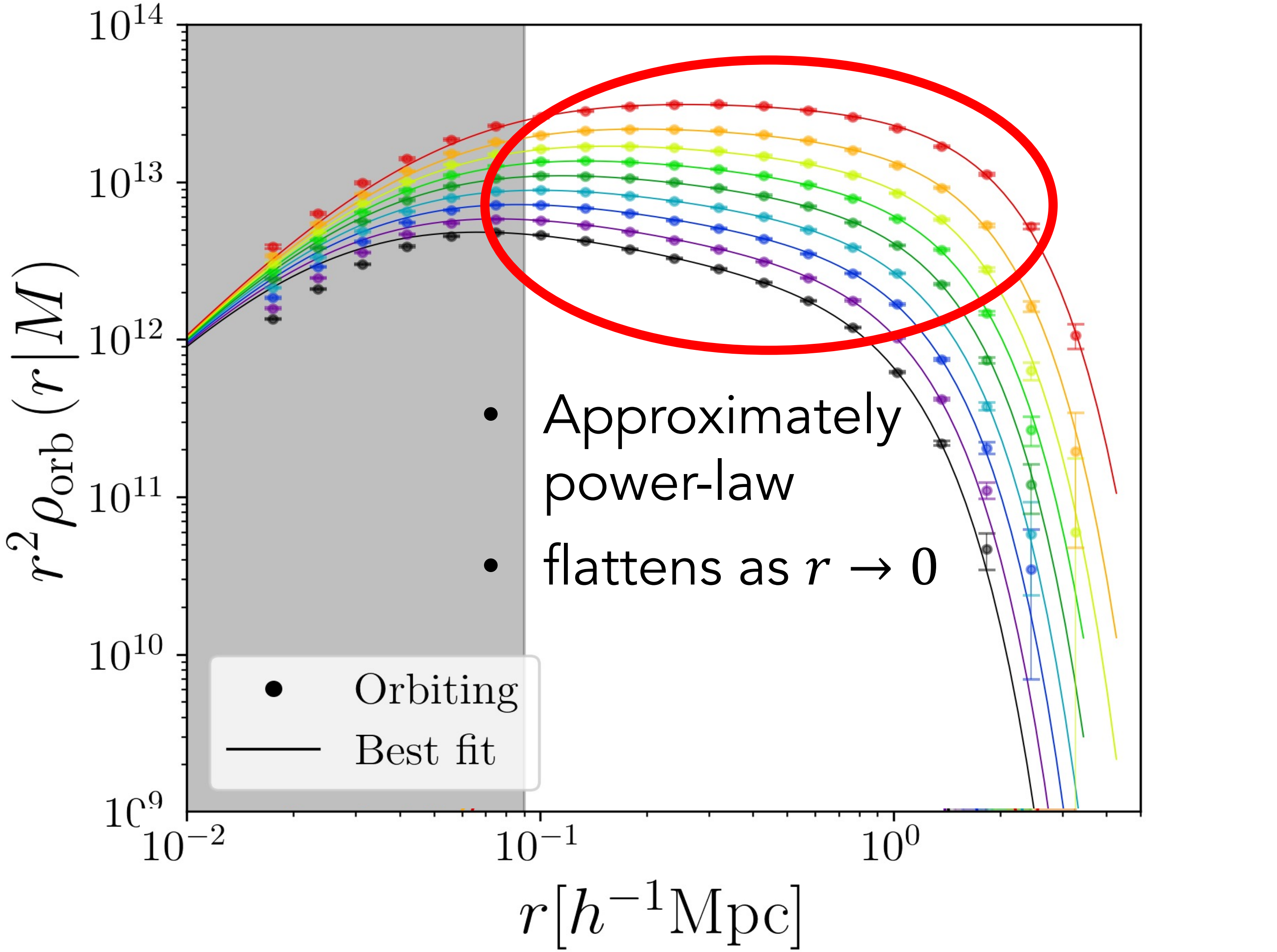


  - PB split is accurate to $\lesssim 4\%$.

Implication no. 2: Halos are not NFW



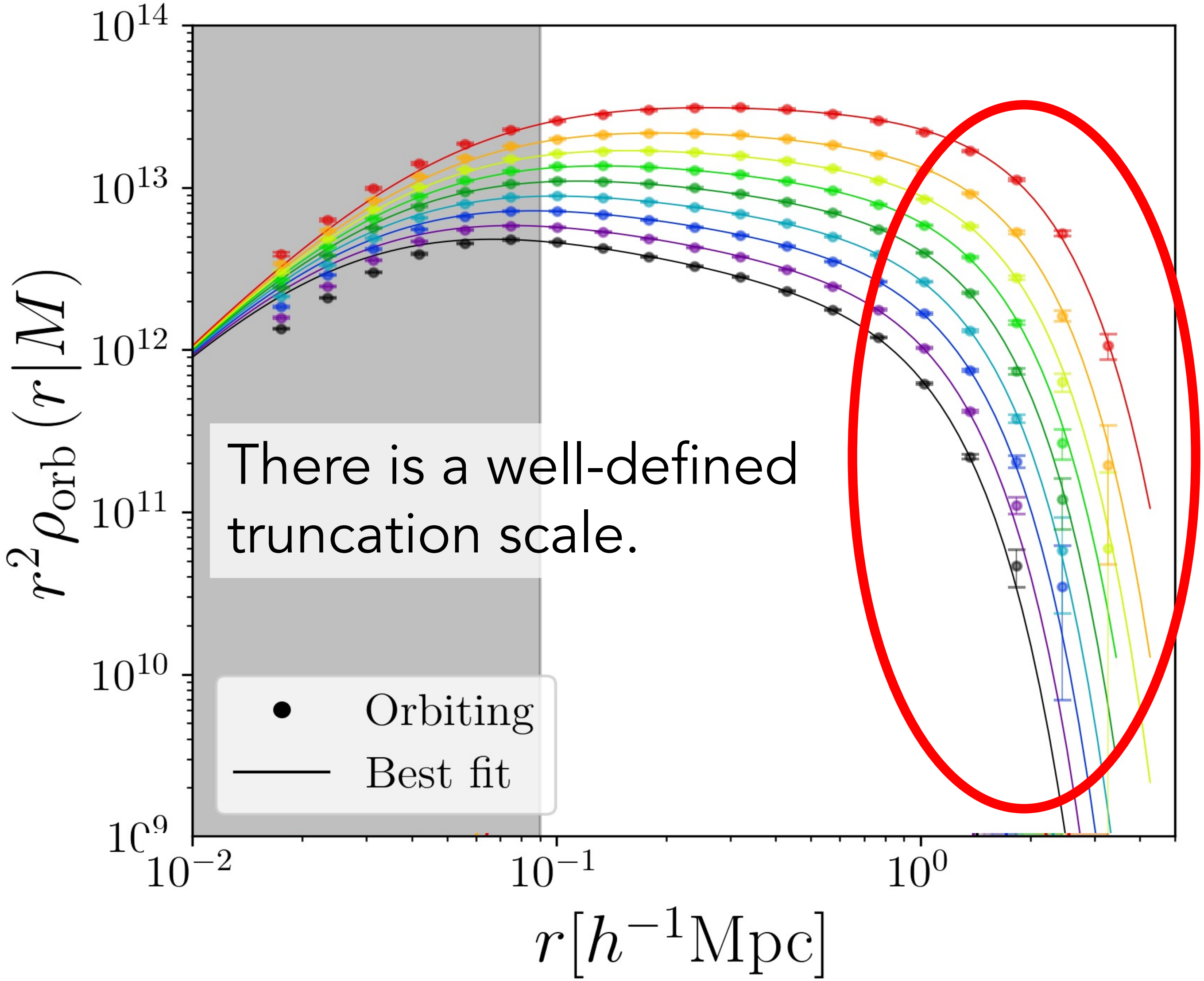
Halos are not NFW



- Approximately power-law
- flattens as $r \to 0$

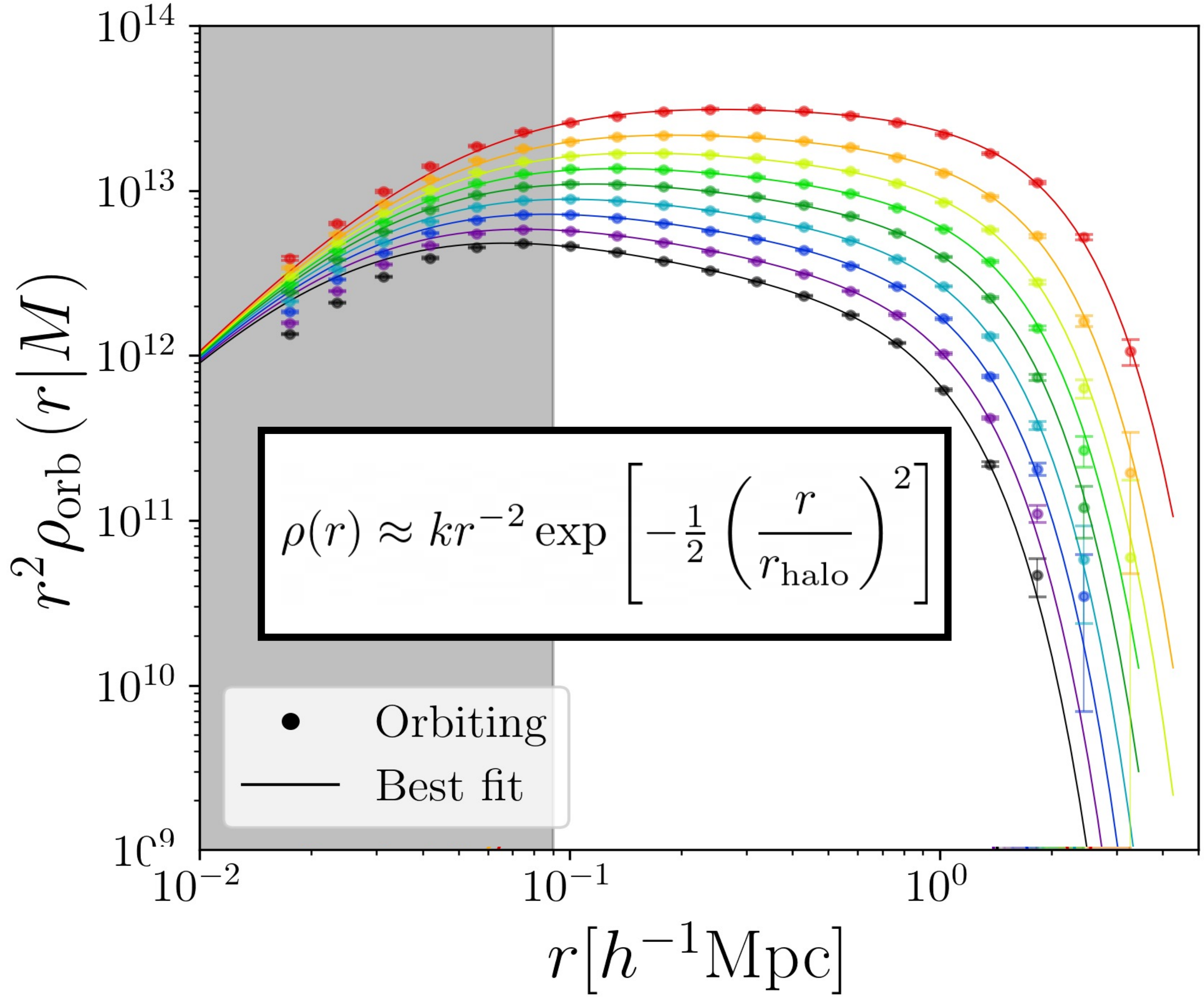
Salazar, ER et al, in prep.

Halos are Finite!



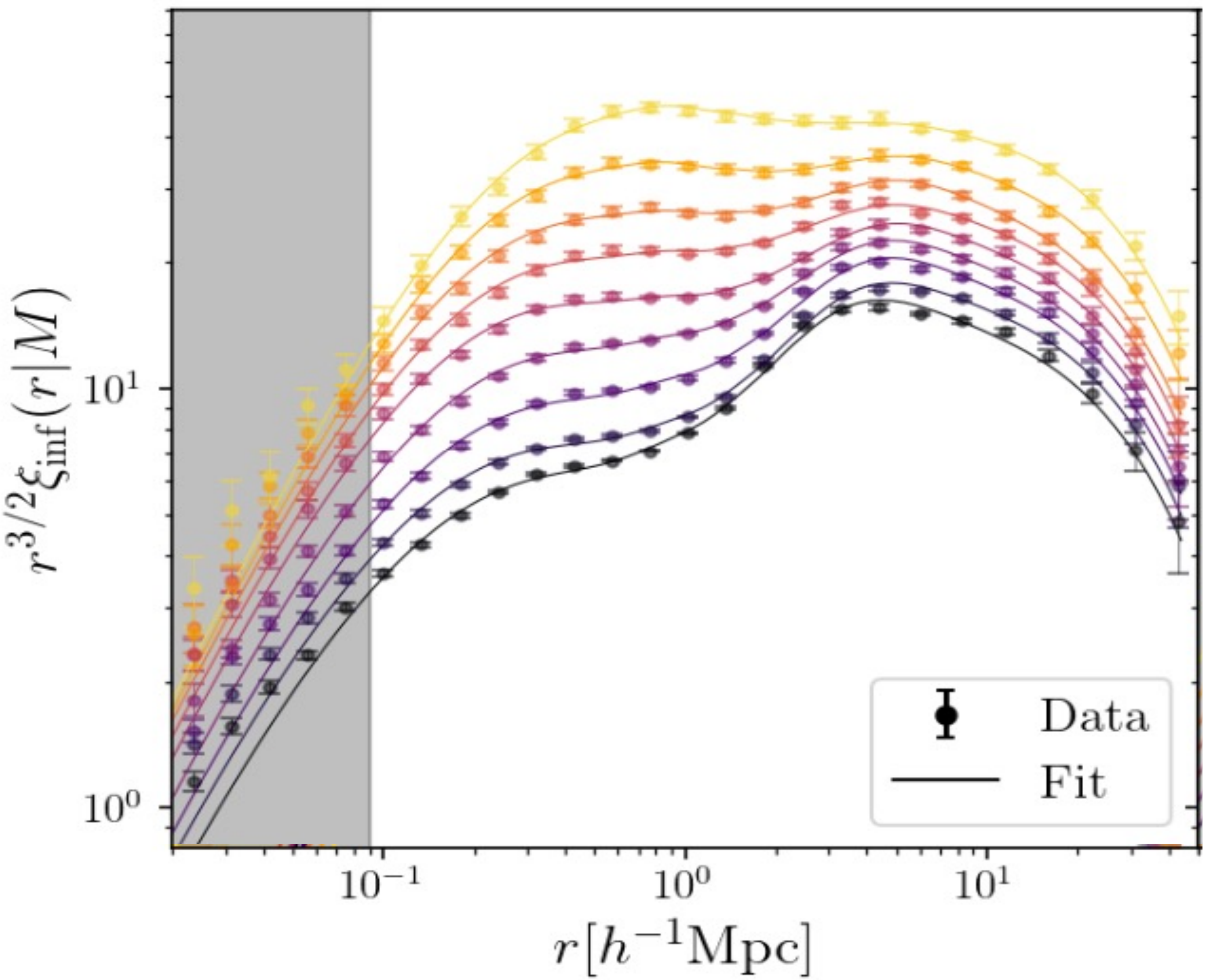
Salazar, ER et al, in prep.

Halo Profile Has Only One Radial Scale



Salazar, ER et al, in prep.

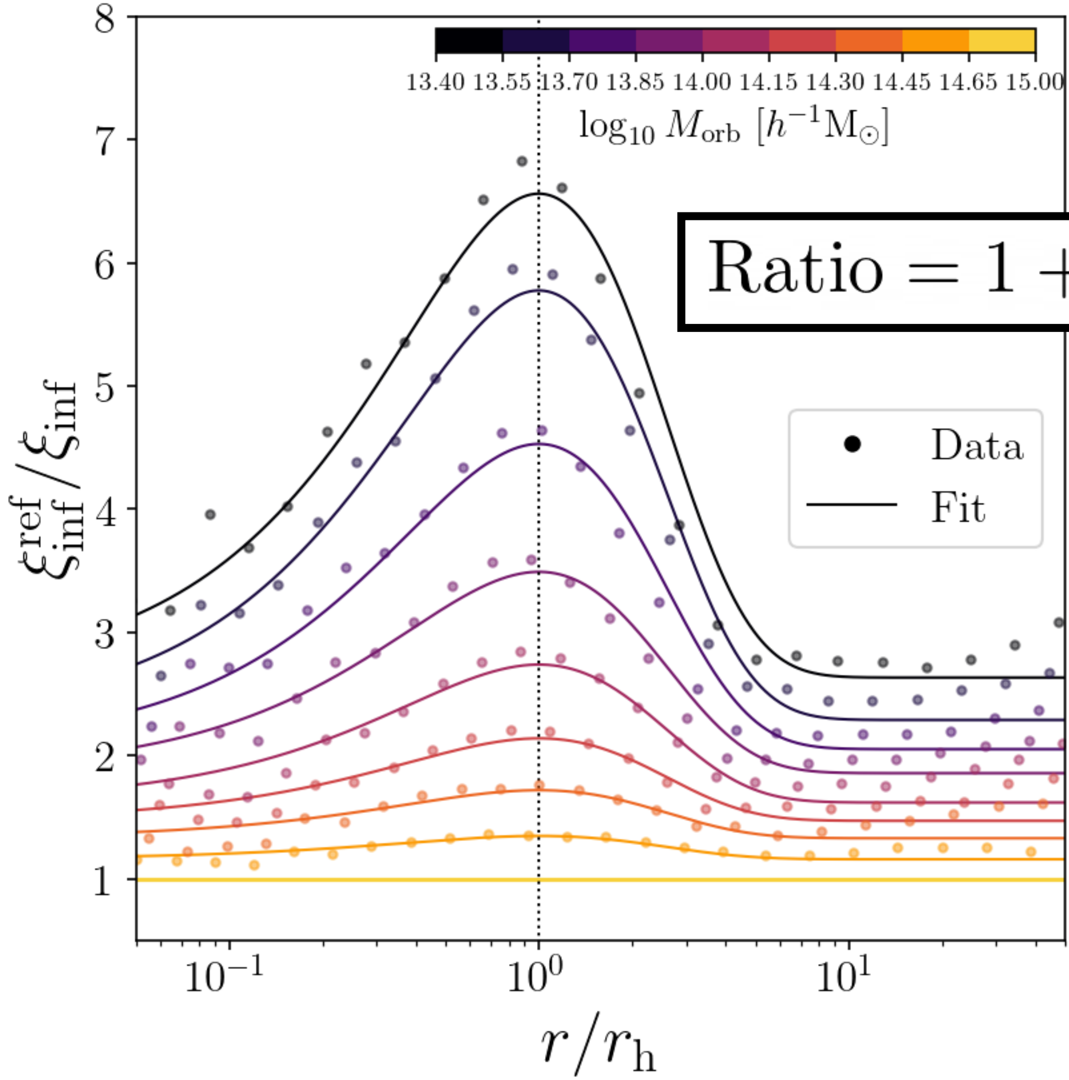
What About the Infall Distribution?



Ask me later if interested.

Salazar, ER et al, in prep.

The Ratio of Corr. Functions Knows About the Halo Radius



$$\mathrm{Ratio} = 1 + ax\exp(-x)$$

Modeling the Infall Profile

- Start w/ simplest possible model:

$$\xi_{\rm inf}(r) \equiv \frac{\rho_{\rm inf}}{\bar{\rho}_{\rm m}} - 1 = b\xi_{\rm lin}(r)$$

↓

Fails to account for non-linear blurring on large scales.

Solution: Replace by Zeldovich correlation function $\xi_{\rm Z}$

$$\xi_{\rm inf} = \frac{\rho_{\rm inf}}{\bar{\rho}} - 1 = b\xi_{\rm Z}$$

Modeling the Infall Profile

- Start w/ simplest possible model:

$$\xi_{\rm inf} = \frac{\rho_{\rm inf}}{\bar{\rho}} - 1 = b\xi_{\rm Z}$$

Modeling the Infall Profile

- Start w/ simplest possible model:

$$\xi_{\rm inf} = \frac{\rho_{\rm inf}}{\bar{\rho}} - 1 = b\xi_{\rm Z}$$

- Adopt model at high mass, add relative ratio model:

$$\xi_{\rm inf} = \frac{b}{1 + ax\exp(-x)}\xi_{\rm Z}$$

Modeling the Infall Profile

- Start w/ simplest possible model:

$$\xi_{\rm inf} = \frac{\rho_{\rm inf}}{\bar{\rho}} - 1 = b\xi_{\rm Z}$$

- Adopt model at high mass, add relative ratio model:

$$\xi_{\rm inf} = \frac{b}{1 + ax\exp(-x)}\xi_{\rm Z}$$

- Add a nearly mass-independent non-linear bias.

$$\xi_{\rm inf} = \frac{b(1+\Delta(r))}{1 + ax\exp(-x)}\xi_{\rm Z}$$

Cored power-law:

$$\Delta(r) = \frac{\Delta_0}{[1 + (r/r_\Delta)]^\gamma}$$

Modeling the Infall Profile

- Final model:

$$\xi_{\rm inf} = \frac{b(1+\Delta(r))}{1+ax\exp(-x)}\xi_{\rm Z}$$

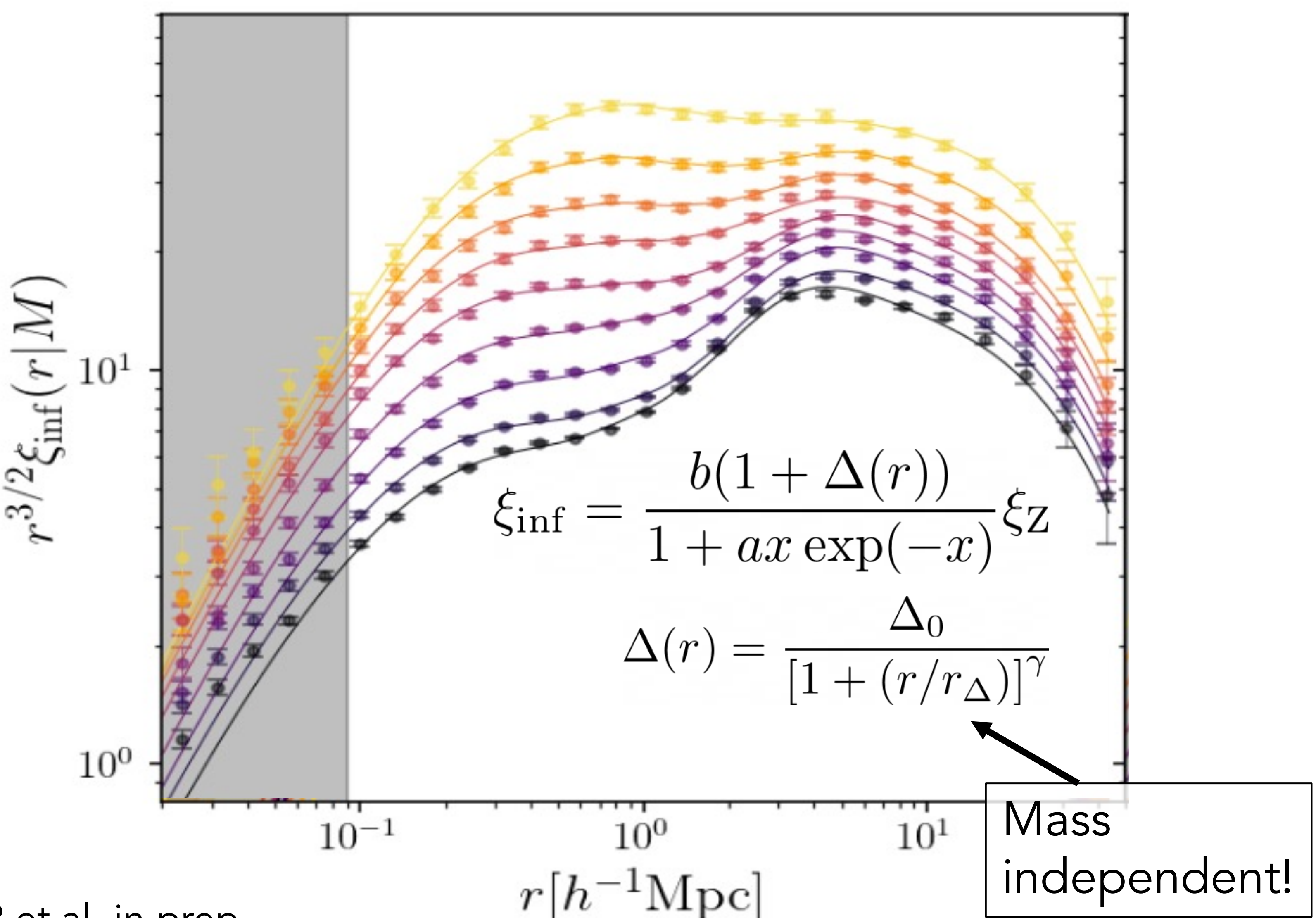
$$\Delta(r) = \frac{\Delta_0}{[1+(r/r_\Delta)]^\gamma}$$

↓

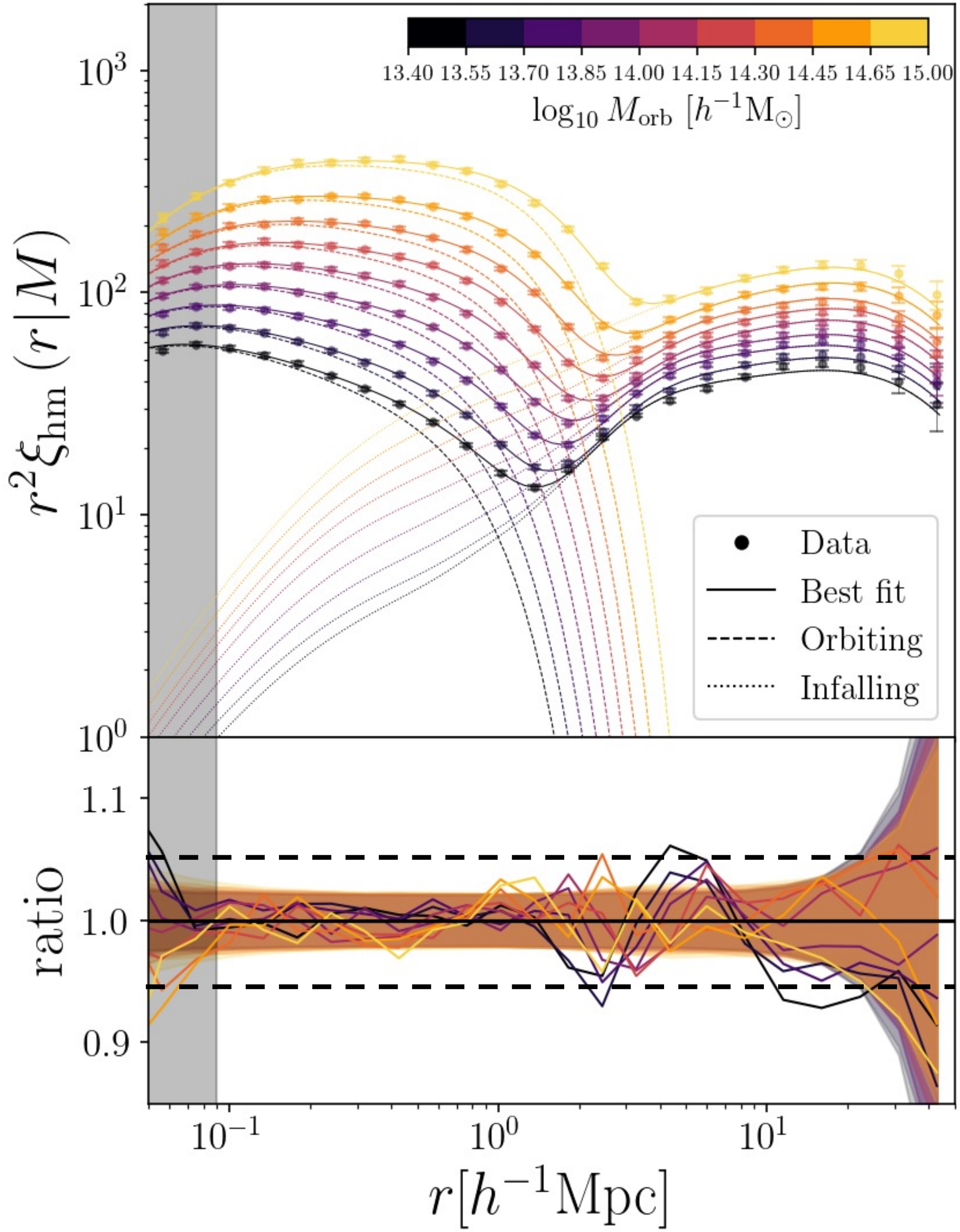
Does not depend on mass.

➢ There are no new radial scales associated with halos as a function of mass.

No New Mass Dependent Scale!



Salazar, ER et al, in prep.



End Result

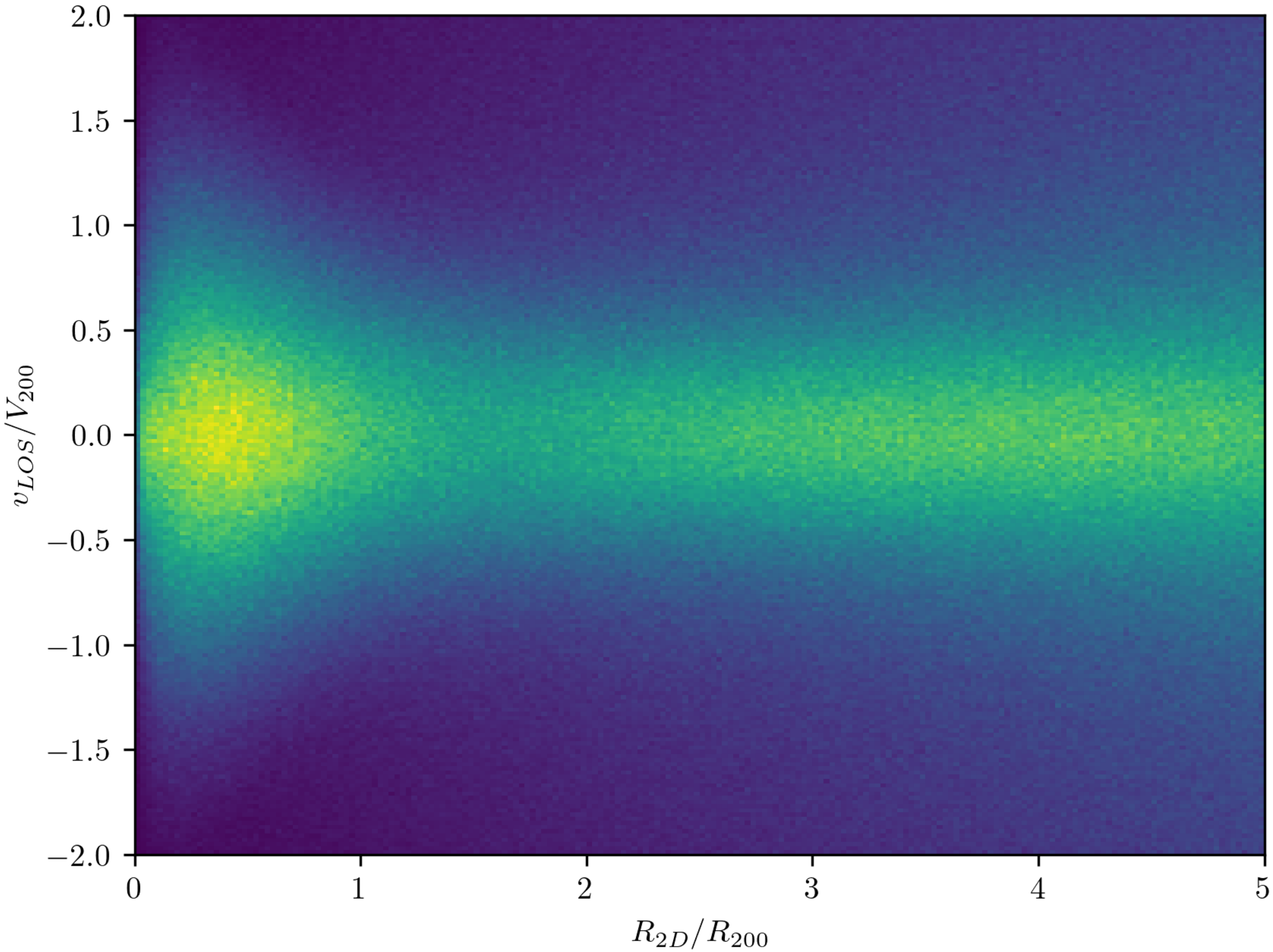
$$\rho(r) = \rho_{\rm orb}(r) + \rho_{\rm inf}(r)$$

- Only 1 radial scale: unique halo radius.

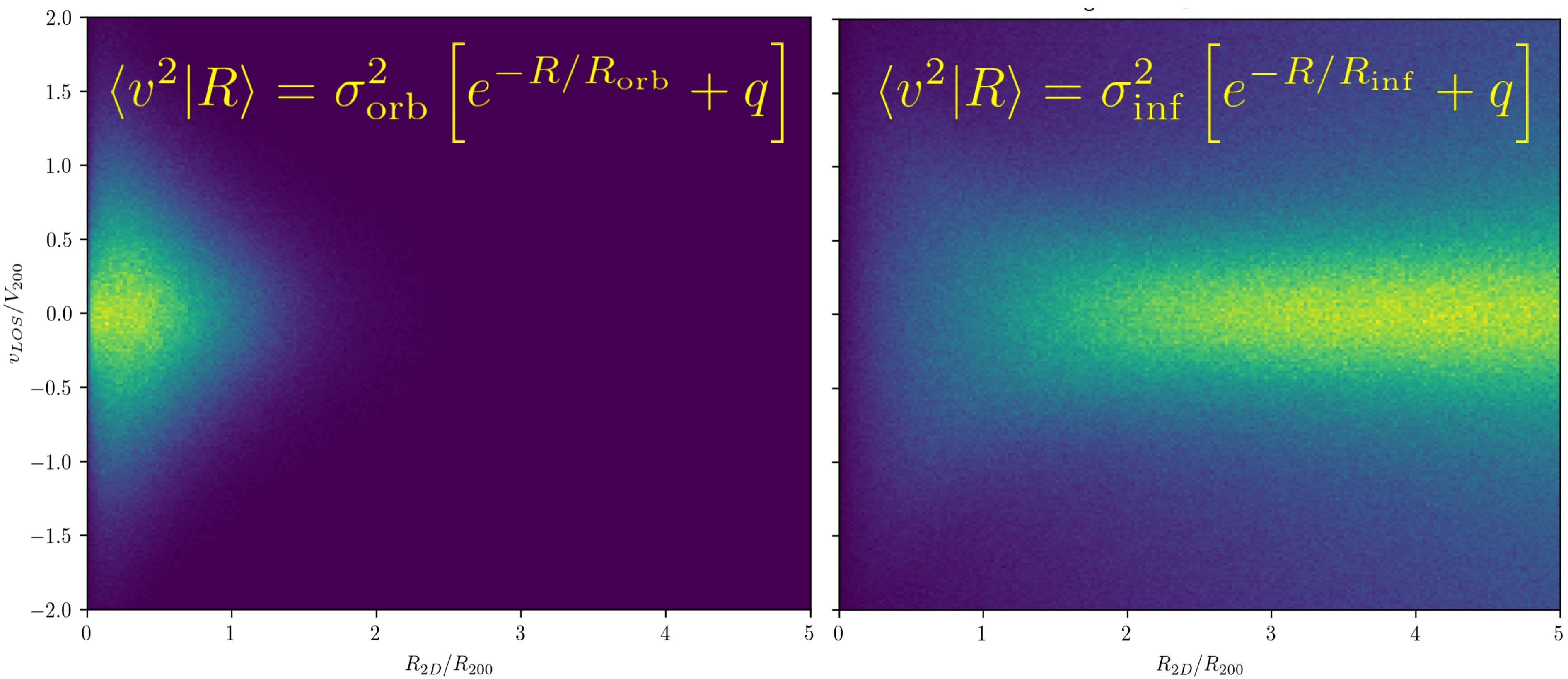
- Much improved fitting function
  - ➢ Directly relevant for mass calibration.

Salazar, ER et al, in prep.

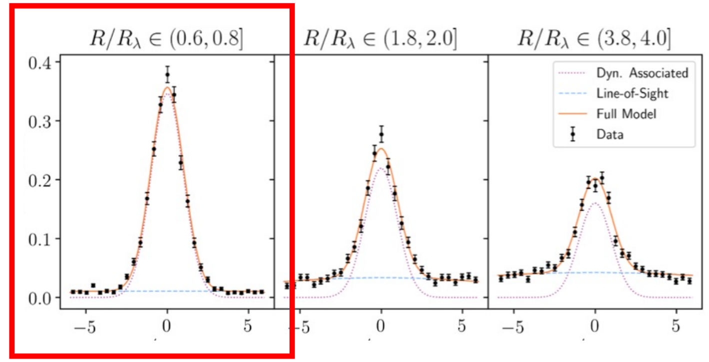
Implication no. 3: Modeling the Projected Phase of Galaxy Clusters



Implication no. 3: Modeling the Projected Phase of Galaxy Clusters

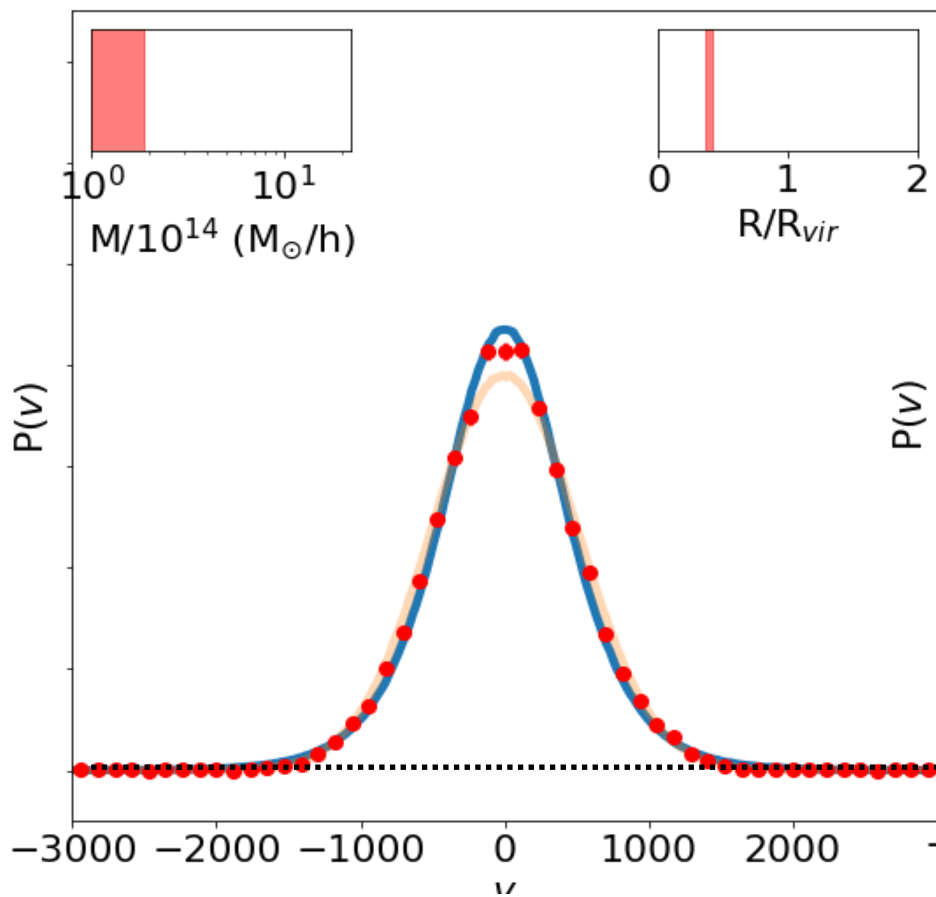


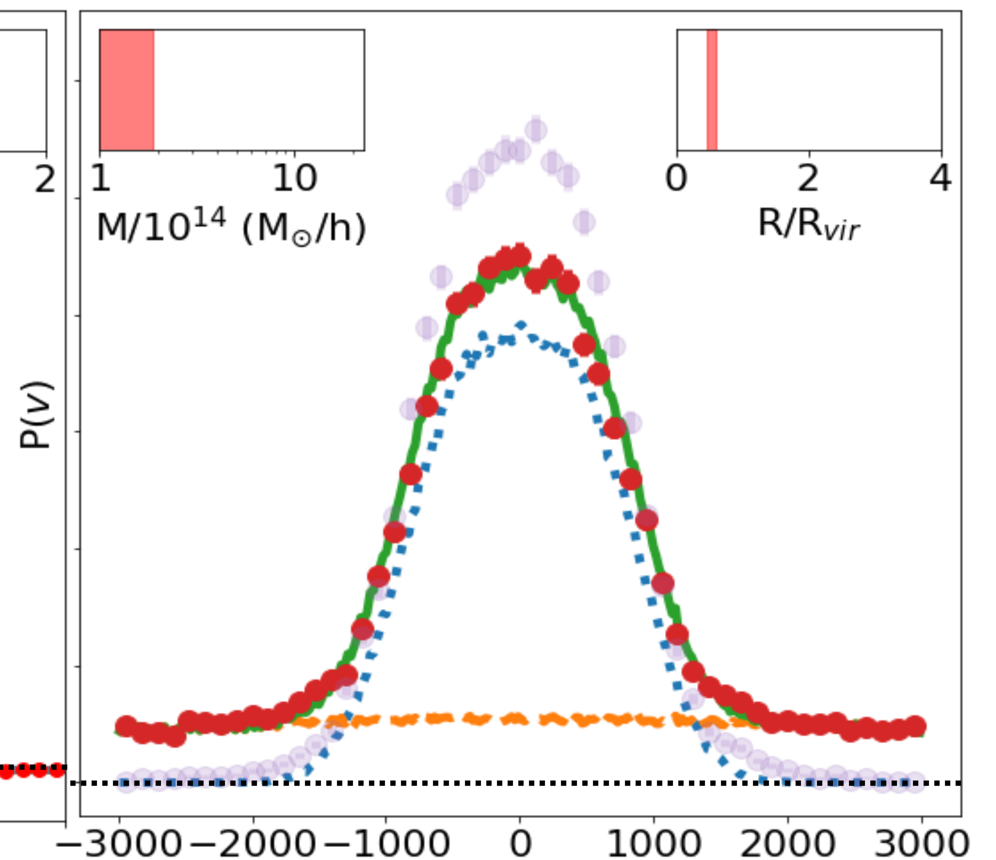
LOS Velocity Distribution of Cluster Galaxies



Orbiting

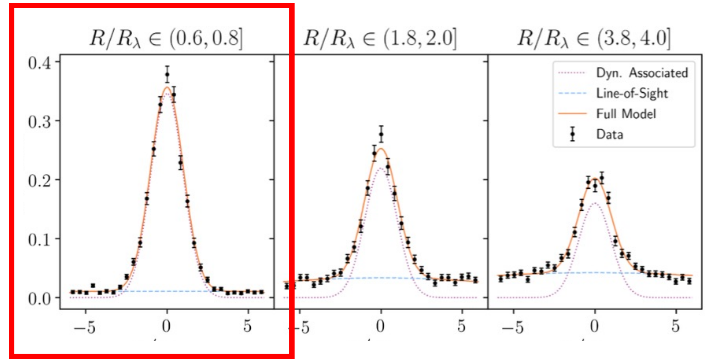
Infalling



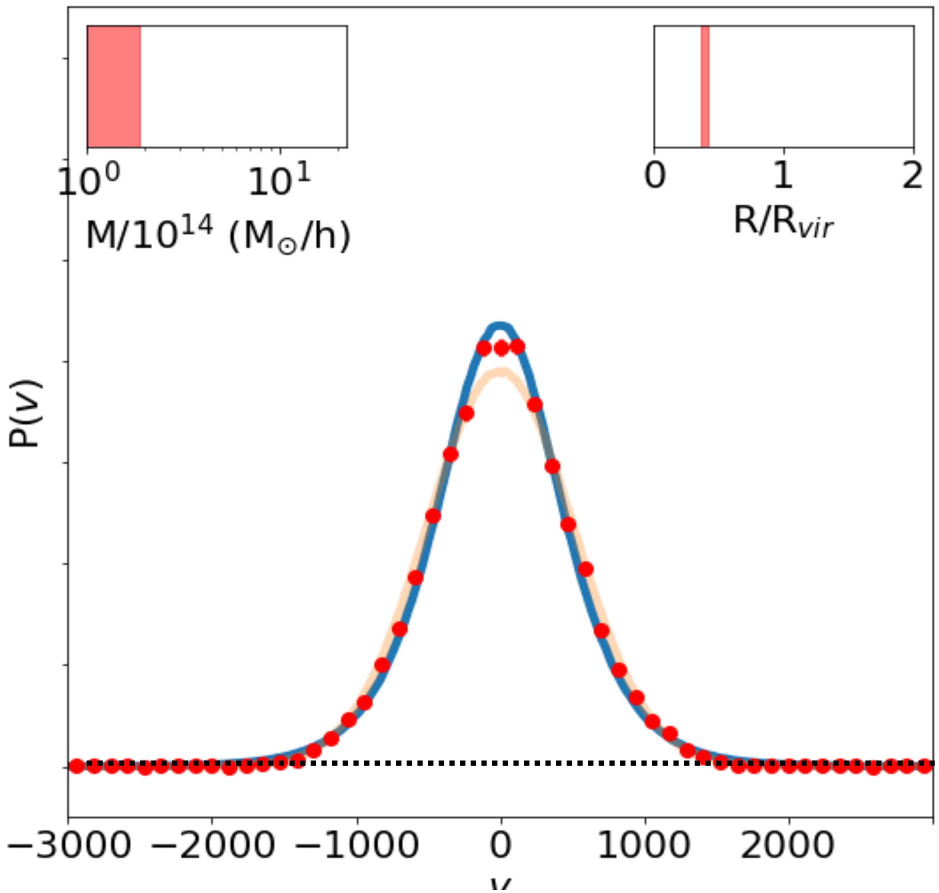


Wolfe, E.R. et al., in prep

LOS Velocity Distribution of Cluster Galaxies



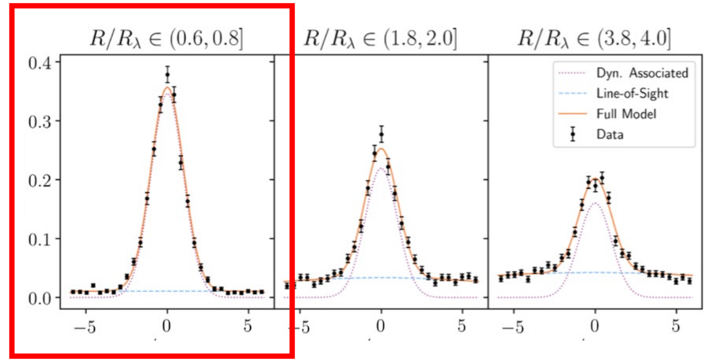
Orbiting



- Orbiting PDF close to but not quite Gaussian
  - $$\rho(v) \propto \frac{1}{\cosh^2(v/\langle v^2 \rangle)}$$
  - $$\langle v^2 | R \rangle = \sigma_{\mathrm{orb}}^2 \left[e^{-R/R_{\mathrm{orb}}} + q \right]$$

Wolfe, E.R. et al., in prep

LOS Velocity Distribution of Cluster Galaxies

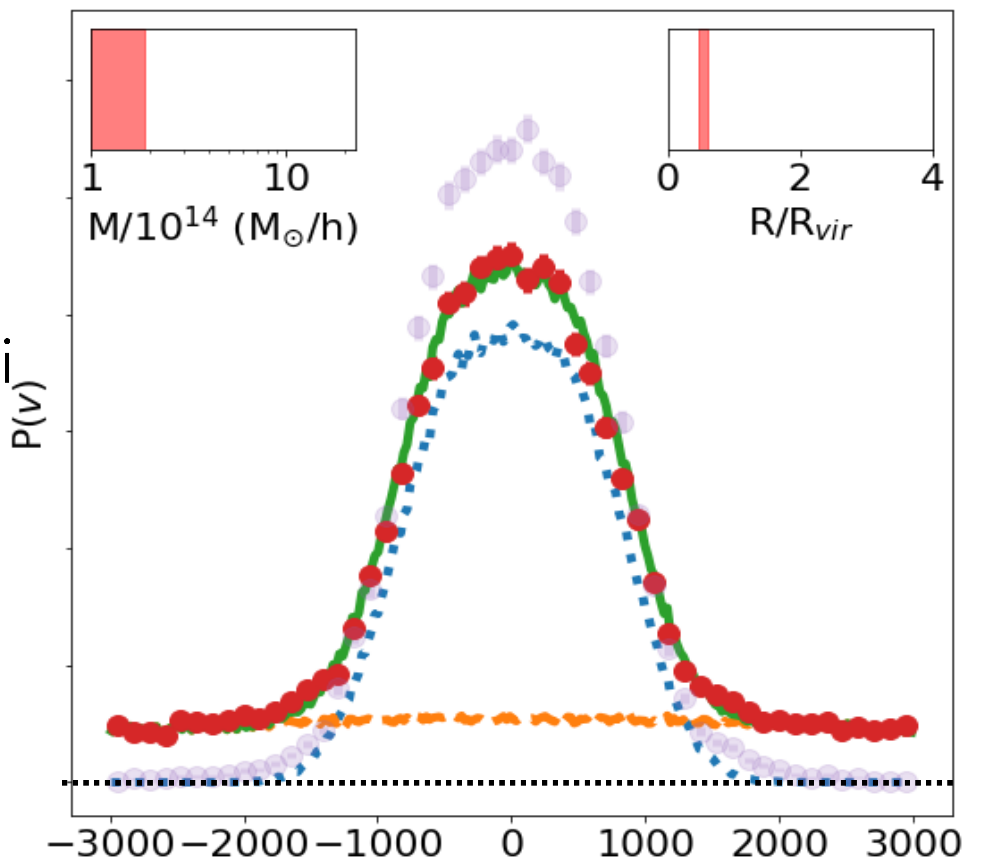


- Fit as peak + shelf
- Shape changes w/ radius:
  - Flat peak at small radii
  - Pointy peak at large radii

➢ Model w/ generalized normal distribution

$$\langle v^2|R\rangle = \sigma_{\rm inf}^2\left[e^{-R/R_{\rm inf}} + q\right]$$

Infalling



Wolfe, E.R. et al., in prep

A Fully Calibrated Model of the Projected Phase Space of Halos

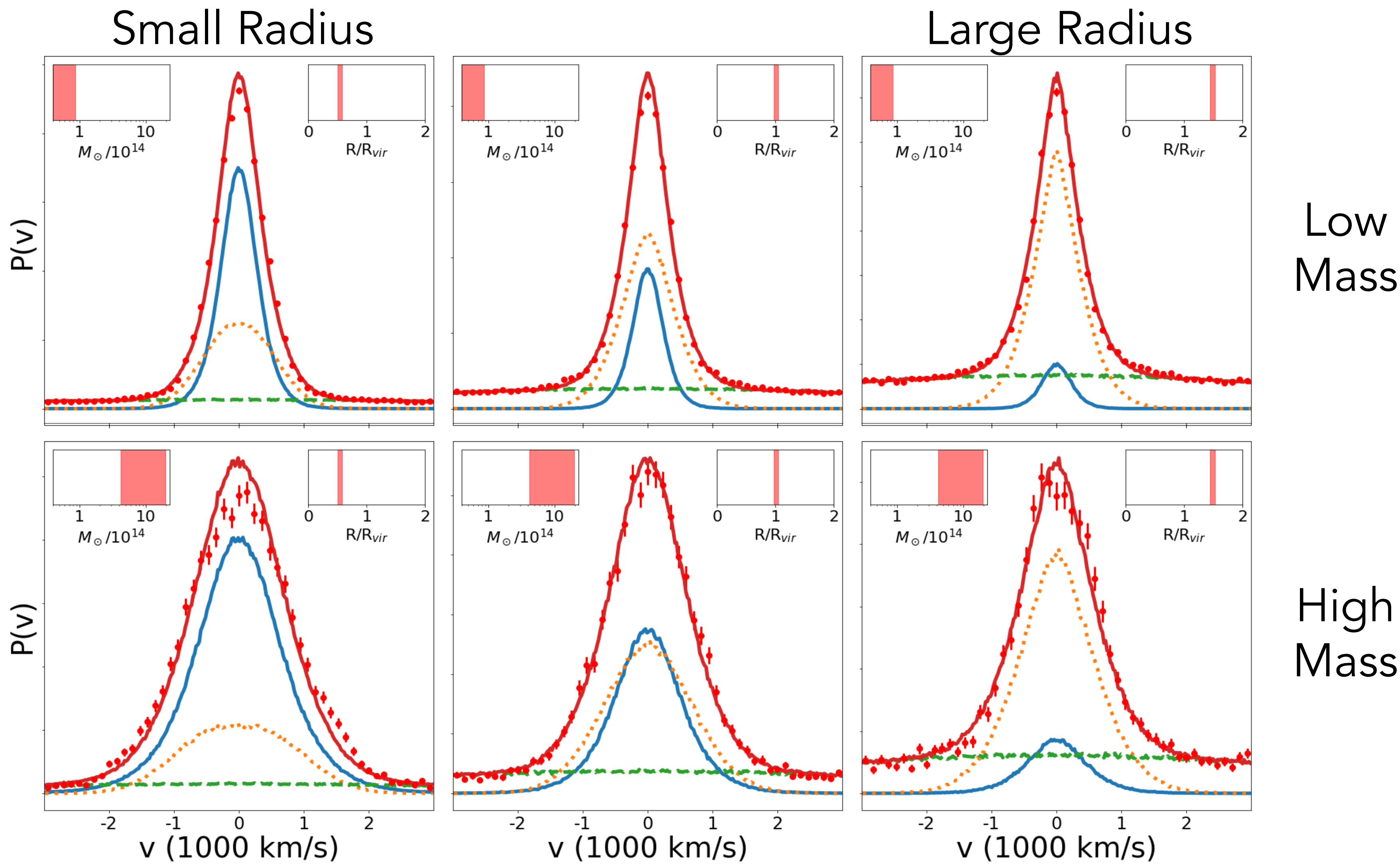
- $\rho_{\rm orb}(r|M)$
- $\rho_{\rm inf}(r|M)$

} Integrated to arrive at 2D profile $\Sigma(R)$

- $P_{\rm los}(v|R,M) = f_{\rm orb} P_{\rm orb}(v|R,M) + (1 - f_{\rm orb}) P_{\rm inf}(v|R,M)$

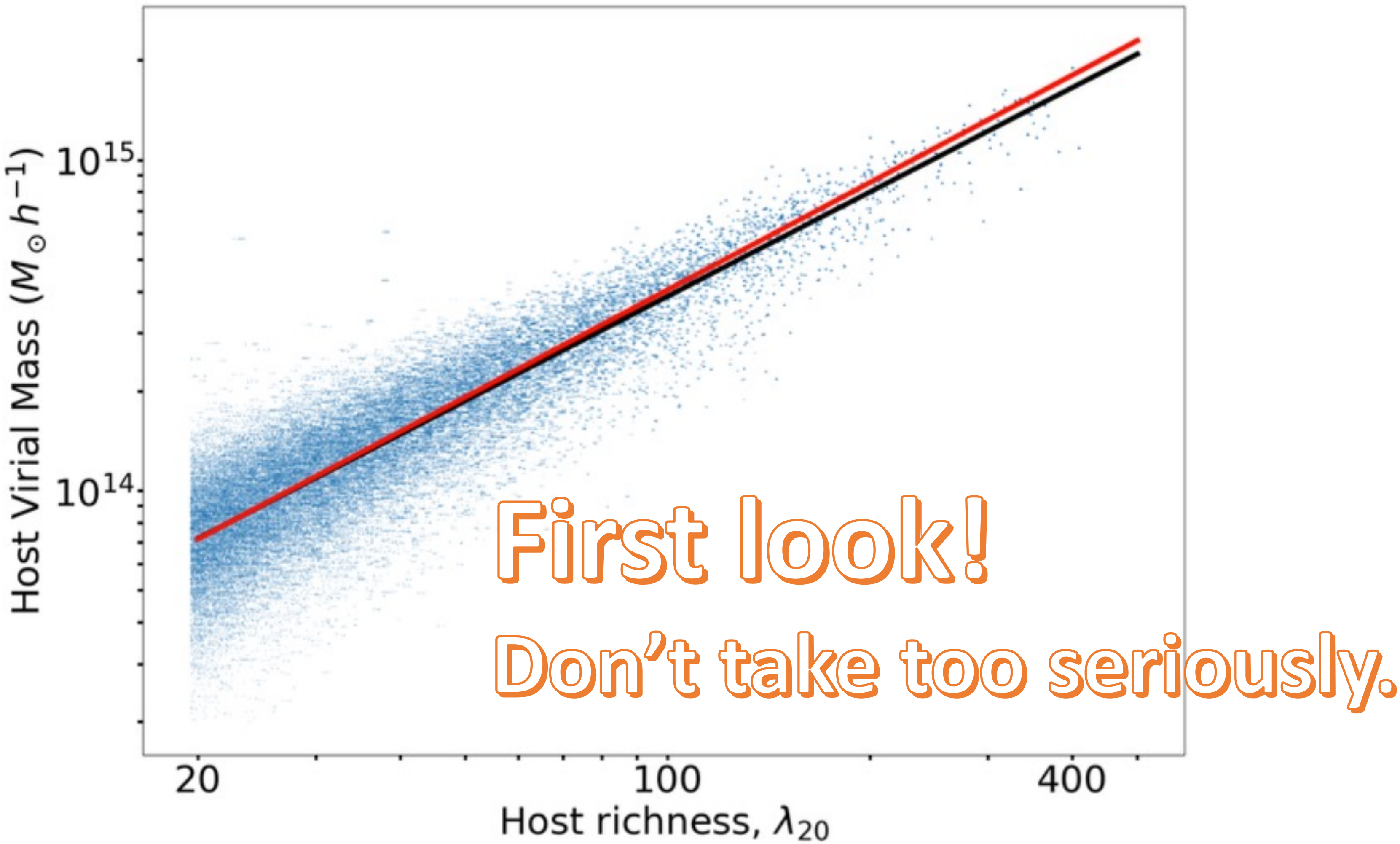
  - $f_{\rm orb}(R|M) = \dfrac{\Sigma_{\rm orb}(R|M)}{\Sigma_{\rm orb}(R|M) + \Sigma_{\rm inf}(R|M)}$

Resulting Model is Simple + Accurate



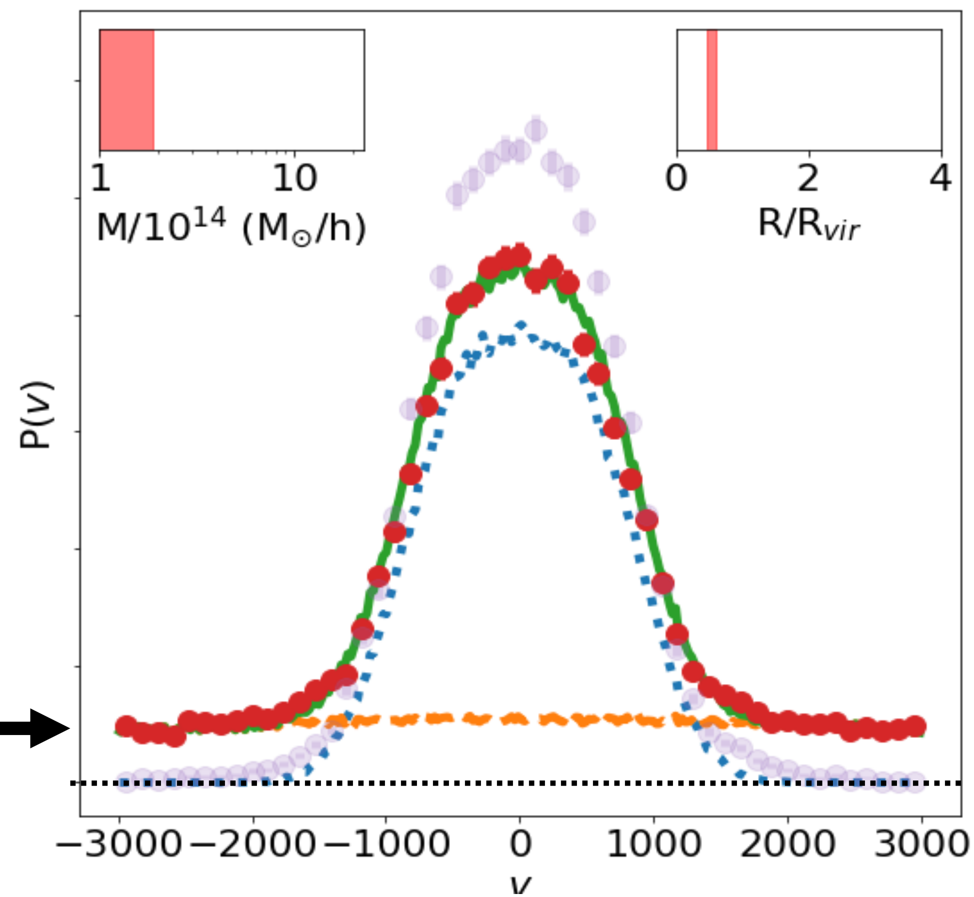
Wolfe, E.R. et al., in prep

Model Opens the Door to Mass Calibration Using Cluster Phase Space



Orbiting/Infall Modeling Leads to Surprising Insights

Infalling



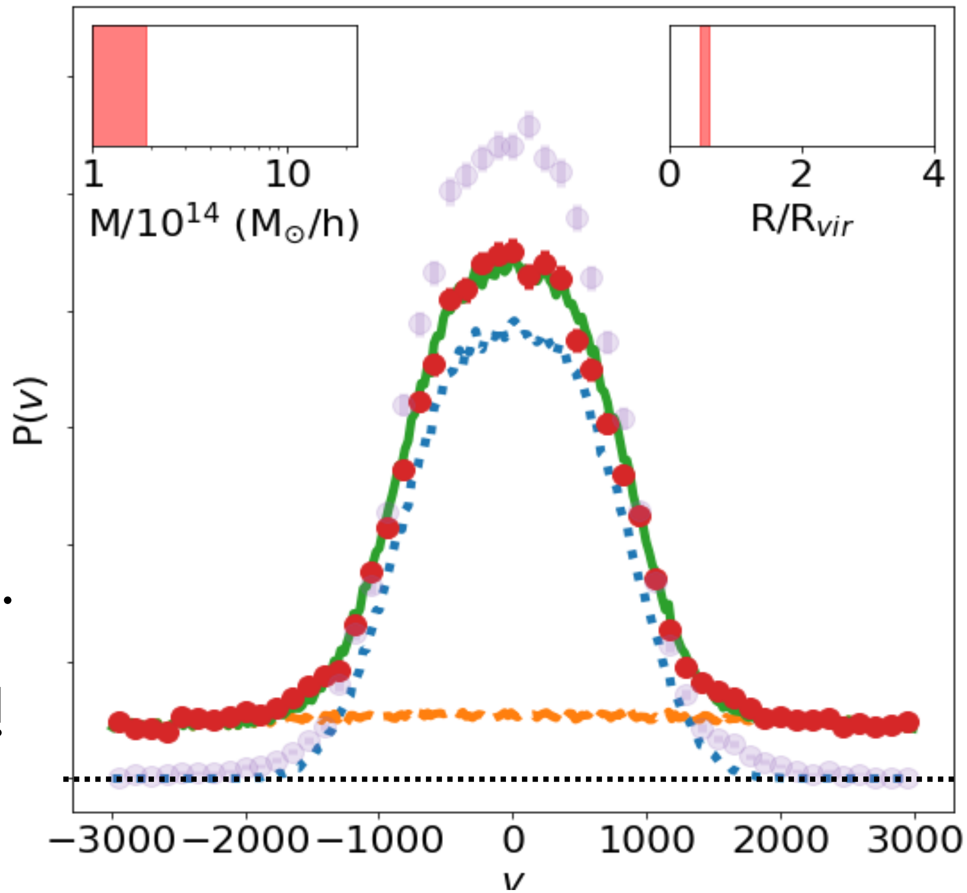
This shelf is NOT due to "background" galaxies.

LOS Velocity Distribution of Cluster Galaxies

Shelf appears only when including Hubble flow

- No such thing as a "background" galaxy
- Correct model: orbiting+infall+Hubble.
- Shelf knows about H(z)!

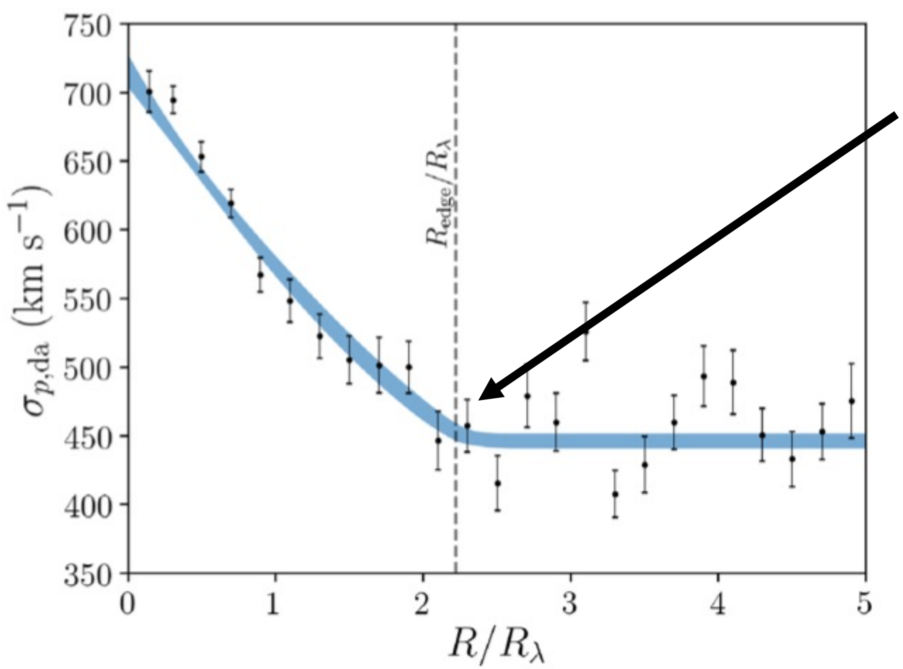
Infalling



Implication no. 4: Measuring H_0

- The "shelf" in the LOS PDF knows about the Hubble constant.

- Not the only way H can be constrained!



This edge is set by the halo radius.

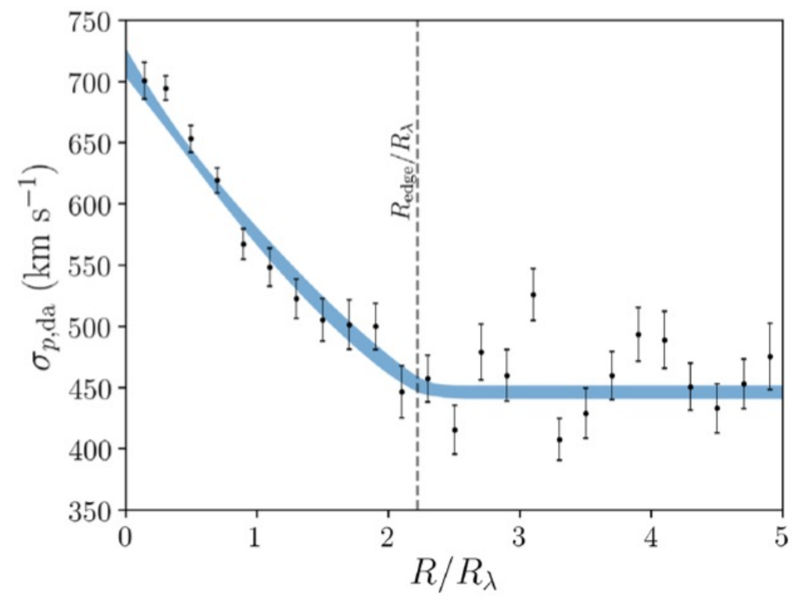
- Feature is observed as an *angular* scale

$$D_{\mathrm{A}}\theta_{\mathrm{edge}} = r_{\mathrm{halo}}$$

Implication no. 4: Measuring H_0

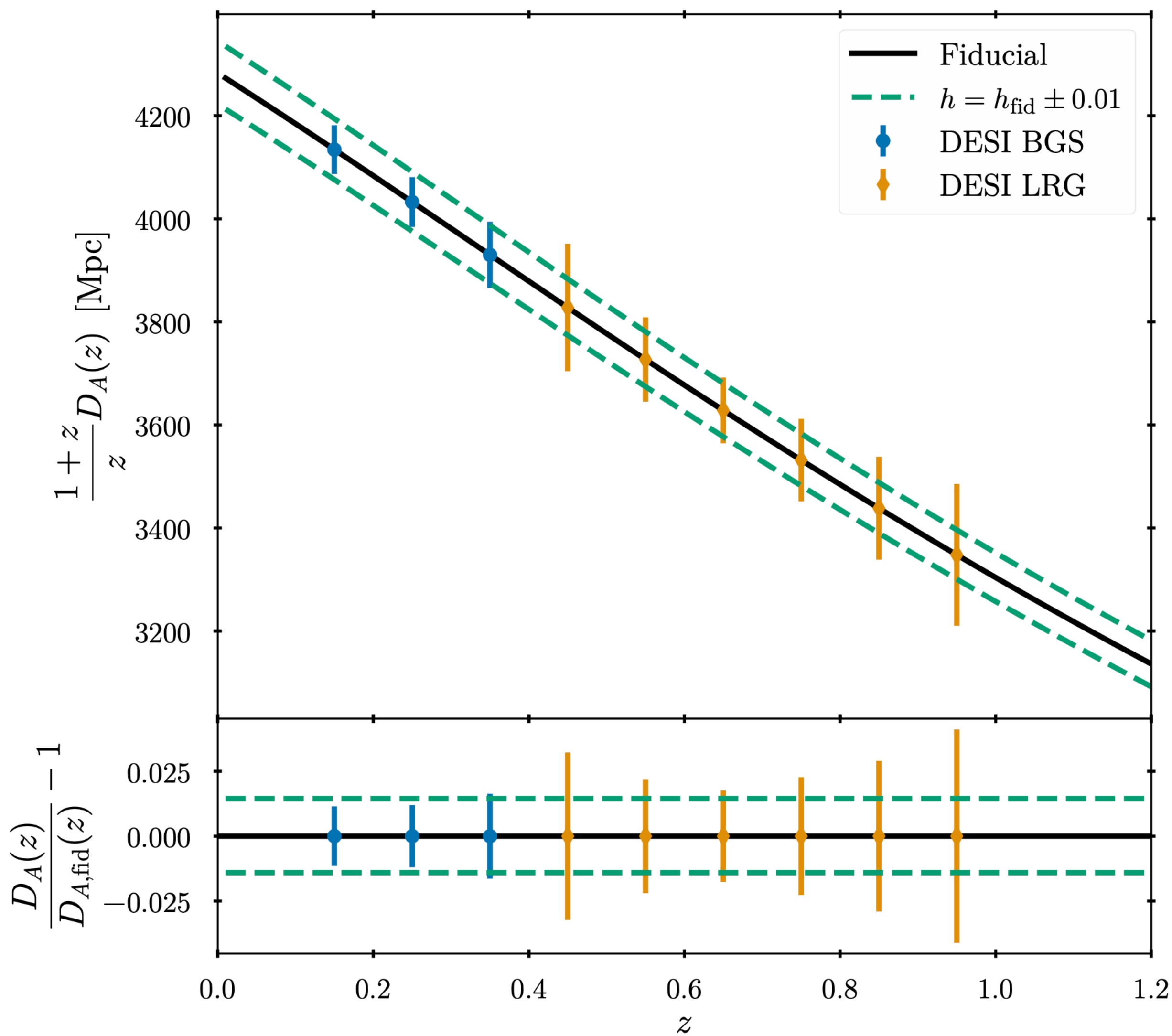
$$D_{\mathrm{A}}\theta_{\mathrm{edge}} = r_{\mathrm{halo}}$$

Measured — Inferred from cluster mass



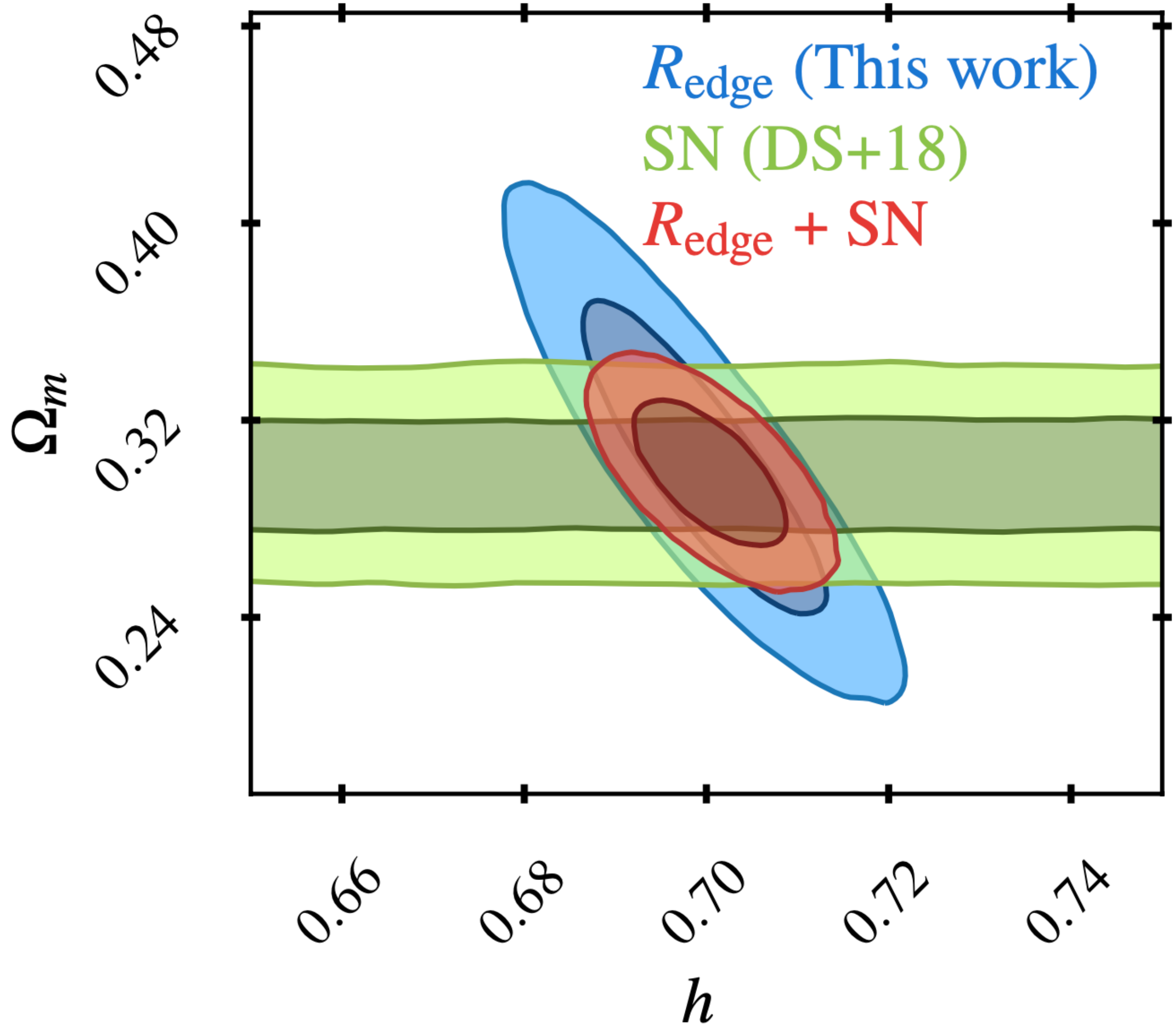
- Multiple cross-checks on mass calibration:
  - Amplitude of vel. dispersion profile
  - Cluster abundance
  - Weak lensing

Measuring H_0 w/ DESI



Wagoner, ER, et al. 2021: 2010.11324

Measuring H_0 w/ DESI



Wagoner, ER, et al. 2021: 2010.11324

Implication no. 5: A Tool for Calibrating Projection Effects

Will projection effects impact the profile of <u>orbiting</u> galaxies? What about infalling?

Implication no. 5: A Tool for Calibrating Projection Effects

Projection effects:

- do NOT impact the profile of orbiting galaxies.
- **boost the profile of infalling galaxies.**

➢ What about the velocity distributions or orbiting galaxies? What about infalling?

Implication no. 5: A Tool for Calibrating Projection Effects

Projection effects:

- do NOT impact the profile of <u>orbiting</u> galaxies.
- **boost the profile of <u>infalling</u> galaxies.**
- do NOT impact the <u>velocity dispersion</u> of either orbiting or infalling galaxies.
    - Impact on velocity distribution comes through the increased number of infalling galaxies.

➢ The impact of projection effects can be disentangled using the orbiting/infall framework.

Summary

- Halos ought to be defined in terms of orbiting vs infalling particles.
  - Simplifies halo statistics
    - Halo mass function is Press-Schechter.*
    - Halo bias is described by peak-background split.
  - Orbiting density profile is nearly isothermal, with an exponential truncation.
    - Truncation radius defines a unique *halo radius*.
    - Enables accurate fitting functions of the halo profile.

Summary

- Halos ought to be defined in terms of orbiting vs infalling particles.
  - Orbiting/infall dichotomy is a powerful framework for describing the projected phase space of clusters.
  - The halo radius is an obvious feature of the projected phase space structure.
  - We can use the projected phase structure of clusters to measure the Hubble constant.