Dark Matter Halo from Inside Out

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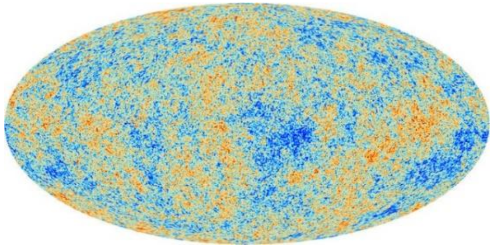
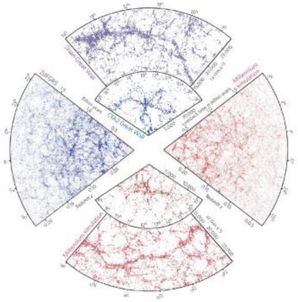
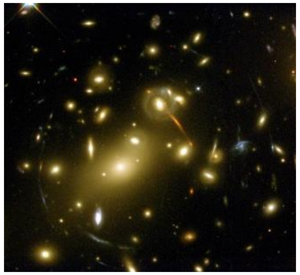
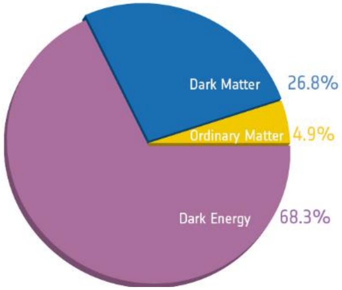
The cold dark matter paradigm

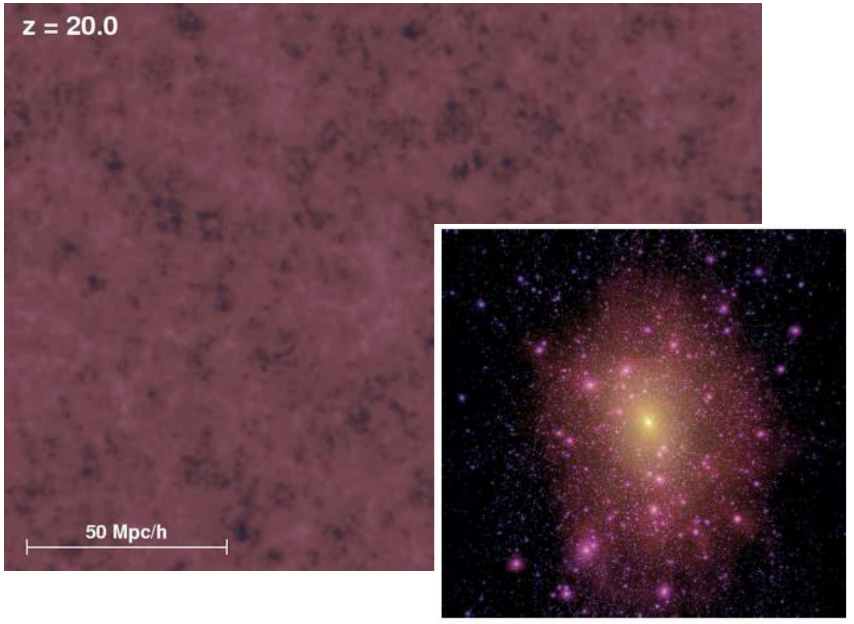






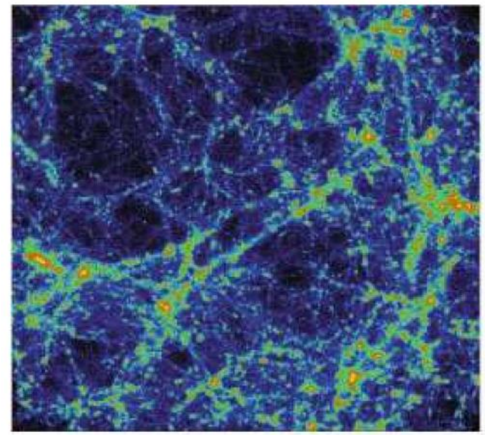
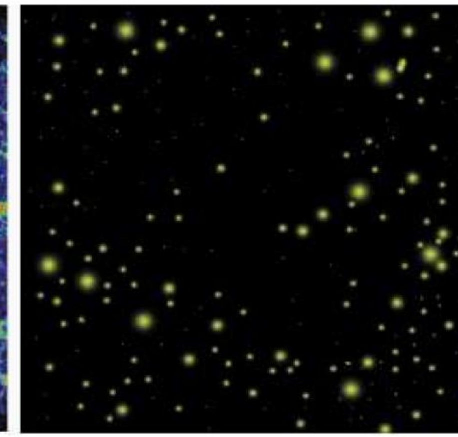


- Concordance cosmology
  - 85% cold dark matter
  - Only gravity, no other interaction
- Numerical simulation
  - Detailed prediction about the distribution of dark matter
- Dark matter halo
  - Approximately virialized (equilibrium) objects
  - Numerical simulation←→Analytical understanding

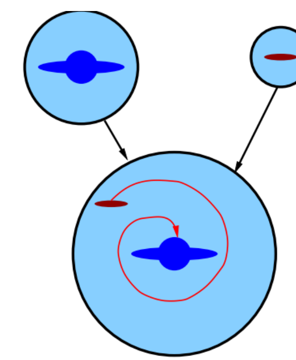


Dark Matter Halos

- Decomposing largescale structure
  - Largescale distribution of halos
  - Internal structure of halos

- Decomposing galaxy formation/distribution
  - Galaxies form within halos
  - Halo formation history→ galaxy formation history
  - Halo distribution→galaxy distribution
    - Subhalo→satellite galaxy

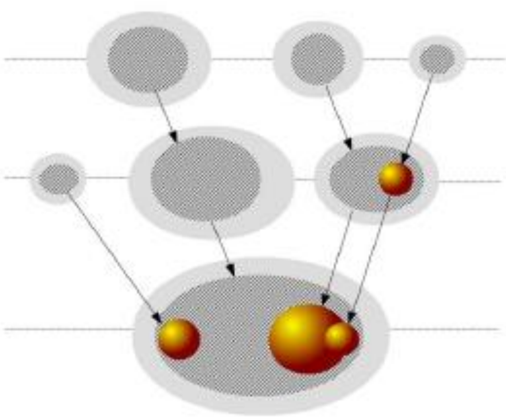



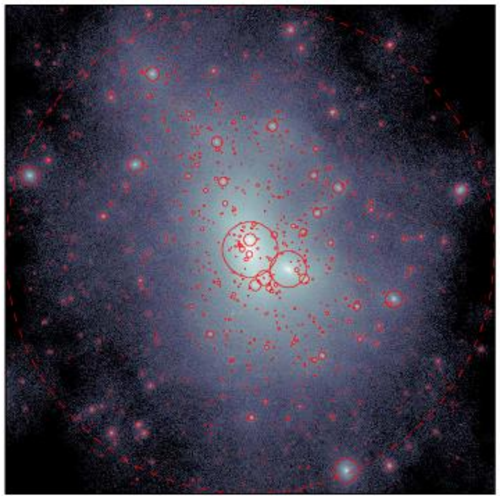
Outline

- The quasi-equilibrium structure of DM halos
- The structure around halo boundary and beyond

Quasi-equilibrium: A halo full of clumps

- Subhalos exist as a result of halo mergers
- Tracking halos→ recover subhalos (HBT)

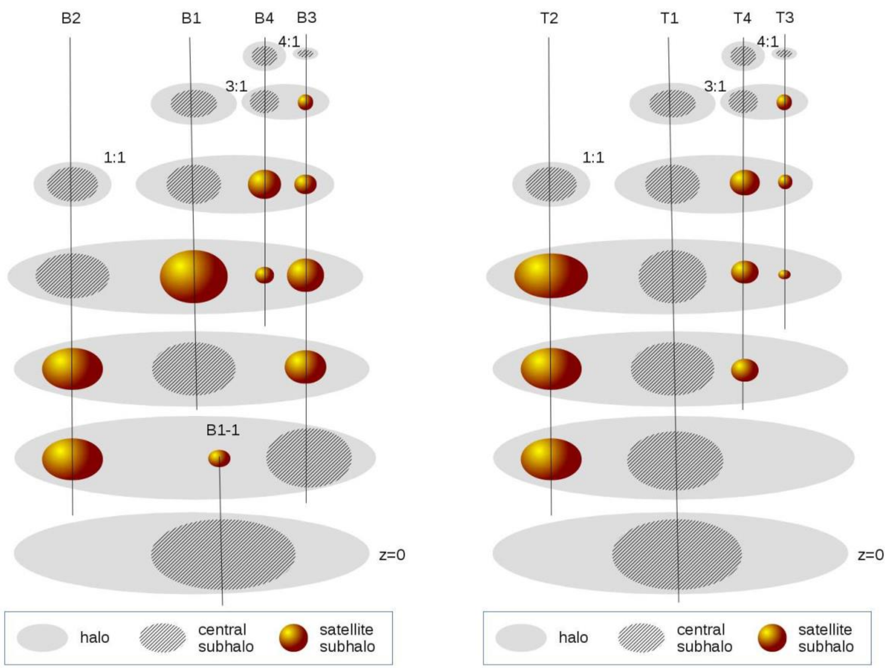




Han+13, 18

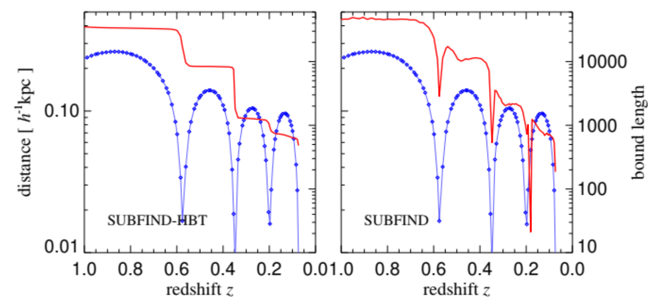
The superior power of HBT

SUBFIND+DTree HBT+



Aq-A2 halo merger graph

Han+, 2018



Simulating cosmic structure formation with the GADGET-4 code

Volker Springel[1]★, Rüdiger Pakmor[1], Oliver Zier[1], and Martin Reinecke[1]

[1]*Max-Planck-Institut für Astrophysik, Karl-Schwarzschild-Straße 1, 85740 Garching bei München, Germany*

9 October 2020

Integrated into GADGET-4 (Springel+ 2020) on-the-fly

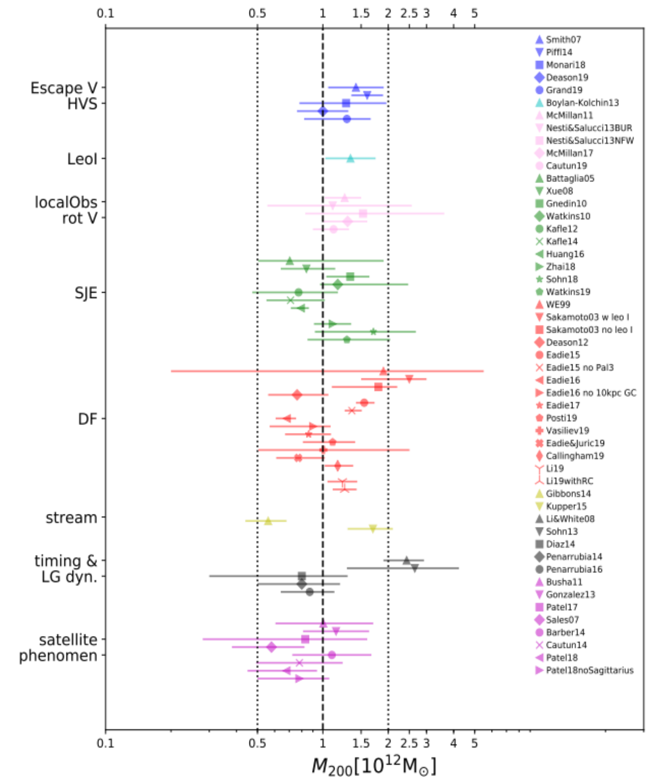
How much is a halo (not) in equilibrium?

- Equilibrium halo

→time-independent phasespace distribution function

→dynamical modelling

  - $P_{\psi}(\vec{x}, \vec{v}) \Rightarrow \psi$
  - Is the MW halo in dynamical equilibrium?

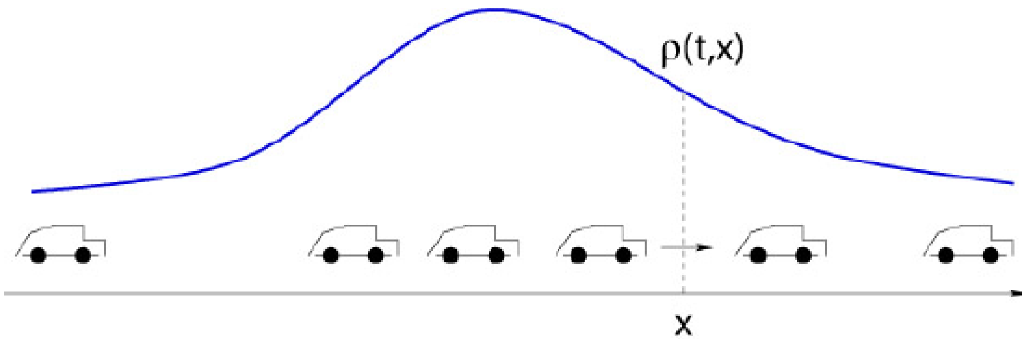


Wang, JH+ 2015, 2020

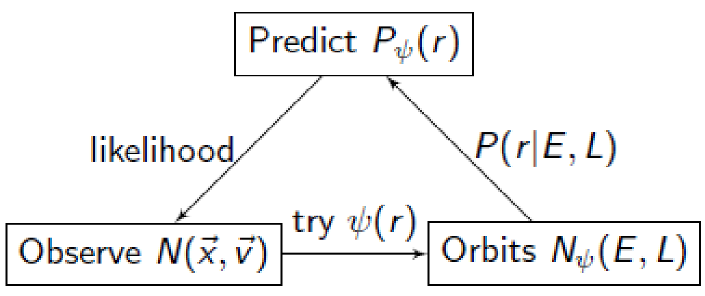
oPDF: a minimal assumption method

Steady-state solution to collisionless Boltzmann equation:

$$dP(x|\text{orbit}) \propto dt$$



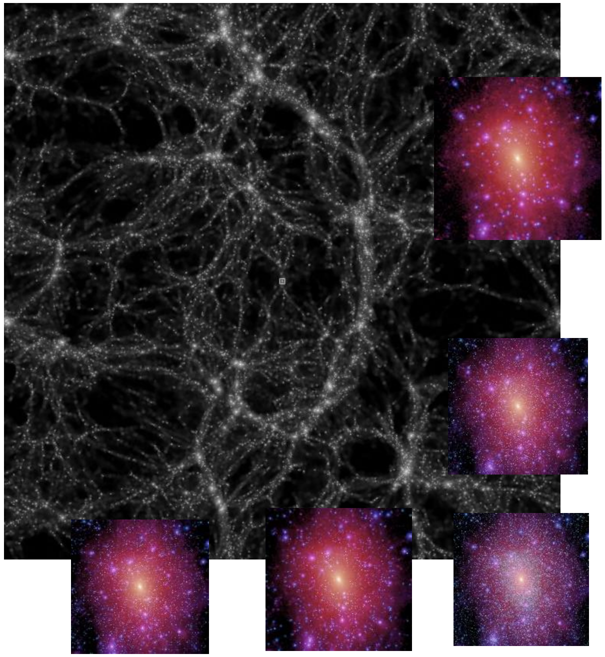
$$dP(r|E,L) = \frac{dr}{v_r(E,L,r)T(E,L)}$$

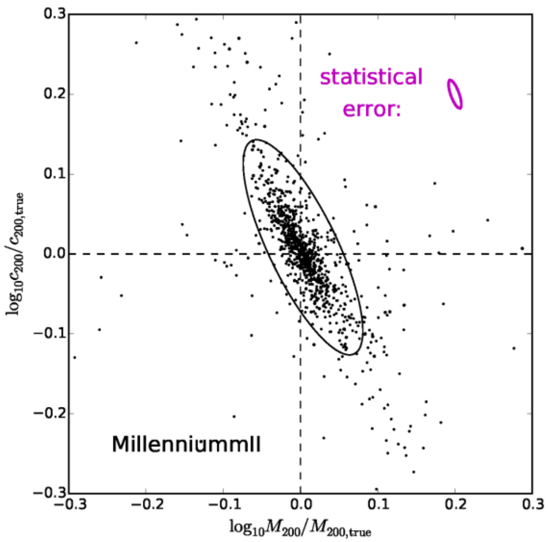


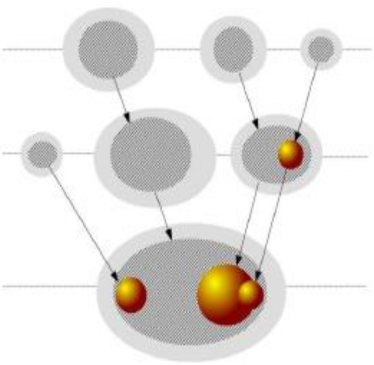
JH+2016a

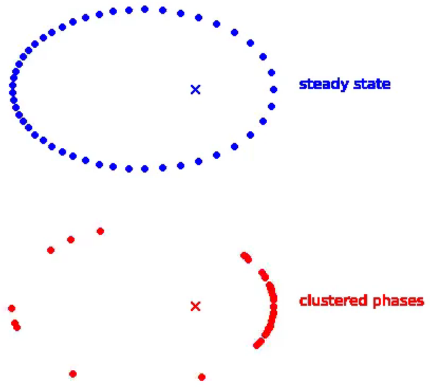
oPDF: fits to many halos

- Significant irreducible bias
  - Stochastic and ensemble unbiased
  - limiting precision $\sigma_M \sim 0.1$ dex (20%) for DM
  - Deviations from steady-state: quasi-equilibrium
    - Limited number of phase independent tracers





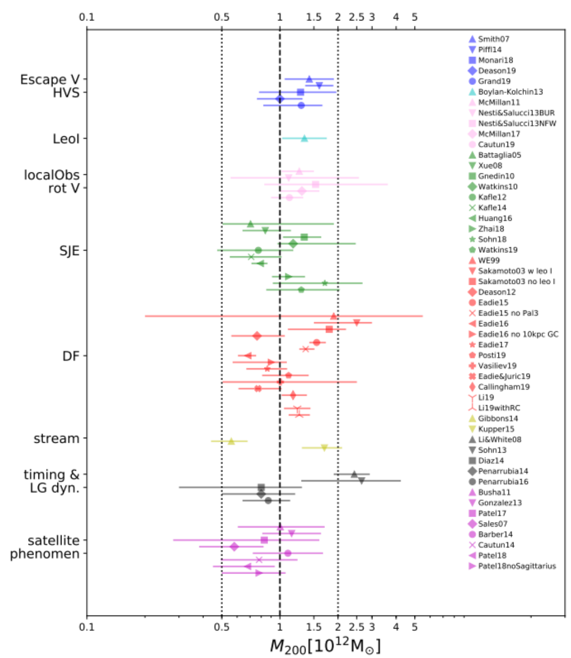


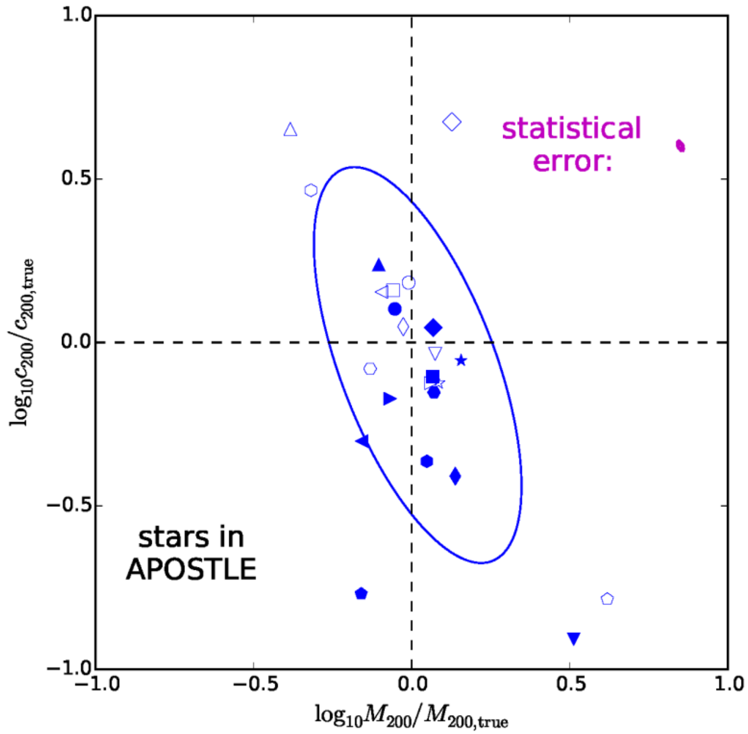


Wang, JH+ 2017

oPDF: fits to stars

- Stars deviate more from steady state
  - 0.3 dex scatter in mass (x2)
  - Comparable to the x5~=2x2 observational scatter!





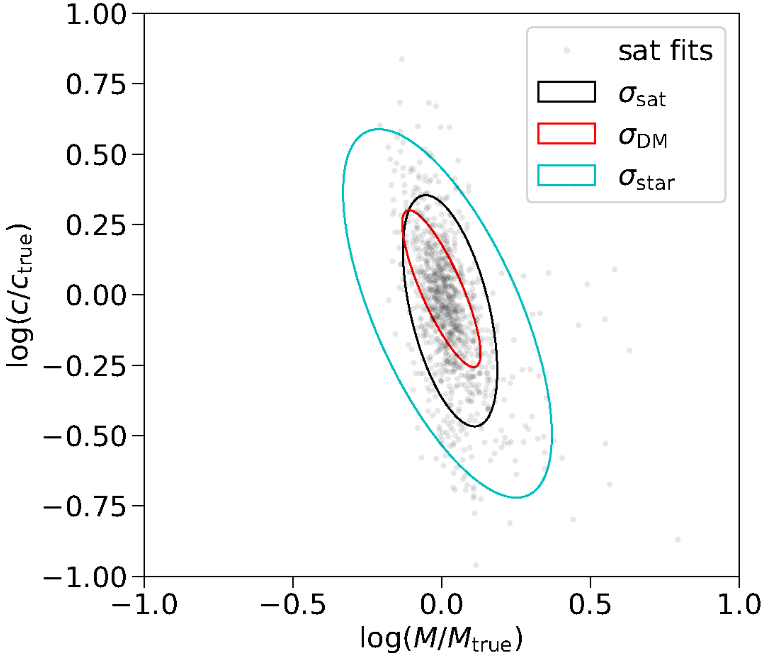
Wang, JH+ 17

Same result from Jeans Eq. (Wang, JH+18)

Overcoming the limiting precision

- Factor of ~2x2 uncertainty
  - Halo star
  - Steady-state modelling
- Improvement
  - Better tracer than star
  - Beyond steady-state

Improving the limiting precision: Satellites as better tracers

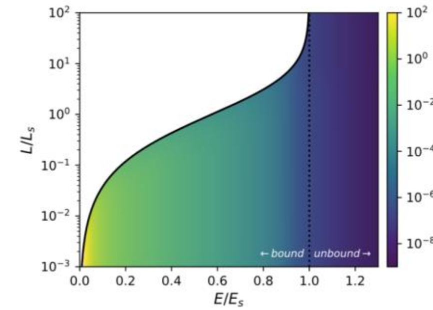


- Satellite systematic biases ~0.1 dex << stars~0.3dex

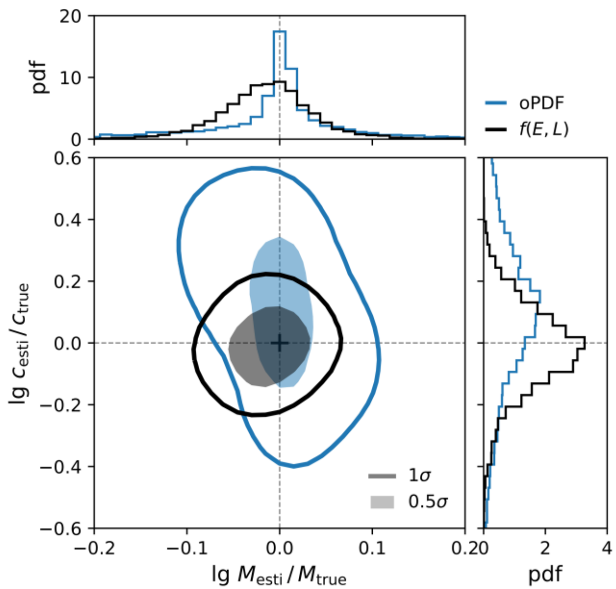
JH+. 2020

Improving the limiting precision: using non-steady-state information

$$f(\boldsymbol{r}, \boldsymbol{v}) = \frac{|v_r|}{8\pi^2 L} p(r|E, L) p(E, L),$$

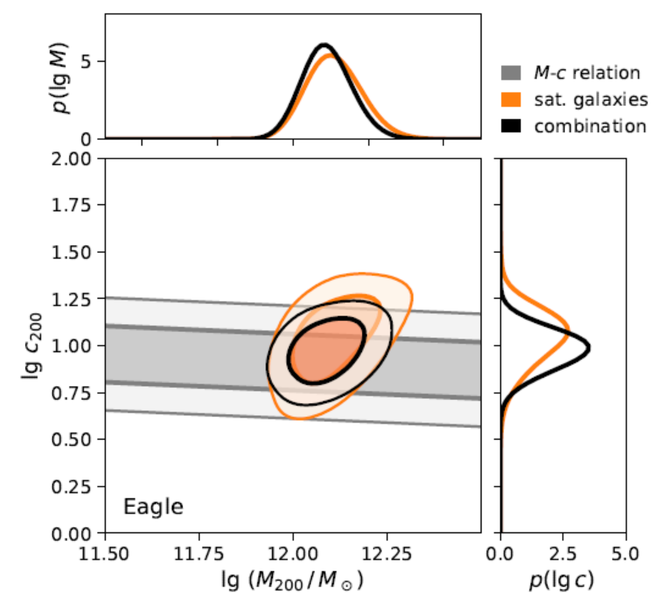


Mock tests



Li, Qian, JH+ 2019

GAIA observations of 28 Satellites



$M = 1.23^{+0.21}_{-0.18} \times 10^{12} M_{\odot}$ $c = 9.4^{+2.8}_{-2.1}$

Li, Qian, JH+ 2020

Outline

- The quasi-equilibrium structure of DM halos
- The structure around halo boundary and beyond

Density distribution out to large scale

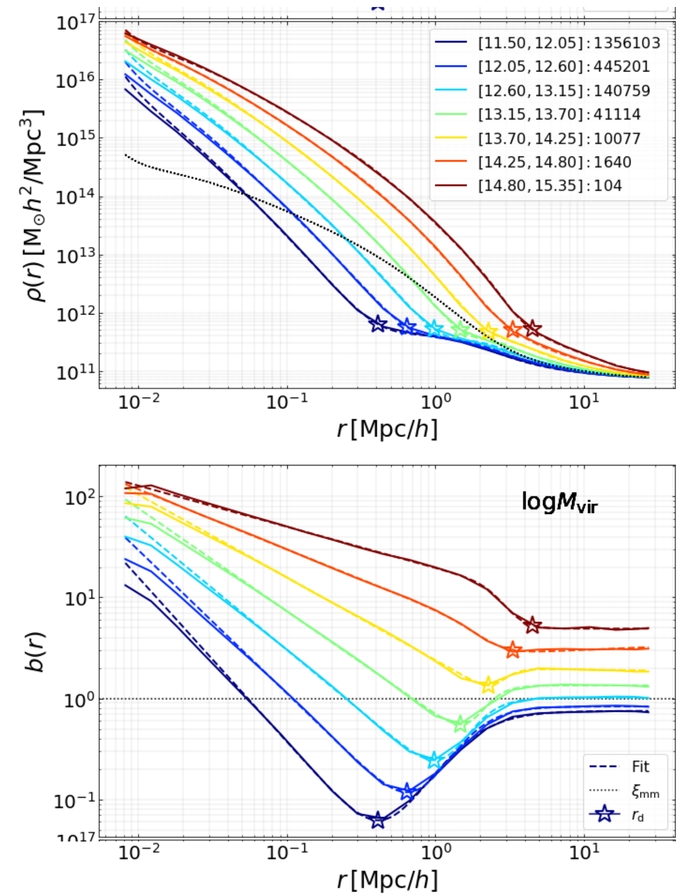
- Correlation function: average overdensity
  - Overdensity $\delta = \rho/\bar{\rho} - 1$

$$\xi_{hm} =< \delta_h \delta_m > =< \delta_m | h >$$

- Bias: relative clustering

$$b(r) = \frac{\xi_{\rm hm}(r)}{\xi_{\rm mm}(r)} = \frac{\langle \delta(r) \rangle}{\xi_{\rm mm}(r)}$$

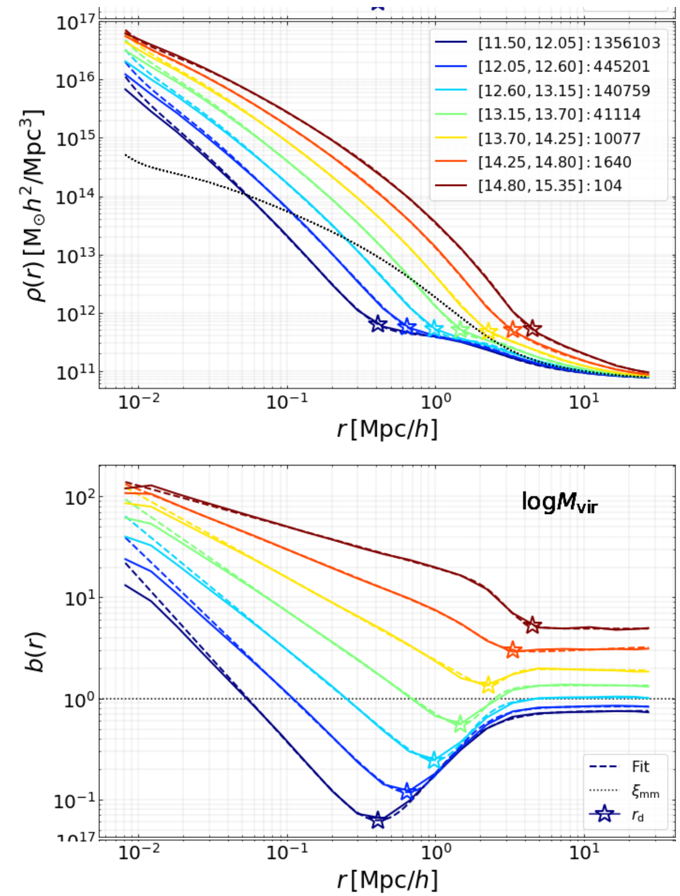
  - Largescale: linear
  - Small scale: one-halo term
  - Characteristic radius



Fong & Han 2020, (arXiv2008.03477)

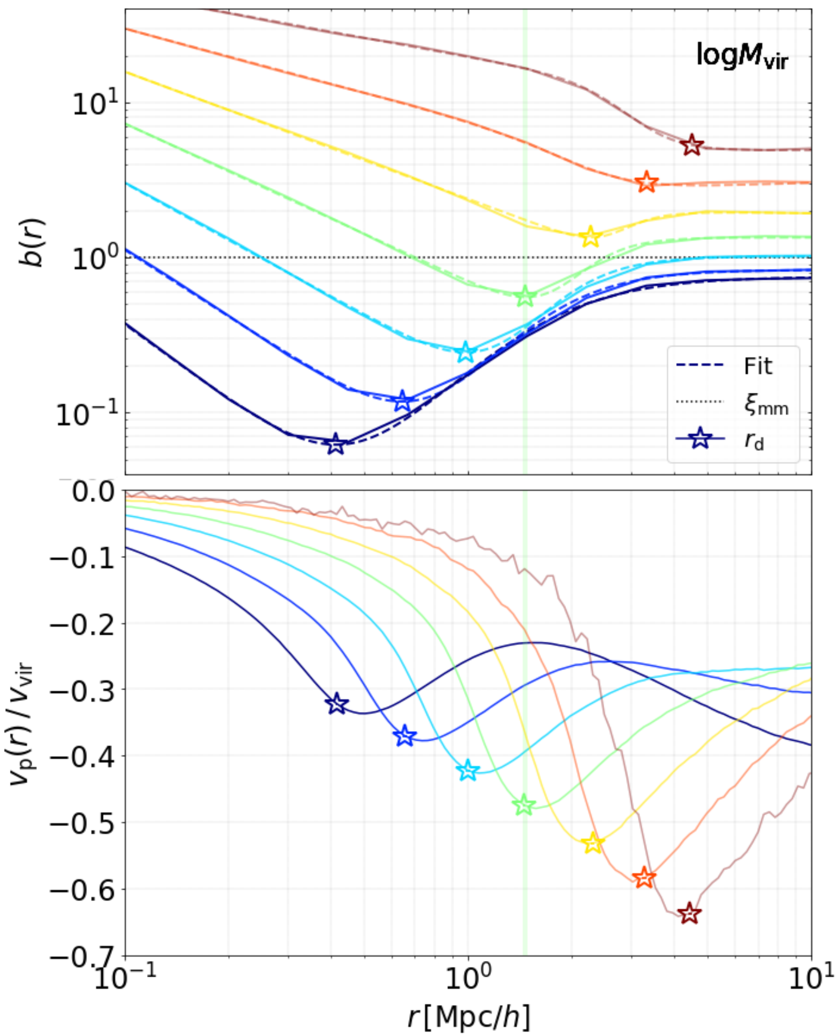
Halo packing boundary

- At the bias minimum:
  - clustering is the weakest (relative to average matter clustering): region of influence
  - Signature of halo exclusion: halos do not overlap each other by def
  - Dynamically: competing accretion between the central halo and the surrounding halos
    - Well formed in low mass
    - Starting to form in high mass

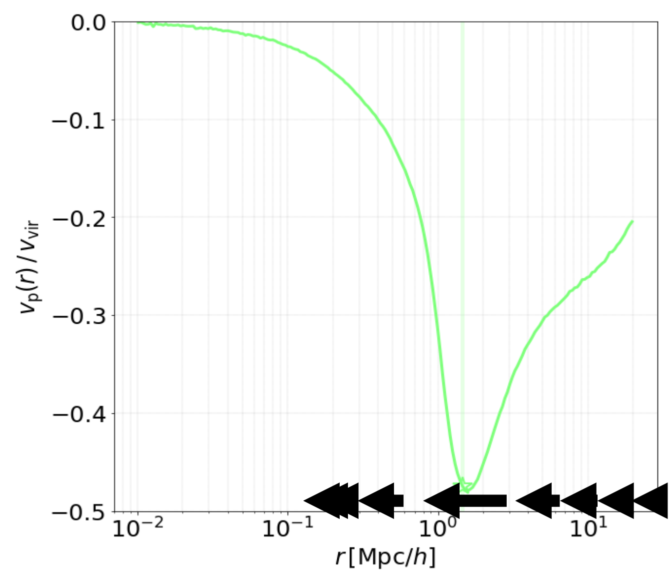


Fong & Han 2020, (arXiv2008.03477)

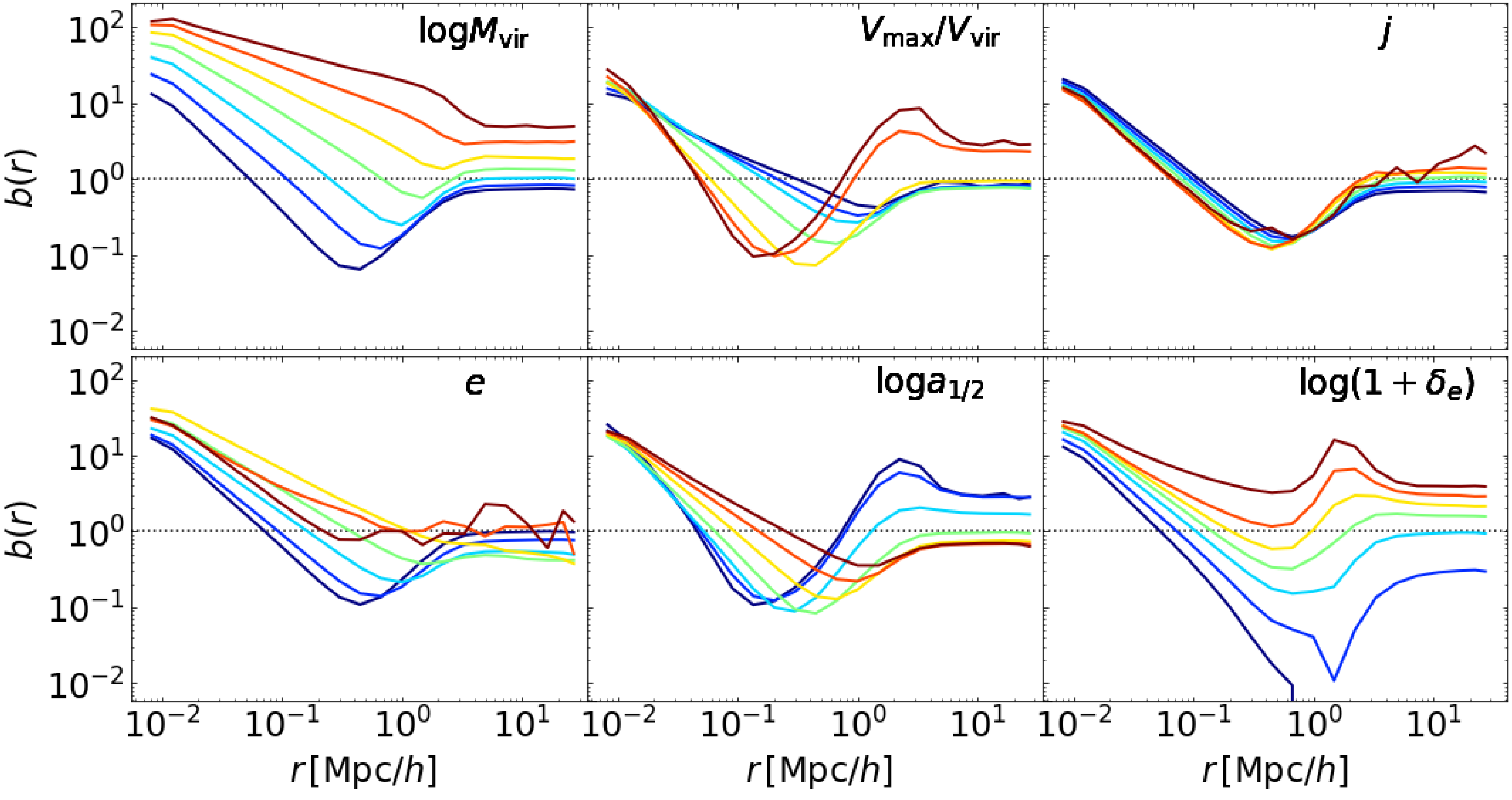
Matches the maximum infall location

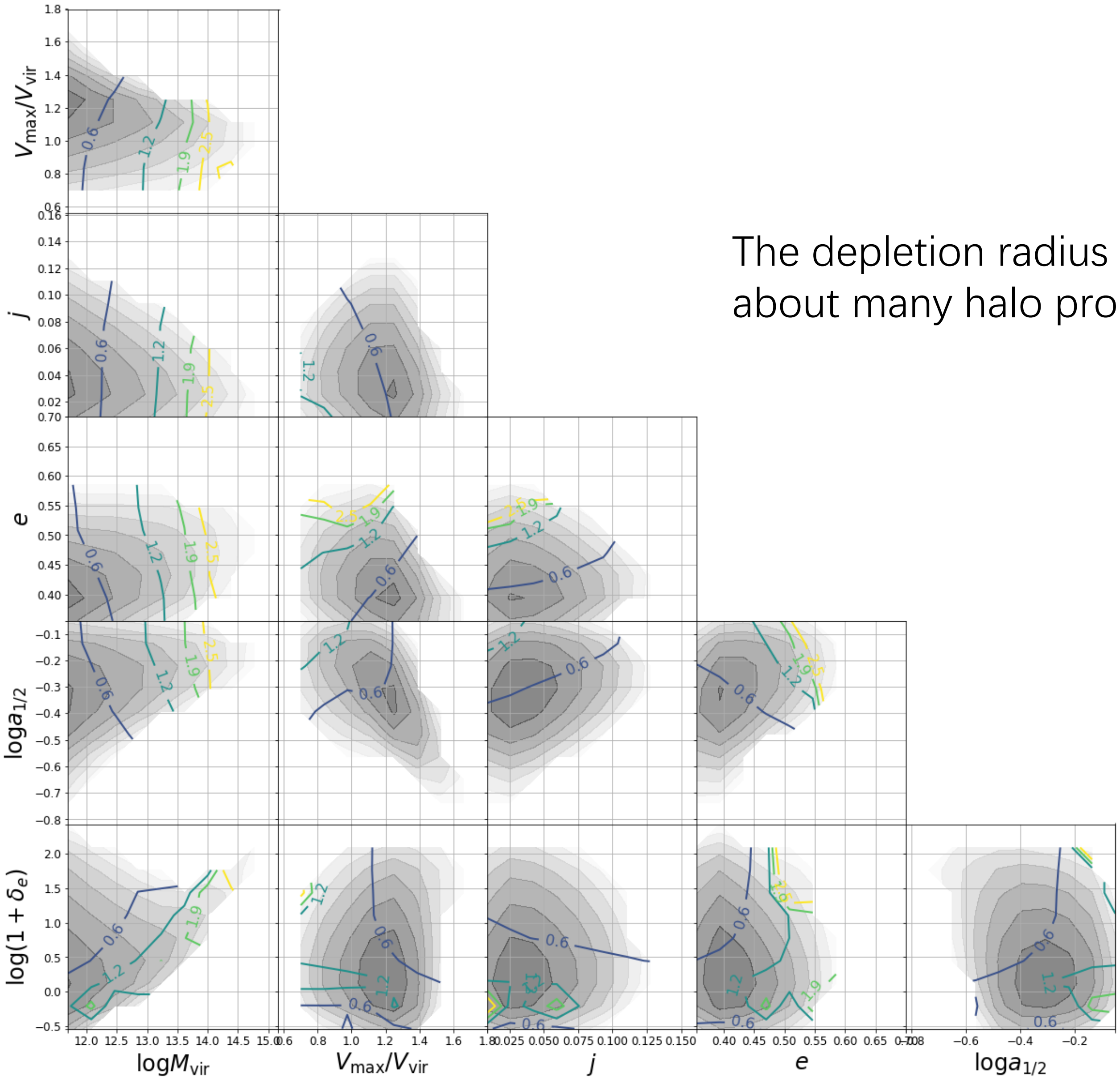


- Maximum infall location
  - Matter drain from outside and dumped inside: depletion radius
  - Competition between accreting halo and environment, creating a relative void



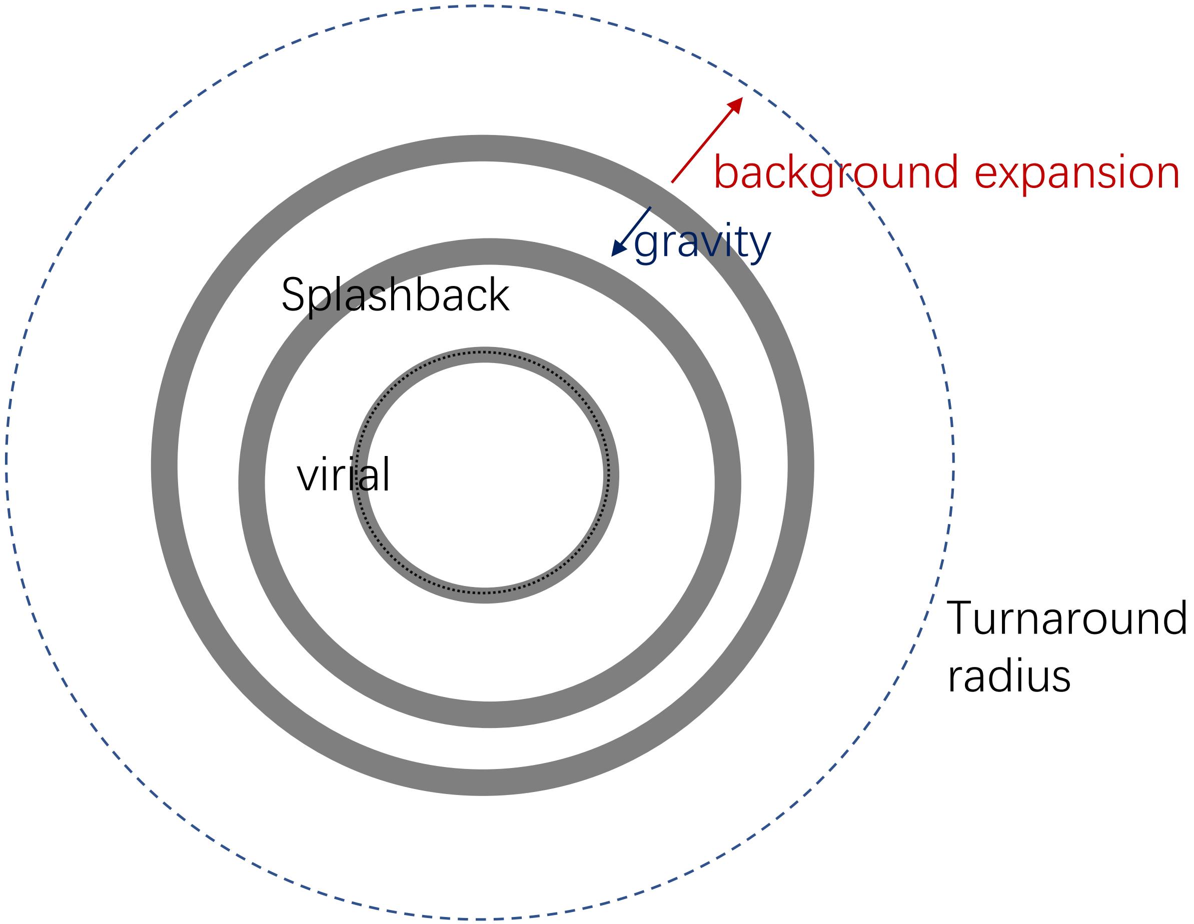
Ubiquitous bias trough



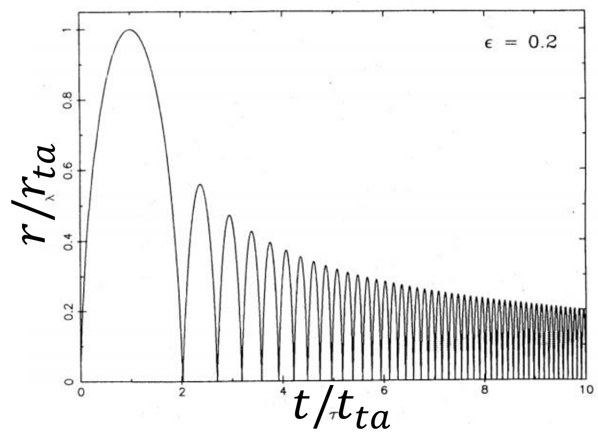


The depletion radius carries information about many halo properties

Characterizations of halo boundary in spherical collapse



Existing characterizations of halo boundary



6 FILLMORE AND GOLDREICH Vol. 281

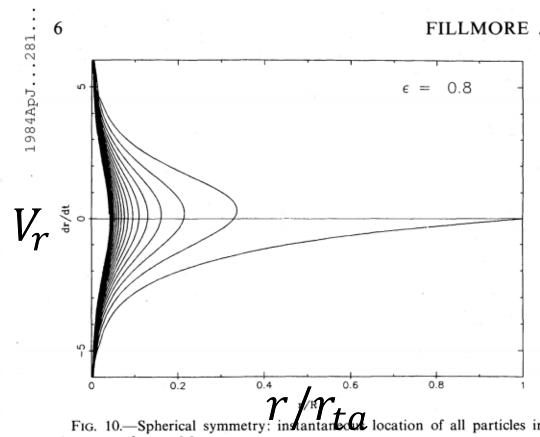


FIG. 10.—Spherical symmetry: instantaneous location of all particles in phase space for $\epsilon = 0.8$.

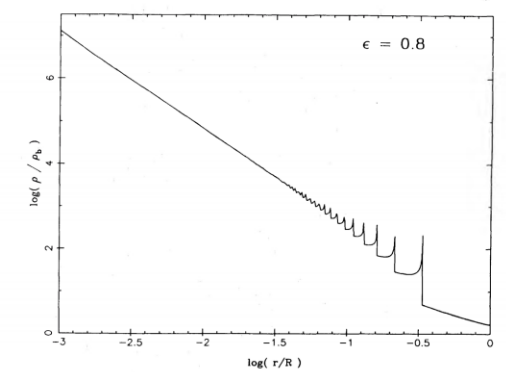
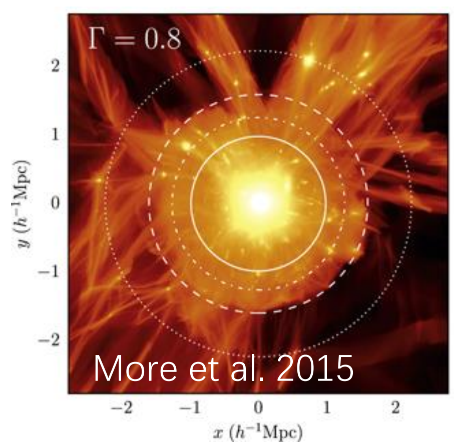
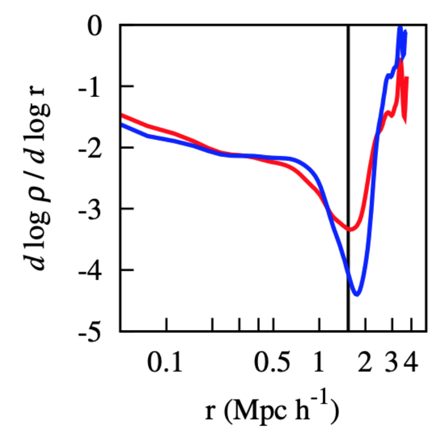


FIG. 11.—Spherical symmetry: ratio of actual to background density for $\epsilon = 0.8$.

- virial radius: equilibrium region
- turnaround radius: collapsing region
- Splashback radius: first apocenter in accreting halo





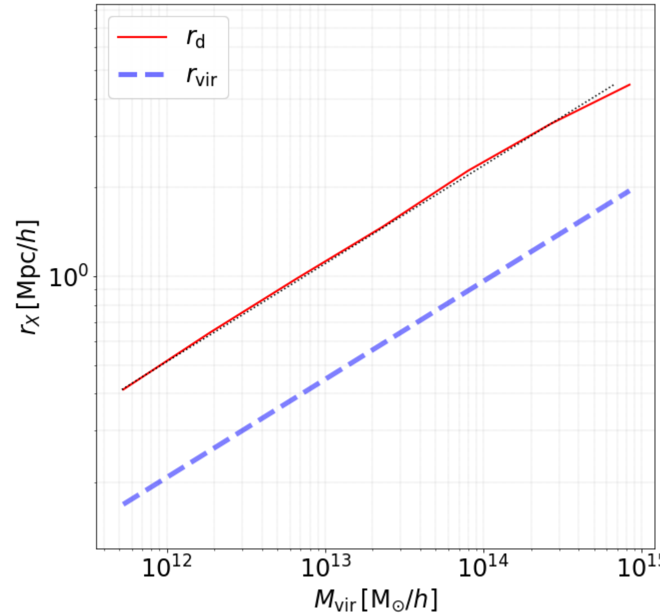
Adhikari et al. 2014

Depletion radius vs virial radius

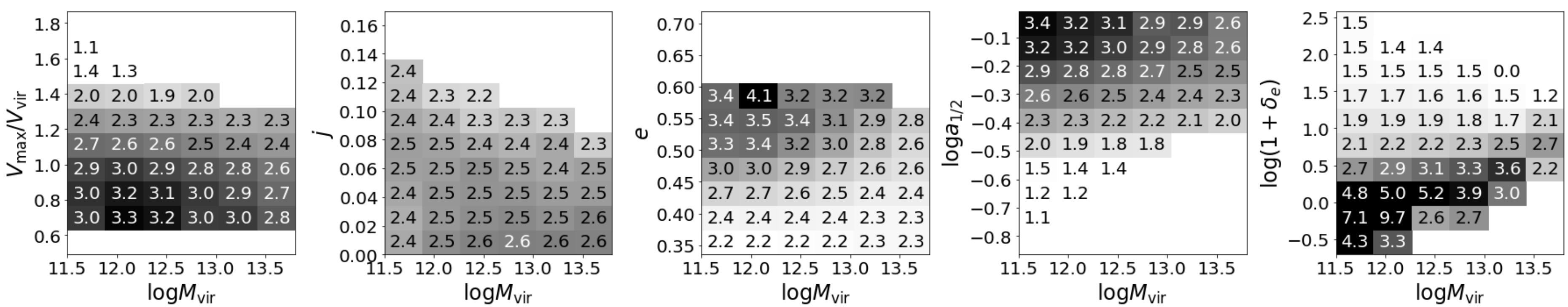
- Depends on mass in a simple way

$r_d = 2.5\, r_{vir}$

- also depends on many other properties

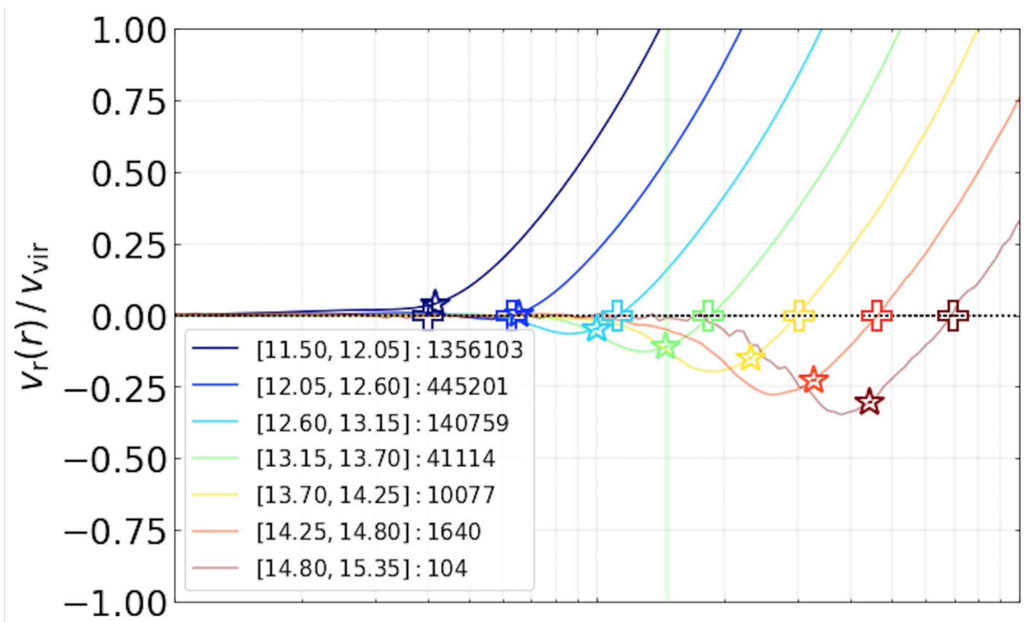


r_d/r_{vir}



Depletion radius v.s. Turnaround radius

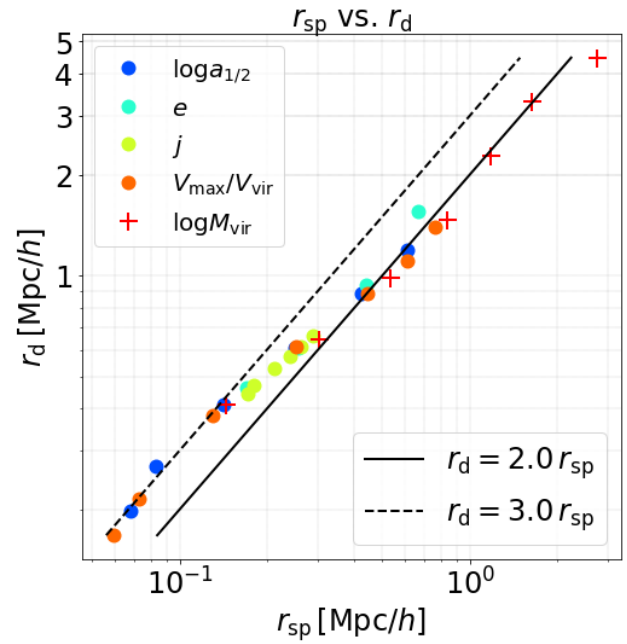
$v_r = v_p + v_H$ v_H = Hubble Flow



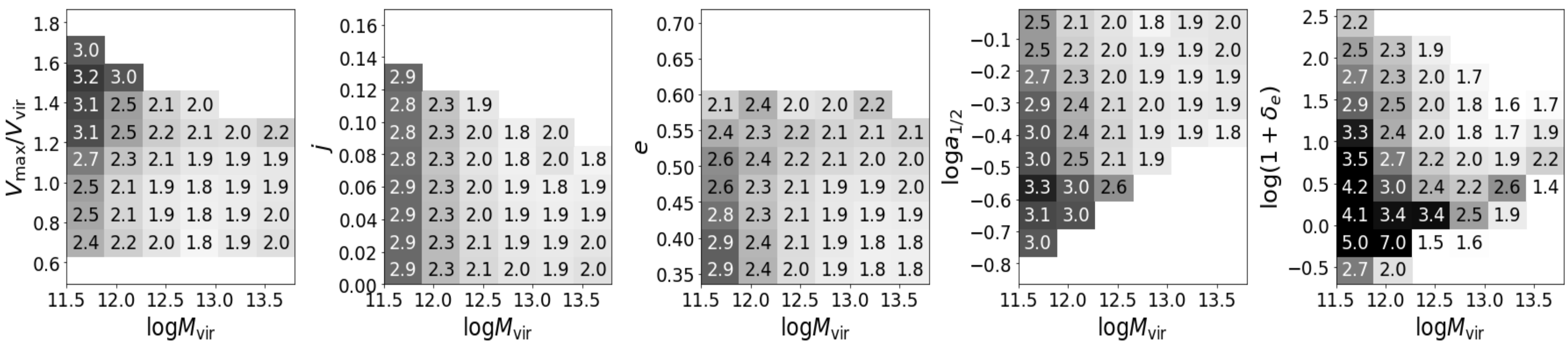
- Low mass halos: depletion radius catch up with turnaround, growth have saturated
- Turnaround radius have also reached maximum (Tanoglidis et al. 2015), so that depletion radius can catch up

Depletion radius v.s. Splashback radius

- Low mass halos more puffy $\frac{r_d}{r_{sp}} \sim 3$ (high mass~2)

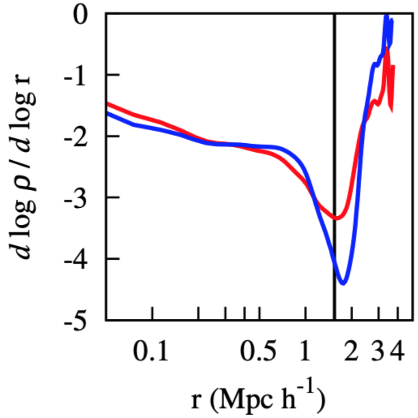


r_d/r_{sp}

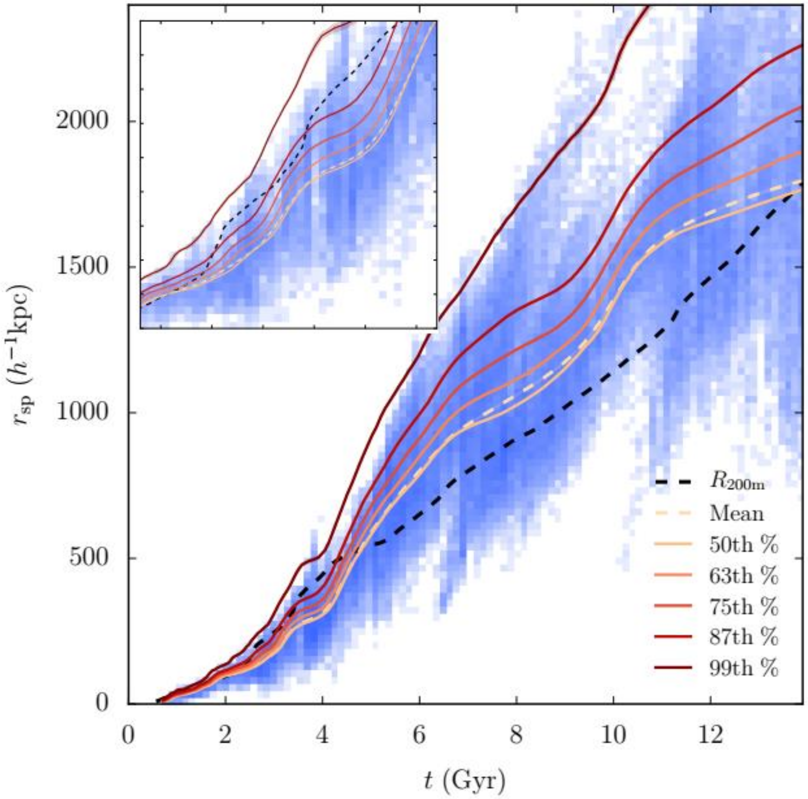


Difficulty in conventional splashback radius

- Wide distribution in splashback radius of different particles
- Ambiguity in defining the splashback radius
- Practically relied on steepest slope location to define splashback statistically



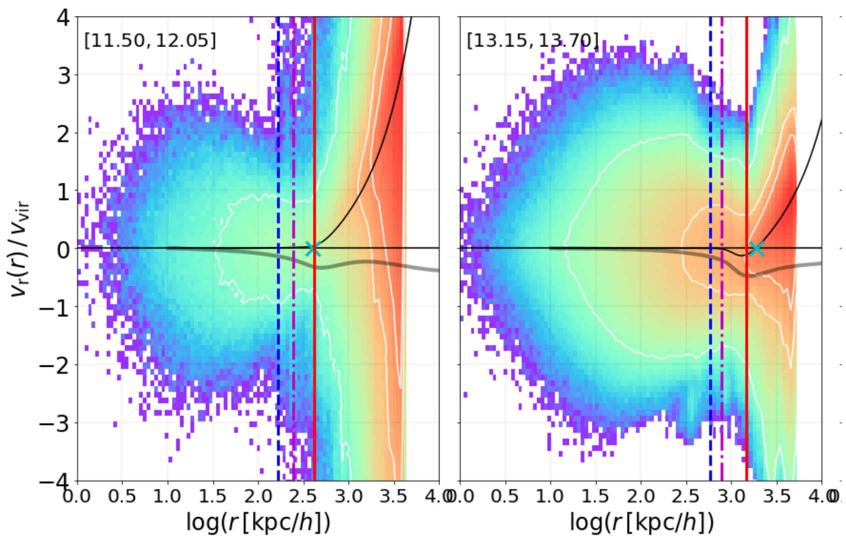
Adhikari et al. 2014

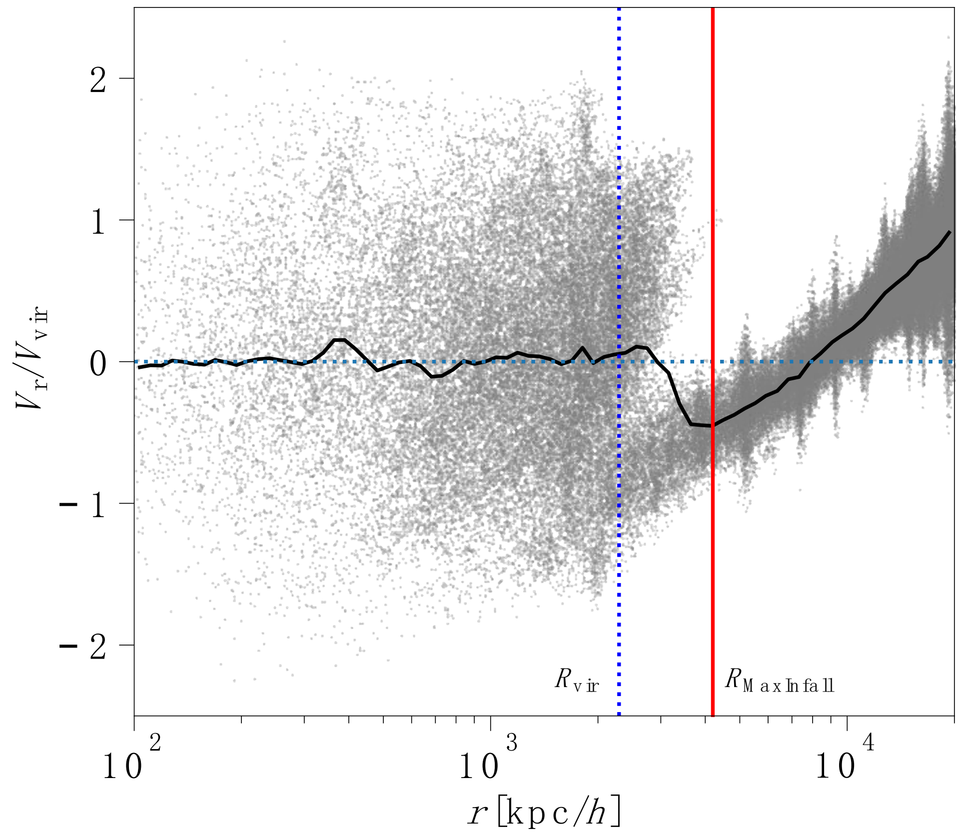


Diemer et al. 2017

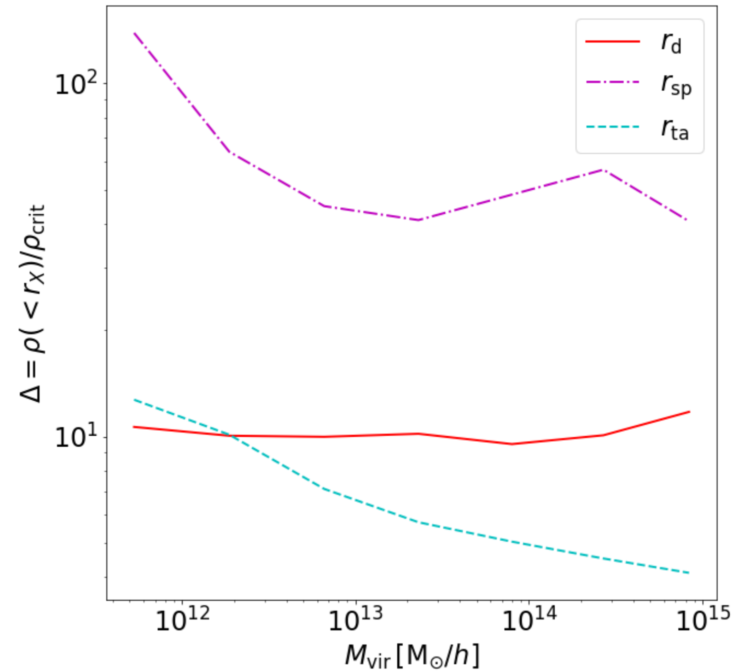
Depletion radius v.s. Splashback radius

- Radius enclosing a highly complete population of splashback orbits
    - Maximum infall due to outgoing material
- Natural boundary in phasespace

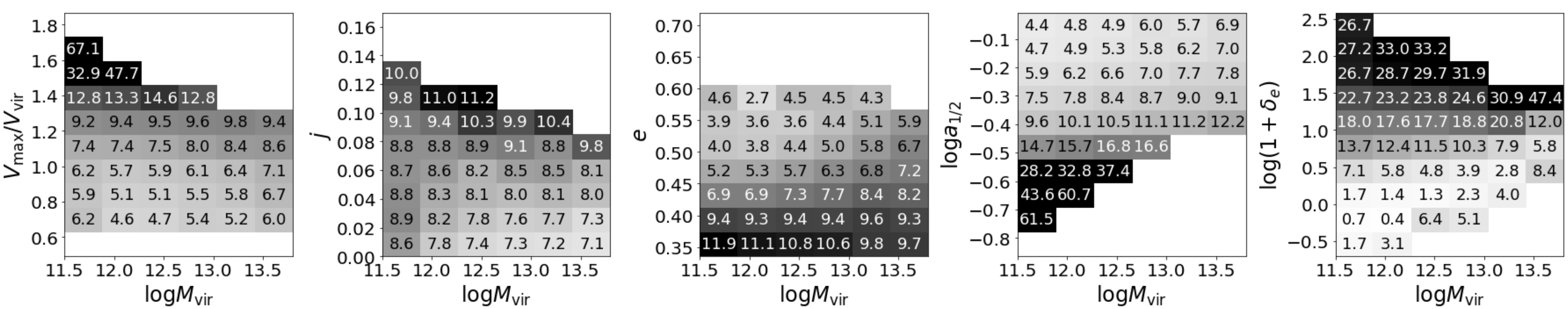




Density Contrast and Depletion radius

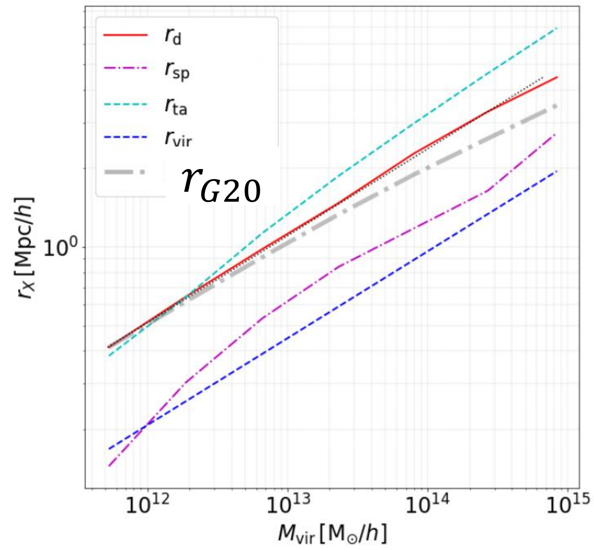


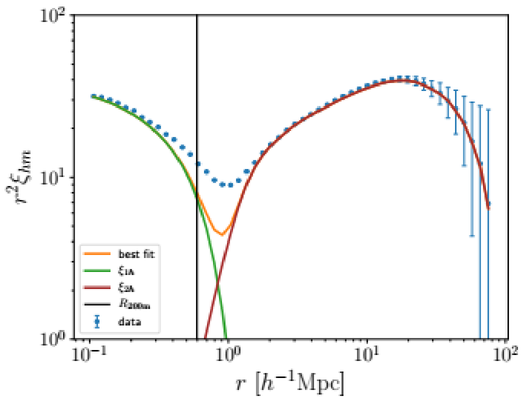
Binned by mass: $\bar{\rho}(< r_d) = 10\rho_{crit}$

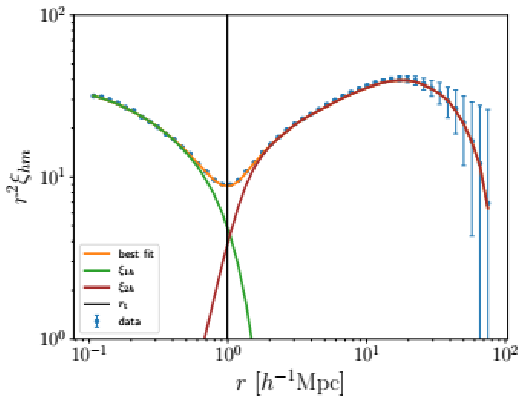


Depletion radius for halo model

- Garcia et. al. 2020 fitted for an optimal exclusion radius to be used in halo model
  - Virial radius not good
  - Best-fit radius close to $r^2\xi$ minimum
- Closely matches our depletion radius
  - Space for tuning







Garcia et. al. 2020

Summary

- The virialized part of DM halo is approximately in equilibrium
  - Hierarchical merging leads to formation of subhalos
  - The smooth halo is not in a steady-state, leading to an intrinsic limiting precision for pure steady-state methods
  - Satellites behave as an optimal dynamical tracer with less phase correlation
  - Dynamical mass precision can be further improved going beyond steady-state information
- We propose the depletion radius to demarcate the growing part of halo from the environment
  - Corresponds to minimum bias (weakest relative clustering)
  - Corresponds to maximum infall (the boundary between positive and negative density growth)
  - Corresponds to optimal halo exclusion radius
  - Simple properties while carrying comprehensive information

Describing the largescale distribution of halo

- The (inhomogeneous) distribution of halos relative to matter distribution ($\delta = \rho/\bar{\rho} - 1$)

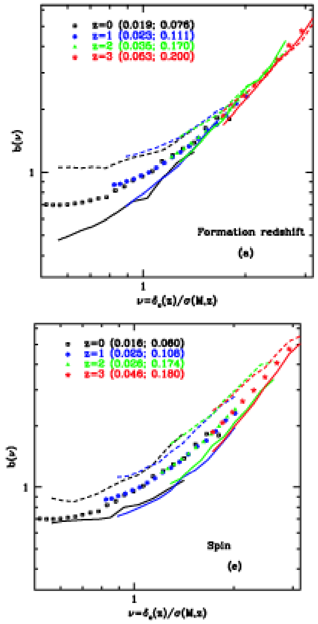
  - Simplest version: $\delta_h \sim b\delta_m$
  - Depends on every detail about the halo sample: multivariate

$$b(M, c, e, j, t_f, \ldots)$$

  - Previous works: marginalized dependences
    - Univariate: $b(M)$ expected from simplest EPS theory
    - Bivariate: assembly bias

$$b(M,c),\ b(M,j),\ b(M,t_f)\ldots$$

      - Debates on detection and unification
  - Ultimate: high-dimension?
    - $b(M) = \int b(M, c, e, j, t_f, \ldots) dP(c, e, j, t_f, \ldots)$



Gao&White07

How do we measure bias?

- Ensemble (statistical) estimator of bias
  - $\boldsymbol{\delta_h \sim b\delta_m \Leftrightarrow \xi_{hm} = b\xi_{mm}}$
- Correlation function: average density profile

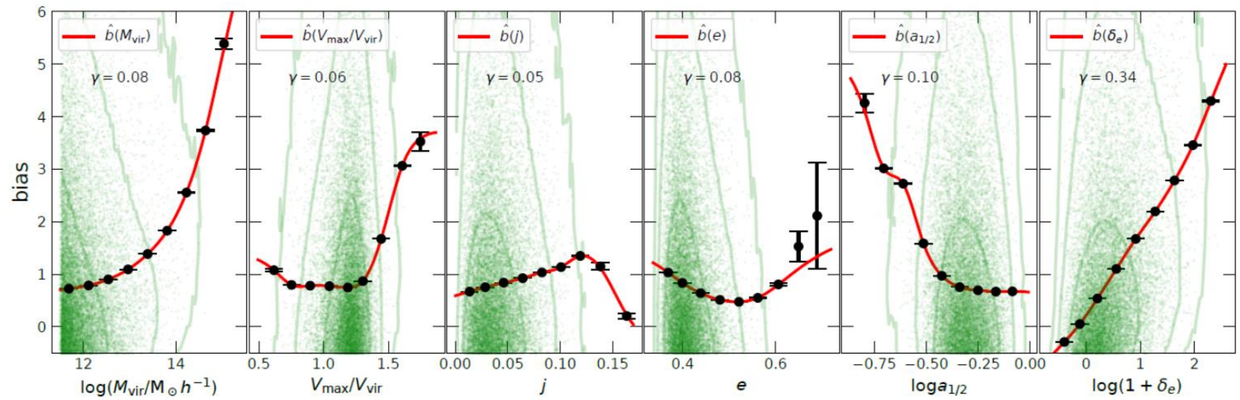
$$\begin{aligned} \xi_{hm} &= <\delta_h \delta_m> \\ &= <\delta_m | h> \end{aligned}$$

- Individual bias estimator

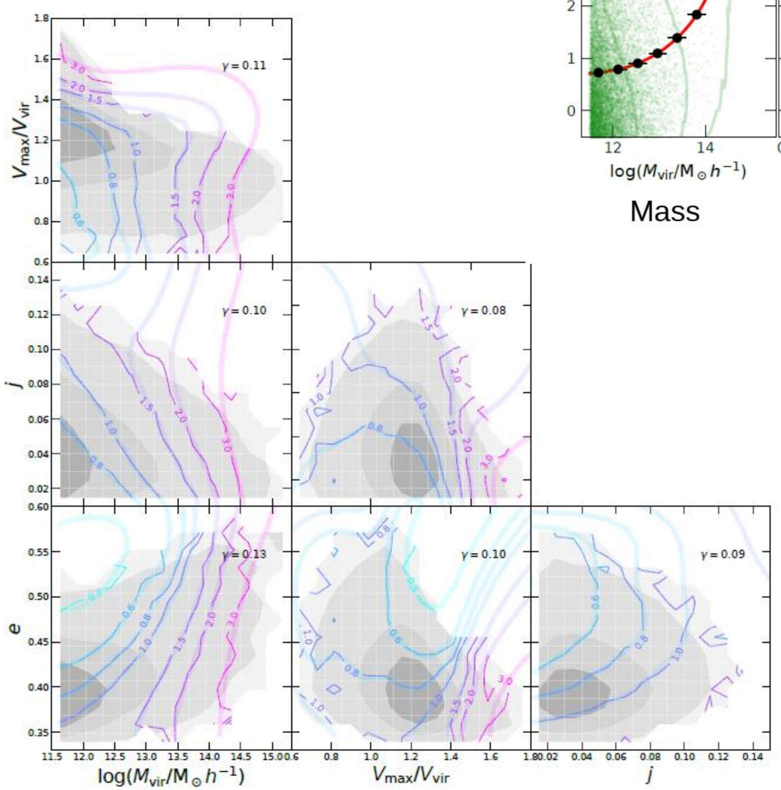
$$\beta(r) = \delta_m(r)/\xi_{mm}(r) \;\Rightarrow b = <\beta>$$

Measurements from simulations

$$b = <\beta>$$



Mass | Concentration | Spin | Shape | Formation Time | Environment



Gaussian Process Regression

- non-parametric fitting of multi-dimensional data

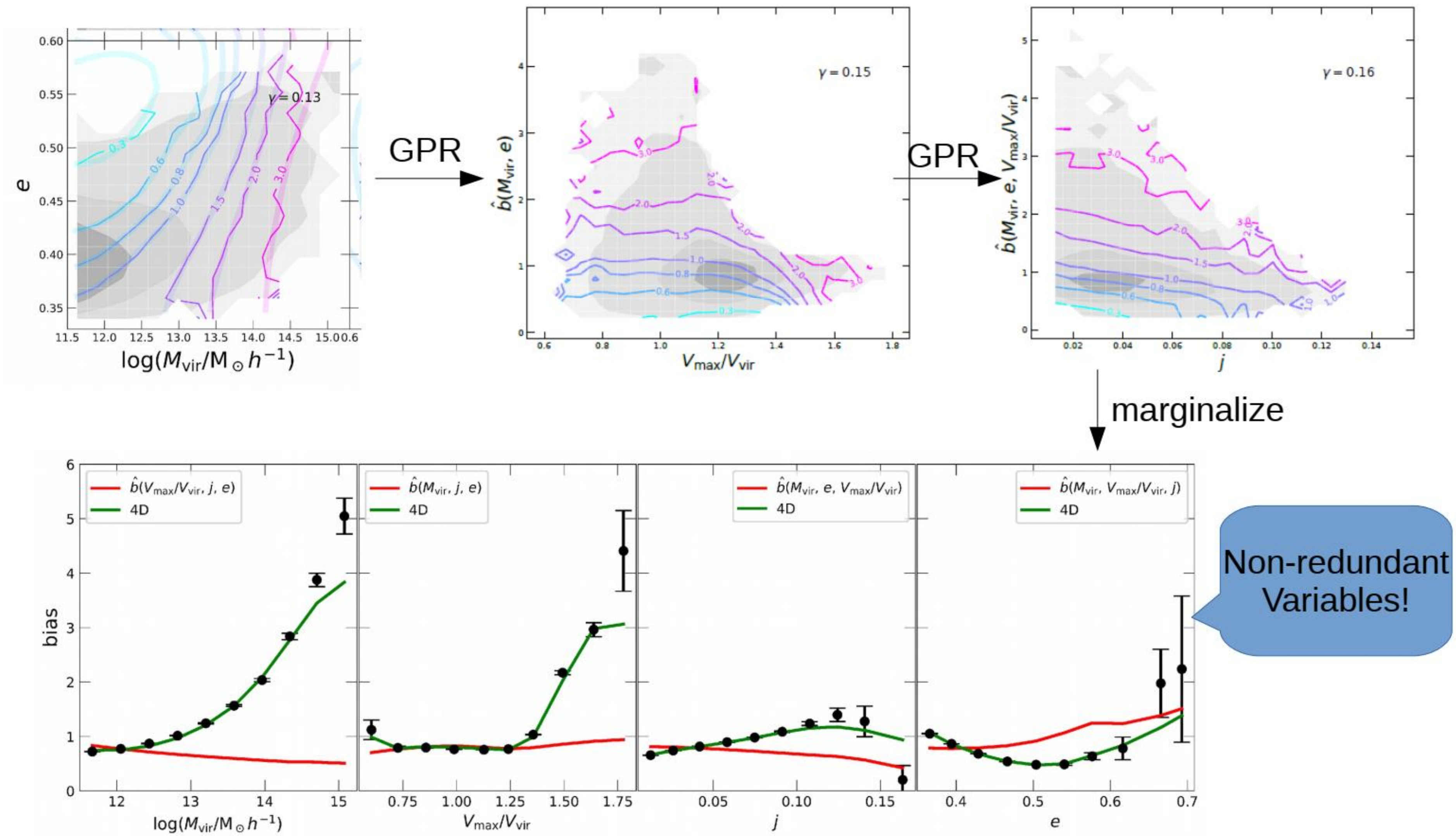
Bias maps

↓ *Gaussian Process Regression*

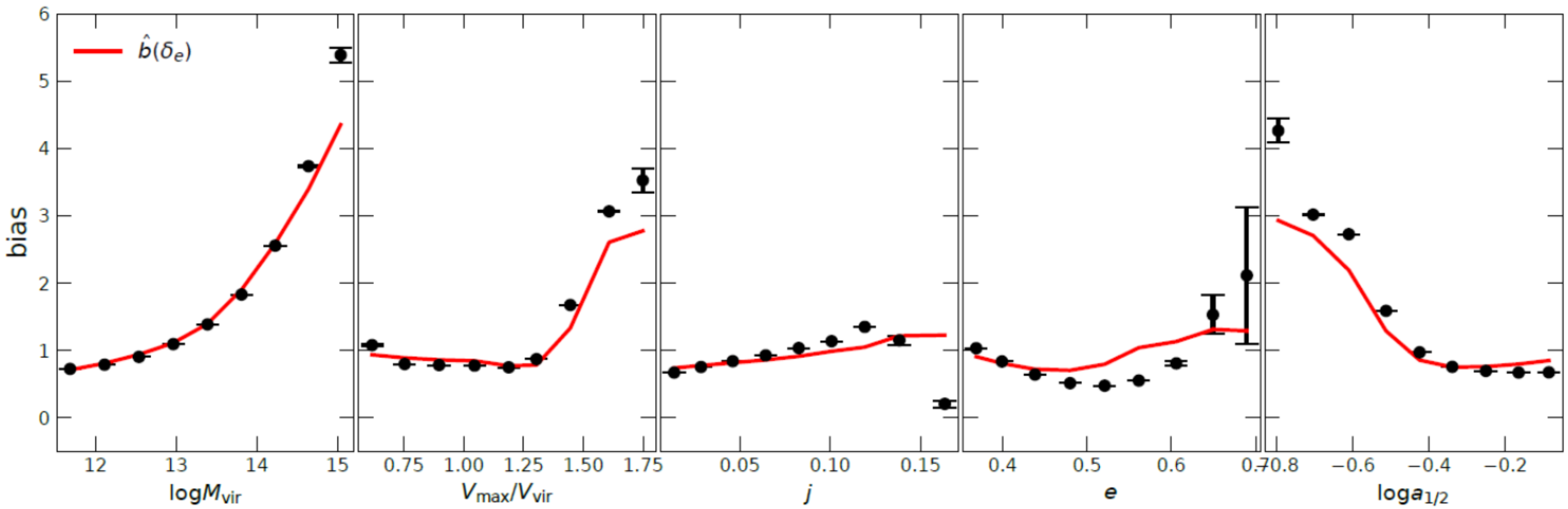
Bias estimators $\hat{b}(x, y)$

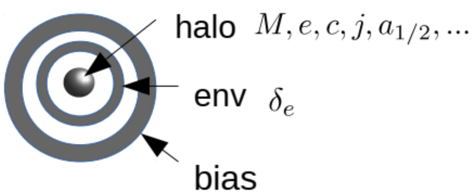
Han et al. 2019

Residual dependence and multivariate estimators

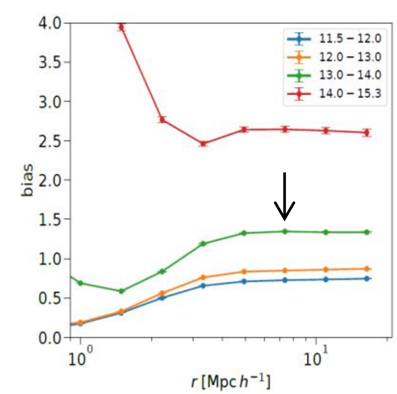


Environment rules over halo property dependence





Environment defined at r~1-2 Mpc

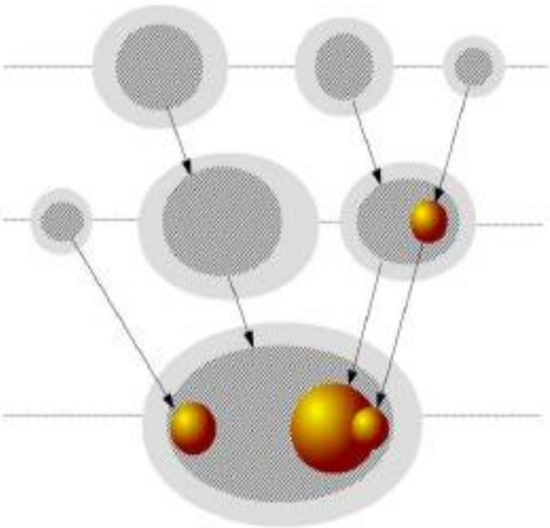


Summary

- The virialized part of DM halo is approximately in equilibrium
  - Hierarchical merging leads to formation of subhalos
  - The smooth halo is not in a steady-state, leading to an intrinsic limiting precision for pure steady-state methods
  - Satellites behave as an optimal dynamical tracer with less phase correlation
  - Dynamical mass precision can be further improved going beyond steady-state
- We propose the depletion radius to demarcate the growing part of halo from the environment
  - Corresponds to minimum bias (weakest relative clustering)
  - Corresponds to maximum infall (the boundary between positive and negative density growth)
  - Corresponds to optimal halo exclusion radius
  - Simple properties while carrying comprehensive information
- The clustering of halos depend on multiple halo properties non-redundantly
  - Environmental density as a super-proxy

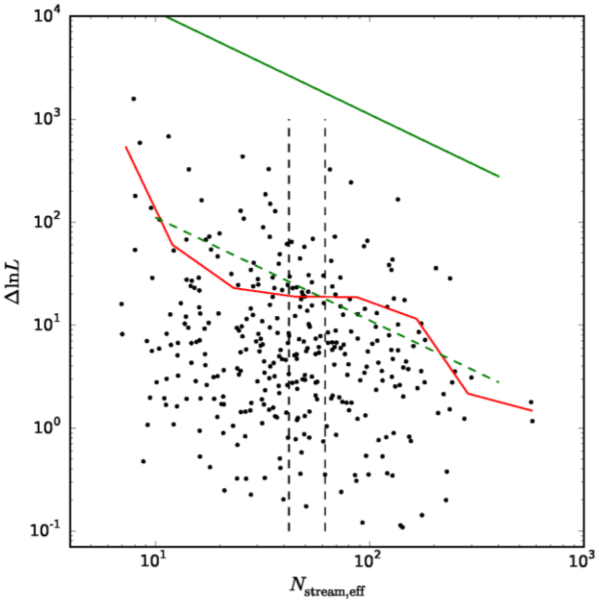
What determines the bias

- MAH-> stream->dynamics->bias



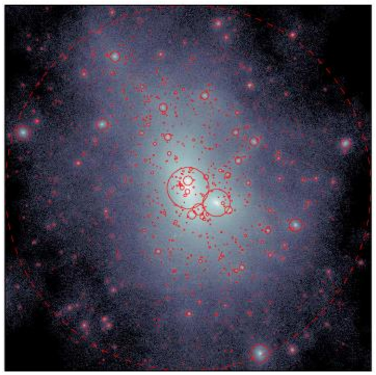
$$N_{\mathrm{stream,eff}} = \frac{(\sum n_i)^2}{\sum n_i^2} \in [1, m]$$

$$\Delta \ln L \sim \frac{N}{N_{\mathrm{eff}}} \chi^2(2)$$

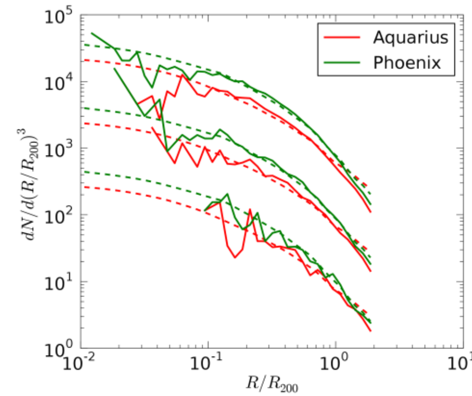


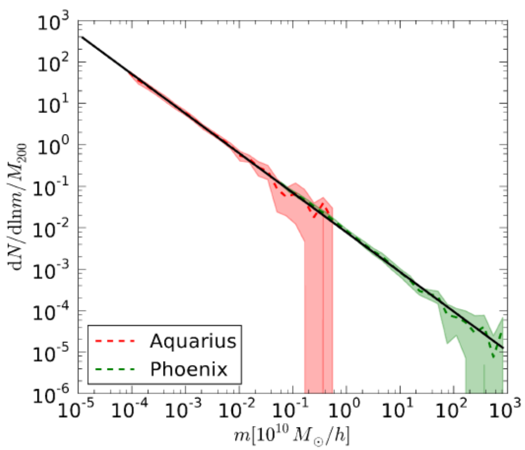
Wang, JH+ 2017

the universal distribution of subhalos

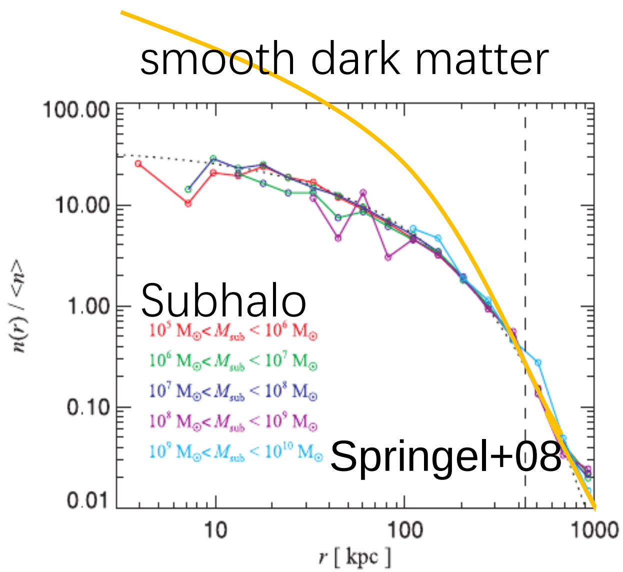


$$\frac{\mathrm{d}N}{\mathrm{d}^3R\mathrm{d}\ln m} \propto \rho_{\mathrm{sub}}(R)m^{-\alpha}$$

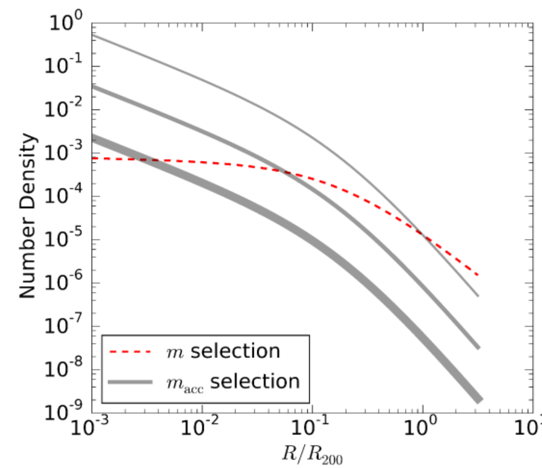




smooth dark matter



Subhalo as an evolving particle



JH+ 2016c