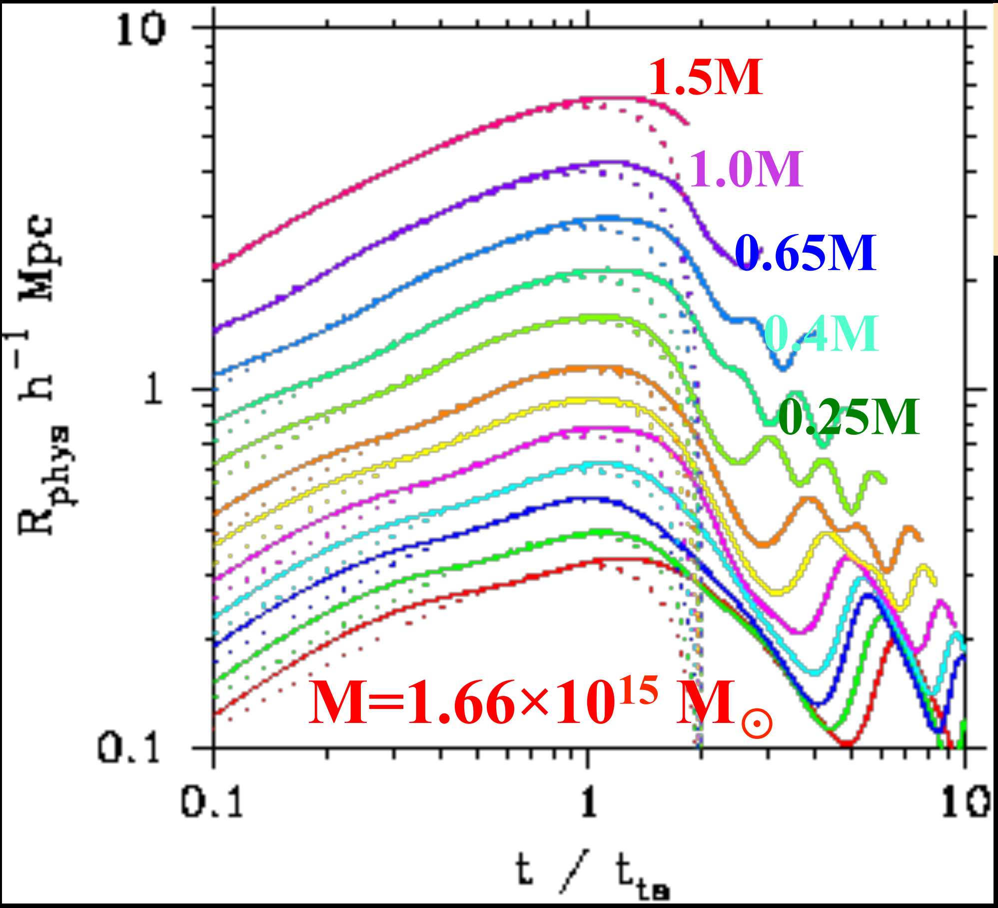
Beyond the spherical dust collapse model



Evolution of radii of different mass shells in a simulated halo

Yasushi Suto

Department of Physics and RESCEU (Research Center for the early Universe) The University of Tokyo

Kyoto workshop
"Vlasov-Poisson: towards numerical methods without particles"
June 2, 2015@Yukawa Institute, Kyoto University

Collaborators

- This talk is based on my collaboration with
  - **Daichi Suto** (Univ. of Tokyo)
  - Ken Osato (Univ. of Tokyo),
  - Tetsu Kitayama (Toho Univ.)
  - Shin Sasaki (Tokyo Metropolitan Univ.)
- Still one-going and preliminary work !

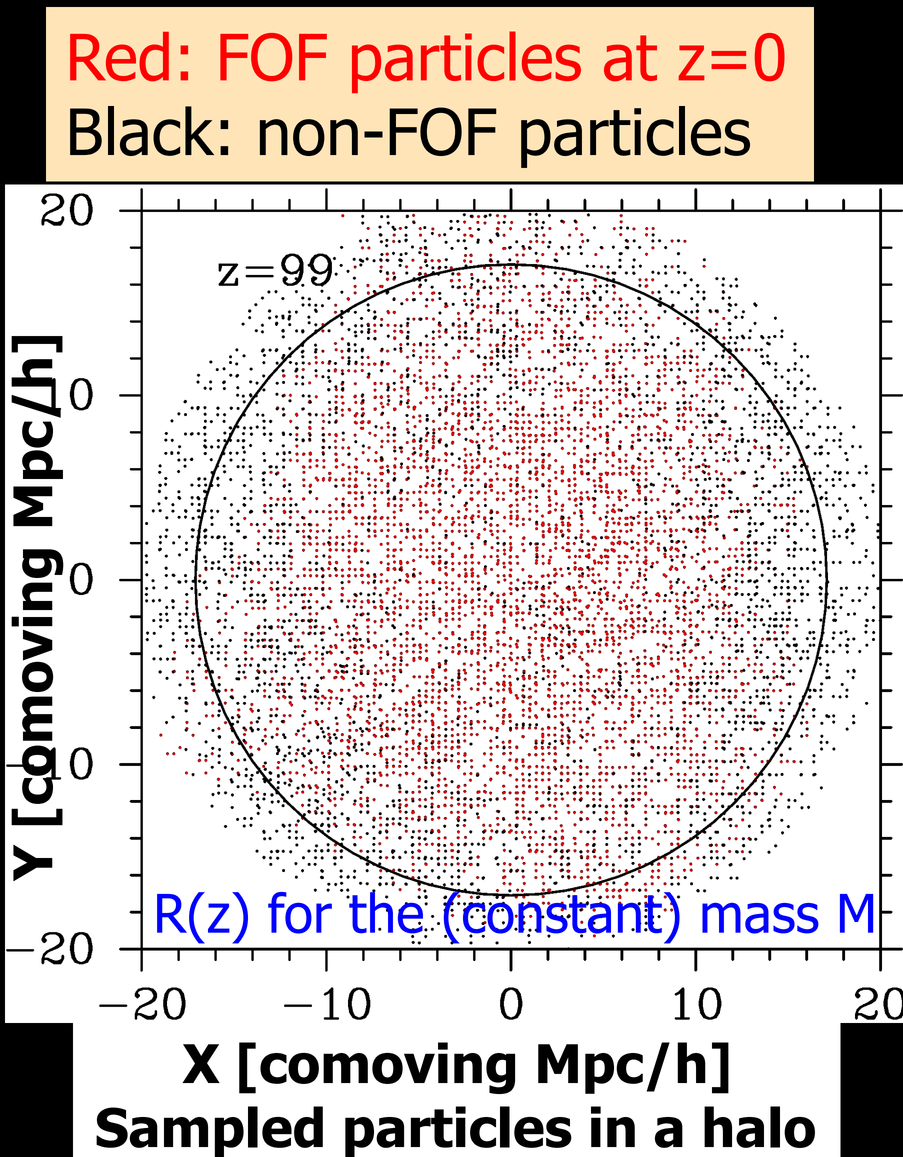
Spherical dust collapse (SDC) model

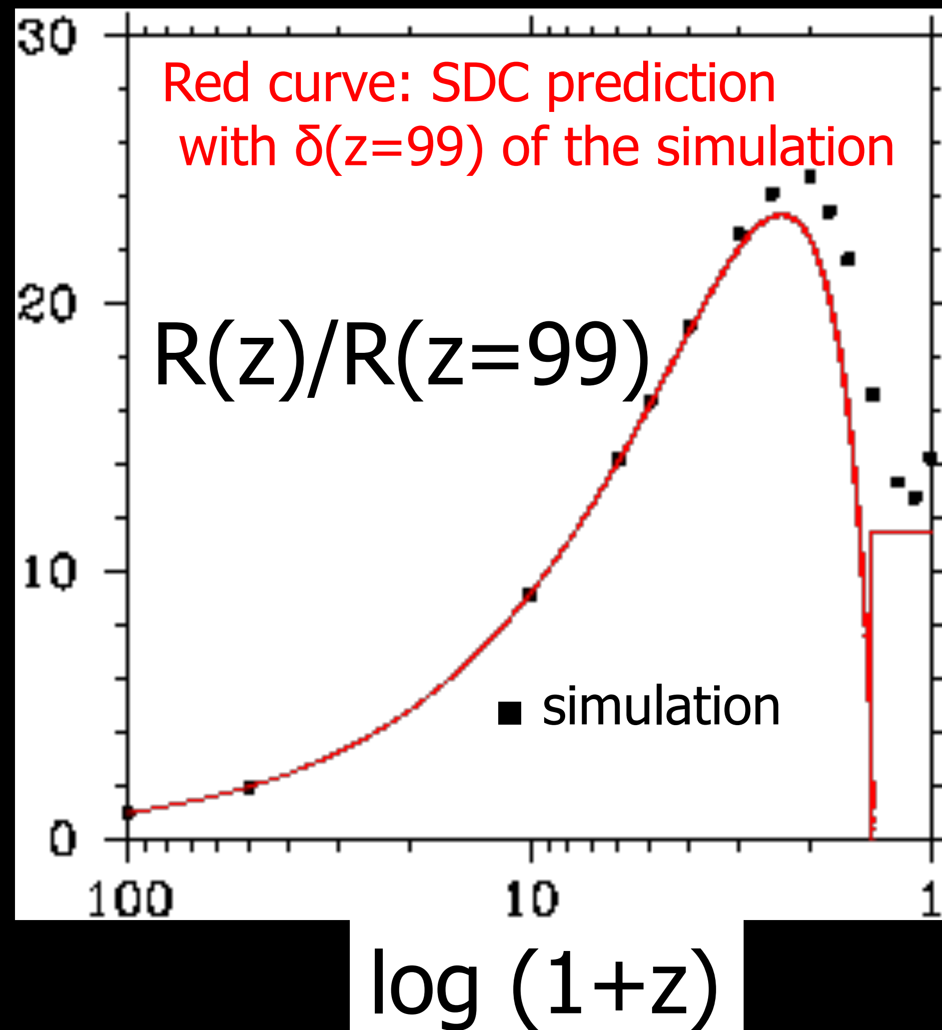
- ***The*** most basic model of structure formation
- Everybody knows that it is just a simple approximation, but still widely used even in precision cosmology:
  - e.g., Dark matter halo abundance vs. cluster mass and temperature functions to determine cosmological parameters
- Attempts for improvement
  - Non-sphericity (e.g., Jing & Suto 2002)
  - inhomogeneities (e.g., Kawahara et al. 2007)
  - shell-crossing and velocity dispersions (this talk)

Comparison of the SDC model predictions against N-body results

- Dark matter only simulations with GADGET-2
  - ΛCDM with WMAP9 cosmological parameters
  - $N=1024^3$ in $L=360$ Mpc h^{-1}
  - $m=3.4 \times 10^9 M_\odot$
- FOF halos identified at $z=0$
  - compute the spherical mass M and radius R of spherical overdensity of $\Delta=\rho/\rho_m=355.4$
  - Identifies the center-of-mass of the $z=0$ FOF halo particles at z, and compute the radius R(z) enclosing the mass M at $0<z<z_{initial} = 99$

The most massive halo with $M=1.66\times10^{15}\ M_{\odot}$

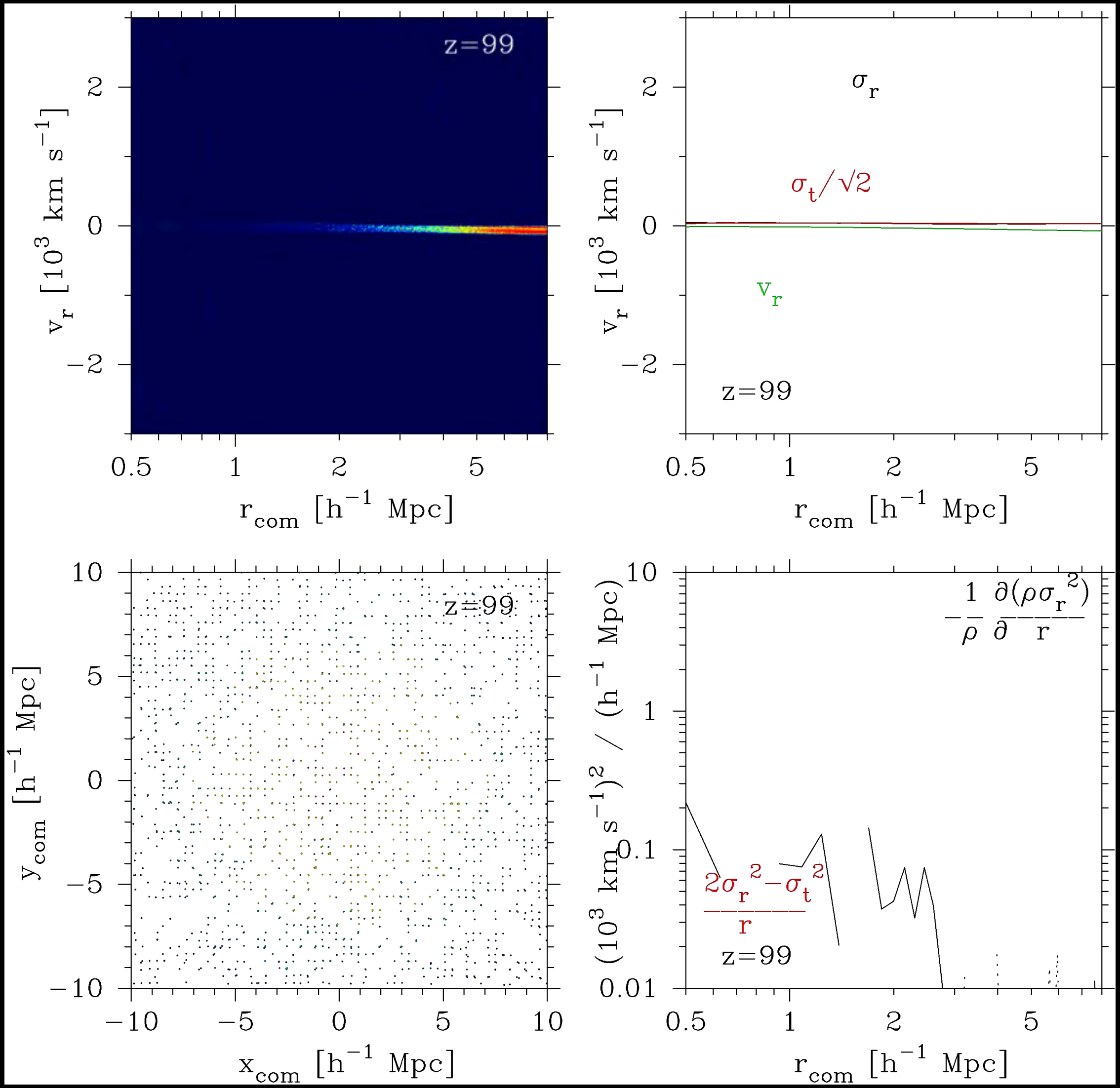




Generic trends from 100 simulated halos

- Very good quantitative agreement until the turn-around epoch
  - may be reasonable but not trivial at all, given the small-scale clumping, subhalo mergers inside, and/or the filamentary structure across the entire region
- Systematic difference relative to SDC predictions after the turn-around epoch
  - Delay of the turn-around epoch
  - Larger turn-around radius
  - Larger “virialized” radius

Evolution of a halo($M=1.66\times10^{15}\ M_\odot$) in phase space (comoving coordinate)



Effect of velocity dispersions

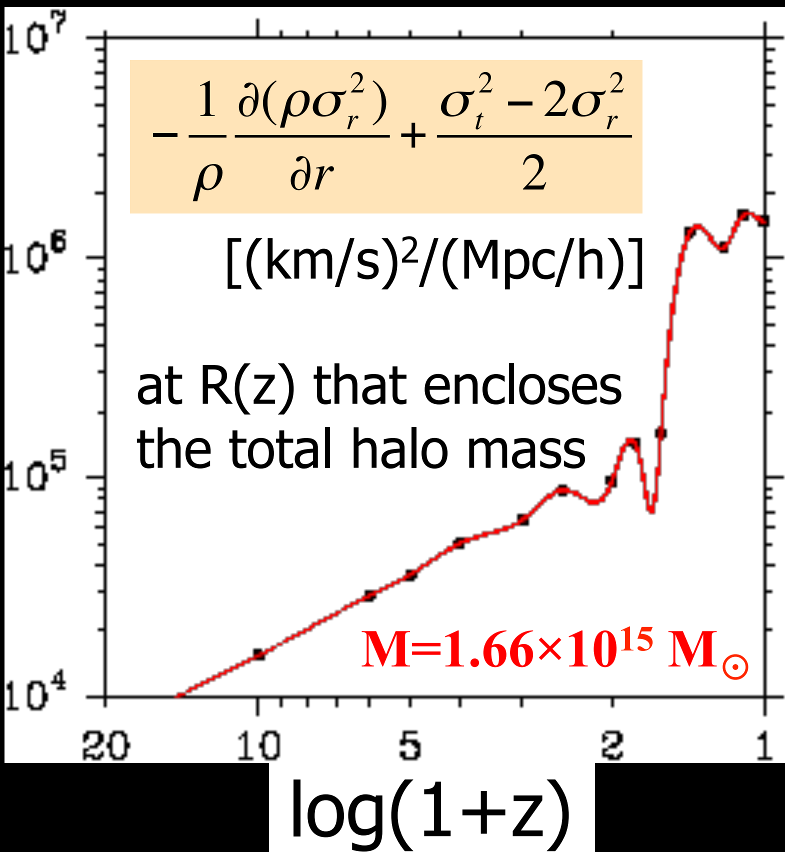
- Jeans equation for spherical collisionless system
  - radial velocity dispersion σ_r^2
  - tangential velocity dispersion σ_t^2

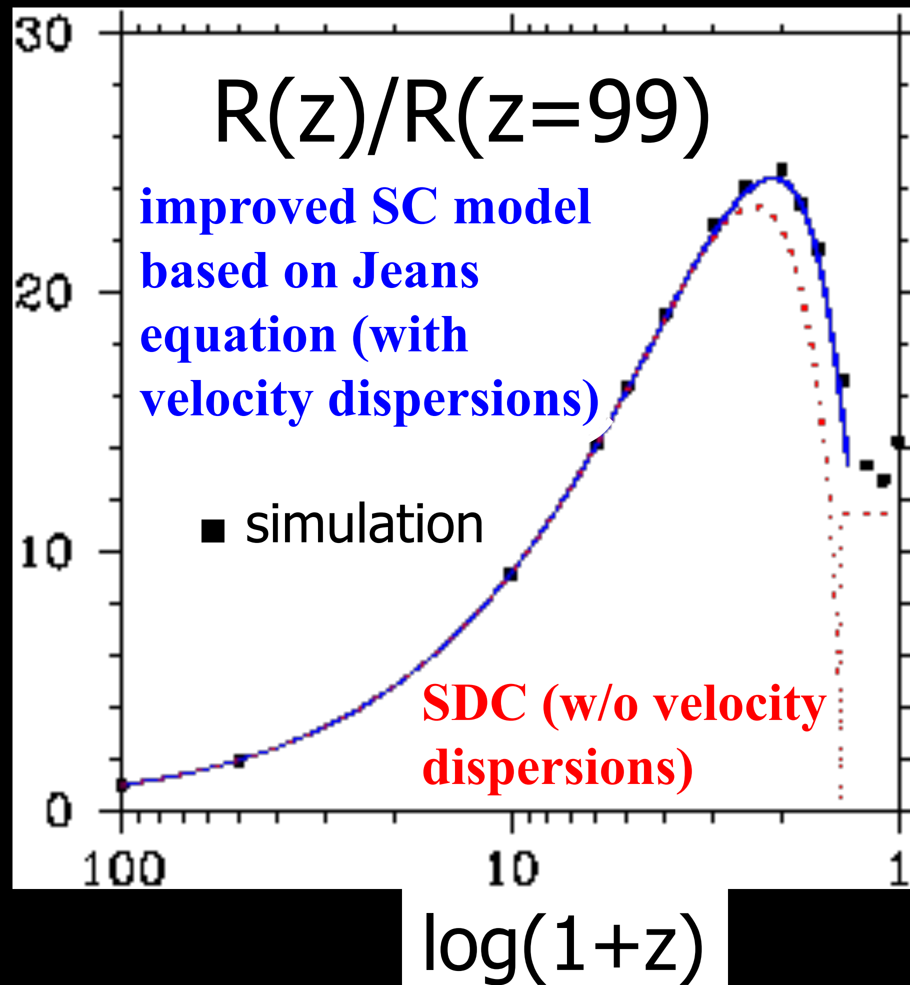
$$\frac{Dv_r}{Dt} = -\frac{1}{\rho}\frac{\partial(\rho\sigma_r^2)}{\partial r} + \frac{\sigma_t^2 - 2\sigma_r^2}{2} - \frac{GM}{r^2}$$

- SDC assumes an initially top-hat (homogeneous) sphere
  - neglects small-scale inhomogeneities, shell-crossing before turn-around, and thus no σ_r^2 or σ_t^2
- Larger $t_{\text{turn-around}}$ and R_{virial} than predicted by SDC

Improvement with velocity dispersions

- Evaluate the velocity dispersions from simulation data and solve the Jean equation
- Greatly improved !





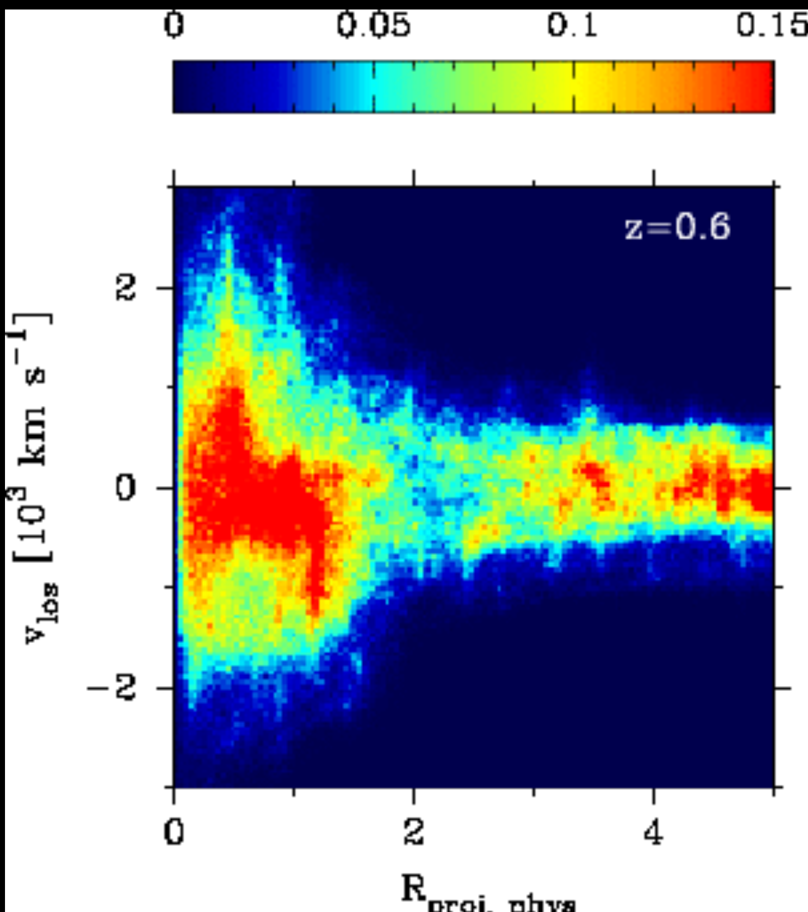
Phase-space distribution in redshift space: line-of-sight velocity vs. projected radius

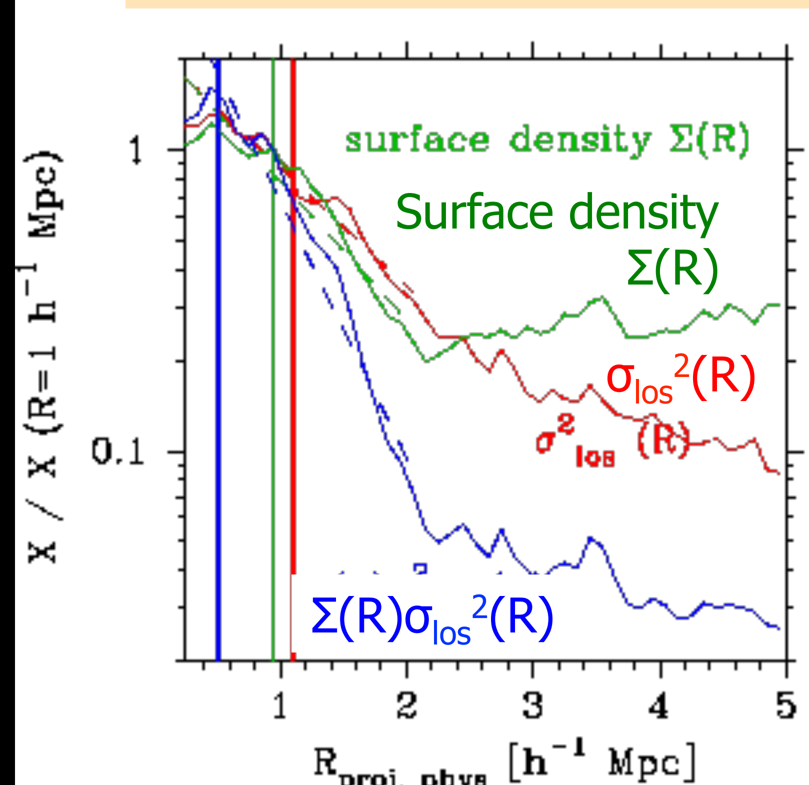
$M=1.66\times 10^{15}\ M_{\odot}$ $z=0.6$

$$\Sigma(R) \propto \exp(-R/R_{\Sigma})$$

$$\sigma^2(R) \propto \exp(-R/R_{\sigma^2})$$

$$\Sigma(R)\sigma^2(R) \propto \exp(-R/R_{\Sigma\sigma^2})$$





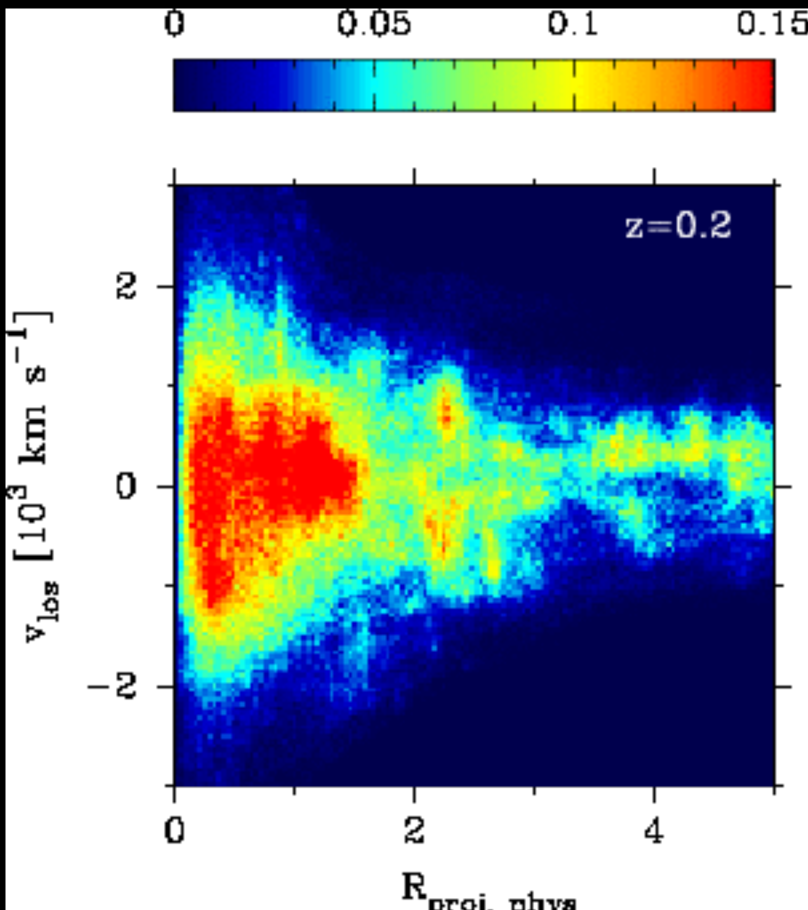
Phase-space distribution in redshift space: line-of-sight velocity vs. projected radius

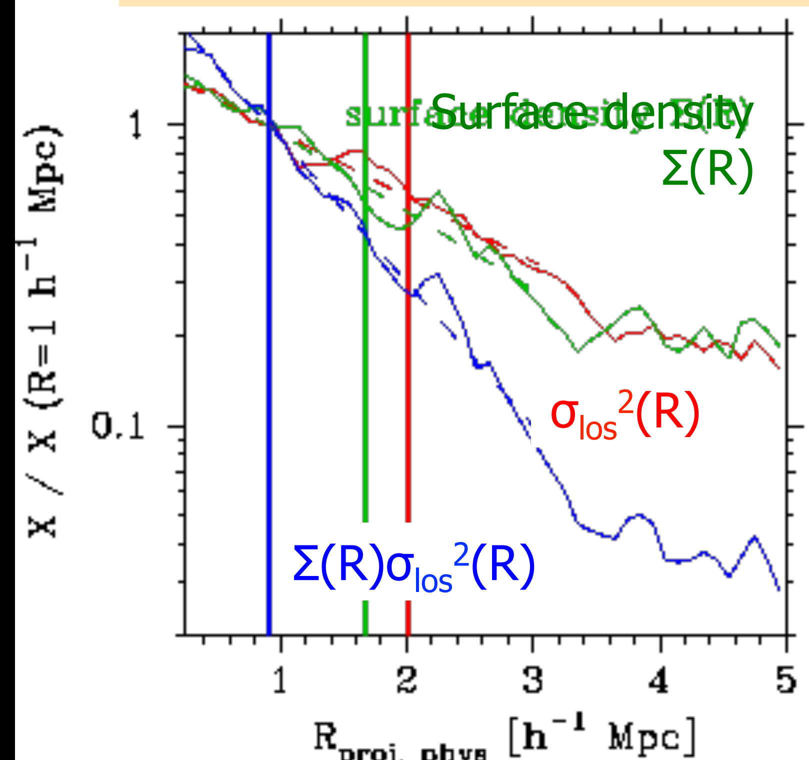
$M=1.66\times 10^{15}\ M_{\odot}$ z=0.2

$$\Sigma(R)\propto \exp(-R/R_{\Sigma})$$

$$\sigma^2(R)\propto \exp(-R/R_{\sigma^2})$$

$$\Sigma(R)\sigma^2(R)\propto \exp(-R/R_{\Sigma\sigma^2})$$

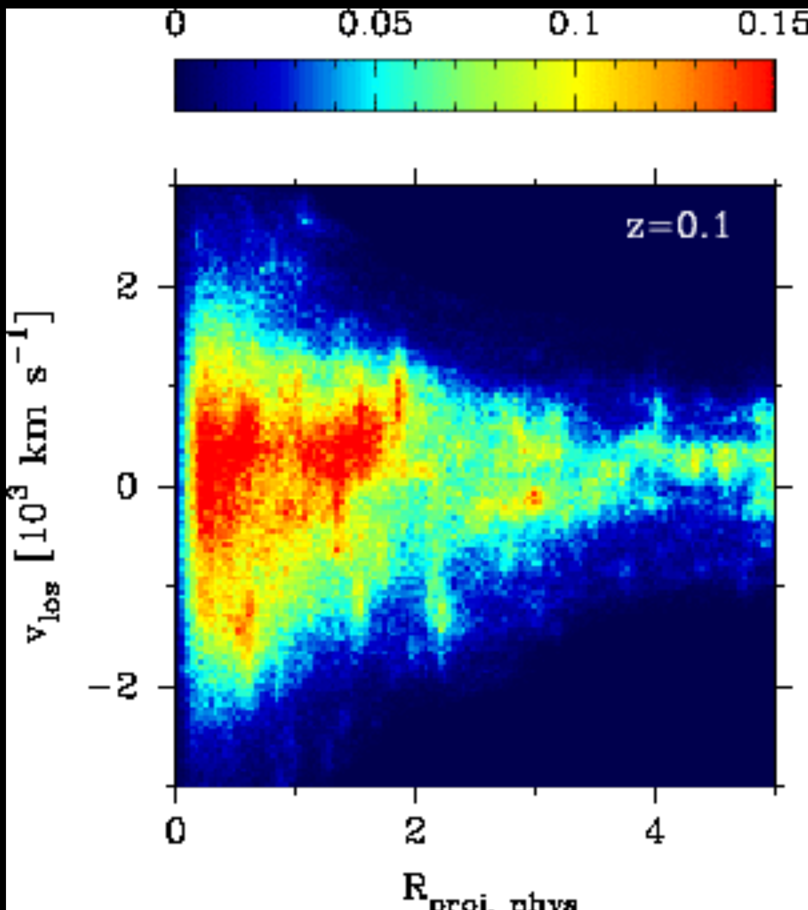


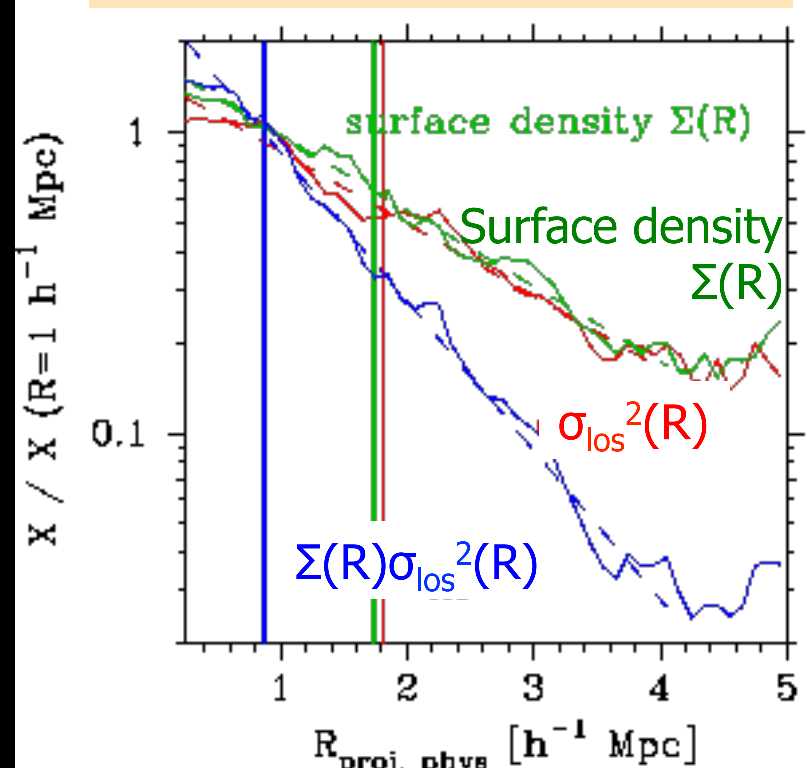


Phase-space distribution in redshift space: line-of-sight velocity vs. projected radius

$M = 1.66 \times 10^{15}\, M_\odot \quad z = 0.1$

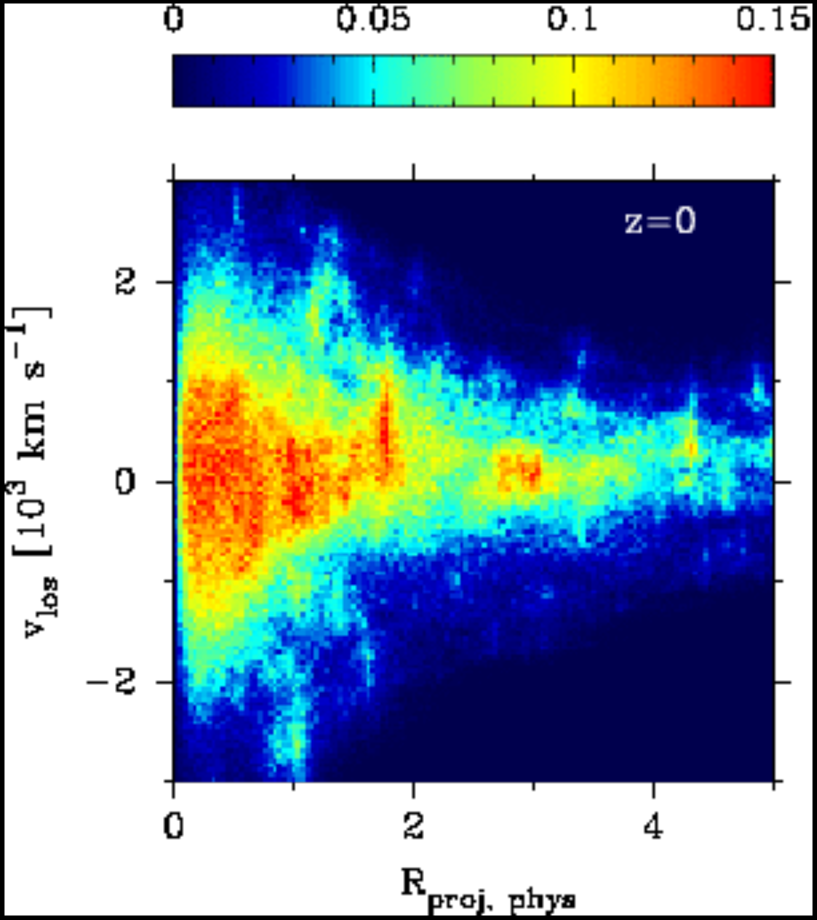
$$\Sigma(R) \propto \exp(-R / R_\Sigma)$$
$$\sigma^2(R) \propto \exp(-R / R_{\sigma^2})$$
$$\Sigma(R)\sigma^2(R) \propto \exp(-R / R_{\Sigma\sigma^2})$$





Phase-space distribution in redshift space: line-of-sight velocity vs. projected radius

$M=1.66\times10^{15}\ M_\odot$ $z=0$



$$\Sigma(R)\propto\exp(-R/R_\Sigma)$$
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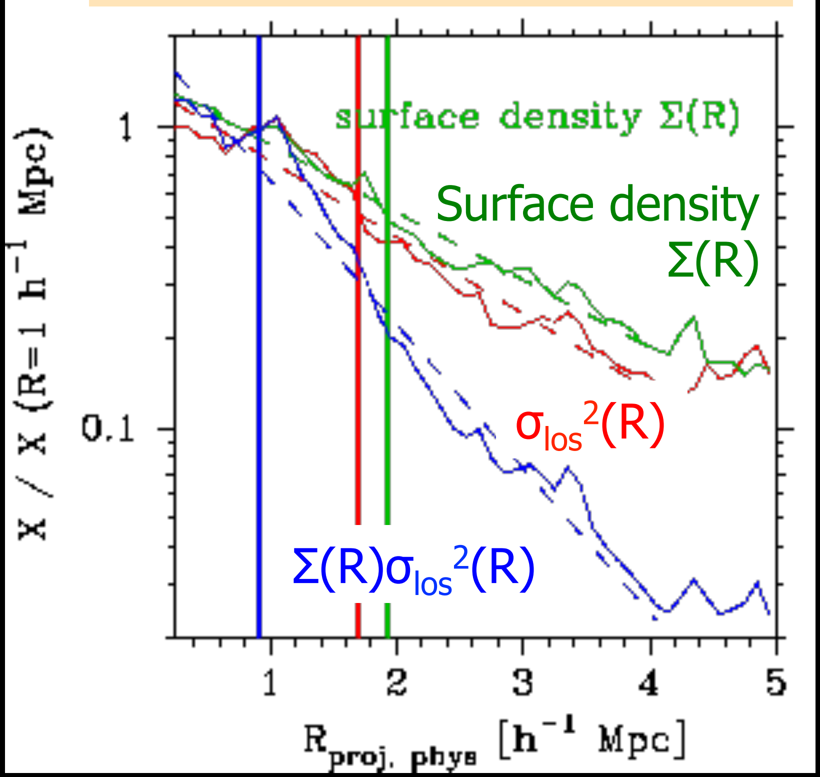
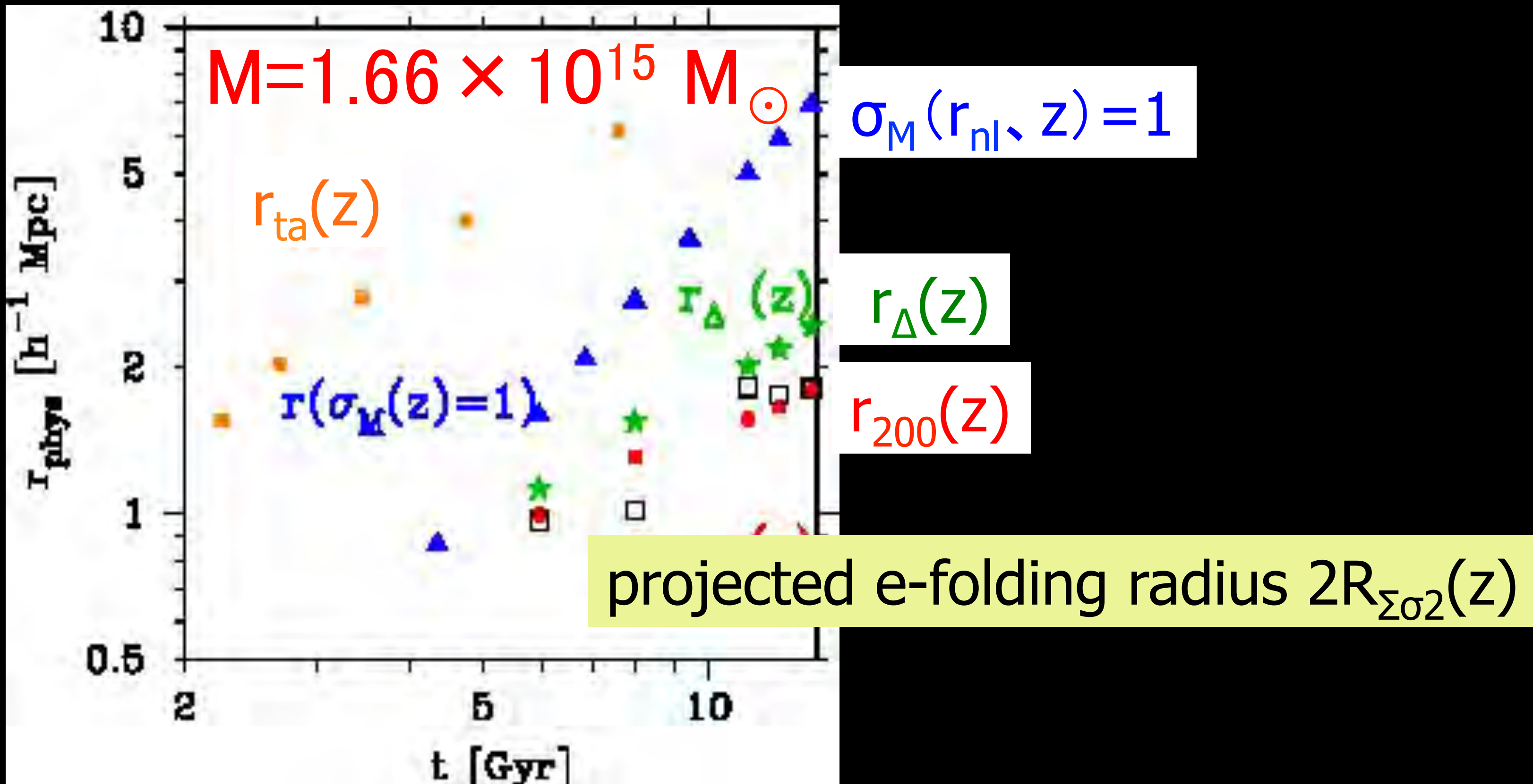
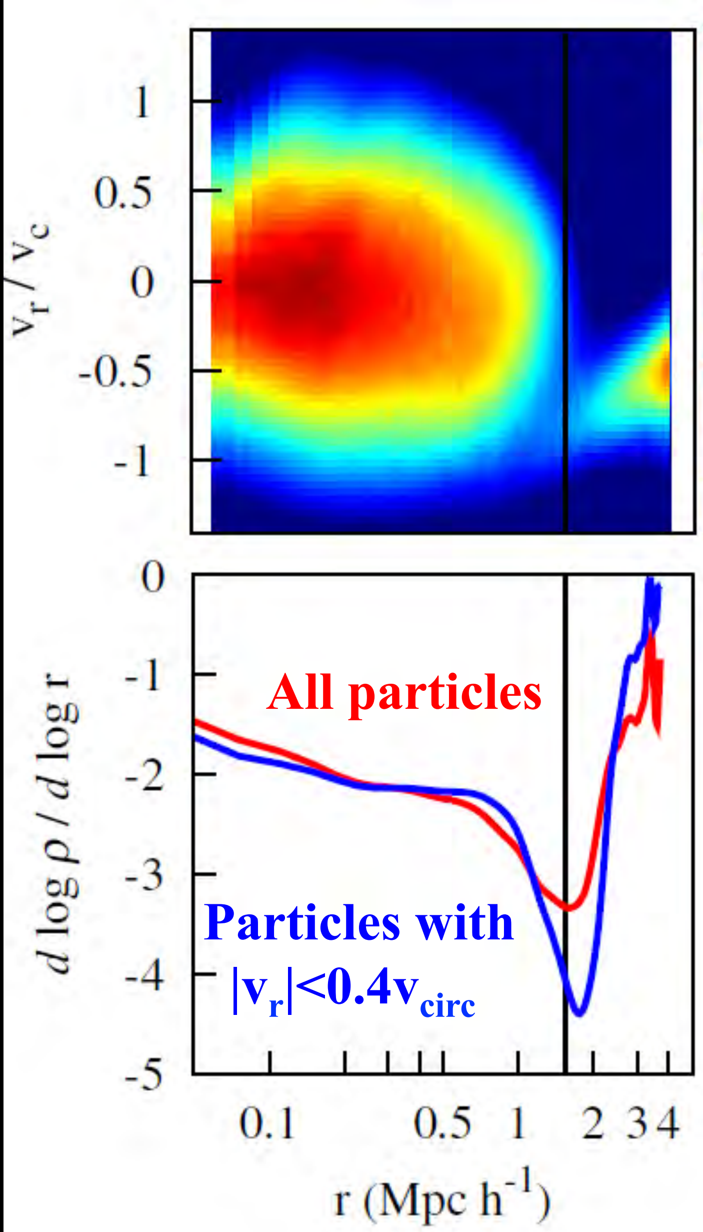


Comparison among characteristic scales



- Projected e-folding scales $2R_{\Sigma\sigma2}(z) \sim R_{\Sigma}(z) \sim R_{\sigma2}(z)$ are close to conventional "virial" radii (r_{200} or r_{Δ})
  - $r_{\text{2nd apocenter}} \sim 0.367 r_{ta}$ and $r_{\text{3rd apocenter}} \sim 0.236 r_{ta}$ in Bertschinger's solution (1985, ApJS, 58, 39)

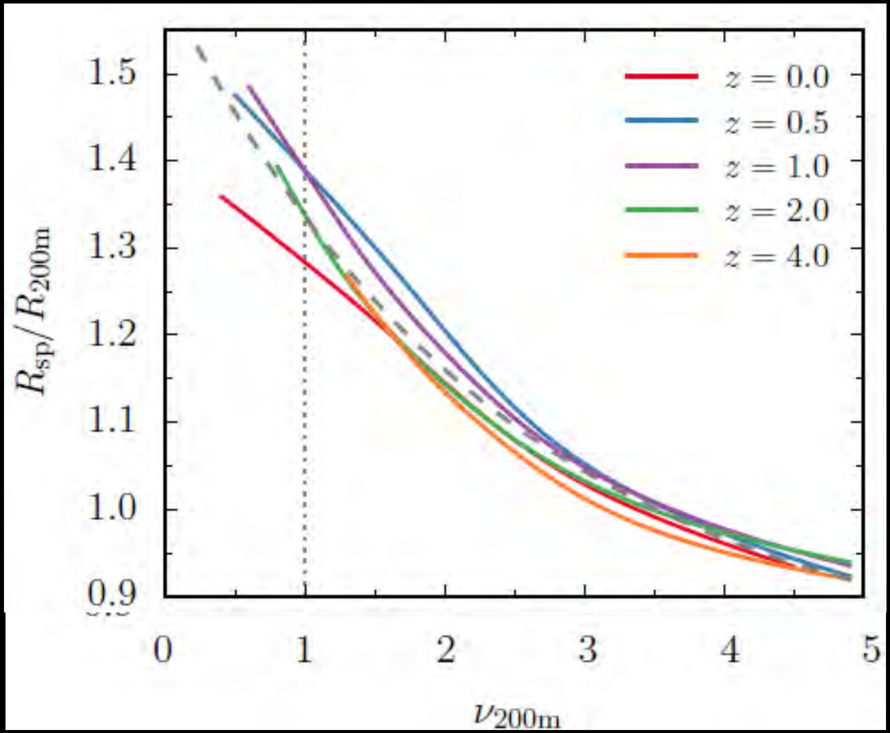
Splashback in accreting dark halos

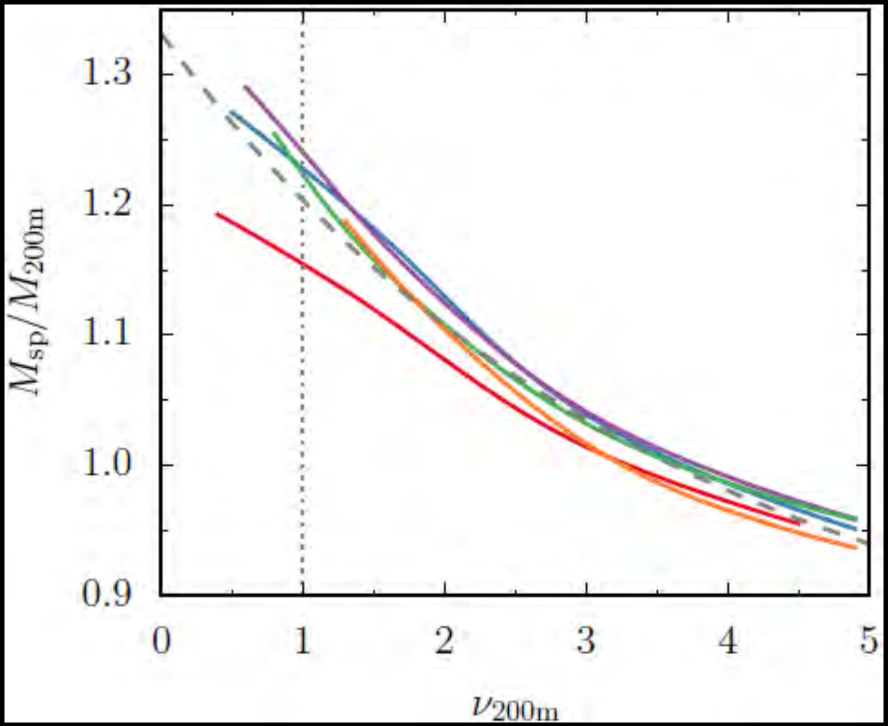


S. Adhikari, N. Dalal & R. T. Chamberlain, arXiv:1409.4482

- Physical definition of halo size = splashback radius ?
  - first apoapse after collapse
- Ensemble of halos from cosmological simulation
  - Clear signature in density profile of ensemble of halos
  - Not easy to determine the splashback radius from a single halo (at least observationally)

The splashback radius as a physical halo boundary and the growth of halo mass



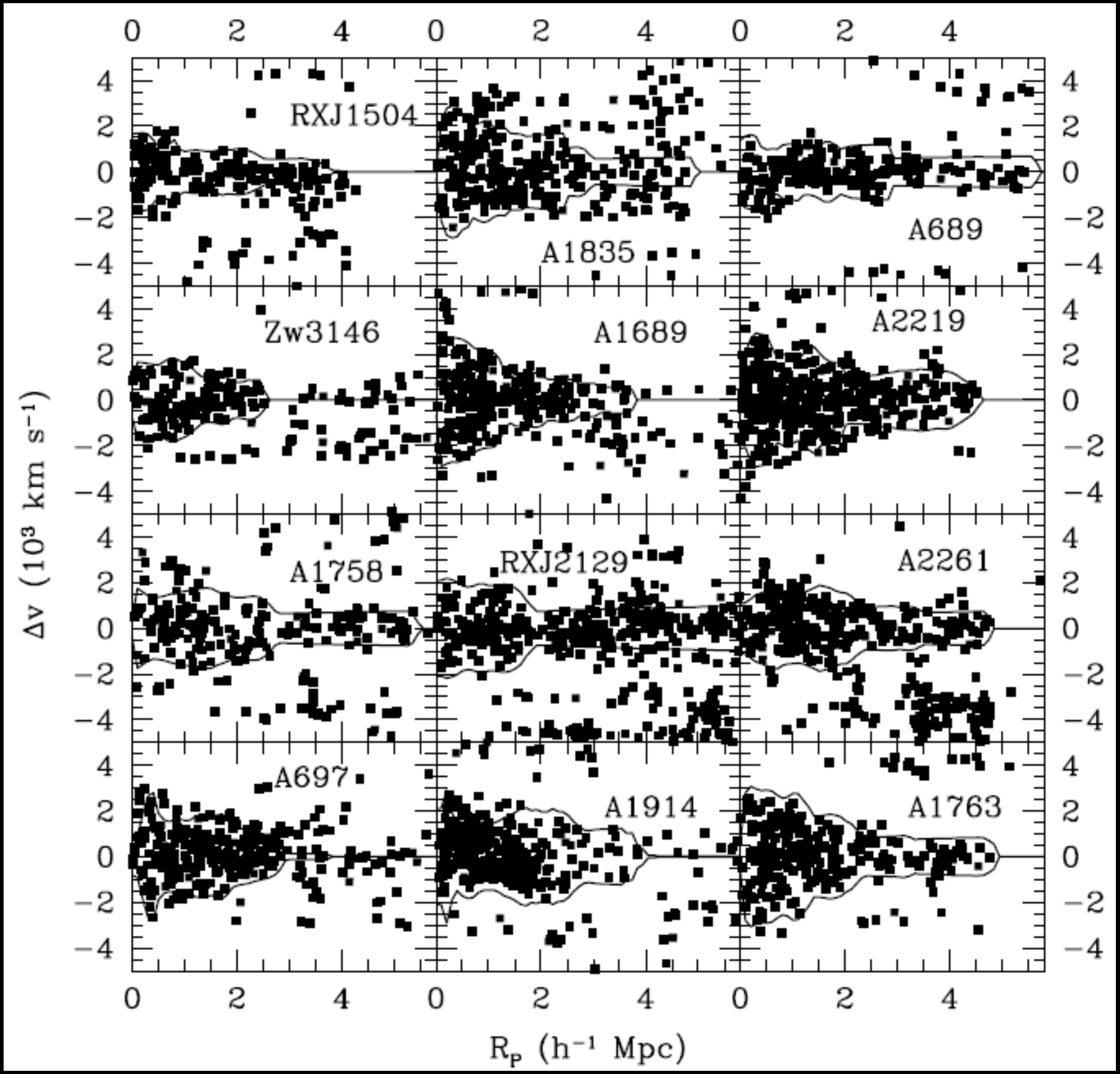


S. More, B. Diemer & A. V. Kravtsov, arXiv:1504.05591

$$\frac{R_{\rm sp}}{R_{\rm 200m}} = 0.81\left(1 + 0.97e^{-\nu/2.44}\right)$$

$$\frac{M_{\rm sp}}{M_{\rm 200m}} = 0.82\left(1 + 0.63e^{-\nu/3.52}\right)$$

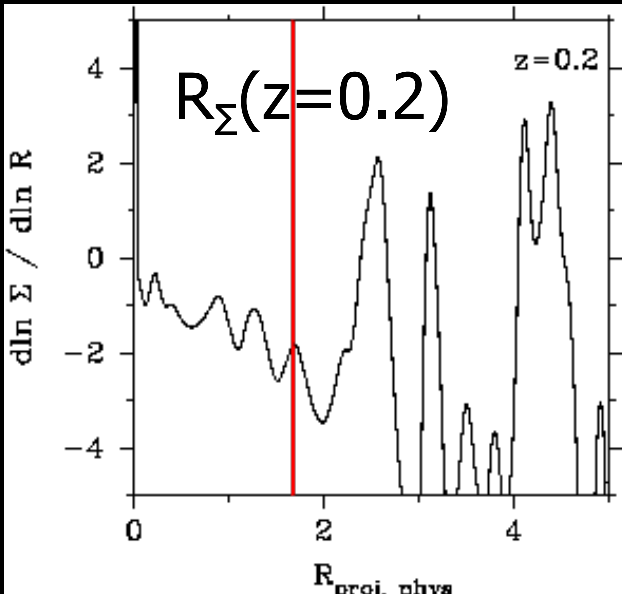
Signature of the splashback radius ?

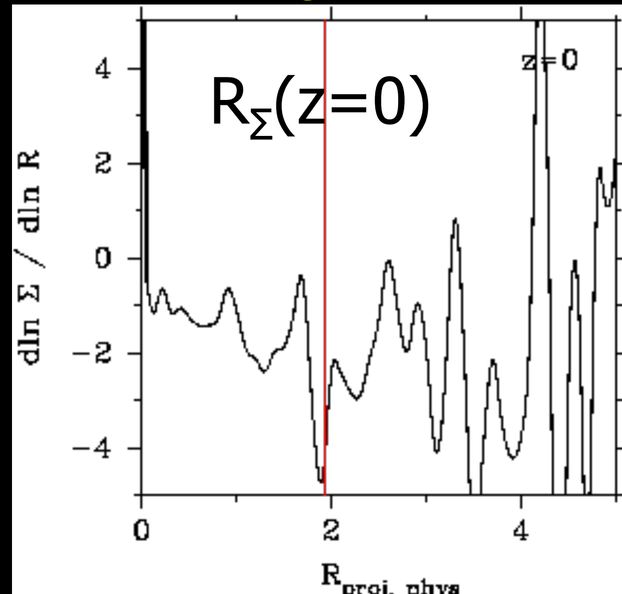


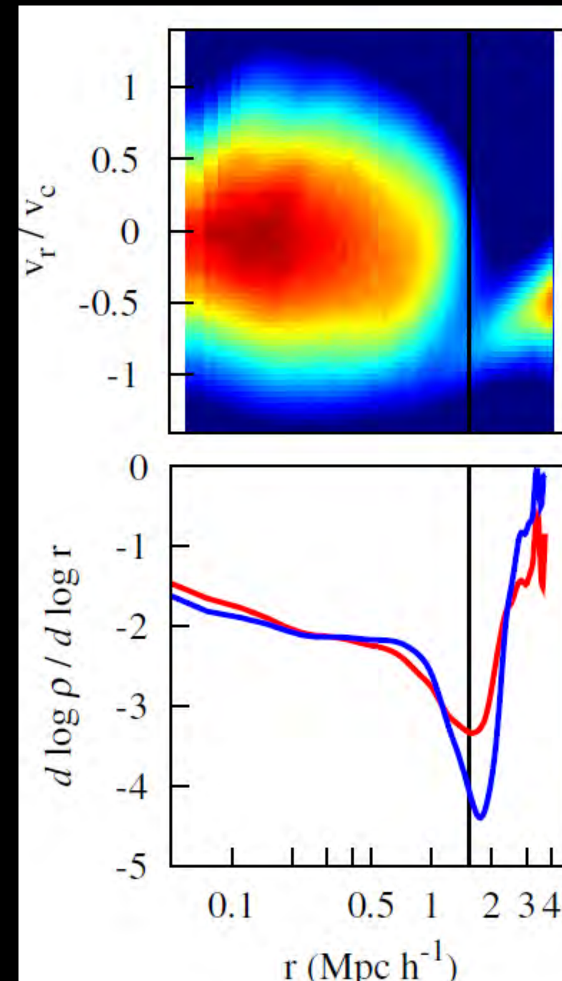
- Line-of-sight velocity of galaxies in X-ray selected clusters
- Rines et al. (2013)

Relation to Splashback radius ?

$M=1.66\times10^{15}\ M_\odot$



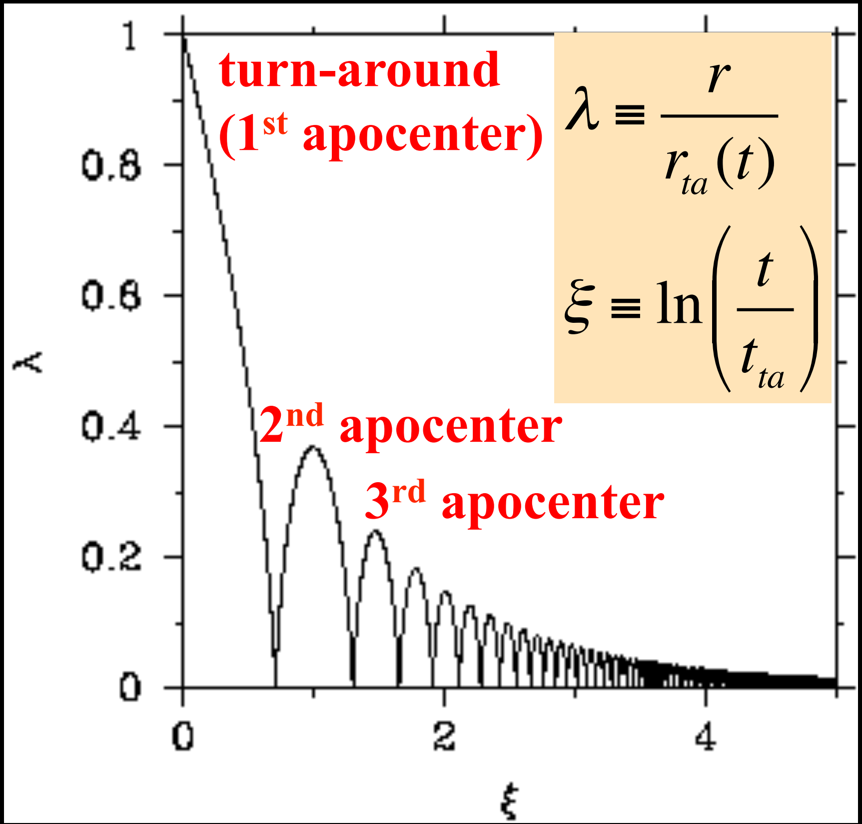


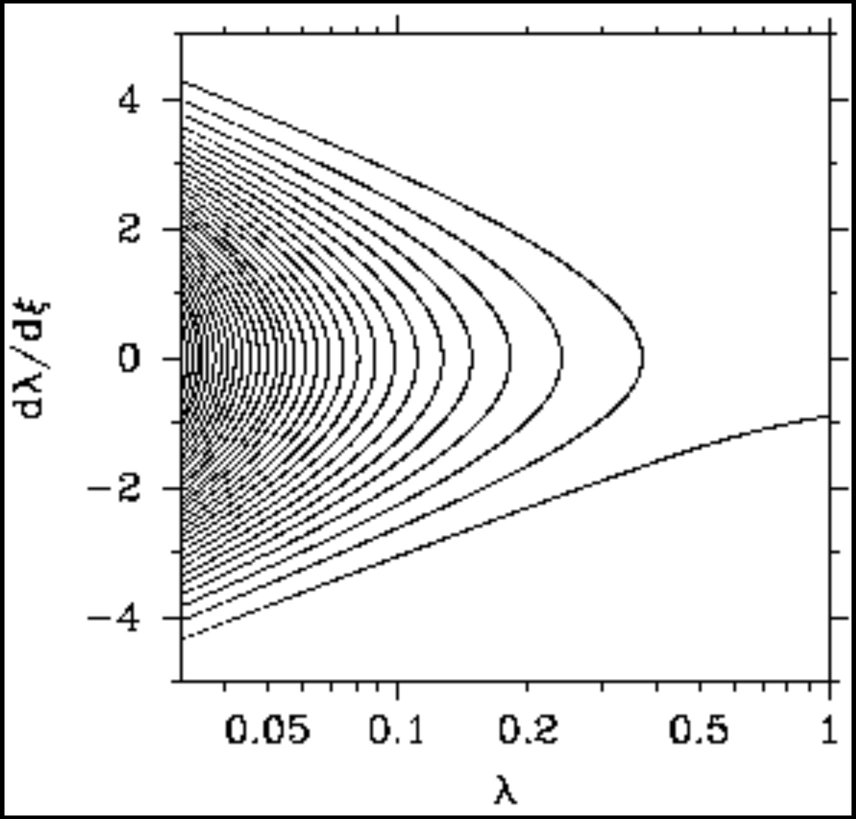


- Qualitative agreement between our projected e-folding radius R and the splashback radius
- Our definition (e-folding scale in redshift space) is more relevant from an observational viewpoint

S. Adhikari, N. Dalal & R. T. Chamberlain, arXiv:1409.4482

Bertschinger's self-similar solution

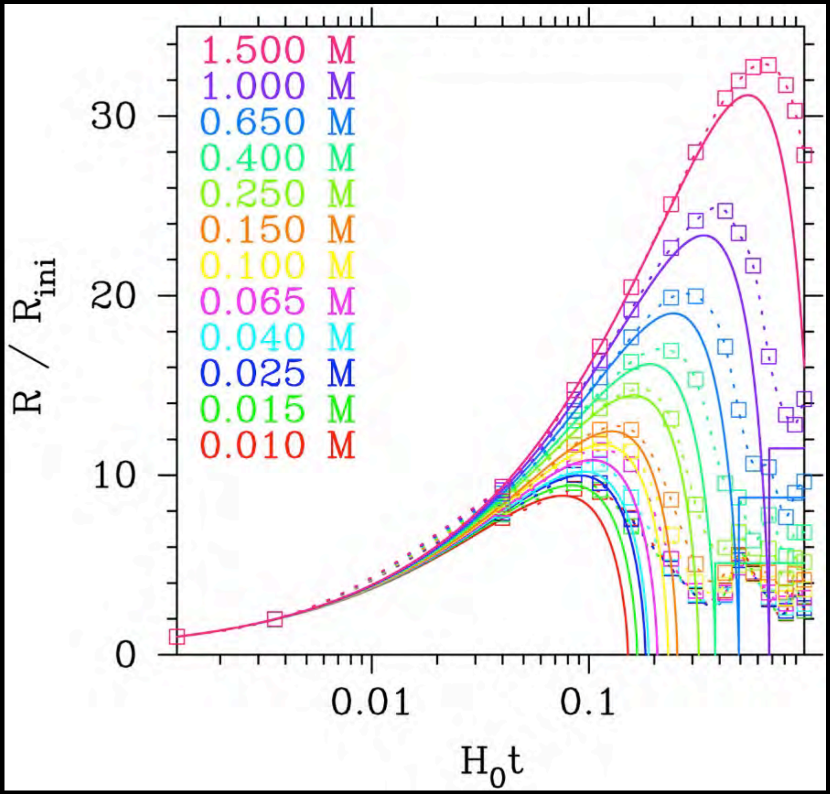


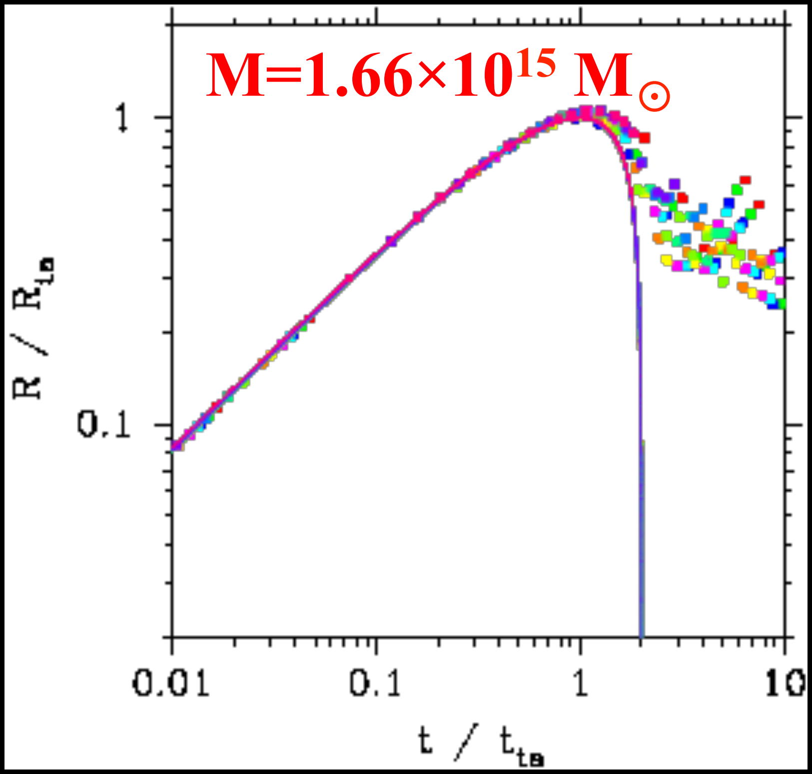


- Self-similar shell crossing of collisionless spherical secondary infall

Bertschinger 1985, ApJS, 58, 39

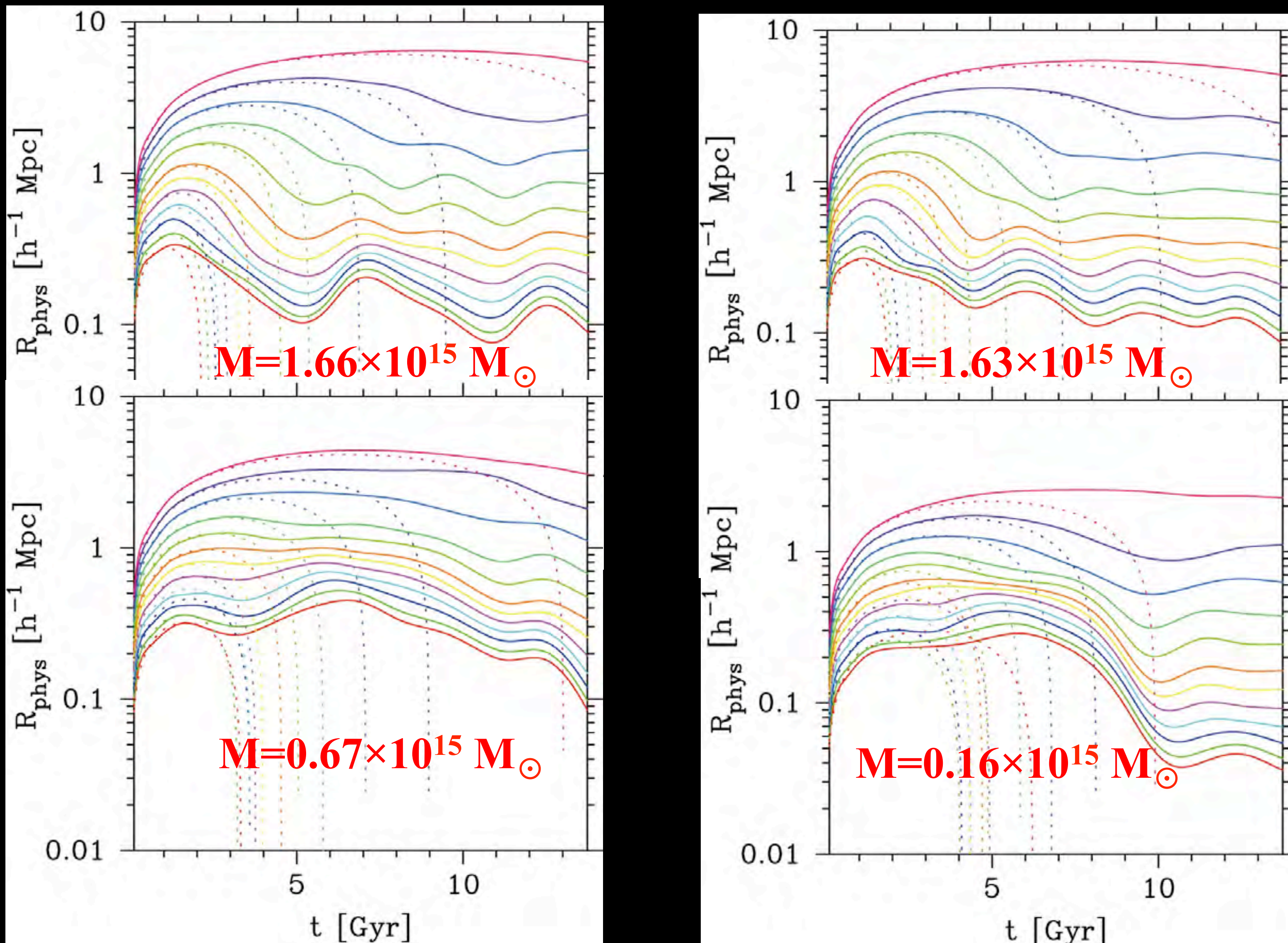
Scaled evolution of constant mass shells: $r_M(z)$ with $M(<r_M)$=const. in the halo



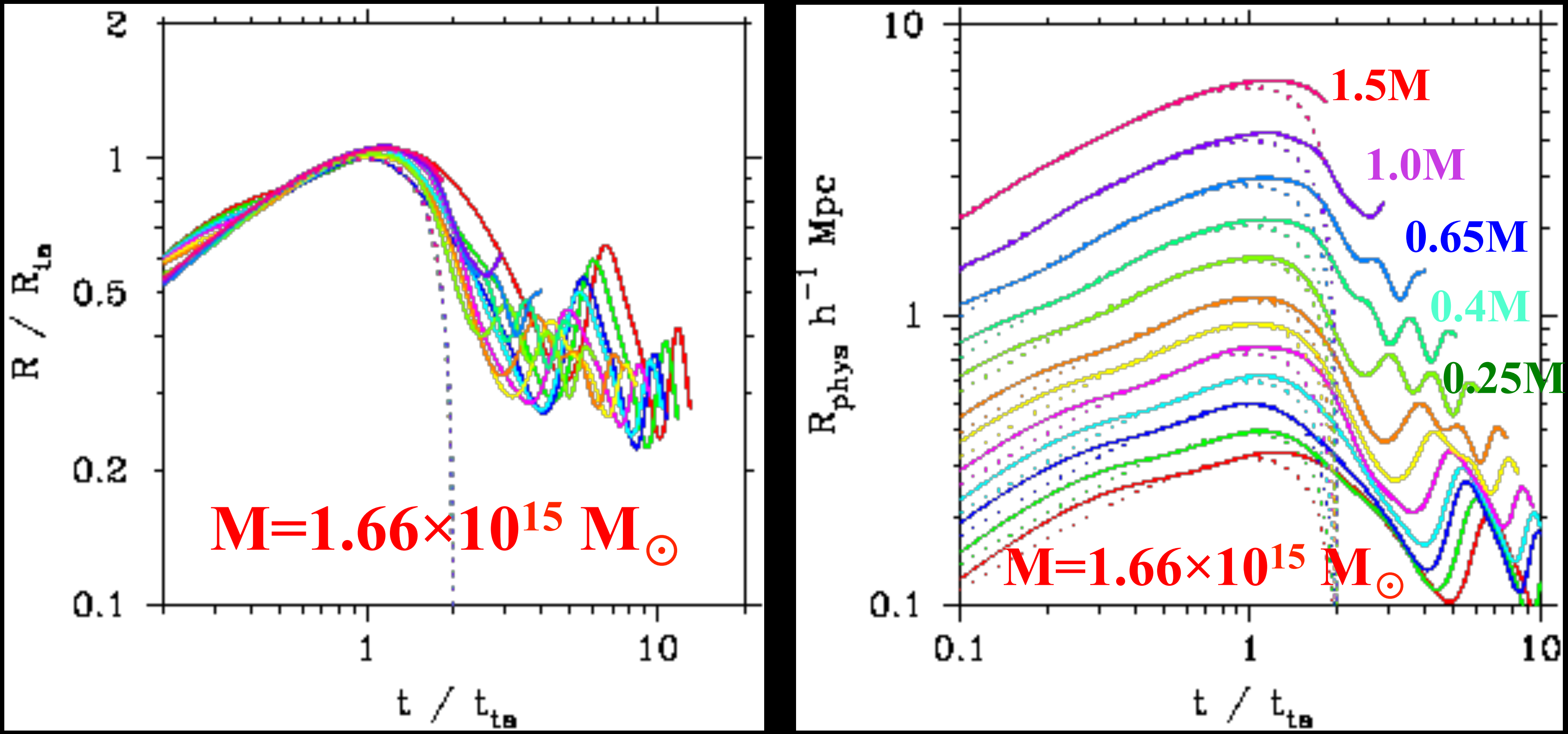


- usual assumption ($r_{vir}=r_{ta}/2$) is not accurate
- Mixing of different mass shells is not complete

Motion of constant mass shells for 4 different halos

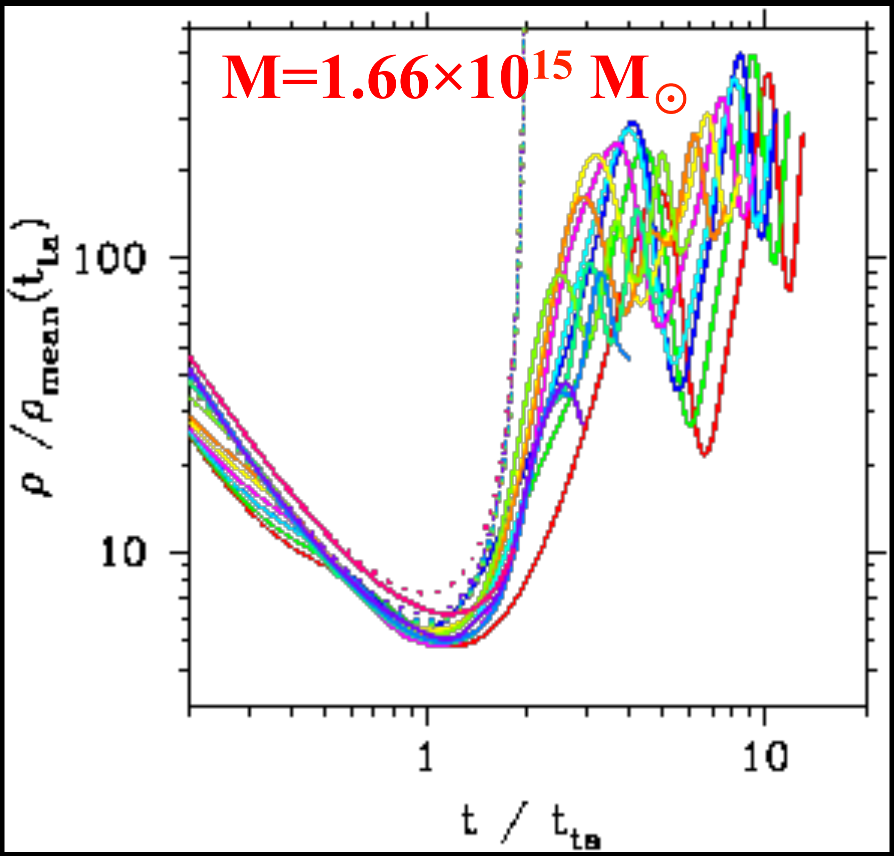


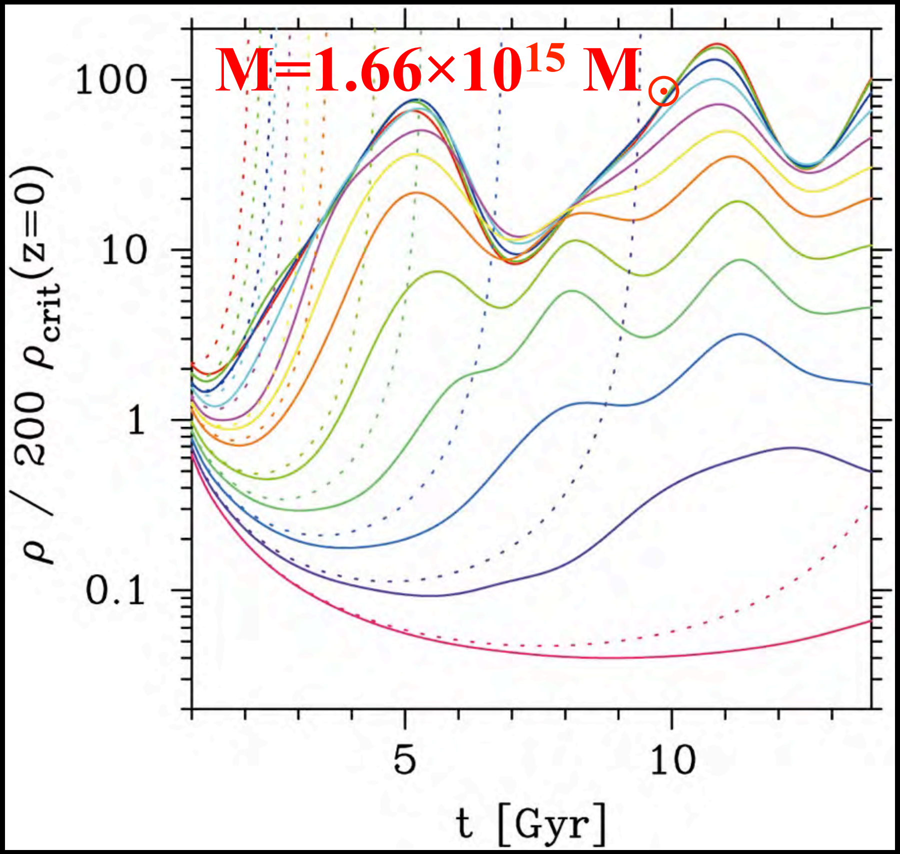
"Virialized" mass shells change: not constant but oscillating



- Each mass shell continues to oscillate within the halo; halos are not static but dynamical

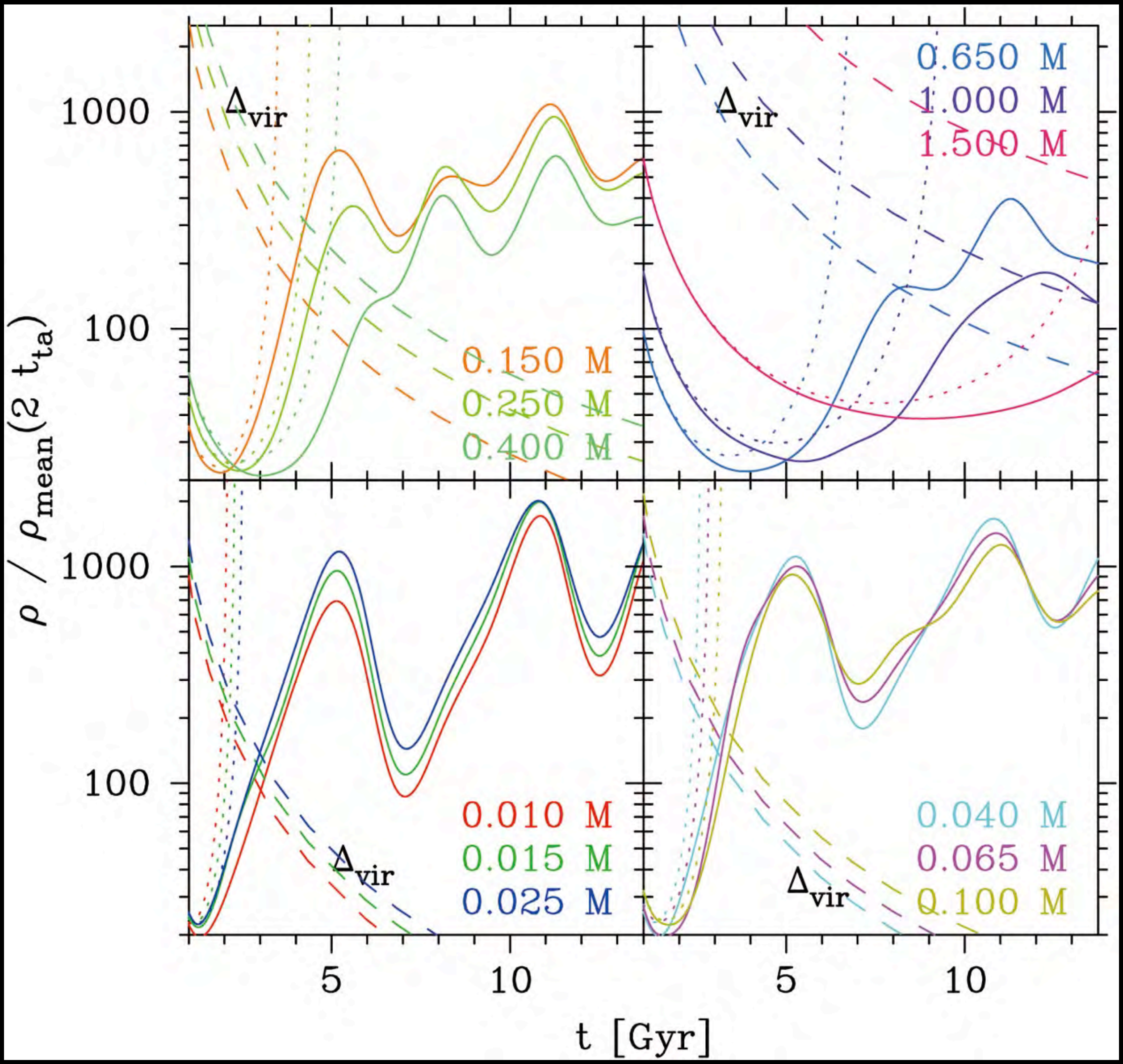
"Virialized" mass shells change: not constant but oscillating





- Each mass shell continues to oscillate within the halo; halos are not static but dynamical

“virialized” densities within different mass shells



$M = 1.66 \times 10^{15}\ M_{\odot}$

- Not constant
- Large coherent modulation

Summary

- Spherical dust collapse model for dark matter halos is oversimplified
  - Better model is required for cluster cosmology, and indeed already overdue
- We focus on the effect of velocity dispersions
  - Delays the turn-around epoch, increases the virial radius
  - Confirmed by solving the Jeans equation
- Interesting scaling behavior of halo collapse
  - "Virialized" halos are not static but dynamical, and indeed oscillating !

Future outlook

- Observational signature of the oscillating feature ?
  - affects the gas dynamics as well ?
  - Hydro-dynamical simulations to check ?
  - X-ray vs. weak lensing ?
- Toy model to describe the oscillation ?
  - Empirical scaling model ?
  - Modeling velocity dispersions ?