Dark Matter Substructure and The Clustering Crisis


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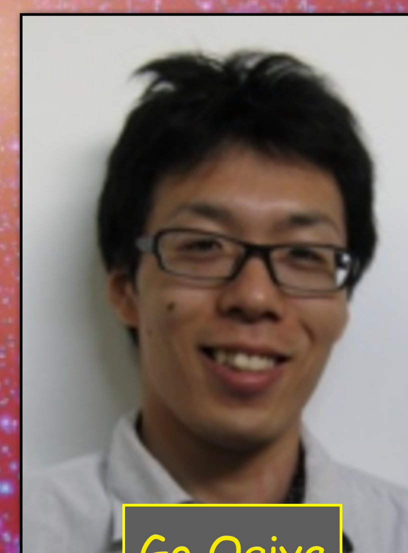

Go Ogiya


Andi Burkert

Frank van den Bosch
Yale University

Halo Occupation Modeling

Used to interpret galaxy clustering and galaxy-galaxy lensing,
to inform models of galaxy formation, and to constrain cosmology

Conditional Luminosity Function (CLF): $\Phi(L|M)$

Yang+03, 09; van den Bosch+03, 07, 13; Cooray -06; Cacciato+13

Halo Occupation Distribution (HOD): $\langle N|M \rangle$

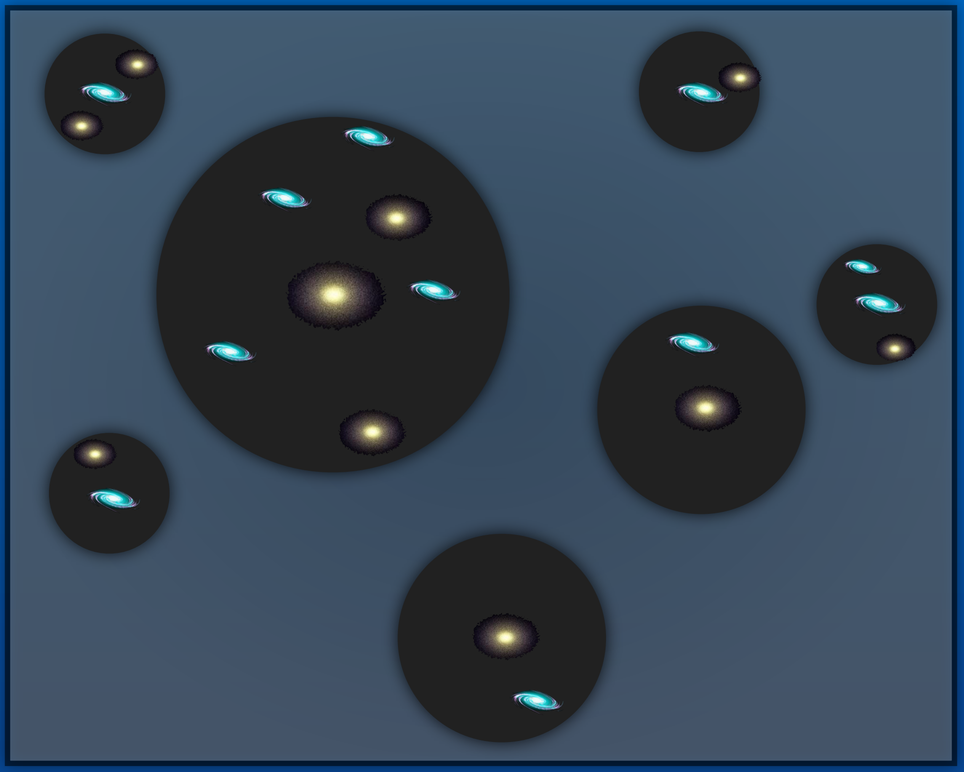
Seljak 00; Berlind & Weinberg 02; Zheng+-05; Tinker+07; Zehavi+11

Decorated HOD: $\langle N|M,Q \rangle$

Hearin+14, 16; Lehmann+15; Paranjape+15; Zentner+16

Subhalo Abundance Matching (SHAM): $n(>L) = n(>M)$

Vale & Ostriker 04; Conroy+06,09; Guo+10; Behroozi+10; Reddick+13



Either of these methods can be applied analytically, using the halo model, or numerically, by directly populating halos and subhalos in numerical simulations.

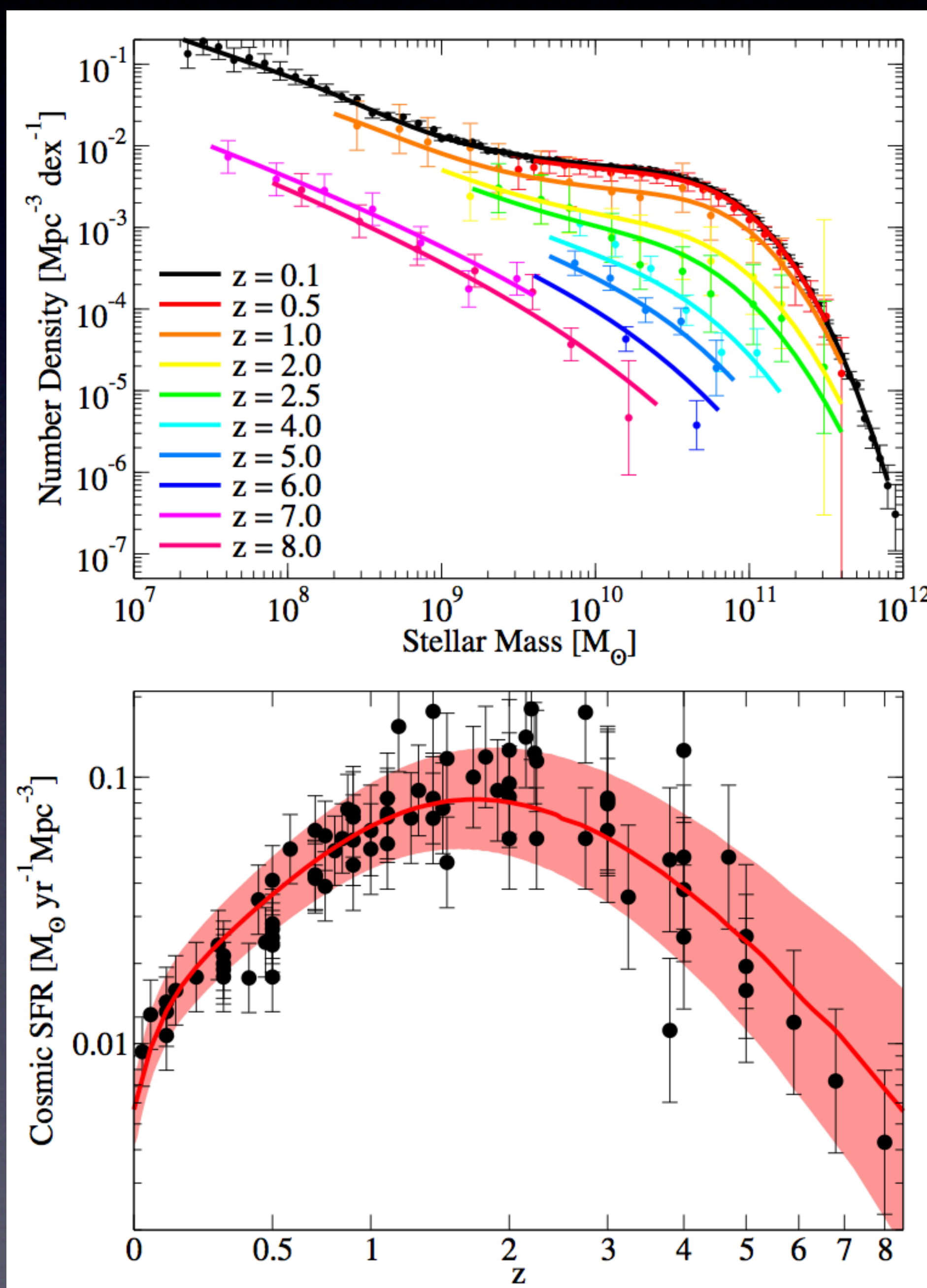
Latter is generally considered more accurate, more flexible, and with the development of Halotools™ , almost as fast as the analytical method.

see Hearin+16

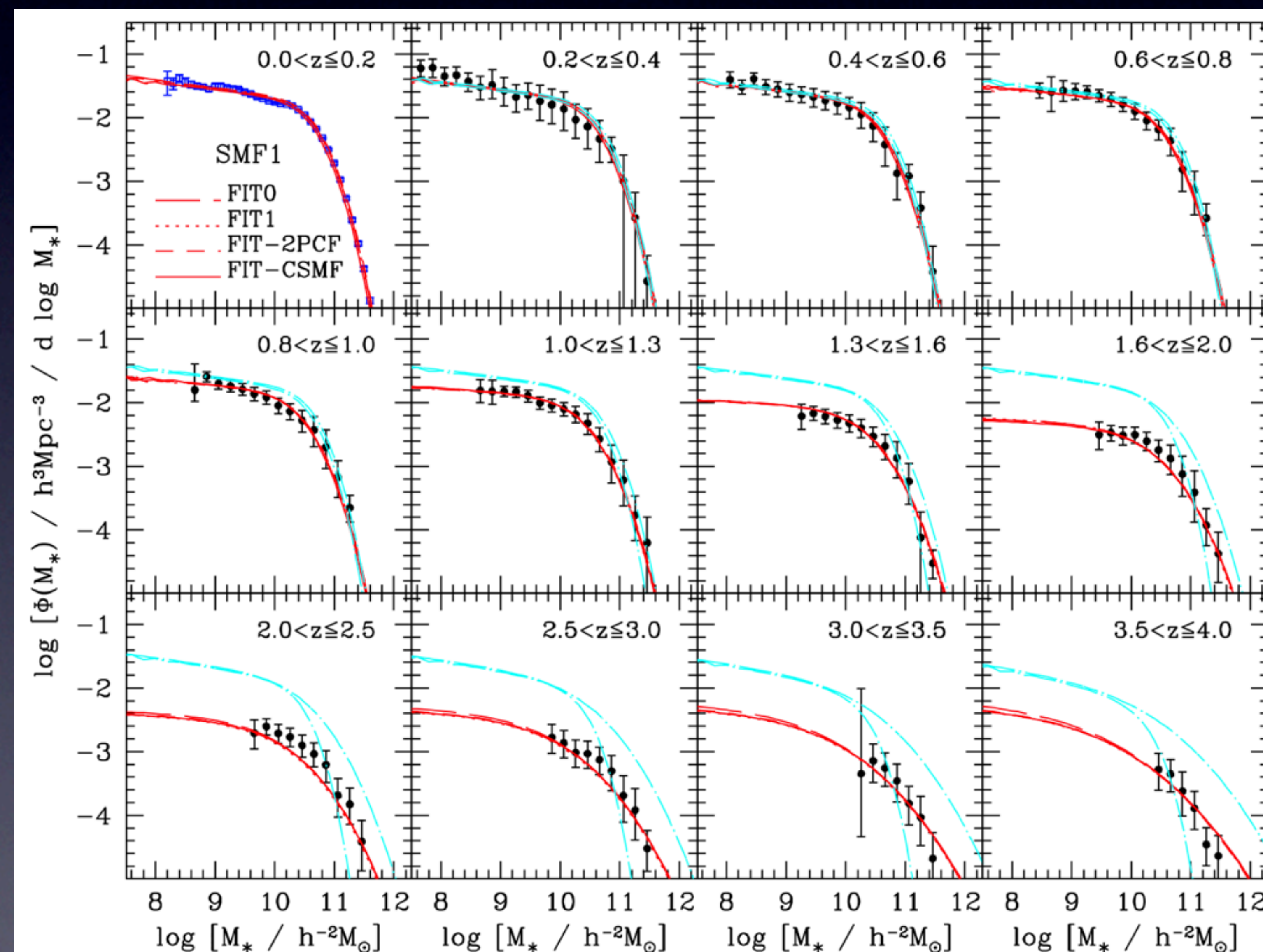
SHAM spin-off: Empirical Modeling

Apply SHAM at different redshifts, using $\Phi(M_\ast,z)$
Combine with halo merger trees $\Longrightarrow$ $SFR(M_\ast,z)$

Yang+09; Conroy & Wechsler 09; Moster+10; Yang+12; Behroozi+13a,b; Moster+13; Wang+13;Bethermin+13; Lu+14

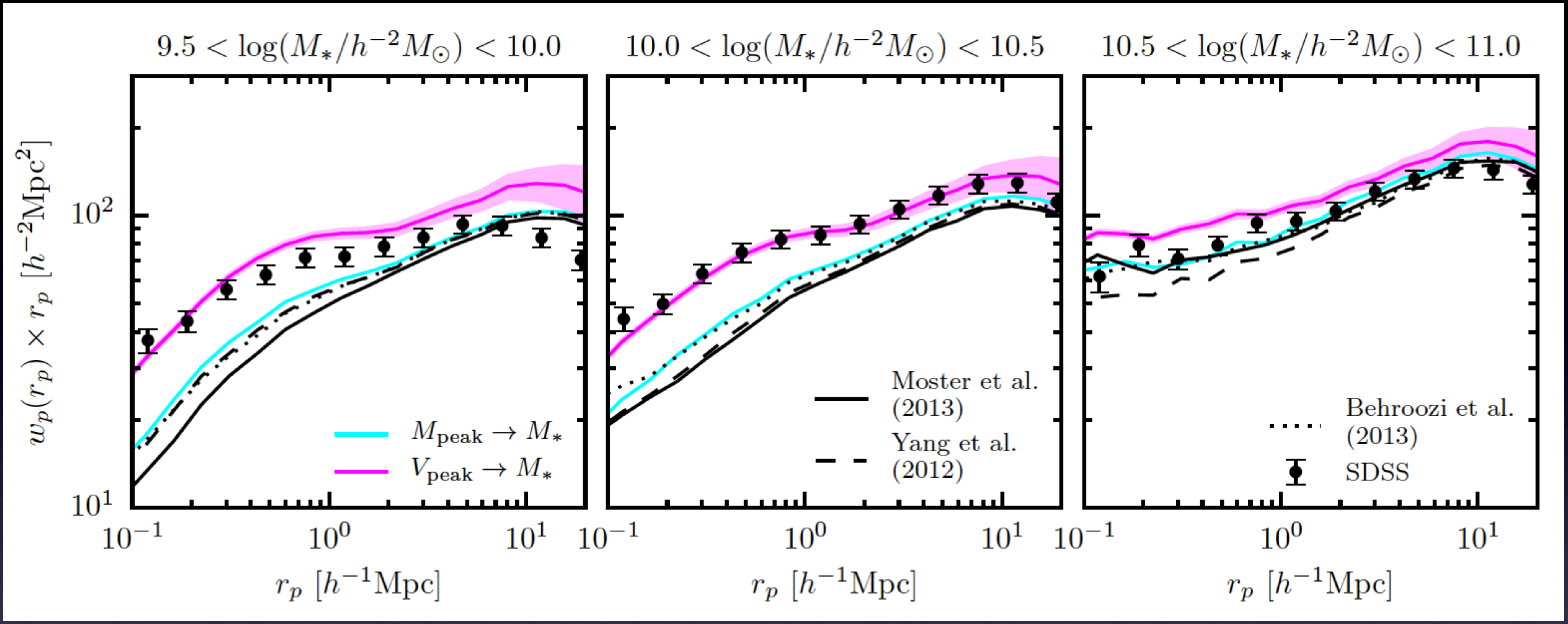


Behroozi et al., 2013



Yang, Mo, vdB et al. 2012

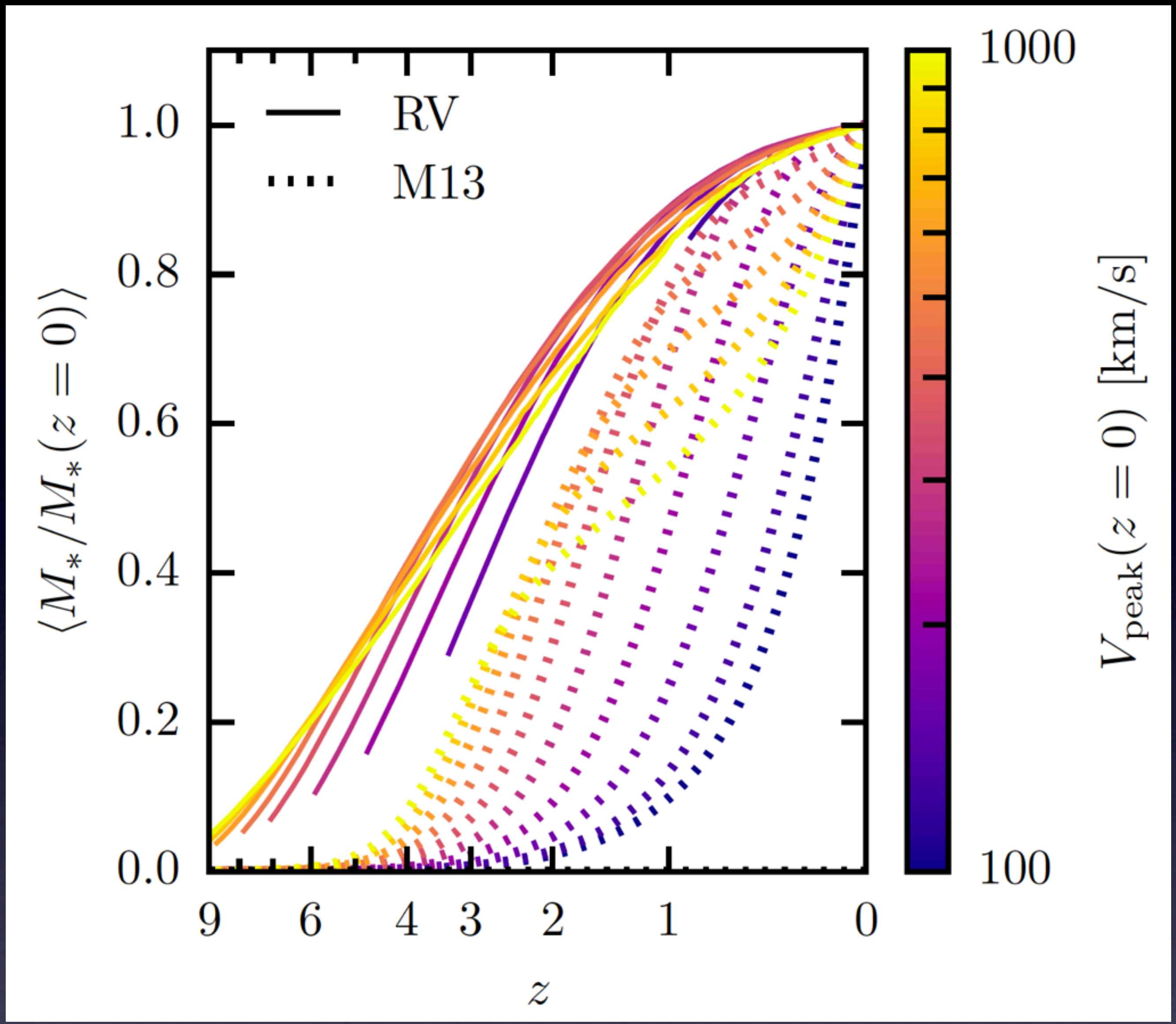
The Clustering Crisis



Campbell, vdB, et al. 2016, in prep.

- Moster+13, Behroozi+13 and Yang+12, which all fit $\Phi(M^*,z)$, underpredict clustering on small scales, especially at low stellar mass...
- Same holds for standard SHAM based on M_{peak}
- V_{peak} based SHAM nicely fits clustering data (see also Reddick+13)

The Clustering Crisis

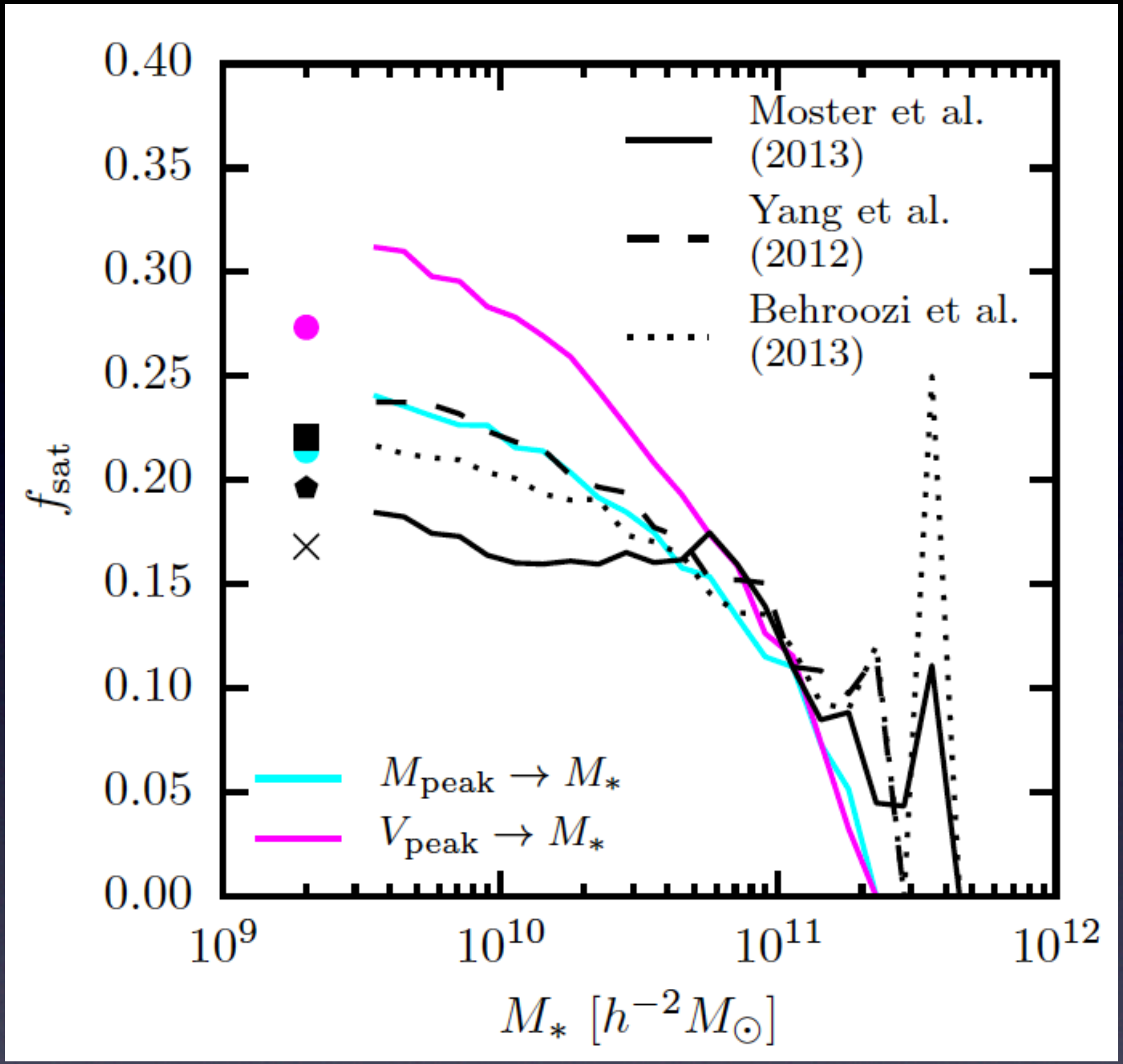


Campbell, vdB, et al. 2016, in prep.

- V_{peak} SHAM implicitely assumes NO evolution in the $V_{peak}(M^*)$ relation with redshift (i.e., no z_{peak} dependence).
- Using average $V_{max}(z)$ histories of vdBosch+14, we can infer the average stellar mass growth histories implied.
- These are very different from those implied by Moster+13, Behroozi+13, or Yang+12, and are thus inconsistent with $\Phi(M^*,z)$

Models that fit the clustering don't fit the evolution in the stellar mass function, and vice versa

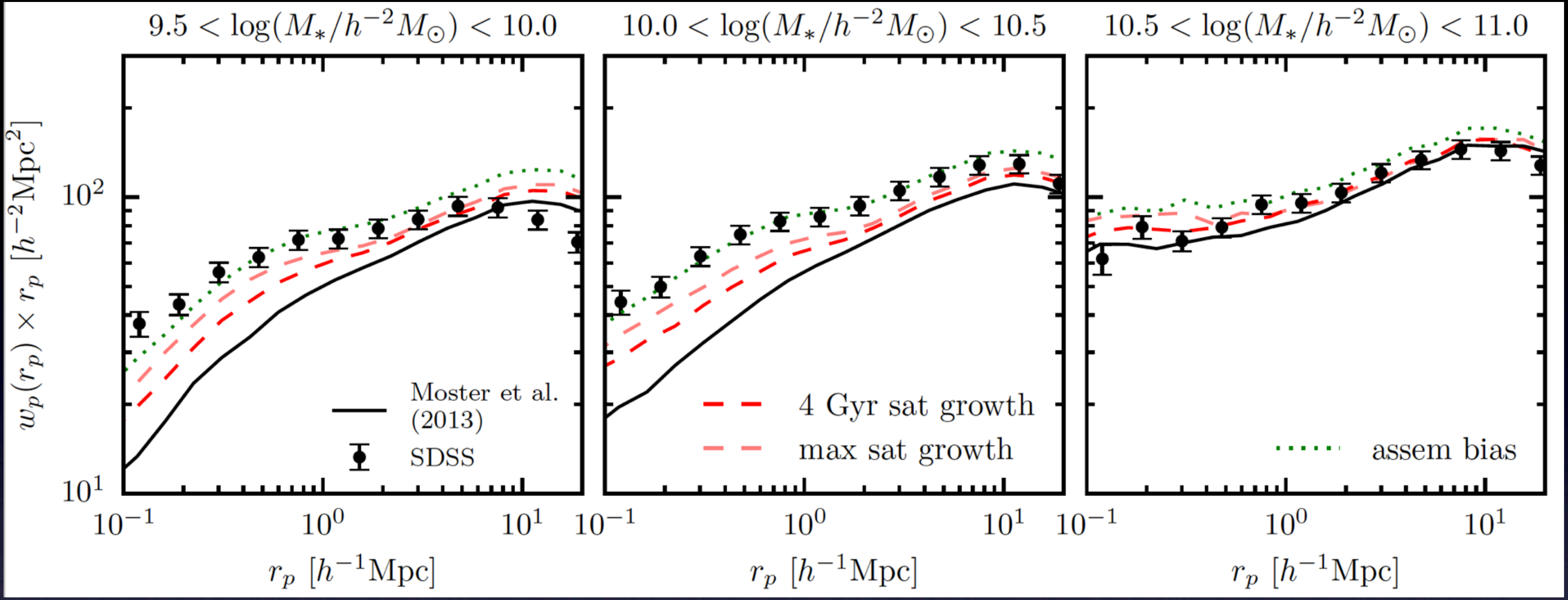
The Clustering Crisis



Campbell, vdB, et al. 2016, in prep.

Problem is with satellites.
Either models need more sub-halos (orphans)
or satellites need to be more massive...

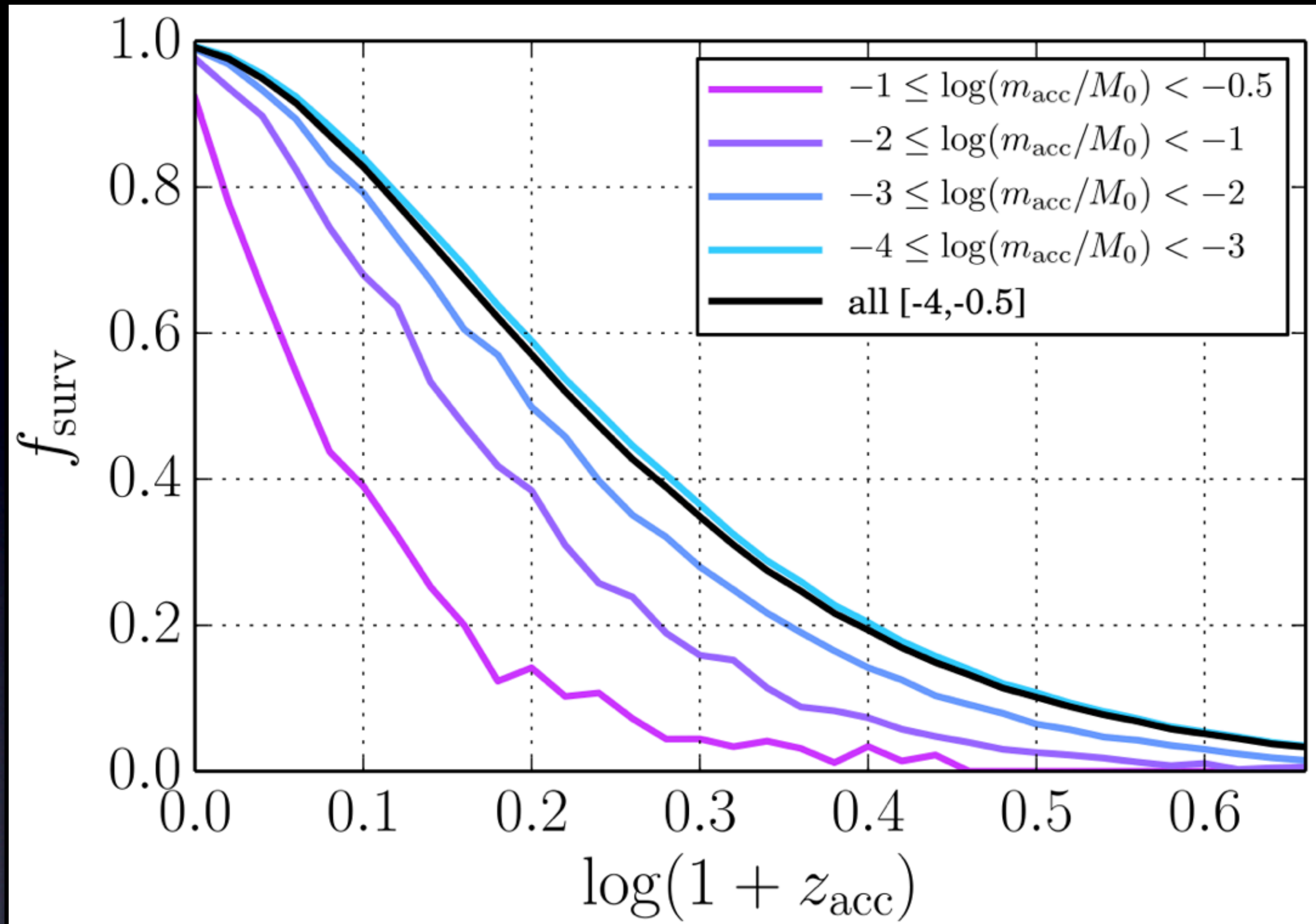
The Clustering Crisis



Solutions to the Clustering Crisis

- Satellite galaxies continue to grow in stellar mass after accretion. This by itself is not enough to solve the problem.
- Assembly bias: satellites at accretion have already overgrown their stellar mass compared to centrals.
- There is too much subhalo disruption in numerical simulations, by roughly a factor two. Need for `orphans'.

Subhalo Disruption in Bolshoi

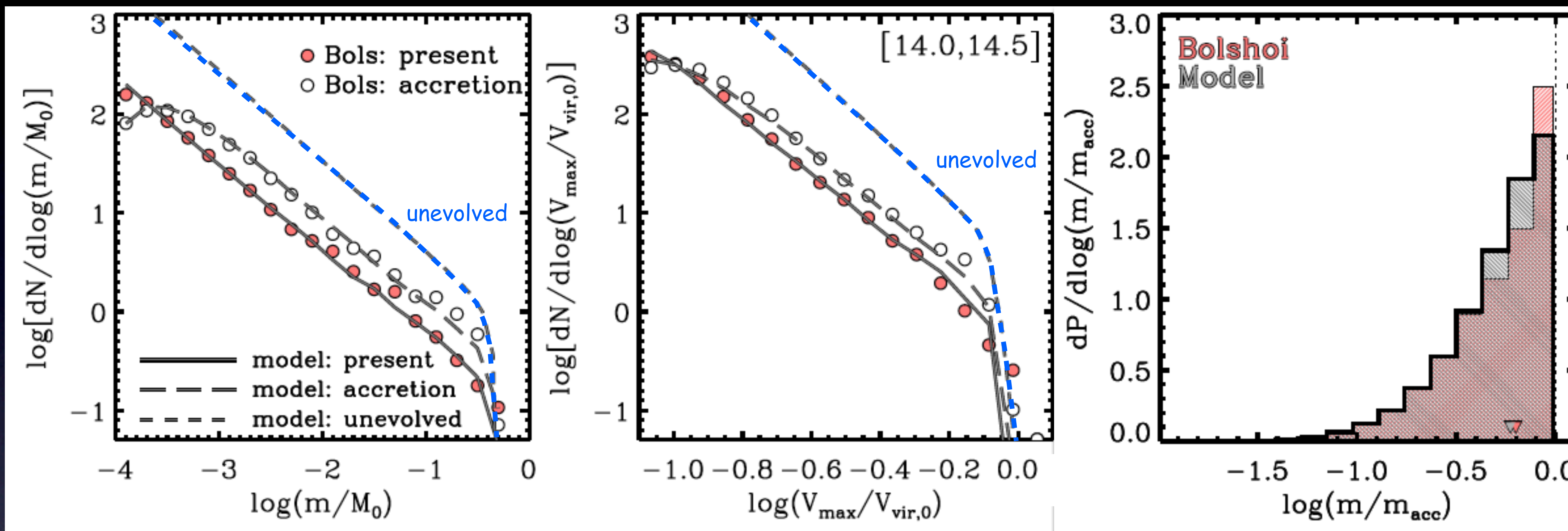


Jiang & vdB, 2016

- Fractional Disruption Rate ≈13 percent per Gyr
- Only ~35 percent of subhaloes accreted at z=1 survive to z=0
- Is tidal disruption real or numerical artifact?
  If real, what are the physical conditions for disruption?

What if ALL disruption is numerical?

subhalo mass function | subhalo V_{max} function | retained mass fractions

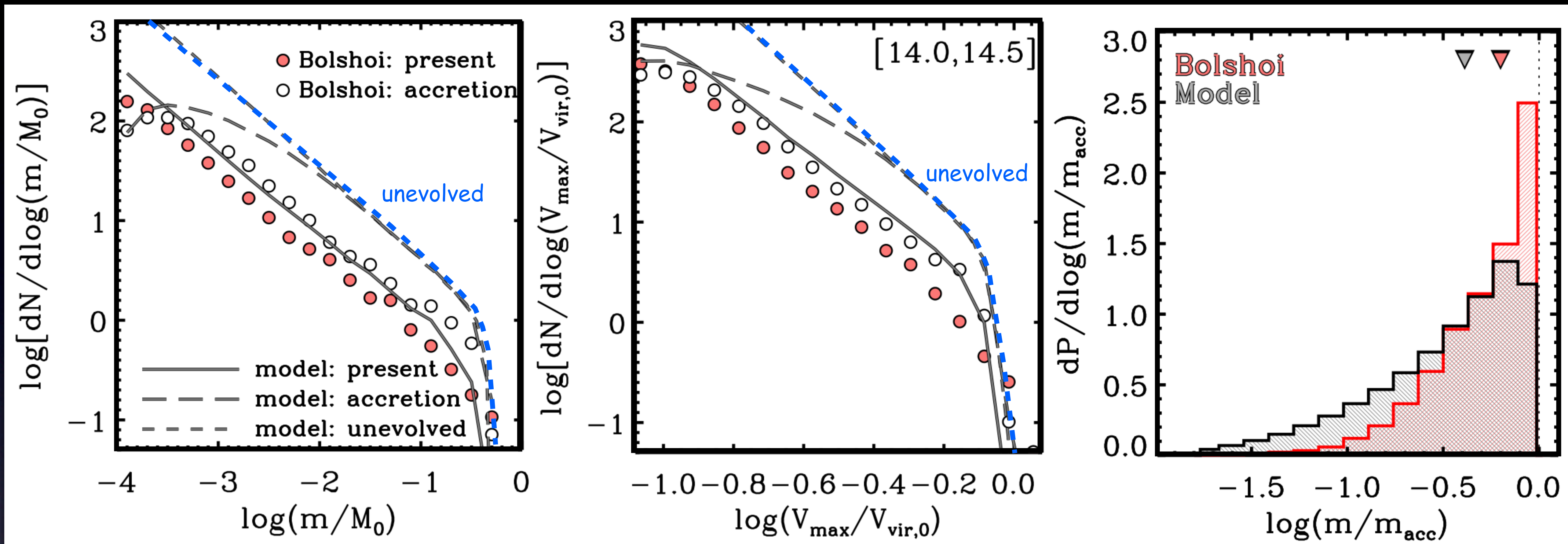


Jiang & vdB, 2016

- Jiang & van den Bosch (2016) developed semi-analytical model for DM substructure
- Model includes treatments of tidal stripping & tidal disruption
- Model is tuned to accurately reproduce the Bolshoi simulation results

What if ALL disruption is numerical?

subhalo mass function subhalo V_{max} function retained mass fractions



- Turning off disruption in model reveals its impact
- Without disruption, abundance of subhalos is boosted by factor ~2, roughly independent of mass or maximum circular velocity.
- This would solve the Clustering Crisis

The Evolution of Dark Matter Substructure

Tidal Stripping

Impulsive Heating

Force Softening

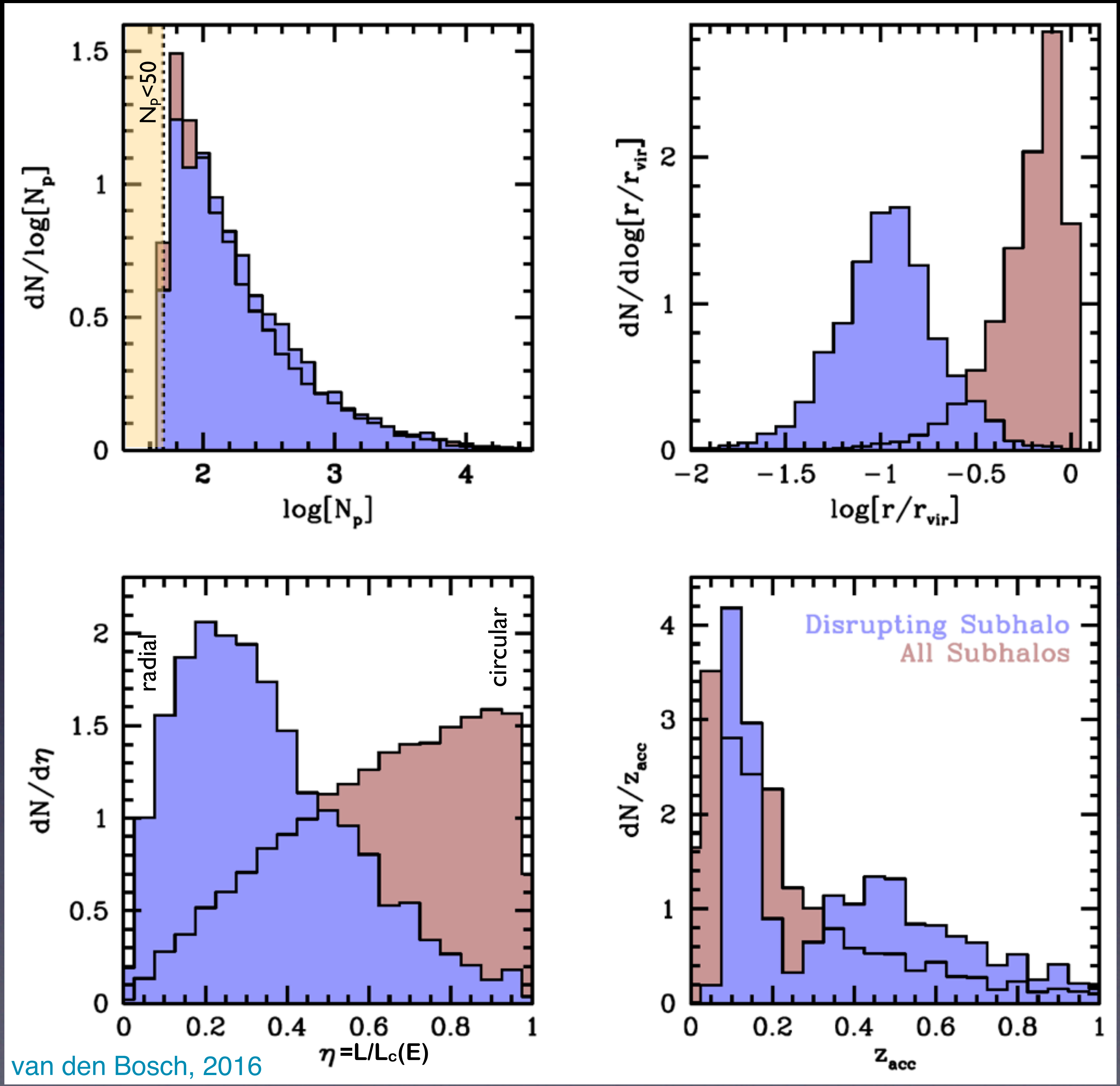
Two-Body Relaxation

Dynamical Friction

Harassment

Limiting Mass Resolution

Statistics of Subhalo Disruption



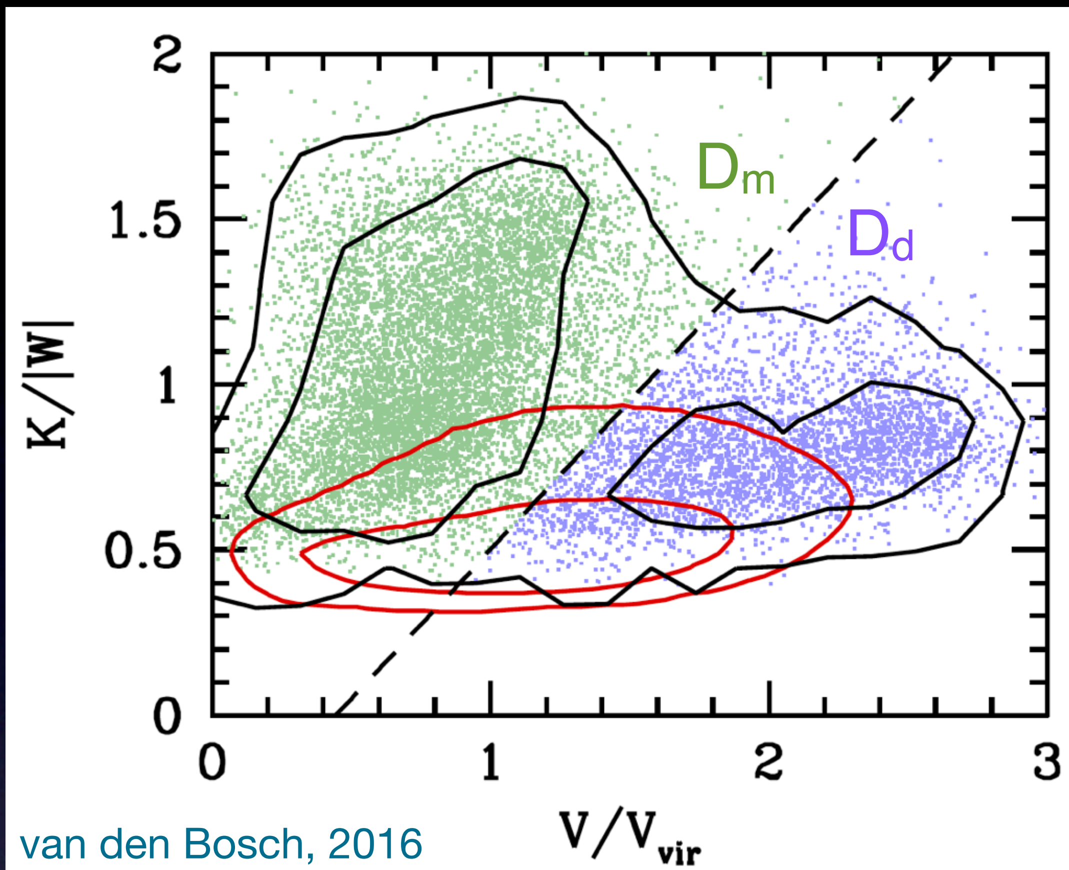
Disruption occurs preferentially at small halo-centric radii, for subhalos on more radial orbits, and at first or second pericentric passage.

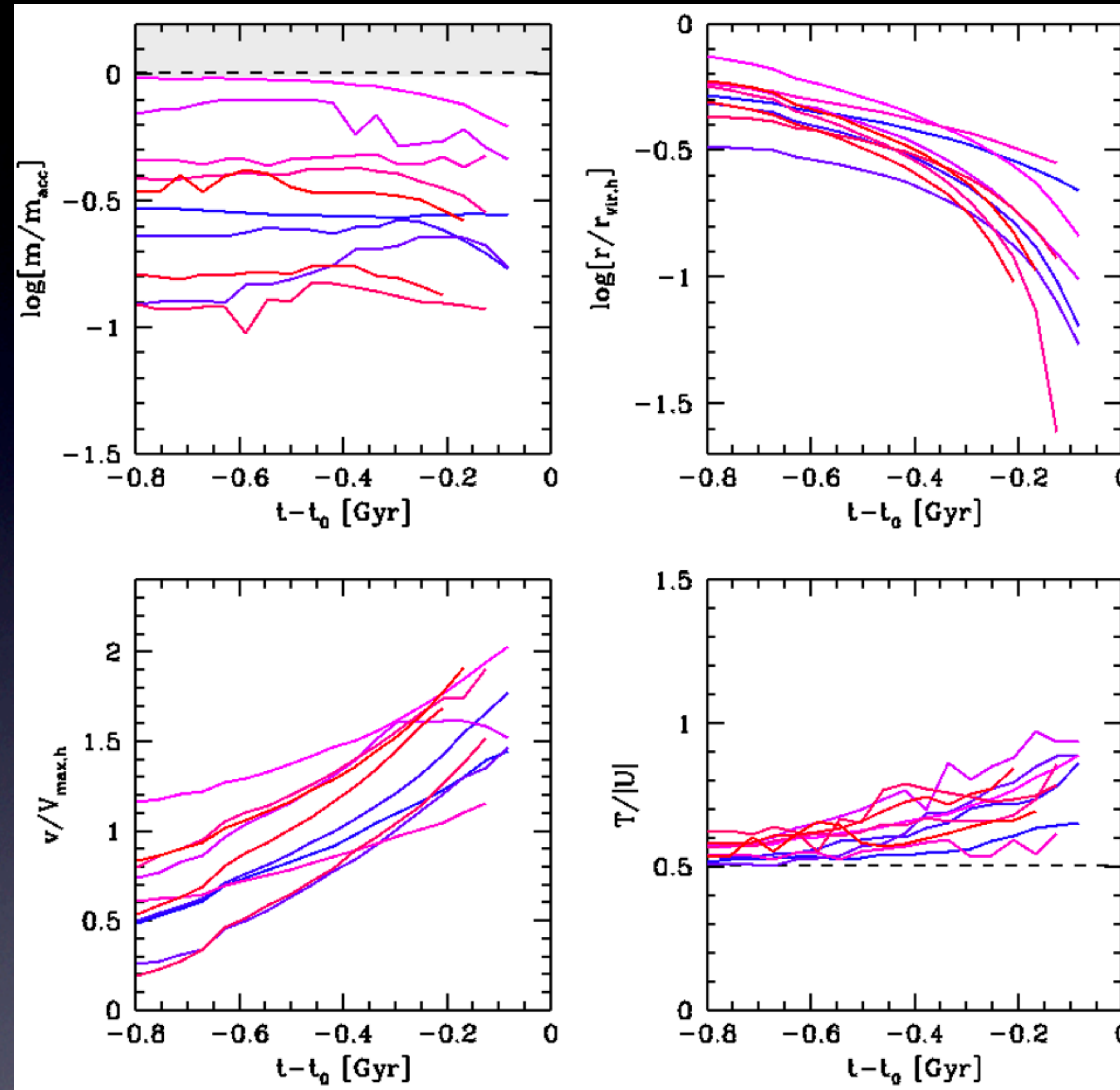
However, disruption is NOT biased with respect to the number of particles in the subhalo...

What causes this disruption???

Based on Bolshoi + Rockstar

Subhalo Disruption in the Bolshoi Simulation





Examples of D_d subhalos the last 0.8Gyr prior to disruption.
All these examples have $N_p > 5000$ at disruption

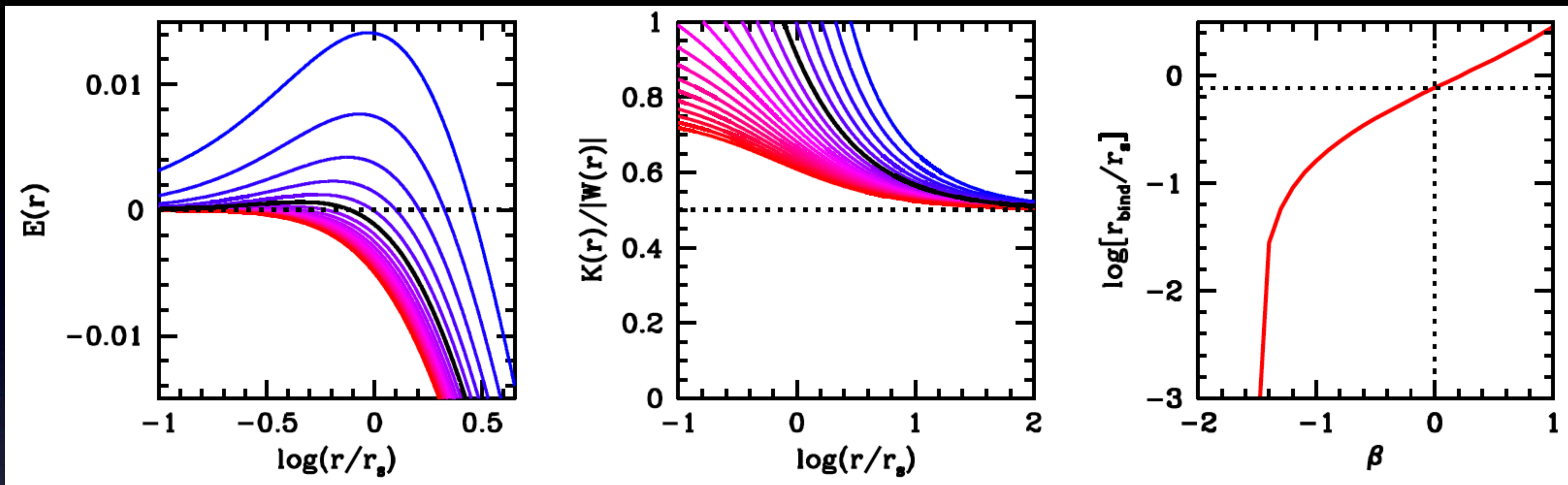
Three modes of disruption in Bolshoi

Withering: subhaloes whose mass is stripped below mass resolution.

Merging (D_m): subhaloes that merge with host halo; driven by dynamical friction.

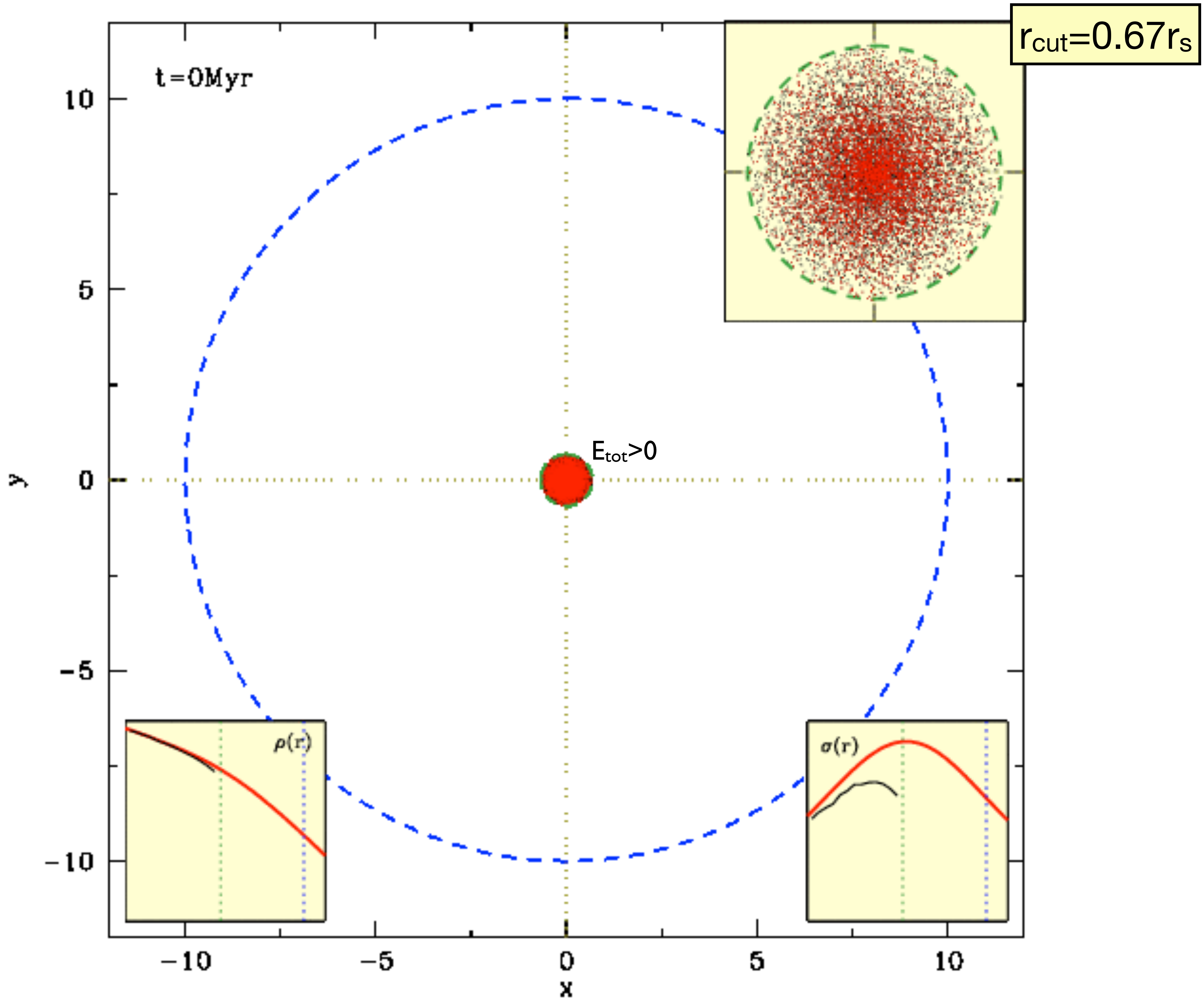
Disintegration (D_d): subhaloes that seem to `spontaneously' disintegrate close to pericenter...

Does Stripping cause Disruption?



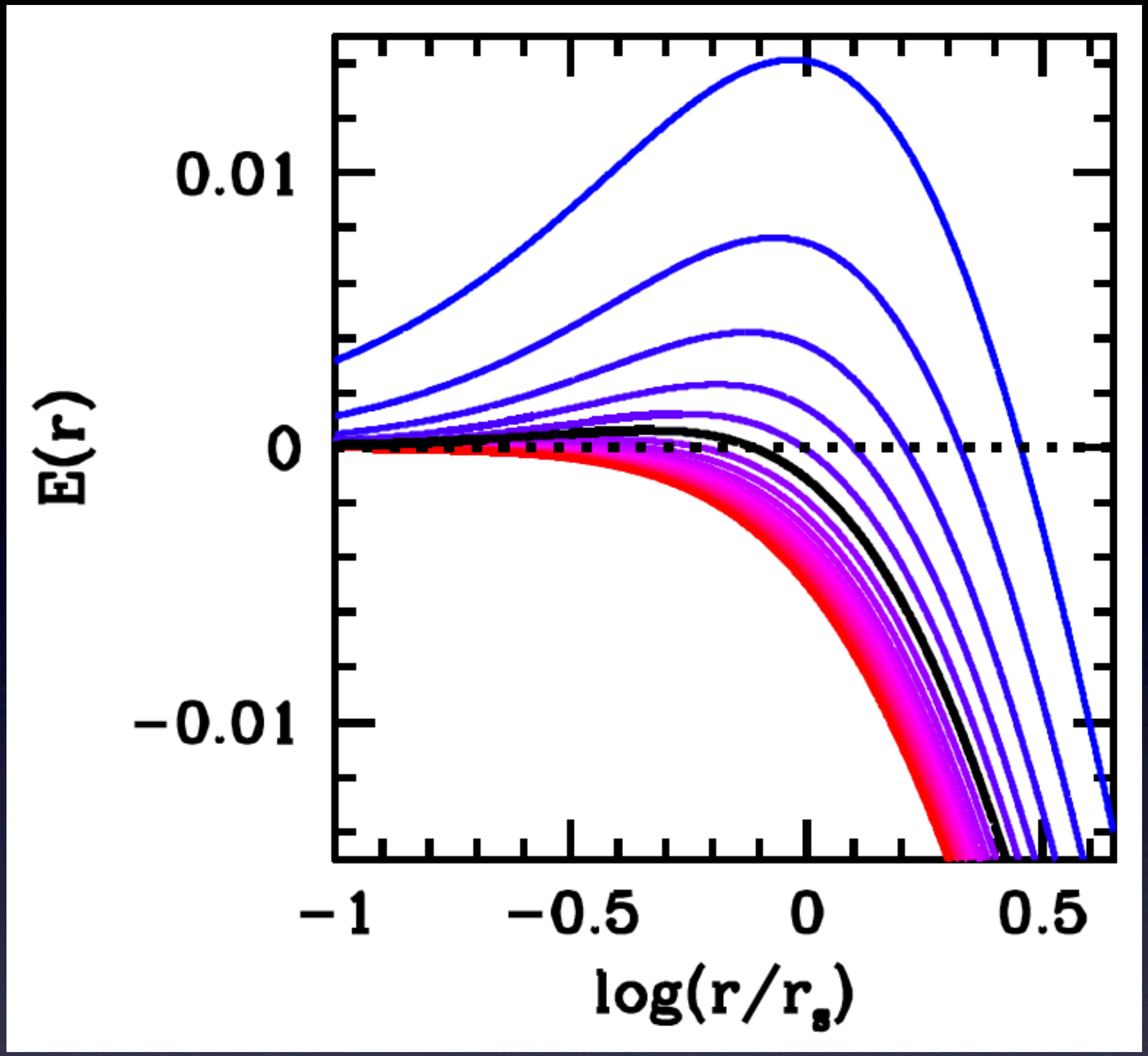
vdB+16, in prep.

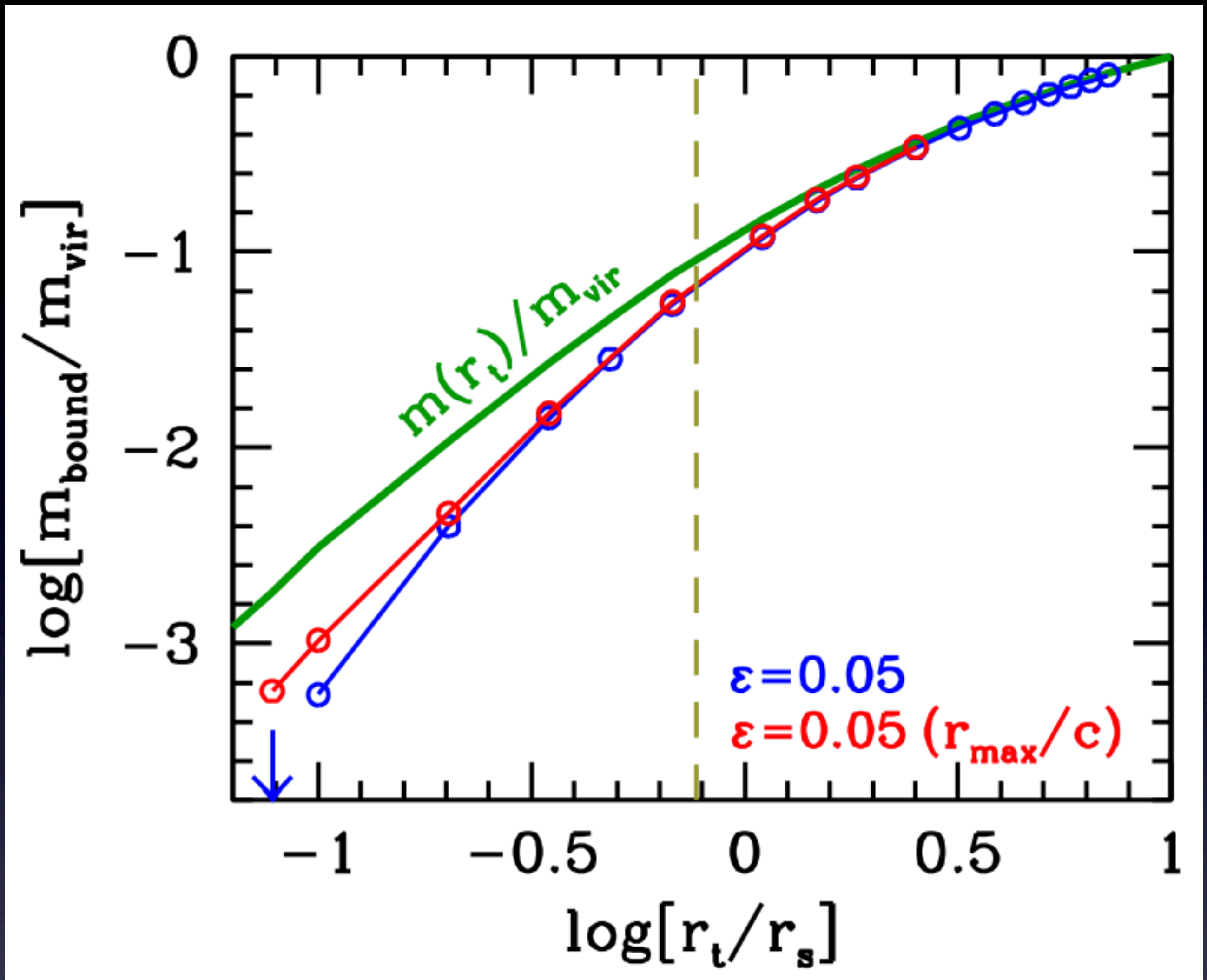
- As first pointed out by Hayashi+03, instantaneous stripping of outer layers of NFW halo can leave a remnant with positive binding energy.
- For an isotropic NFW halo (β=0), the core has positive binding energy if $r_{cut} < r_{bind} = 0.77\ r_s$. (corresponding core mass is ~$0.08\ M_{vir}$)
- Hayashi+03 therefore suggest that subhaloes will spontaneously disintegrate once their tidal radius, r_{tid} becomes smaller than r_{cut}



r_cut=0.67r_s
t=0Myr
E_tot>0
ρ(r)
σ(r)
y
x
10
5
0
−5
−10
−10
−5
0
5
10

Does Stripping cause Disruption? NO!

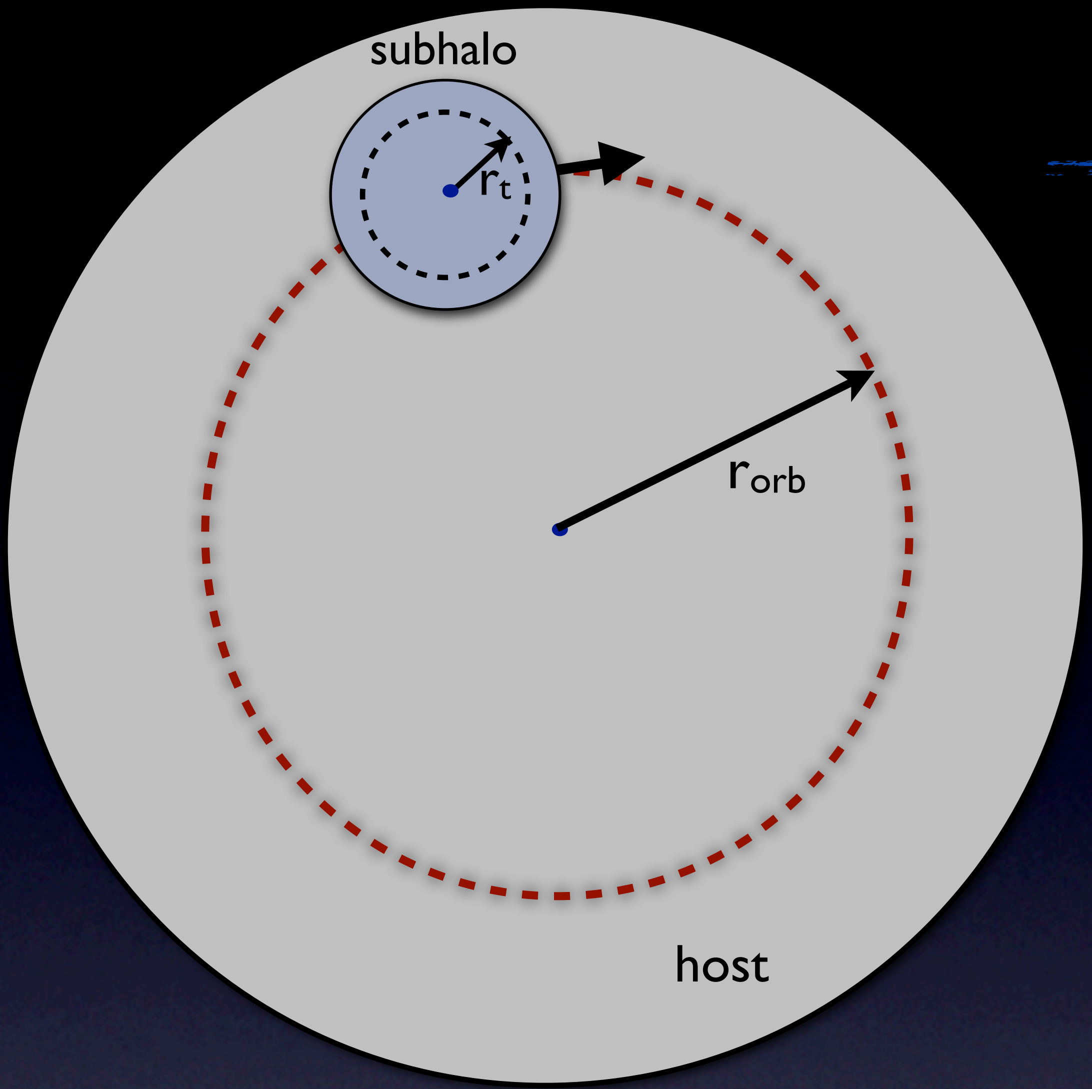




vdB+16, in prep.

- As first pointed out by Hayashi+03, instantaneous stripping of outer layers of NFW halo can leave a remnant with positive binding energy.
- However, contrary to their claim, this does NOT result in disruption...

Numerical Simulations



Simulate NFW halo orbiting on circular orbit inside static potential of host halo.

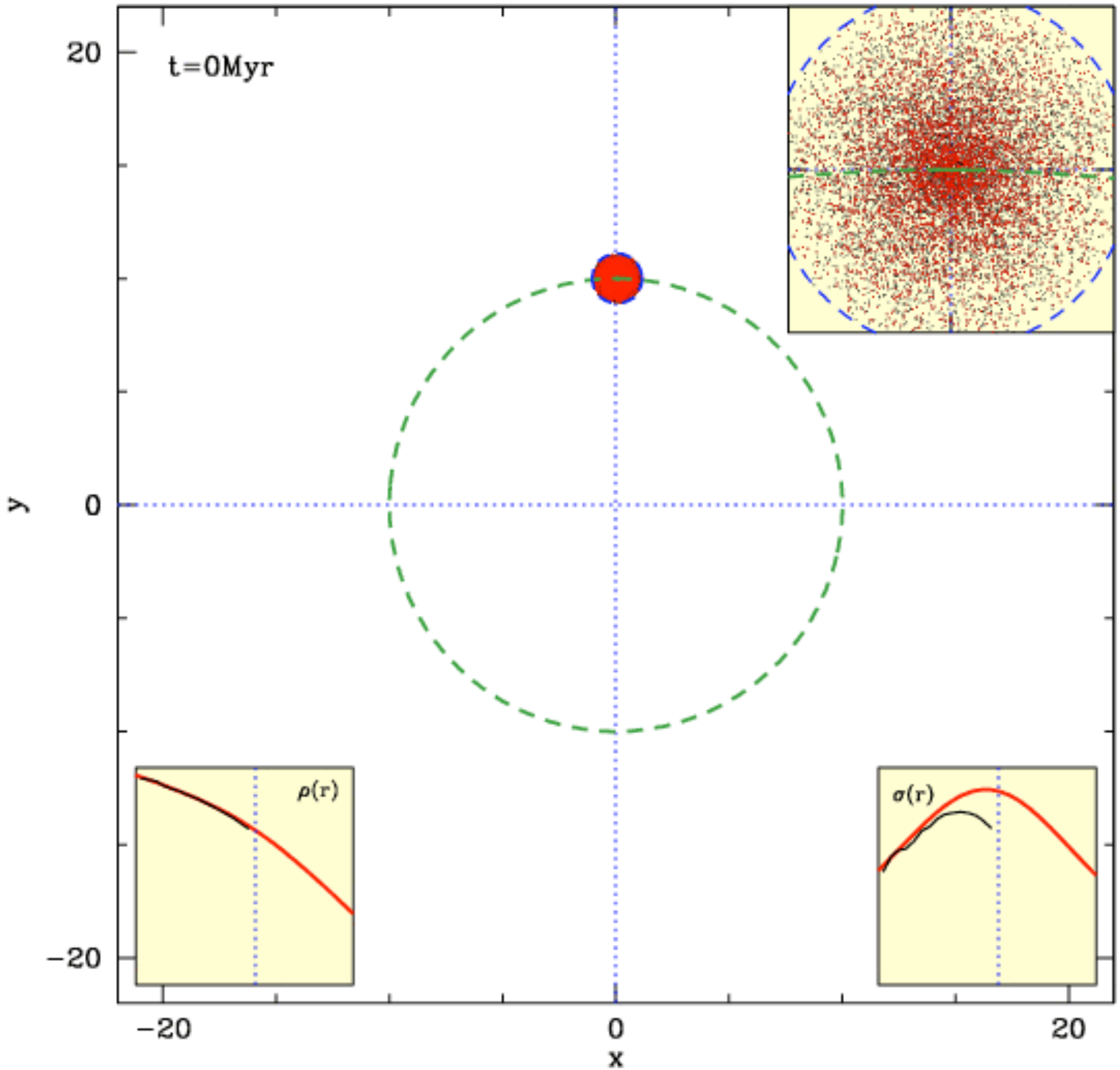
- No impulsive (tidal) heating
- No dynamical friction

Naive Prediction:

all matter outside of tidal radius will be stripped of over time...

More `Sophisticated' Prediction:

all matter with an apocenter $r_{apo} > r_t$ will be stripped of over time...

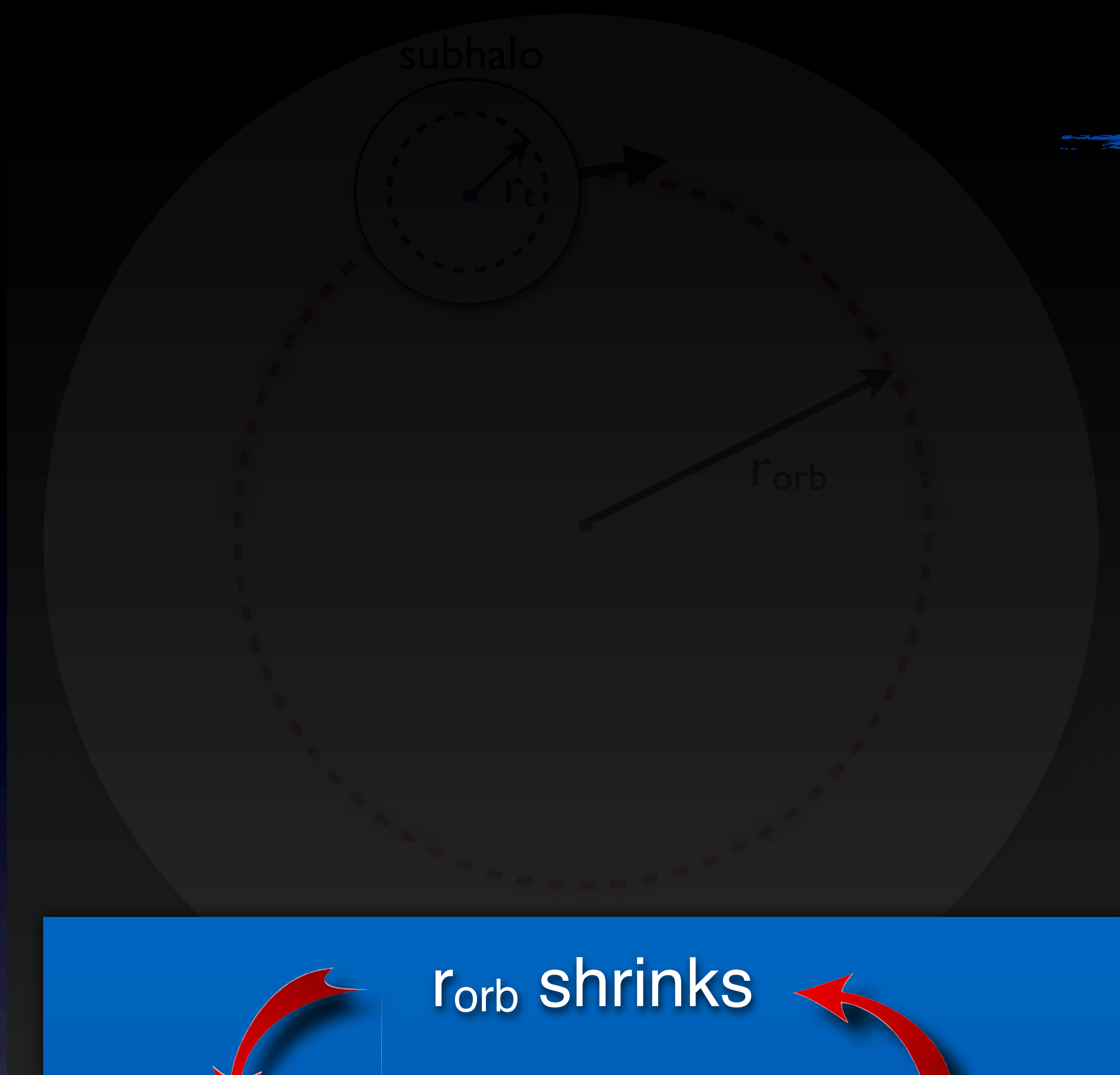


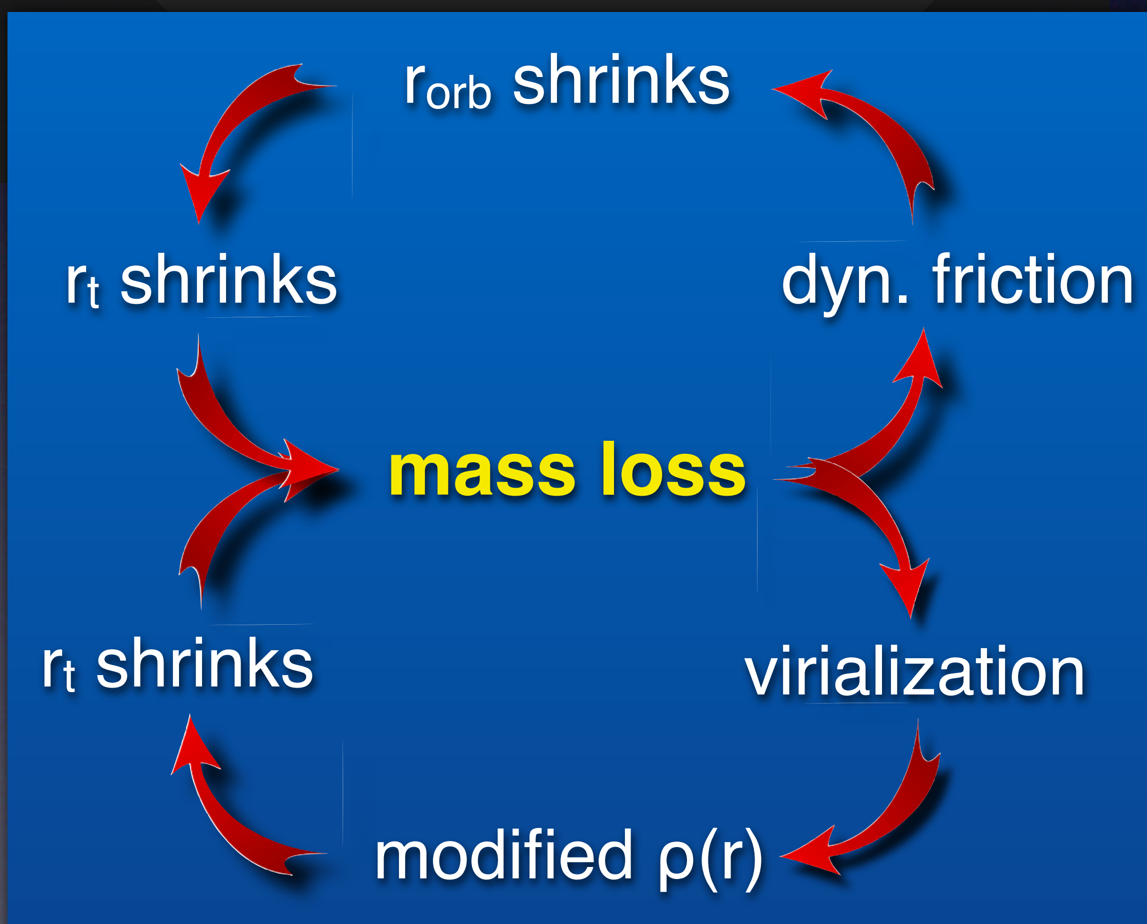
r_{orb}=0.1 $r_{vir,h}$

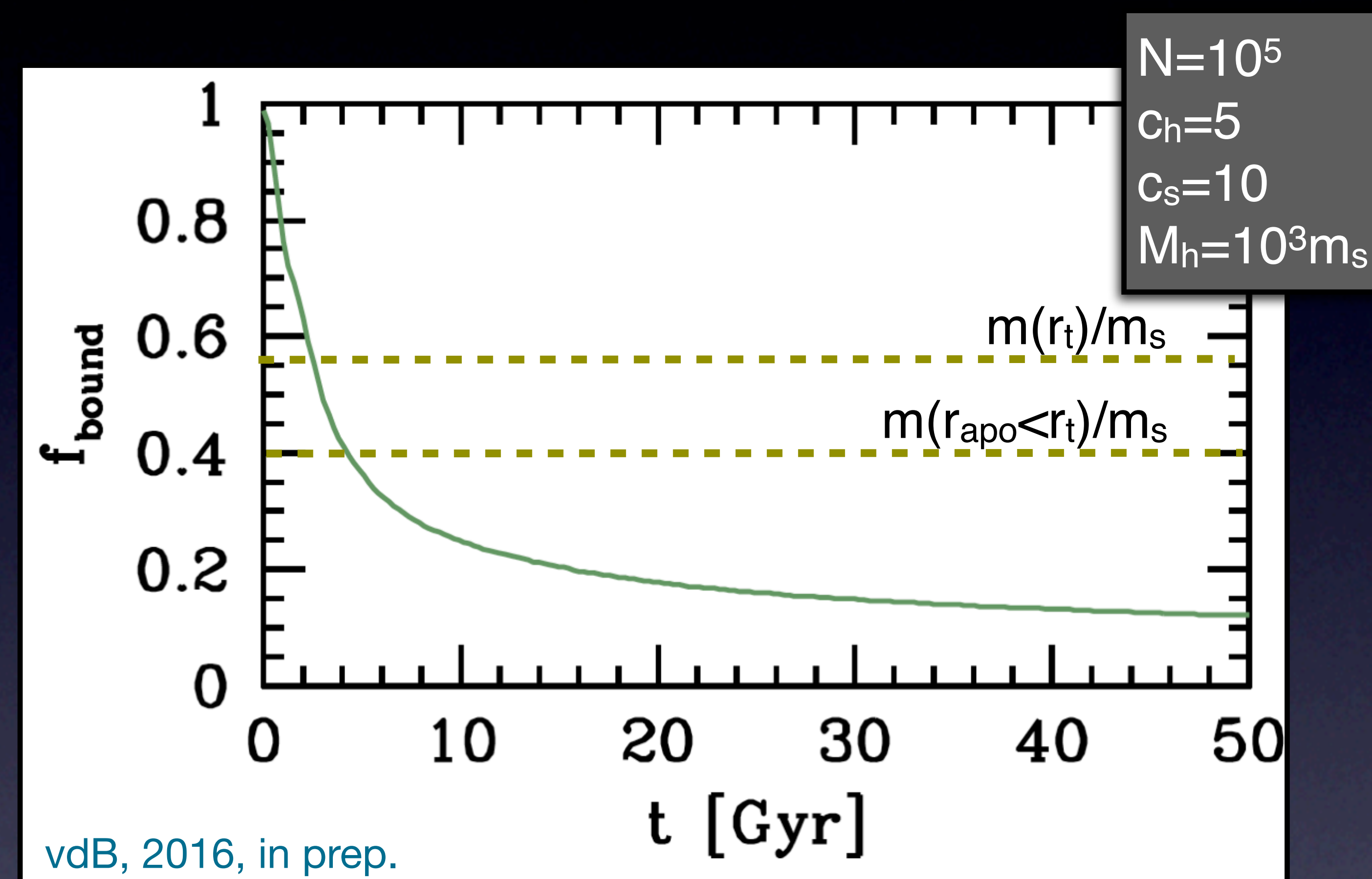
r_t=0.11 r_s

Numerical Simulations

Simulate NFW halo orbiting on circular orbit inside static potential of host halo.

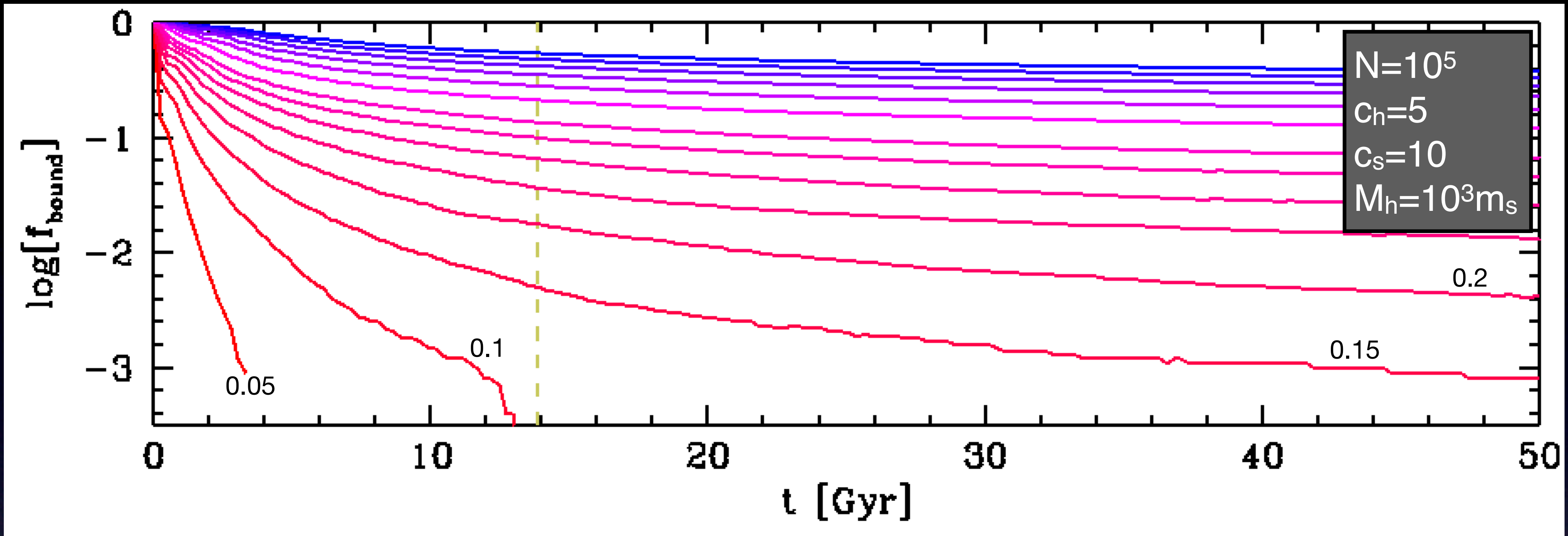




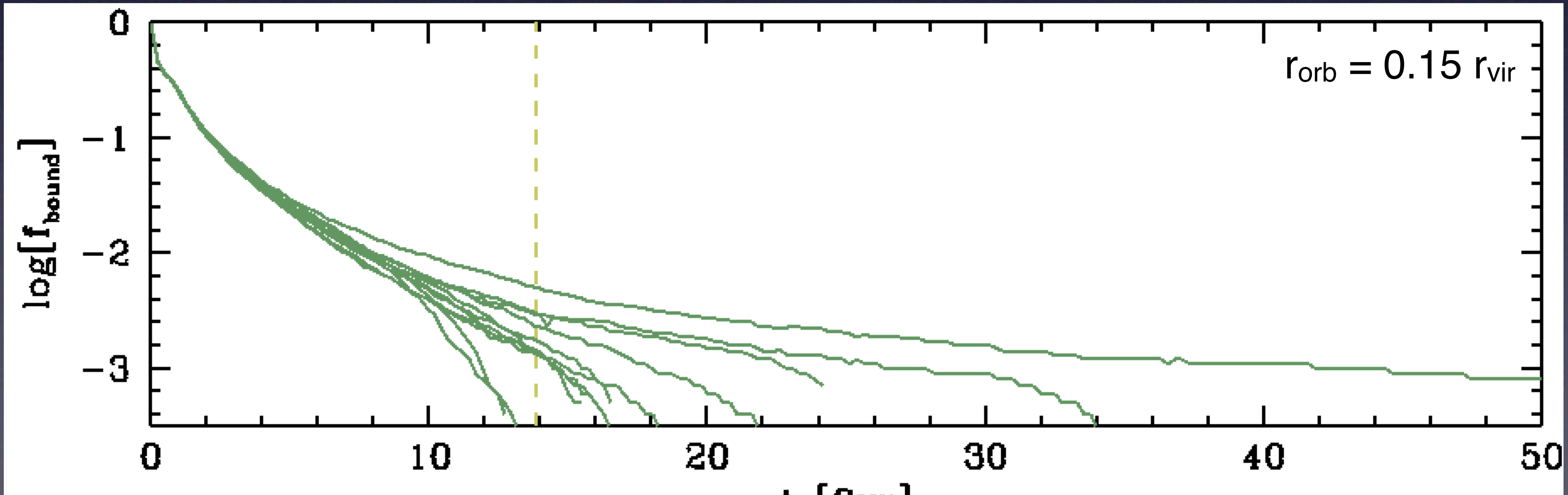


- Analytical predictions fail to predict amount of mass stripped
- Mass loss continues for >50 Gyr

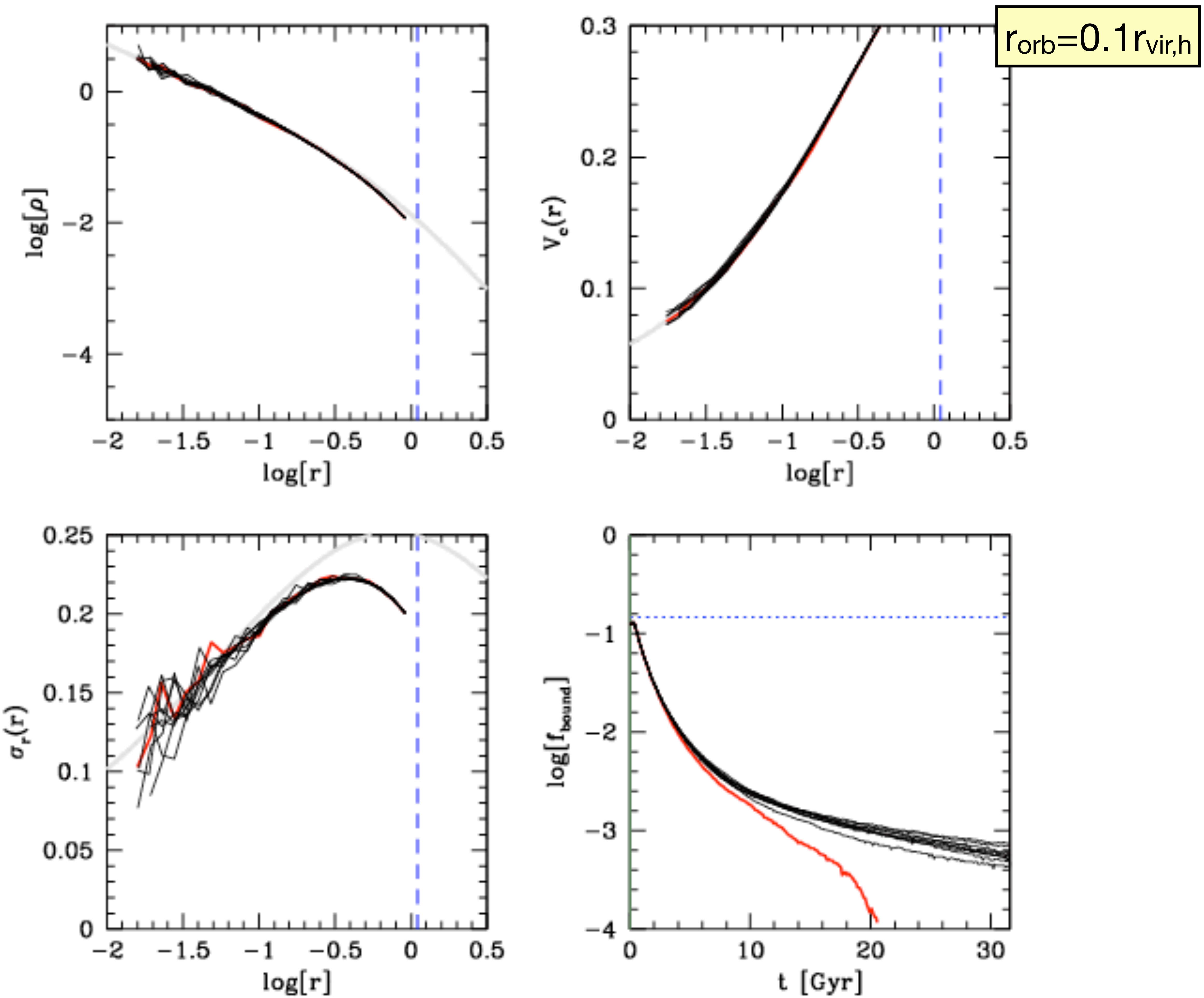
Tidal Stripping on Circular Orbits



Disruption for $r_{orb} < 0.15\ r_{vir}$......or numerical artefacts?

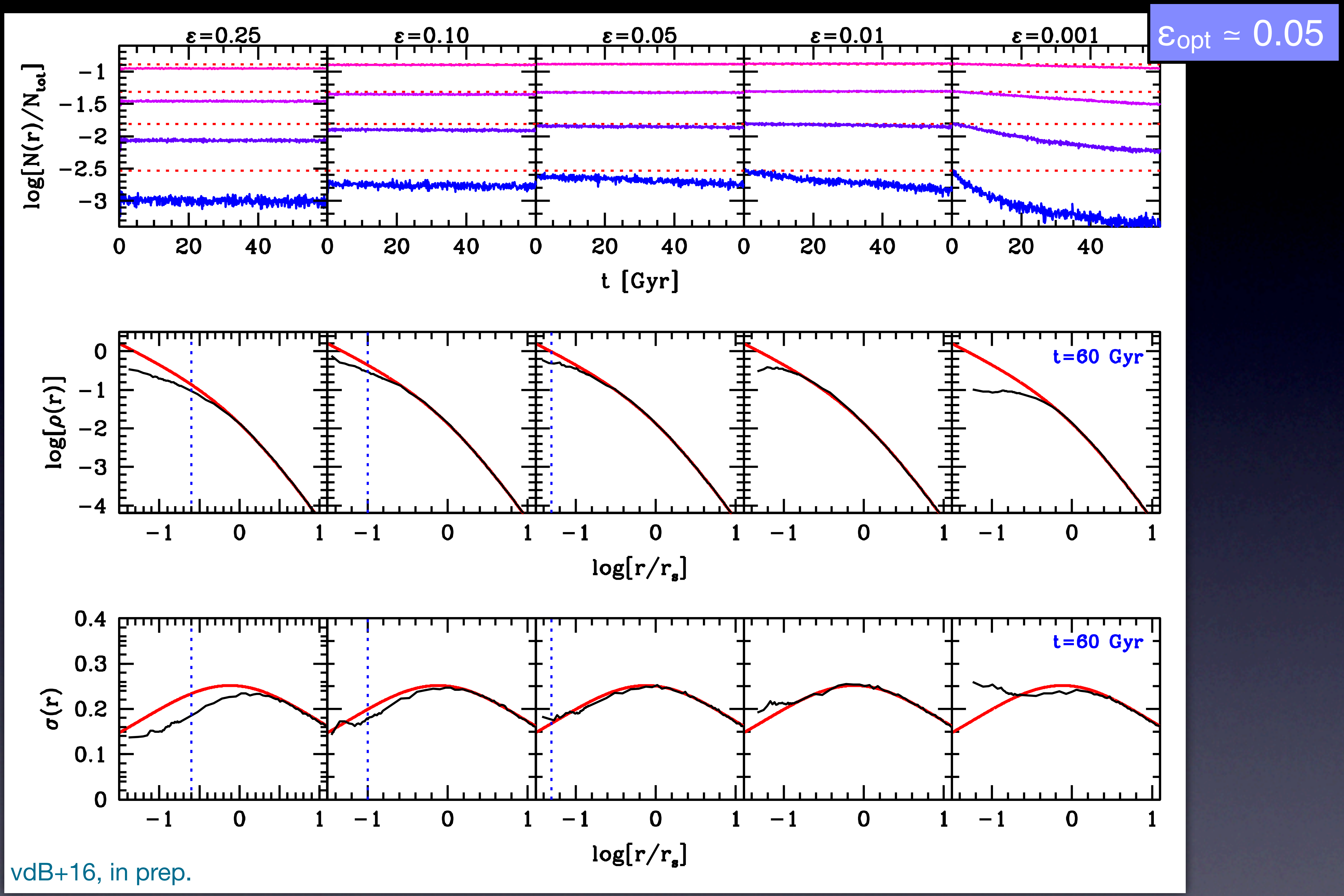


vdB, 2016, in prep.



r$_{orb}$=0.1r$_{vir,h}$
log[ρ]
log[r]
V$_c$(r)
σ$_r$(r)
log[f$_{bound}$]
t [Gyr]

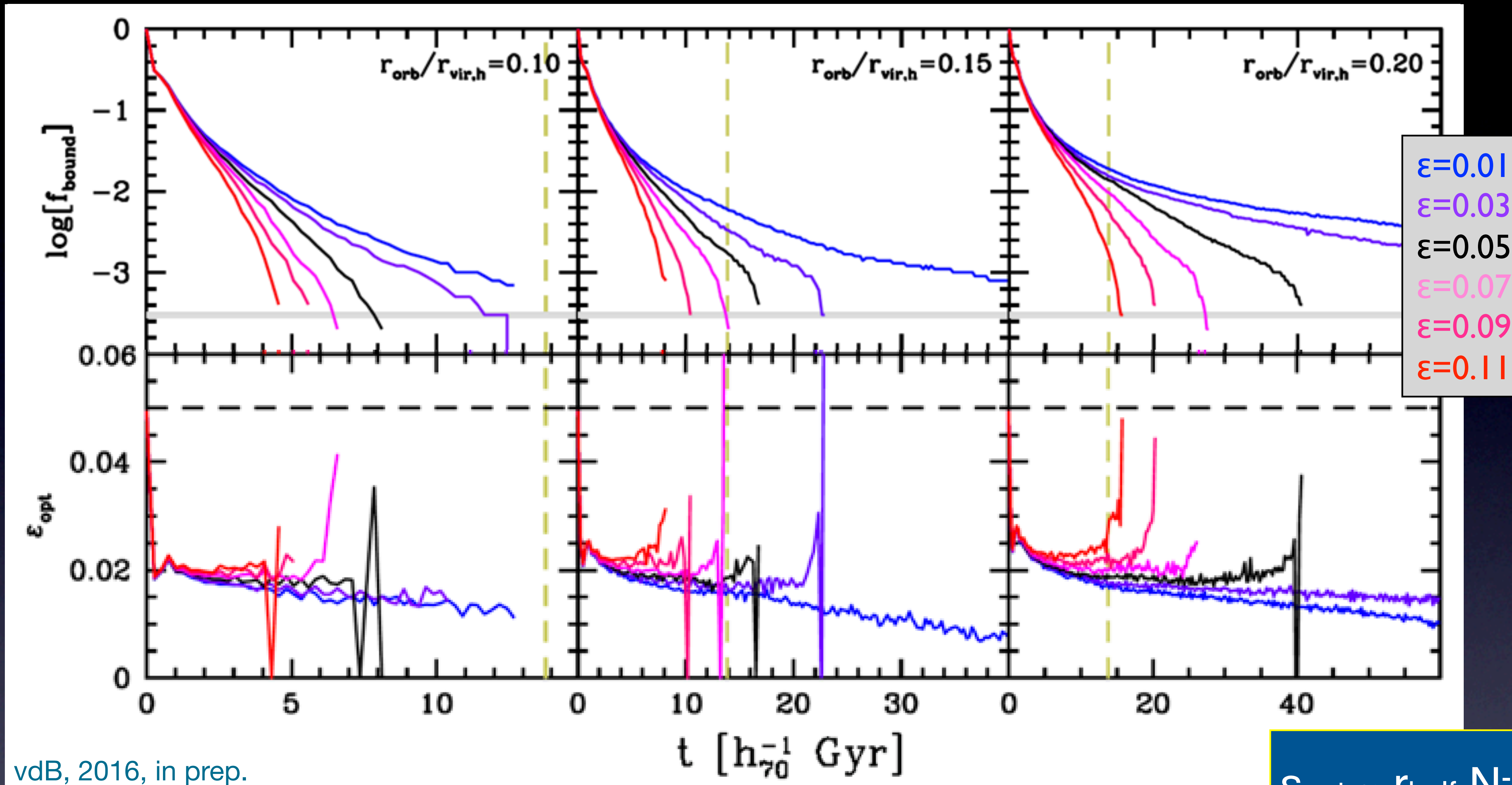
Tuning the Softening Length



ε too large ➢ force bias ➢ central cusp unresolved

ε too small ➢ force noise ➢ artificial large-angle deflections ➢ isothermal core

Force Softening

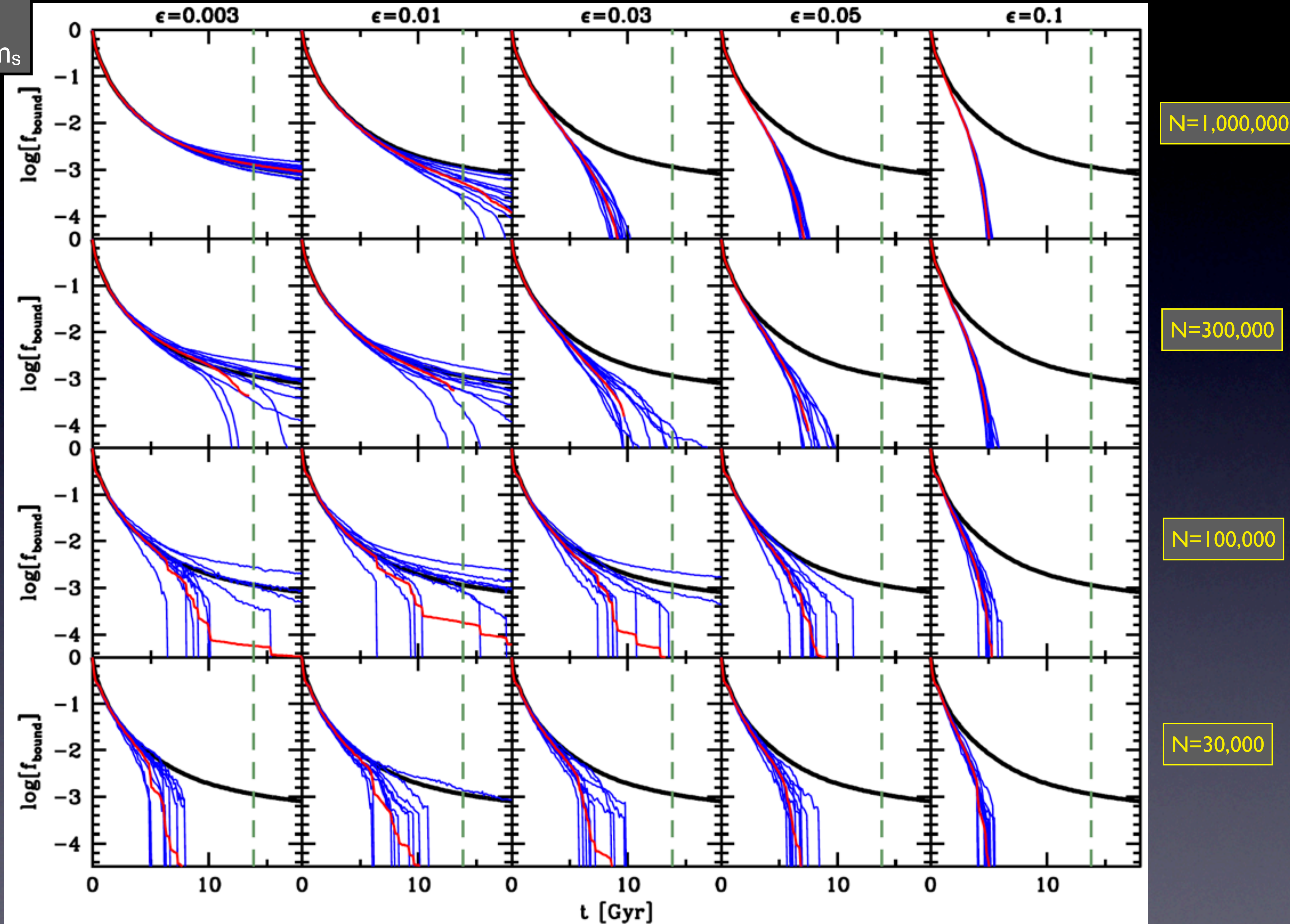


$\varepsilon_{opt} \propto r_{half}\, N^{-1/3}$

- Mass evolution and disruption extremely sensitive to softening length
- As subhalo looses mass, its optimal softening length decreases
- Adaptive, individual softening may be required (e.g., Iannuzzi & Dolag 11; Hobbs+15)

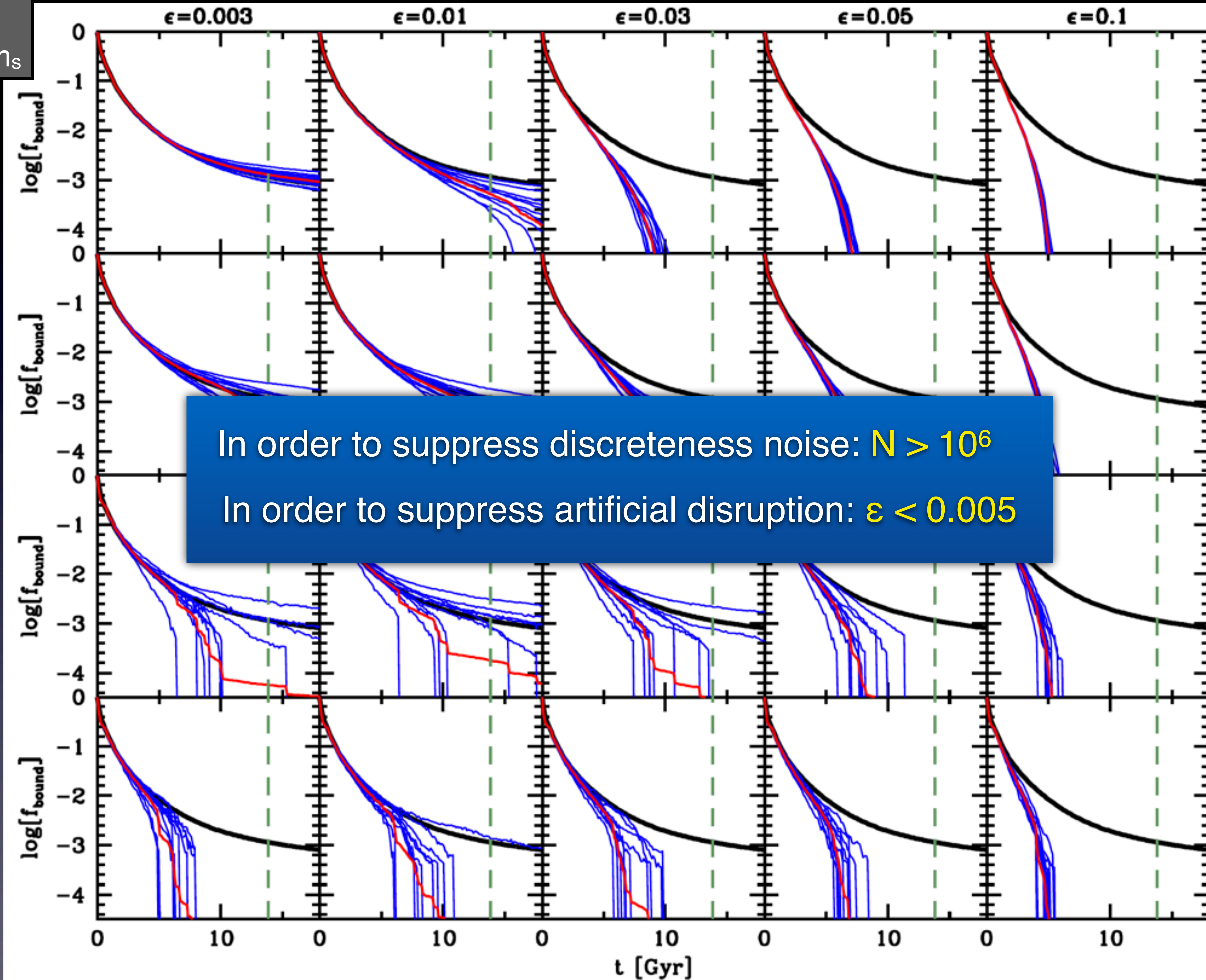
Towards Numerical Convergence

r_{orb}=0.1
c_h=5
c_s=10
M_h=$10^3 m_s$



Towards Numerical Convergence

$r_{orb}=0.1$
$c_h=5$
$c_s=10$
$M_h=10^3 m_s$



N=1,000,000

N=300,000

N=100,000

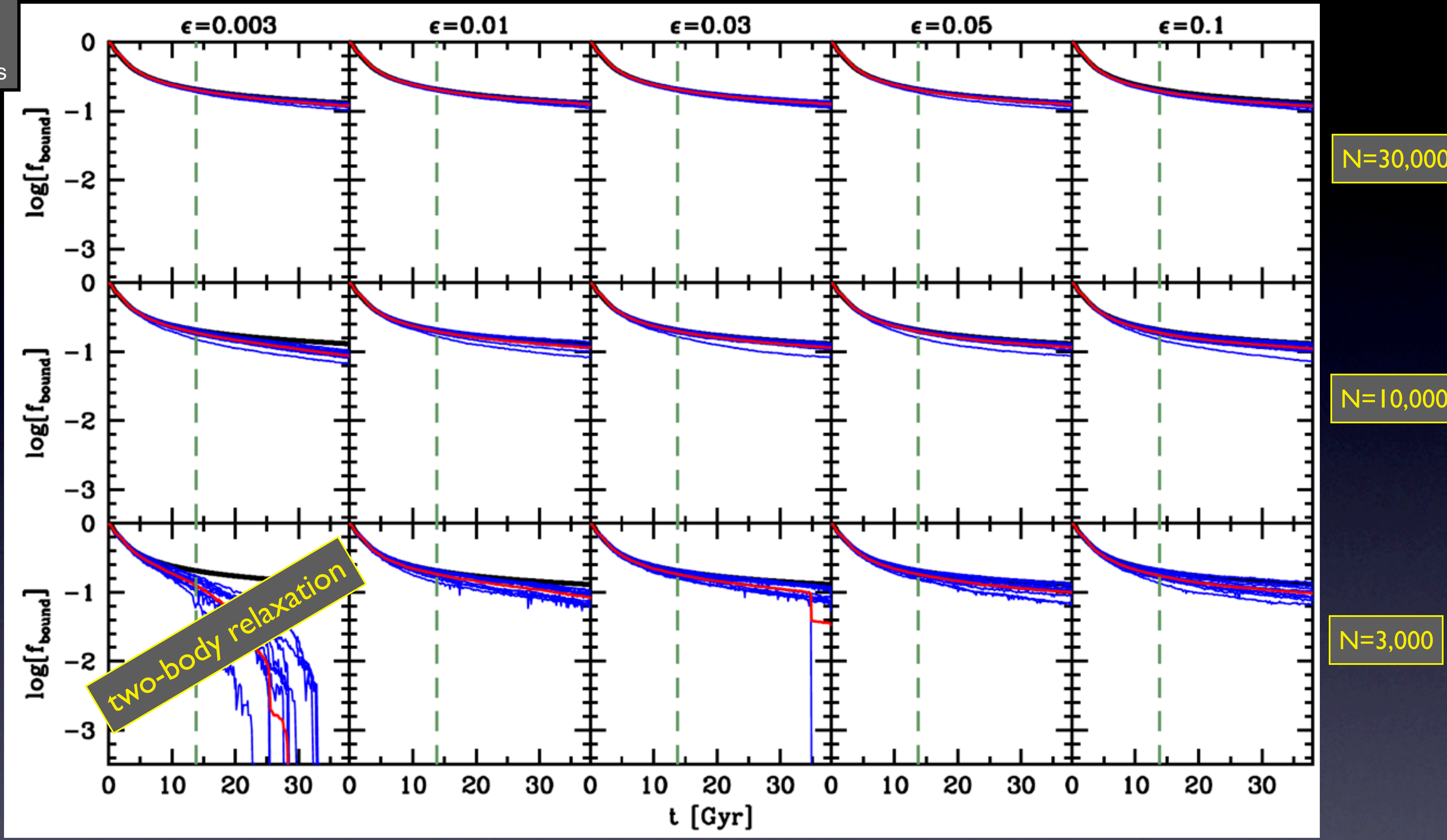
N=30,000

In order to suppress discreteness noise: $N > 10^6$

In order to suppress artificial disruption: $\varepsilon < 0.005$

Towards Numerical Convergence

$r_{orb}=0.5$
$c_h=5$
$c_s=10$
$M_h=10^3 m_s$



Ability to resolve dynamics is a strong function of

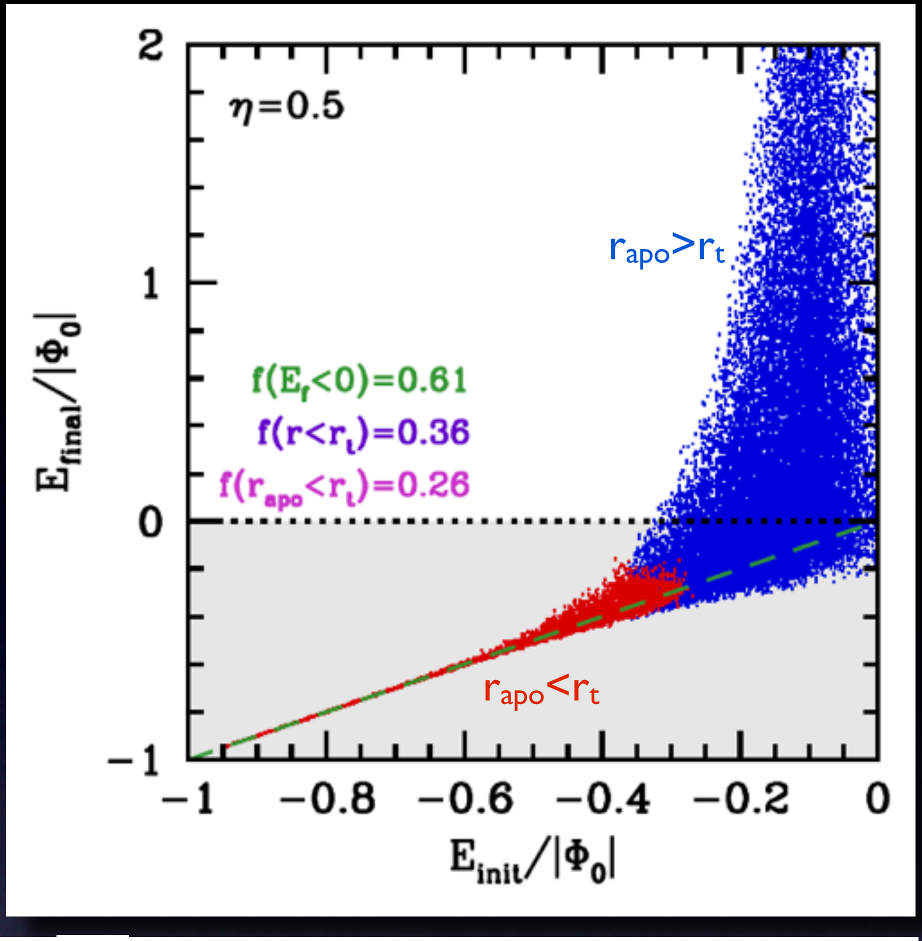
- number of particles
- force softening
- strength of tidal field

What about Tidal (Impulsive) Heating?

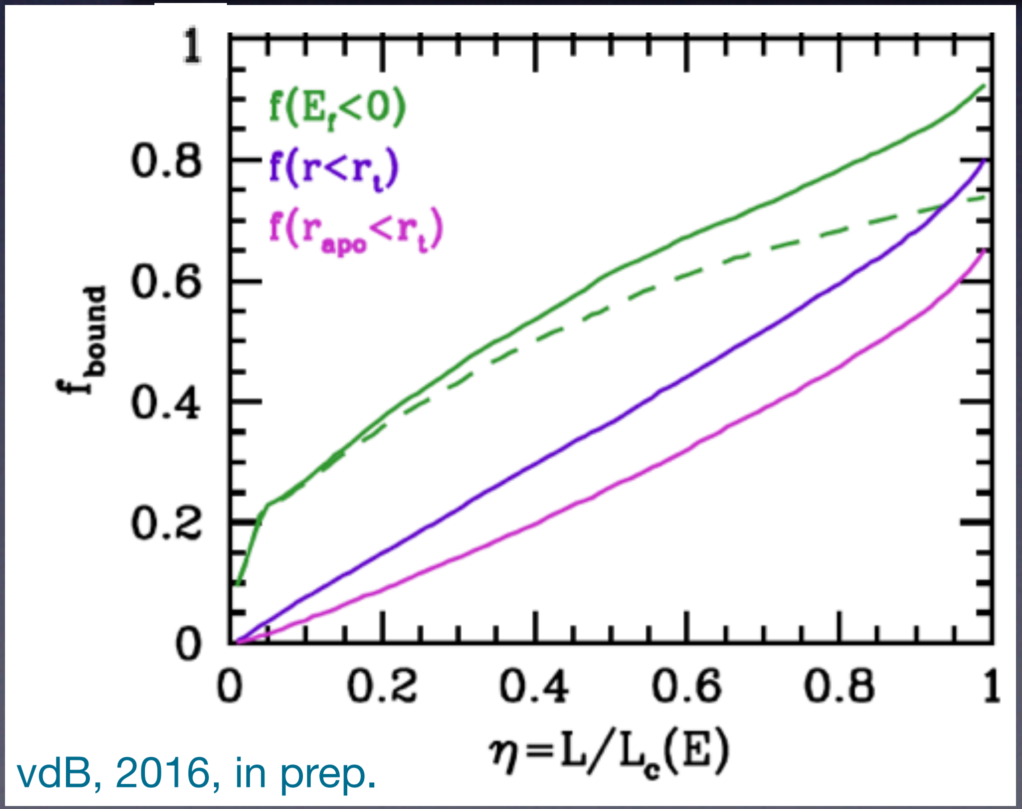
We model tidal heating by integrating the impulse approximation along the subhalo's orbit using detailed model of Gnedin, Hernquist & Ostriker (1999).

We add adiabatic correction using the model of Weinberg (1994) and Gnedin & Ostriker (1999).

We apply this method to Monte-Carlo realizations of a NFW subhalo on a typical orbit in a NFW host halo, and compute ΔE for each individual DM particle

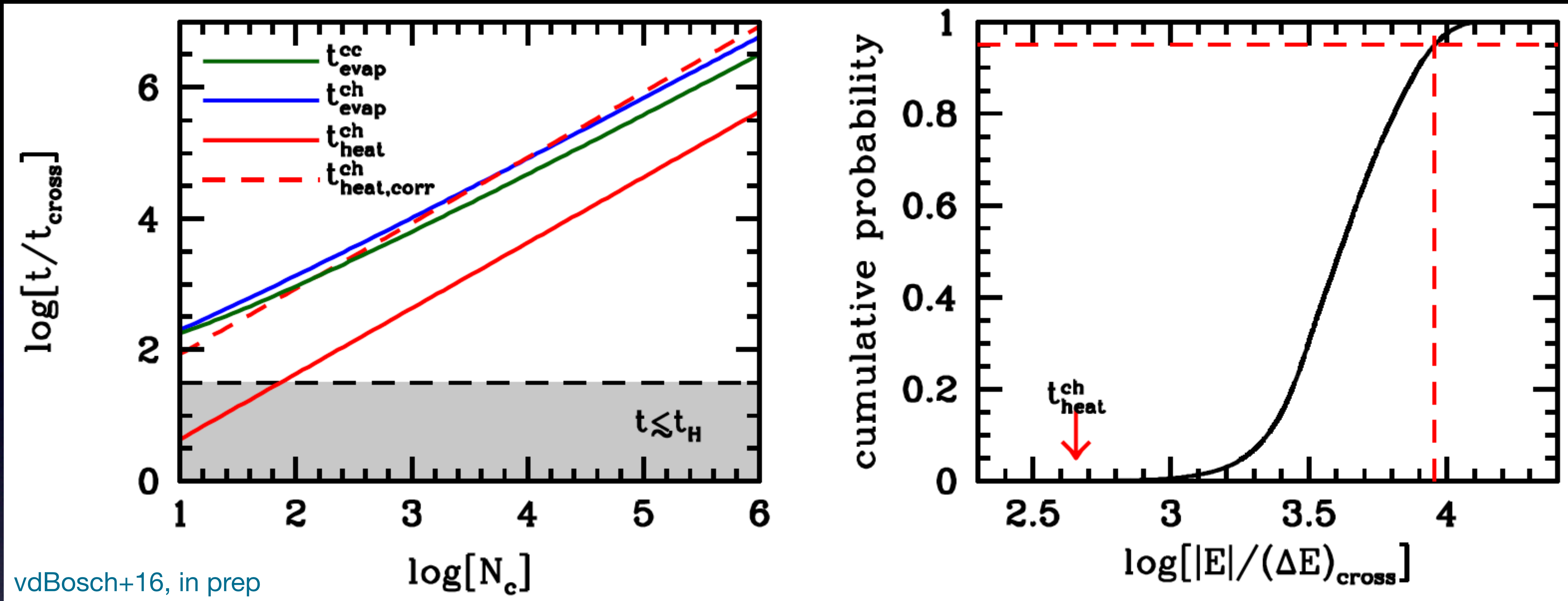


- Impulsive heating injects large amounts of energy.
- Central region is unaffected and remains bound.
- Material that becomes unbound due to tidal heating, is anyways stripped of due to tidal force



Impulsive, tidal heating is sub-dominant

What about Tidal (Impulsive) Heating?



vdBosch+16, in prep

- Two-body relaxation due to interactions of subhalo particles with (hotter) host halo particles is similar to that due to interactions with (colder) subhalo particles.

  [Despite claims to the contrary; Carlberg 1994; van Kampen 1995, 2000]

- Impulsive heating due to encounters with hotter (overly massive) host halo particles has similar (negligble) impact as two-body relaxation

  [Despite claims to the contrary; Moore, Katz & Lake 1996]

CAUTION: $E_{tot} \neq \sum E_i$

Conclusions

★ Clustering Crisis: Halo Occupation Models that fit clustering, do not fit $\Phi(M_\star,z)$ and vice versa

Solution requires at least one of the following

- very significant satellite growth after accretion
- assembly bias; $M_{\star,\rm sat}(M_h,z_{\rm acc}) > M_{\star,\rm cen}(M_h,z_{\rm acc})$
- orphans (i.e., more satellites than subhalos)

★ Subhalo Disruption: resolving dynamics of subhalos requires

- huge N (to suppress discreteness noise)
- small softening length (~1/10 of that for isolated halos)

★ Current generation of cosmological simulations still suffers from severe overmerging.

- serious road-block for small-scale cosmology program
- serious road-block for understanding galaxy formation

Conclusions

★ What causes subhalo disruption?

- Dynamical friction (physical)
- Inadequate force resolution (numerical)
- Discreteness noise (numerical)

★ In absence of dynamical friction, subhaloes never disrupt.

★ How to proceed?

Only hope is to characterize shortcomings of N-body simulations, and complement simulation results with semi-analytical model.