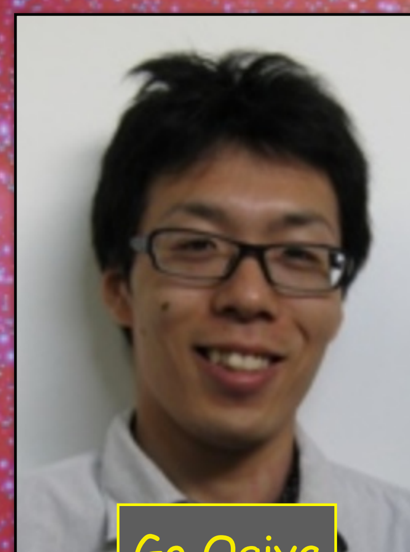
Dark Matter Substructure
Cosmological Treasure Trove or a Pandora's Box?


Fangzhou Jiang

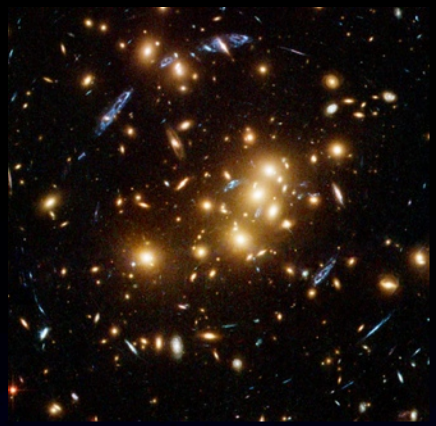

Go Ogiya


Oliver Hahn

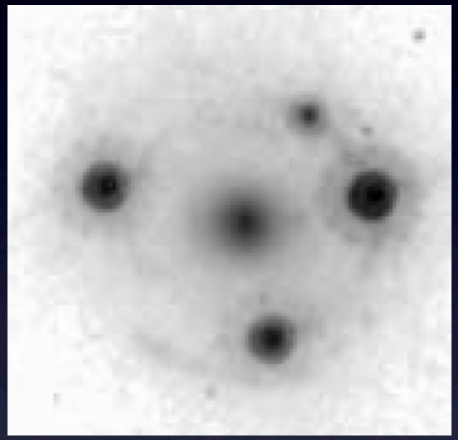

Andi Burkert

FRANK VAN DEN BOSCH
YALE UNIVERSITY

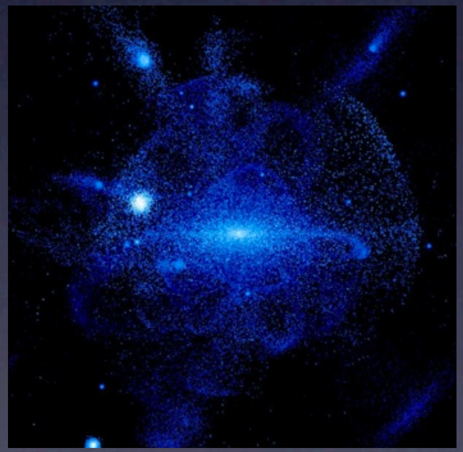
Why do we care about substructure



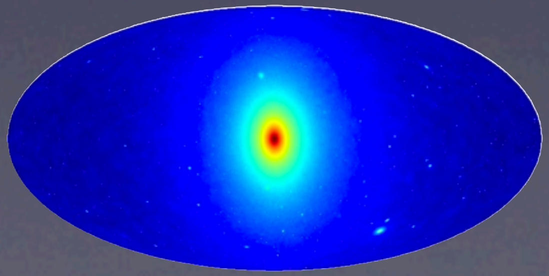
Halo Occupation Modeling:
subhaloes host satellite galaxies



Subhaloes cause flux-ratio anomalies and time-delays in gravitational lensing



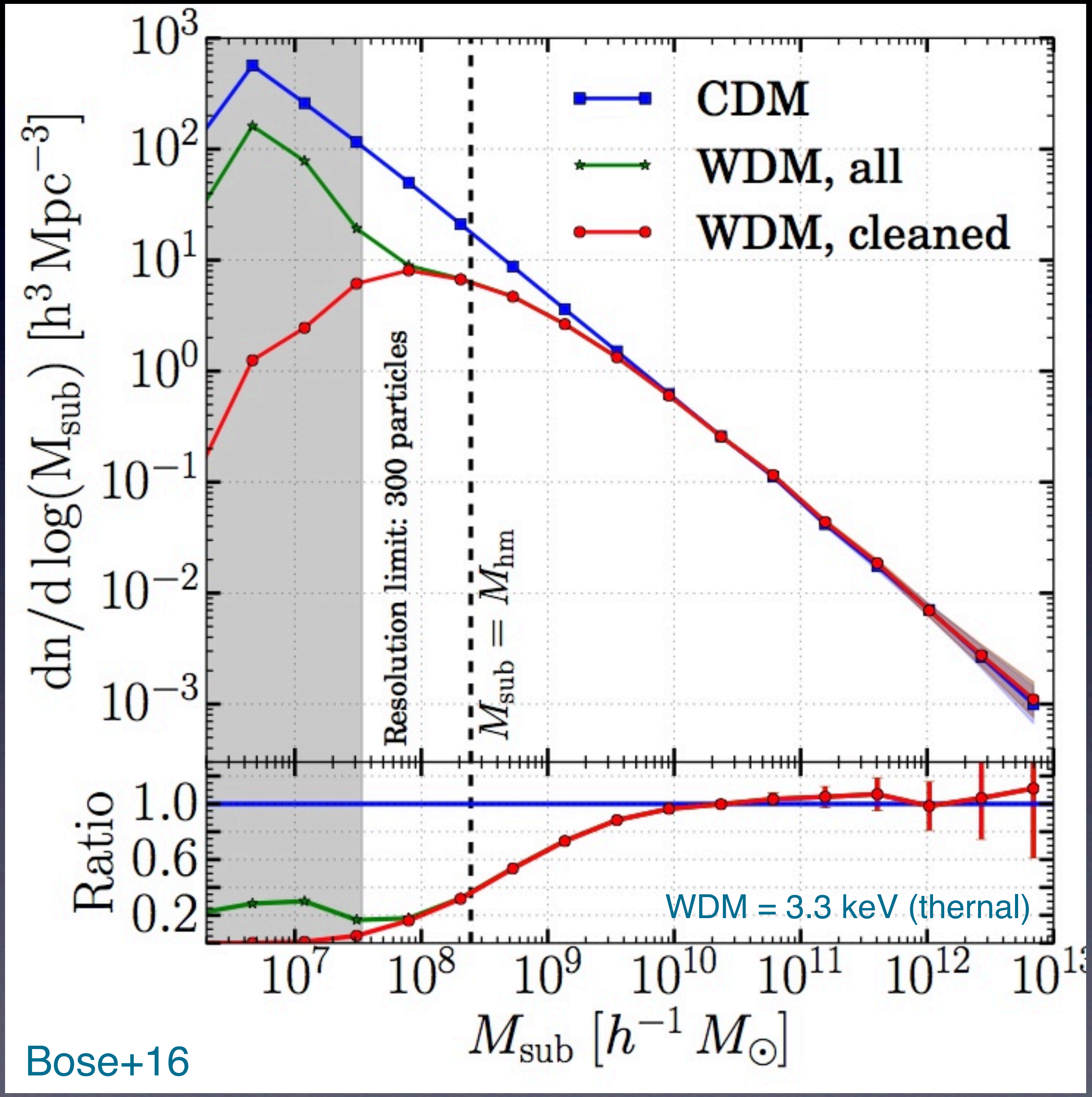
Subhaloes can heat stellar disks and tidal streams



Subhaloes boost dark mattter annihilation signal

Testing the Nature of Dark Matter

The abundance & demographics of dark matter substructure depends sensitively on the nature of the dark matter: CDM vs WDM vs SIDM



Different models mainly differ for abundance of low mass halos, where galaxy formation is expected to be supressed due to re-ionization.

If these low mass halos are dark, how are we to detect them?

- gaps in stellar streams

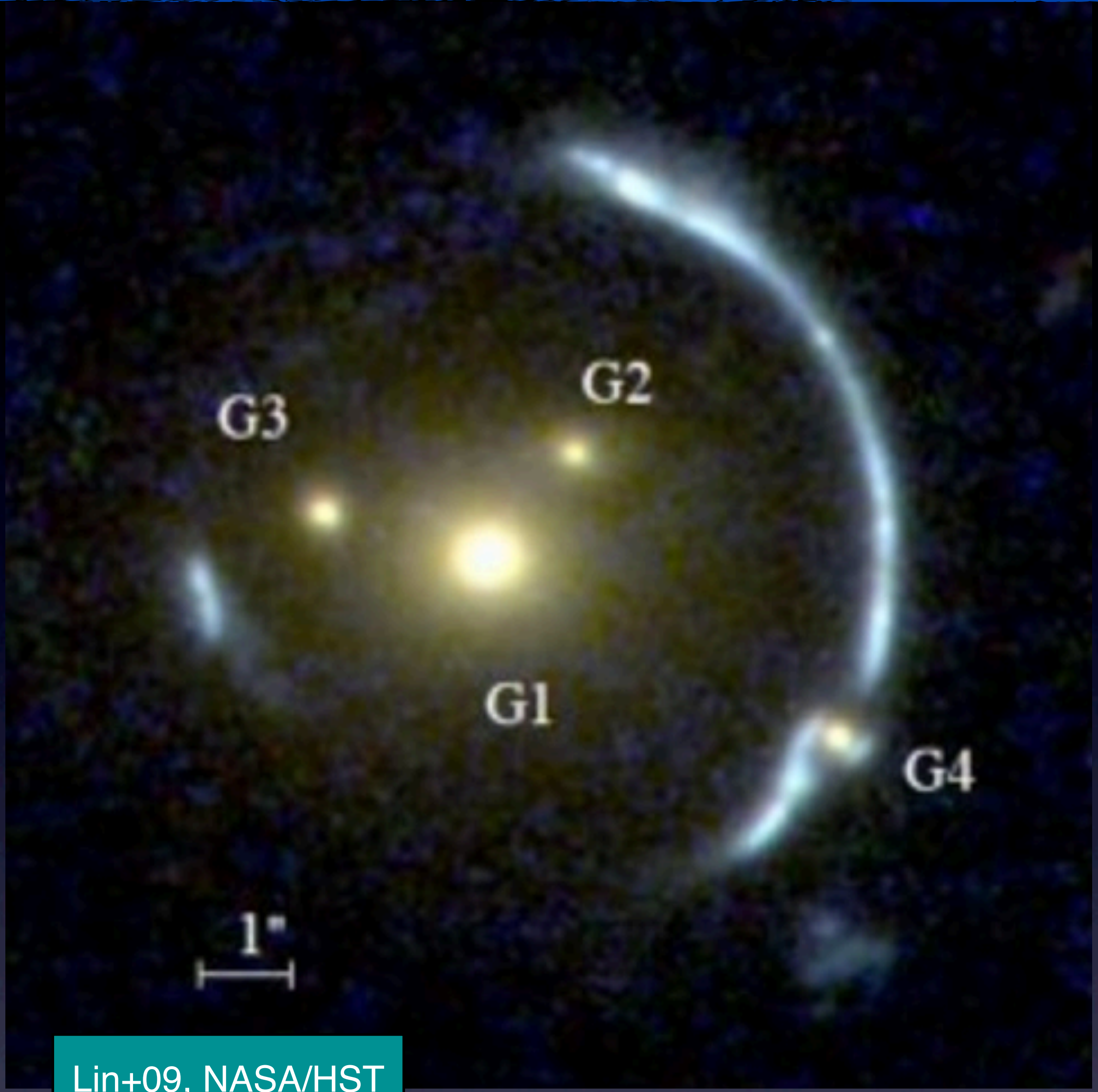
  Carlberg+09; Erkal+16

- gravitational lensing

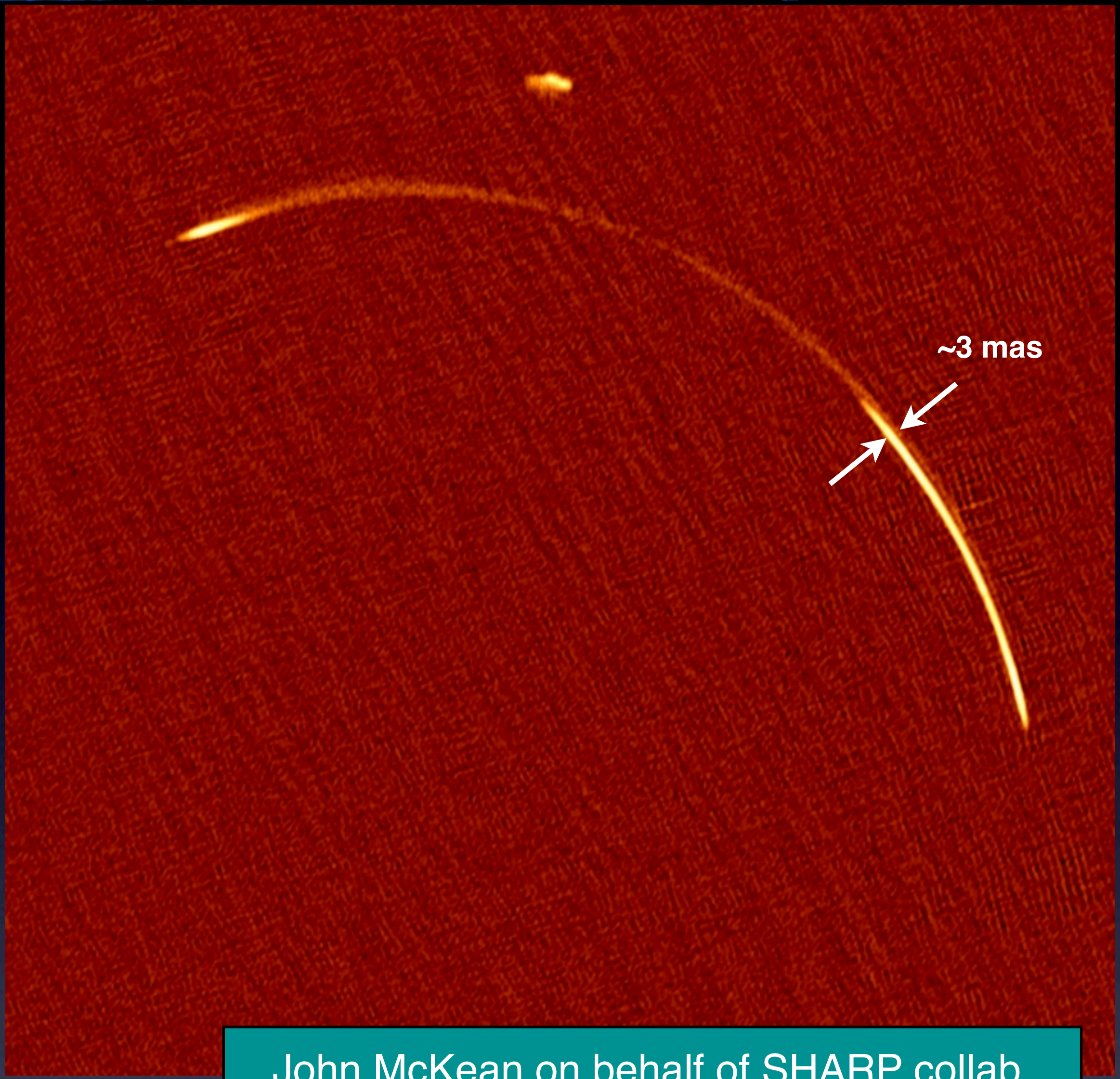
  flux-ratio anomalies Metcalf & Madau, 01

  image distortions Vegetti+09,14

Testing the Nature of Dark Matter



Lin+09, NASA/HST



John McKean on behalf of SHARP collab.

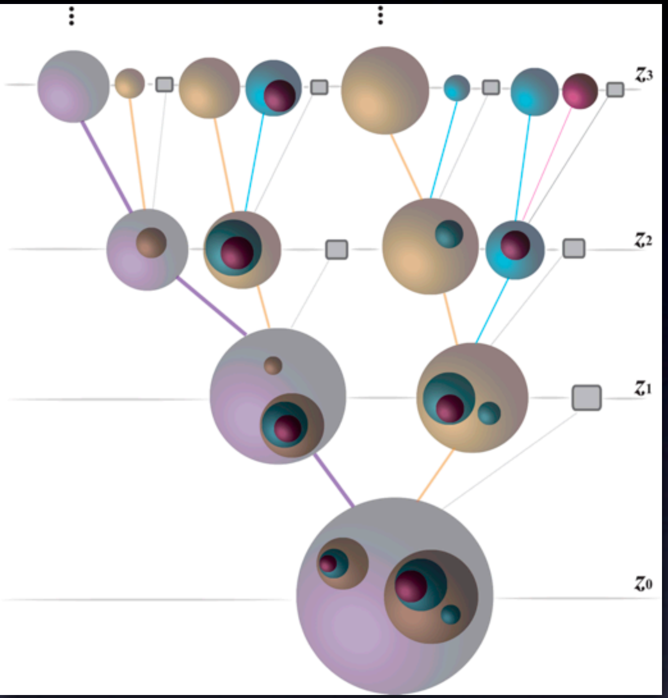
- Substructure in lens causes image distortions of lensed arcs
- Sensitivity depends on thickness of the observed arc
- In radio (using VLBI), razor-thin arcs (< few mas) can be detected, which reach sensitivities of $10^6\ M_\odot$

Numerous astrophysical applications require accurate predictions regarding the abundances and demographics of dark matter substructure

Modeling Dark Matter Substructure

Semi-Analytical Models

Taylor & Babul 01,04,05 ; Benson+02; Taffoni+03; Oguri & Lee 04; Zentner+05; vdB+05; Purcell & Zentner 2012; Jiang & vdB 2016



Construct merger tree

Integrate orbits of subhalos

Model tidal stripping, tidal heating, and dynamical friction.

PROS: Fast & Flexible

Provides insight

CONS: Treatment of tidal evolution approximate at best; requires calibration against simulations

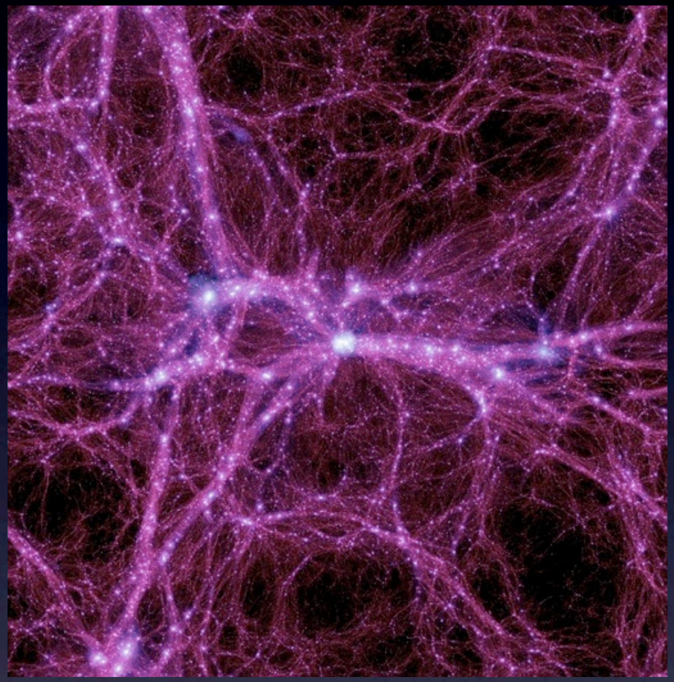
Numerical N-body Simulations

Tormen 97; Ghigna+98; Moore+99; Klypin+99; Diemand+04; Gill+04; Gao+04; Springel+08; Springel+08; Giocoli+10

Run (cosmological) N-body simulation

Use halo finder to identify host and sub-halos

Link (sub)halo across snapshots



PROS: Proper cosmological setting

All the relevant physics is included

CONS: Halo identification far from trivial

Simulations are subject to numerical artefacts...

Substructure in Simulations; historical perspective

Prior to 1998, N-body simulations of structure formation in a CDM cosmology lacked substructure; halos were smooth blobs of virialized matter.

What causes over-merging?

- Collisional two-body heating due to encounters with particles of hot host halo (Carlberg 94; van Kampen 2000a,b)
- Impulsive, tidal heating due to encounters with particles of hot host halo (van Kampen 2000a,b)
- Inadequate force softening (N too small ⇒ softening length too large) (Moore, Katz & Lake 1996)

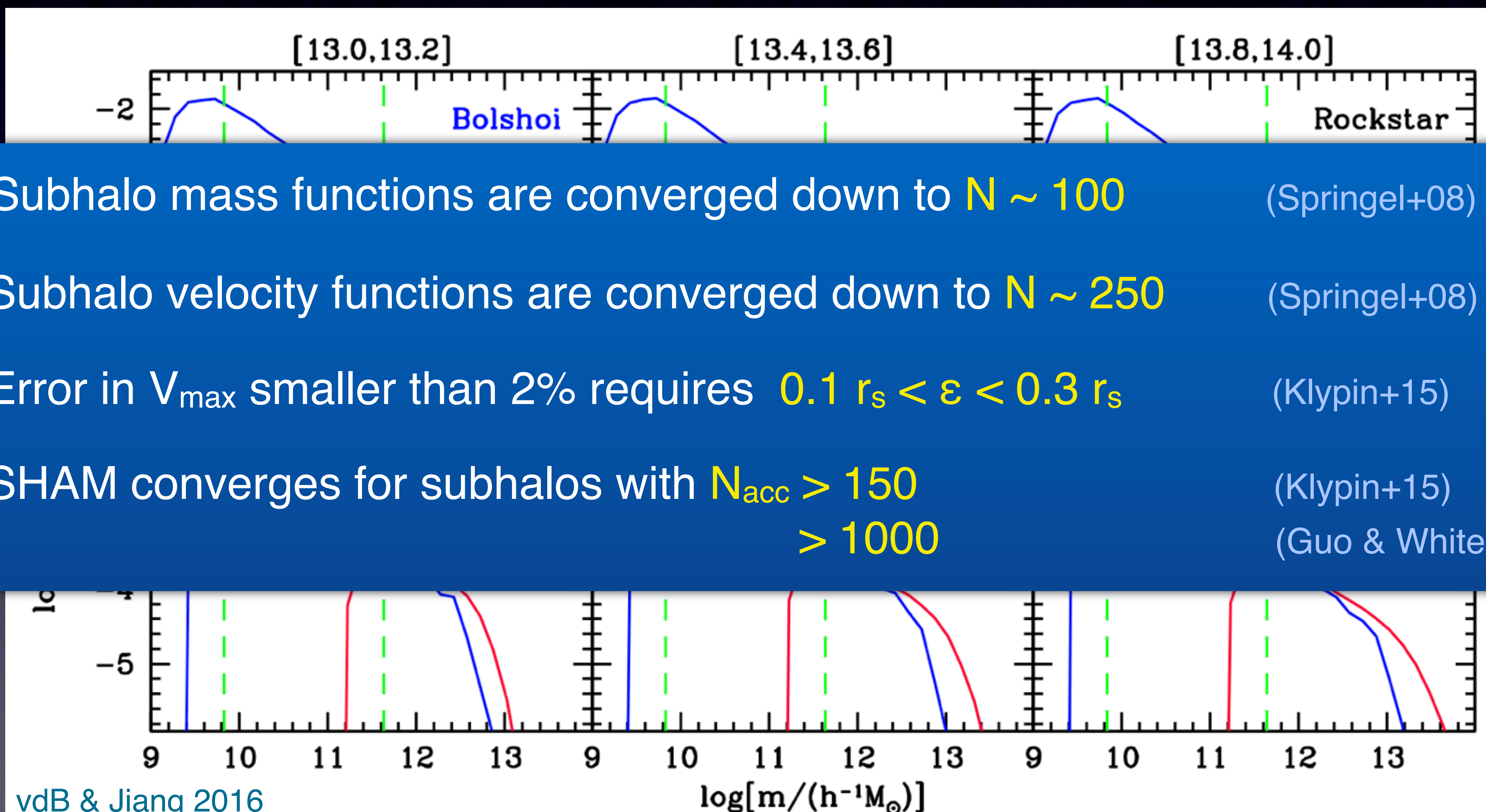
The Substructure Revolution:

- In late 1990s various groups presented simulations that actually revealed substructure surviving (Tormen 97; Ghigna+98; Moore+98; Klypin+98)
- Dark matter haloes are self-similar ⇒ \`missing satellite problem' (Moore+99; Klypin+99)

What about overmerging?

Resolution Studies: numerical simulations still suffer from overmerging, but only at the low mass end of the subhalo mass function.

(Springel+08; Guo & White 14; Klypin+15)



- Subhalo mass functions are converged down to N ~ 100 (Springel+08)
- Subhalo velocity functions are converged down to N ~ 250 (Springel+08)
- Error in V_{max} smaller than 2% requires $0.1\, r_s < \varepsilon < 0.3\, r_s$ (Klypin+15)
- SHAM converges for subhalos with $N_{acc} > 150$ (Klypin+15)

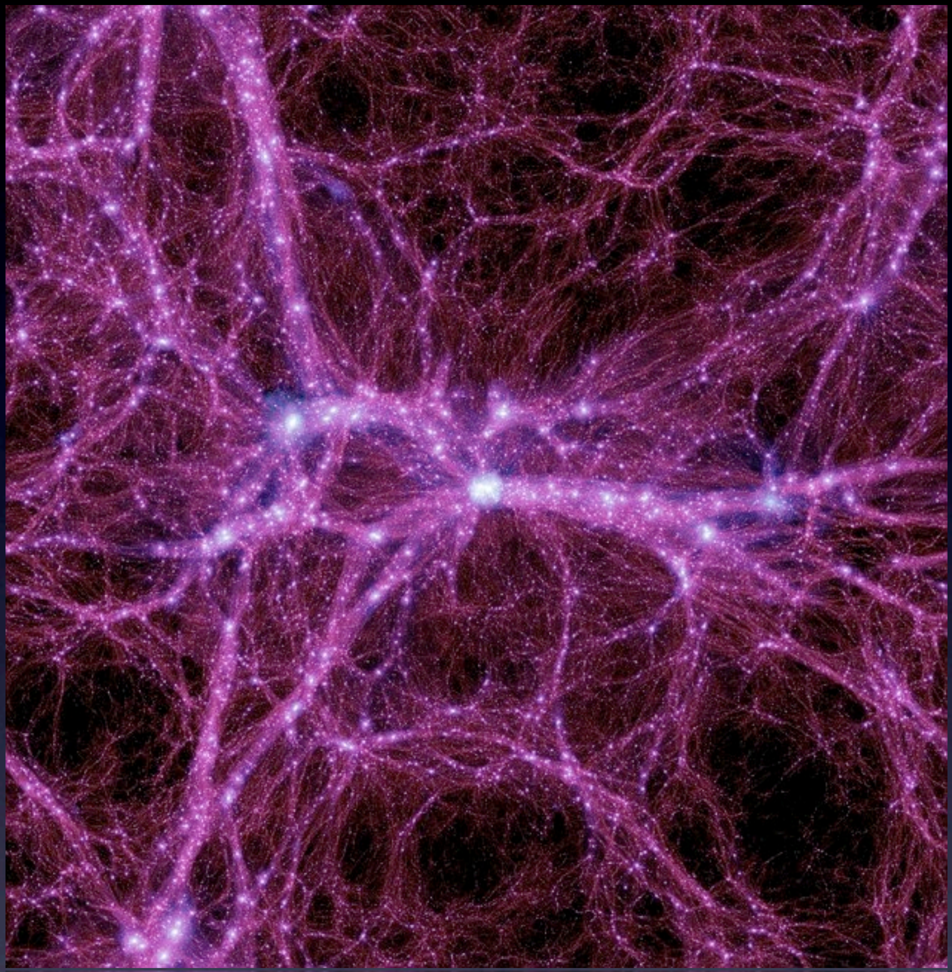
  > 1000 (Guo & White 14)

Dissecting Subhalo Evolution

The Bolshoi Simulation

$\Omega_m = 0.27$	$h = 0.7$	$L_{box} = 250\ h^{-1}$ Mpc
$\Omega_\Lambda = 0.73$	$\sigma_8 = 0.82$	$N_p = 2048^3$
$\Omega_b = 0.047$	$n_s = 0.95$	$m_p = 1.35\times10^8\ h^{-1} M_\odot$

Klypin, Trujillo-Gomez & Primack, 2011, ApJ, 740, 102



Halos and subhalos identified with the 6D phase-space finder RockStar

Behroozi, Wechsler & Wu, 2013, ApJ, 762, 109

Merger Trees constructed using the Consistent Merger Trees code

Behroozi et al., 2013, ApJ, 763, 18

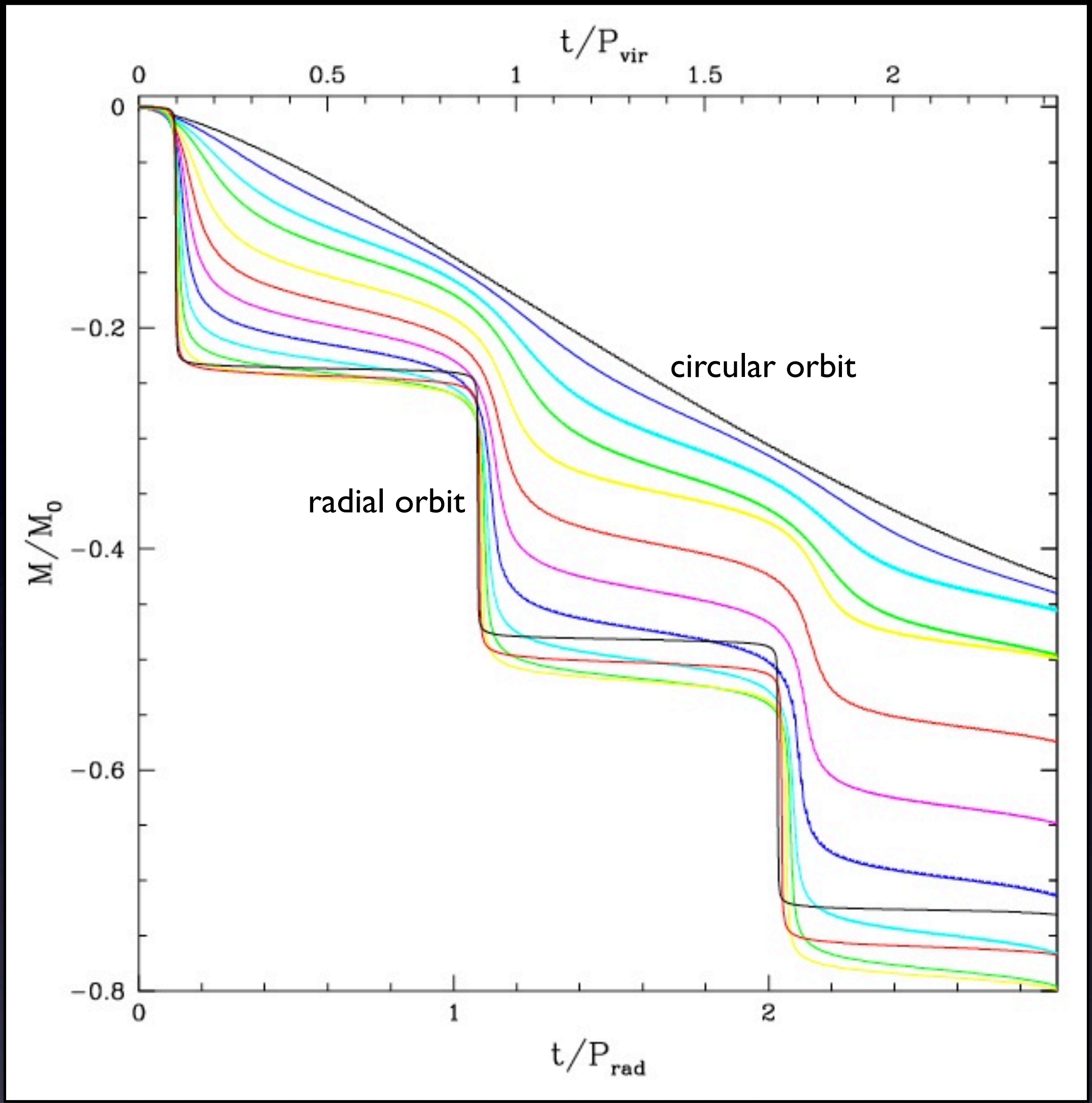
Halo catalogs & Merger Trees publicly available

http://astronomy.nmsu.edu/aklypin/Bolshoi/index.html

http://hipacc.ucsc.edu/Bolshoi/MergerTrees.html

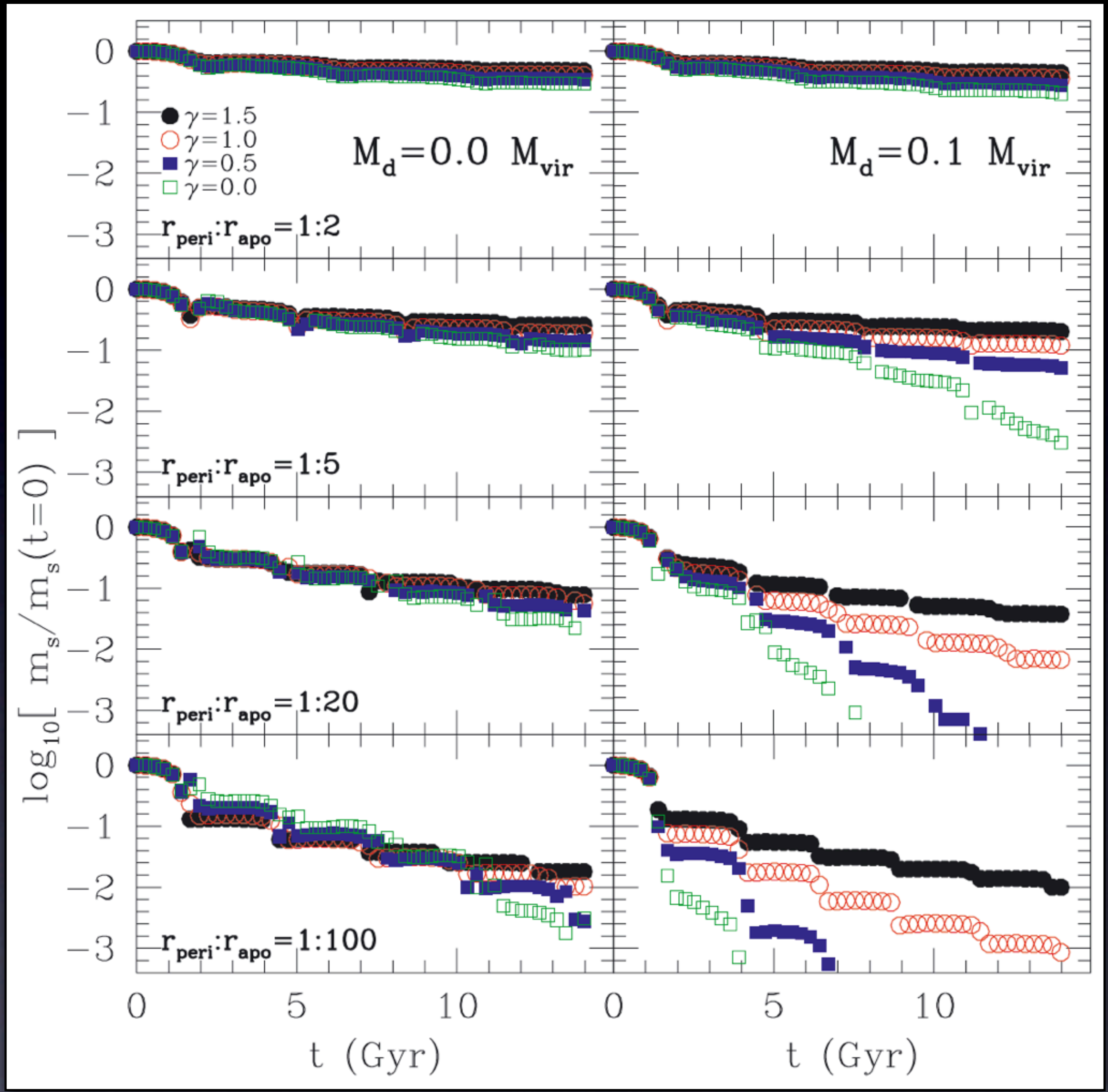
The Mass Evolution of Dark Matter Subhaloes

Analytical Model with Orbit Integration



Taylor & Babul, 2004

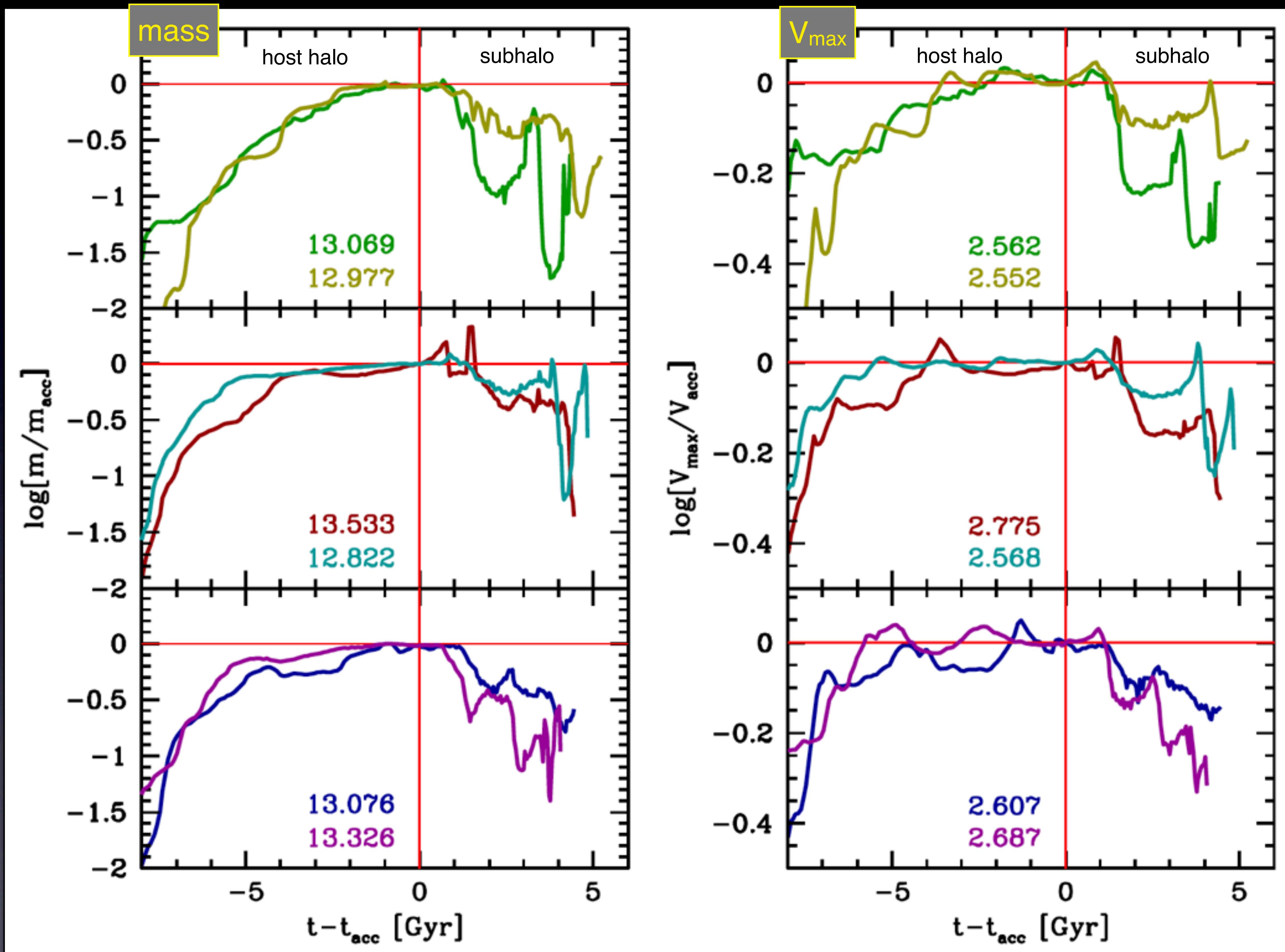
Idealized Simulation of NFW halo in fixed potential



Penarrubia et al. 2010

Note the stair-case like evolution of subhalo mass...

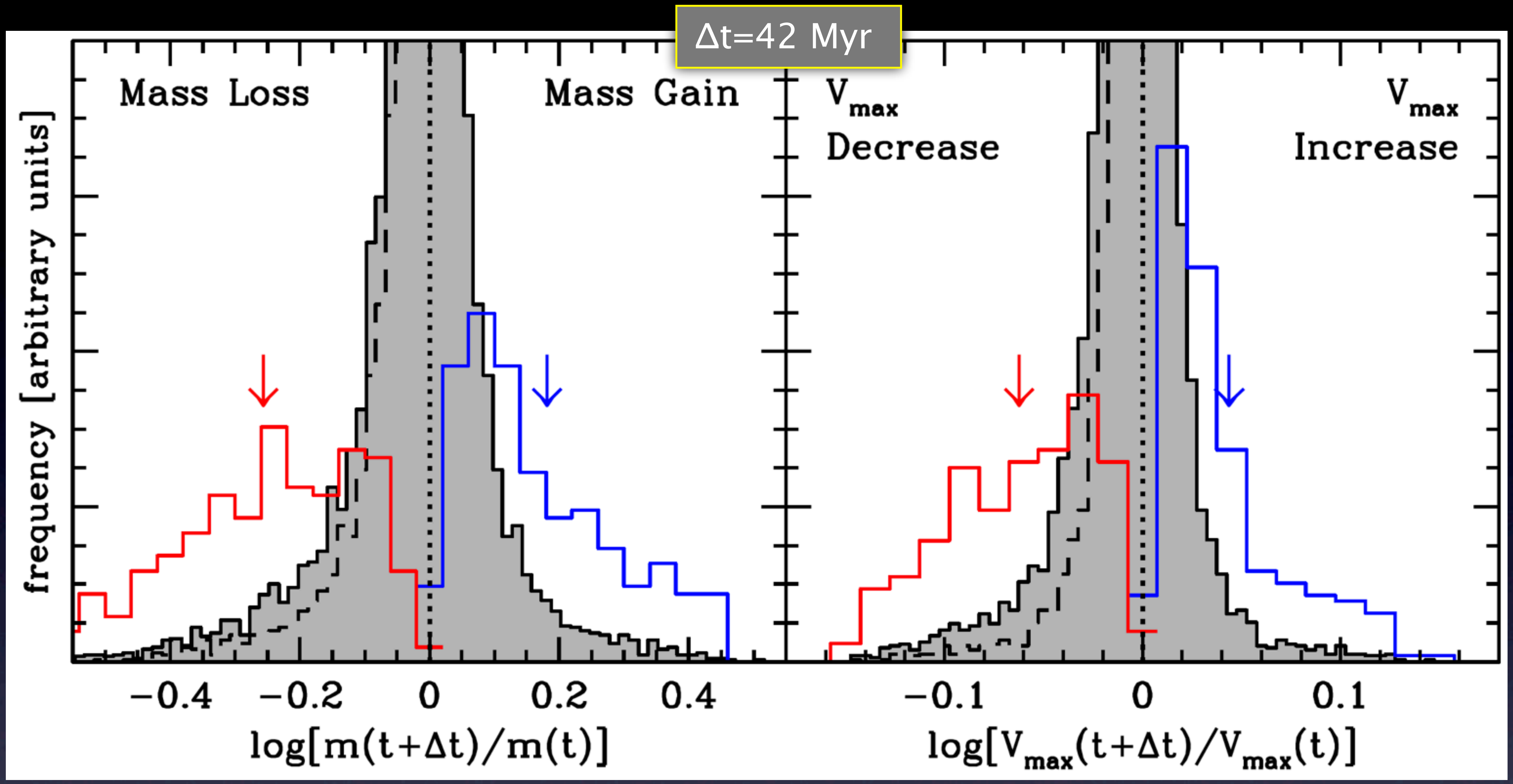
Bolshoi Simulation: Mass and V_{max} histories



Based on Bolshoi + Rockstar

van den Bosch, 2016

Mass and V_{max} histories

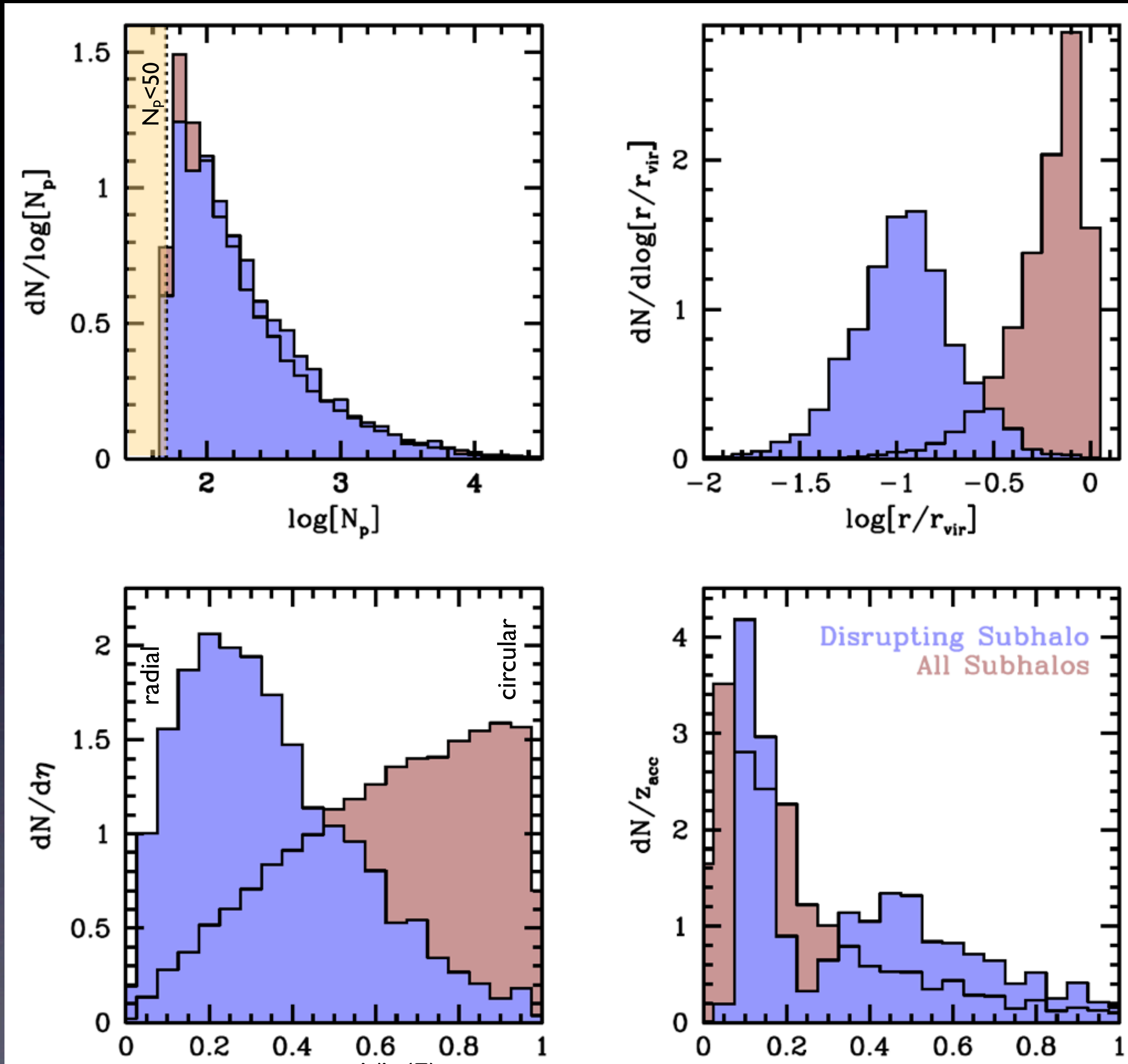


Based on Bolshoi + Rockstar

van den Bosch, 2016

- ★ Net mass loss is consequence of small asymmetry in dm/dt
- ★ Typical m(t) and V_{max}(t) of subhalo are extremely `jagged'. This cannot be physical, and most likely is consequence of unbinding algorithm used.
- ★ Instantaneous subhalo mass and maximum circular velocity are unreliable, almost stochastic parameters...

Statistics of Subhalo Disruption



van den Bosch, 2016

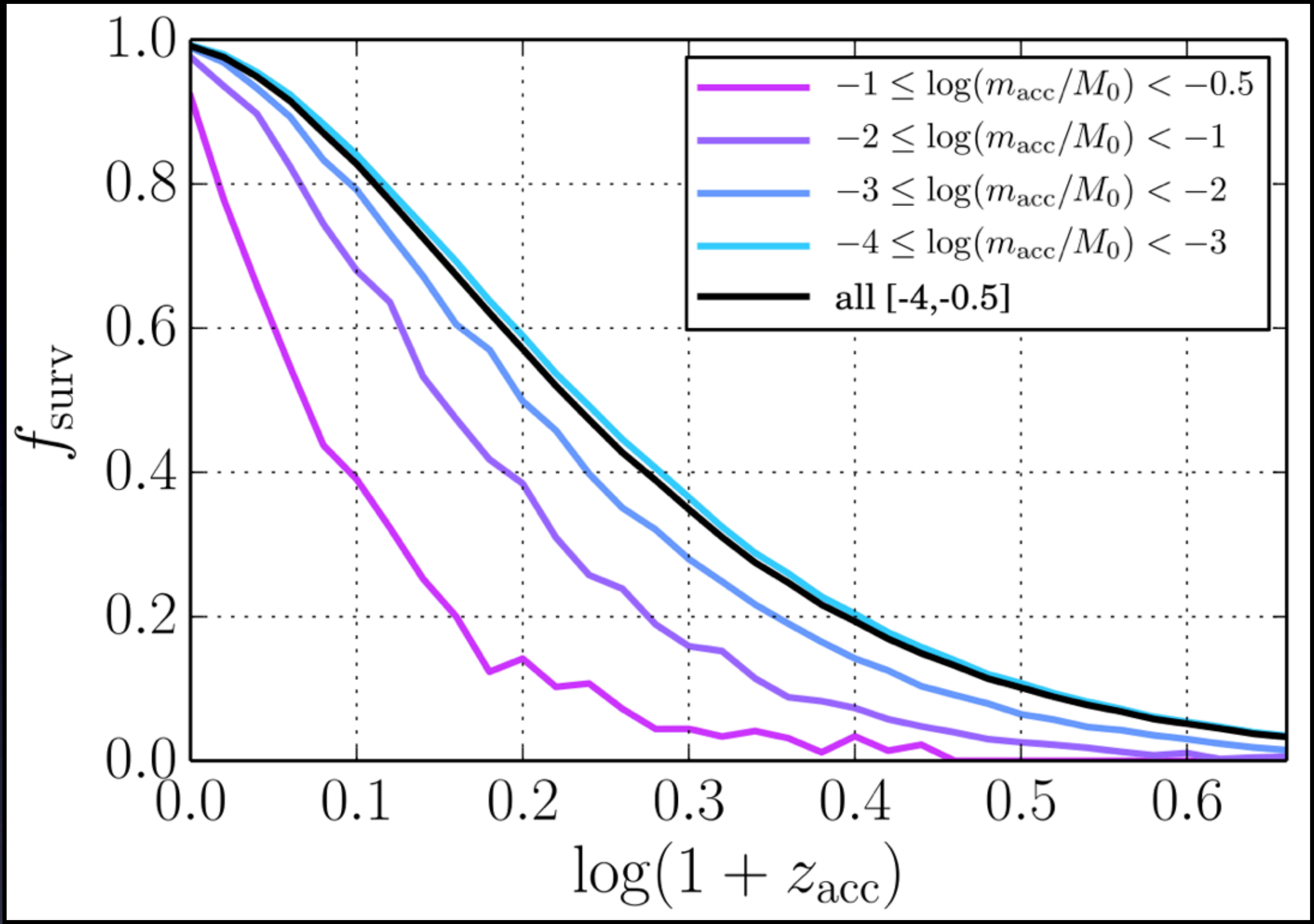
Disruption occurs preferentially:
- at small halo-centric radii
- along more radial orbits,
- at first or second pericentric passage.

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 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?

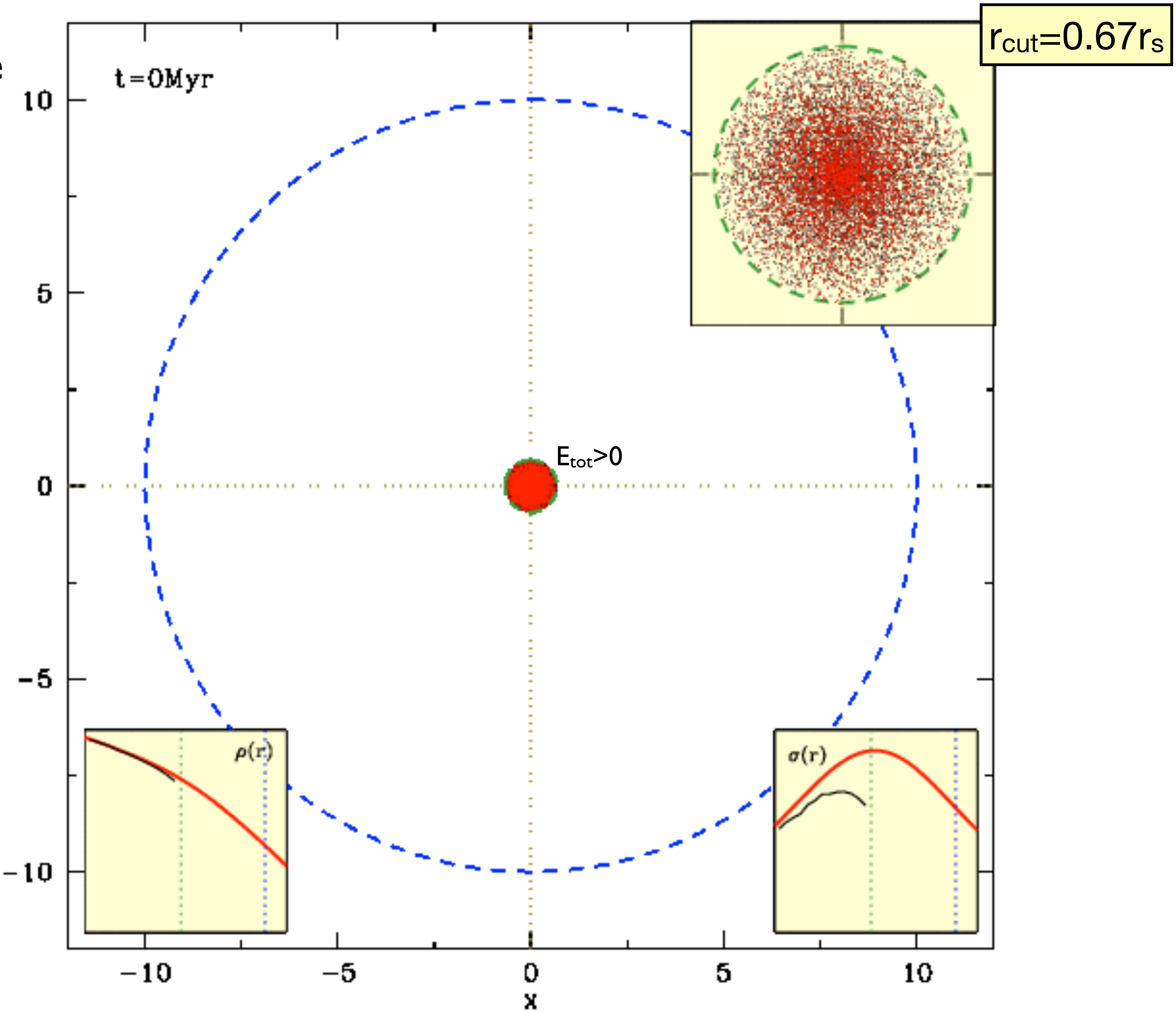
Subhalo Disruption Mechanisms

- Tidal Stripping
- Tidal Heating
  - Pericentric Passage
  - Subhalo-Subhalo Encounter
- Dynamical Friction
- Numerical overmerging

Does Stripping cause Disruption?

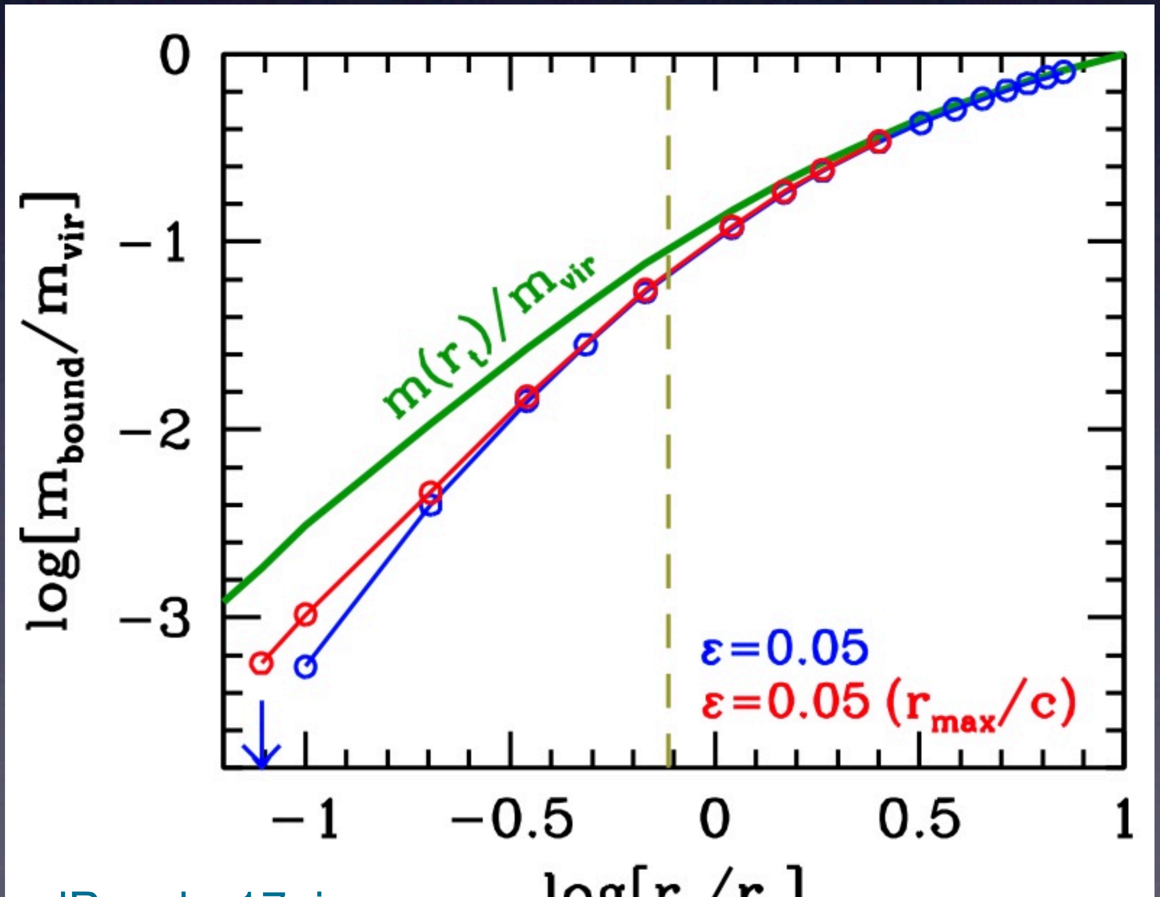
- As first pointed out by Hayashi+03, instantaneous stripping of outer layers of NFW halo can leave a remnant with positive binding energy.
- For an isotropic NFW halo (β=0), the core has positive binding energy if $r_{cut} < r_{bind} = 0.77\ r_s$. (corresponding core mass is ~0.08 M_{vir})
- Hayashi+03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

N=10^5
tree-code



Does Stripping cause Disruption? NO!

- 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}



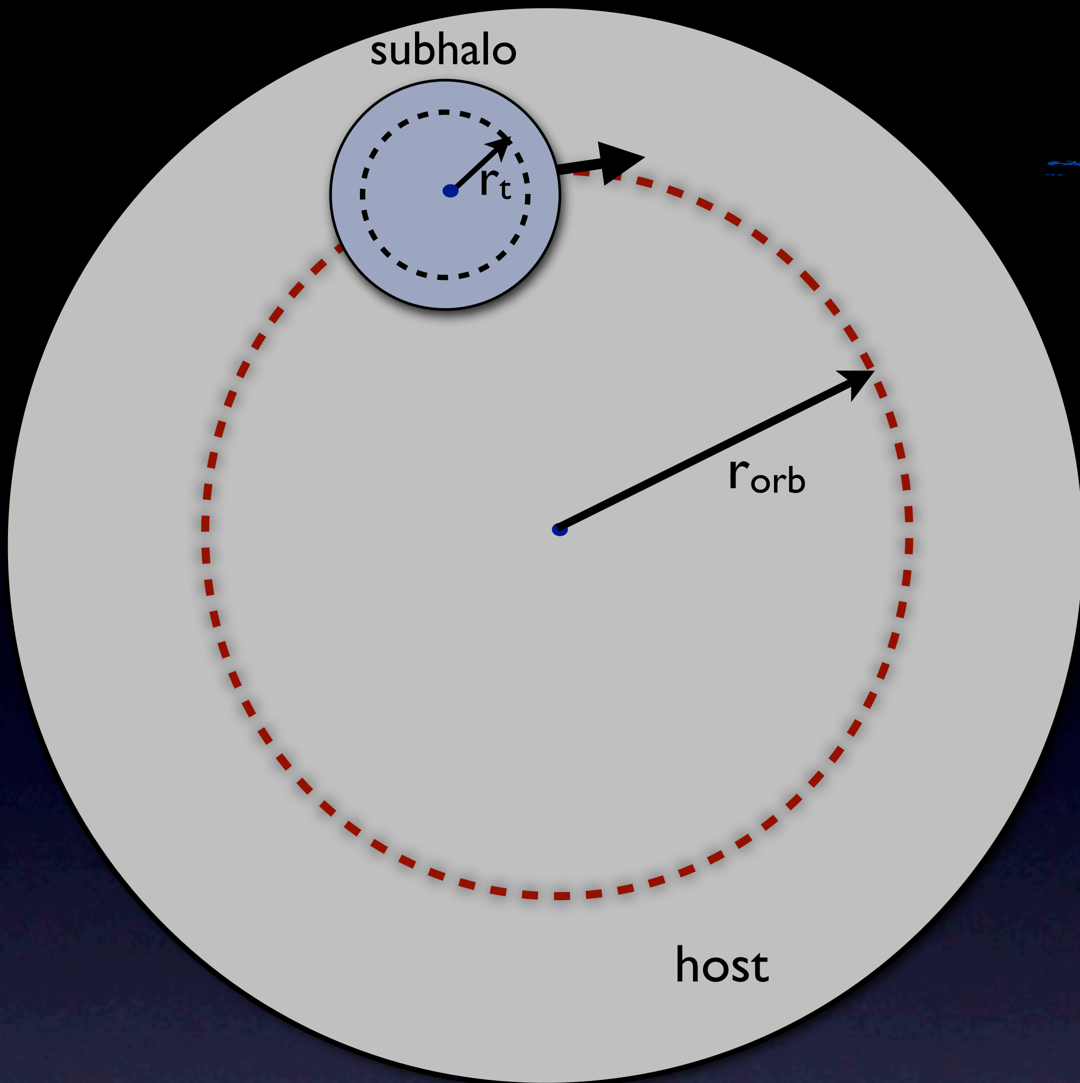
vdBosch+17, in prep.

However:

particles have broad distribution of binding energies, and majority of particles remain bound.

Simulations confirm that remnant rapidly re-virializes to a bound system with somewhat smaller, but non-zero mass.

Numerical Simulations



Simulate NFW halo orbiting on <u>circular</u> orbit inside <u>static</u> potential of host halo.

- No impulsive (tidal) heating
- No dynamical friction

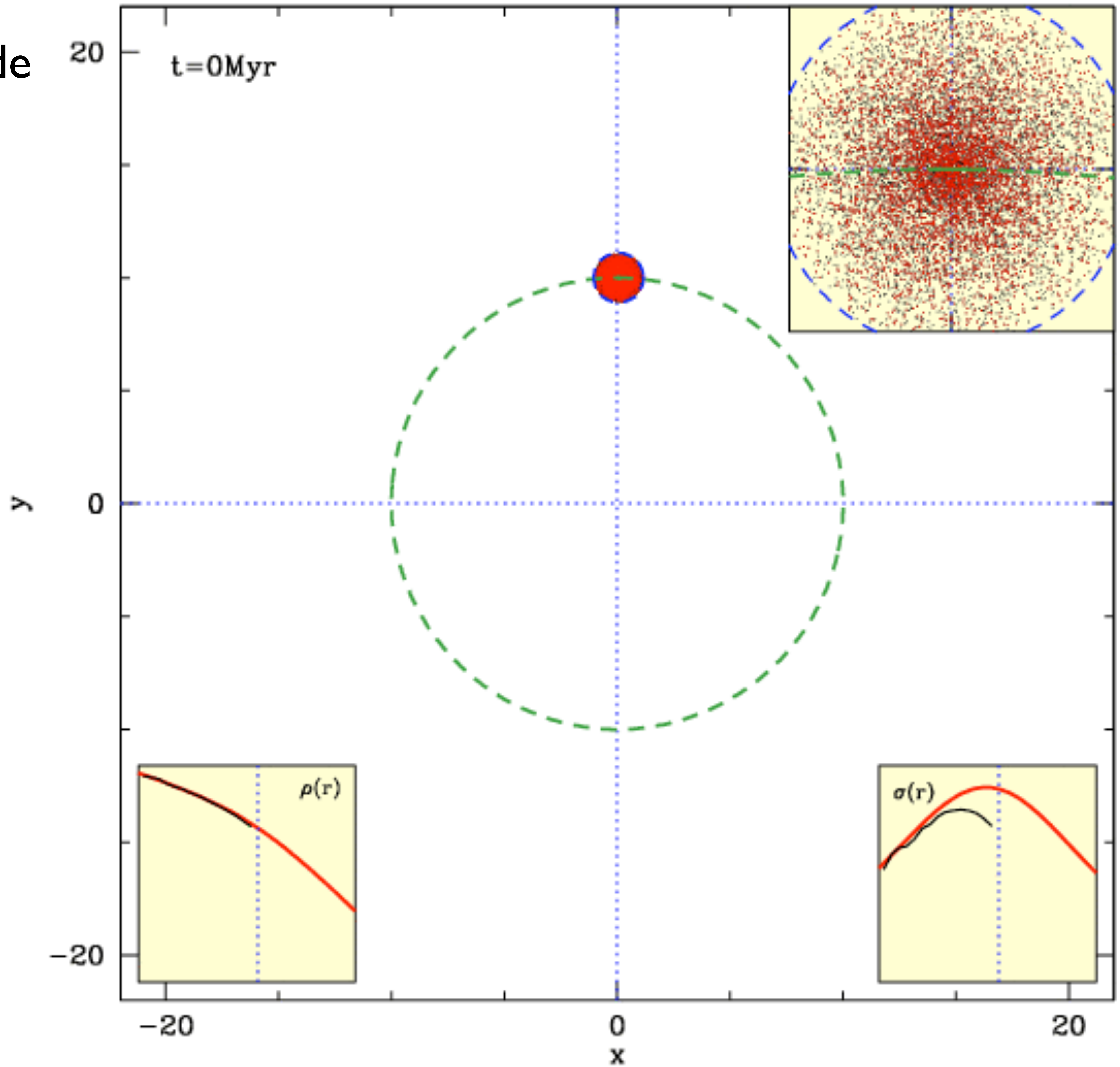
<u>Naive Prediction:</u>

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

<u>More `Sophisticated' Prediction:</u>

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

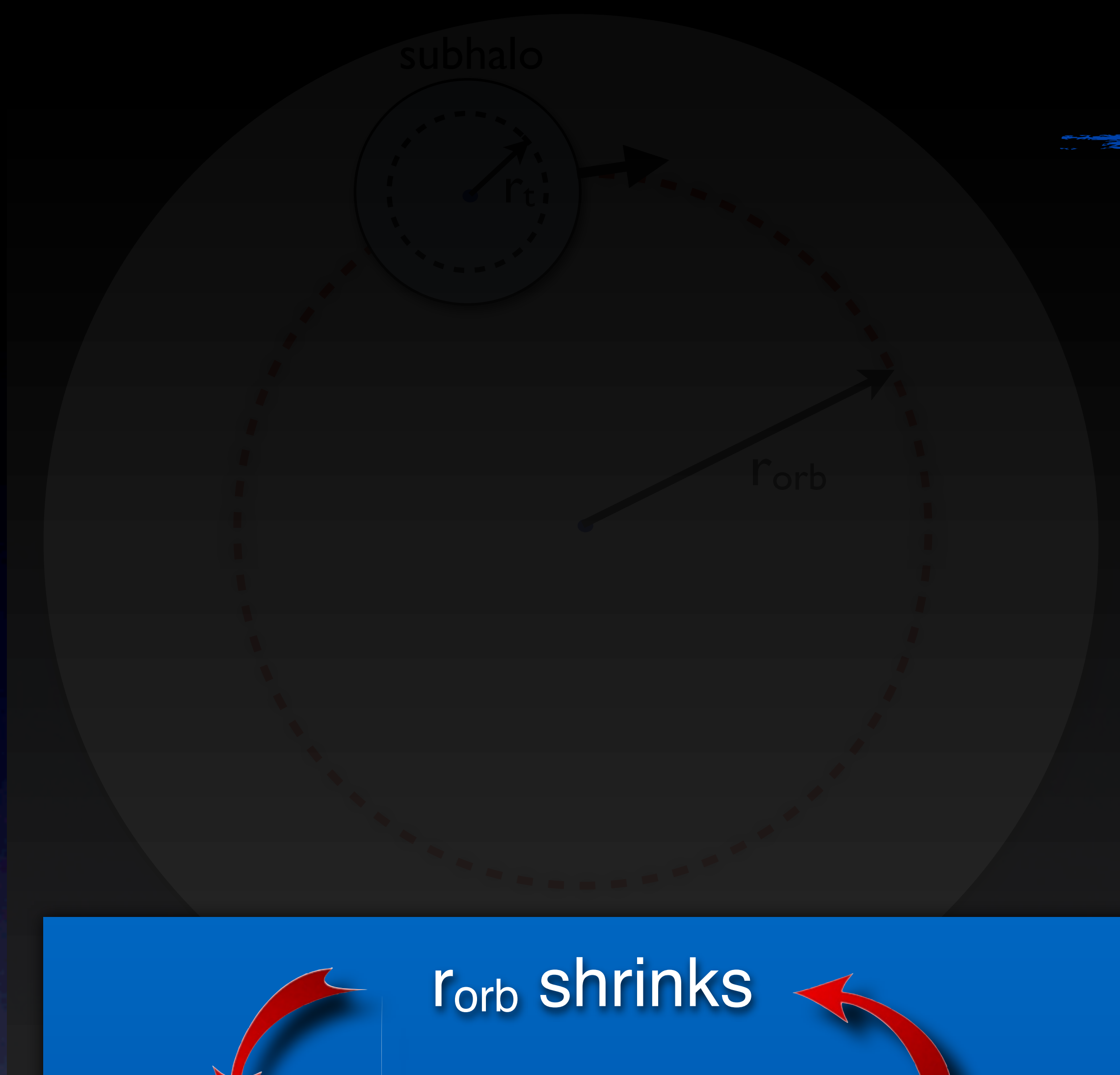
N=10^5
tree-code



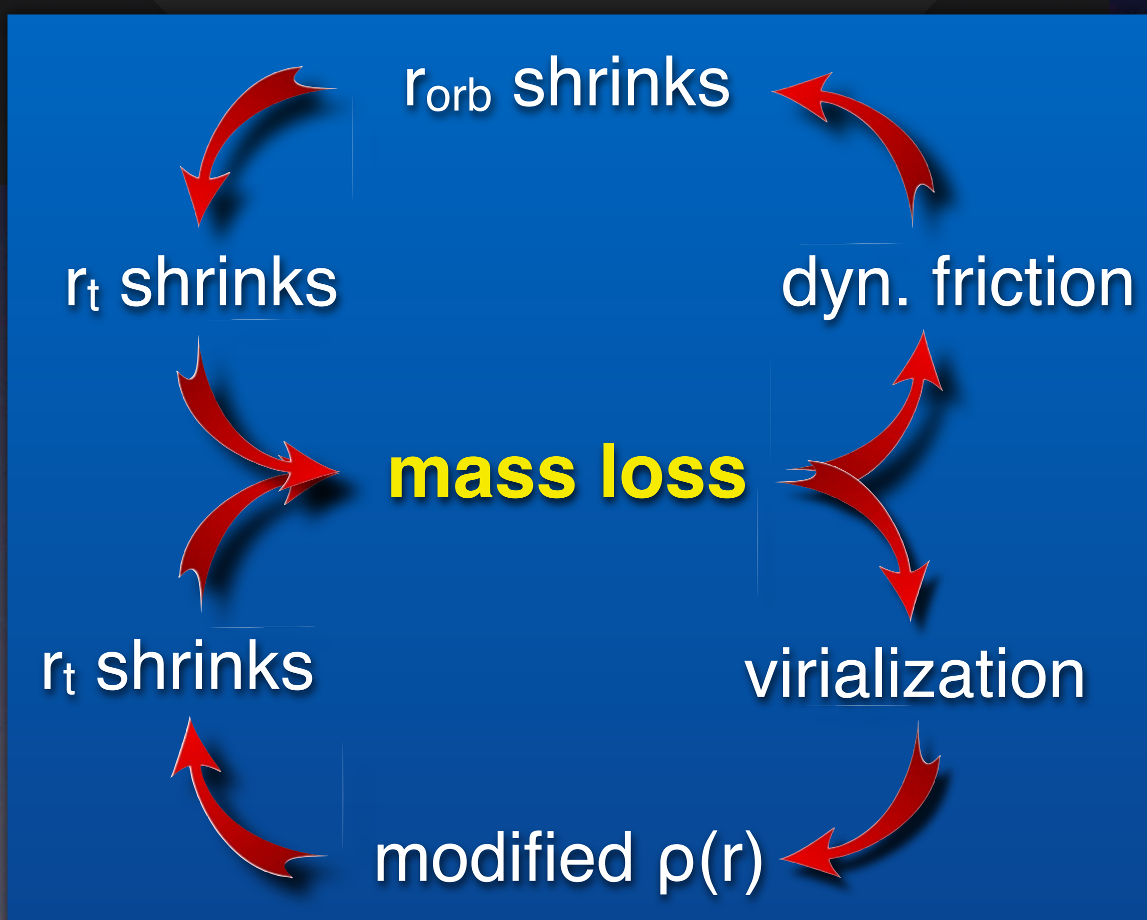
r_{orb}=0.1 $r_{vir,h}$

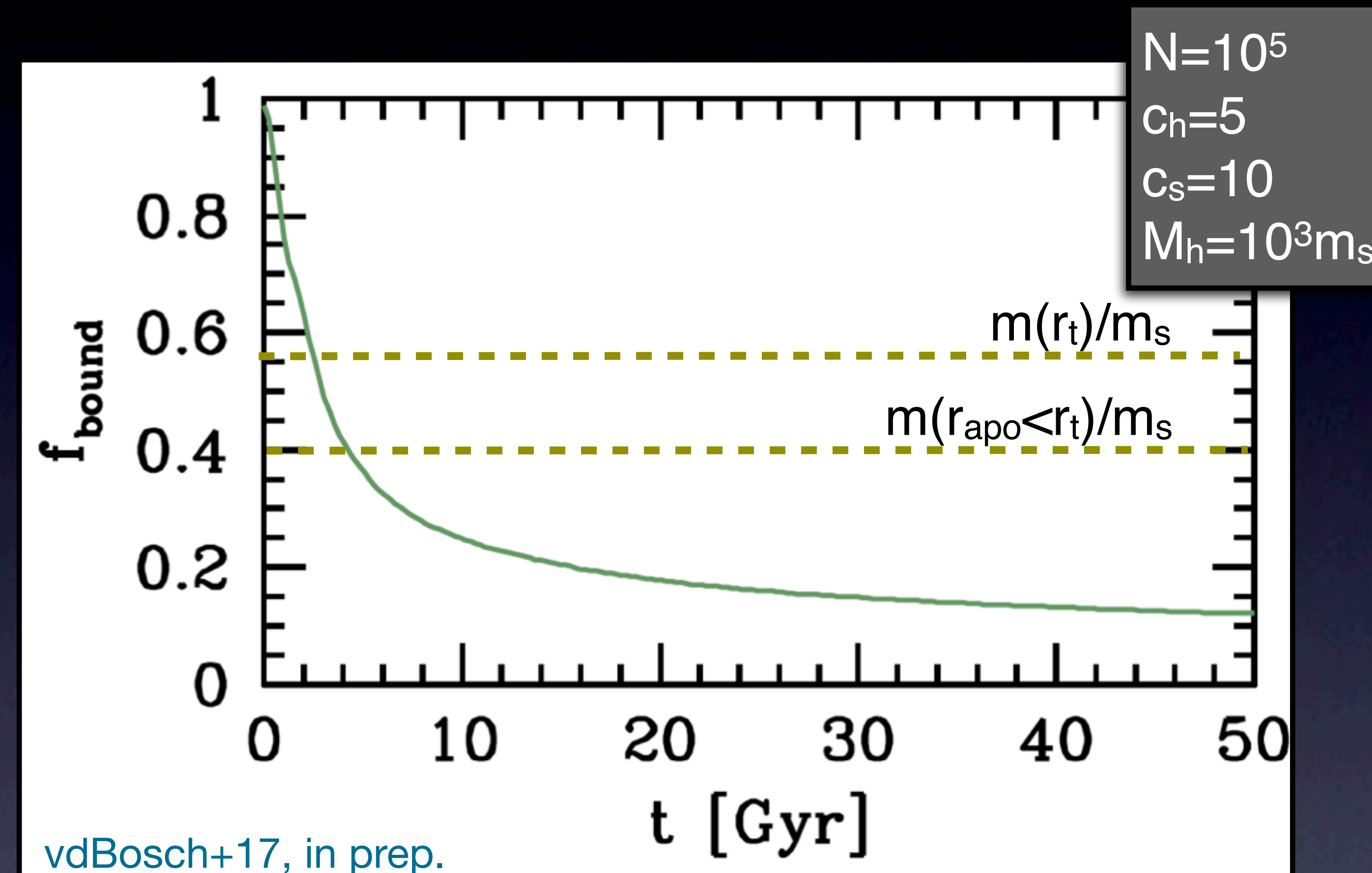
r_t=0.11 r_s

Numerical Simulations



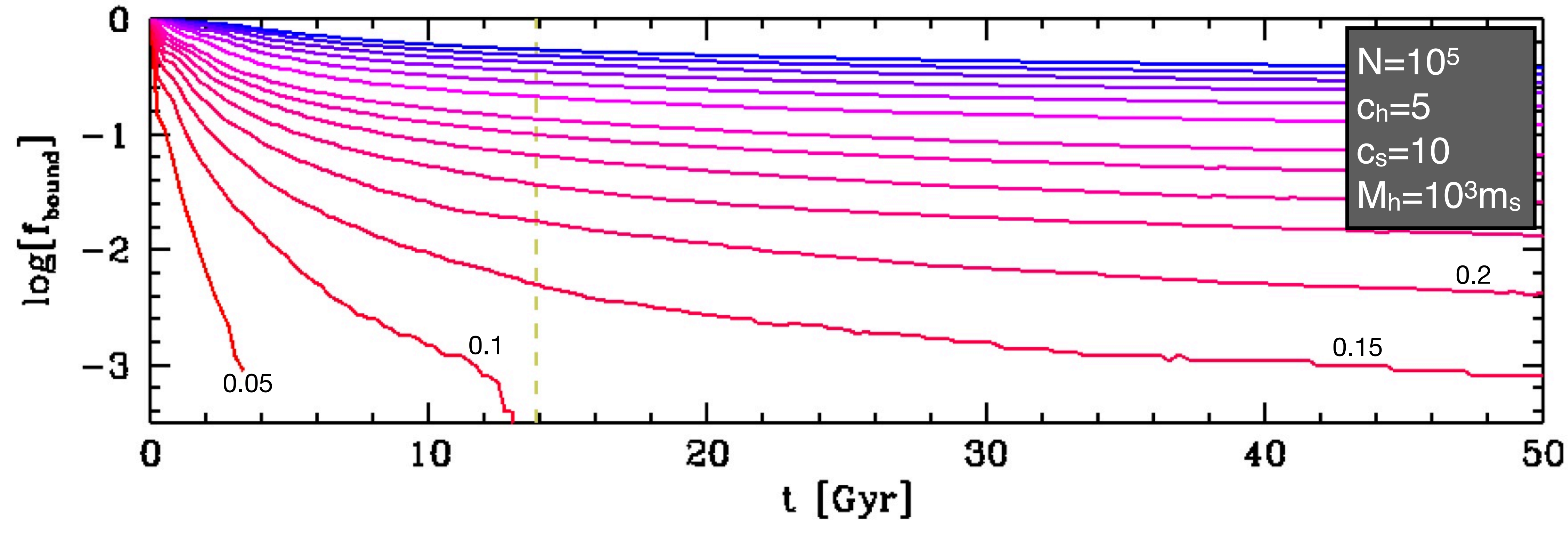
Simulate NFW halo orbiting on <u>circular</u> orbit inside <u>static</u> potential of host halo.



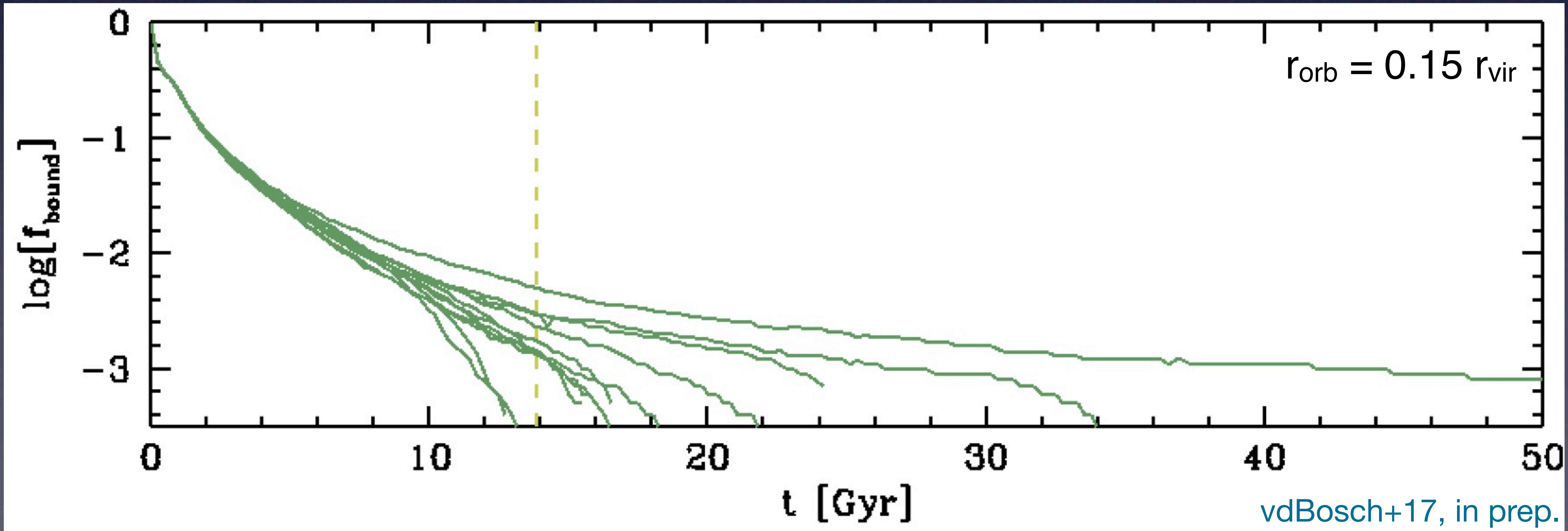


- Analytical predictions fail to predict amount of mass stripped
- Mass loss continues for >50 Gyr

Tidal Stripping on Circular Orbits



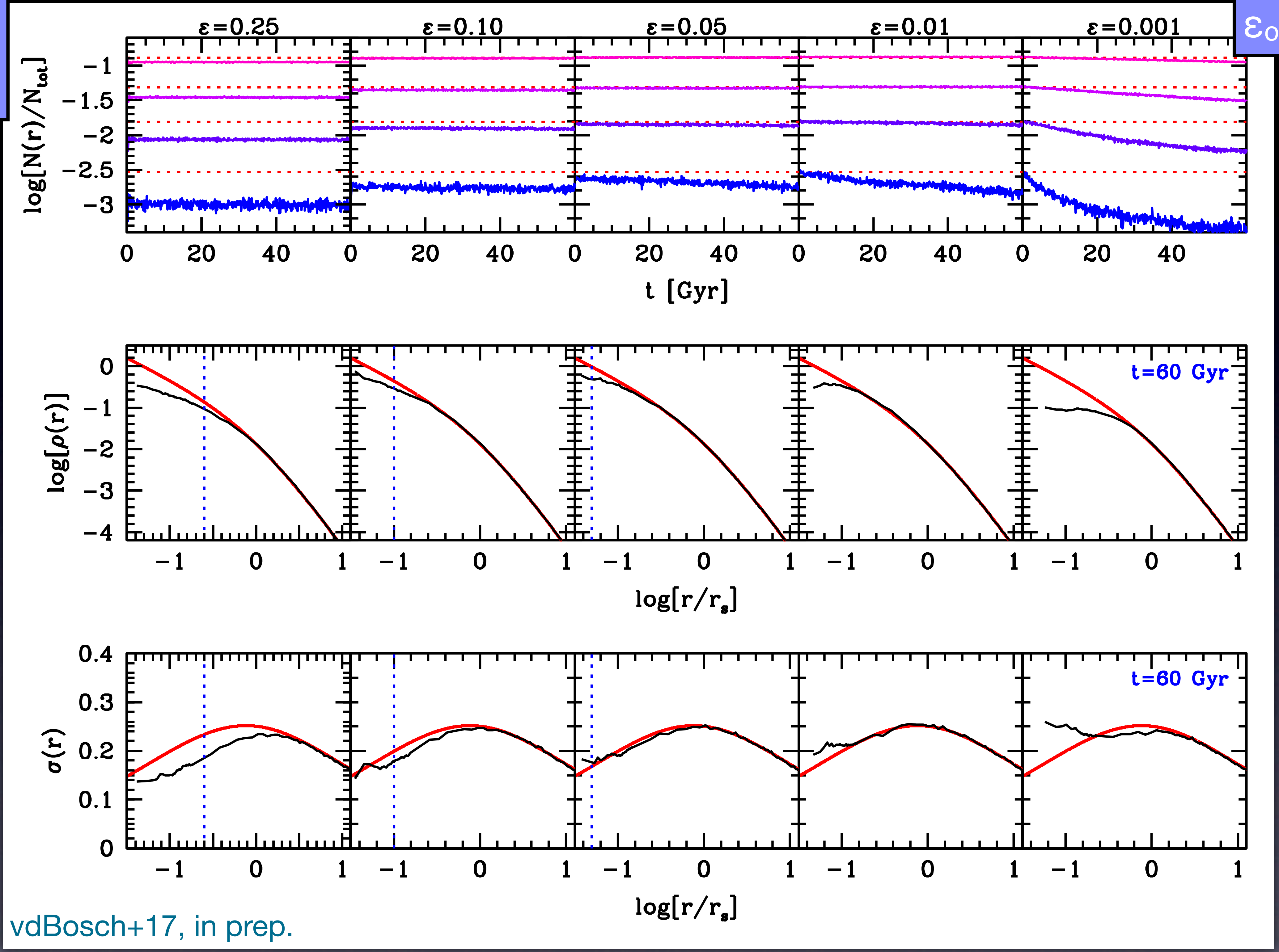
Disruption for $r_{orb} < 0.15\ r_{vir}$......or numerical artefacts?



Tuning the Softening Length

NFW halo
N=10^5

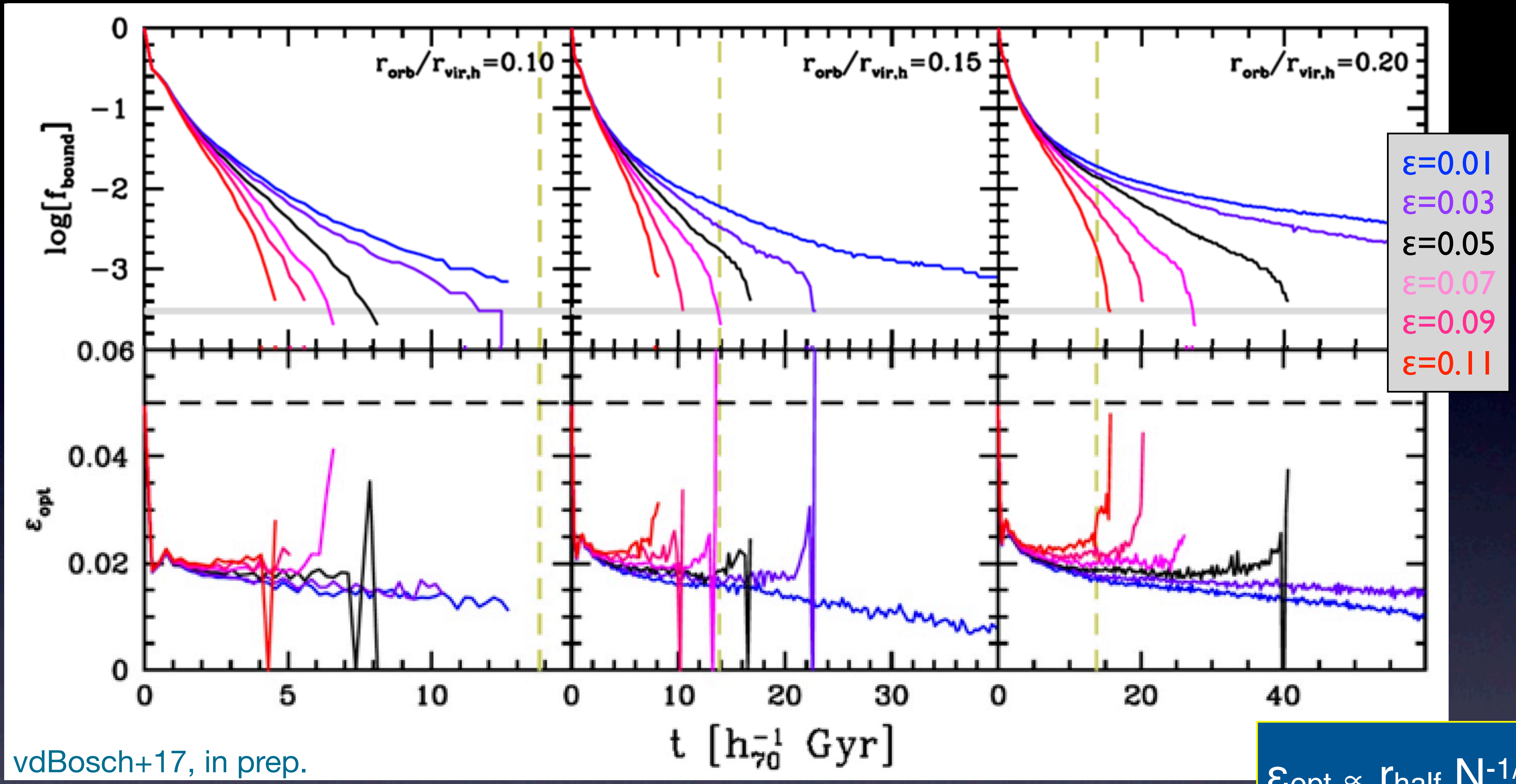
$\varepsilon_{opt} \simeq 0.05$



ε too large ➢ force bias ➢ central cusp unresolved

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

Force Softening



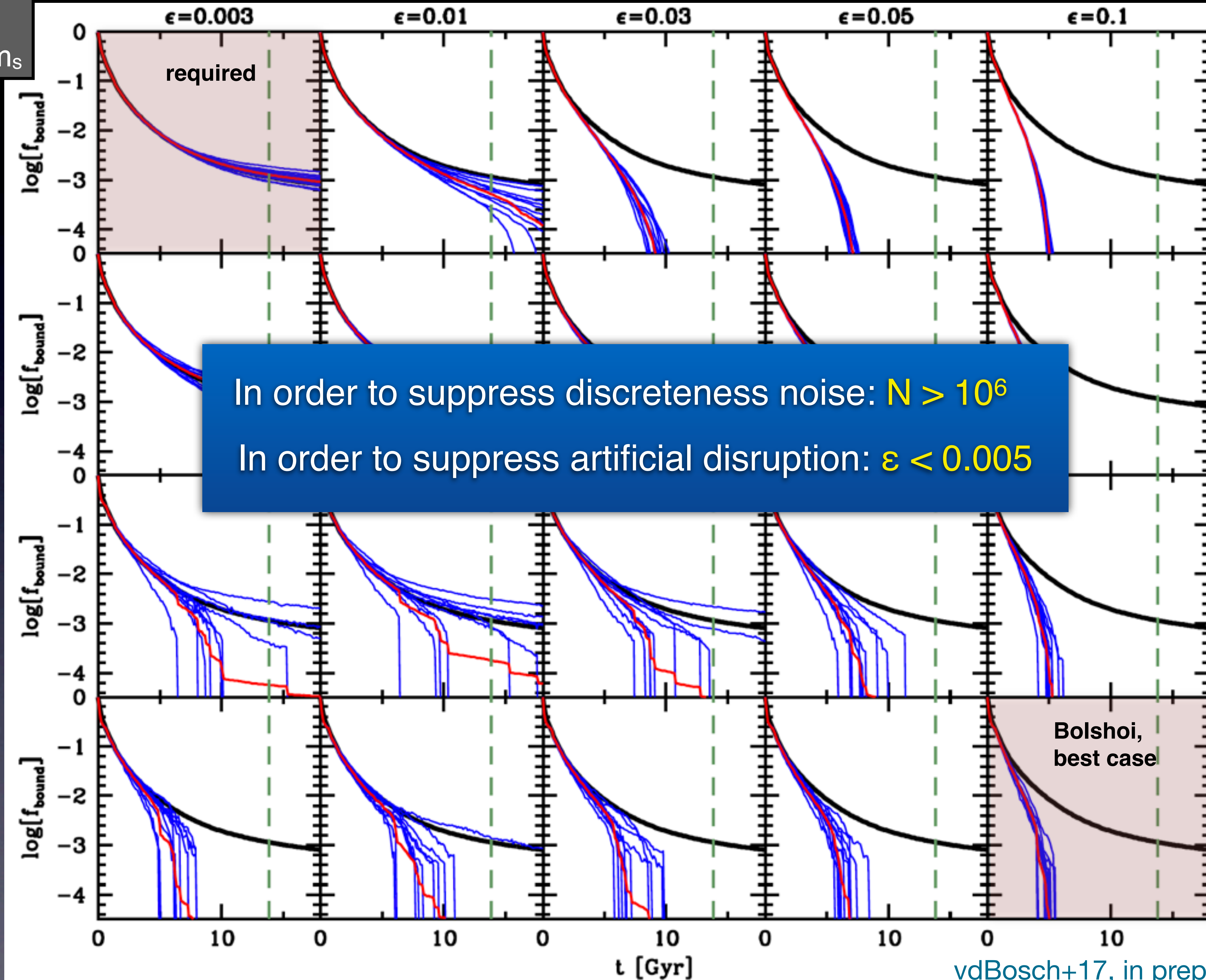
$\varepsilon_{opt} \propto r_{half}\ N^{-1/3}$

(Dehnen+01; Power+03)

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

Towards Numerical Convergence

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



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

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

N=1,000,000

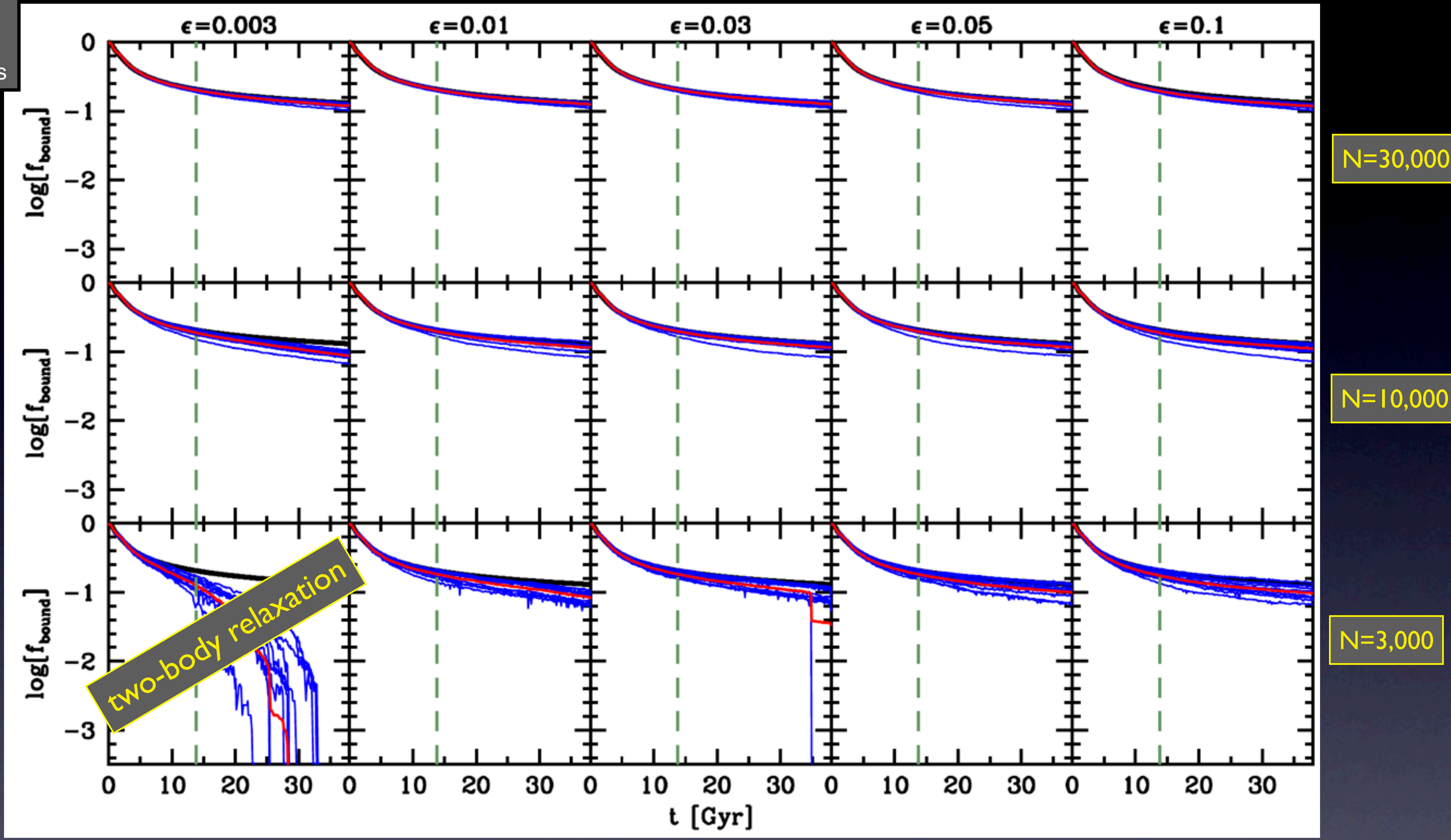
N=300,000

N=100,000

N=30,000

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

Towards Numerical Convergence

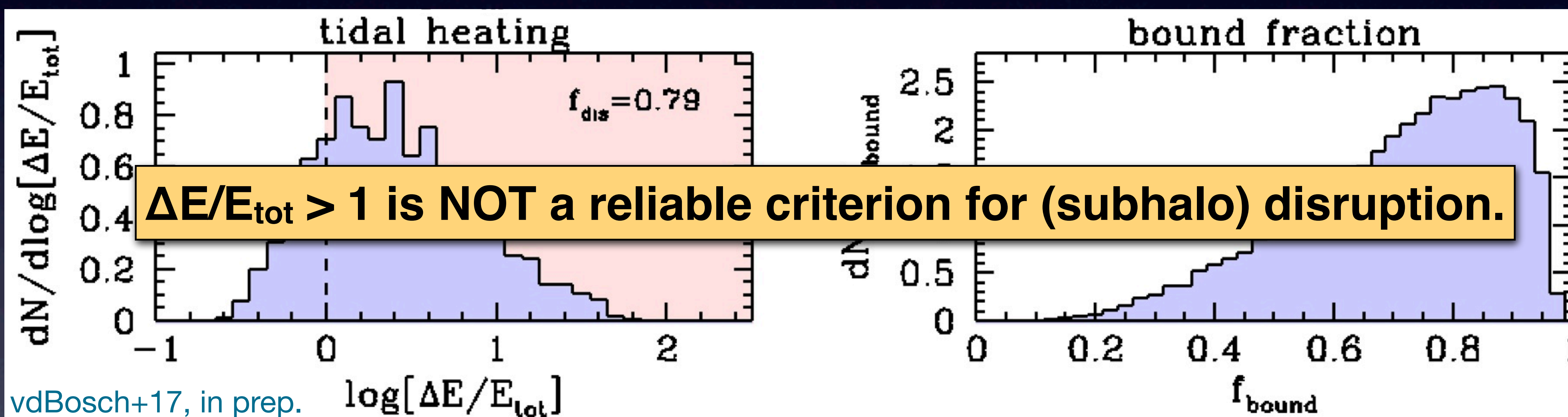


Ability to resolve dynamics is a strong function of

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

What about Tidal (Impulsive) Heating?

- For each subhalo in Bolshoi, compute orbital energy & circularity at accretion.
- Compute tidal heating, $\Delta E/E_{tot}$, by integrating impulse approximation along subhalo's orbit (one period) using detailed model of Gnedin, Hernquist & Ostriker (1999).
- Apply same method to Monte-Carlo realizations of NFW subhalos to compute ΔE_i and E_i for each individual DM particle. Determine $f_{bound} = f(\Delta E_i/E_i < 1)$



vdBosch+17, in prep.

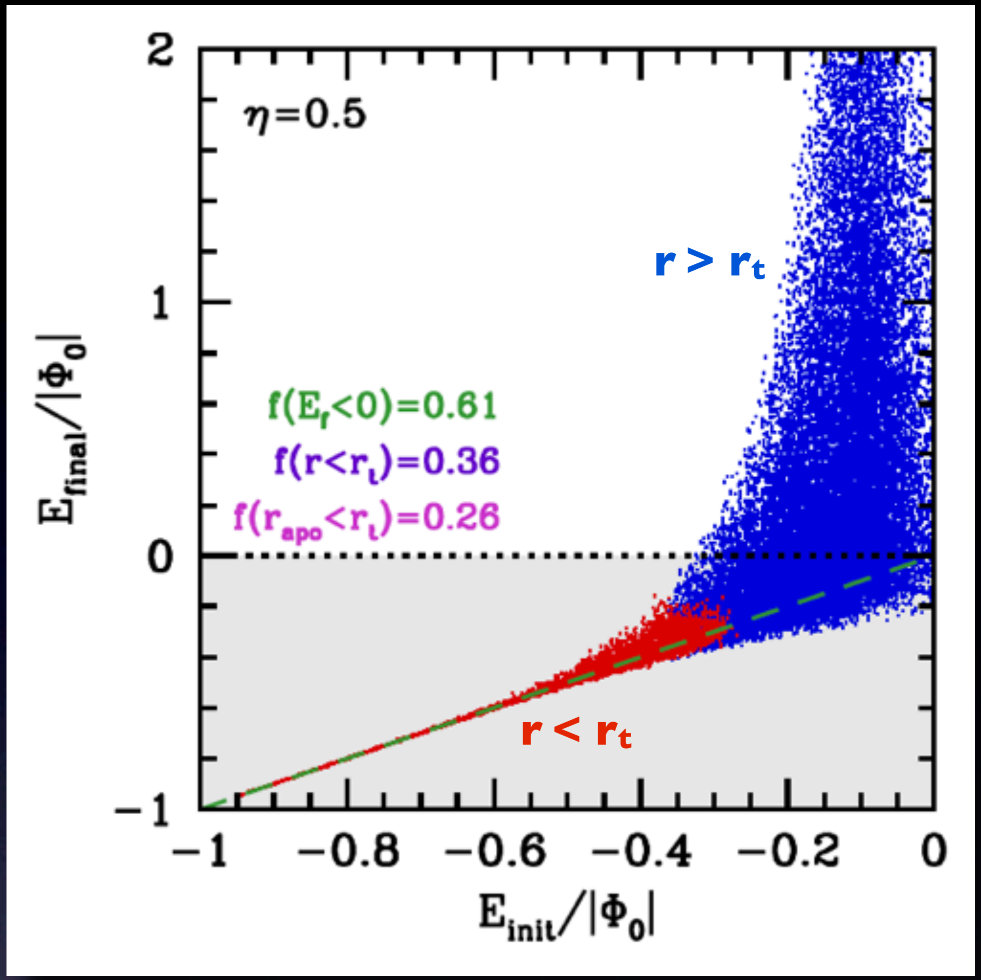
$\Delta E/E_{tot} > 1$ is NOT a reliable criterion for (subhalo) disruption.

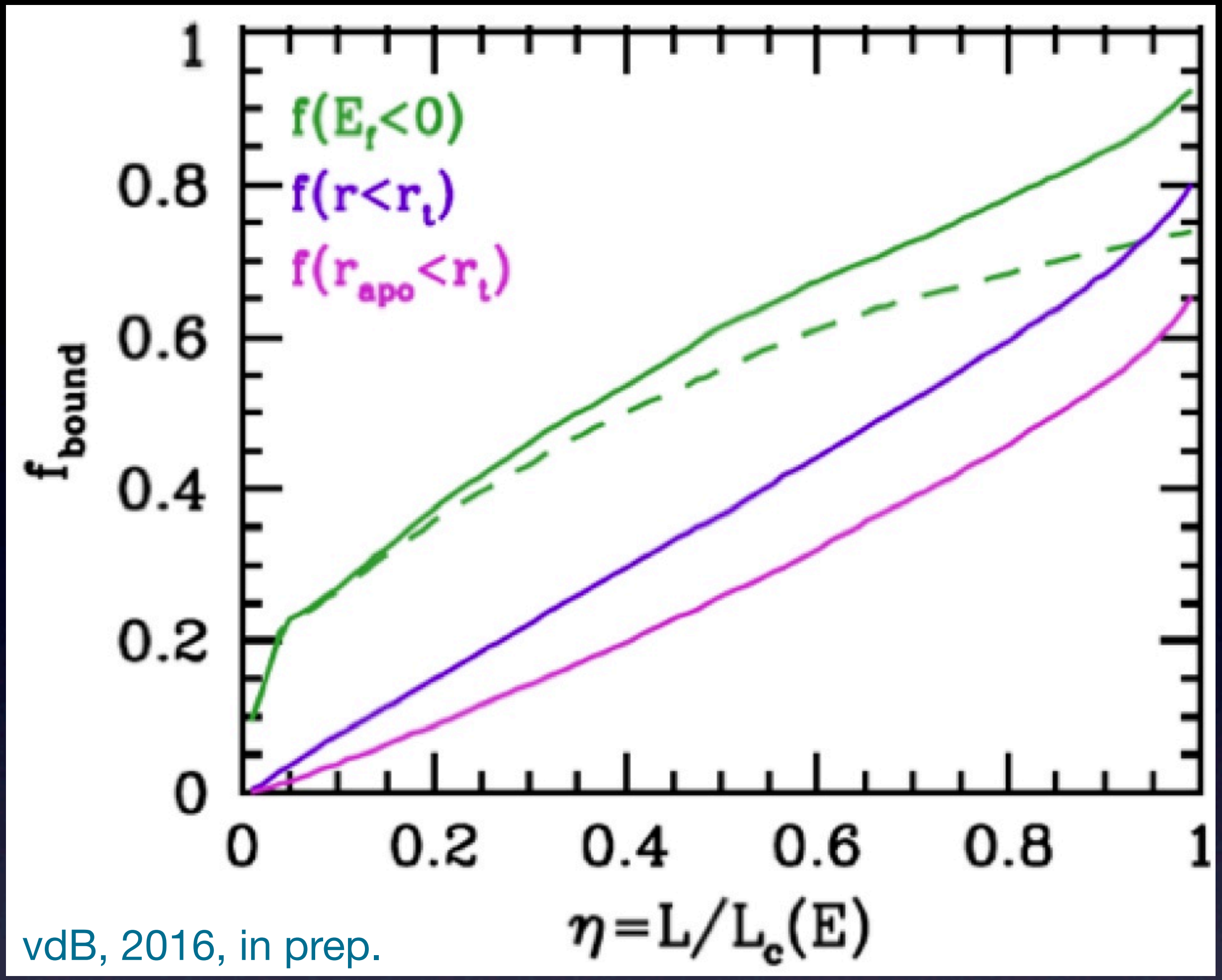
Energy input exceeds subhalo binding energy for ~80 percent of all subhalos.

Yet, on average only ~25 percent of subhalo particles become unbound.

Even when $\Delta E/E_{tot}$ = 100 as much as 20 percent of subhalo remains bound!!!

Tidal Heating *vs* Tidal Stripping

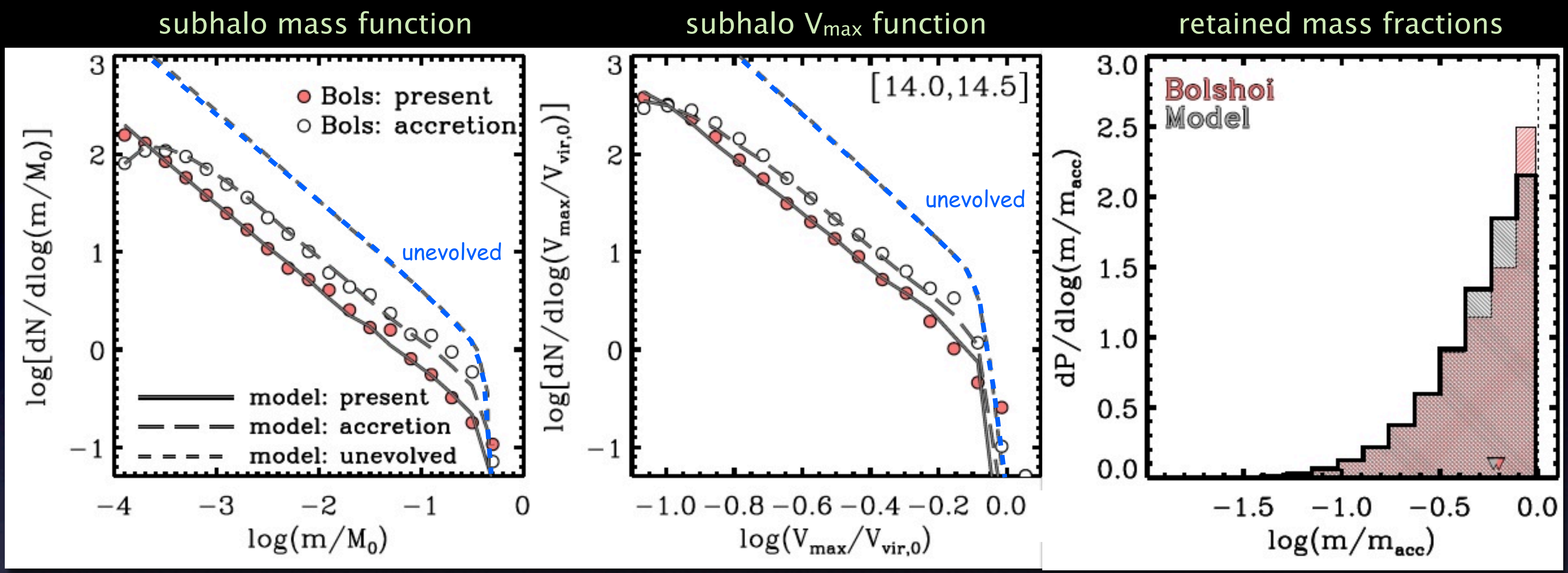




- Impulsive heating injects large amounts of energy.
- Central region is unaffected and remains bound.
- Material that unbinds due to tidal heating, is anyways stripped off due to tidal force

Tidal stripping dominates over impulsive, tidal heating

What if ALL disruption is numerical?



Jiang & vdB, 2016

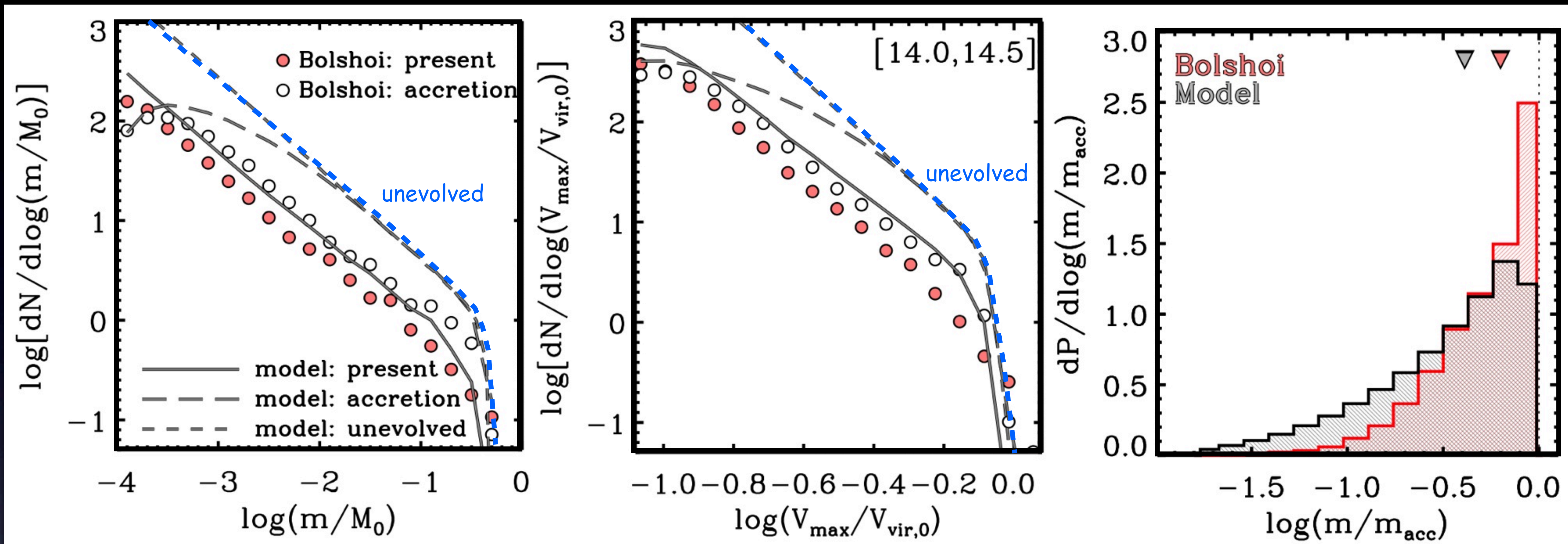
- Jiang & van den Bosch (2016) developed semi-analytical model for DM substructure
- Model includes treatments of both tidal stripping and tidal disruption
- Model is tuned to accurately reproduce the Bolshoi simulation results

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 an important, outstanding problem with SHAM

Campbell, vdB et al. 2017, in prep

Conclusions

- Abundance & demographics of dark matter substructure important for variety of astrophysical applications.
- Subhalo disruption is prevalent in numerical simulations
- What causes subhalo disruption?
  - Dynamical friction (physical)
  - Inadequate force resolution (numerical)
  - Discreteness noise (numerical)
- Properly resolving dynamics of subhalos requires
  - huge N (to suppress discreteness noise)
  - small softening length (~1/10 of that for isolated halos)
- Tidal heating is subdominant to tidal stripping
  In absence of dynamical friction, subhaloes never disrupt.

Conclusions

- 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

- How to proceed?
  - Use adaptive softening (has to adapt to local tidal field)
    (e.g., Iannuzzi & Dolag 11; Hobbs+15)
  - Characterize shortcomings of N-body simulations, and complement simulation results with semi-analytical model.