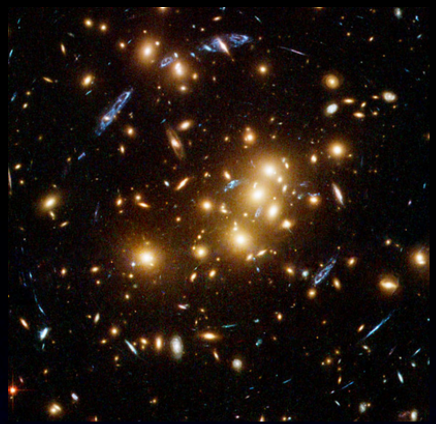
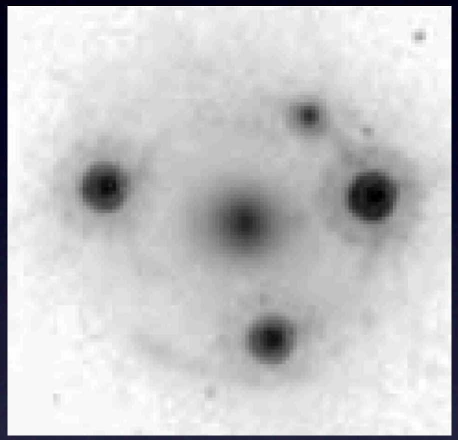
Dark Matter Substructure
Cosmological Treasure Trove or a Pandora's Box?

Frank van den Bosch
Yale University

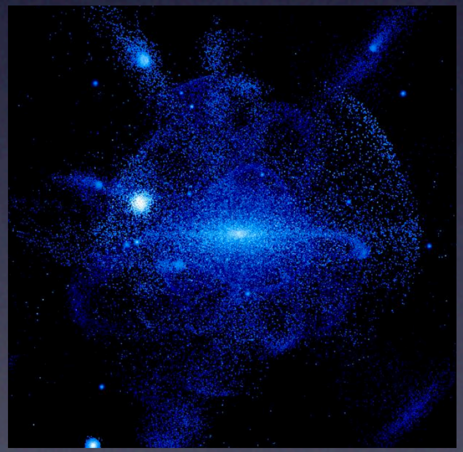
Why do we care about substructure



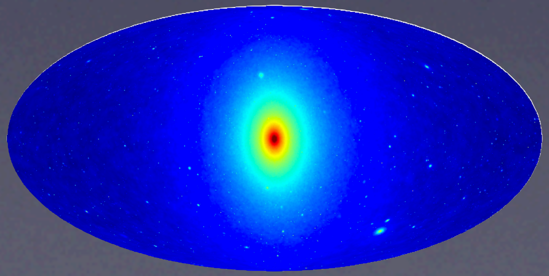
Halo Occupation Modeling:
subhaloes host satellite galaxies



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



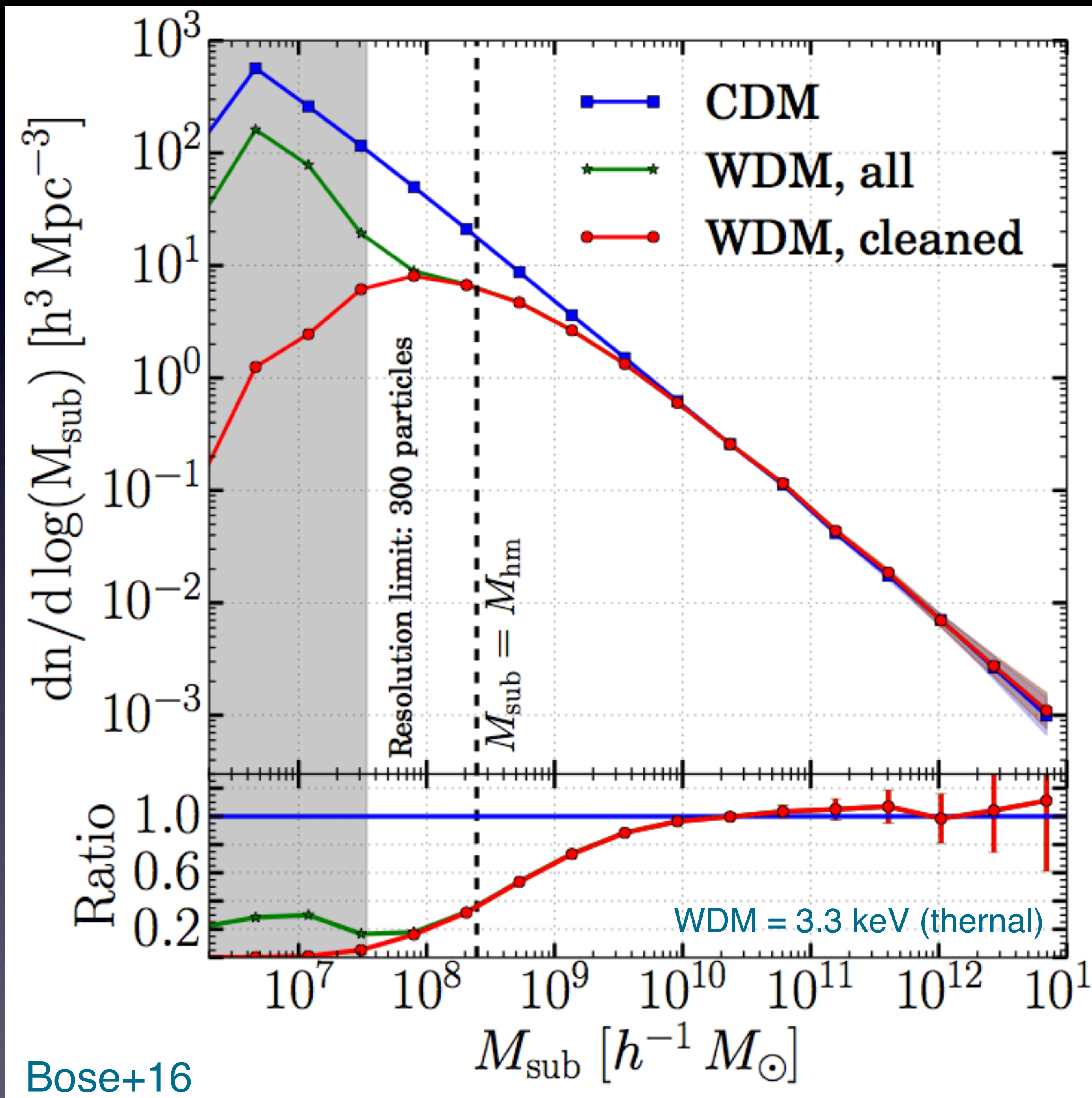
Subhaloes can heat stellar disks and tidal streams



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



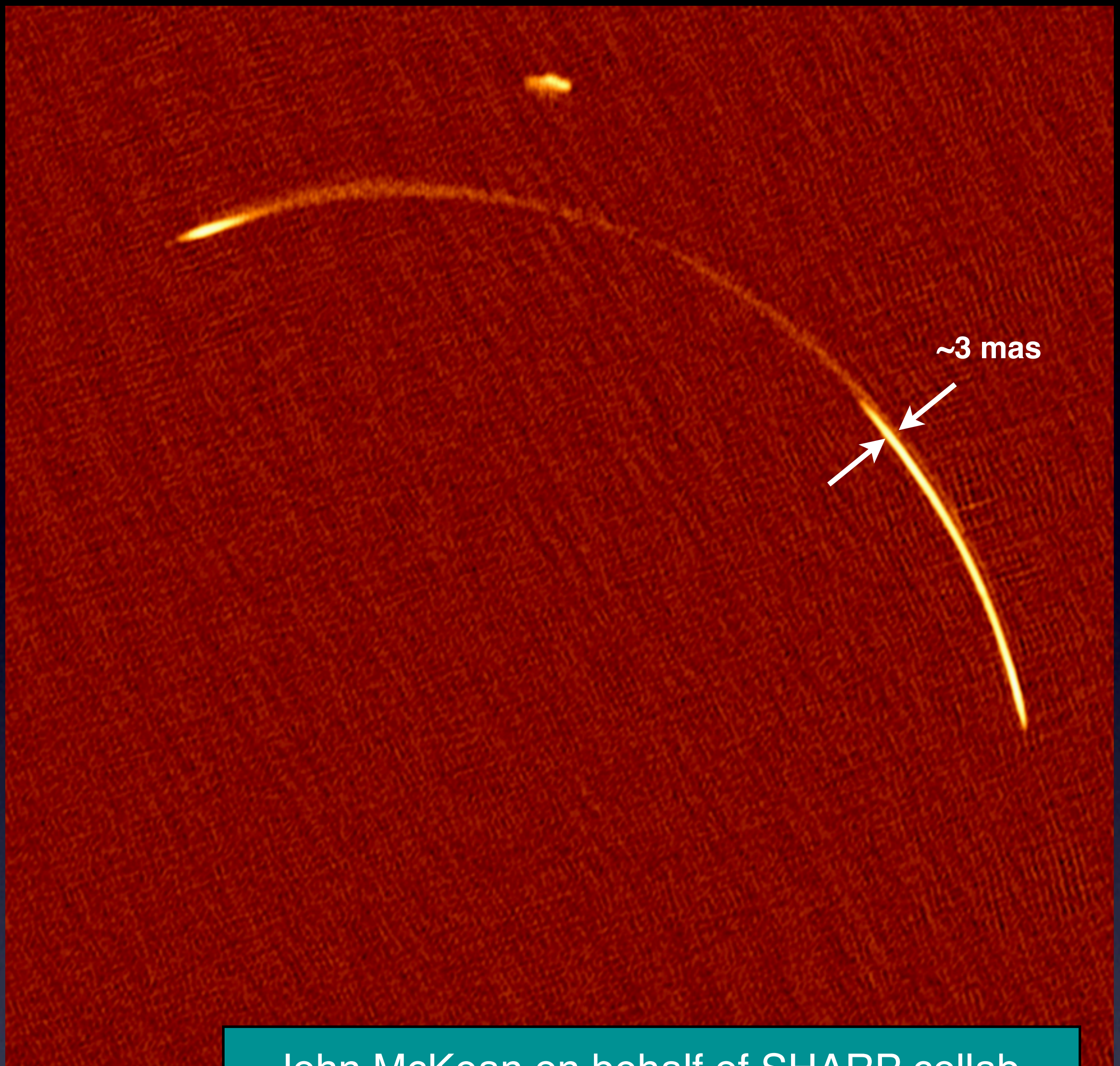
Different models mainly differ in the abundance of low mass halos, where galaxy formation is expected to be supressed due to re-ionization.

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.

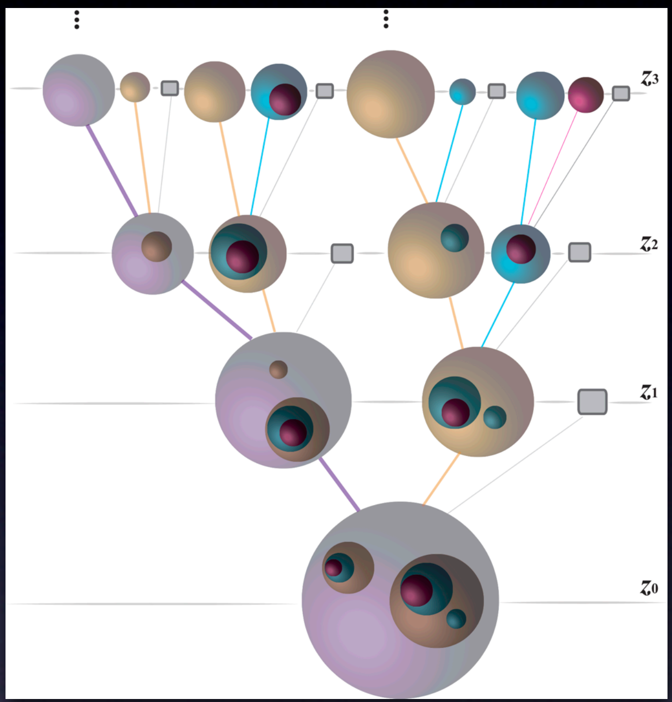
- Substructure in lens causes image distortions of lensed arcs
- Sensitivity depends on thickness of the observed arc
- In radio (using VLBI), razor-thin arcs (< few mas) can be detected, which reach sensitivities of $10^6\ M_\odot$

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

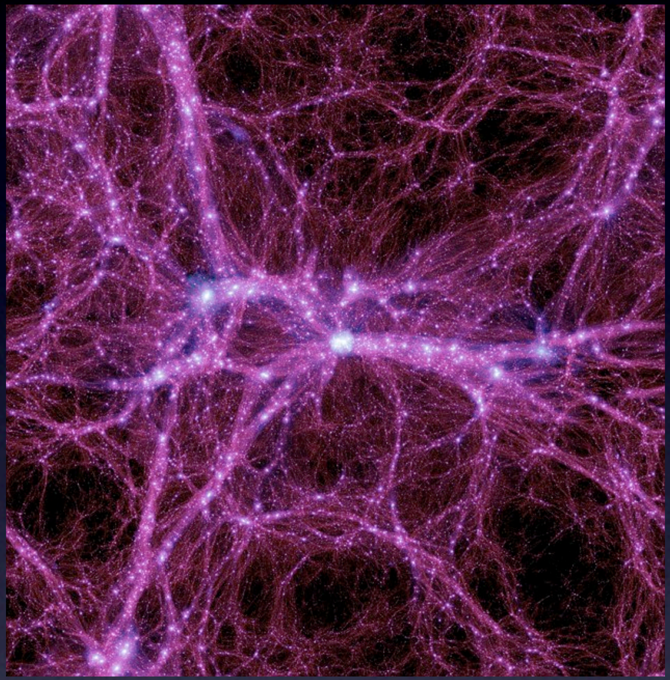
Numerical N-body Simulations

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)

see vdBosch+17, in prep. for detailed discussion

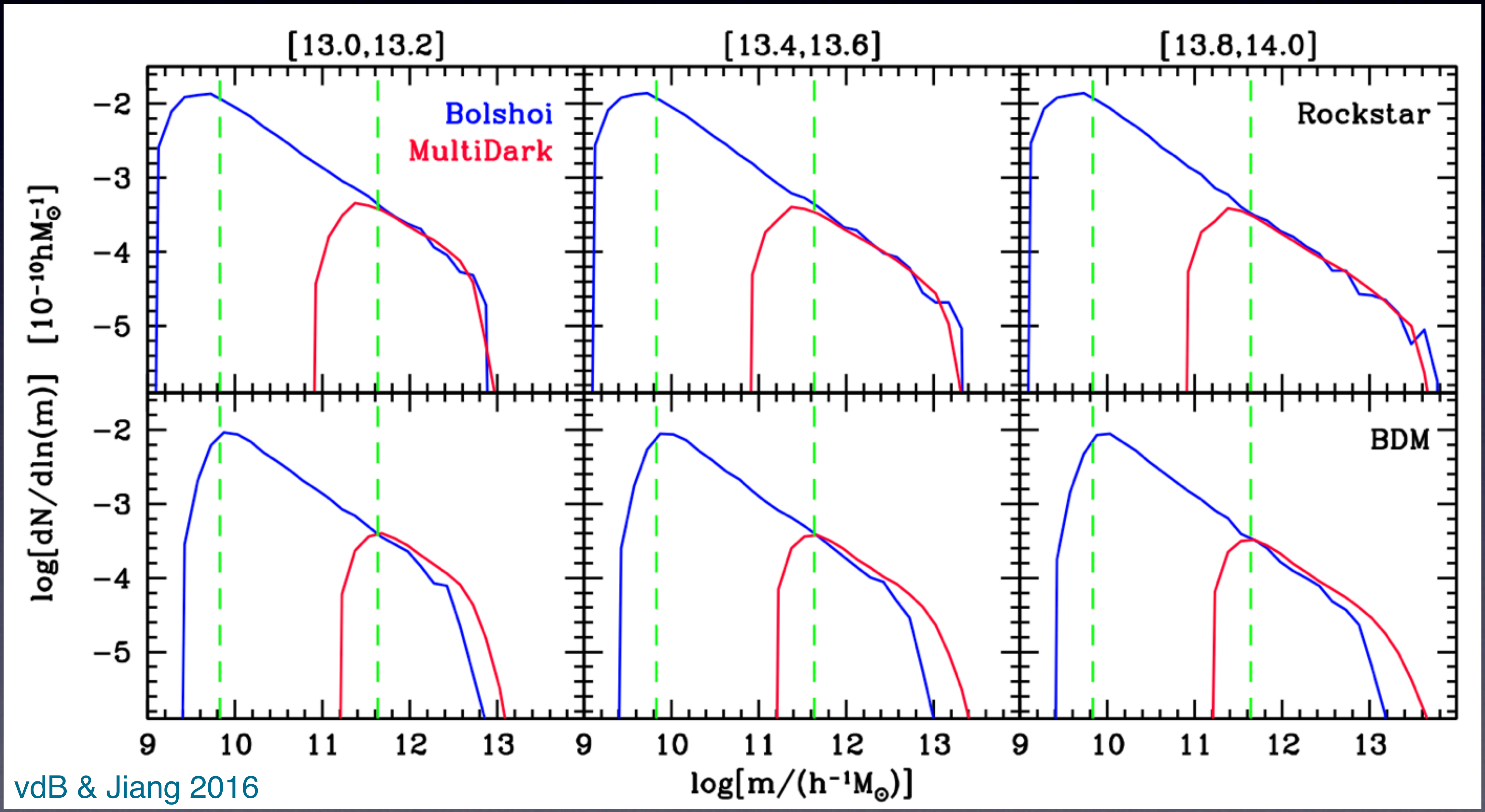
The Substructure Revolution:

- 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)



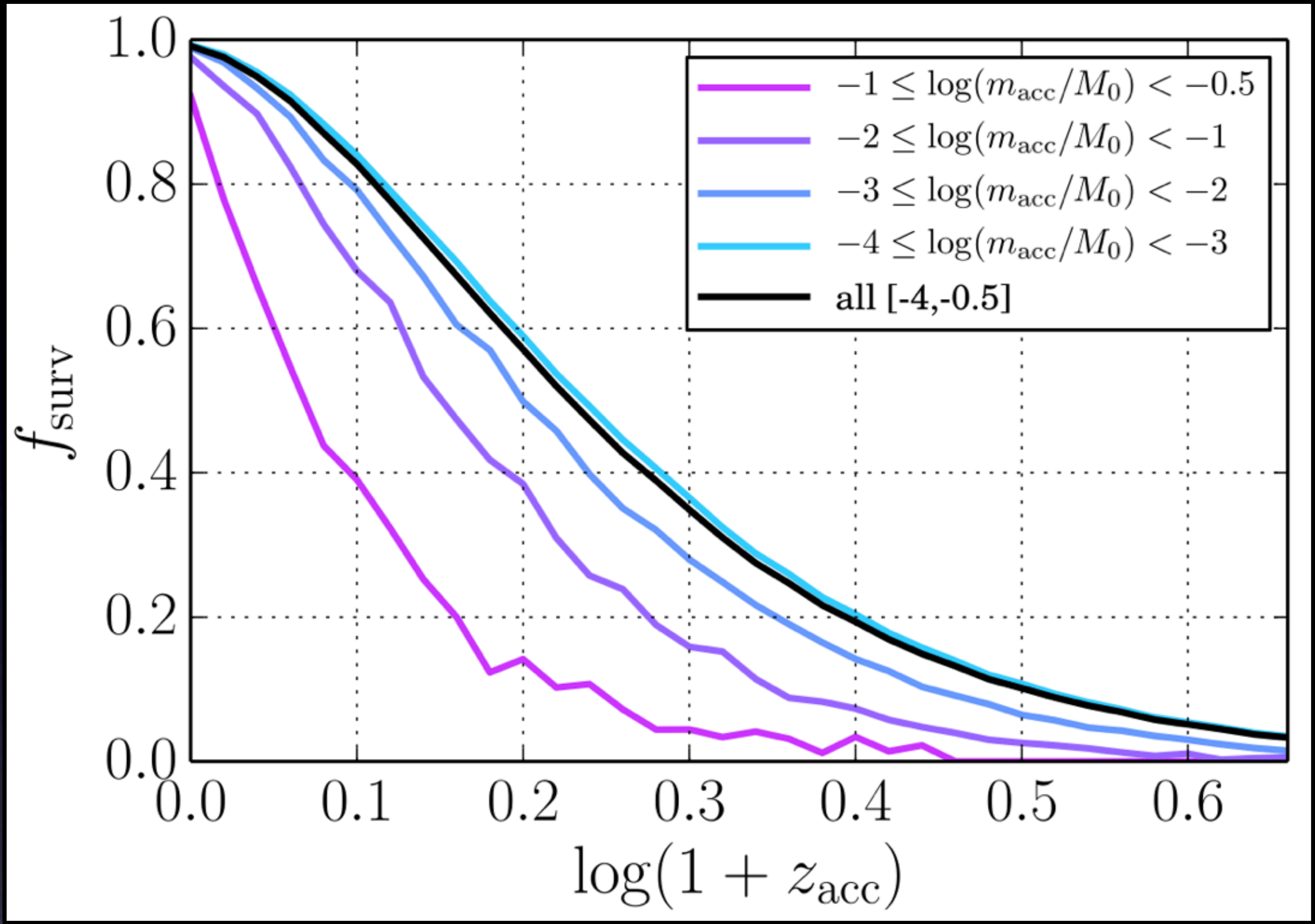
What about overmerging?

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 $N \sim 100$ (Springel+08)
- Subhalo velocity functions are converged down to $N \sim 250$ (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)

Subhalo Disruption in Bolshoi



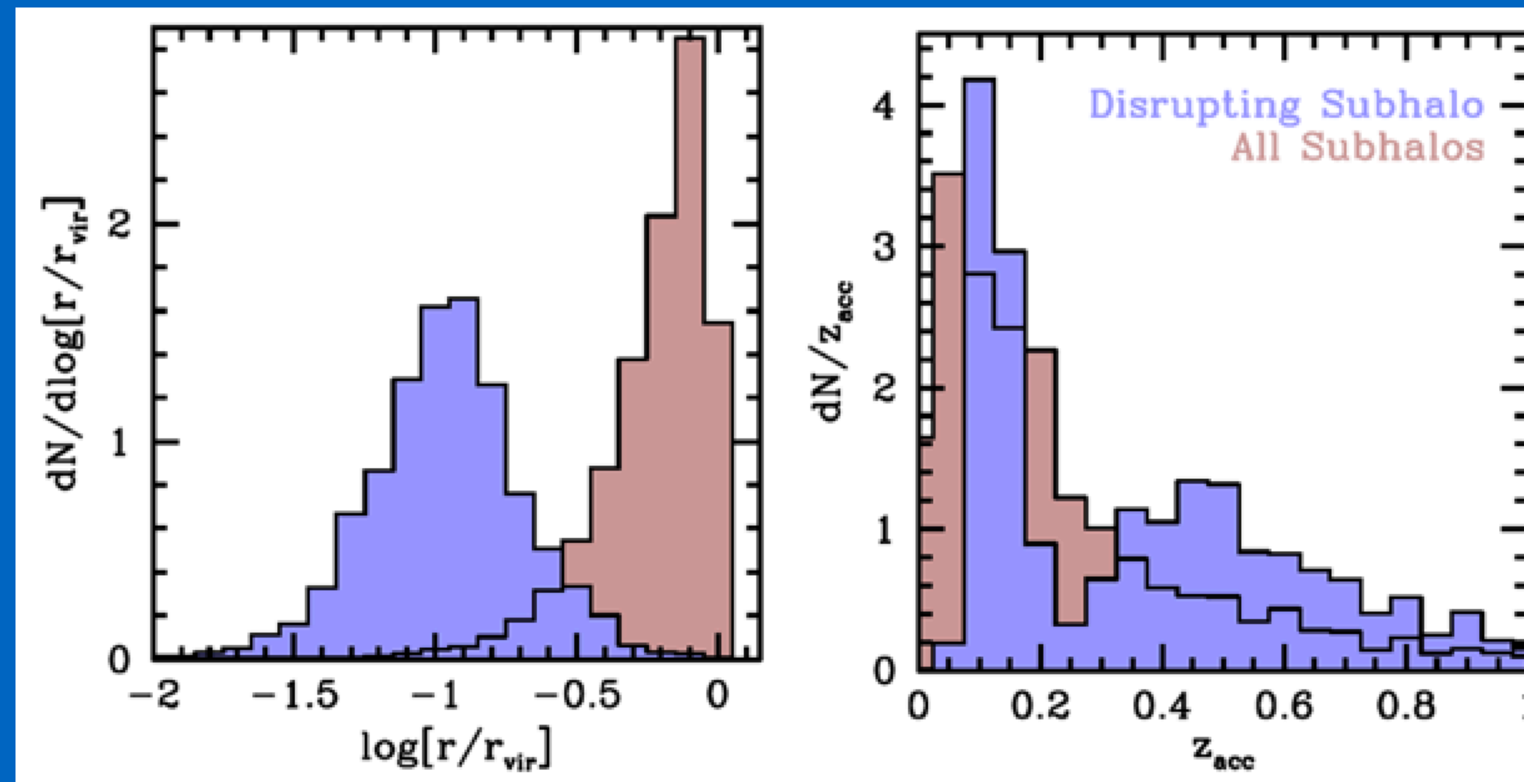
Jiang & vdB, 2016

- 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

Disruption Demographics

- Most subhalo disruption occurs near $r \simeq 0.1 r_{vir,h}$
- Significant fraction of subhalos disrupt during first peri-centric passage



vdBosch 2017

Disruption Mechanisms

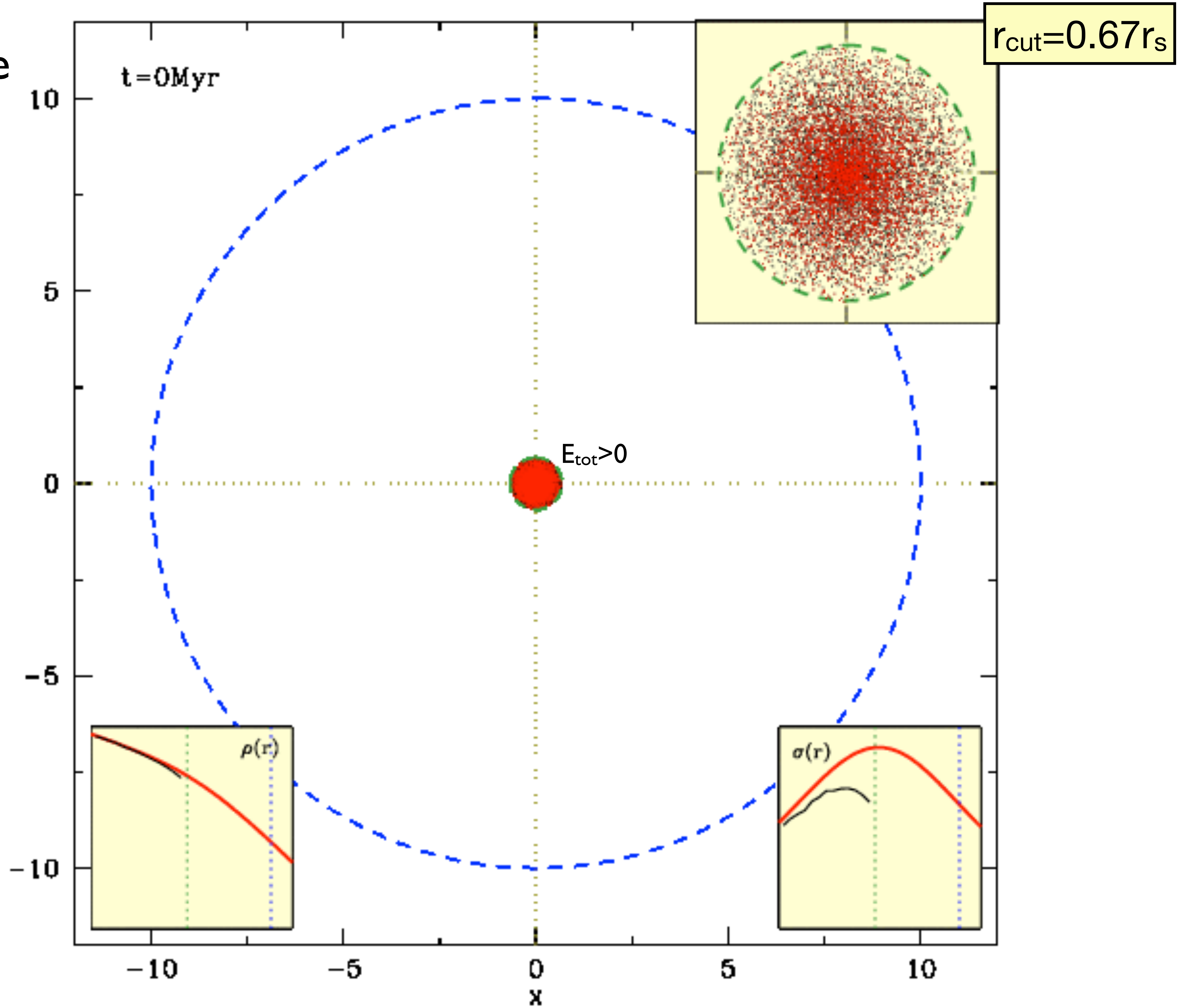
- Tidal Stripping
- Tidal Heating
  - Pericentric Passage
  - Subhalo-Subhalo Encounter
- Numerical overmerging

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, the core has positive binding energy if $r_{cut} < r_{bind} = 0.77\, r_{s.}$ (corresponding core mass is $\sim 0.08\, M_{vir}$)
- Spontaneous disintegration once $r_{tid} < r_{cut}$?

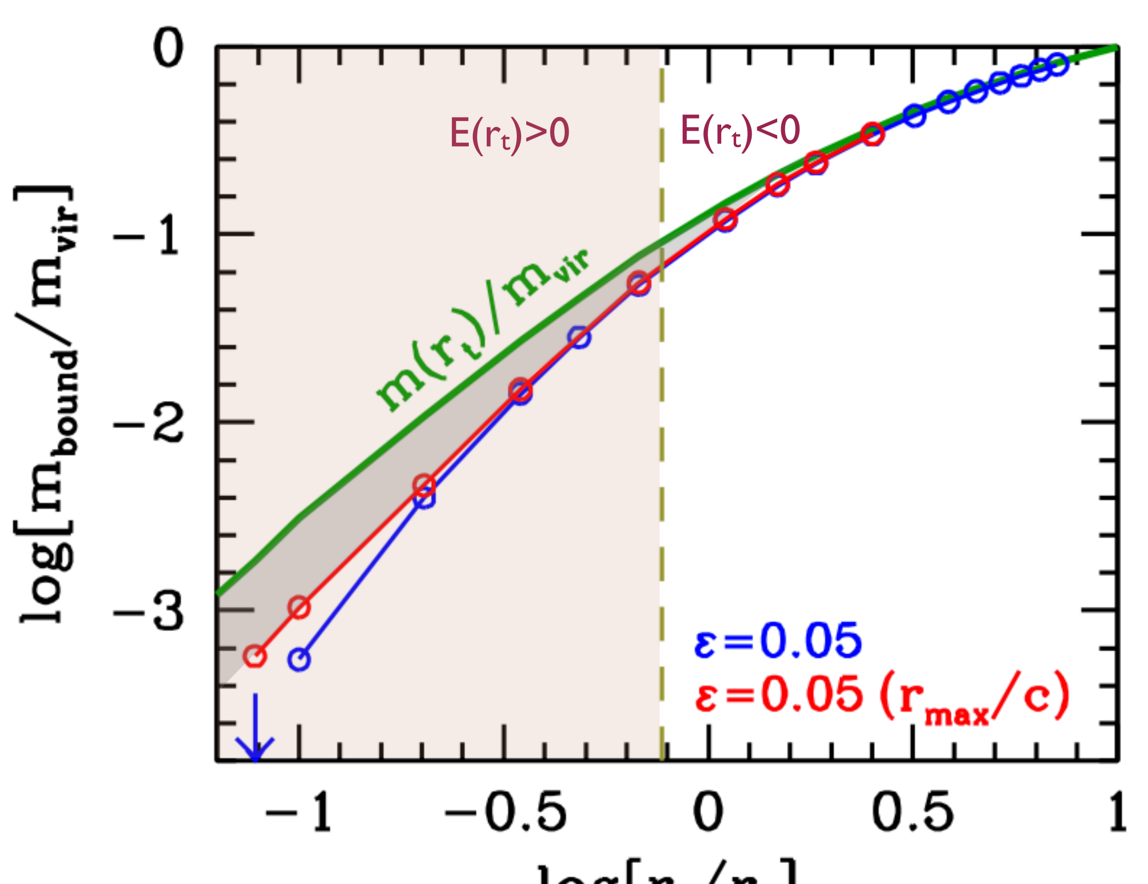
This assumption is made in several models or subhalo evolution
(e.g., Zentner & Bullock 2003; Taylor & Babul 2004; Klypin et al. 2015)

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, the core has positive binding energy if $r_{cut} < r_{bind} = 0.77\ r_s$. (corresponding core mass is $\sim 0.08\ M_{vir}$)
- Spontaneous disintegration once $r_{tid} < r_{cut}$?



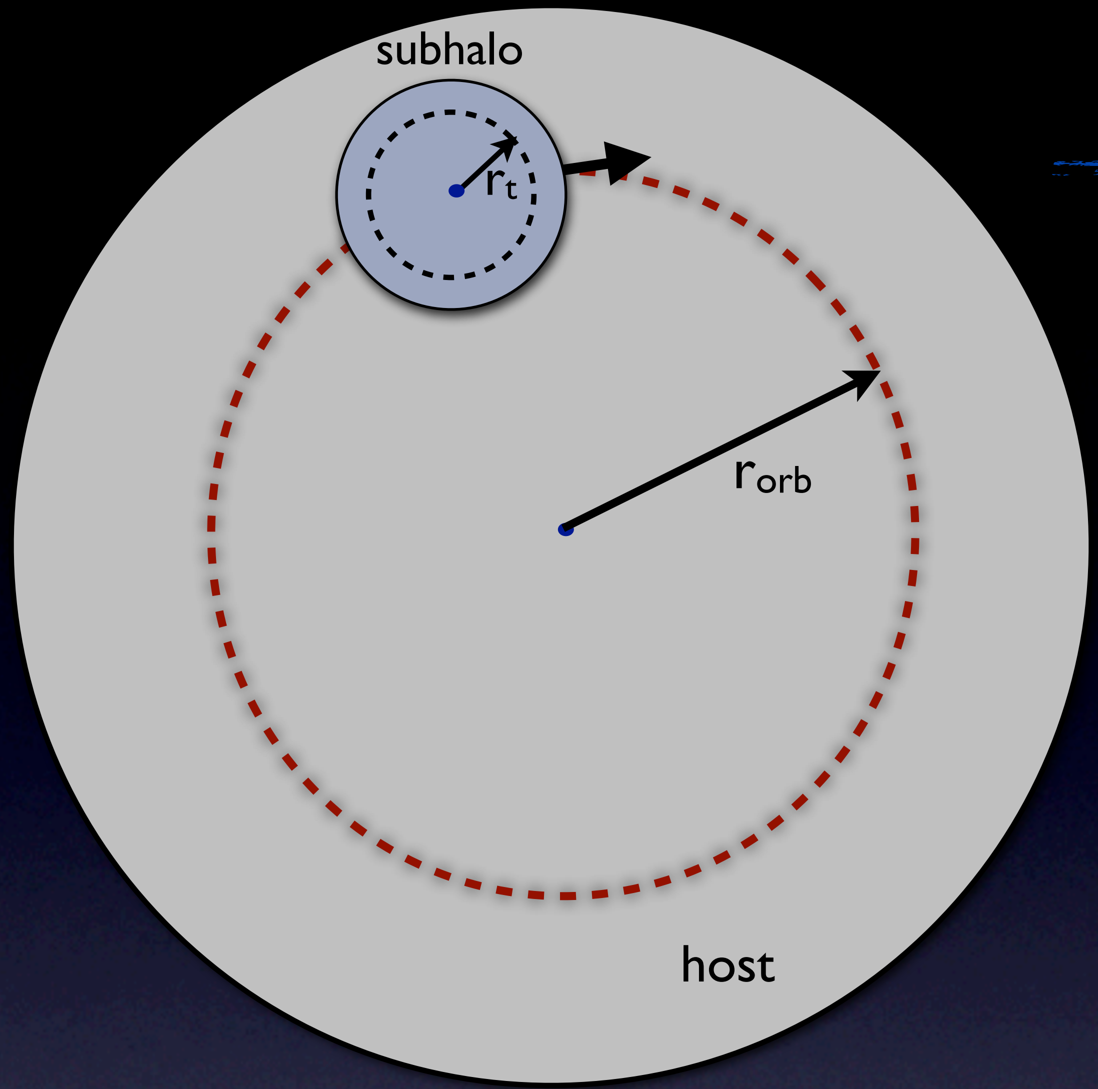
vdBosch+17, in prep.

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



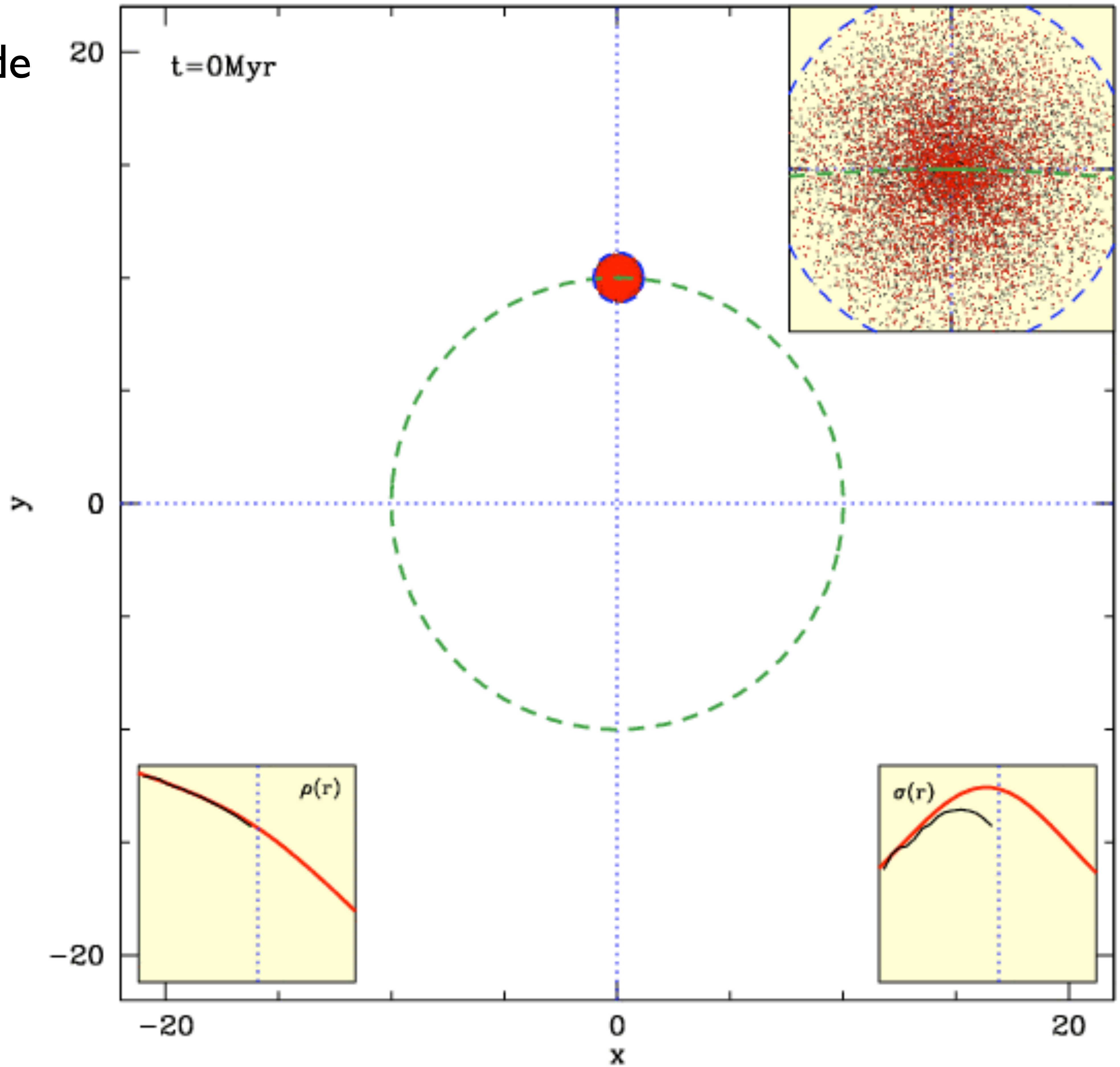
Simulate NFW halo orbiting on circular orbit inside static potential of host halo.

- 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...

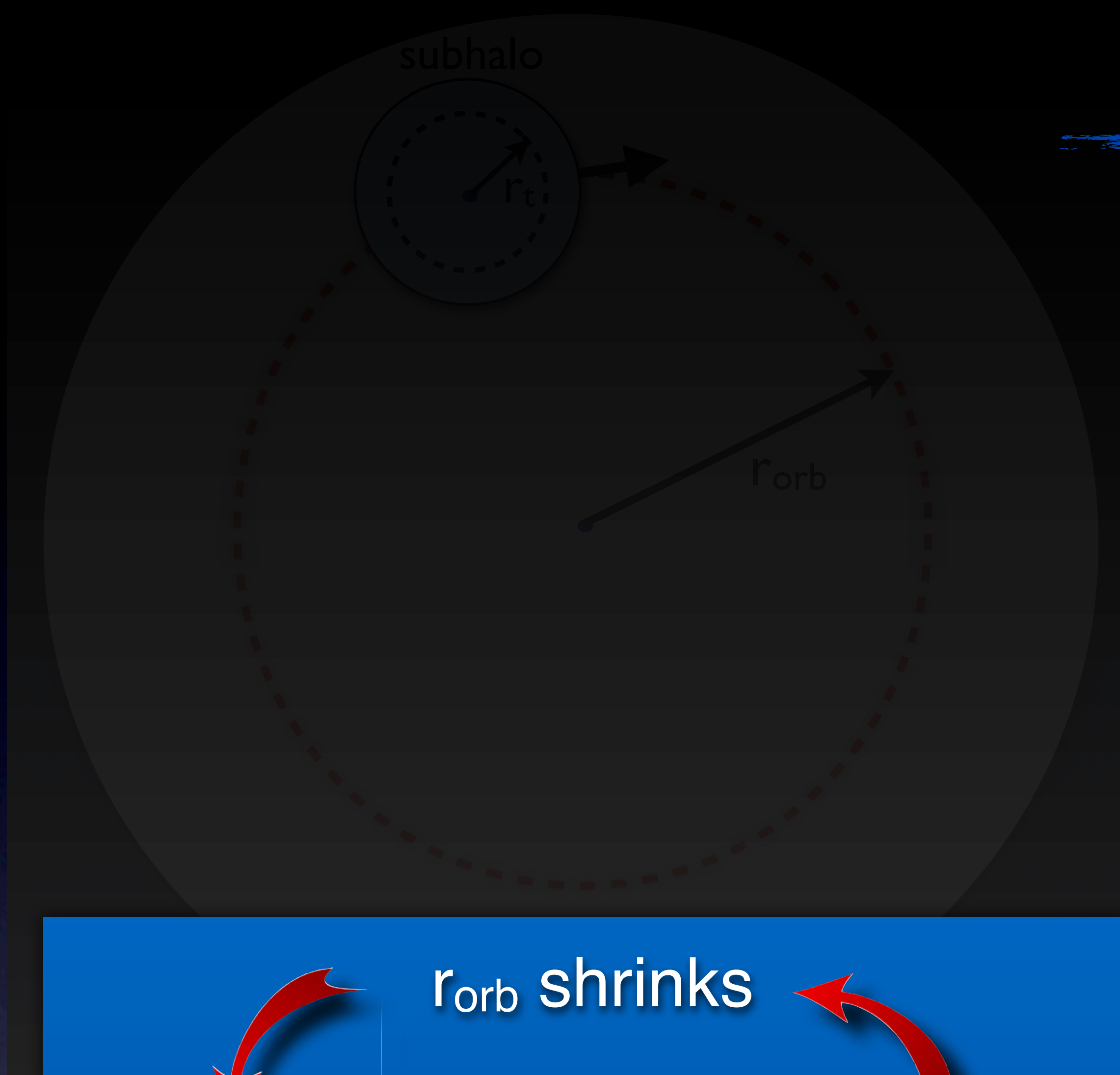
N=10^5
tree-code

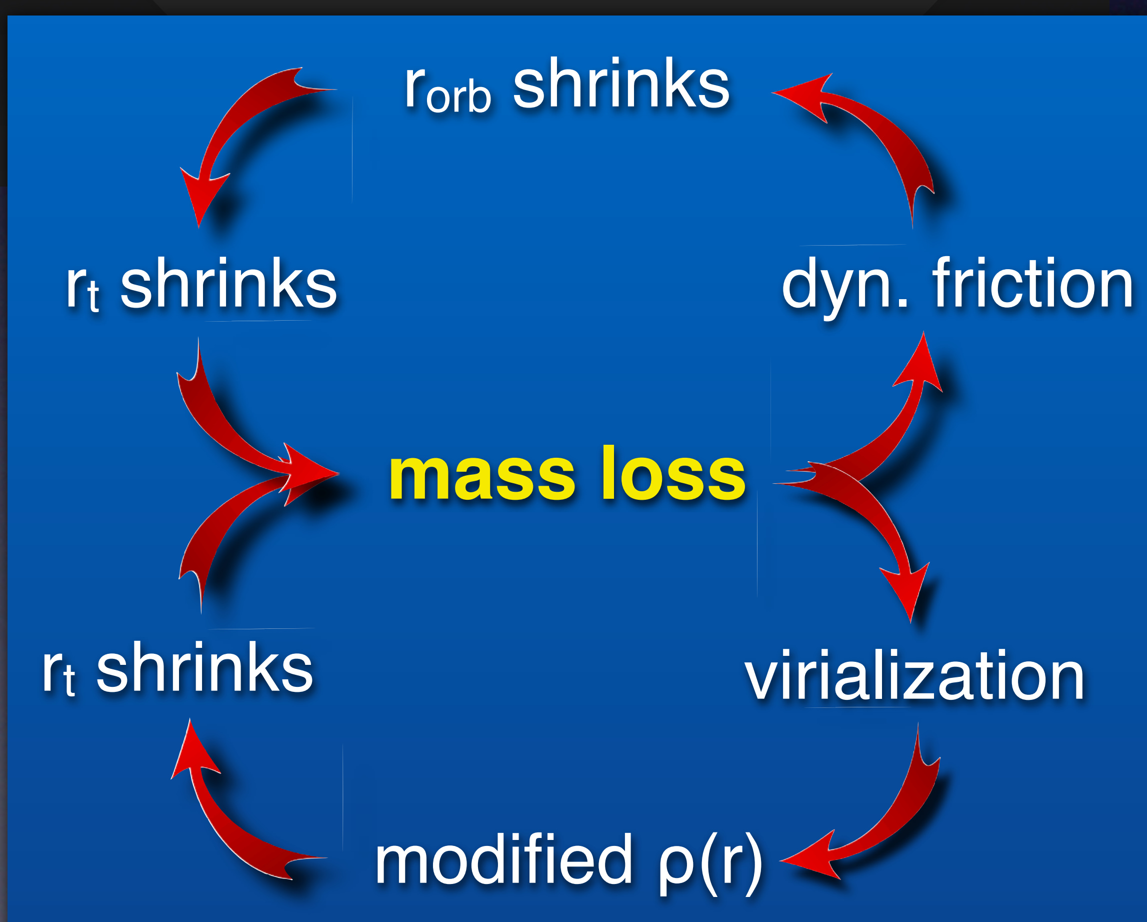


r_{orb}=0.1 $r_{vir,h}$

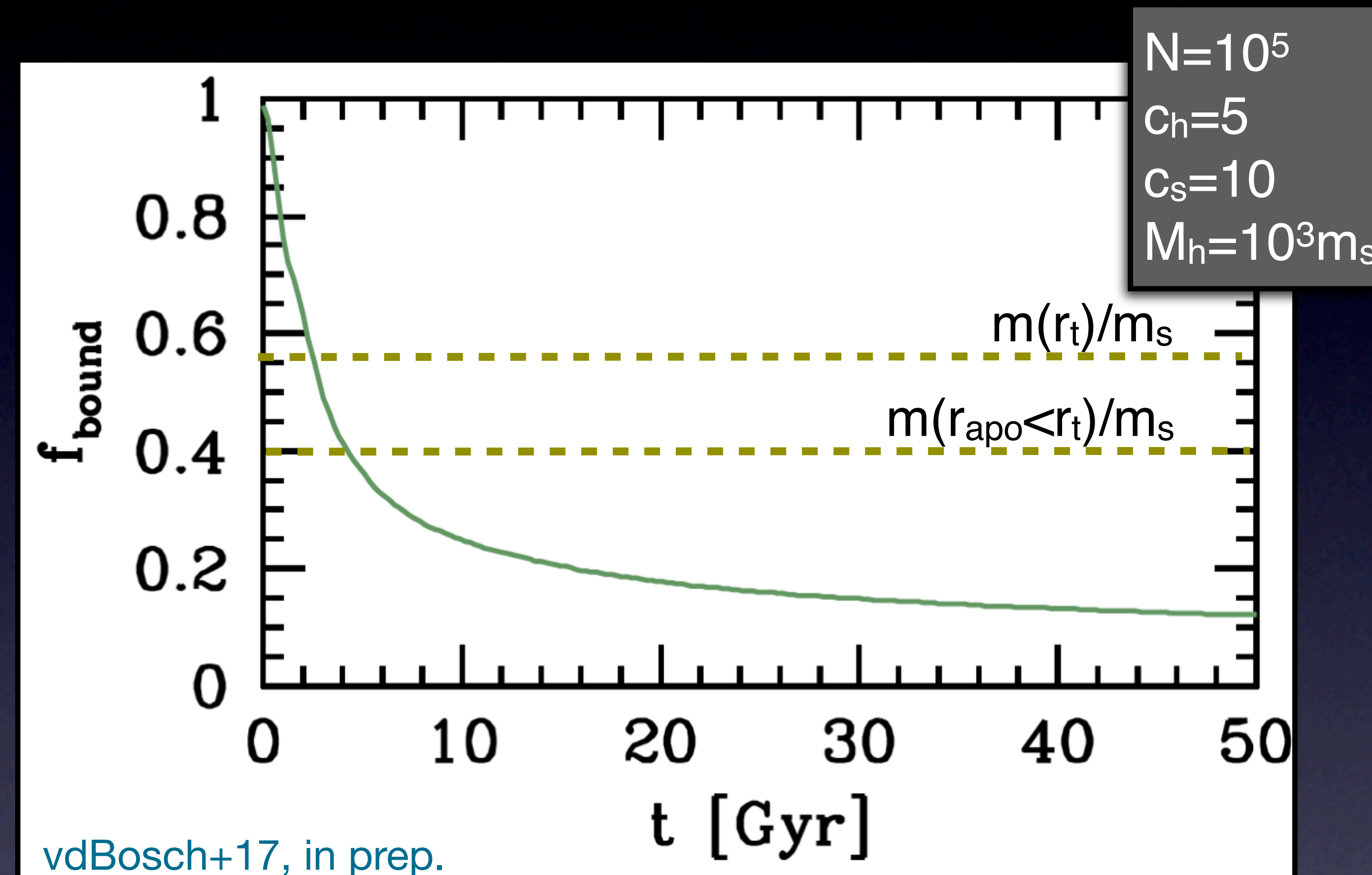
r_t=0.11 r_s

Numerical Simulations



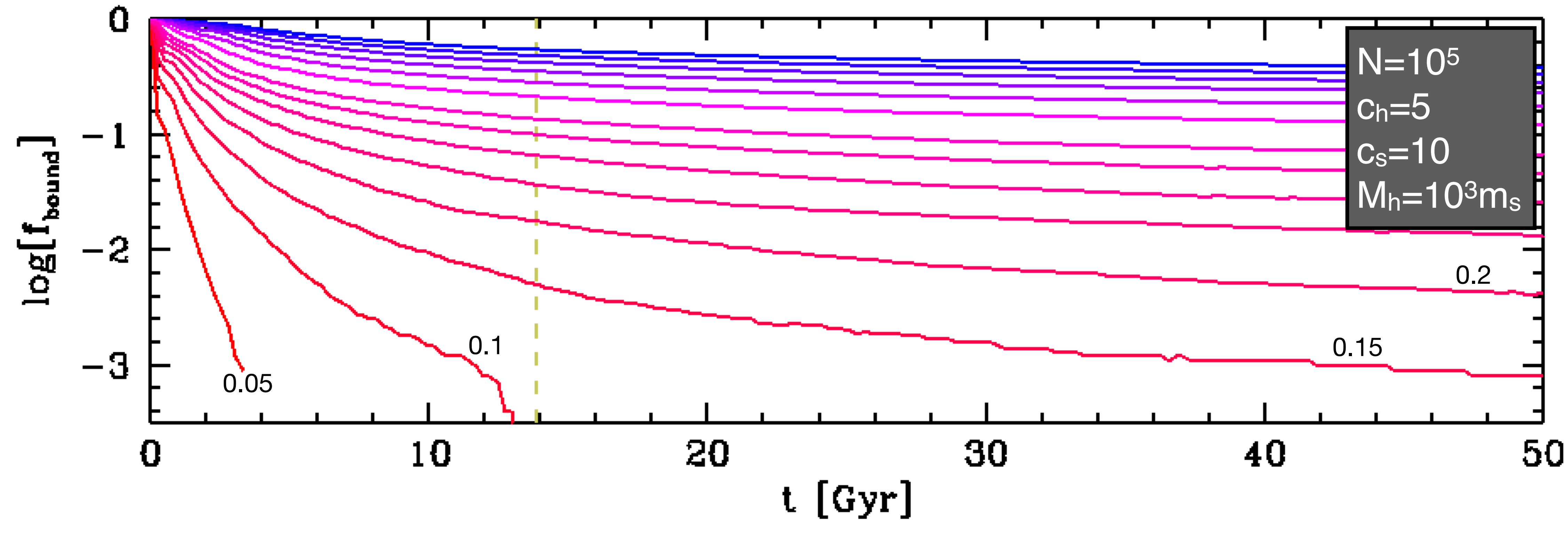


Simulate NFW halo orbiting on <u>circular</u> orbit inside <u>static</u> potential of host halo.

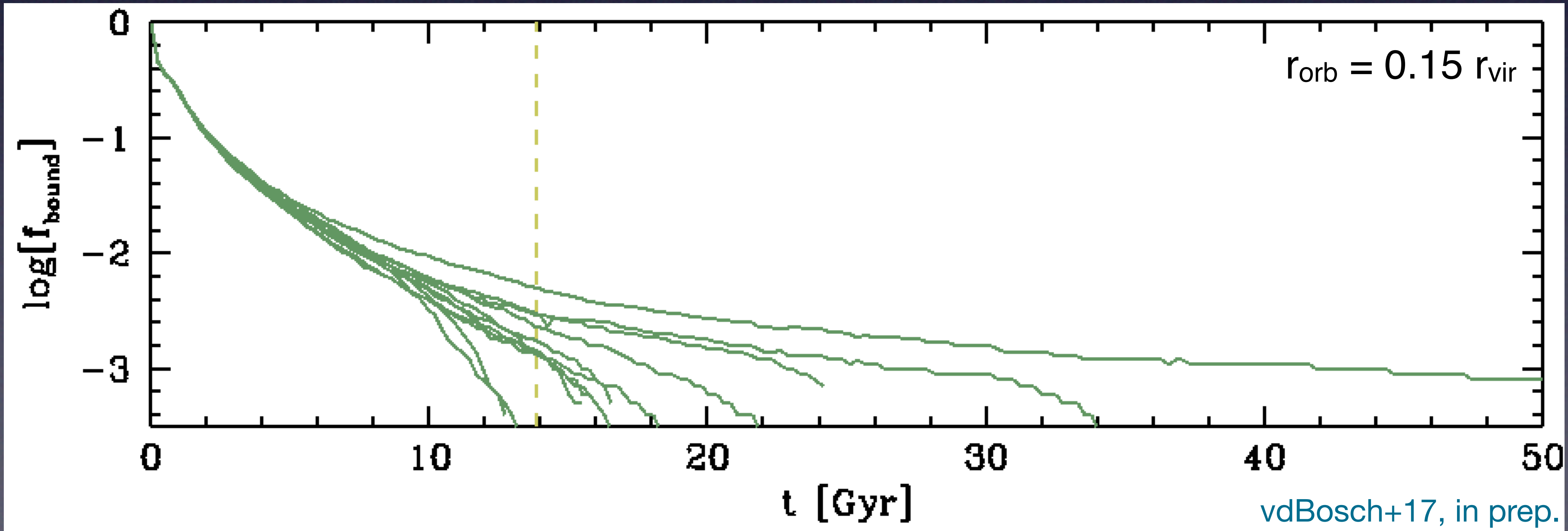


- Analytical predictions fail to predict amount of mass stripped
- Mass loss continues for >50 Gyr

Tidal Stripping on Circular Orbits



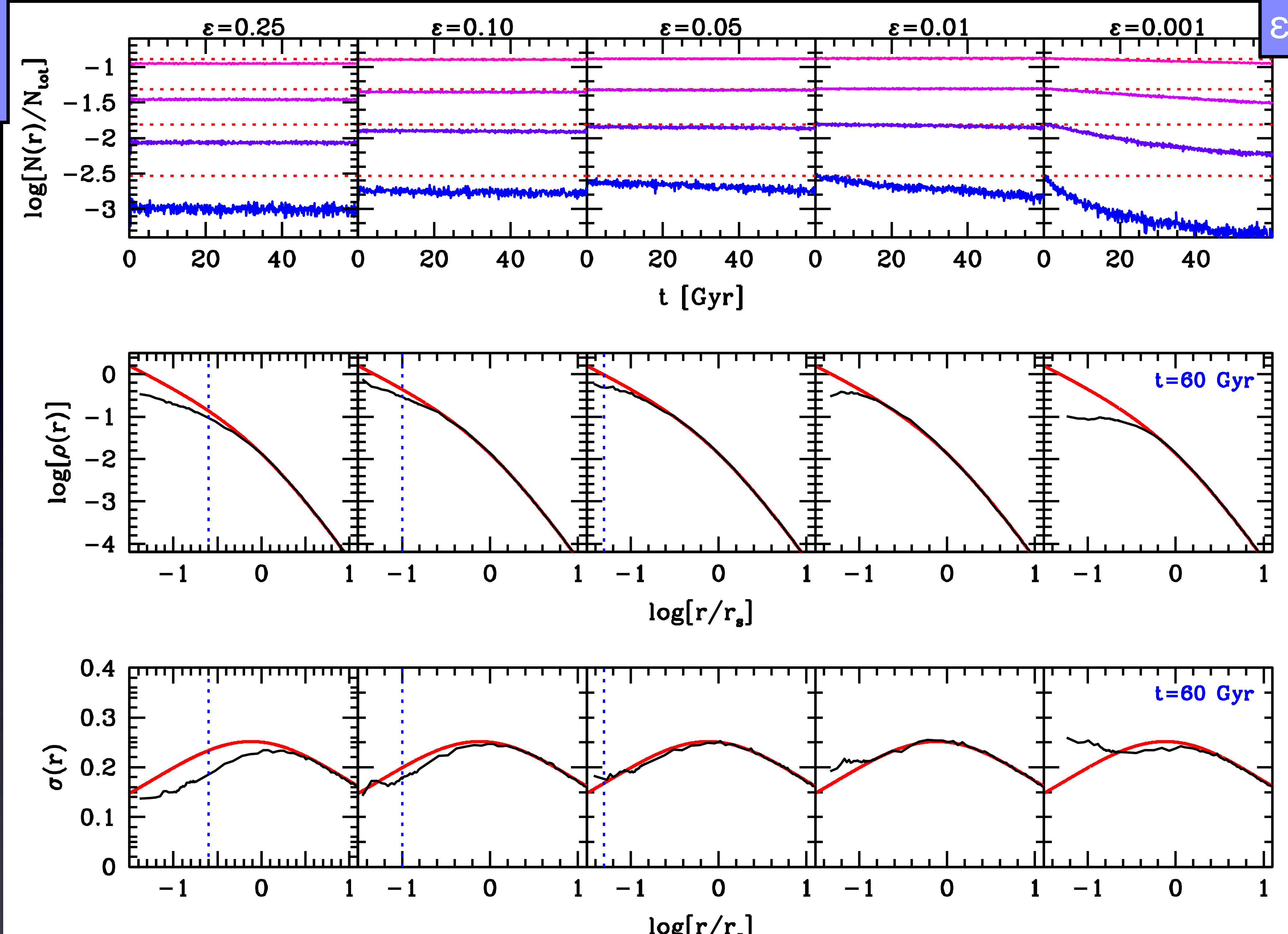
Disruption for $r_{orb} < 0.15\ r_{vir}$......or numerical artefacts?



Tuning the Softening Length

NFW halo
N=10^5

$\varepsilon_{opt} \simeq 0.05$

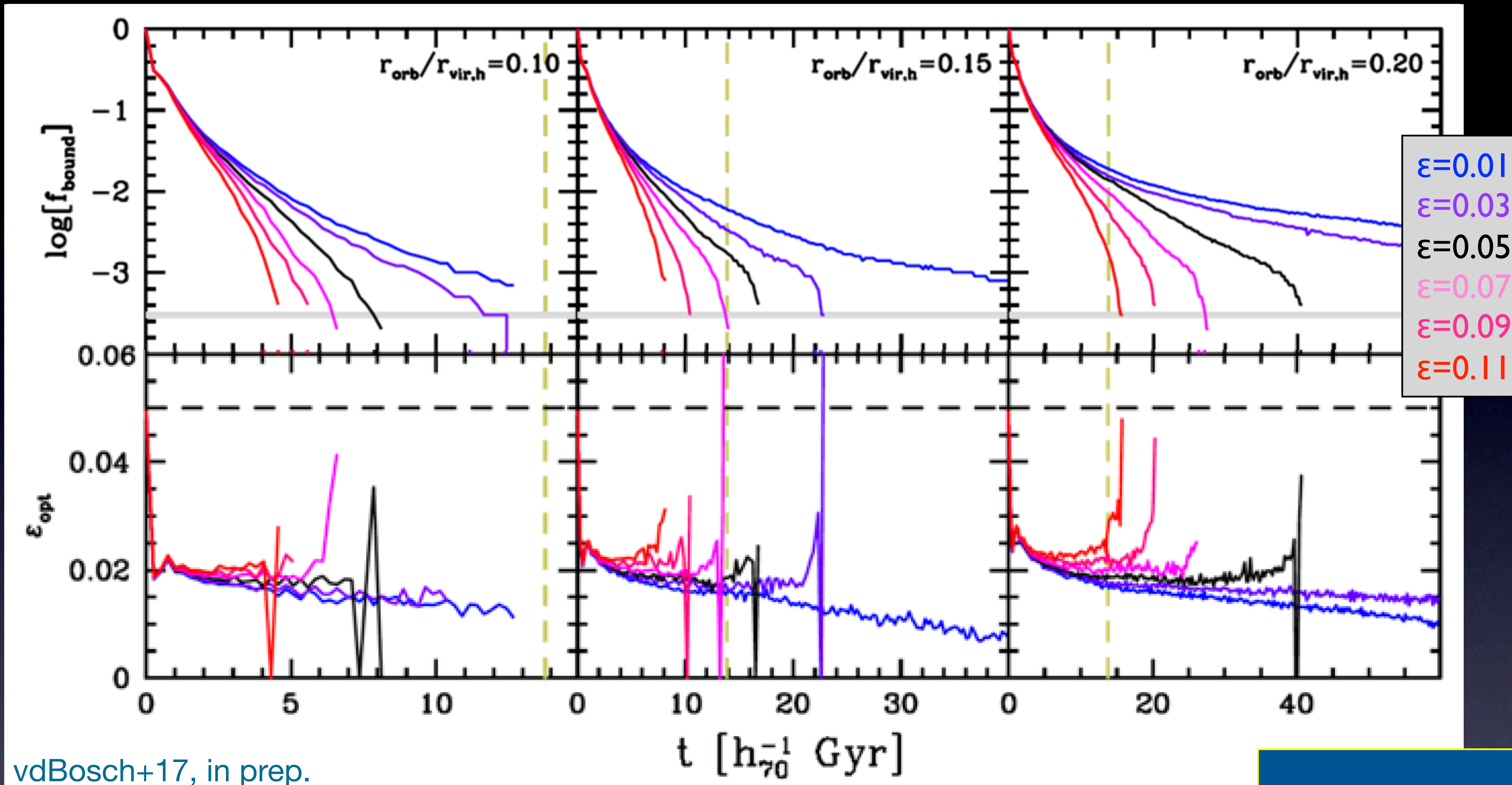


vdBosch+17, in prep.

ε too large ➢ force bias ➢ central cusp unresolved

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

Force Softening



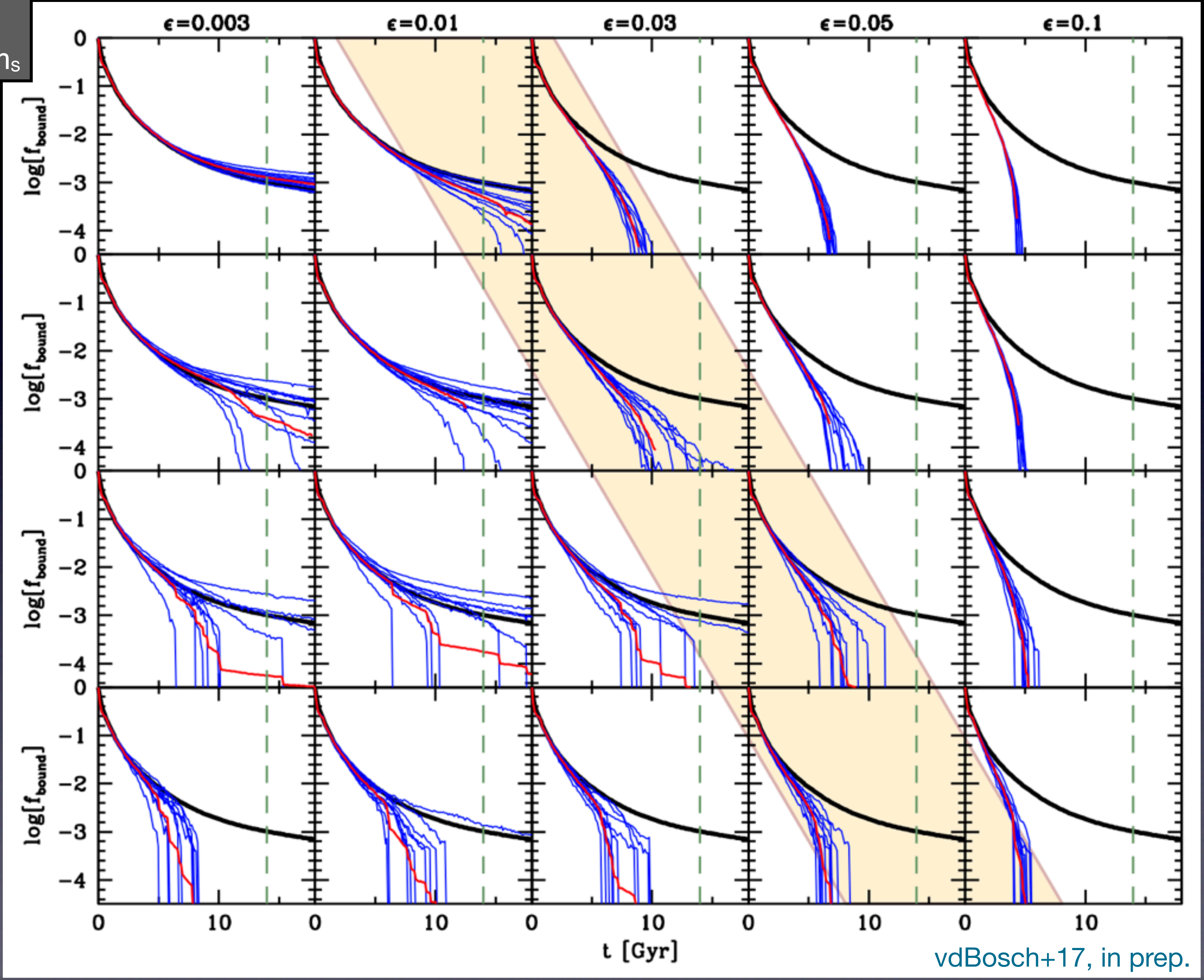
$\varepsilon_{opt} \propto r_{half}\ N^{-1/3}$

(Dehnen+01; Power+03)

- Mass evolution and disruption extremely sensitive to softening length
- As subhalo looses mass, its optimal softening length decreases

Towards Numerical Convergence

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



N=1,000,000

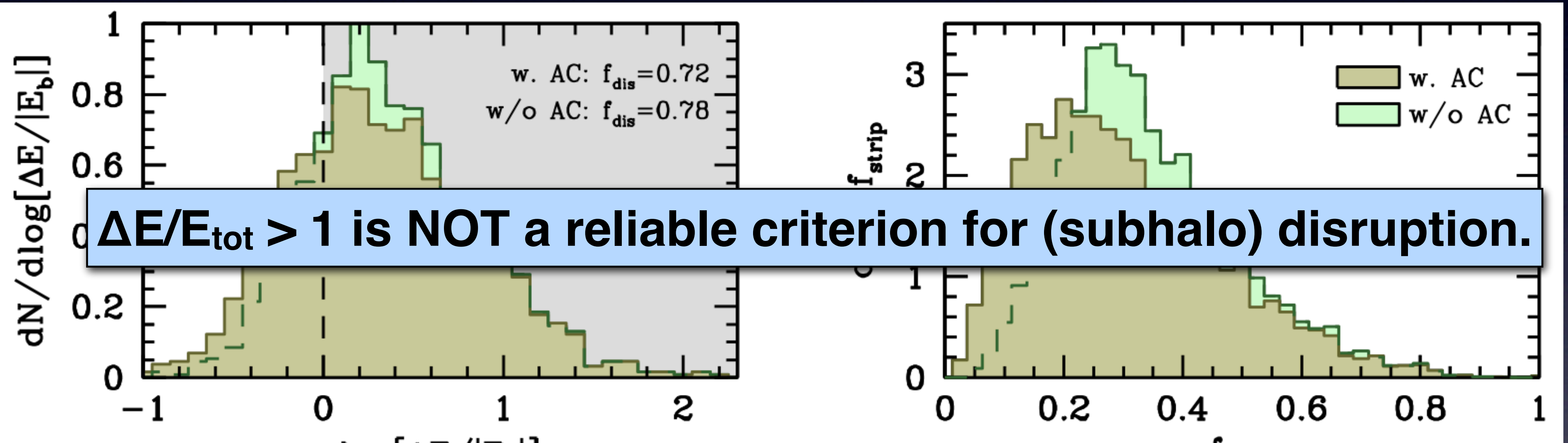
N=300,000

N=100,000

N=30,000

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.

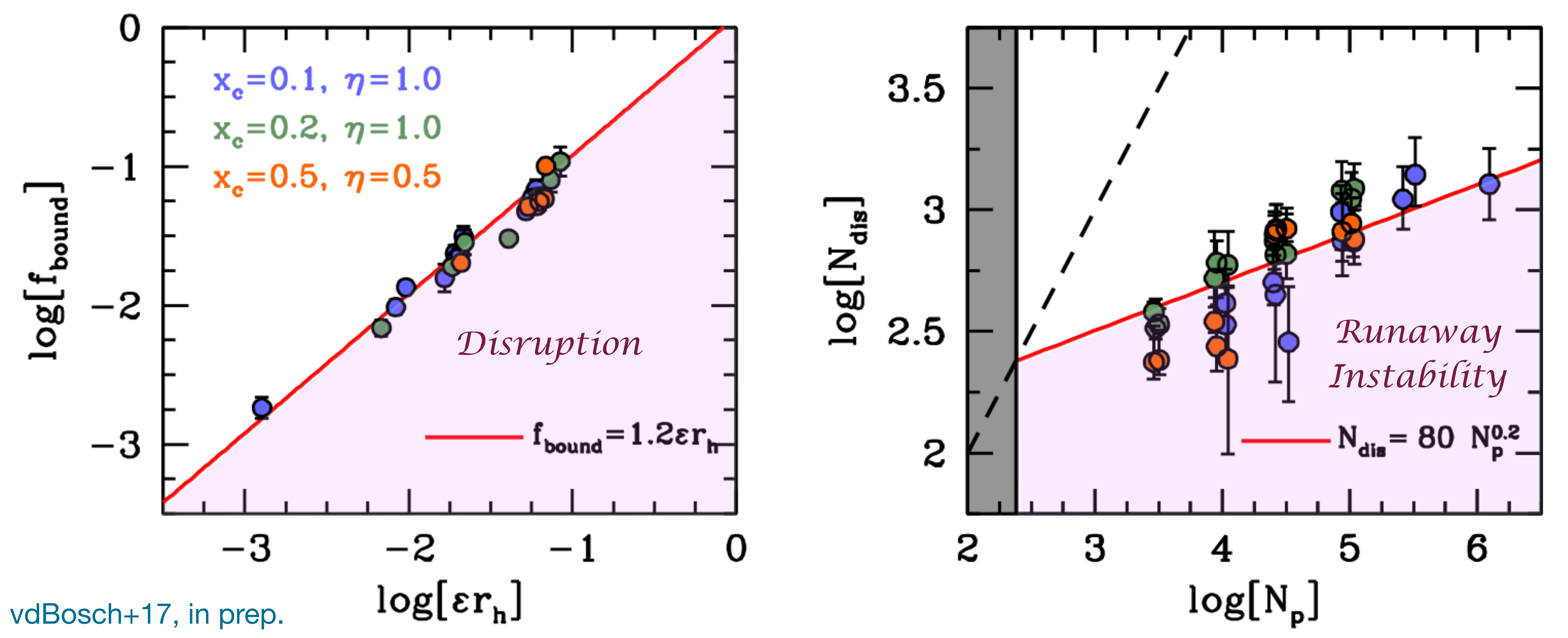
$\Delta E/E_{tot} > 1$ is NOT a reliable criterion for (subhalo) disruption.

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!!!

Numerical Criteria to Judge Reliability



- Disruption if characteristic acceleration drops below central acceleration: $a_{\rm char}/a_0 < 1.2$

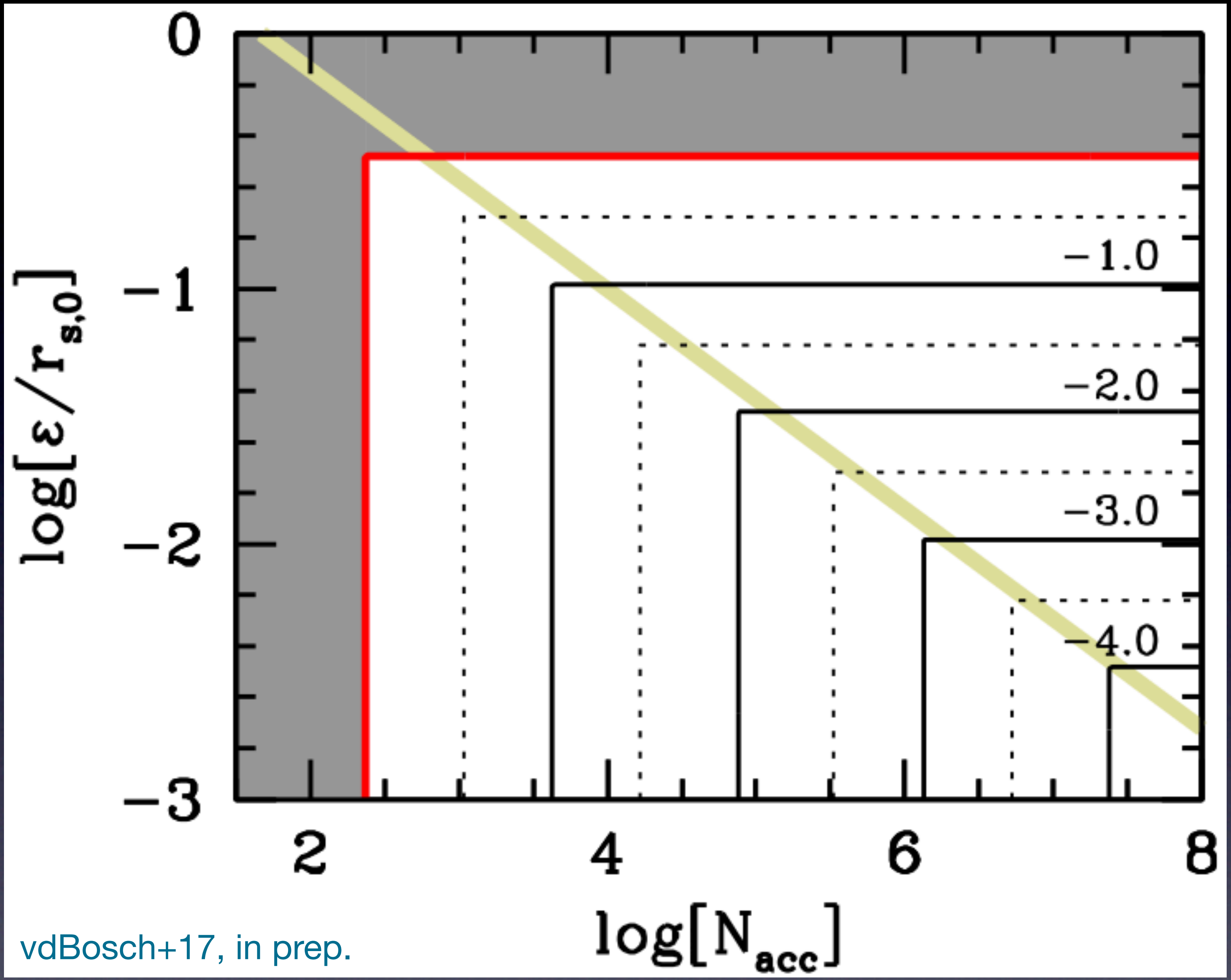
$$a_0 = \lim_{r\downarrow 0} \frac{G\,M(r)}{r^2} \qquad a_{\rm char} = \frac{G\,M(r_{\rm h})}{\varepsilon\, r_{\rm h}}$$

(Power+03)

- Discreteness driven runaway instability kicks in when |dN/dt| > 100/$\tau_{\rm dyn}$

  For average subhalo mass loss rate this implies $N < 80\, N_{\rm acc}^{0.2}$

Numerical Requirements



Resolving the tidal evolution of a subhalo down to f_{bound}=0.01 (0.001) requires N_{acc} ~ 10^5 (10^6) and a softening length ε ~ (0.03) 0.01 r_s

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 (~1/5 of that for isolated halos)

- We lack proper analytical models to describe subhalo evolution ...all we have are numerical simulations....

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)
  - Use adaptively-refined phase-space element method, rather than N-body method (e.g., Hahn & Angulo 16)
  - Characterize shortcomings of N-body simulations, and complement simulation results with semi-analytical model.

Related Papers

- *Dissecting the evolution of dark matter subhaloes in the Bolshoi simulation*
  van den Bosch F., 2017, MNRAS, 468, 885

- *Disruption of Dark Matter Substructure: Fact of Fiction?*
  van den Bosch F., Ogiya G., Hahn O., Burkert A., 2017, MNRAS, submitted

- *Dark Matter Substructure in Numerical Simulations: A Tale of Discreteness Noise, Runaway Instabilities and Artificial Disruption*
  van den Bosch F., Ogiya G., 2017, MNRAS, submitted