The Tidal Disruption of Dark Matter Substructure: Fact or Fiction?

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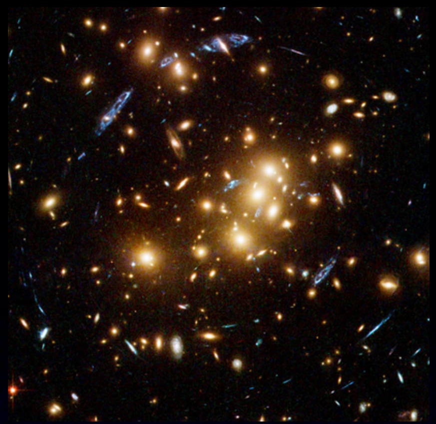
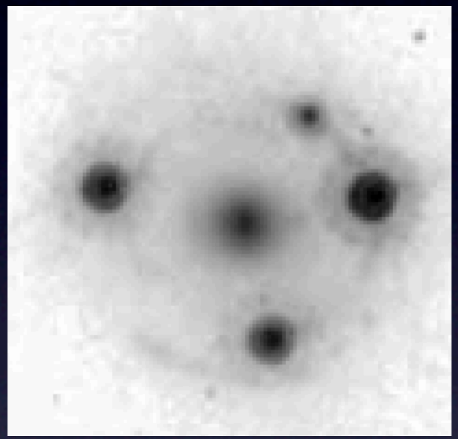
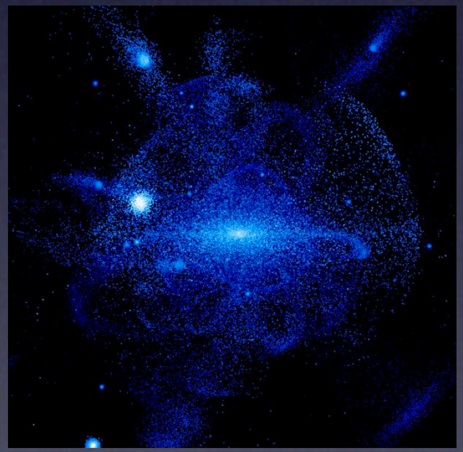
Why do we care about substructure



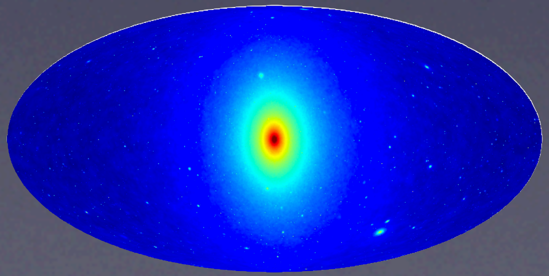
Halo Occupation Modeling:
subhaloes host satellite galaxies



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

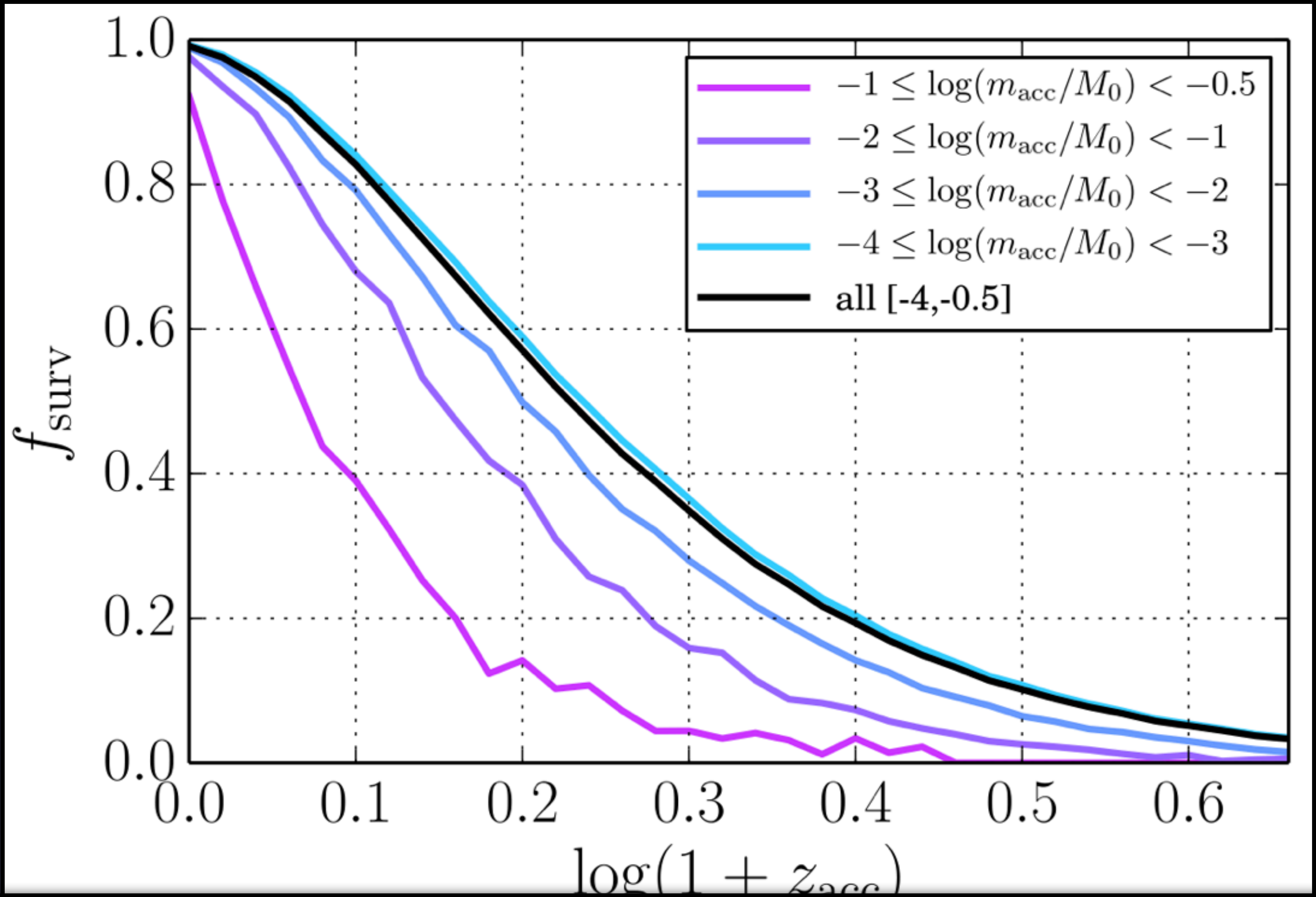


Subhaloes can heat stellar disks and tidal streams



Subhaloes boost dark mattter annihilation signal

Subhalo Disruption in Bolshoi



Jiang & vdB, 2016

Disruption Mechanisms

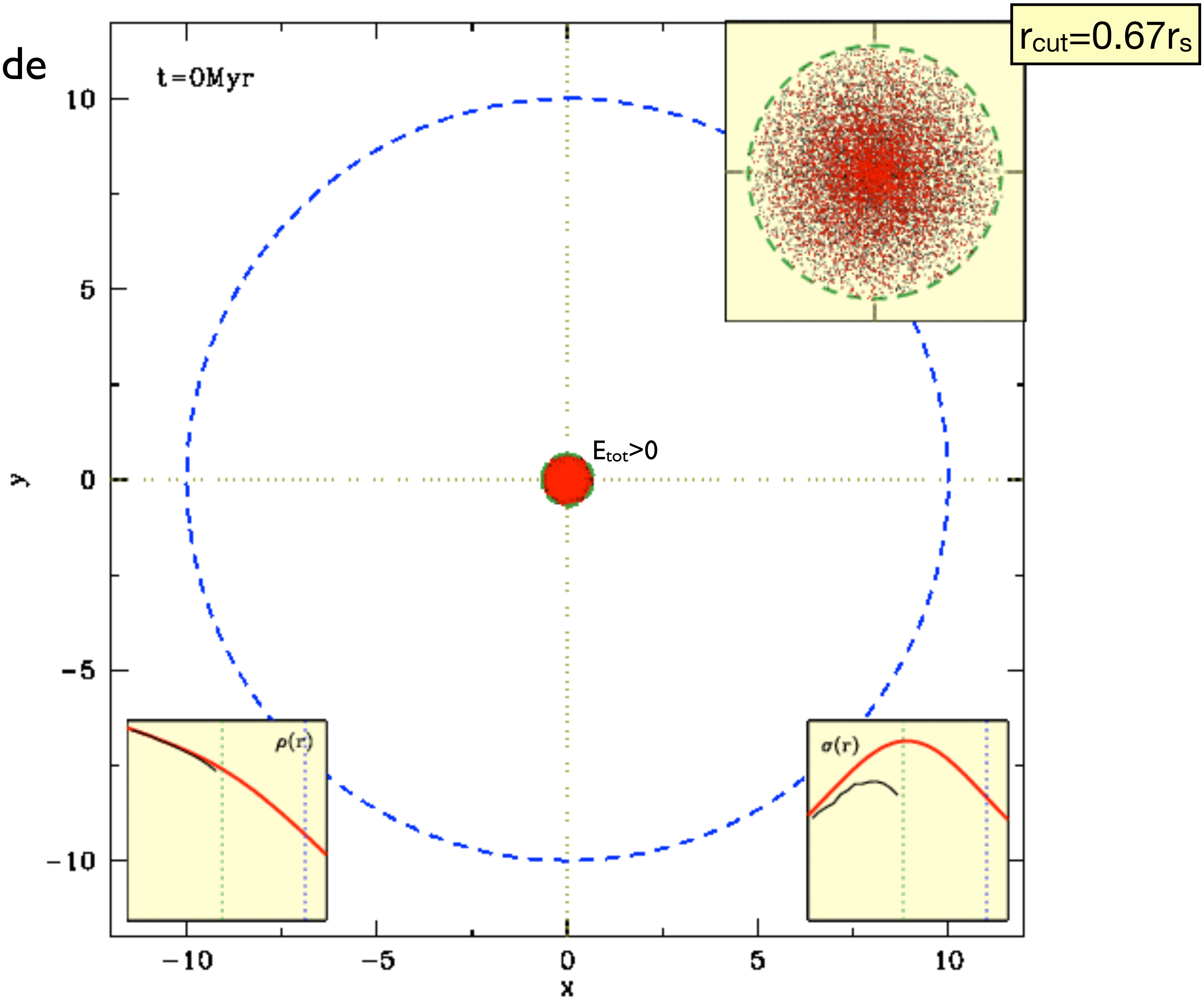
- Tidal Stripping
- Tidal Heating
  - Pericentric Passage
  - Subhalo-Subhalo Encounter
- Numerical overmerging

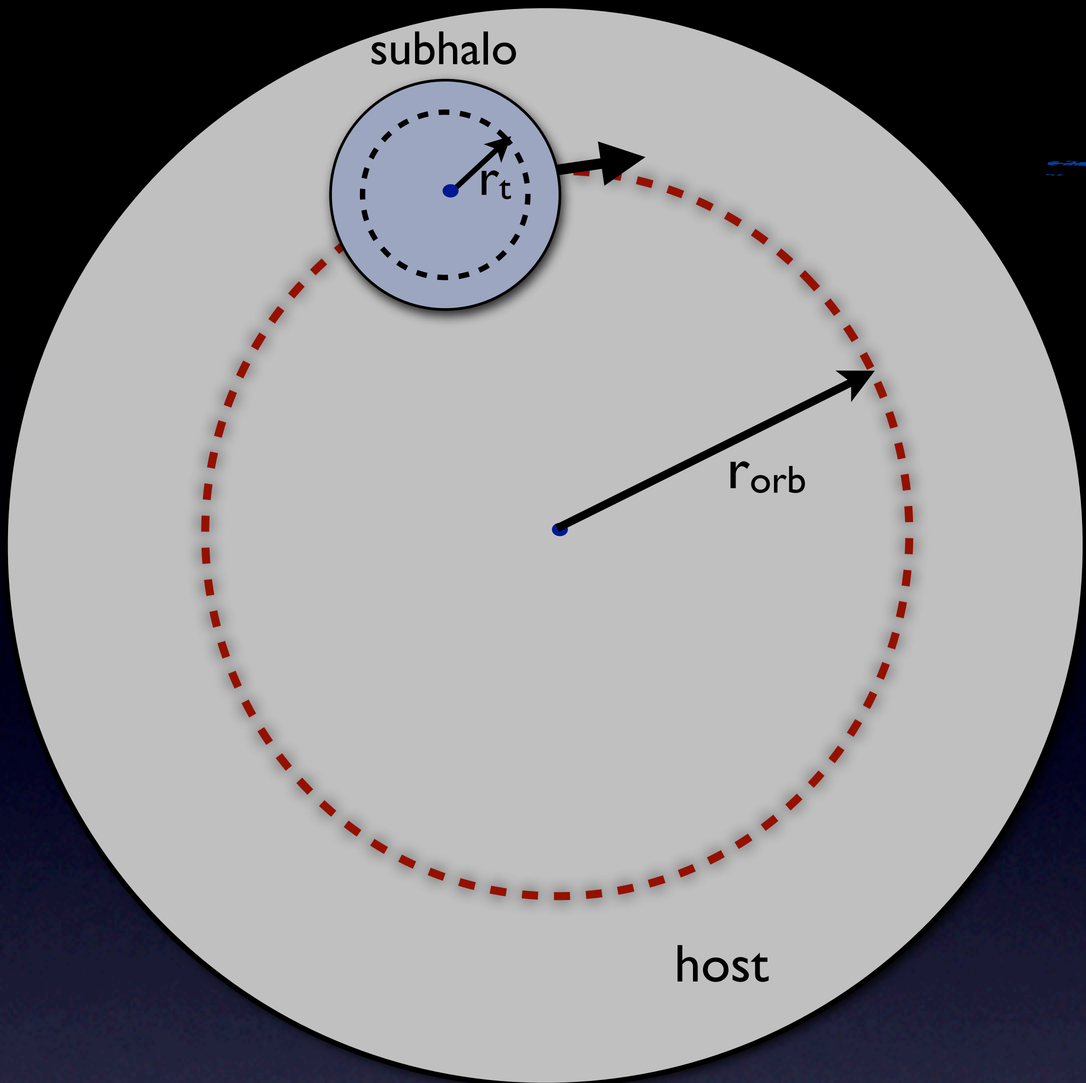
Does Stripping cause Disruption?

- 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





Numerical Simulations

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

- No impulsive (tidal) heating
- No dynamical friction

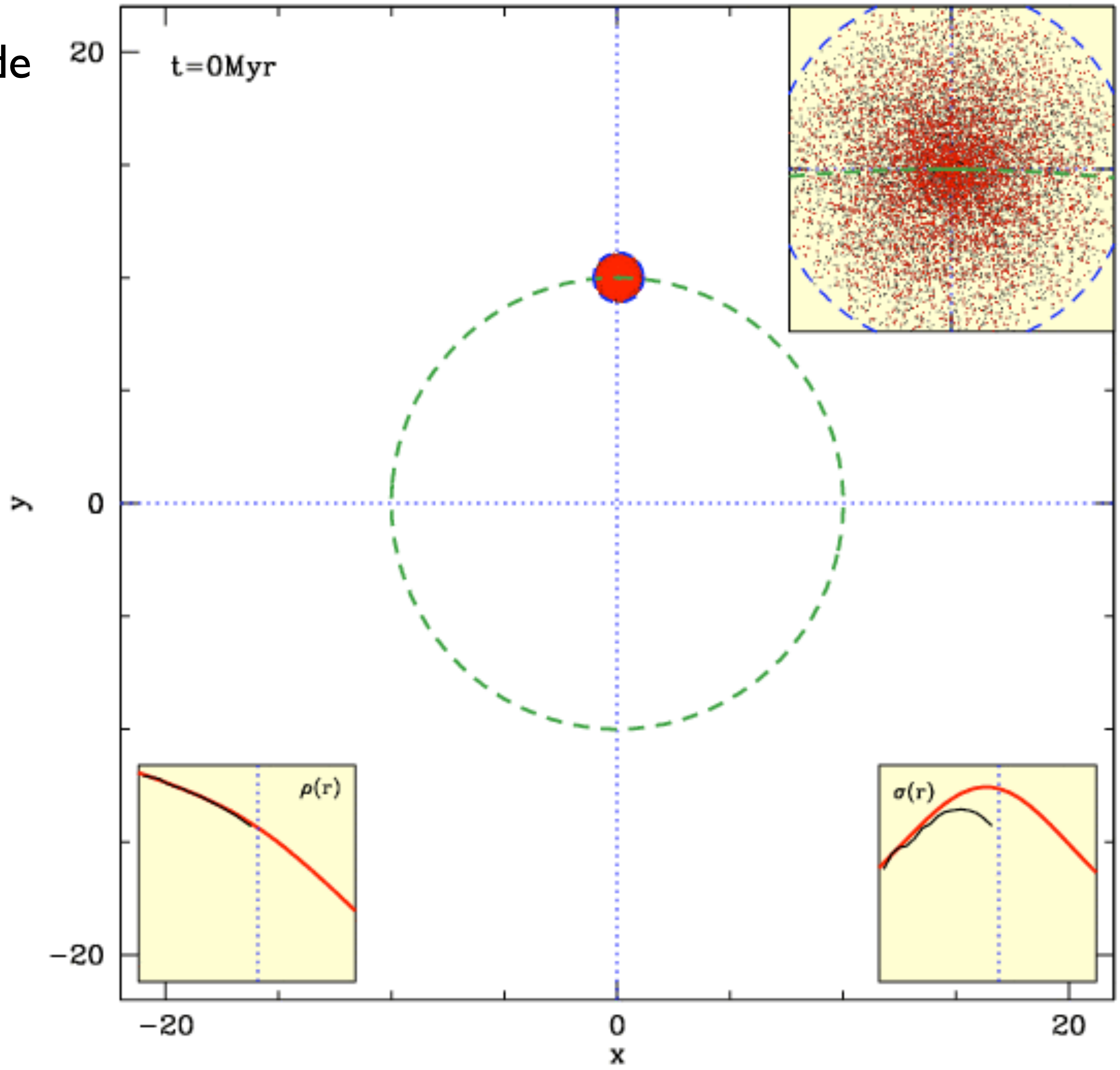
Naive Prediction:

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...

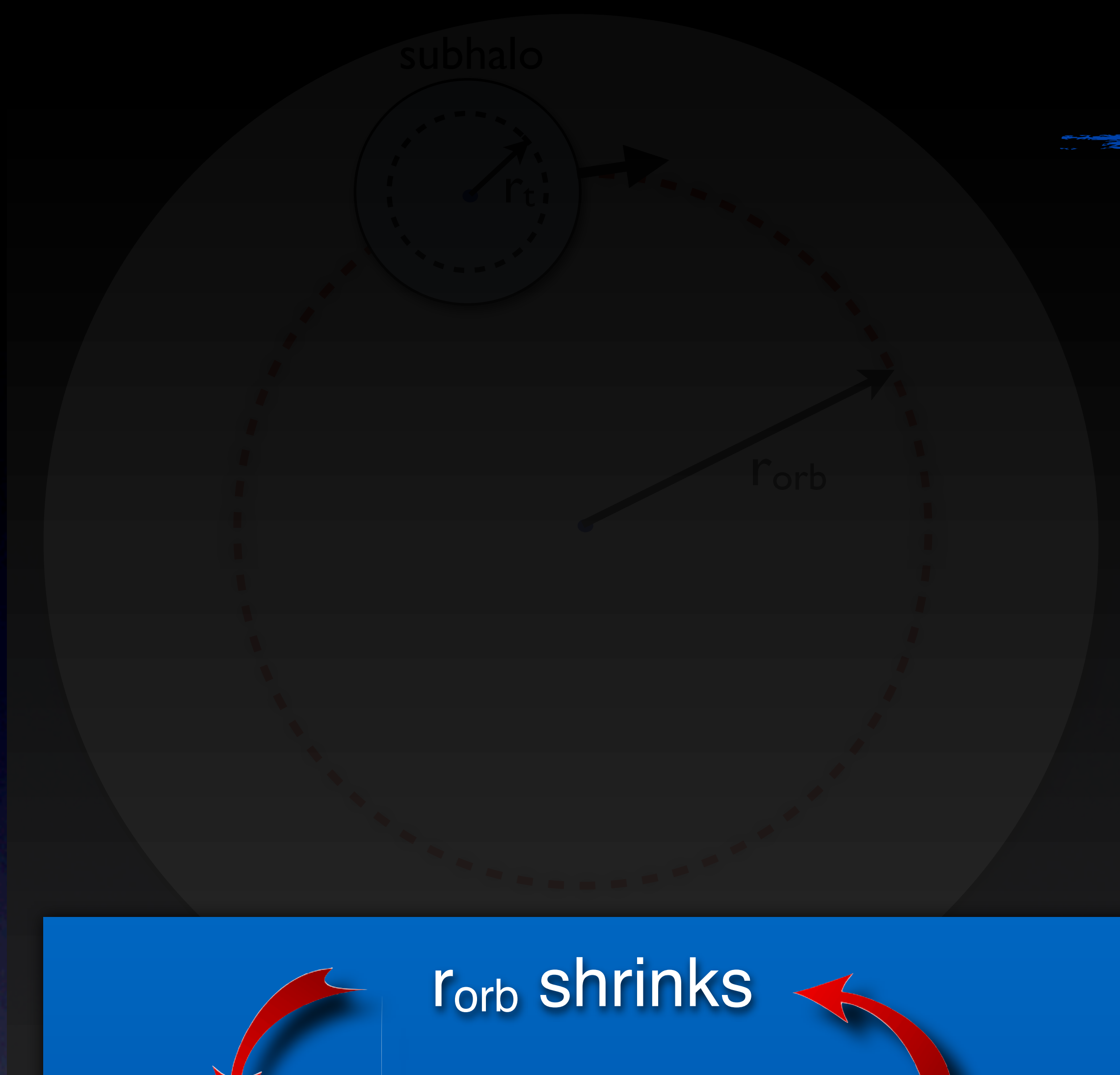
$N=10^5$
tree-code



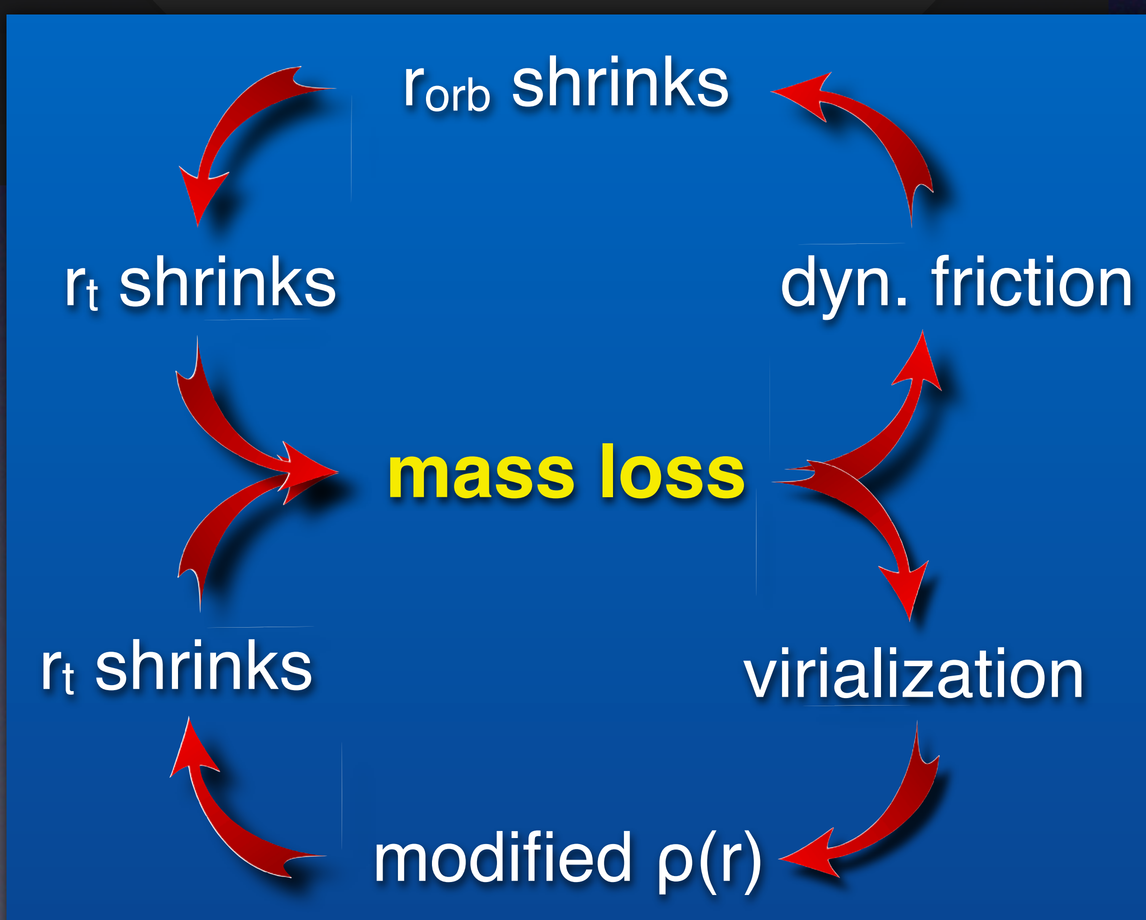
$r_{orb}=0.1\ r_{vir,h}$

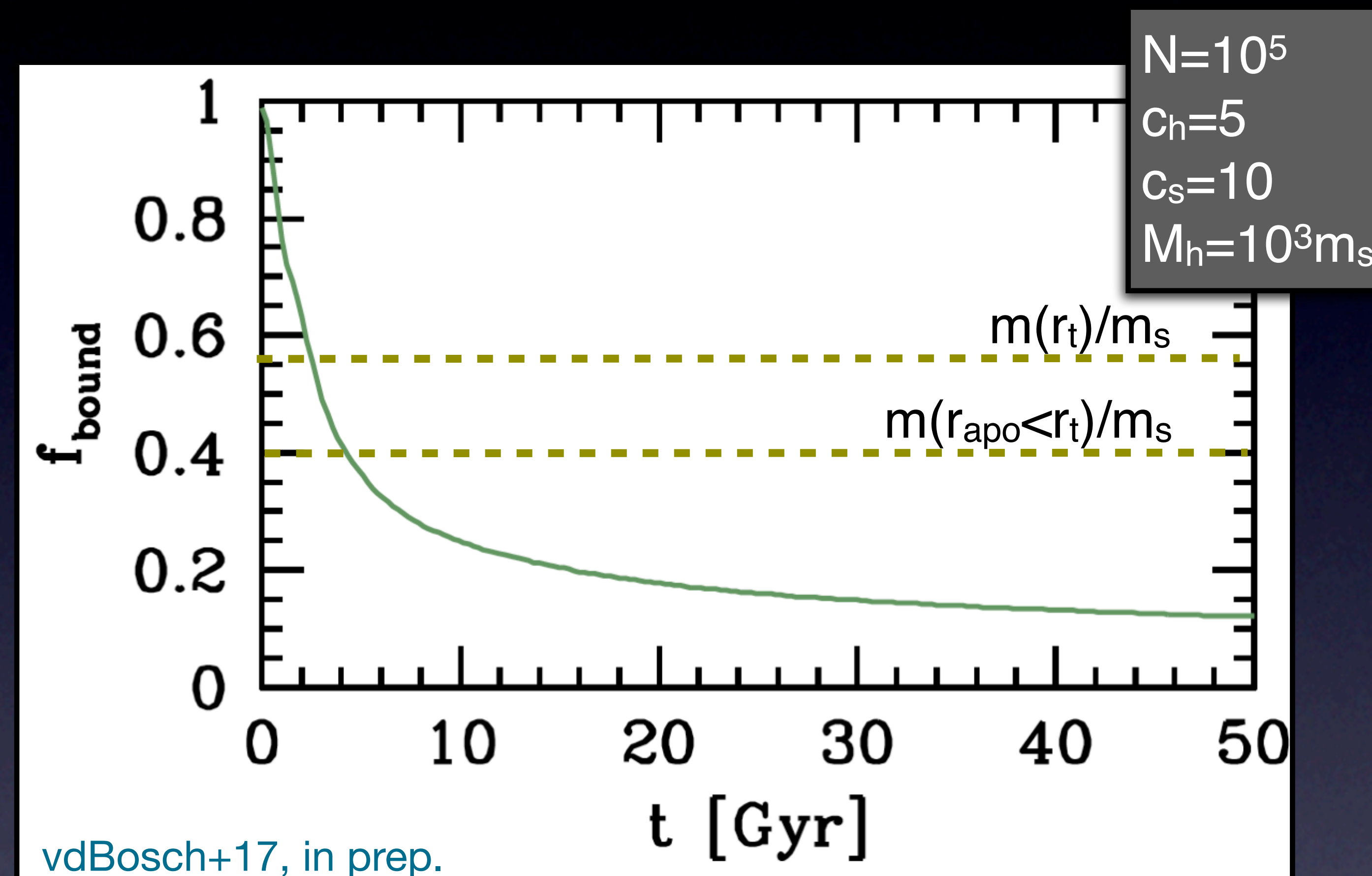
$r_t=0.11\ r_s$

Numerical Simulations



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

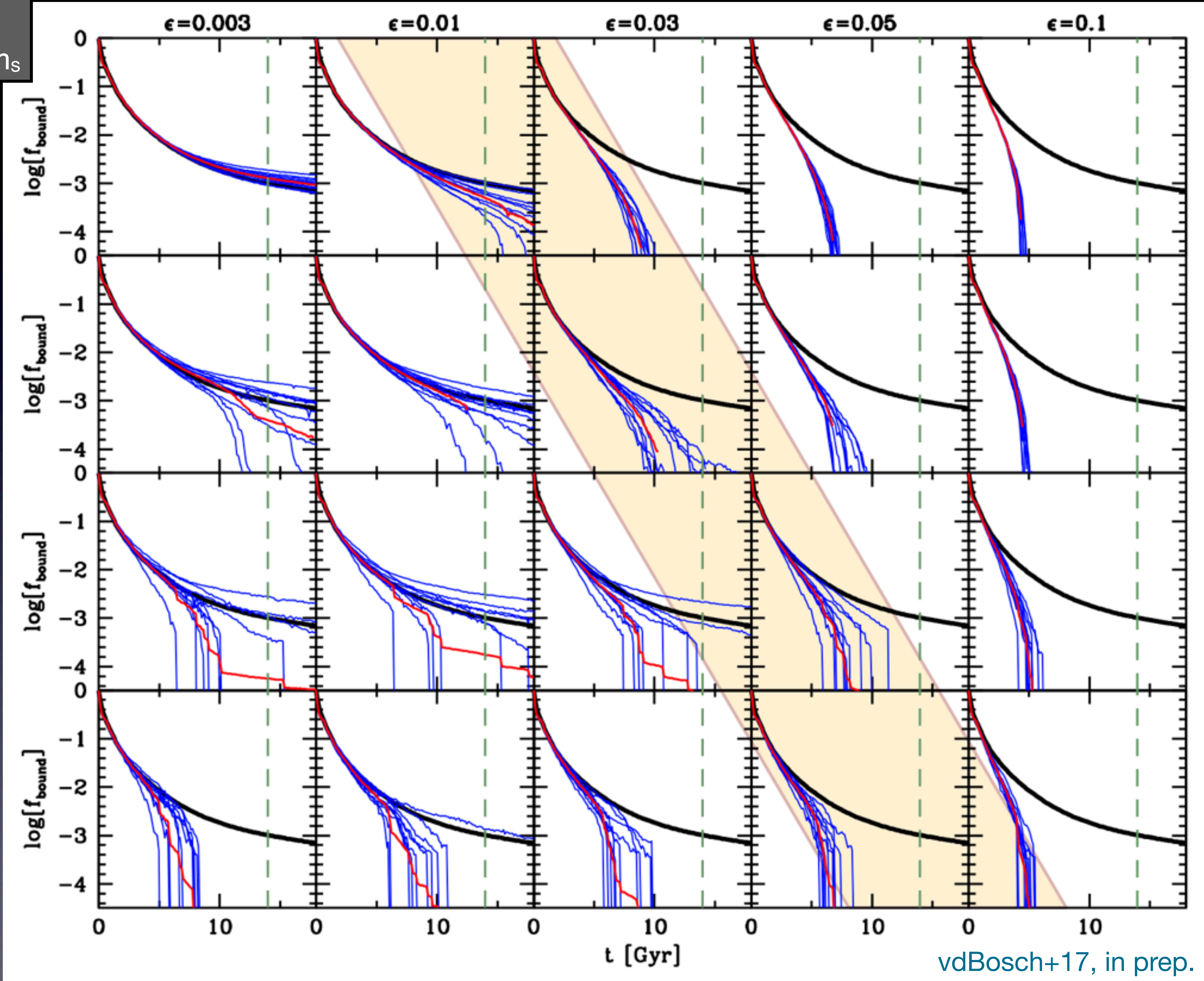




- Analytical predictions fail to predict amount of mass stripped
- Mass loss continues for >50 Gyr

Towards Numerical Convergence

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

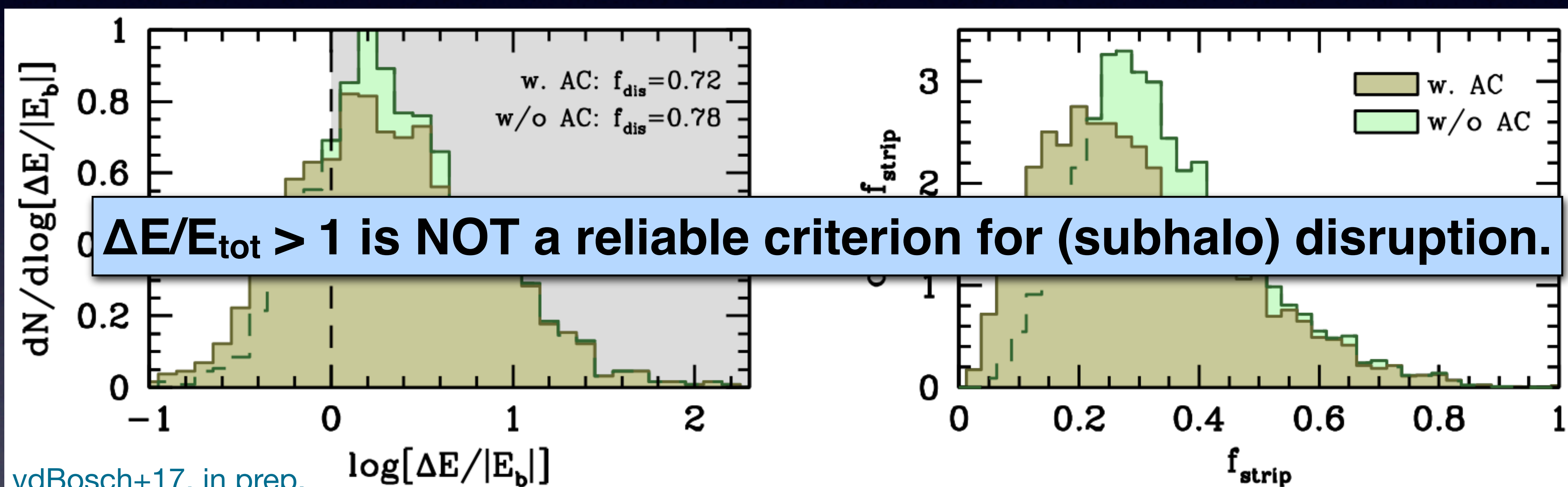


N=1,000,000
N=300,000
N=100,000
N=30,000

vdBosch+17, in prep.

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 $f_{bound} = f(\Delta E_i/E_i < 1)$



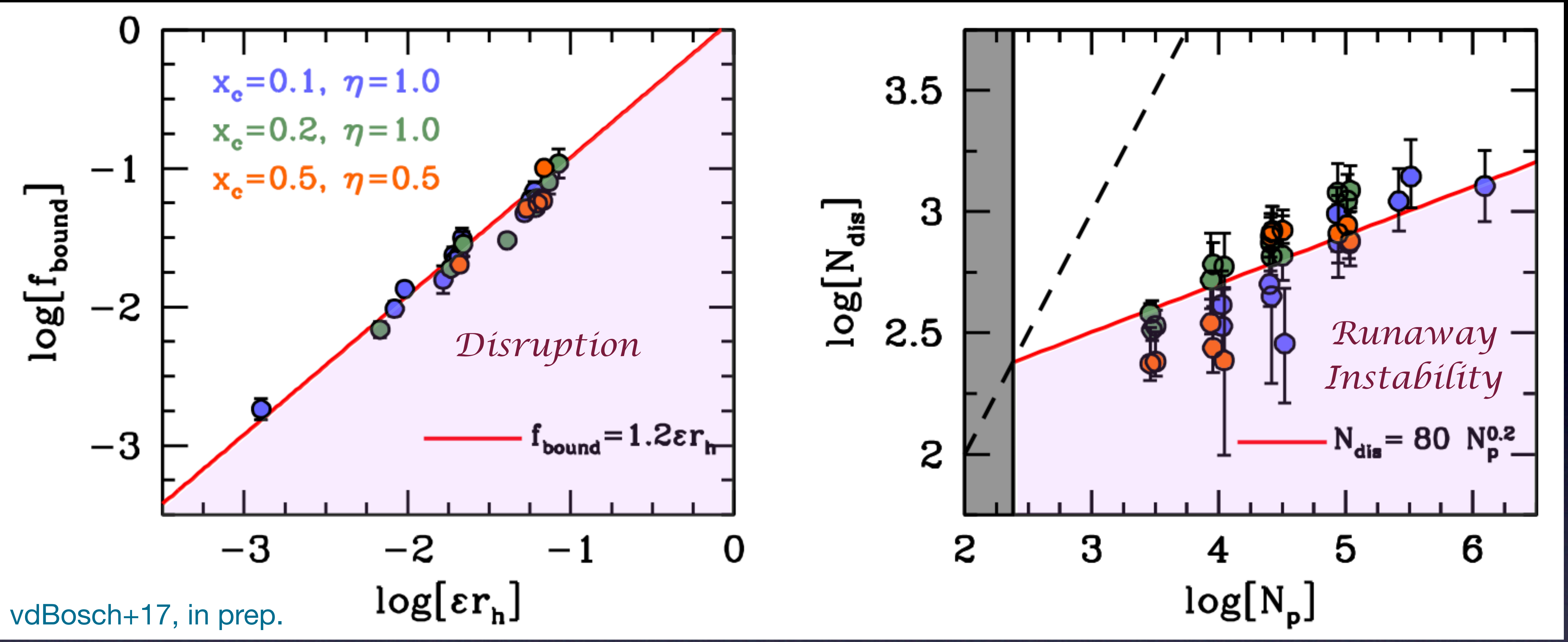
$\Delta E/E_{tot} > 1$ is NOT a reliable criterion for (subhalo) disruption.

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 $N < 80\, N_{\rm acc}^{0.2}$

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)

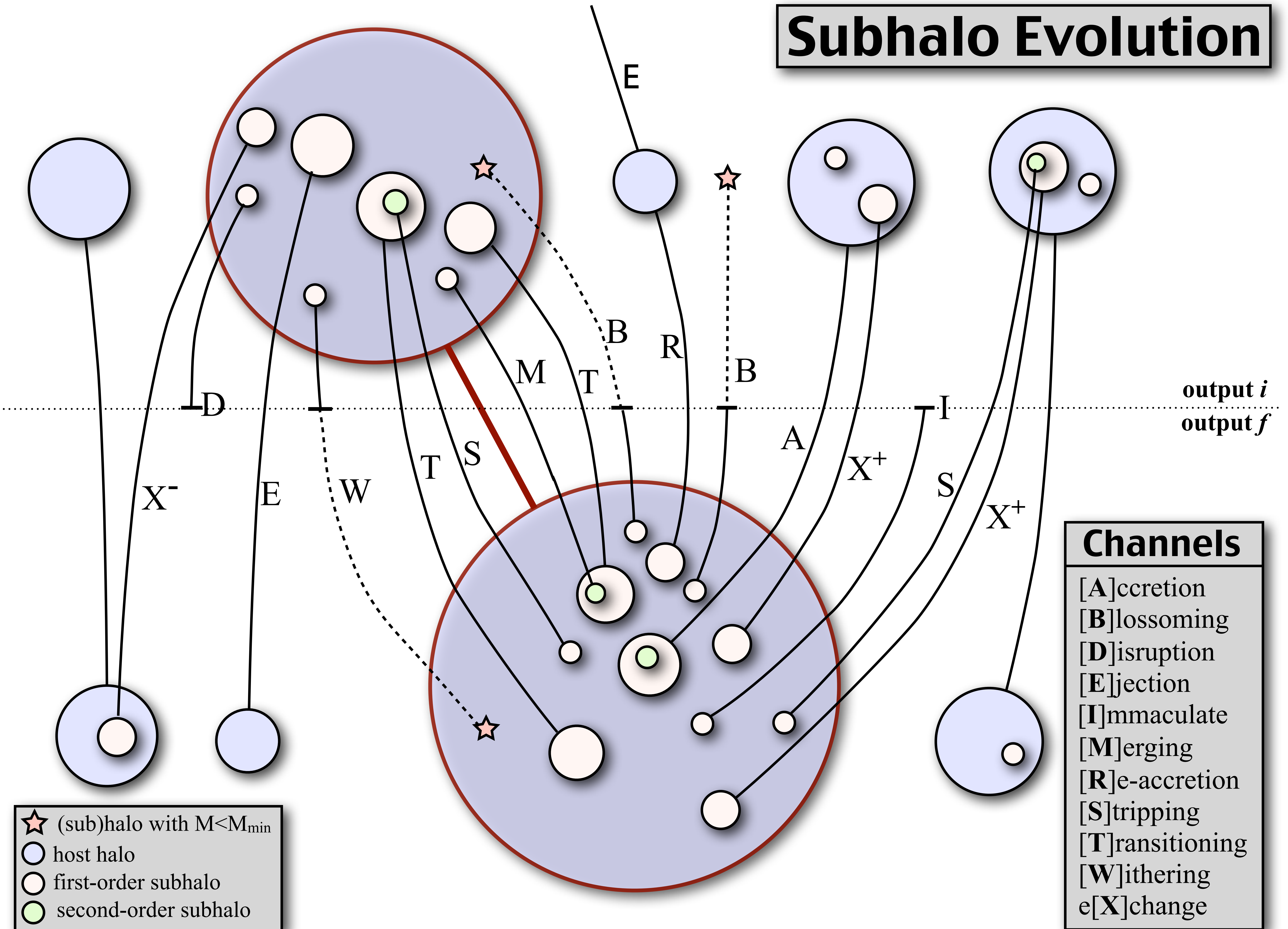
- ★ Current generation of cosmological simulations still suffers from severe overmerging.
  - serious road-block for small-scale cosmology program
  - serious road-block for understanding galaxy formation

Related Papers

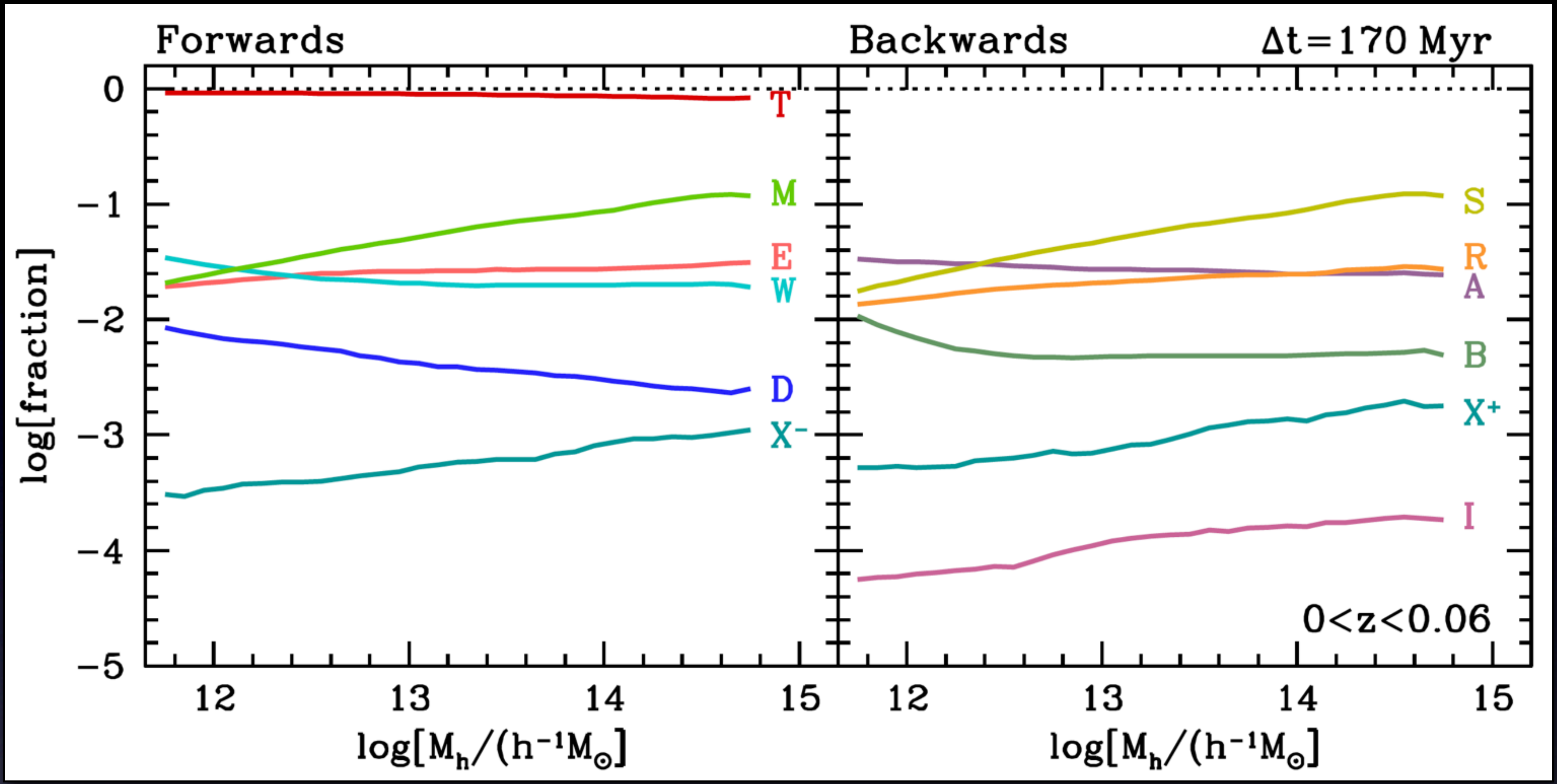
- *Dissecting the evolution of dark matter subhaloes in the Bolshoi simulation*
  van den Bosch F., 2017, MNRAS, 468, 885

- *Disruption of Dark Matter Substructure: Fact of Fiction?*
  van den Bosch F., Ogiya G., Hahn O., Burkert A., 2017, MNRAS, in press
  (arXiv:1711.05276)

- *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


Subhalo Evolution
E
B
R
B
M
T
output i
output f
D
I
A
X+
S
T
S
W
E
X-
S
X+
Channels
[A]ccretion
[B]lossoming
[D]isruption
[E]jection
[I]mmaculate
[M]erging
[R]e-accretion
[S]tripping
[T]ransitioning
[W]ithering
e[X]change
(sub)halo with M<Mmin
host halo
first-order subhalo
second-order subhalo

The Relative Importance of Evolution-Channels

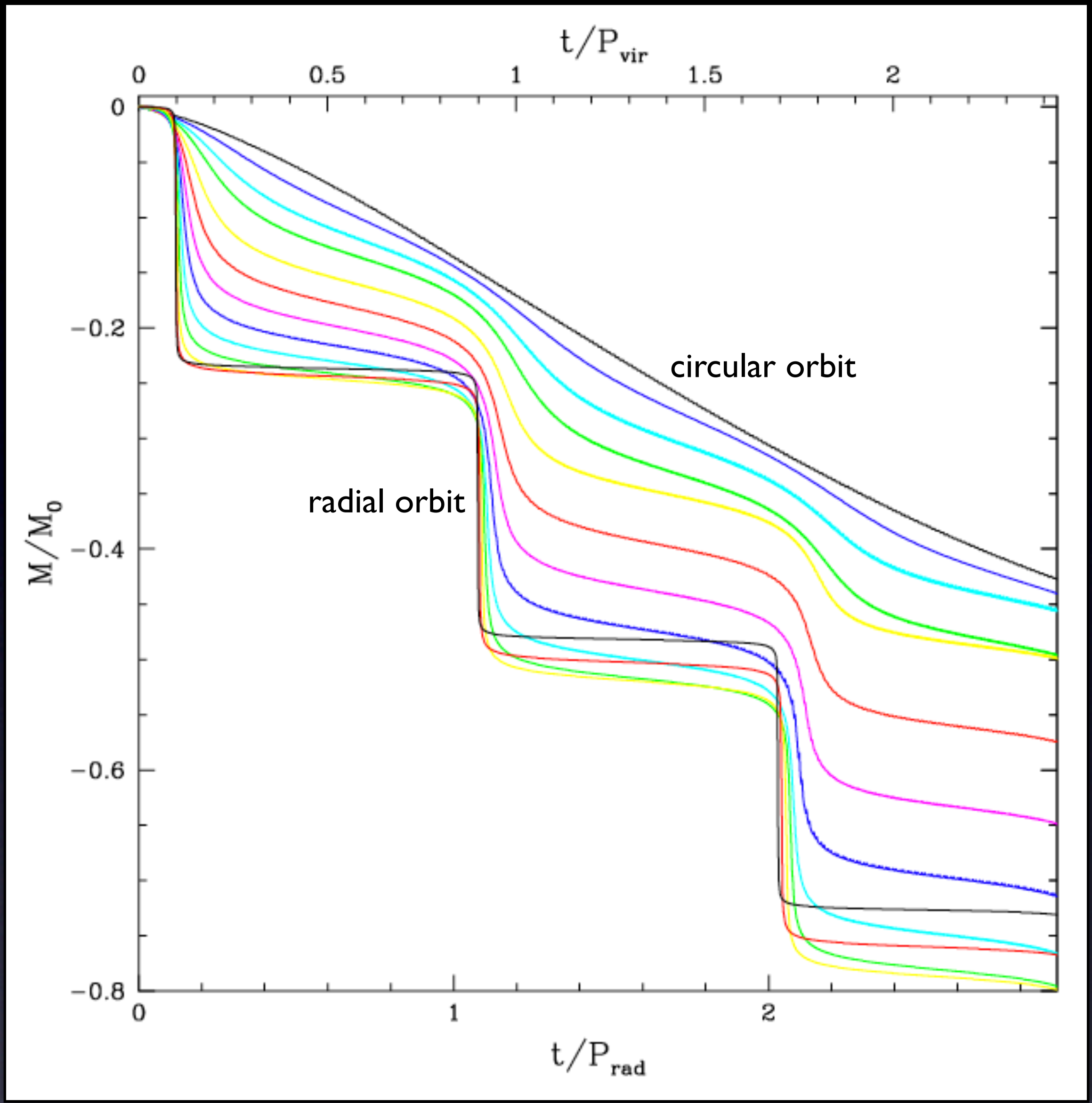


van den Bosch, 2016

- ★ Stripping of higher-order subhalos is dominant addition channel
- ★ Re-accretion gain roughly balanced by ejection loss (R ≈ -E)
- ★ Exchange gain roughly balanced by exchange loss ($X^+ \approx -X^-$)
- ★ Accretion gain roughly balanced by withering loss (A ≈ -W)

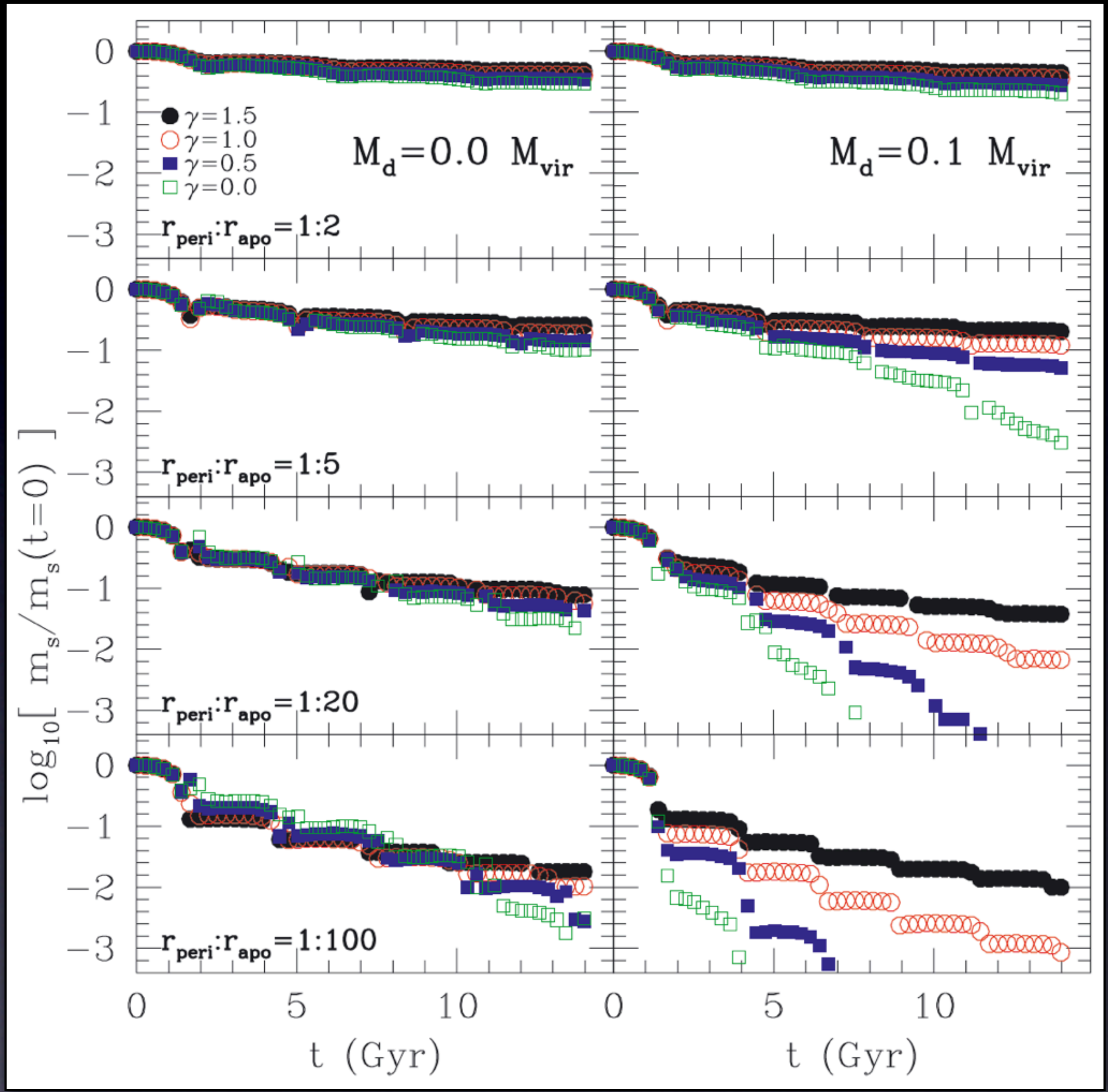
The Mass Evolution of Dark Matter Subhaloes

Analytical Model with Orbit Integration



Taylor & Babul, 2004

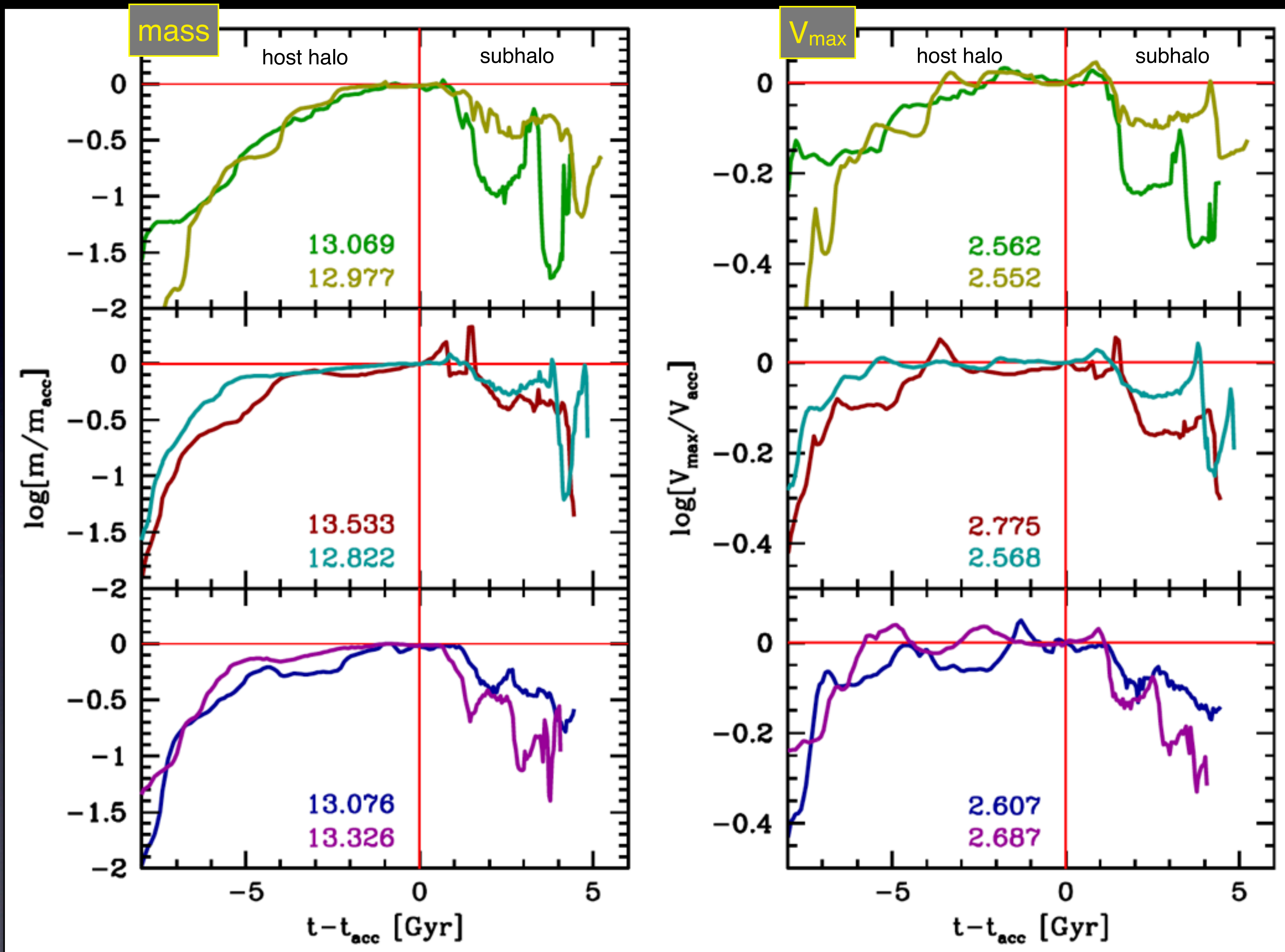
Idealized Simulation of NFW halo in fixed potential



Penarrubia et al. 2010

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

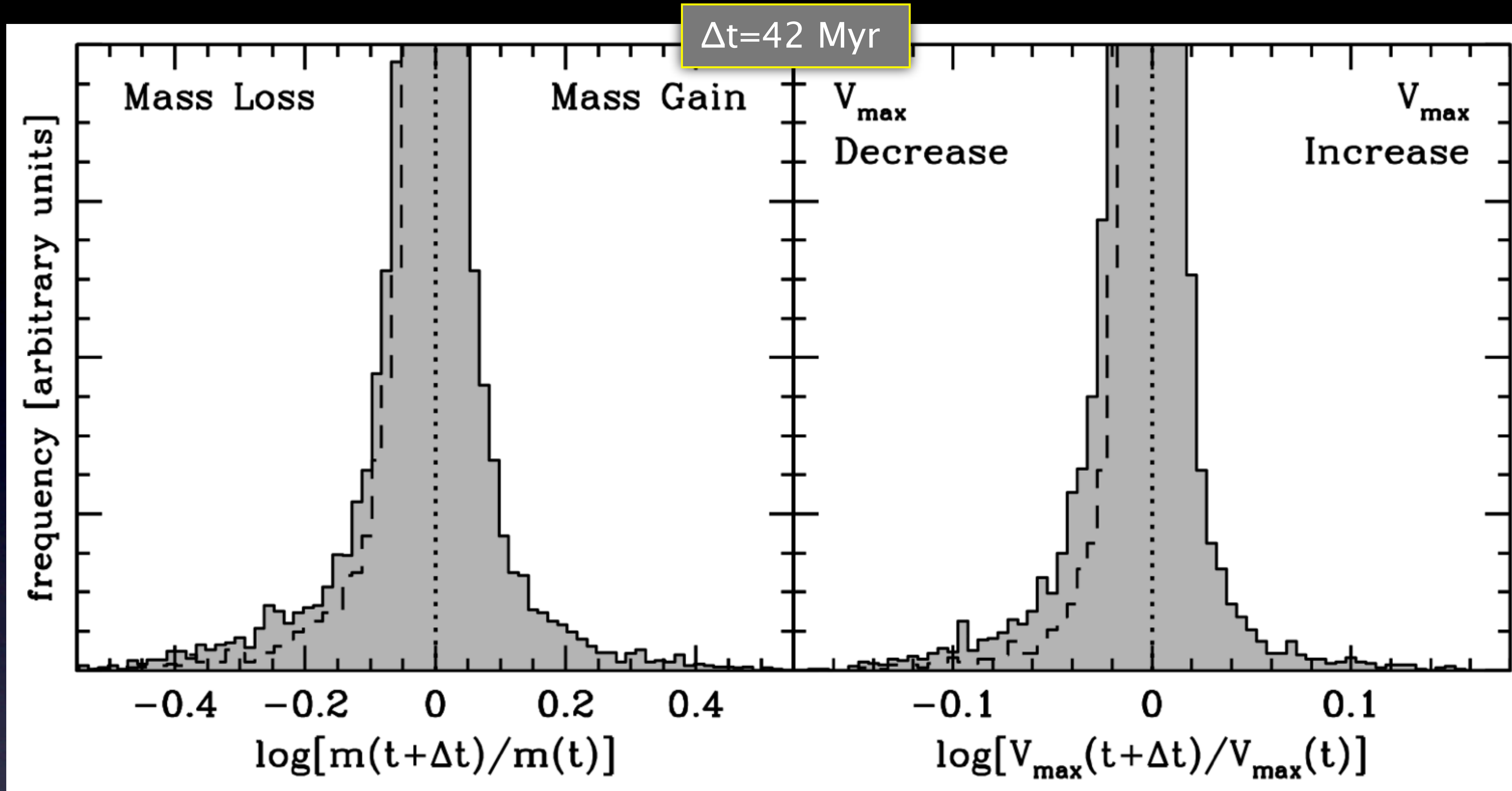
Bolshoi Simulation: Mass and V_{max} histories



Based on Bolshoi + Rockstar

van den Bosch, 2016

Mass and V_{max} histories

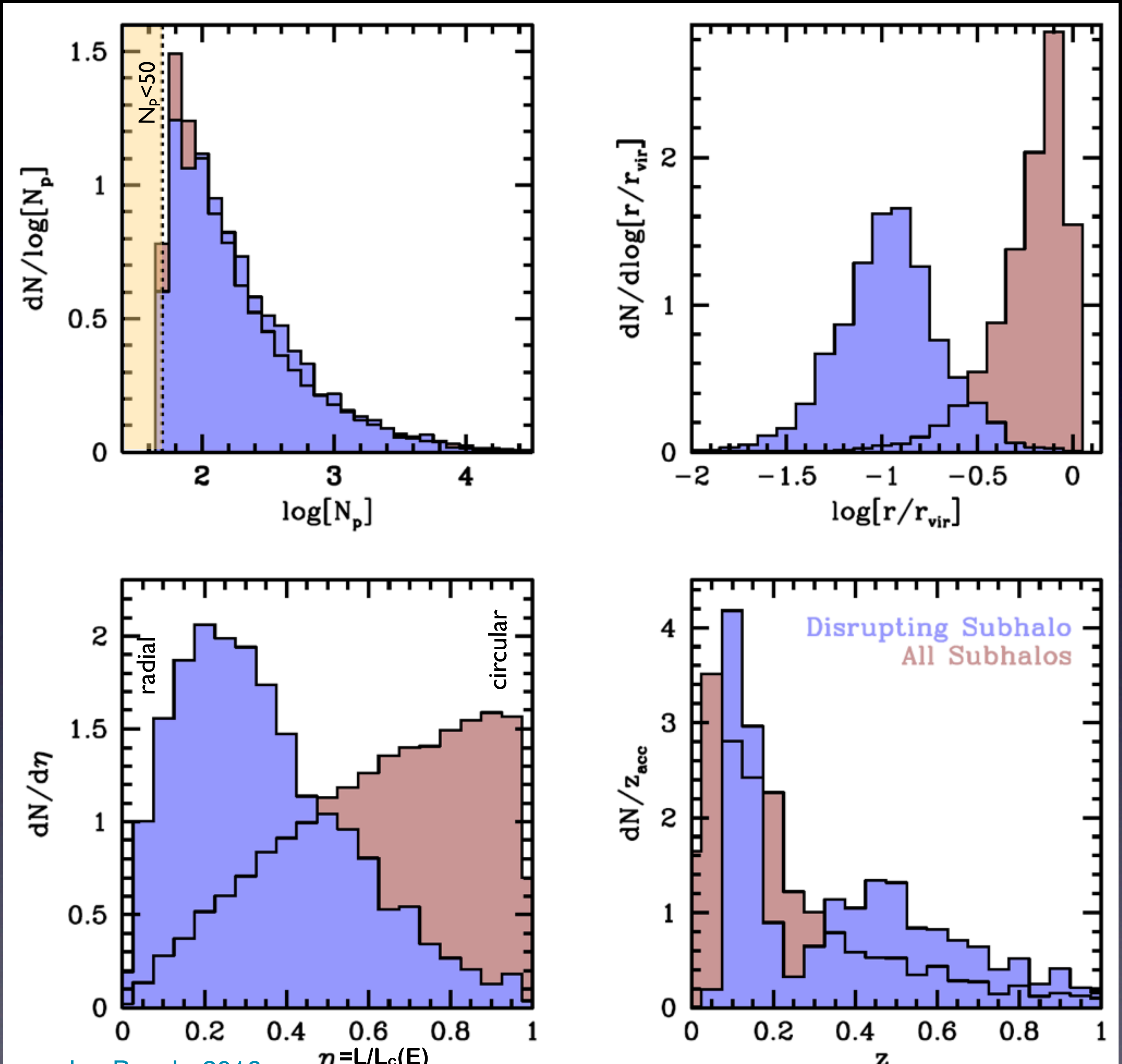


Based on Bolshoi + Rockstar

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

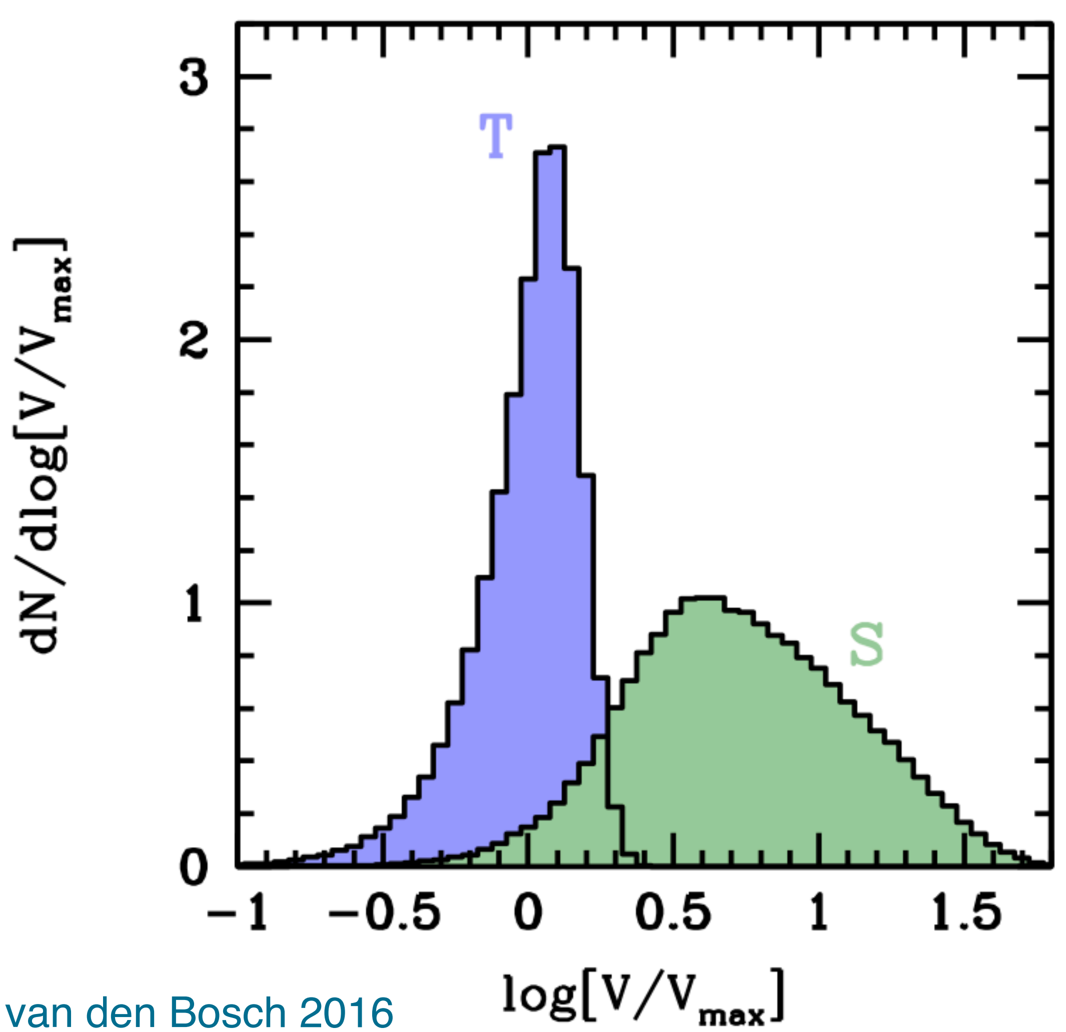
Disruption occurs preferentially:
- at small halo-centric radii
- along more radial orbits,
- at first or second pericentric passage.

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

What causes this disruption???

Based on Bolshoi + Rockstar

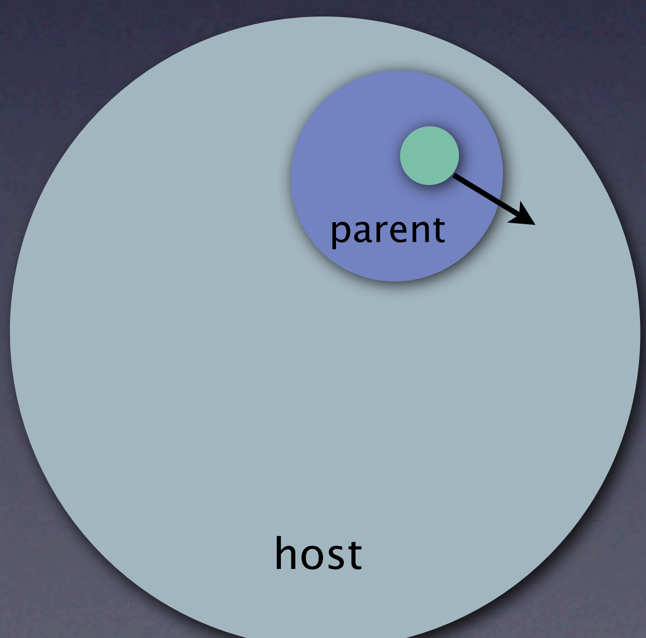
Stripping & Merging Channels



van den Bosch 2016

Subhalos in S(tripping) channel have velocity wrt parent sub-halo that is 3-10x larger than V_{max} of parent.

S(tripping) and M(erging) correspond to high-speed (impulsive) penetrating encounters among subhaloes

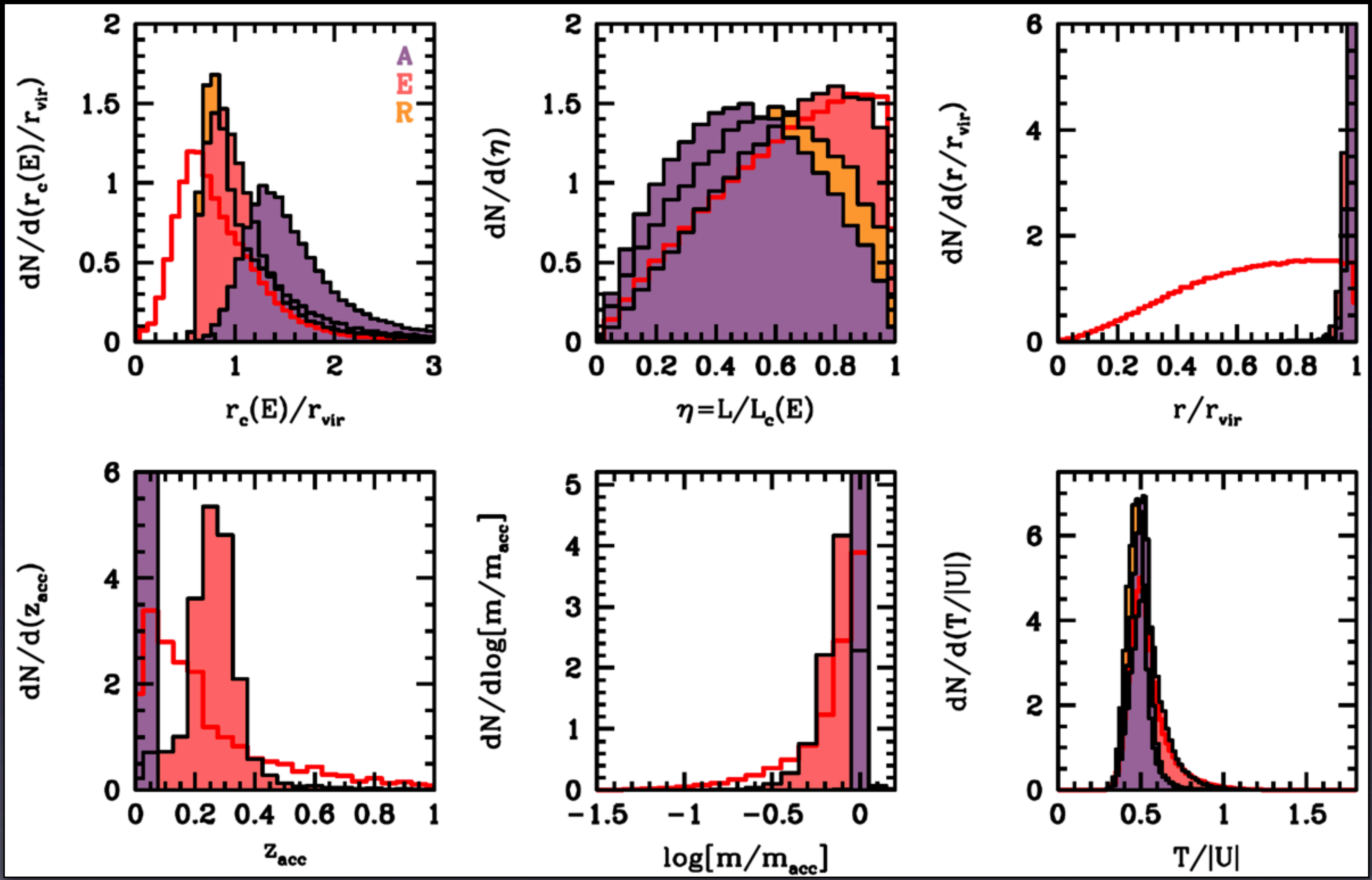


Rate of penetrating encounters with more massive subhalos

$$\mathcal{R}_{\rm enc} = (0.33 \pm 0.04){\rm Gyr}^{-1}\, M_{12}^{0.1} \left(\frac{m_{\rm min}/M}{10^{-4}}\right)^{-0.23}$$

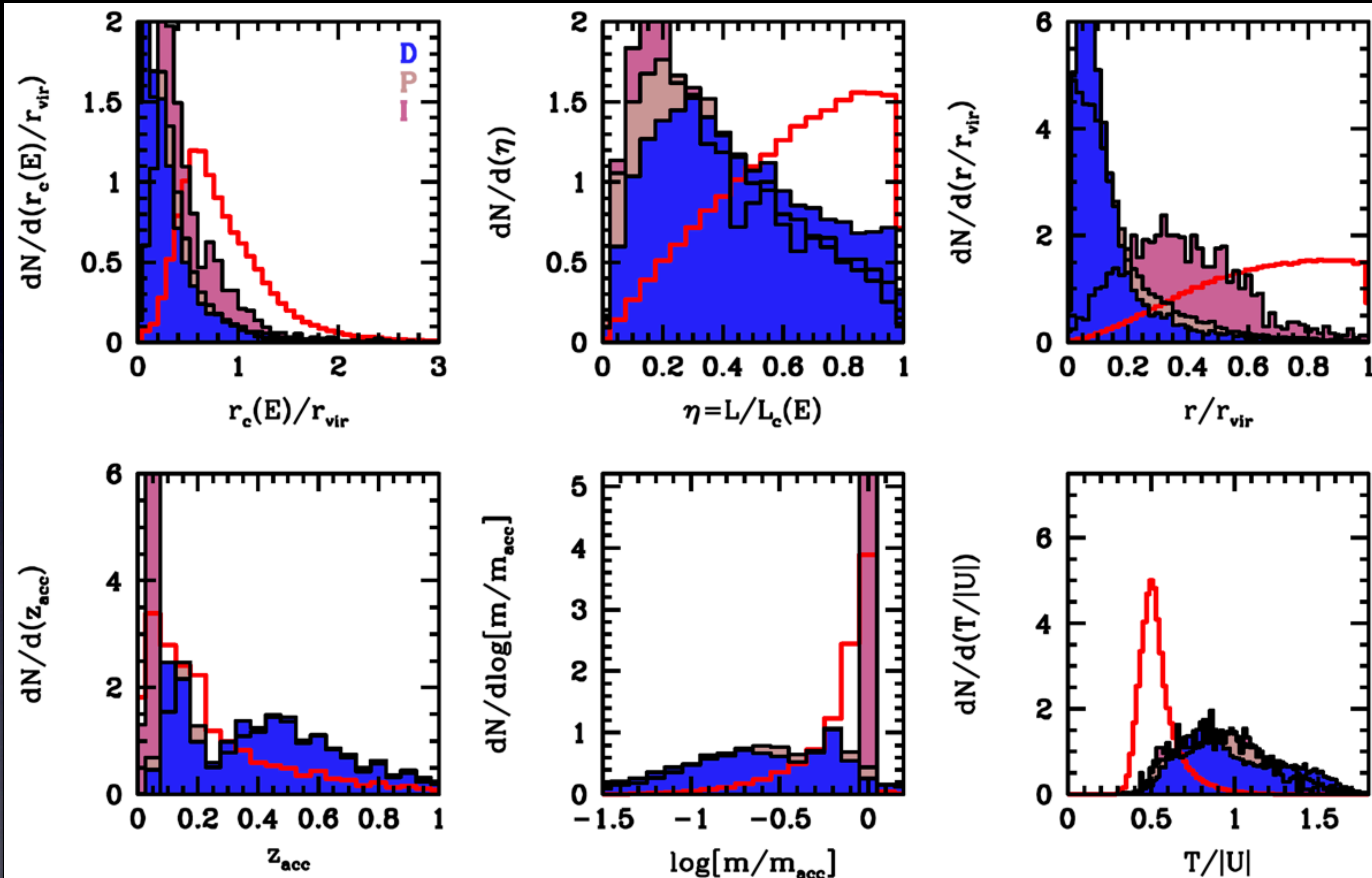
Typical subhalo experience roughly one penetrating encounter per dynamical time

Demographics of Accretion & Ejection



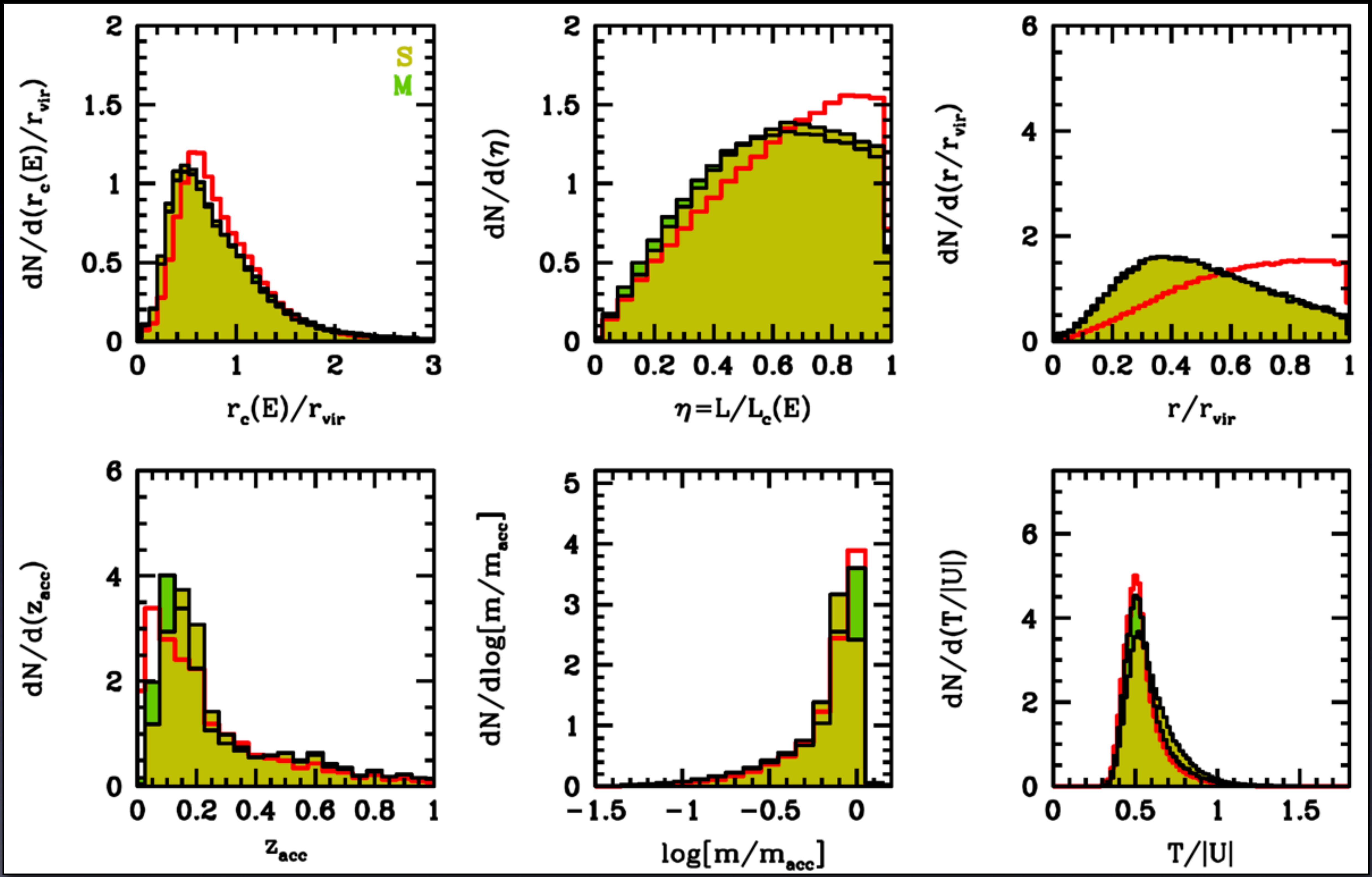
vdB & Jiang, 2016, in prep

Disruption Demographics



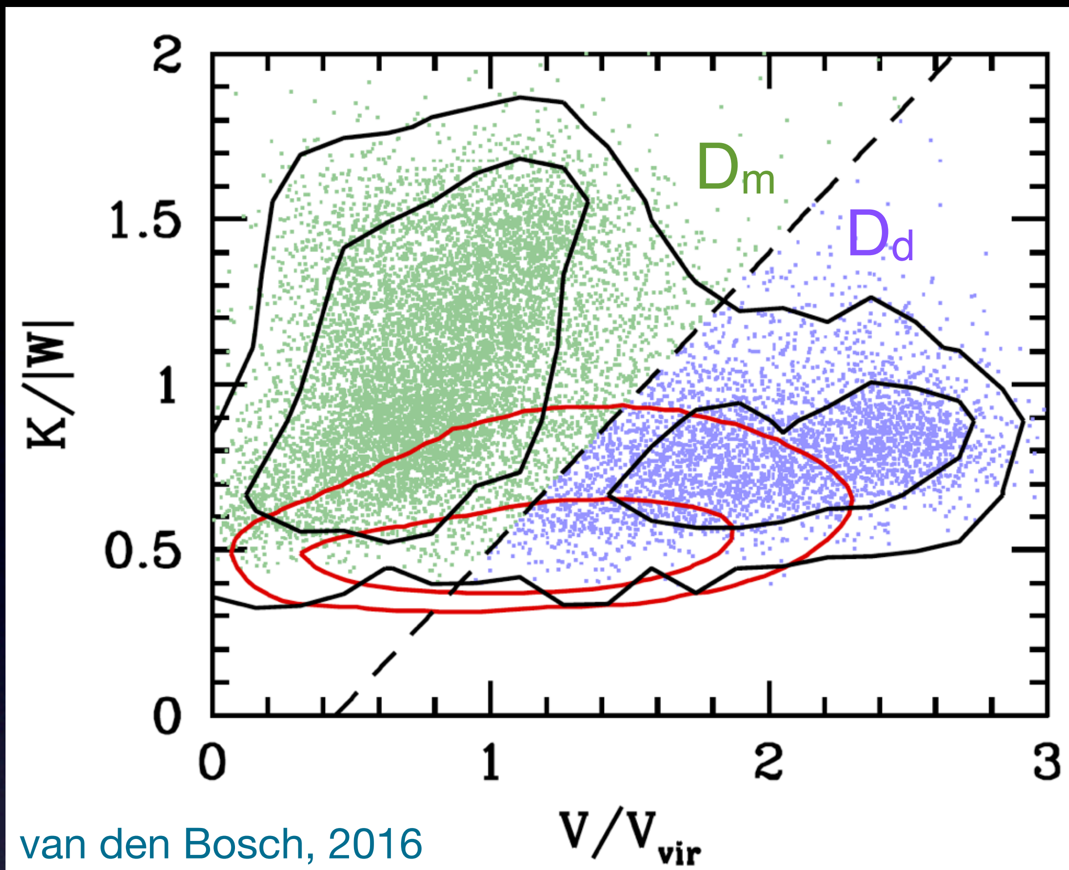
vdB & Jiang, 2016, in prep

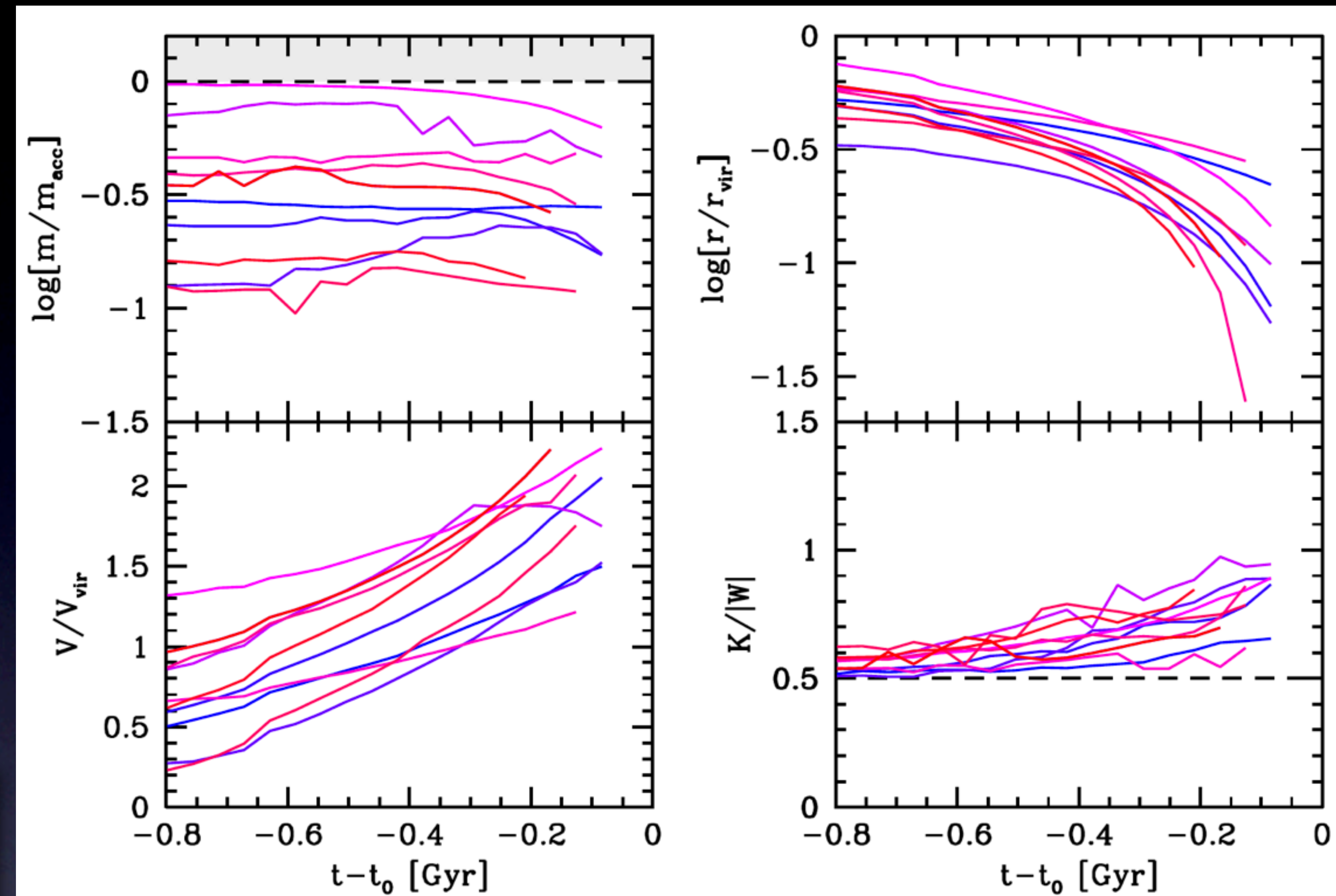
Demographics of S & M Channels



vdB & Jiang, 2016, in prep

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

<u>**Three modes of disruption in Bolshoi**</u>

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...