What can we learn from one-halo clustering?

Frank van den Bosch
Yale University

Introduction

Subhalo Abundance Matching (SHAM) has a number of advantages over Halo Model + HOD/CLF:

- No parameterization required (except for scatter)

  (e.g., Vale & Ostriker 04; Kravtsov+04; Conroy+06; Guo & White 10; Reddick+13)

- Halo Assembly Bias $b_h(r \mid M, z_f, \lambda, \ldots)$

  (Tinker+05; Gao & White 2005; Wechsler+06; Zentner 07; Dalal+08; Sunayama+16; Yao+17; Villareal+17)

- Halo Occupation Bias $\langle N_s \mid M \rangle \rightarrow \langle N_s \mid M, z_f \rangle$

  (vdB+05; Zentner+05; Giocoli+10; Yao+15; Jiang & vdB 16)

- Radial segregation of subhalos/satellite galaxies

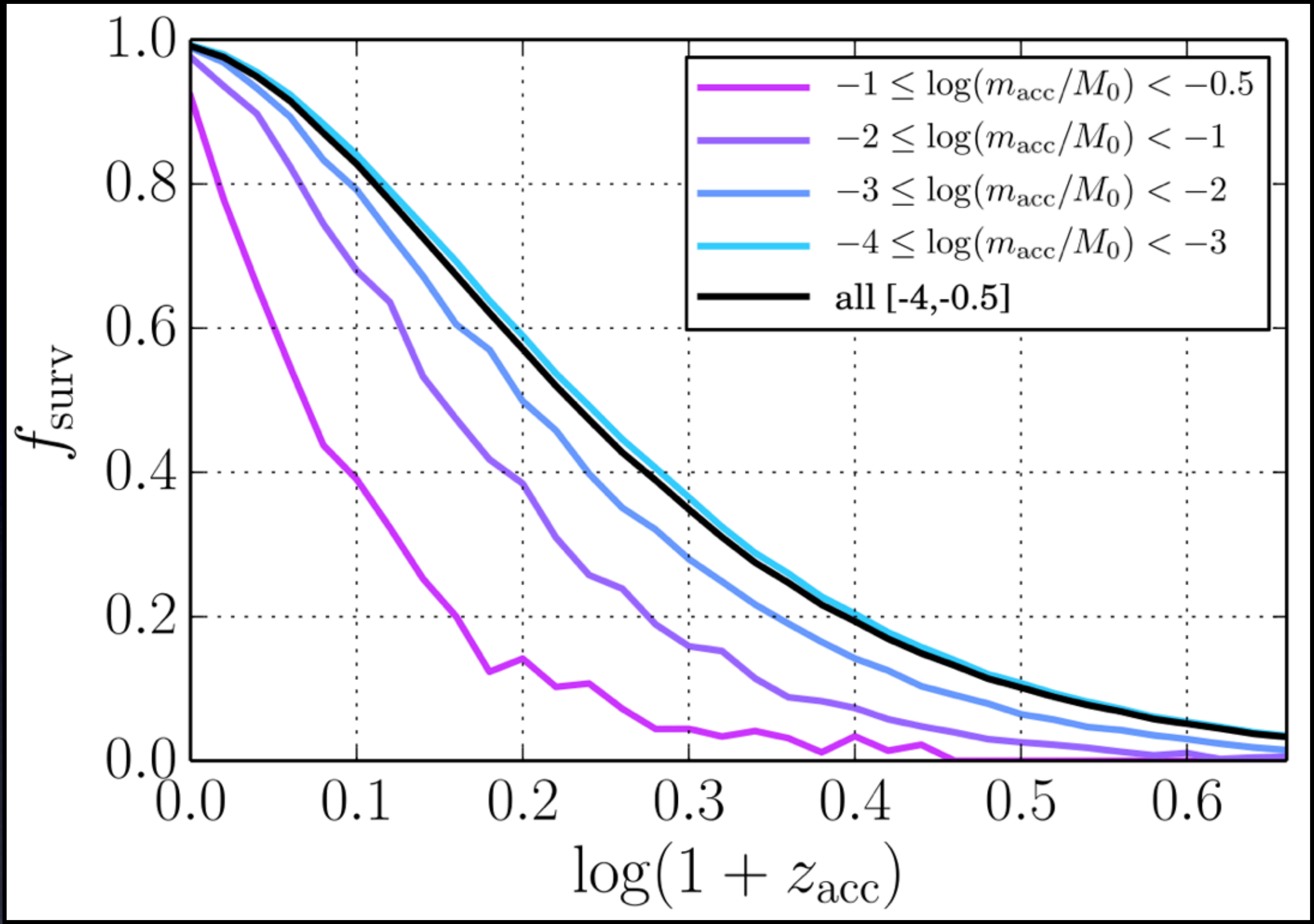
  (Gao+04; Nagai & Kravtsov 05; Faltenbacher & Diemand 06; vdB+17)

- Non-Poissonian nature of $P(N_s|M)$

  (Boylan-Kolchin+10; Busha+11; Wu+13; Mao+15; Jiang & vdB 16)

But: SHAM is only as accurate as the simulation used....

Subhalo Disruption in Bolshoi



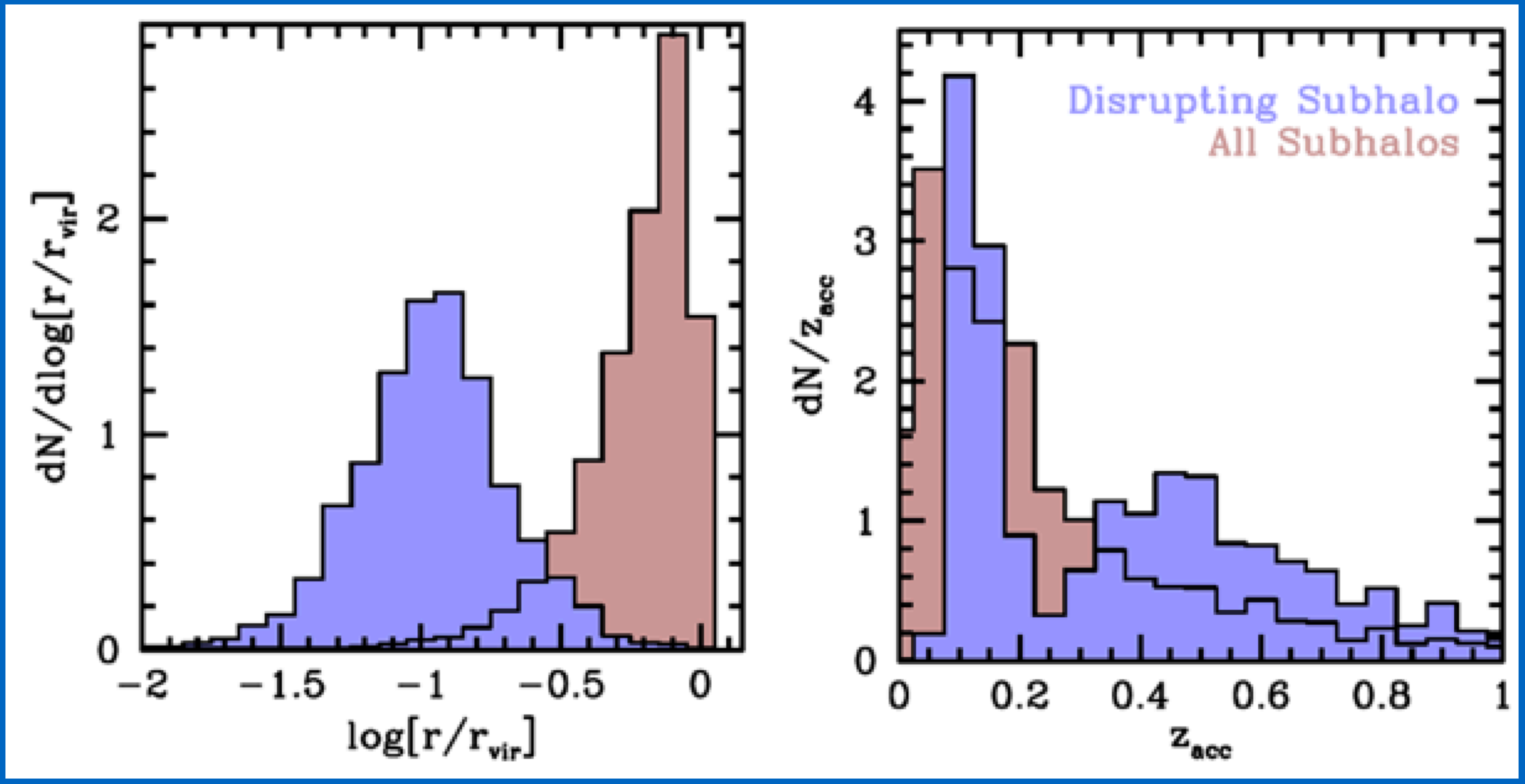
Jiang & vdB, 2016

- 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? NO!

- Instantaneous stripping of NFW halo can leave remnant with $E_b > 0$.

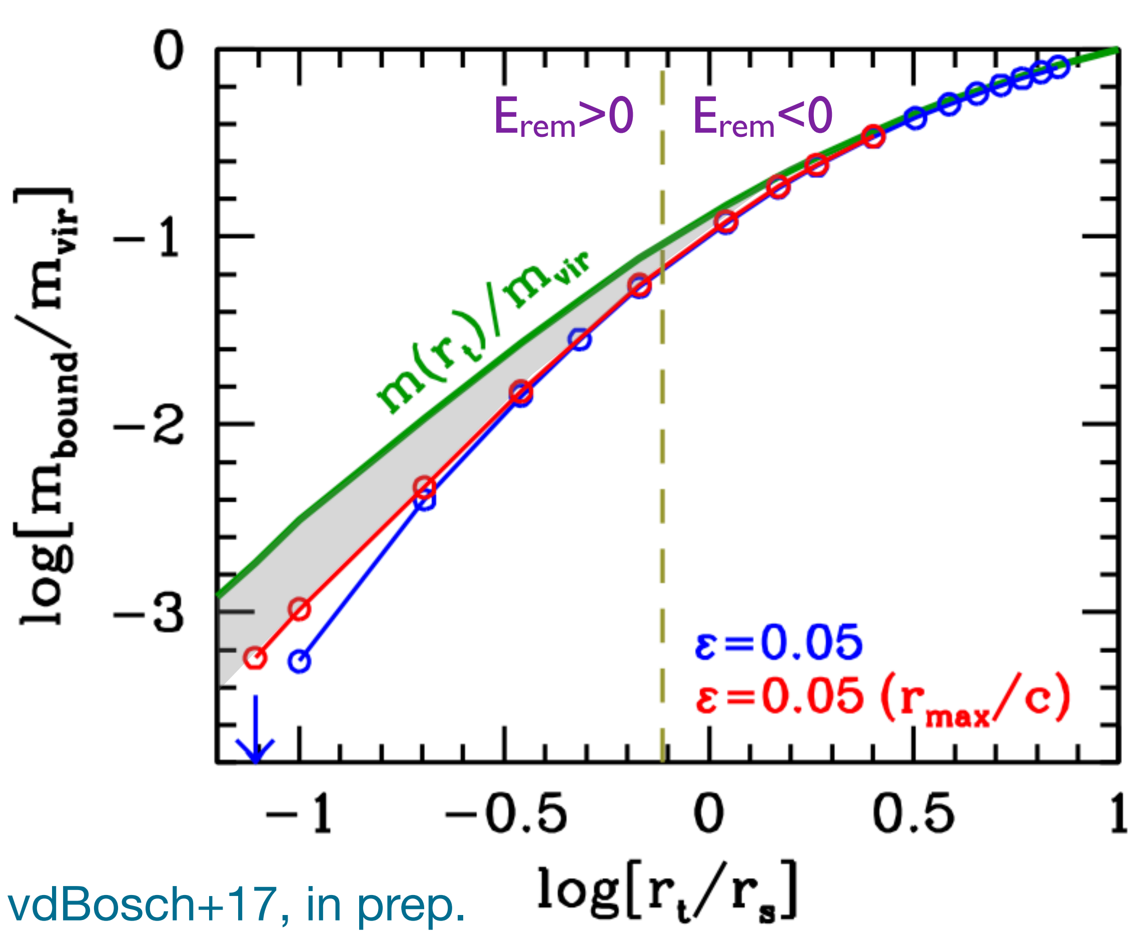
(Hayashi et al. 2003)

- For isotropic halo, this happens when $r_{trunc} < 0.77\ r_s$ $[M(r_{trunc}) < 0.08\ M_{vir}]$

- Subhalos spontaneous disintegrate once $r_{tid} < 0.77\ r_s$?

This assumption is made in several models or subhalo evolution

(e.g., Zentner & Bullock 2003; Taylor & Babul 2004; Klypin et al. 2015)



vdBosch+17, in prep.

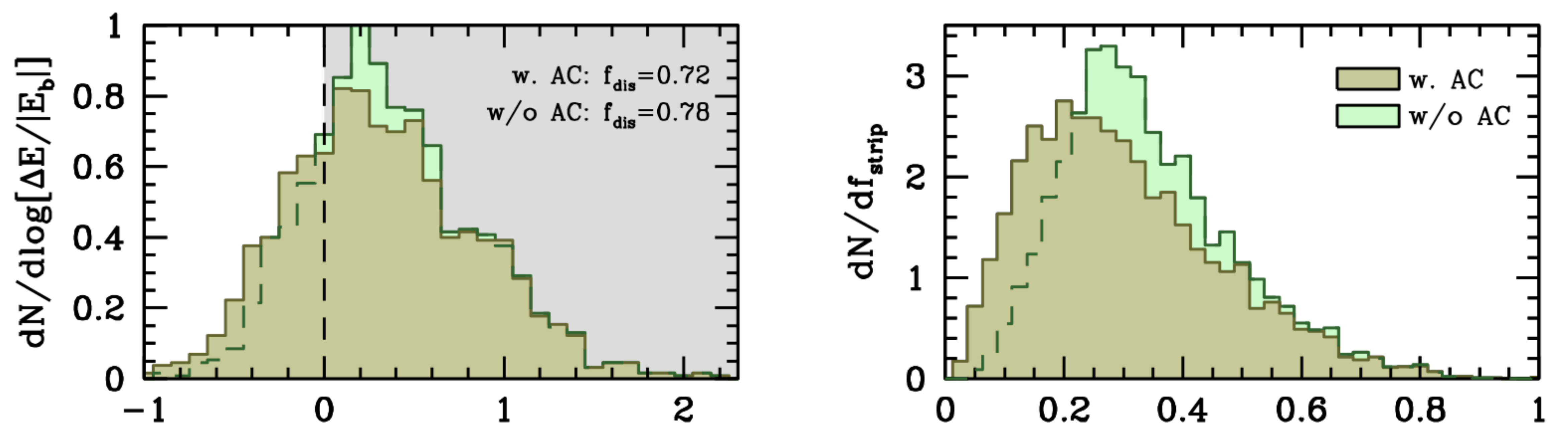
However:

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.

What about Tidal (Impulsive) Heating?

- For each subhalo in Bolshoi, compute orbital energy & circularity *at accretion*.
- Compute tidal heating, $\Delta E/|E_b|$, 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 $f_{strip} = f(\Delta E_i/E_i > 1)$



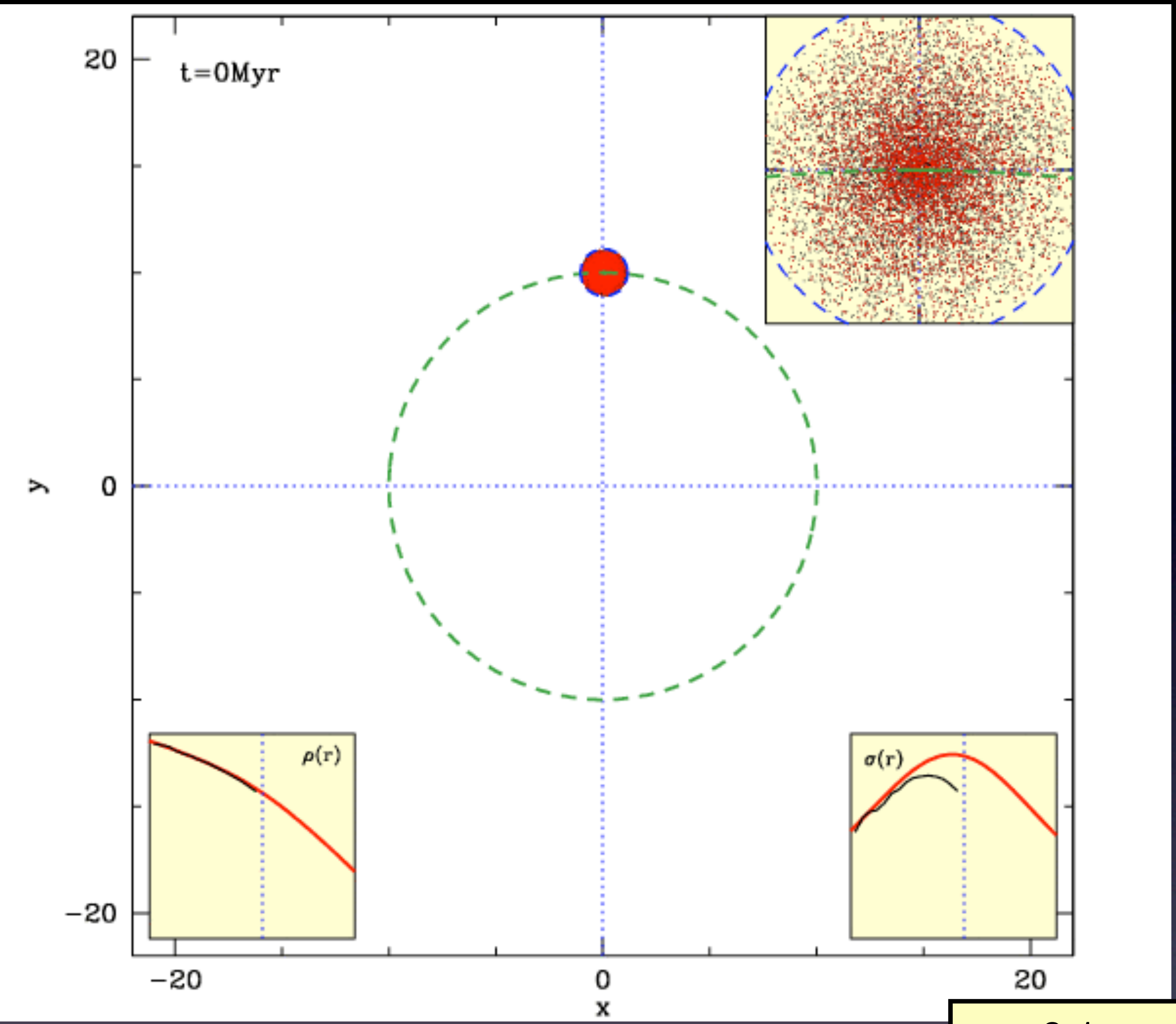
vdBosch+17, in prep.

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 $\Delta E/|E_b| = 100$ as much as 20 percent of subhalo remains bound!!!

Idealized Numerical Simulations



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

Simulate N-body NFW subhalo orbiting inside the static potential of a NFW host halo.

We consider both circular orbits (static tidal field; no impulsive heating) as well as eccentric orbits.

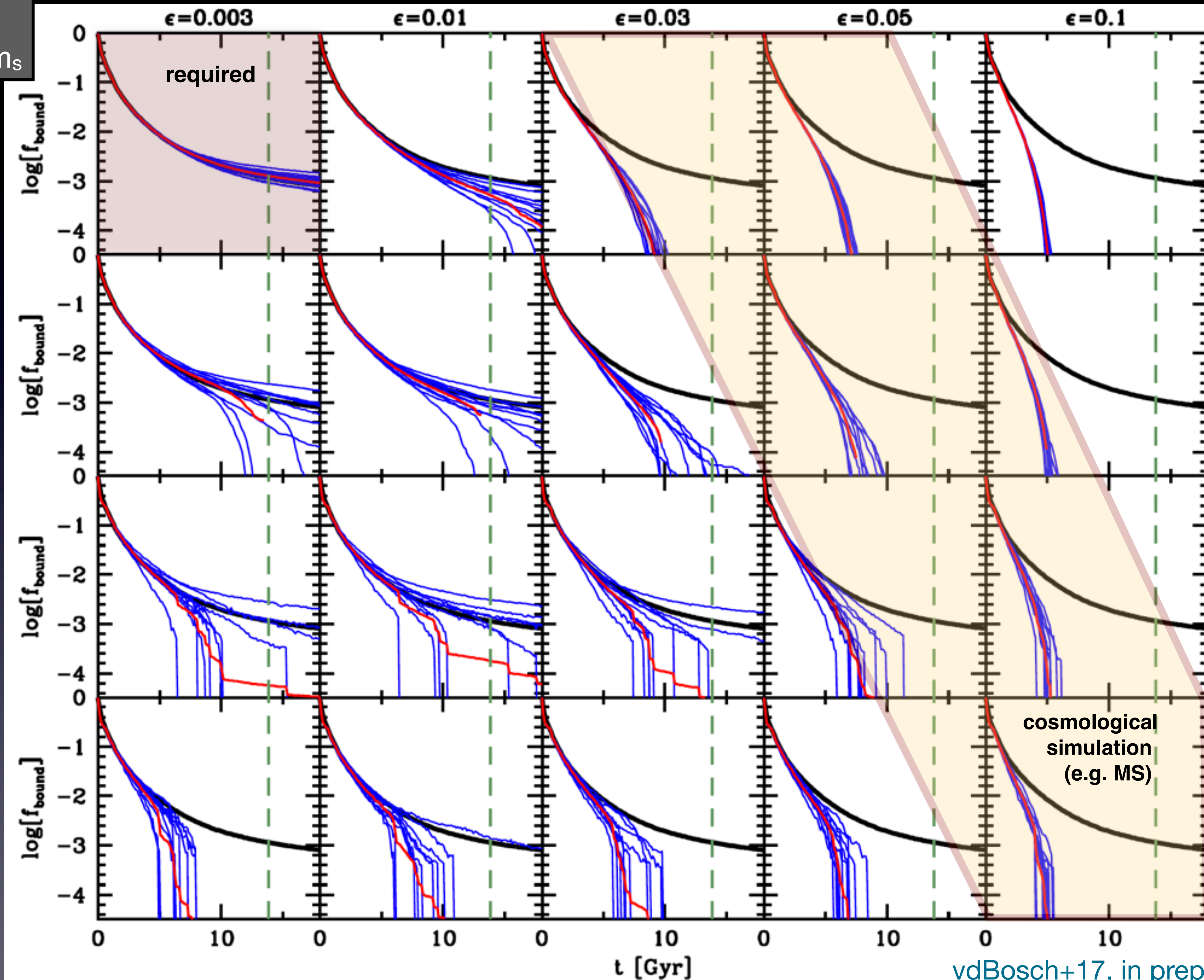
We have run 1000+ such simulations to determine the resolution (N,ε) required to properly resolve the subhalo's mass evolution, $f_{bound}(t)$.

Goals:

- Determine under what conditions physical disruption occurs.
- Determine under what conditions numerical disruption occurs.

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

Lessons Learned

- We have explored vast areas of parameter space:

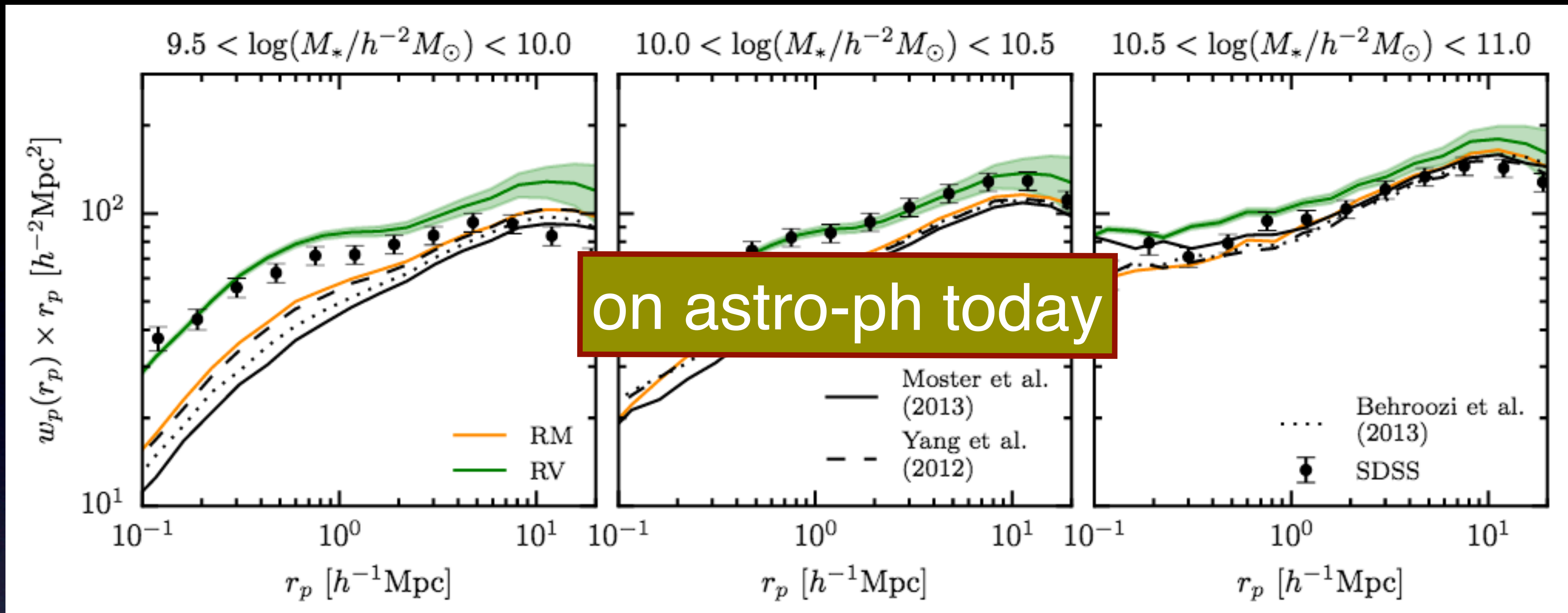
  subhalo orbit: E_{orb}, L_{orb}
  halo properties: c_{host}, c_{sub}
  numerical params: N, ε, Δt, θ_{tree}

- With sufficient numerical resolution (large N, small ε), we never find any *physical* disruption (in absence of baryonic effects & dynamical friction).

- Evolution of substructure in N-body simulations suffers from two problems:
  - Discreteness-driven run-away instability whenever $N < 1000$
  - Artificial disruption due to over-softening

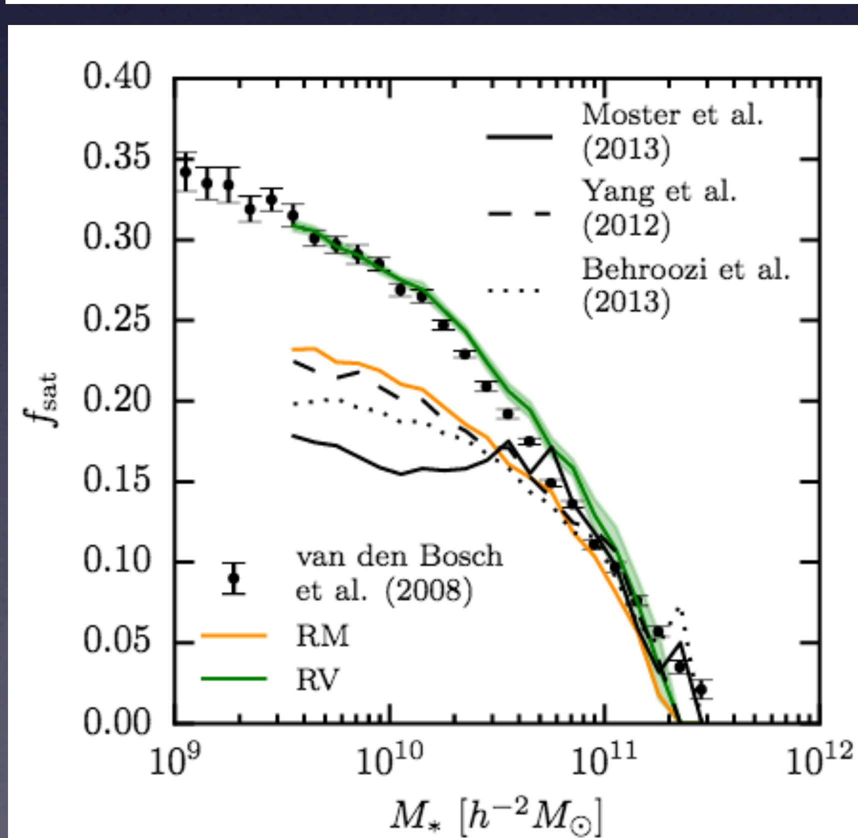
- Properly resolving dynamics within inner region of host ($r \lesssim 0.2\, r_{vir}$) requires very high mass resolution (large N) and force resolution (small ε).

The Galaxy Clustering Crisis



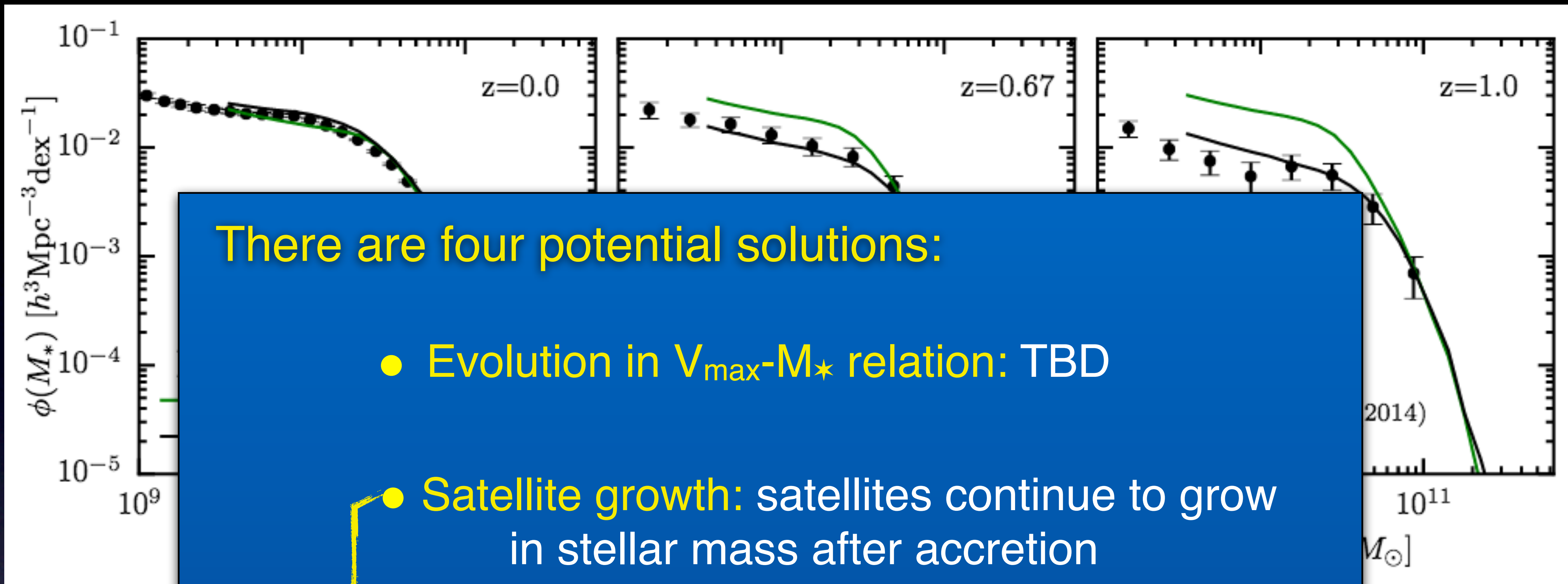
on astro-ph today

Campbell, vdB et al. 2017

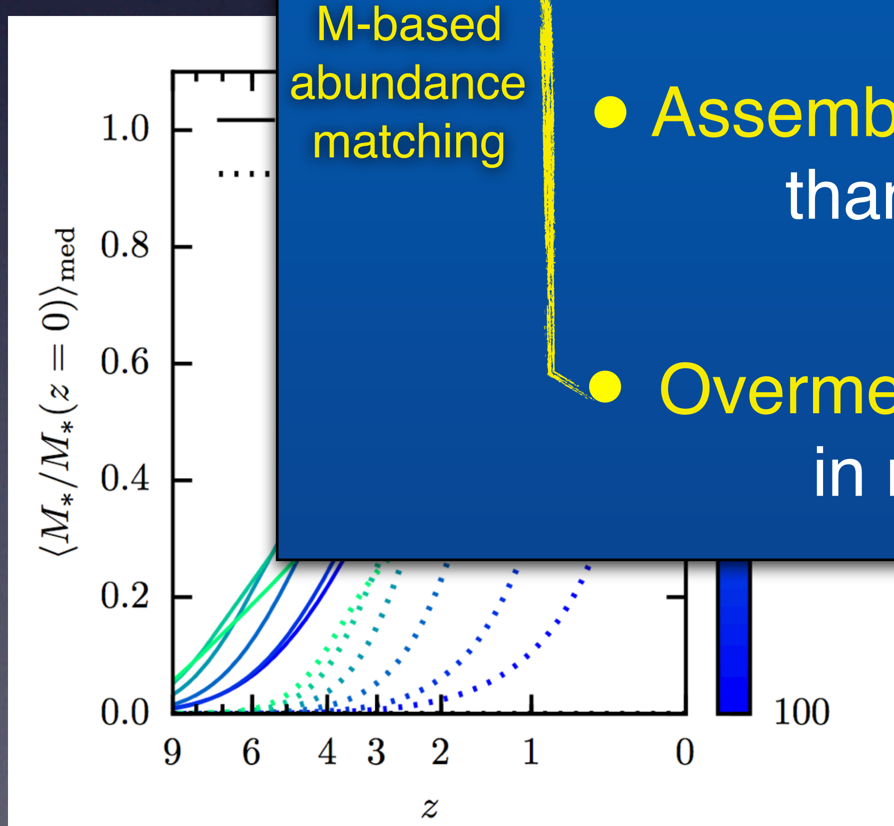


- M_{peak} based SHAM (RM) dramatically underestimates clustering on small scales.
- Same is true for `evolving SHAM' models (Yang+12, Moster+13, Behroozi+13)
- V_{peak} based SHAM (RV) fits clustering well (e.g. Conroy+06, Reddick+13)

The Galaxy Clustering Crisis



ll, vdB et al. 2017



There are four potential solutions:

- Evolution in V_{max}-M_* relation: TBD

M-based abundance matching

- Satellite growth: satellites continue to grow in stellar mass after accretion (Effect not strong enough)
- Assembly Bias: satellites are more massive than centrals at moment of accretion (No success yet...really difficult)
- Overmerging: artificial disruption of subhalos in numerical simulations (requires orphans)

consistent

unction.

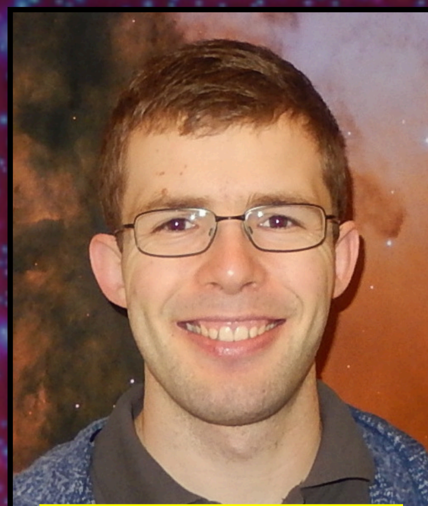
vdB+14).

models predict that stellar masses are assembled early, overpredicting $\Phi(M_*)$ at high z.

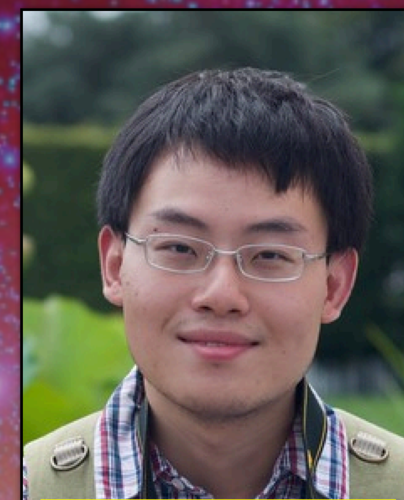
Conclusions

- ★ Current generation of cosmological simulations still suffers from severe overmerging. (cf.,Kazantzidis, Moore & Mayer 2004)
  - serious road-block for small-scale cosmology program
  - serious road-block for understanding galaxy formation
- ★ SHAM needs to include `orphan galaxies', but without knowing how many orphans to add, and where, the information content of the 1-halo term is extremely limited.

with thanks to my collaborators


Johannes Lange


Duncan Campbell

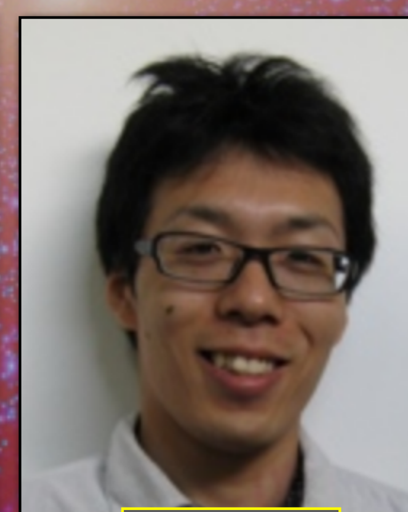

Fangzhou Jiang


Andrew Hearin

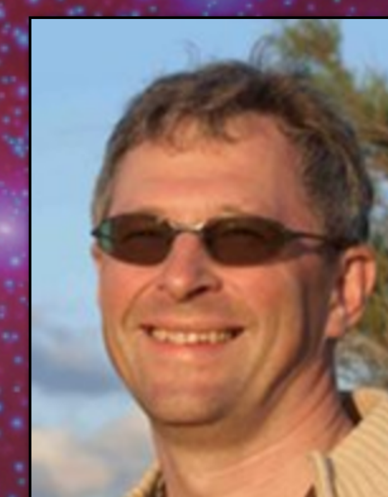

Andrew Zentner


Yao-Yuan Mao


Antonio Villareal


Go Ogiya


Oliver Hahn


Andi Burkert