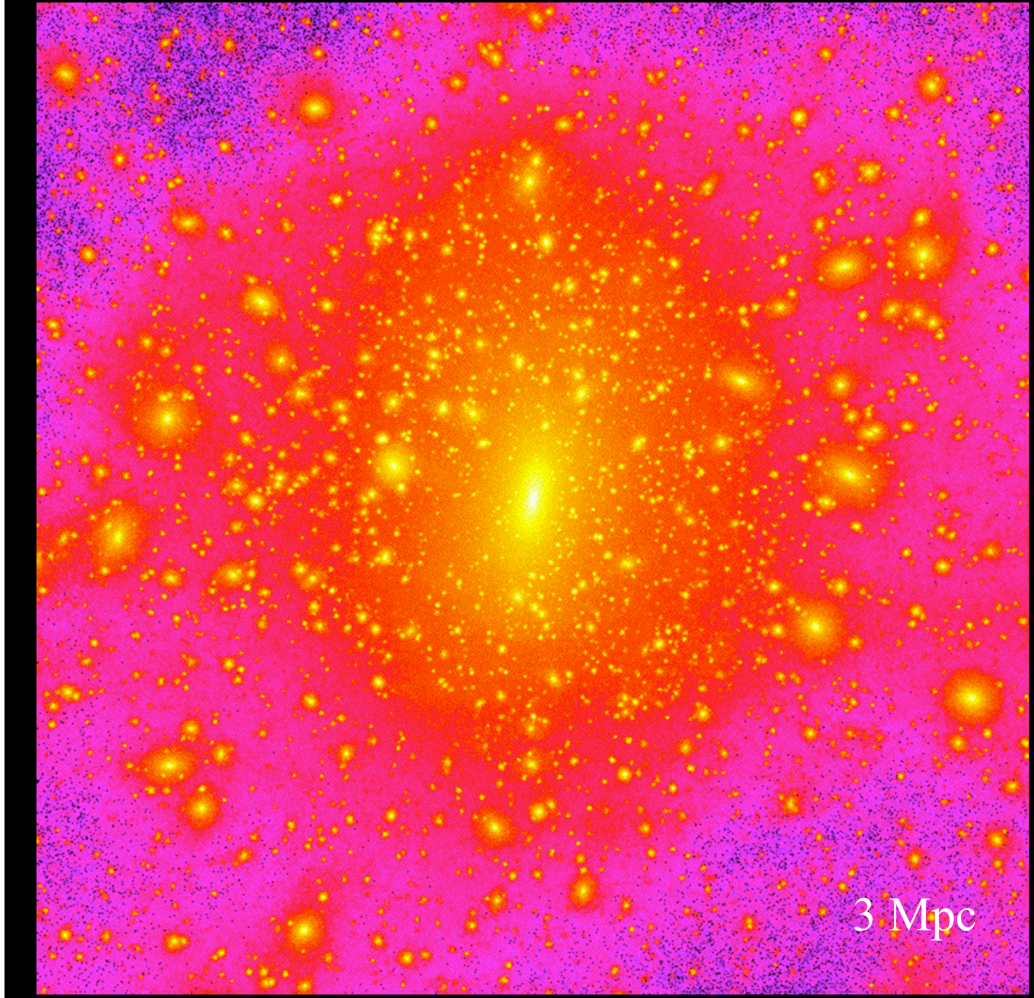
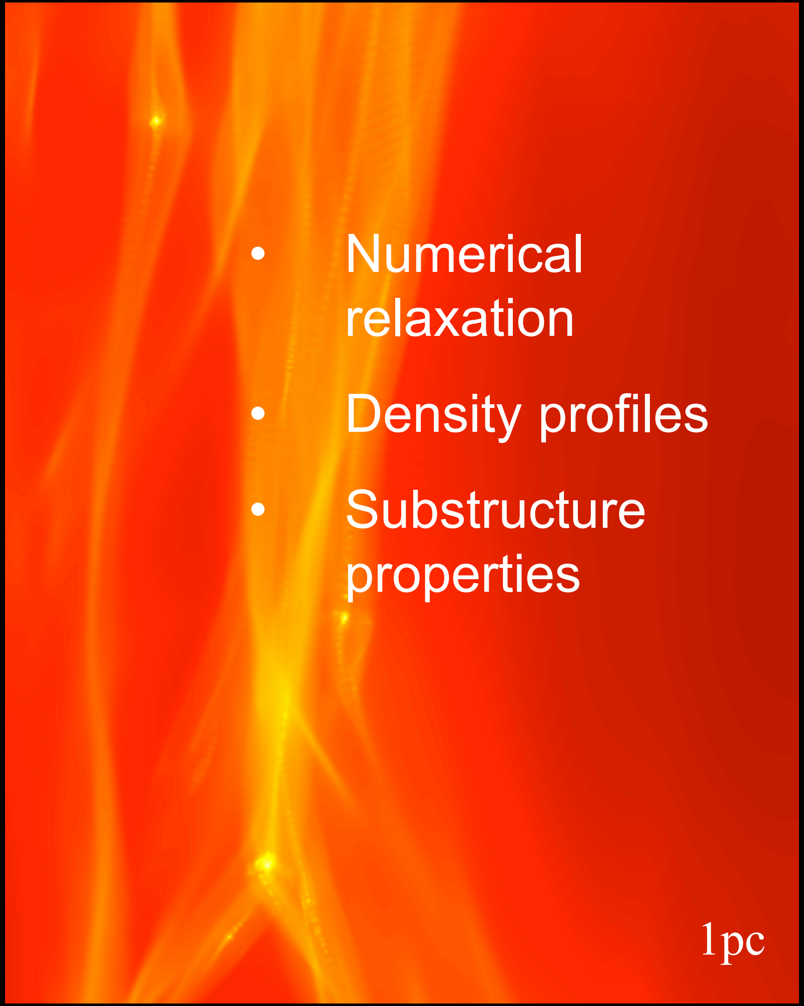
Density profiles and substructure: Approximating CDM halos with N-body models





- Numerical relaxation
- Density profiles
- Substructure properties

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Ben Moore, Joachim Stadel (University of Zurich)

Why detailed CDM only simulations of individual halos?

Well defined problem (no free parameters), well suited for numerical simulation.
Simulations revealed much about DM halo structure, some questions remain:

➢ Density profile within 1% of the virial radius:
Singular (‘cuspy’) or approaching a constant density core?

Galaxy rotation curves*
strong lensing*
DM annihilation signal from the Galactic center*

➢ Subhalo inner structure, abundance, spatial & velocity distribution?

Cluster galaxies and satellite galaxies *
DM annihilation signal form subhalos (*) small ones always DM dominated
anomalous flux ratios in strong lensing (*)

➢ Local dark matter distribution in real- and phase-space?

Direct detection of dark matter

* Caution: realistic gas-simulations are needed to fully address these questions…

Method

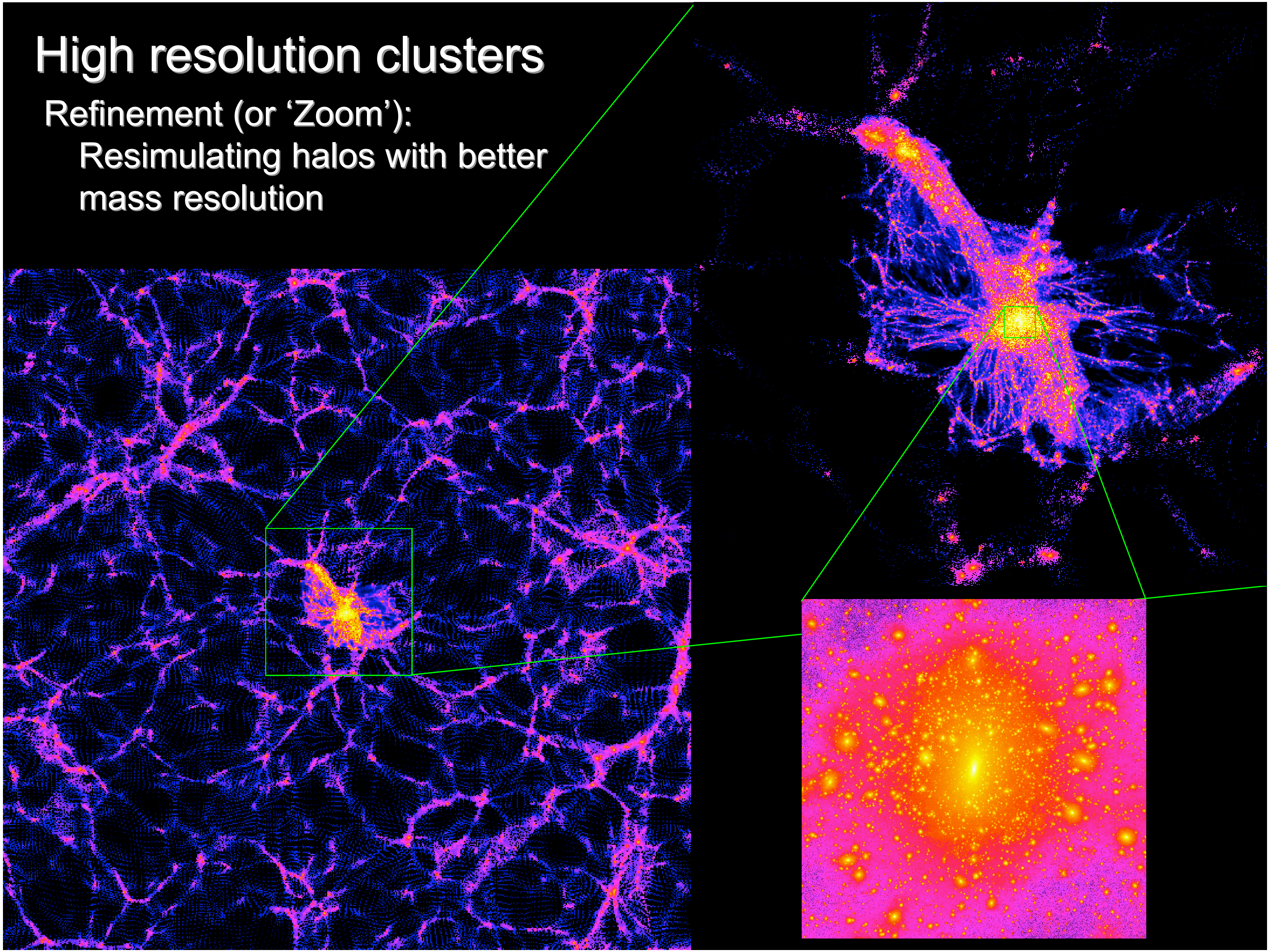
- Cosmological inital conditions for a LambdaCDM Universe (0.27, 0.73) realised with particles displaced from cubic grid positions using GRAFICS by E. Bertschinger

- Solve gravitational interactions between these particles with PKDGRAV by J. Stadel & T. Quinn

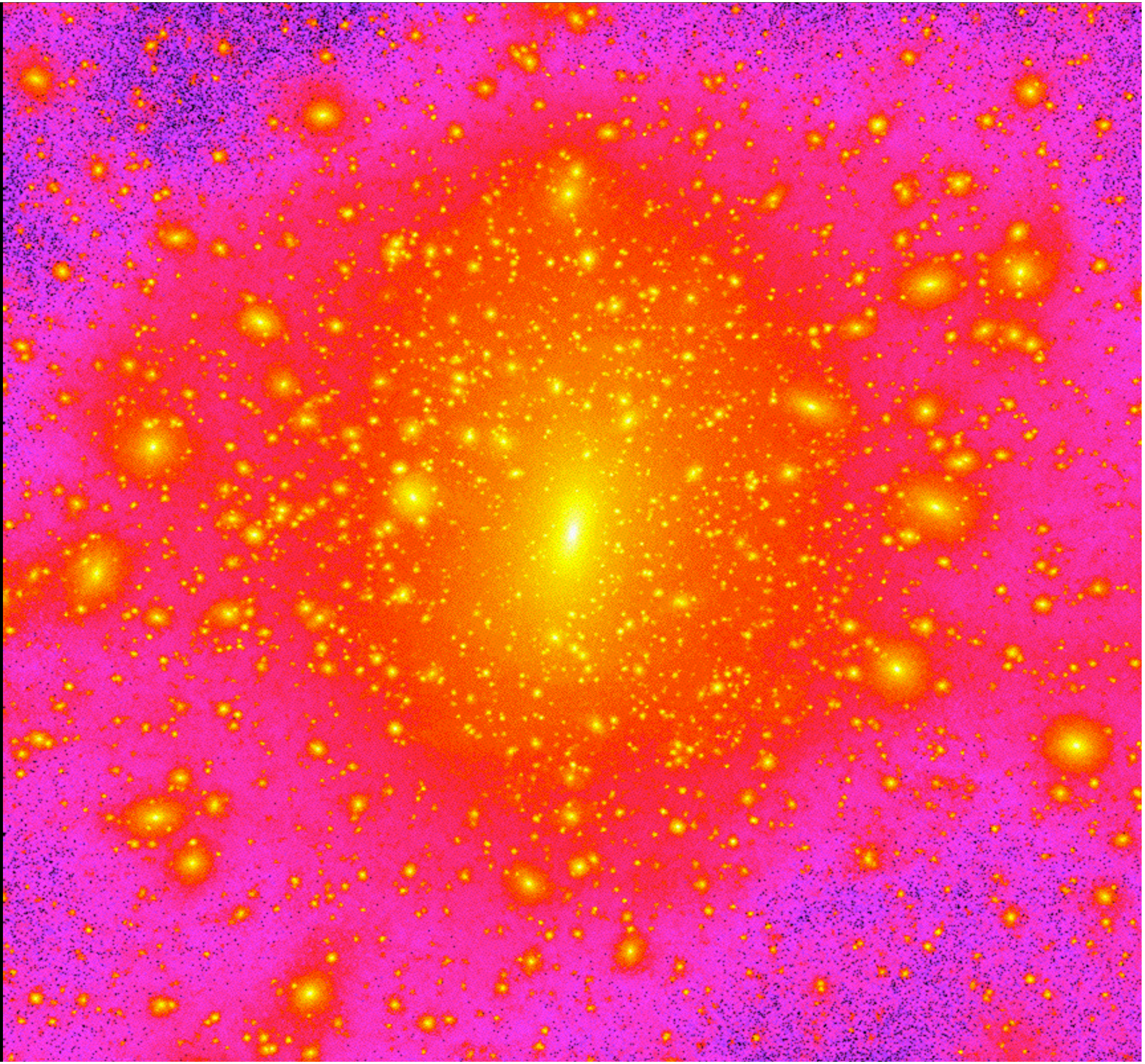
High resolution clusters

Refinement (or ‘Zoom’):

- Resimulating halos with better mass resolution



Highest resolution numerical simulations of the structure of dark matter halos



10^5 steps

10^8 particles (25 million inside the virial radius)

High mass and force resolution

Formation of a CDM cluster

Why such large N? Reducing numerical relaxation

CDM in a galaxy halo: T _ 10^{65} yr >> relaxation time of any N-body halo!
“Ant-Elephant Bias” (W. Xiao et al. ApJL 2004)???

Focker-Planck estimate of the relaxation time:

$$T_{relax} = 0.34 \frac{\sigma^3}{G^2 m \rho \ln(b_{max}/b_{min})} \simeq \frac{N}{8 \ln(N)} T_{cross}$$

Every decade in impact parameter contributes equally to ‘two-body’ relaxation. The softening length sets b_min. Softening can only avoid large angle scattering but there is always numerical relaxation from particle noise on larger scales. (also in adaptive grid codes like ART)

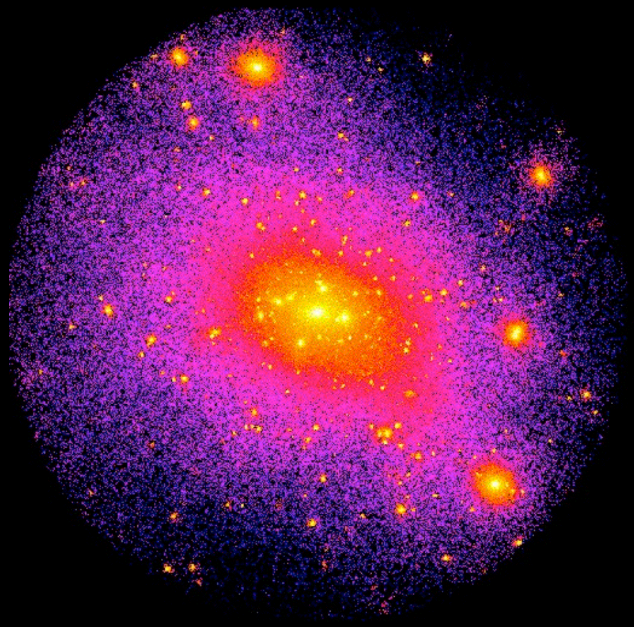
Additional concern for cosmological runs:
N is always small in the first CDM objects, also at high resolution!
(Moore, AIPC 2001; Binney & Knebe, MNRAS 2002)

Additional concern for cosmological SPH runs:
Moving dark particles can heat up the gas particles
(Steinmetz & White, 1997)

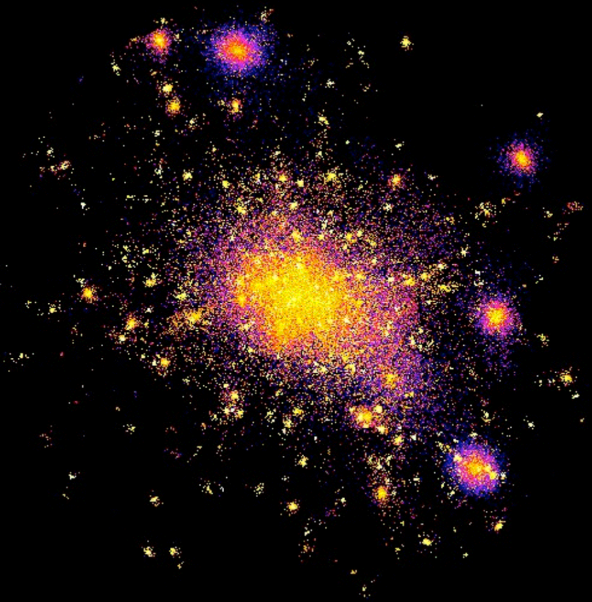
Relaxation in cosmological runs

Estimated with a local Fokker-Planck type counter, gauged using spherical halos.

A cluster at z=0, resolved with 650'000 particles:



log density



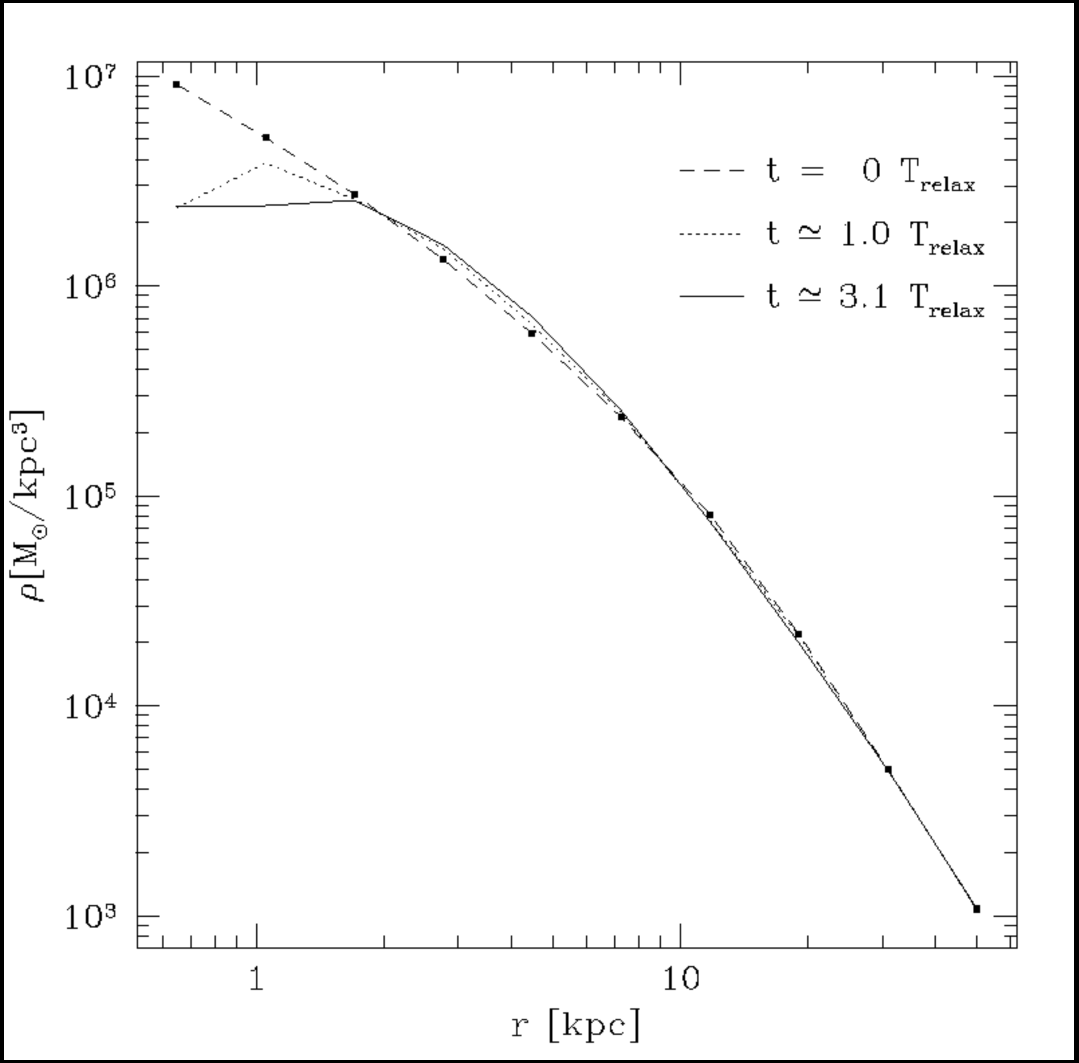
log “relaxation” average is 1.2

=> relaxation is an issue, but it decreases slowly when using more particles: $N^{-0.25}$

=> go to very large number of particles

Numerical relaxation reduces central inner halo density

N=4'000 Hernquist halo, IC and
after 1 and 3 mean relaxation times



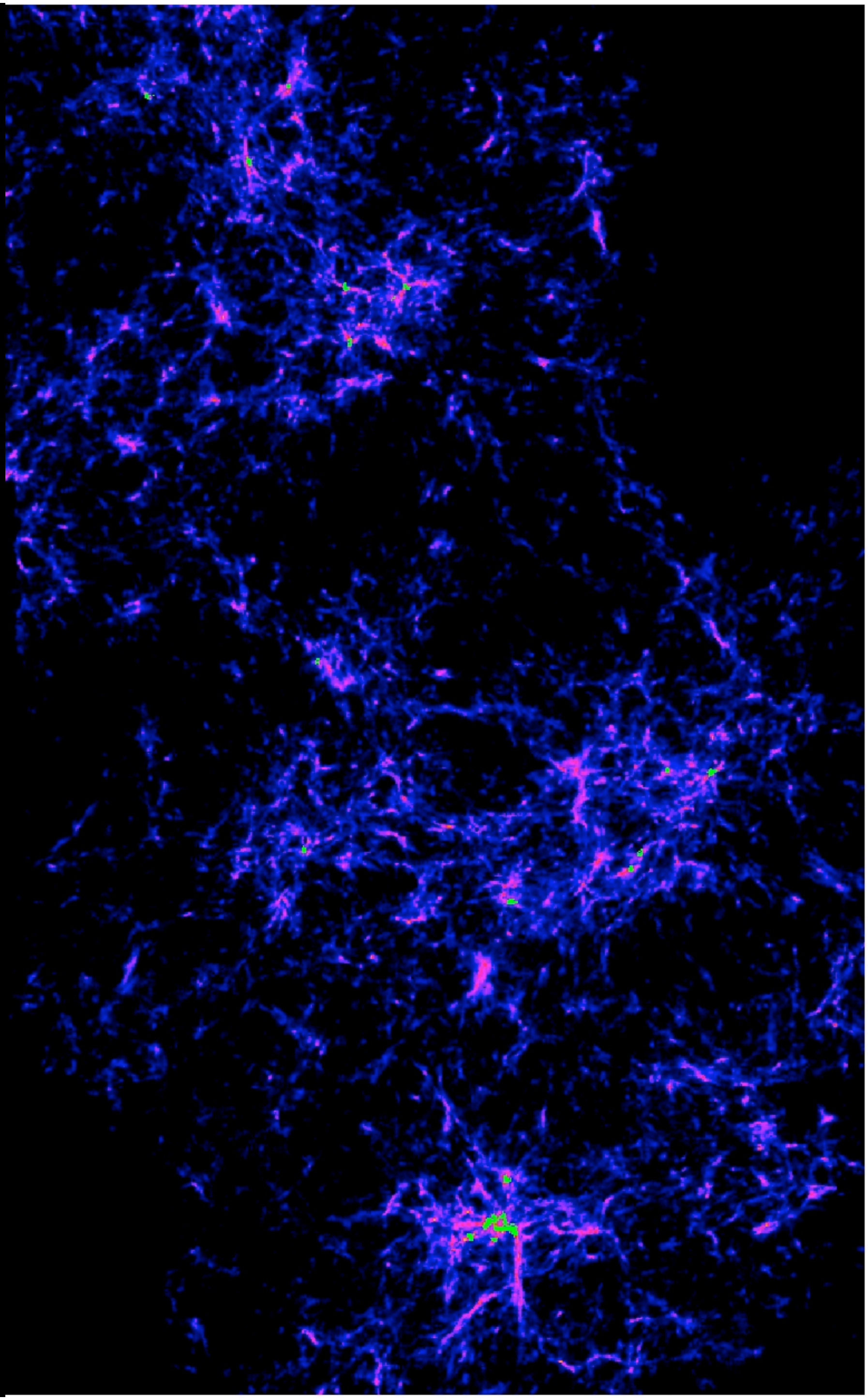
merging...

final profile also shallower

Where does the inner part of CDM halos come from ?

In this example halos more massive than 5e7 Msun halos at redshift 18 are marked (green).

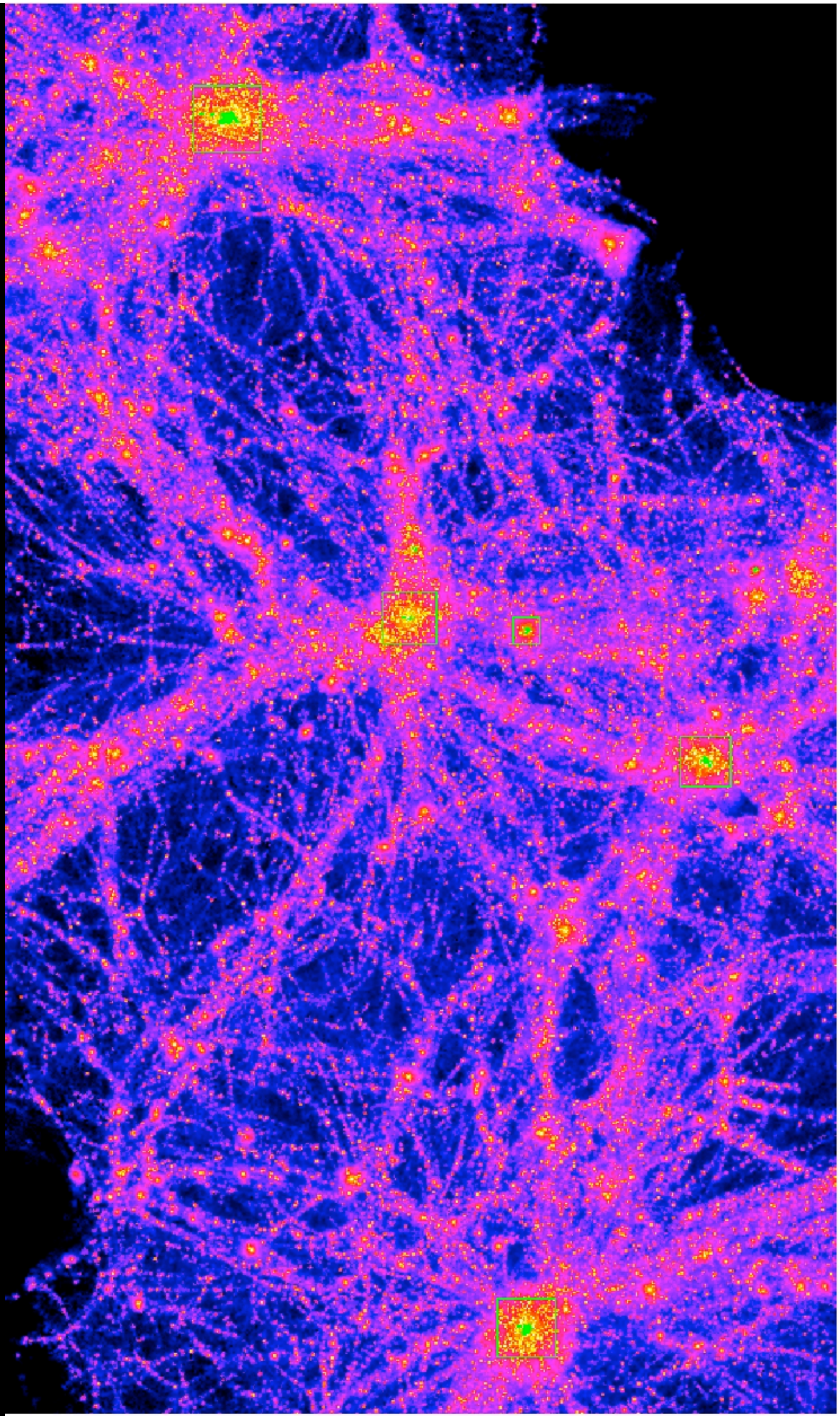
These are rare (>3.5 sigma) fluctuations



Where does the inner part of CDM halos come from ?

Structure formation is strongly biased:

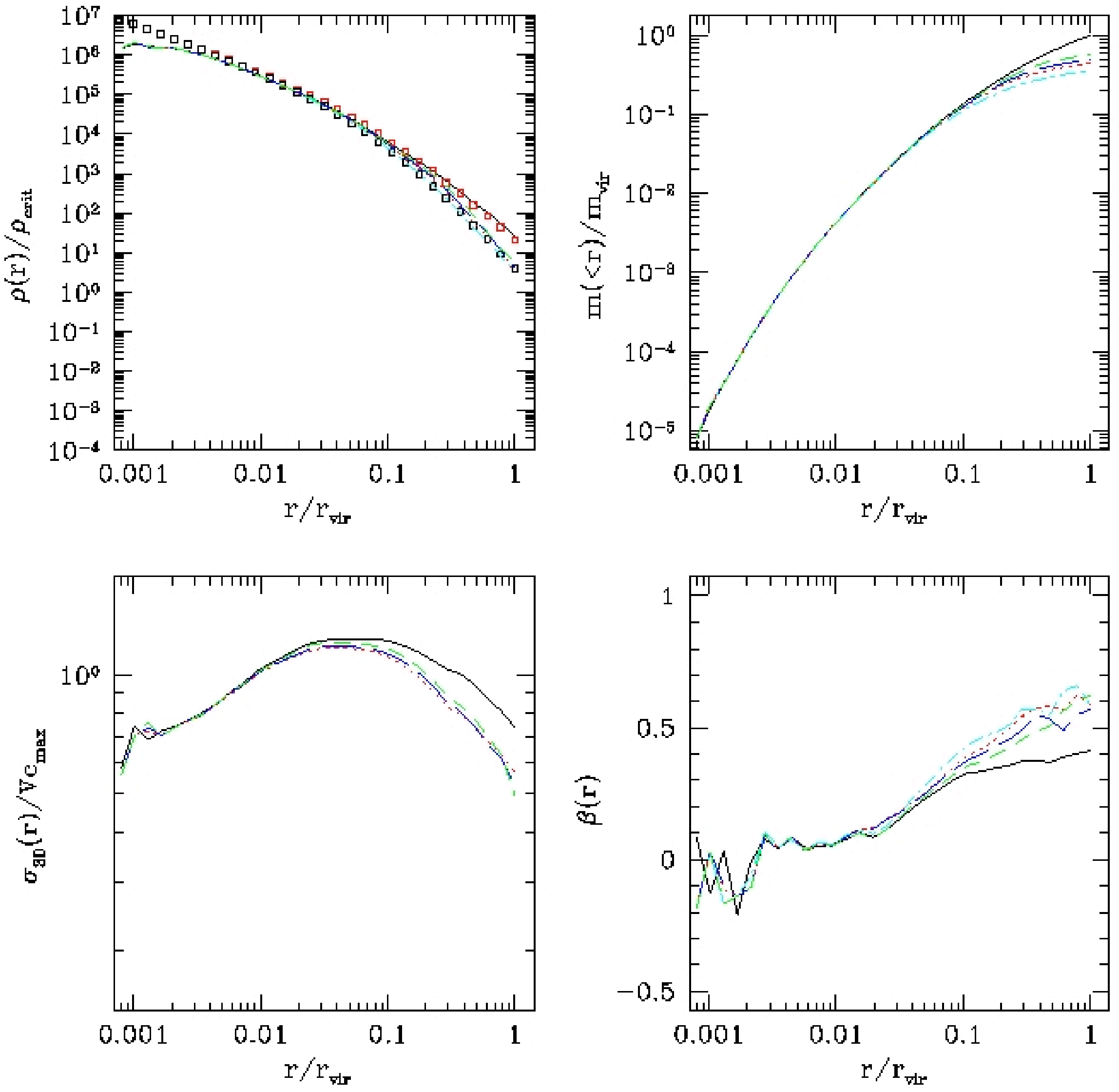
Most of the > 3.5 sigma material ends up in the centers of the largest halos today.



Present distribution of this fossil material mostly depends on how rare peaks it comes form:

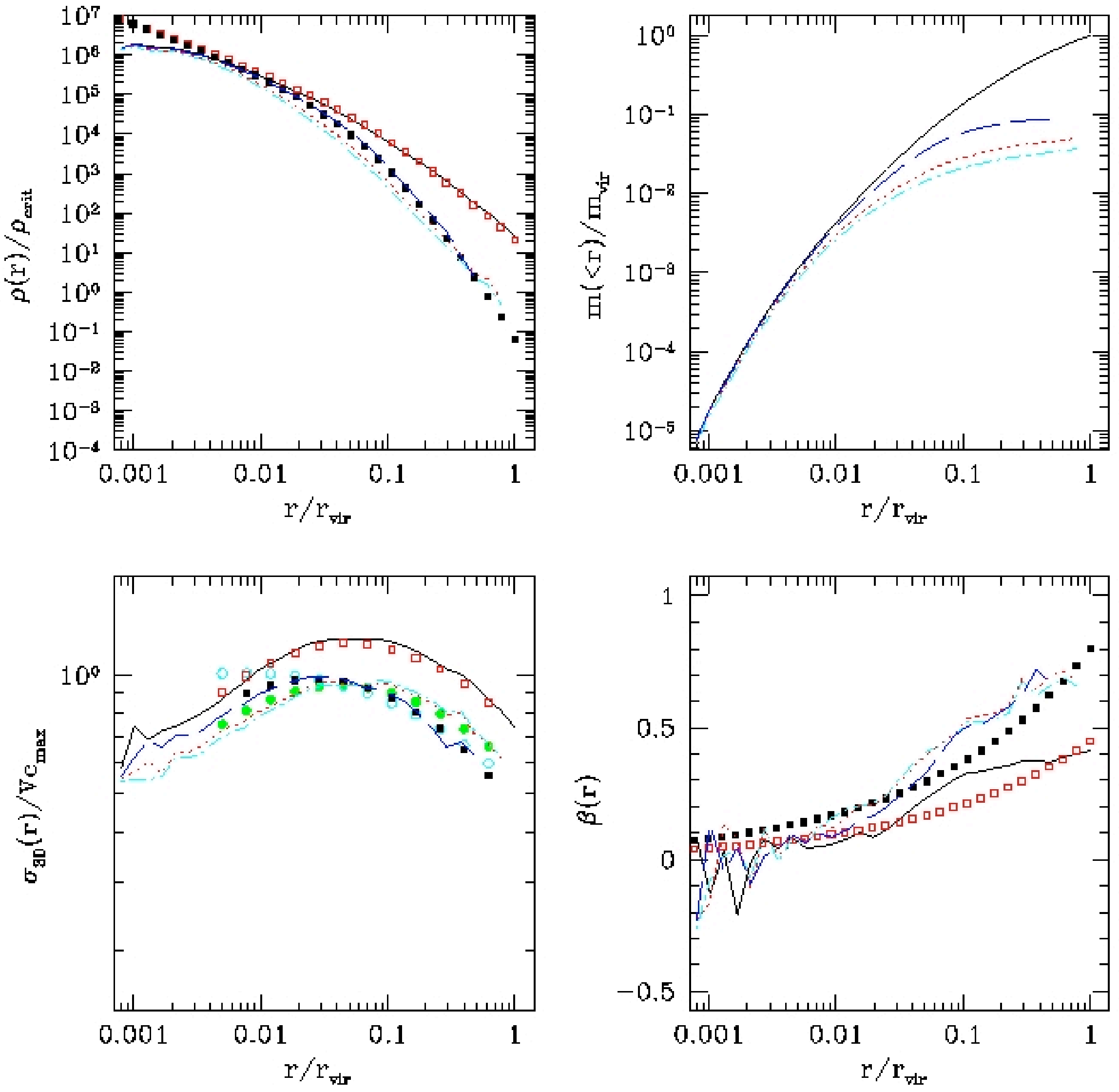
>1 sigma peaks

(JD, Madau, Moore, in prep.)



Present distribution of this fossil material mostly depends on how rare peaks it comes form:

> 2 sigma peaks

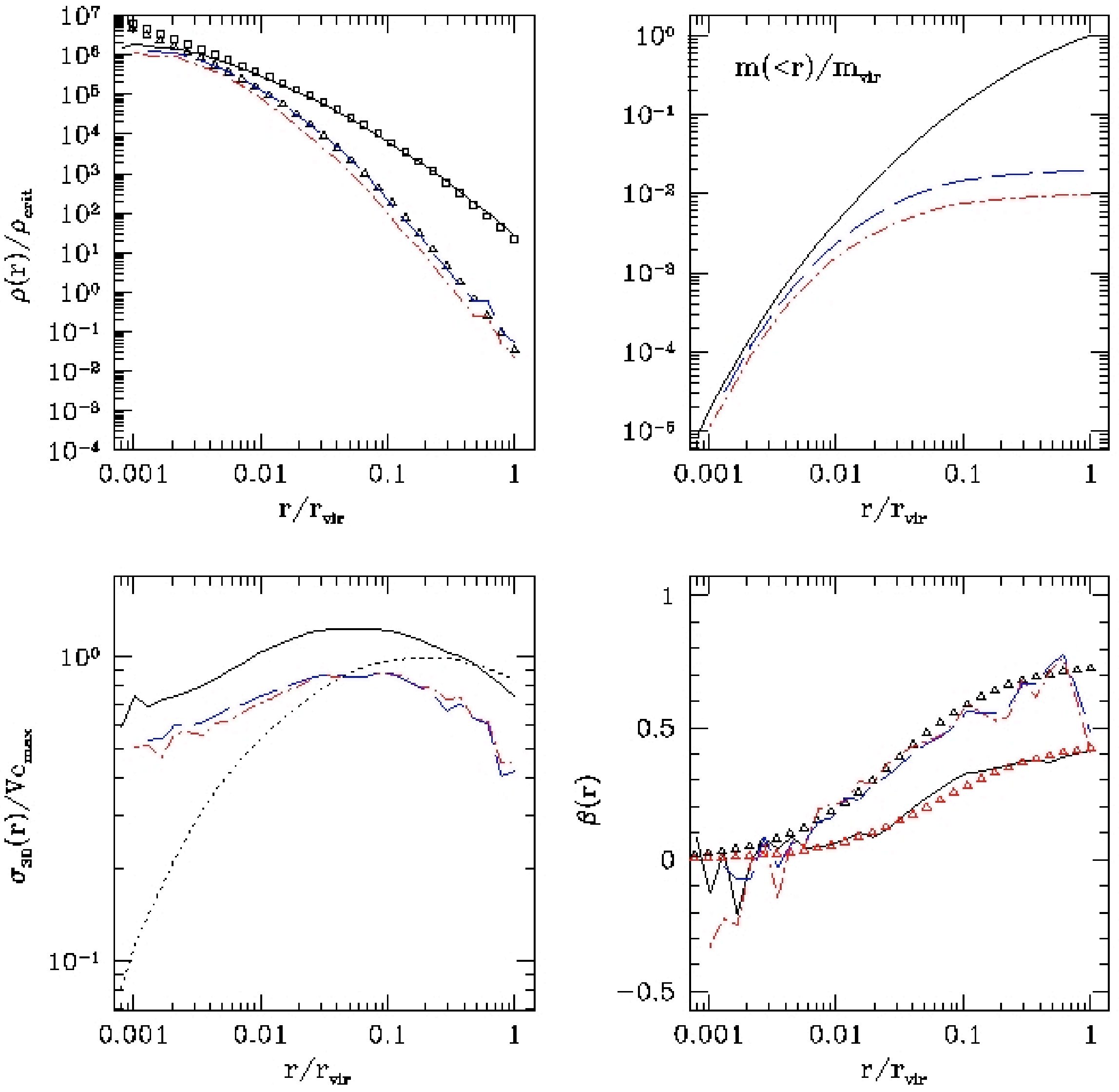


Present distribution of this fossil material mostly depends on how rare peaks it comes form:

> 2.5 sigma peaks

These selections have similar properties as the stellar halo of the Milky Way

(Moore, JD, et al. 2005)

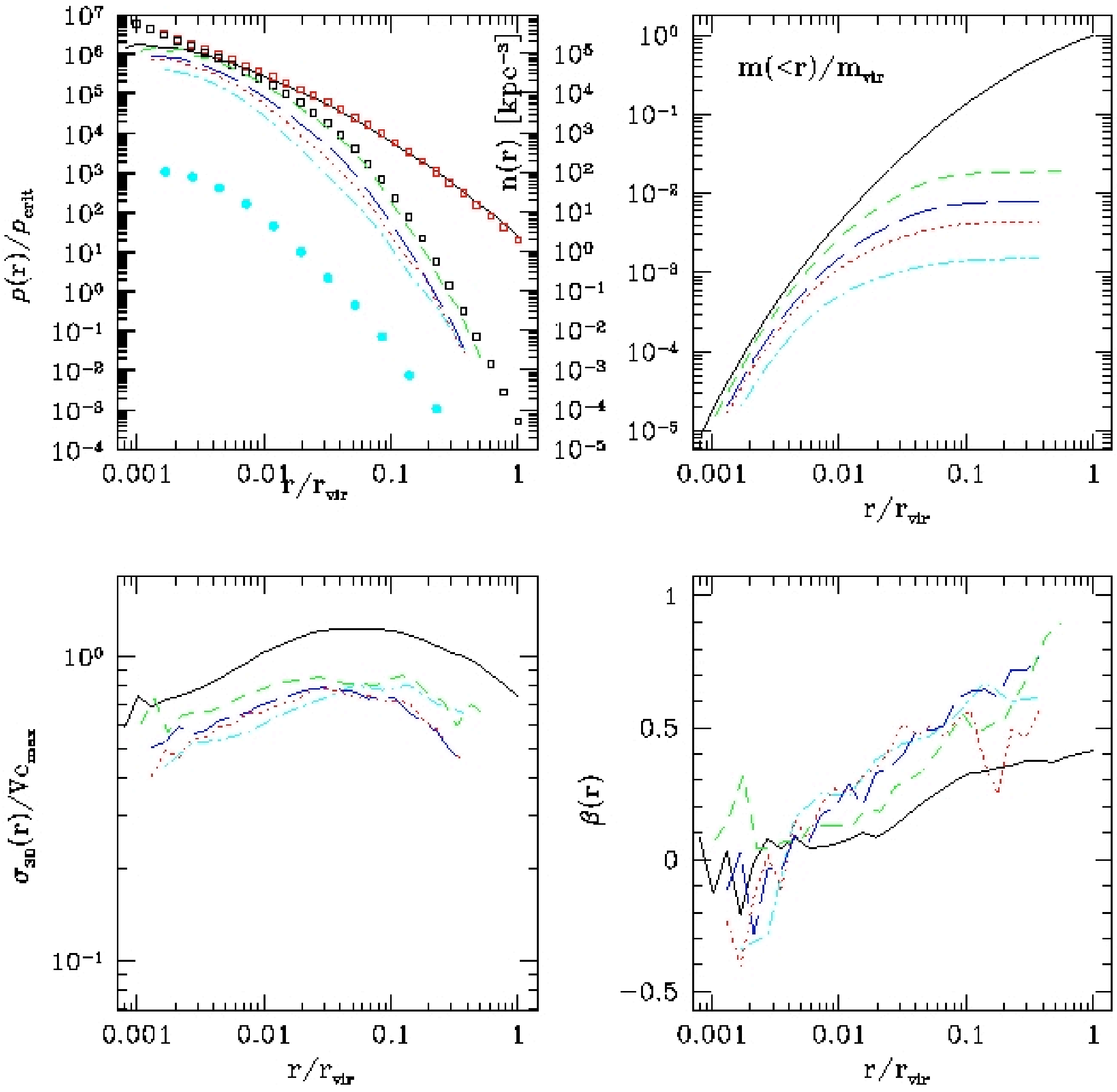


Present distribution of this fossil material mostly depends on how rare peaks it comes form:

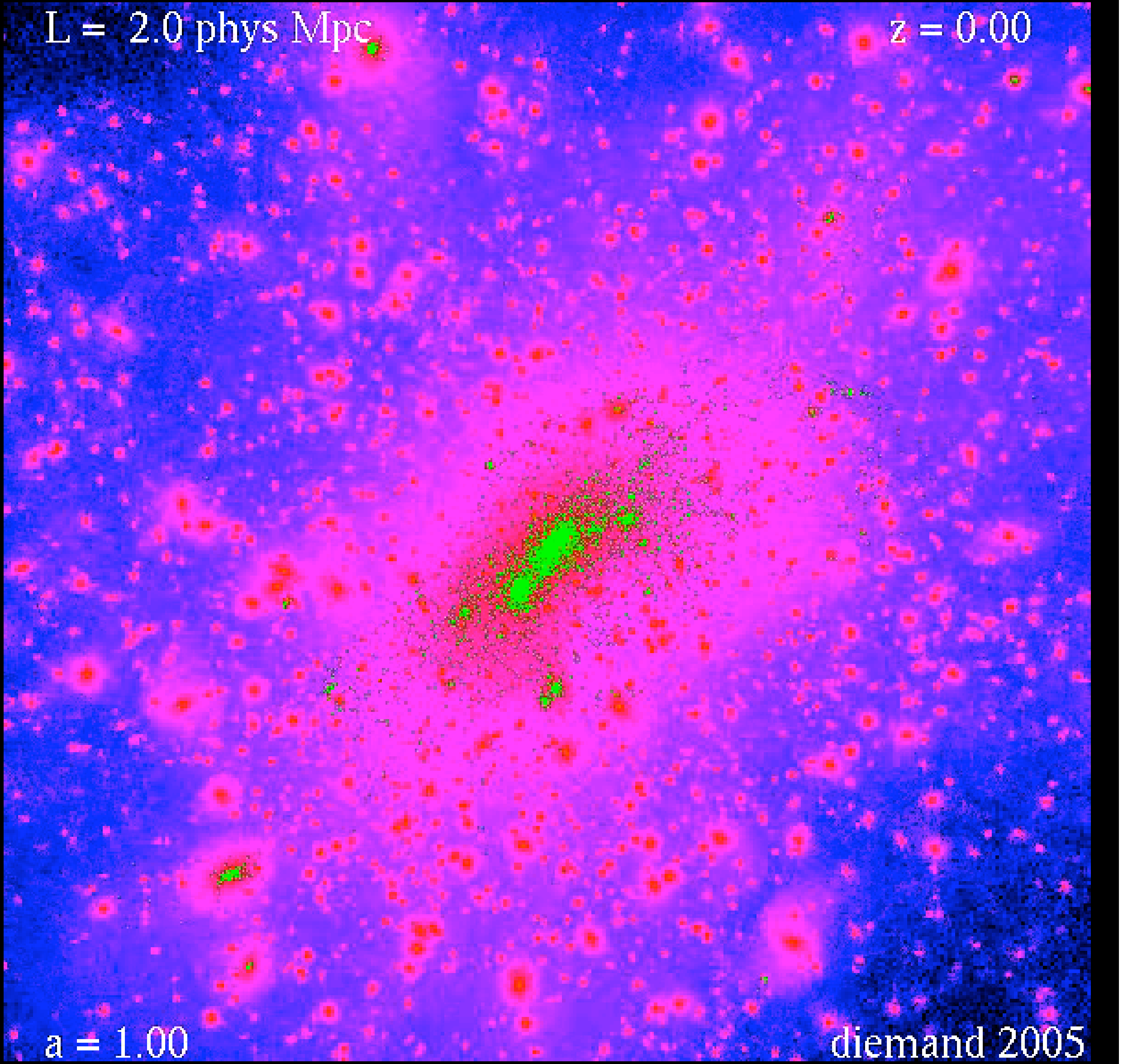
> 3 sigma peaks

-> The inner halo is dominated by material from small, early, high sigma peaks.

That’s why is so difficult to resolve this region numerically.



Present distribution of this fossil material mostly depends on how rare peaks it comes form:



Material form early halos above 3.2 sigma in a z=0 cluster.

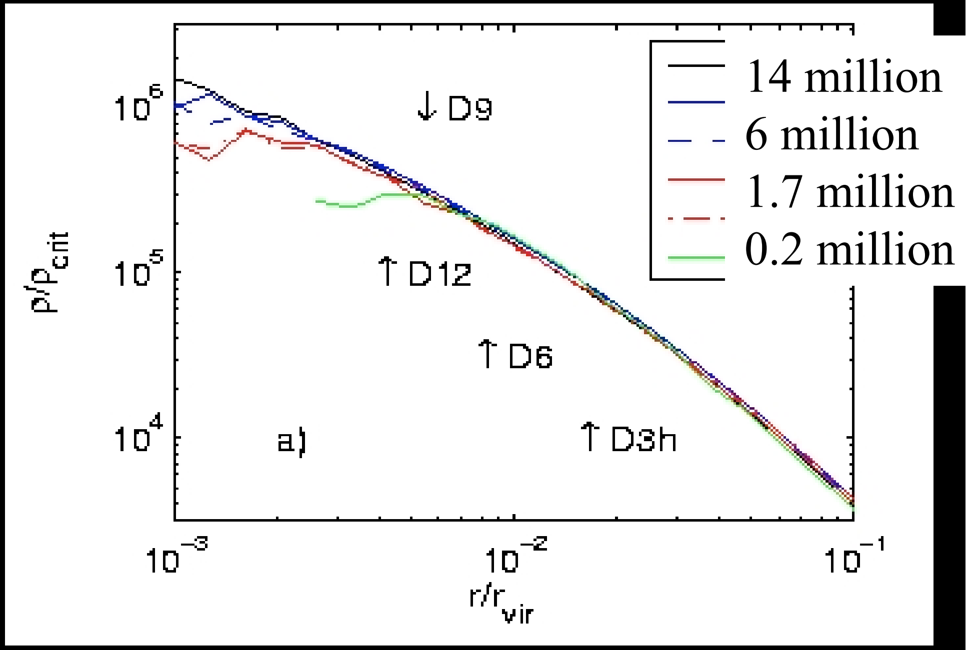
Progenitors were selected at z=10.2 with a minimal mass of 5.2e8 Msun

High sigma subsets have more elongated shapes than the total halo
typically a:b:c=3:1:1 for > 3 sigma material

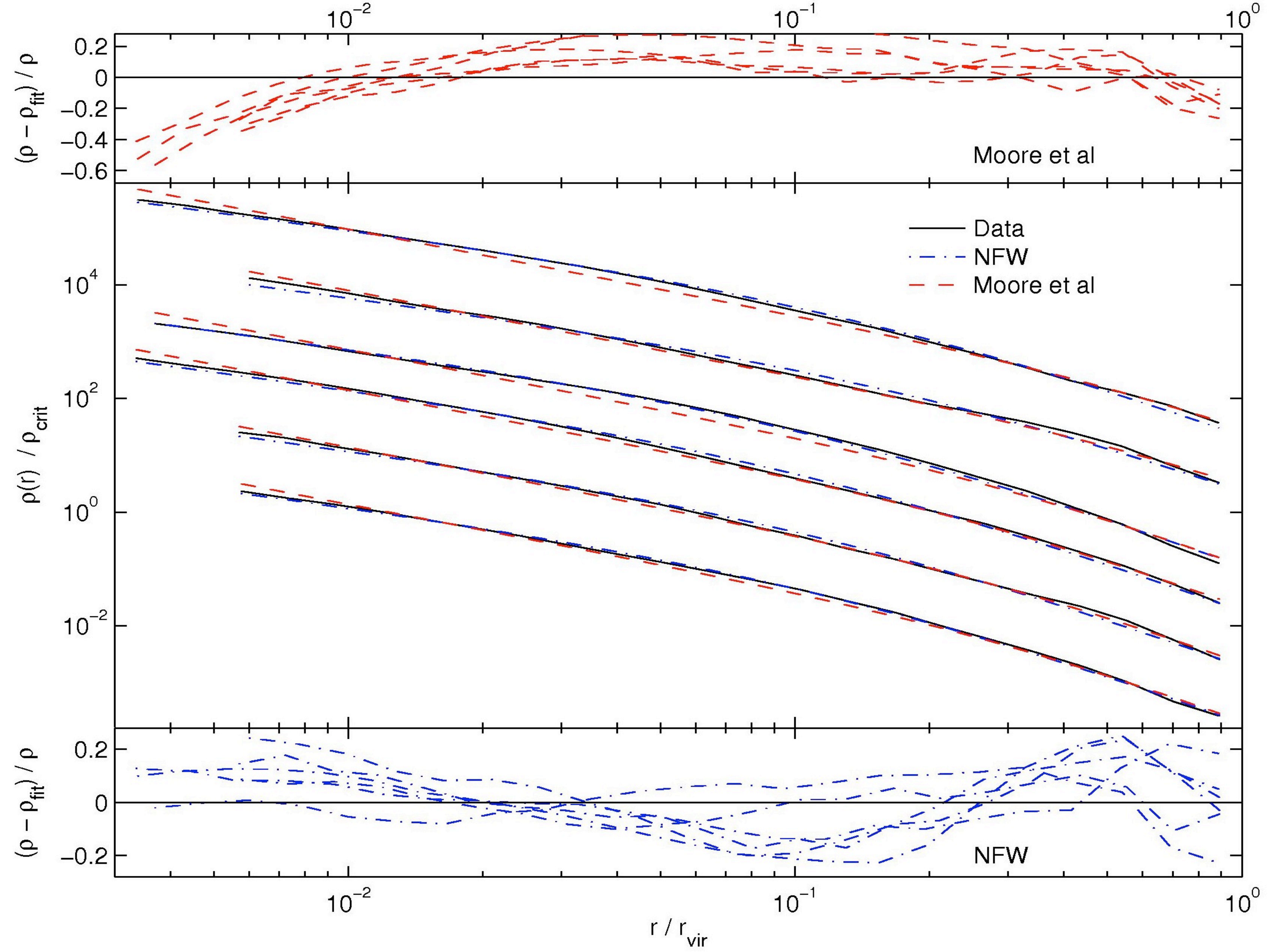
Density Profiles: Convergence tests

- Numerical flattening due to two body relaxation:
  slow convergence, r ~ $N^{-1/3}$
  1 million to resolve 1% of Rvirial,
  1000 to resolve 10%

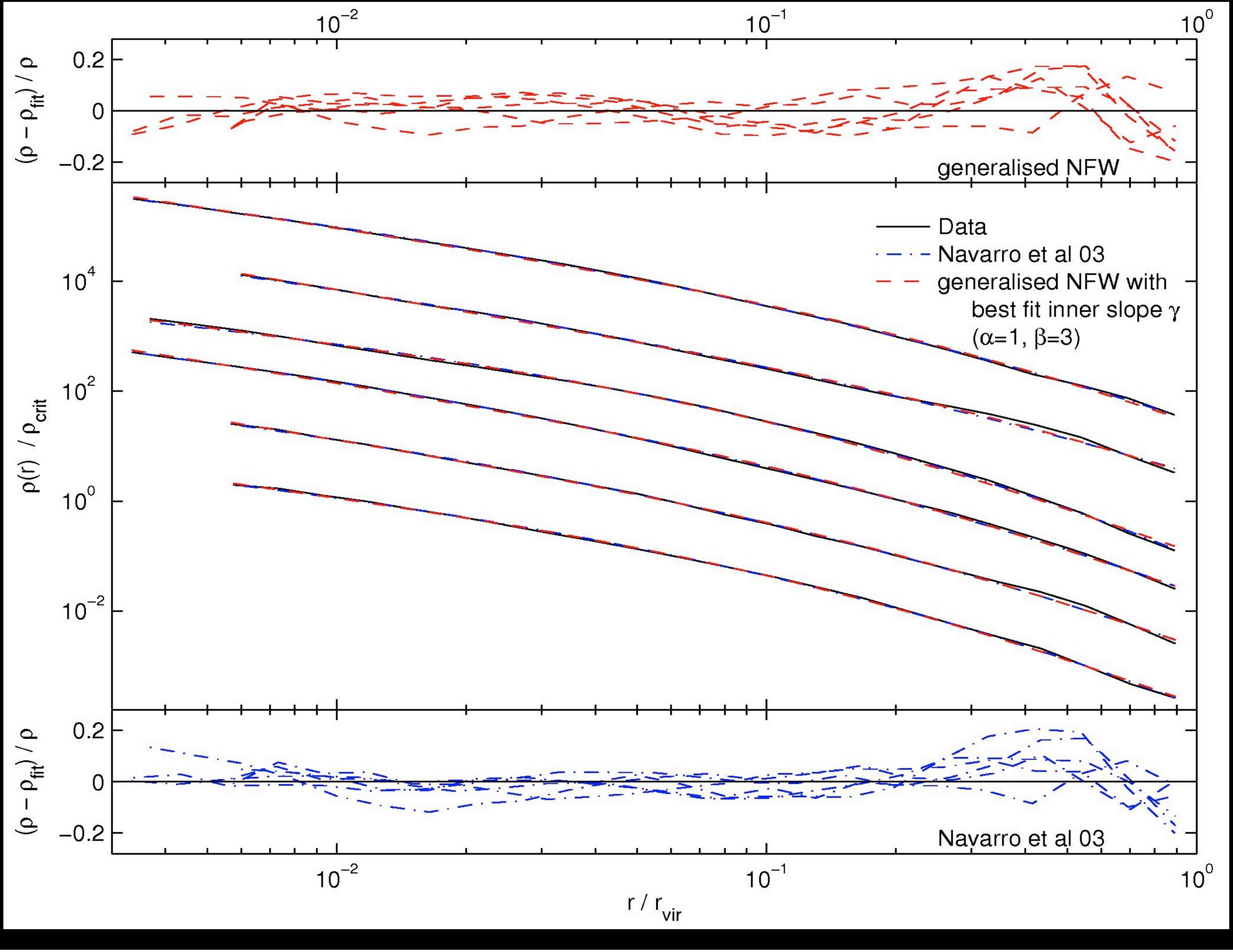
(Moore etal. ApJ 1998; JD etal. MNRAS 2004)



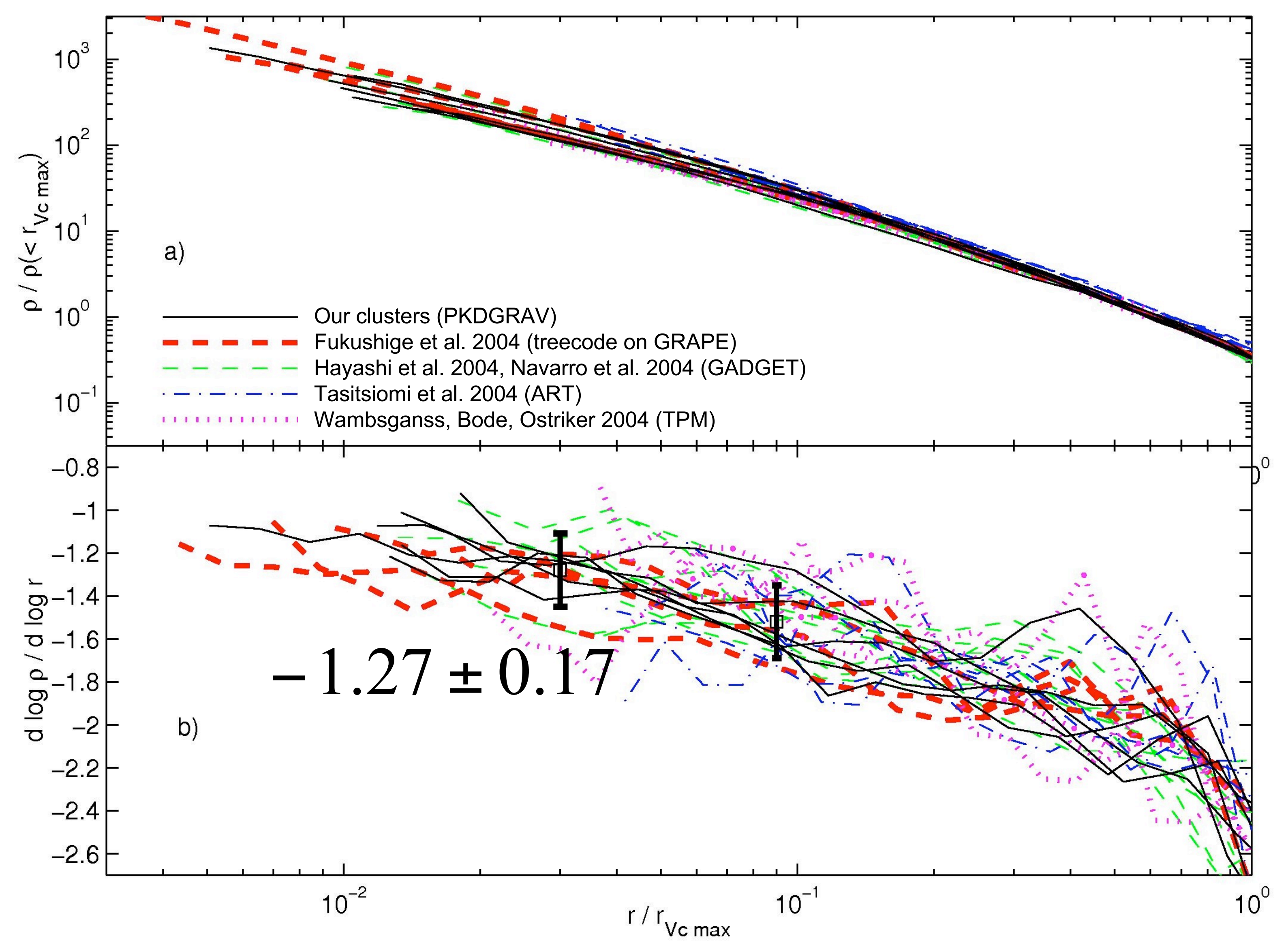
CDM cluster density profiles



CDM cluster density profiles



CDM cluster density profiles



CDM halo profiles

- Agreement among simulators. 5 different groups using different codes and initial conditions.

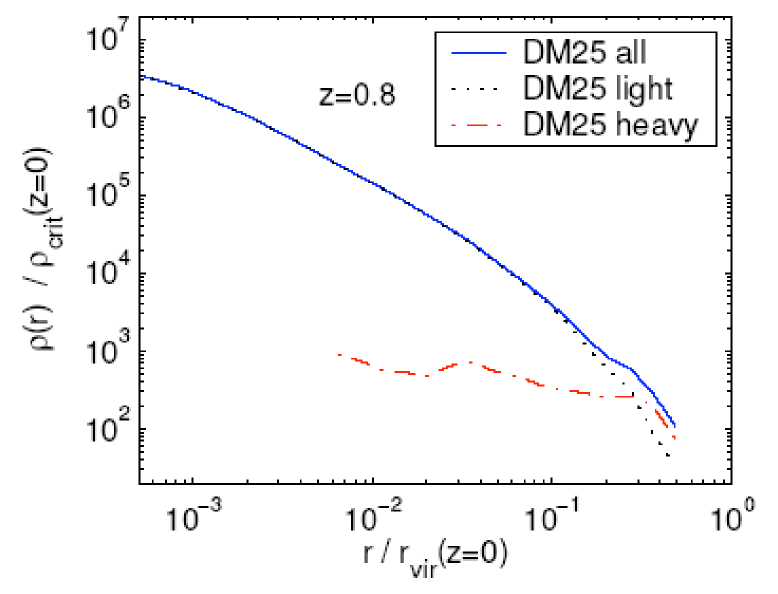
- Generalized NFW profiles with inner slopes of
  -1.2 +- 0.14 fit our 6 cluster profiles very well.
- Cored or cusped in the center? Still open at this resolution...

Resolving the inner halo with a multimass approach

Reducing the high resolution region to the core forming part can reduce the CPU time by more than a factor of 10 !

Now we have also heavier particles inside of the halo. They need to have large force softenings (~0.01 rvir) to avoid mass segregation.

Multimass approach reproduces the density profile for the 6 million particles cluster:

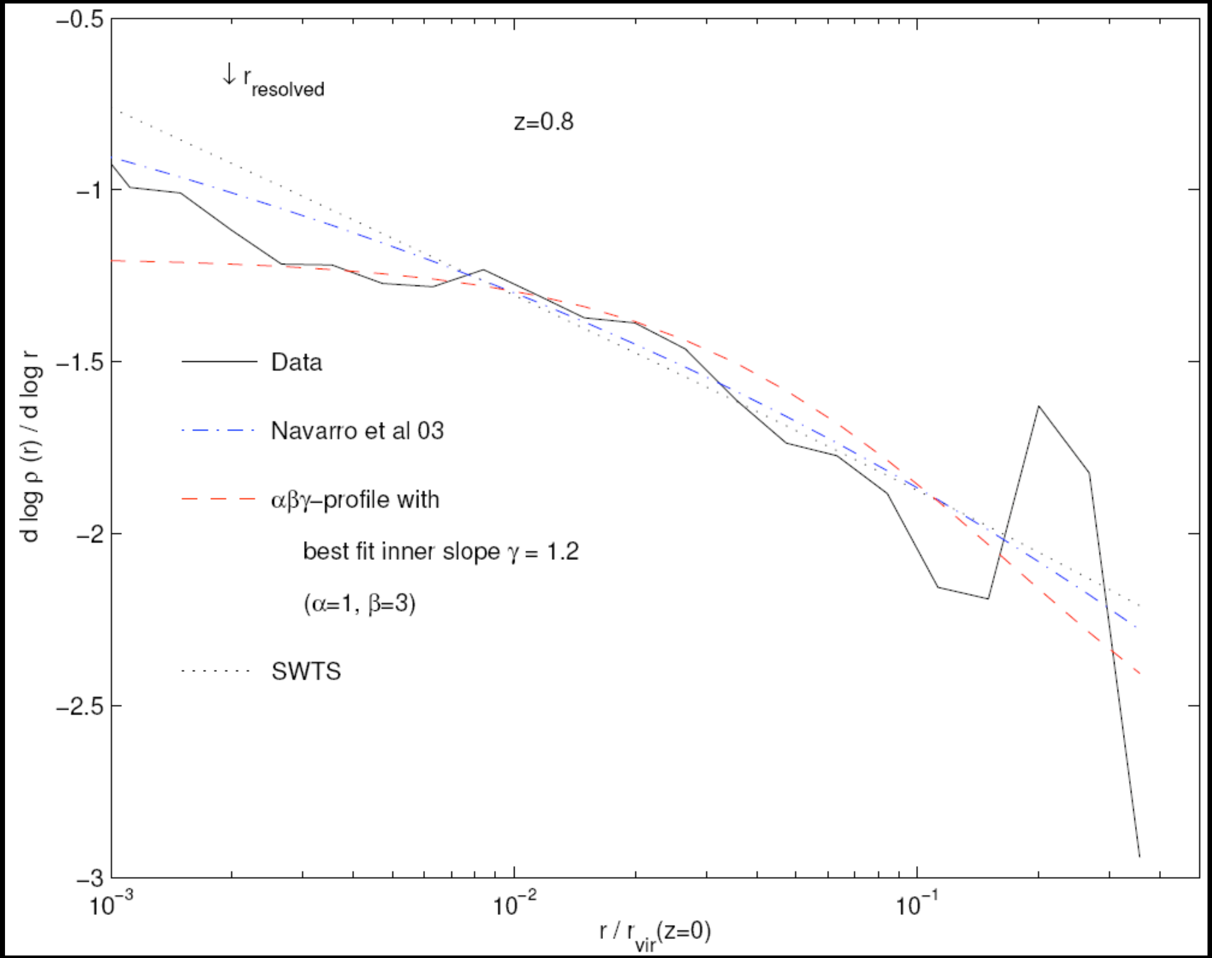


(JD, et al. astro-ph/0504215)

Resolving the inner halo with a multimass approach

Run DM25: effective resolution of 130 million particles in Rvir, stopped at z=0.8

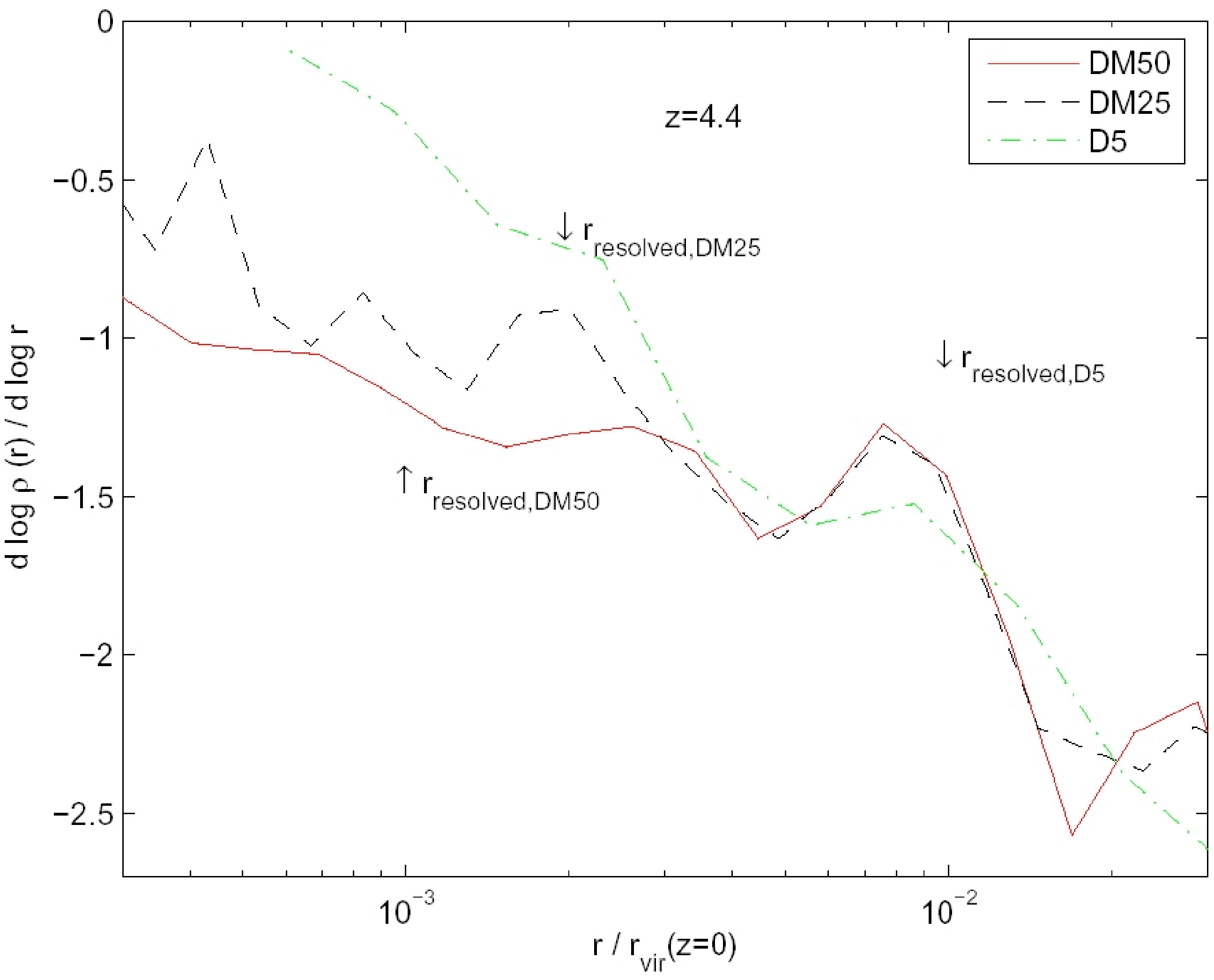
logarithmic slope:



Resolving the inner halo with a multimass approach

Run DM50: effective resolution of one billion particles in Rvir, stopped at z=4.4

logarithmic slope:



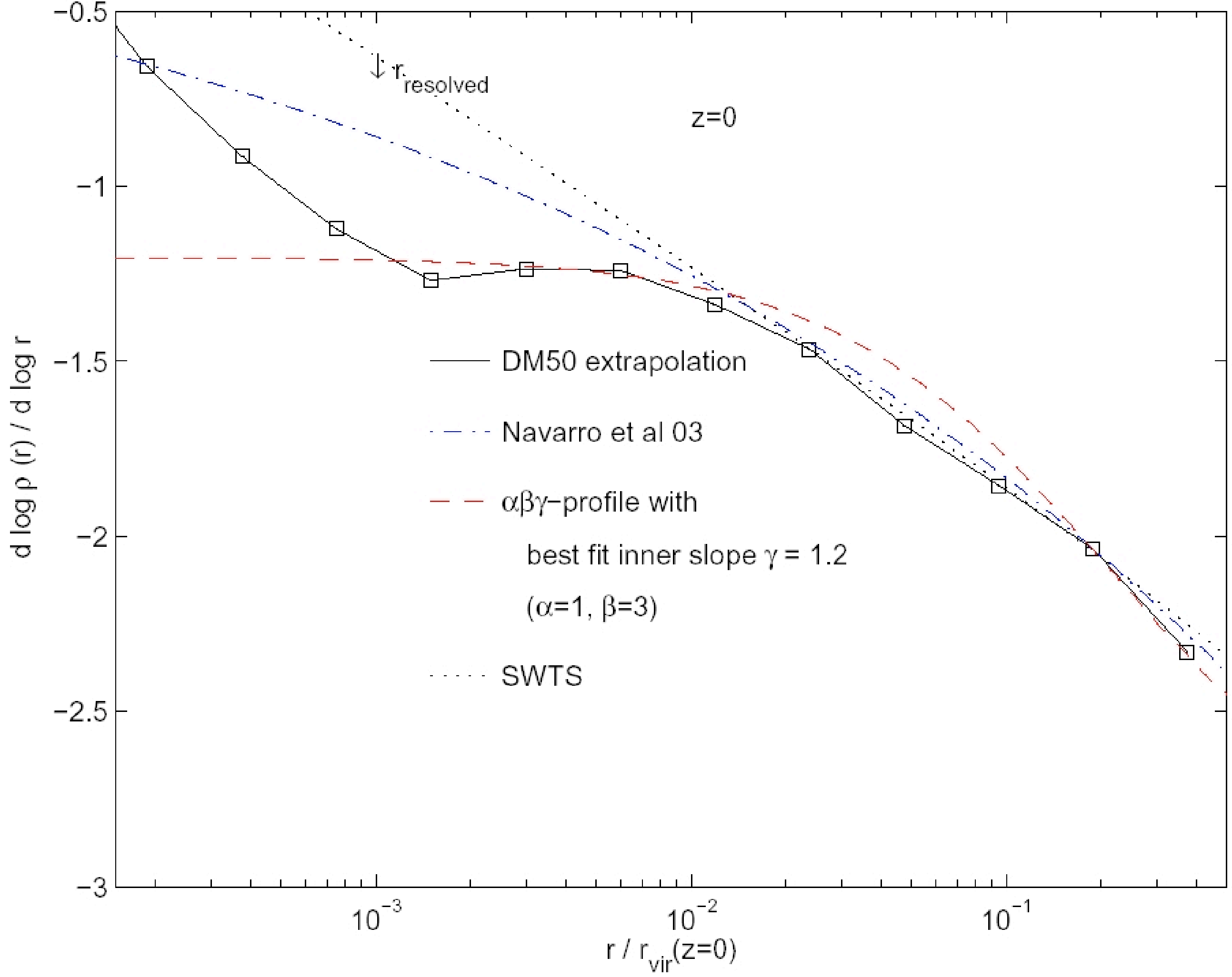
Resolving the inner halo with a multimass approach

Combining run DM50 with lower resolution runs of the same system one can estimate the profile of a billion particle cluster at z=0:

logarithmic slope:

-> indicates that cuspy profiles describe the very inner part better

(JD, et al. astro-ph/0504215)



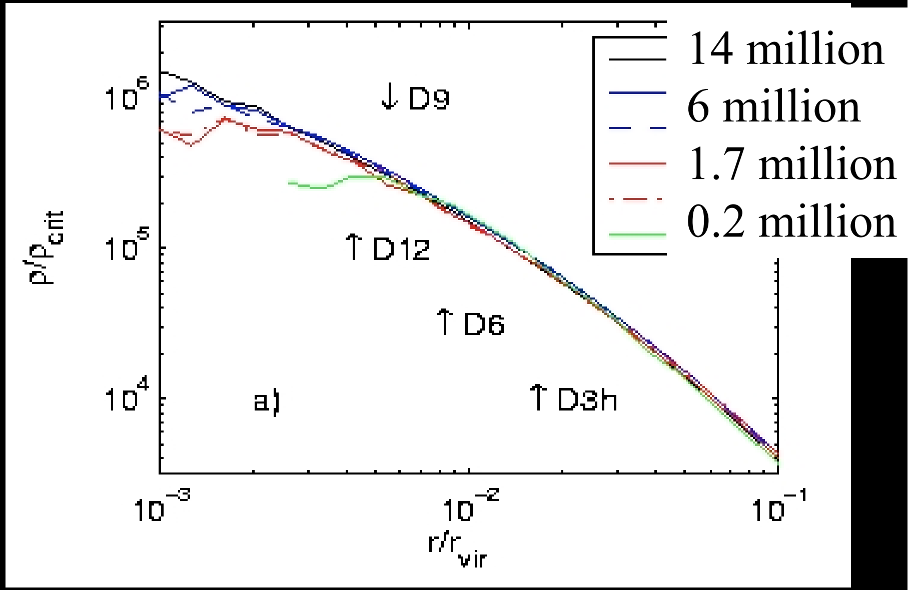
Substructure: Convergence tests

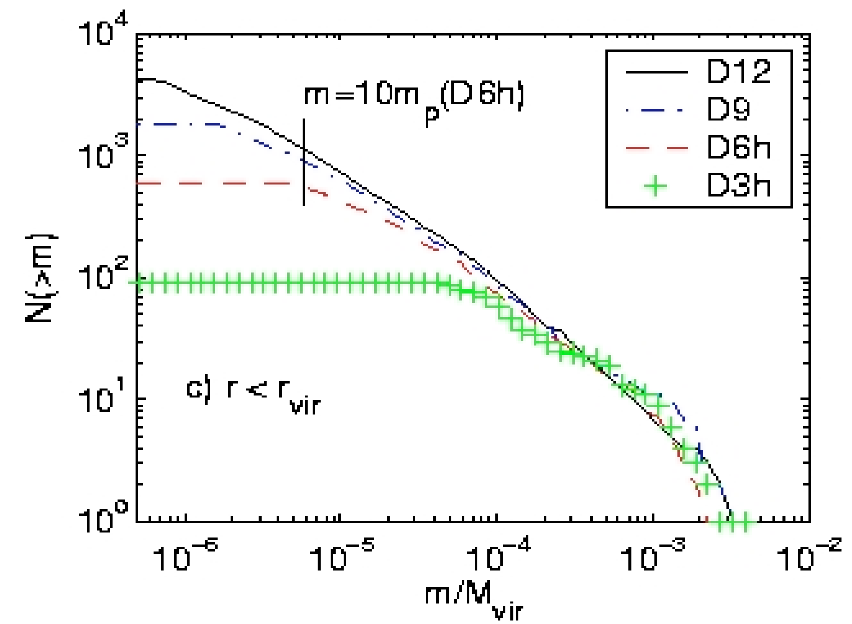
- Numerical flattening due to two body relaxation:
  slow convergence, r ~ $N^{-1/3}$
  1 million to resolve 1% of Rvirial,
  1000 to resolve 10%

  (Moore etal. ApJ 1998; JD etal. MNRAS 2004)

- Numerical Overmerging:

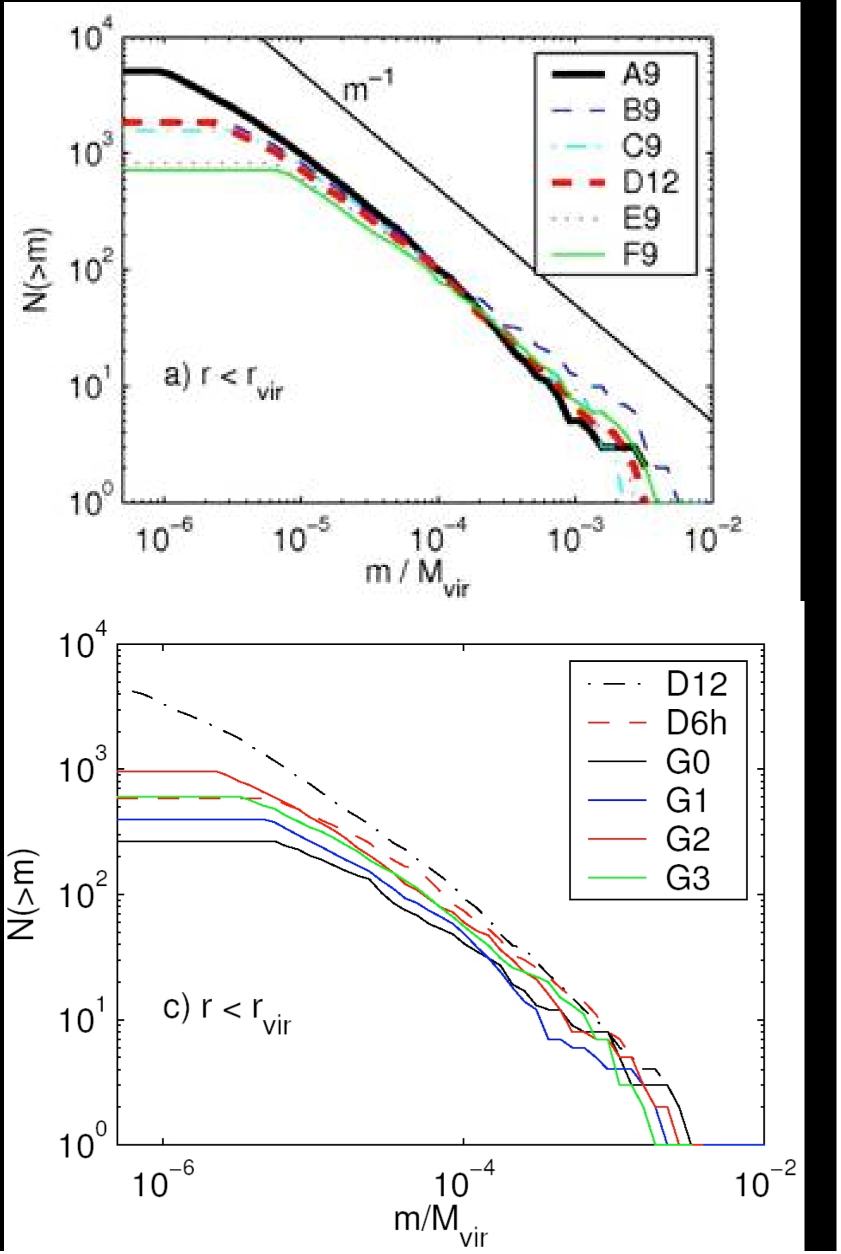
  => incomplete subhalo sample for N<100





Substructure abundance

Steep cumulative mass functions, close to $N(>m) \sim m^{-1}$

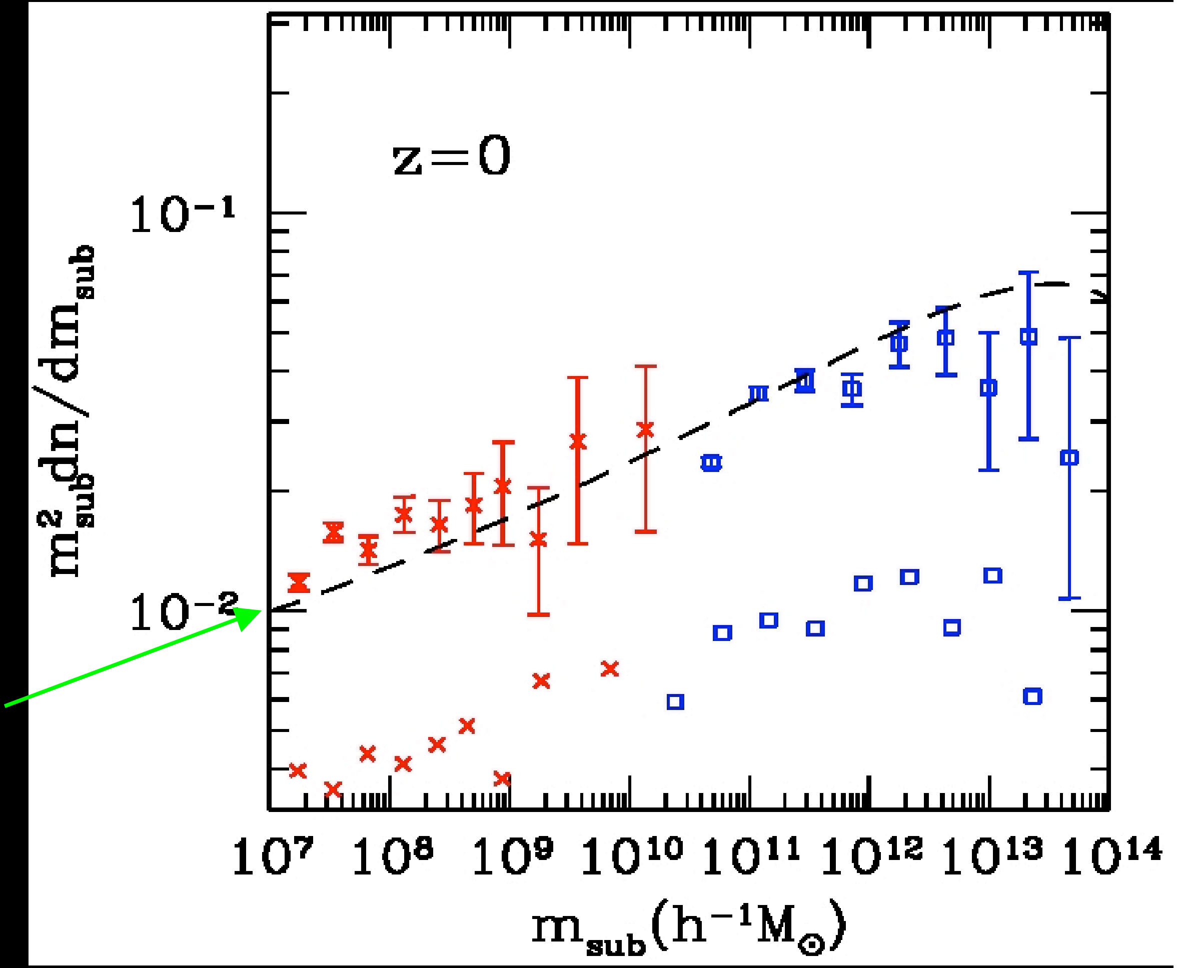


The absolute z=0 abundance depends on the host mass, galaxies have about a factor of 2 less substructure. (Gao et al. 2004)

Hosts of equal similar age and concentration are expected to have similar subhalo abundances.

Substructure abundance

Abundance per unit host mass is independent of the host mass
(Kravtsov et al 2004;
Gao et al. 2004)



From Gao et al., MNRAS, 2004

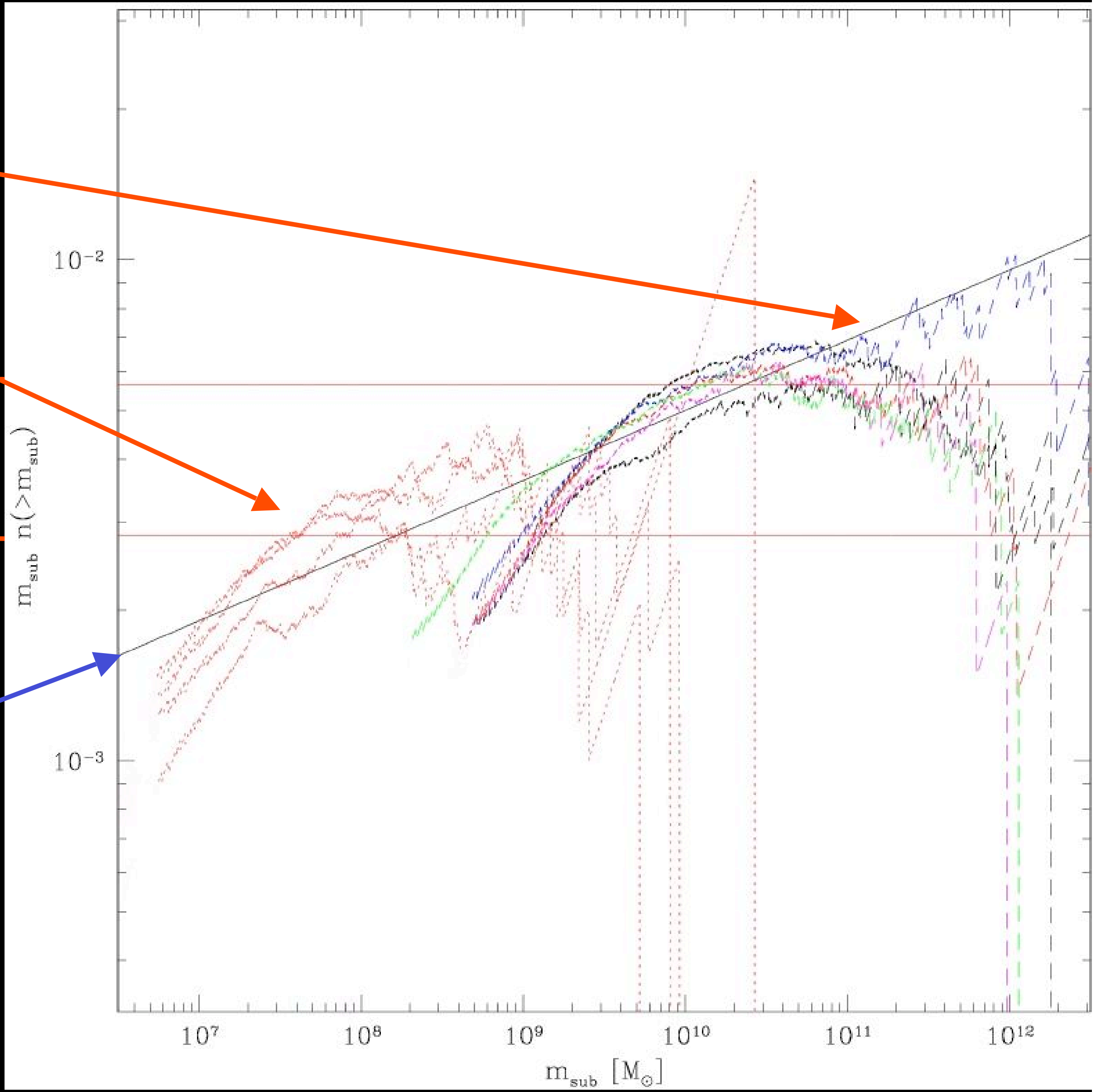
And similar to field halo mass function

Substructure abundance

Same result from our six clusters
and
four galaxies

factor of two between galaxies and clusters

$dn/dm \sim m^{-1.86}$



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Same result from our
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factor of two between
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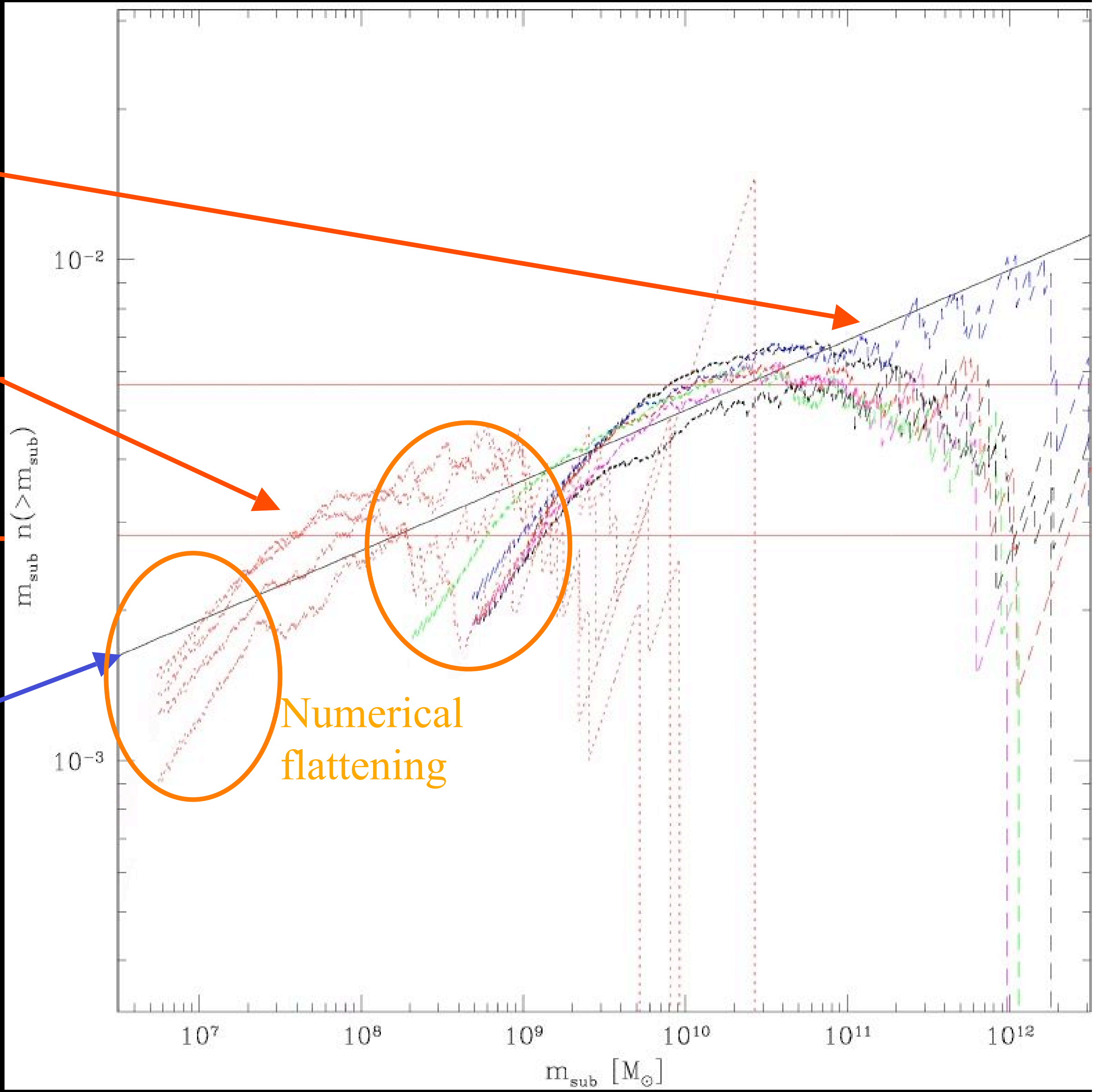
dn/dm ~ $m^{-1.86}$



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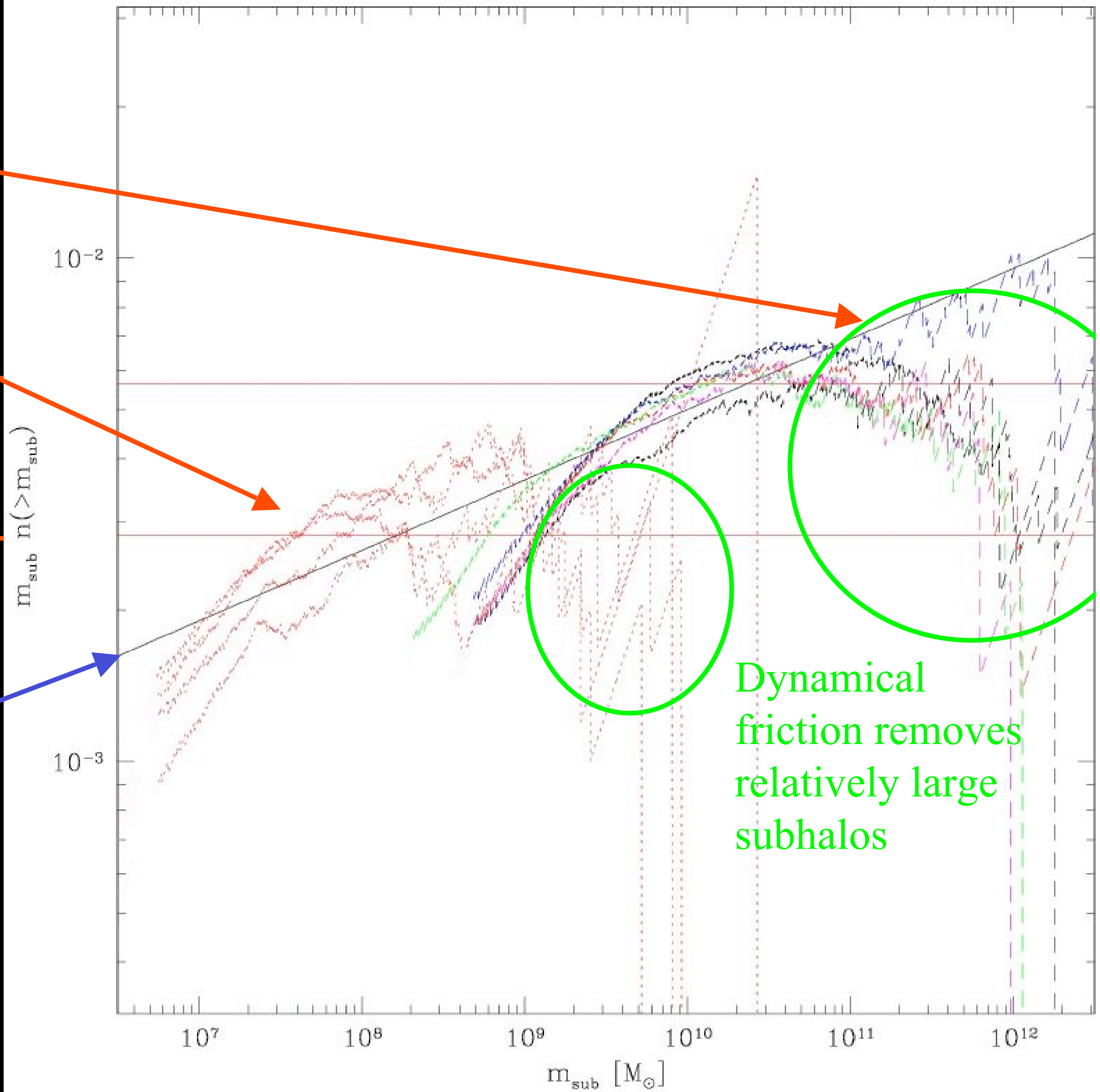
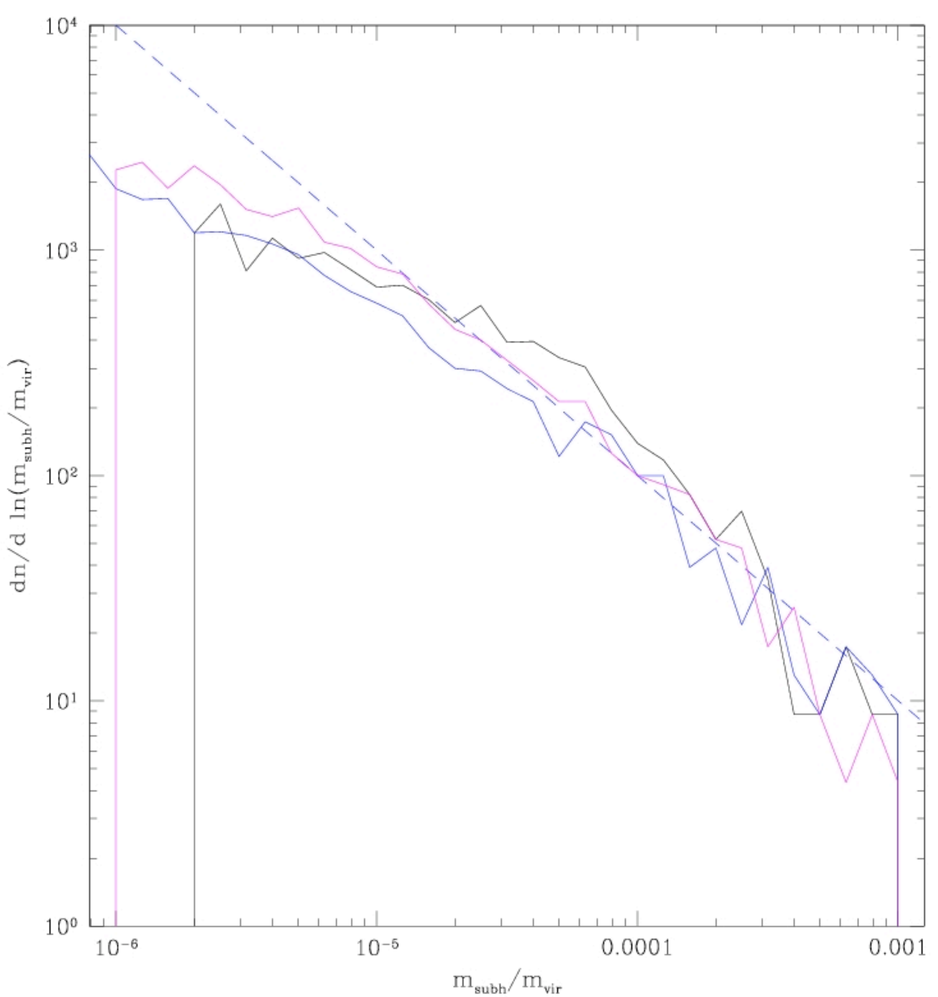


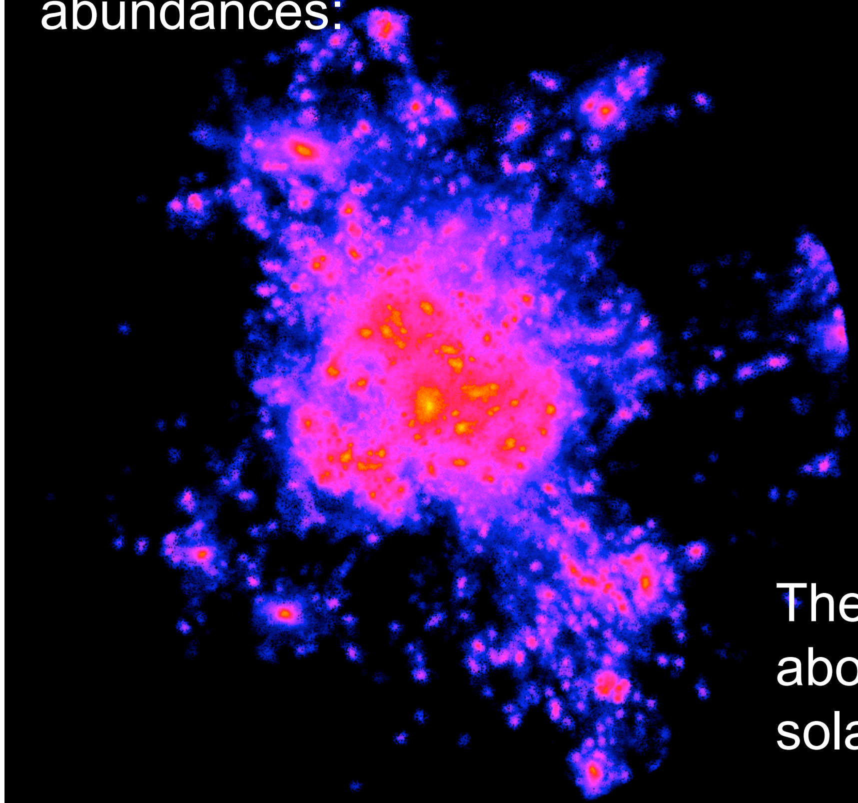
Dynamical friction removes relatively large subhalos

Substructure abundance

Here we compare z=0 clusters with a 0.005 solar mass halo at z=76, mass resolution 10^{-9} solar masses; black line

These are young, low c (~4) systems and we find similar subhalo abundances:





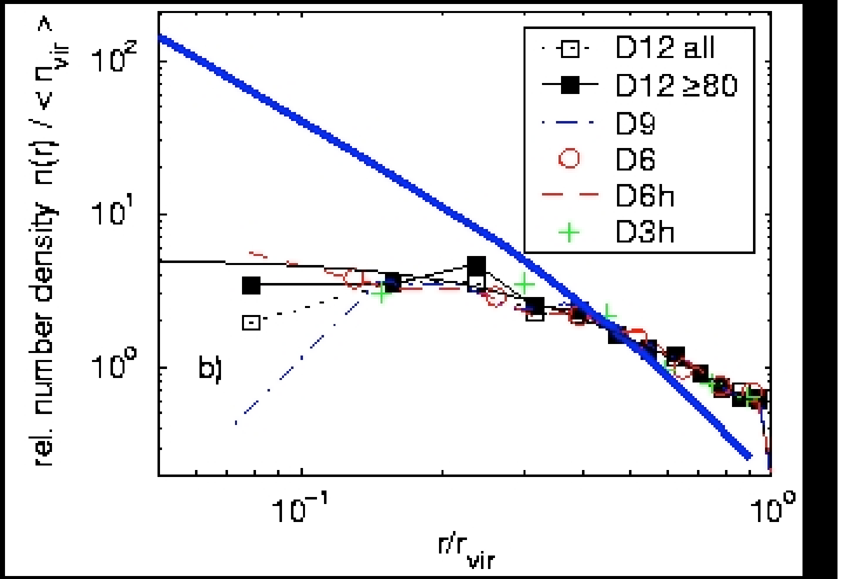
The Milk Way halo has about $5x10^{15}$ subhalos above the SUSY free streaming scale of 10^{-6} solar masses. (JD, Moore, Stadel, 2005)

Substructure number density profiles

Number density profile selected by bound mass (or circular velocity) today is shallower than the DM profile.

Profile is independent of subhalo mass.

n(r) ~ 1/(1+(r/rH)^2) , rH = 1.3 rsNFW

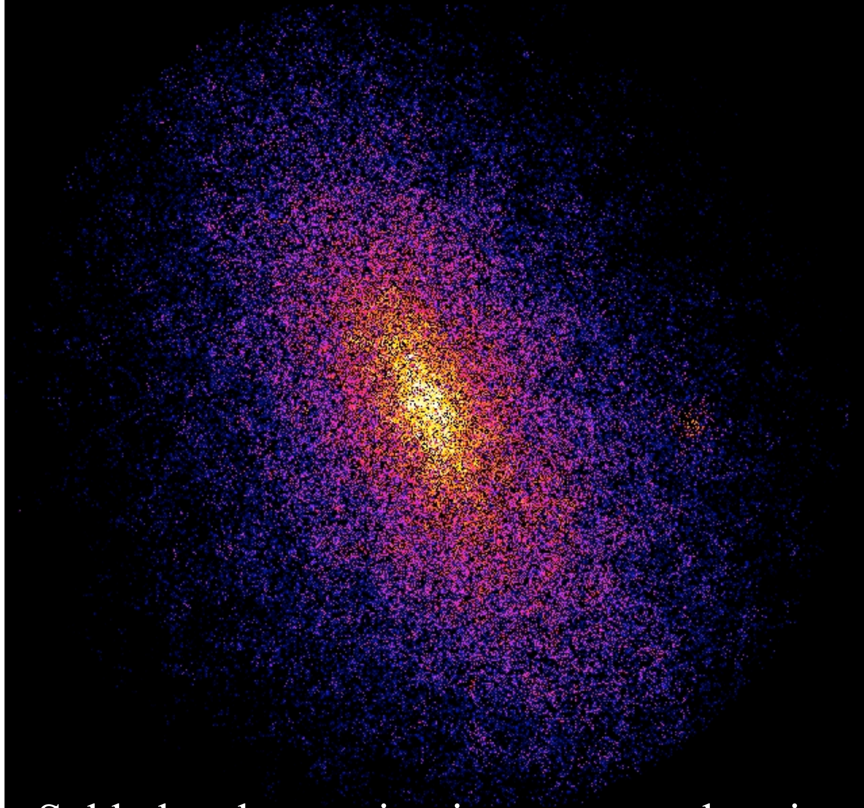


(JD et al. MNRAS 2004)

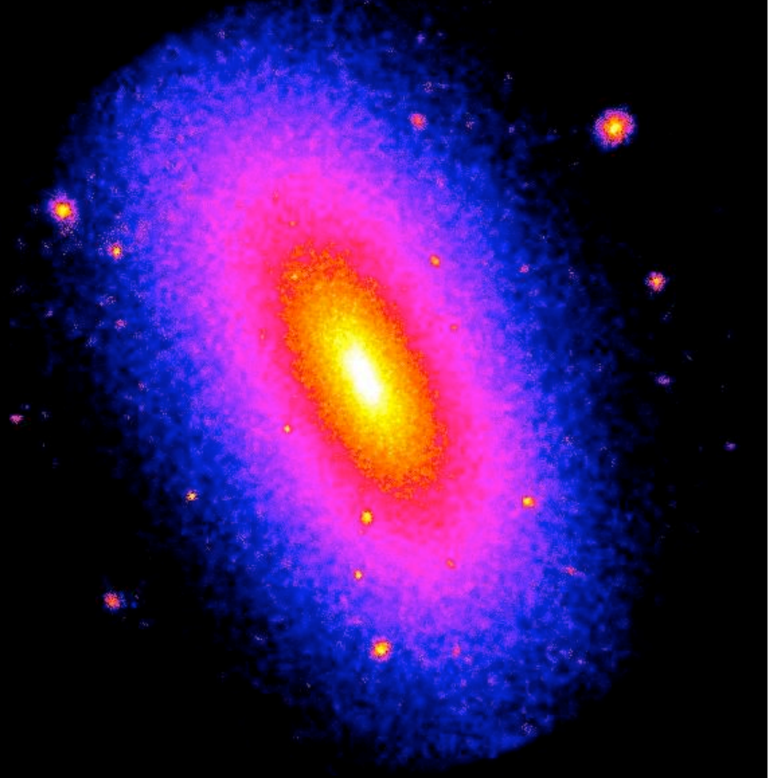
Substructure number density profiles

Subhalos in the inner part of CDM halos have usually lost most of their mass due to tidal striping (Kravtsov et al. 2004; Gao et al. 2004). They only survive in high resolution simulations:

The inner 10% of a galaxy halo
resolved with 1 million particles in Rvir



Same region and object
resolved with 27 million p.



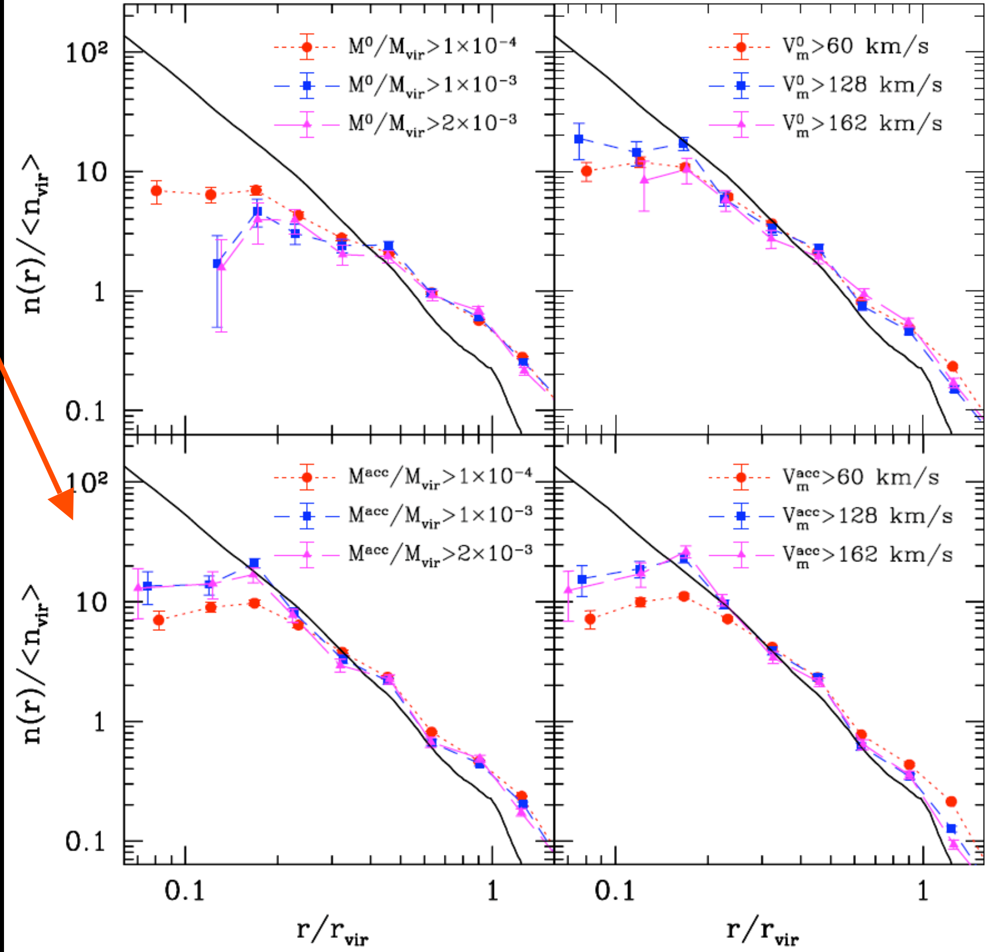
Subhalos destruction is rare, mass loss is common: 83% of the well resolved (over 100 particles) halos in a cluster forming region at z=2 survive as subhalos (with at least 10 bound particles) until z=0. (Ghigna et al. 2000, JD et al. 2004)

Substructure number density profiles

The number density of galaxies in groups and clusters roughly trace the mass, and not the z=0 selected subhalos. Three related ways to obtain a realistic galaxy distribution in CDM subhalos:

1) Simply select halos by mass or circular velocity <u>before accretion</u>

from Nagai & Kravtsov, ApJ 2004



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1) Simply select halos by mass or circular velocity <u>before accretion</u> (Nagai & Kravtsov, ApJ 2004)

2) Use a semi analytic model to populate N-body halos (Springel et al. MNRAS 2001, Gao et al. MNRAS 2004, Kravtsov et al. ApJ 2004)

Substructure number density profiles

The number density of galaxies in groups and clusters roughly traces the mass and not the z=0 selected subhalos. Three related ways to obtain a realistic galaxy distribution in CDM subhalos:

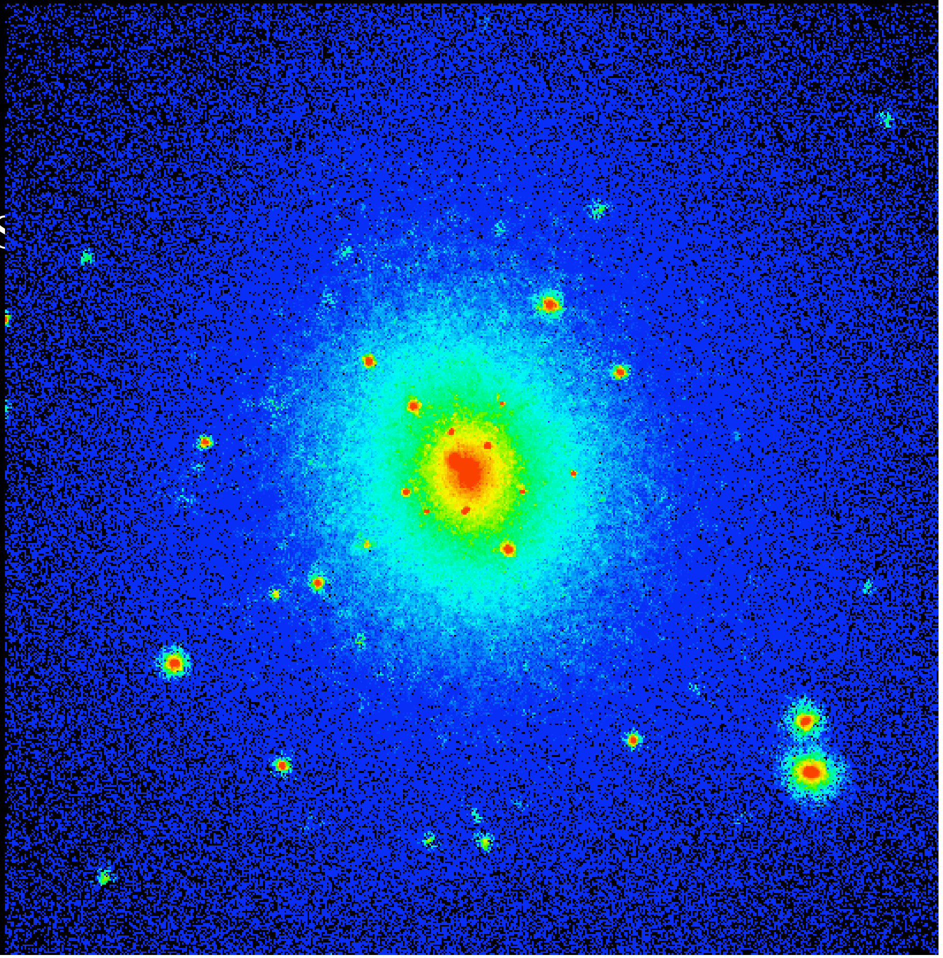
1) Simply select halos by mass or circular velocity before accretion (Nagai &

2) Use a semi analytic model to populate
(Springel et al. MNRAS 2001, Gao et al. MNRAS

3) High resolution hydro simulations:

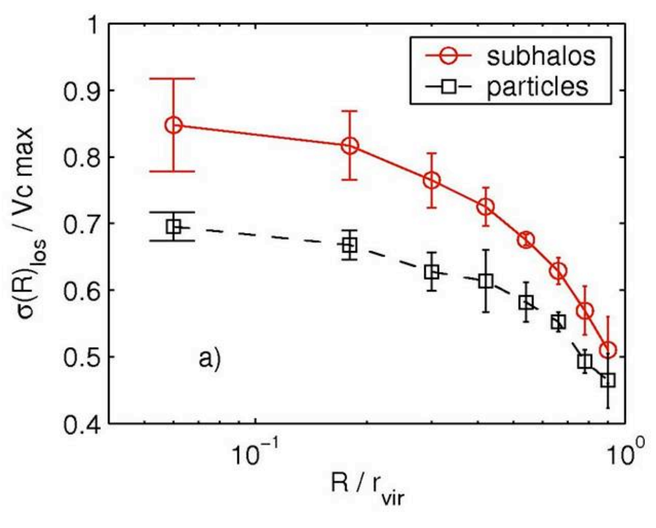
n_SUB(r) now follows the dark matter density profile down to 5% of the virial radius

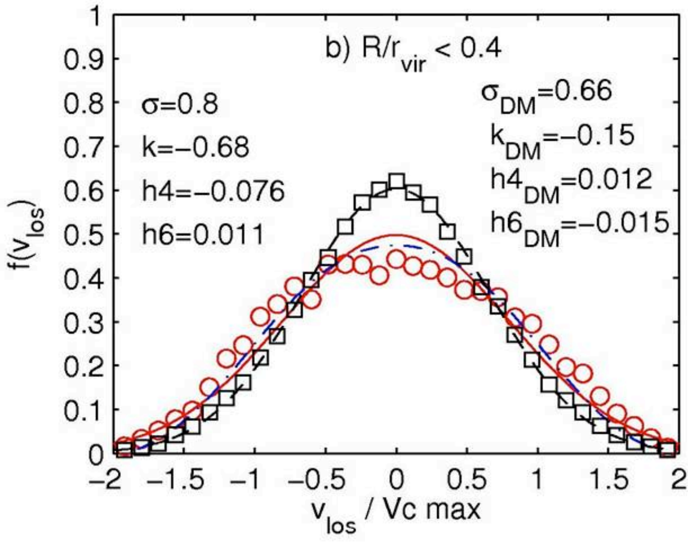
from A. Maccio et al. 2005



Other substructure properties

•Subhalos move faster than the DM background, and their velocities distributions are not Maxwellian
(JD etal, MNRAS, 352, 535, 2004)





• Inner density profiles resemble those in field halos (Kazantzidis etal, ApJ, 608, 663, 2004) and subhalos are slightly more spherical (Moore etal, MNRAS 354, 522, 2004)

•Cluster SUBhalo orbits extend out to 3 virial radii (Moore et al, IAU195, 2004)

Summary

- inner density profiles seem to have steep cusps, on average $\sim r^{-1.2}$. Cusps are very difficult to resolve since they only show on small scales which are usually affected by numerical relaxation.
- over 100 particles per subhalo are needed to overcome numerical overmerging.
- large abundance of subhalos and steep mass functions similar to field halo mass functions.
- same age halos have self similar substrucure properties, from cluster to subsolar mass scales.
- resolved subhalos are more extended than the dark matter