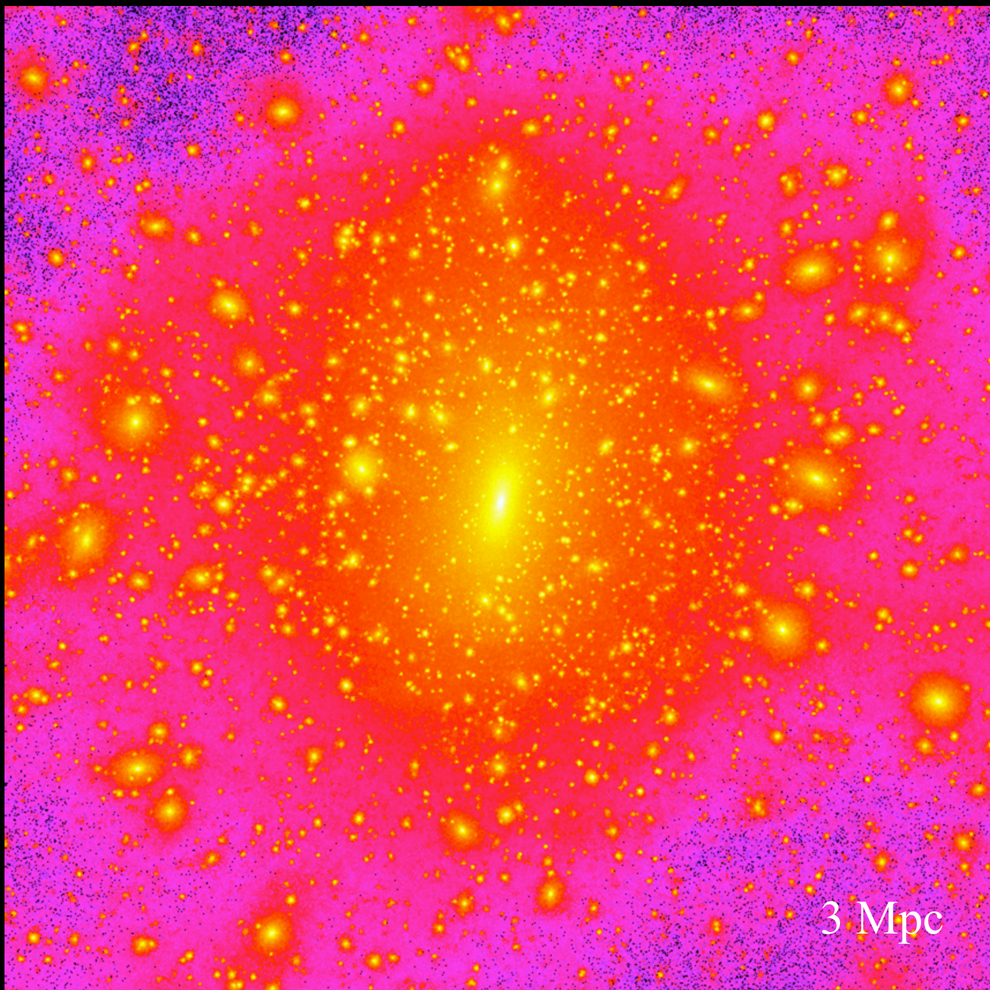
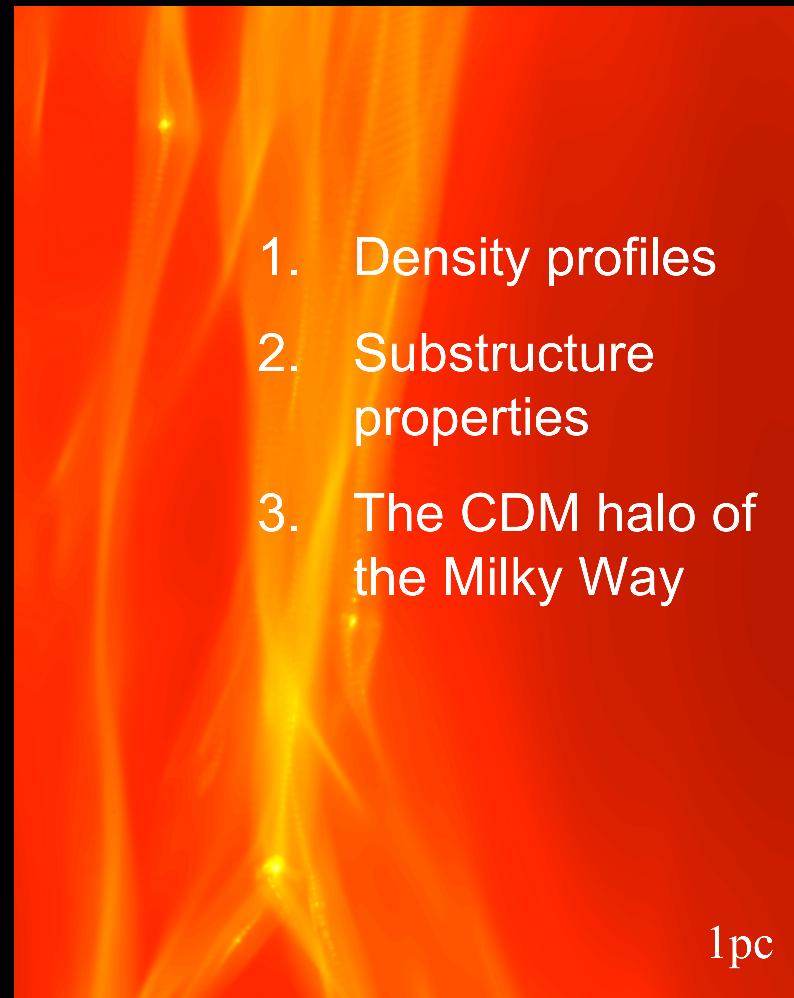
The distribution of cold dark matter in our Galaxy





1. Density profiles
2. Substructure properties
3. The CDM halo of the Milky Way

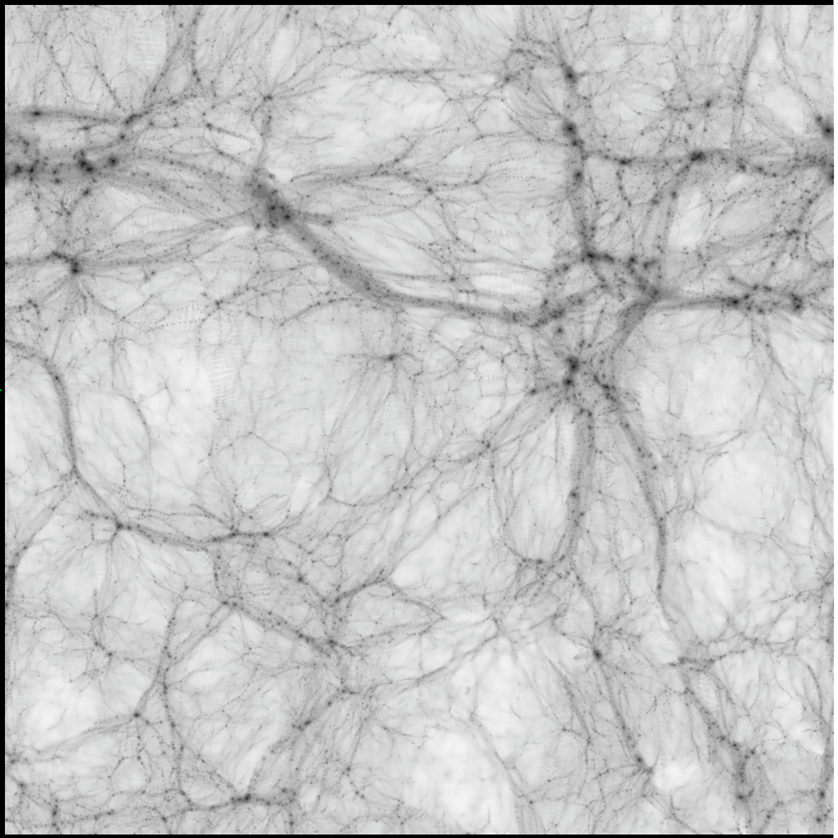
Jürg Diemand, Piero Madau (UCSC) and
Ben Moore, Joachim Stadel (University of Zurich)

Why Cold Dark Matter ?

- Cluster dynamics (Zwicky ~1930), galaxy dynamics

- BBN, CMB, IaSNe + Cluster abundance -> non-baryonic dark matter dominates structure formation

- The large scale dark matter distribution of the concordance LCDM model agrees well with galaxy surveys (SDSS, 2dF, …) using plausible recipes to populate halos with galaxies



…

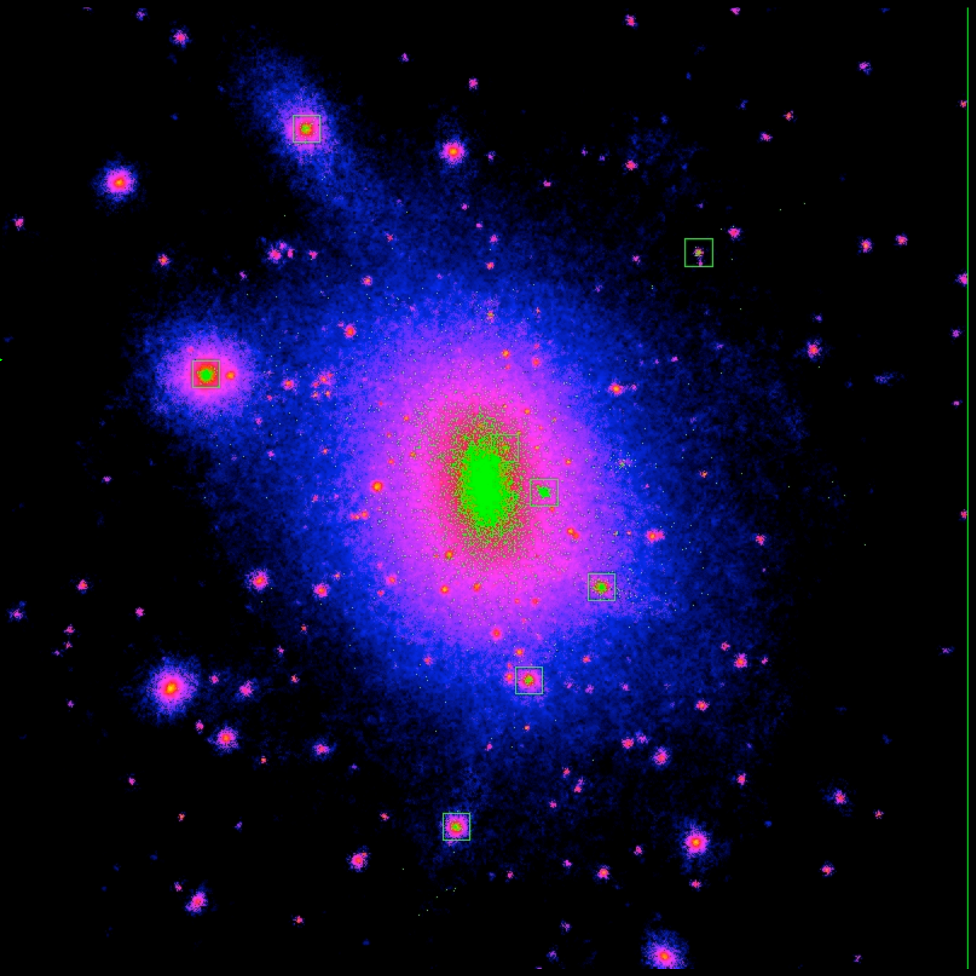
- Lyman-alpha forest observations and the early reionisation (1st year WMAP data) favour the concordance LCDM model over models with less small scale power (like WDM)

- There is a promising CDM candidate: The neutralino. It would form structures down to 10^{-6} solar mass scales

And why not CDM …?

On smaller scales
(i.e. inside the halos)
there could be problems with
CDM:

a) too much substructure
b) too steep density profiles
c) angular momentum
distribution



But all three points depend
enough on complicated, not well
understood and modelled gas-
physics to leave hope for
reconciliation.

This talk: Halo structure in a CDM only Universe

Well defined problem (no free parameters),
well suited for numerical simulation.

Simulations have revealed much about DM halo structure,
some open questions remain:

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

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

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

CAUTION:
Only some of these results can be applied directly to the real Universe

Method : Cosmological N-body simulations

- 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 (softened) gravitational interactions between these particles with PKDGRAV by J. Stadel & T. Quinn

- Limitation : Finite resolution leads to:

-> flatter inner density profiles due to numerical relaxation

(JD et al. MNRAS, 348, 977, 2004)

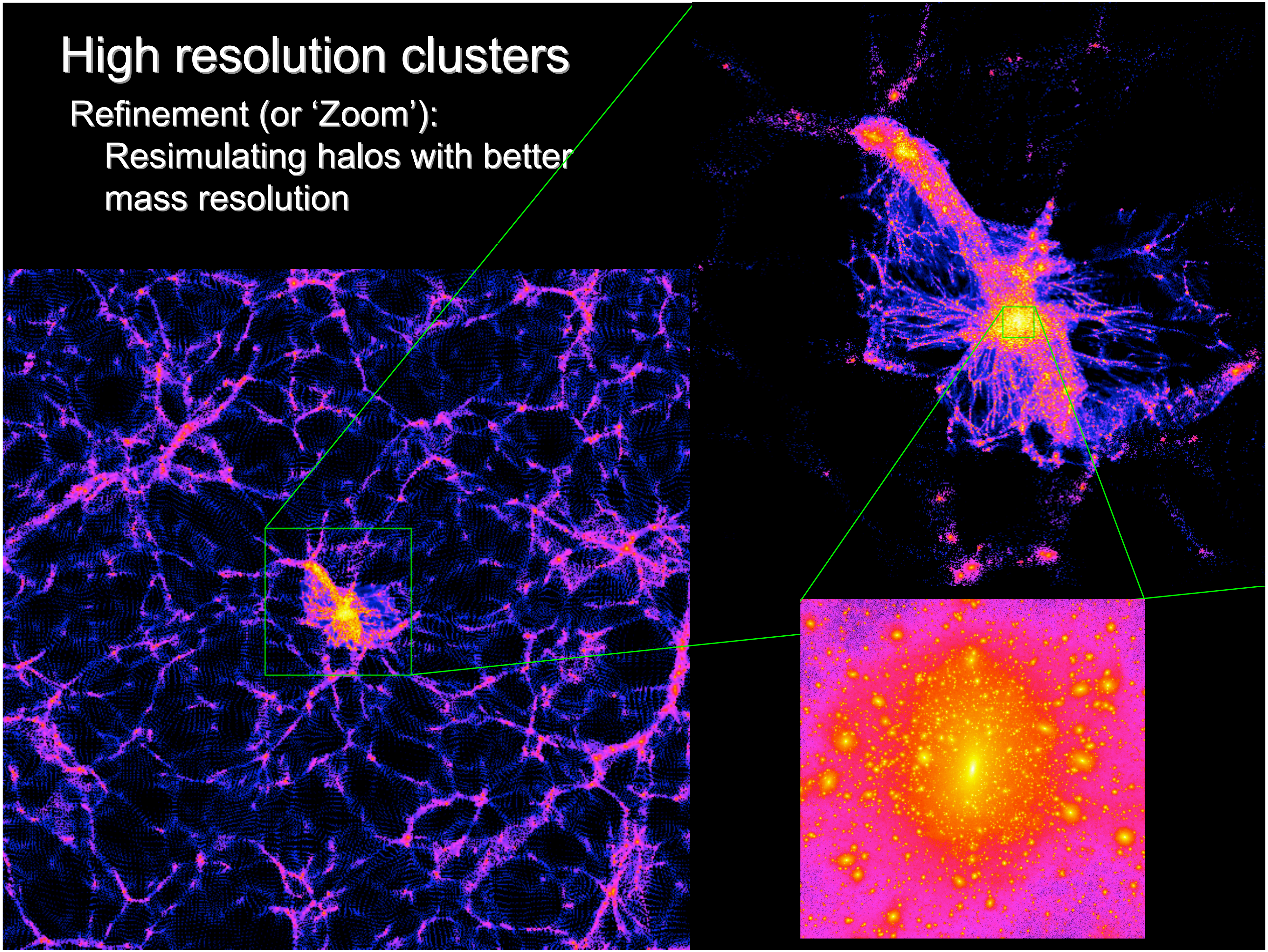
-> numerical overmerging (halos appear too smooth)

(Moore et al. ApJ, 457, 455, 1996)

High resolution clusters

Refinement (or 'Zoom'):

- Resimulating halos with better mass resolution

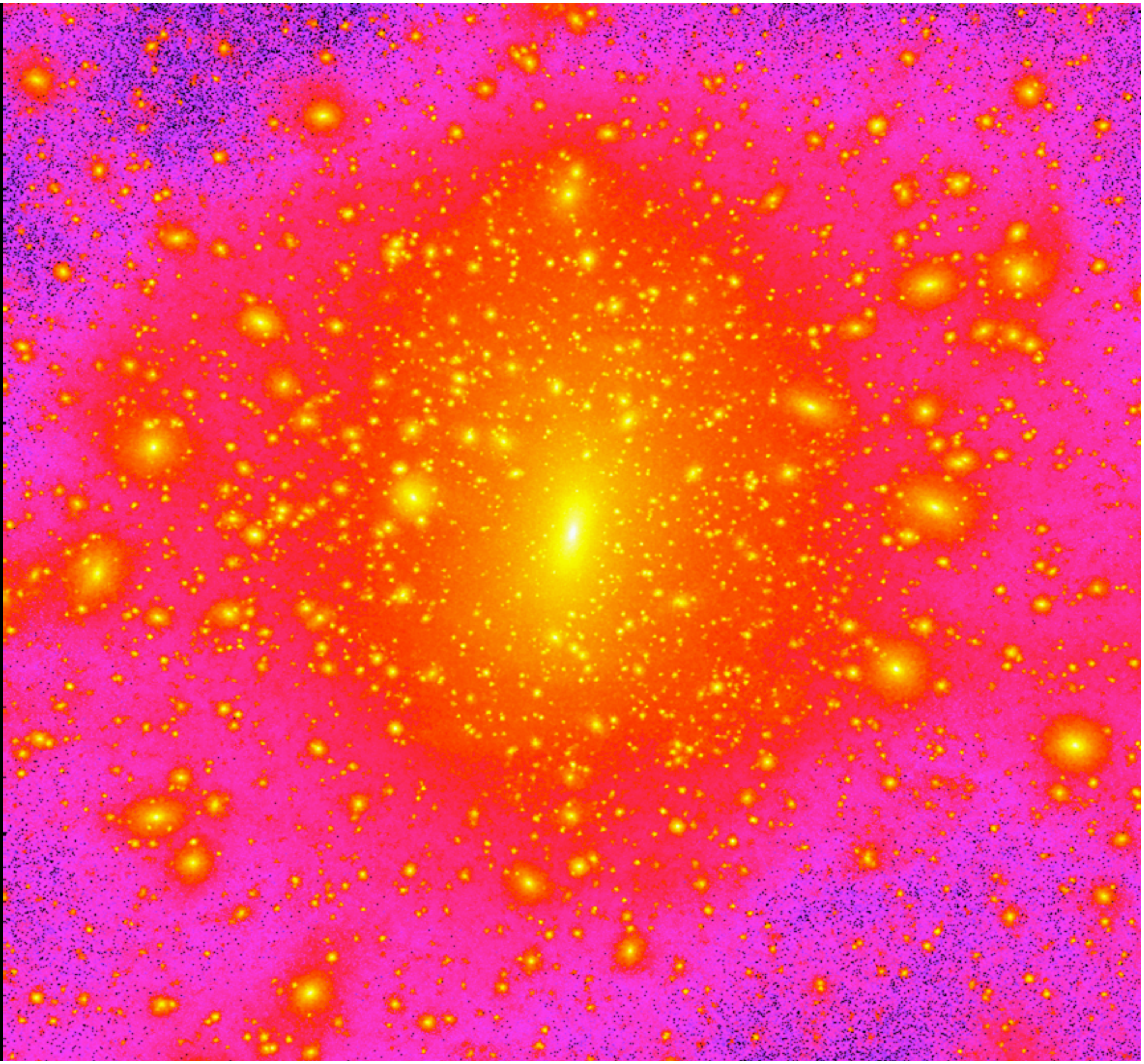


Highest resolution numerical simulations of the structure of dark matter halos

10^5 steps

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

High mass and force resolution



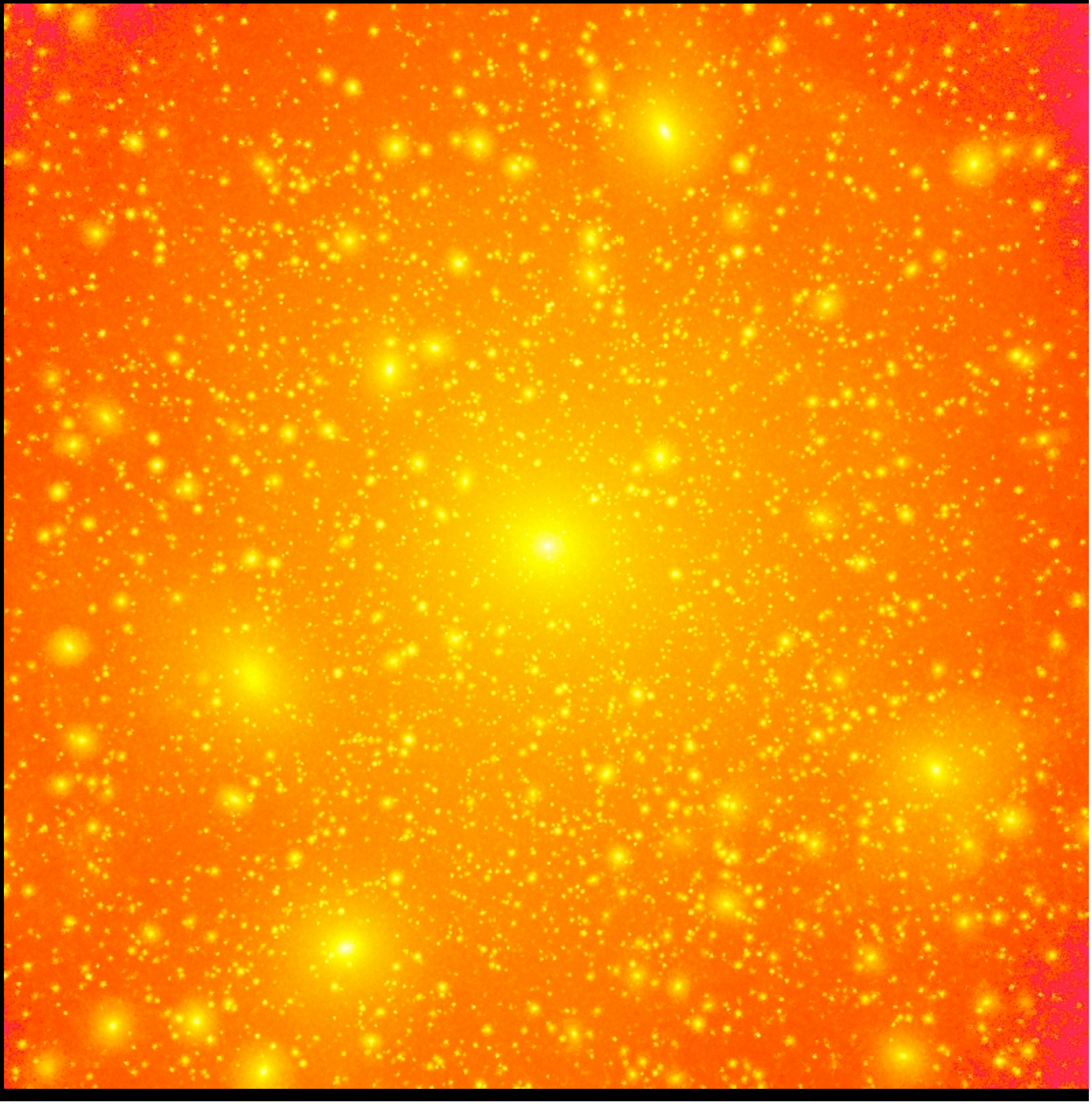
Formation of a CDM cluster

movies are available at www.nbody.net

Now running:
A galaxy halo
with
Nvir = 130 million

Here only half of the virial radius at z=0.5 is shown

In total this run will take about 300’000 CPU hours on NASA’s Columbia Supercomputer



CDM density profiles: adiabatic contraction

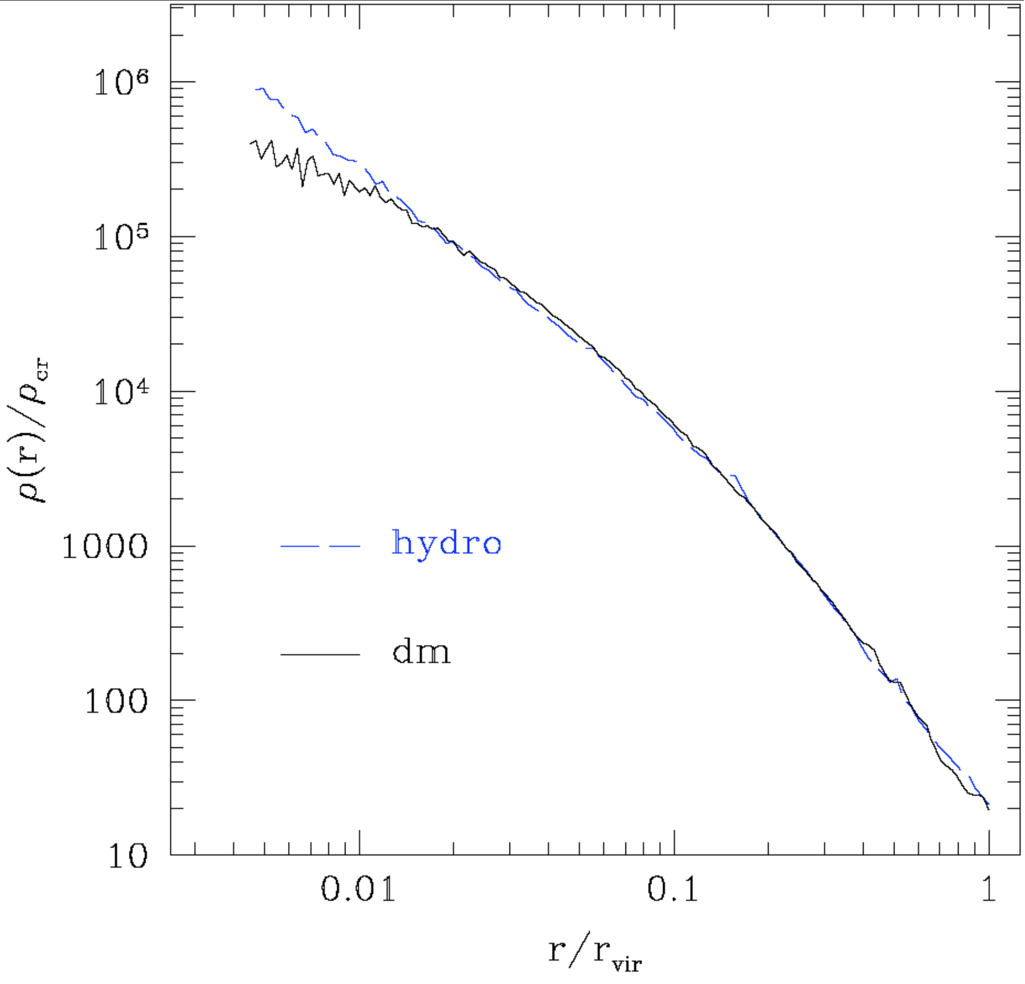
The baryons cool and go into the inner region of the halo where the galaxy forms

The dark matter contracts in response to the deepening potential well, the DM profile becomes steeper

This greatly increases the expected DM annihilation signal from the Galactic centre (Prada et al, PRL, 2005)

The slope of their final DM cusp (-1.4 to -1.9) depends on the assumed DM only profile (-1 to -1.5)

-> How steep are DM only inner density profiles?



Maccio et al. astro-ph/0506125

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-> How steep are DM only inner density profiles?

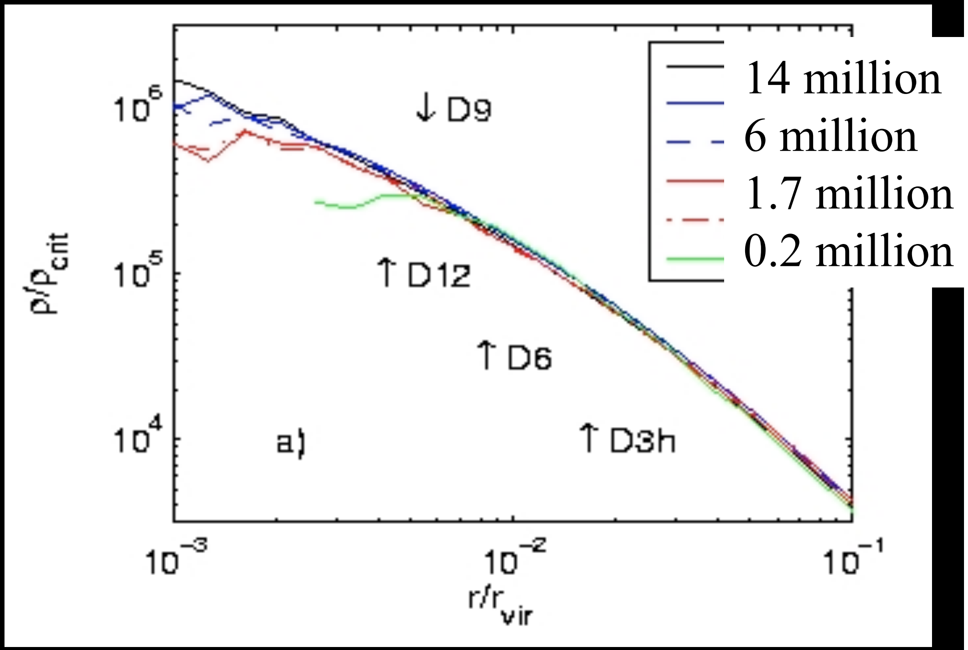
Substructure inner profiles resemble those of field halos
(Kazantzidis et al., ApJ, 608,663,2004)

Most of them are dark matter dominated
(dwarf galaxies, dark DM sattelites)
-> little or no adiabatic contraction

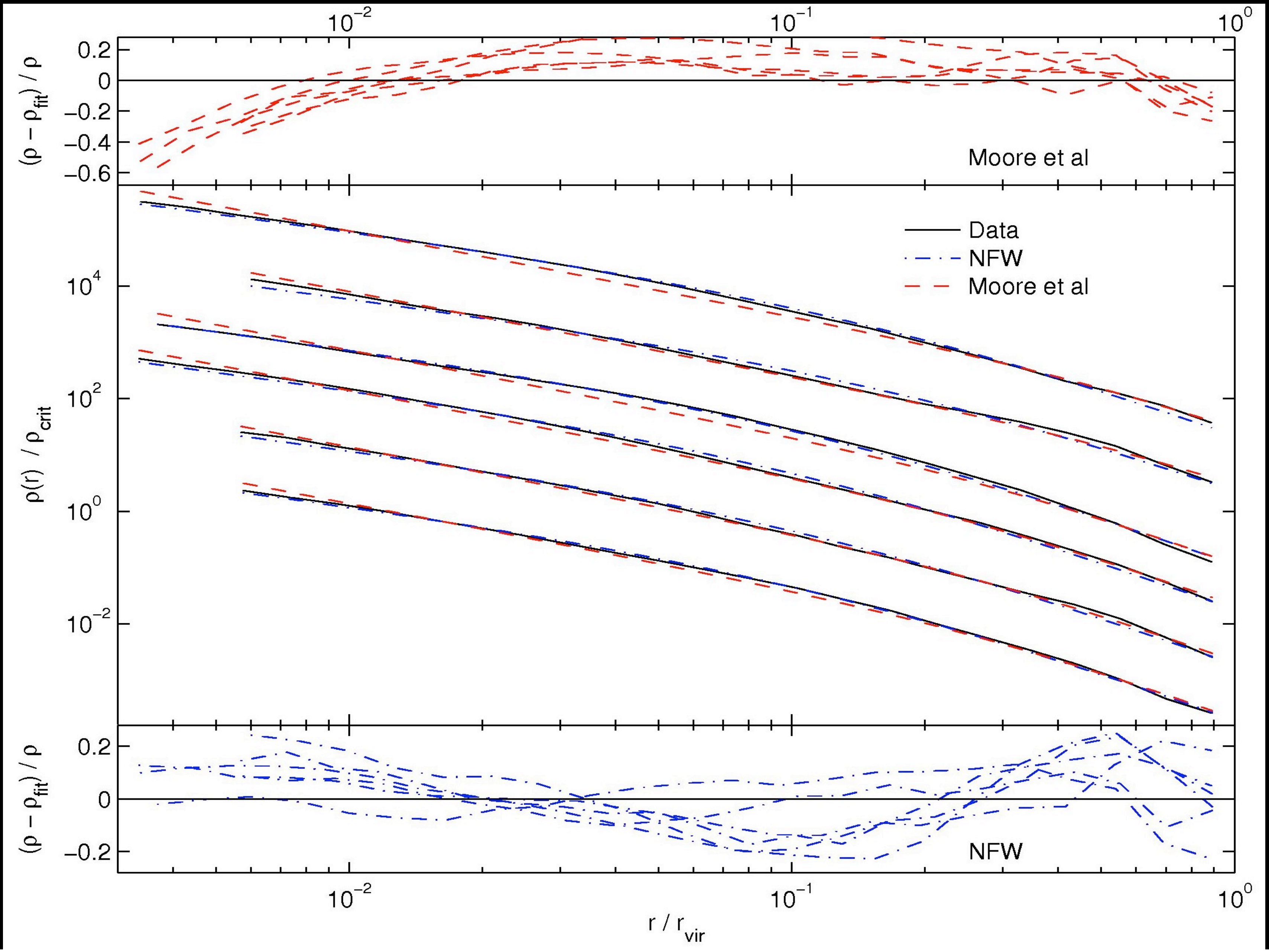
CDM density profiles: convergence tests

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

(JD et al. MNRAS, 353, 624, 2004)



CDM cluster density profiles



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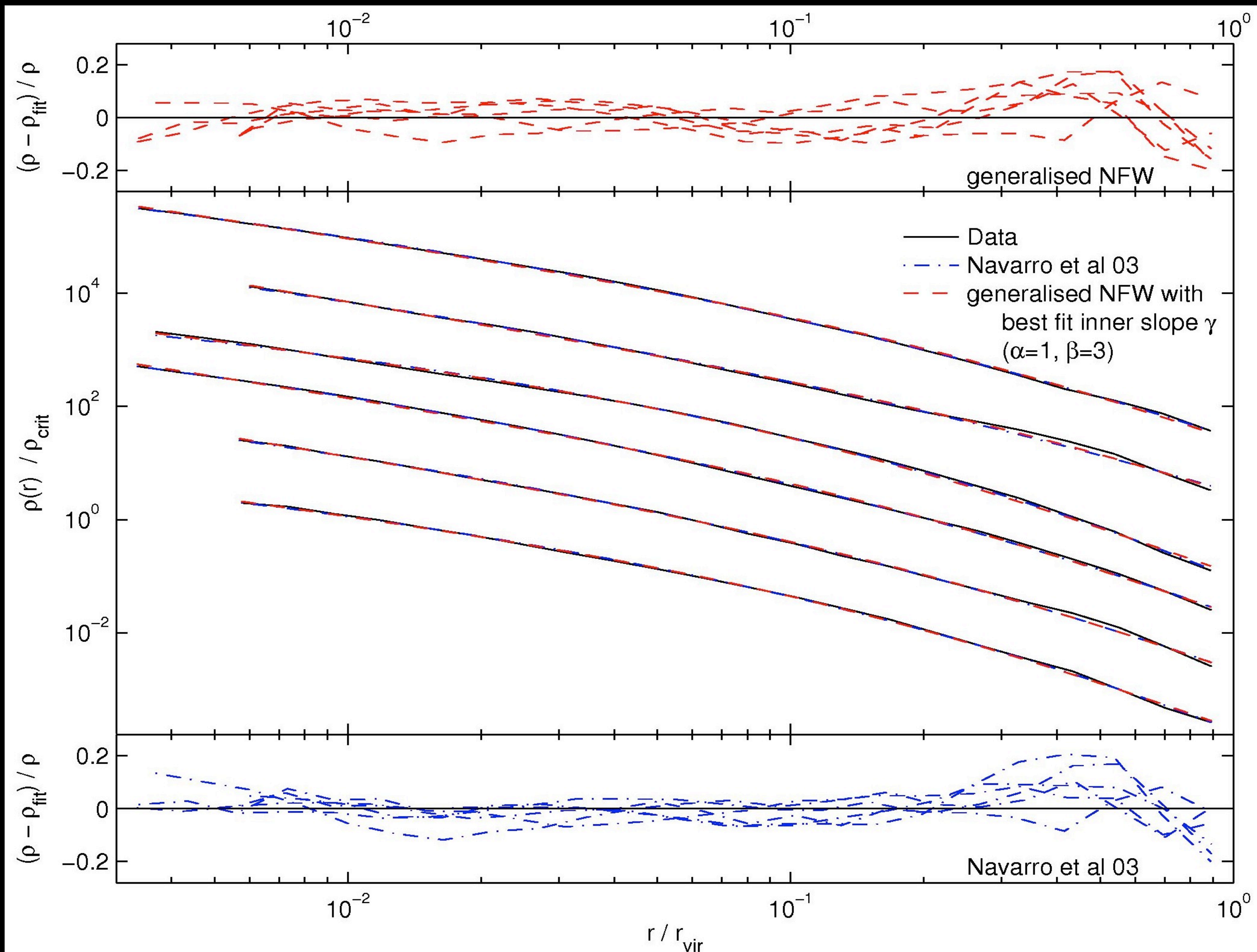
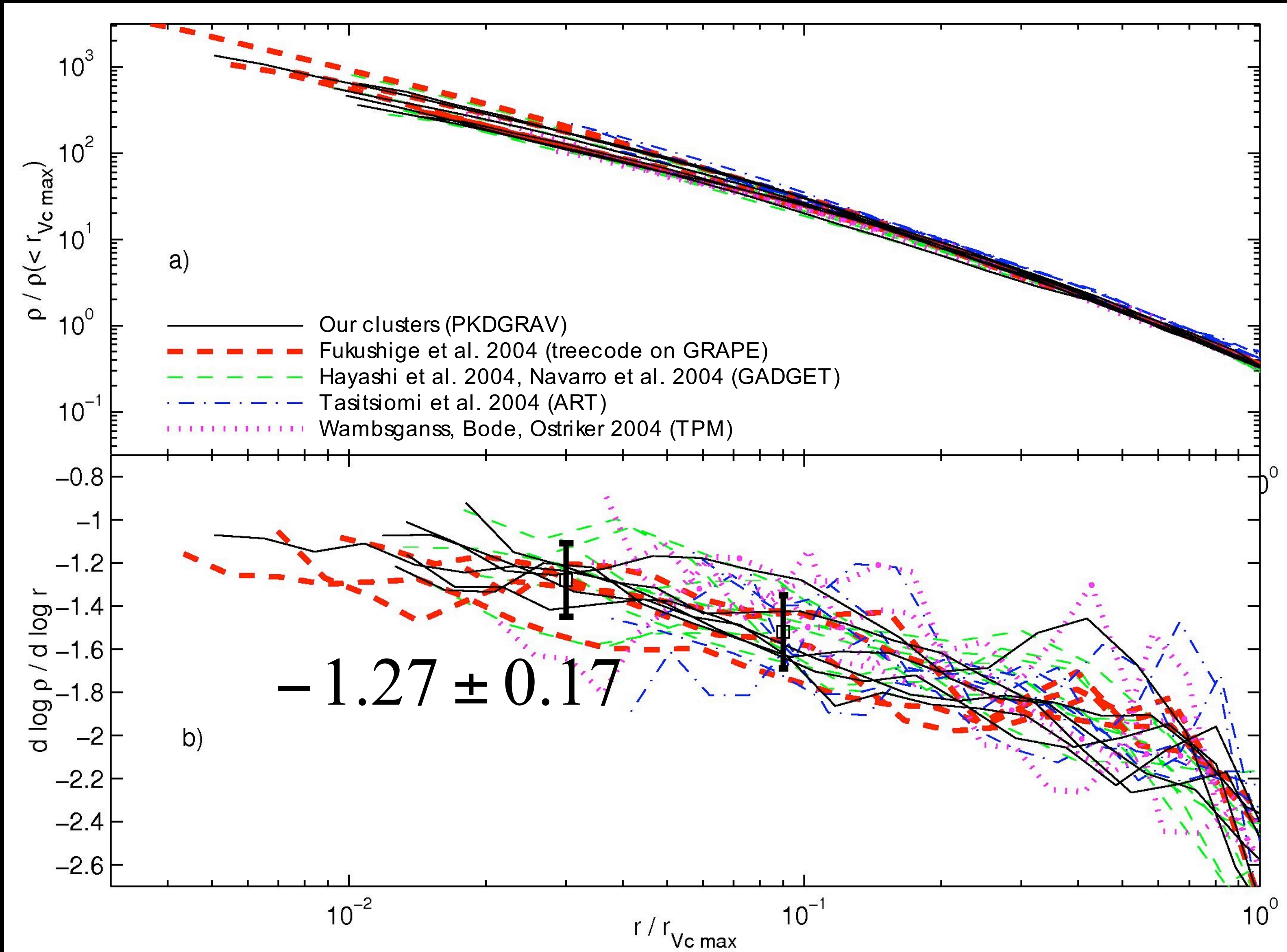


CDM cluster density profiles



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... (of up to 25 million inside Rvir)

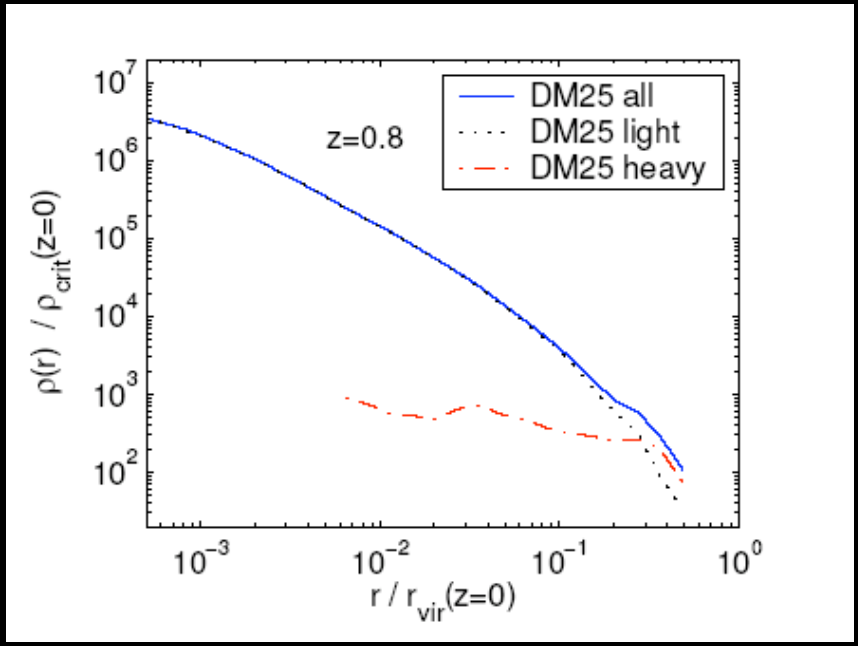
Resolving the inner halo with a multimass approach

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)



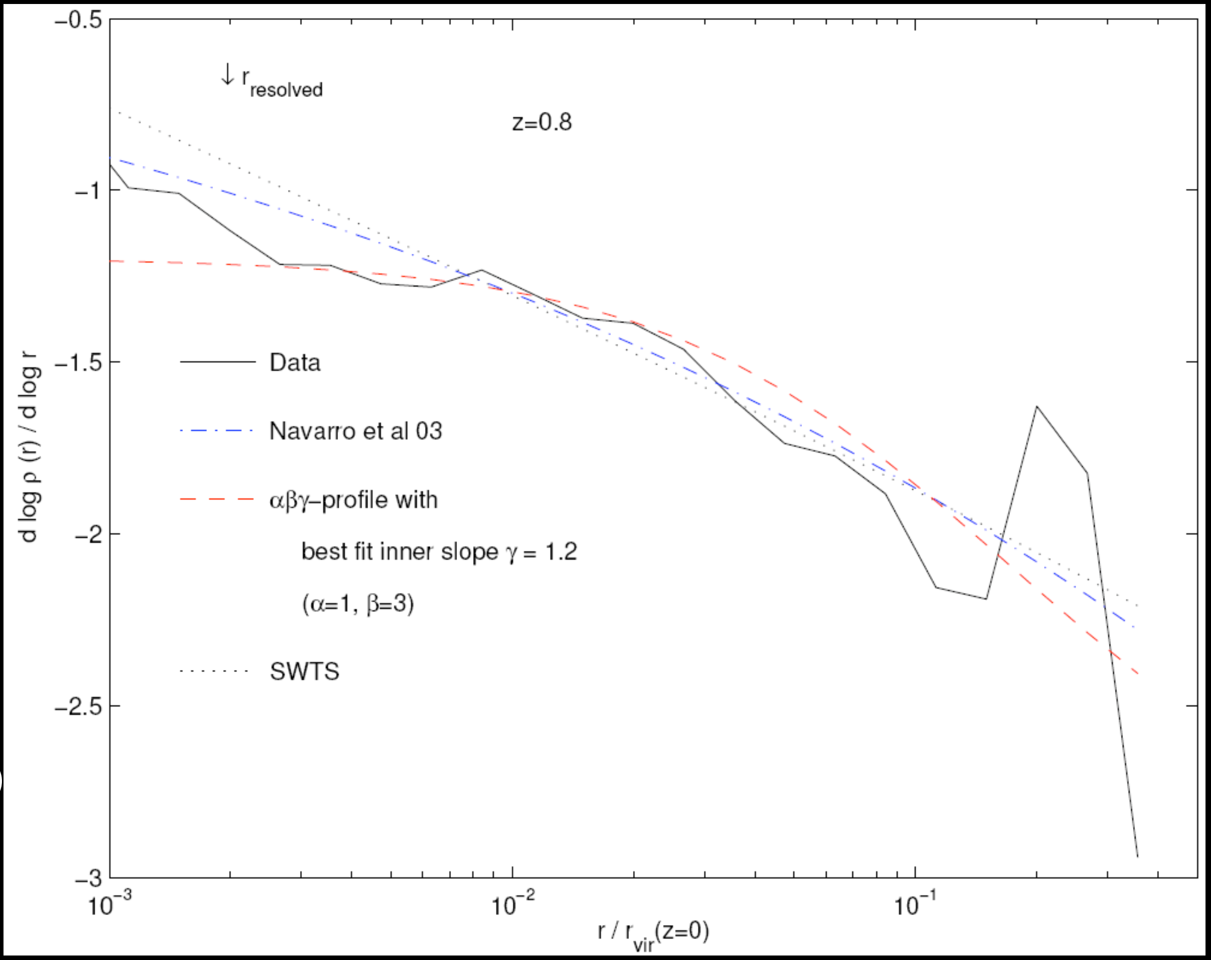
Resolving the inner halo with a multimass approach

Run DM25: effective resolution of 130 million particles in Rvir, run down to z=0.8

logarithmic slope:

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

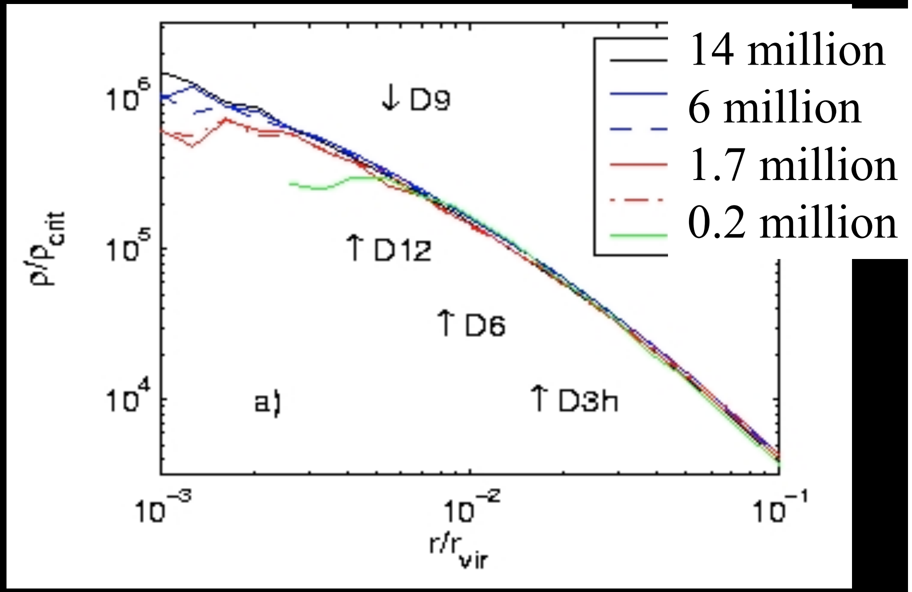
(JD et al. astro-ph/0504215)



2) Substructure: Convergence tests

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

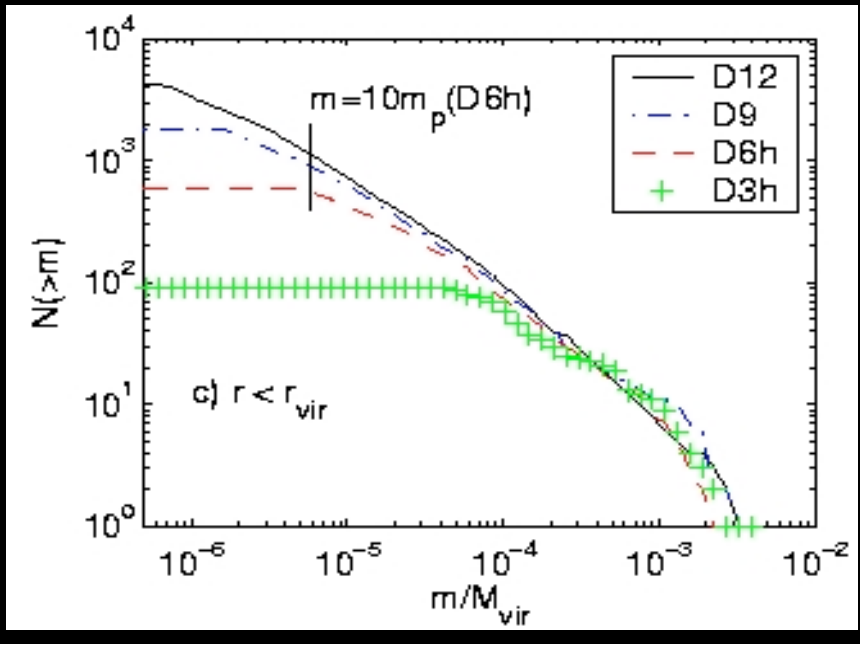
  (Moore etal. ApJ 1998; JD etal. MNRAS 2004)



- Numerical Overmerging:

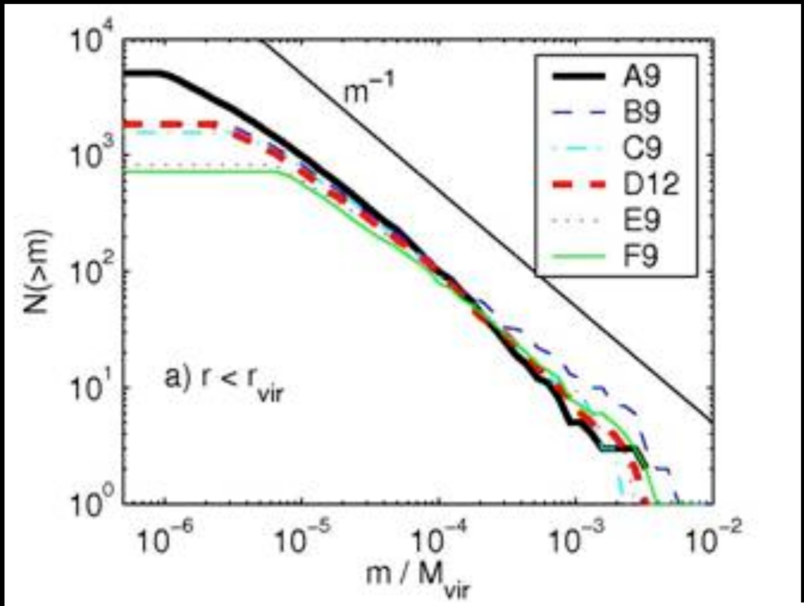
  => incomplete subhalo sample for N<100

  (JD etal. MNRAS, 352, 535, 2004)



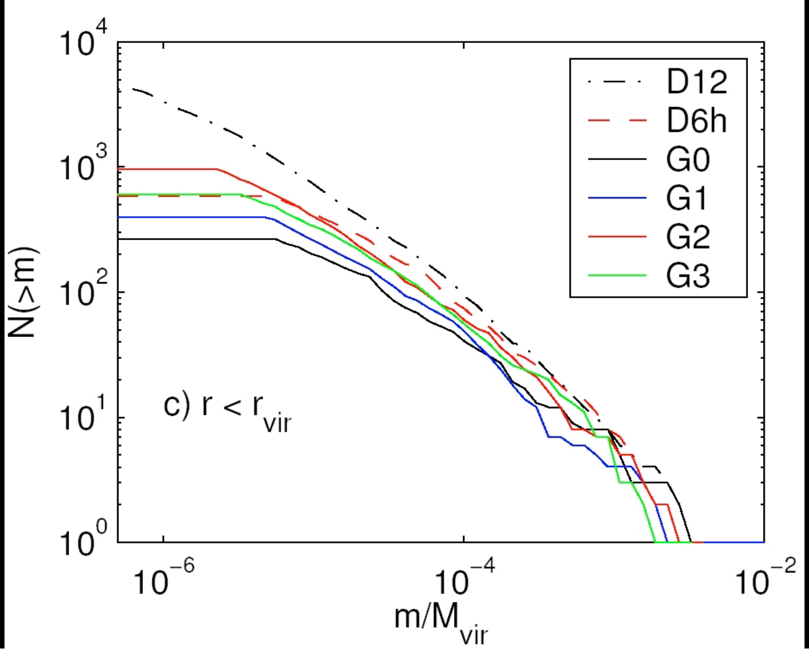
Substructure abundance

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



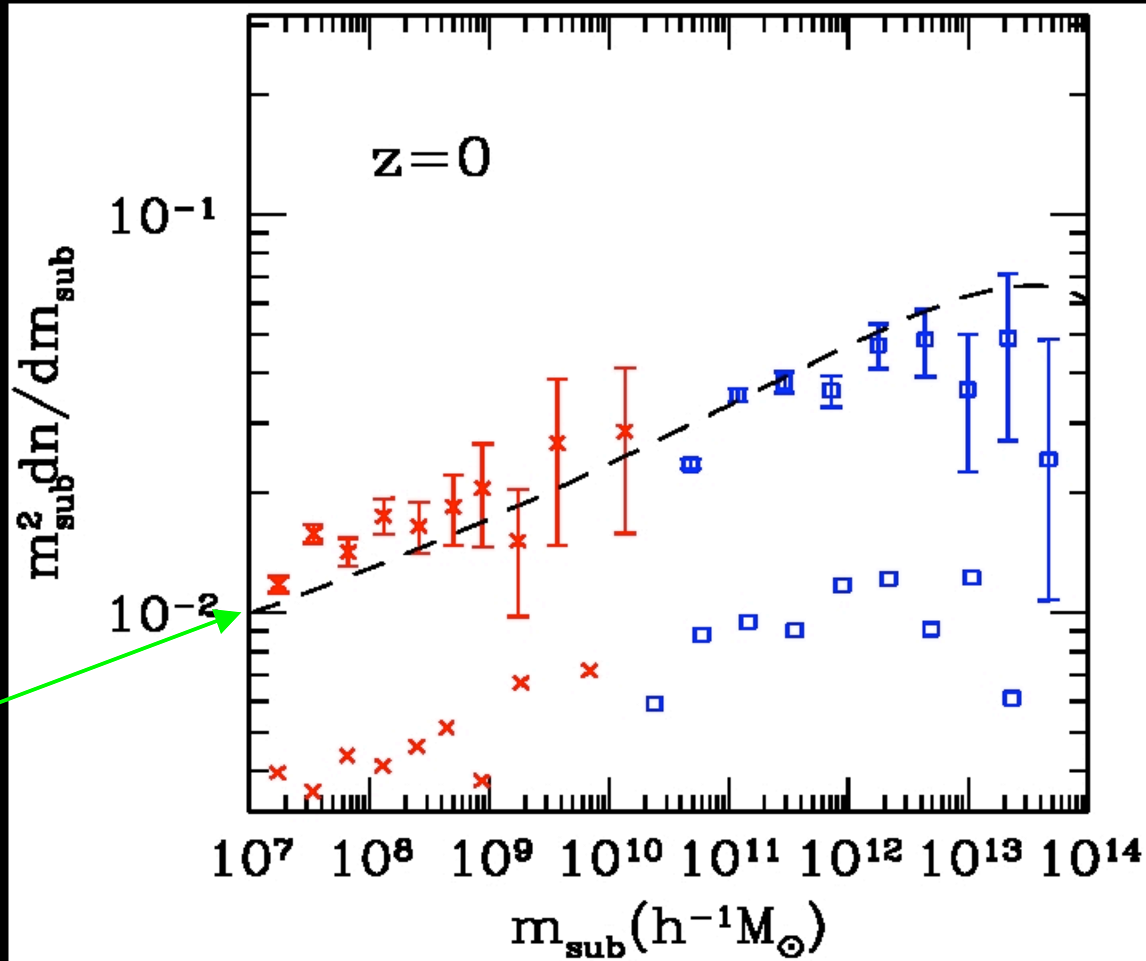
The absolute z=0 abundance depends on the host mass, galaxies have about a factor of 2 less substructure. (Gao et al. 2004)

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

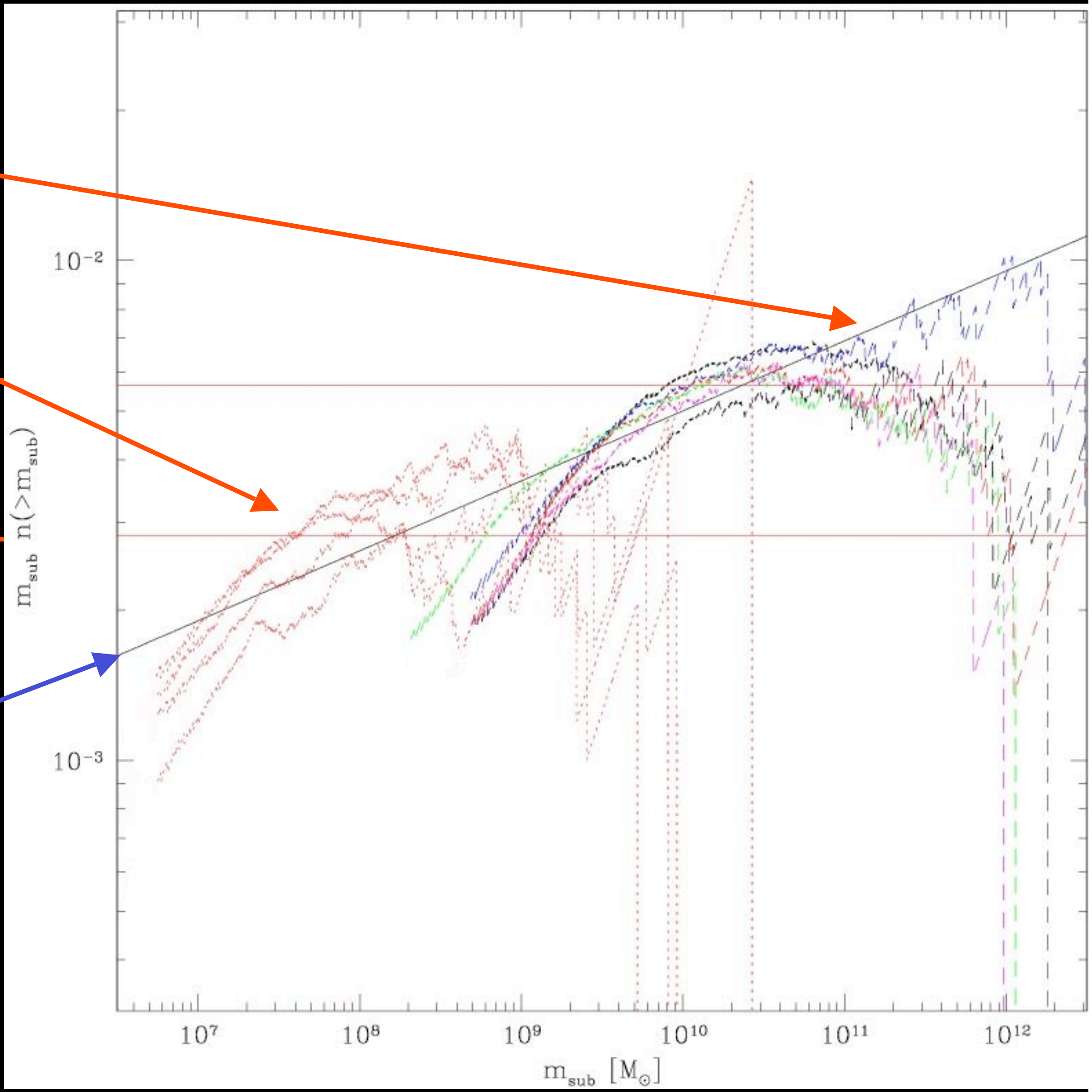
And similar to field halo mass function

Substructure abundance

Same result from our six clusters and four galaxies

factor of two between galaxies and clusters

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



Substructure abundance

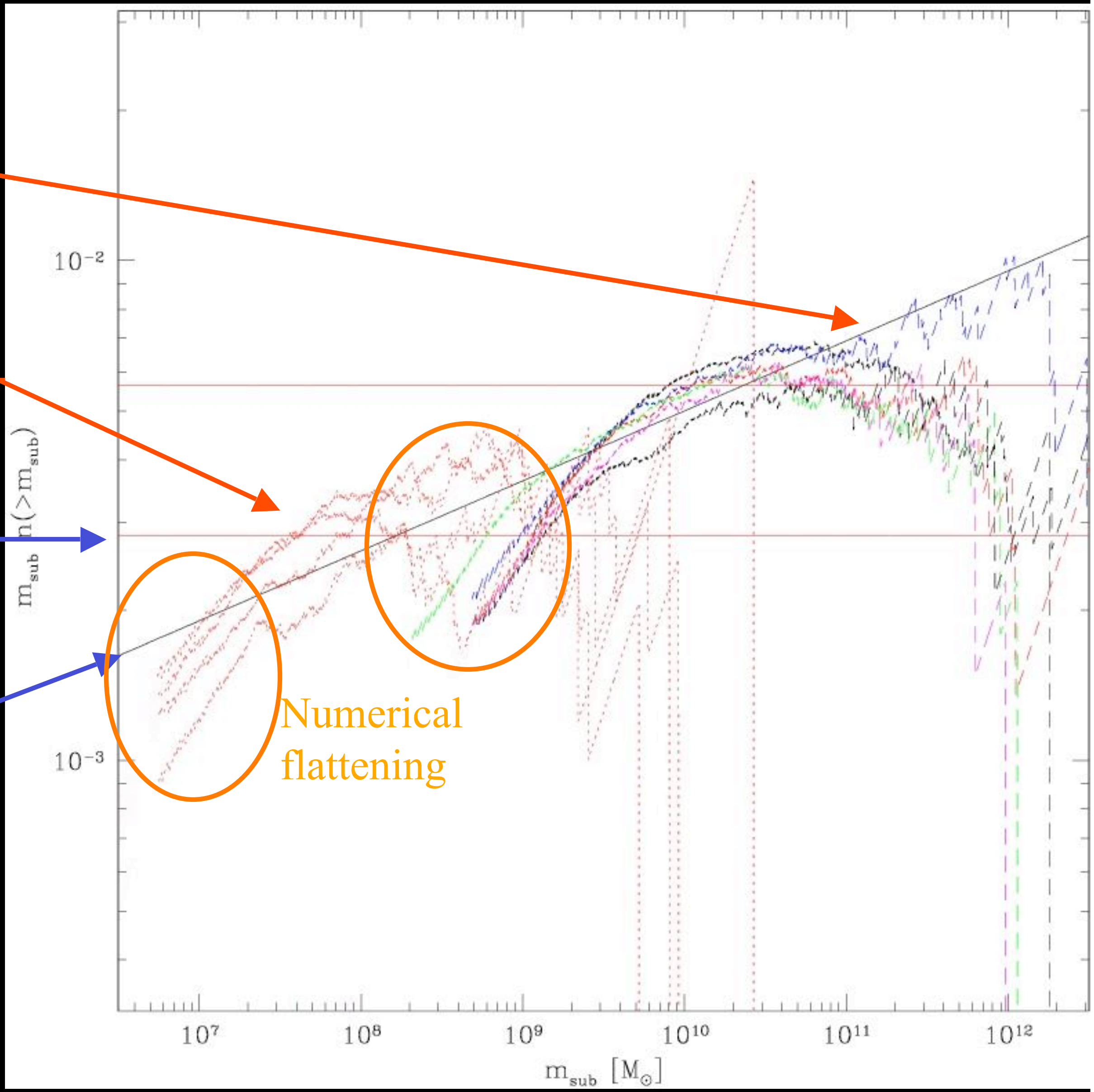
Same result from our six clusters and four galaxies

factor of two between galaxies and clusters

dn/dm ~ m^{-2}

dn/dm ~ $m^{-1.86}$

-> similar to field halo mass function n(M,z=0) steeper due to sub-substructure? max_z n(M,z)?



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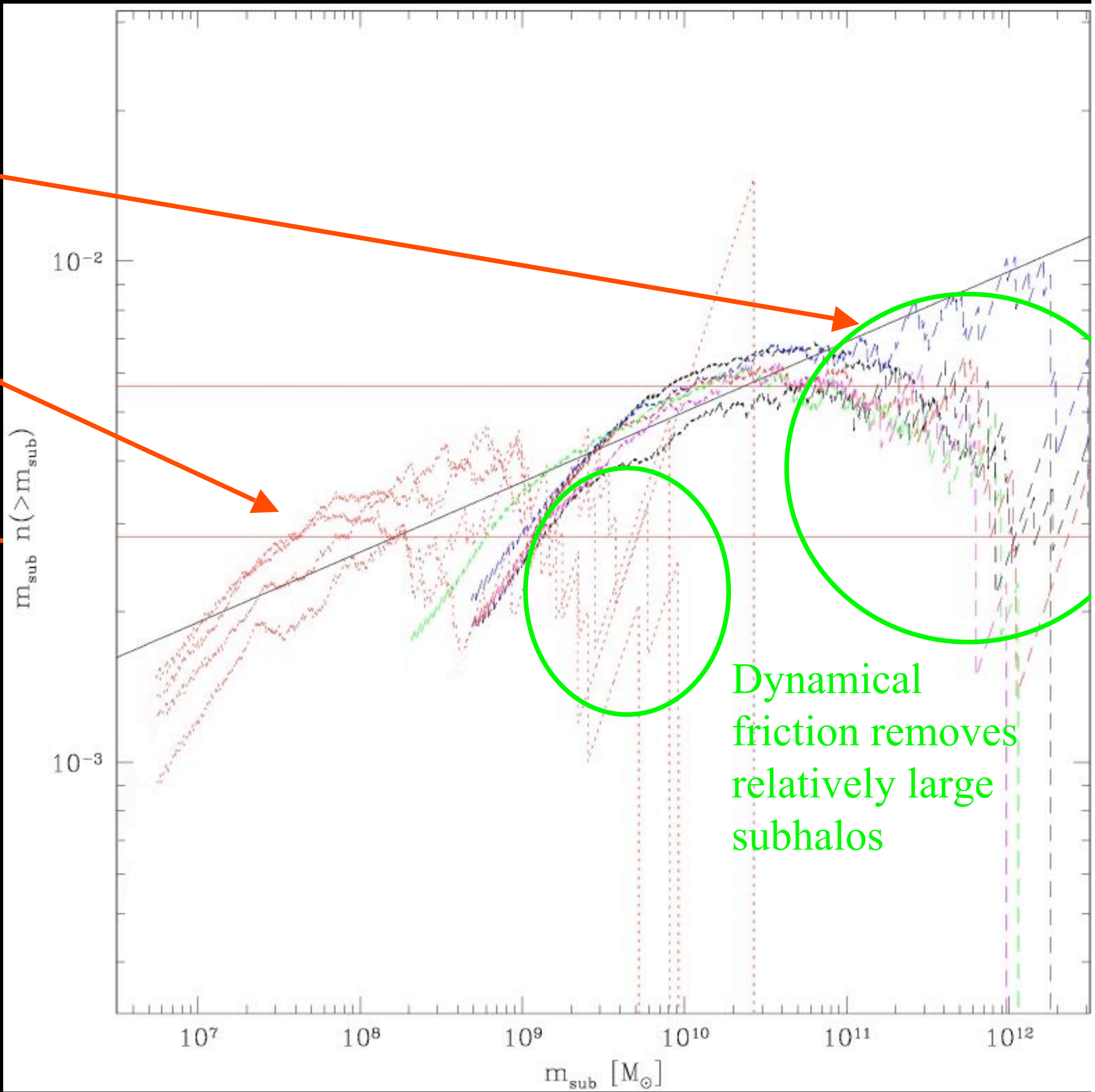
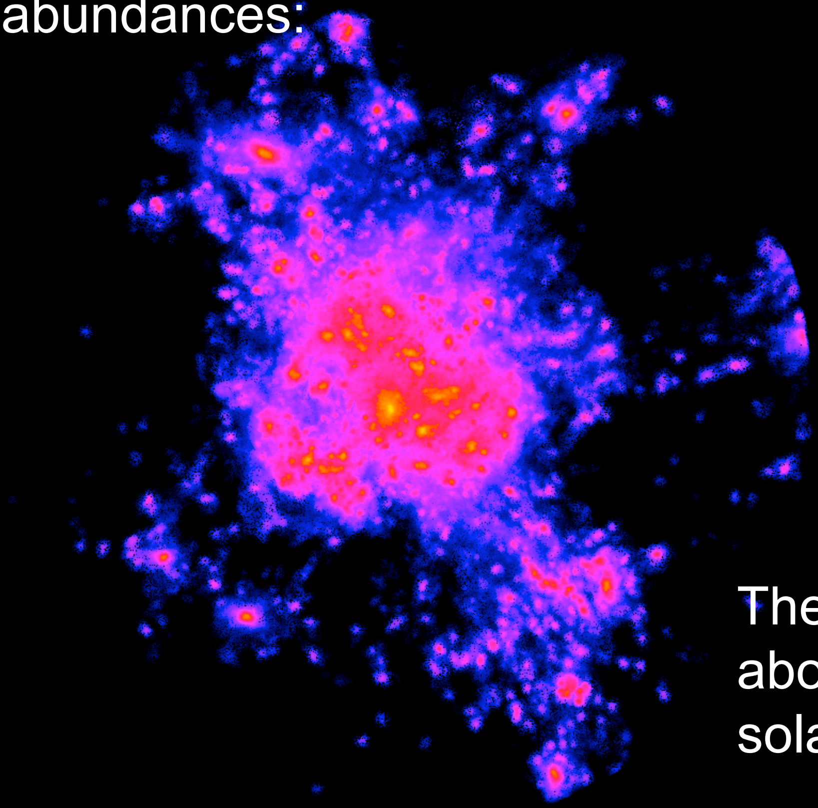
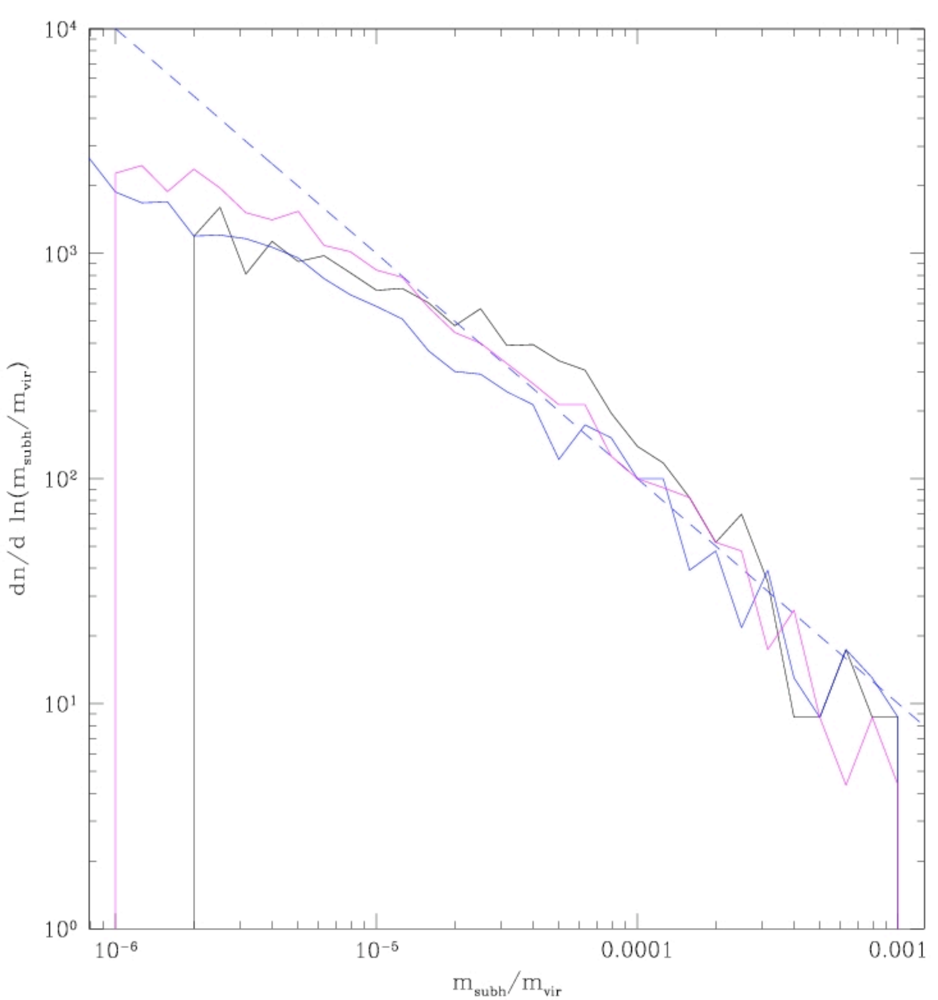


Substructure abundance

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

Substructure abundance

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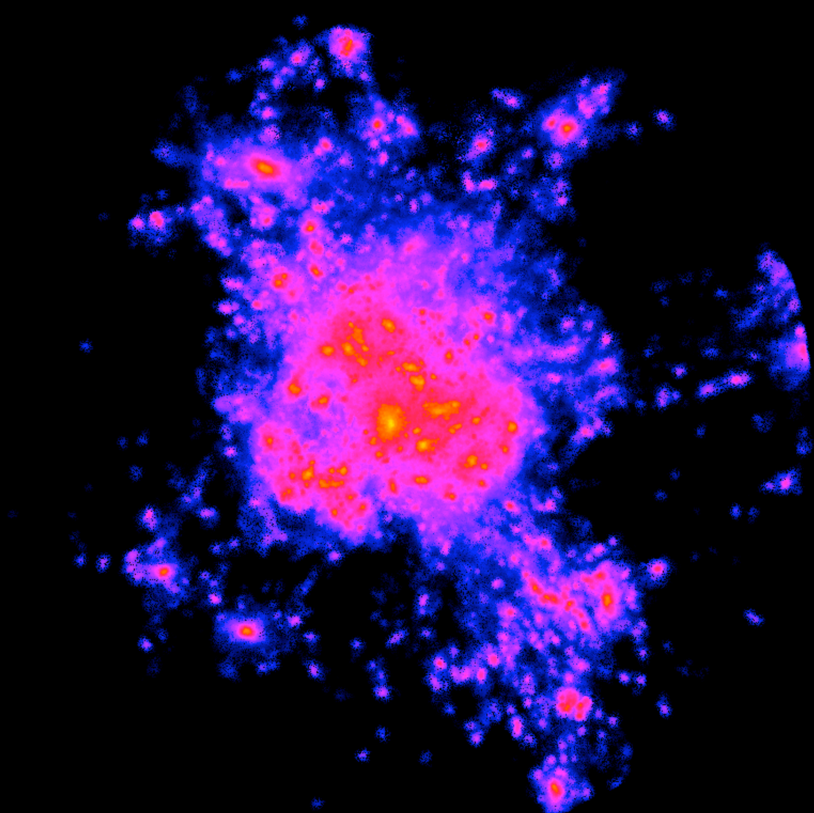


Impulsive heating approximation suggests that some micro-halos are disrupted by stars.

But this approximation is inadequate to decide disruption:

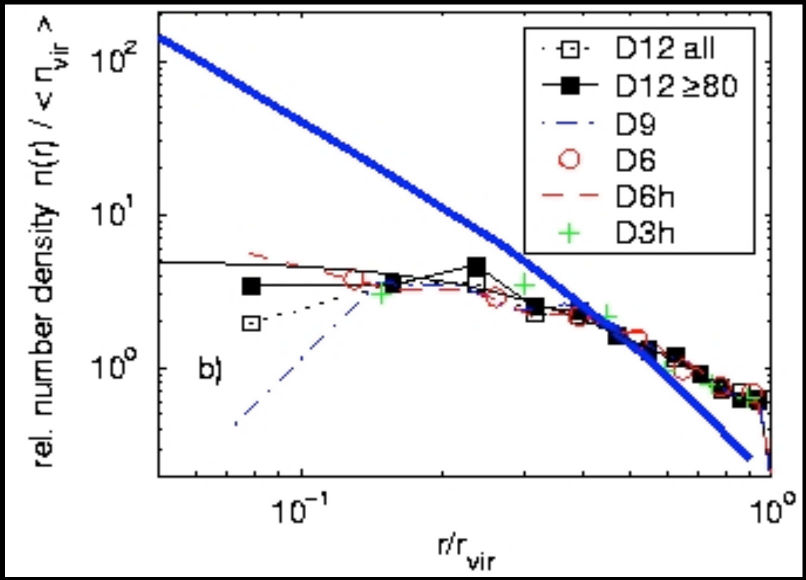
In simulated “disruptive” encounters with stars the minihalo only looses some of its mass in the outer part where tides are most effective and the cusp survives.

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

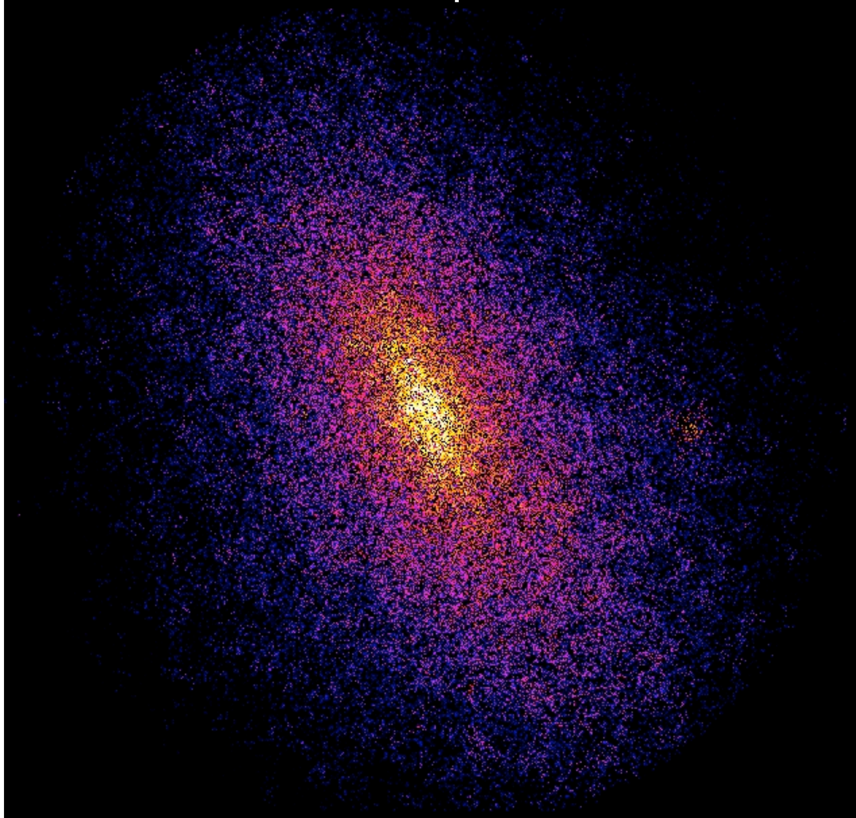


(JD et al. MNRAS, 352, 535, 2004)

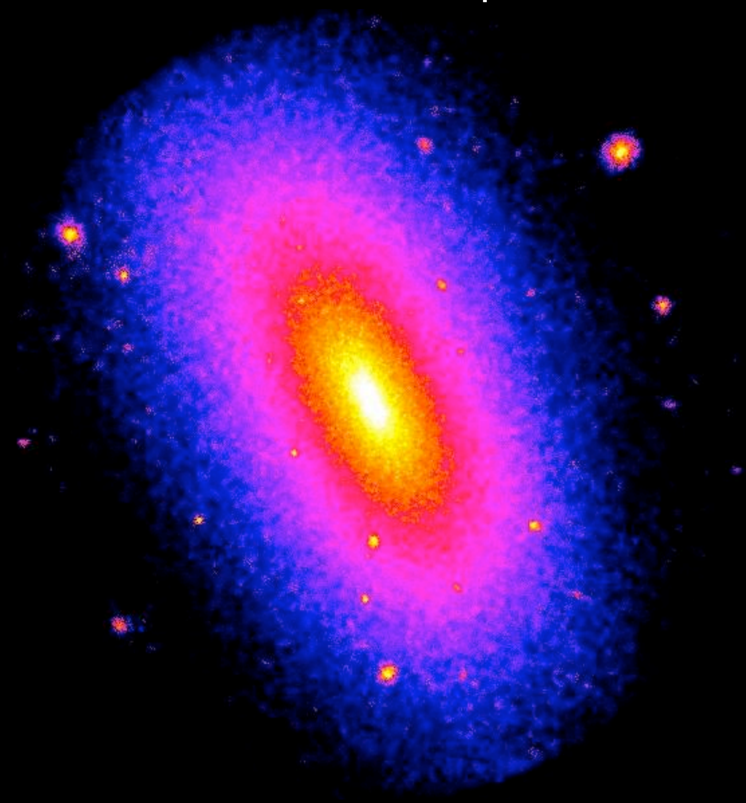
Substructure number density profiles

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.



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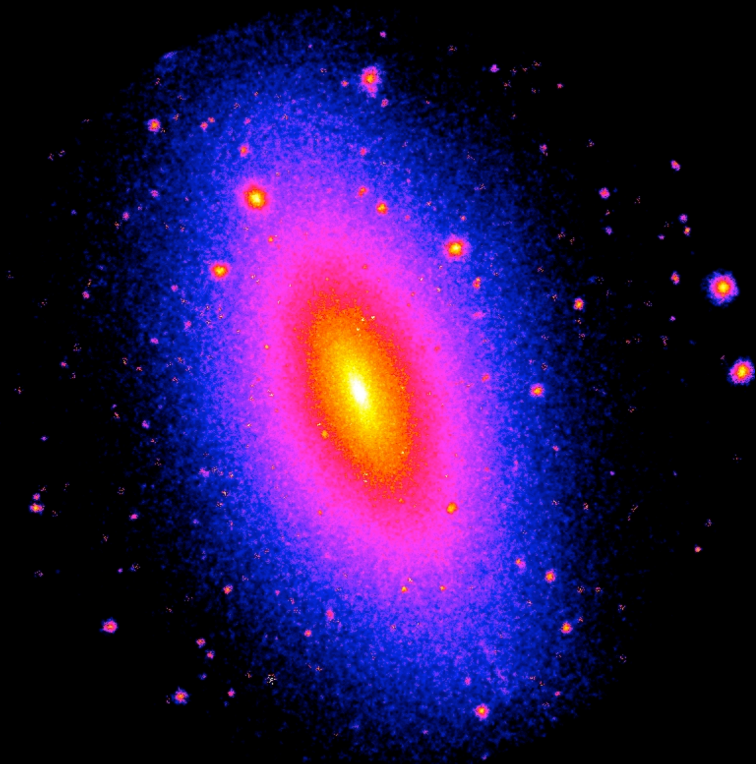
The inner 10% of a galaxy halo resolved with 130 million particles in Rvir



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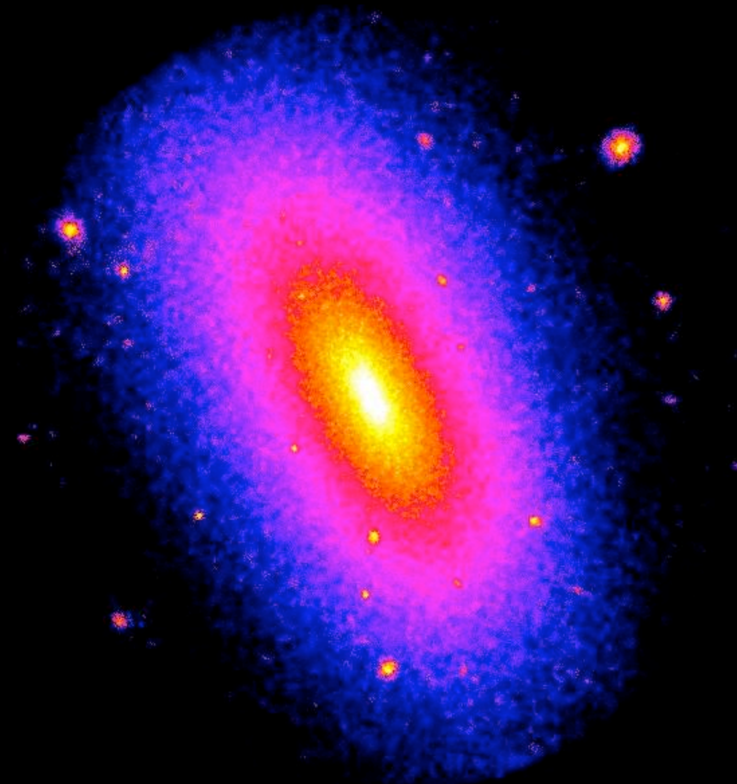


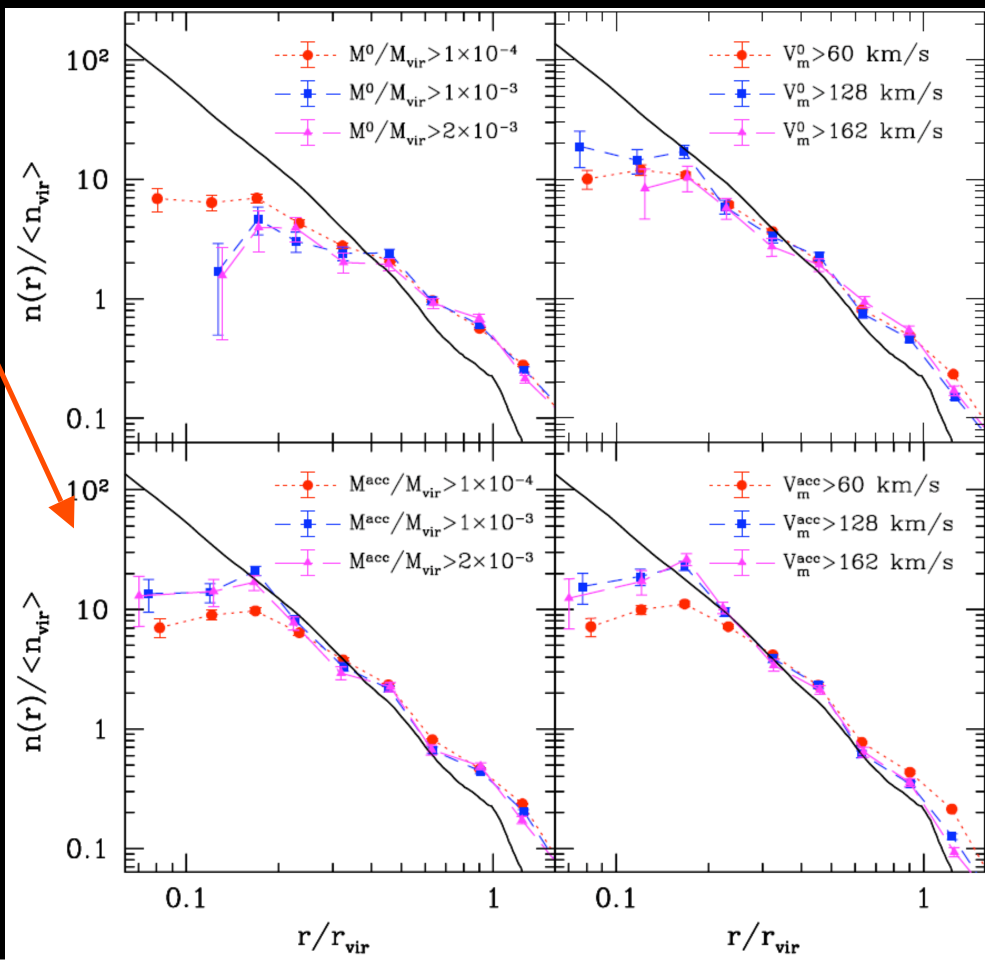
Subhalos destruction is rare, mass loss is common: 83% of the well resolved (over 100 particles) halos in a cluster forming region at z=2 survive as subhalos (with at least 10 bound particles) until z=0. (Ghigna et al. 2000, JD et al. 2004)

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 before accretion (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

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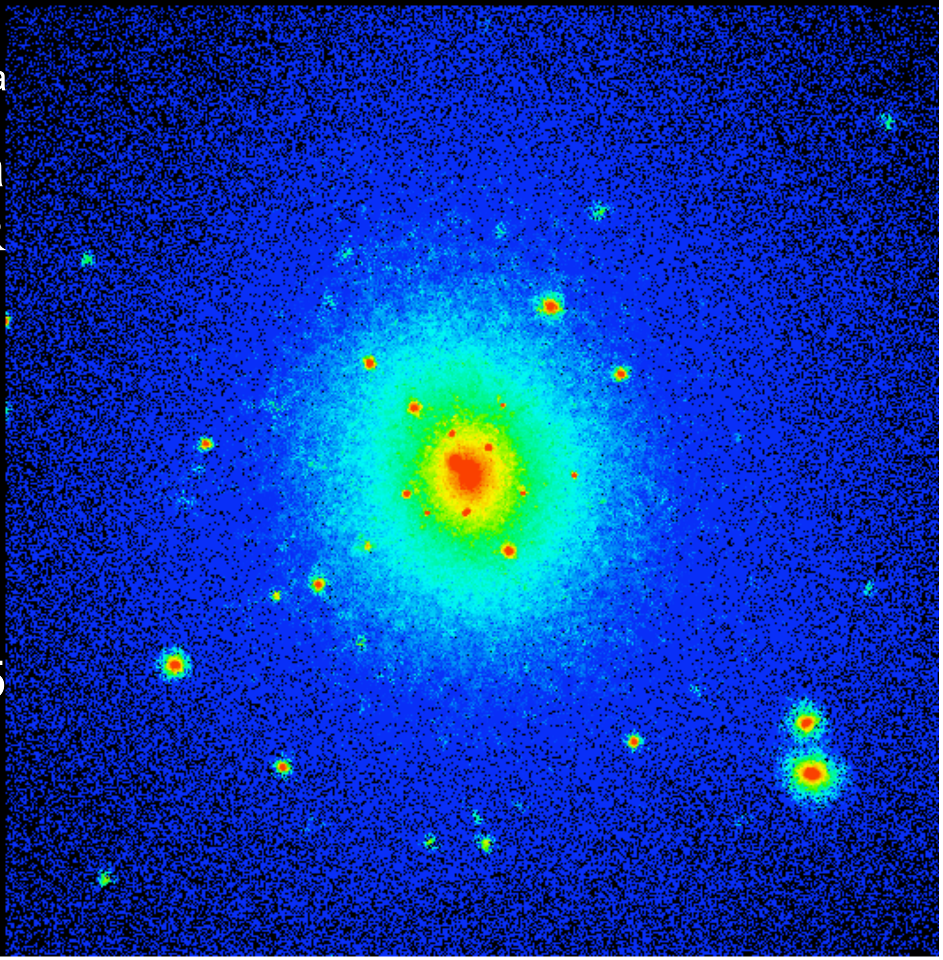
1) Simply select halos by mass or circular velocity before accretion (Naga

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

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. astro-ph/0506125



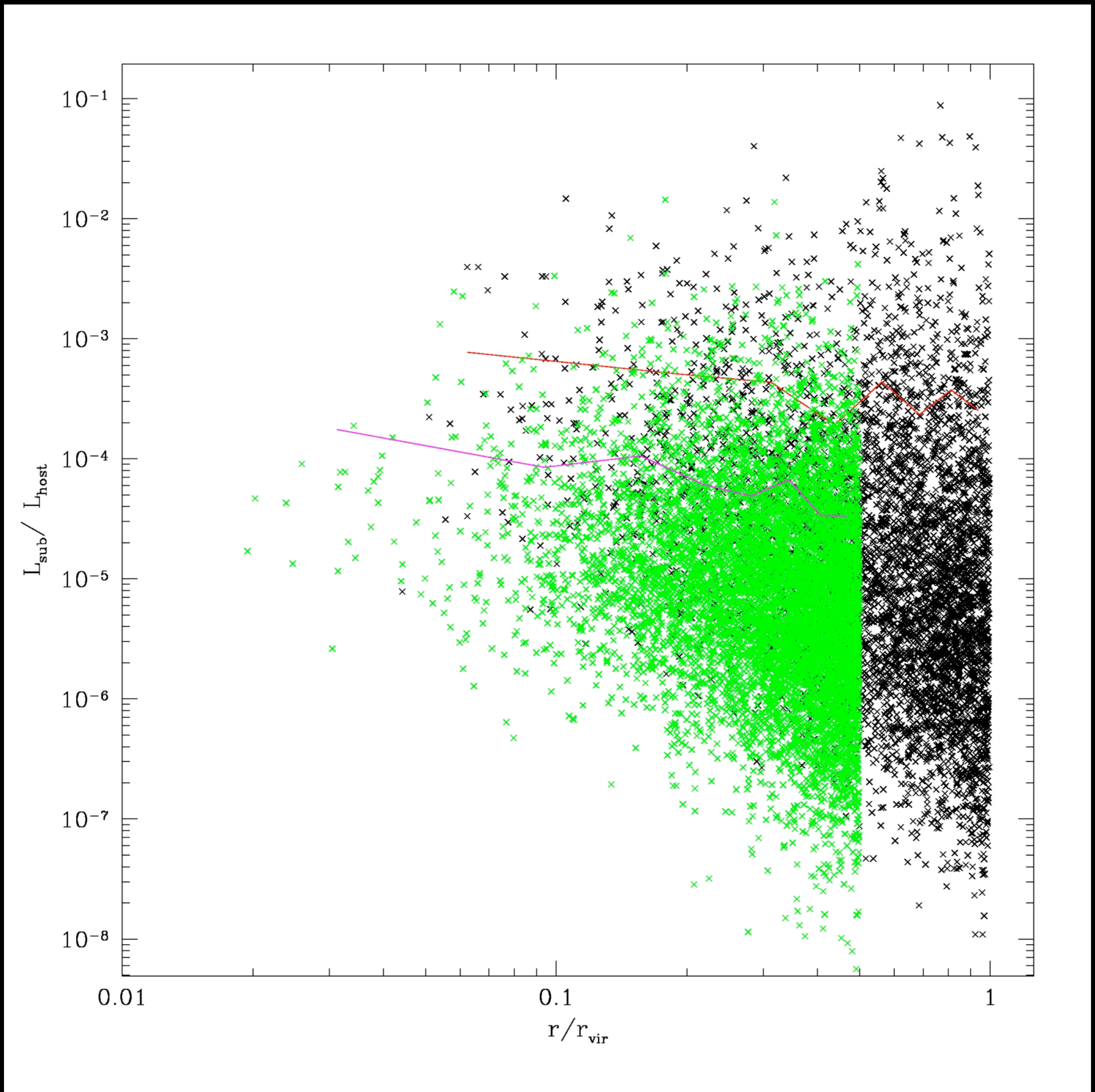
Substructure number density profiles

Assuming NFW density profiles the DM annihilation luminosity of a halo is
$L \sim rho_S^2\ r_S^3$

The luminosity of the <u>resolved</u> subhalos is about twice the one of the host halo, this gives a <u>lower limit</u> for the boost factor of about 3.

It could be > 100
(Calcaneo-Roldan & Moore,PRD,2000)

Inner subhalos are more luminous …



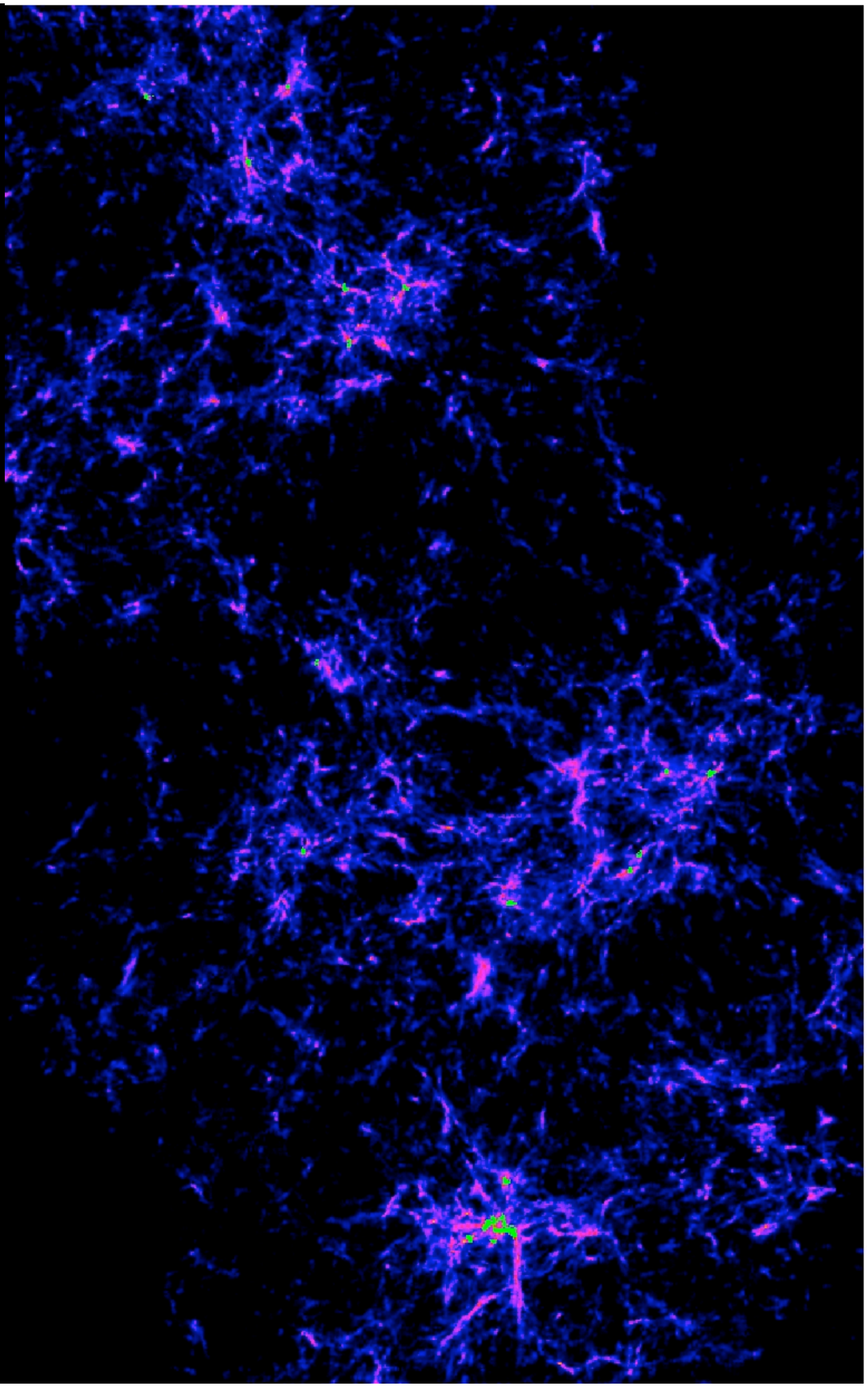
Substructure number density profiles

Inner subhalos are more
luminous … because
they formed earlier and are denser:

Early forming halos are strongly
clustered around the centers of
larger scale fluctuations.

In this example halos more massive
than 5e7 Msun halos at
redshift 18 are marked (green).
These are rare (>3.5 sigma) fluctuations

(JD et al. astro-ph/0506615)



Substructure number density profiles

Inner subhalos are more luminous … because they formed earlier and are denser:

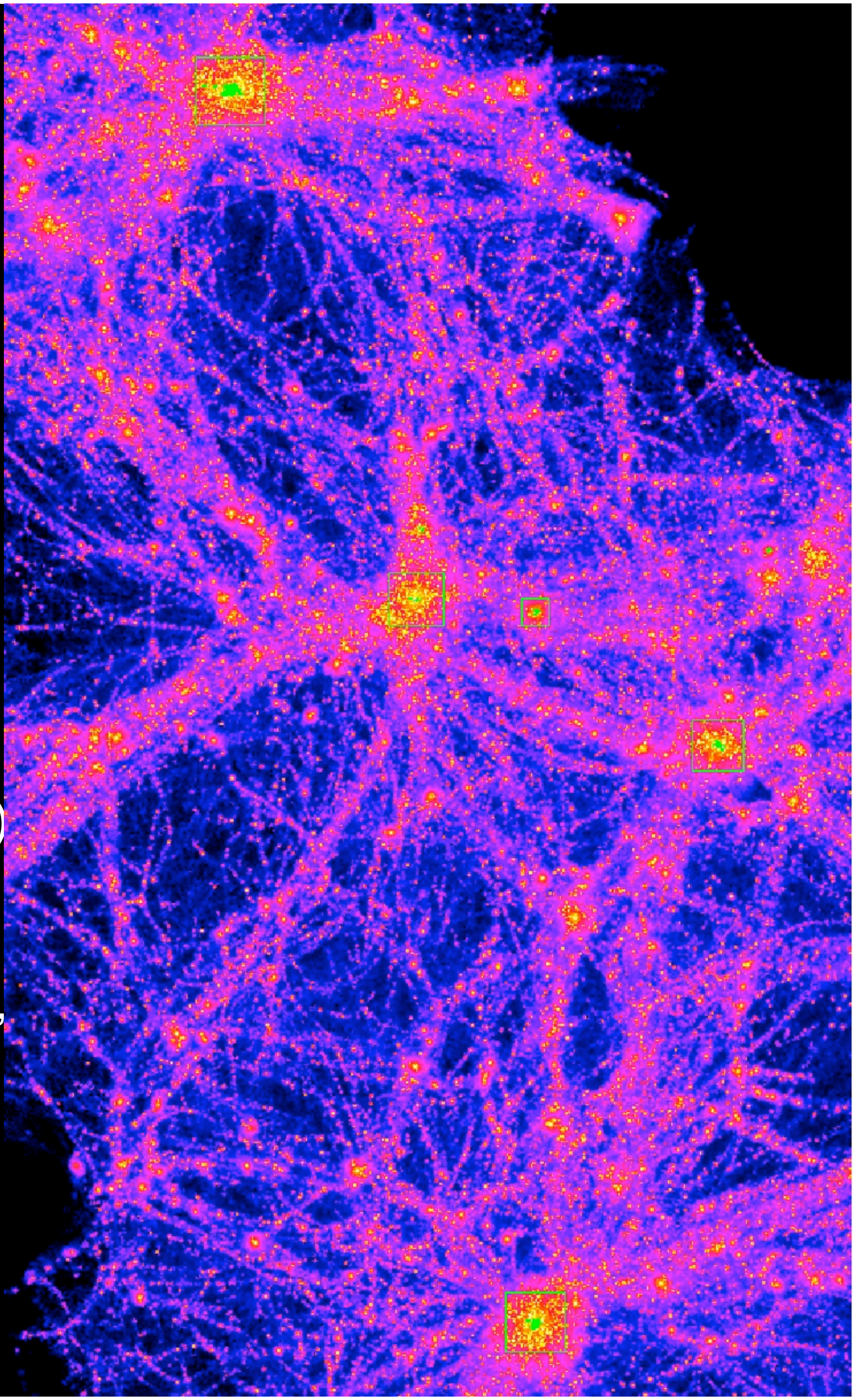
Early forming halos are strongly clustered around the centers of larger scale fluctuations.

Most of the marked material ends up near the centers of the largest z=0 halos. (->massive BHs from PopIII near the GC)

(JD et al. astro-ph/0506615)

Also "Age dependence of halo clustering"
(Gao, Springel & White, astro-ph/0506510)

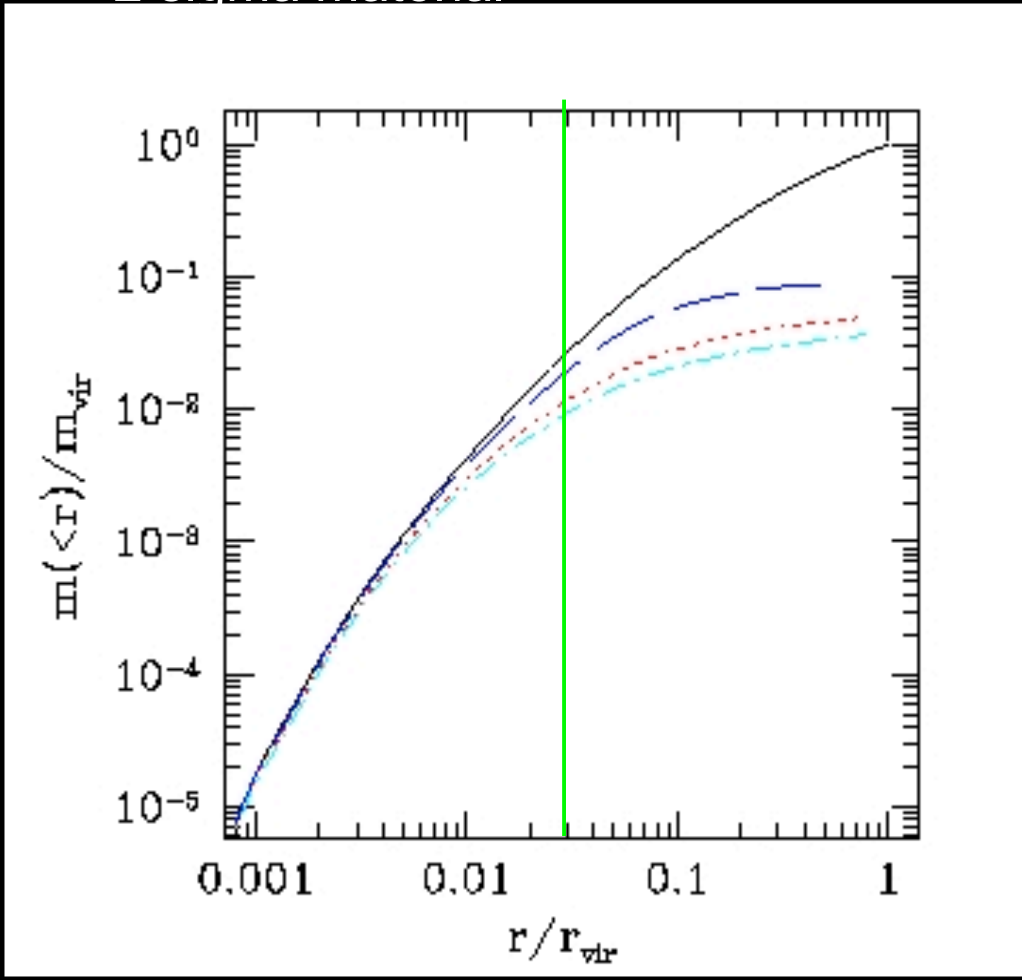
This important property of hierarchical structure formation is missing in current semi-analytic models.



Substructure number density profiles

Inner subhalos are more luminous …

> 2 sigma material



For DM around us the halo formation times were typically (z+1) = 2 (zf + 1)

i.e. local subhalos are twice as concentrated and eight times more luminous than an average subhalo

JD et al. astro-ph/0506615

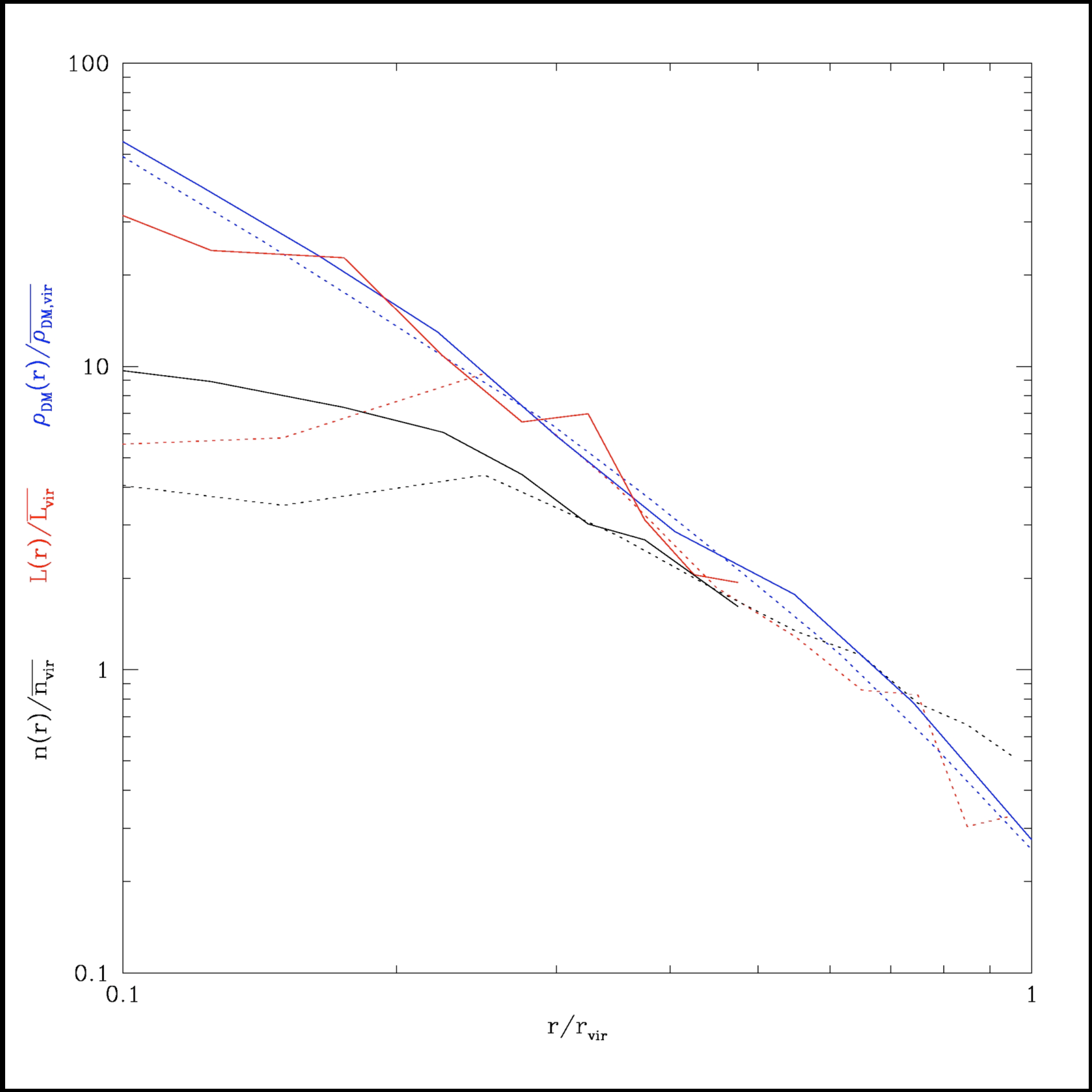
Substructure number density profiles

DM annihilation luminosity of subhalos

$L \sim rho_S^2 \, r_S^3$

traces the mass:

-> substructure increases the global sky brightness in any given direction

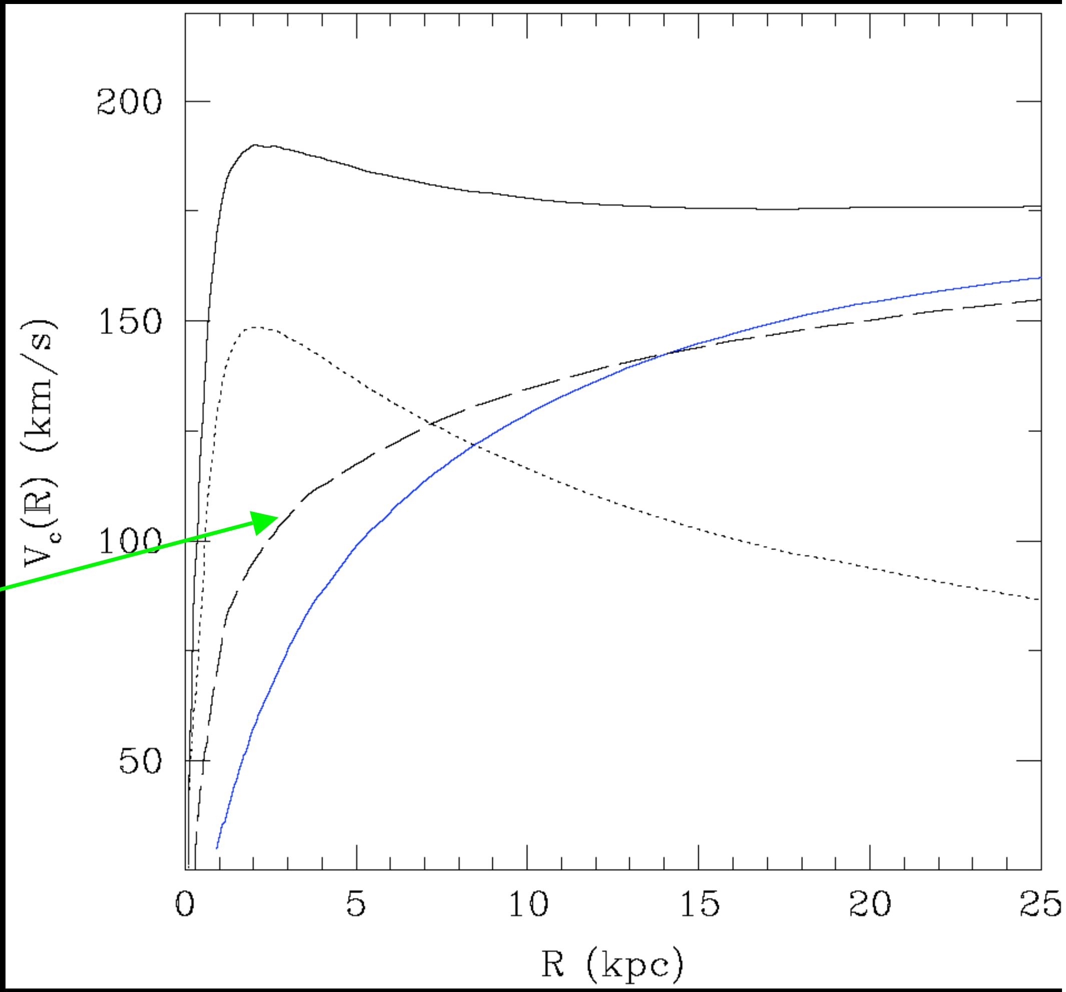


3) DM in the Milky Way

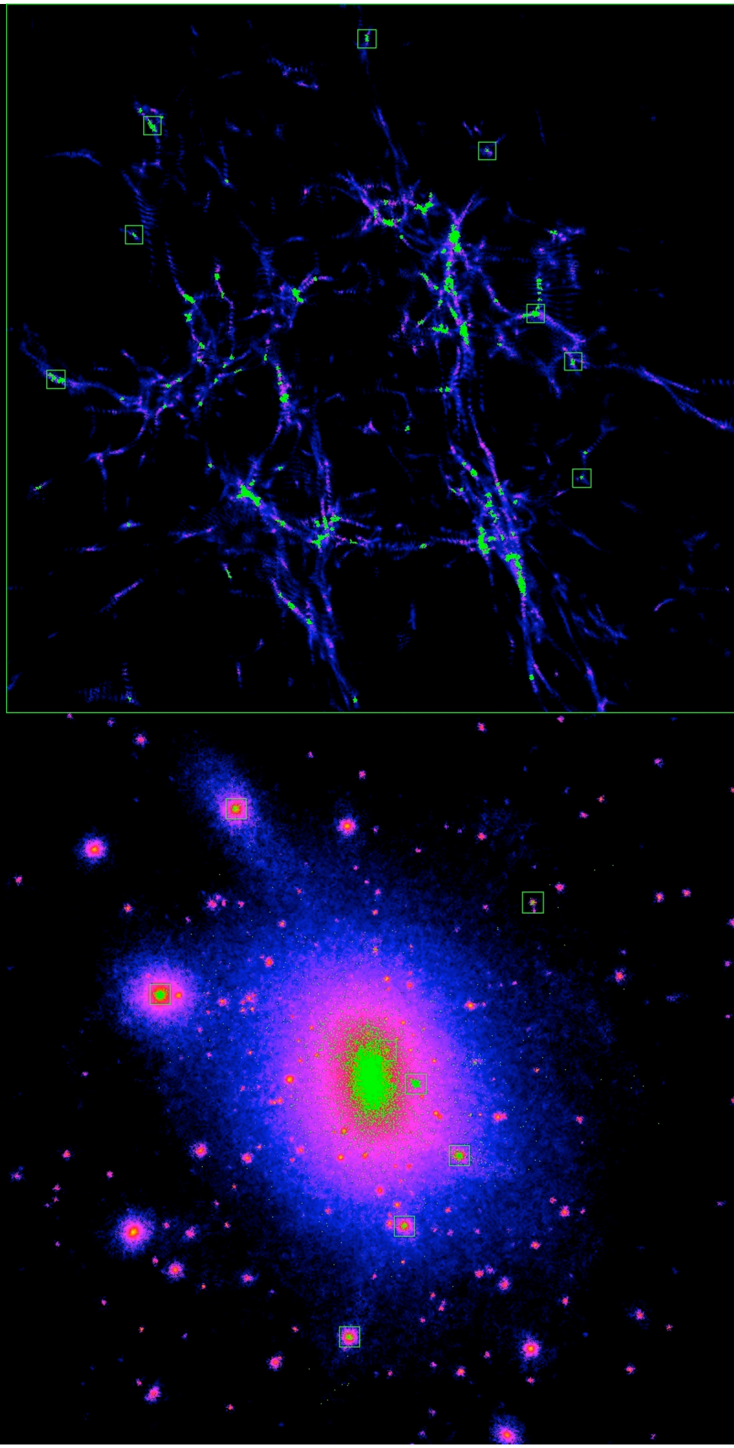
To reproduce the local circular velocity of 220 km/s after adiabatic contraction, the Milky Way could have formed in a dark halo with a maximum circular velocity of 190 km/s before contraction

The inner DM cusp gets steeper

(Maccio et al. astro-ph/0506125)



Such LCDM halos have 300+-100 subhalos with vcmax > 10 km/s, but around the Milky Way there are only about 10 satellite galaxies: "Missing satellites problem"…



Milky Way stellar halo and dwarf satellites:

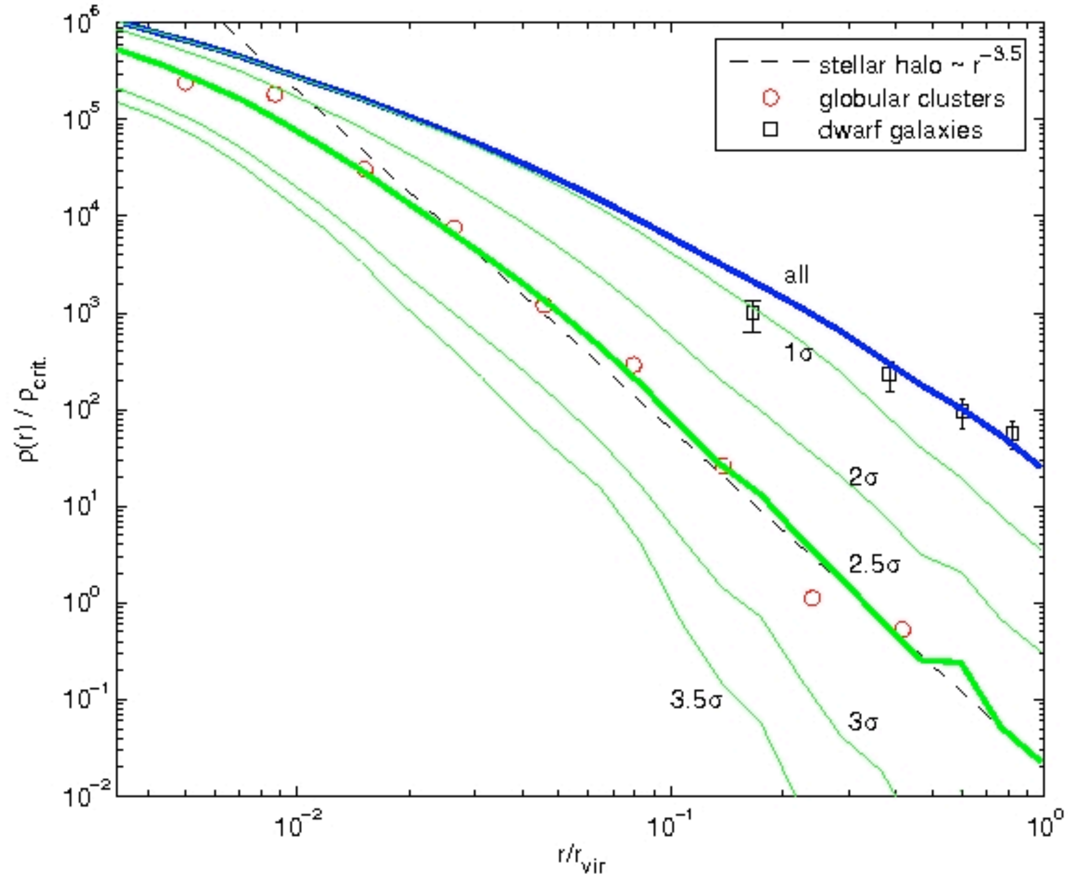
Assume proto-galaxies formed in halos above 10^8 solar masses (Tvir > 10^4 K) which formed before reionisation.

After reionisation gas accretion into small halos is suppressed (Bullock et al. ApJ 2000)

A few (~5%), most remote proto-galaxies survive as dwarfs satellites with radial profile, velocity function and total number like observed around the Milky Way.

Most join the MW early (bias!) and are disrupted producing a realistic, concentrated halo of old, metal poor stars (Moore et al 2005, submitted)

Building blocks of the Milky Way halo

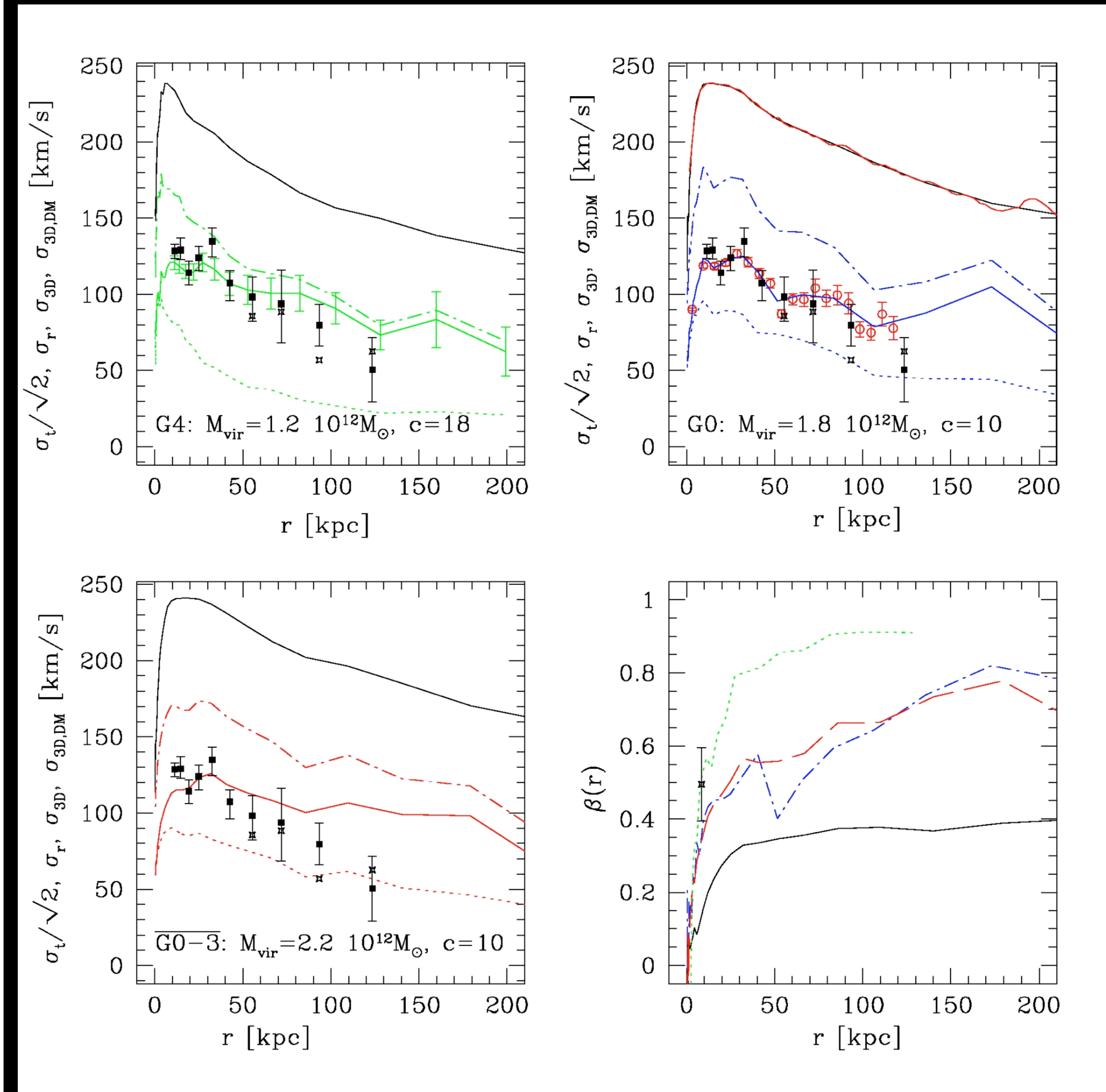


If reionisation is at z=12 our proto-galaxies are rare peaks above 2 .5 sigma. They are strongly clustered towards the galaxy center and produce a concentrated stellar halo.

(Moore et al 2005, submitted)

Data from W. E. Harris (physun.physics.mcmaster.ca/Globular.html)

Milky Way stellar halo



Our model stellar halo also has similar kinematics as observed.

The outer halo and therefore the virial mass are not well constrained yet, but better data will be available soon (RAVE, GAIA)

JD et al. astro-ph/0506615

Summary

• inner density profiles seem to have steep cusps, on average $\sim r^{-1.2}$. They are very difficult to resolve due to numerical relaxation.

• large abundance of subhalos and steep mass functions similar to field halo mass functions.

• same age halos have self similar substructure properties, from cluster to sub-solar mass scales.

• resolved subhalos are more extended than the dark matter but their annihilation luminosity follows the mass.

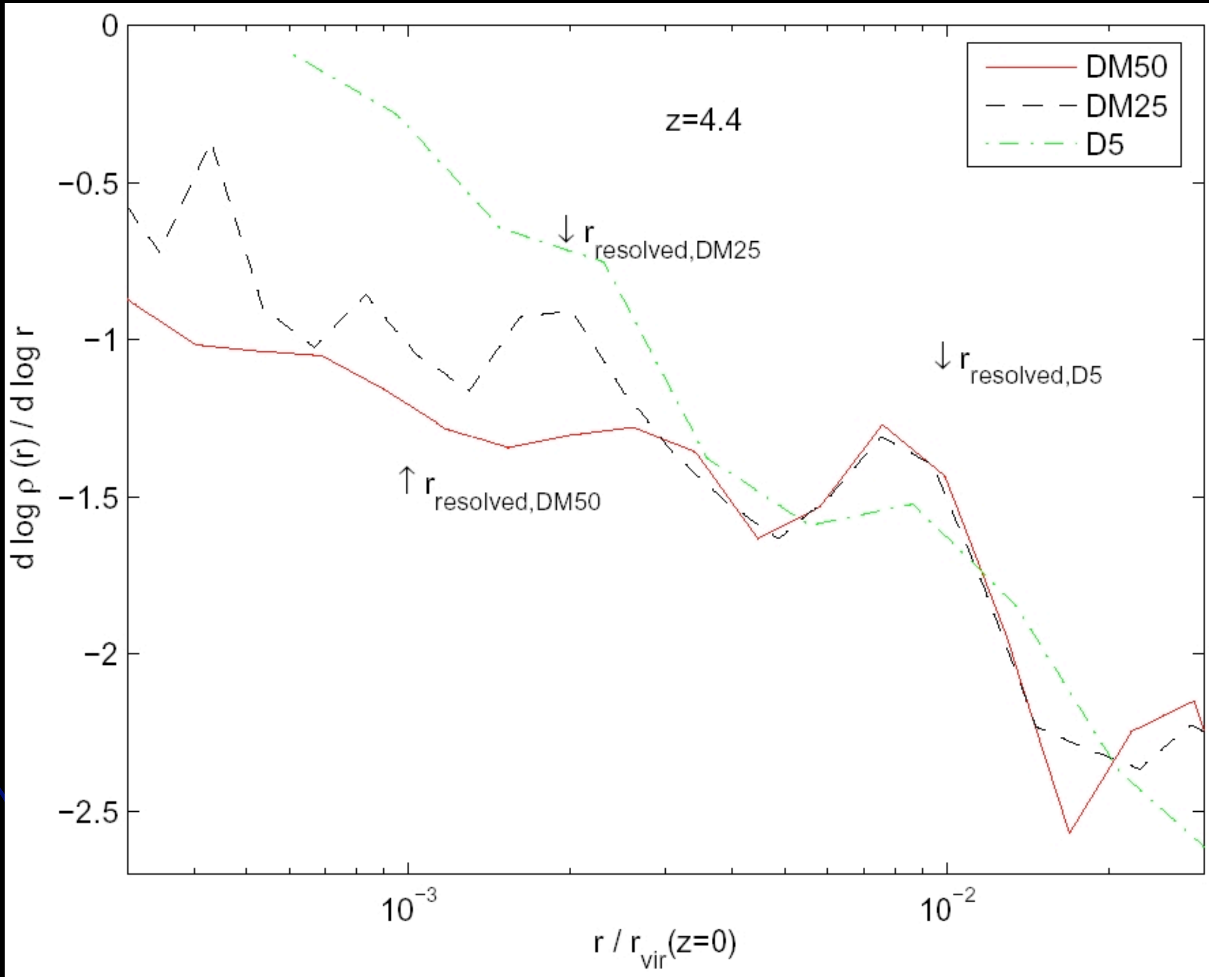
• if proto-galaxies formed only in those small halos which reach 10^8 Msun before z=12, they will build up a realistic stellar halo and satellite galaxy population.

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:

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



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)