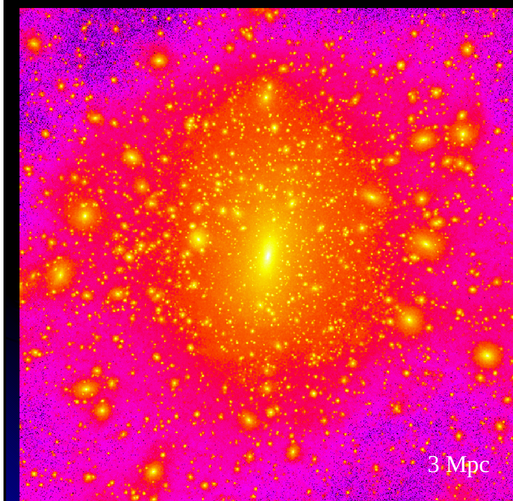




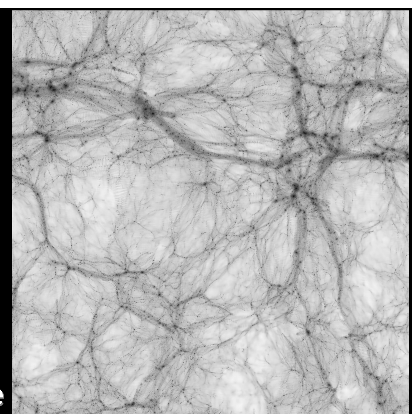
1. Density profiles
2. Substructure properties
3. Reionisation epoch from metal poor globular clusters

Jürg Diemand (->UCSC), Ben Moore and
Joachim Stadel, University of Zurich

- Omega_matter ~ 0.27
  Omega_baryon ~ 0.04

- Some well known CDM results from Nbody simulations:

Properties of large scale structure



NFW (-1) or Moore (-1.5) functions fit the density profiles down to 1% of the virial radius. Concentration reflects the density of the universe at the halo's formation time, smaller halos have higher concentrations. The inner profiles of relaxed systems do not depend on mass.

Large abundance of substructure, N(>m) ~ m^(-1)

- Density profile within 1% of the virial radius:
Still cuspy or approaching a constant density core?

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

- Subhalo inner structure?

Cluster galaxy and satellite galaxy rotation curves*, DM anihilation signal

- Subhalo abundance, spatial & velocity distribution?

Galactic satellite problem*, cluster galaxies*, anomalous flux ratios in strong lensing ("mililensing")

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

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

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

- CDM in a galaxy halo: T □ $10^{65}$ yr >> relaxation time of any N-body halo! “Ant-Elephant Bias”???
- DM in N-body simulation: T = one Hubble time in a halo with N = 5'000, and
- T(r) = one Hubble time, for r = 0.01 rvir in a system with N = 1 million. (Power et al. 2003)
- "Resolved radius" ~ $N^{-0.5}$

BUT:
N is always small in the first CDM objects, also at high resolution!
(Moore 2001, Binney & Knebe, 2002)

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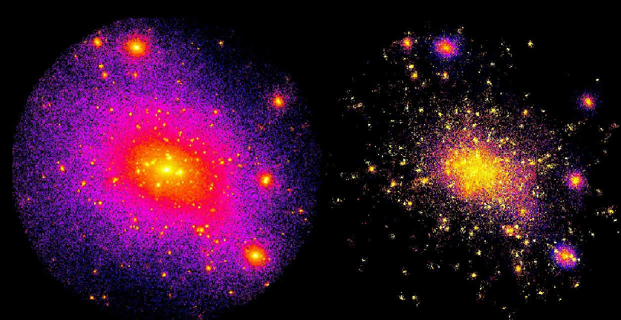
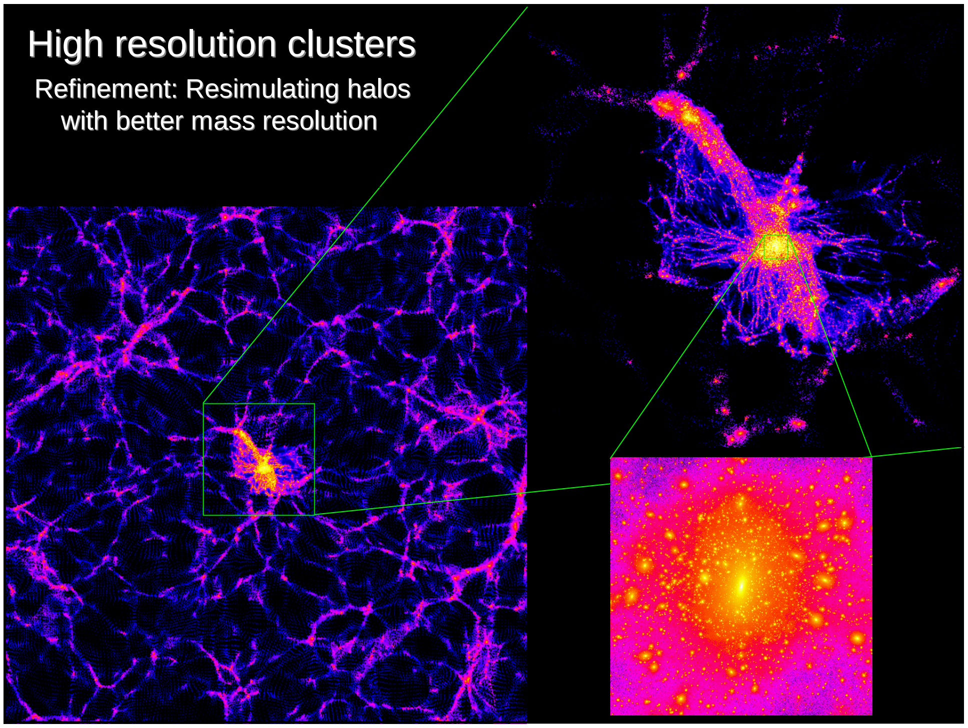
Estimated with a local Fokker-Planck type counter, gauged using spherical halos.

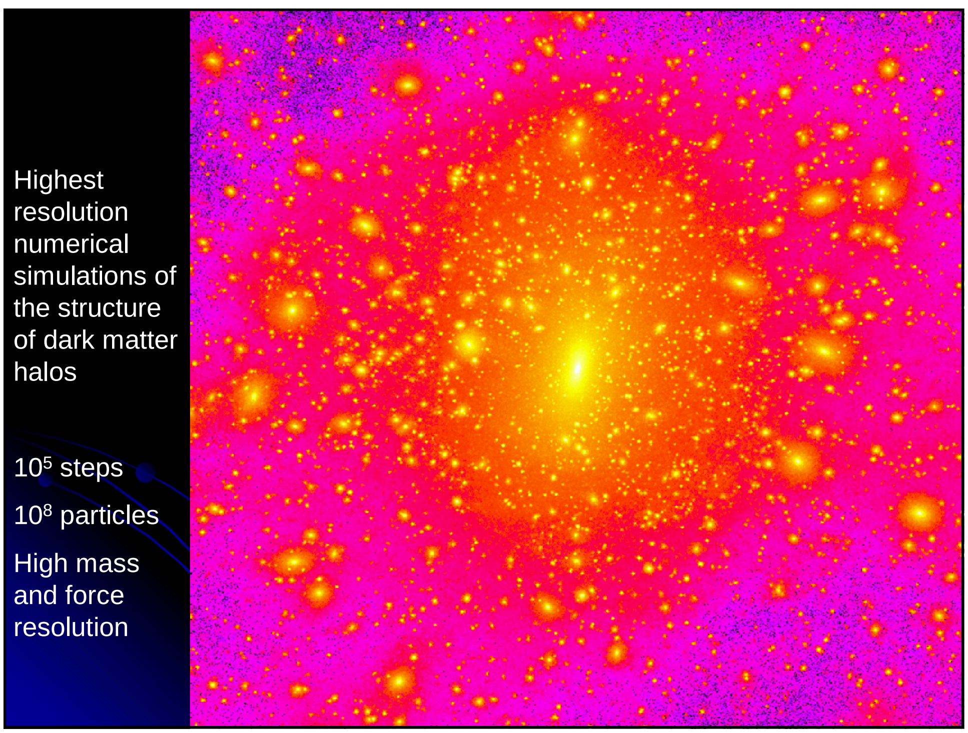
A cluster at z=0, resolved with 650'000 particles:

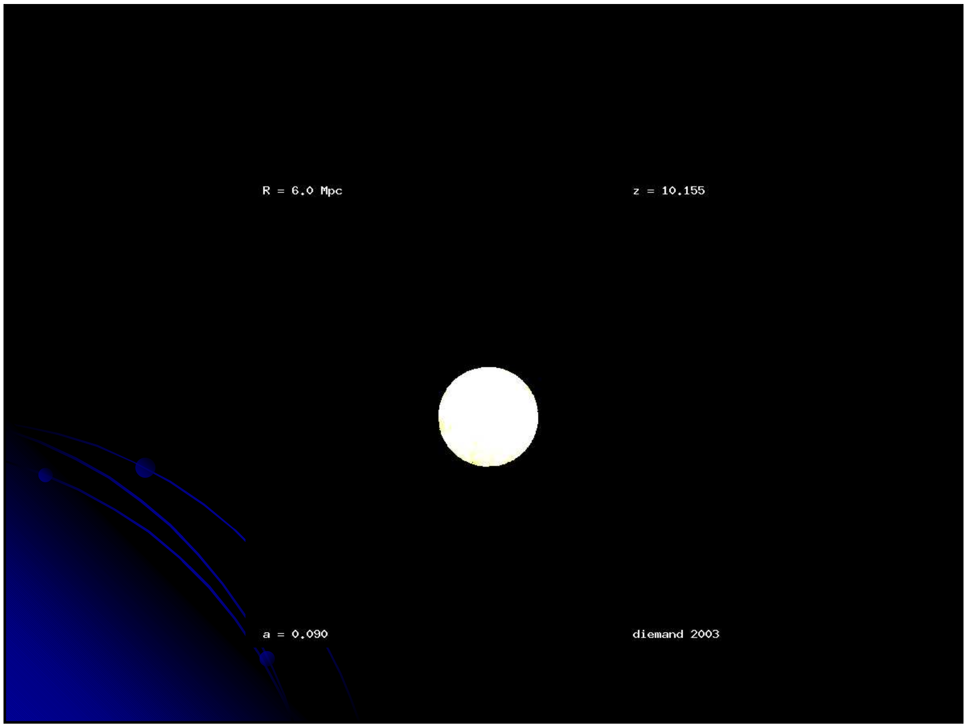


log density log “relaxation” average is 1.2

=> relaxation is an issue, but it decrases slowly when using more particles: $N^{-0.25}$
=> go to very large number of particles

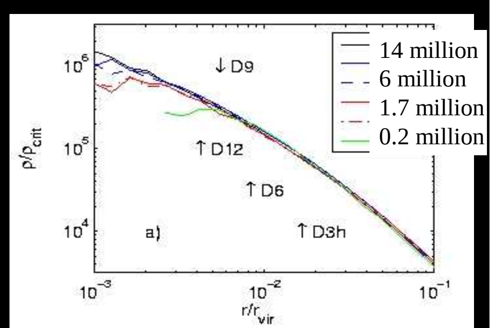

High resolution clusters
Refinement: Resimulating halos with better mass resolution

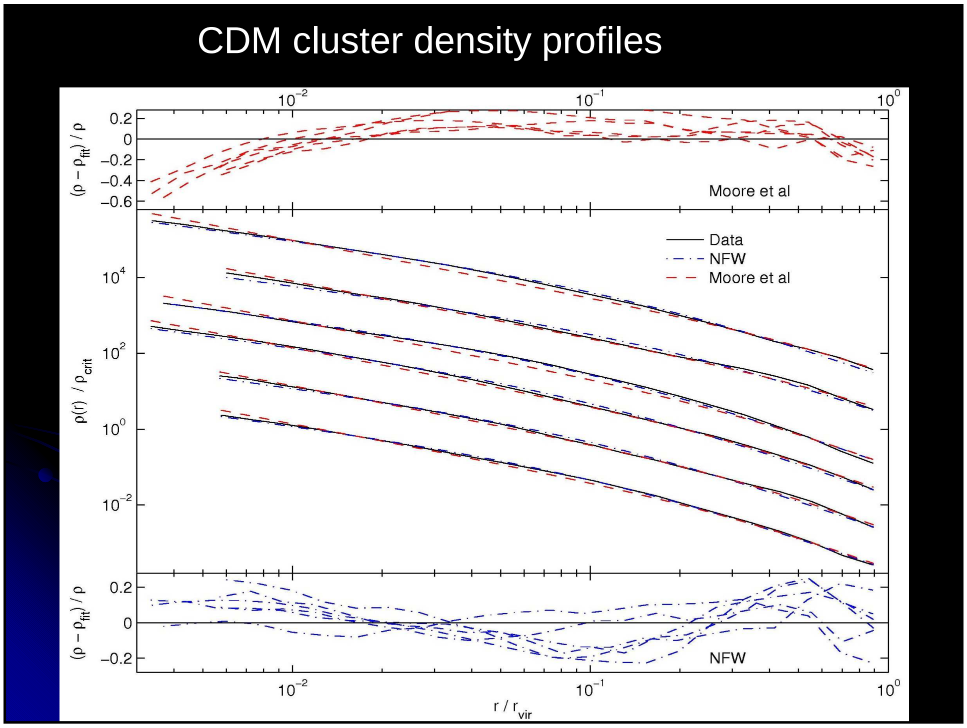

Highest resolution numerical simulations of the structure of dark matter halos
$10^5$ steps
$10^8$ particles
High mass and force resolution

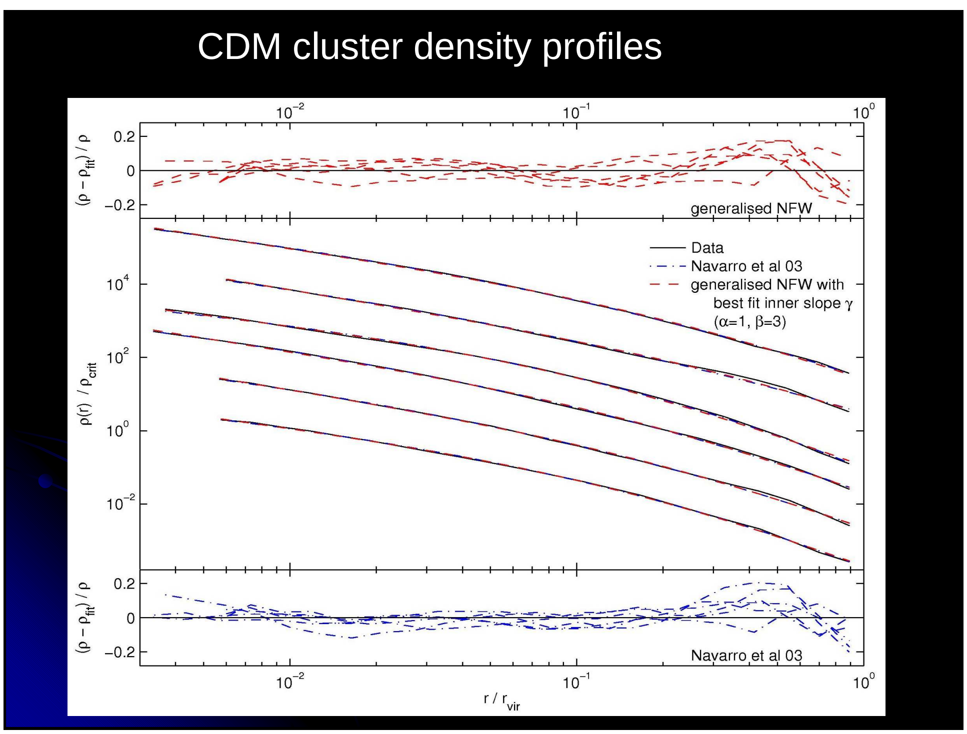



- Numerical flattening due to two body relaxation:
  slow convergence, $r \sim N^{-1/3}$
  1 million to resolve 1% of Rvirial,
  1000 to resolve 10%

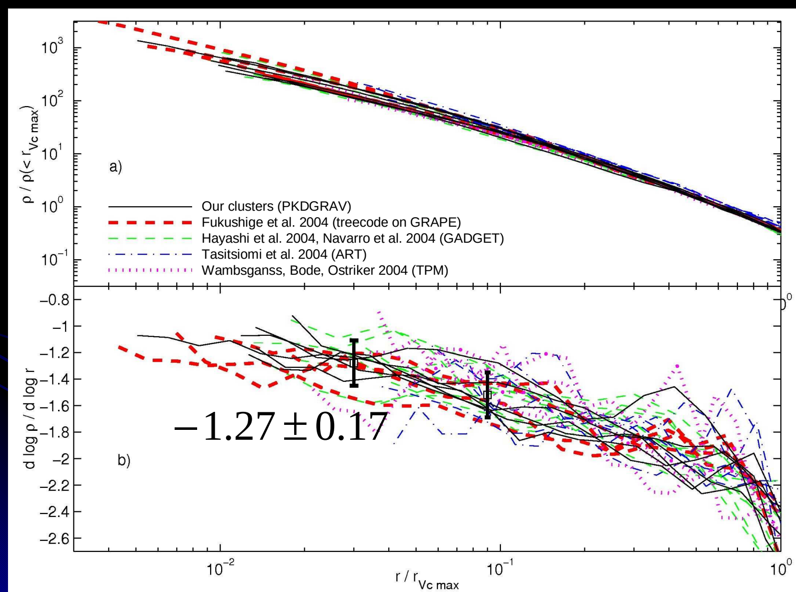
(Moore etal. 1998; JD etal. MNRAS 2004)




CDM cluster density profiles
(ρ − ρfit) / ρ
Moore et al
Data
NFW
Moore et al
ρ(r) / ρcrit
NFW
r / rvir


CDM cluster density profiles
(ρ − ρfit) / ρ
generalised NFW
Data
Navarro et al 03
generalised NFW with
best fit inner slope γ
(α=1, β=3)
ρ(r) / ρcrit
Navarro et al 03
r / rvir

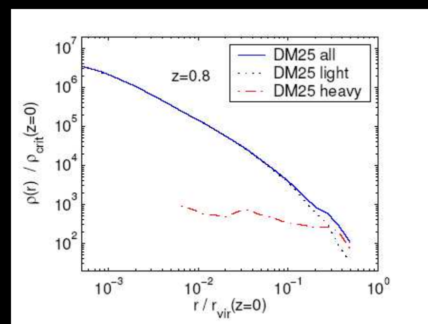
## CDM cluster density profiles




- Agreement among simulators. 5 different groups using different codes and initial conditions.
- Generalized NFW profiles with inner slopes of -1.16 +- 0.14 fit our 6 cluster profiles very well.
- Cored or cusped in the center? Still open at this resolution...

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

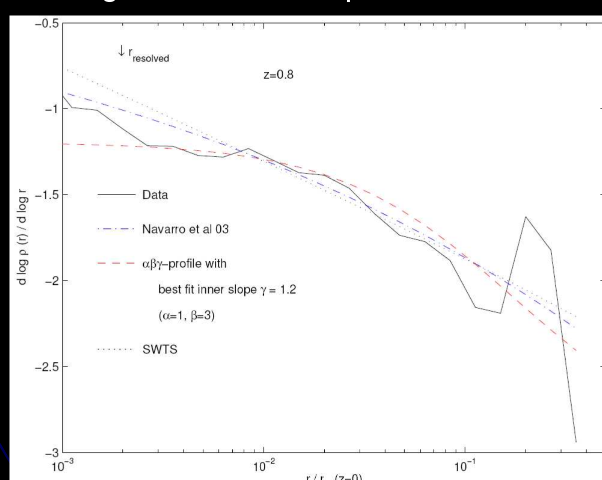
Works well for the 6 million particles cluster




Now we are running the same system at an effective resolution of 130 million particles inside the virial radius

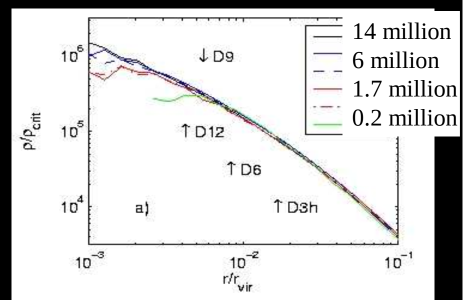
First results show convergence towards a power-law inner profile

logarithmic slope:



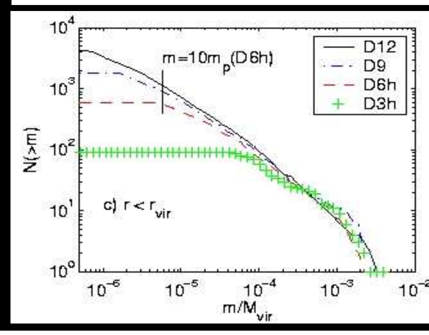
- Numerical flattening due to two body relaxation: slow convergence, $r \sim N^{-1/3}$
  1 million to resolve 1% of Rvirial, 1000 to resolve 10%

  (Moore etal. 1998;
  JD etal. MNRAS 353, 624, 2004)

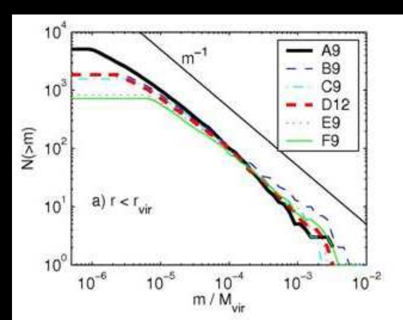



- Numerical Overmerging:

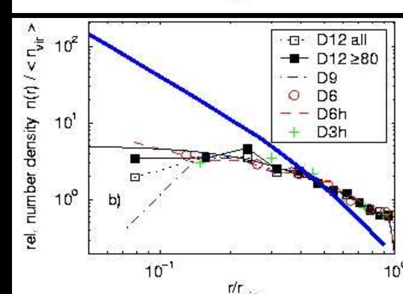
  => incomplete subhalo sample for N<100



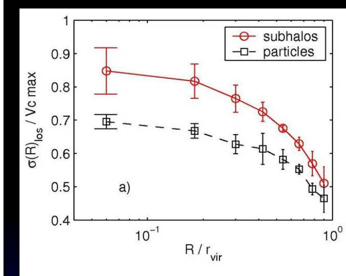

Steep cumulative mass functions, about $N(>m) \sim m^{-1}$

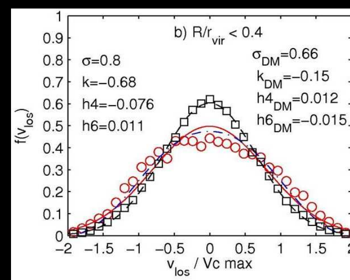



Number density profile is shallower than the DM profile



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




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

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

## Reionisation and metal poor globular clusters

Simulations: four galaxy halos resolved with 2 to 4 million particles

- just dark matter, no gas

\+ resolve all the progenitors above $10^7$ solar masses, i.e. all relevant star formation sites

Two Assumptions:

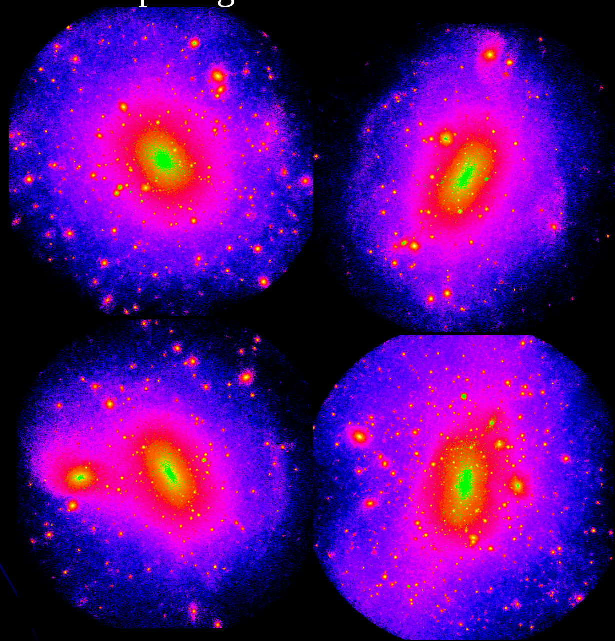
- Metal poor GC's form in DM halos more massive than 2 x $10^8$ solar masses
- Metal poor GC's form before reionisation, which removes the gas from these small halos (eg. Shaviv&Dekel 2003)

=> just have to mark all particles in these halos at the reionisation time to get the right spatial distribution of GC's in the Milky Way today.

Picture: The marked and other halos build up bigger systems > $10^{10}$ solar masses (the direct progenitors of the MW and its satellites) which start forming stars again (Kravtsov etal. 2004)

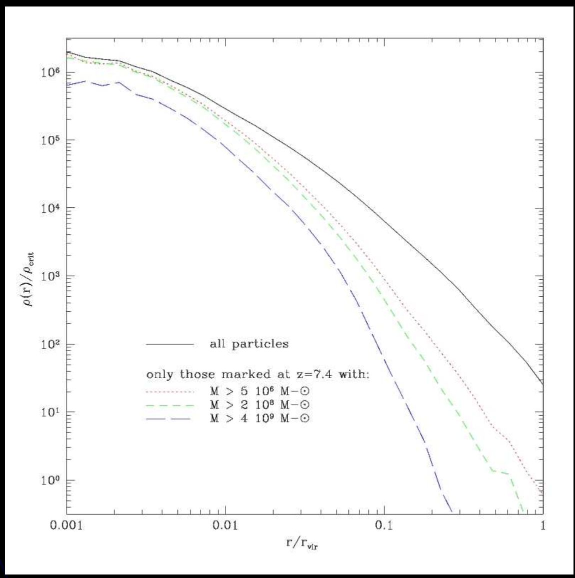
## Reionisation and metal poor globular clusters

Matter marked in halos at z=10.5 ends up near the centers of today's galaxies (and their satellites). The individual halos are tidally stripped below the resolution scale and he GC's in their cores would survive containing little dark matter and without an extended dark halo.



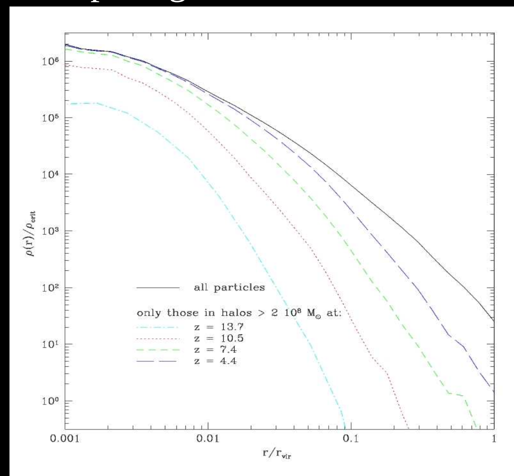
## Reionisation and metal poor globular clusters

Density profiles of the marked material depends weakly on the assumed mass (or density) threshold, …



## Reionisation and metal poor globular clusters

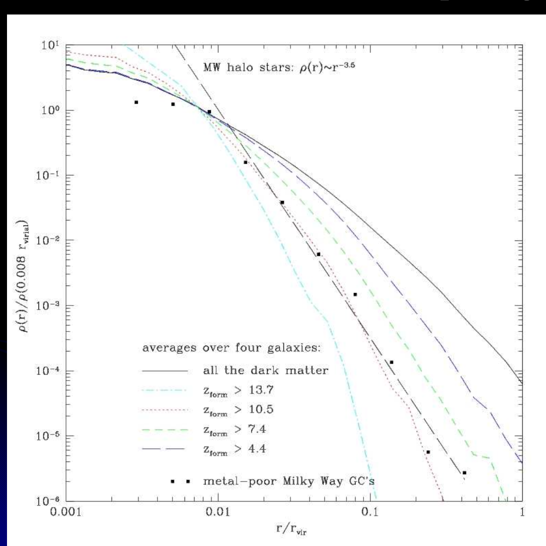
… and the profiles depend strongly on the reionisation time:




Milky Way GC's profile fits these parameter pairs:

| | | | | |
|---|---|---|---|---|
| z : | 13.7 | 10.5 | 7.5 | |
| M: | $5 \times 10^6$ | $2 \times 10^8$ | $4 \times 10^9$ | [solar masses] |
| | m* too small | | protogalaxies, higher metallicity? | |

## Reionisation and metal poor globular clusters




-> the local universe was reionised around redshift 10.5

-> higher frequency in cD galaxies implies that cluster forming regions were NOT reionised earlier

next steps:

- Use GC data form other galaxies in the field and in clusters
- compare kinematics

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

- inner density profiles seem to have steep cusps, on average $\sim r^{-1.2}$, but they are very difficult to resolve.
- over 100 particles per subhalo are needed to overcome numerical overmerging.
- Large abundance of subhalos and steep mass functions, $N(>m) \sim m^{-1}$
- today's number density profile of metal poor globular clusters in the Milky Way could result from their formation in small dark matter halos before z=10.