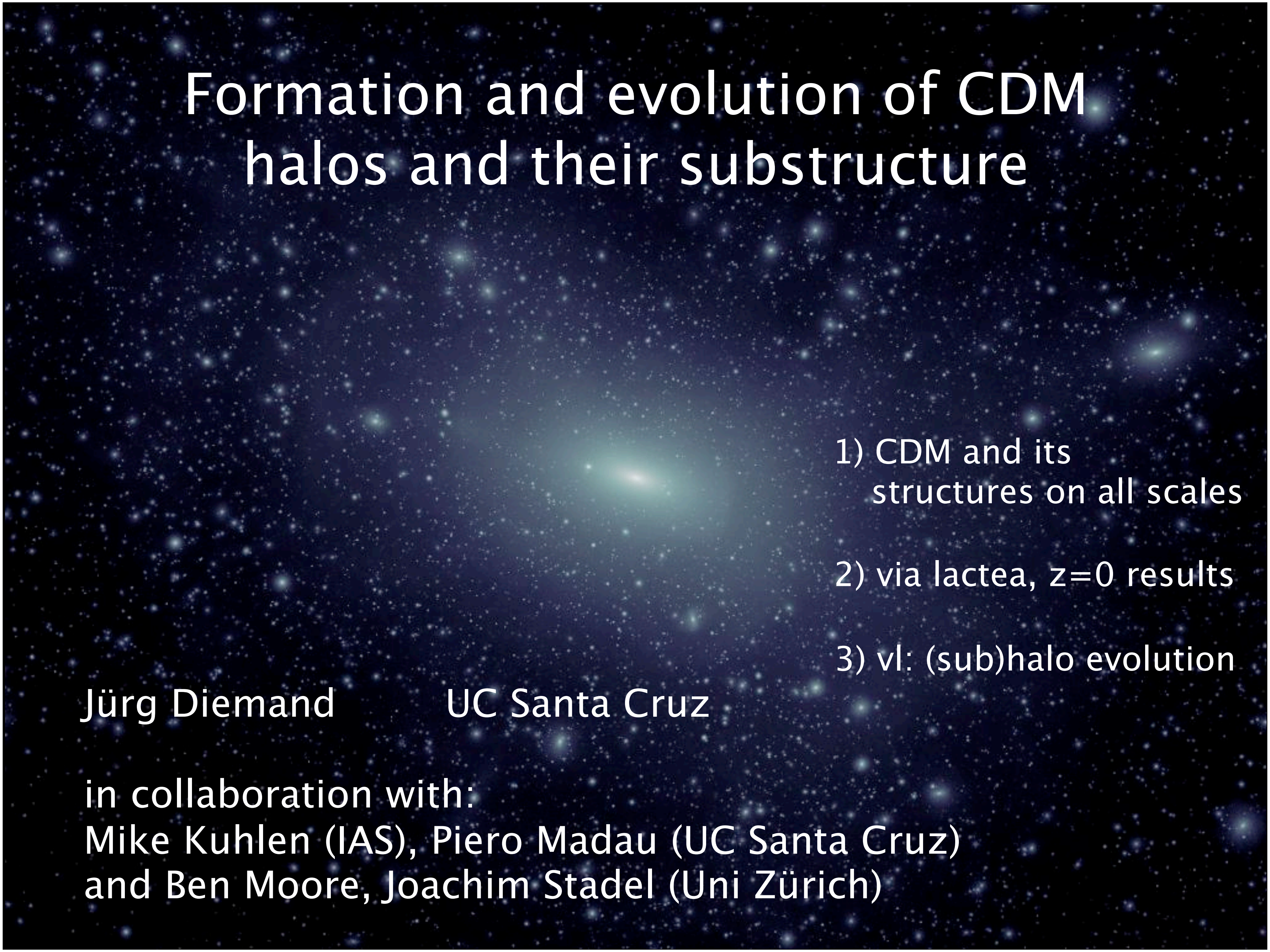


Formation and evolution of CDM halos and their substructure

1) CDM and its structures on all scales

2) via lactea, z=0 results

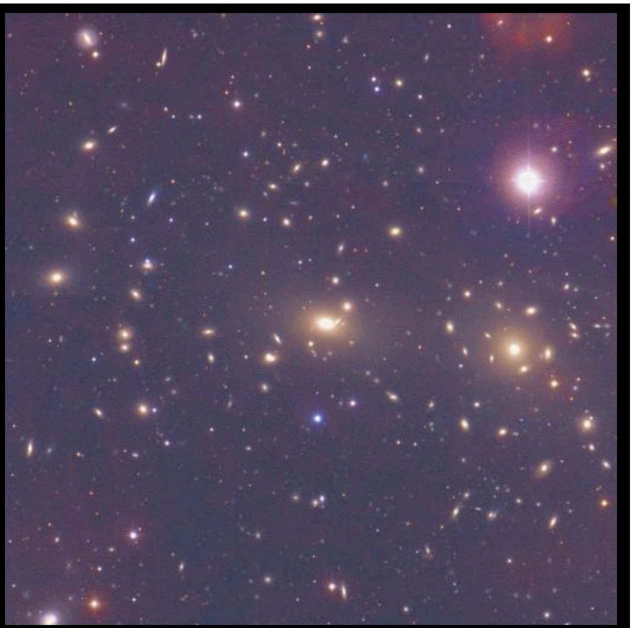
3) vl: (sub)halo evolution

Jürg Diemand UC Santa Cruz

in collaboration with:
Mike Kuhlen (IAS), Piero Madau (UC Santa Cruz)
and Ben Moore, Joachim Stadel (Uni Zürich)

What is dark matter ?

Evidence for DM on a wide range of scales:
- Galaxy cluster dynamics (Zwicky, 1933)
- Spiral galaxy rotation curves
- X-rays from galaxy groups and clusters
- Kinematics of stellar halos
  - and globular cluster systems
- Dwarf galaxy velocity dispersions
- Strong and weak lensing
- ...

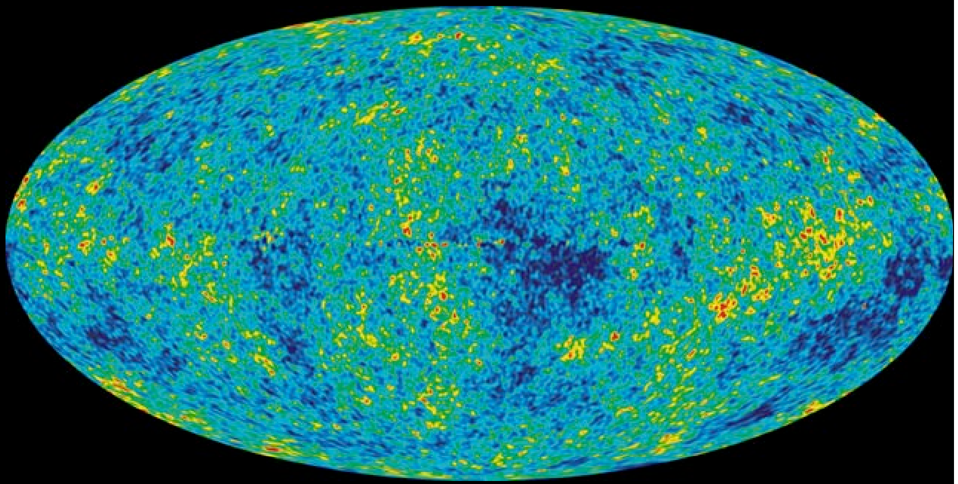


Coma, Credit: Lopez-Cruz et al

CMB, LSS, SN Ia, BBN → LambdaCDM

WMAP-3yr (alone, flat prior):
Omega_m=0.238
of which Omega_b is only 0.042
with small errors (less than 10%)

DM is "cold", or at least "cool":
Lyman-alpha forest, early reionisation



Credit: NASA/WMAP

→ 83% of the clustering matter is some non-baryonic,
very weakly interacting, "cold" dark matter

We don't know yet what the DM is, but we can still simulate its clustering ...

Simulating structure formation

our approach:
collision-less (pure N-body, dark matter only) simulations

- treat all of Omega_m like dark matter
- bad approximation near galaxies, OK for dwarf galaxies and smaller scales
- simple physics: just gravity
- allows high resolution
- no free parameters (ICs known thanks to CMB)

→ accurate solution of the idealized problem

complementary approach:
hydrodynamical simulations

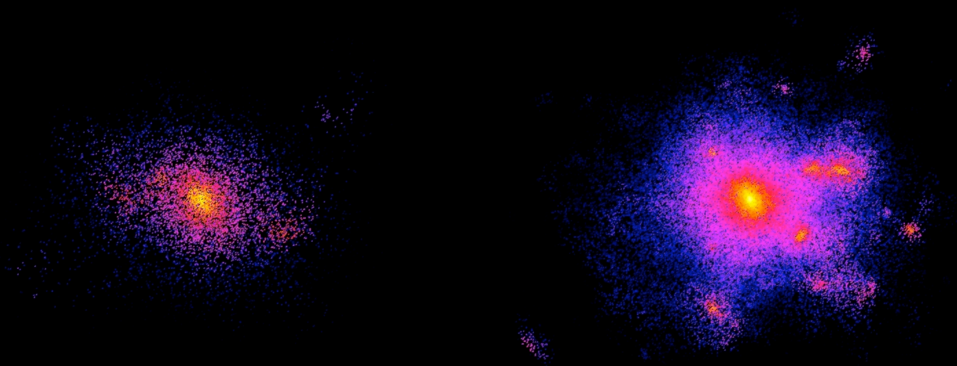
- computationally expensive, resolution relatively low
- hydro is not trivial (SPH and grid codes often disagree)
- important physical processes far below the resolved scales (star formation,SN, ... ?) implemented through uncertain functions and free parameters

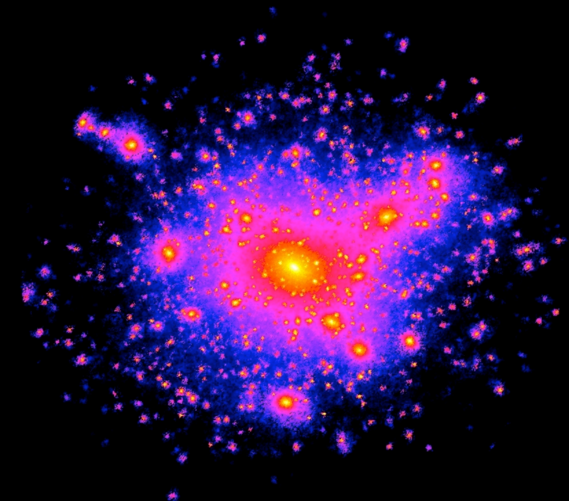
→ approximate solution to the more realistic problem

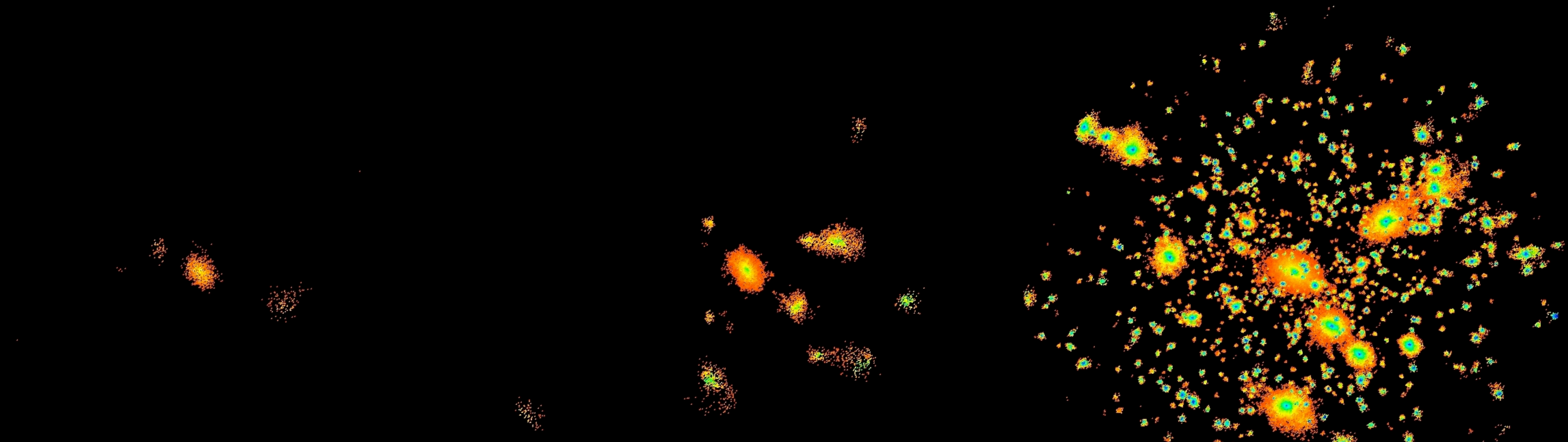
Simulating structure formation

N-body models approximating CDM halos (about 1995 to 2000)

log density



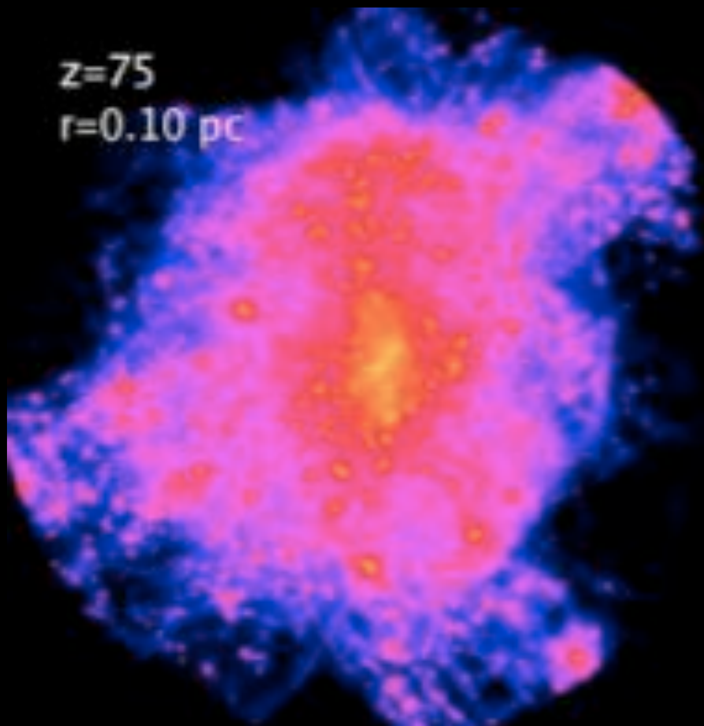


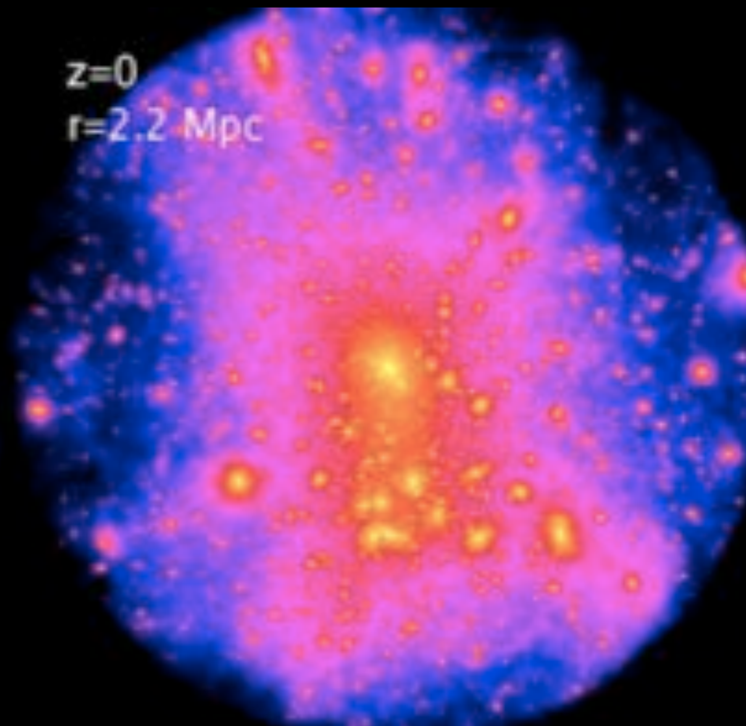


log phase space density

from Ben Moore : www.nbody.net

CDM forms (sub)structures on many scales





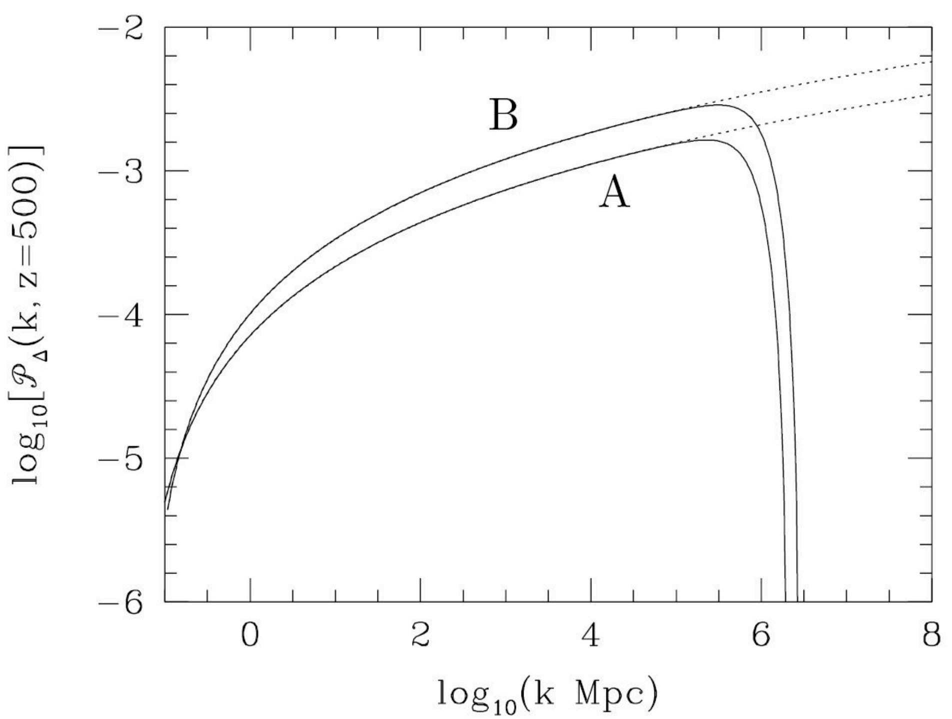
M ~ 0.01 Msun microhalo   M=6e14 Msun galaxy cluster

no baryons, dark DM structure, but relevant for DM annihilation signal:
extragalactic background, M31, Draco ... nearby dark subhalos

smallest scale CDM structures in the field

For a 100 GeV SUSY neutralino (a WIMP) there is a cutoff at about 10^{-6} Msun due to free streaming

from Green, Hoffmann & Schwarz 2003



→ small, “micro”-halos should forming around z=40 are the first and smallest CDM structures

smallest scale CDM structures in the field

CDM microhalos seem to be cuspy

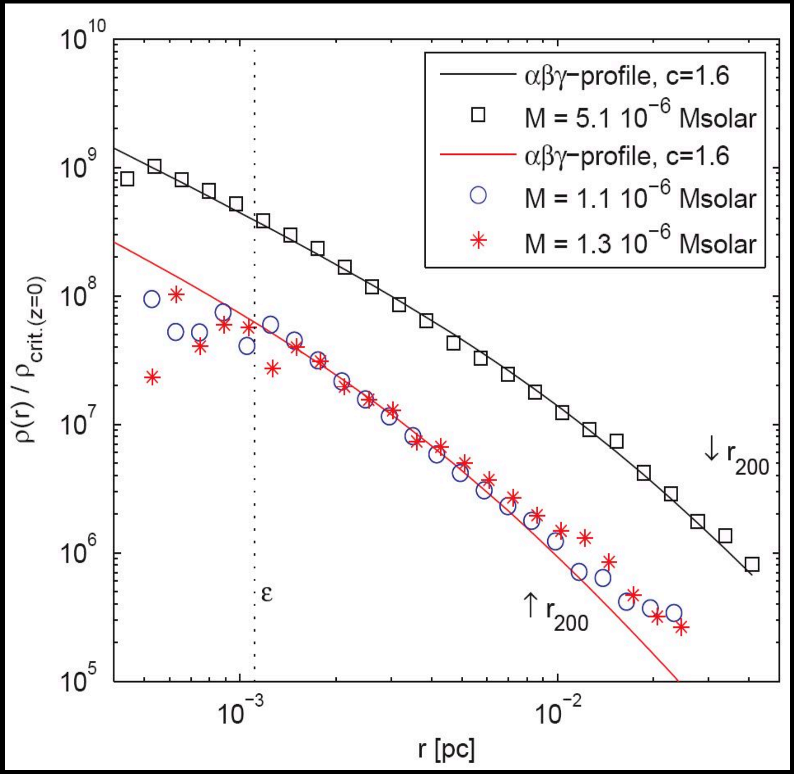
like the larger halos that formed in mergers

they are very concentrated
c~3.3 at z=26
evolves into c~90 by z=0
consistent with Bullock etal model

-> they are stable against tides caused
by the MW potential if the live more
than about 3 kpc form the galactic center

i.e. a huge number ~ 5×10^{15} could be
orbiting in the MW halo today

JD, Moore,Stadel, astro-ph/0501589



some tidal mass loss and disruption due to

encounters with stars (see Goerdt etal astro-ph/0608495)

smallest scale CDM substructures

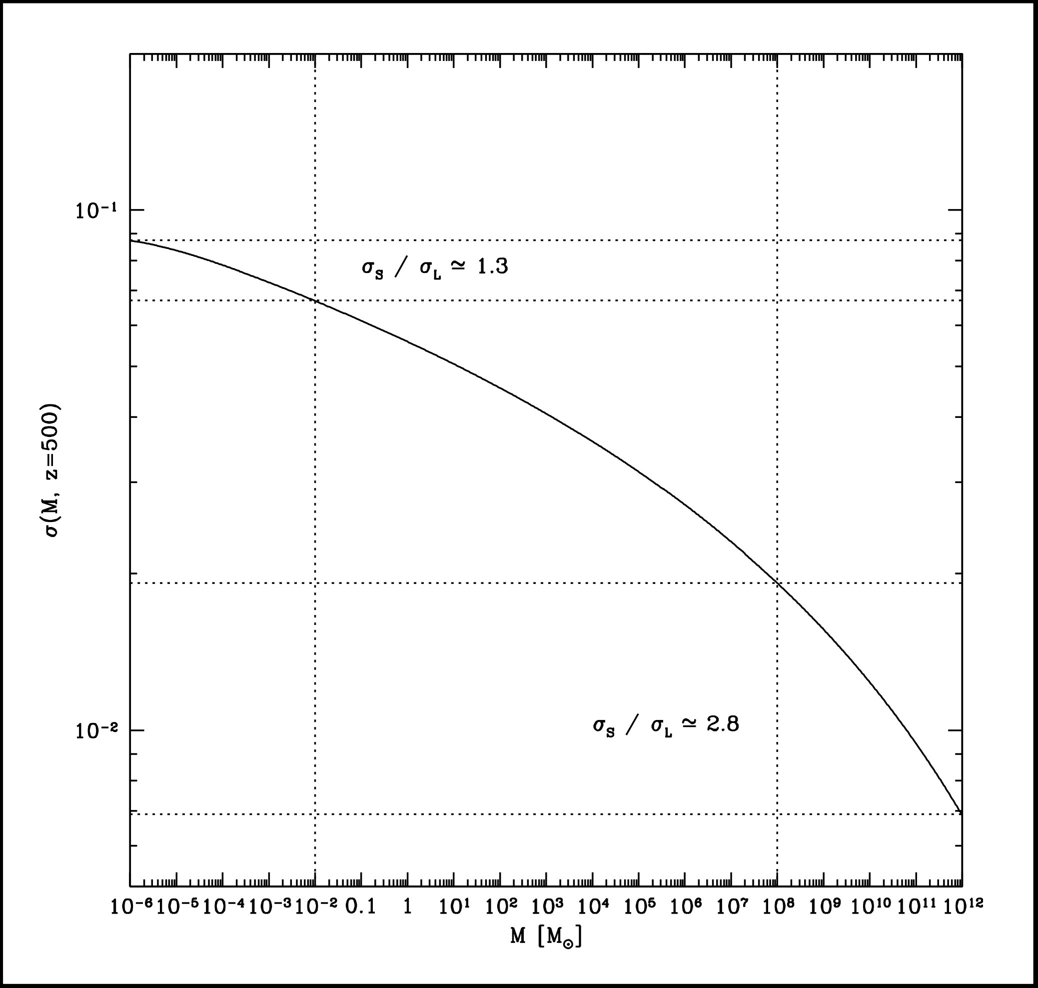
since P(k) ~ $k^{-2.9}$
sigma(M) almost constant on microhalo scales

structures of different mass form almost simultaneous

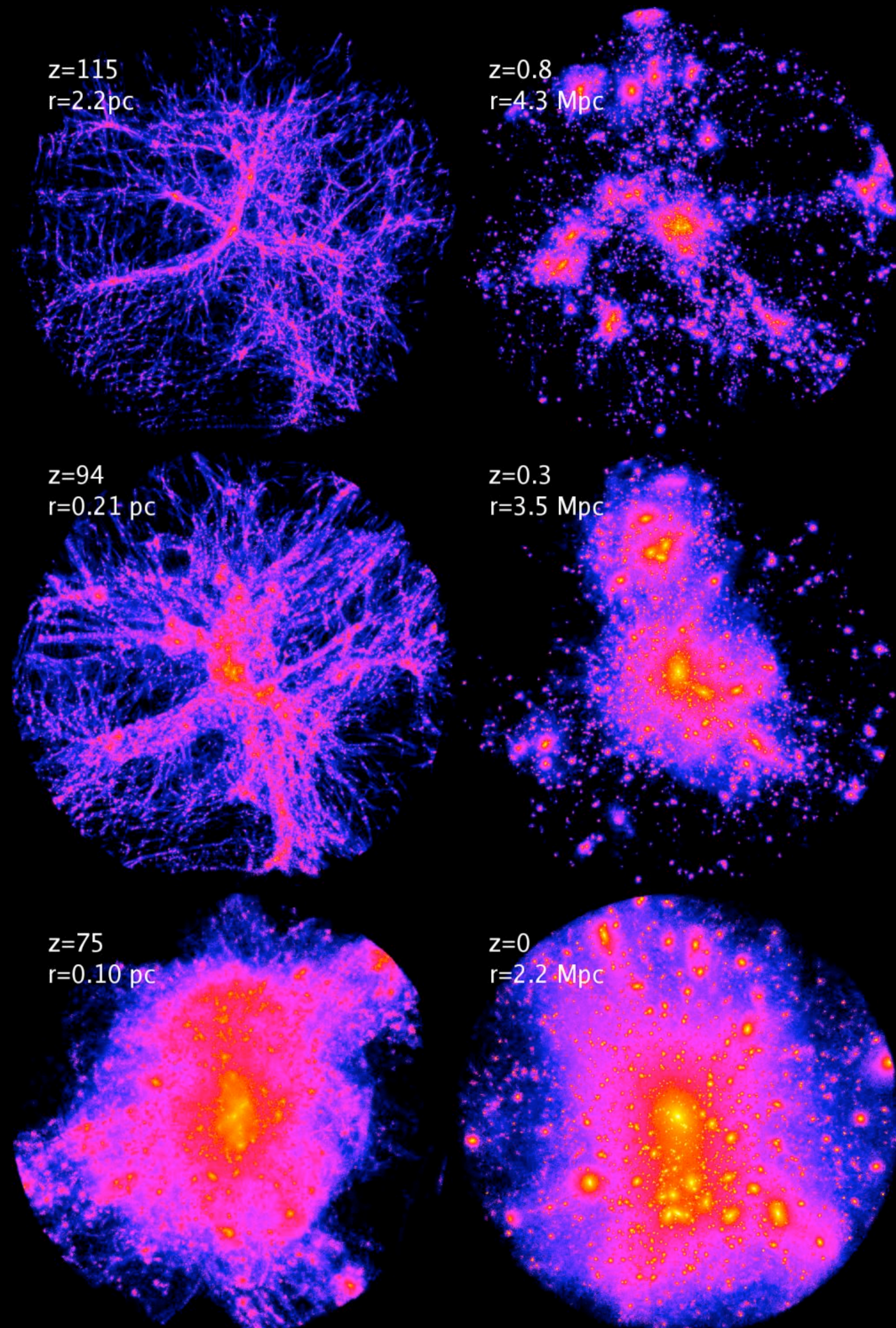
only true for the average field halo

not true for subhalos, they form on top of a lager perturbation, and therefore earlier

is there enough time for them to virialize and survive accretion into a larger host?



almost simultaneous collapse of a 0.01 Msun halo at z=75



hierarchical formation of a z=0 cluster

same comoving DM density scale from 10 to 10^6 times the critical density

in each panel the final M_{vir} ~ 20 million particles are shown

lower density contrast, but similar subhalo abundance as in a z=0 cluster

JD,Kuhlen,Madau
astro-ph/0603250

2) z=0 results form “via lactea”

a Milky Way halo simulated with over 200 million particles

- JD, Kuhlen, Madau astro-ph/0611370

- largest DM simulation to date
  320,000 cpu-hours on NASA's Project Columbia supercomputer.

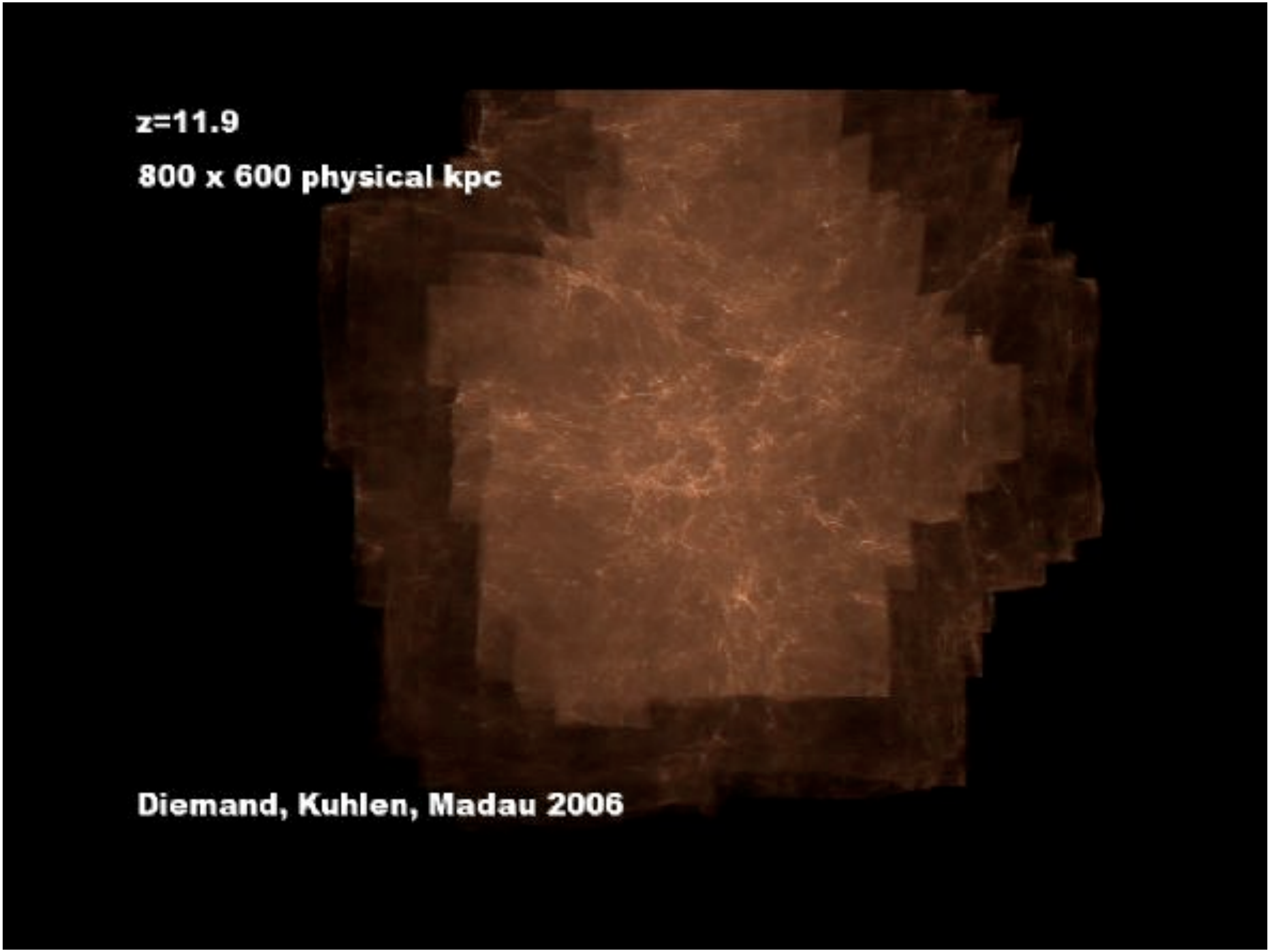
- 213 million high resolution particles, embedded in a periodic 90 Mpc box sampled at lower resolution to account for tidal field.

- WMAP (year 3) cosmology:
  Omega_m=0.238, Omega_L=0.762, H_0=73 km/s/Mpc, n_s=0.951, $sigma_8$=0.74.

- force resolution: 90 parsec

- time resolution: adaptive time steps as small as 68,500 years

- mass resolution: 20,900 $M_\odot$


z=11.9
800 x 600 physical kpc
Diemand, Kuhlen, Madau 2006

www.ucolick.org/~diemand/vl

a Milky Way dark matter halo simulated with 234 million particles on NASA's Project Columbia supercomputer

main

movies

images

publications

data (full snapshots, subhalo properties, histories etc. will become available in summer 2007)

movies

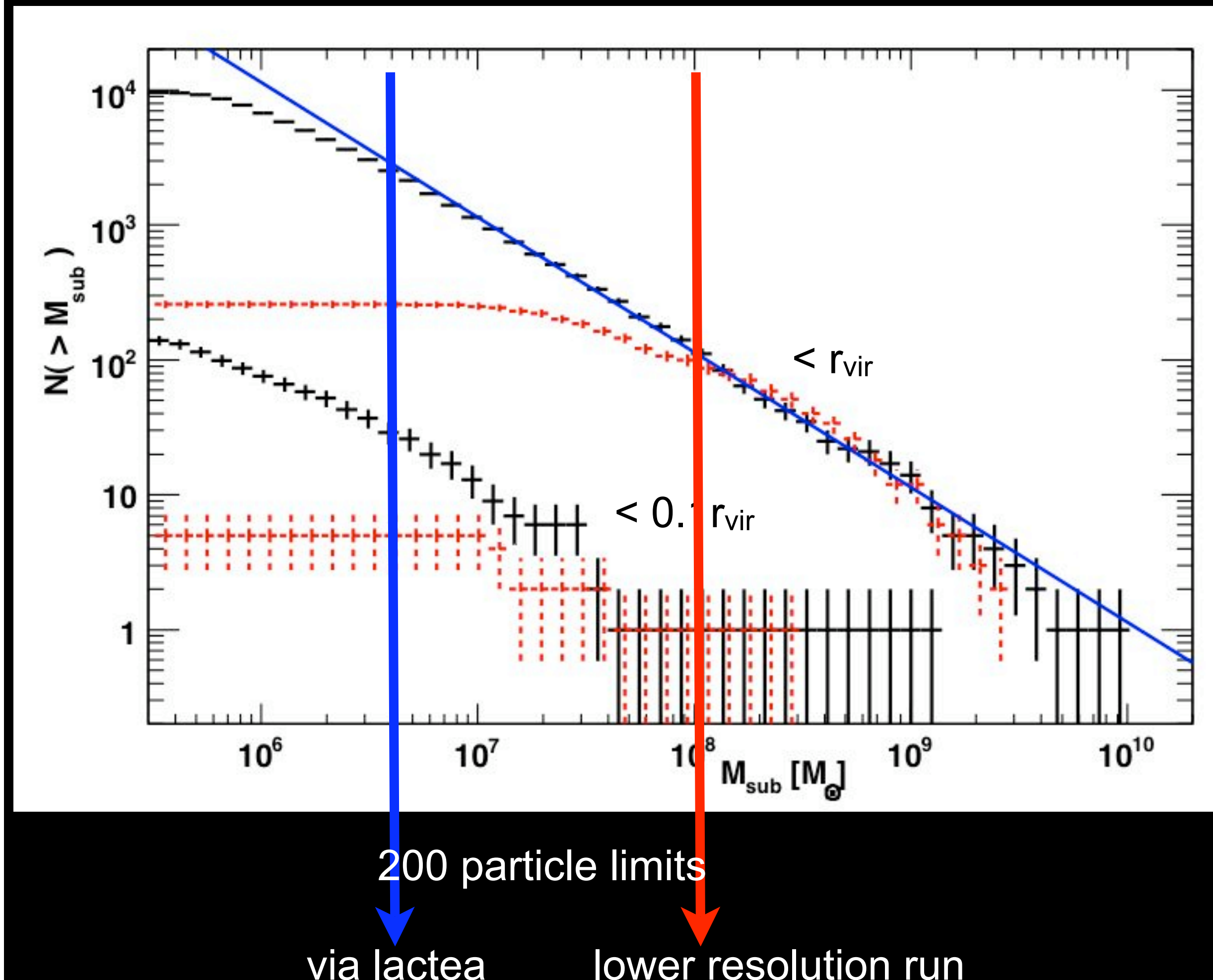
These animations show the projected dark matter density-square maps of the simulated Milky Way-size halo Via Lactea. The logarithmic color scale covers the same 20 decades in projected density-square in physical units in each frame. All movies are encoded in MPEG format and some are available in different quality versions.

the formation of the Via Lactea halo

- entire formation history (z=12 to 0): high quality (218MB) smaller frames, quality: high(55MB) medium(11MB) low(4.7MB)
- entire formation history, plus rotation and zoom at z=0: quality: high(433MB) medium(72MB)
- early, active phase of merging and mass assembly (z=12 to 1.3): (81MB)
- late, passive and stationary phase (z=1.3 to 0): (137MB)

rotation and zoom into the Via Lactea halo at z=0 (today)

subhalo mass functions



N(>M) ~ M^{-a}

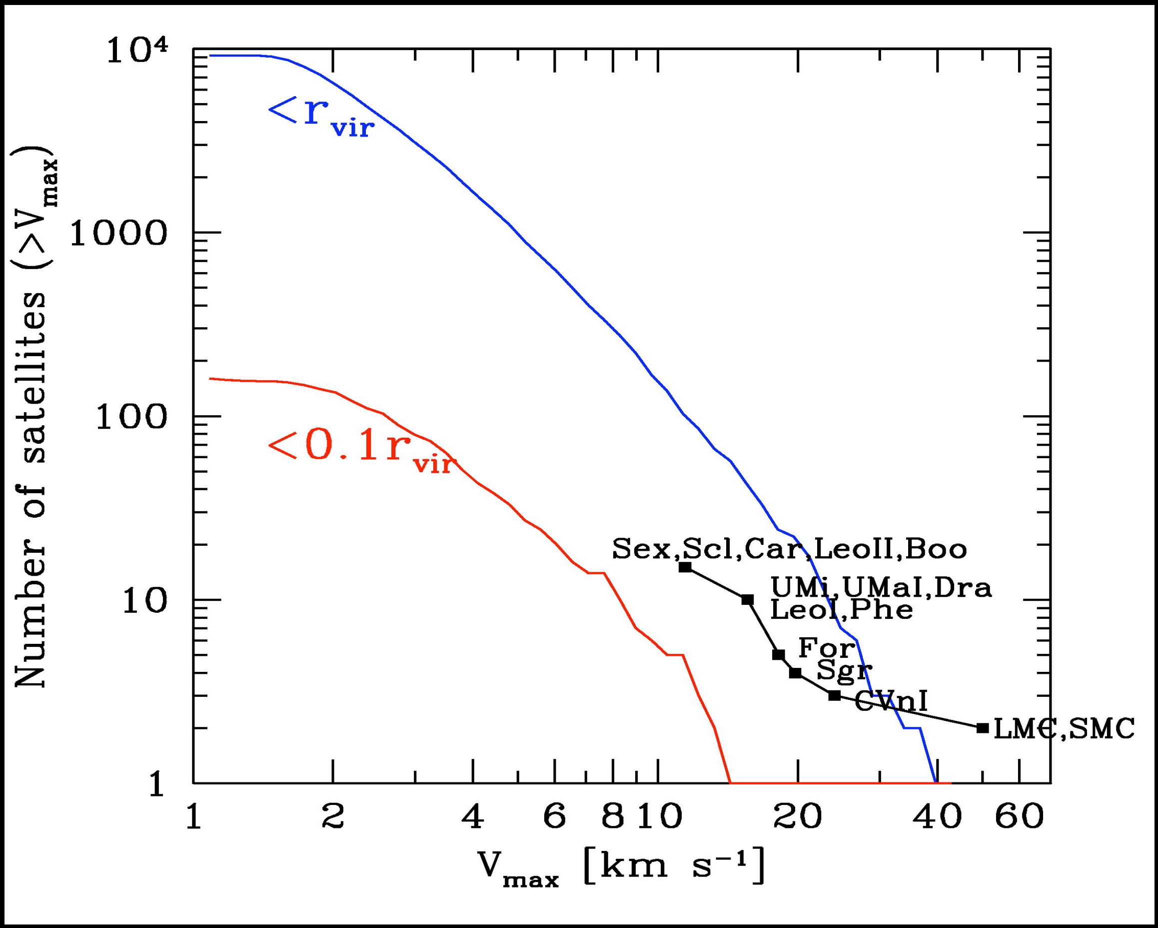
with a between 0.9 and 1.1, depending on mass range used

steeper at high M
due to dynamical friction

shallower at low M
due to numerical limitations

Close to constant contribution to mass in subhalos per decade in subhalo mass

subhalo velocity functions



$N(>V) \sim V^{-a}$

with a = 3

down to about 8 km/s,
again shallower due to
numerical limitations below that

about 100 subhalos large
enough to host small Local
Group dwarfs like Sextans

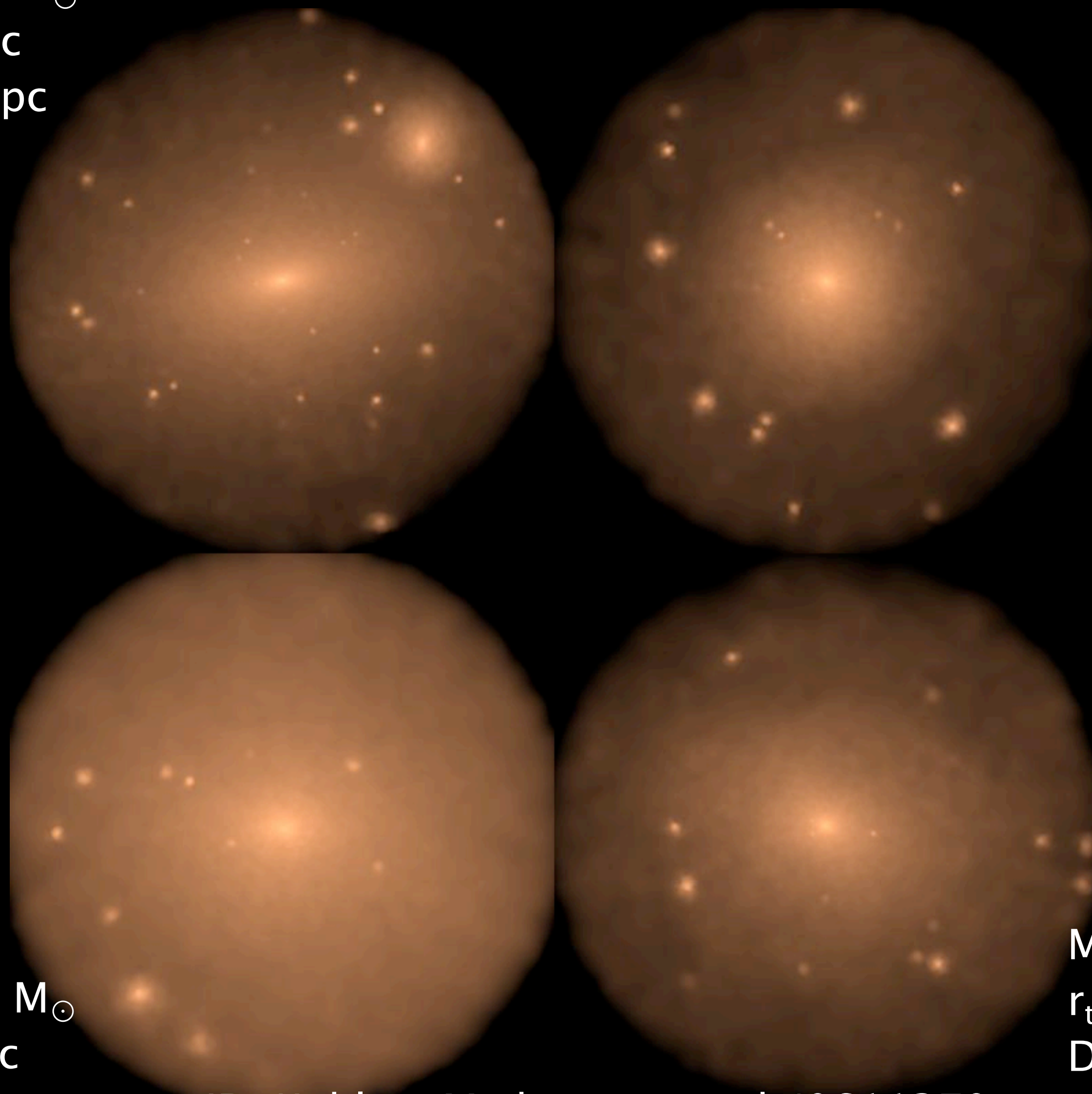
NOTE: this comparison assumes sqrt(3) sigma* = Vmax
as suggested by simulations

More accurate comparisons are now possible (in preparation with L. Strigari, J. Bullock, etal)

sub-subhalos in all well resolved subhalos

M_{sub}=9.8 10^9 $M_\odot$
r_{tidal}=40.1 kpc
D_{center}=345 kpc

M_{sub}=3.7 10^9 $M_\odot$
r_{tidal}=33.4 kpc
D_{center}=374 kpc

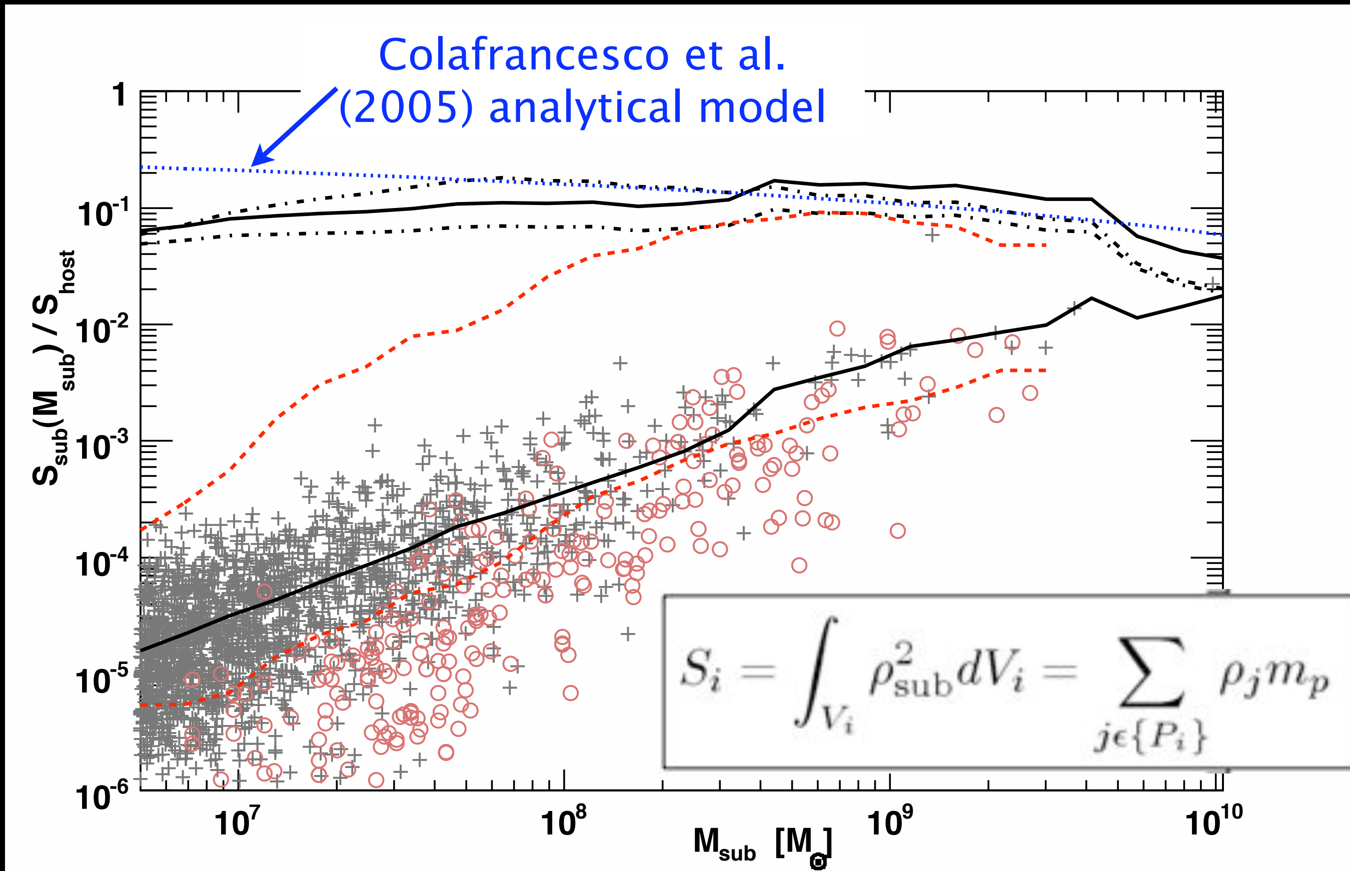


M_{sub}=2.4 10^9 $M_\odot$
r_{tidal}=14.7 kpc
D_{center}=185 kpc

M_{sub}=3.0 10^9 $M_\odot$
r_{tidal}=28.0 kpc
D_{center}=280 kpc

JD, Kuhlen, Madau, astro-ph/0611370

DM annihilation signal from subhalos



$$S_i = \int_{V_i} \rho_{\rm sub}^2 dV_i = \sum_{j\epsilon\{P_i\}} \rho_j m_p$$

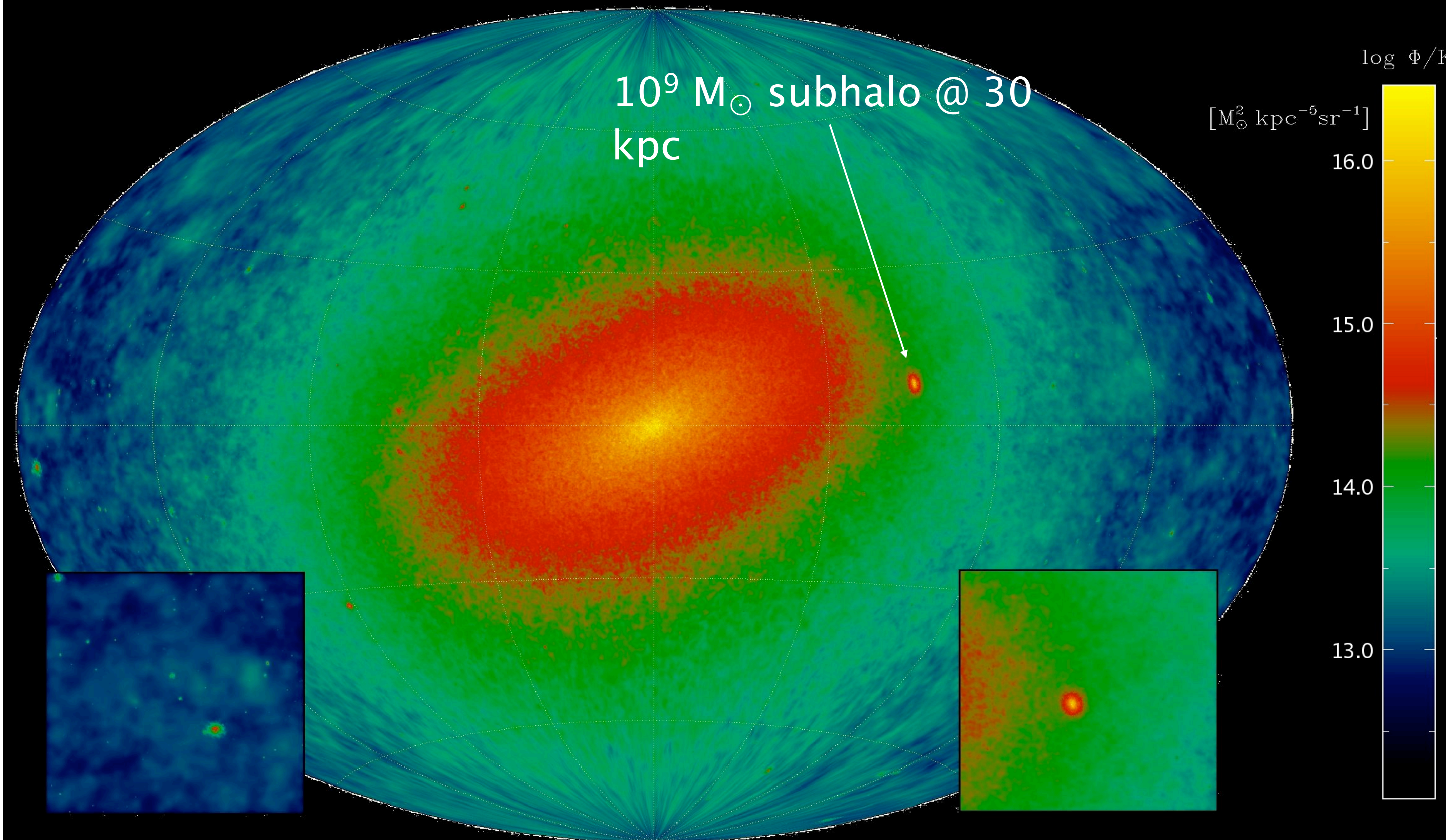
Total signal from subhalos is constant per decade in subhalo mass

The spherically averaged signal is about half of the total in Via Lactea, but the total signal has not converged yet

total boost factor from subhalos: between 3 (constant) and 8 (more form small subs)

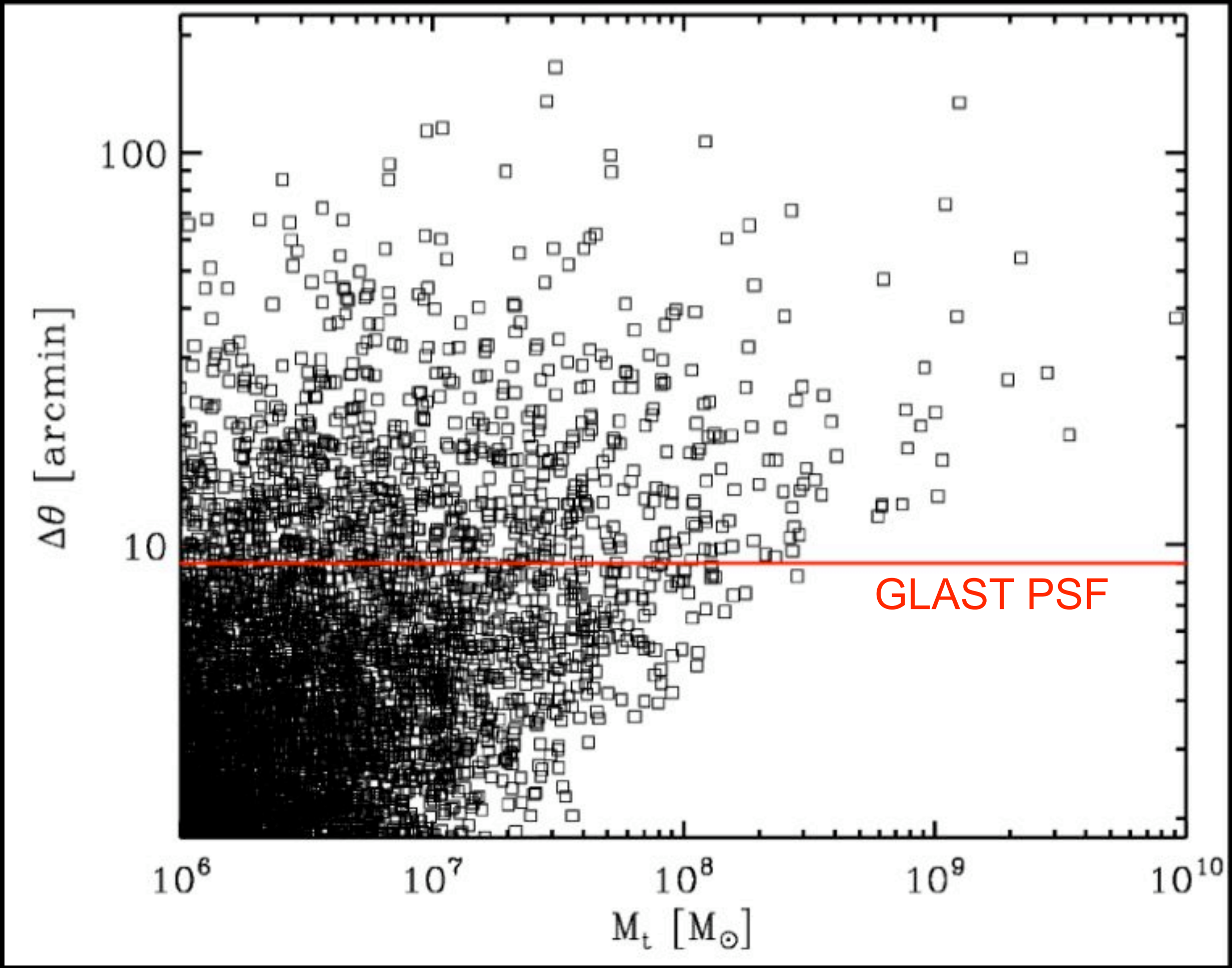
total boost factor including sub-sub-....-halos: between 13 (constant) and about 80

allsky map of gamma-ray annihilation “flux”



Observer located at 8.0 kpc from halo center

angular size vs. mass



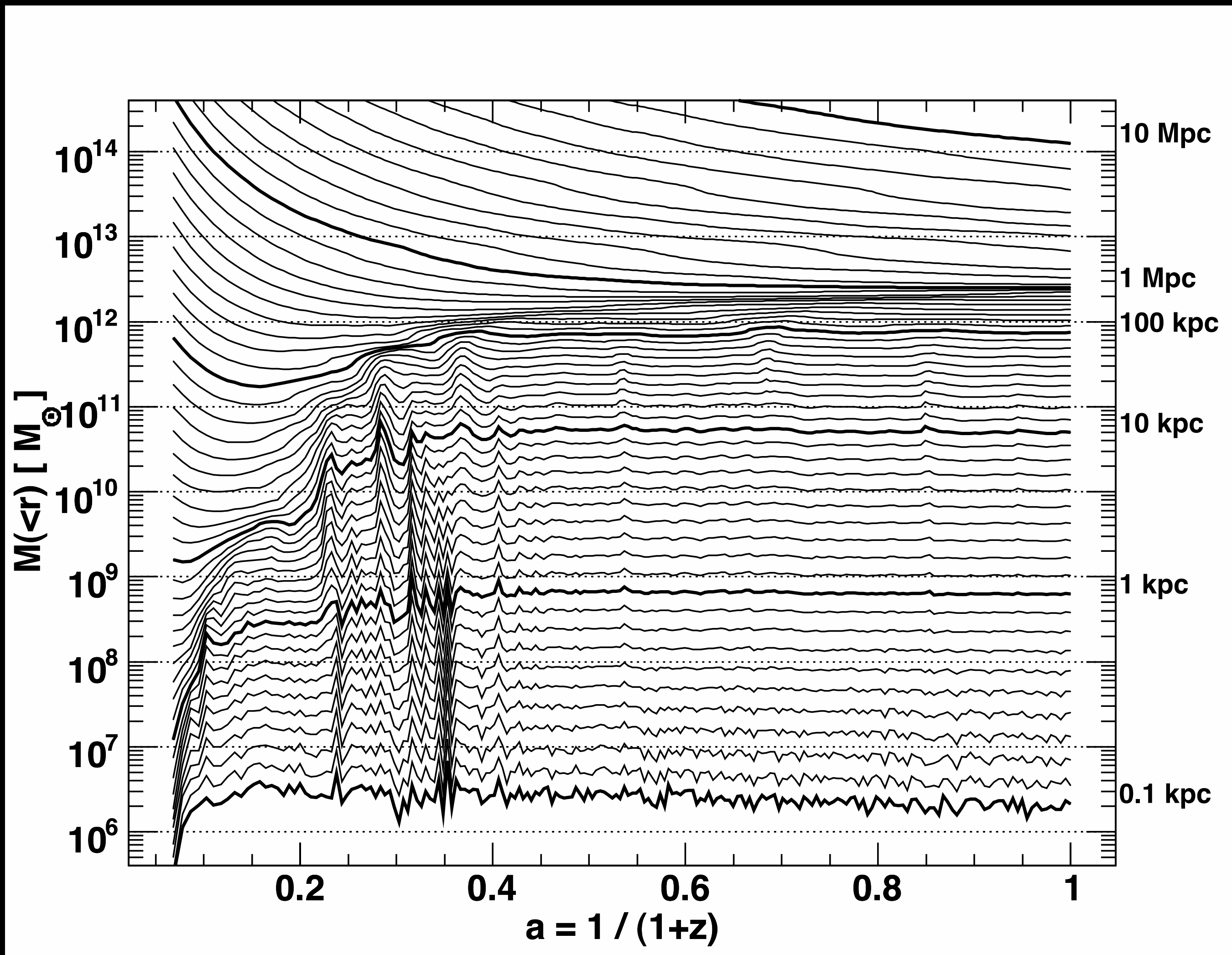
Δθ = angle subtended by twice the subhalo's scale radius r_s.

For an NFW profile 90% of the flux originates from within r_s.

the brightest subhalos would be extended sources for GLAST (PSF 9 arcmin at 10 GeV)

3) (sub)halo evolution

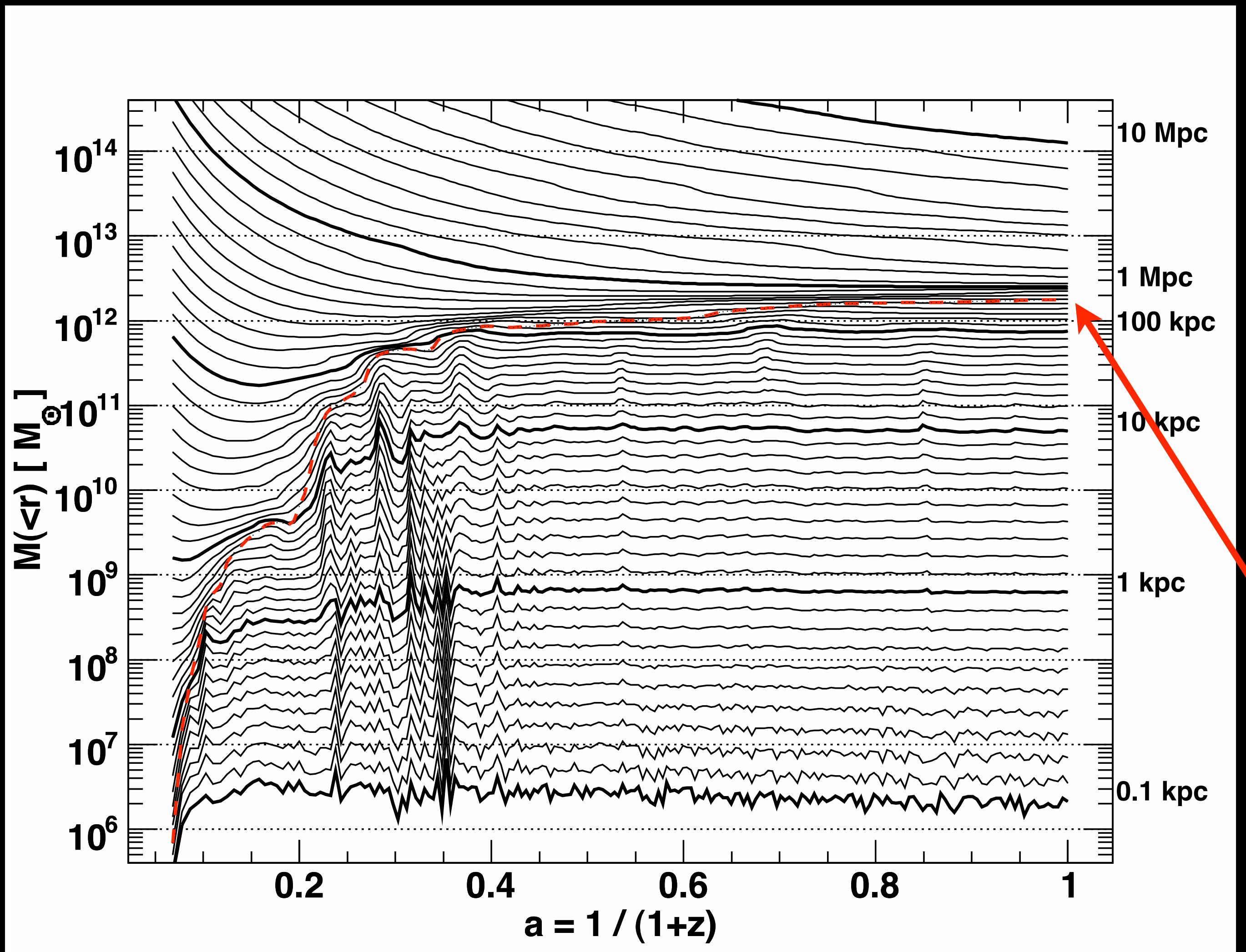
JD,Kuhlen,Madau astro-ph/0703337



How big is this halo at each time?

3) (sub)halo evolution

JD,Kuhlen,Madau astro-ph/0703337



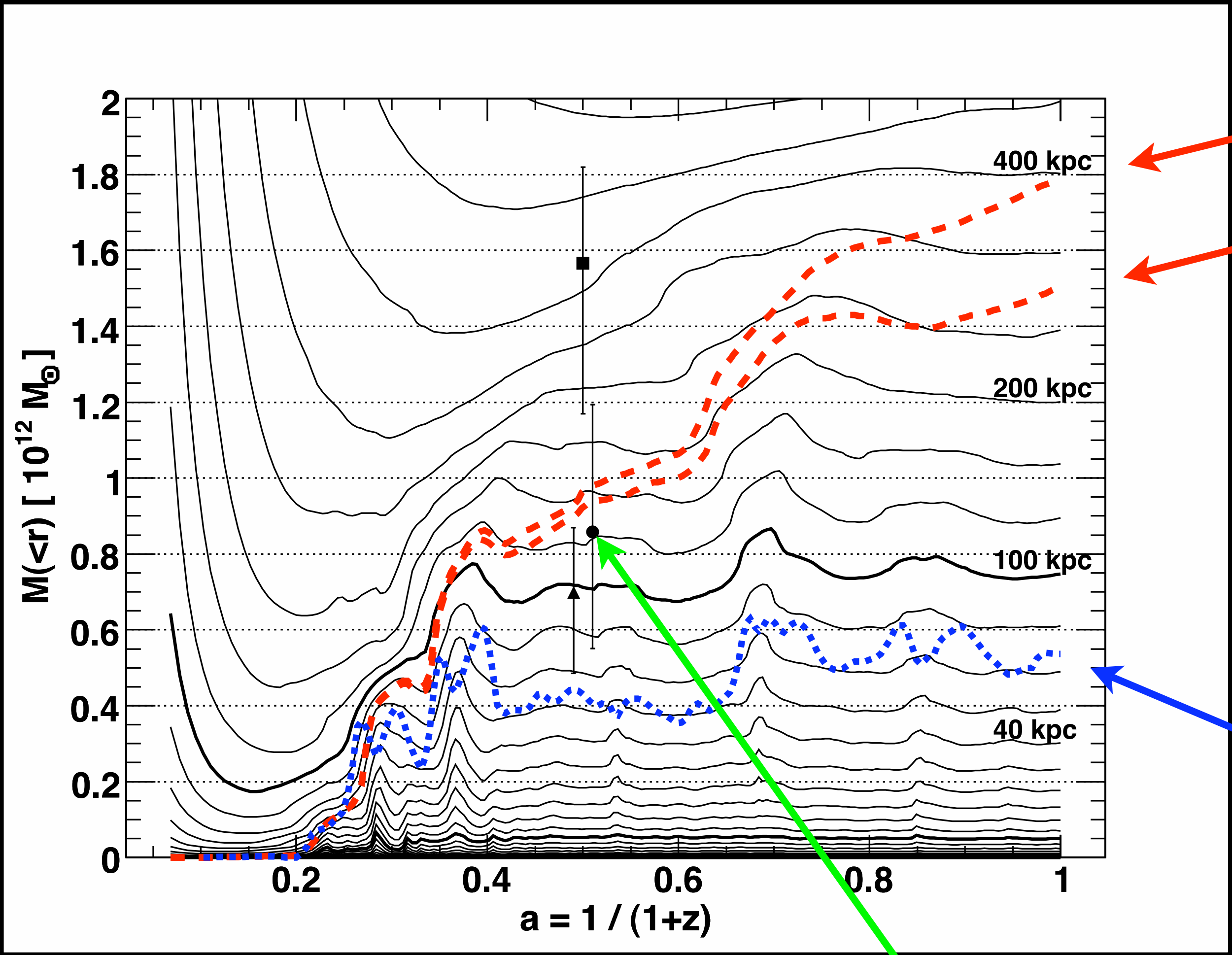
How big is this halo at each time?

Spherical, radial tophat collapse gives a density contrast of about 200 for the virialized region

M_{200} is one common definition of halo mass

in LambdaCDM also the smaller, but similar M_{vir} and $M_{200crit}$ are often used

halo assembly



M_{200}

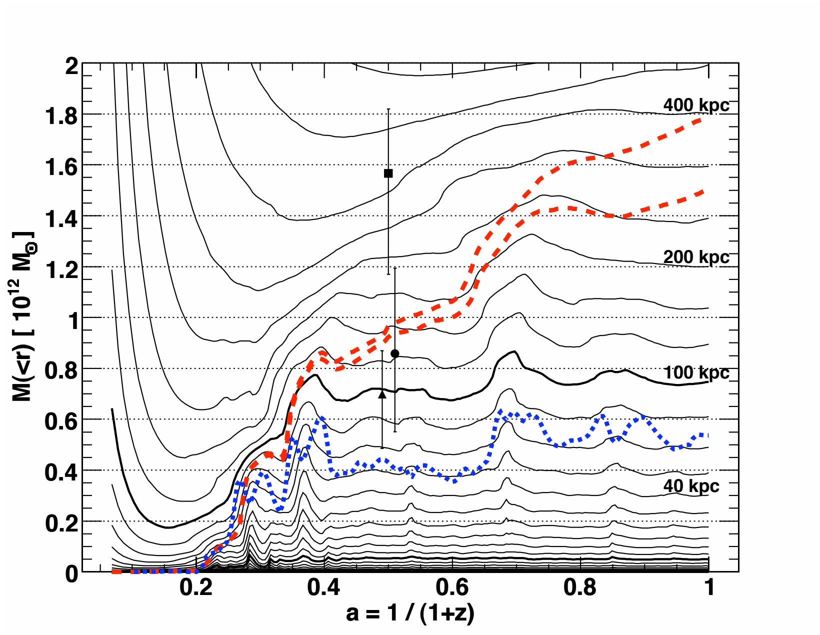
M_{vir}

both of these co-moving halo mass definitions grow even when the physical mass distribution is stationary

the mass inside r_{Vmax} is a physical mass scale: constant when no mass is accreted

large apparent accretion is typical for galaxy halos
median $f(M_{200})$ and 68% range
of a large lowres sample

physical definitions



we define halo formation times using Vmax(z) instead of M_{200} (z)

$$V_{\max}(z_{\rm form}) \equiv 0.85 \ \max_z \{V_{\max}(z)\}$$

using the final Vmax makes a difference for subhalos and fieldhalos (tidal stripping)

$$V_{\max}(z_{85}) \equiv 0.85 \ V_{\max}(z=0)$$

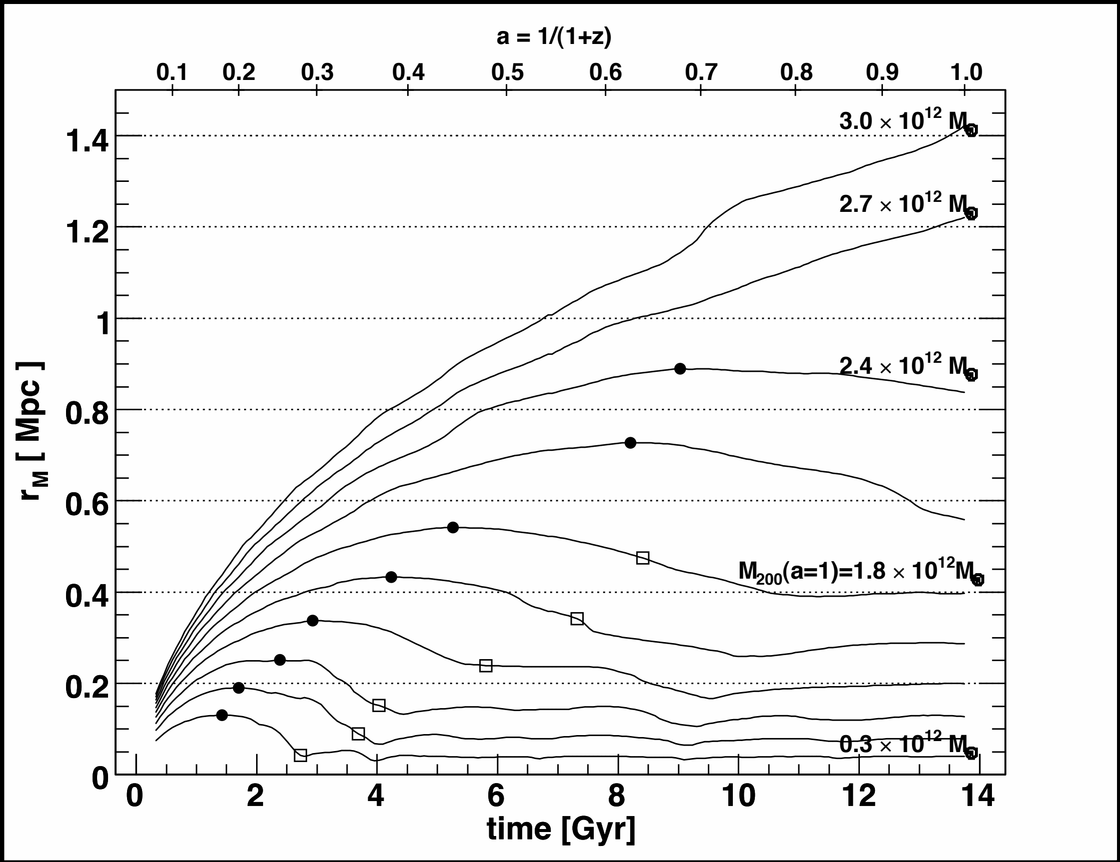
$$c_{\rm vir} = r_{\rm vir}/r_s$$

evolves, just as r_{vir} and M_{vir} , even in stationary epochs

$$c_V \equiv \frac{\bar{\rho}(< r_{\rm Vmax})}{\rho_{\rm crit,0}}$$

the physical density within r_{Vmax} does not and it is well defined for subhalos too

halo assembly



M_{200} and M_{vir} are dominated by apparent accretion at low z

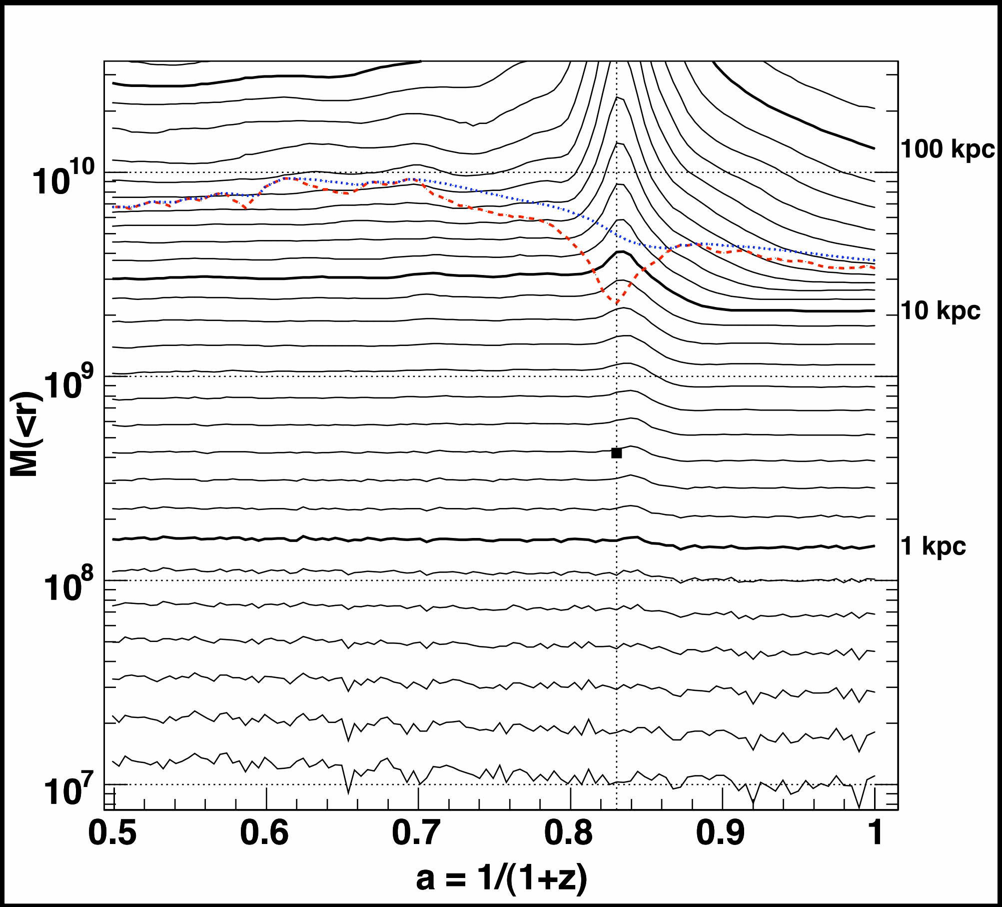
Why do they fail?

because CDM halo assembly has little in common with the spherical tophat collapse model these definitions are based upon:

collapse factors are very different from 2

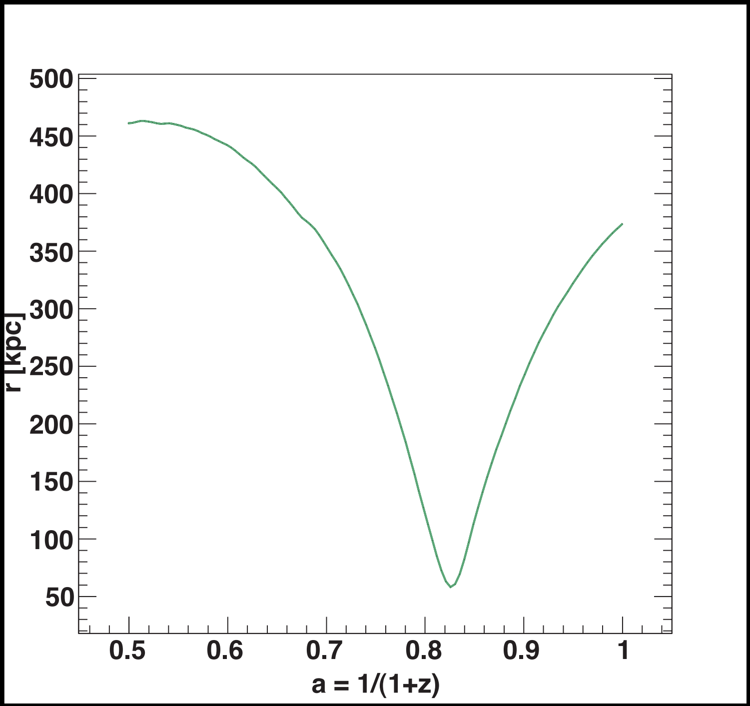
3.3 2.4 2.0 1.7 1.5 1.4
from inside out

evolution of subhalo density profiles



total mass in spheres around subhalo center

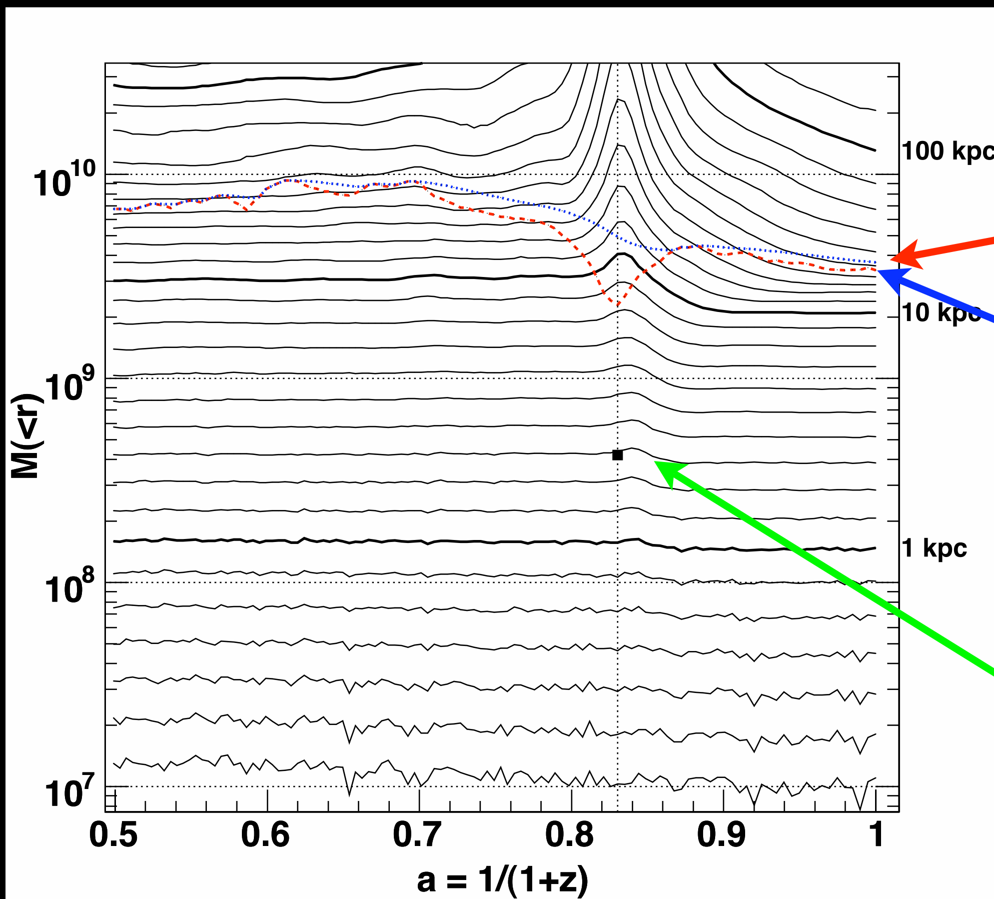
this subhalo has one pericenter passage at 56 kpc



weak, long tidal shock

duration : $\tau = \pi(56\,\mathrm{kpc})/(423\,\mathrm{km/s}) = 406\ \mathrm{Myr}$

evolution of subhalo density profiles



total mass in spheres around subhalo center

tidal mass, smaller than the bound mass at pericenter

“delayed” tidal mass

$$\Delta m = M(> r_t)\delta t/T_s$$

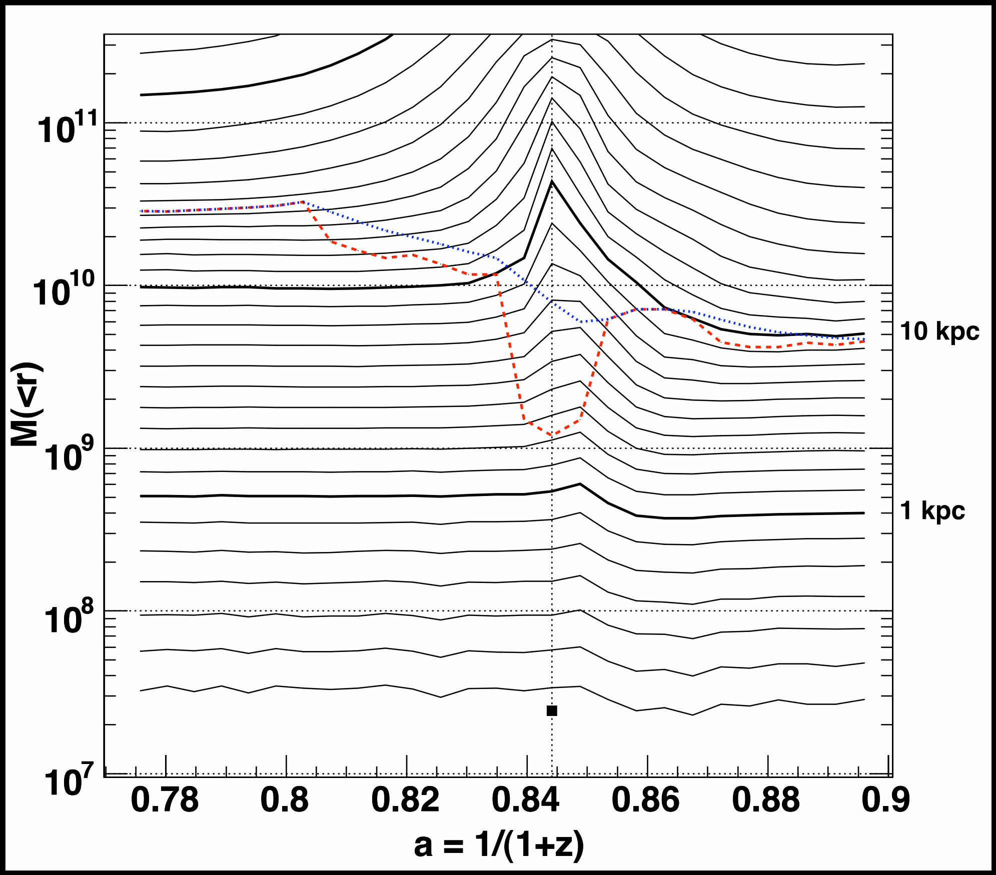
with $T_s = T_{\mathrm{orbit}}/6$

shock duration = internal subhalo orbital time

weak, long tidal shock
causes quick compression followed by expansion

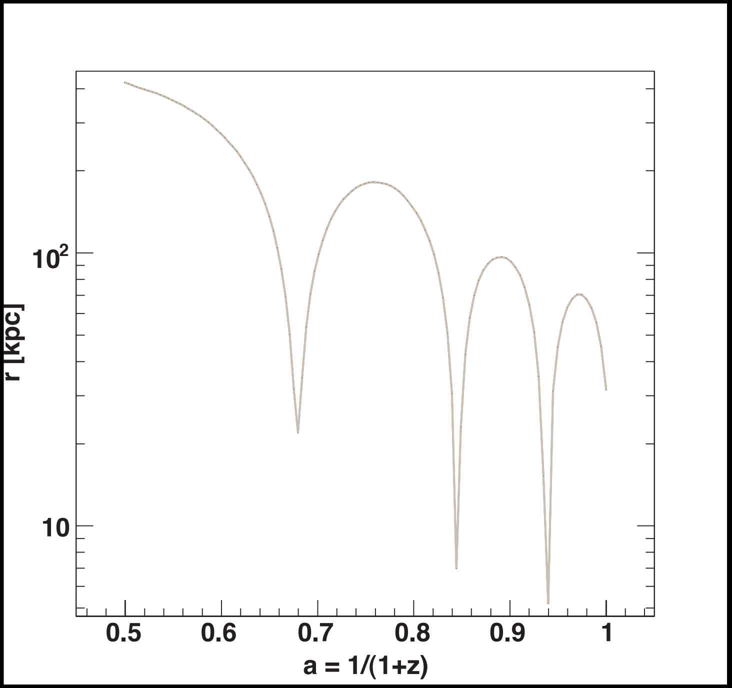
mass loss is larger further out

evolution of subhalo density profiles



total mass in spheres around subhalo center

this subhalo has its second of three pericenter passages at 7.0 kpc



strong, short tidal shock

short duration : 43 Myr → also affects inner halo, but mass loss still grows with radius

at pericenter $r_{tidal} = 0.2\ r_{Vmax}$, but the subhalo survives this and even the next pericenter

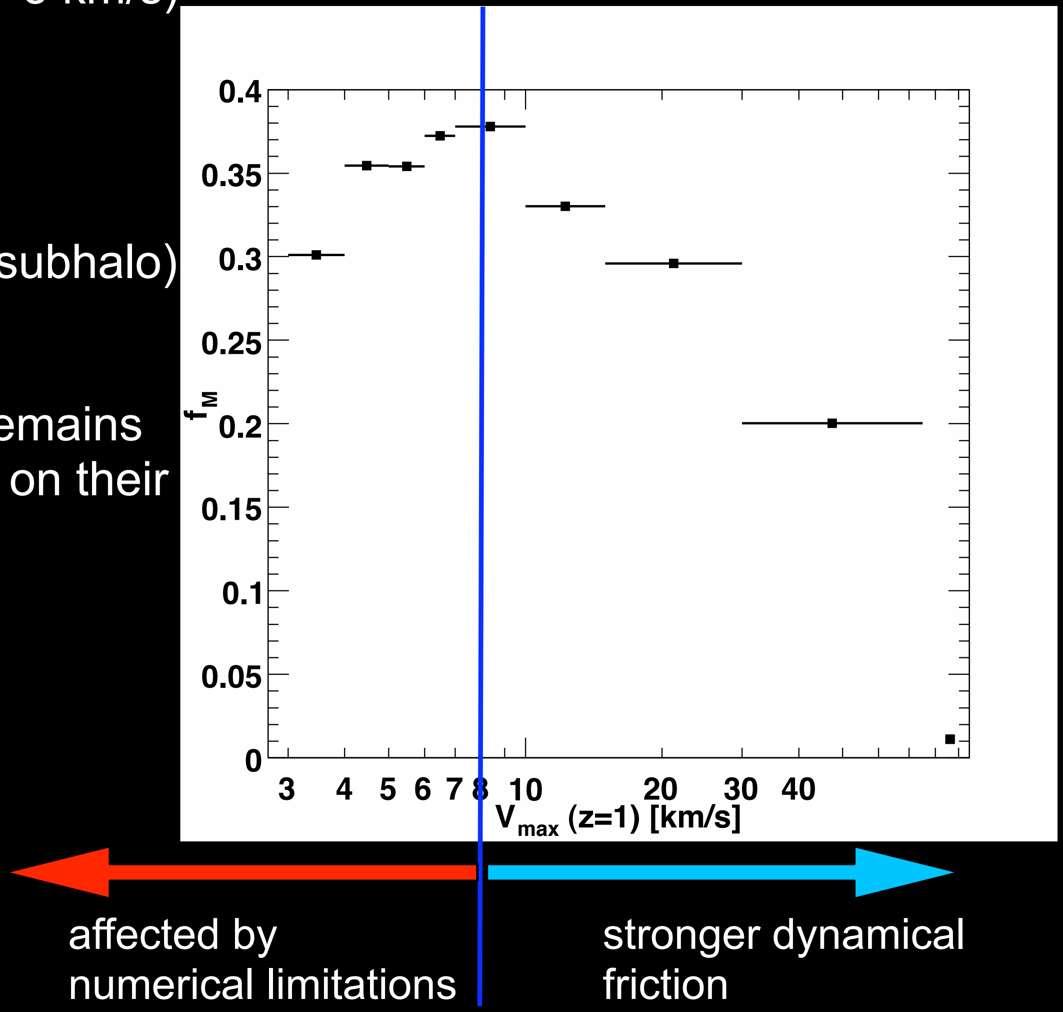
subhalo survival and merging

out of 1542 well resolved (Vmax >5 km/s) z=1 subhalos:

97 % survive until z=0

(only 1.3% merge into a larger subhalo)

The average mass fraction that remains bound to them until z=0 depends on their (inital) size



possible hosts for Local Group dwarfs

early forming (EF) sample:

the 10 subhalos which had Vmax > 16 km/s at z=10
motivated by reionisation, which might suppress further accretion of gas into small halos (e.g. Bullock etal 2000, Moore etal 2006)

largest before accretion (LBA) sample:

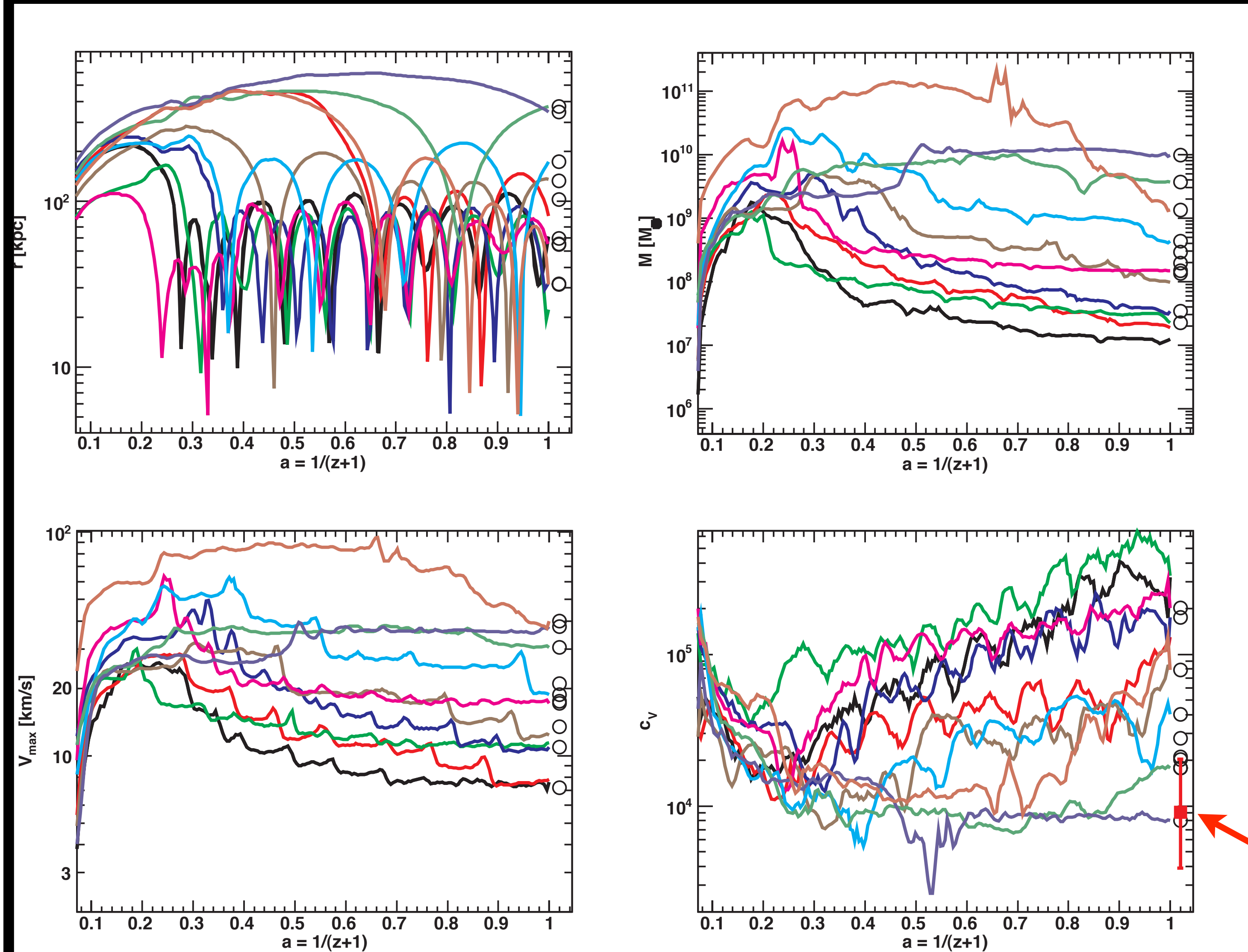
the 10 subhalos which had Vmax > 37 km/s at some time
if star formation is always inefficient in small halos

Kravtsov, Gendin & Klypin 2004 model lies in between these two selections

EF and LBA have 6 common objects, out of 10

we show EF sample tracks and only LBA z=0 properties of the LBA sample ...

possible hosts for Local Group dwarfs



diverse histories:

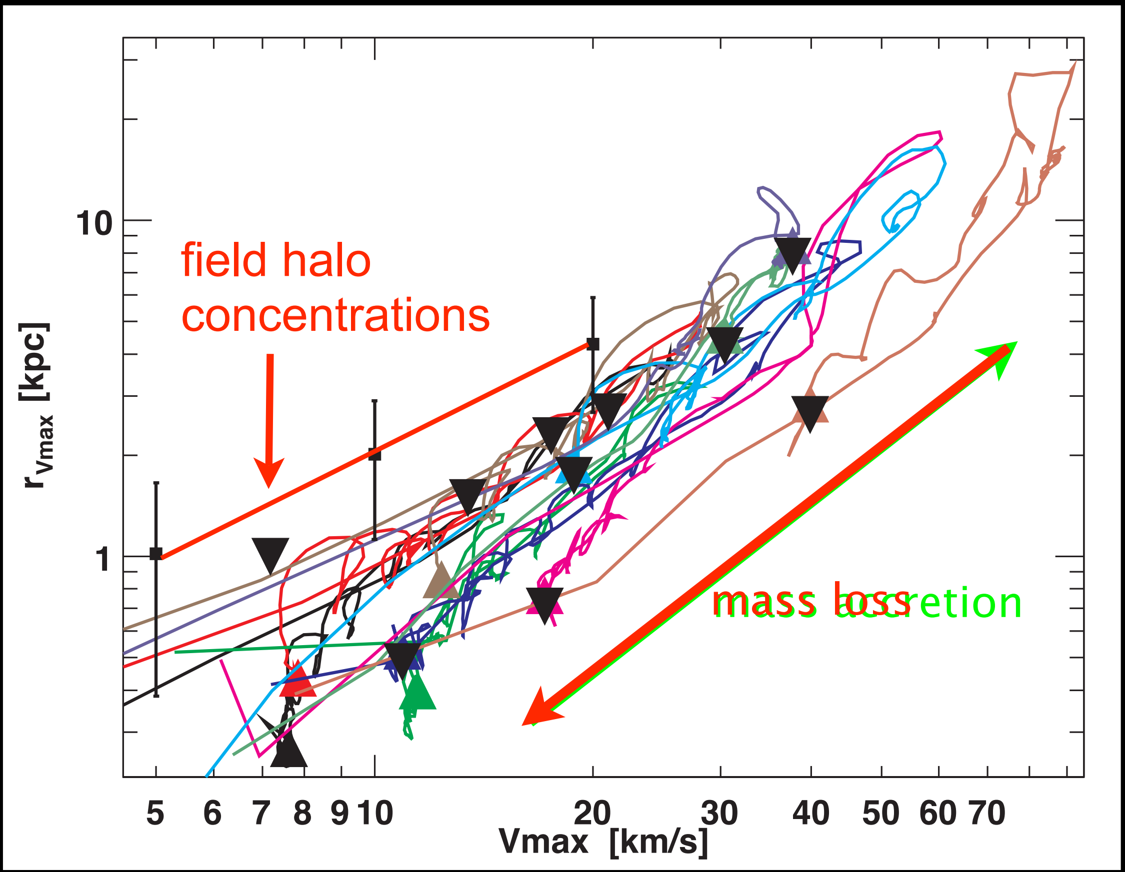
0 to 11 pericenters
inner subhalos
tend to have more
of them and
starting earlier

none to very large
mass loss

concentrations
increase during
tidal mass loss

field halo
concentrations

possible hosts for Local Group dwarfs



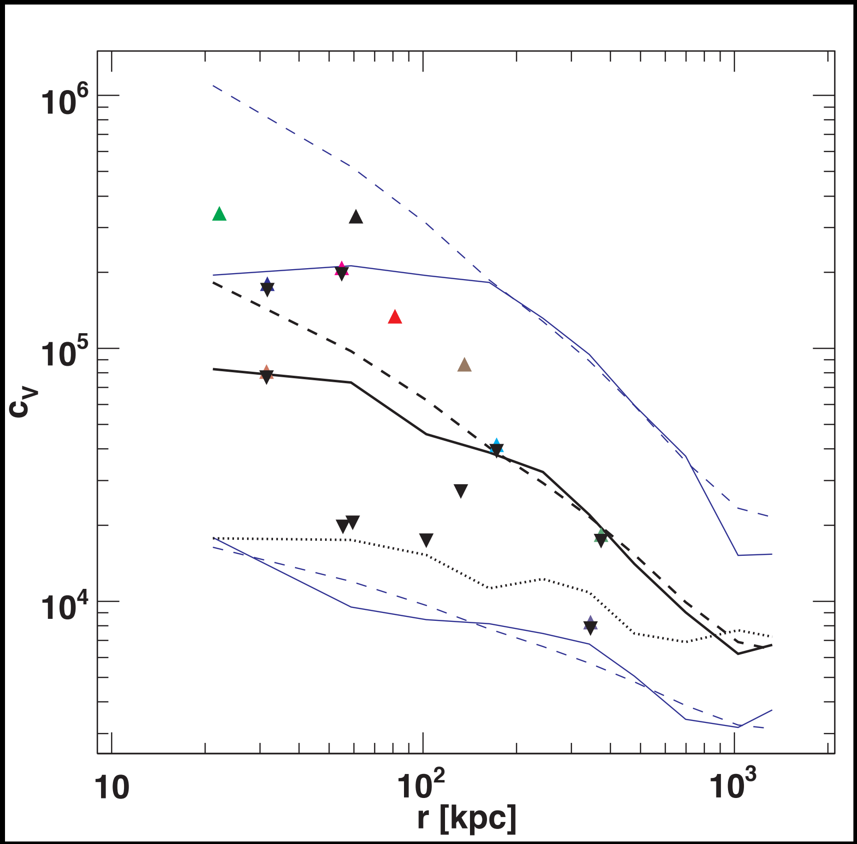
same 10 EF tracks

and 10 LBA halos at z=0
(black triangles)

tidal mass loss from the outside in partially undoes the inside out halo assembly

- stripped halos resemble high redshift systems
- they have high concentrations

subhalo concentrations



median concentrations increase towards the galactic center

the 68% scatter also increases

EF and LBA samples also follow this trend

earlier formation times alone cannot fully explain this trend (dotted line)

finite resolution limits c_V to below 2e5 for the smaller subhalos

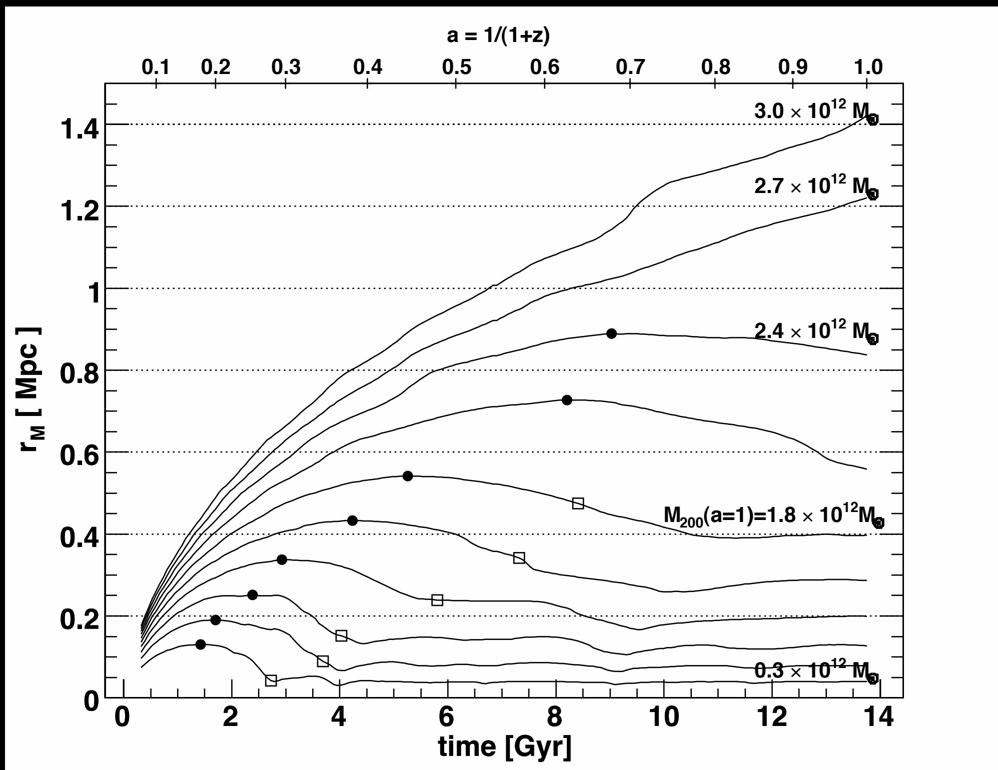
dashed lines give fits of

$$c_V(r) = a \left[\frac{\rho_{bg}(r)}{\rho_{\mathrm{crit},0}} \right]^b$$

to the values beyond 100 kpc

average subhalo tracks

using all with Vmax > 5 km/s at some time



and grouped into ten bins by their z=0 distance from the galactic center

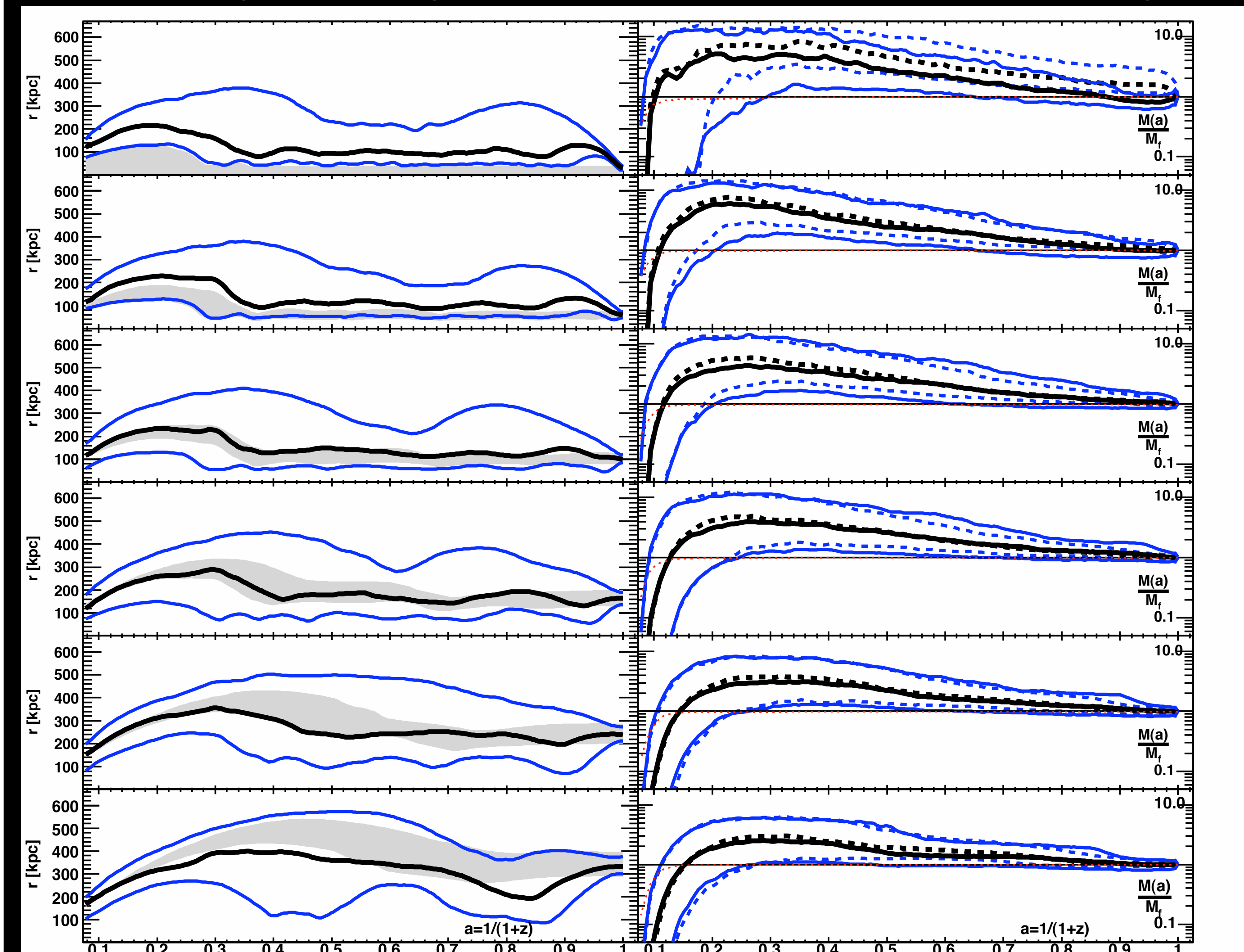
bins 1 to 6 lie within r_{200}

bins 7 to 10 go from r_{200} to 3.5 r_{200}

average subhalo tracks

using all with Vmax > 5 km/s at some time

bins 1 to 6 (within r_{200}): radius mass relative to z=0 (dashed)



[Vmax / Vmax(a=1)]4

(solid lines)

evolves like the tidal mass during stripping

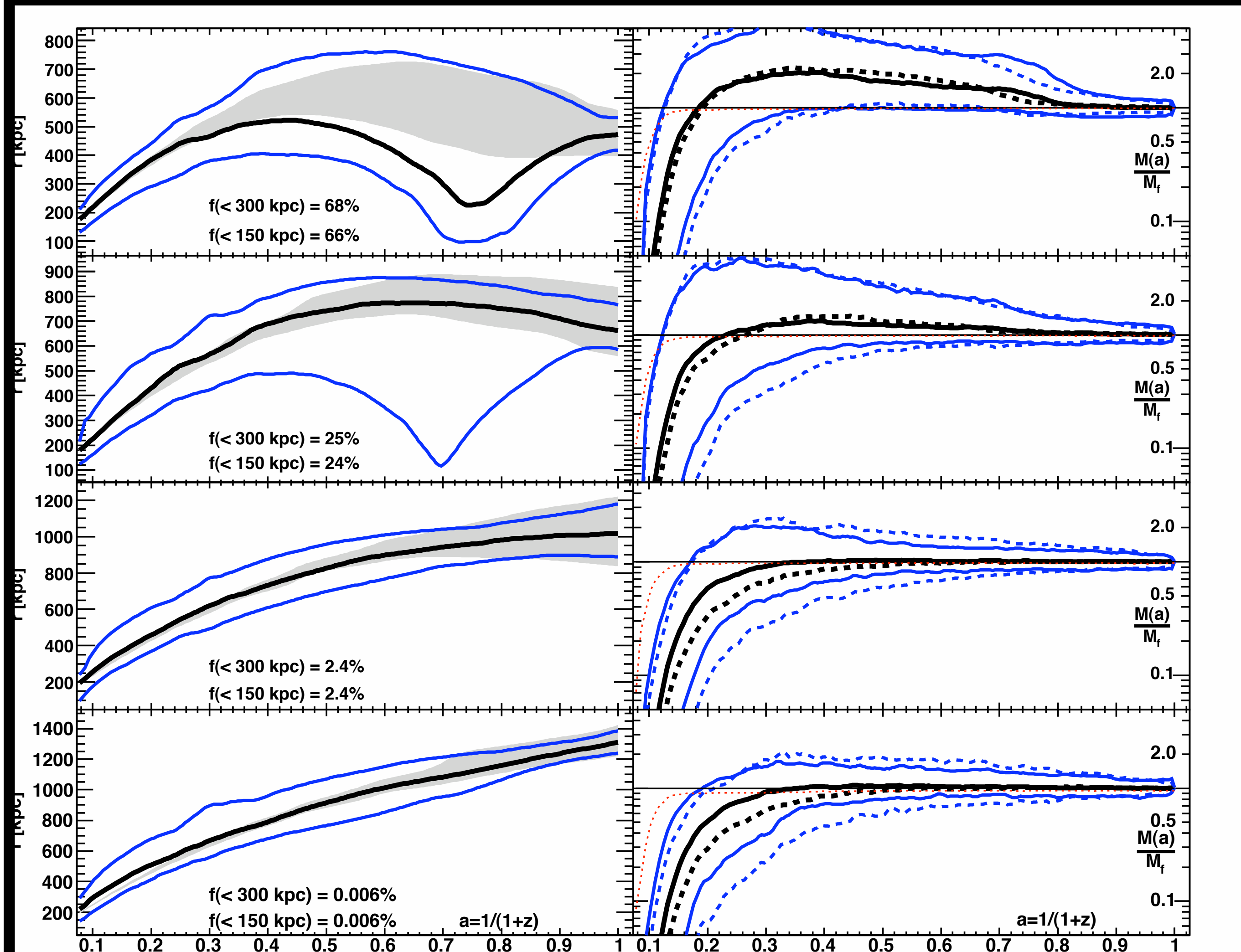
$\rightarrow$ $V_{\max} \propto M^{1/4}$

more mass loss for inner subhalos

most of it happens early! before a=0.5

average subhalo tracks

bins 7 to 10 (beyond r_{200})

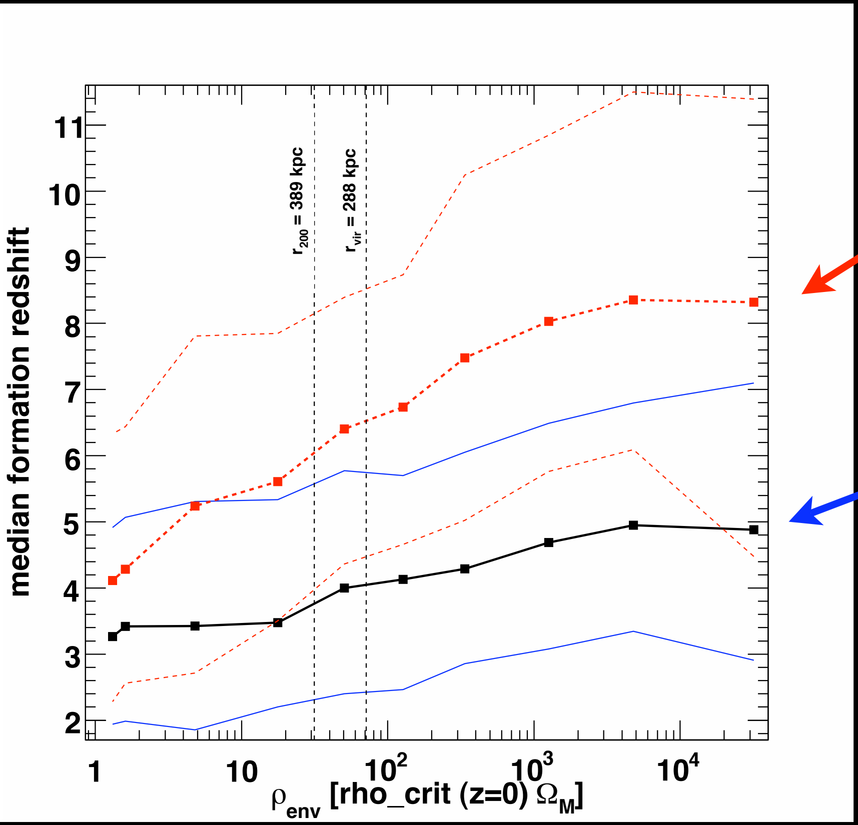


many of these “field” halos were inside the host halo earlier

they have lost mass

these former subhalos have formed very early, when formation times are defined relative to the z=0 mass or Vmax

(sub)halo formation times



z_{85} (def. relative to z=0)
strong trend with environment
also for field halos

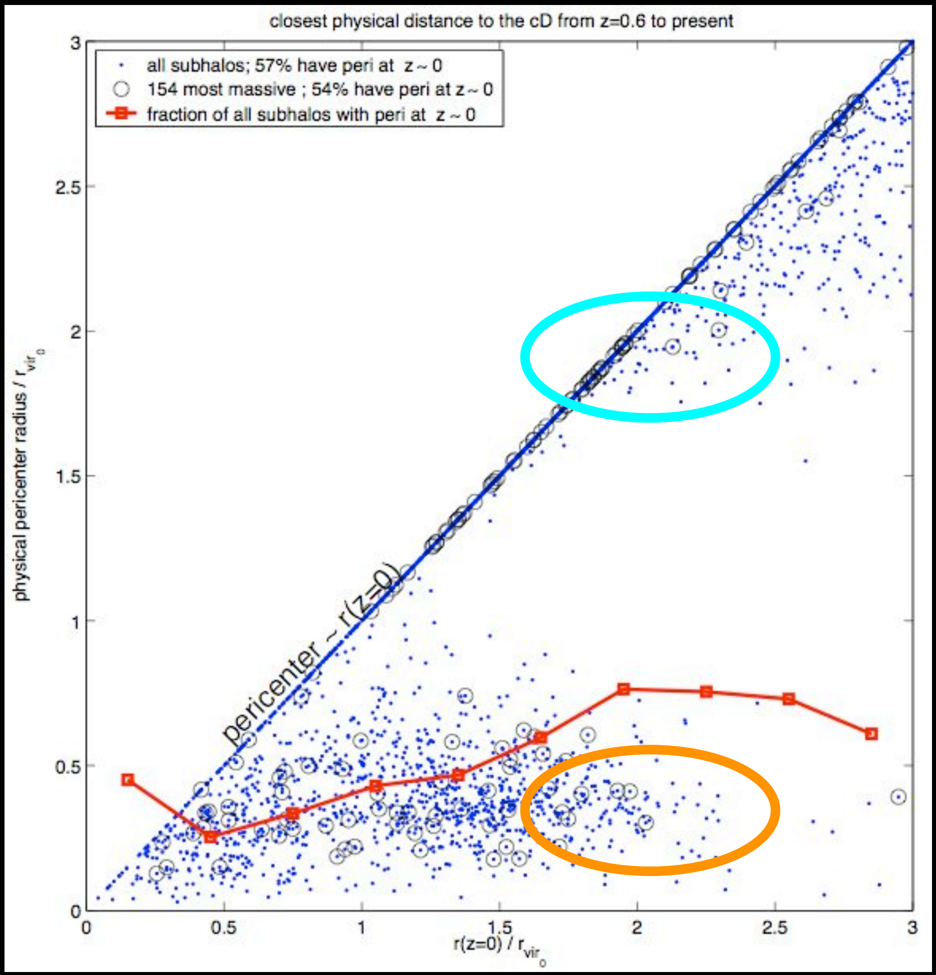
z_f (def. relative maximal size)
weak trend with environment
and only for subhalos

assembly histories of sub M*-field halos does depend on environment:
oldest ones more strongly clustered (Gao, Springel & White 2005)
earlier formation in dense environments (Harker et al 2006)

defining formation times relative to size before tidal mass loss removes the trend in the formation times, but the assembly histories still do depend on environment, in agreement with Gao et al and Harker et al.

(sub)halo formation times

environment dependence of field halo assembly histories significantly affects galaxy clustering (Gao etal 2005, Croton etal 2007)



from Moore,JD&Stadel astro-ph/0406615
also Gill, Knebe & Gibson 2005

some models of galaxy clustering assume a HOD or conditional luminosity function which only depends on the final mass of a halo

consider a true field halo and
a former subhalo of equal mass at z=0

the galaxy/ies in the former subhalo might be:
1) larger, if stripping only affects the DM
2) dimmer & redder, due to ram pressure
3) brighter & bluer, it the tidal shock had triggered a star-burst

need to understand these before galaxy clustering can be modeled accurately ...

summary

CDM has structures and substructures on a wide range of scales

small subhalos contribute significantly to the mass fraction in subhalos and to the total DM annihilation signal. therefore both quantities have not converged yet in current simulations

galaxy halos are assembled early in a series of mergers. the later “slow” accretion is mostly apparent accretion caused by the comoving definitions of M_{vir} and M_{200}

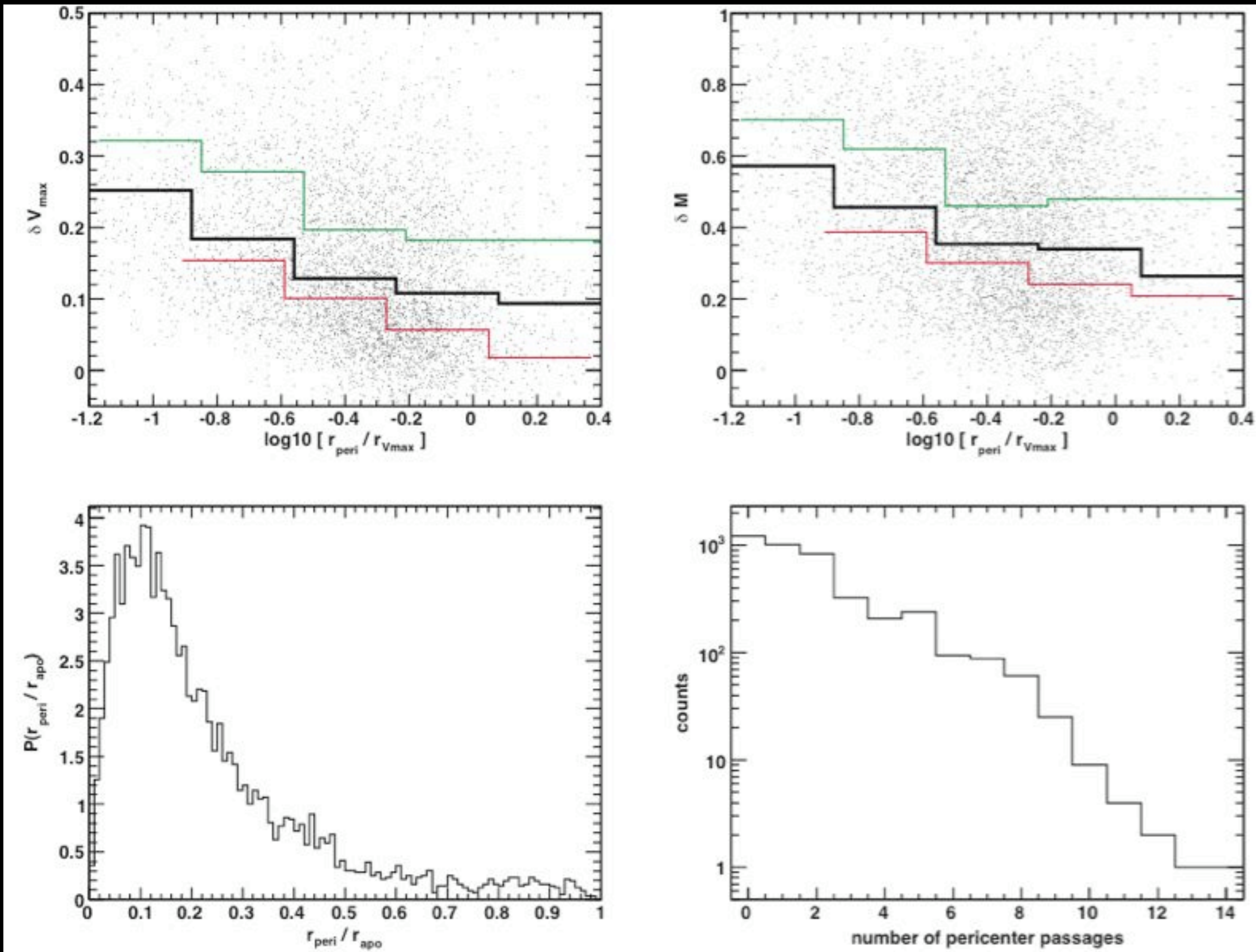
M_{vir} and M_{200} fail because CDM halo formation differs strongly from the spherical tophat model

tides remove subhalo mass from the outside in and lead to higher concentrations for subhalo. near the galactic center this effect is stronger

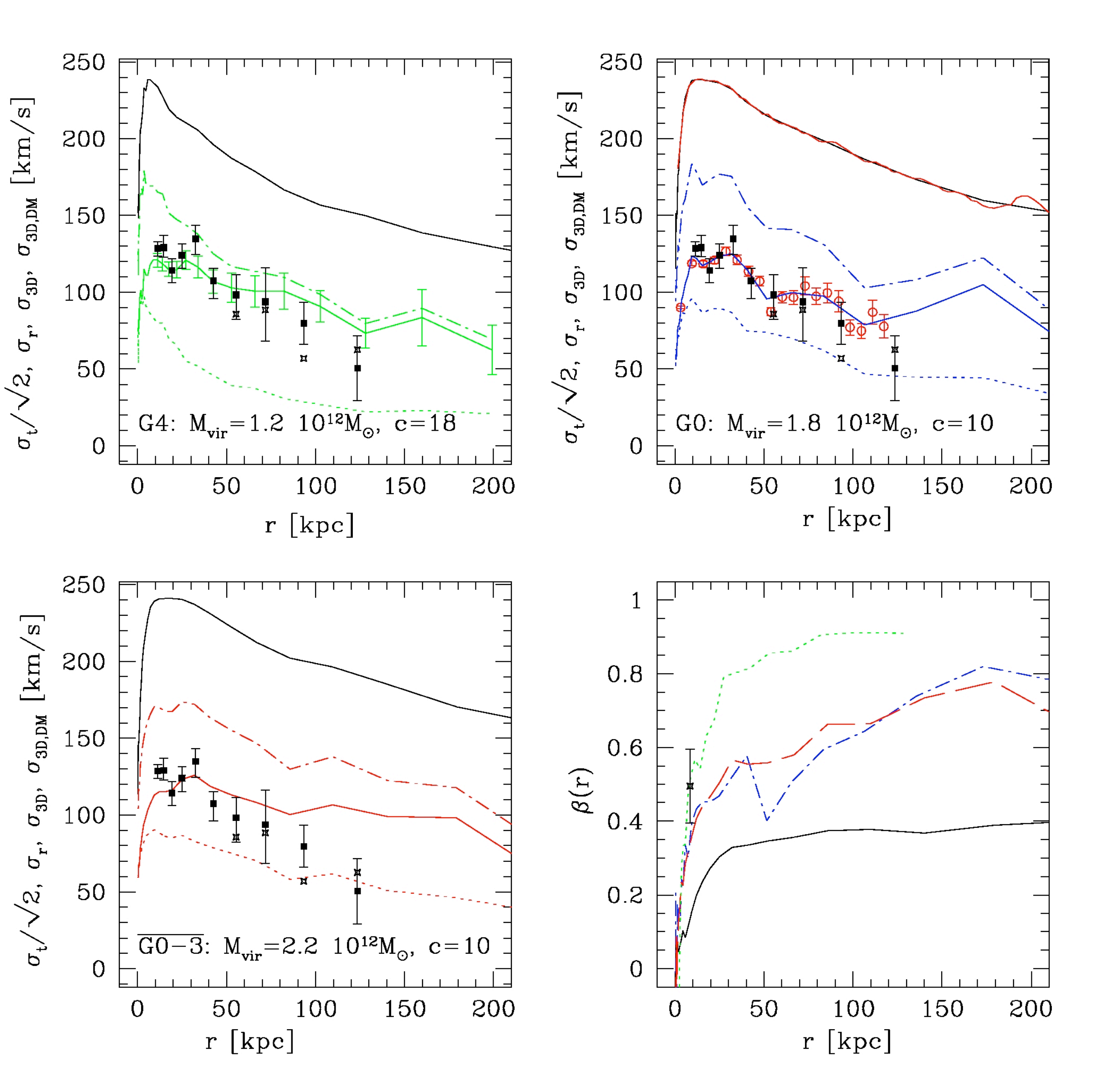
most (97%) subhalos survive from z=1 until today. smaller ones loose less mass

assembly histories of sub M*-field halos depend on environment, because of earlier tidal interactions with nearby larger hosts

larger mass loss at first pericenter



Milky Way halo mass form stellar halo radial velocities?



cosmological stellar halo kinematics fit the observations well

The outer halo and therefore the virial mass are not well constrained

low Mvir / high c
high Mvir / low c
both possible

beta(r) follows relates to tracer profile slope as in Hansen&Moore, 2004

JD,Madau, Moore 2005