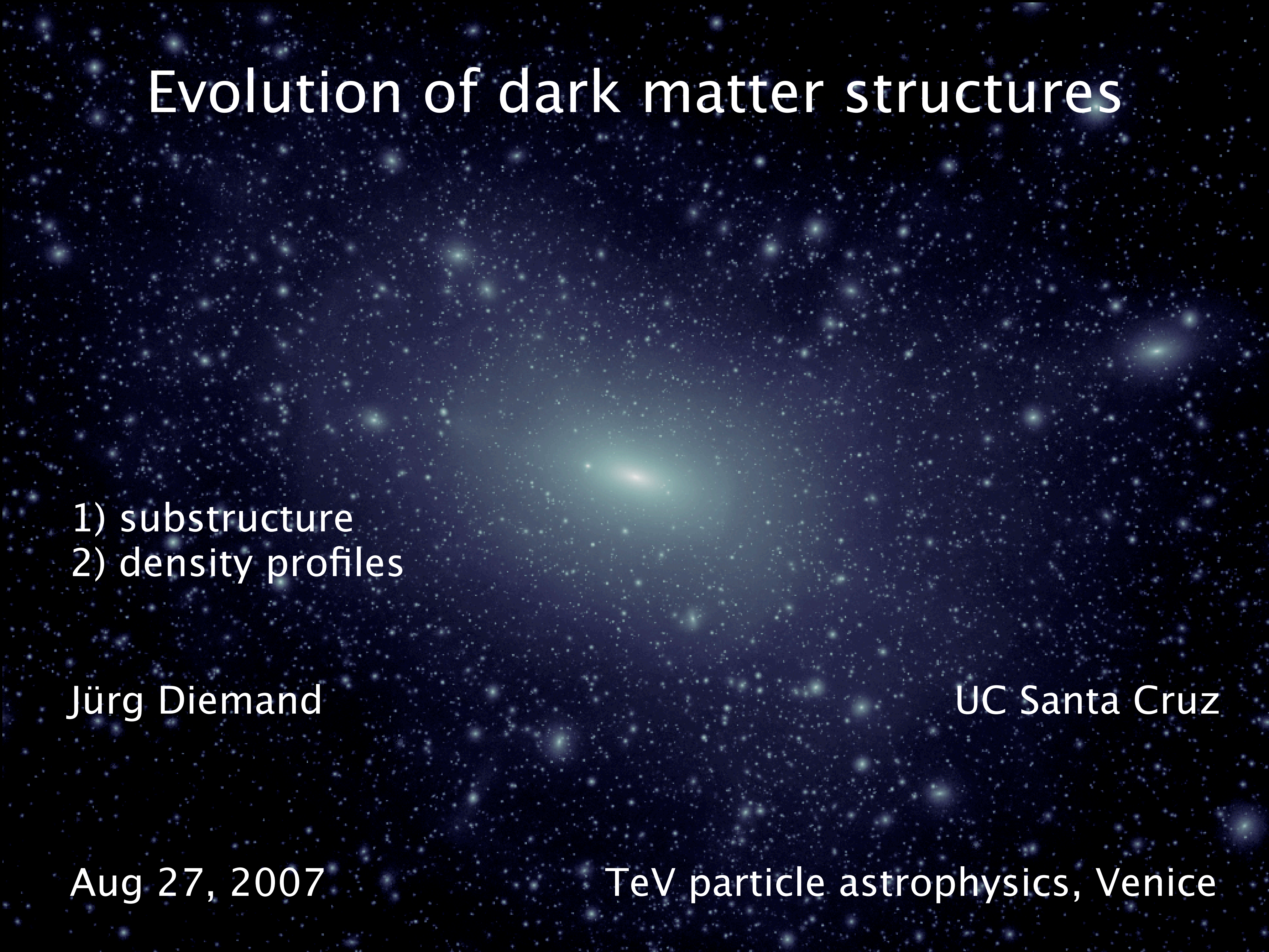


Evolution of dark matter structures

1) substructure
2) density profiles

Jürg Diemand

UC Santa Cruz

Aug 27, 2007

TeV particle astrophysics, Venice

the "via lactea" simulation

a Milky Way halo simulated with over 200 million particles

- collision-less (no hydro) → accurate solution of an idealized problem
  no free parameters, no subgrid physics

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

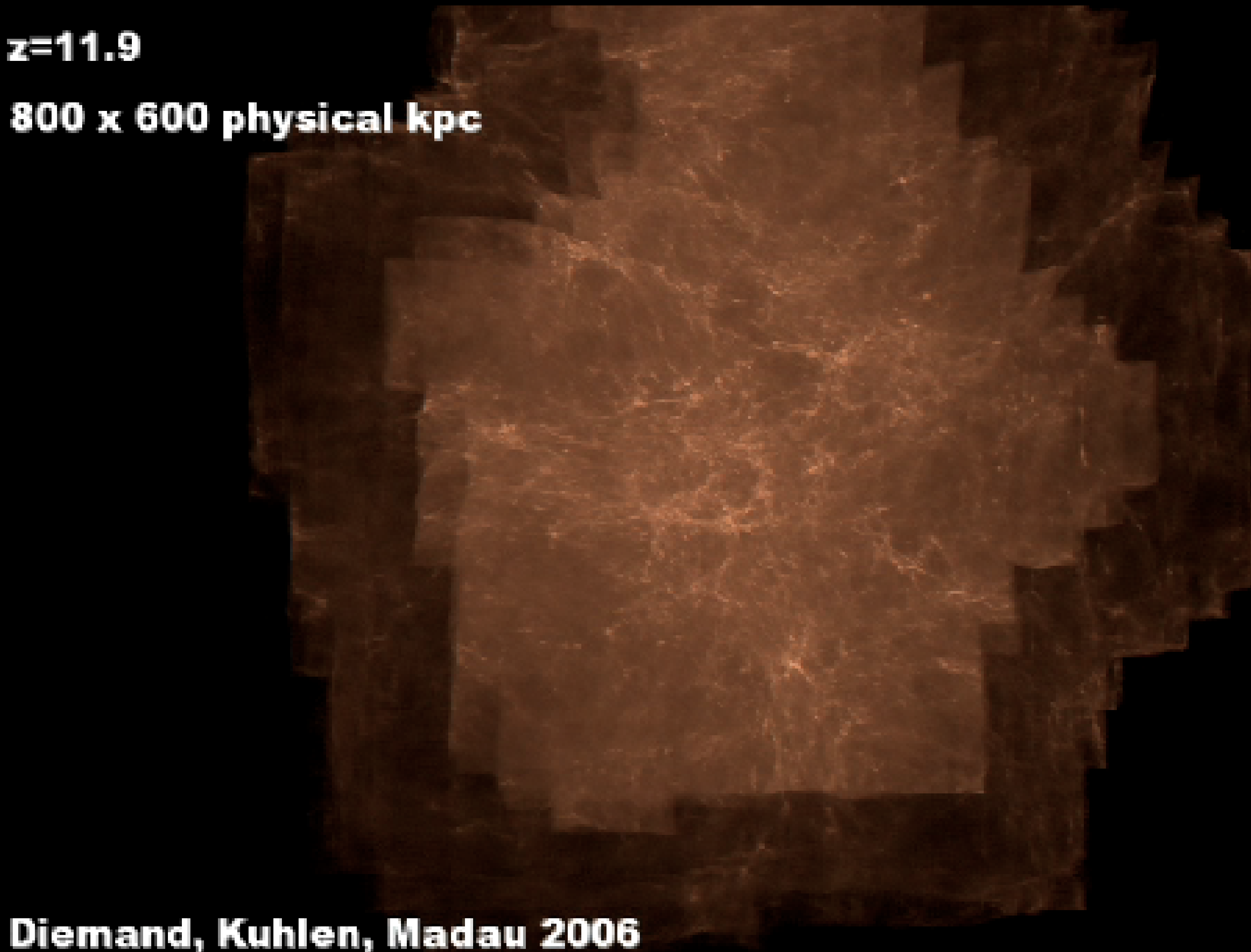
- 213 million high resolution particles, embedded in a periodic 90 Mpc box sampled at lower resolution to account for tidal field.

- 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

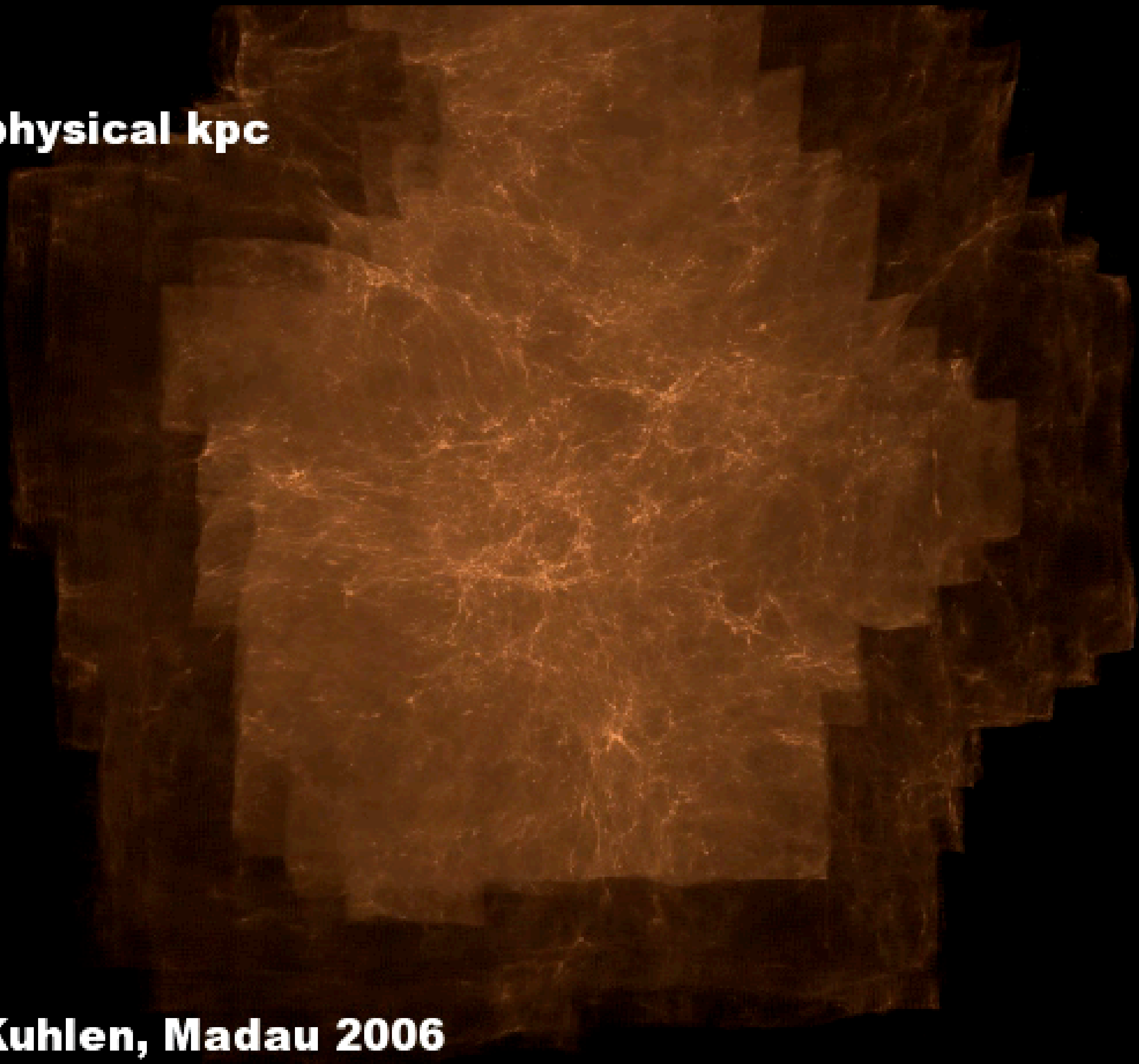
- time resolution: adaptive time steps as small as 68,500 years

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


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

z=11.9

800 x 600 physical kpc



Diemand, Kuhlen, Madau 2006

www.ucolick.org/~diemand/vl

via lactea

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

main

movies

images

publications

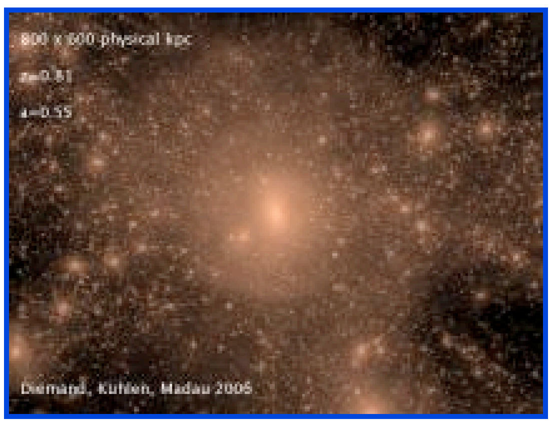
data

screensavers

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

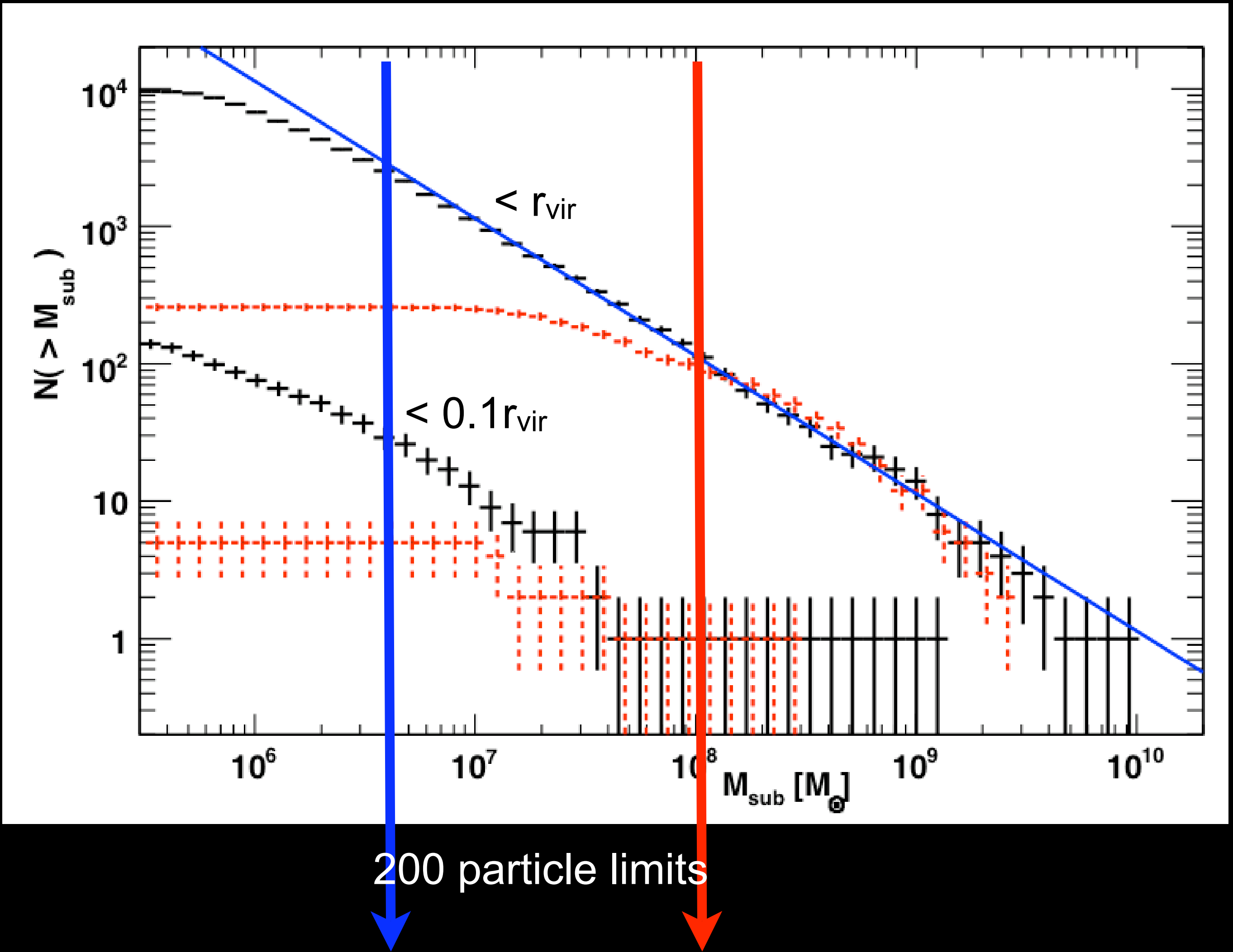


- entire formation history (z=12 to 0): high quality (218 MB)
  smaller frames, quality: high(55 MB) medium(11 MB) low(4.7 MB)
- entire formation history, plus rotation and zoom at z=0:
  quality: high(433 MB) medium(72 MB)
- early, active phase of merging and mass assembly (z=12 to 1.3): (81 MB)
- late,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

rotation and zoom into the via lactea halo at z=0 (today)

z=0 results from "via lactea"
subhalo mass functions

JD, Kuhlen, Madau, astro-ph/0611370



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

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

steeper at high M due to dynamical friction

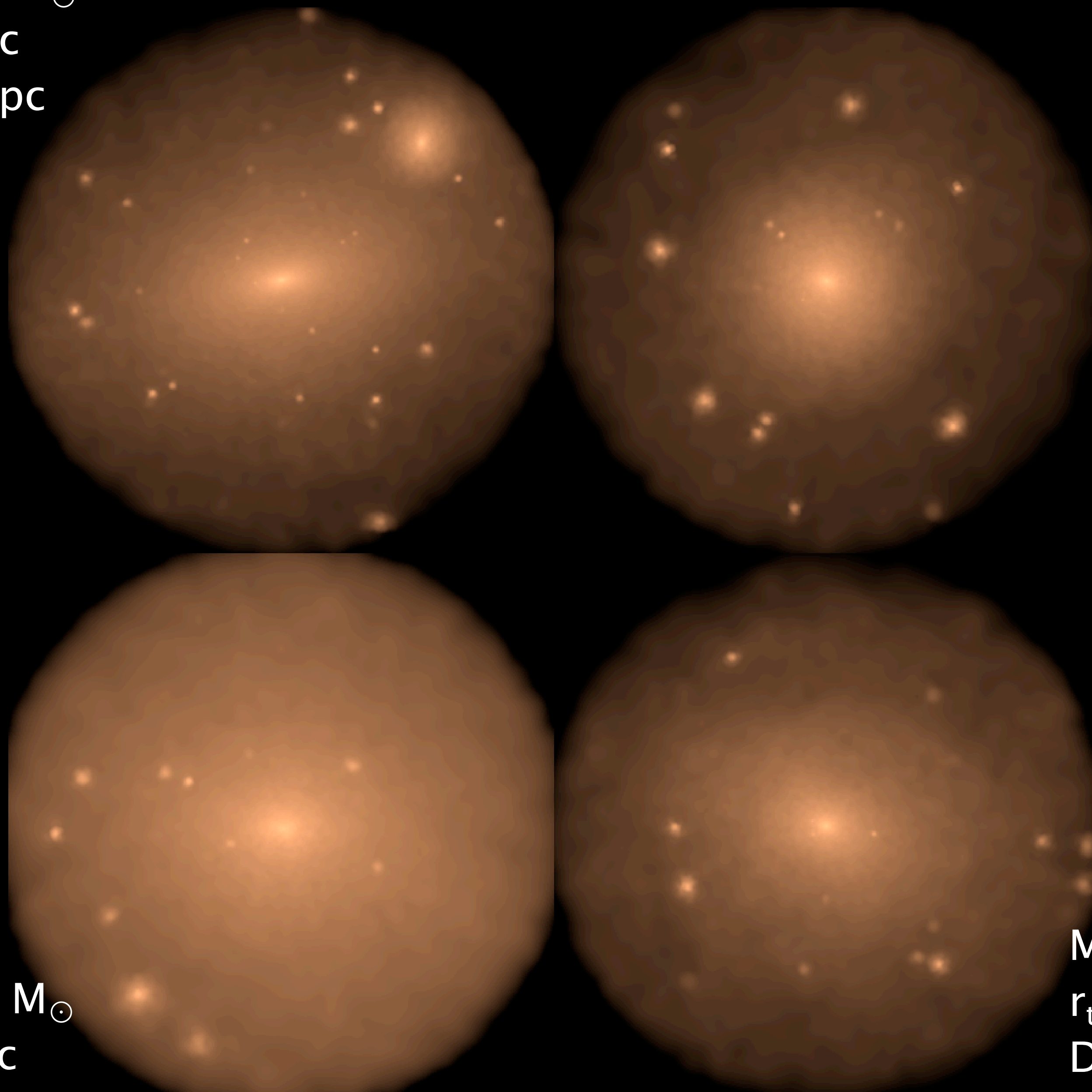
shallower at low M due to numerical limitations

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

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

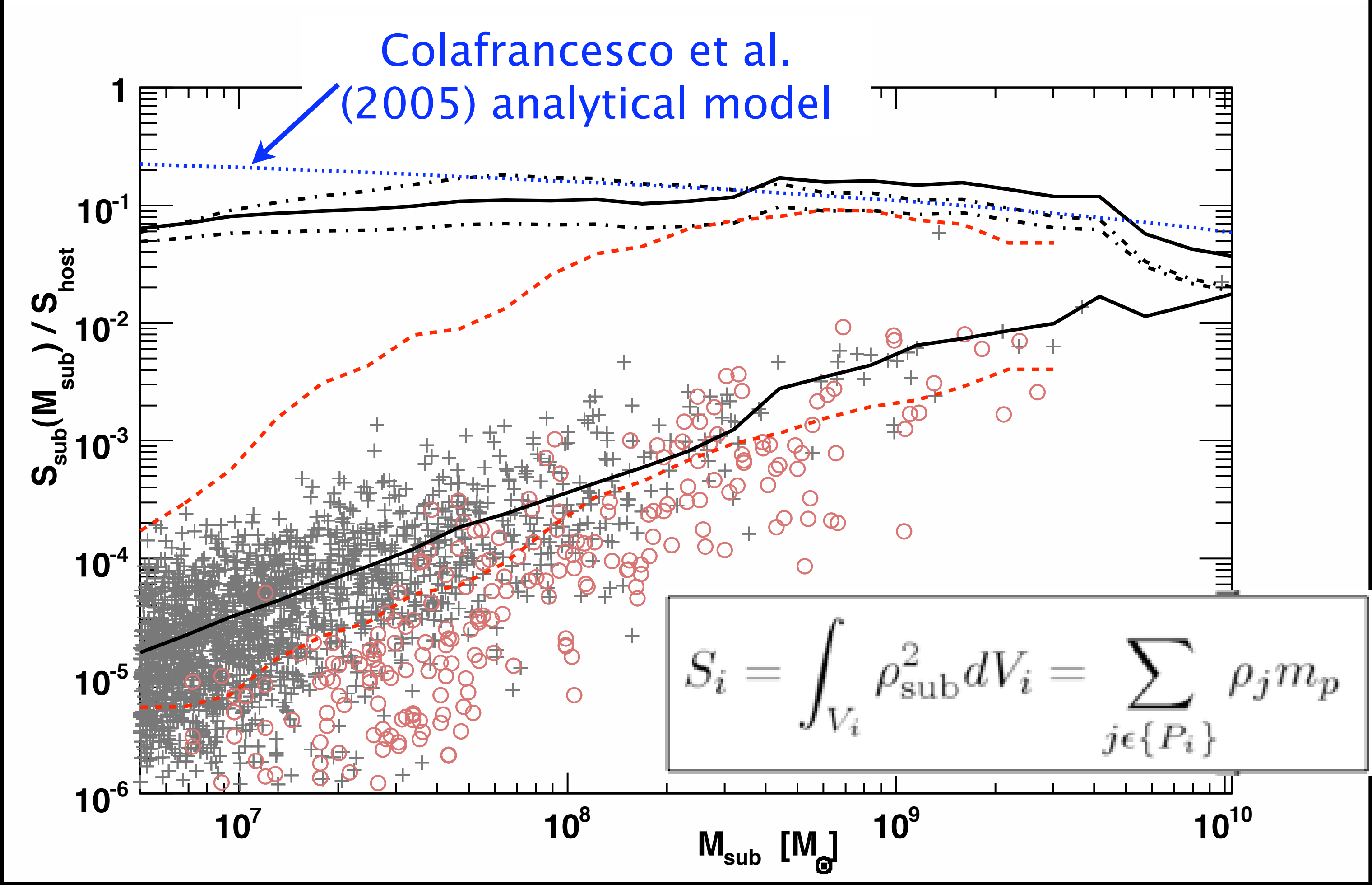


M_{sub}=2.4 10^9 $M_\odot$
r_{tidal}=14.7 kpc
D_{center}=185 kpc

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



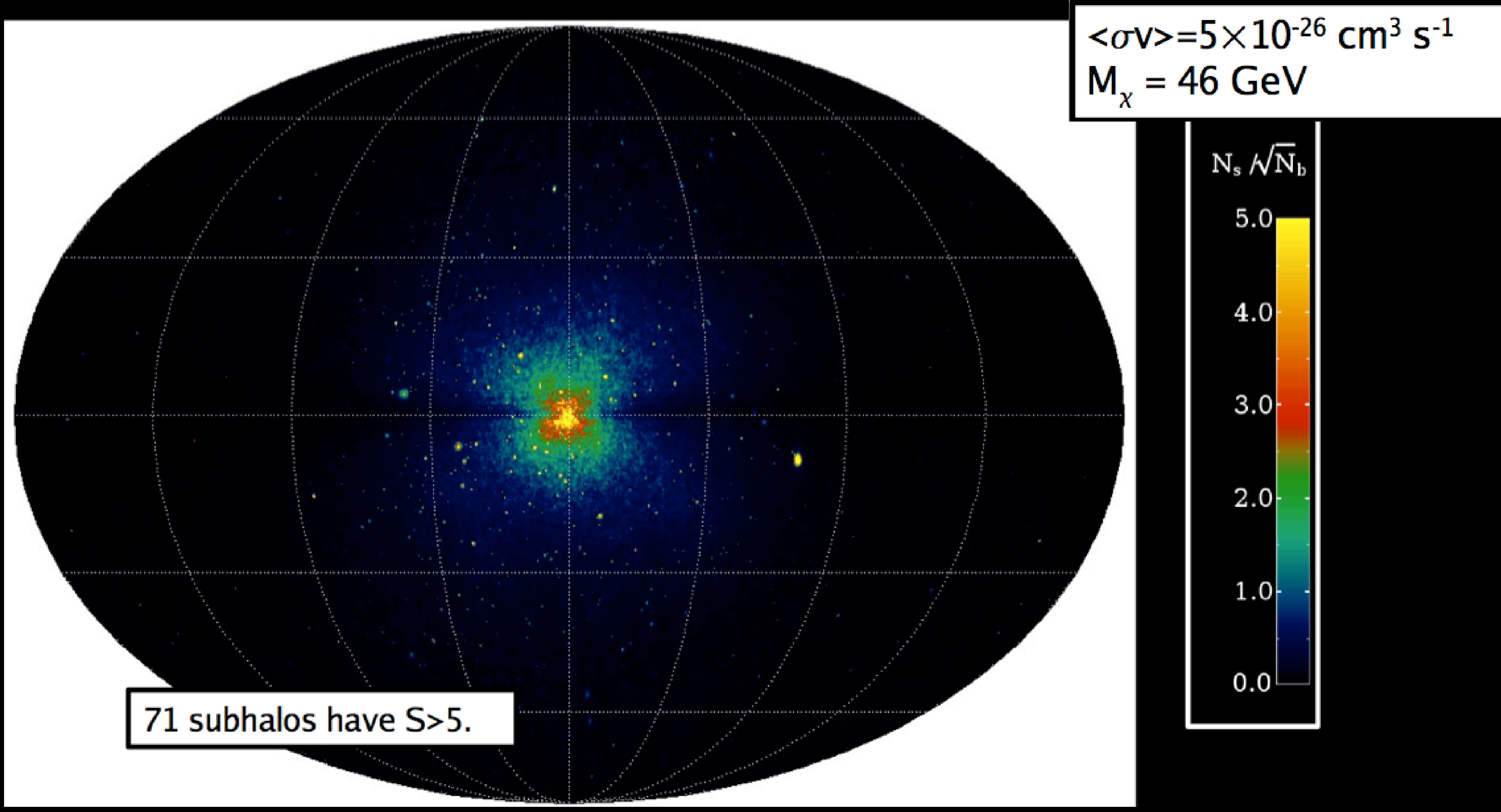
Total signal from subhalos is constant per decade in subhalo mass

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

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

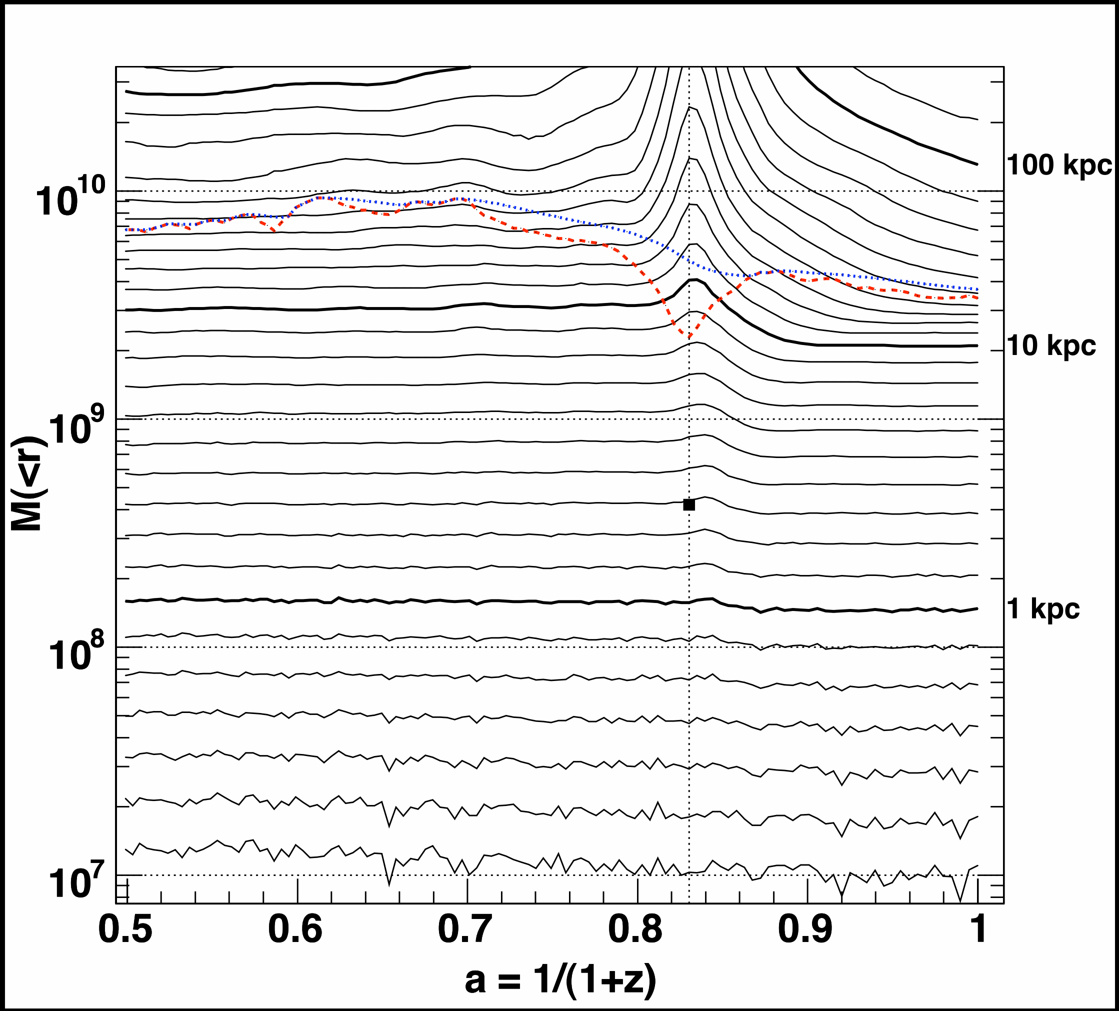
total boost factor including sub-sub-....-halos:
between 13 (constant) and about 80

(optimistic) detection significance for GLAST



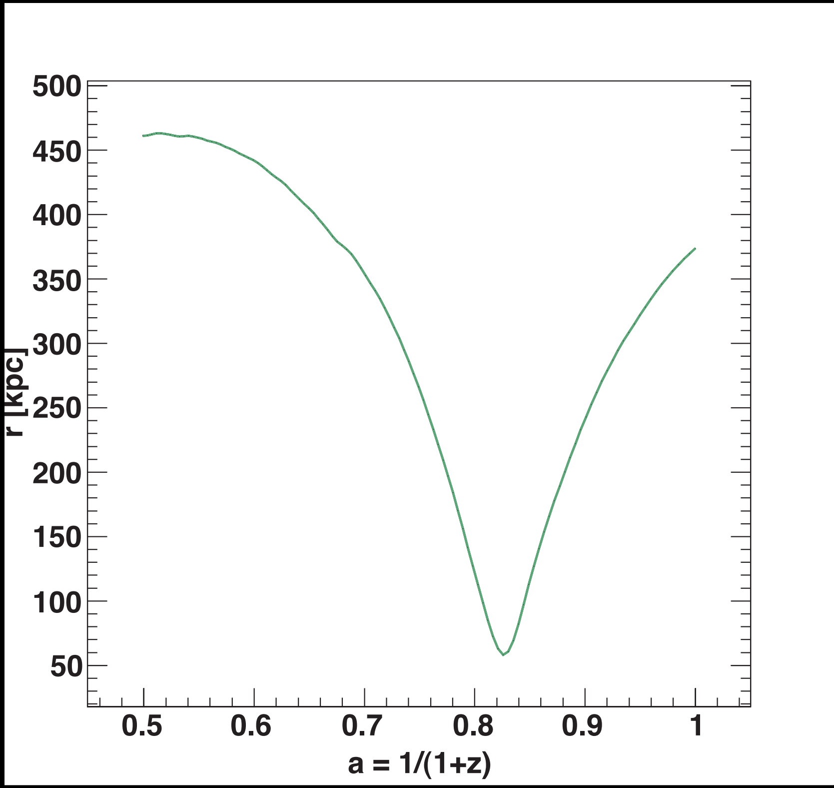
PRELIMINARY allsky map by Mike Kuhlen
assuming sub-substructure boosts subhalo luminosities by a factor of 10
includes extragalactic and galactic (cosmic ray protons on H) backgrounds (Baltz et al 1999)
NOTE: We do not resolve all relevant subhalos yet !

evolution of subhalo density profiles



total mass in spheres around subhalo center

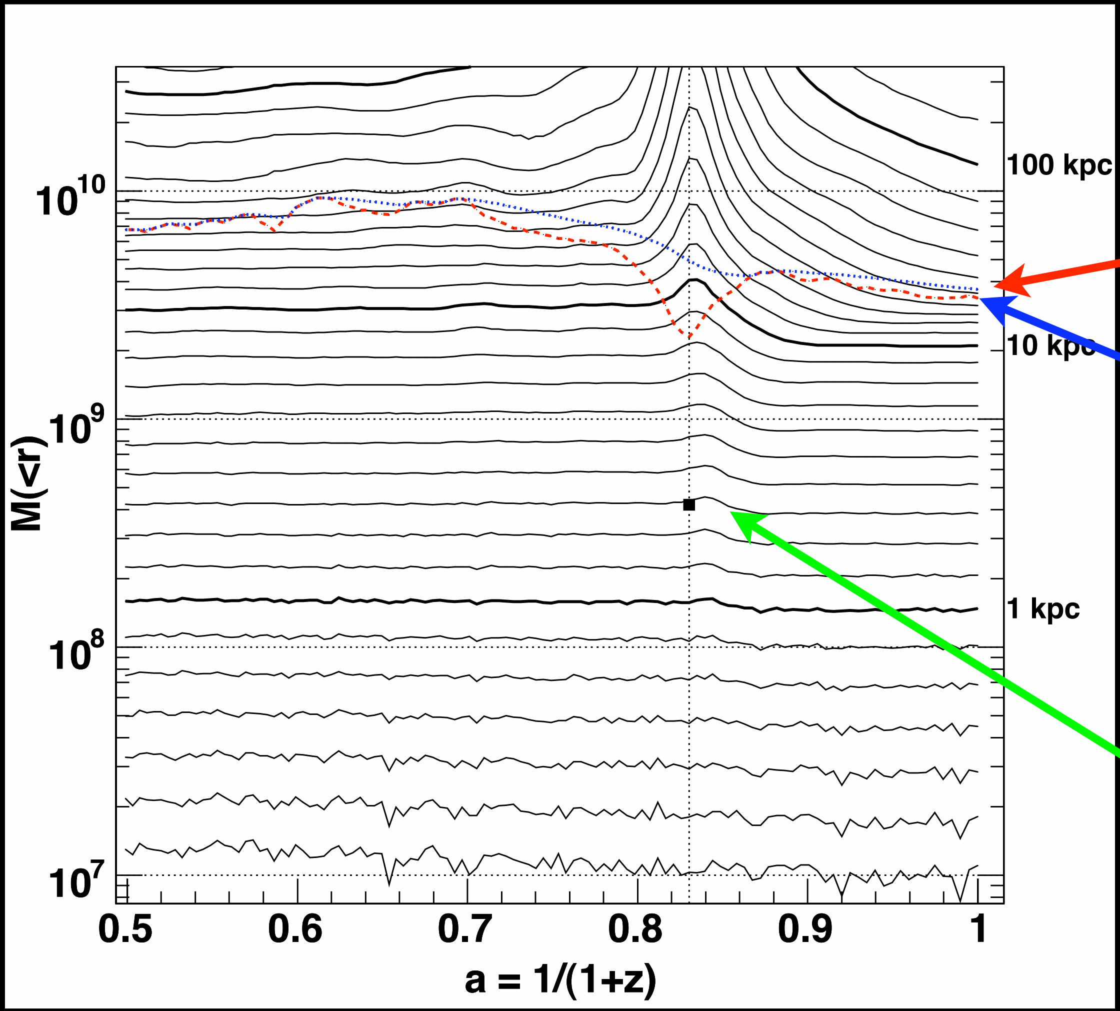
this subhalo has one pericenter passage at 56 kpc



weak, long tidal shock

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

evolution of subhalo density profiles



tidal mass is smaller than the bound mass at pericenter

"delayed" tidal mass

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

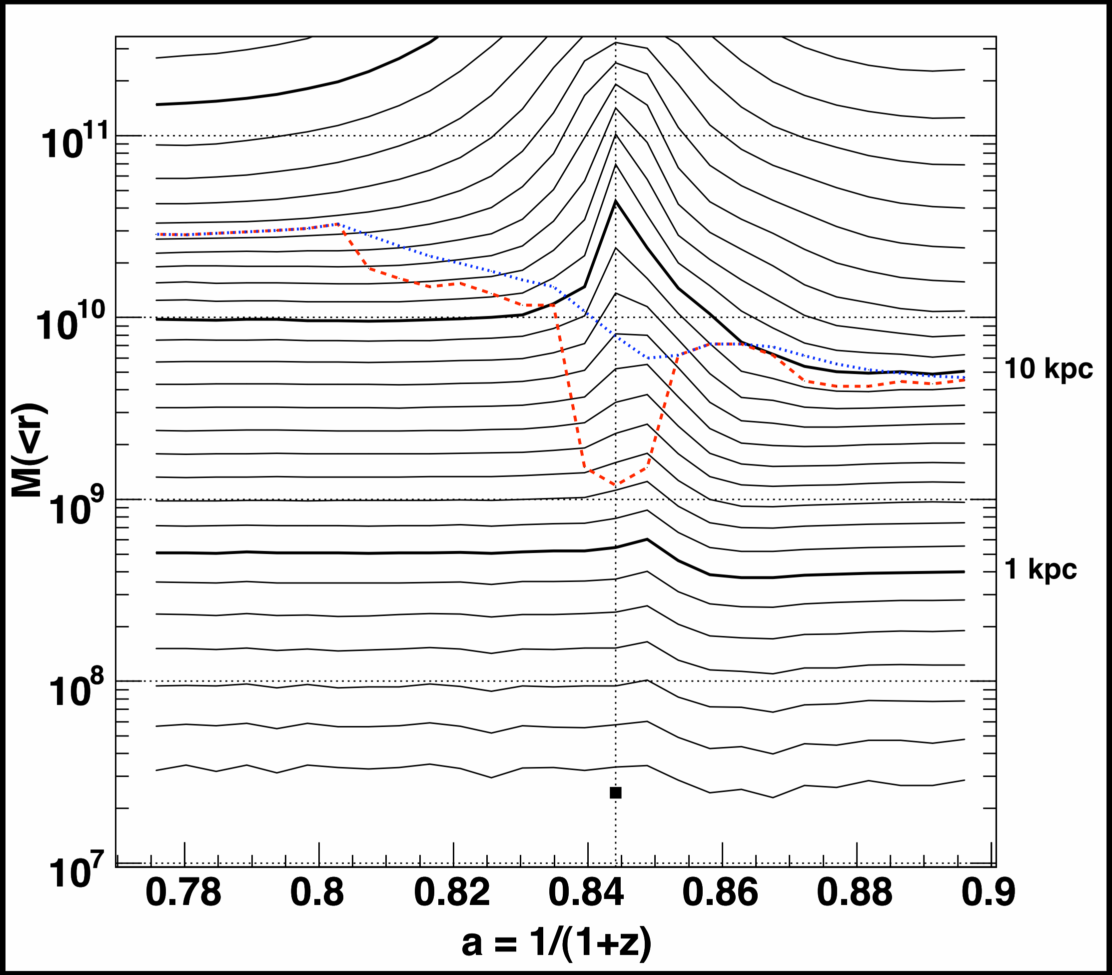
with $T_s = T_{\rm orbit}/6$

shock duration = internal subhalo orbital time

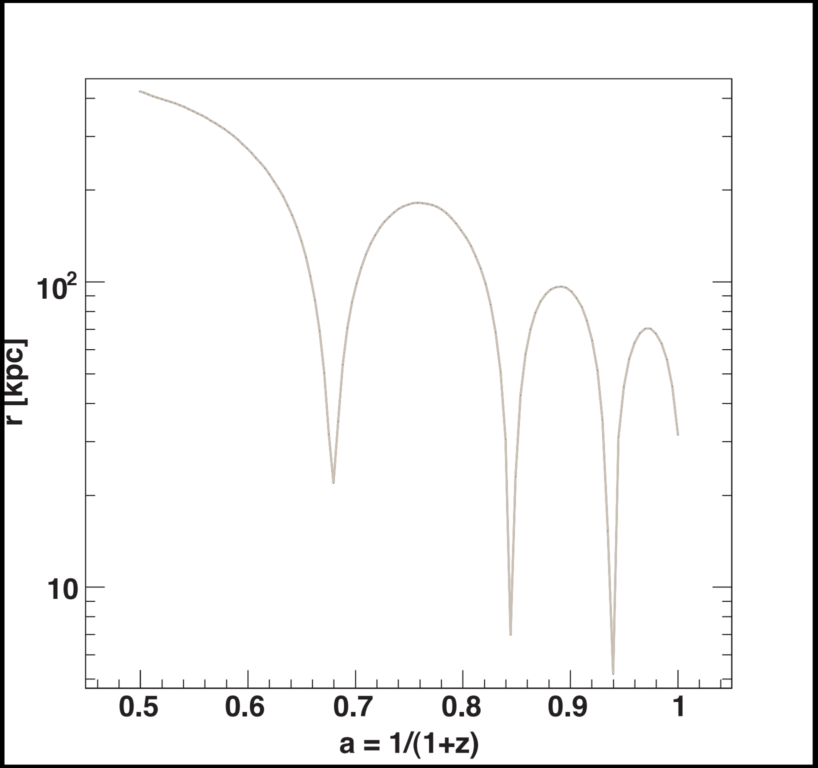
weak, long tidal shock
causes quick compression followed by expansion

mass loss is larger further out

evolution of subhalo density profiles



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

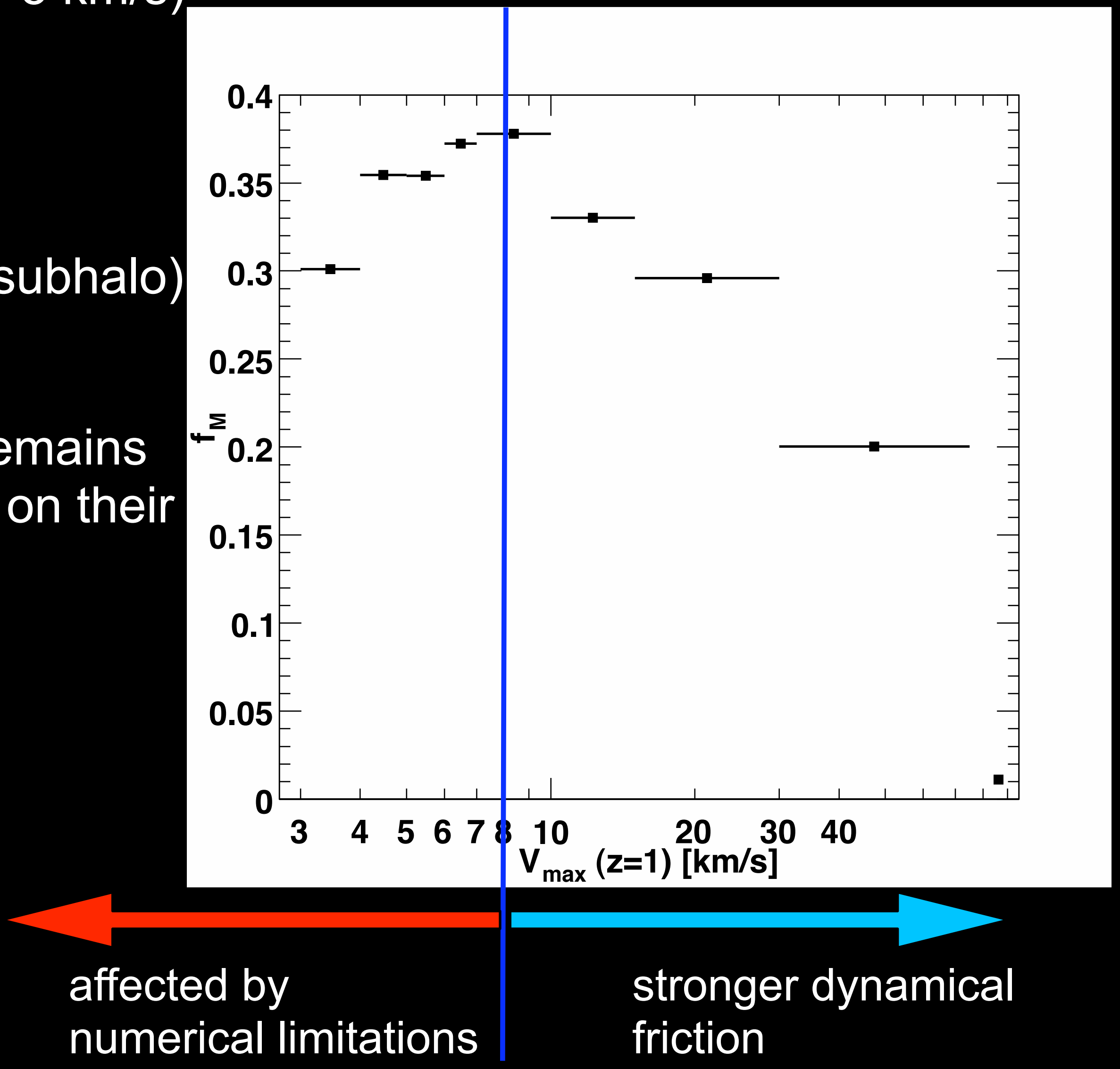
subhalo survival and merging

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

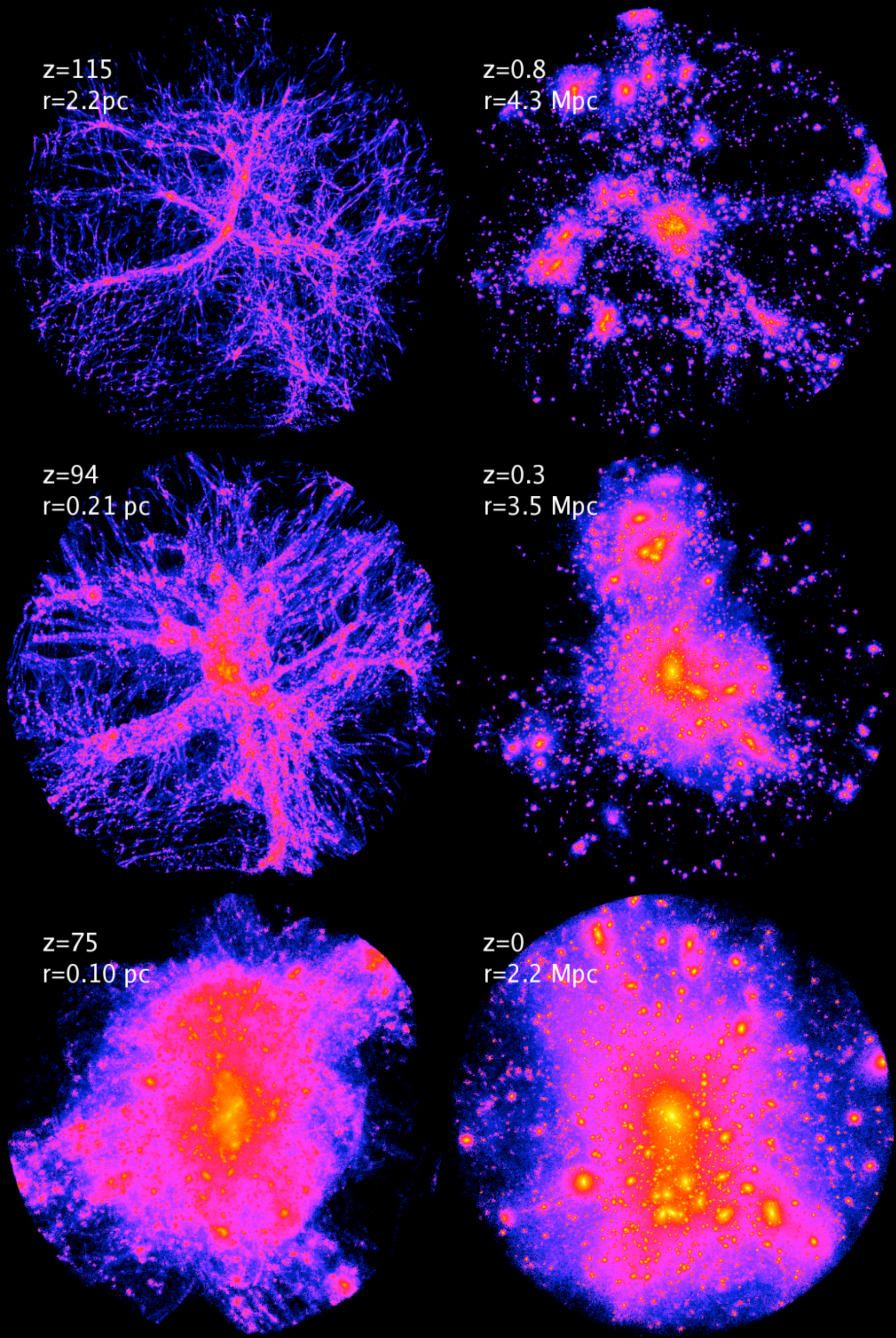


high redshift micro-subhalos are only slightly more fragile despite the flat sigma(M)

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

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

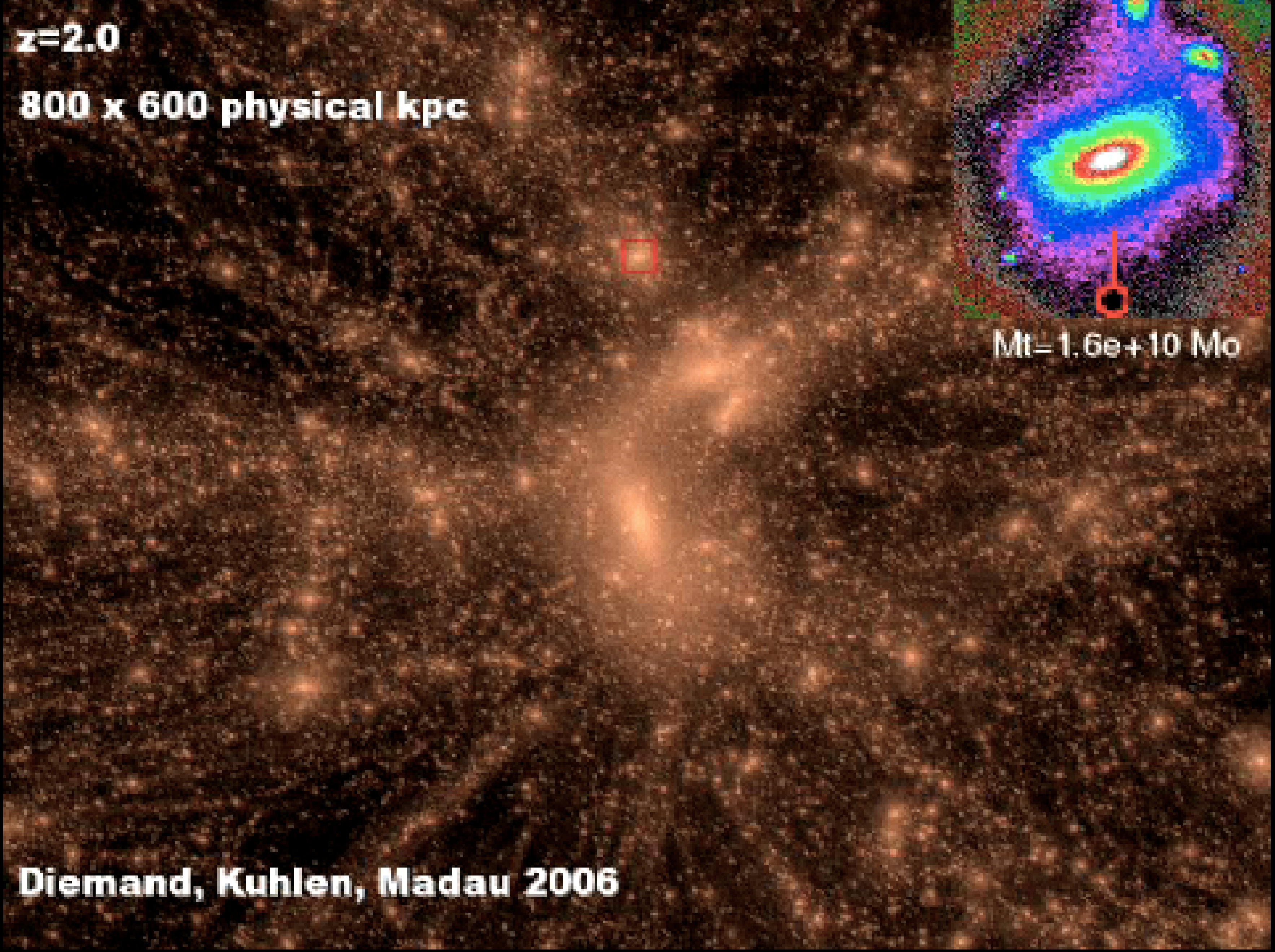
JD,Kuhlen,Madau
astro-ph/0603250



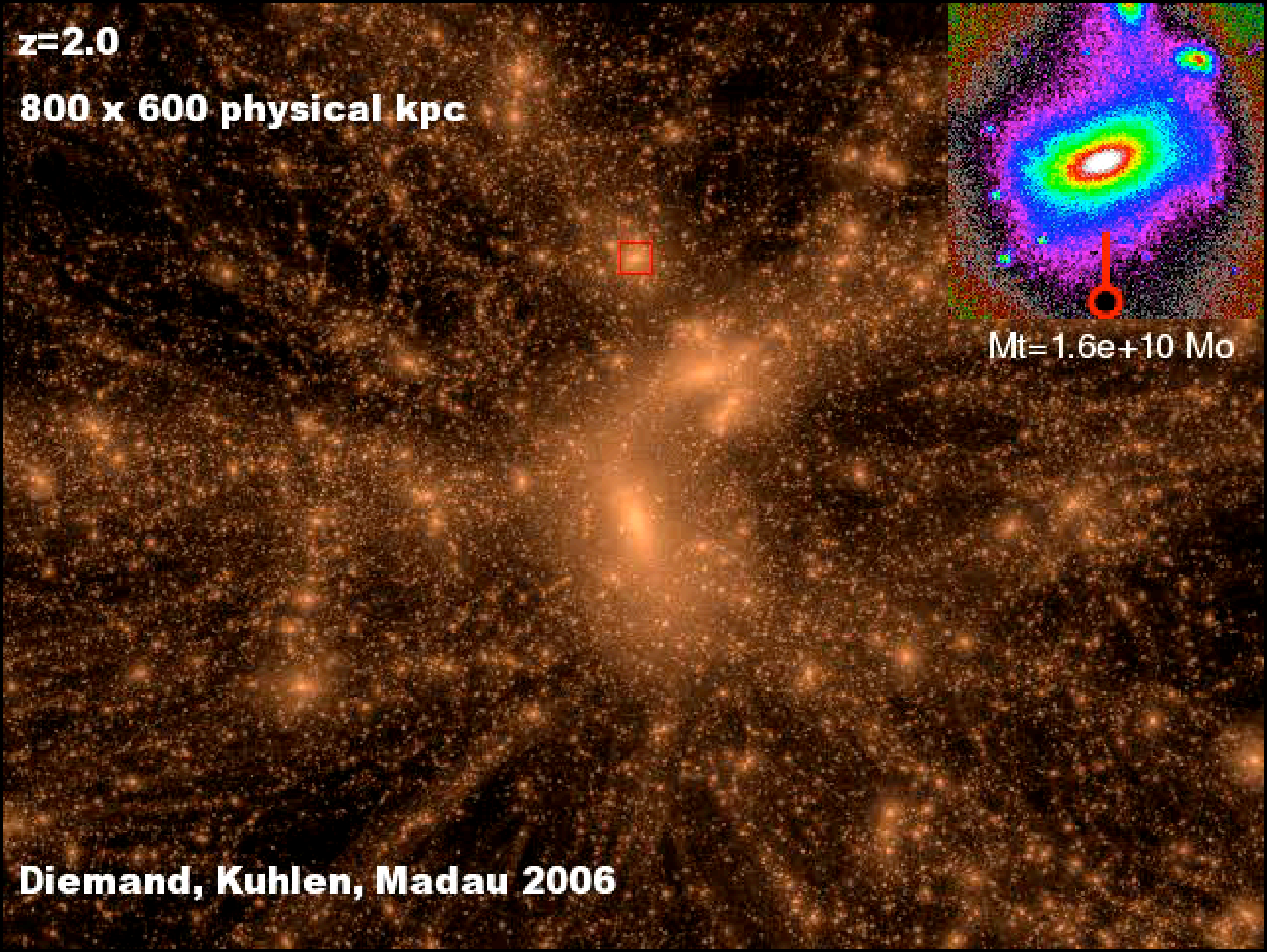
hierarchical formation of a z=0 cluster

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



subhalos becomes rounder with time
major axes tend to point towards the host center
(Kuhlen, JD, Madau 0705.2037, Faltenbacher+0706.0262, Pereira+0707.1702



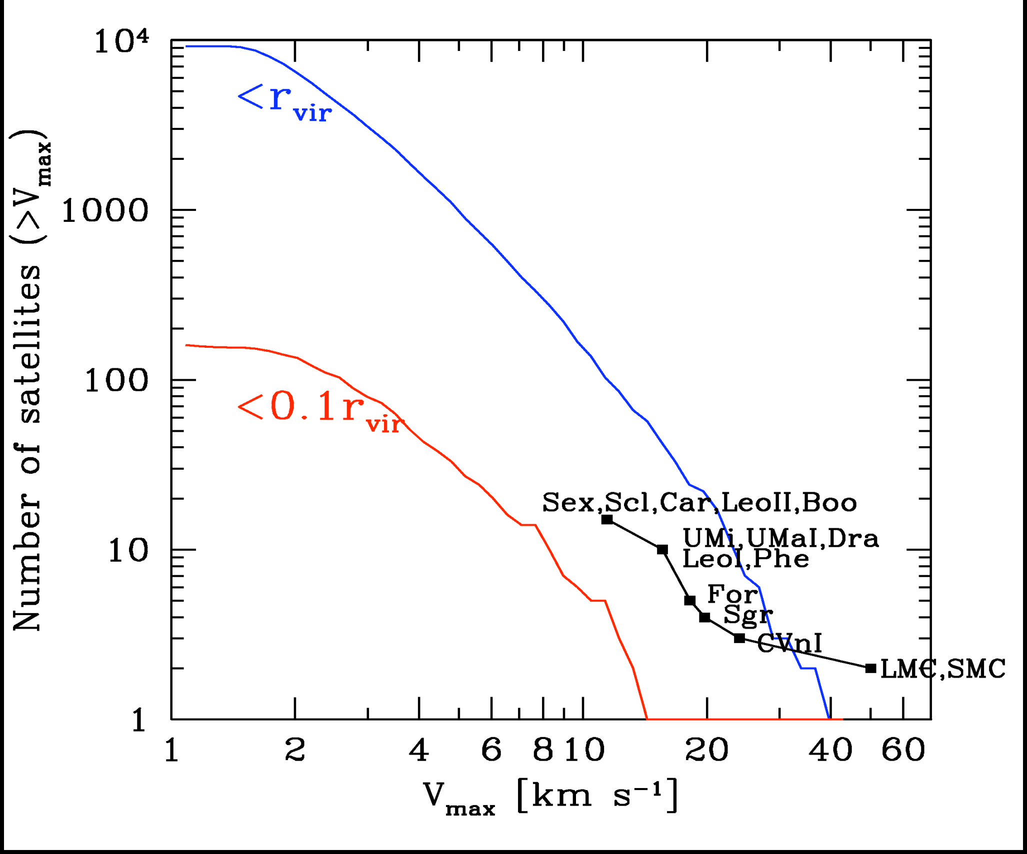
subhalos becomes rounder with time
major axes tend to point towards the host center
(Kuhlen, JD, Madau 0705.2037, Faltenbacher+0706.0262, Pereira+0707.1702

missing satellites?

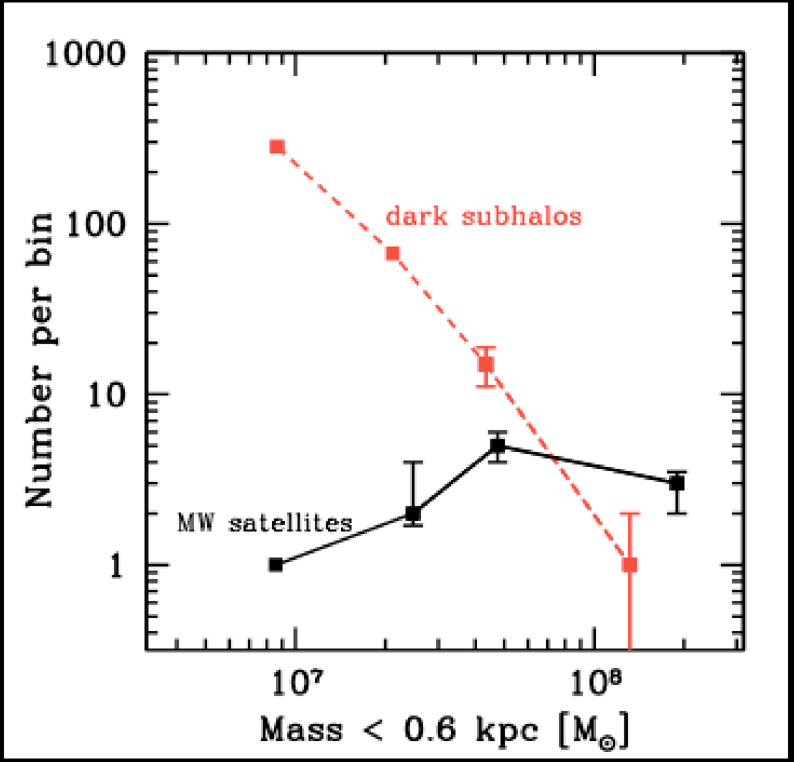
CDM only predicts subhalos, not dwarf galaxies. Luckily, CDM predicts (more than) enough structures to host all known Local Group satellites.

Plausible galaxy formation models roughly reproduce the observed numbers of dwarfs. Many CDM subhalos remain dark (Governato et al. 2007)

As in the original (Moore+99, Klypin+99) comparisons we assumed
sqrt(3) sigma* = Vmax

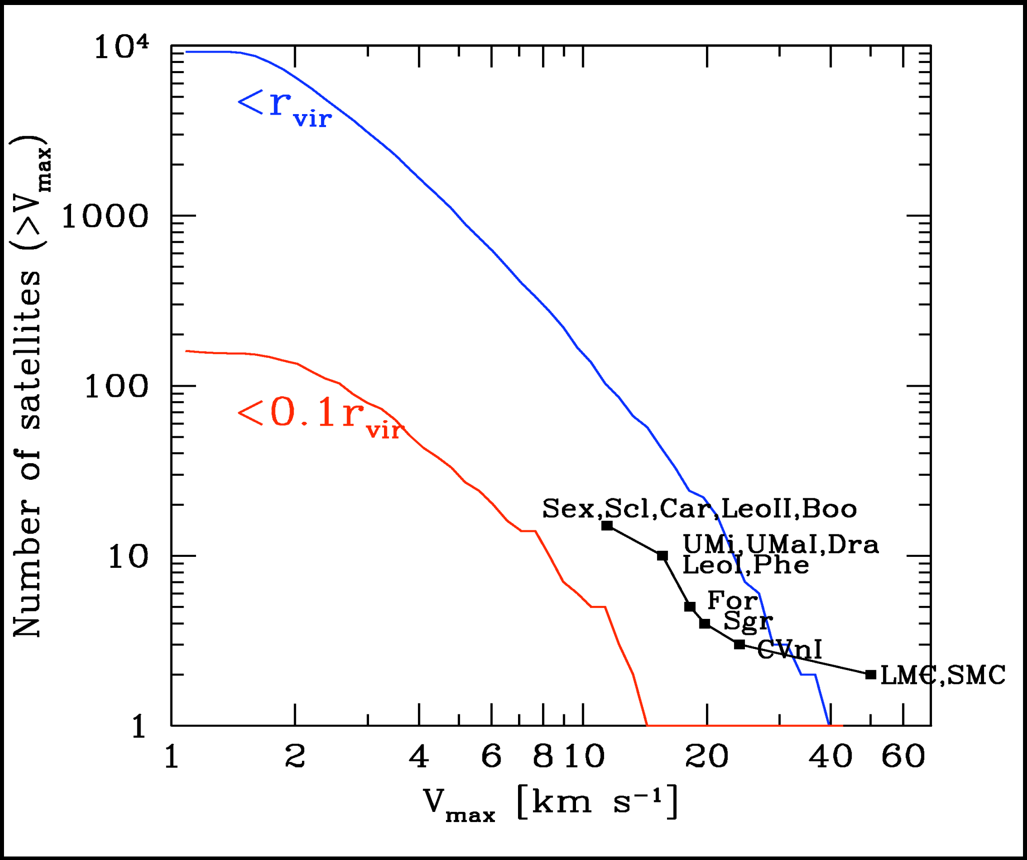


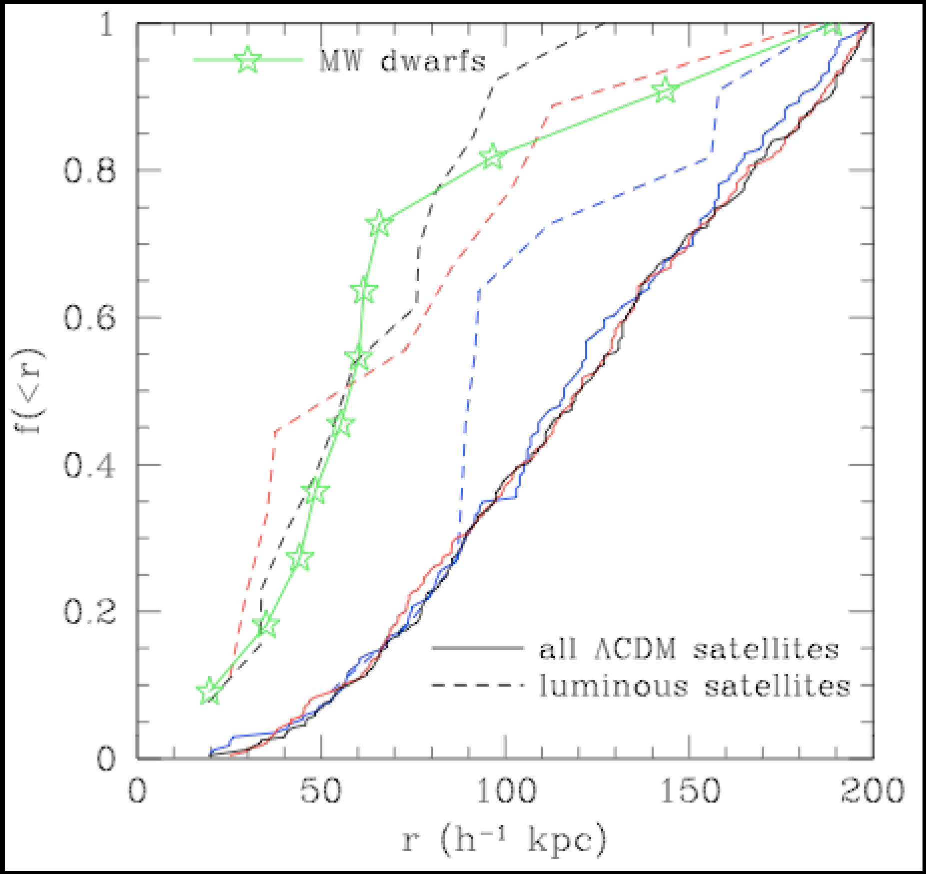
this seems to be roughly right (Strigari+0704.1817):



missing satellites?

the largest subhalos are much further away (Taylor+2003, Kravtsov+2004):



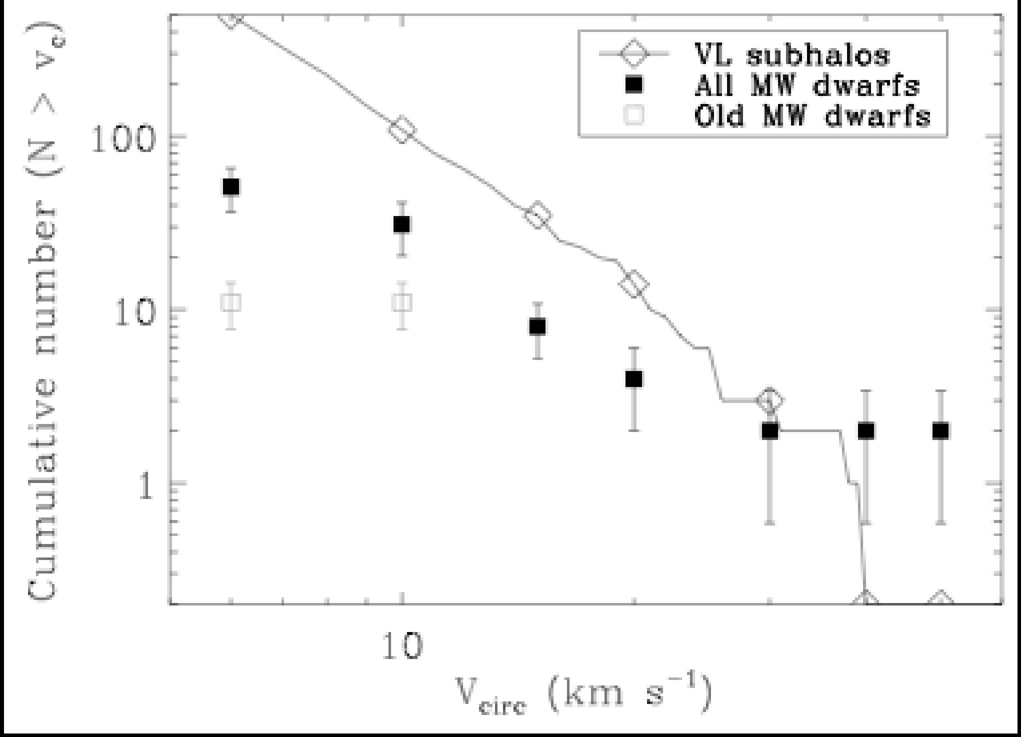


we need more subhalos than dwarf at a given size to find enough that are also at the correct distances!

(lowering the normalization would be a problem on LMC/SMC scales
Via Lactea is near the median, rms halo to halo scatter is about a factor of two)

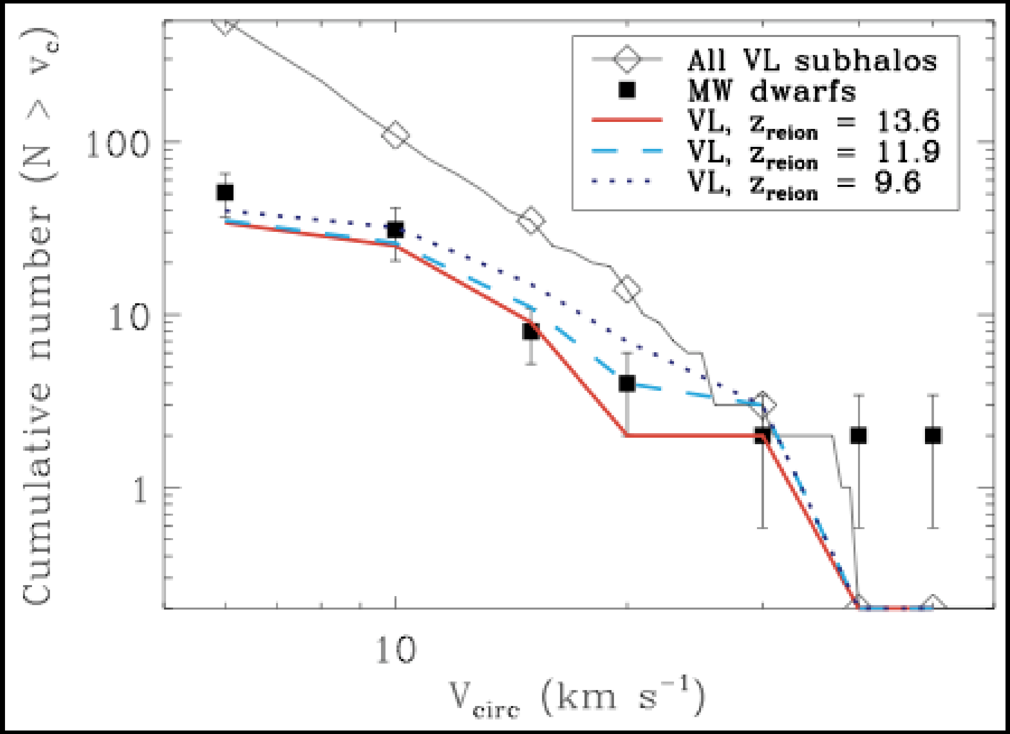
missing satellites?

adding the new ultra faint dwarfs from SDSS helps (Simon+Geha2007):

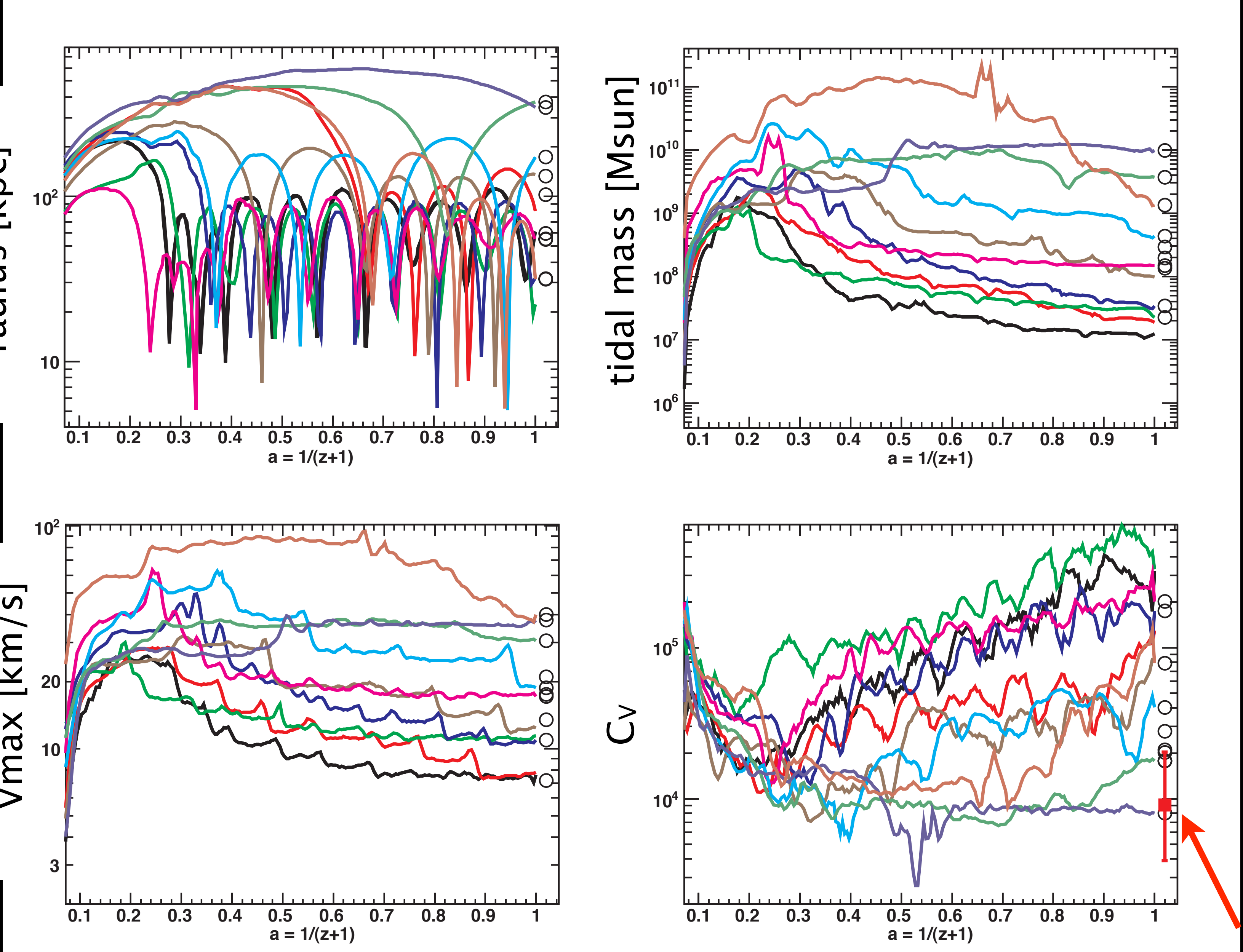


early forming subhalos would have the right sizes (Simon+Geha2007)

and also the right spatial distribution (Moore+2006)



possible hosts for Local Group dwarfs



diverse histories:

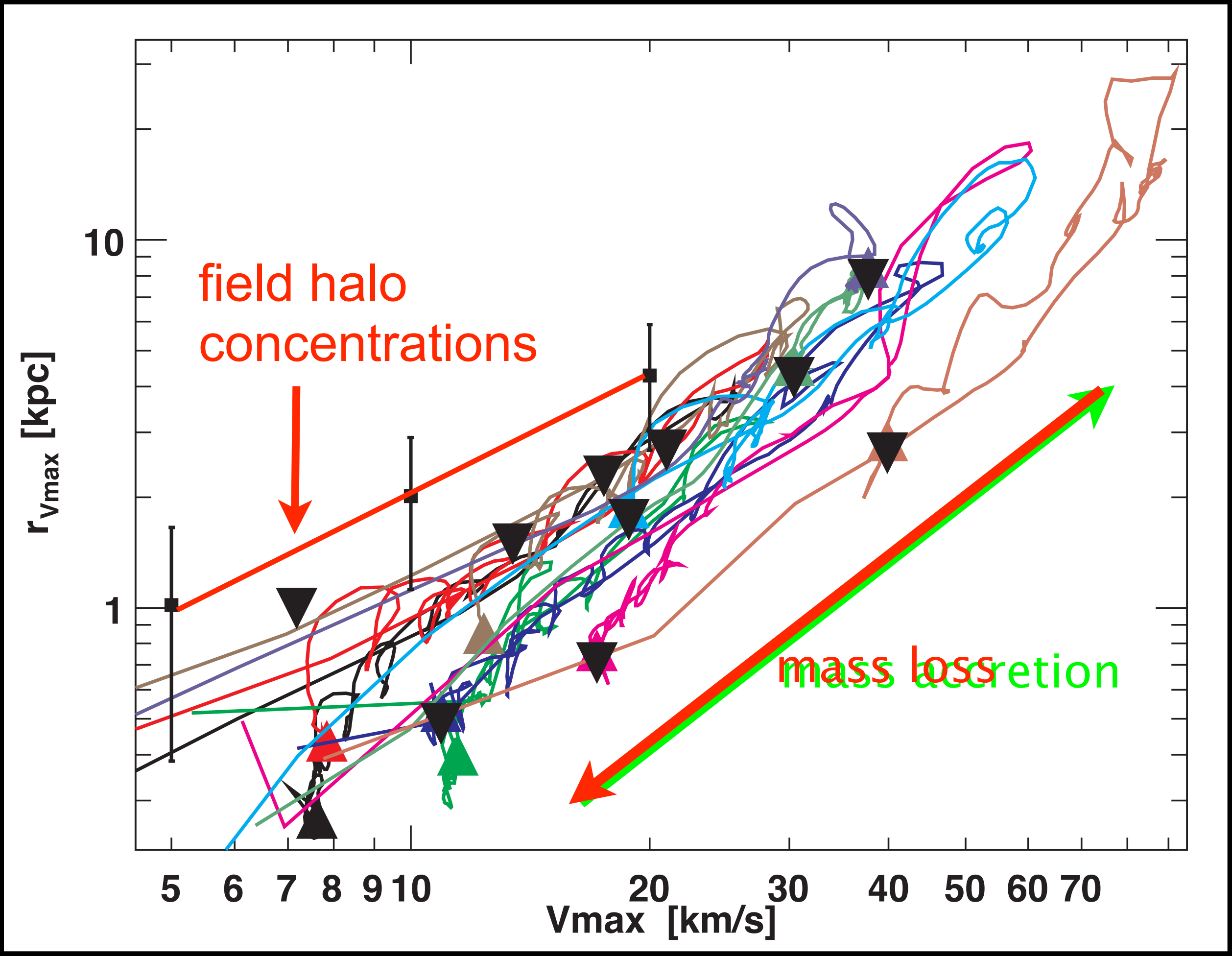
0 to 11 pericenters
inner subhalos tend to have more of them and starting earlier

none to very large mass loss

concentrations increase during tidal mass loss

field halo concentrations

possible hosts for Local Group dwarfs

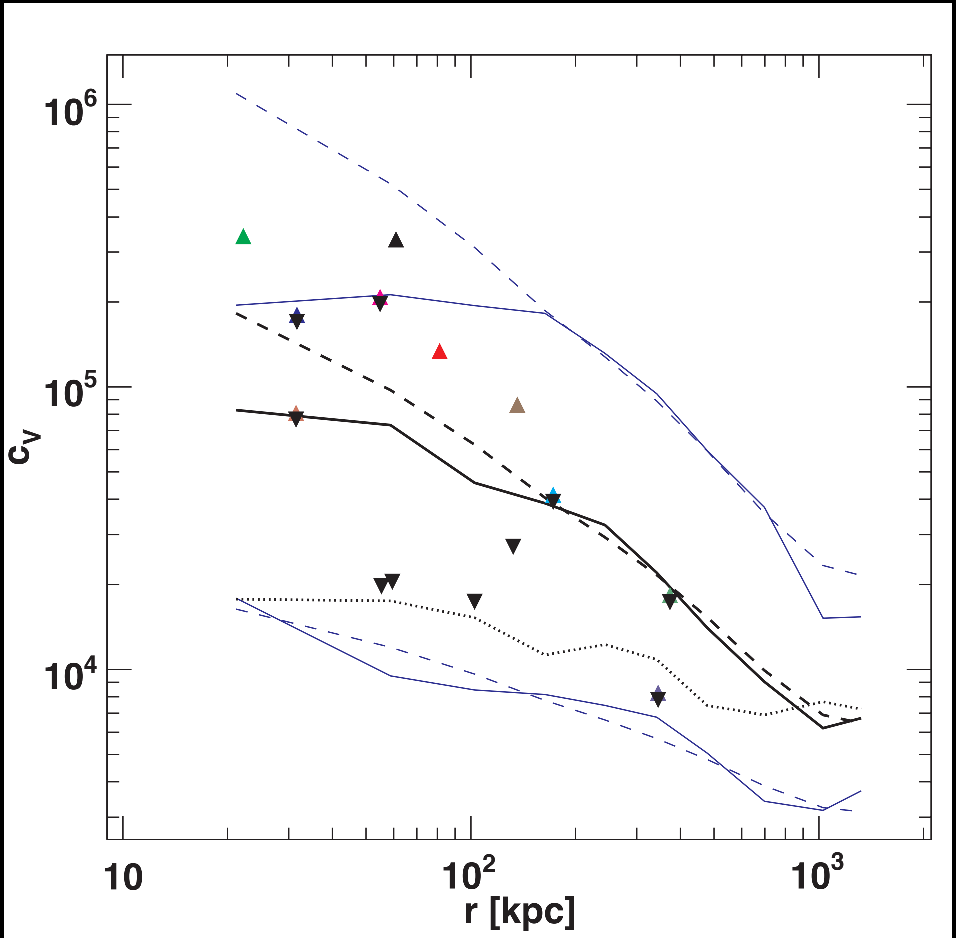


same 10 EF tracks

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

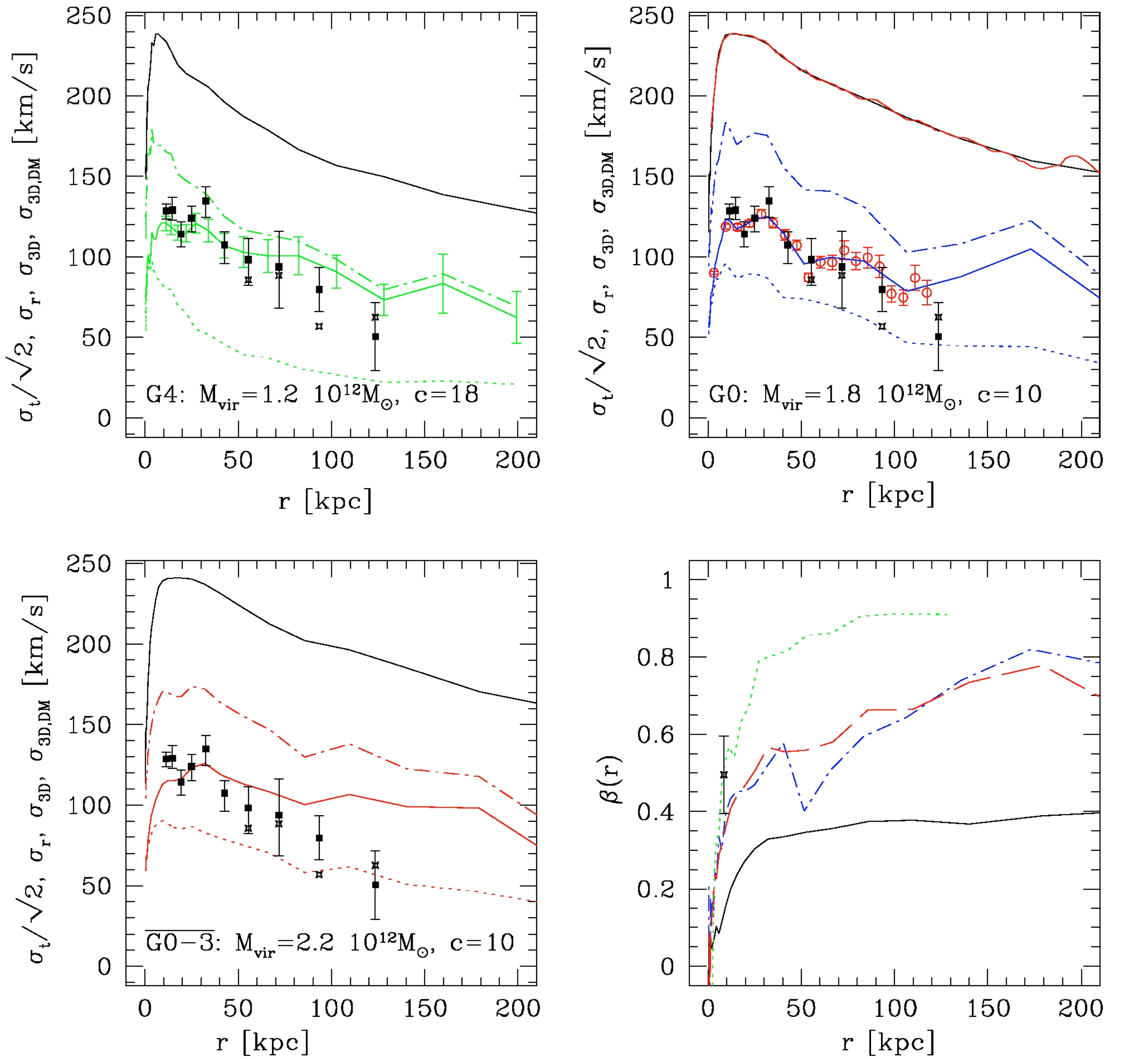


median concentrations increase towards the galactic center

the 68% scatter also increases

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

EF model fits Milky Way stellar halo radial velocities



cosmological stellar halo kinematics fit the observations well

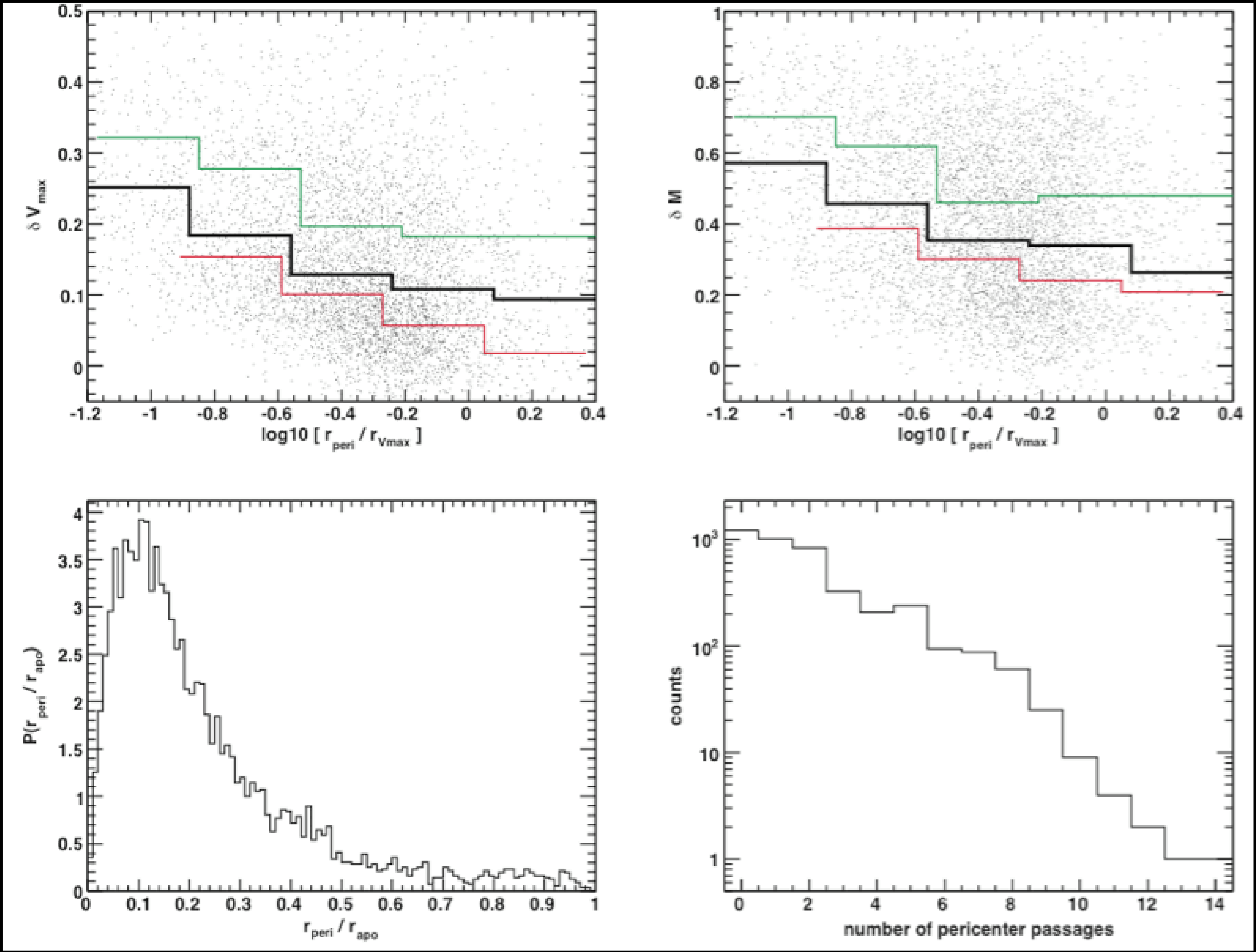
The outer halo is not well constrained:

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

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

JD,Madau, Moore 2005

larger mass loss at first pericenter



summary : substructure

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

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

CDM predicts enough subhalos to host all the currently known Local Group dwarfs

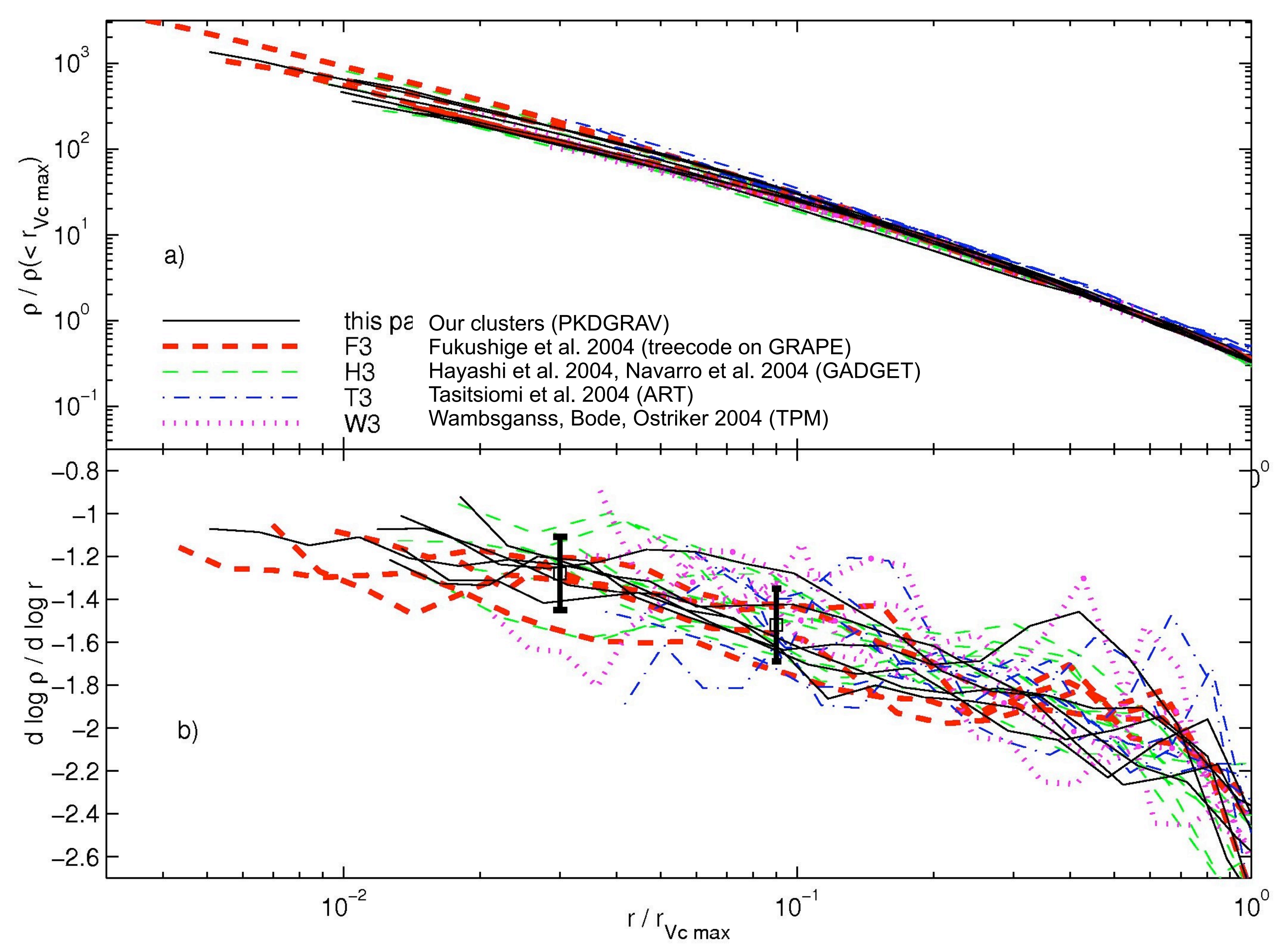
most (97%) subhalos survive from z=1 until today. smaller ones loose less mass

high redshift micro-subhalos are only slighly more fragile despite thier flat sigma(M)

scatter in CDM cluster density profiles

eg. Fukushige etal 2004, Navarro et al 2004, JD etal 2004

CDM density profiles are close to universal (e.g. NFW), but individual halo density profile shapes have scatter:



JD, Moore, Stadel, MNRAS, 2004

scatter in CDM cluster density profiles

	$1\% r_{\rm vir}$	$3\% r_{\rm vir}$	$3\% r_{\rm Vcmax}$	$9\% r_{\rm Vcmax}$
A9	1.22	1.36	1.24	1.64
B9	1.33	1.43	1.21	1.63
C9	1.24	1.21	1.25	1.26
D12	1.28	1.54	1.32	1.58
E9	1.31	1.44	1.41	1.62
F9cm	1.19	1.47	1.22	1.43
a) A-F	1.26 ± 0.05	1.41 ± 0.11	1.28 ± 0.08	1.53 ± 0.15
b) F03	1.25 ± 0.05	1.52 ± 0.06	1.33 ± 0.15	1.54 ± 0.15
c) H03	1.18 ± 0.13	1.38 ± 0.14	1.23 ± 0.17	1.50 ± 0.14
d) T03	1.50 ± 0.14	1.79 ± 0.07	–	1.56 ± 0.12
e) W03	1.11 ± 0.04	1.41 ± 0.13	–	1.35 ± 0.06
avg.(a-e)	1.26	1.50	–	1.49
avg.(a-c)	1.23	1.44	1.28	1.52
NFW			1.12	1.32
Moore et al.			1.54	1.65

JD, Moore, Stadel, MNRAS, 2004, 353, 624

why are profiles nearly universal? what causes the scatter?

fitting functions

2 parameter functions (only two 'scaling' parameters):

NFW

$$\rho = \frac{\rho_s}{x(1+x)^2}$$

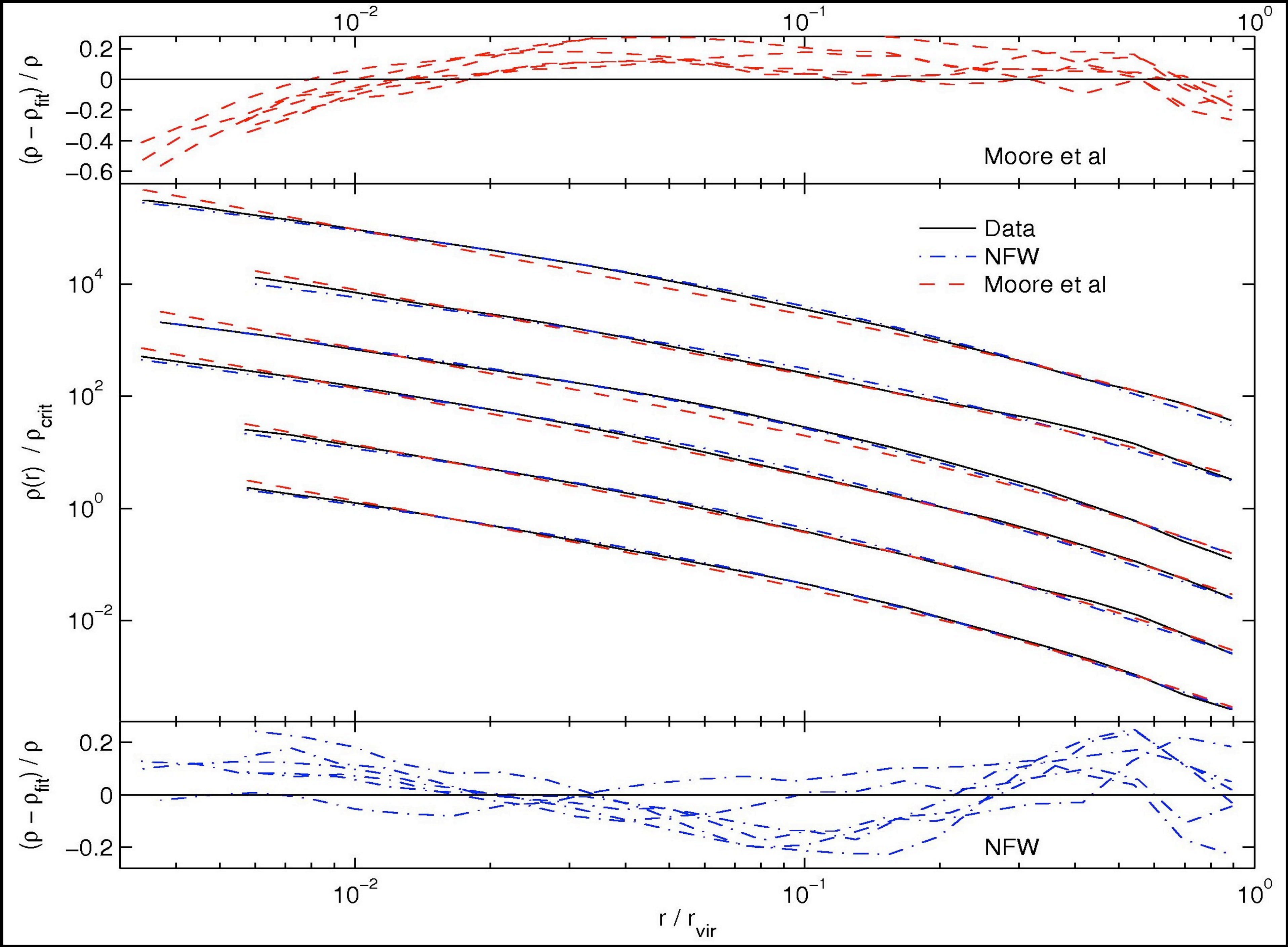
$$x = r/r_s$$

Moore et al 1999

$$\rho = \frac{\rho_s}{x^{1.5}(1+x)^{1.5}}$$

2 parameter functions (only two 'scaling' parameters):

JD, Moore, Stadel, MNRAS, 2004



more fitting functions

2 parameter functions (only two 'scaling' parameters):

NFW

$$\rho = \frac{\rho_s}{x(1+x)^2}$$

Moore et al 1999

$$\rho = \frac{\rho_s}{x^{1.5}(1+x)^{1.5}}$$

$$x = r/r_s$$

3 parameter functions (one additional 'profile shape' parameter):

gamma model (cusp)
JD, Moore, Stadel, 2004

$$\rho_{\rm G}(r) = \frac{\rho_s}{(r/r_s)^{\gamma}(1+(r/r_s)^{\alpha})^{(\beta-\gamma)/\alpha}} \, .$$

$\alpha = 1$ $\beta = 3$

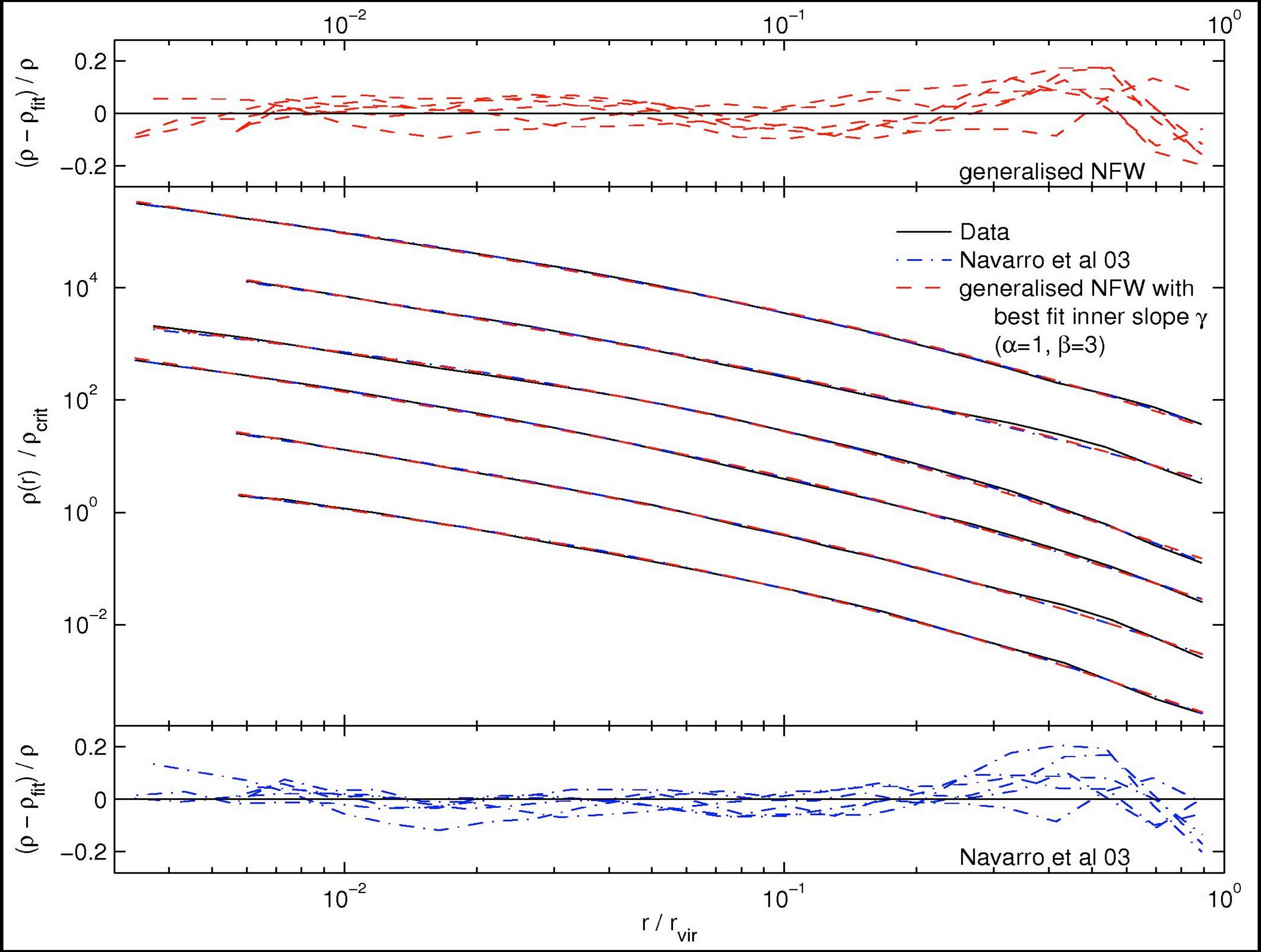
Sersic/Einasto (core)
Navarro etal 2004
Merrit etal 2005/2006

$$\rho(r) = \rho_{\rm e} \exp\left\{-d_n\left[(r/r_{\rm e})^{1/n} - 1\right]\right\}$$

Prugniel-Simien (deprojected Sersic)
Merritt, Navarro, Ludlow, Jenkins, 2005
Merritt, Graham, Moore, JD, Terzic, 2006
Graham etal 2006

$$\rho(r) = \rho' \left(\frac{r}{R_{\rm e}}\right)^{-p} \exp\left[-b\,(r/R_{\rm e})^{1/n}\right]$$

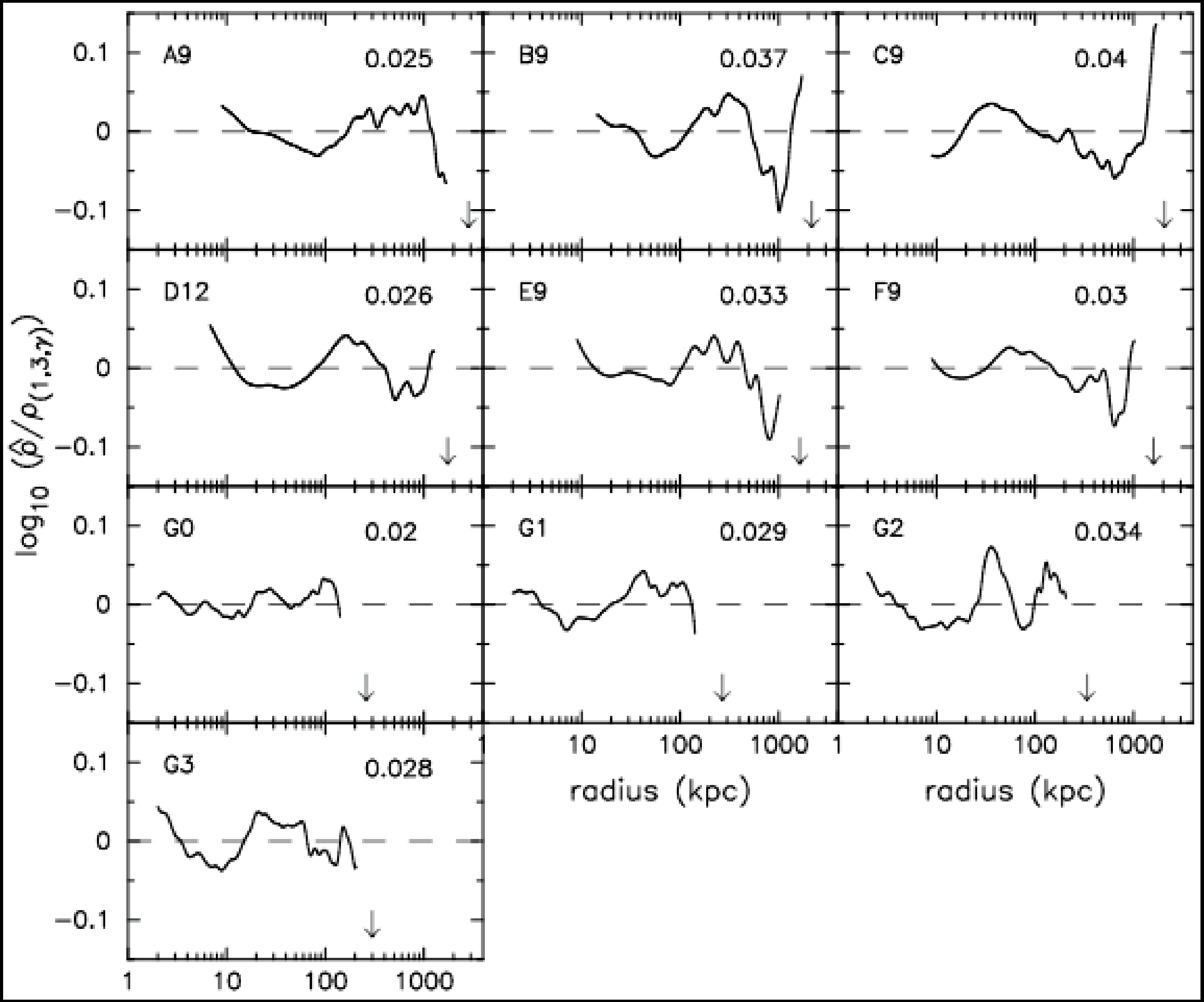
3 parameter functions (one additional 'profile shape' parameter): JD, Moore, Stadel, MNRAS, 2004



3 parameter functions (one additional ‘profile shape’ parameter):

gamma-model

fitted to non-parametric density profiles



Merritt, Graham, Moore, JD, Terzic, AJ in press

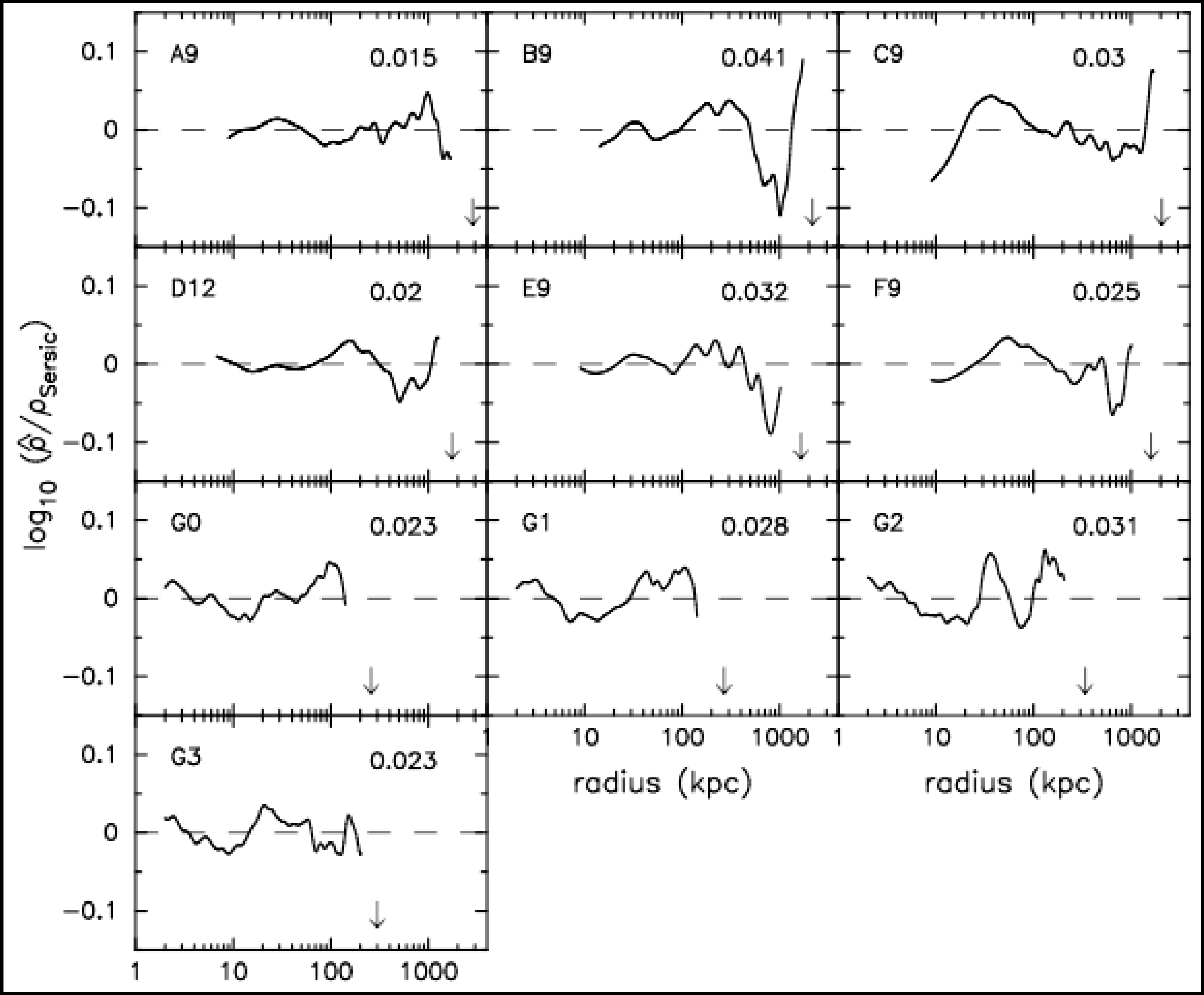
3 parameter functions (one additional 'profile shape' parameter):

Sersic-model

rms deviations are often smaller than for the gamma-model

both have largest deviations in the outer halo

which one fits the inner halo better?



Merritt, Graham, Moore, JD, Terzic, AJ in press

resolving the very inner profile

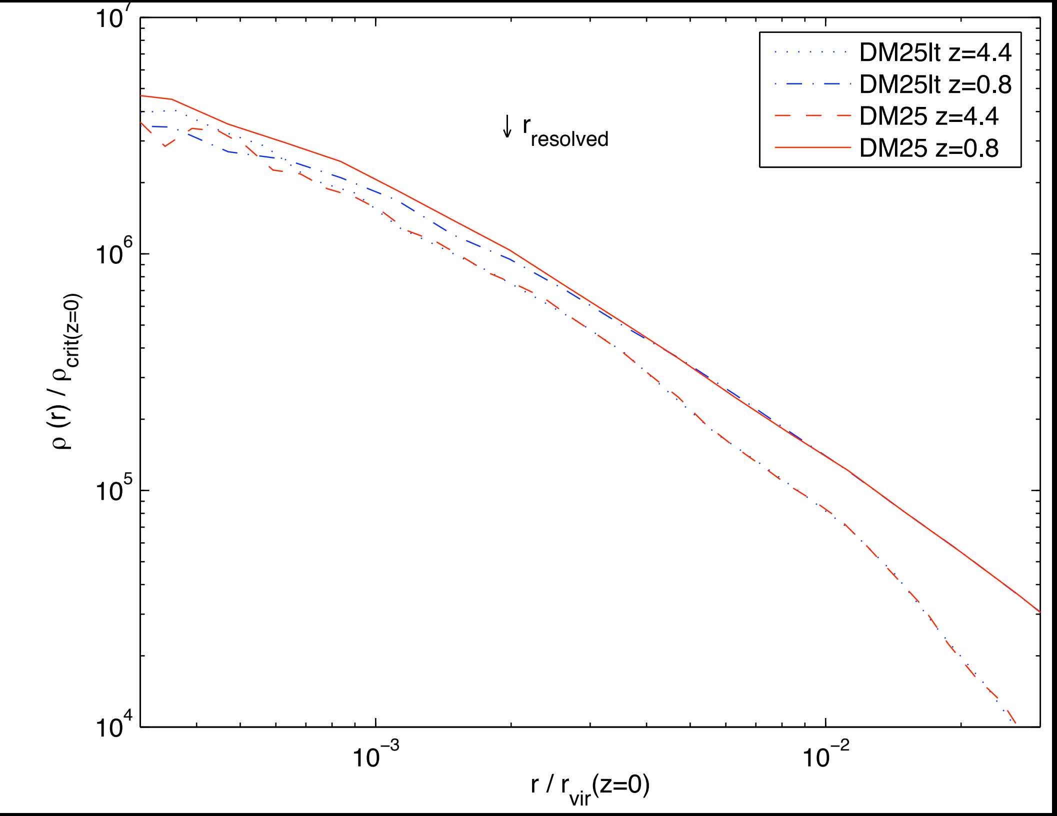
JD, Zemp, Moore, Stadel, Carollo, MNRAS, 2005, 364, 665

physical time-steps:

the empirical $\Delta t_i < \eta\sqrt{\epsilon/a_i}$, eta=0.25 is no longer sufficient

using $\Delta t < \min(\eta\sqrt{\epsilon/a_i}, \eta/4\sqrt{G\rho_i})$ instead

this ensures step are at least 12 times smaller than the local dynamical time $1/\sqrt{G\rho(< r_i)}$
but increases CPU time by a factor of two



recently Zemp, Stadel, Moore, Carollo (2006) have implemented a more efficient algorithm which scales with the local dynamical time everywhere.

summary : density profiles

CDM density profile shapes are not exactly universal:

inner slopes at a give fraction of the scale radius have about 0.2 rms halo to halo scatter

outer slopes (near Rvir) are very noisy

most CDM clusters are denser than NFW at 0.01 Rvir,
but not as dense as the Moore et al 1999 fit

CDM cluster profiles resolved with around 20 million particles can be fitted equally well with a cuspy gamma-model and with the cored Sersic function

the one halo resolved with substantially higher mass, force and time-resolution is consistent with a -1.2 cusp.
its inner halo is denser than the best fit Sersic-model