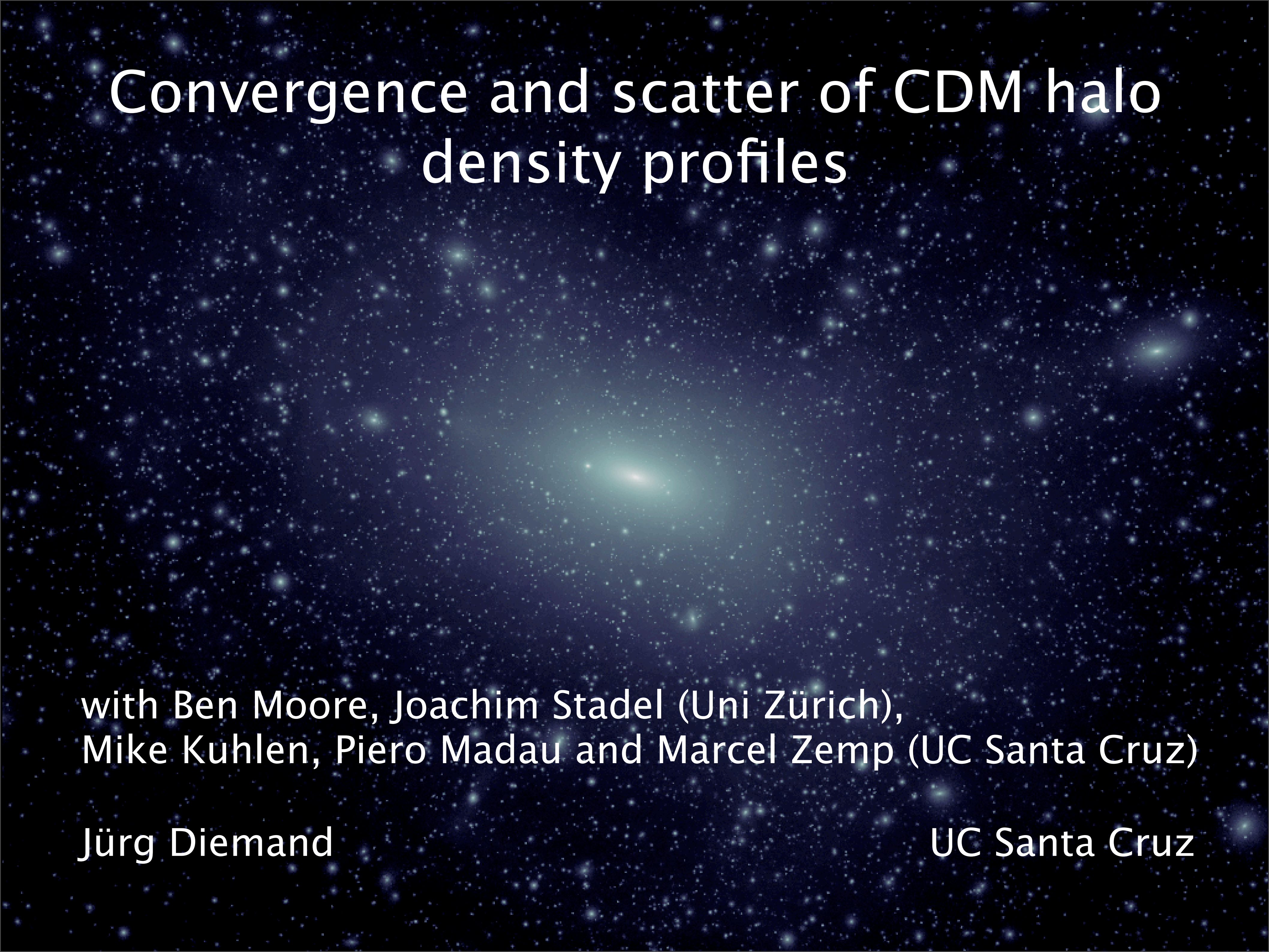


Convergence and scatter of CDM halo density profiles

with Ben Moore, Joachim Stadel (Uni Zürich),
Mike Kuhlen, Piero Madau and Marcel Zemp (UC Santa Cruz)

Jürg Diemand UC Santa Cruz

method:
n-body re-simulations of CDM halos

refined initial conditions (GRAFICS, Bertschinger 2001)

evolve from z~50 to present with PKDGRAV (Stadel 2001)

small sample sizes, results depend on halo selection

no hydro; no stars, no galaxies ...

much higher resolution
(relative to uniform resolution CDM cubes and halos with hydro)

ideal for convergence tests

no hydro; no recipes for sub-grid physics, no free parameters, no overcooling, ...

our latest run: “Via Lactea”

a Milky Way halo simulated with over 200 million particles

-

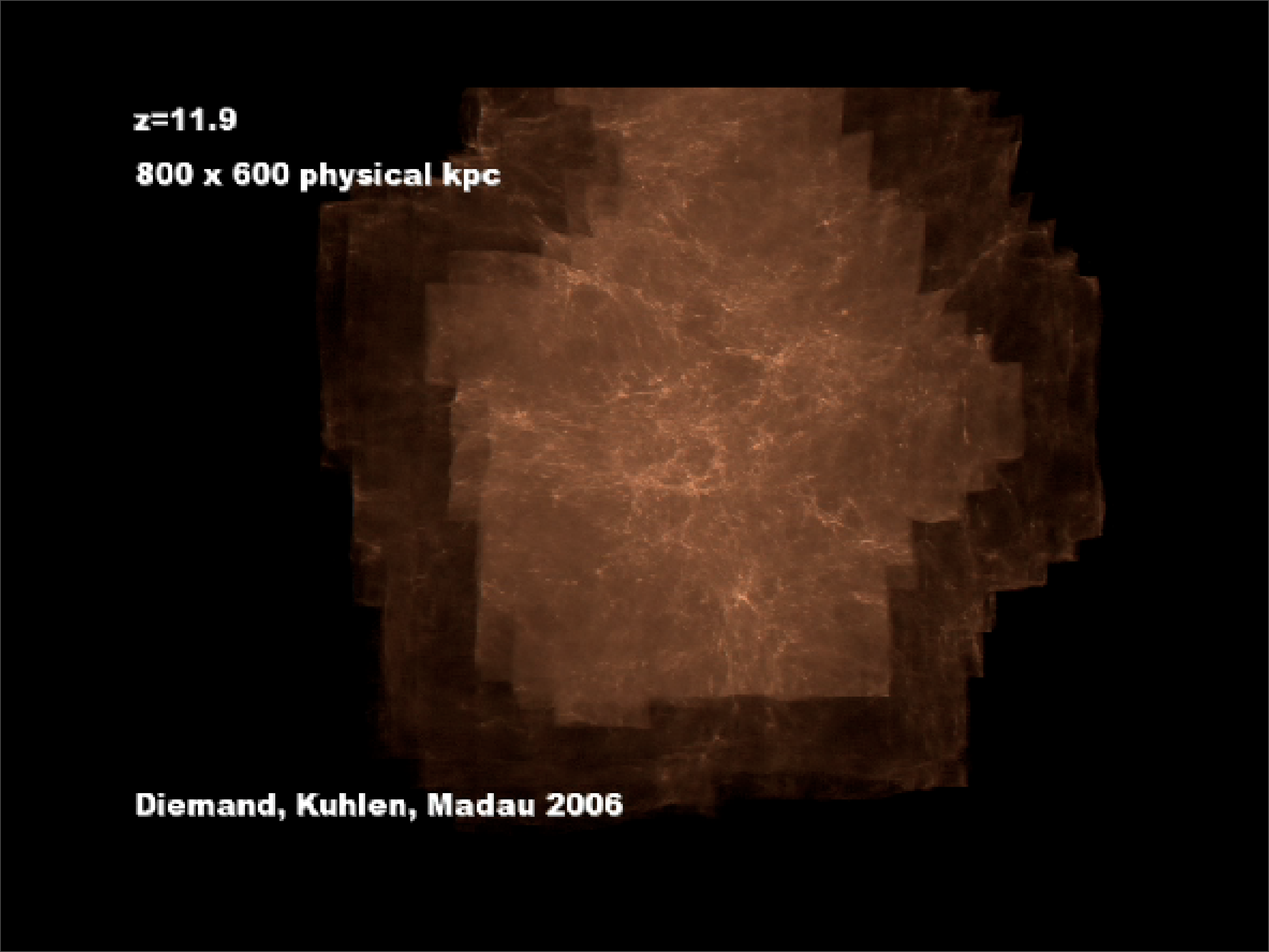
- largest DM simulation to date at these scales.
  320,000 cpu-hours on NASA's Project Columbia supercomputer.

- 213,217,920 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

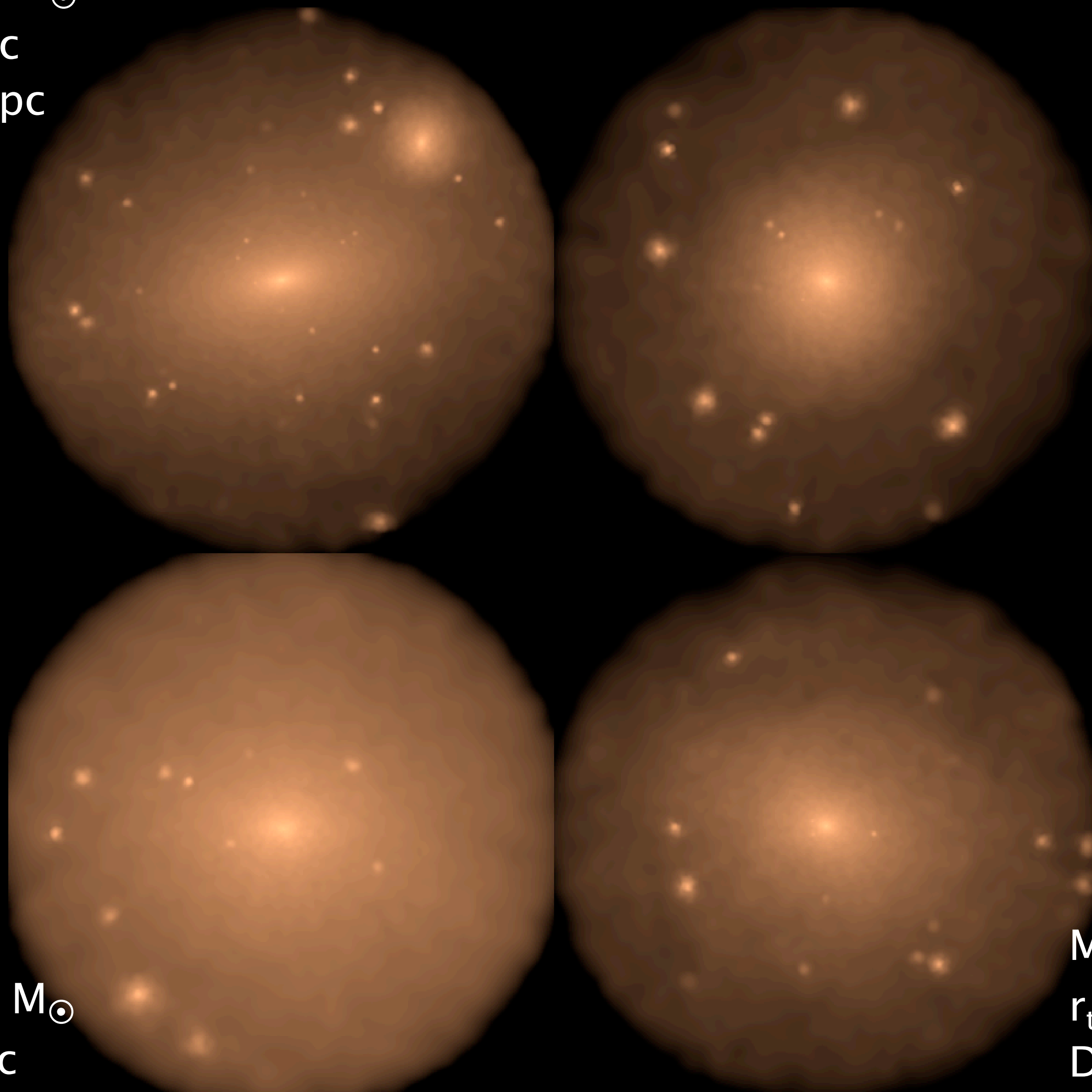
- mass resolution: 20,900 $M_\odot$


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

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, ApJ submitted

www.ucolick.org/~diemand/vl

Via Lactea : A Milky Way dark matter halo simulated with over 200 million particles – Mozilla

Back Forward Reload Stop http://www.ucolick.org/~diemand/vl/index.html Search Print

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via lactea

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

main

movies

images

publications

data (subhalo properties, histories etc. will be available soon. Please contact diemand 'at' ucolick.org with requests and suggestions)

Simulation description

The simulation was performed with PKDGRAV (principal author Joachim Stadel; Stadel, J. 2001, PhD thesis, U. Washington) and employed multiple mass particle grid initial conditions generated with the GRAFICS package (Bertschinger, E. 2001, ApJSS, 137, 1). The high resolution region is embedded within a periodic box of comoving size 90 Mpc, which is sampled at lower resolution to account for the large scale tidal forces.

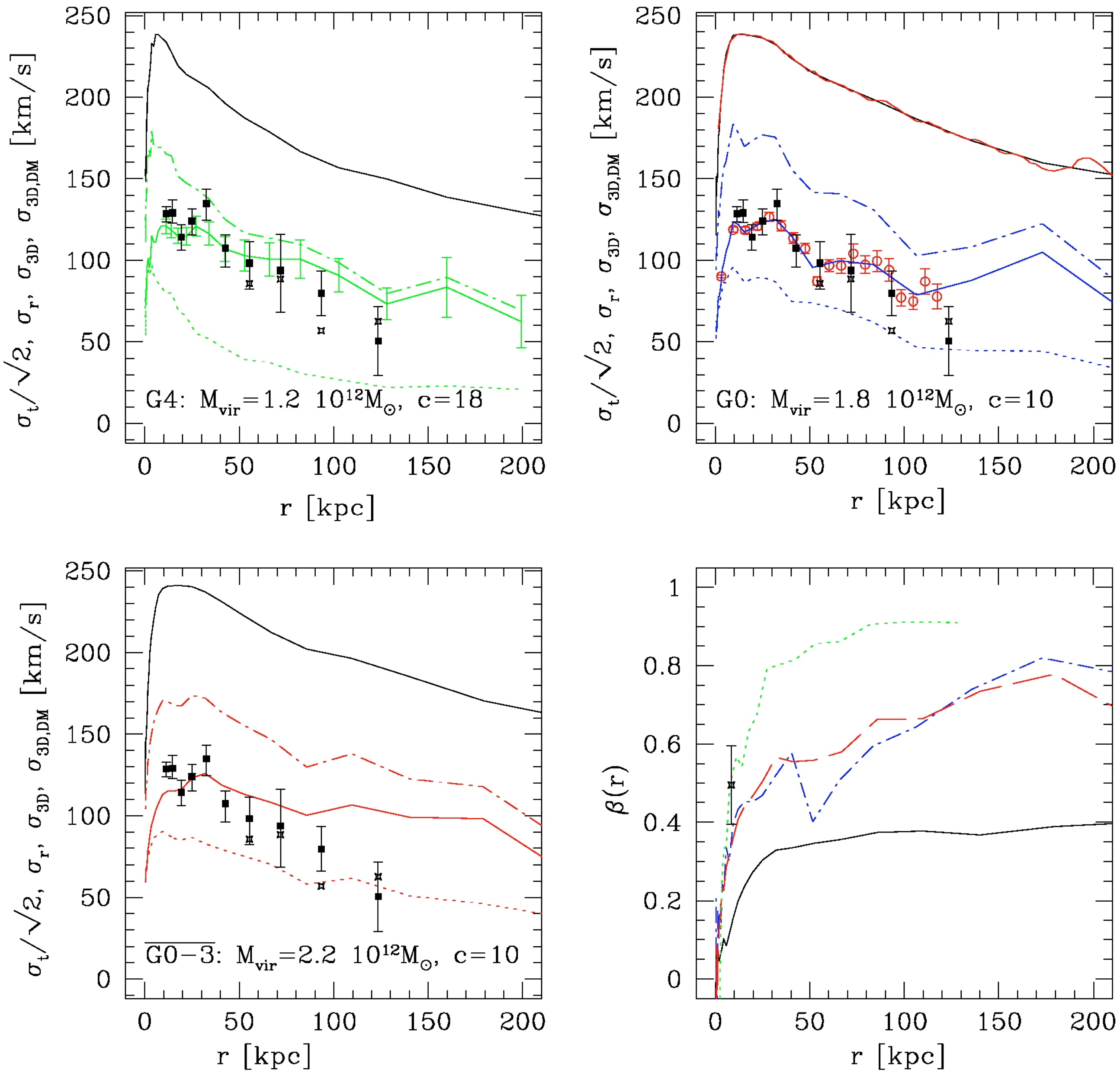
We adopt the best-fit cosmological parameters from the WMAP three-year data release (Spergel, D. N. et al. 2006): Omega_M = 0.238, Omega_Lambda = 0.762, H_0= 73 km/s/Mpc, n=0.951, and sigma_8=0.74.

The high resolution region was centered on a isolated halo that had no major merger after z=1.7, making it a suitable host for a Milky Way-like disk galaxy. Its mass at z=0 is Mvir=1.77e12 solar masses within a radius of Rvir=389 kpc (Mvir is the radius within which the enclosed average density is 200 times the mean matter value).

The "Via Lactea" run features adaptive time-steps as short as the age of the universe divided by 200'000, which is about 68'500 years, a force resolution of 90 pc and particle masses of 20'900 solar masses.

Last Updated: September 15, 2006, by J. Diemand

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

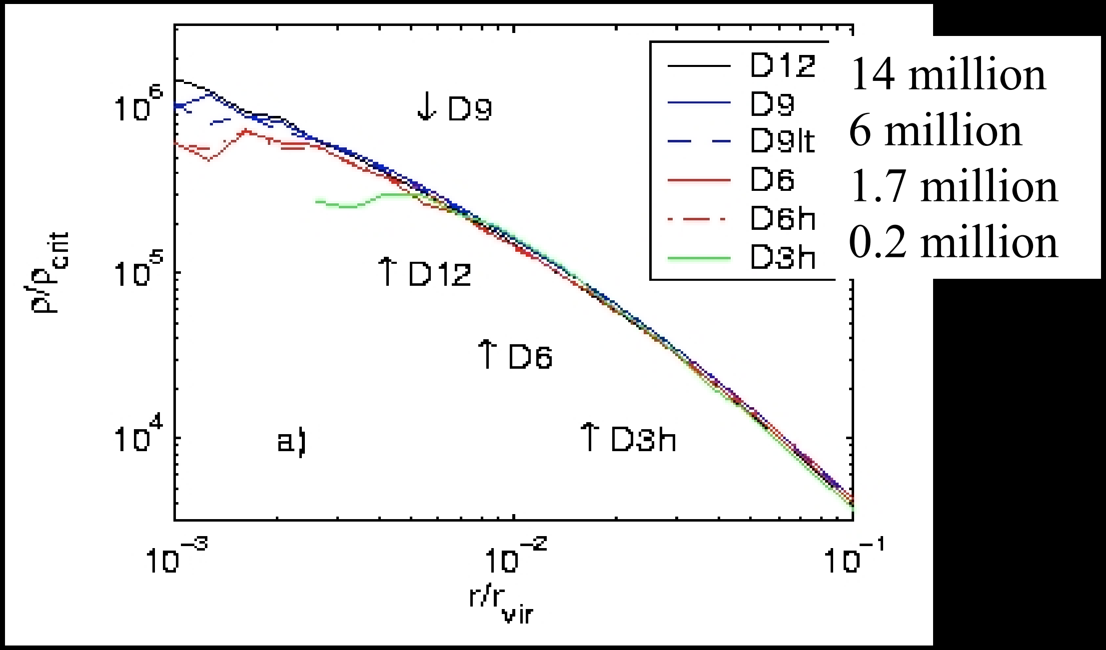
JD,Madau, Moore 2005

numerical convergence of density profiles

eg. Moore etal 1998, Klypin etal 2001, Power etal 2003, Fukushige etal 2004, JD etal 2004

1) convergence radius ~ 3 force softening lengths

2) 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%



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

numerical convergence of density profiles

eg. Moore etal 1998, Klypin etal 2001, Power etal 2003, Fukushige etal 2004, JD etal 2004

1) convergence radius ~ 3 force softening lengths

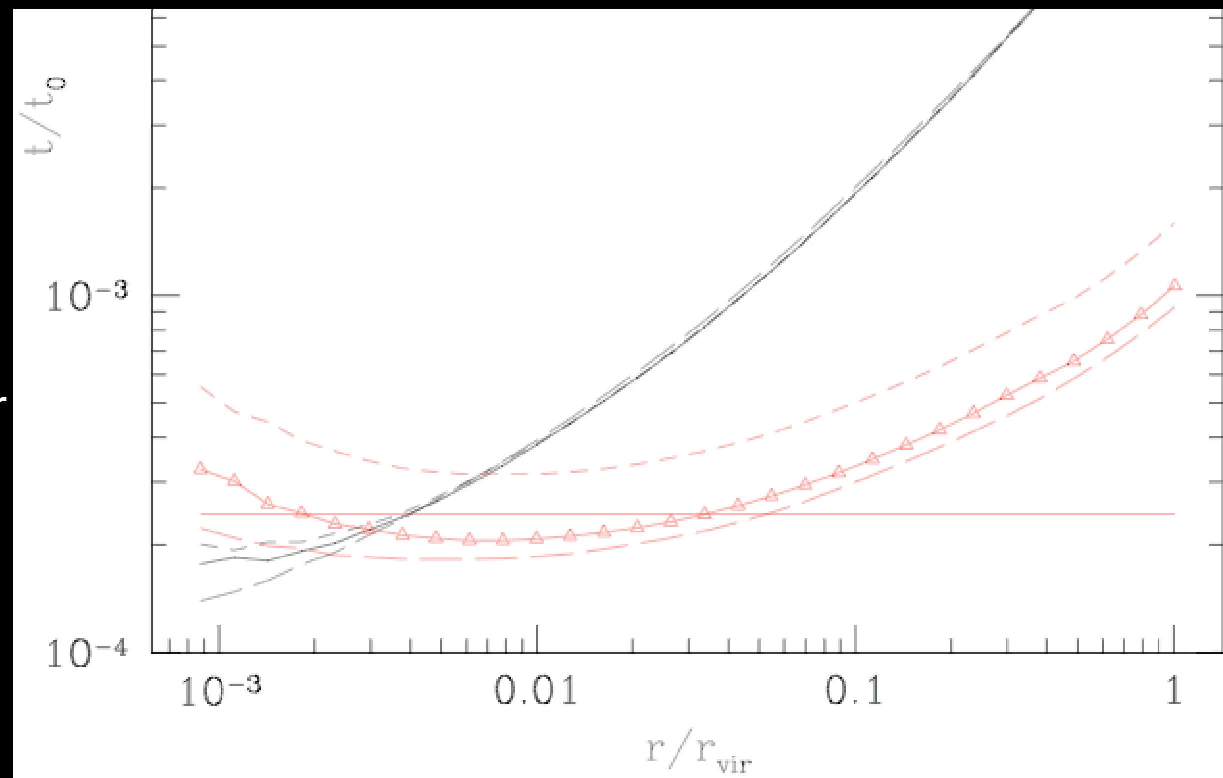
2) Numerical flattening due to two body relaxation:
slow convergence, r ~ $N^{-1/3}$
1 million to resolve 1% of Rvirial
1000 to resolve 10%

3) about 15 time-steps per local dynamical time

Note: the empirical criterion

$\eta\sqrt{\epsilon(z)/a}$ scales much slower

with radius than the local dynamical time



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

numerical convergence of density profiles

eg. Moore etal 1998, Klypin etal 2001, Power etal 2003, Fukushige etal 2004, JD etal 2004

1) convergence radius is limited to at least 2 to 3 force softening lengths

2) 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%

3) about 15 time-steps per
local dynamical time

Note: the empirical criterion

$\eta\sqrt{\epsilon(z)/a}$ scales much slower

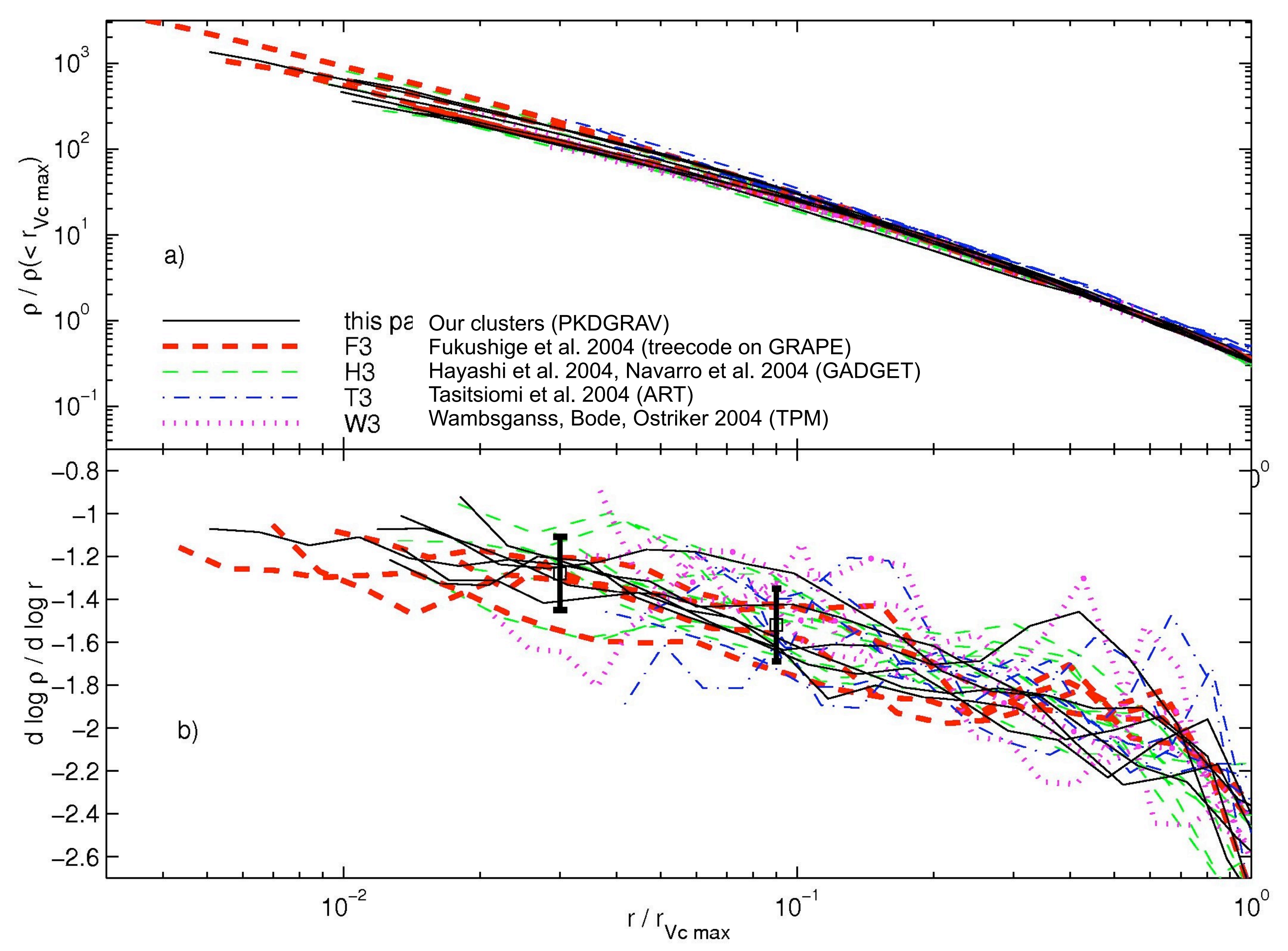
with radius than the local
dynamical time

caution: a) effects of finite force, mass and time resolution are not independent
b) different codes might have different requirements
c) "convergence radius" is the largest of the the radii above
at r_conv the error in local density should be < 10%
larger errors in Mencl, vc, slopes. subhalo abundance, shape, ...

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

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

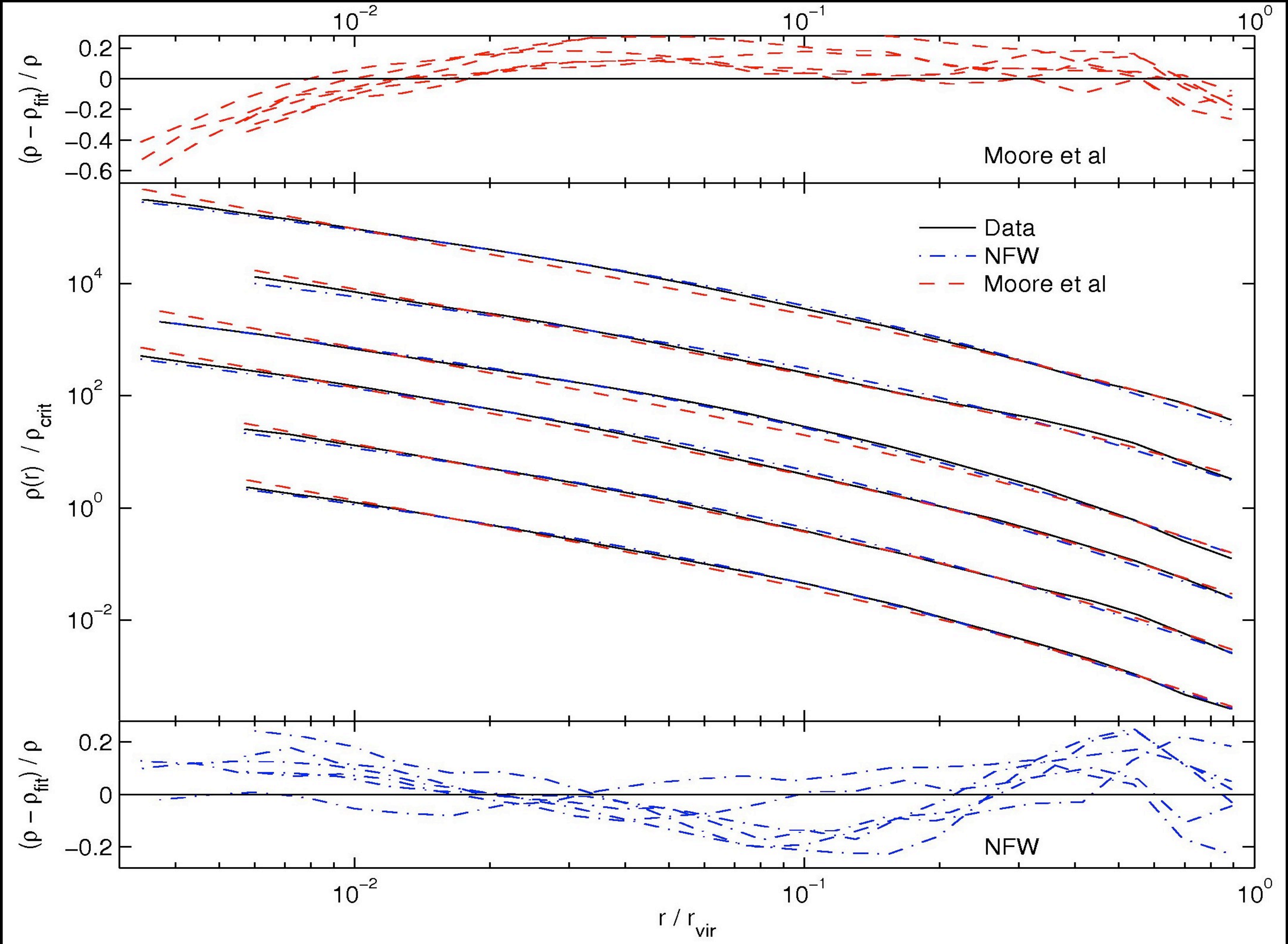
$$x = r/r_s$$

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

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

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

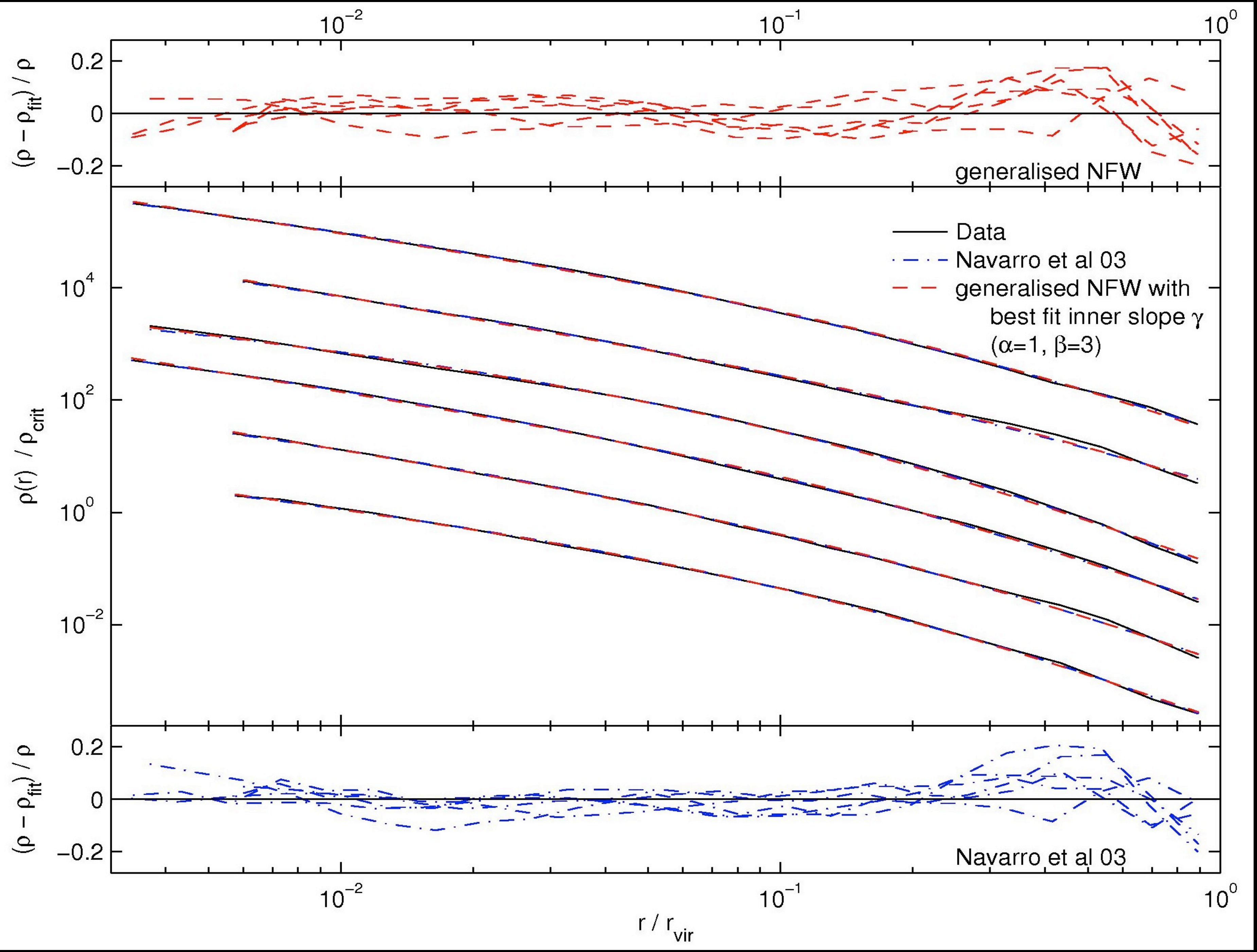
Sersic/Einasto (core)
Navarro etal 2004
Merrit etal 2005/2006

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

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

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

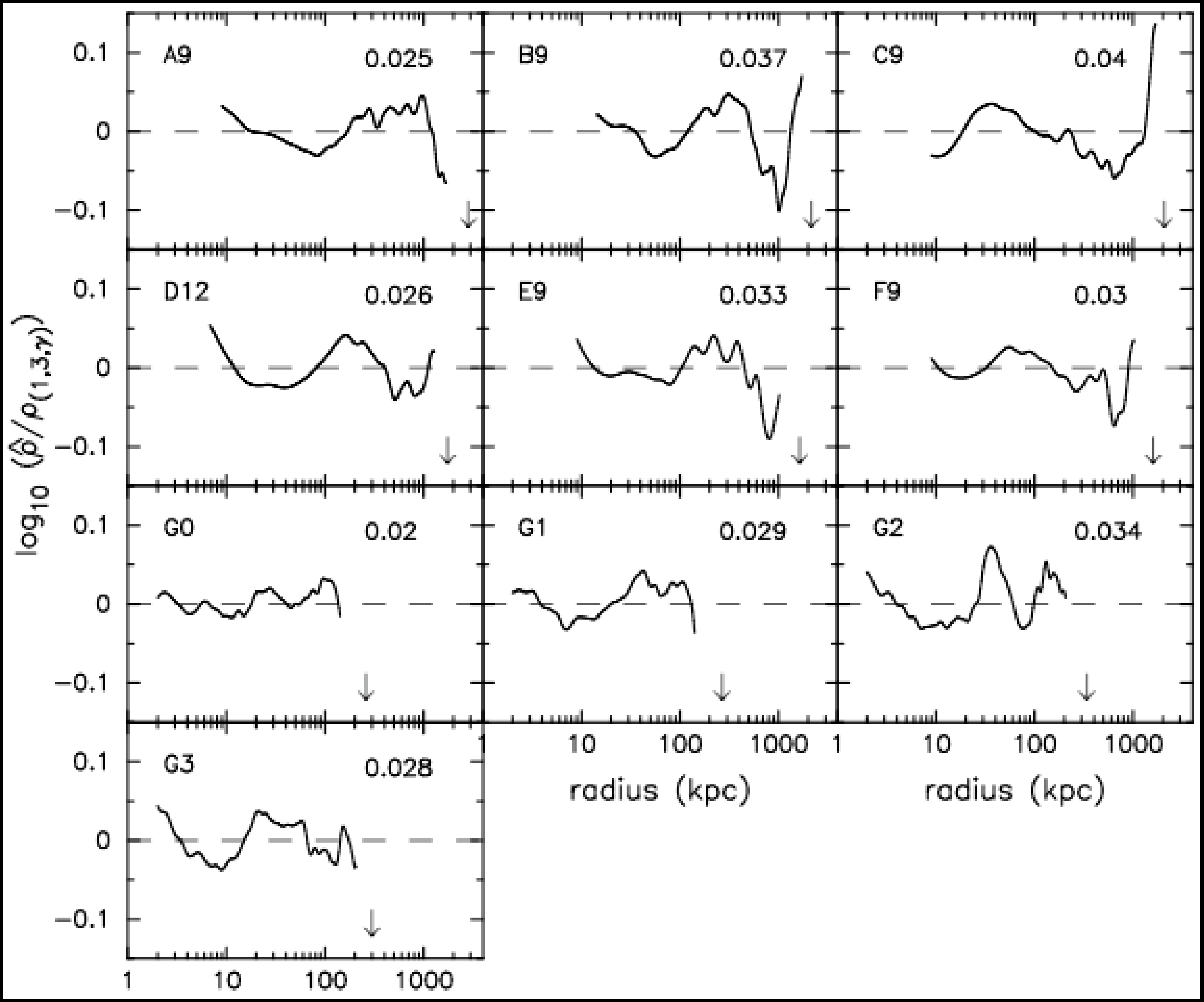
3 parameter functions (one additional ‘profile shape’ parameter): JD, Moore, Stadel, MNRAS, 2004



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

gamma-model

fitted to non-parametric density profiles



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

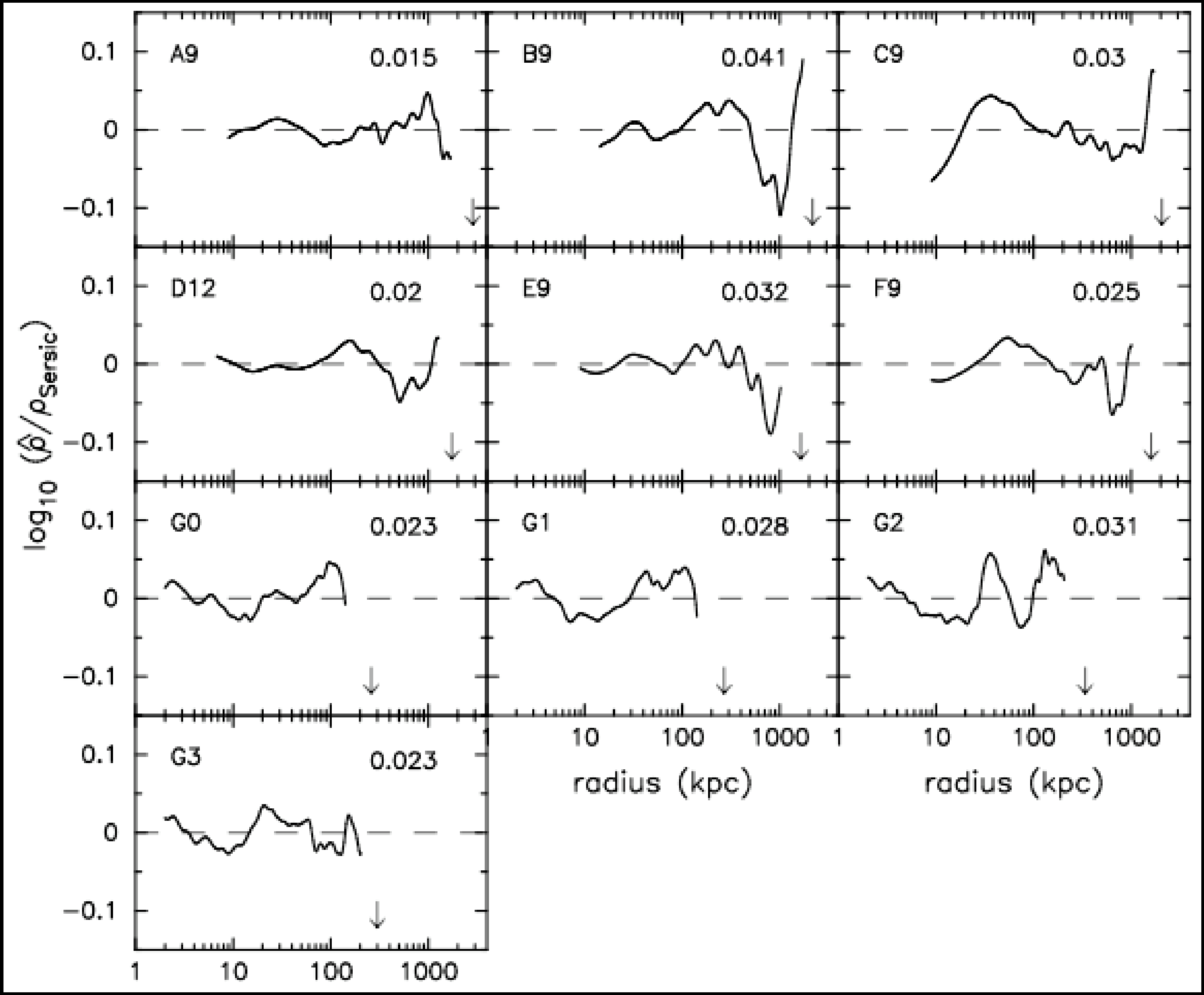
3 parameter functions (one additional ‘profile shape’ parameter):

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

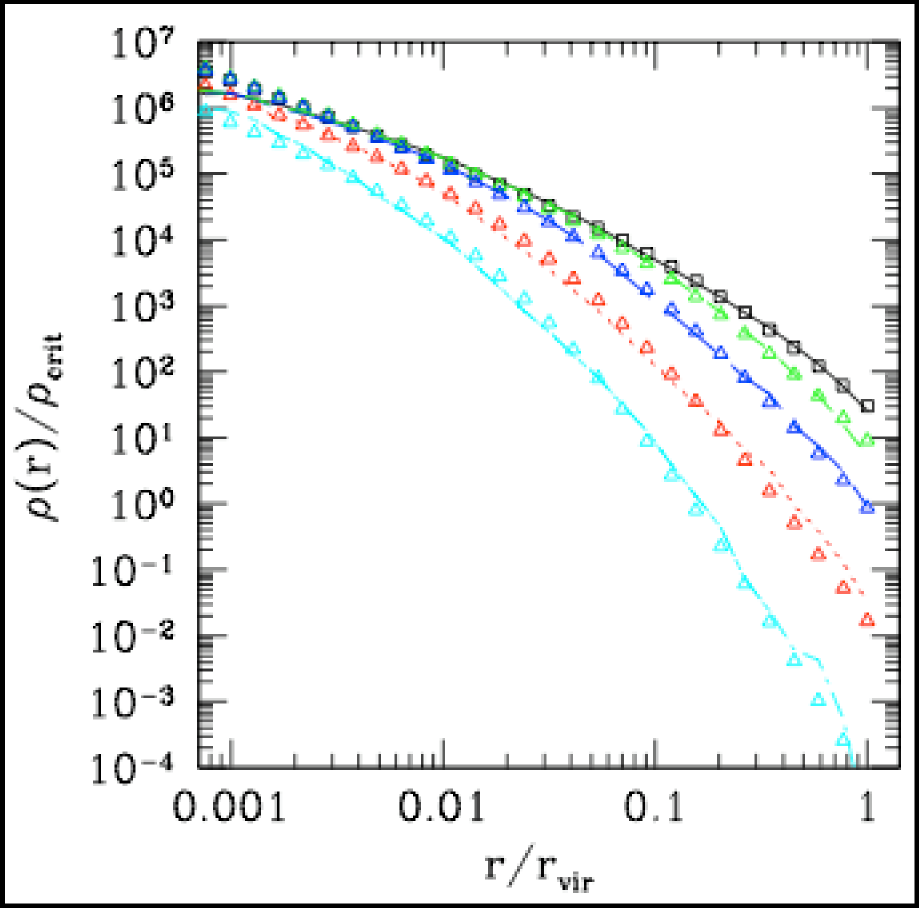
resolving the very inner profile

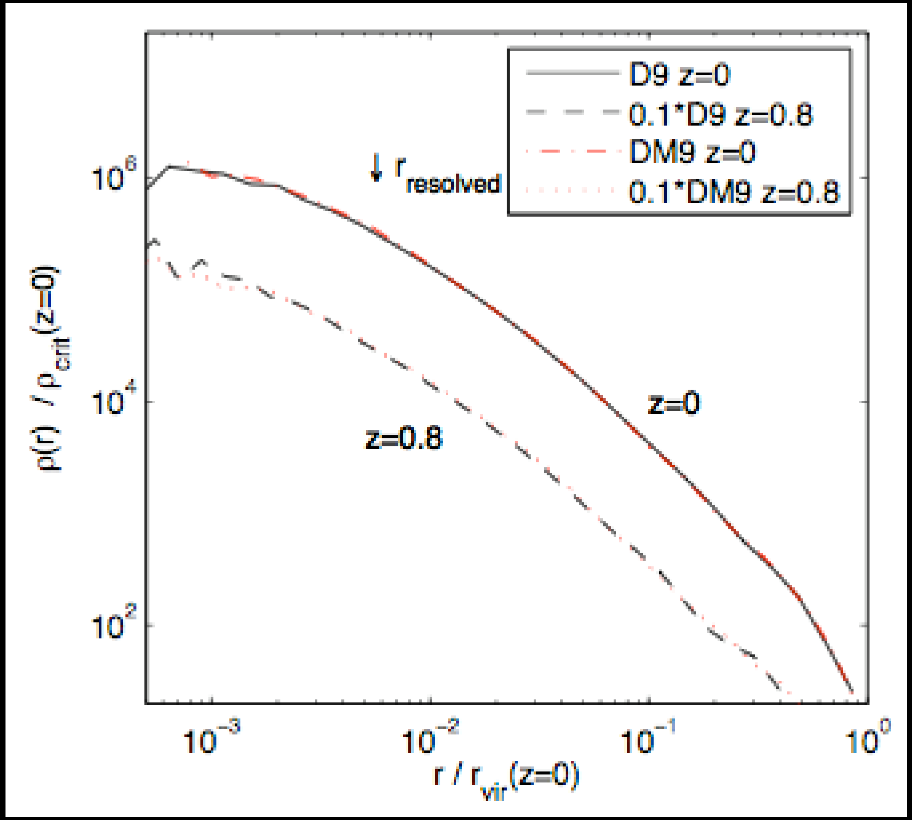
JD, Zemp, Moore, Stadel, Carollo, MNRAS, 2005, 364, 665

Multi-mass technique:

inner profile is dominated by material form rare > 2 sigma peaks (JD, Madau, Moore 2005)

sufficient to sample these regions at the highest mass resolution





same density profiles with both Nvir = 6 million and Nvir,effective=6 million

the later takes 10 times less CPU time

resolving the very inner profile

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

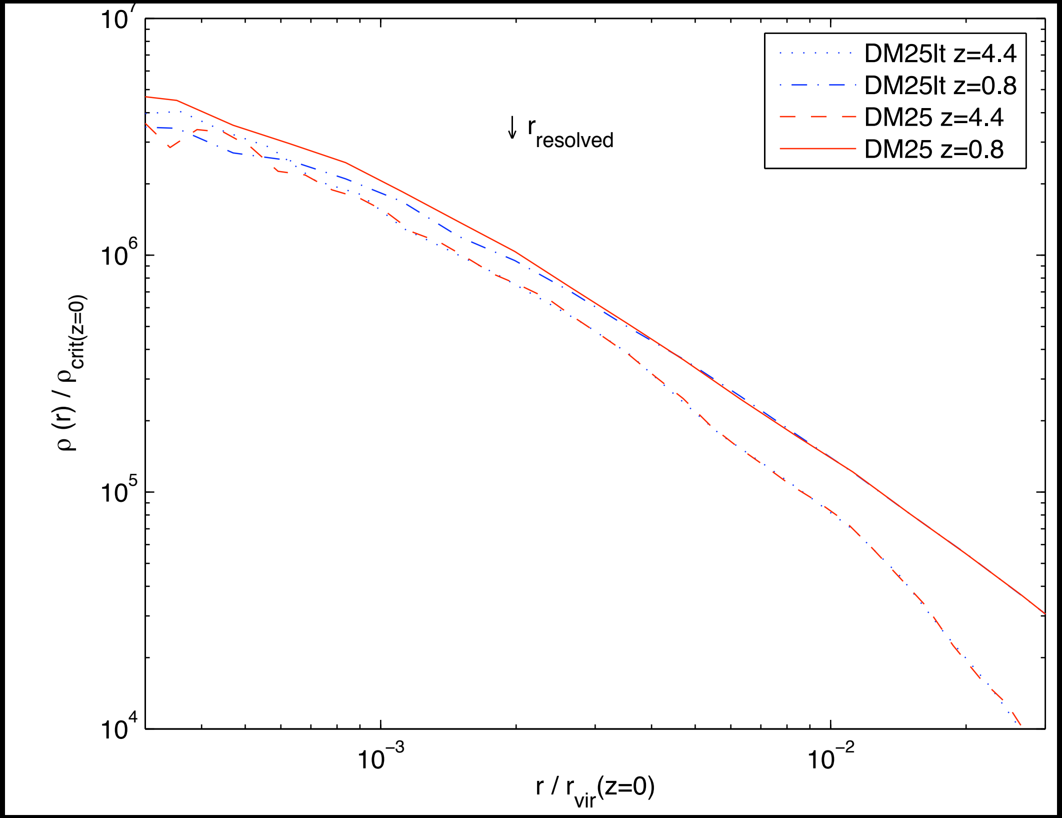
physical time-steps:

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.

resolving the very inner profile

Via Lactea run:
great for substructure, but
not for very inner profile:

resolved scale is set by the

$$\Delta t_i < \eta\sqrt{\epsilon/a_i}$$

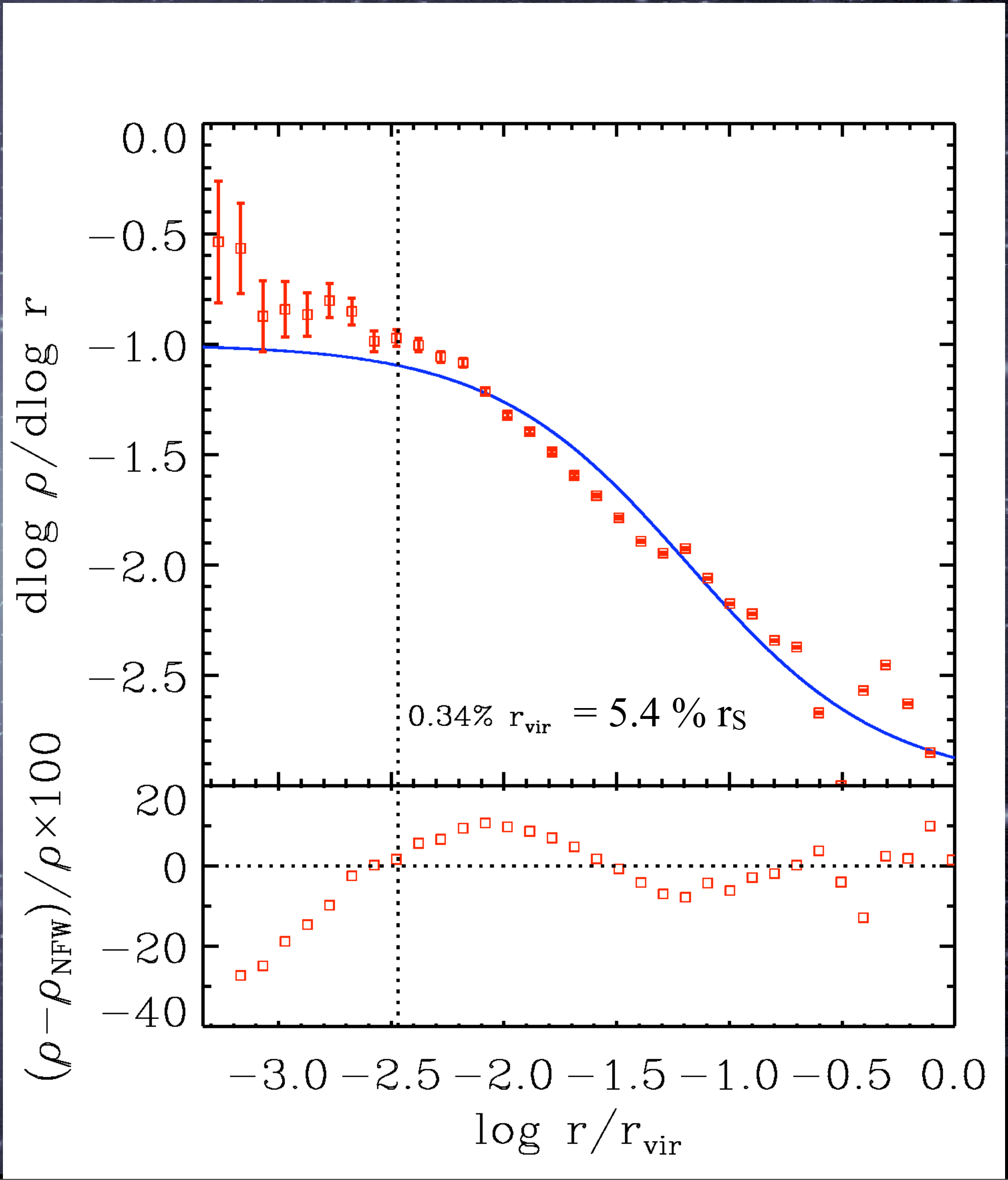
eta=0.2 time-step,
not by mass or force resolution

NFW fit with c=15.8 is passable

denser than NFW around 0.01 r_vir,
but shallower below 0.8% r_vir

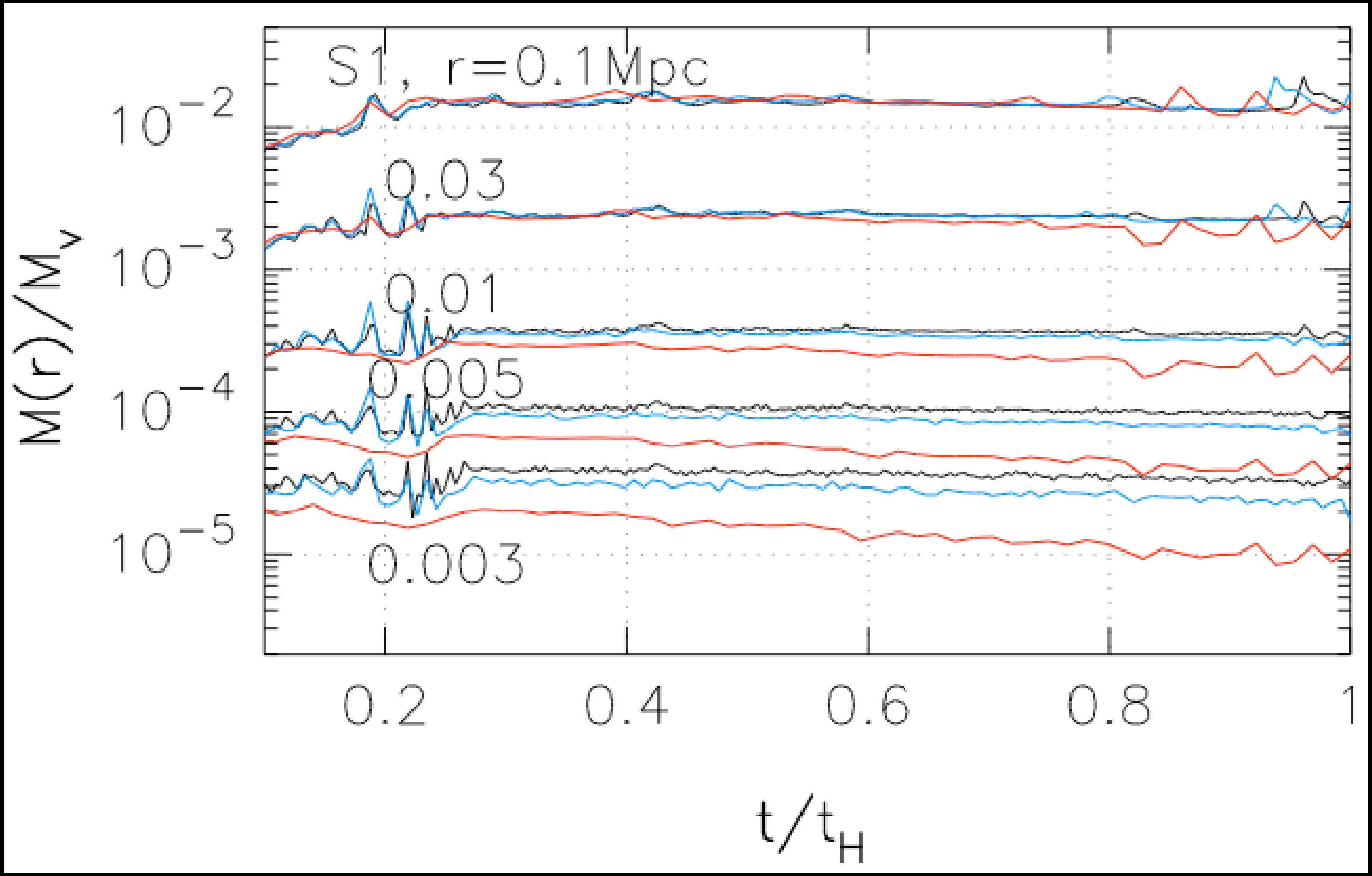
Caution:
r_converged = 0.34% r_vir
was estimated from cluster scale
convergence tests, requirements
for galaxy halos might differ

JD, Kuhlen, Madau, ApJ submitted



resolving the very inner profile

inner halo is assembled early:



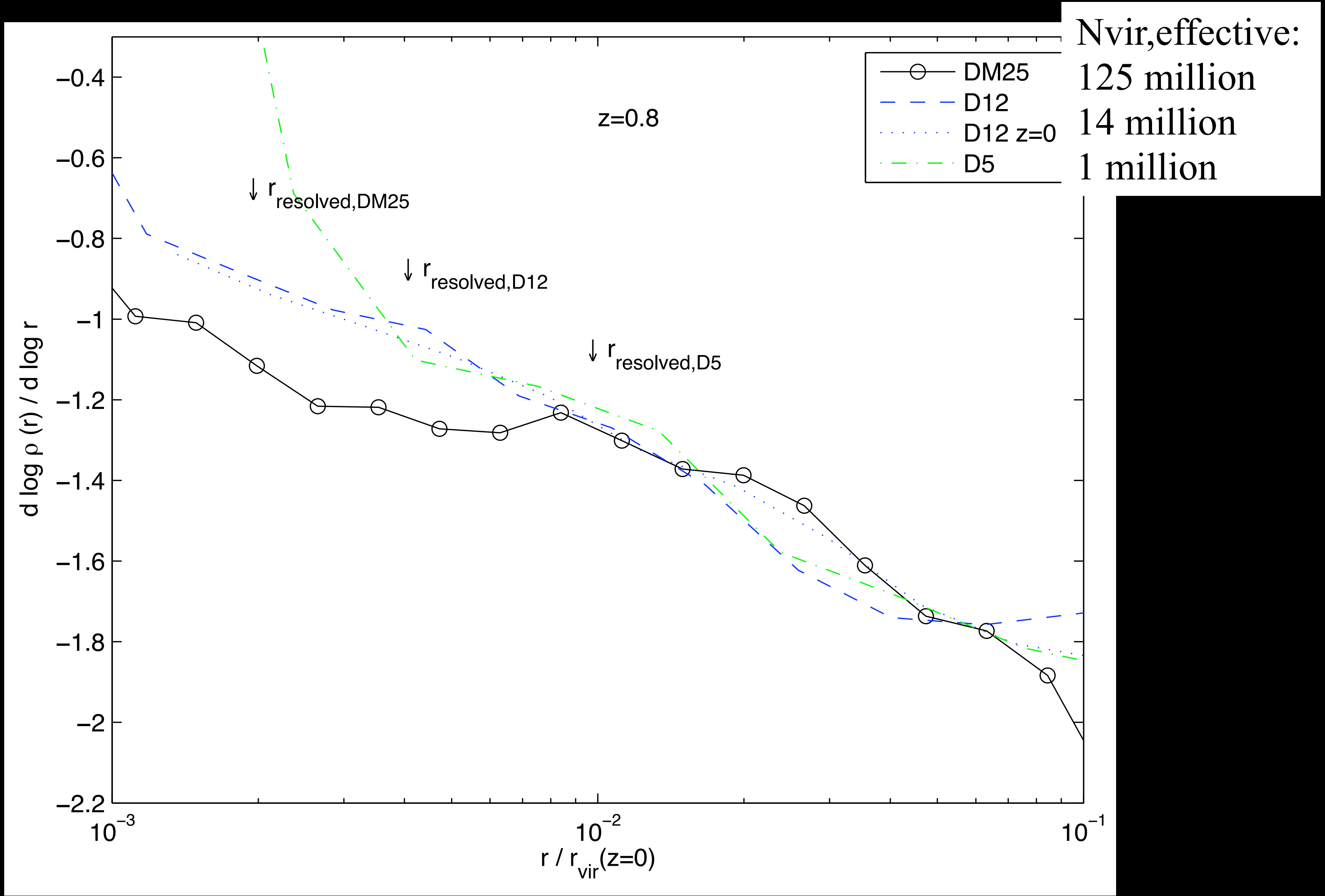
from Fukushige, Kawai, Makino, ApJ, 2004

resolving the very inner profile

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

steeper slopes with increasing mass resolution:

the “D” cluster had an inner slope near the mean of our 6 cluster sample



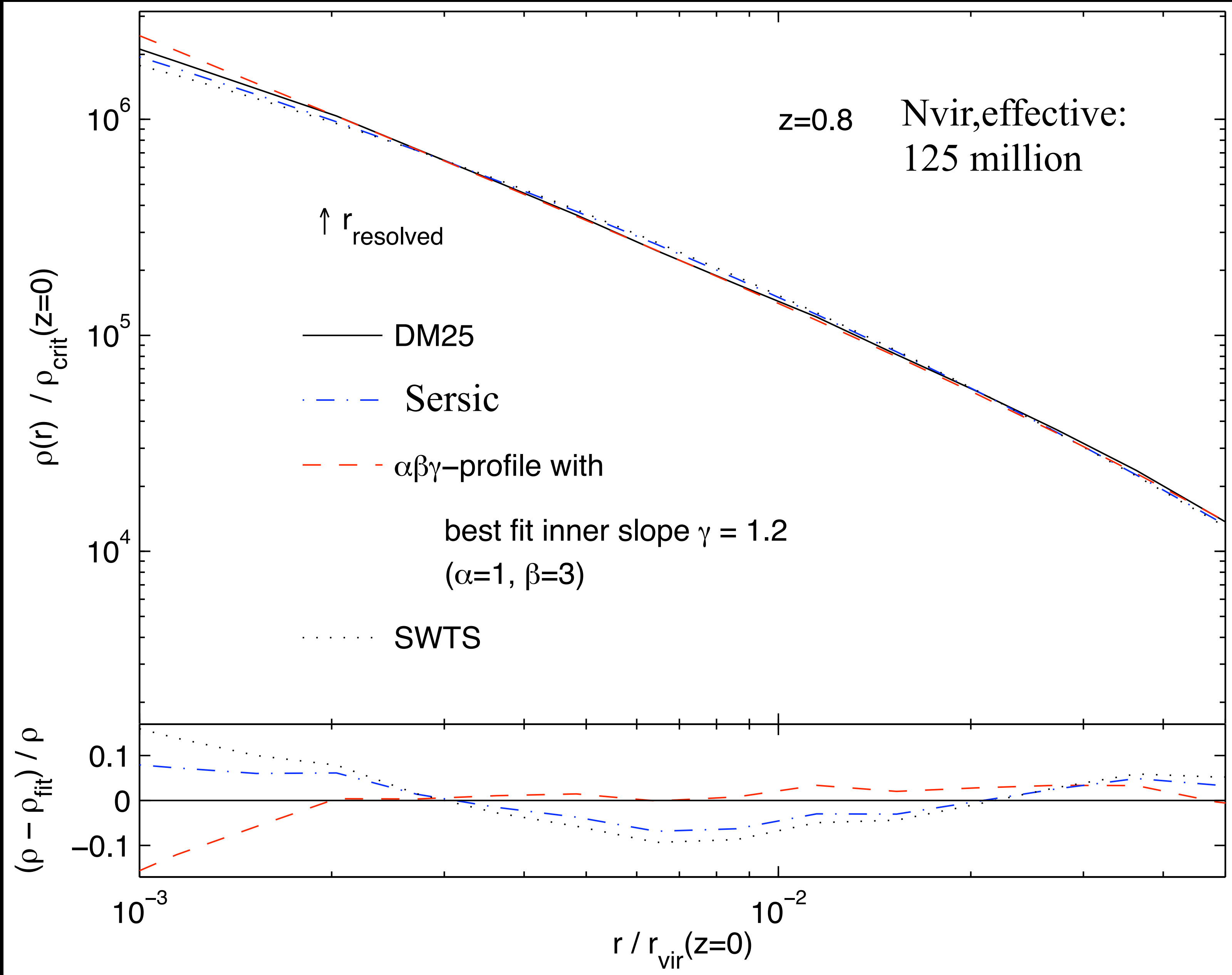
resolving the very inner profile

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

3 parameter fitting functions

Sersic fit tends to underestimate the very inner densities

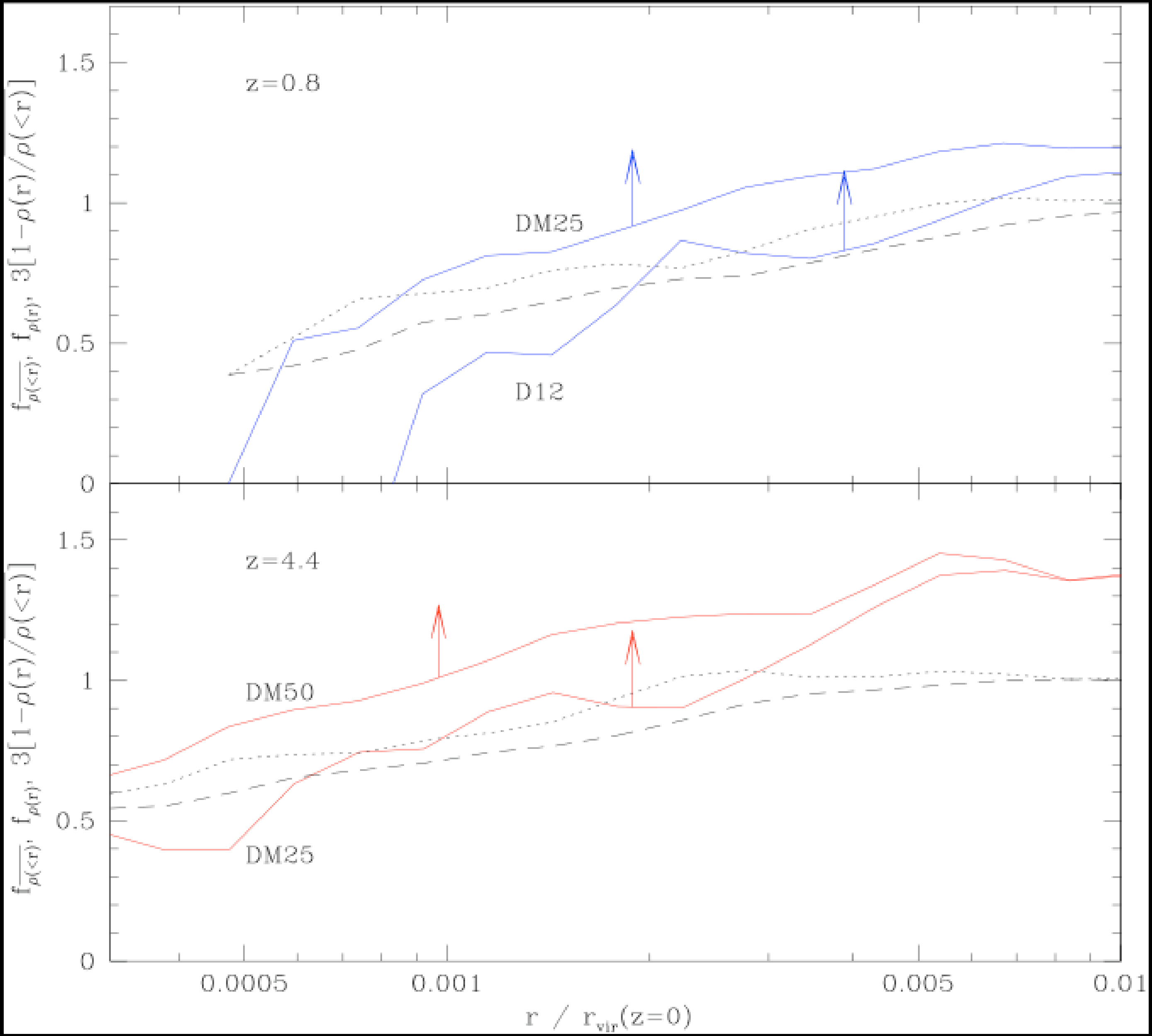
even within R_resolved, where the simulated densities are probably too low



resolving the very inner profile

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

using enclosed mass to estimate the maximum inner slope?



enclosed mass converges slower (further out) than the local density

estimate biased low

Conclusions

- 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 halos are denser than NFW at 0.01 Rvir, but not as dense as the Moore et al 1999 fits
- 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