dark matter distribution in the Milky Way halo

1) observational evidence
2) substructure
3) density profiles

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TAUP 2007, Sendai

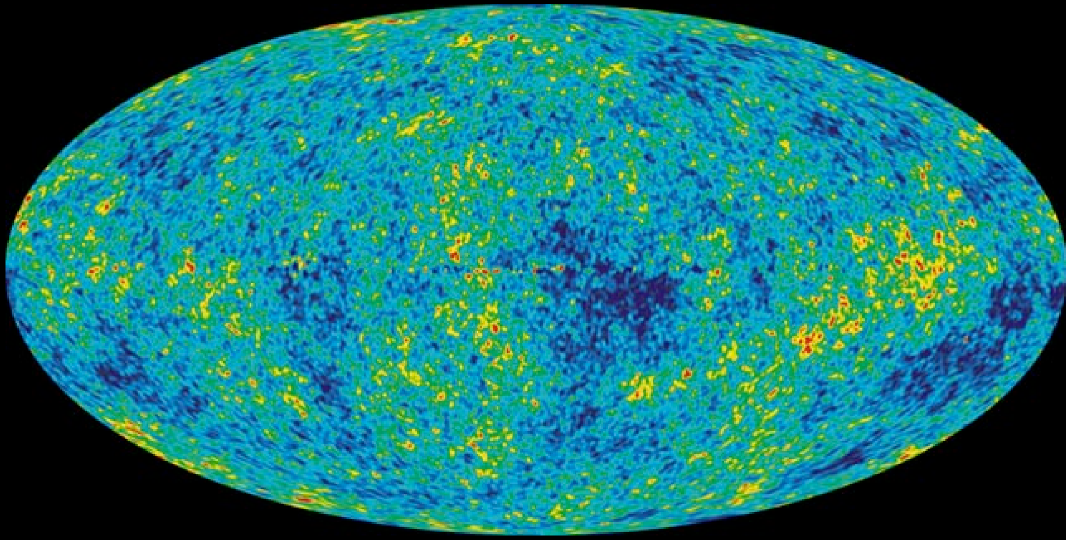
What is dark matter ?

Evidence for DM on a wide range of scales:
- Galaxy cluster dynamics (Zwicky, 1933)
- Galaxy rotation curves
- X-rays from galaxy groups and clusters
- Kinematics of stellar halos,
  satellite galaxy 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%)



Credit: NASA/WMAP

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

→ 83% of the clustering matter is
non-baryonic, quite “cold”, dark matter

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

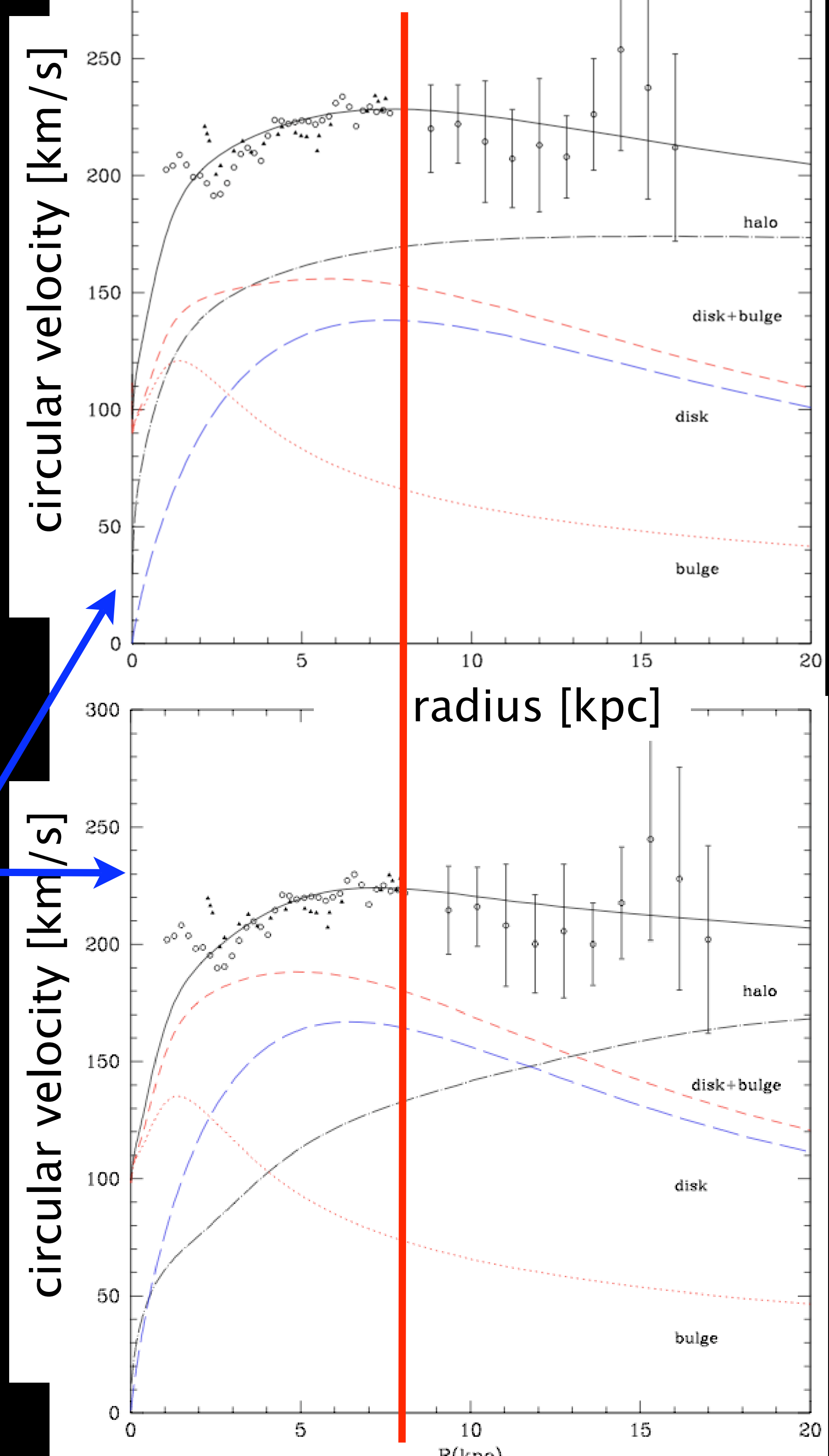
evidence for DM in the Milky Way

using rotation curve, satellites, local vertical force, Klypin et al 2001 find:

Virial mass $M_{\rm vir}$ $(\mathrm{M}_\odot) = 1.0 \times 10^{12}$
preferred range: 0.7 – 2.0

Concentration = 12
preferred range: 10 – 17

no exchange of angular momentum
with exchange



significant amounts of DM inside 8 kpc

35 to 60 percent of total enclosed mass

evidence for DM in the Milky Way

same two models from Klypin et al 2001

➡ significant amounts of DM at 8 kpc

about 0.007 to 0.012 Msun/pc^3

standard halo:
0.3 GeV/cm^3 = 0.008 Msun/pc^3

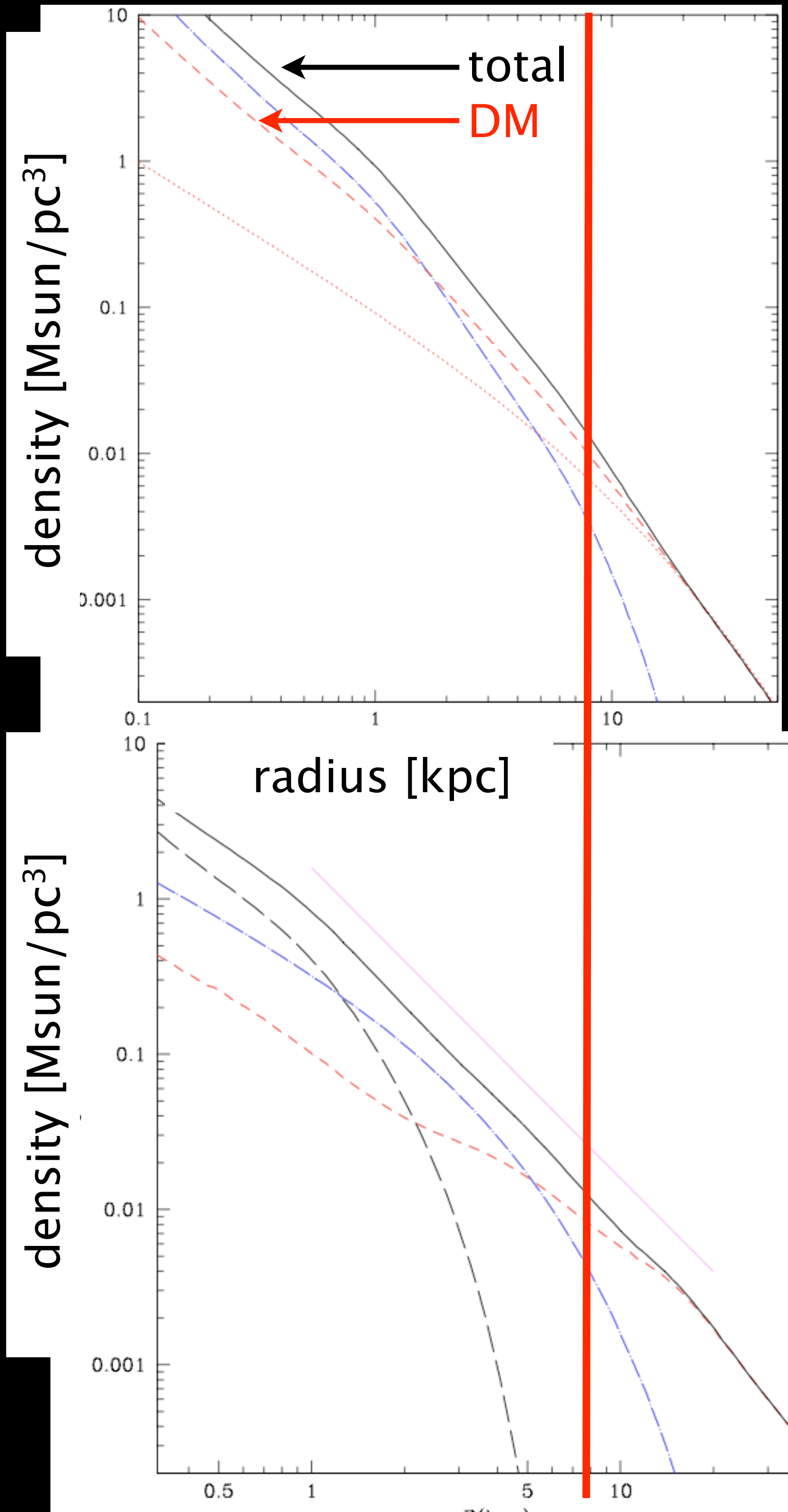
local surface density (Kuijken&Gilmore1989/91):

$$\Sigma_{\mathrm{stars+gas}} = 48 \pm 8\,\mathrm{M_\odot pc^{-2}}$$

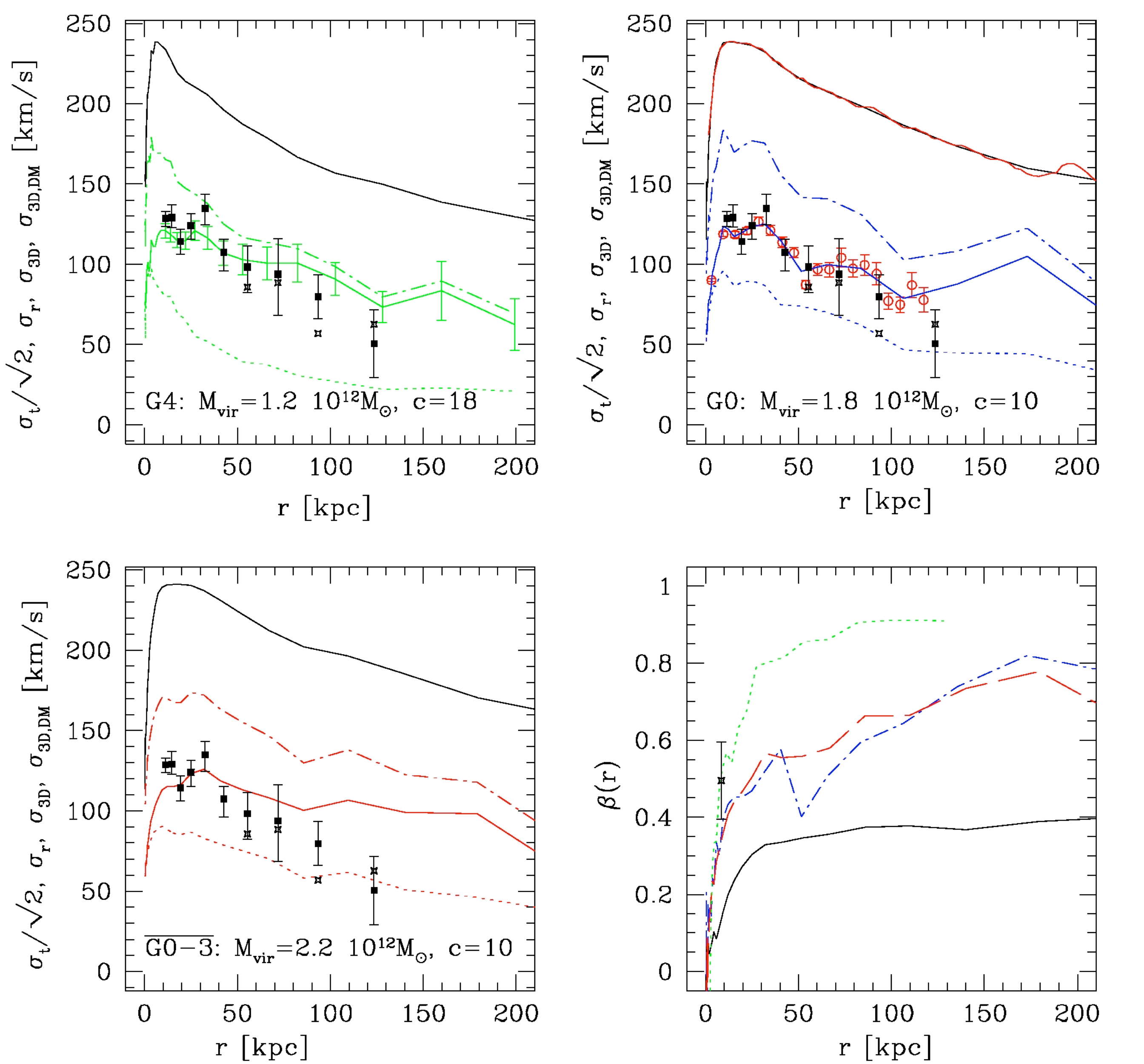
total (inside 1.1 kpc) = 71+-6 Msun/pc^2

also gives a mean local DM density of about 0.01 Msun/pc^3

(but, how smooth is DM locally ???)



DM around the Milky Way: stellar halo radial velocities



from JD,Madau,Moore 2005

cosmological stellar halo models fit the observed kinematics from G. Battaglia et al 2005

The outer halo is
not well constrained yet:
low Mvir / high c
high Mvir / low c
both possible

$$\beta = 1 - 0.5\sigma_t^2/\sigma_r^2$$

depends on tracer
profile slope as in
Hansen&Moore 2004
local stellar halo: beta ~ 0.5
local DM: beta ~ 0.12 (via lactea)

great observational advances
expected:
RAVE, SDSS SEGUE, GAIA,
SIM(?), ...

CDM around the Milky Way: stellar halo radial velocities

local escape velocity v_{esc}

using the RAVE survey and archival data from Beers et al 2000 M. C. Smith et al 2007 find:

$$498\,\mathrm{km\,s^{-1}} < v_{esc} < 608\,\mathrm{km\,s^{-1}}$$

at 90 % confidence

$v_{esc} >> 1.41 \times 220$ km/s

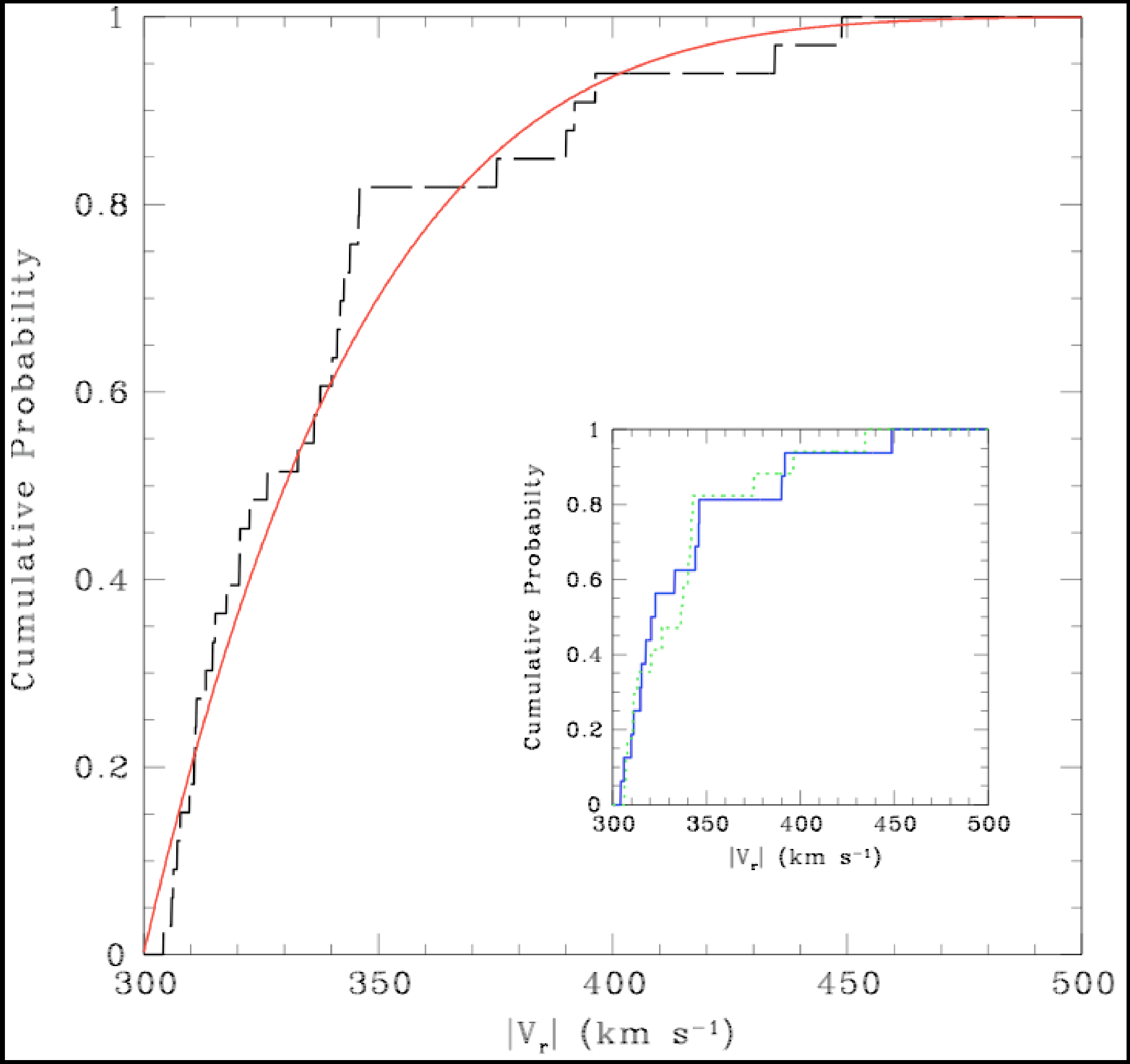
→ there must be a massive halo around the Milky Way!

comparison with model stellar halos gives virial masses of:

$$1.42^{+1.14}_{-0.54} \times 10^{12} M_\odot$$

at 90 % confidence

if stellar v_{esc} < dynamical v_{esc} these masses would be only lower limits



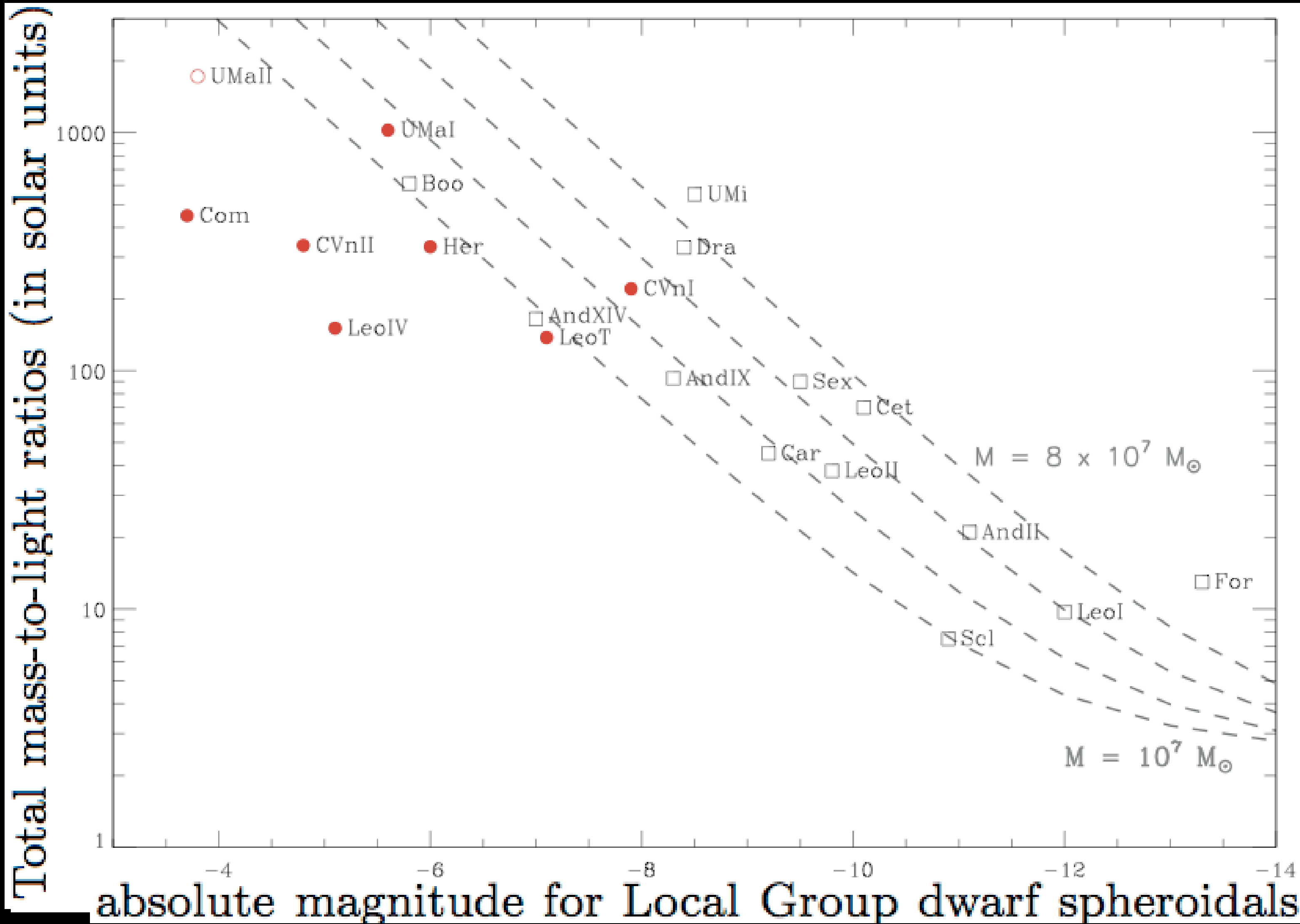
evidence for DM substructure in the Milky Way

survival of faint, old Local Group dSphs in the tidal field of the Milky Way

their kinematics confirm that they are dominated by dark matter (Simon&Geha 2007)

higher mass-to-light-ratios for fainter systems

might go to infinity on smaller scales ...



from Simon & Geha 2007

2) 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

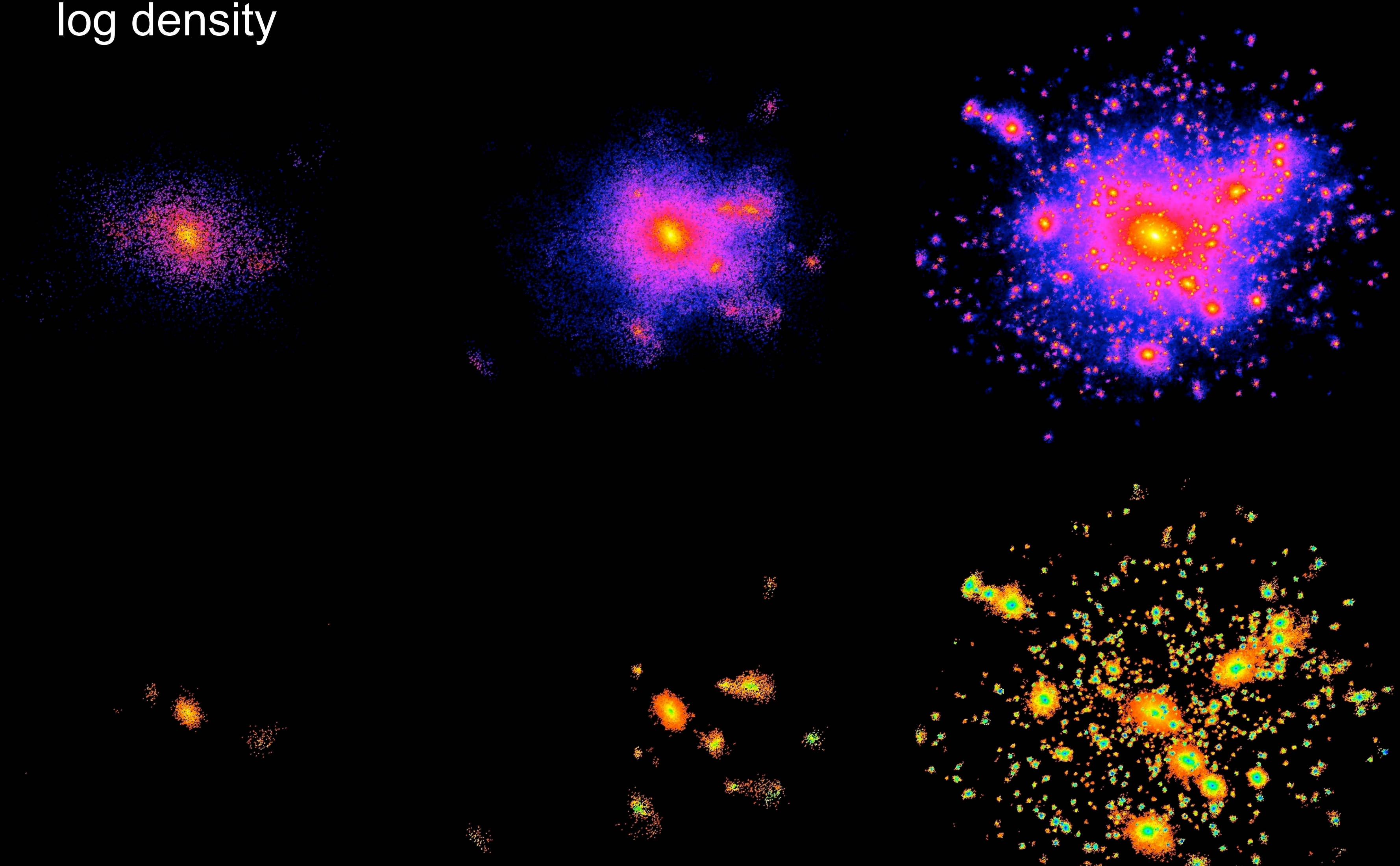
- computationally expensive, resolution relatively low
- hydro is not trivial (SPH and grid disagree even in simple tests, Agertz et al 2007)
- important physical processes far below the resolved scales (star formation,SN, ... ?) implemented through uncertain functions and free parameters

→ 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

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.

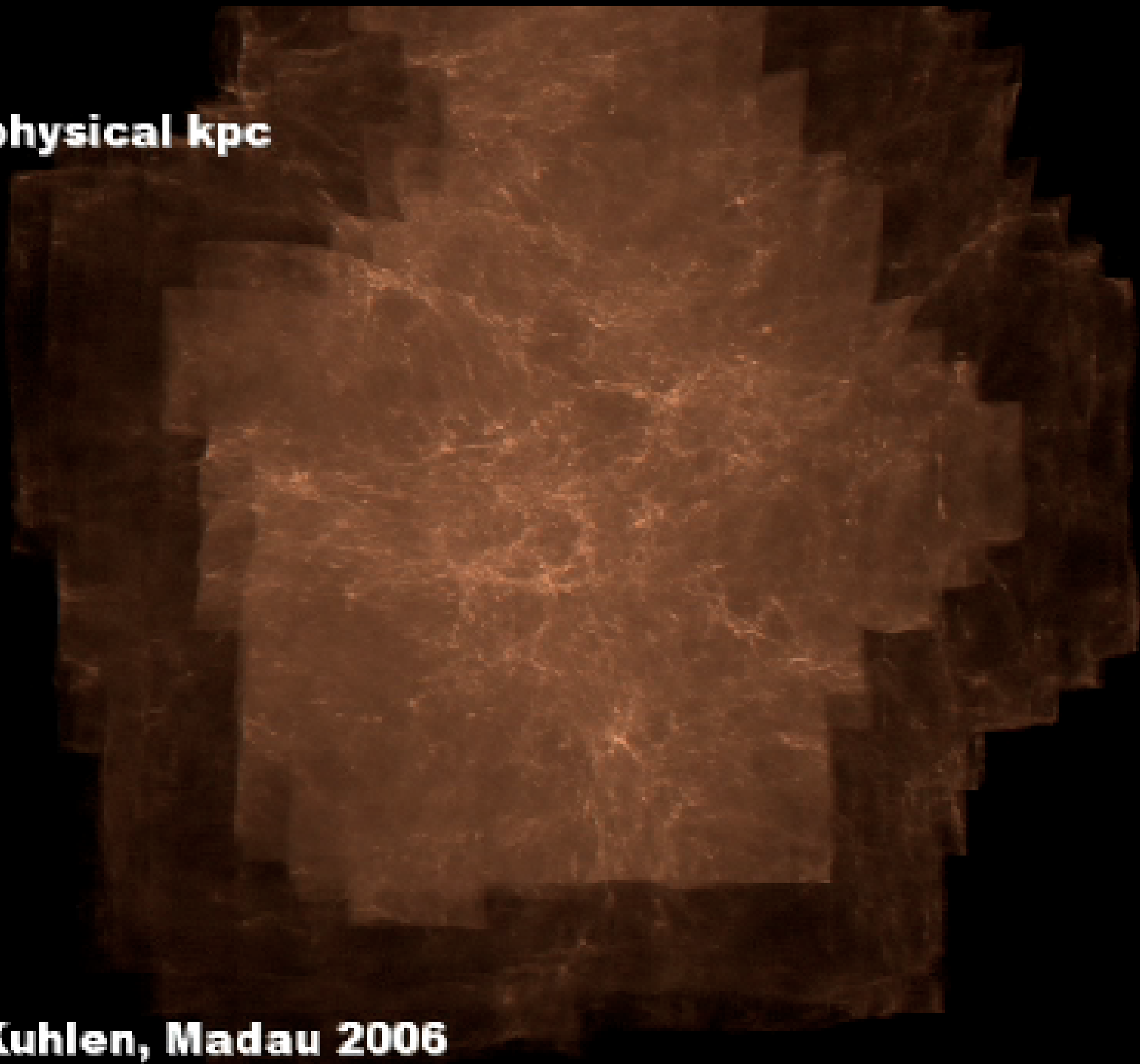
- force resolution: 90 parsec

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

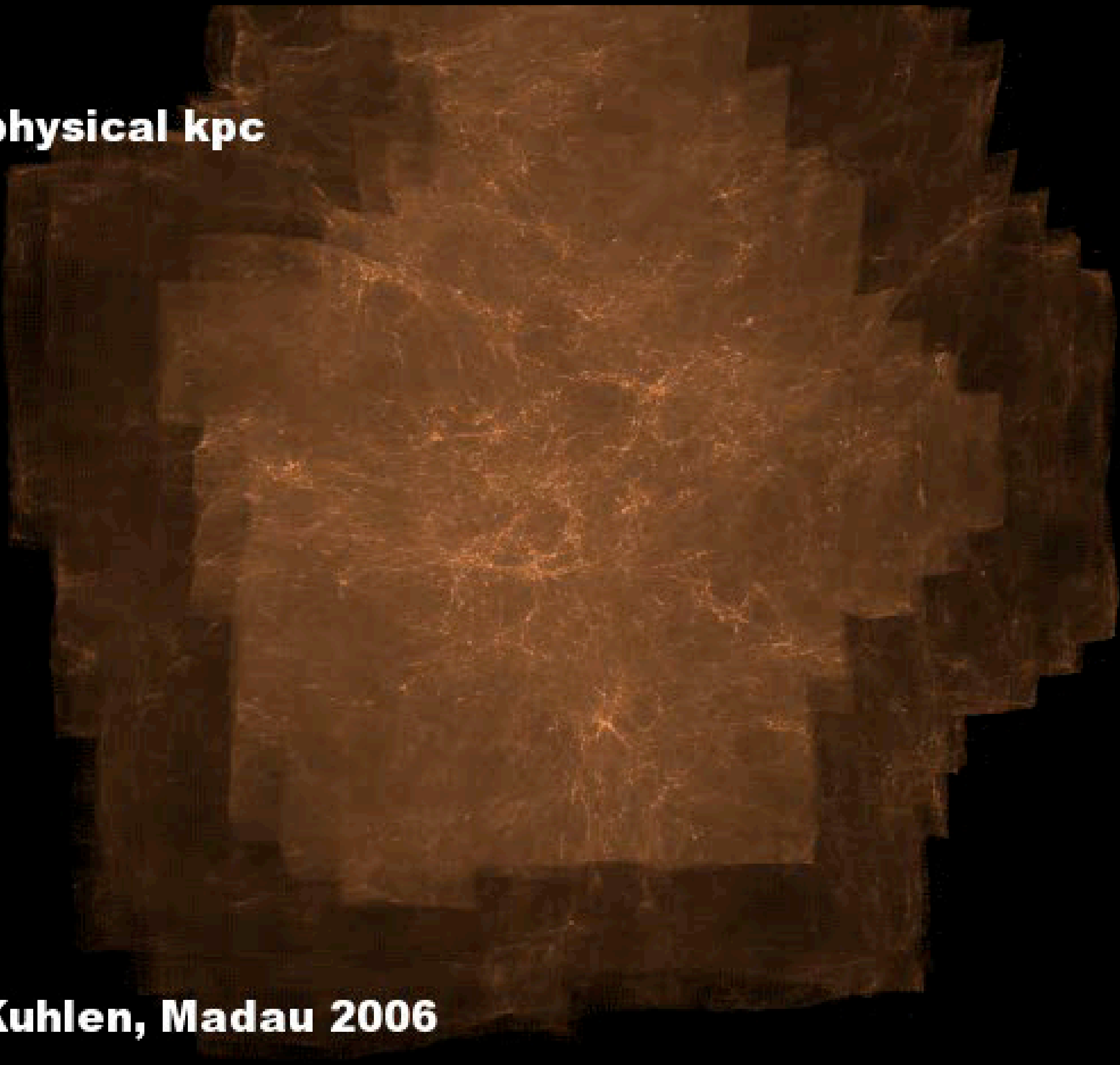
- mass resolution: 20,900 $M_\odot$

z=11.9

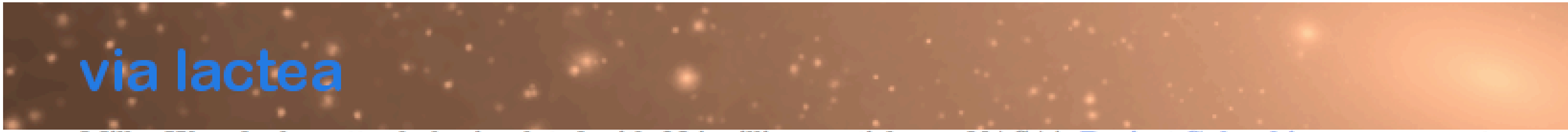
800 x 600 physical kpc



Diemand, Kuhlen, Madau 2006


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

www.ucolick.org/~diemand/vl



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

main

movies

images

publications

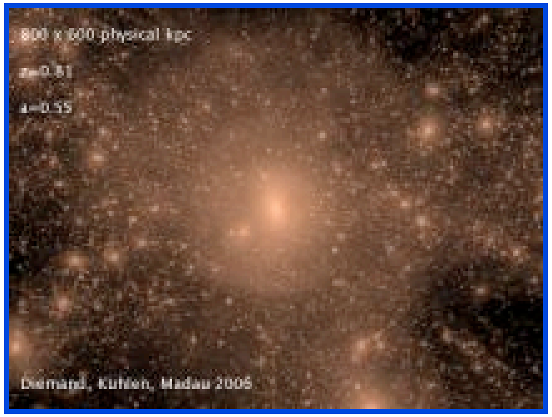
data

screensavers

movies

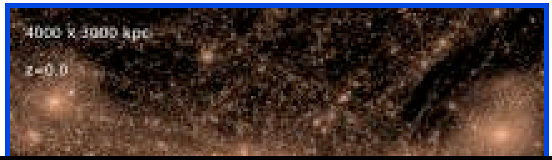
These animations show the projected dark matter density-square maps of the simulated Milky Way-size halo Via Lactea. The logarithmic color scale covers the same 20 decades in projected density-square in physical units in each frame. All movies are encoded in MPEG format and some are available in different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

the formation of the via lactea halo



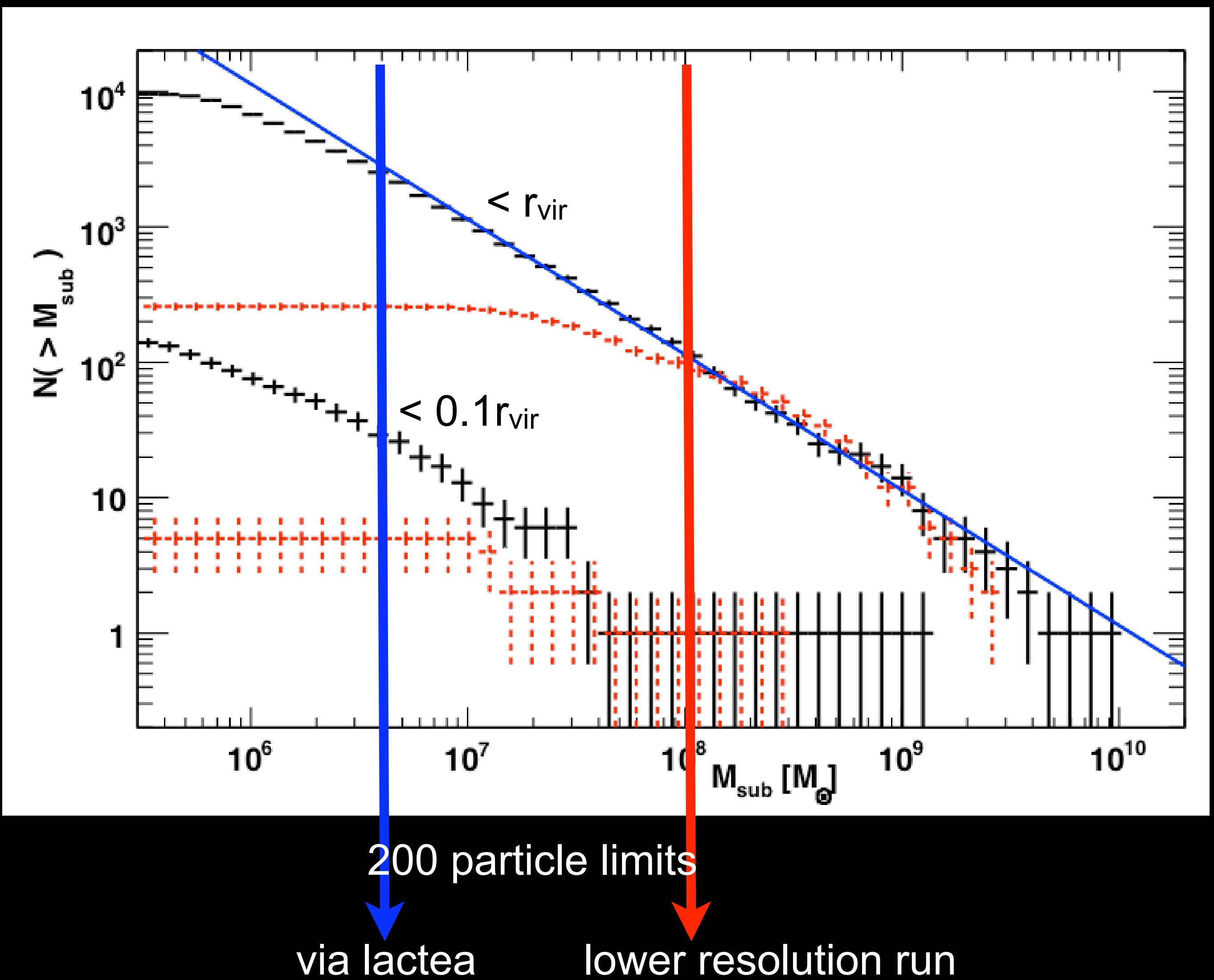
- entire formation history (z=12 to 0): high quality (218 MB)
  smaller frames, quality: high(55 MB) medium(11 MB) low(4.7 MB)
- entire formation history, plus rotation and zoom at z=0:
  quality: high(433 MB) medium(72 MB)
- early, active phase of merging and mass assembly (z=12 to 1.3): (81 MB)
- late,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

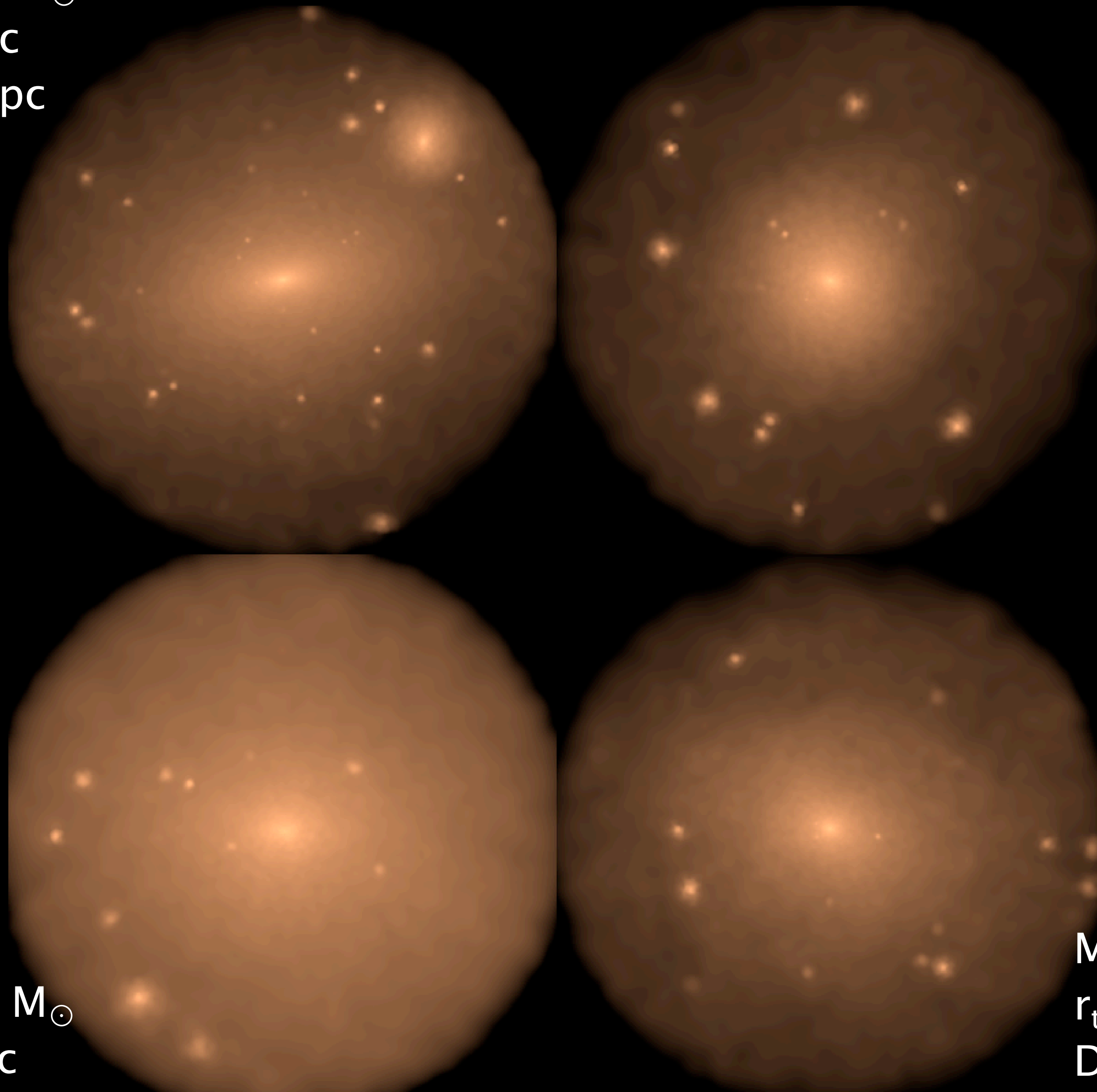
shallower at low M due to numerical limitations

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

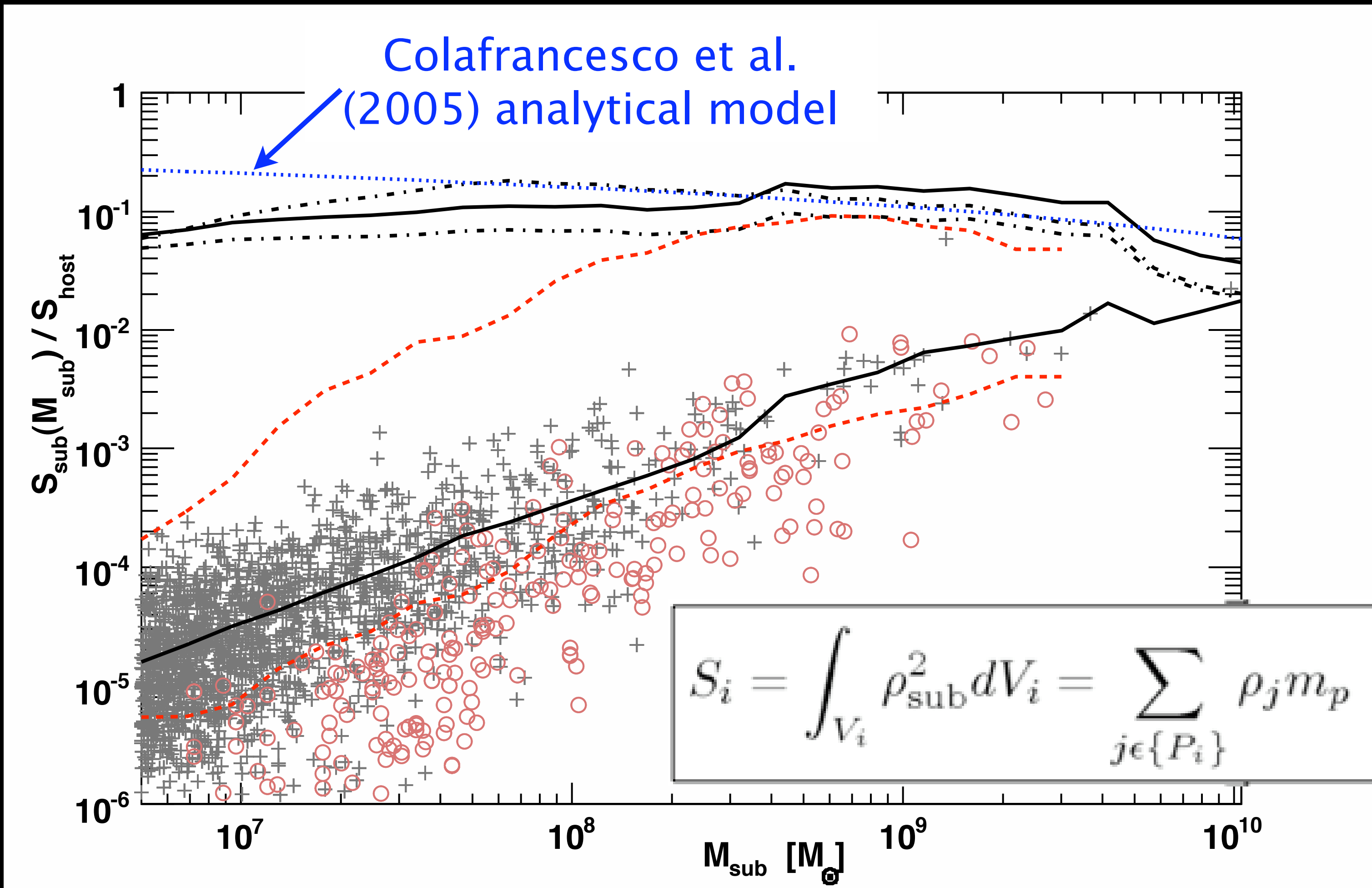


M_{sub}=2.4 10^9 $M_\odot$
r_{tidal}=14.7 kpc
D_{center}=185 kpc

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



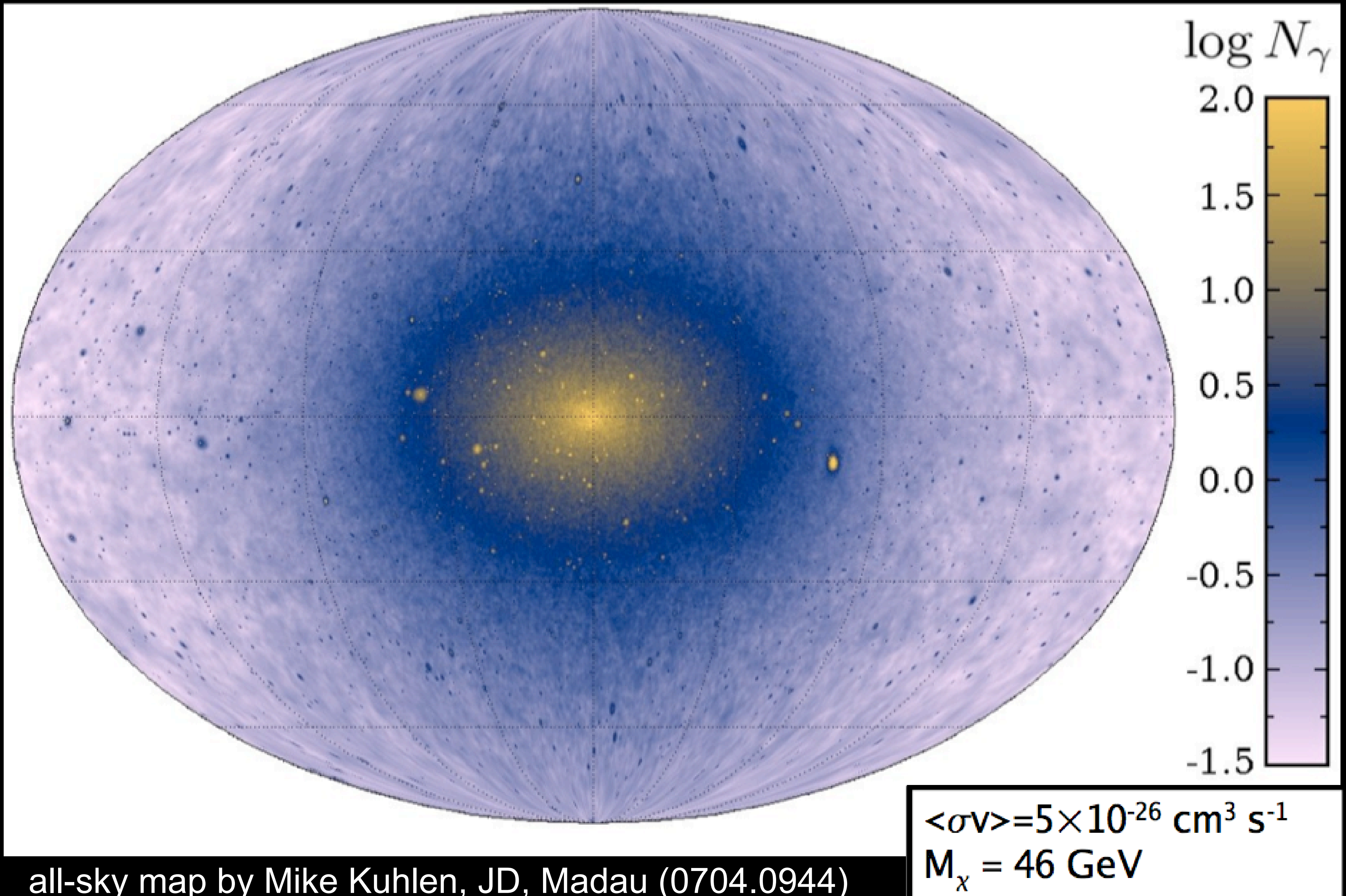
Total signal from subhalos is constant per decade in subhalo mass

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)

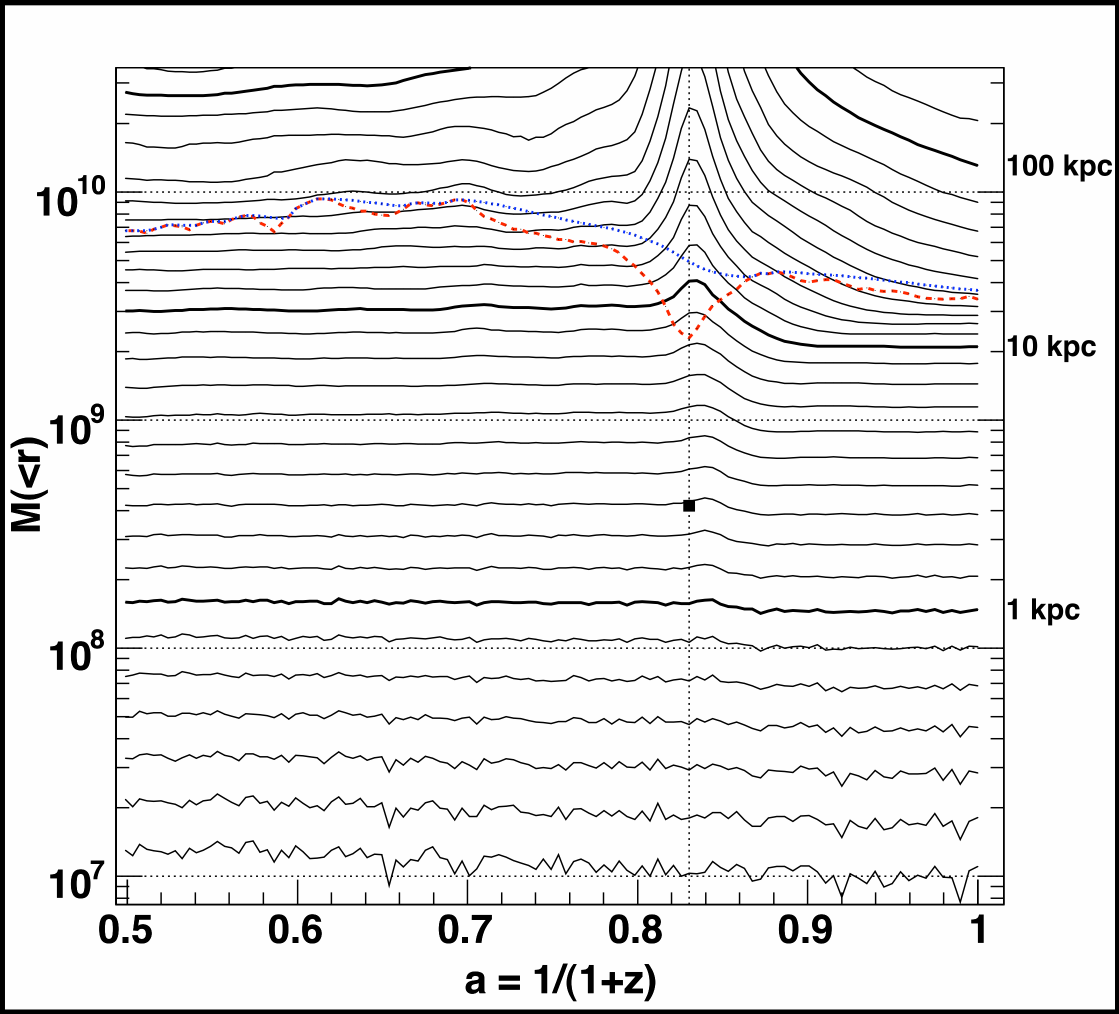
total boost factor including sub-sub-....-halos:
between 13 (constant) and about 80

(optimistic) photon counts for GLAST (2yr exp.)



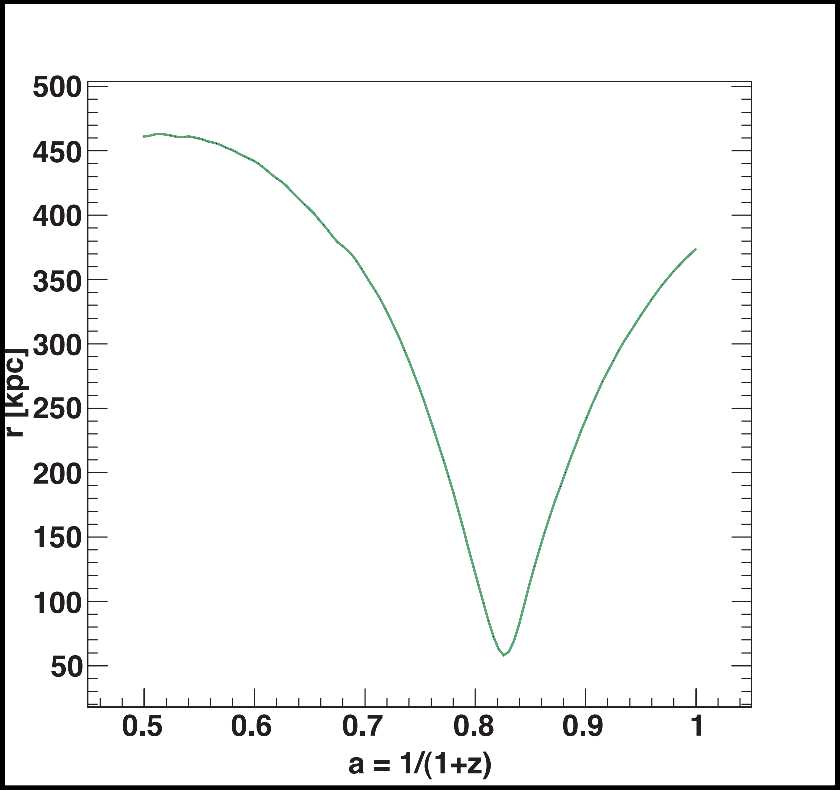
all-sky map by Mike Kuhlen, JD, Madau (0704.0944)
assuming sub-substructure boosts subhalo luminosities by a factor of 10
NOTE: We do not resolve all relevant subhalos yet !
boost of the unresolved component not included (see Pieri et al 2007)

evolution of subhalo density profiles



total mass in spheres around subhalo center

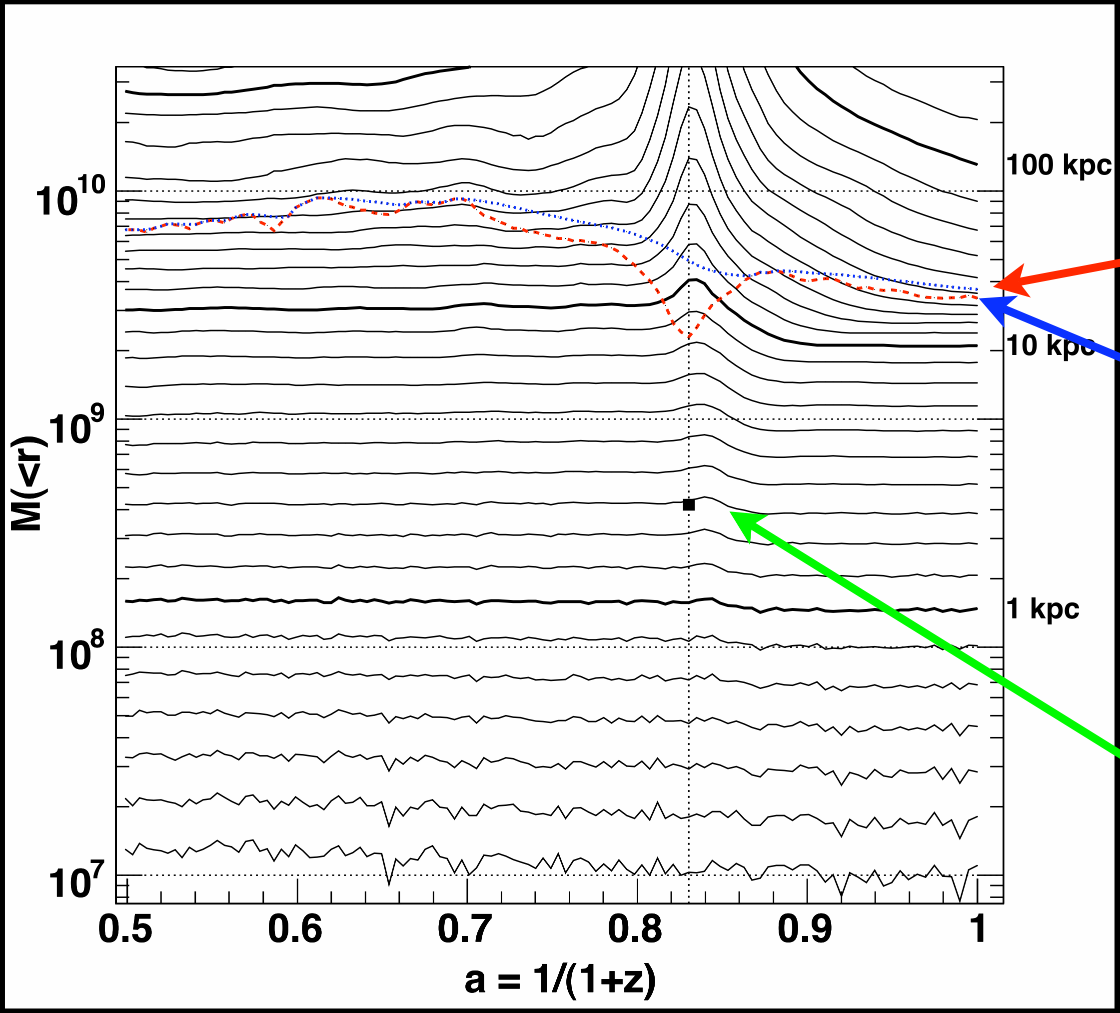
this subhalo has one pericenter passage at 56 kpc



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

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

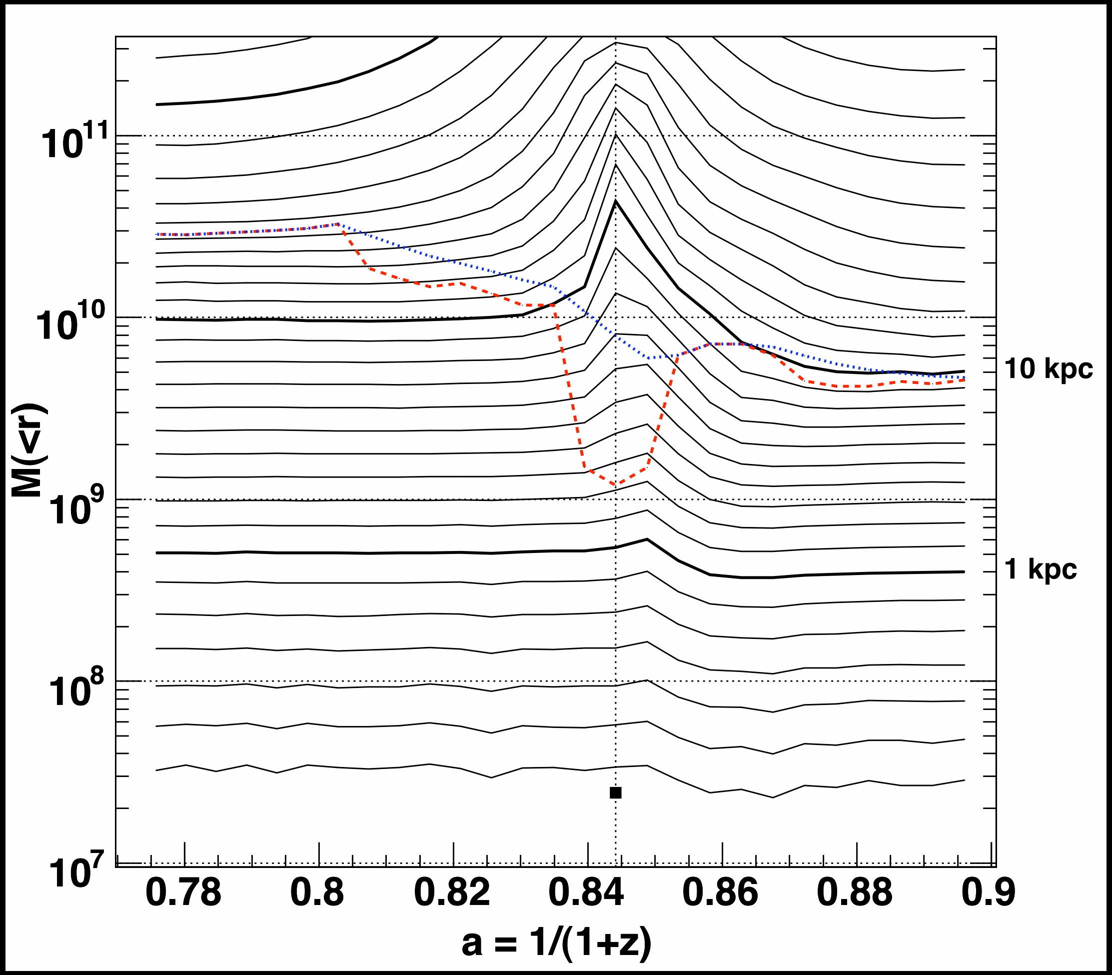
with $T_s = T_{\mathrm{orbit}}/6$

shock duration = internal subhalo orbital time

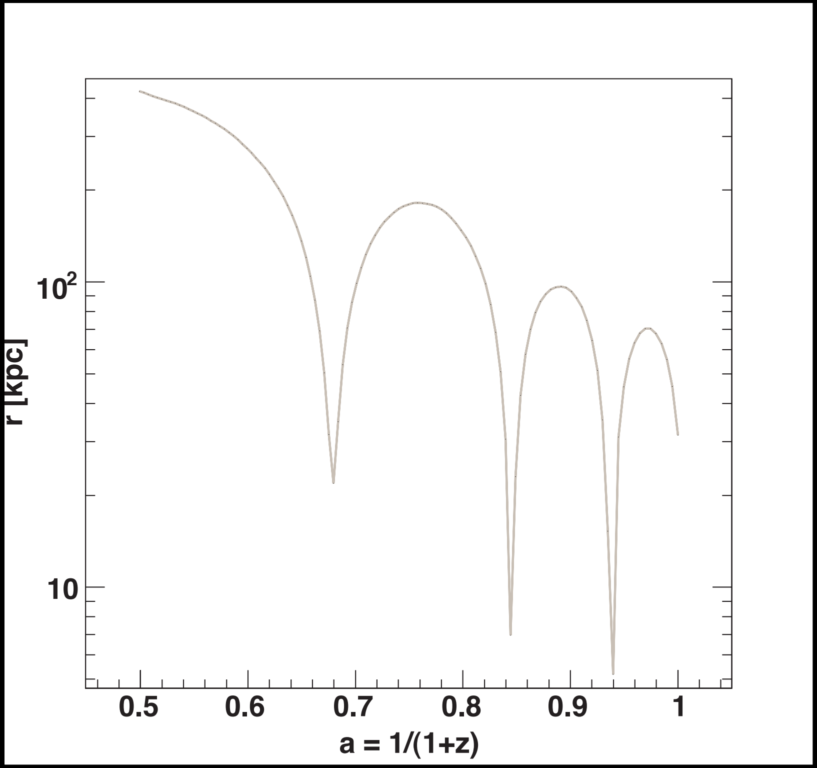
weak, long tidal shock
causes quick compression followed by expansion

mass loss is larger further out

evolution of subhalo density profiles



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

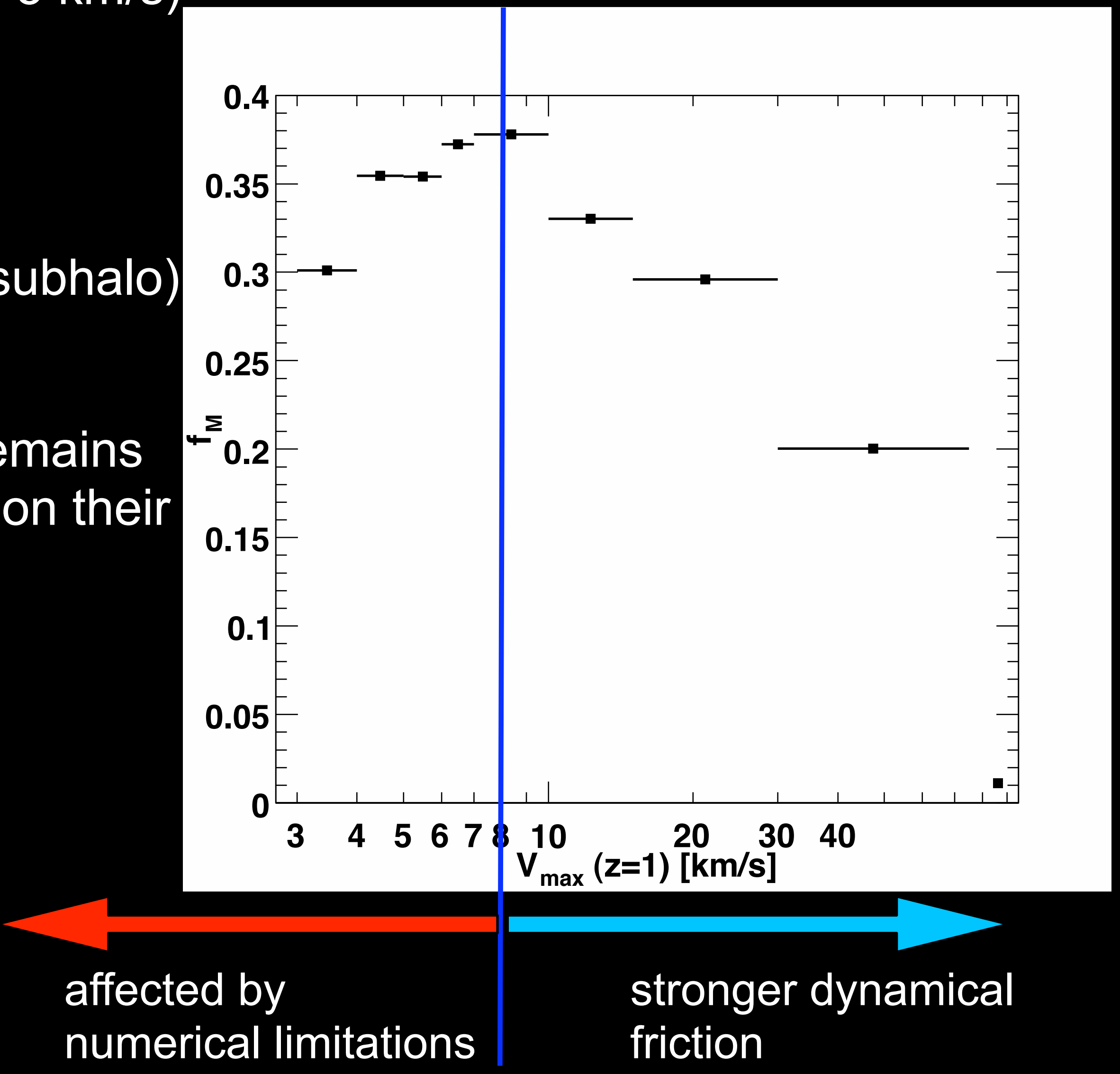
subhalo survival and merging

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

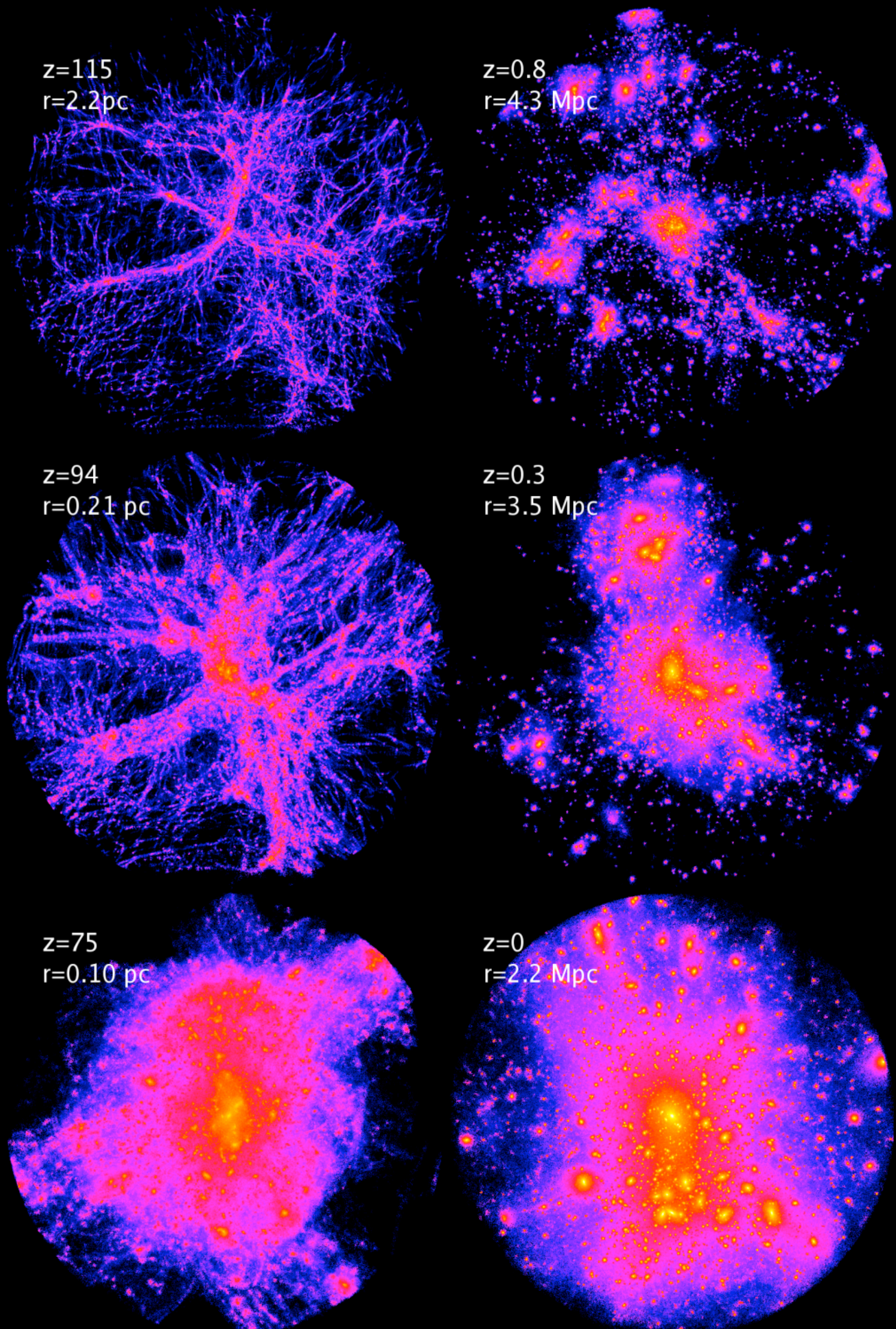


high redshift micro-subhalos are only slightly more fragile despite their flat sigma(M)

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

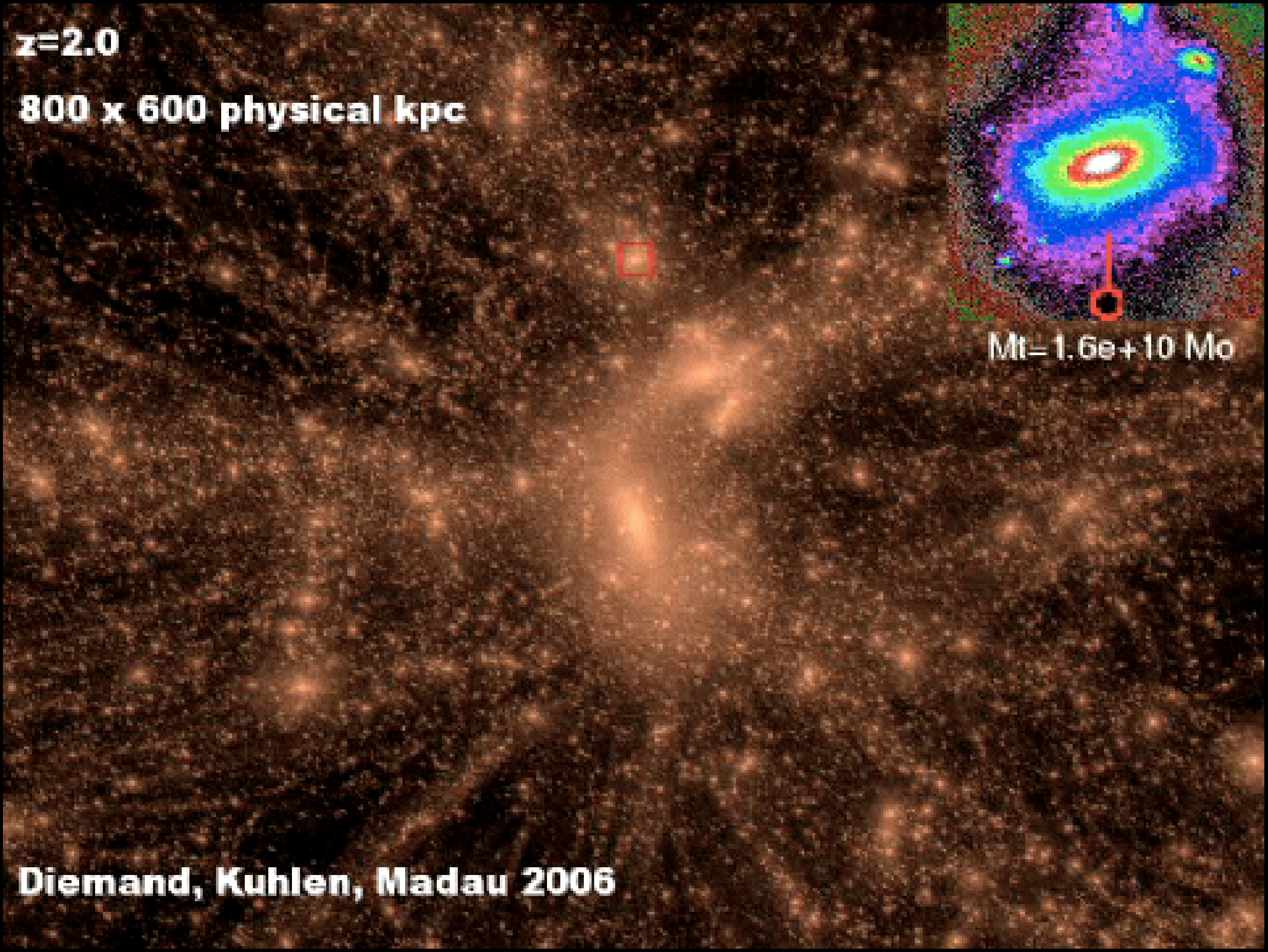
JD,Kuhlen,Madau
astro-ph/0603250



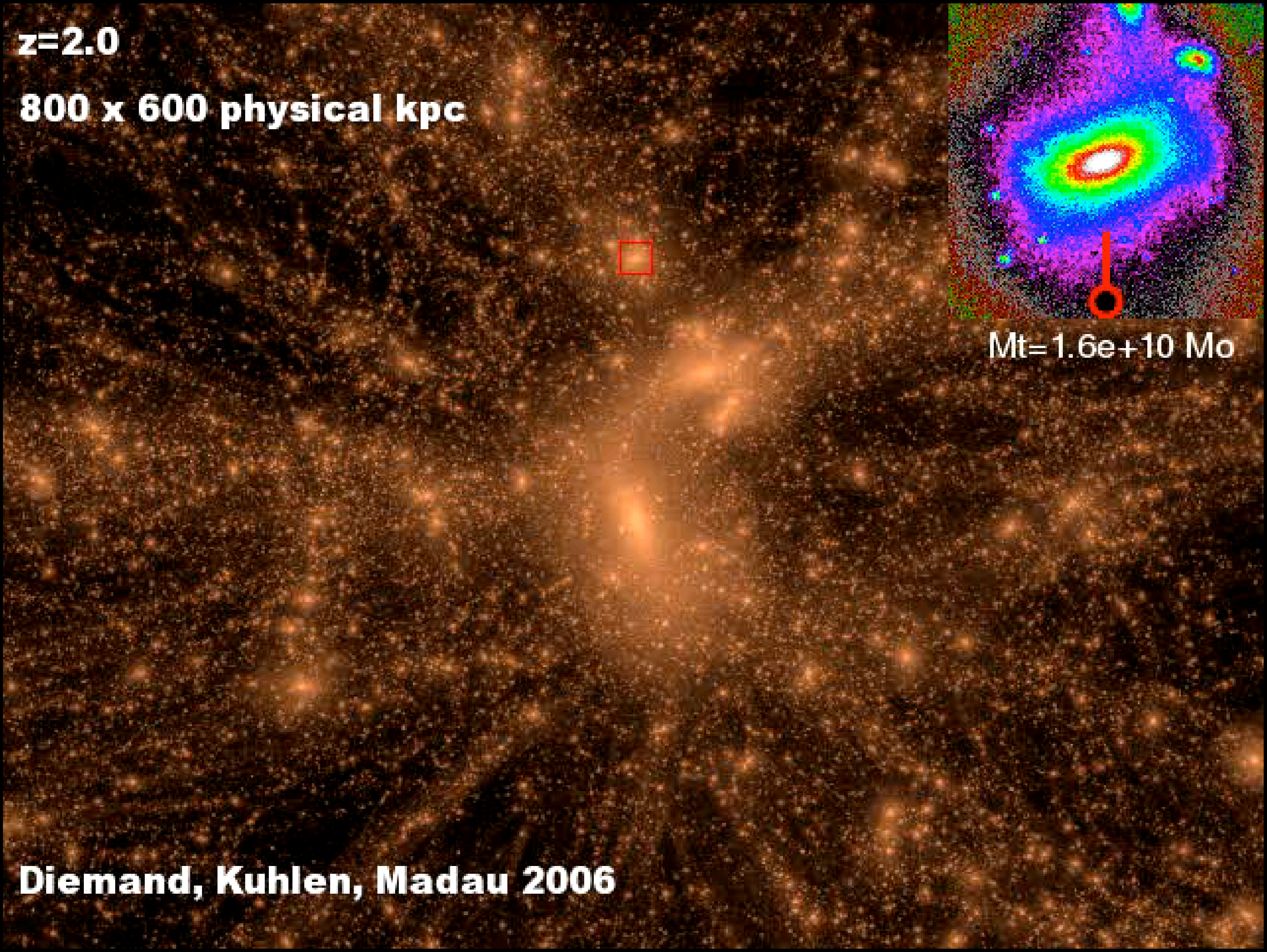
hierarchical formation of a z=0 cluster

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



survives several close pericenter passages (comes within 5.1 kpc)
becomes rounder with time and major axes tend to point towards the host center
(Kuhlen, JD, Madau 0705.2037, Faltenbacher+0706.0262, Pereira+0707.1702)



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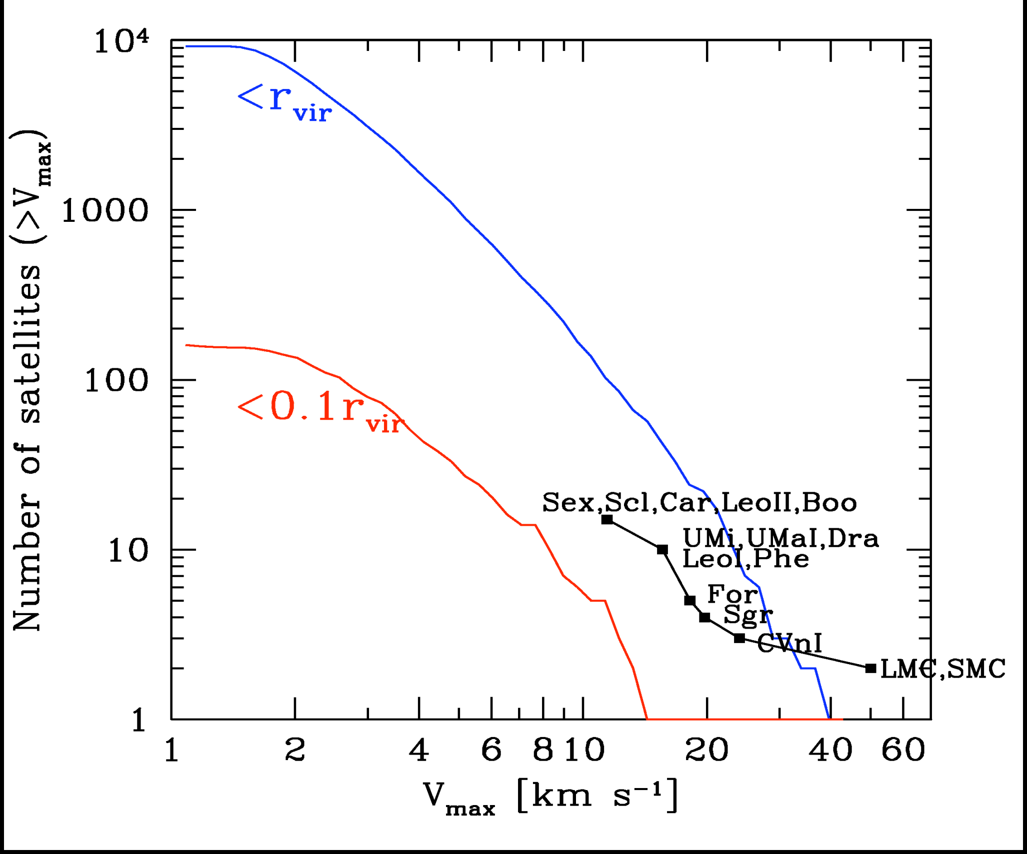
missing satellites?

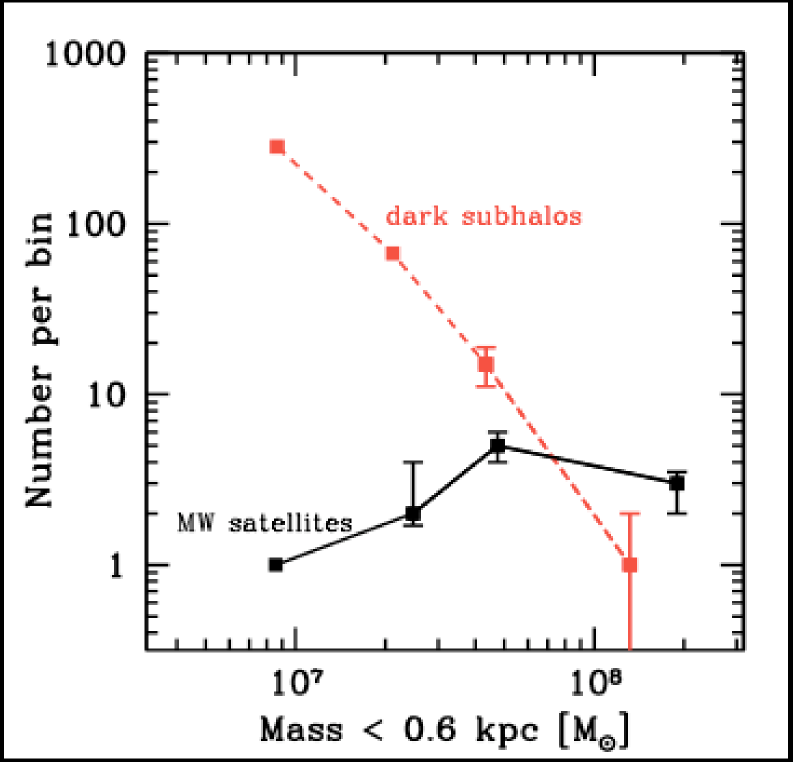
CDM only predicts subhalos, not dwarf galaxies. Luckily, CDM predicts (more than) enough structures to host all known Local Group satellites.

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_1D* = Vmax

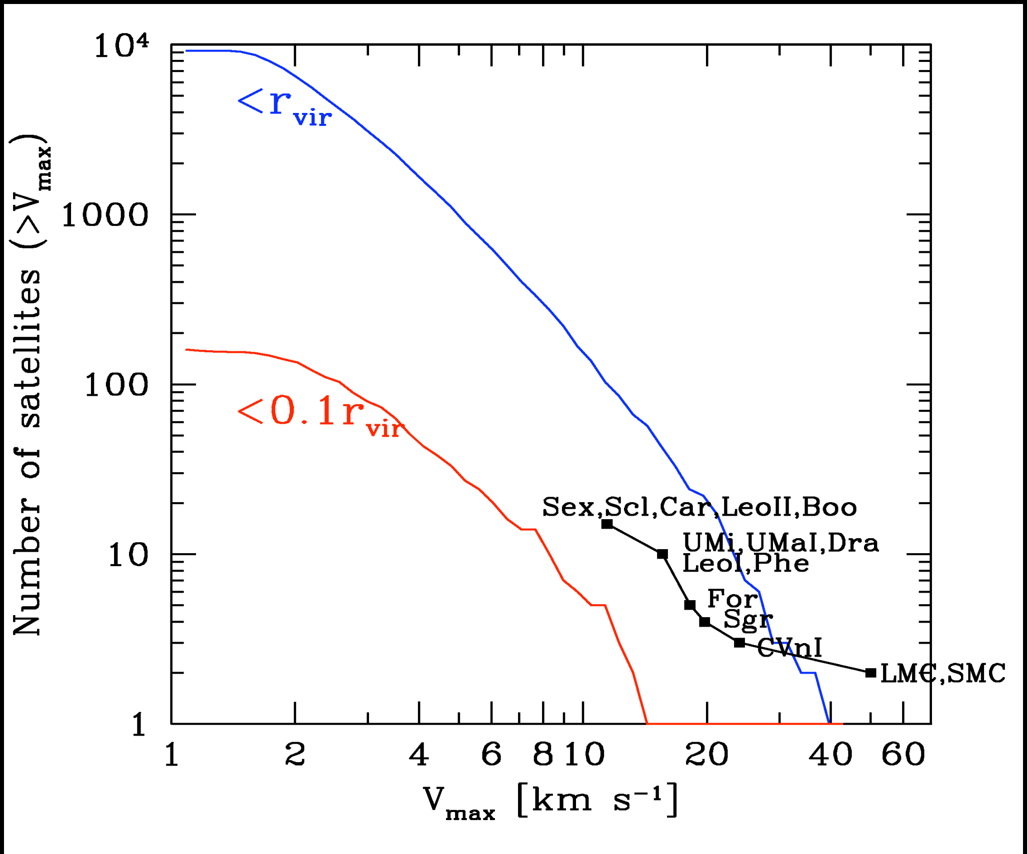


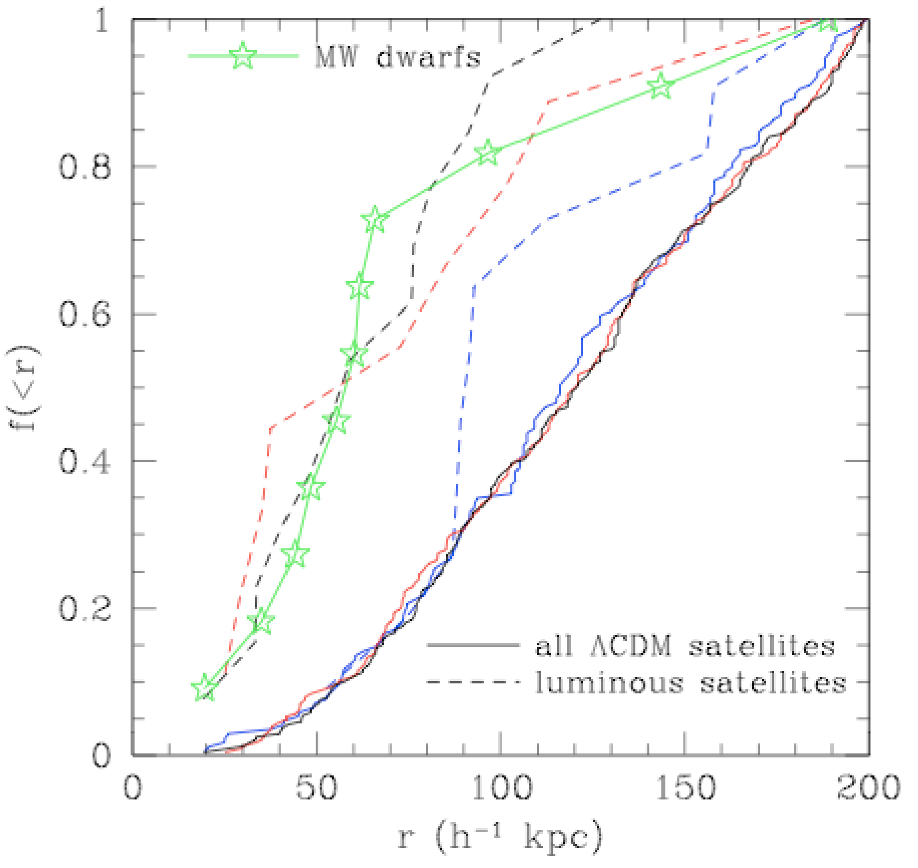
this seems to be roughly right (Strigari+0704.1817):



missing satellites?

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



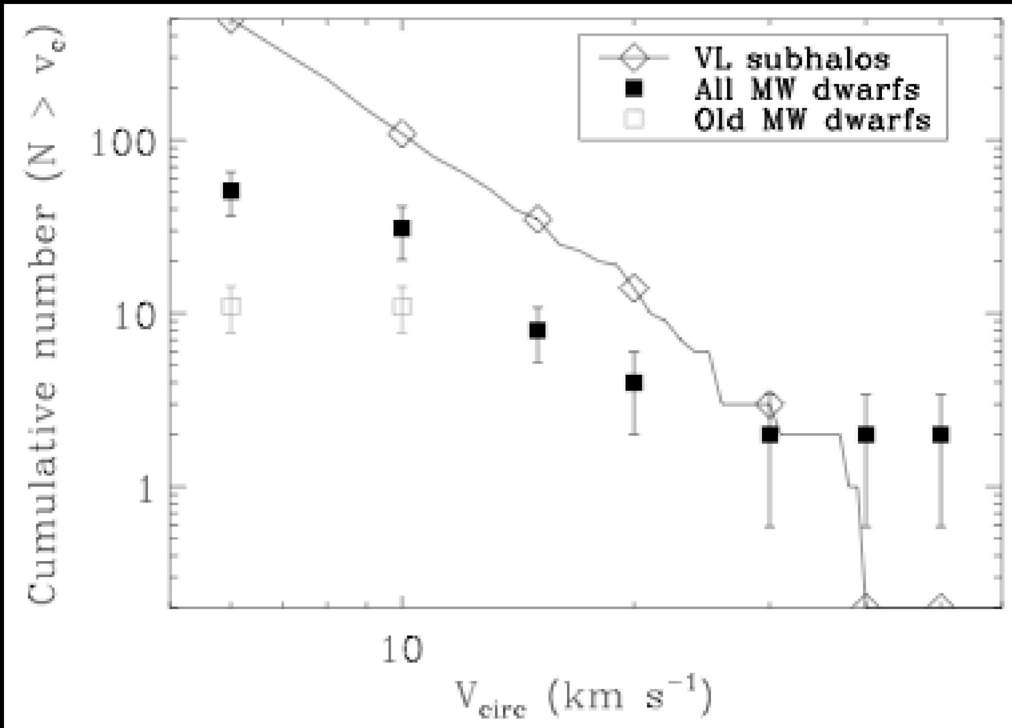


we need more subhalos than dwarfs at a given size
to have enough hosts at the correct distances!

(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)

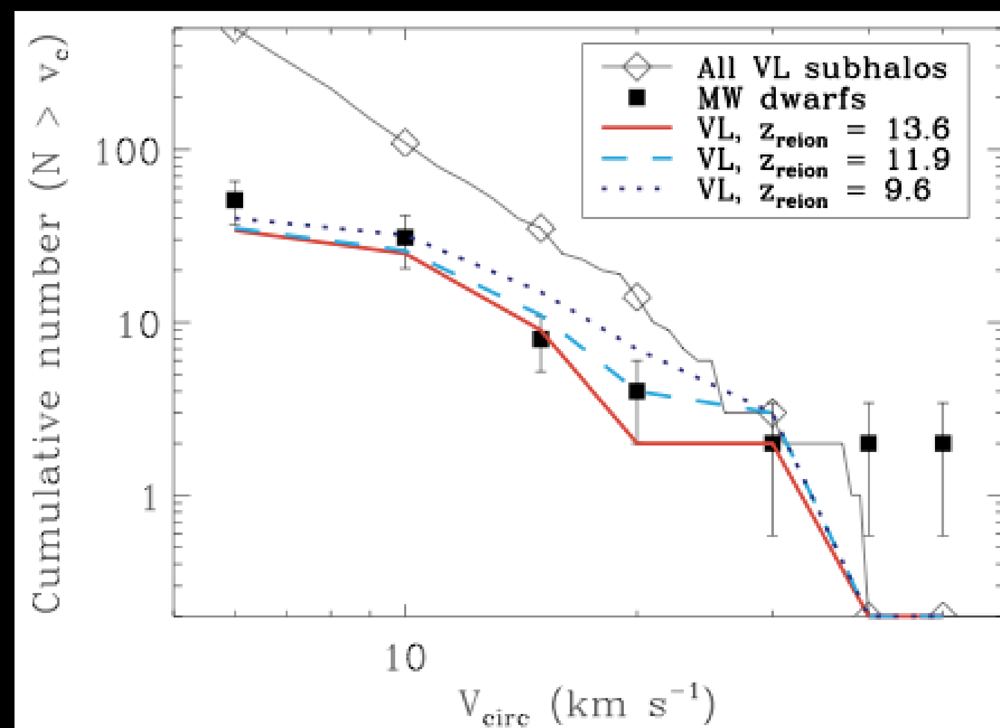
missing satellites?

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

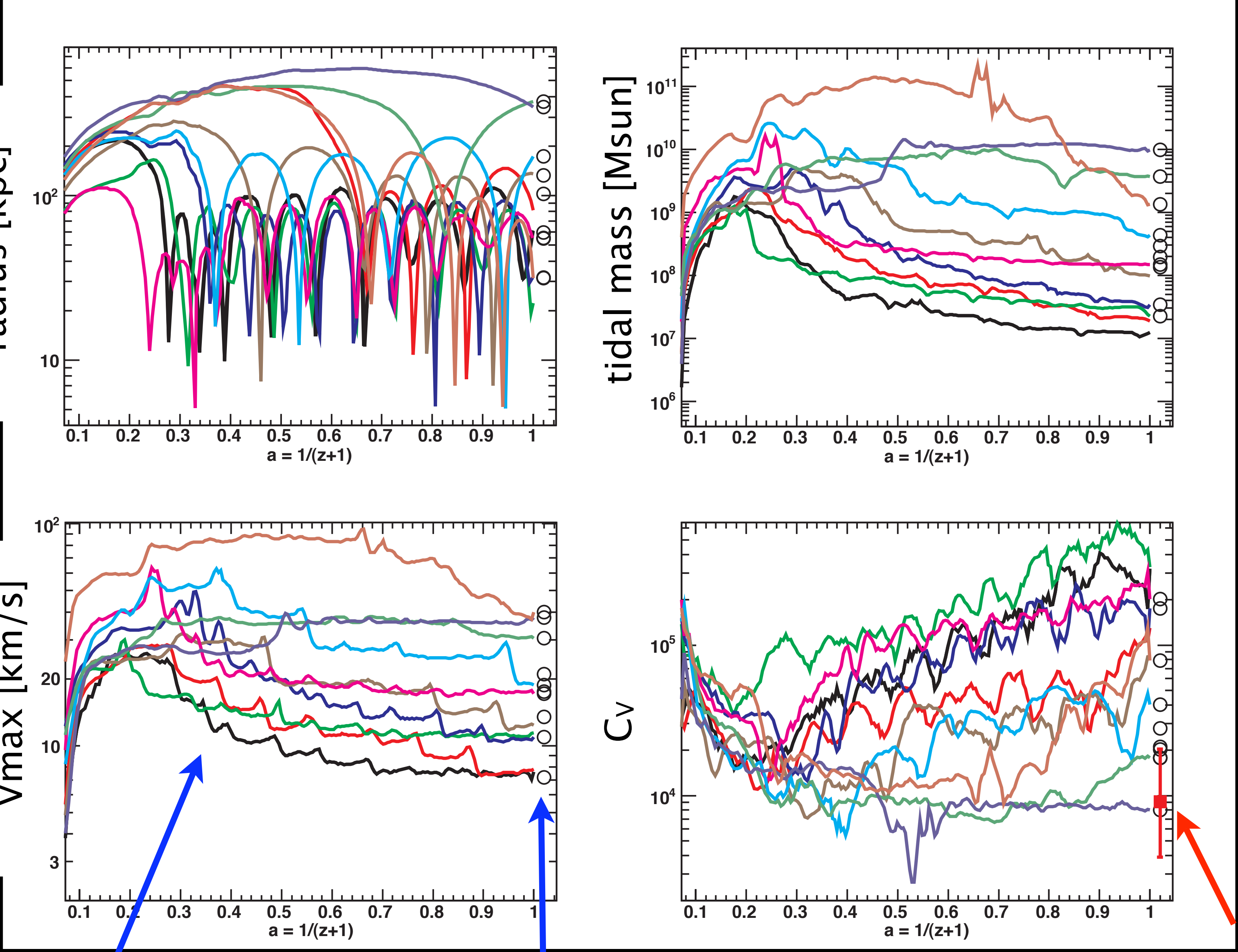


earliest forming “EF” subhalos
(or the largest before accretion “LBA”)
would have roughly the right masses

and also the correct spatial distribution
(Moore,JD et al 2006)



possible hosts of 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

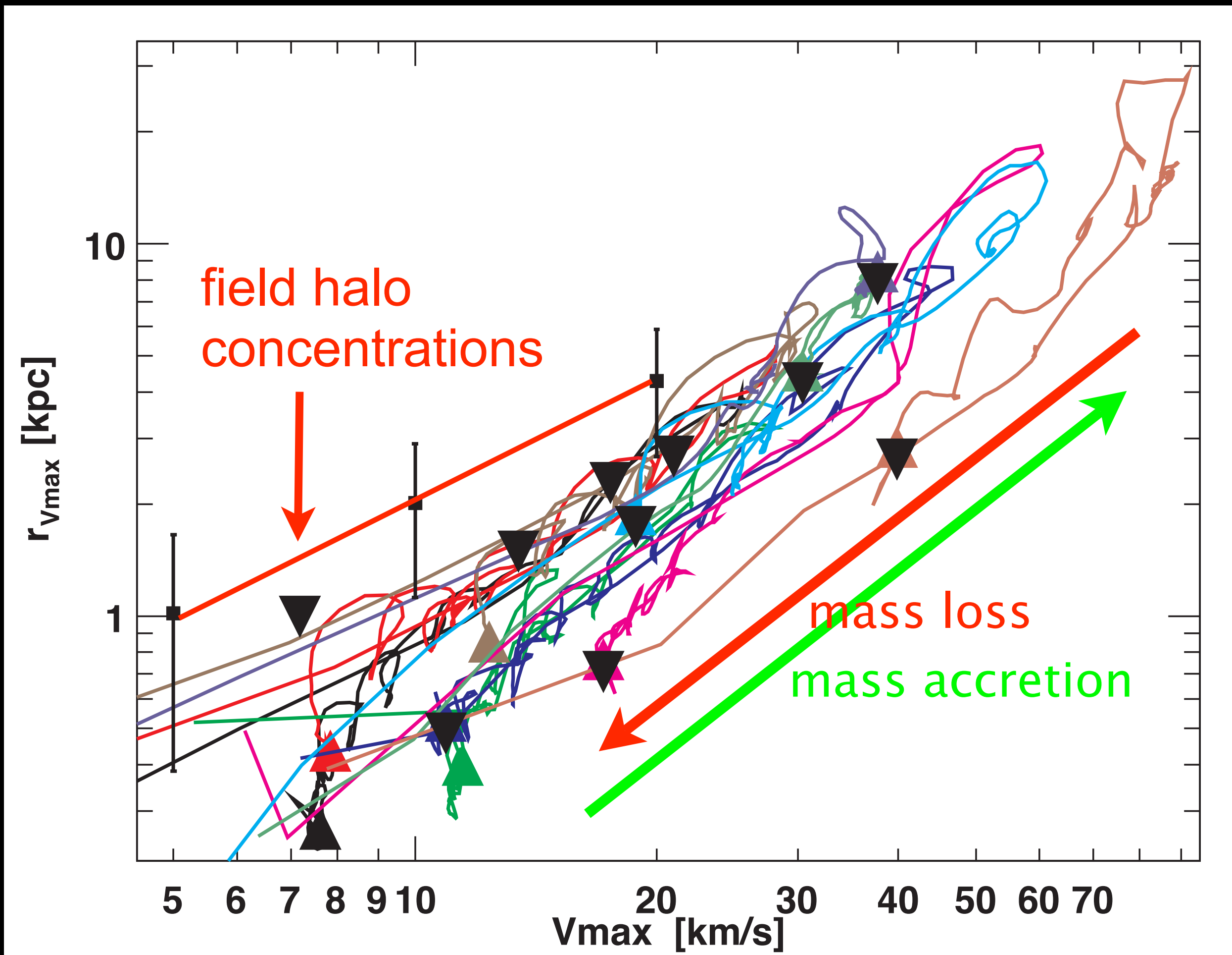
concentrations increase during tidal mass loss

field halo concentrations

tracks of 10 EF subhalos

z=0 properties of LBA

possible hosts of Local Group dwarfs

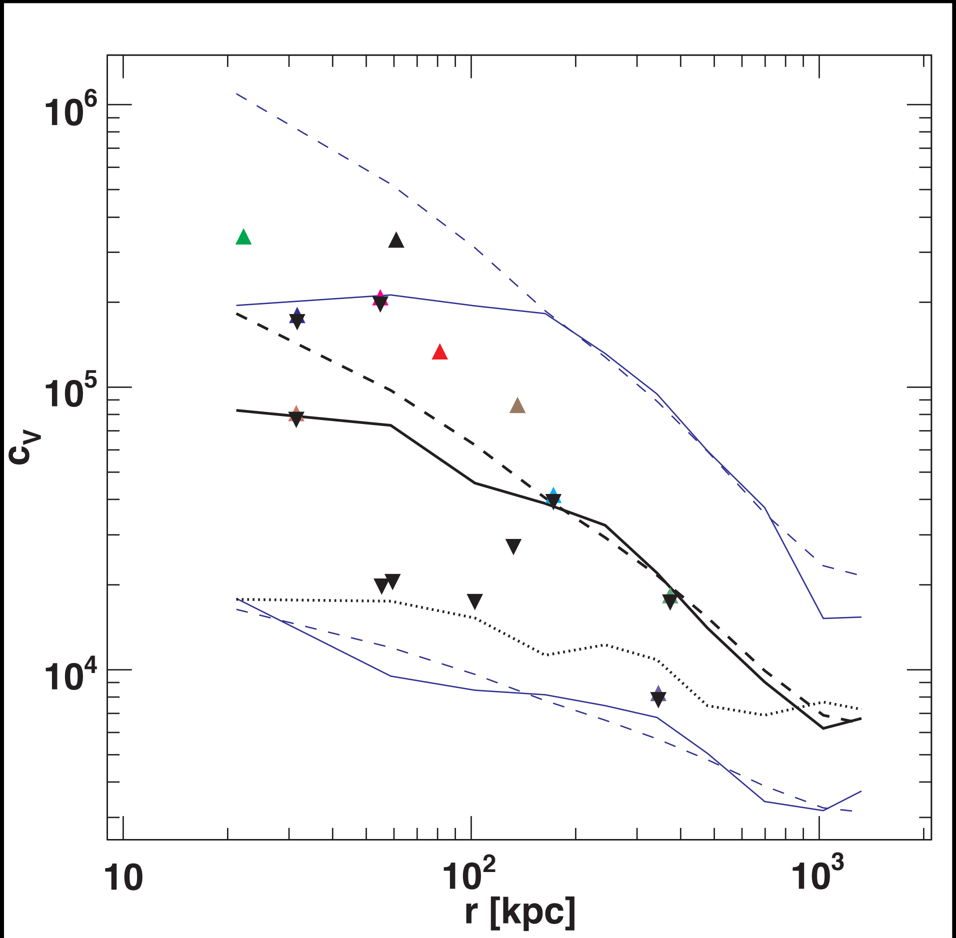


same 10 tracks

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

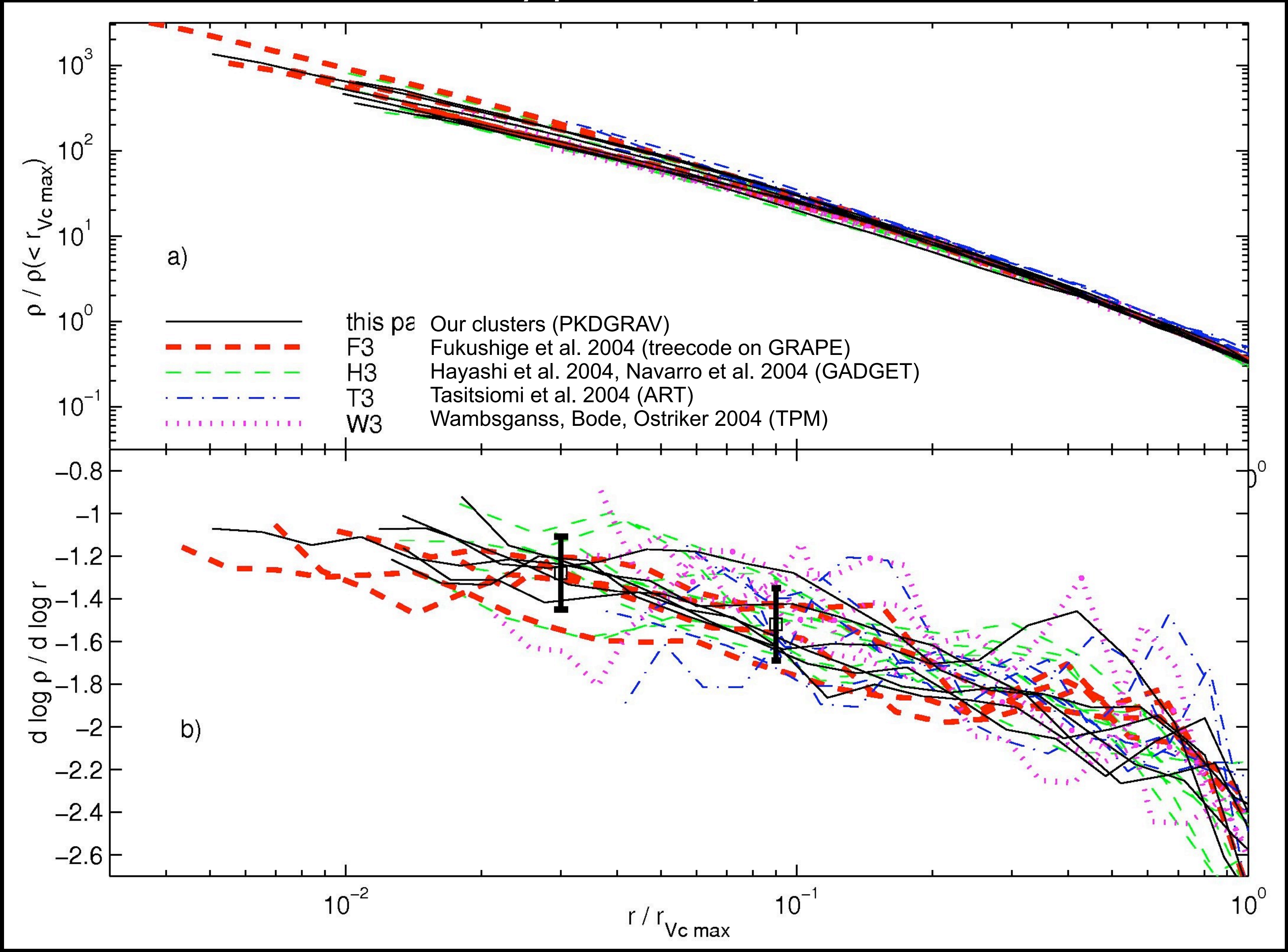
the 68% scatter also increases

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

3) CDM density profiles

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

CDM cluster 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

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

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

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

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

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

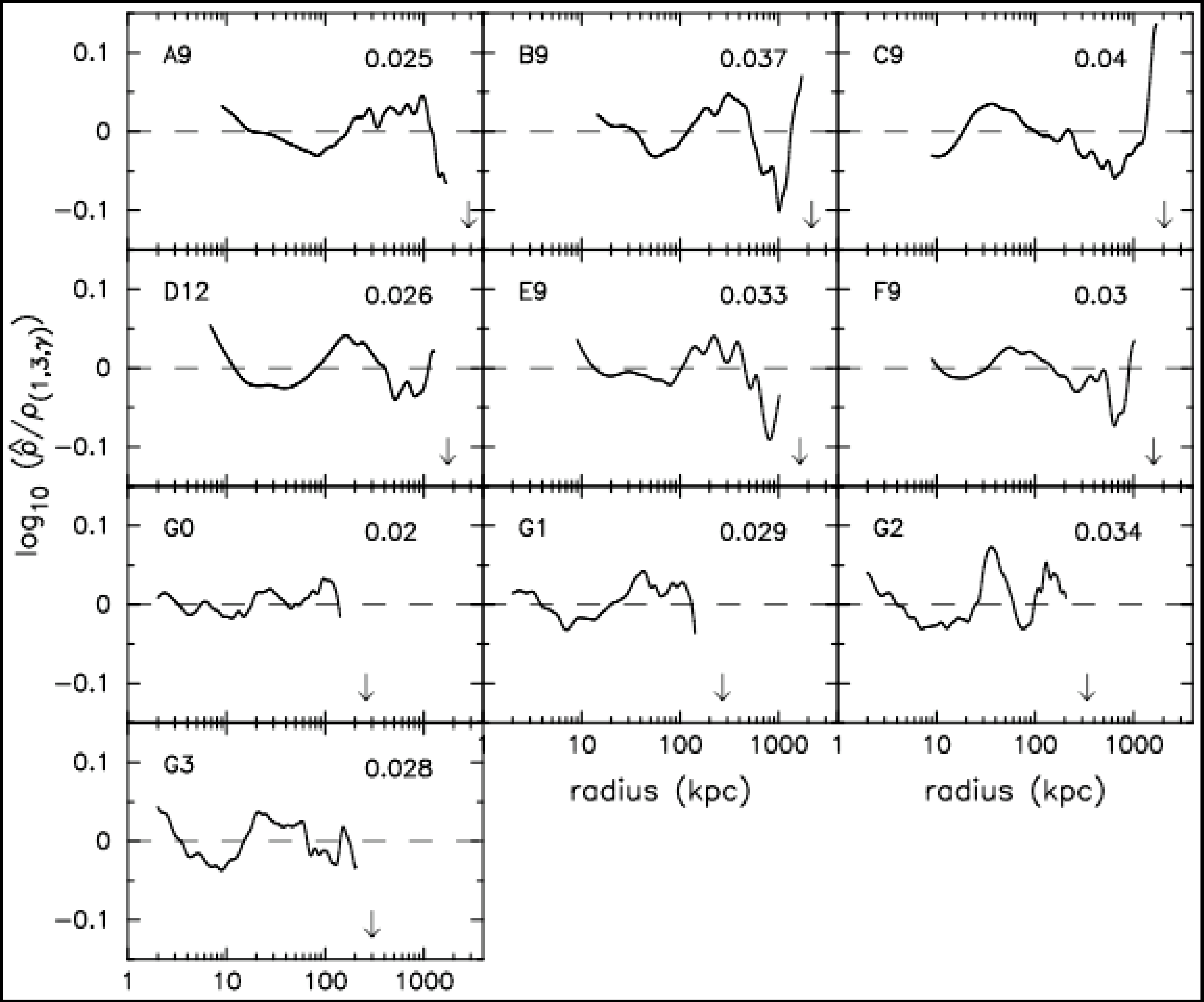
Einasto-model (core)
Navarro etal 2004
Merrit etal 2005/2006

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

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

gamma-model

fitted to non-parametric density profiles



Merritt, Graham, Moore, JD, Terzic, AJ 2006

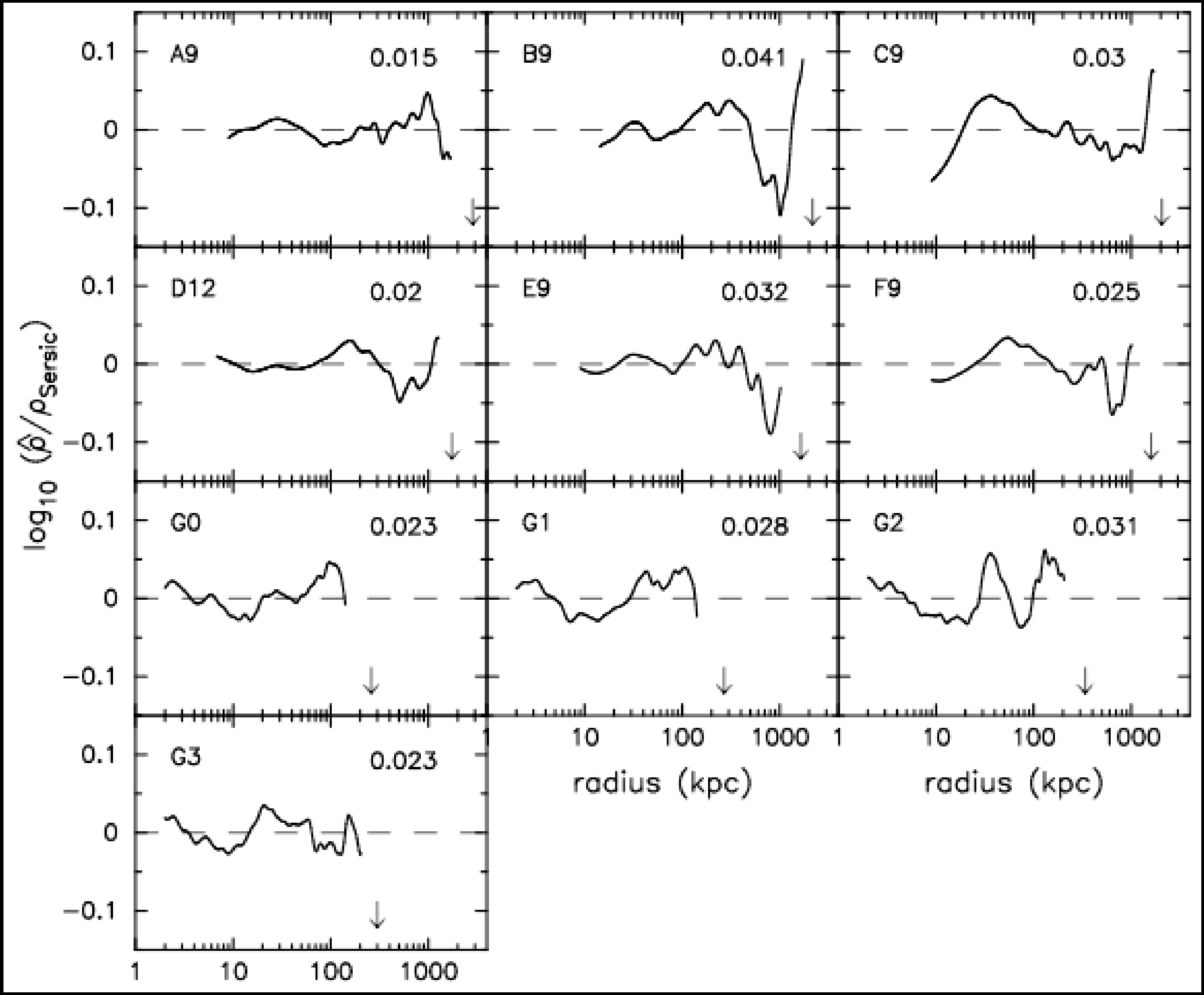
3 parameter functions (one additional ‘profile shape’ parameter):

Einasto-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 2006

resolving the very inner profile

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

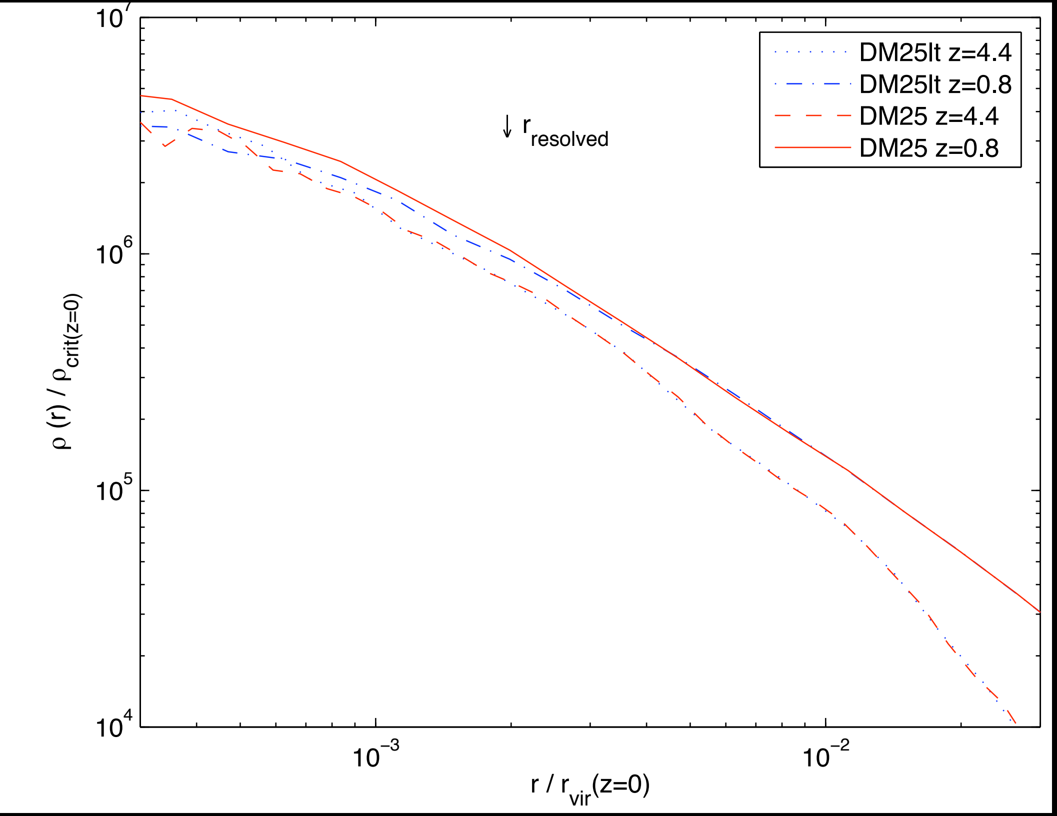
physical time-steps:

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 steps 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+2006 have implemented a more efficient algorithm which scales with the local dynamical time everywhere



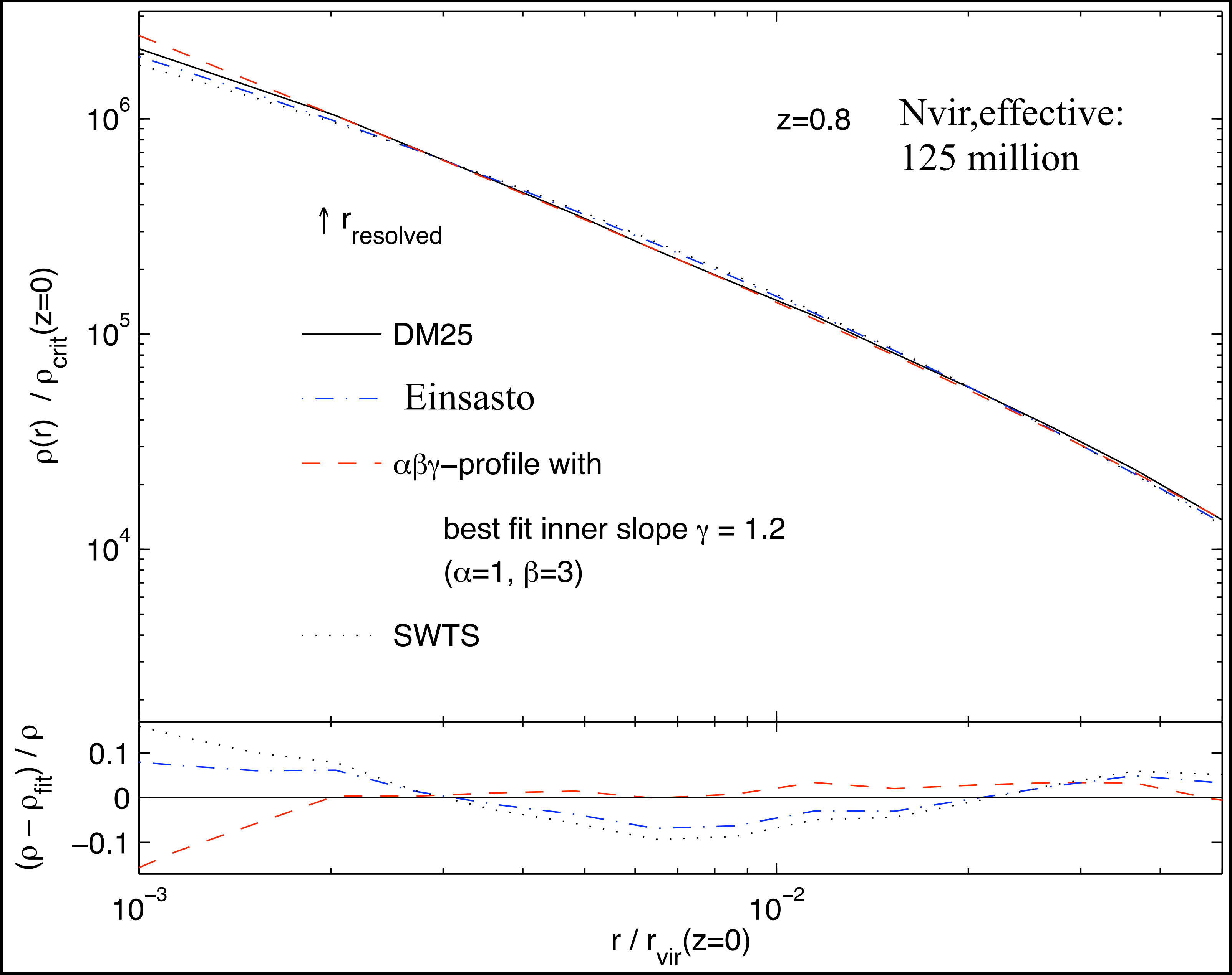
resolving the very inner profile

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

3 parameter fitting functions

Einasto fit tends to underestimate the very inner densities

even inside of r_resolved, where the simulated densities are probably too low



summary : CDM* density profiles

(*) NOTE: in the real universe these profiles would be
altered by galaxy formation on some scales

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 Einasto 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 Einasto-model

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 yet

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 slightly more fragile despite their flat sigma(M)