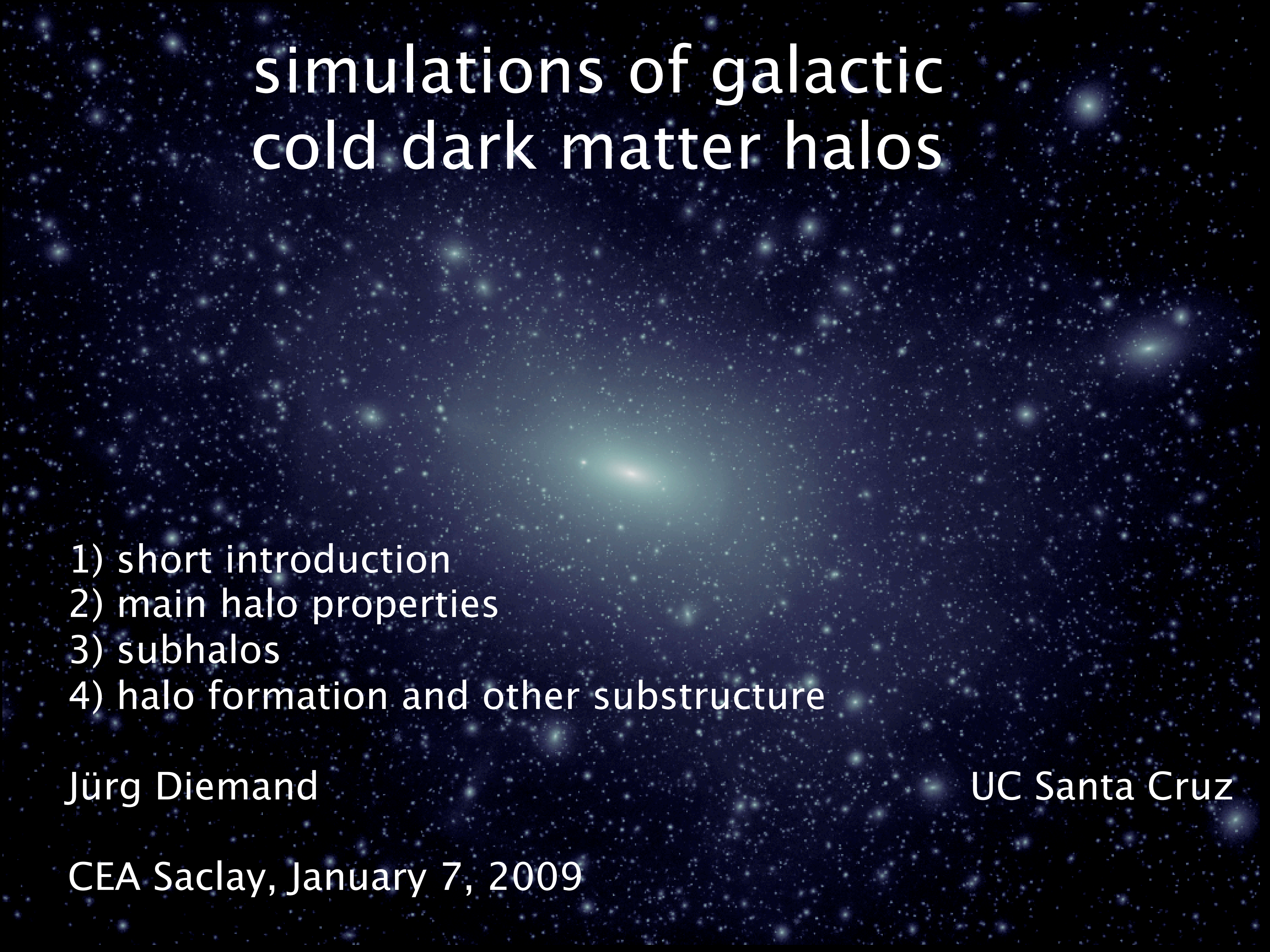
simulations of galactic cold dark matter halos



1) short introduction
2) main halo properties
3) subhalos
4) halo formation and other substructure

Jürg Diemand

UC Santa Cruz

CEA Saclay, January 7, 2009

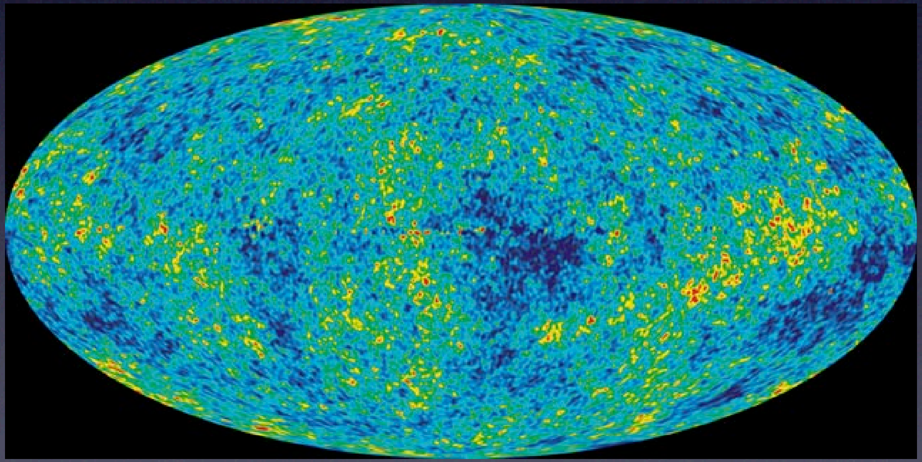
What is dark matter ?

from Lopez-Cruz et al

Indirect evidence 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 galaxies and globular clusters
- Dwarf galaxy velocity dispersions
- Strong and weak lensing

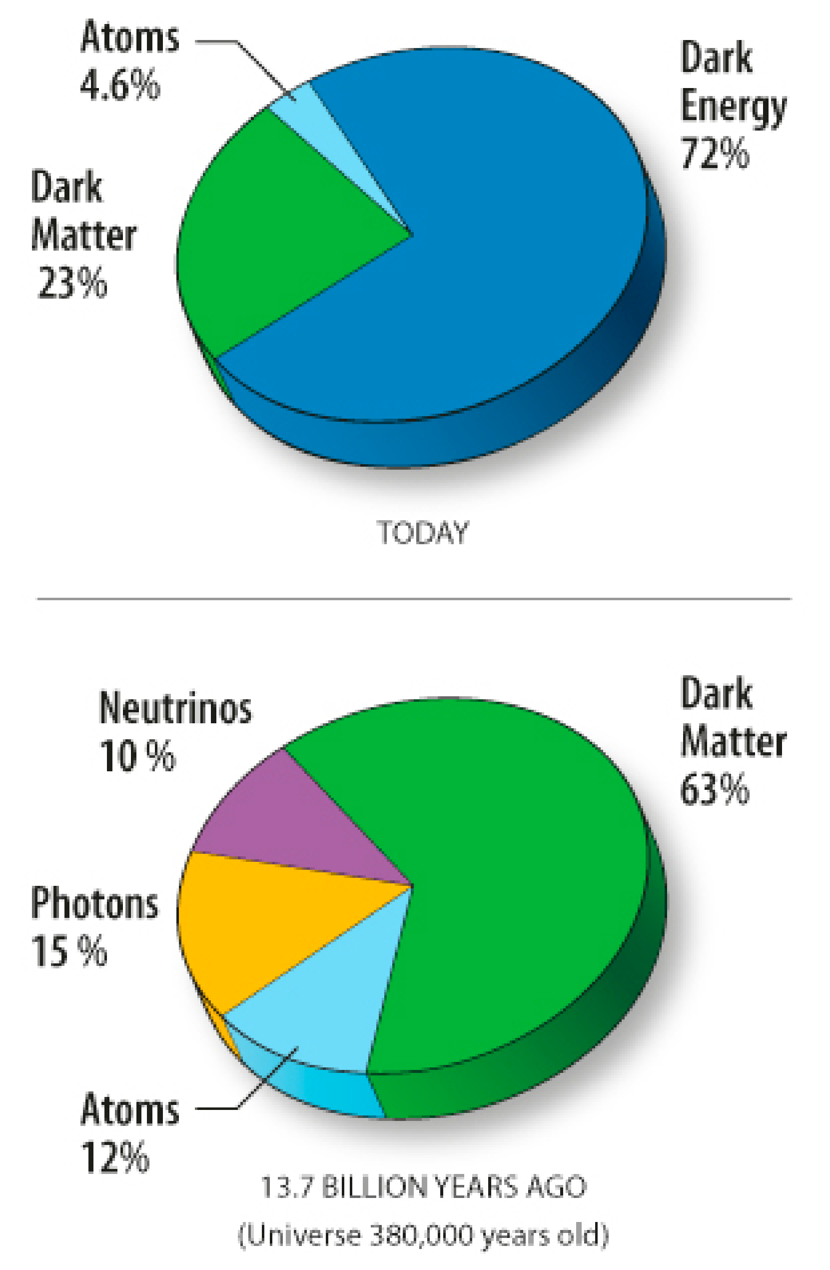


NASA/WMAP

CMB, LSS, SN Ia, BBN → LambdaCDM

DM is "cold", or at most "tepid":
Lyman-alpha forest, early reionisation

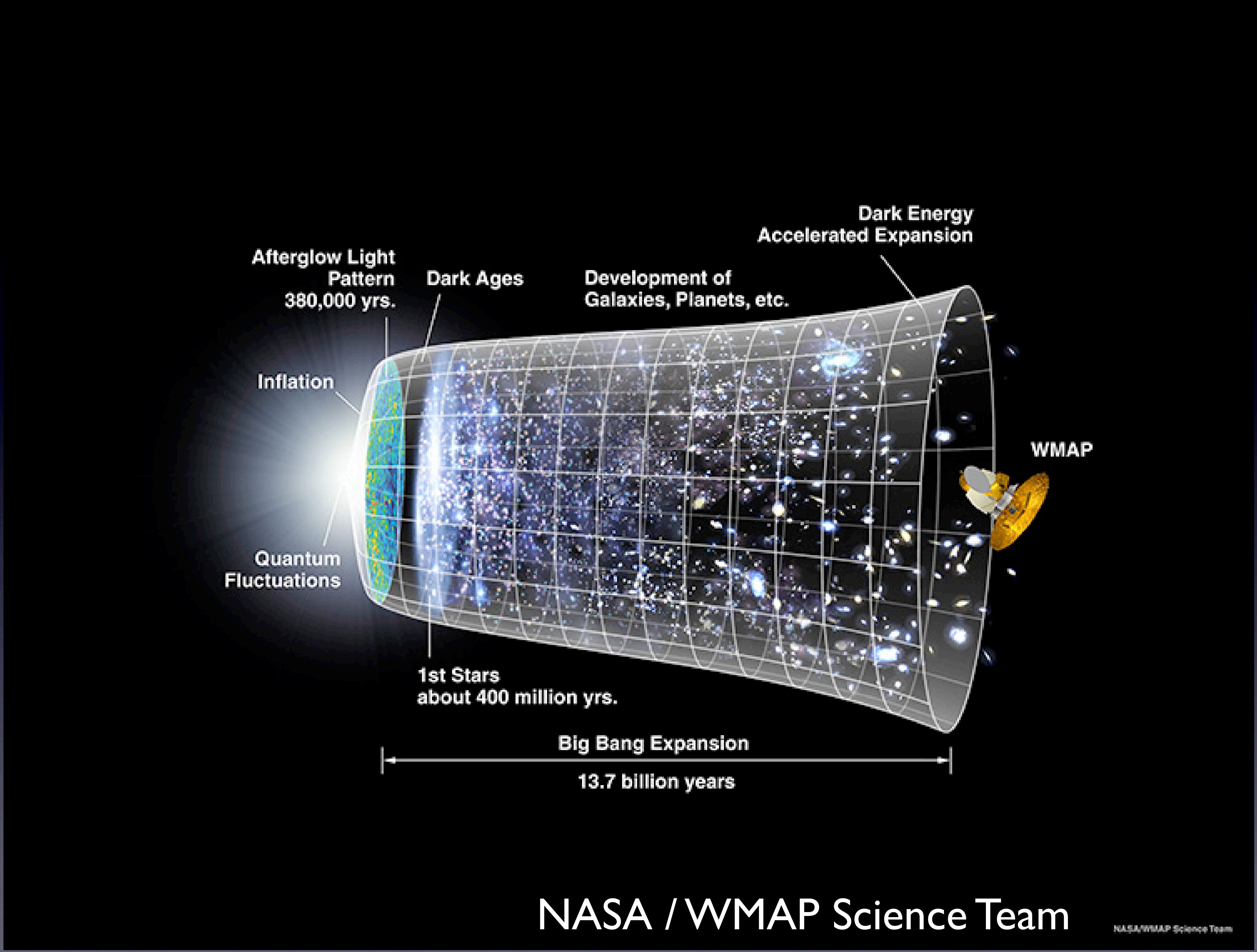
→ 83% of the clustering matter is
non-baryonic, "tepid" or "cold", dark matter
Nature of DM unknown, but we can still simulate its clustering ...



z=0

z ~ 1100

NASA / WMAP Science Team



NASA / WMAP Science Team

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

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

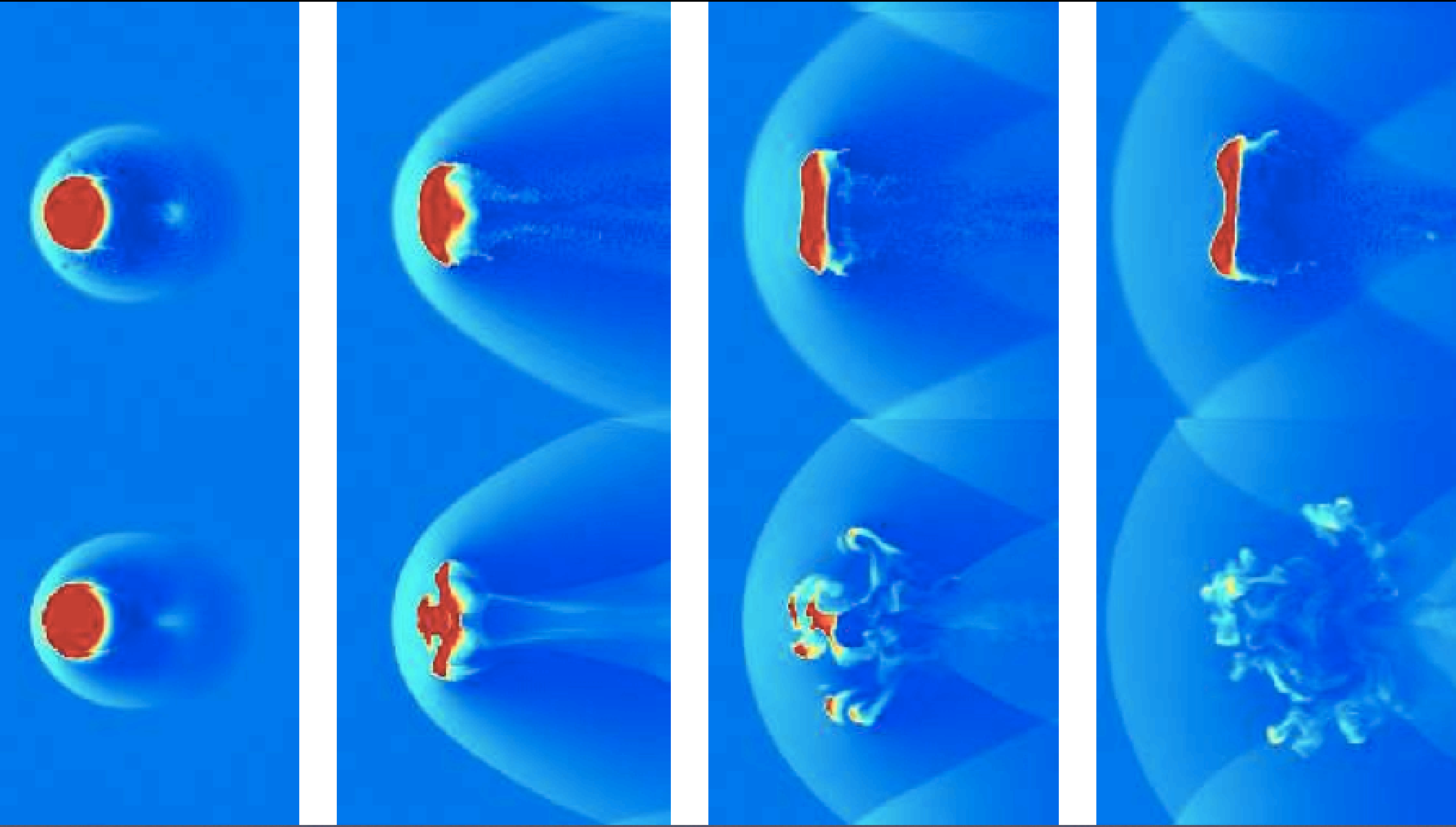
→ accurate solution of the idealized problem

complementary approach:
hydrodynamical simulations

- computationally expensive, resolution relatively low
- SPH and grid disagree even in simple tests, Agertz et al 2007
- processes far below the resolved scales (star formation,SN, ... ?)
  implemented through uncertain functions and free parameters

→ approximate solution to the more realistic problem

Smoothed Particle Hydro (SPH)



grid code with adaptive mesh refinement (AMR)

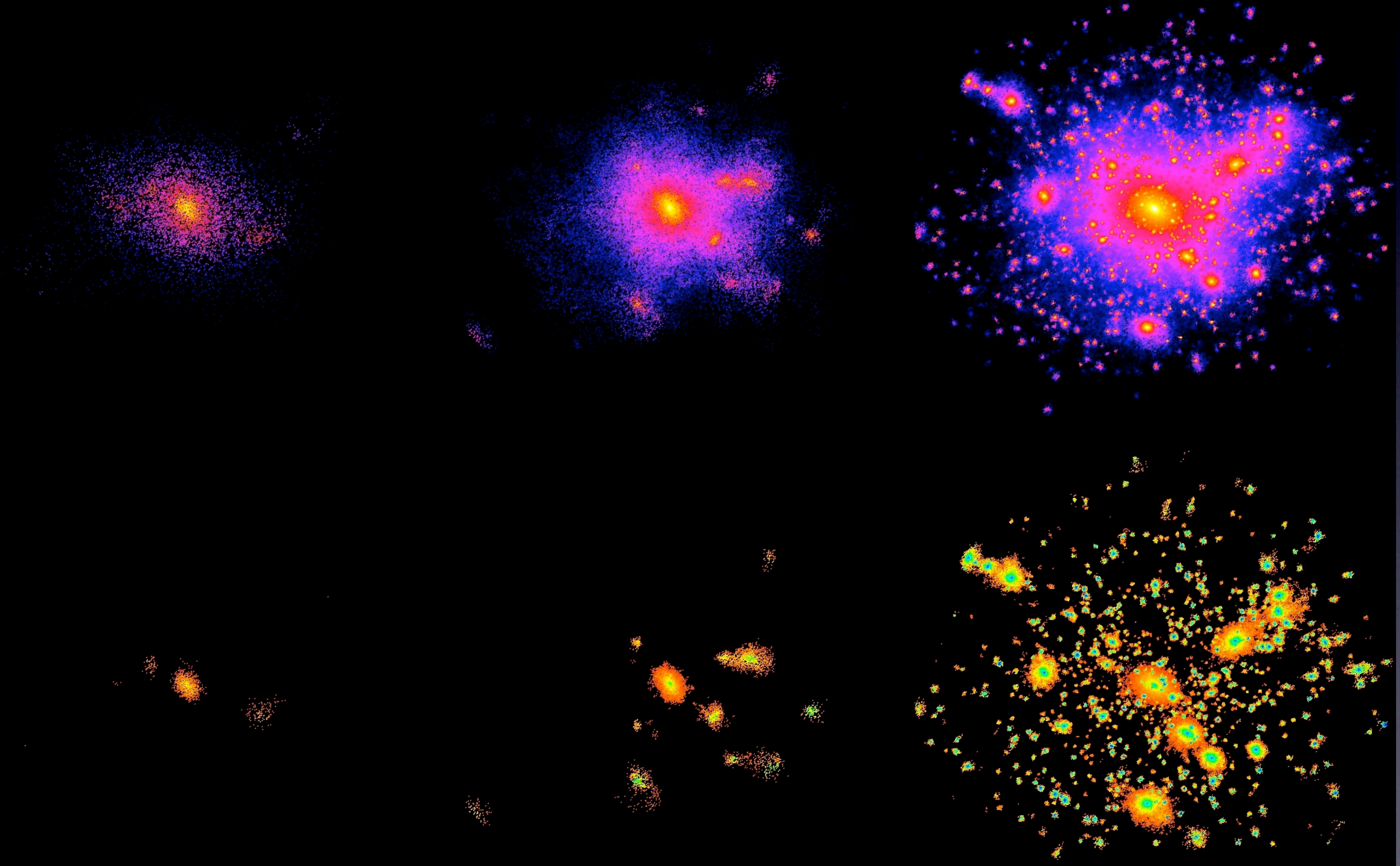
Agertz, Moore etal 2007

Simulating structure formation

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

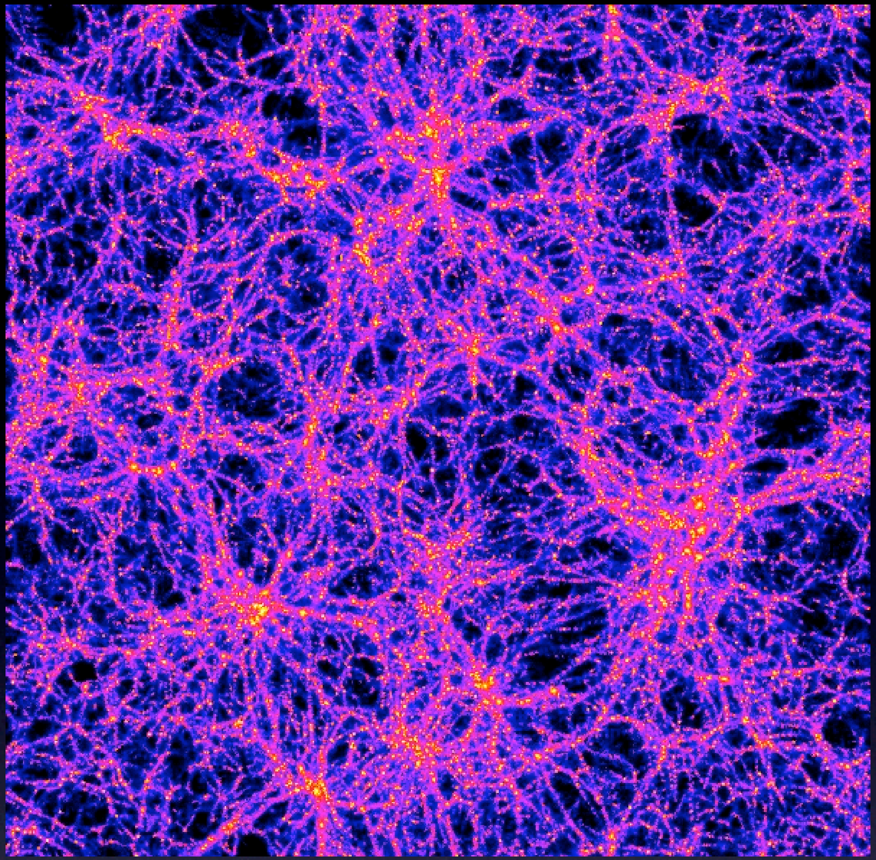
log density

N_halo from about 10k to a million



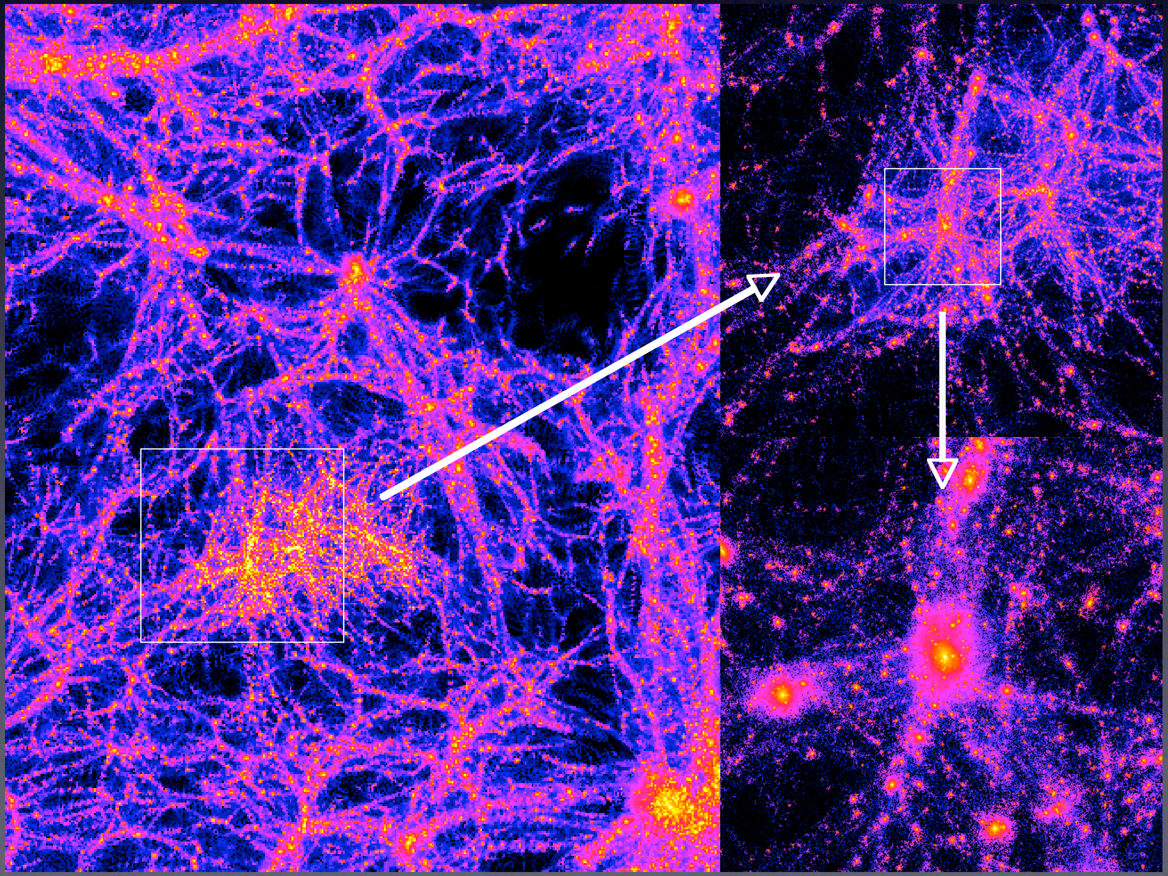
log phase space density

from Ben Moore : www.nbody.net



uniform resolution, periodic cubes

- good statistics, lower resolution
- large scale structure
- fair sample of halos and environments



refined, resimulations of individual halos

- low statistics, high resolution
- selection effects?
  see e.g. Ishiama et al 2008

the via lactea project : increasing N_halo

2003 : several clusters and galaxies with N_halo from 2M to 25M

2006 : Via Lactea, N_halo ~ 100 M
WMAP-3yr, but n_s=0.90 due to bug in IC generator

2007 : Via Lactea II, N_halo ~ 500 M
WMAP-3yr (n_s=0.95)
improved, physical time-steps (Zemp+2007)

2008 : N_halo ~ 1 G
GHALO (WMAP-5yr) and Aquarius (WMAP-1yr, n_s=1.0)

via lactea II and aquarius: discrepancies?

Using the old WMAP-1yr parameters instead of 3yr or 5yr values increases:

- halo and subhalo concentrations (e.g. Maccio et al 2008)

- subhalo abundance given by peak velocity functions (Zenter & Bullock 2003)

This is sufficient to explain the different concentrations and subhalo velocity functions found in VL-II and Aquarius

Claimed ‘discrepancies’ (Springel et al. 0809.0898v1) are not backed up by evidence

motivation for the via lactea project

1) **indirect detection** of dark matter via
its annihilation products

gamma ray signal

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

is dominated by small clumps (JD etal 2007)

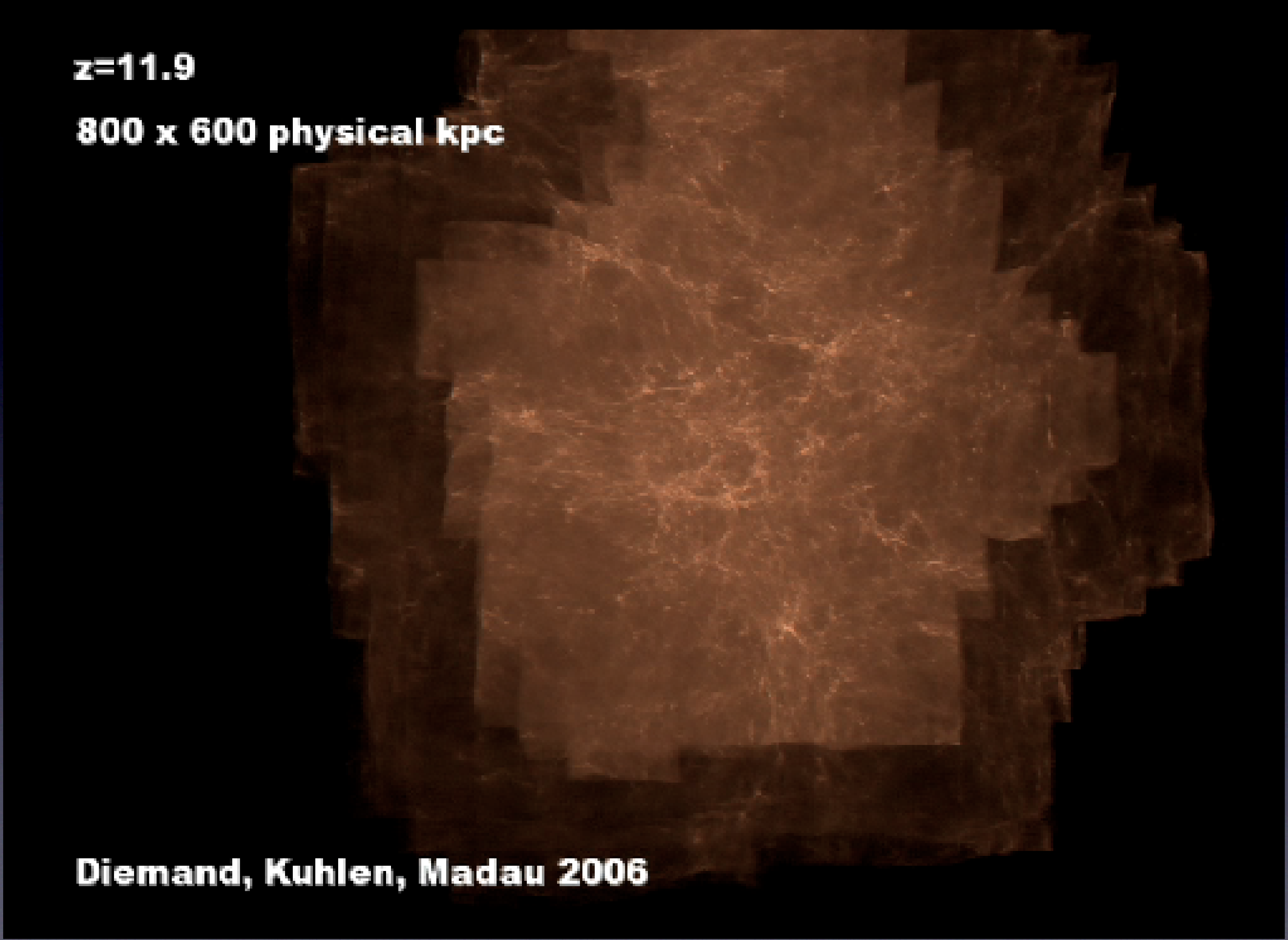
Fermi (GLAST)
launched June 2008

charged particle production within a few kilo-parsecs (PAMELA, AMS-01)
boosted by local clumpiness?

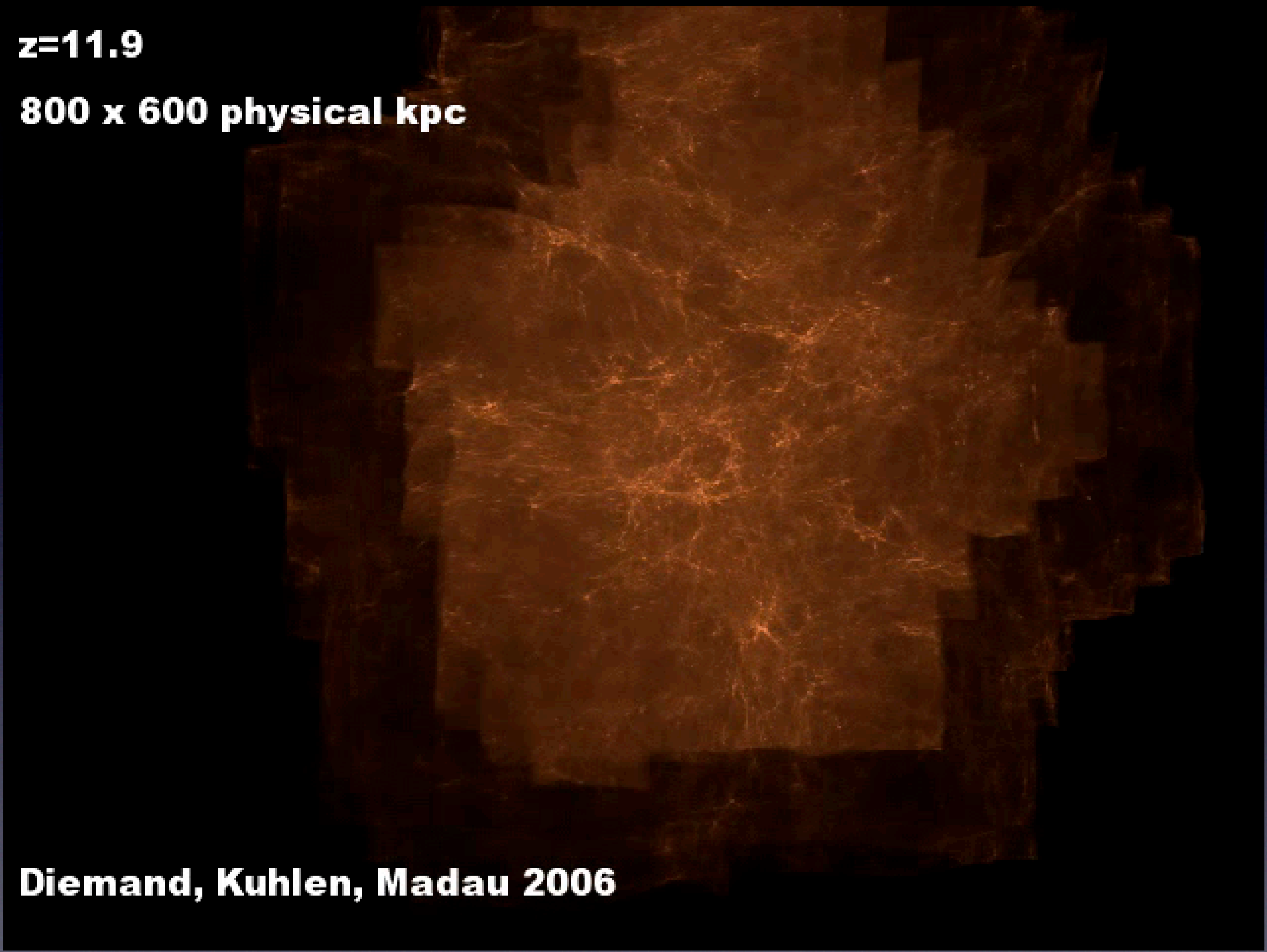
2) **direct detection** of dark matter : how is DM distributed locally?

3) **dwarf satellite galaxies:**
mass distribution in these dark matter dominated systems?
abundance and radial distribution?

4) **stellar halos:** streams from hierarchical buildup,
extend vs. formation history, halo mass indicator



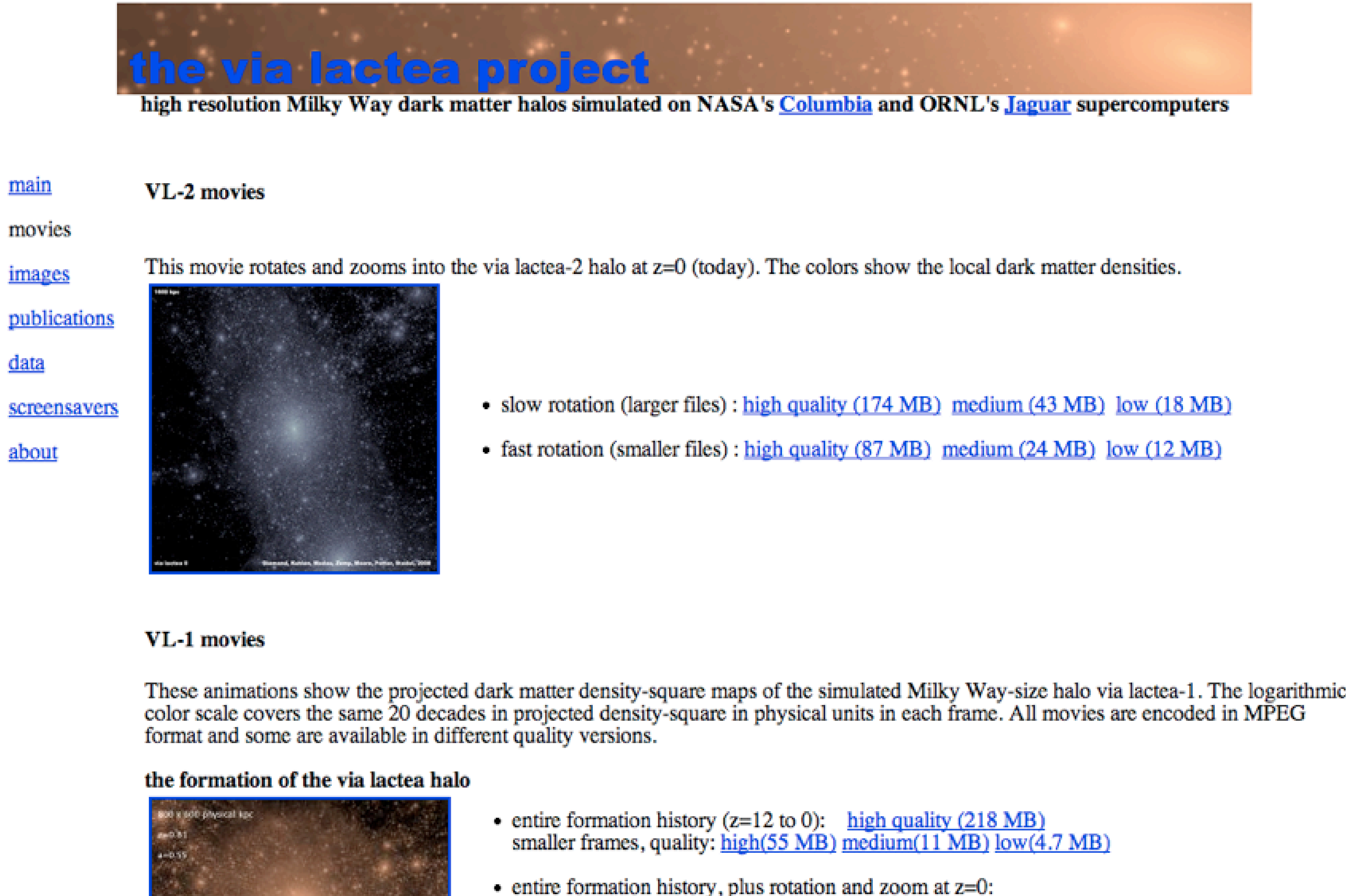
Diemand, Kuhlen, Madau 2006



Diemand, Kuhlen, Madau 2006

via lactea II at redshift zero

www.ucolick.org/~diemand/vl



high resolution Milky Way dark matter halos simulated on NASA's Columbia and ORNL's Jaguar supercomputers

- main
- movies
- images
- publications
- data
- screensavers
- about

VL-2 movies

This movie rotates and zooms into the via lactea-2 halo at z=0 (today). The colors show the local dark matter densities.

- slow rotation (larger files) : high quality (174 MB) medium (43 MB) low (18 MB)
- fast rotation (smaller files) : high quality (87 MB) medium (24 MB) low (12 MB)

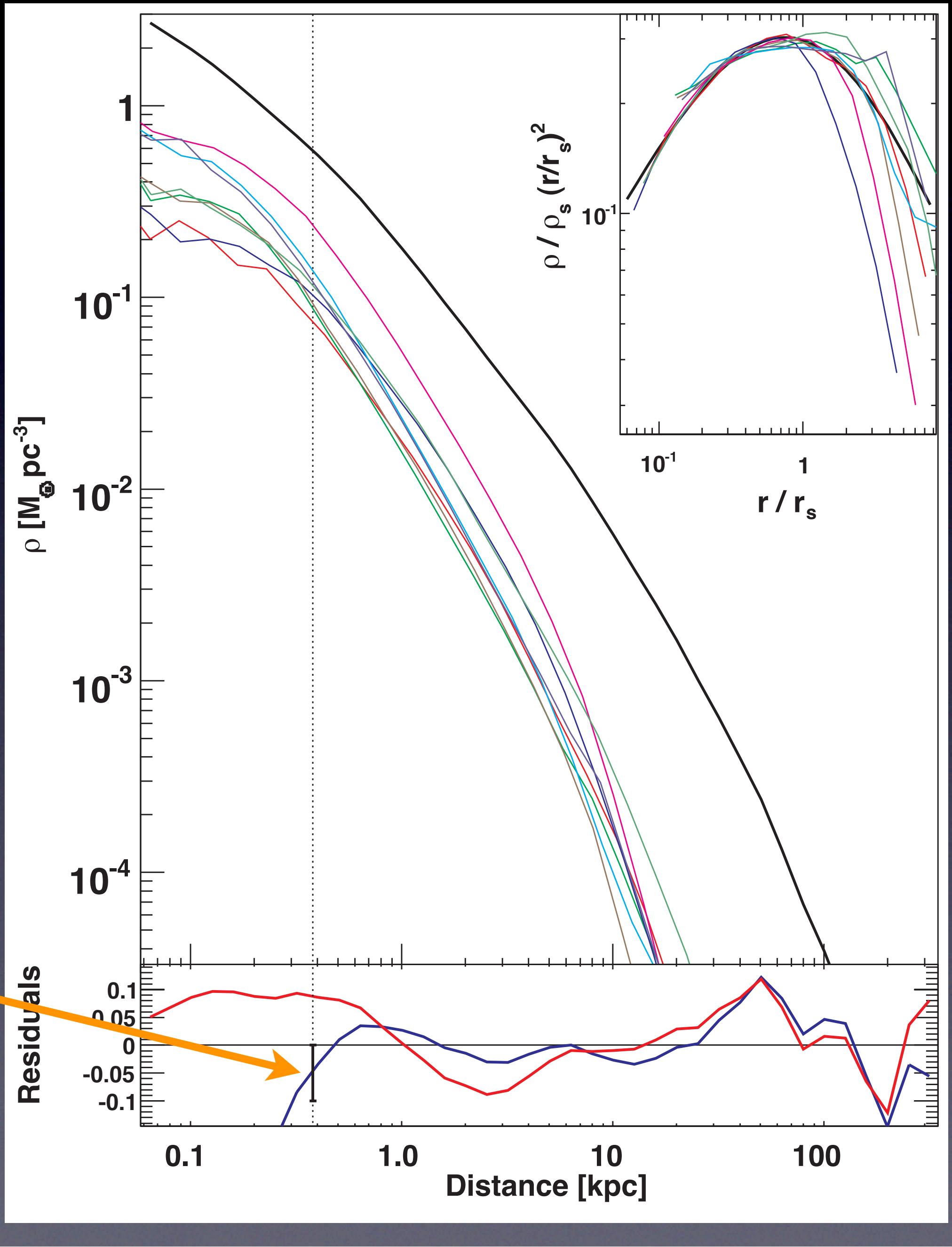
VL-1 movies

These animations show the projected dark matter density-square maps of the simulated Milky Way-size halo via lactea-1. 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:

host and subhalo density profiles



subhalos:

inner parts
like host

outer parts
steeper

inner halo:
rho ~ r^-1.24
power law fits better
than a finite density
Einasto profile

JD+ Nature 2008

down to 400 pc (0.1% rVir), shallower on smaller scales, convergence?

inner density profiles depend on time stepping

widely use empirical time step criterion

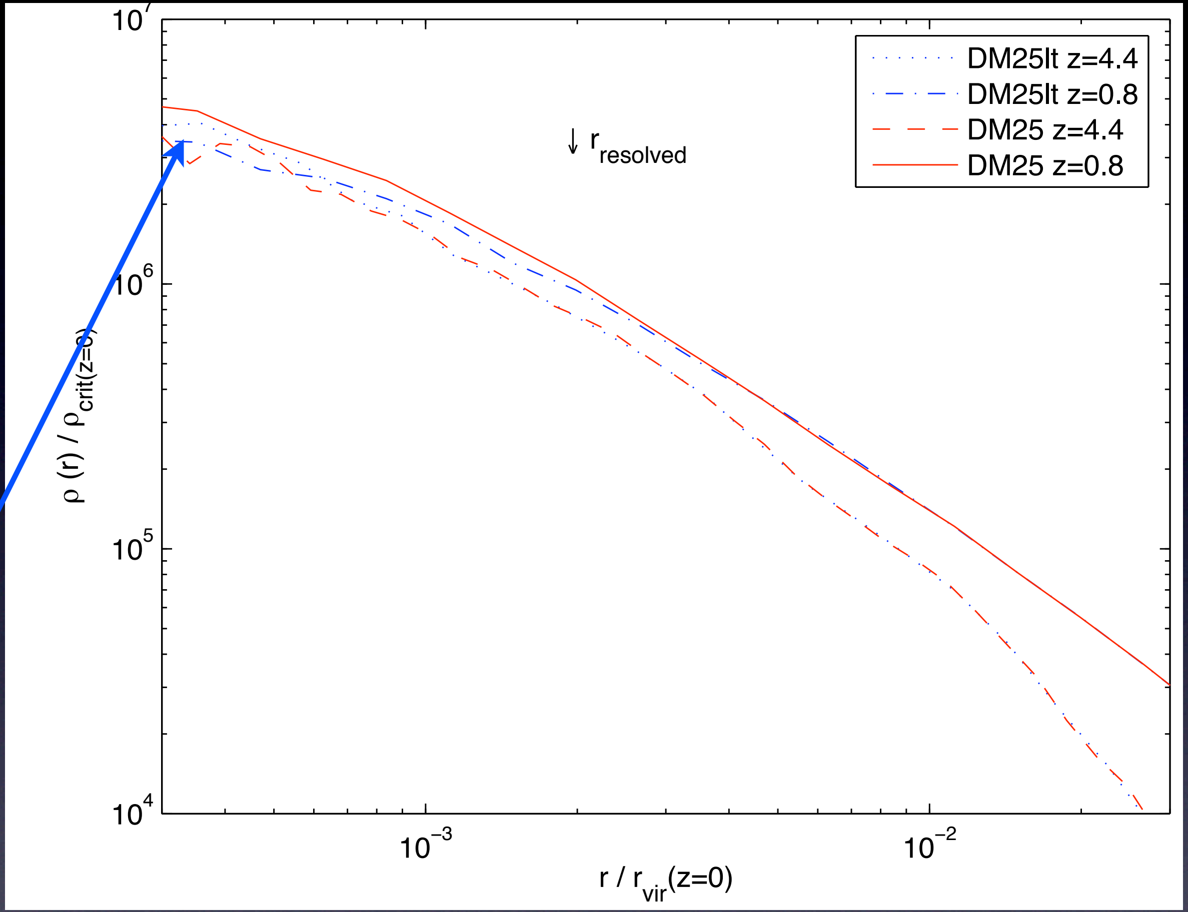
$$\Delta t_i < \eta\sqrt{\epsilon/a_i}$$

does not scale like the dynamical time

$$1/\sqrt{G\rho(< r_i)}$$

and limits the densities a simulation is able to resolve

VL-II and GHALO use the dynamical time, implemented as in Zemp et. al 2006



JD et al. 2005

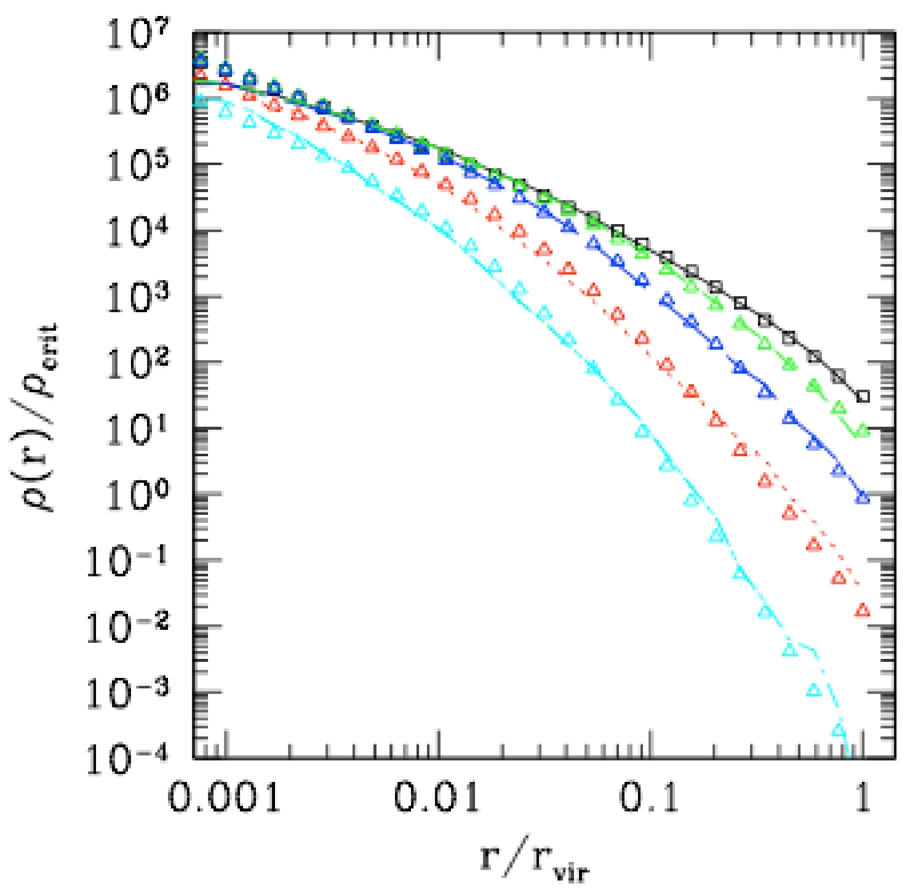
inner material comes from high sigma progenitor halos

4 sigma progenitor halo bring in most of the material which ends up within 0.1 % rVir

typical CDM simulations start at a redshift, when a one sigma fluctuation has an over-density of 0.1 (VL-II) to 0.2 (GHALO)

i.e. 4 sigma peak are already (mildly) non-linear at the beginning; this could delay their formation and lower their density artificially

convergence at 0.1% rVir?
more work is needed ...



JD, Madau, Moore 2005

CDM densities within 0.1 % rVir remain uncertain

but that’s a question of little ‘practical’ importance:

- few hundred pc in galaxies: potential by far dominated by baryons and DM altered by galaxy formation. contraction or expansion?

- only ~ten pc in dwarf satellite galaxies: not distinguishable from current stellar kinematics (maybe with SIM ?)

- inner 0.1 % rVir contribute little to subhalo annihilation signal (because inner slope < 1.5)

this uncertainty in the idealized pure CDM case also casts doubt on hydro+SMBH+AGN-feedback galaxy simulations

evidence for DM in the Milky Way

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

$\text{Virial mass } M_{\text{vir}}\ (\text{M}_\odot) = 1.0 \times 10^{12}$

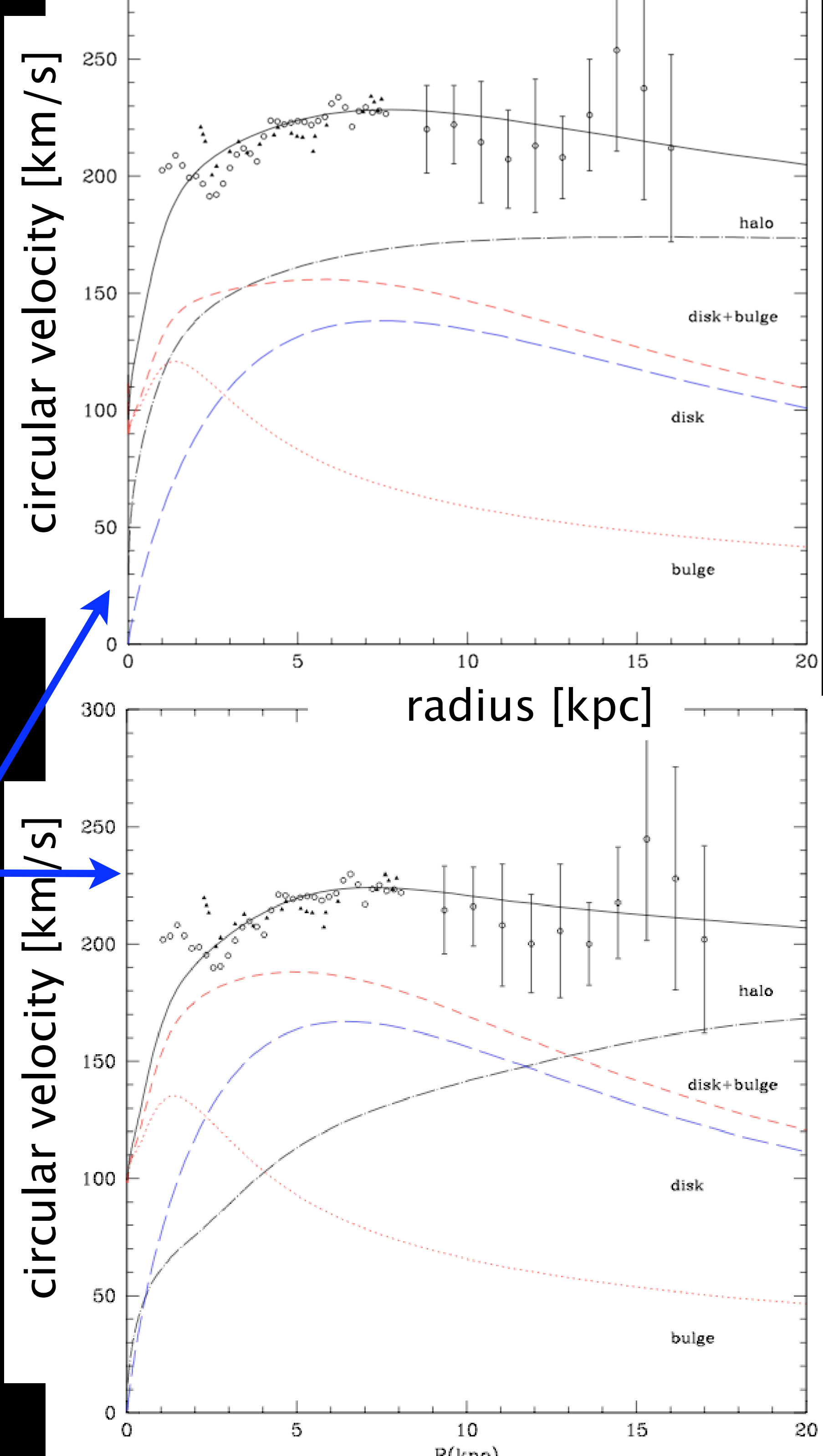
preferred range: 0.7 – 2.0

Concentration = 12

preferred range: 10 – 17

no exchange of angular momentum

with exchange



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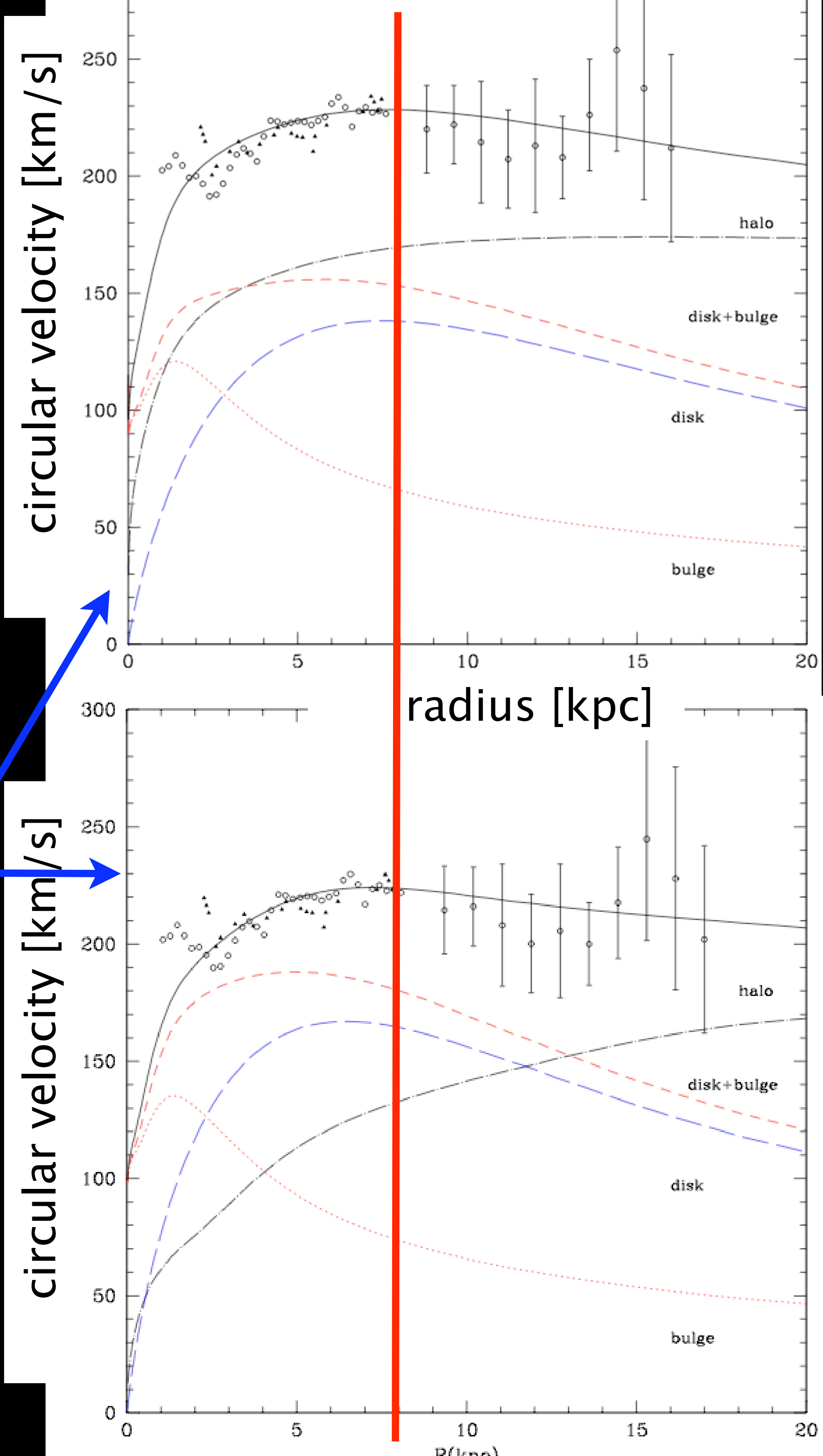


no exchange of angular momentum

with exchange

significant amounts of DM inside 8 kpc

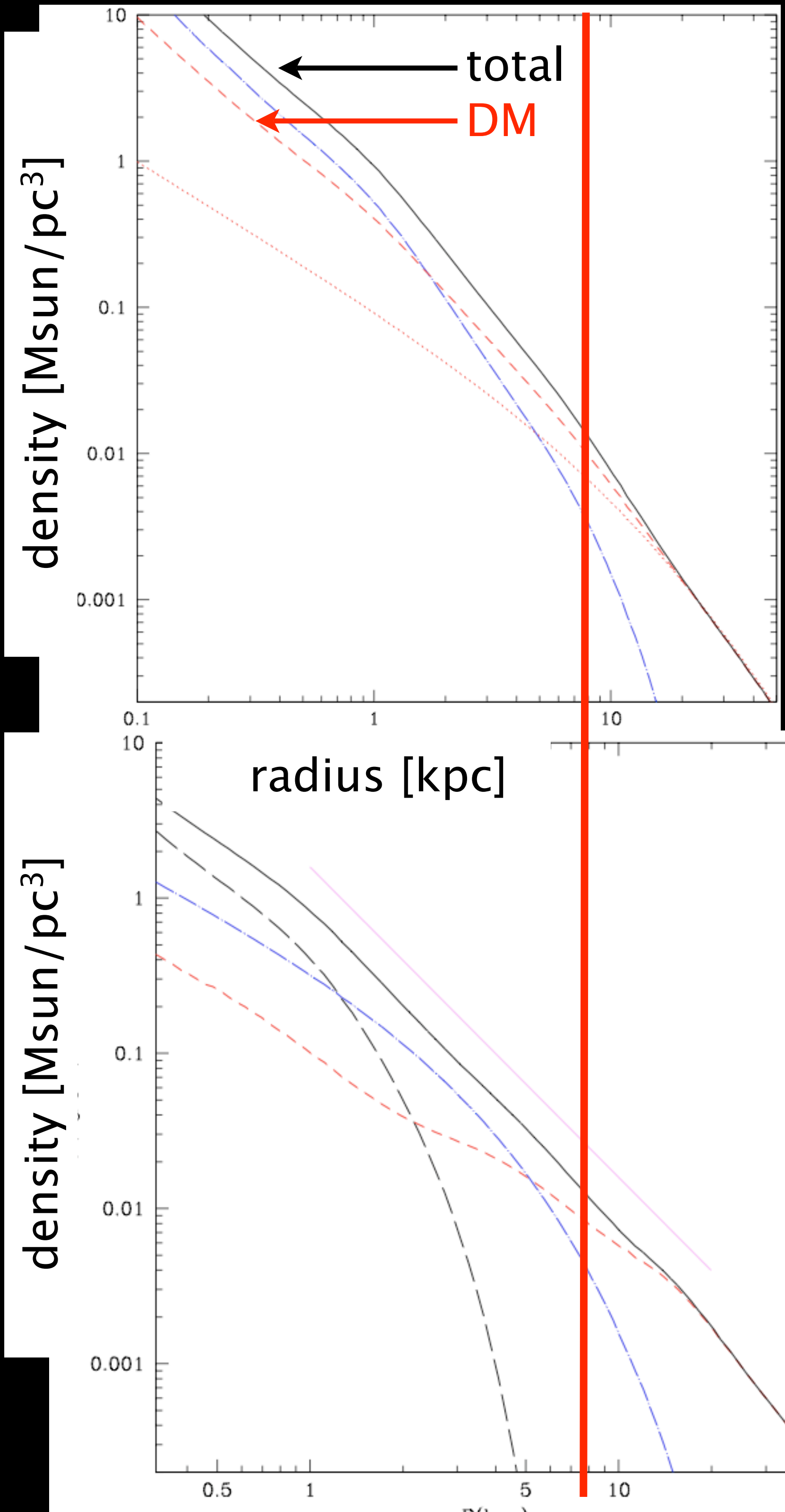
35 to 60 percent of total enclosed mass

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



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

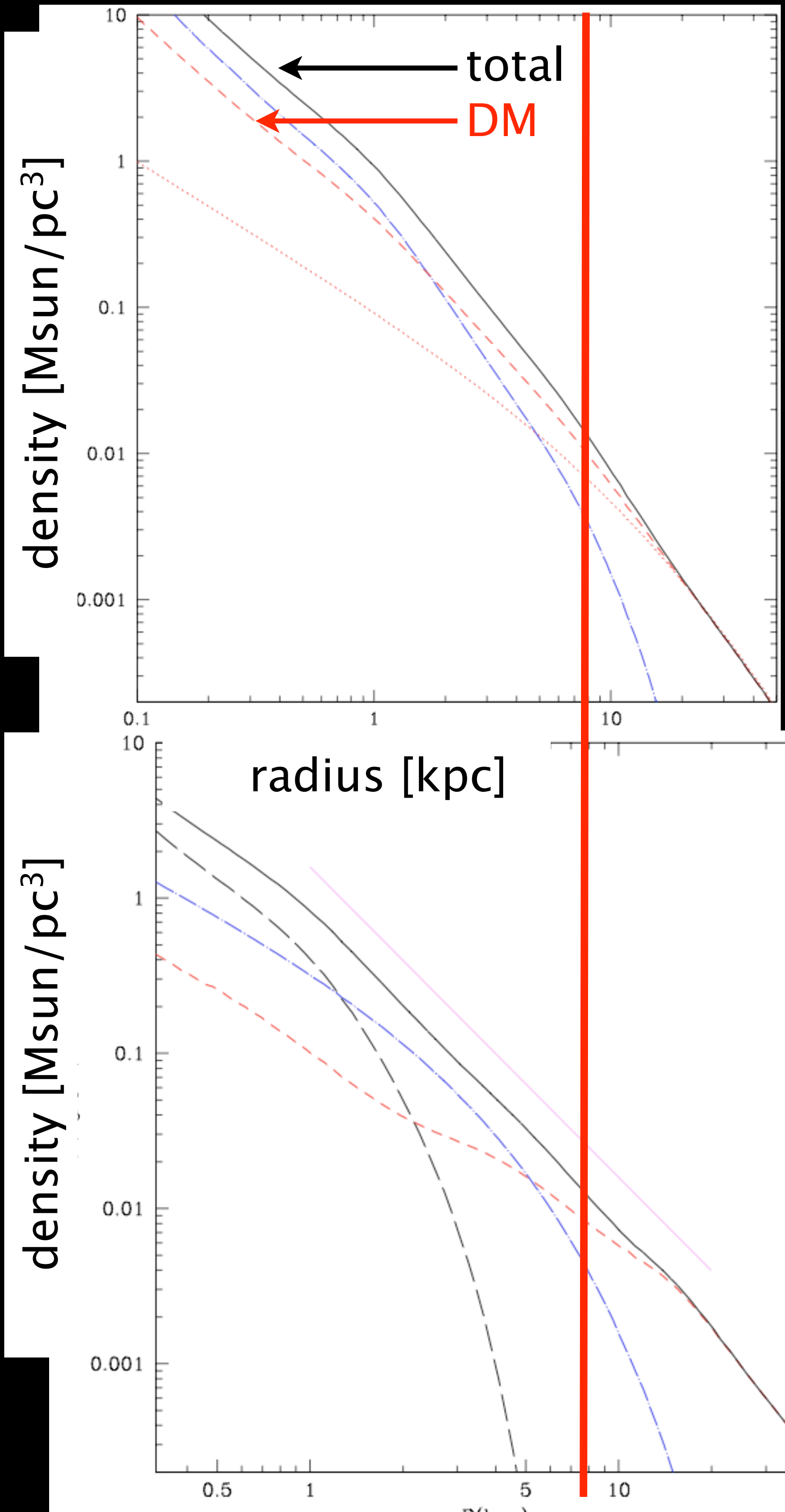
standard halo:
0.3 GeV/cm^3 = 0.008 Msun/pc^3

local surface density (Kuijken&Gilmore1989/91):

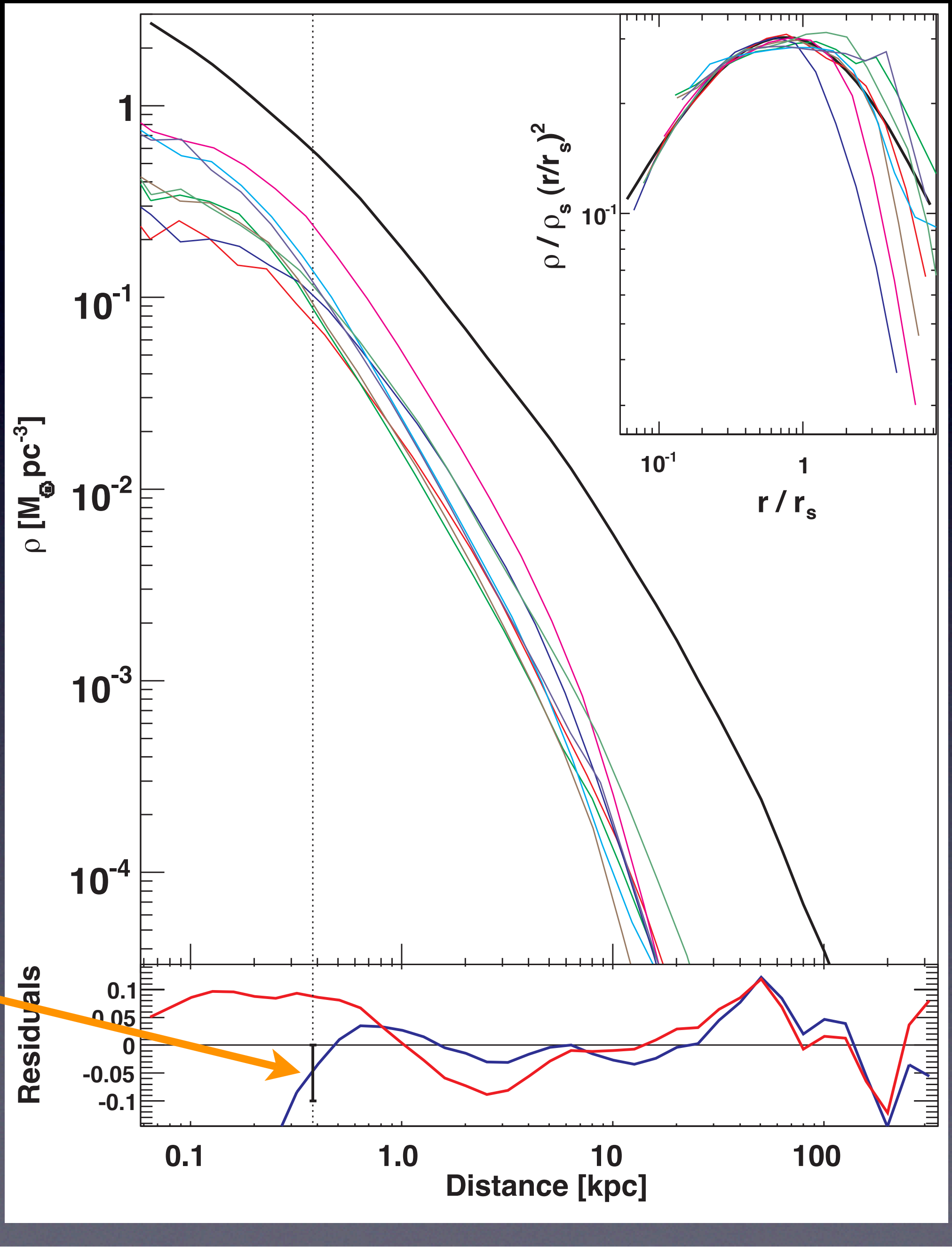
$$\Sigma_{\mathrm{stars+gas}} = 48 \pm 8\,\mathrm{M_\odot pc^{-2}}$$

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

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



host and subhalo density profiles



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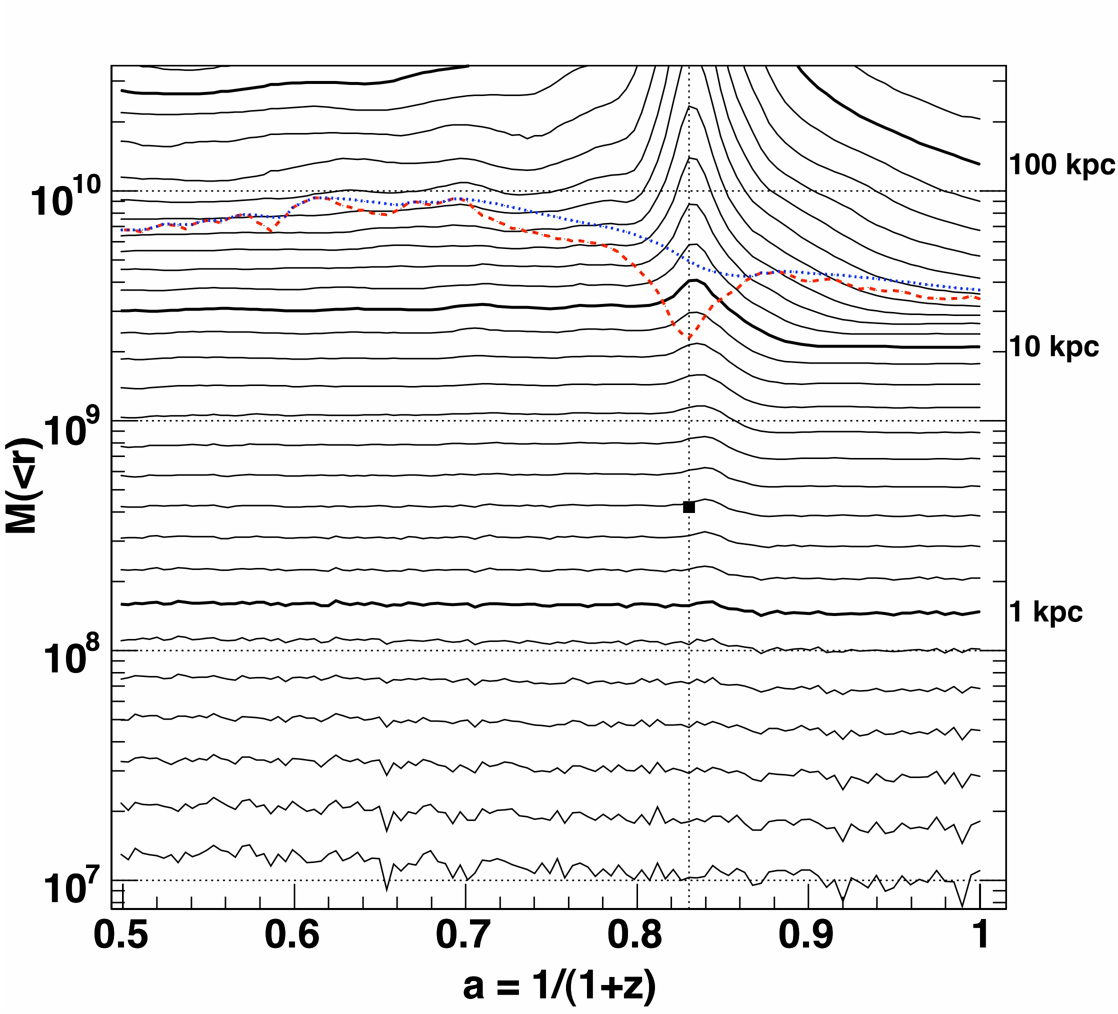
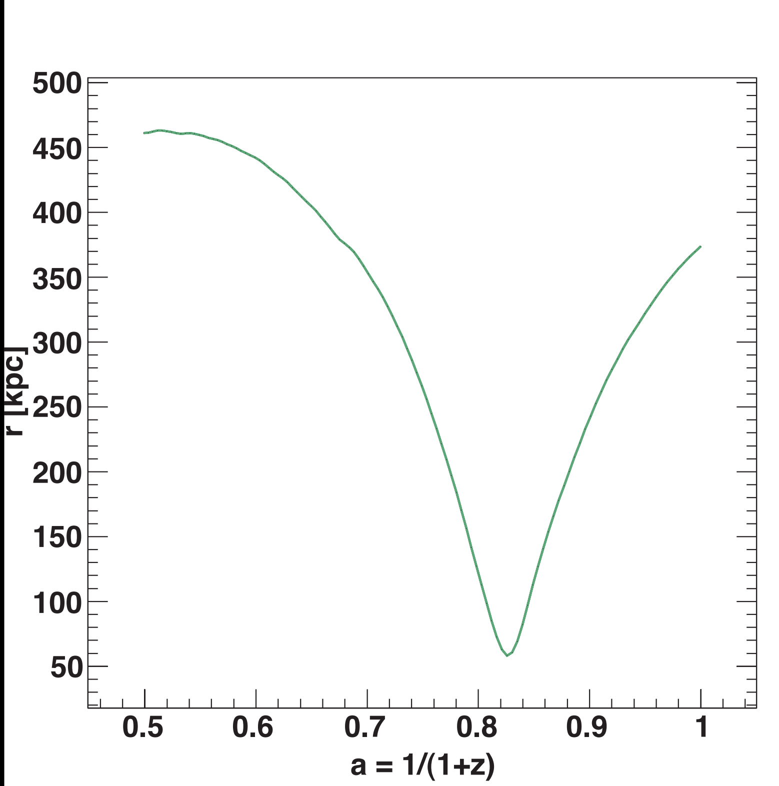
evolution of subhalo density profiles



total mass in spheres around subhalo center

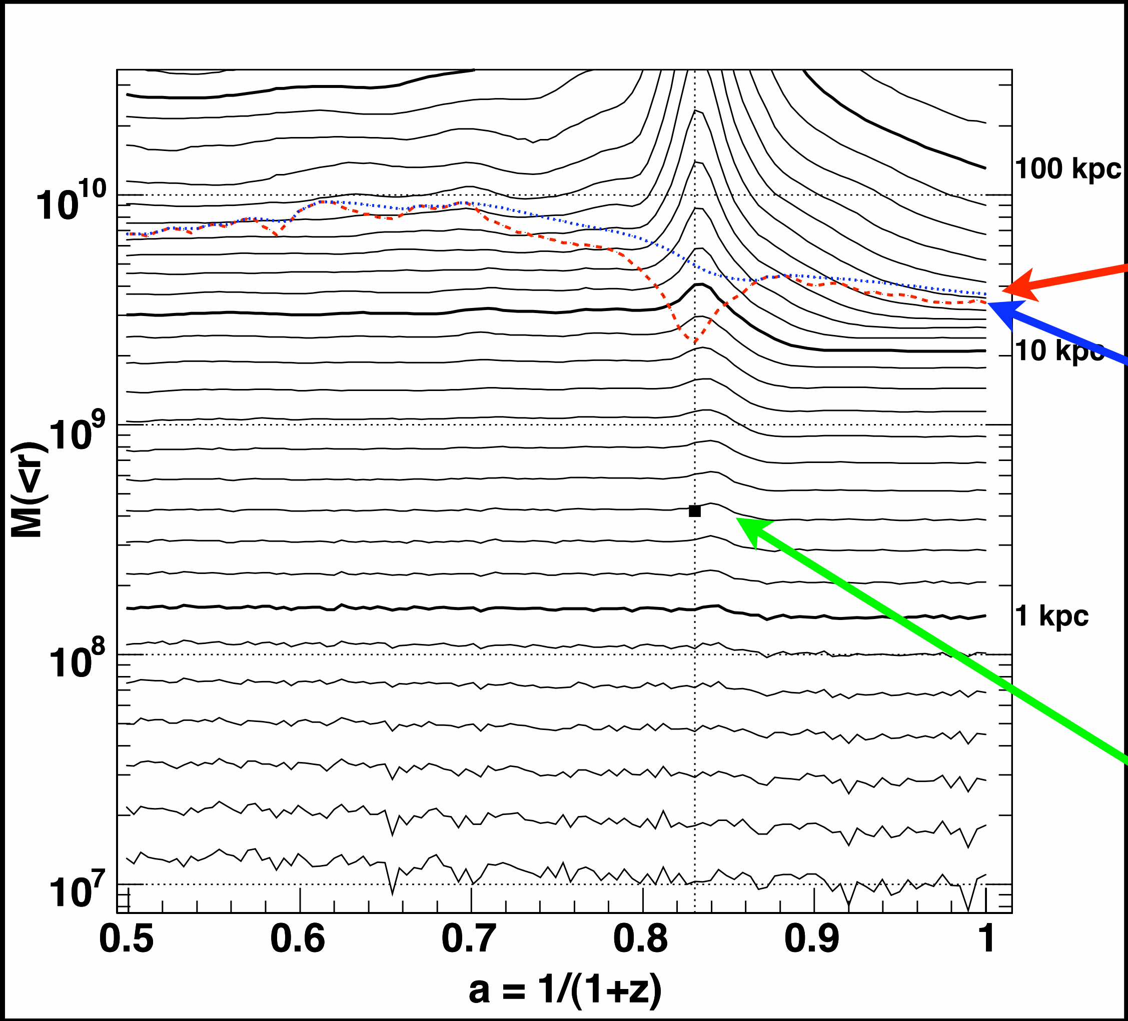
this subhalo has one pericenter passage at 56 kpc



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

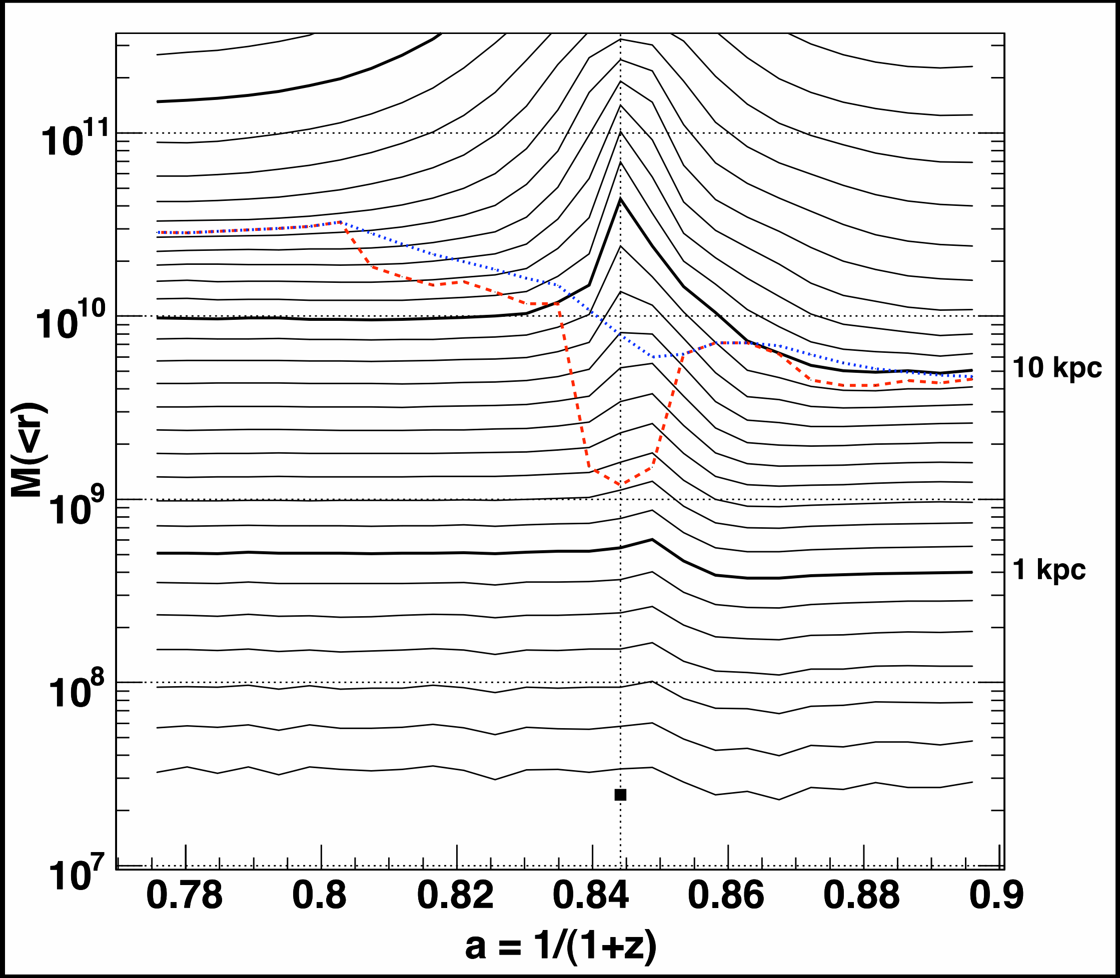
shock duration = internal subhalo orbital time

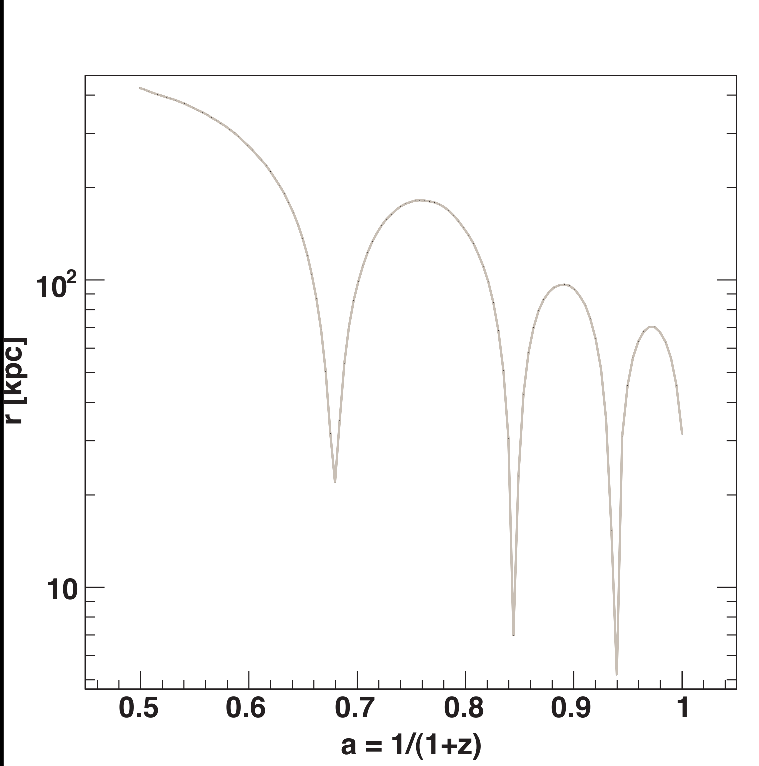
weak, long tidal shock
causes quick compression followed by expansion

mass loss is larger further out

evolution of subhalo density profiles

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



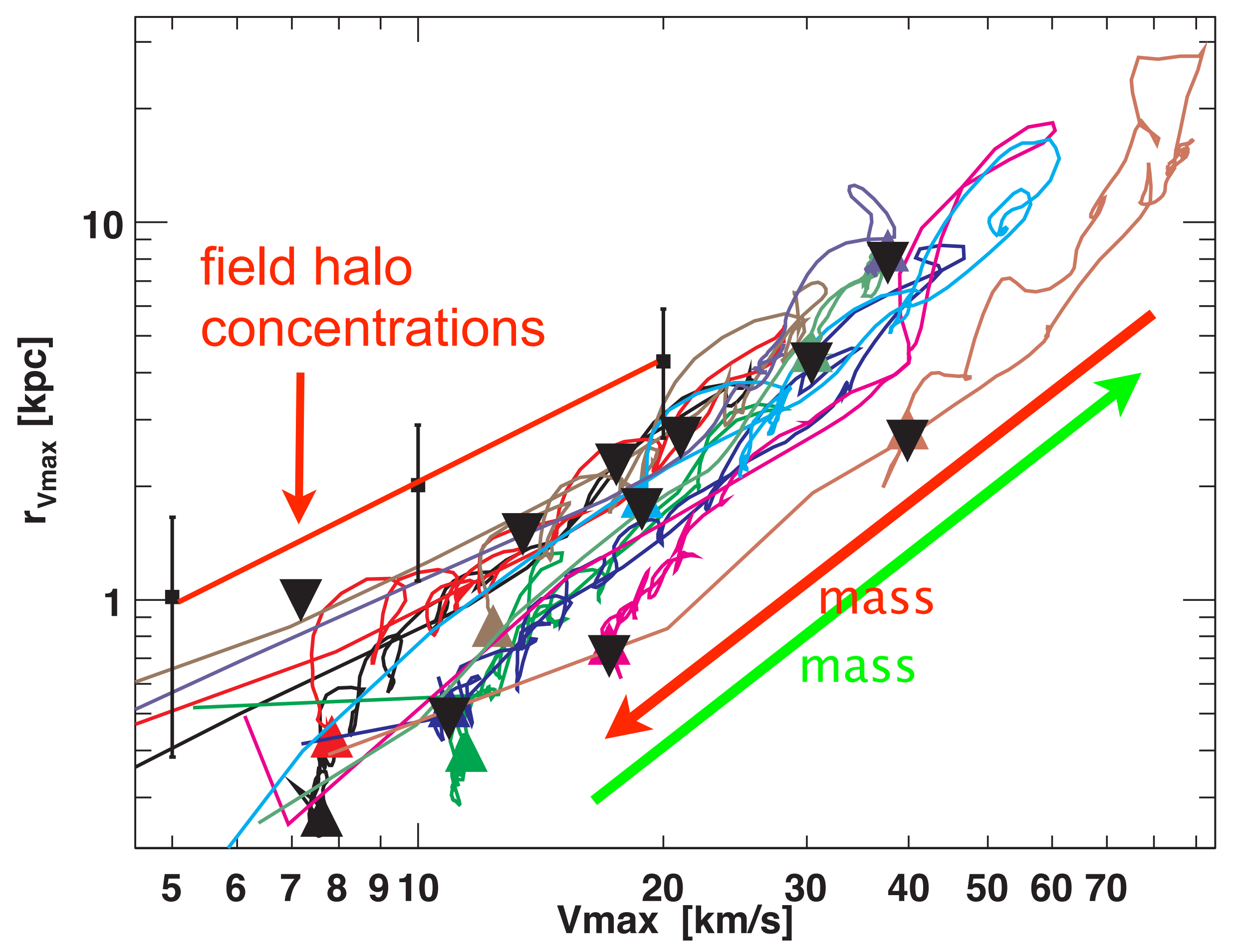


strong, short tidal shock

short duration : 43 Myr , but mass loss still grows with radius

at pericenter $r_{\mathrm{tidal}} = 0.2\ r_{V\mathrm{max}}$, but the subhalo survives this and even the next pericenter (cf. Hayashi, Navarro et al 2003)

evolution of subhalo density profiles



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

➡ stripped halos resemble high redshift systems

➡ they have higher concentrations

(not lower as claimed by Stoehr, White et al 2002/03, Hayashi,Navarro et al 2003)

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)

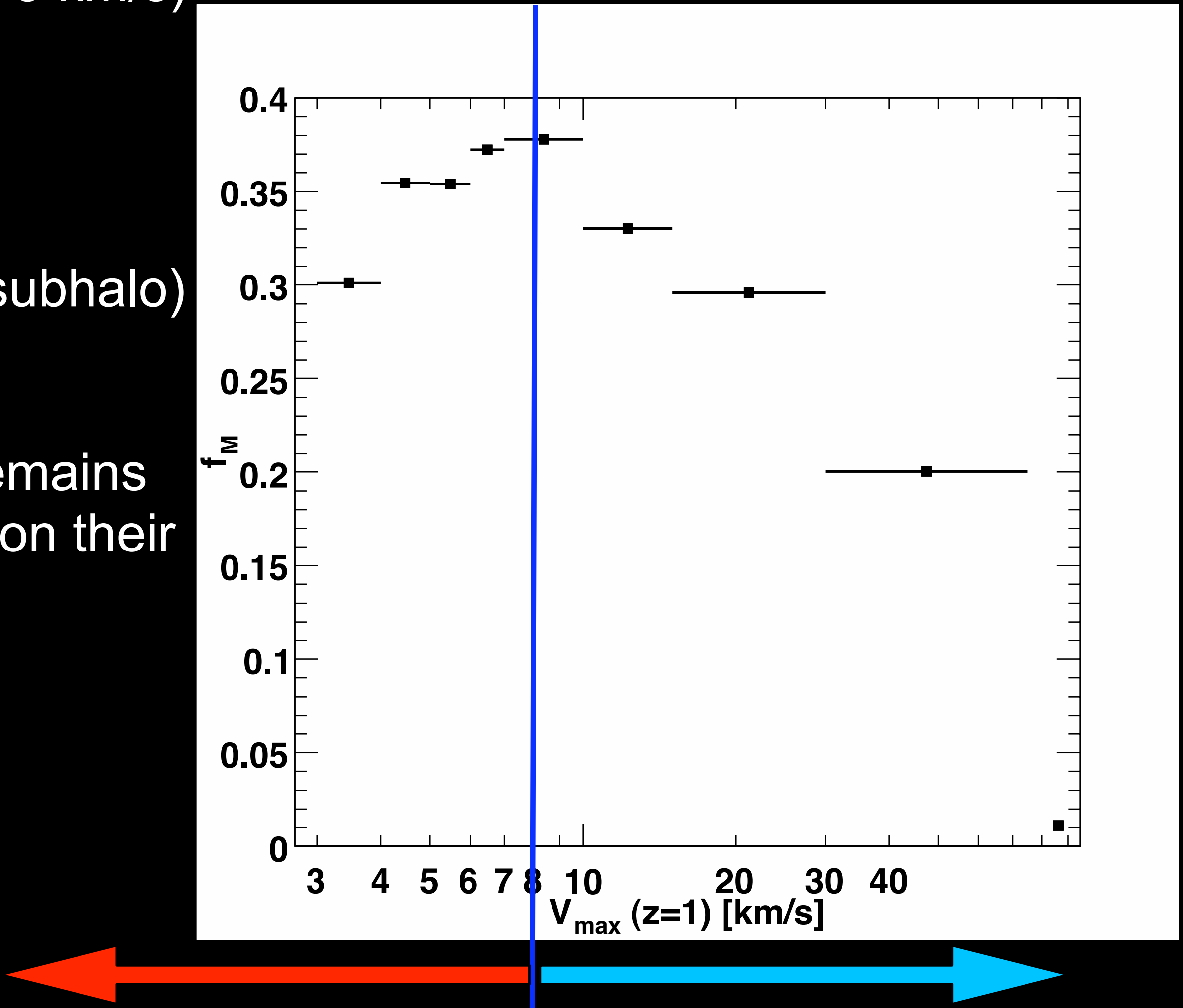
subhalo survival and merging

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

97 % survive until z=0

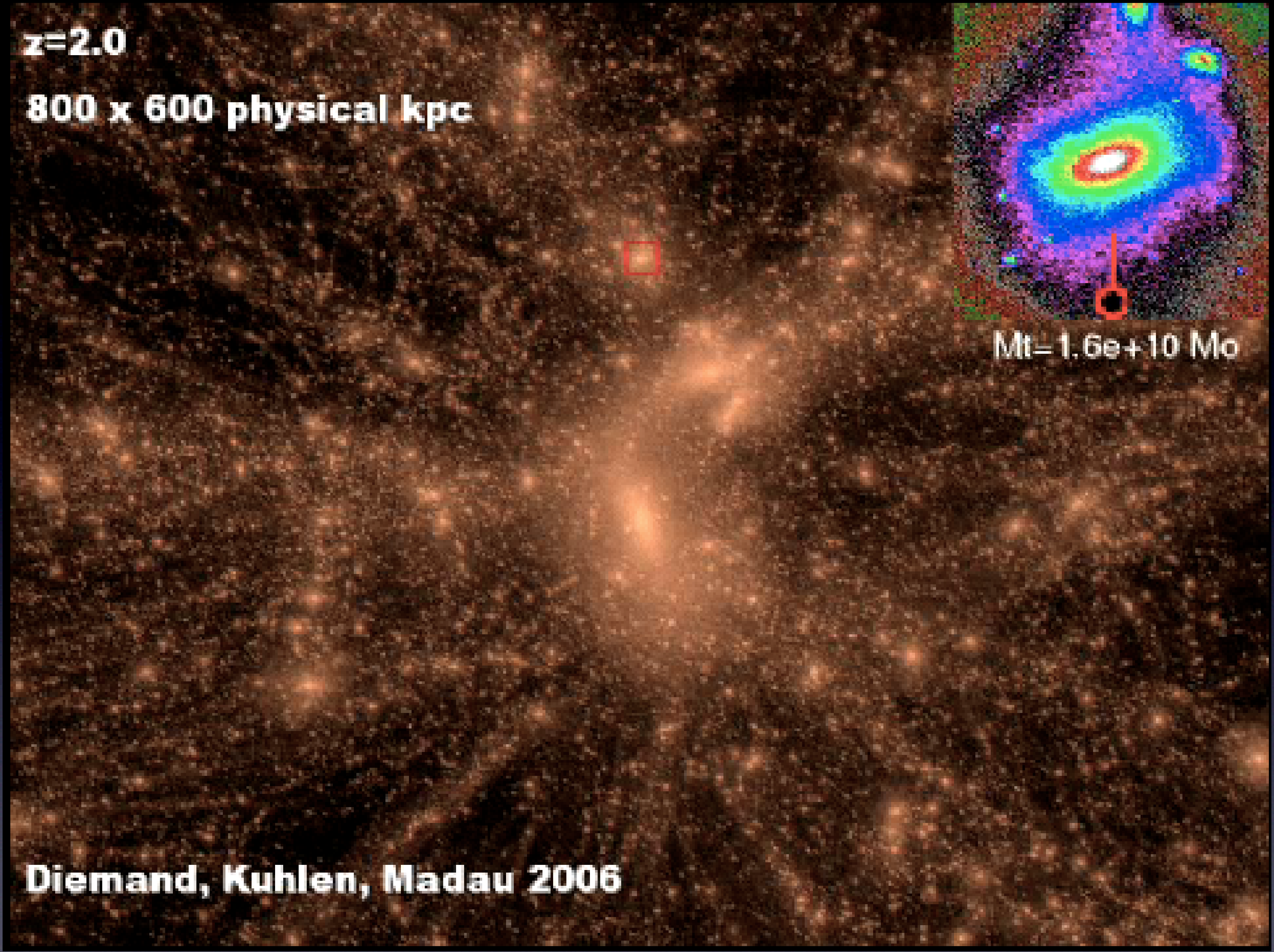
(only 1.3% merge into a larger subhalo)

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

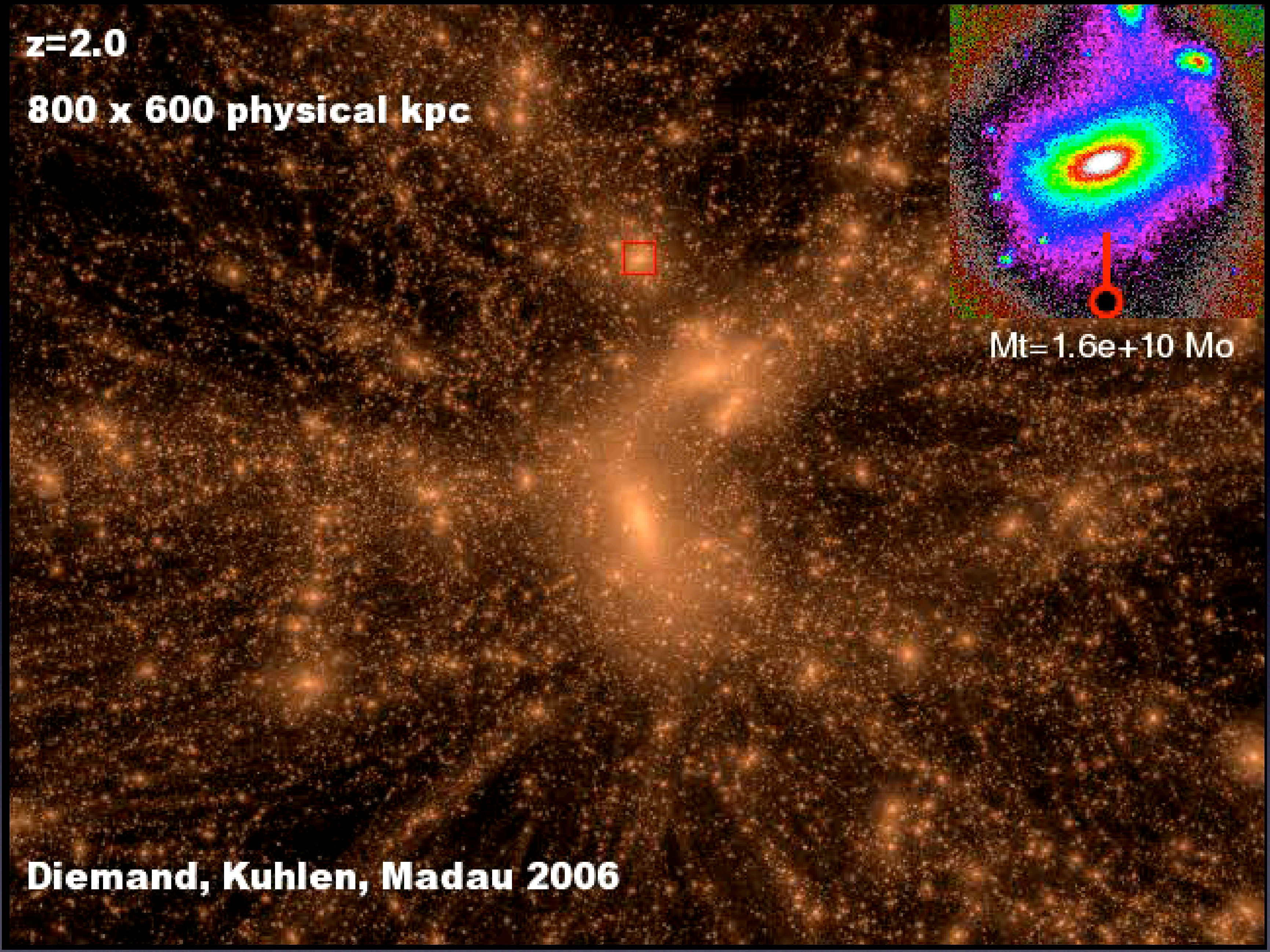


affected by numerical limitations

stronger dynamical friction



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, Knebe+2008)



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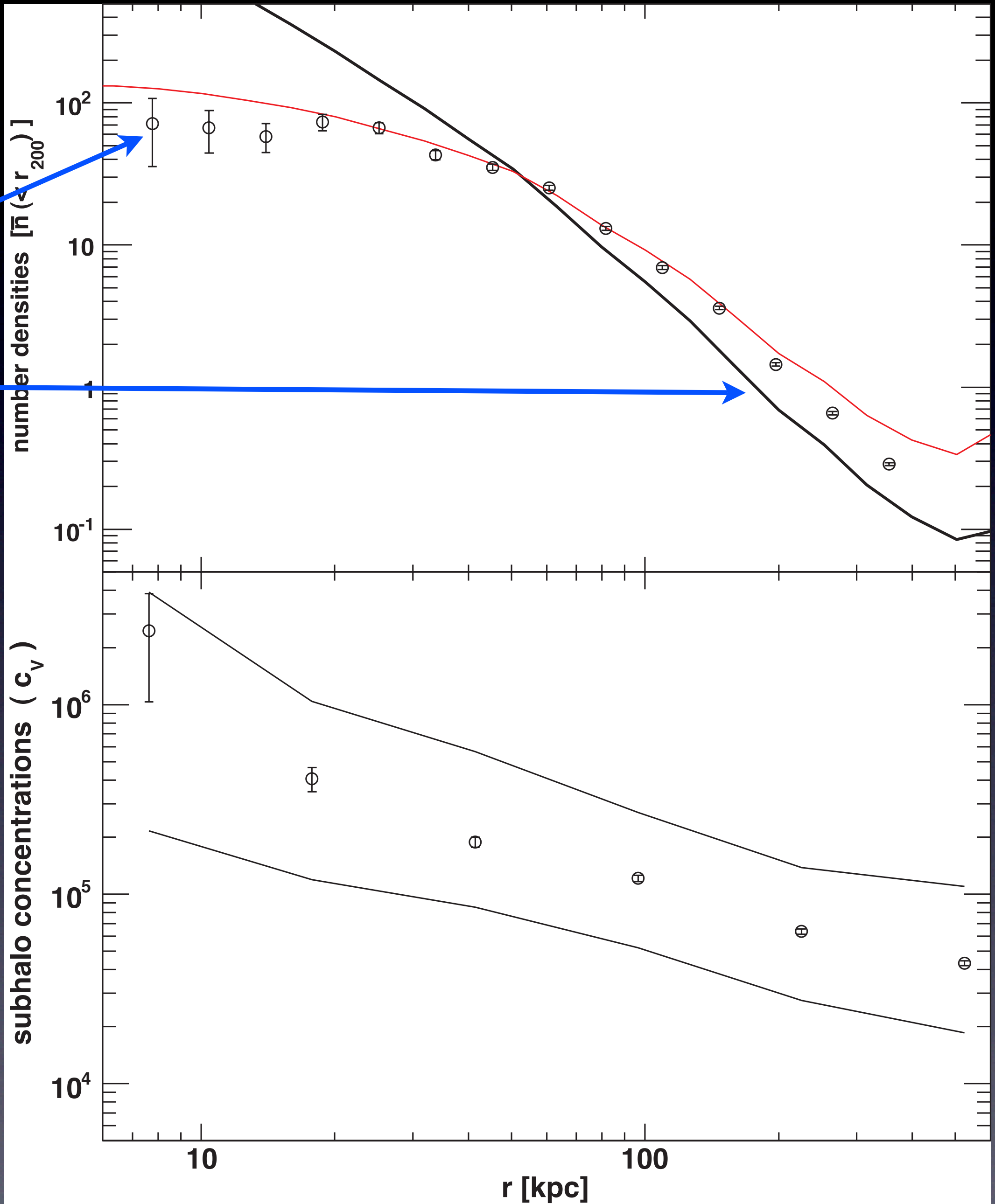
(Kuhlen, JD, Madau 0705.2037, Faltenbacher+0706.0262, Pereira+0707.1702, Knebe+2008)

VL-II : first significant sample of local subhalos

local mass fraction is low because of efficient tidal mass loss

Vmax(at z=0) > 5 km/s subhalos are found at larger radii than the dark matter

this ‘anti-bias’ is larger in mass(z=0) samples



JD et al. Nature 2008

denser parts survive, subhalo concentrations increase towards the galactic center

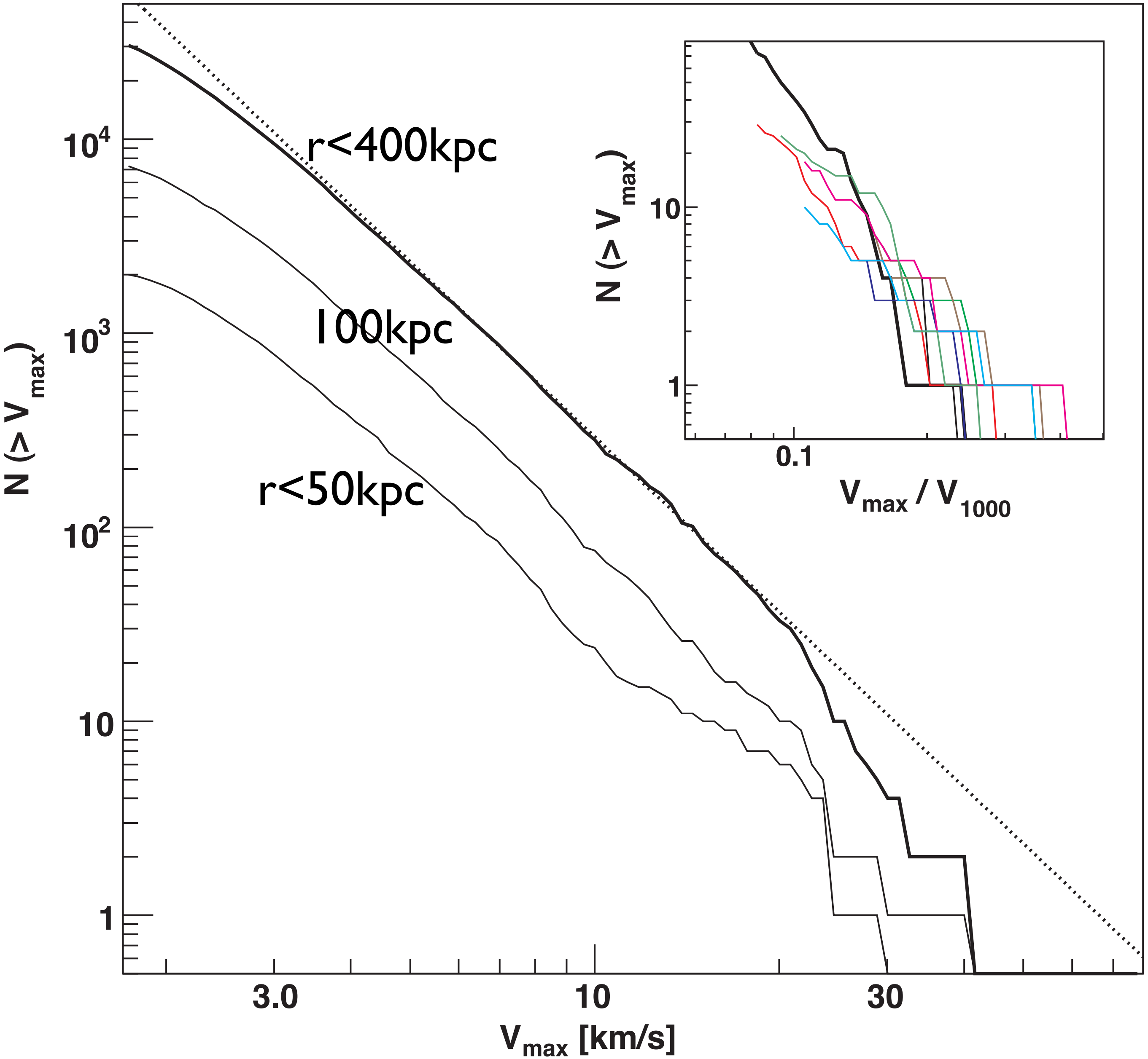
subhalo luminosity :

$$L \propto \rho_s^2 r_s^3 \propto V_{\rm max}^4/r_{\rm Vmax} \propto V_{\rm max}^3\sqrt{c_V}$$

is practically unbiased in the well resolved radial range

subhalo and sub-subhalo abundance

$$L \propto \rho_s^2 r_s^3 \propto V_{\rm max}^4 / r_{\rm Vmax} \propto V_{\rm max}^3 \sqrt{c_V}$$



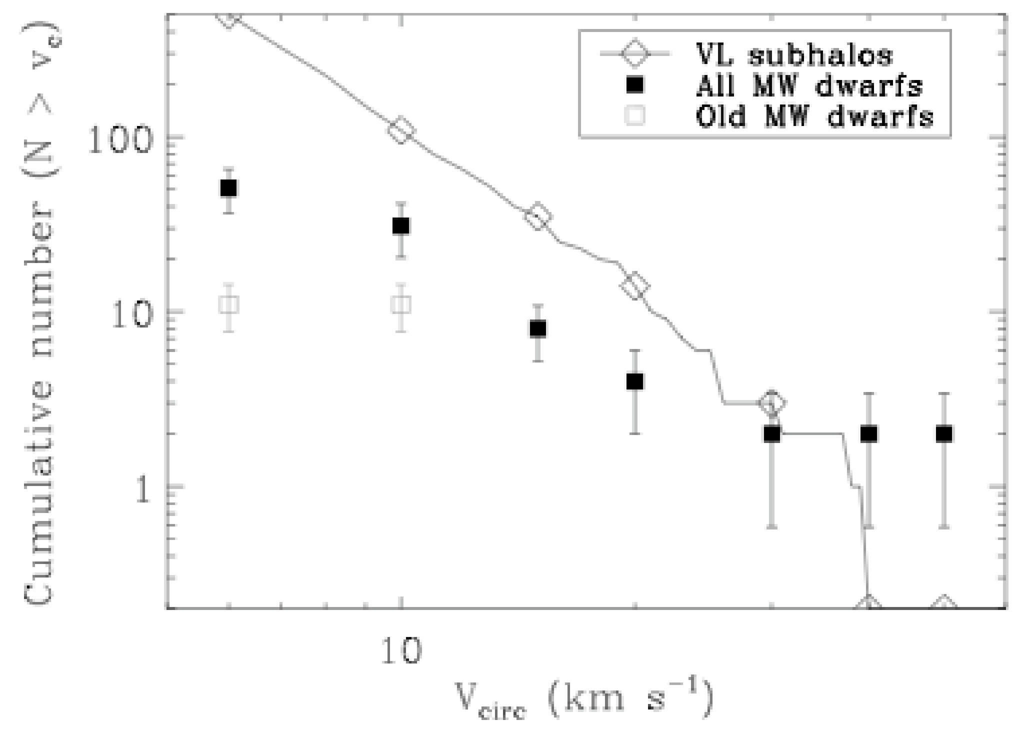
$N(>V) \sim V^{-3}$
annihilation singal has not converged yet

$N(>M) \sim M^{-alpha}$
alpha = 0.93 - 1.0
mass in subhalos not converged

Milky Way scale still uncertain:
160 - 220 km/s
VL-II : Vmax=201 km/s

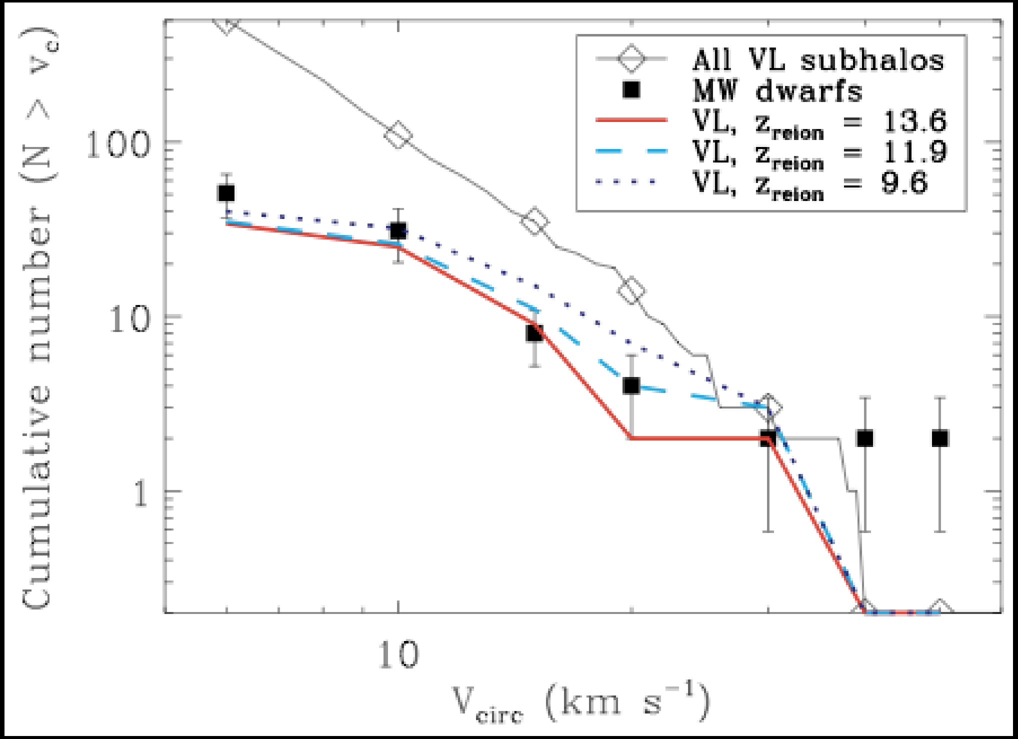
missing satellites?

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

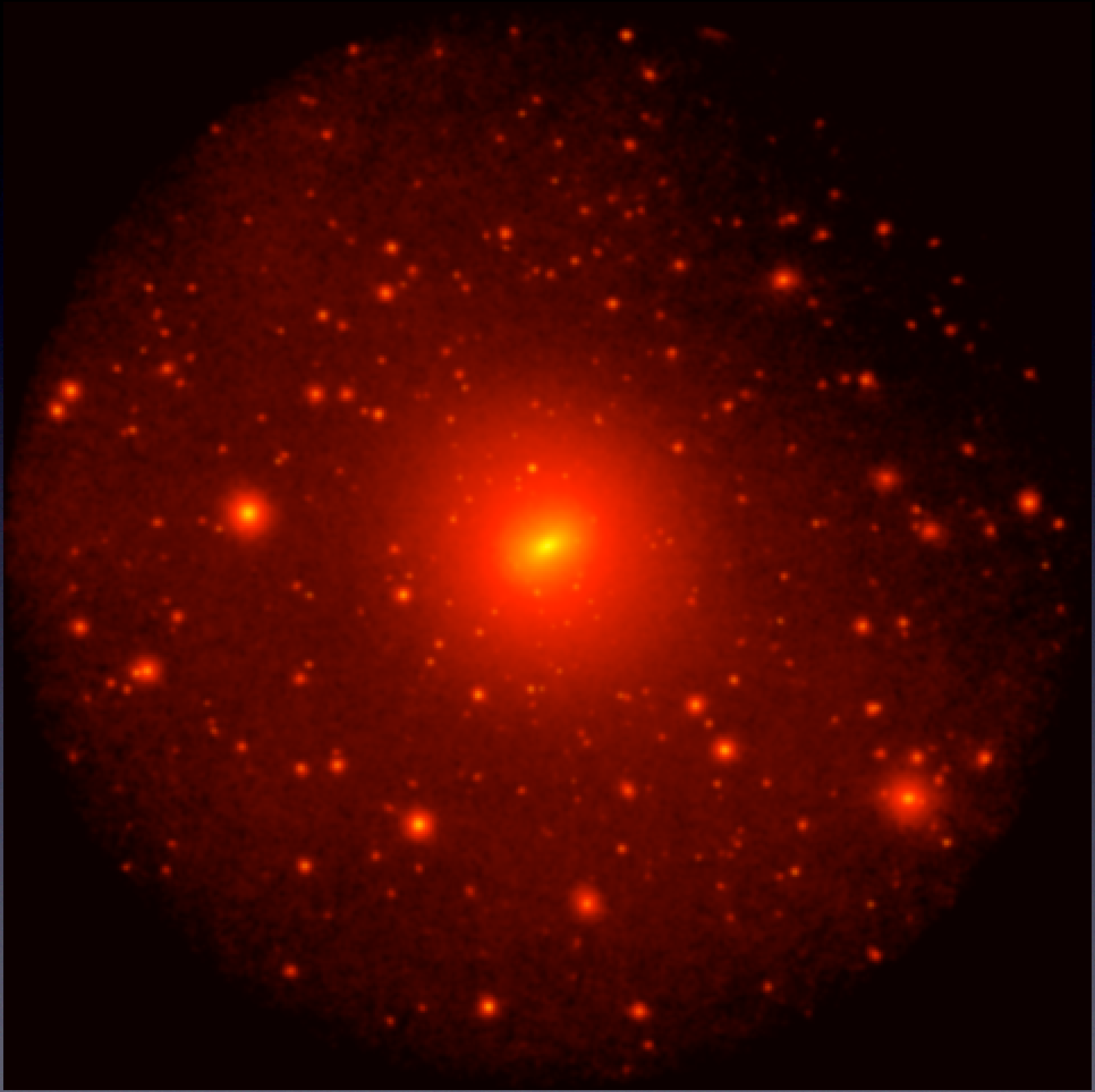


earliest forming subhalos
(or the largest before accretion)
would have roughly the right masses
and the correct spatial distribution
(Moore,JD et al 2006)

there might be ~1000 dwarf satellites
(Tollerud+2008)
CDM does have enough host halos



substructure inside subhalos



‘boost factors’

$$\text{halo boost factor} = \frac{\text{total halo luminosity}}{\text{spherical, smooth halo luminosity}}$$

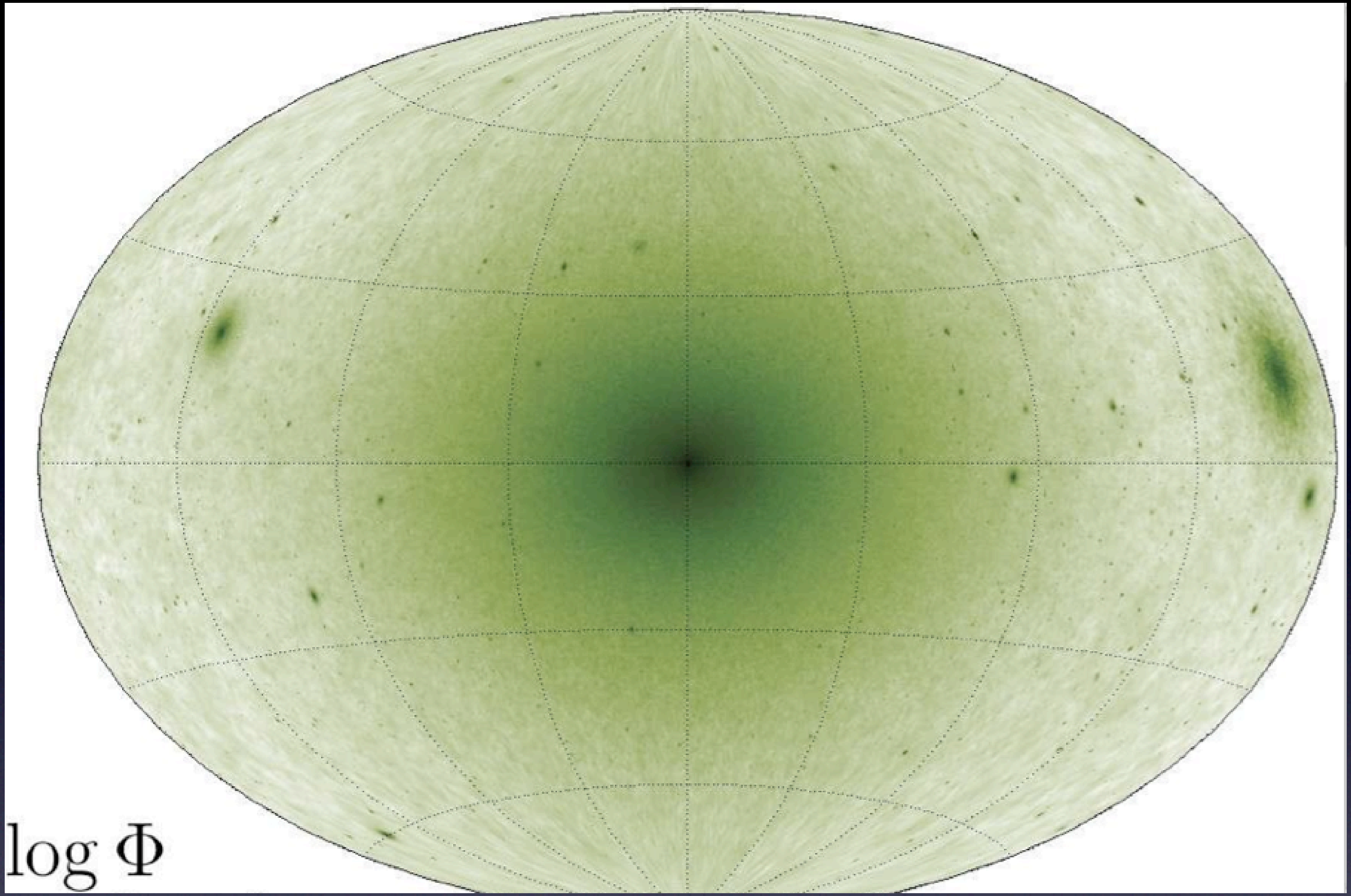
~ 4 - 15	JD et al 2006 and astro-ph/0805.1244
not ~1.7	Stoehr, White, Springel et al. 2003
not 232	Springel et al. Nature, 2008

$$\text{local boost factor} = \frac{\text{total local luminosity}}{\text{smooth local halo luminosity}}$$

~ 1.4 (larger than 10 in only 1% of all locations at 8 kpc)
probably too low to explain HEAT/PAMELA e+ with DM

JD et al astro-ph/0805.1244

Allsky map of DM annihilation signal from via lactea II



main halo obviously the brightest source, but poorly constrained, diffuse, astrophysical foregrounds (e.g. Strong & Mosch XX) make subhalos the more promising sources (Baltz et al. 2008)

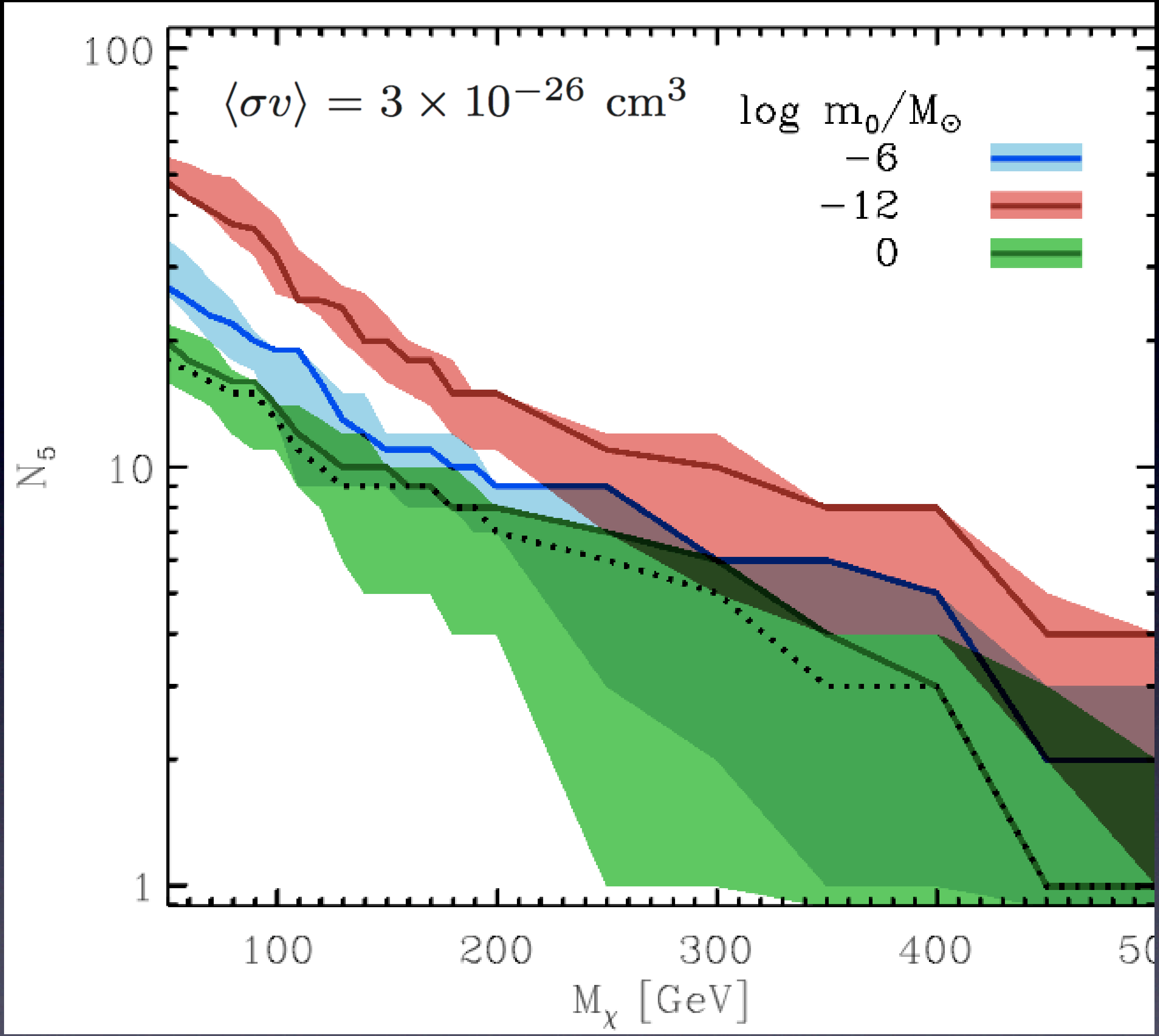
number of 5 sigma subhalo detection by GLAST/Fermi in 2★ years

optimistic boost from unresolved small scale structure

fiducial

pessimistic

no boost : dotted

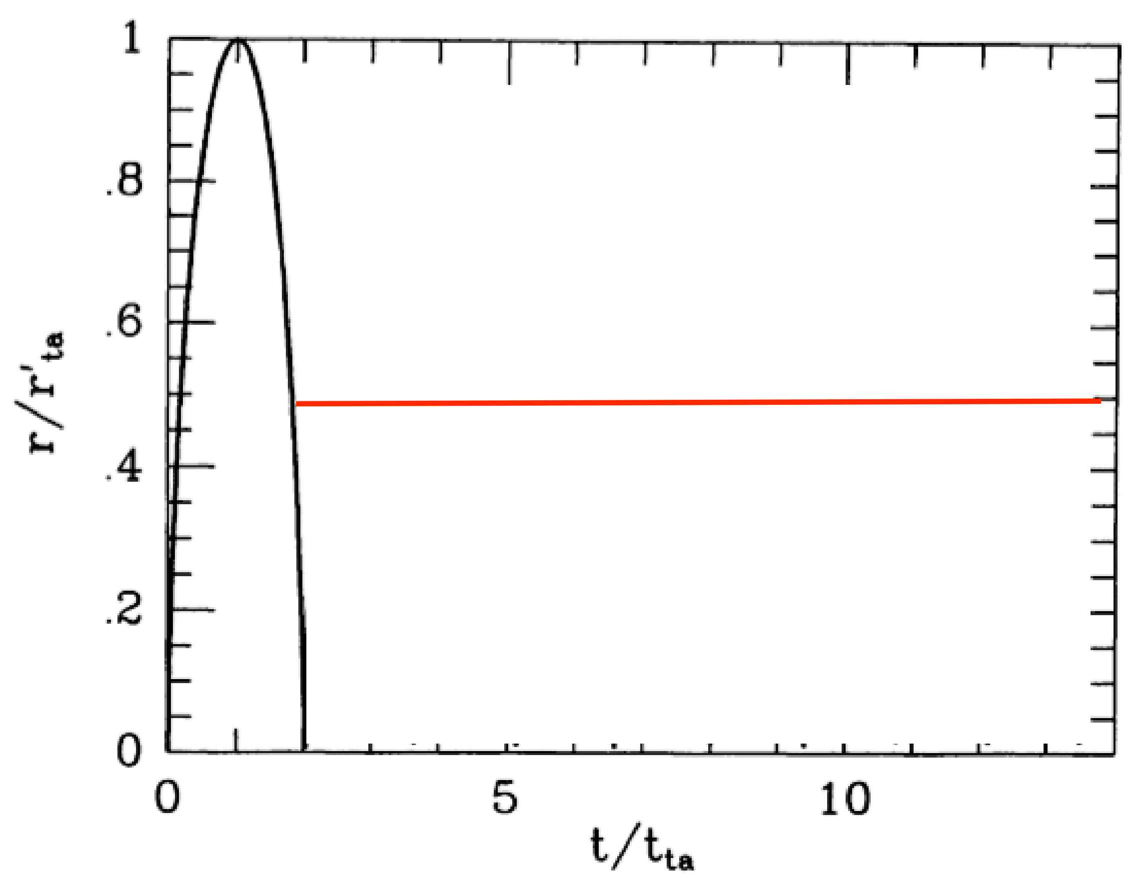


small scales structure not crucial for detection
promising numbers typical WIMP properties
(Kuhlen, JD & Madau 2008)

★ 2yr allsky integration~10yr of flight

2) how do halos accrete their mass?

spherical radial top-hat collapse

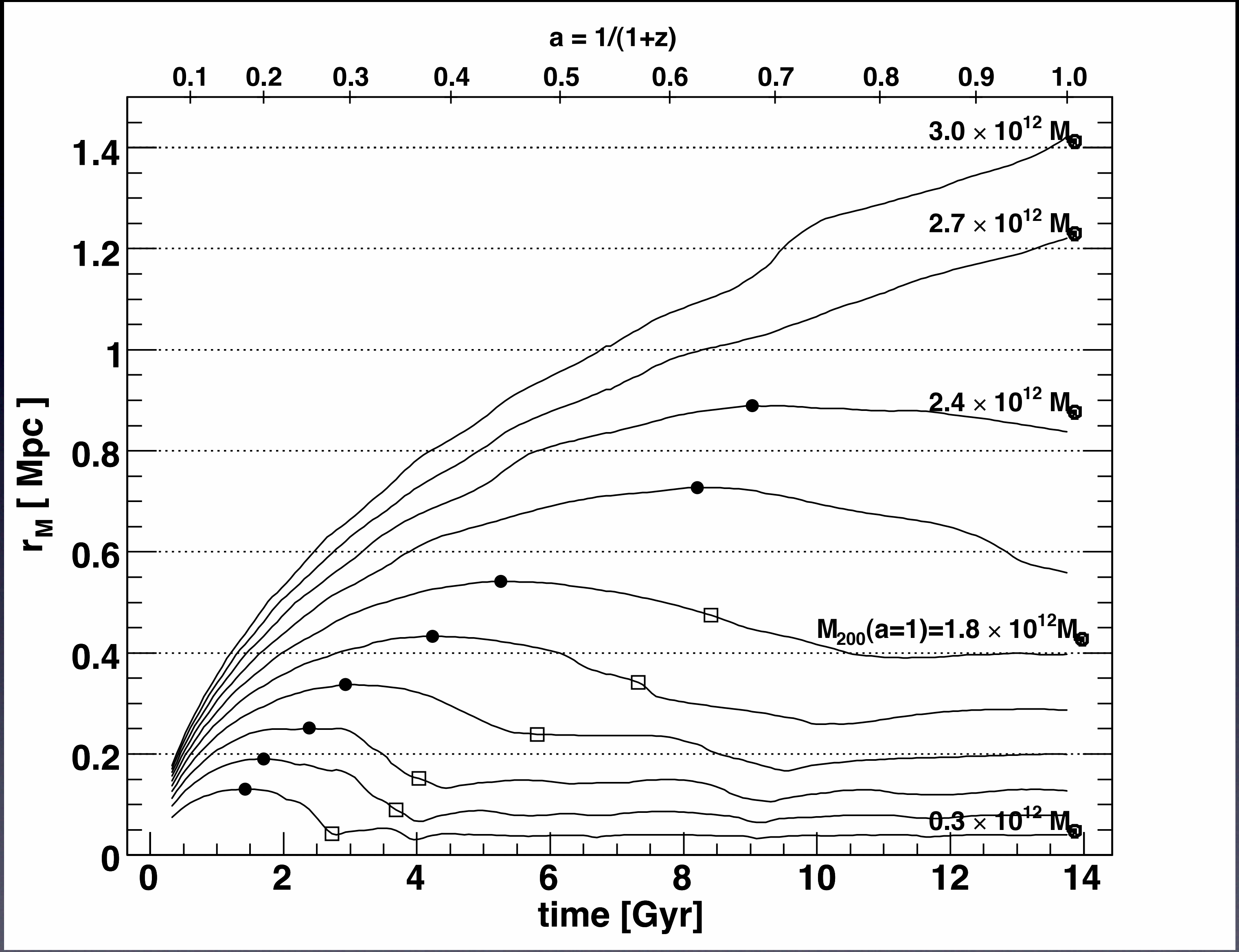


assumes virialisation at
half the turnaround radius

basis for definition of
'virial' radius:
r_178 for EdS
r_340 LambdaCDM z=0
(contrast over mean
matter density)

(Gunn, Gott ... 1970ies)

Spherical shells of fixed mass



JD, Kuhlen, Madau 2007

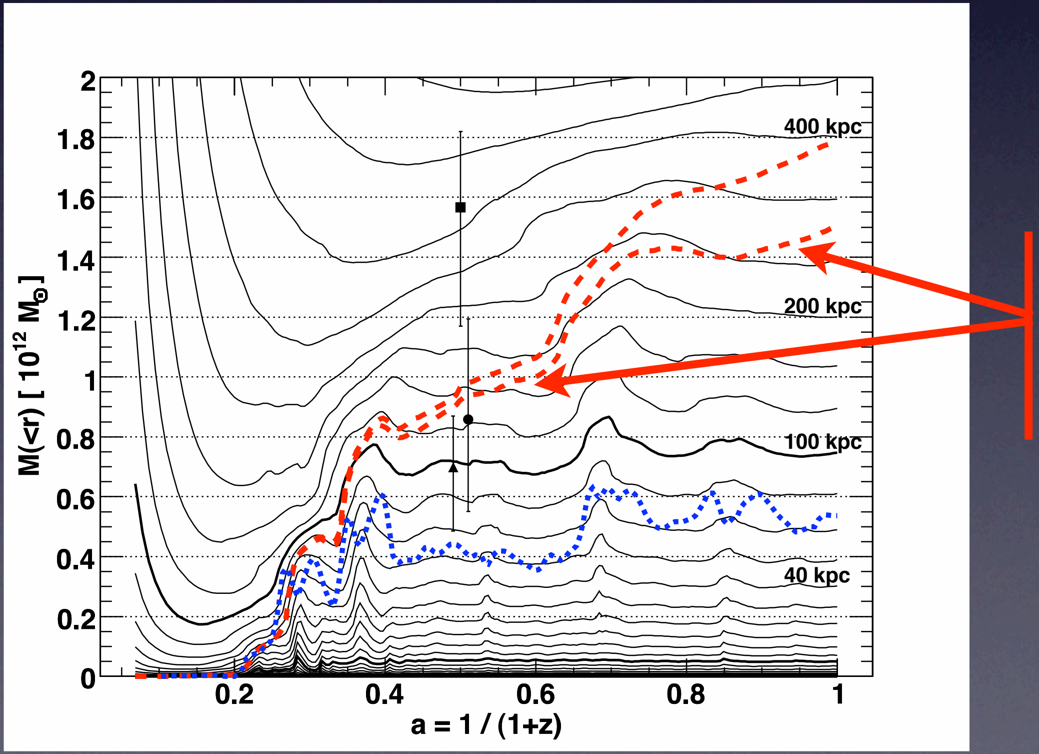
2) how do halos accrete their mass?

spherical radial top-hat collapse : problems

- galaxy halos are stationary to about 2 virial radii (Prada,Klypin+2005)
- mass accretion history ≠ M_vir(z)

  collapse factor only 1.36 not 2 for the virial mass shell

  shells constantly exchange mass (JD,Kuhlen,Madau2007)

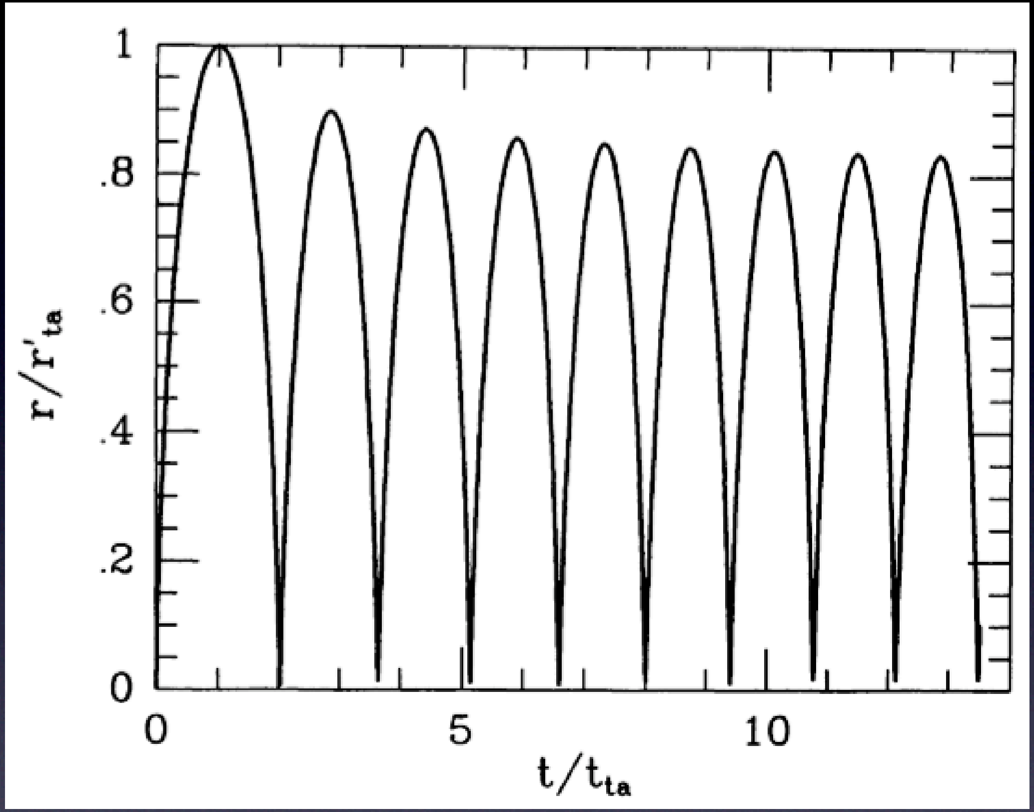


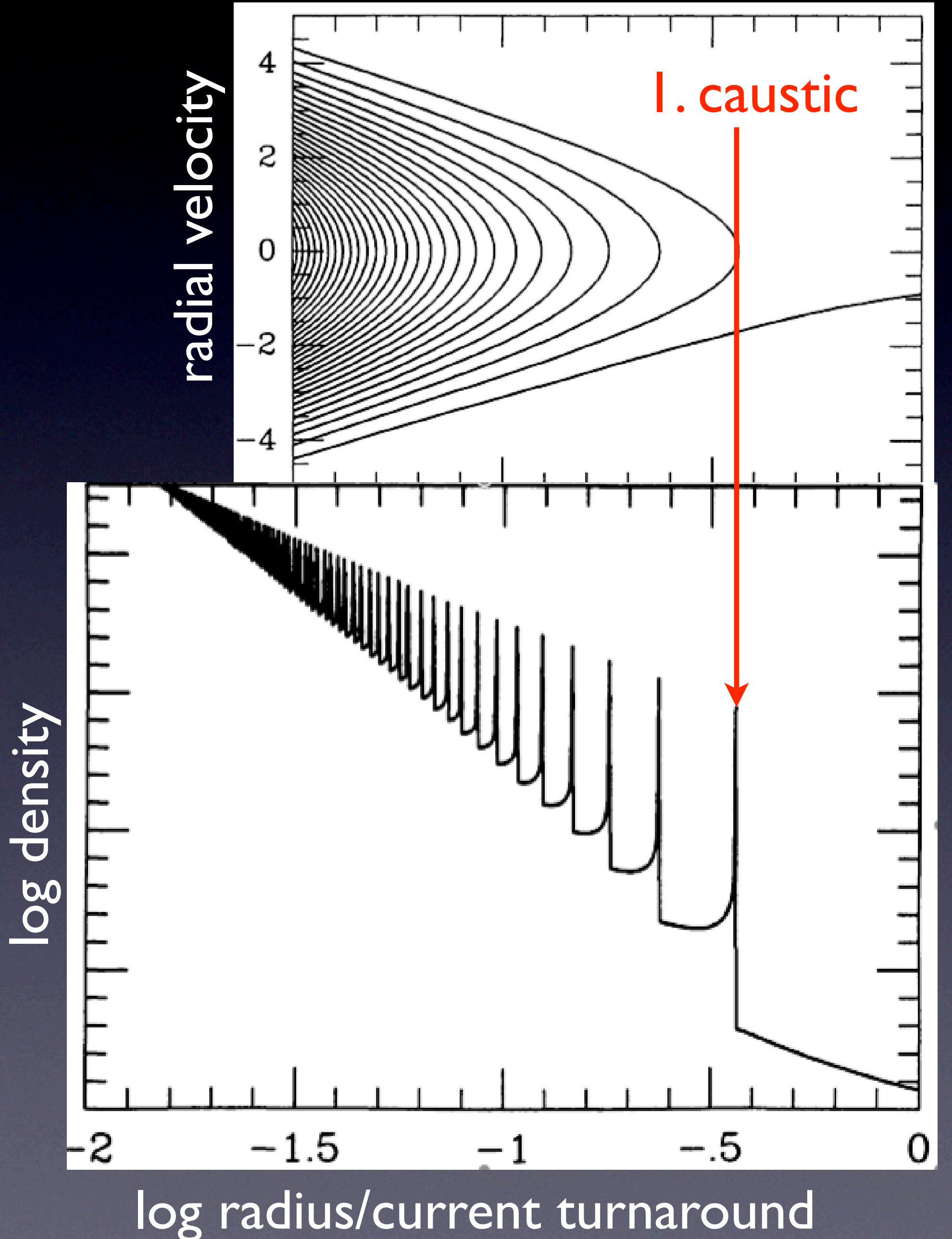
nominal growth in M_vir
in epochs without real growth

97.5% contributed by infalling, resolved clumps
no smooth accretion (Madau+2008)

2) how do halos accrete their mass?

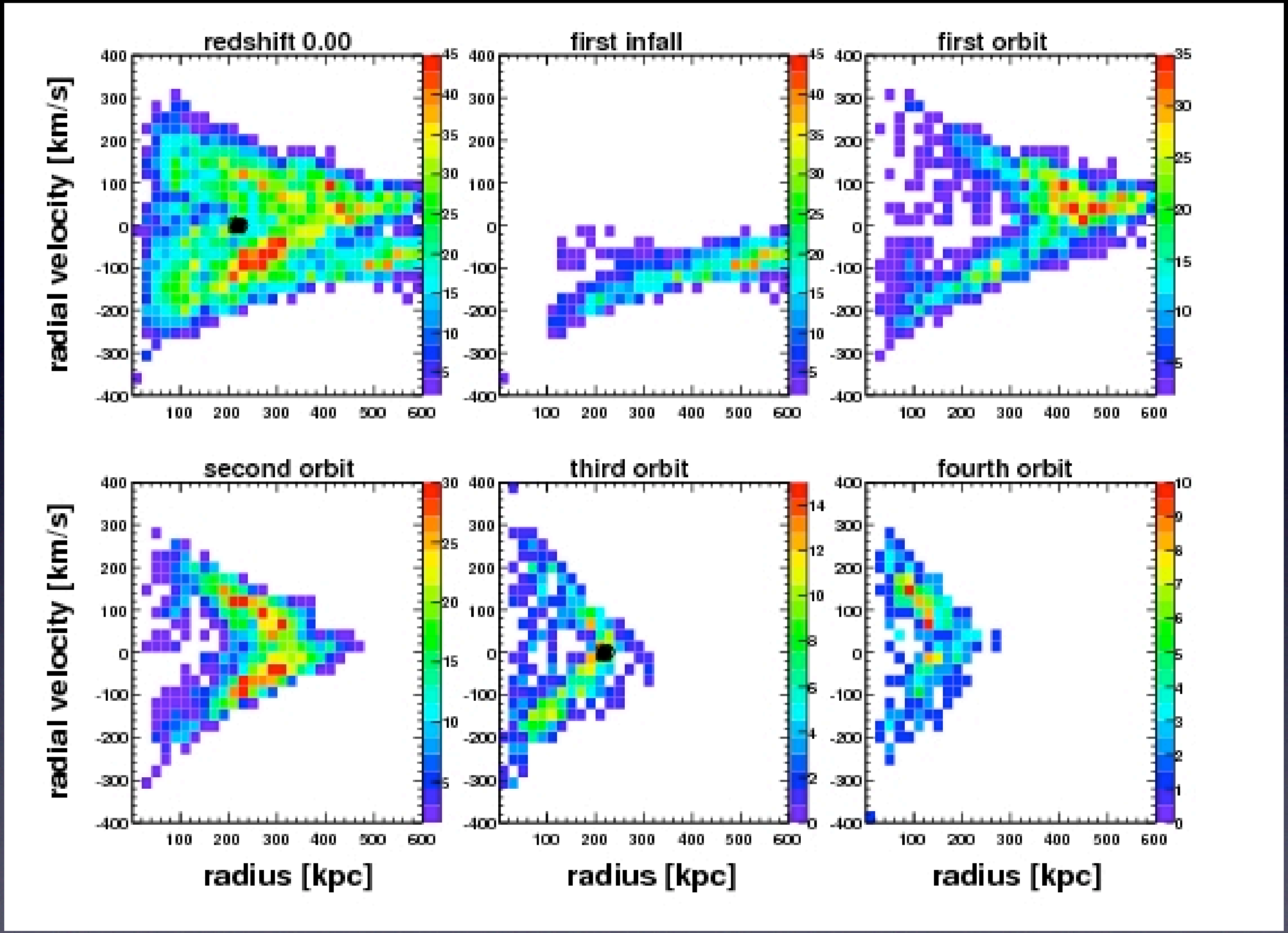
self-similar secondary spherical radial infall model:



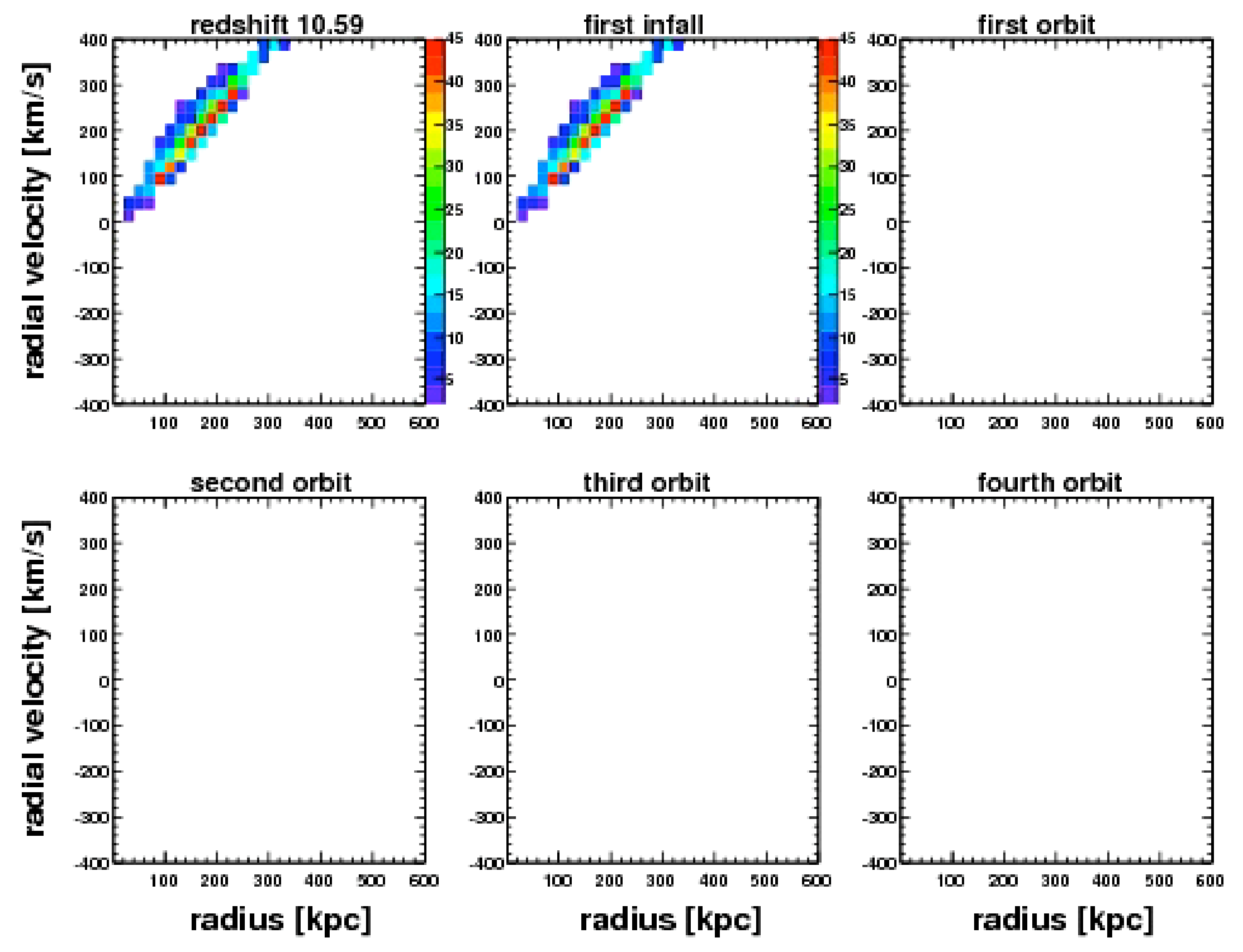


Fillmore&Goldreich1984;Bertschinger1985

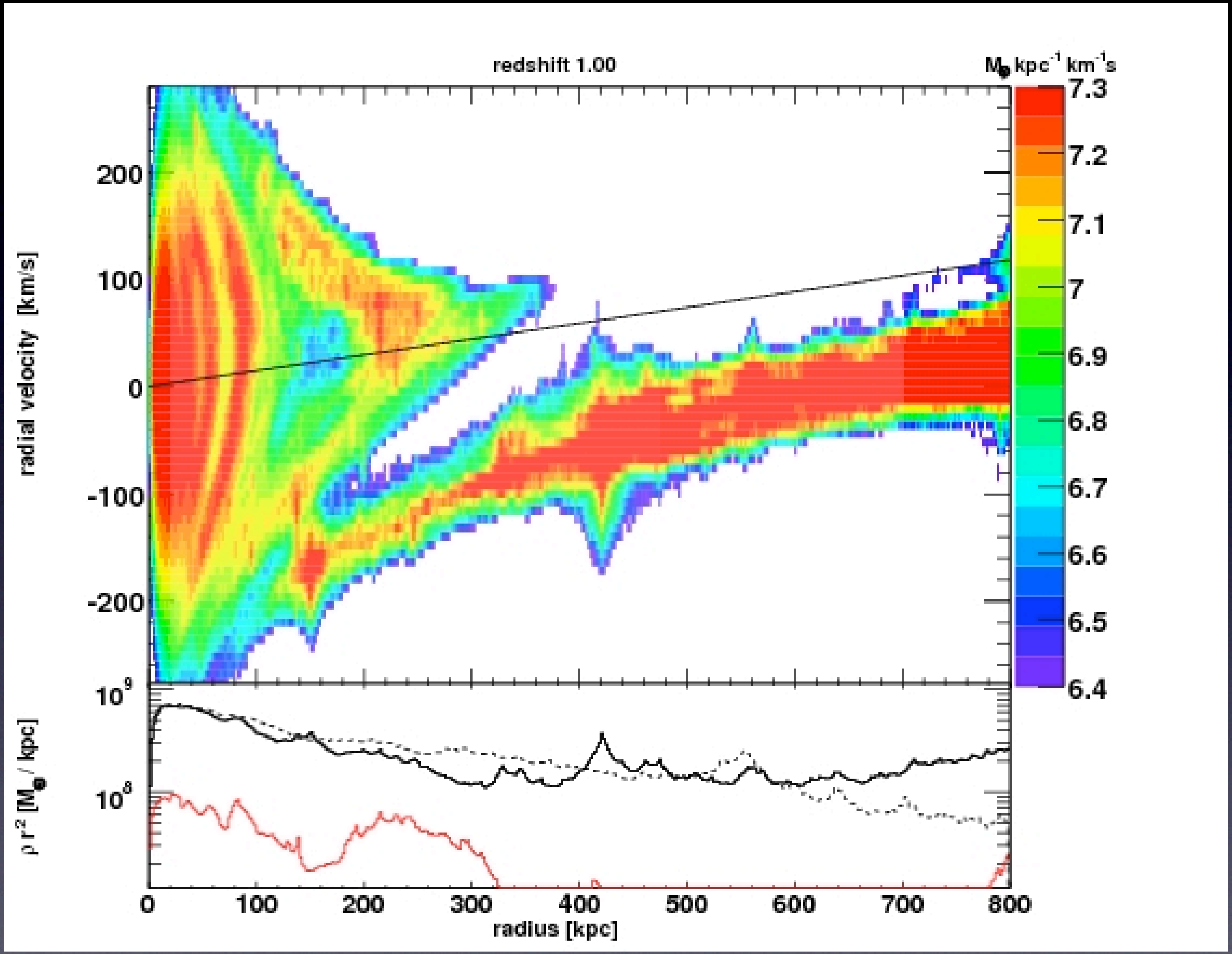
small collapse factors of 12% to 18%
rho ~ r^-2.25 with infinite density caustics



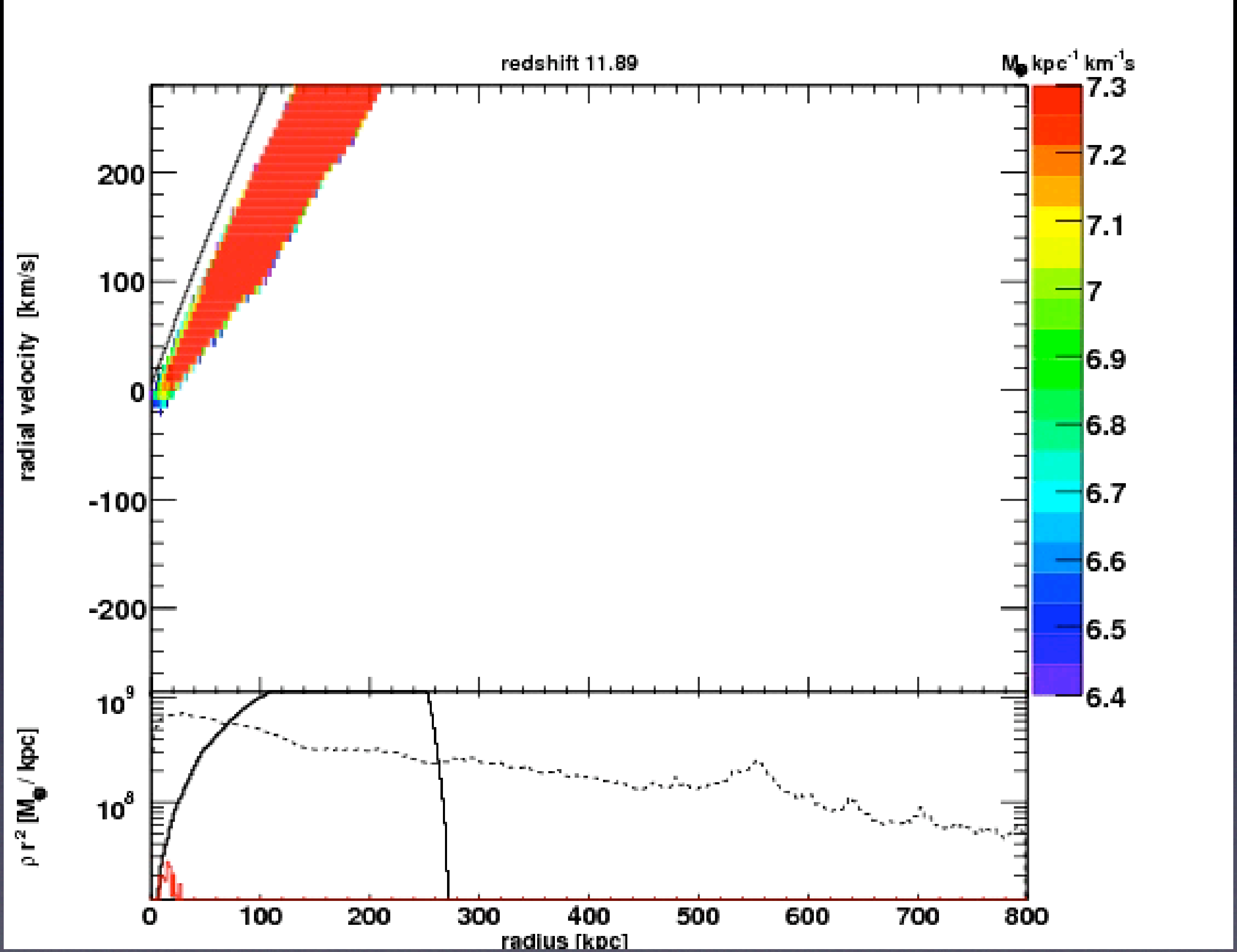
JD, Kuhlen, ApJL 2008



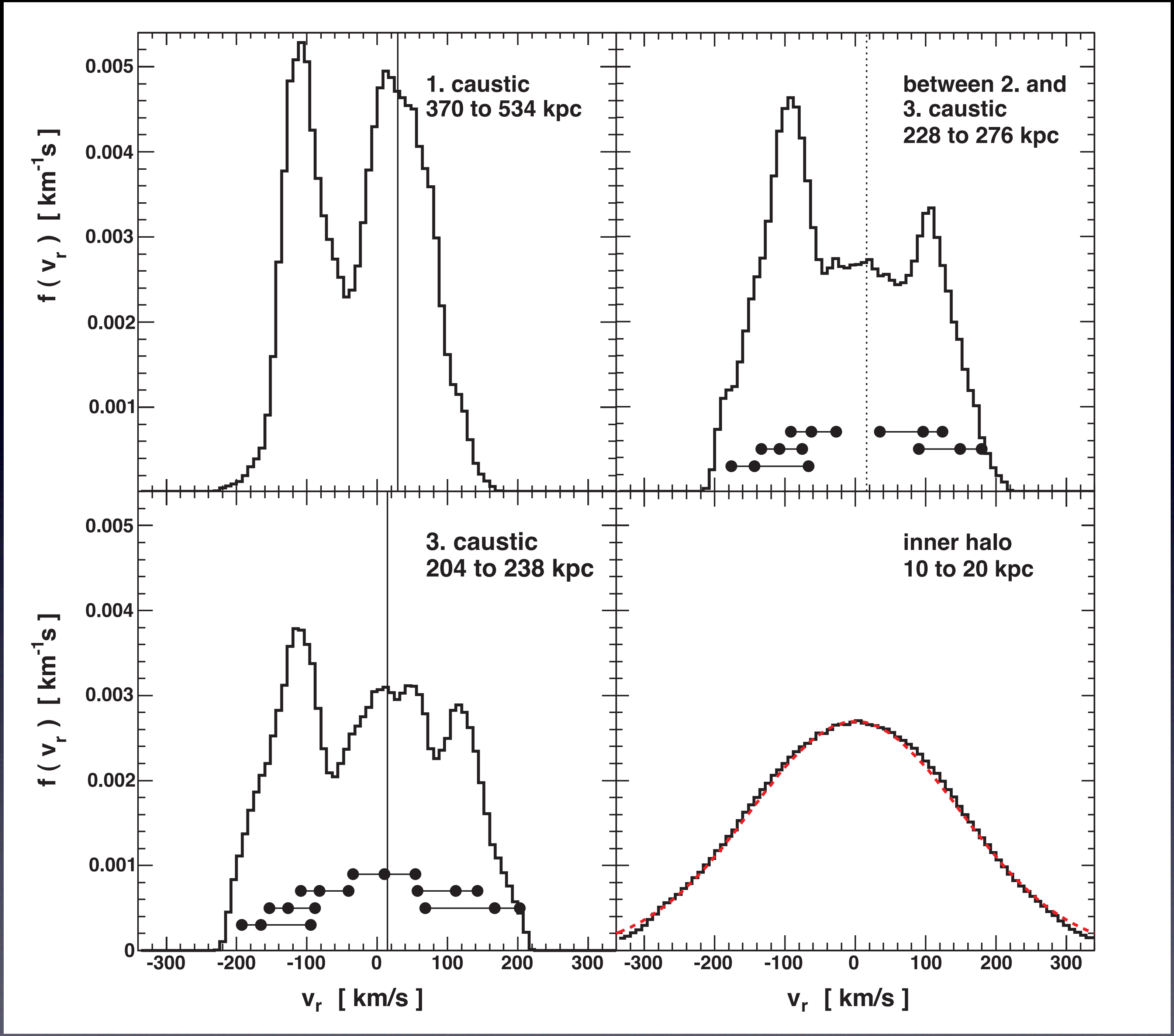
JD, Kuhlen, ApJL 2008



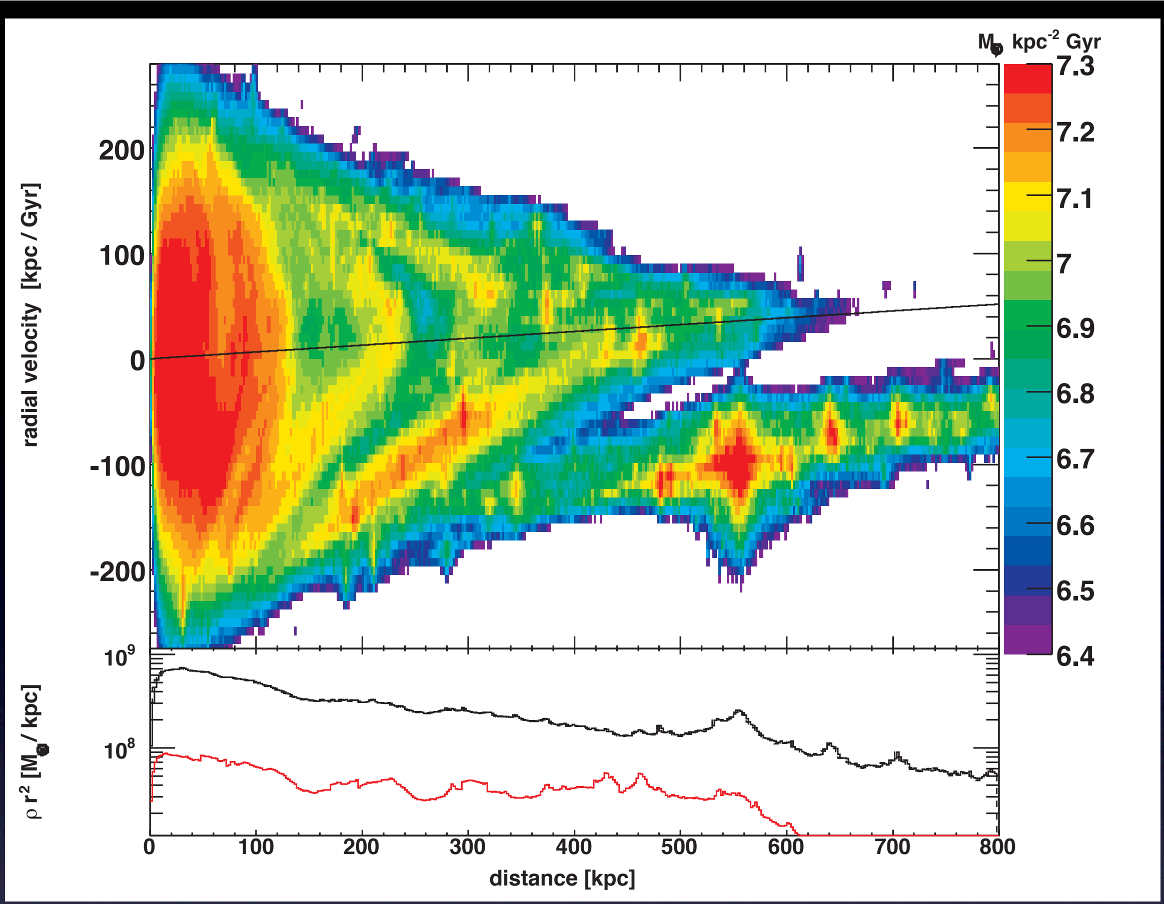
JD, Kuhlen, ApJL 2008



JD, Kuhlen, ApJL 2008



JD, Kuhlen, ApJL 2008



typical particles and subhalos go out to 0.8 to 0.9 of where they turned around, as in the FGB model

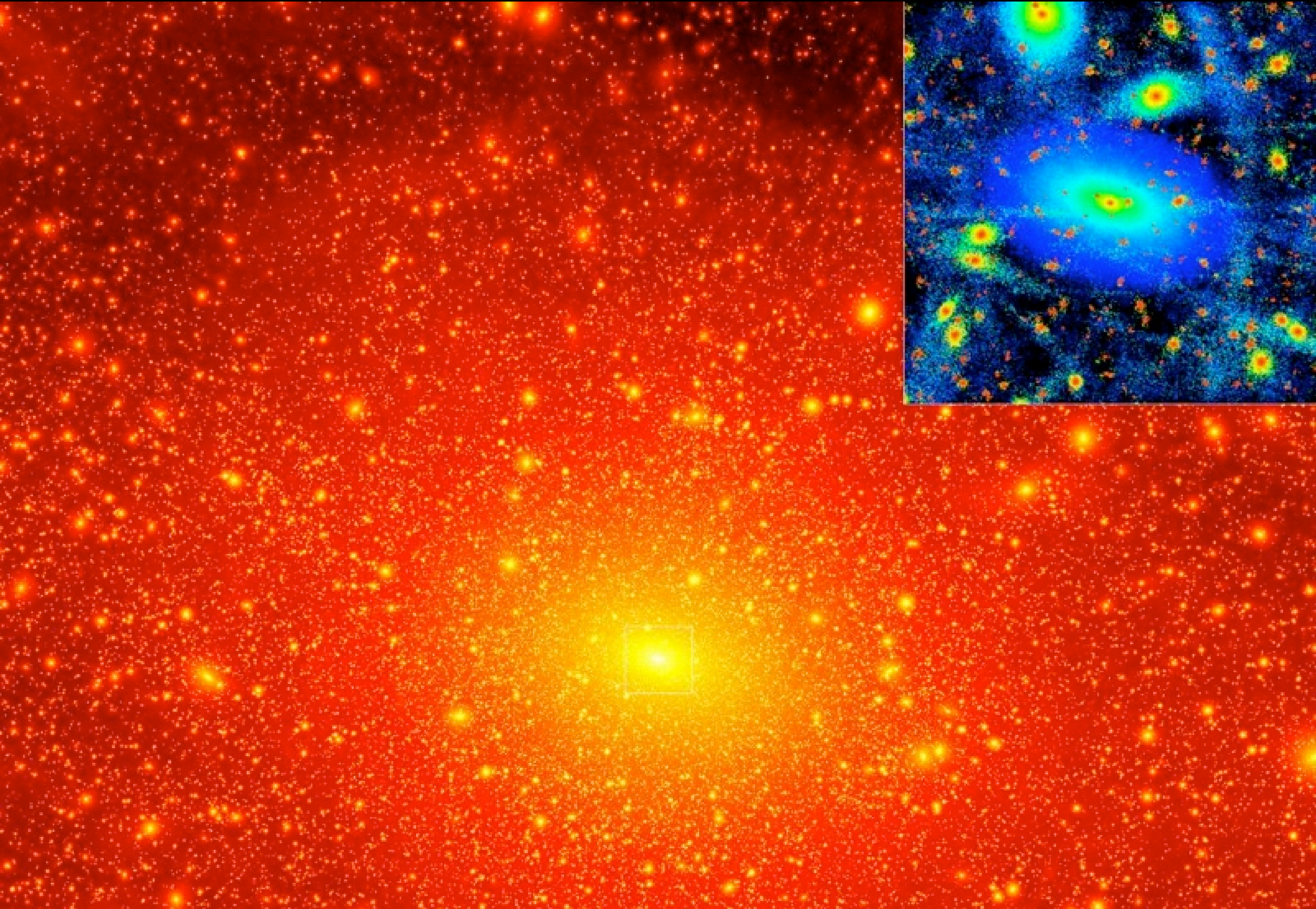
But the scatter is too large to allow the formation of high density caustics

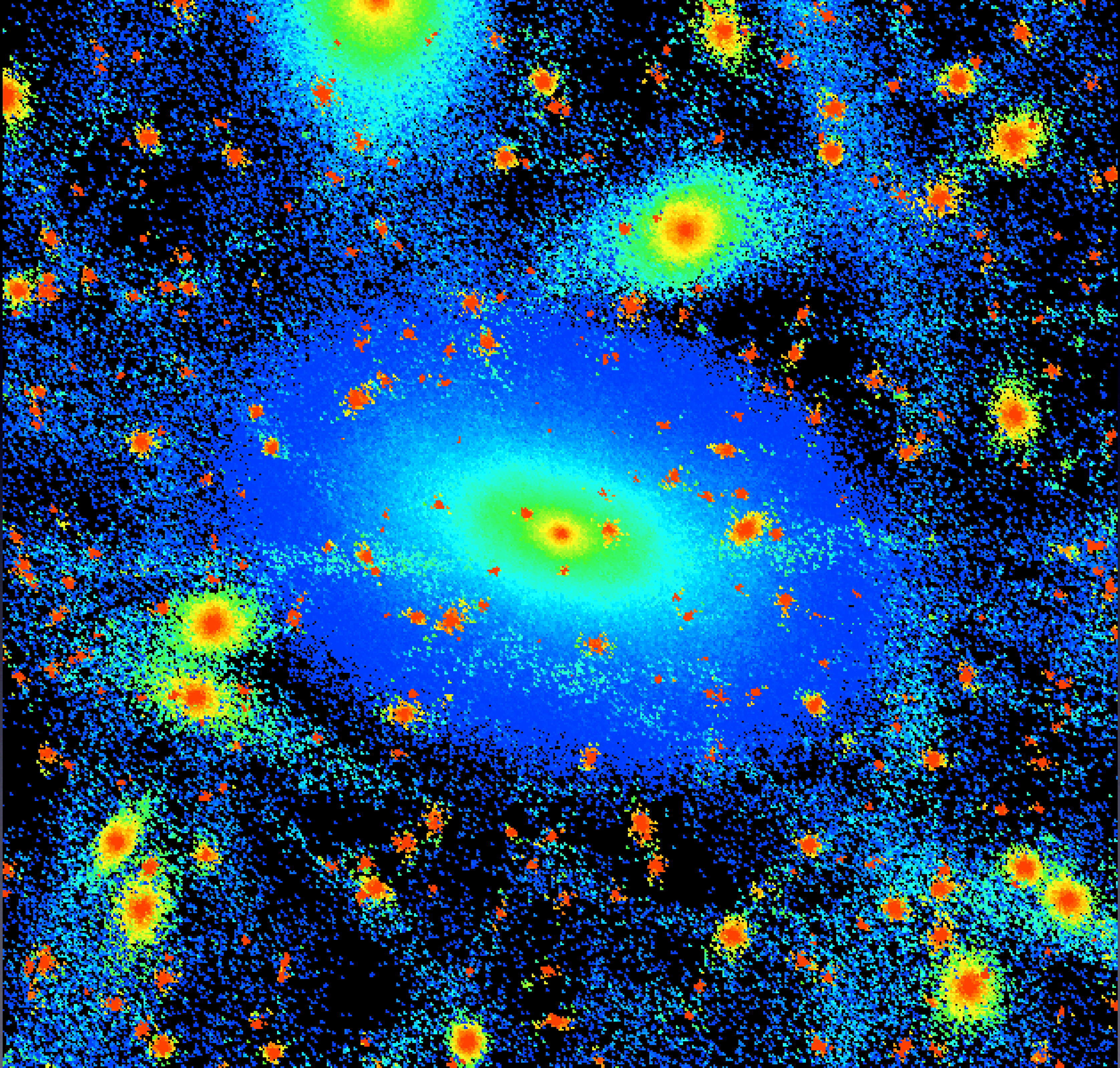
only weak features in v_r - r plane detection extremely challenging!

note r_vir = 289 kpc

$r_{k,\rm med}$ [kpc]	$r_{k,68\%}$ [kpc]	$\frac{\Delta r_k}{r_{k,\rm med}}$	$t_{k,\rm med}$ [kpc]	$t_{k,68\%}$ [kpc]	$\frac{\Delta t_k}{t_{k,\rm med}}$	$\left(\frac{r_k}{t_k}\right)_{\rm med}$	$\left(\frac{r_k}{t_k}\right)_{68\%}$	$\left(\frac{r_k}{t_k}\right)_{\rm FGB}$
453	370−534	0.36	491	443−551	0.22	0.92	0.77−1.12	0.876
310	242−384	0.46	343	297−407	0.32	0.93	0.57−1.24	0.864
220	204−237	0.15	261	211−316	0.40	0.84	0.67−1.10	0.856
173	137−207	0.41	222	180−266	0.39	0.78	0.58−1.25	0.843
141	110−191	0.57	179	131−229	0.55	0.78	0.52−1.46	0.832
121	89−170	0.67	157	105−201	0.61	0.81	0.54−1.46	0.834

via lactea II : local density phase-space density





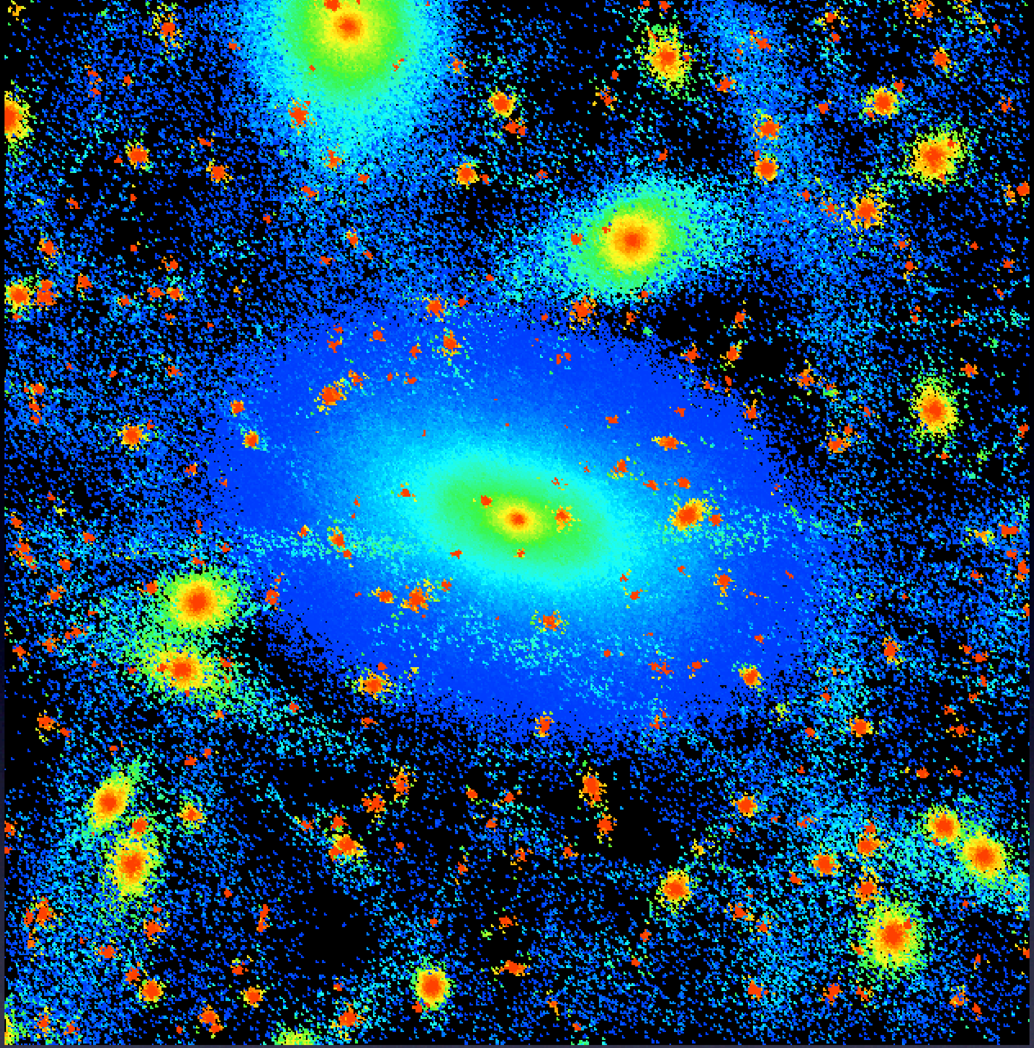
direct detection

at 8 kpc VL-II is almost smooth, there is little mass in subhalos

'local' kpc-scale velocity distributions are close to Gaussians

anisotropy depends on location, Zemp et al. submitted

dark disk component when Galaxy is included
J. Read et al astro-ph/0803.2714



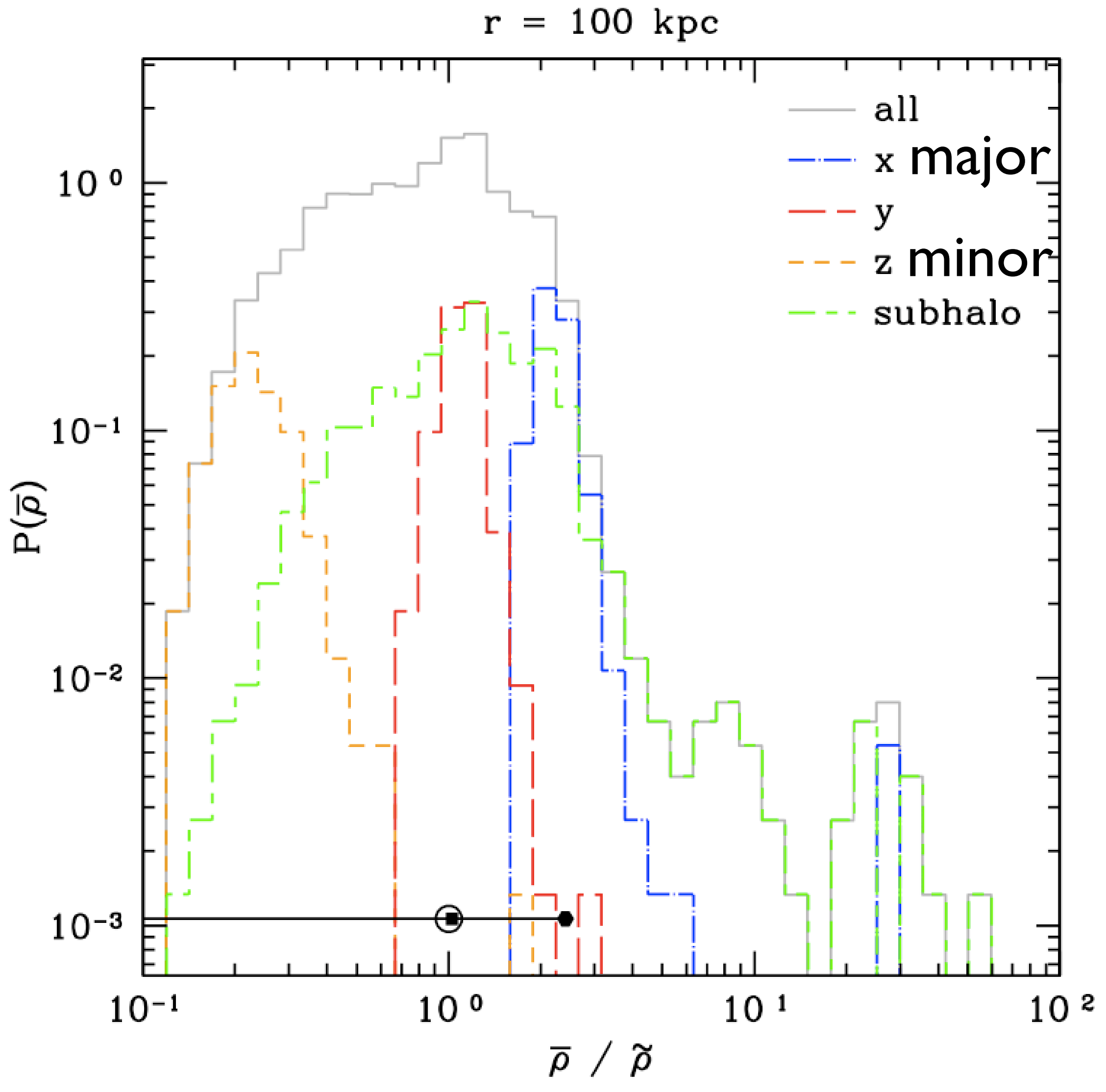
some obvious streams visible in phase space density, but they contain less than 0.01 of the local density
JD et al Nature 2008

additional lumpiness from tidal streams

streams are poorly mixed in the **outer** halo

additional fluctuations in local densities; more than just a smooth triaxial halo plus subhalos

but clumpiness is still dominated by subhalos, i.e no significant extra annihilation boost from streams (see also Afshordi et al. 0811.1582)



Zemp, JD et al, submitted

summary

small subhalos contribute significantly to the total DM annihilation signal

subhalo annihilation signals might be detectable by GLAST/Fermi

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

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

typical subhalo and particle orbits go out to nearly their turnaround radius, as in the secondary infall model. But scatter prevents the formation of caustics

other substructure like infall caustics and tidal streams seem to have little effect on direct and indirect DM detection