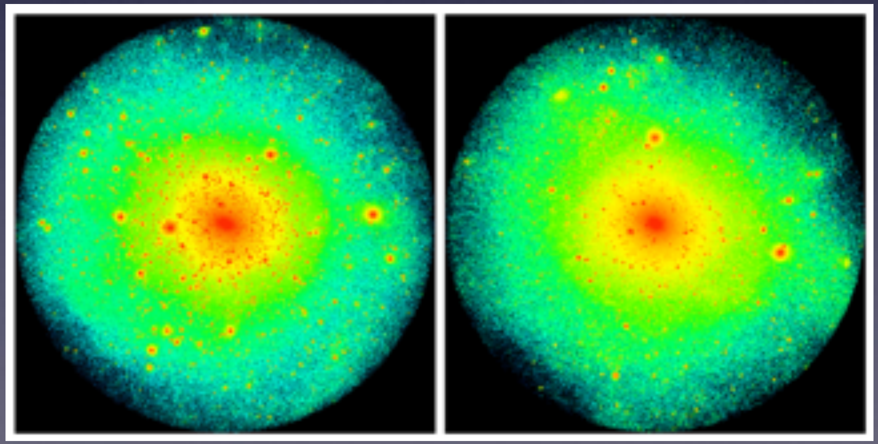
Program update:
now two talks, instead of only the WDM talk

1. Review of LCDM and implications for indirect detection

   ~ 30 + 5 minutes



2. Warm Dark Matter and Mixed Dark Matter Models

   ~ 15 + 5 minutes

Jürg Diemand, Institute for Computational Sciences, Uni Zürich

Review of LCDM and implications for indirect detection

0. introduction
1. density profiles
2. subhalos and indirect detection
3. other substructure
4. microhalos revisited

for details see reviews:
Diemand & Moore, ASL, 2011
Kuhlen, Vogelsberger, Angulo, PDU, 2012

recent microhalo results:
Ishiyama+, ApJ 2010; Anderhalden & Diemand, JCAP 2014; Ishiyama, ApJ 2014

SciNeGHE Workshop, Lisboa, June 4-6, 2014

Jürg Diemand, ICS, Uni Zürich

a very short history of dark matter

Coma, Credit: Lopez-Cruz et al

- high velocity dispersion of
  Coma cluster galaxies (Zwicky 1933)

- flat rotation curves in spiral galaxies
  (Rubin, Ford 1975)

Markevitch et al.; Clowe et al.

- x-rays and lensing observations
  in galaxy custers (e.g. bullet cluster)

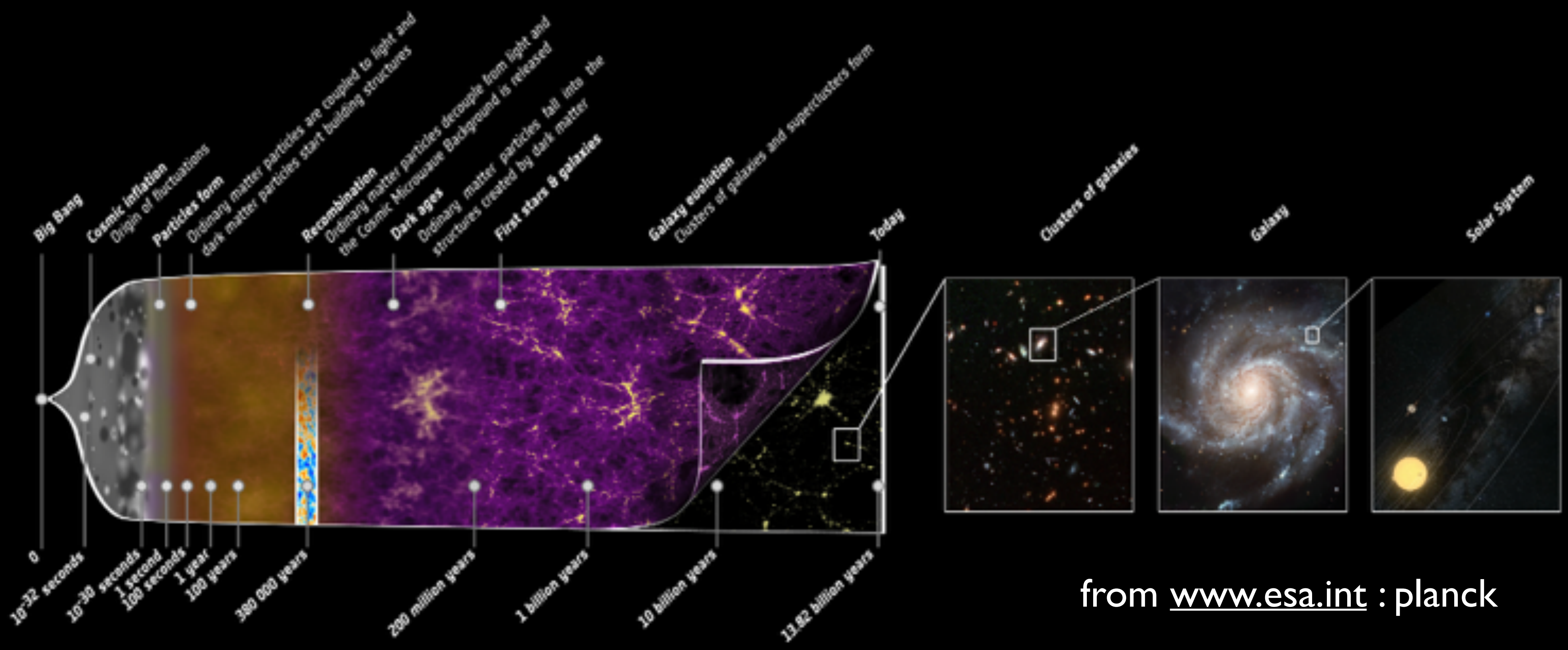
- kinematics of galactic stellar halo and satellite galaxies
- mass-to-light ratios dwarf galaxies

a very short history of dark matter

today we have wide range of different cosmological observations:

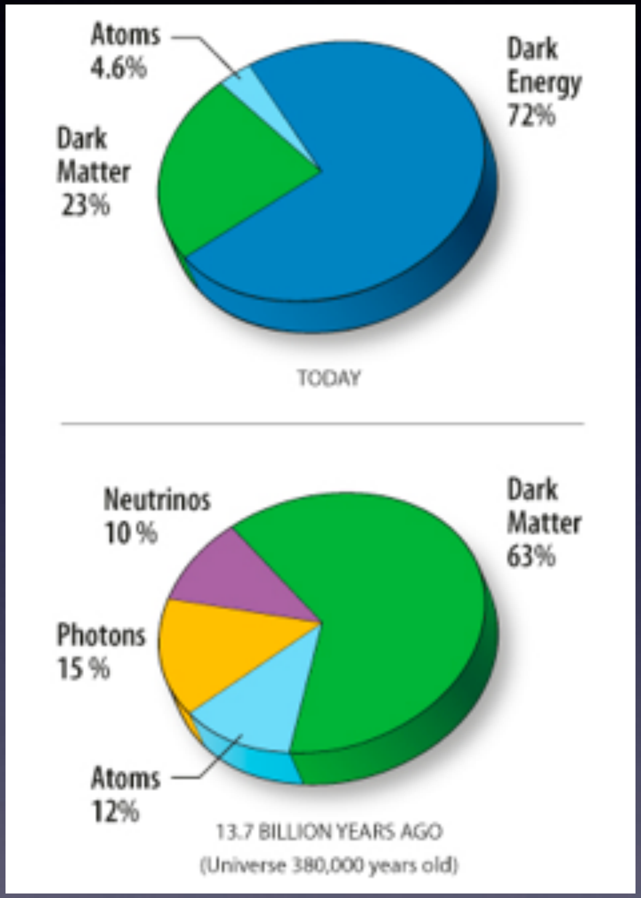
cosmic microwave background, supernovae 1a, large scale structure

all are consistent with the LCDM model !



from www.esa.int : planck

dark matter dominates structure formation



NASA / WMAP Science Team

collision-less simulations
(pure N-body, dark matter only)
treat all matter like dark matter

no free parameters
high resolution, good scaling

good approximation for dwarf galaxy halos and for smaller, dark halos and subhalos

not accurate near centers of galaxies

accurate solution of idealized problem

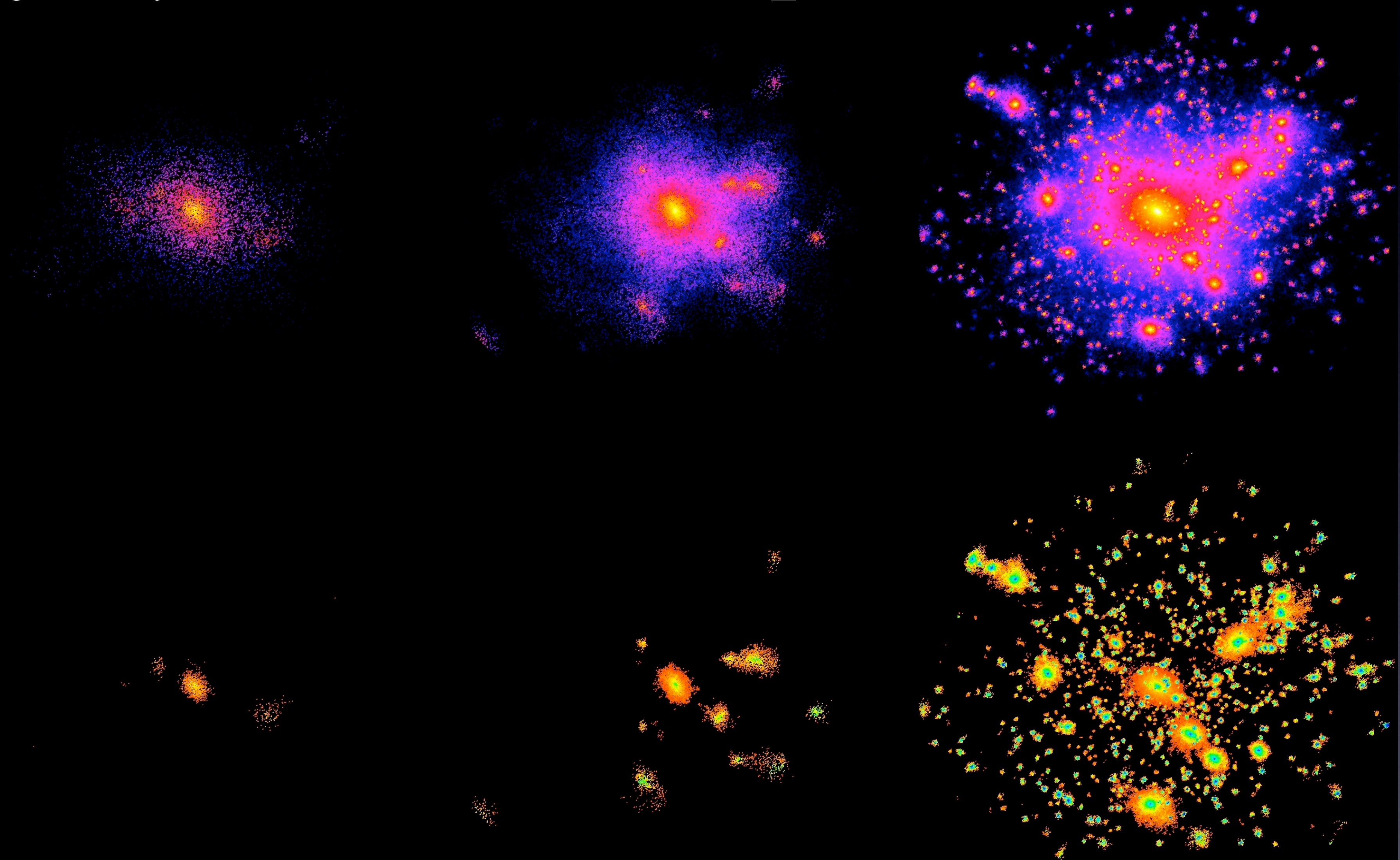
one main motivation:
DM annihilation signal ~ density^2
i.e. structures on all scales increase the signal

Simulating structure formation

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

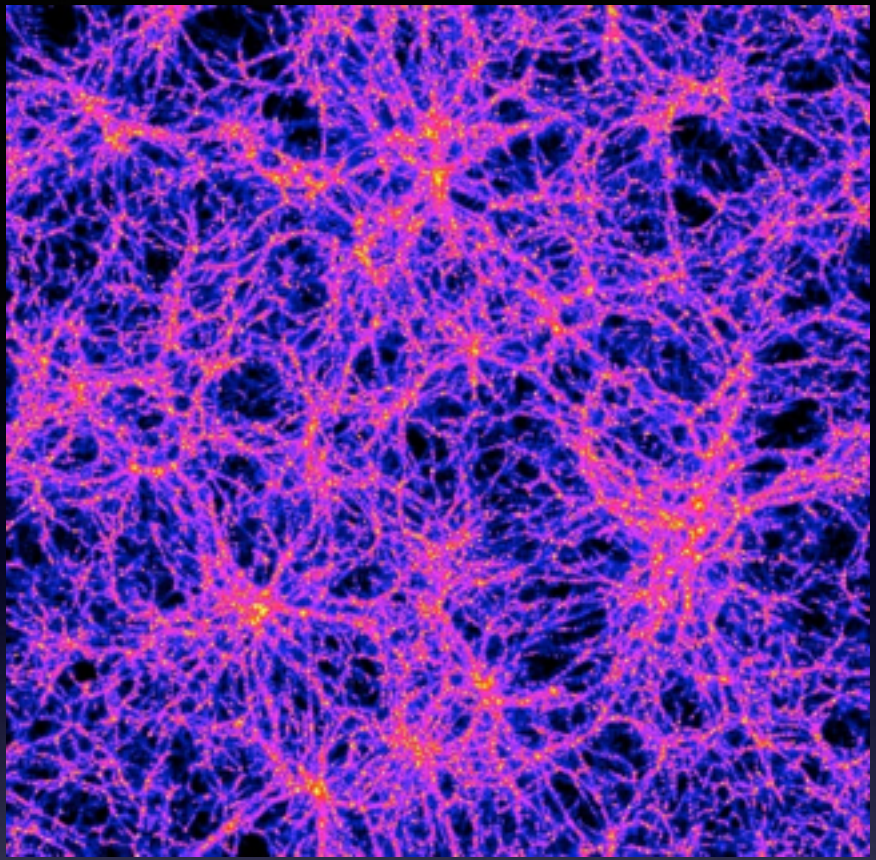
log density

N_halo from about 10k to a million



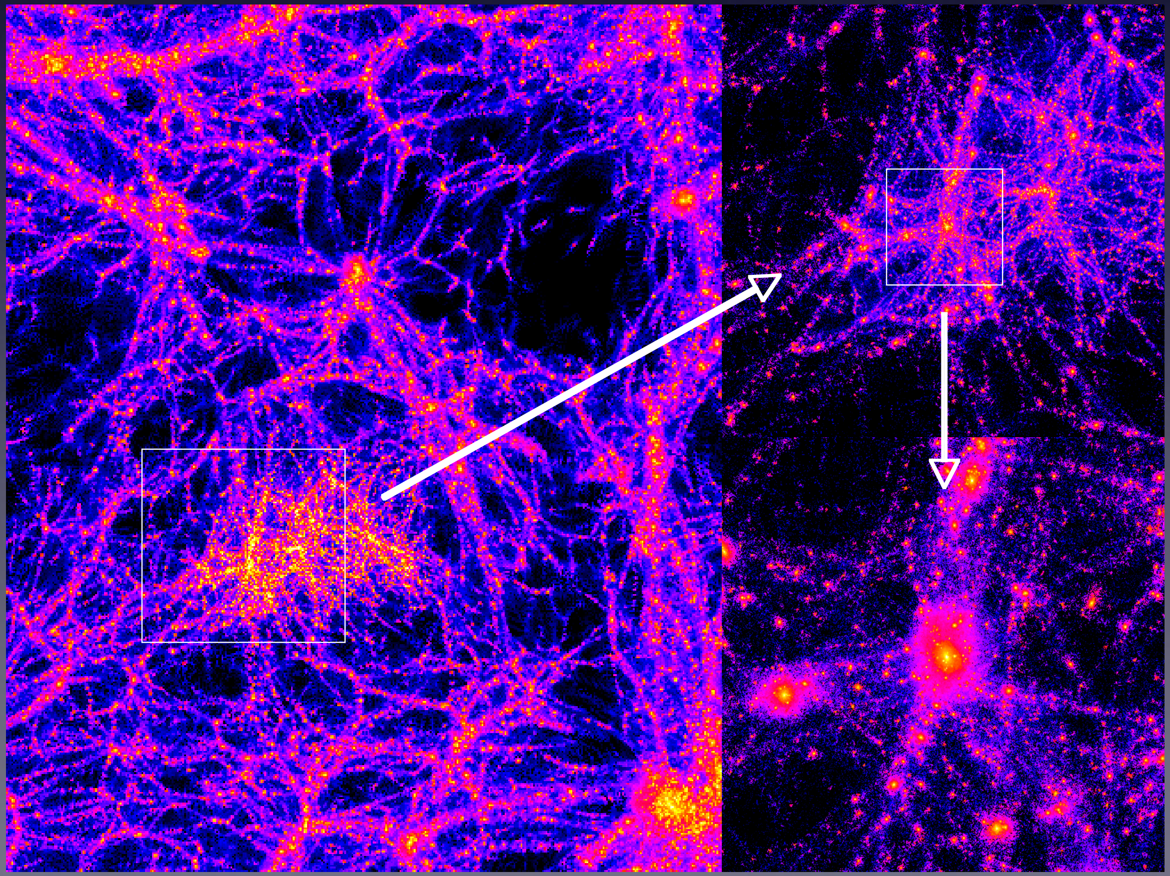
log phase space density

from Ben Moore : www.nbody.net



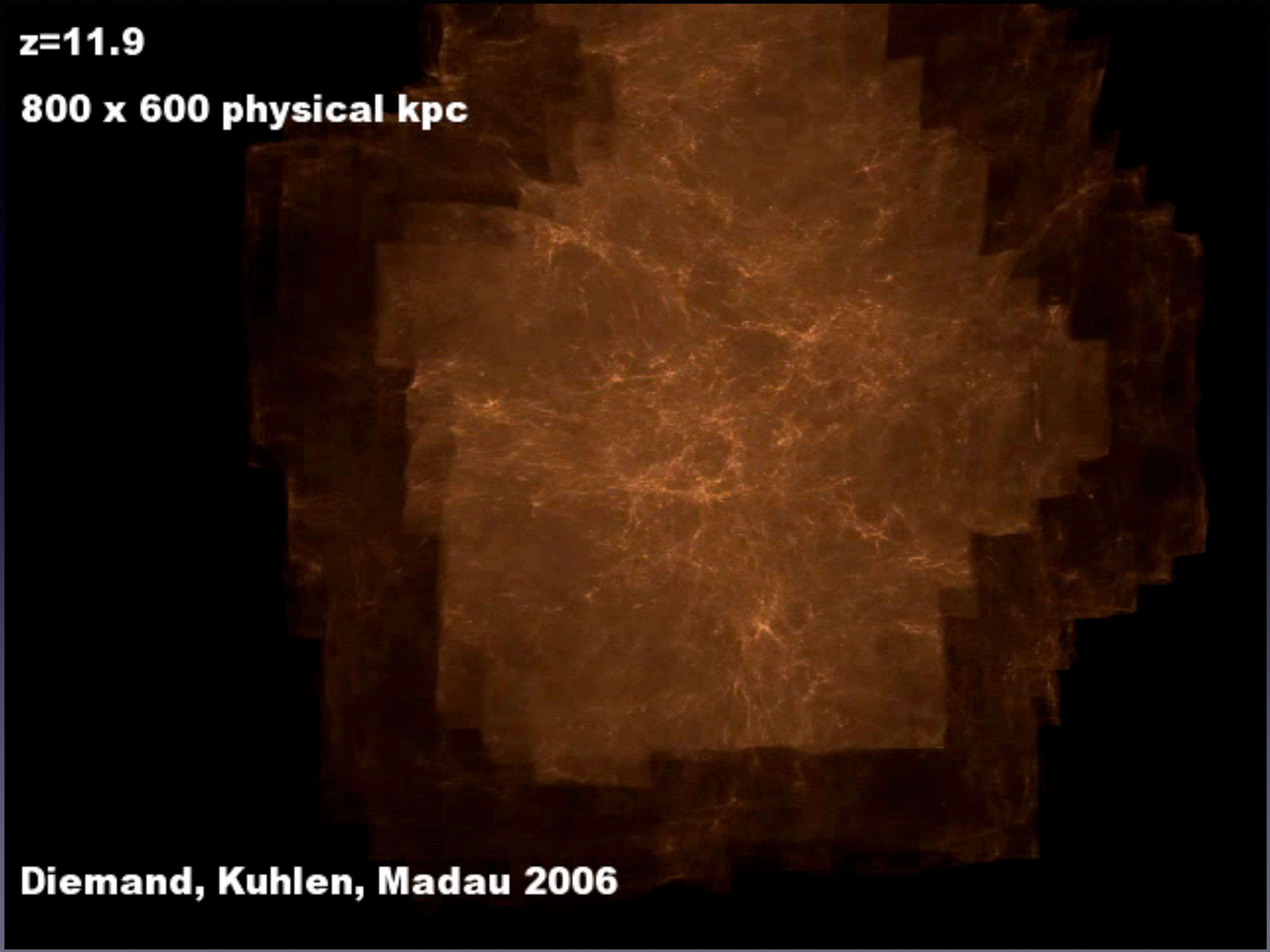
uniform resolution, periodic cubes

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



refined, re-simulations of individual halos

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


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

via lactea II at redshift zero

www.ics.uzh.ch/~diemand/vl

the via lactea project

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

main

movies

images

publications

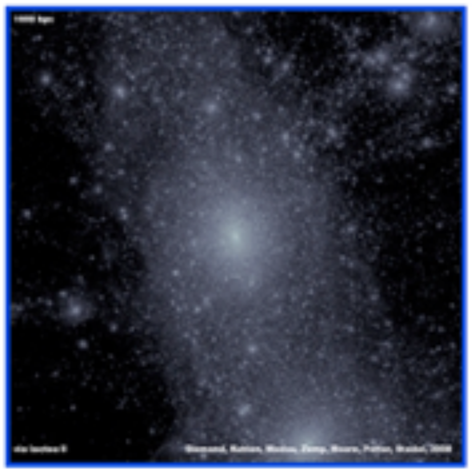
data

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:

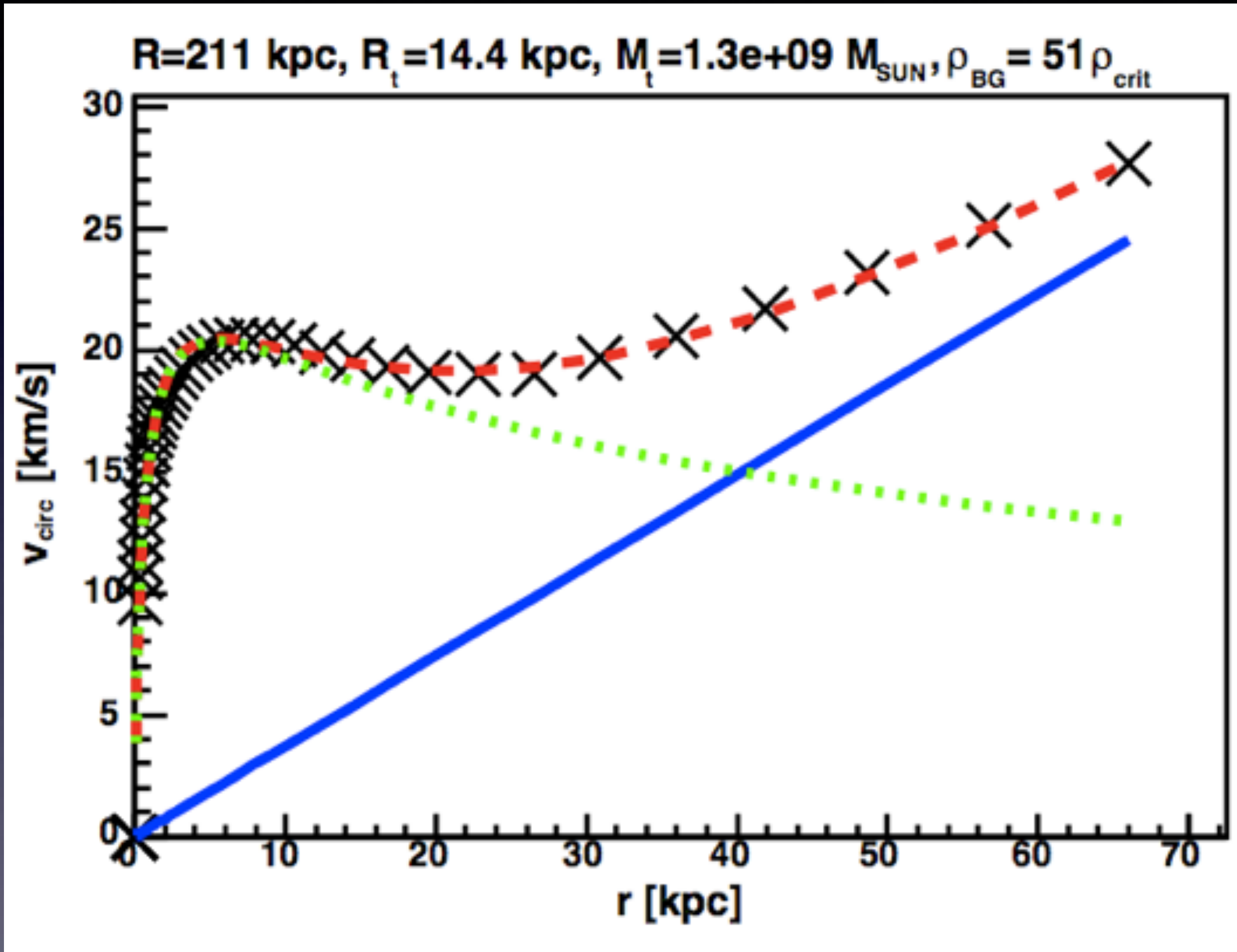
What is a (sub)halo? Operational definitions

mass profiles around peaks in (phase-space) density

$V_{circ}^2 = GM(<r)/r$
has a well defined peak:
V_{max} at r_{Vmax}

no clear outer boundary:
"virial" radius is a simple, but arbitrary scale
Anderhalden&JD 2011

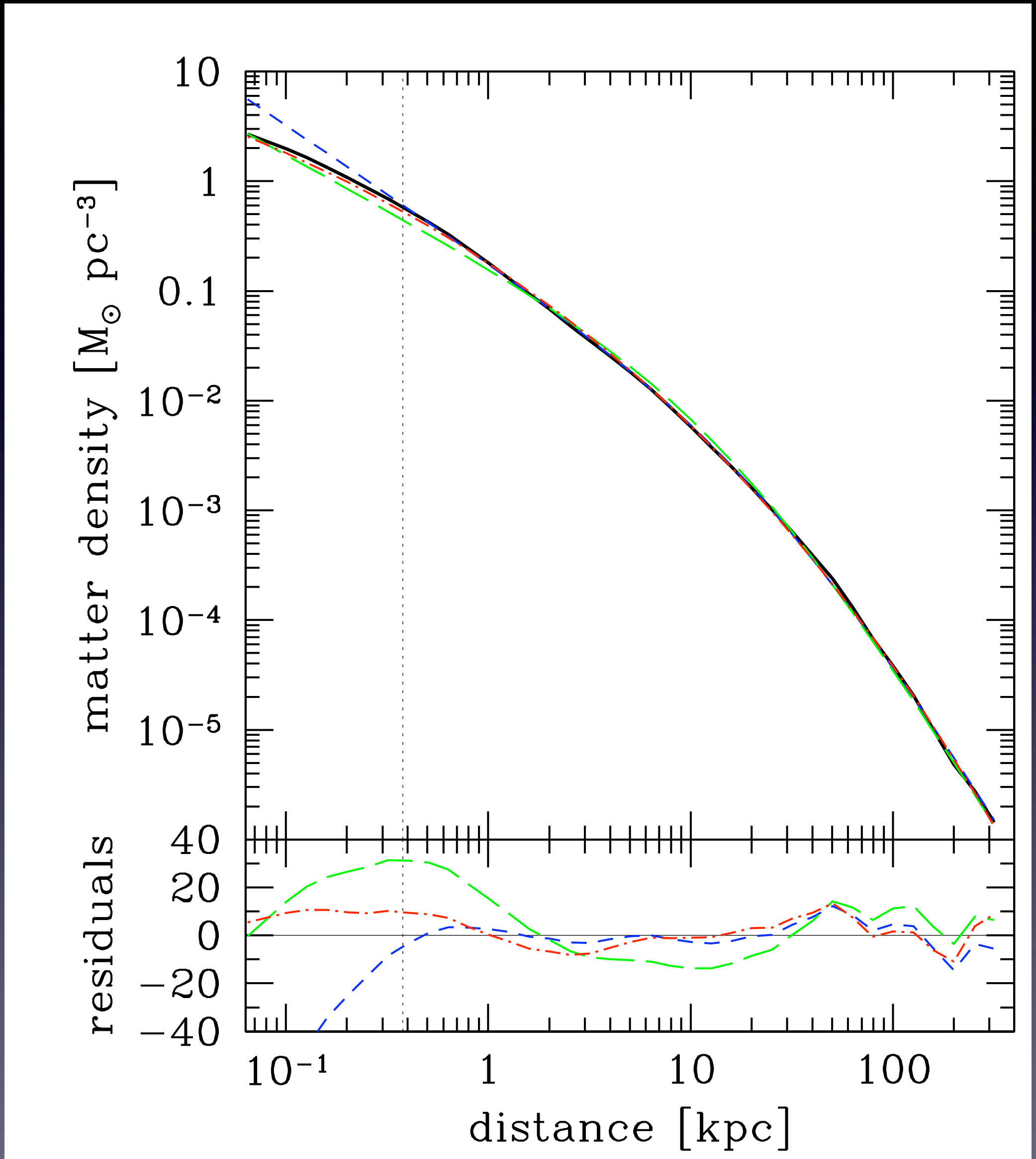
halos with the virial radius of another are called subhalos



(sub)halo concentrations:
$c_V = \mathrm{rho}(<r_{Vmax}) / \mathrm{rho}_{crit,z=0}$
$c_{NWF} = r_{vir} / r_s$, $r_s = r_{Vmax} / 2.16$

1. density profiles

main halo density profile



NFW

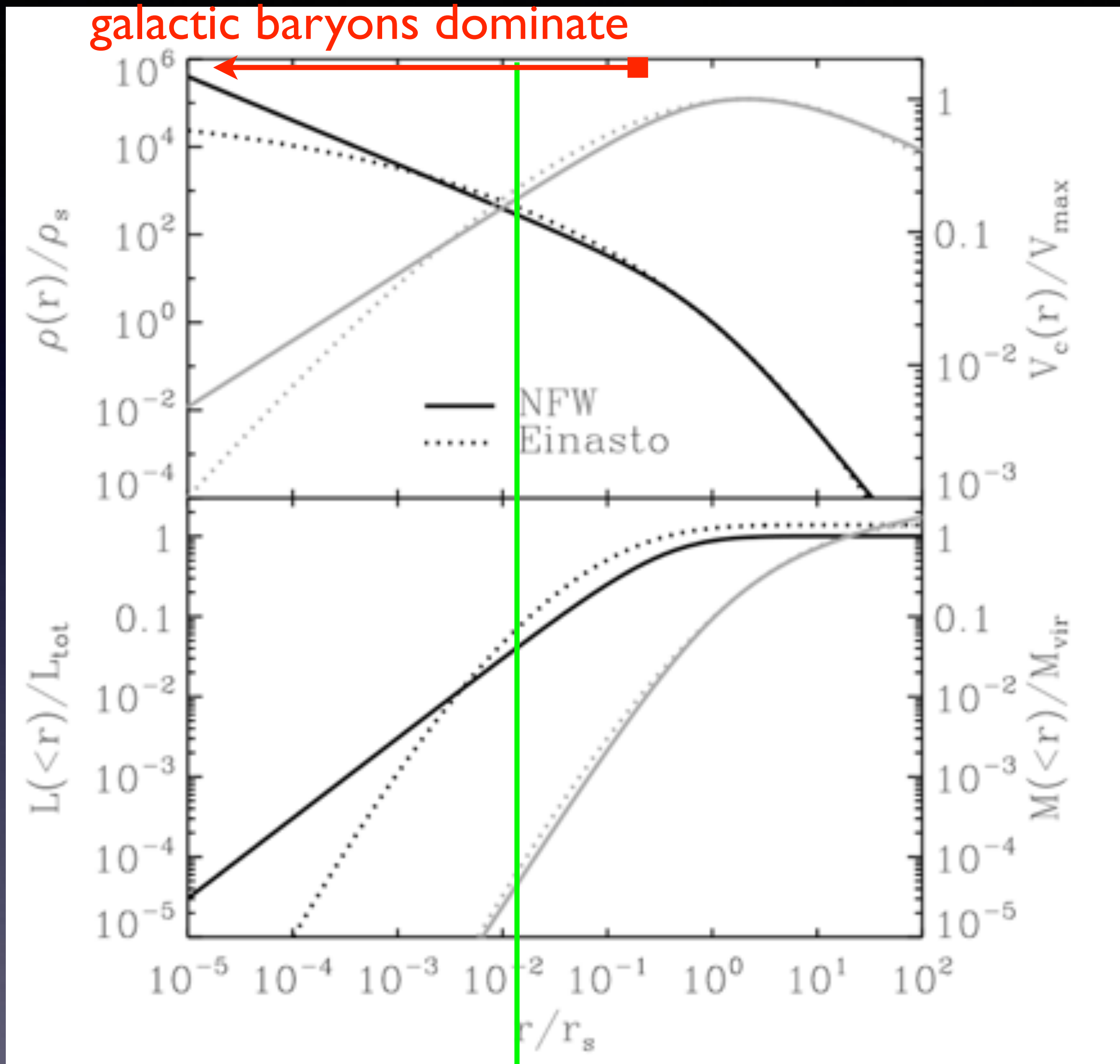
Einasto

$r^{-1.24}$ inner profile

JD et al. Nature 2008

inner region is denser than NFW: Einasto and $r^{-1.24}$ fit well down to 400 pc. probably shallower than $r^{-1.24}$ on very small scales (scatter / convergence?).

main halo density profile



Kuhlen, AdAst 2010

comparison of NFW and Einasto (alpha=0.17) profiles

normalized at Vmax and rVmax

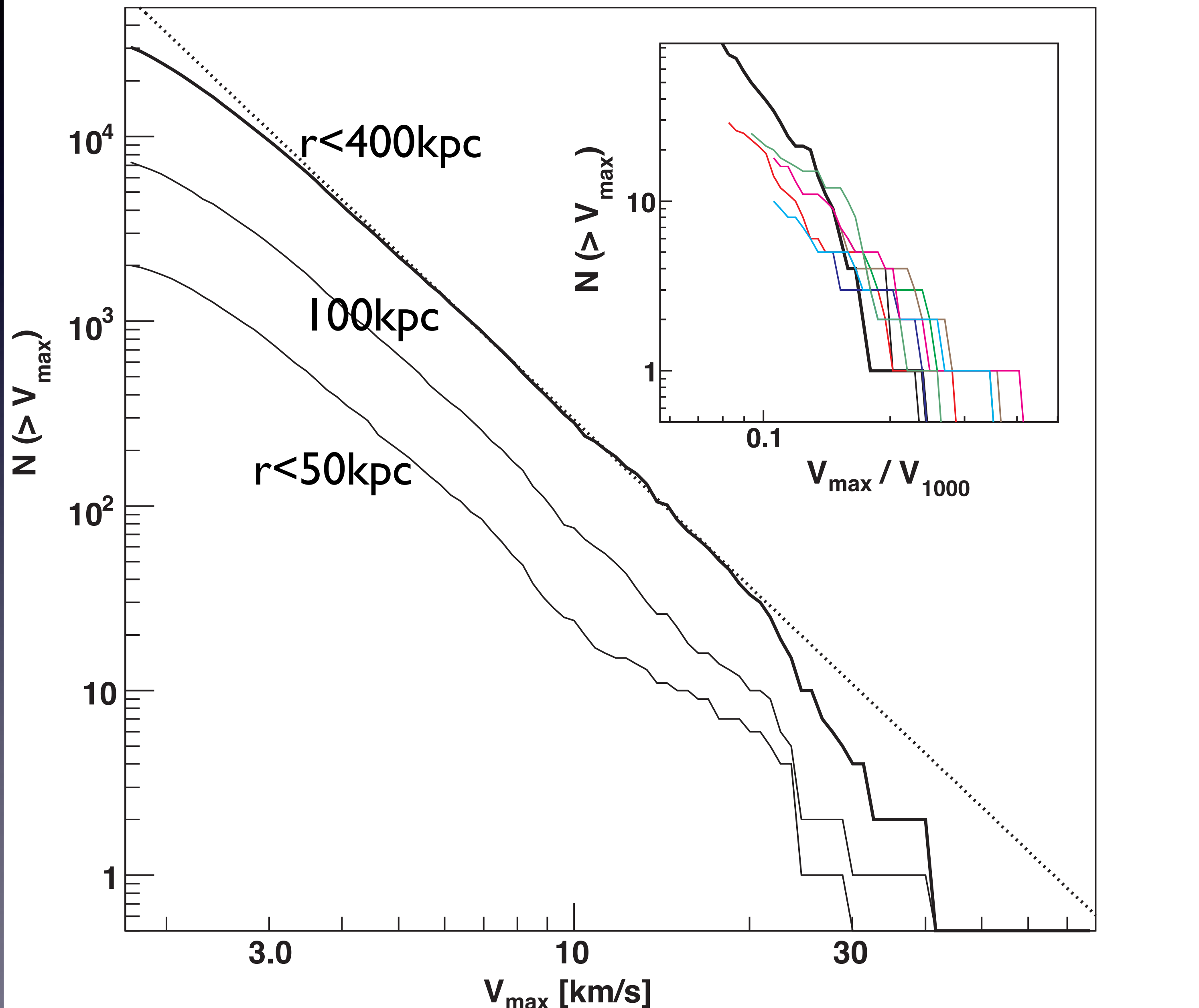
$L_{Einasto} = 1.41\ L_{NFW}$

well resolved region in pure dark matter simulations contains > 99 percent of the annihilation luminosity L (Einasto and $r^{-1.24}$ inner profile are very similar here)

2. subhalos and indirect detection

subhalo and sub-subhalo abundance

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



velocity function
$N(>V) \sim V^{-3}$

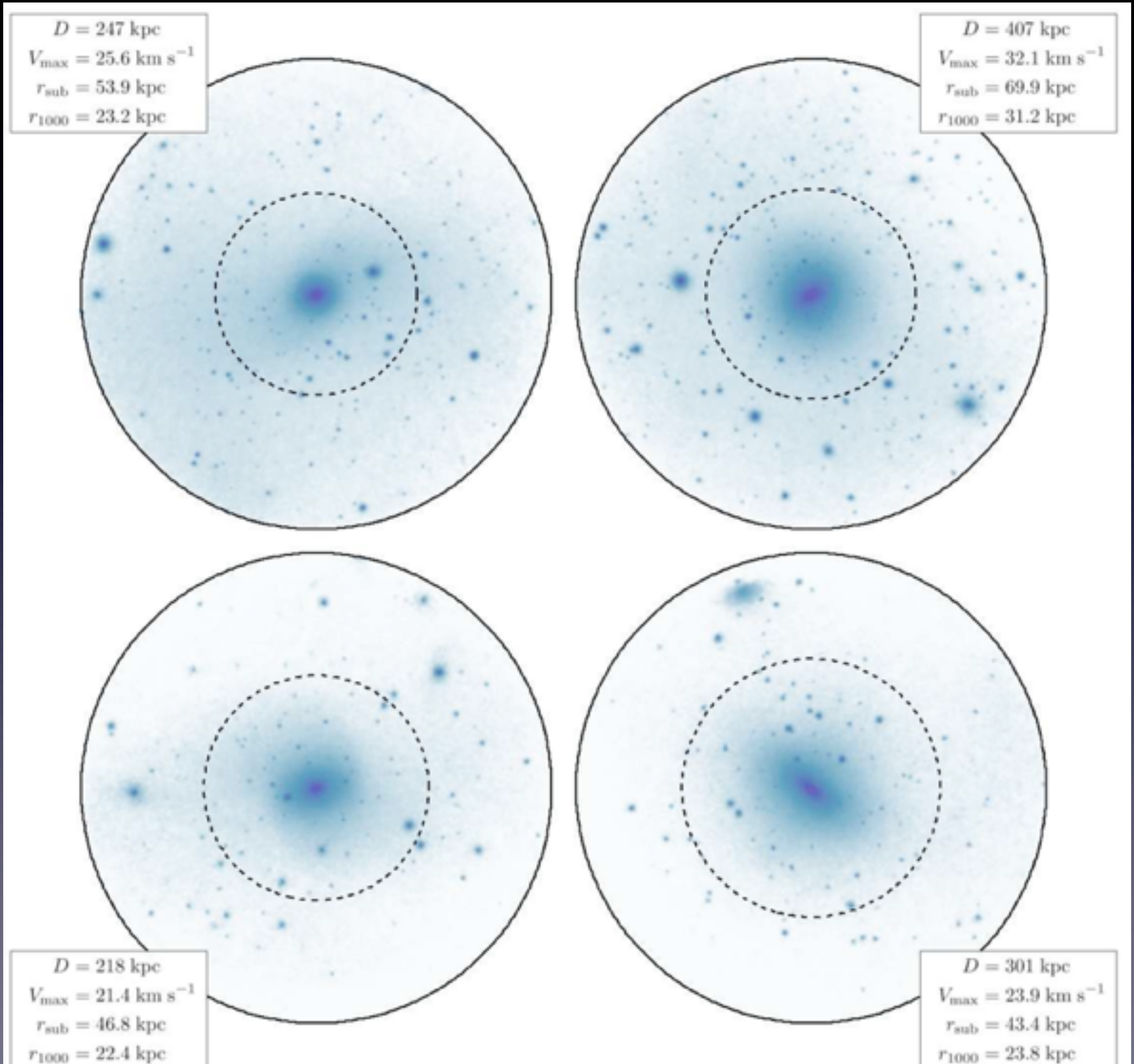
annihilation signal has not converged yet in simulations

both for main halos and for subhalos

mass functions
$N(>M) \sim M^{-(0.9 \text{ to } 1.0)}$
give same conclusion

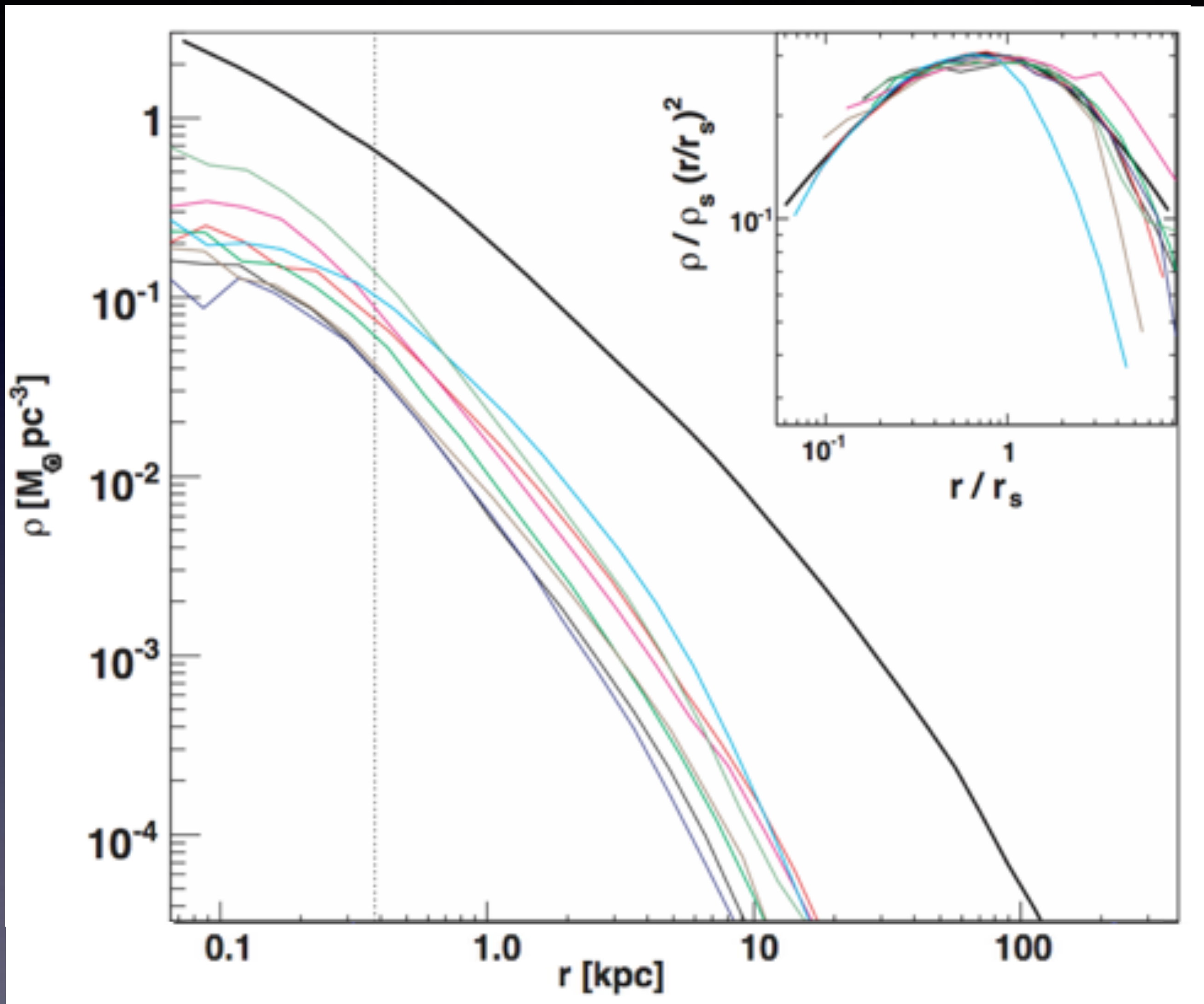
JD et al. Nature 2008

sub-subhalos in all well resolved subhalos



Kuhlen, JD, Madau ApJ 2008

inner subhalo density profiles resemble main halo profiles



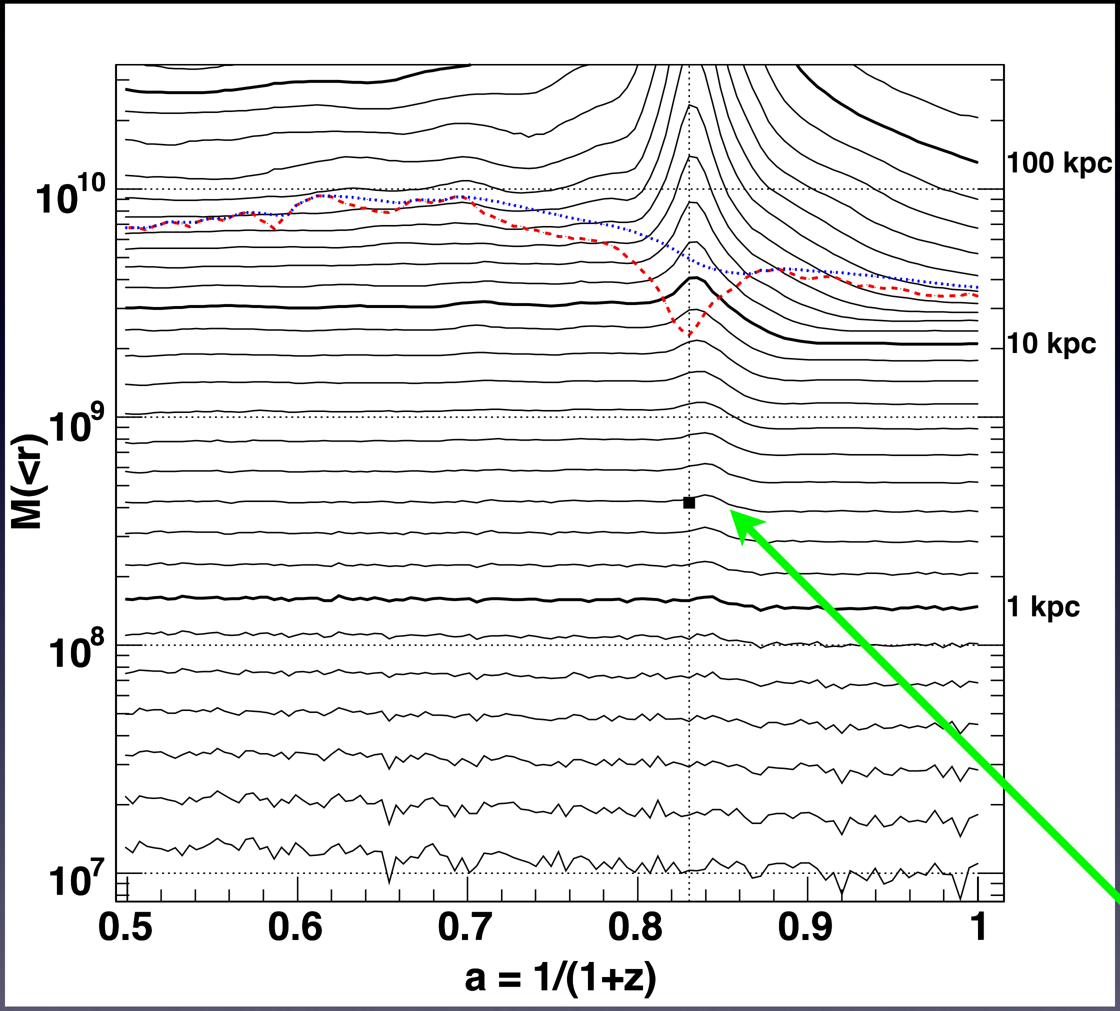
JD et al. Nature 2008

normalized profiles

overlap in inner regions

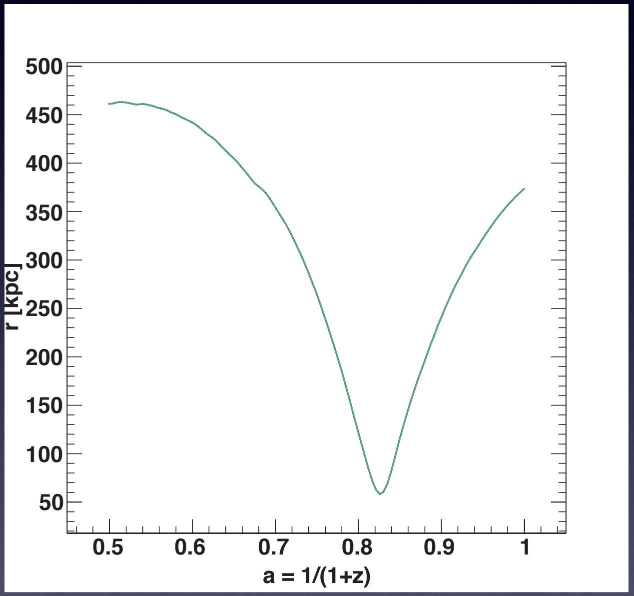
subhalos fall off steeper in the outer parts

subhalo evolution (JD, Kuhlen, Madau, ApJ, 2007)



total mass in spheres around subhalo center

this subhalo has one pericenter passage at 56 kpc



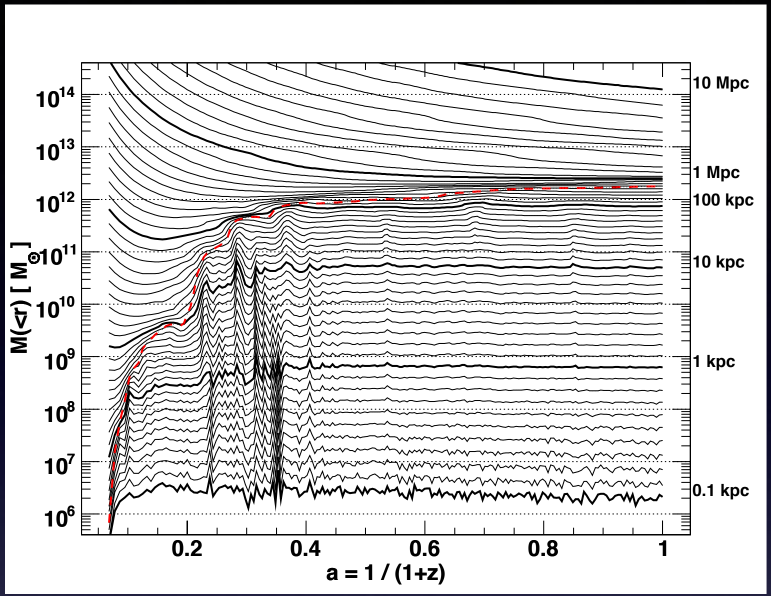
shock duration =
internal subhalo orbital time

weak, long tidal shock
causes quick compression followed by expansion

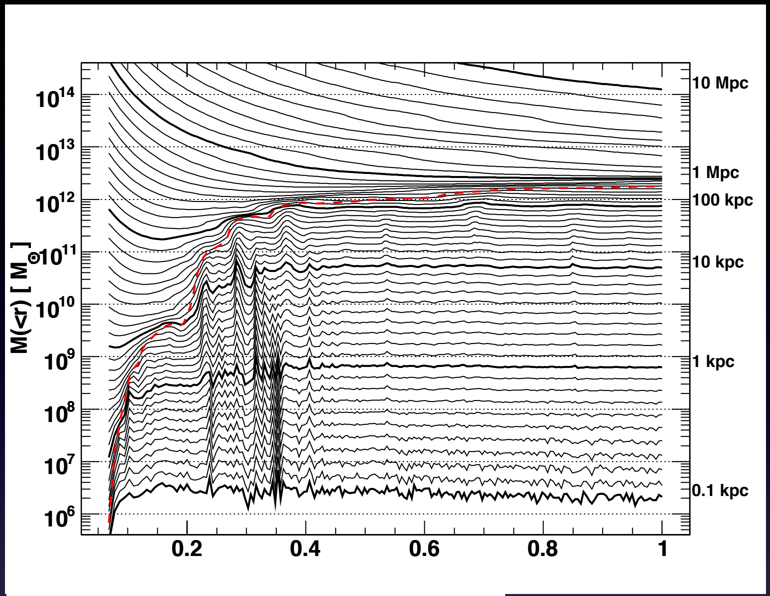
mass loss increases with radius, subhalo inner regions remain unaffected

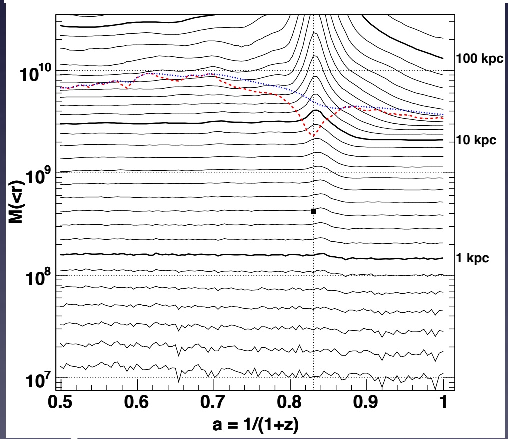
isolated halo

subhalo



formation



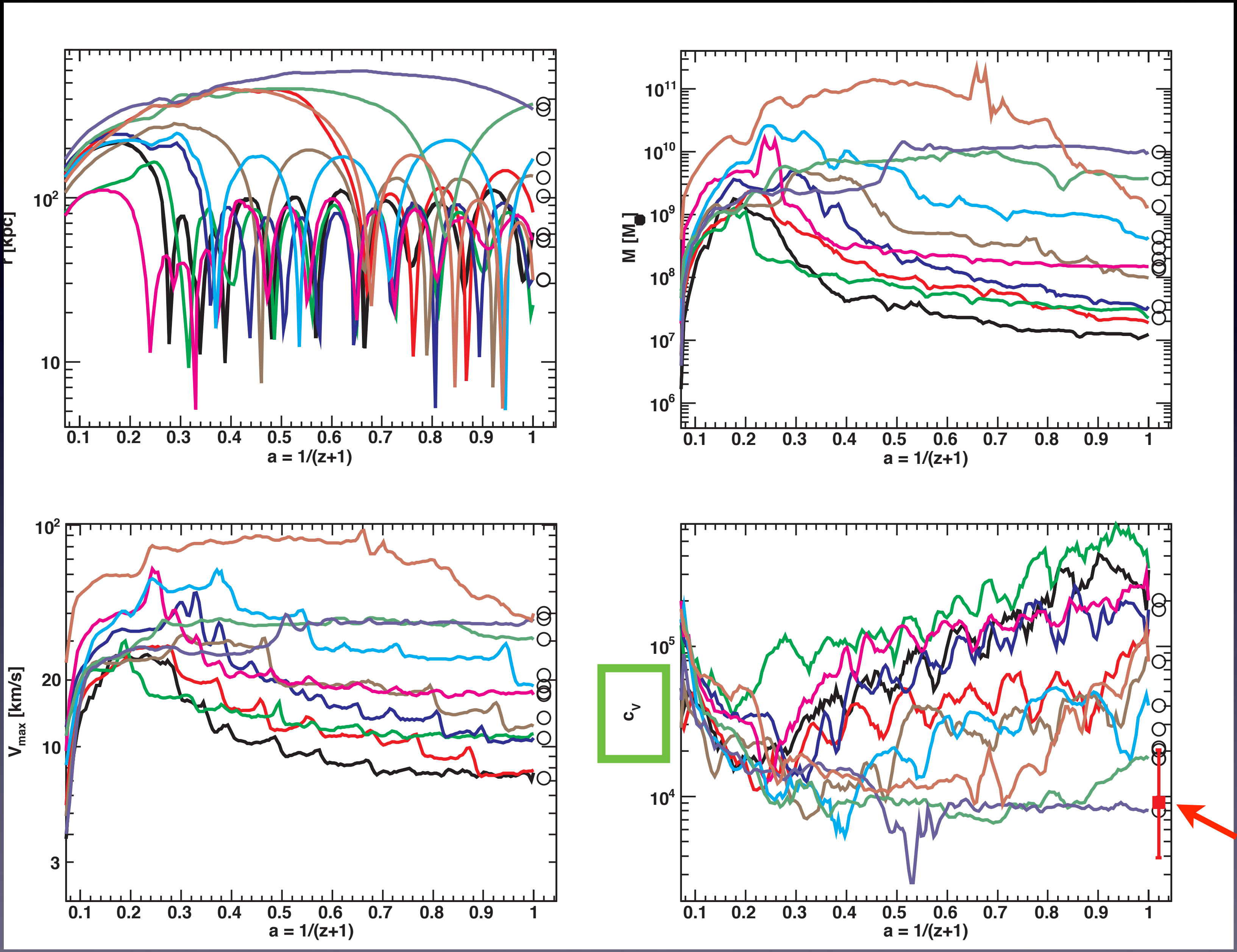


passive evolution

tidal stripping

same mass and substructure distribution in the inner parts

subhalo evolution (JD, Kuhlen, Madau, ApJ, 2007)



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

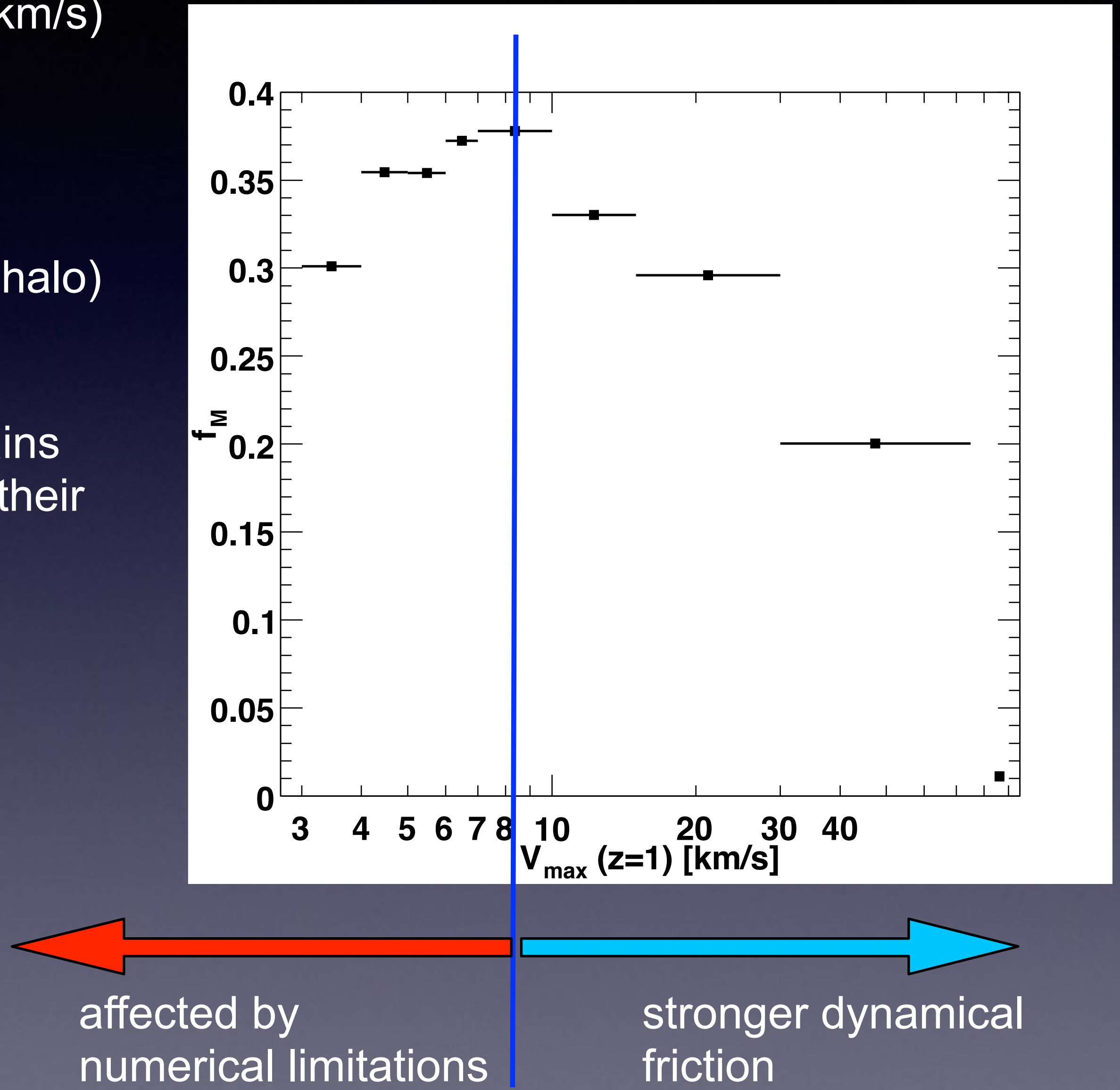
subhalo survival and merging (JD, Kuhlen, Madau, ApJ, 2007)

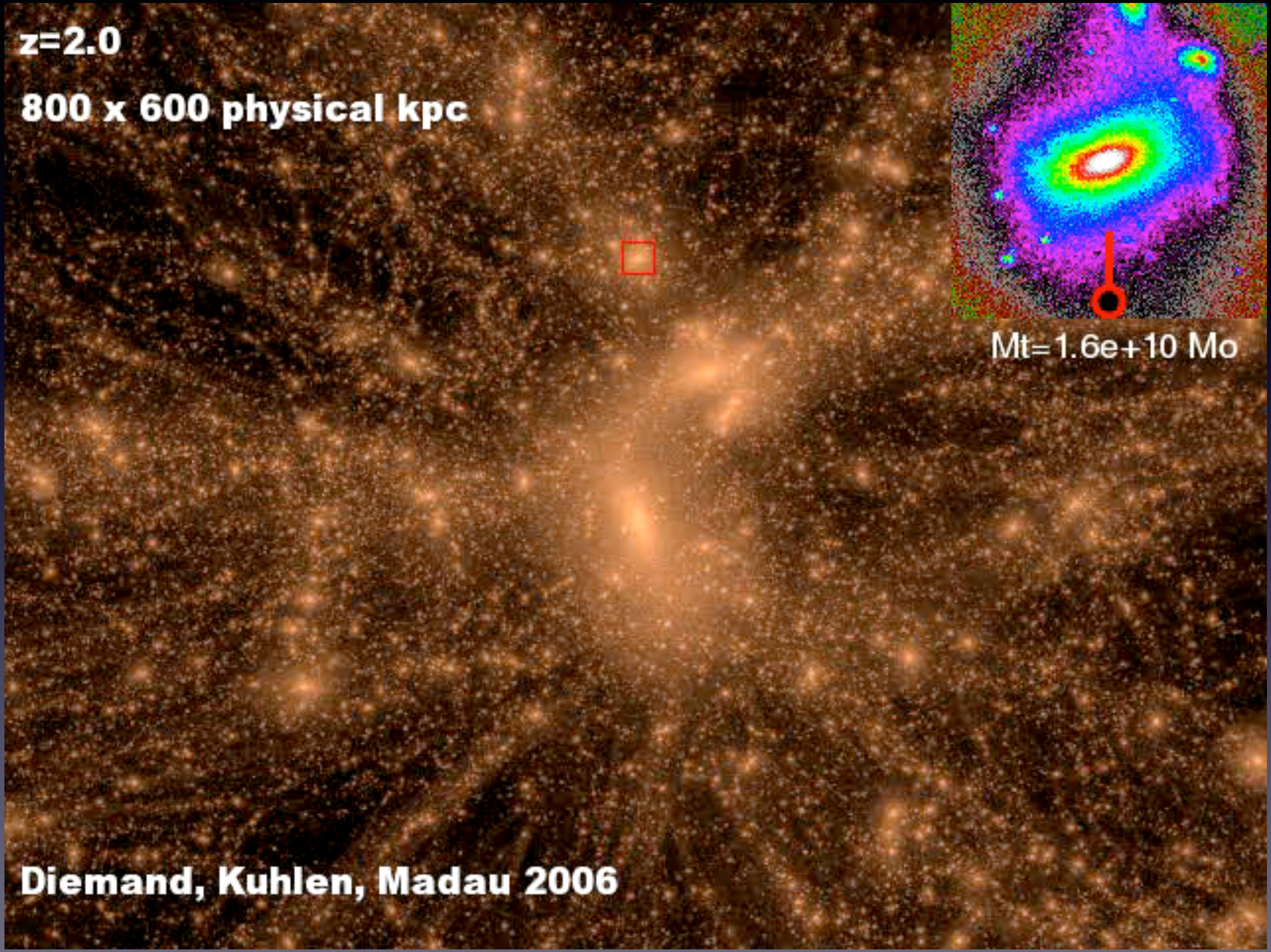
out of 1542 well resolved (Vmax >5 km/s) z=1 subhalos:

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




z=2.0
800 x 600 physical kpc
Mt=1.6e+10 Mo
Diemand, Kuhlen, Madau 2006

where are the subhalos?

spatial distribution **depends strongly** on how the subhalo sample is **selected**

mass selected subhalos
are found at larger radii than
the dark matter
this 'anti-bias' is smaller in V_{max} selected samples

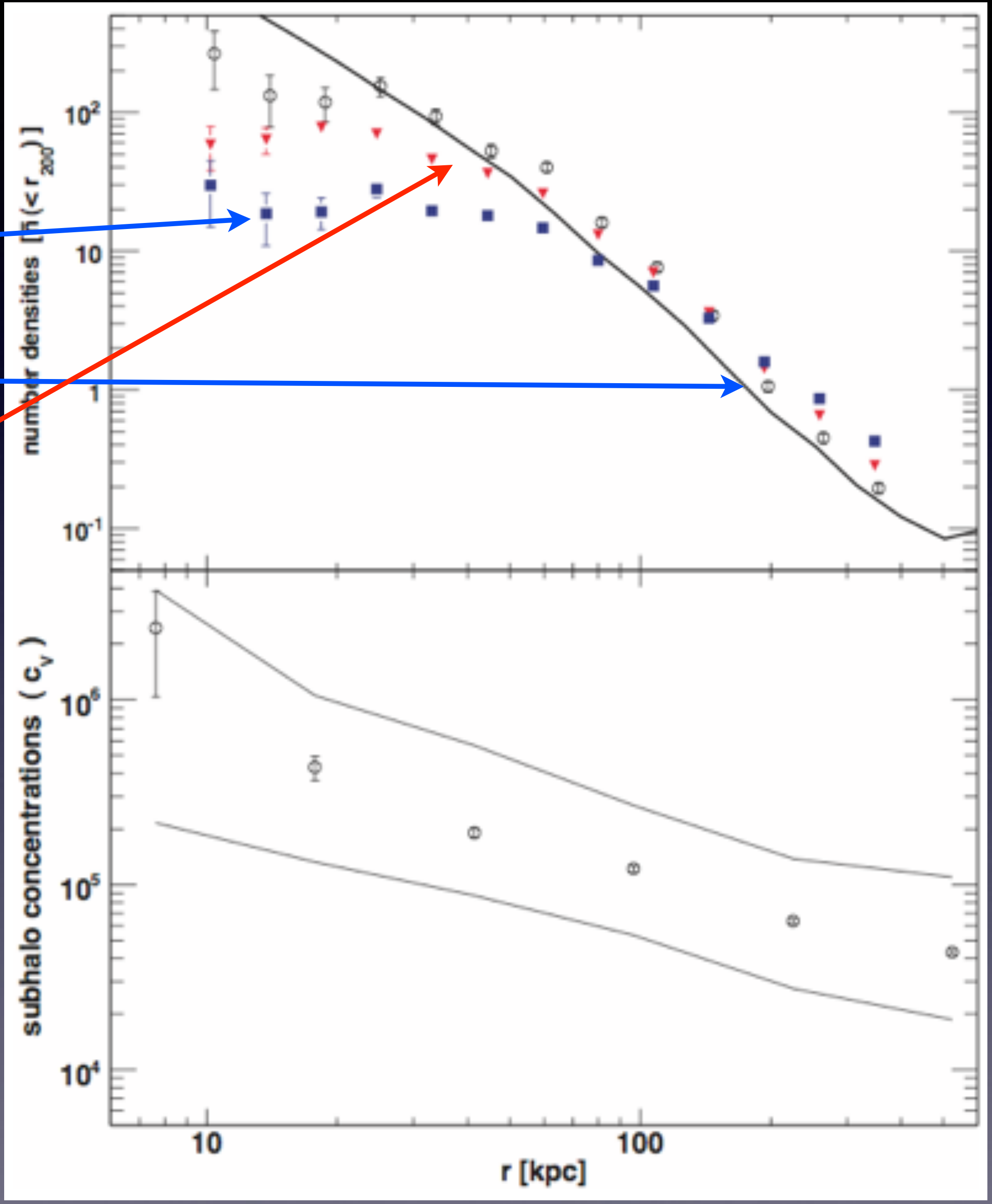
no bias when size at accretion is used
Faltenbacher & JD 2005

denser parts survive, subhalo concentrations increase towards the galactic center

subhalo luminosity

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

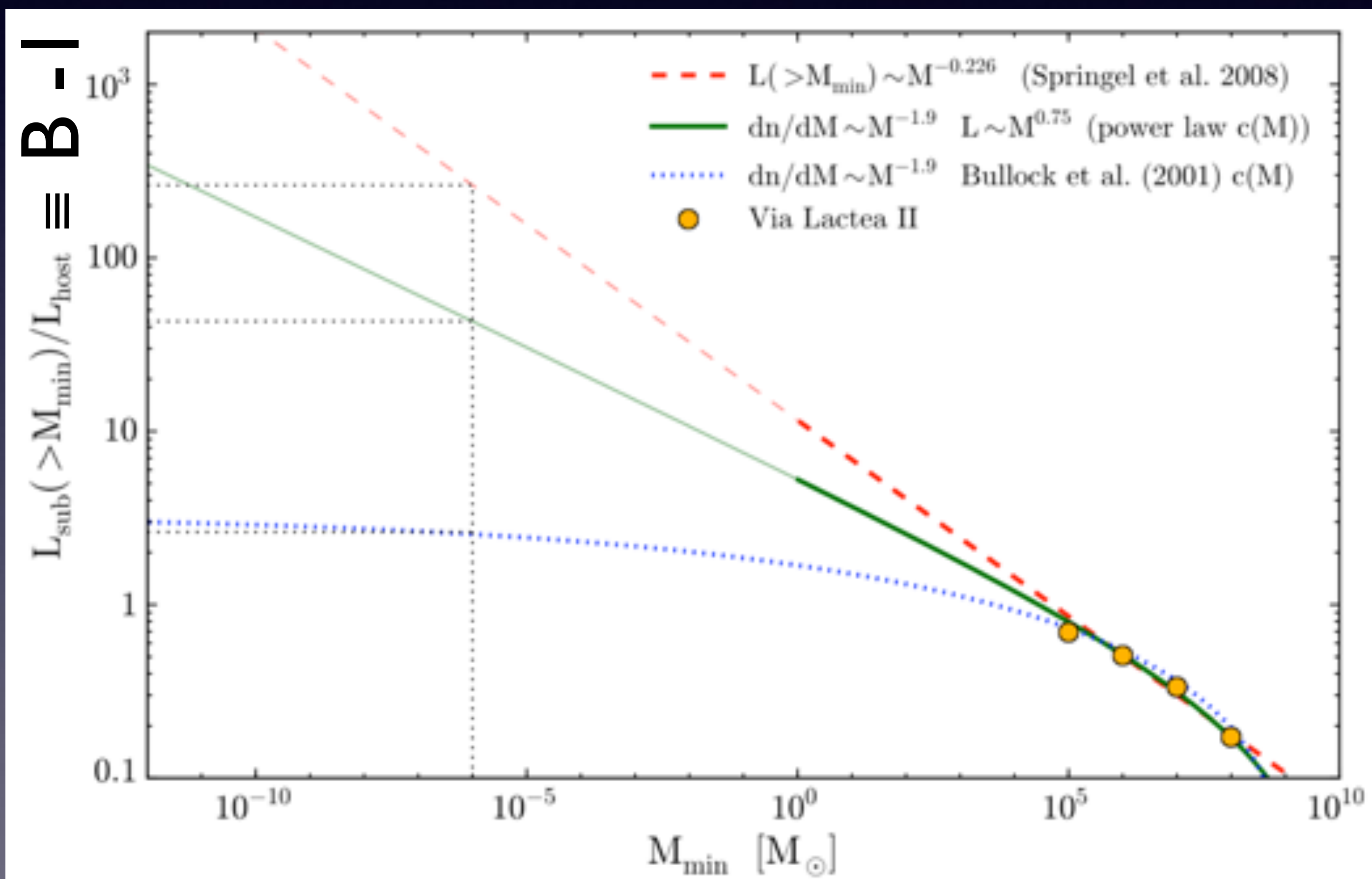
is practically unbiased,
i.e. proportional to DM density



JD&Moore, ASL 2011

galaxy halo boost factor

halo boost factor: $B = \dfrac{\text{total halo luminosity}}{\text{spherical, smooth halo luminosity}}$



from Kuhlen et al. PDU, 2012

B ~ 4 - 15
JD et al ApJ 2006 and Nature 2008

maybe as high as B ~ 30
Kamionkowski et al. PRD 2010
Sanchez-Conde, Prada, MNRAS 2014

not ~1.7
Stoehr, White, Springel et al. 2003

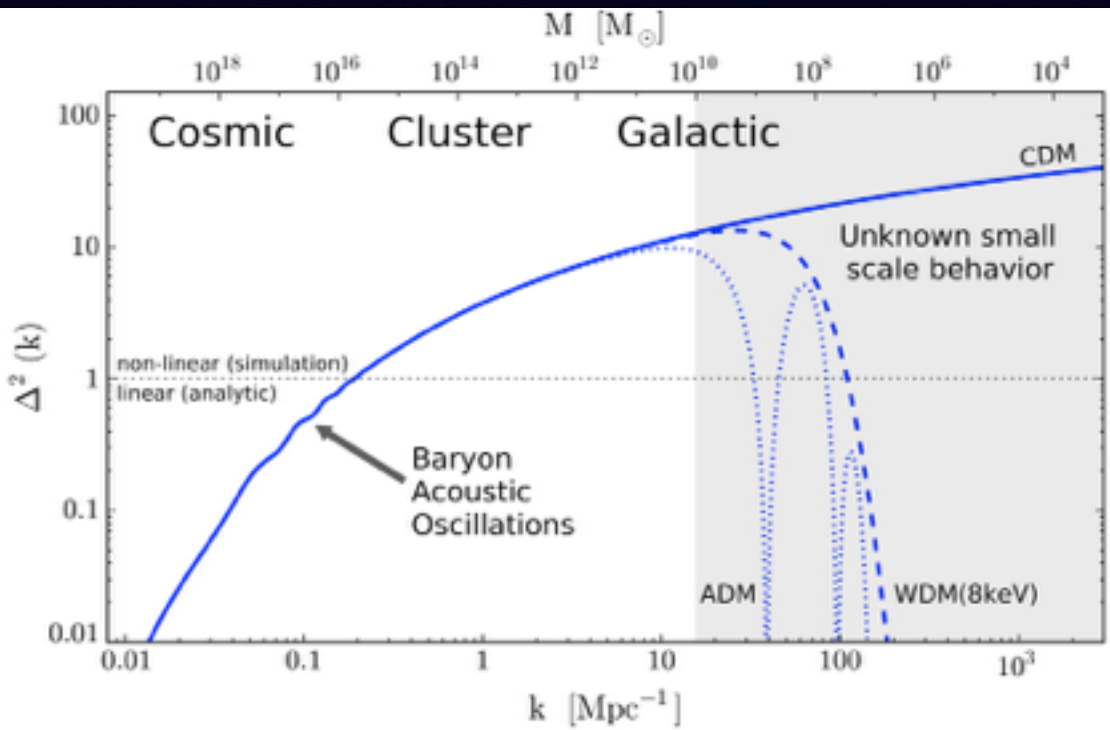
certainly not 232
Springel et al. Nature, 2008

certainly not 100 to 5000
Gao, Frenk et al. 2012

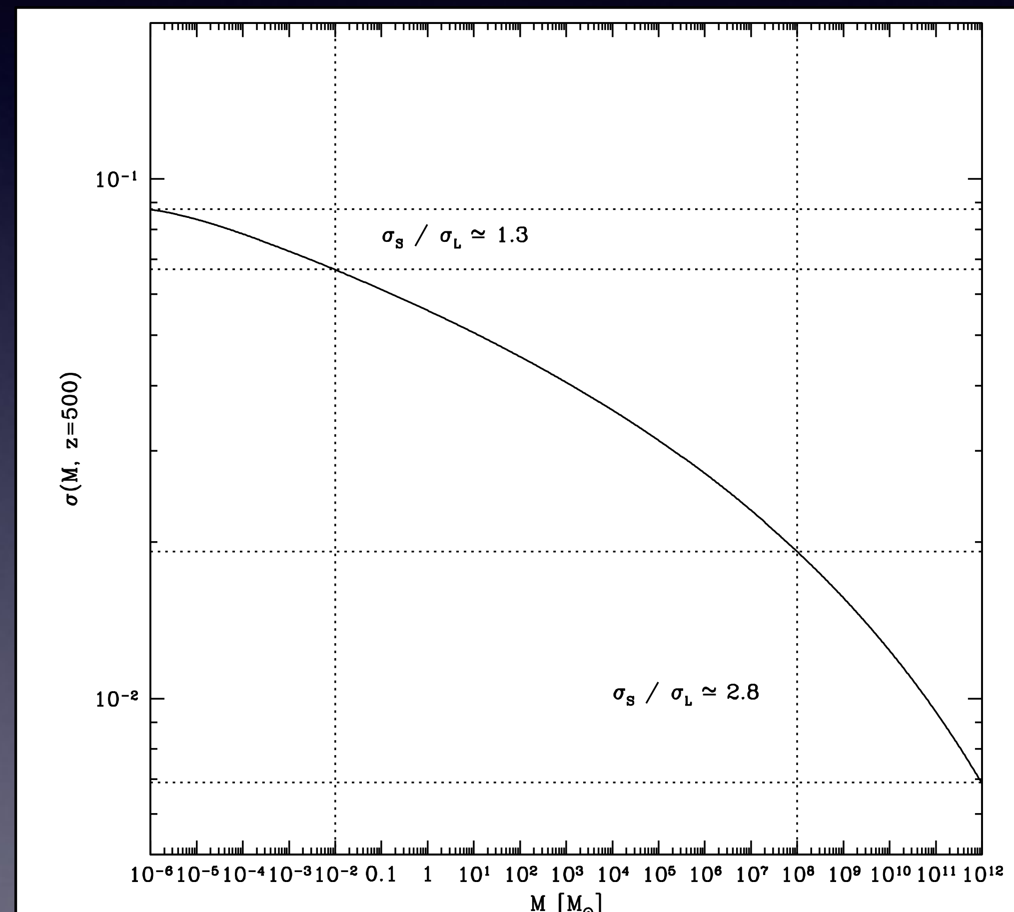
galaxy halo boost factor

$L_{sub}(>M_{min})$ and $c(M)$ are not simple power laws

CDM power spectrum ⟶ mass fluctuations ⟶ formation times



from Kuhlen et al. 2012

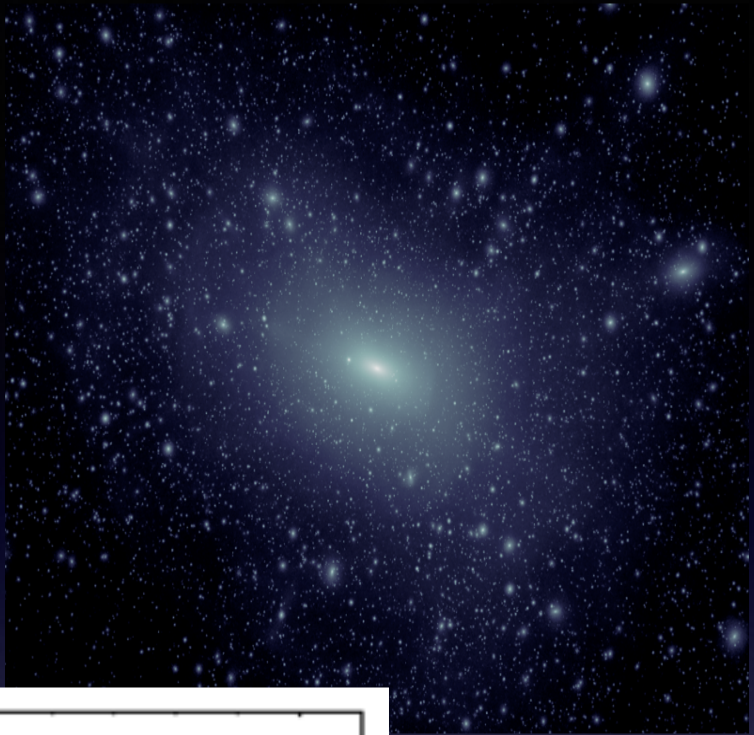


because p(k), sigma(M) and $a_{form}(M)$ are not power laws.

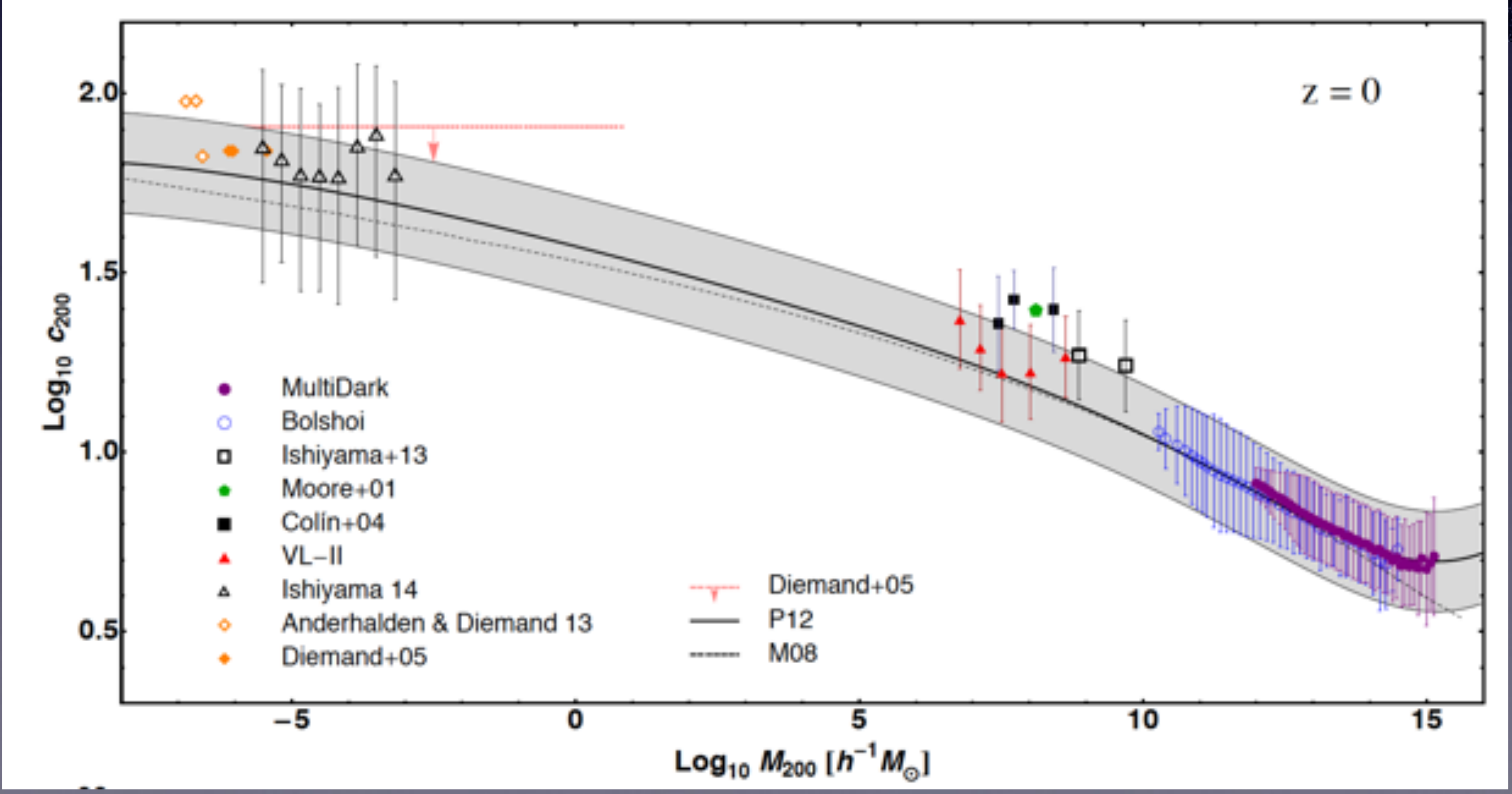
boost factors

extrapolations to smallest
CDM subhalos depends on
the concentration - mass relation

Bullock et al. 2001 or Prada et al. 2012 models
fit the simulation results well



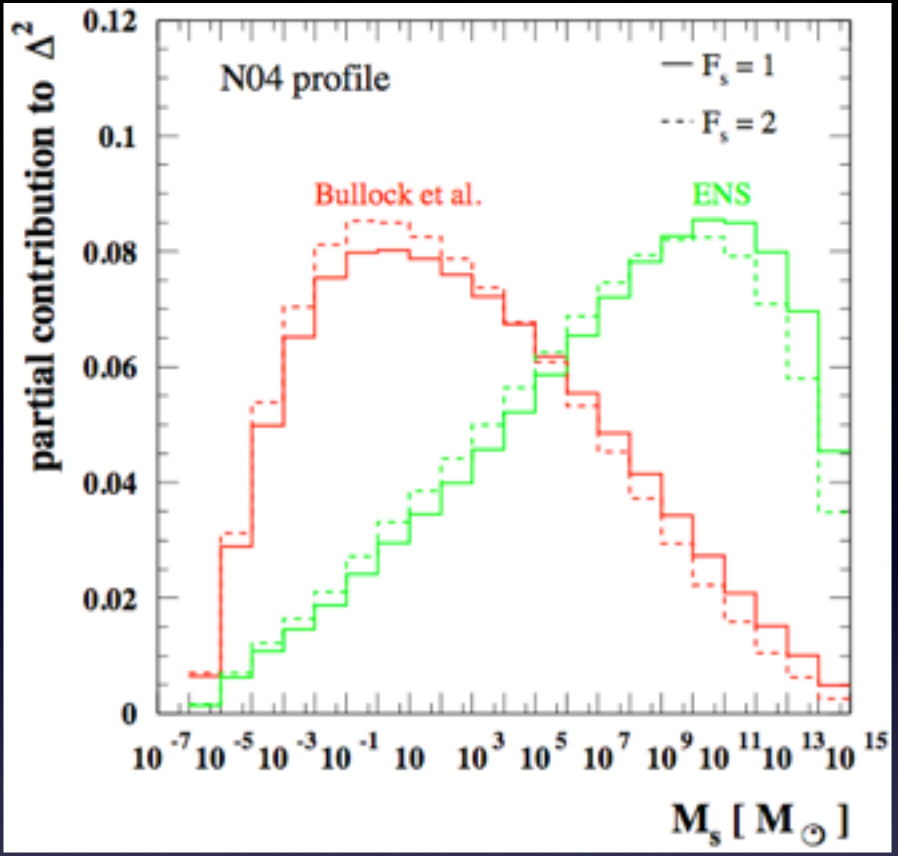
Colafrancesco, Profumo, Ullio AA 2006



Sanchez-Conde, Prada, MNRAS 2014

boost factors

subhalos in mass decade around one solar mass contribute most to total boost

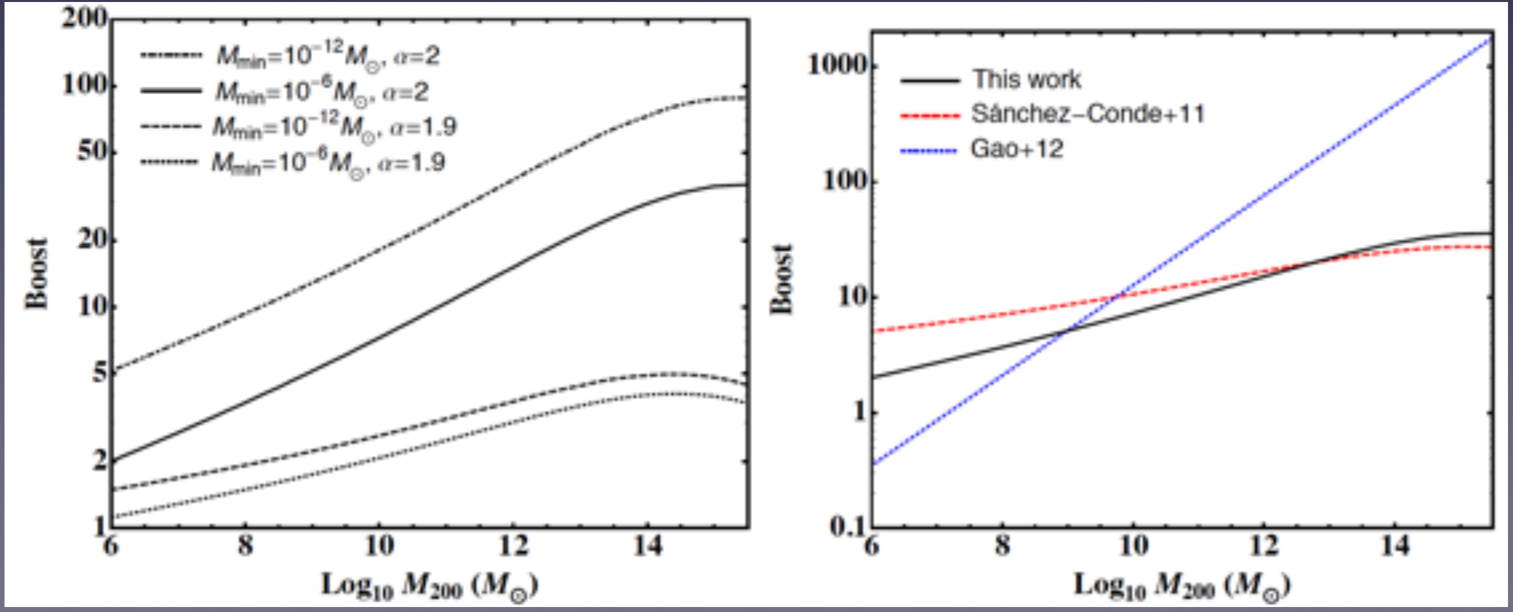


Colafrancesco, Profumo, Ullio AA 2006

→ moderate boost: B ~ 10
weak dependence on CDM cutoff

Colafrancesco, Profumo, Ullio AA 2006
JD et al. 2006/08, Kamionkowski+ PRD 2010
Anderhalden & JD, 2013; Sanchez-Conde+2011,2014

Boost ≡ B - 1
vs.
halo mass



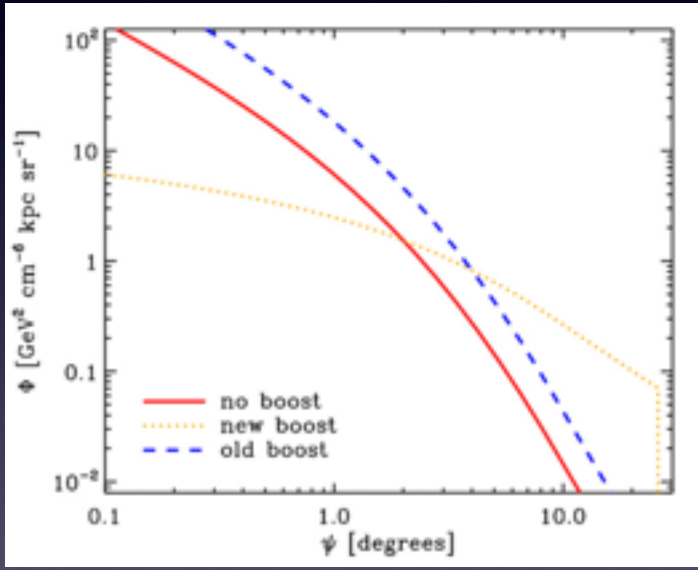
Sanchez-Conde,Prada MNRAS 2014

boost factors depend on location

- halo boost factor = $\frac{\text{total halo luminosity}}{\text{spherical, smooth halo luminosity}}$ ~ 4 - 15

JD et al ApJ 2006 and Nature 2008

- boost factors in actual observations depend on angle:



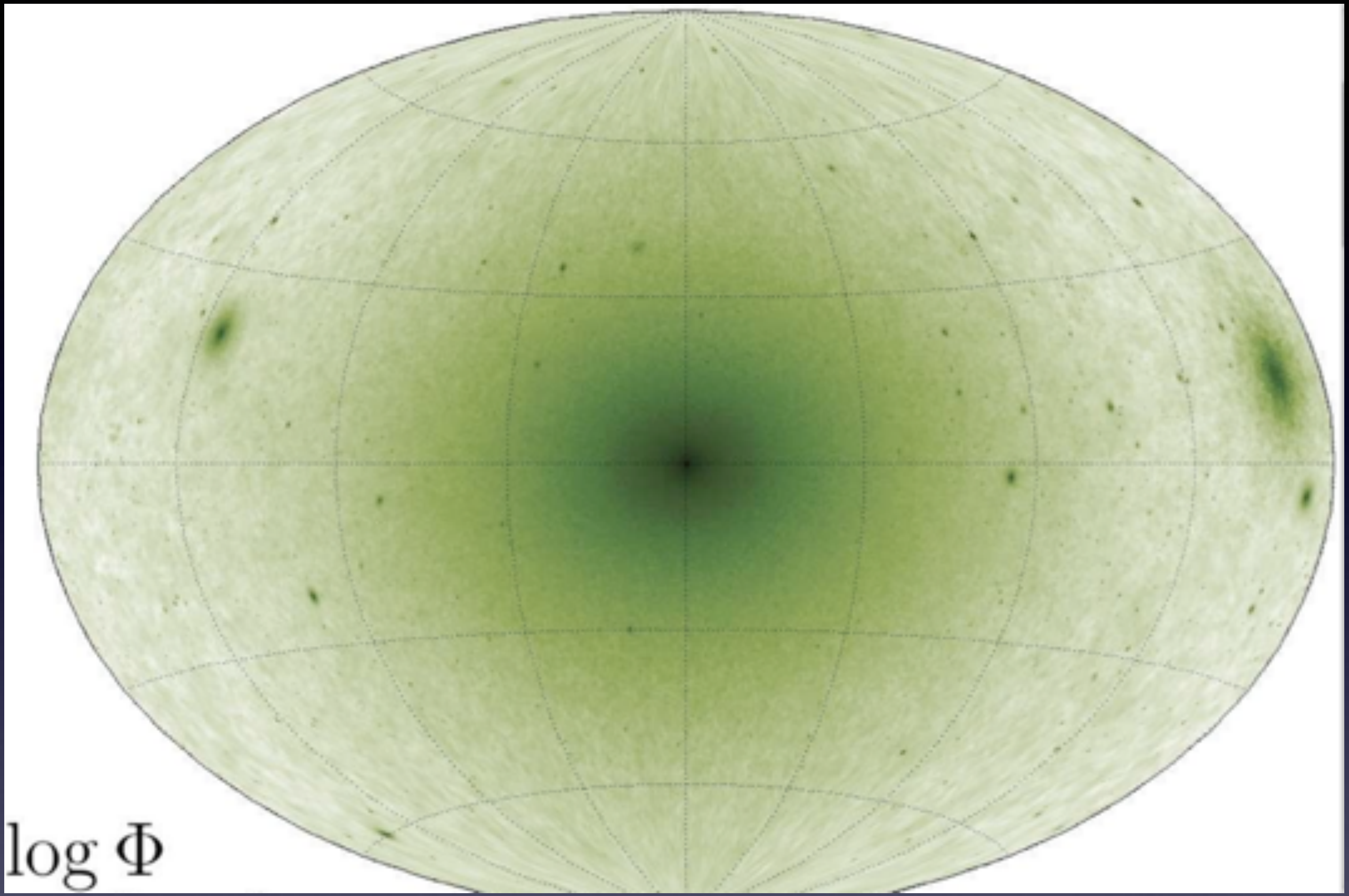
Anderson, Kuhlen, JD, Johnson, Madau, ApJ 2011

- local boost factor = $\frac{\text{total local luminosity}}{\text{smooth local halo luminosity}}$ ~ 1.4 +- 0.2

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

JD et al, Nature 2008, Brun et al 2010

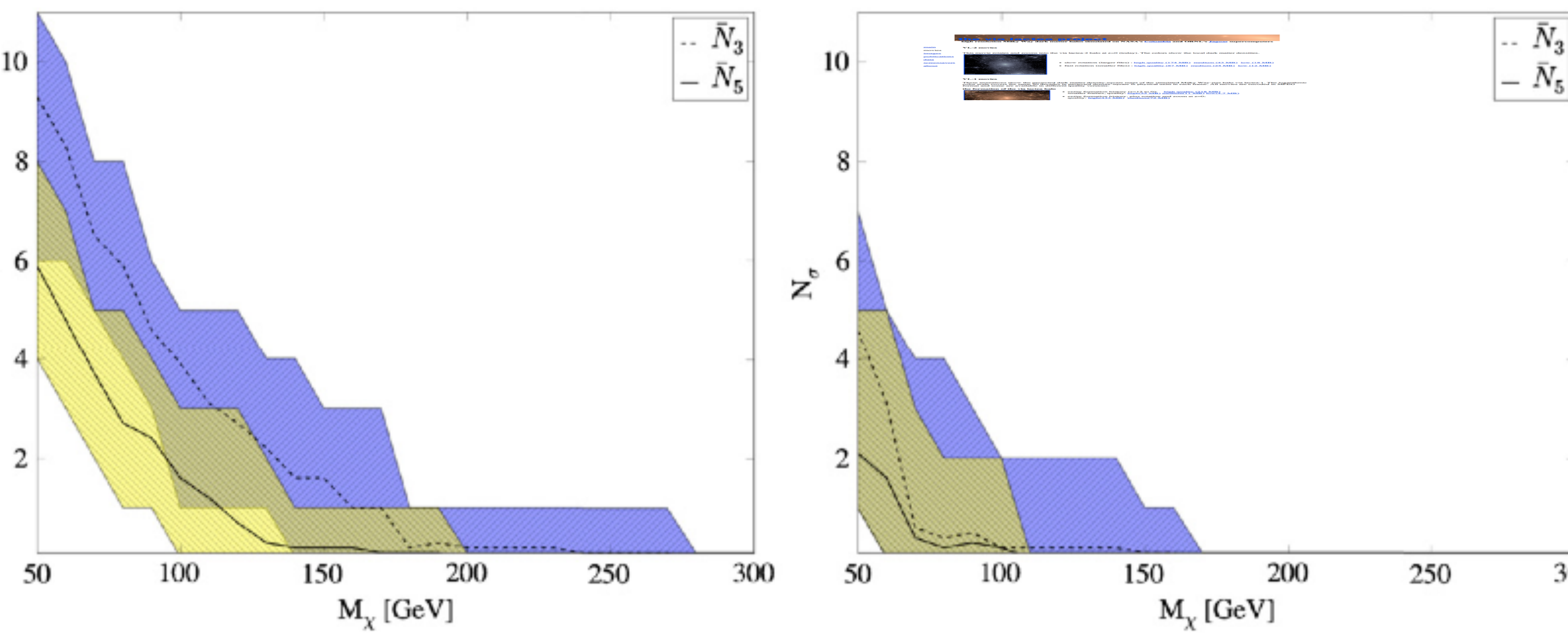
Allsky map of DM annihilation signal from via lactea II



the main halo is obviously the brightest source

but due to poorly constrained, diffuse, astrophysical foregrounds
(e.g. Strong,Moskalenko,Riemer 2004),
subhalos are the more promising gamma ray sources (Baltz et al. 2008)

Number of 3 and 5 sigma subhalo detection by Fermi over 10 years



including unresolved small sub-subhalos

assuming no sub-subhalos

small scale sub-sub-structure is not crucial for detection, but it helps.

promising numbers when using commonly assumed WIMP properties

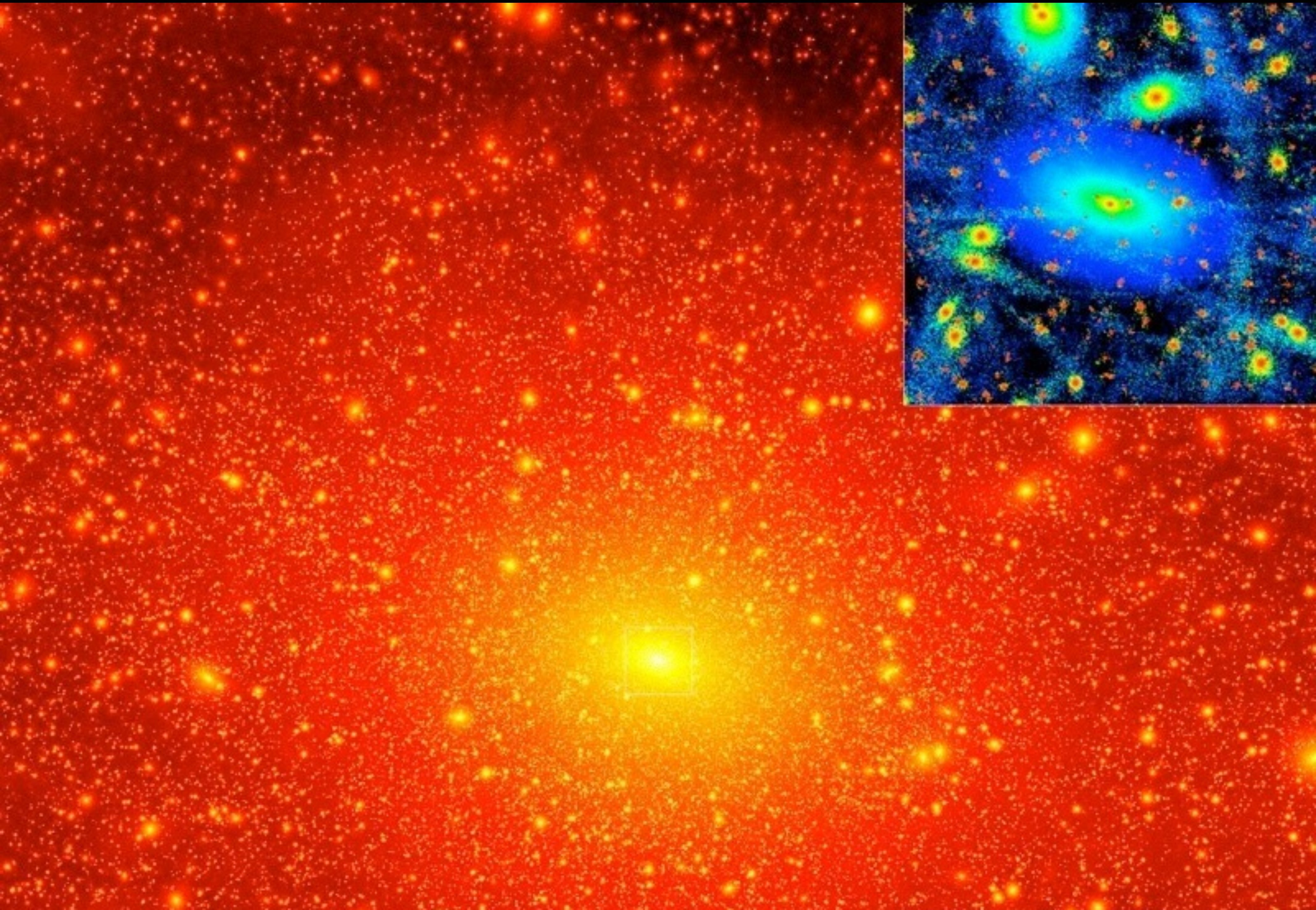
Anderson, Kuhlen, JD, Johnson, Madau, ApJ 2011

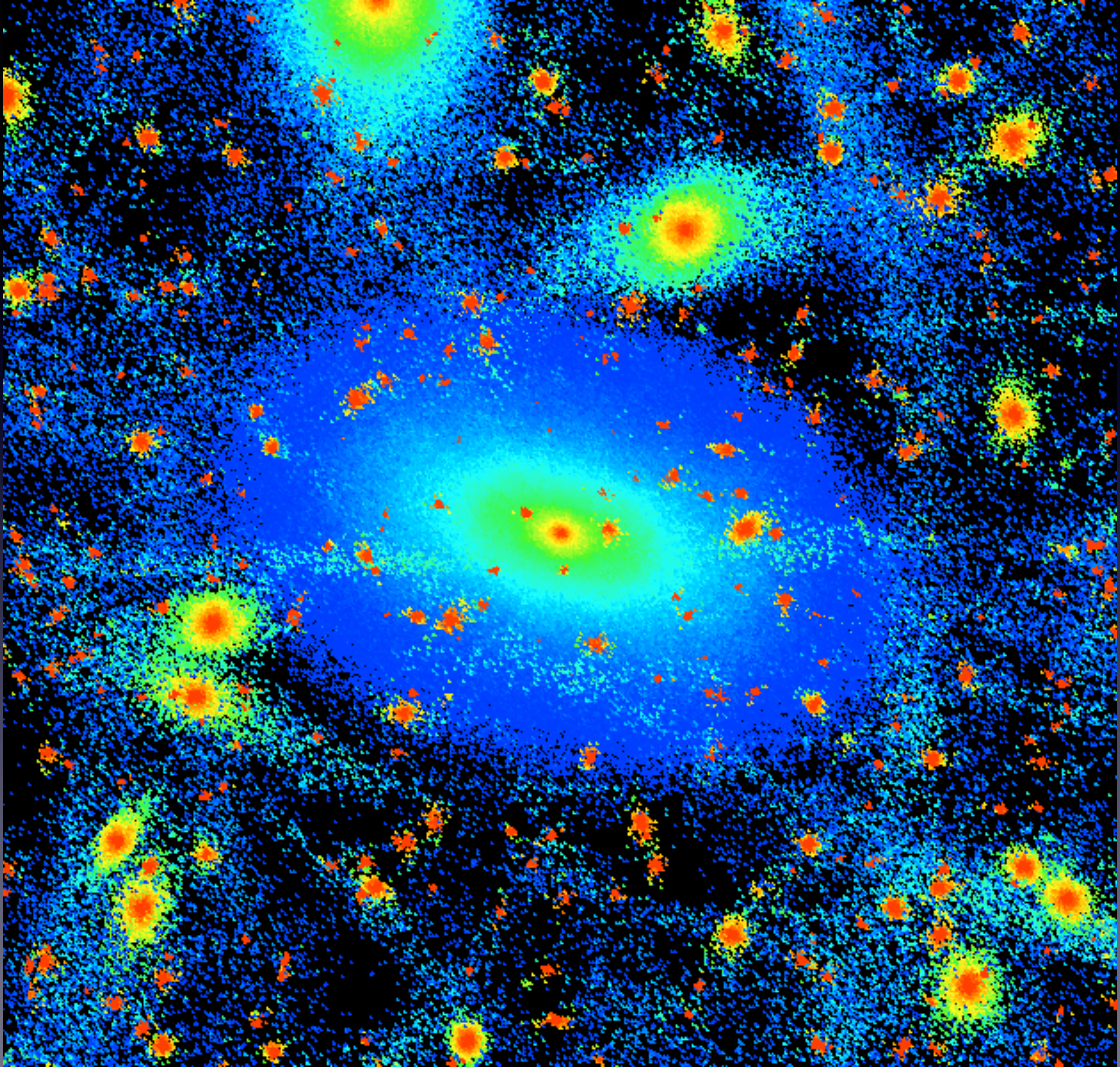
3. other substructure

everything but subhalos,

e.g.
streams
graininess
caustics

via lactea II : local density phase-space density

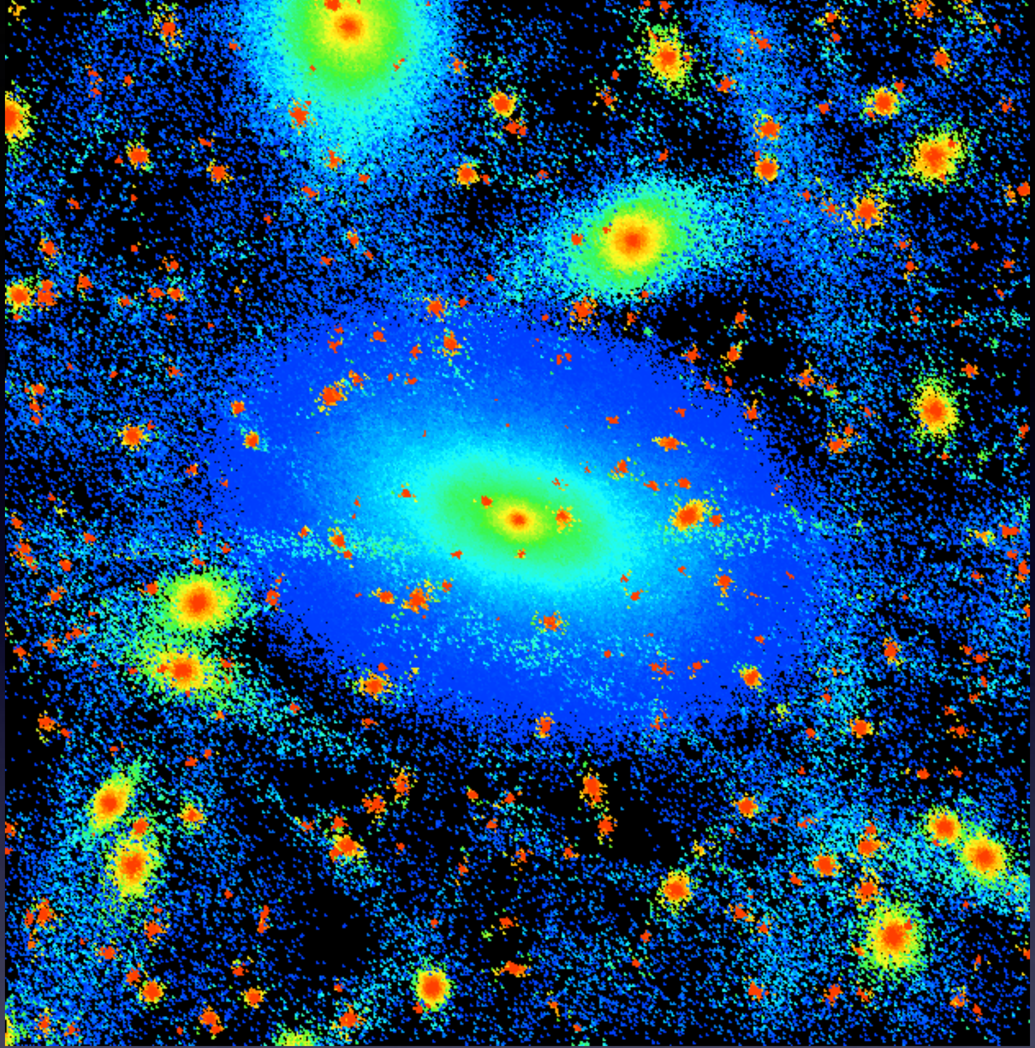




direct detection

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

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



some obvious streams visible in phase space density, but they contain less than 0.01 of the local density

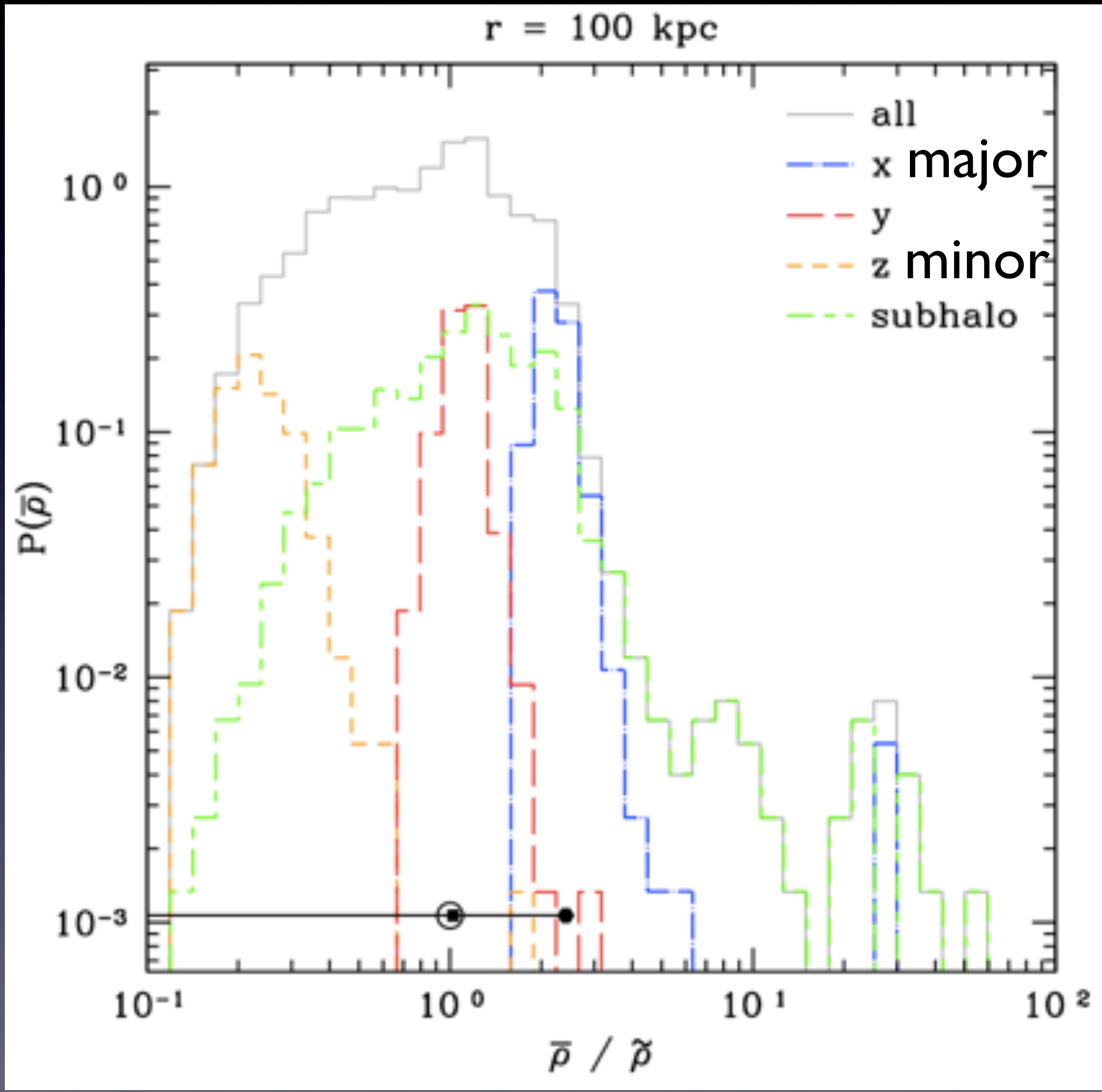
JD et al Nature 2008

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

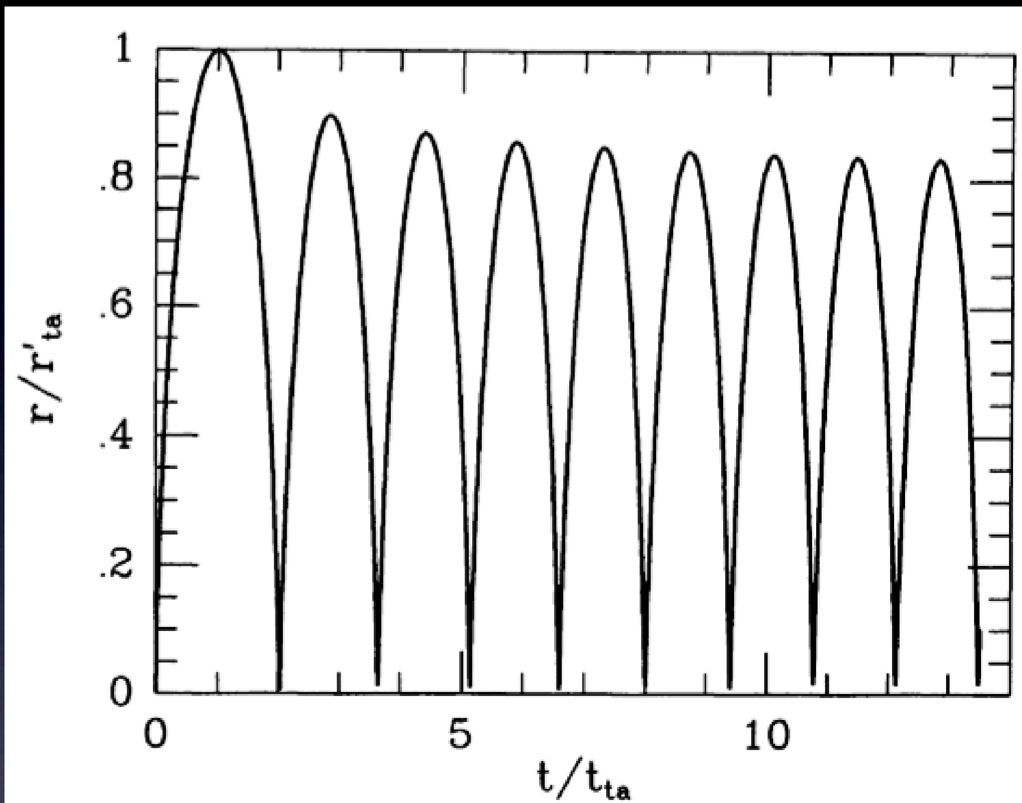
but clumpiness is still dominated by subhalos, i.e no significant extra annihilation boost from streams (see also Afshordi et al. 0811.1582)

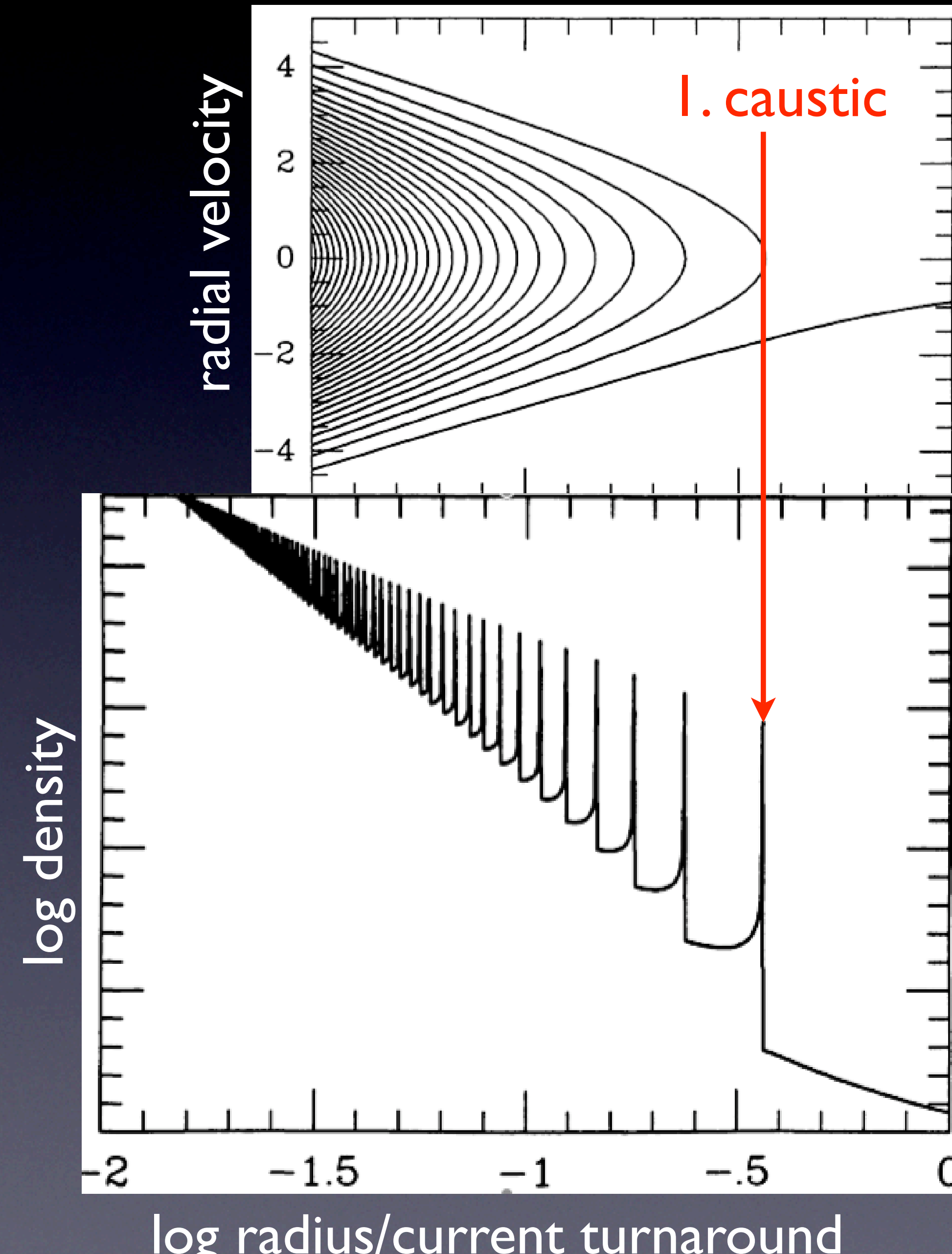


Zemp, JD et al, 2009

infall caustics

self-similar secondary spherical radial infall model:

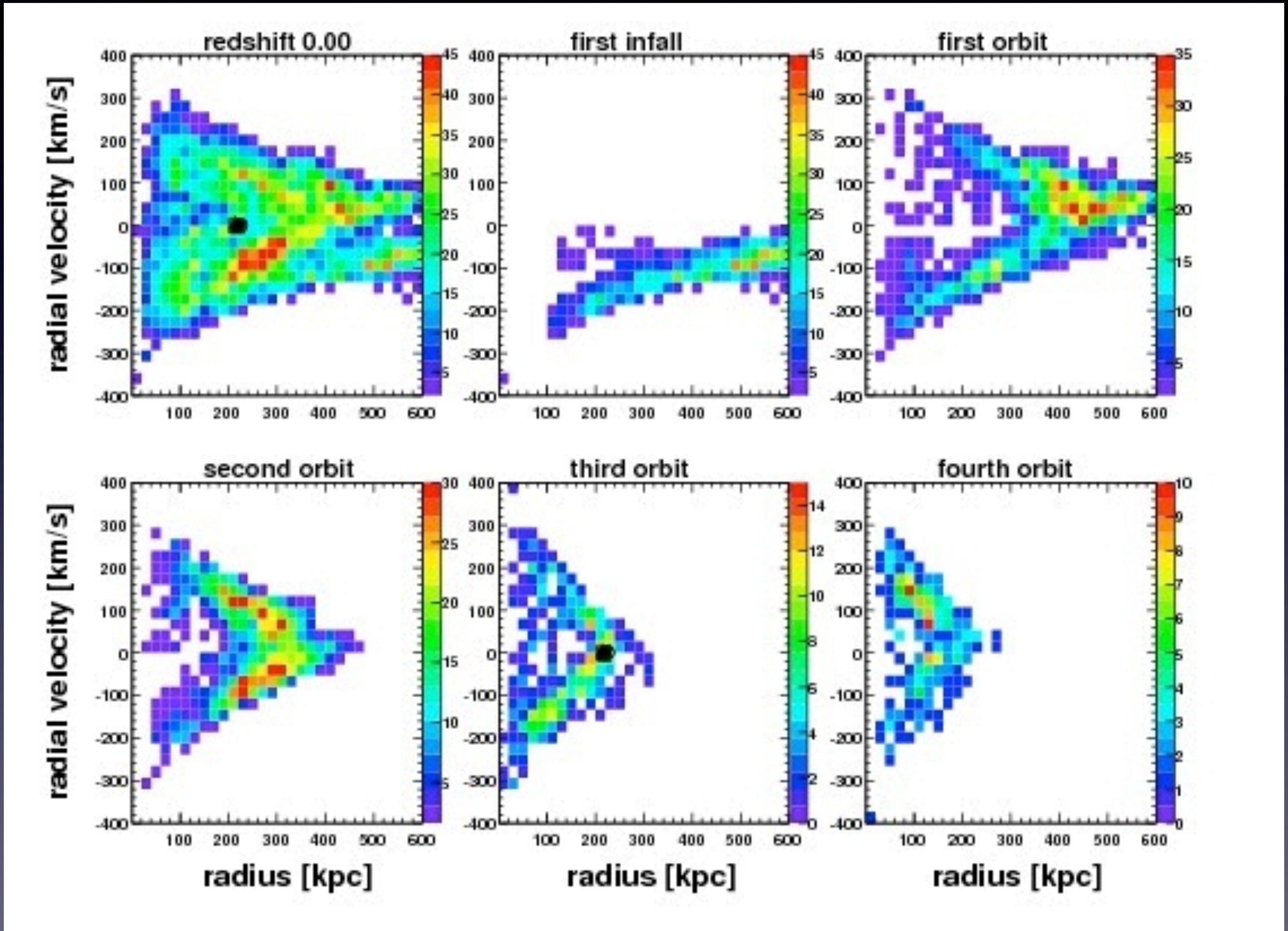




Fillmore&Goldreich1984;Bertschinger1985

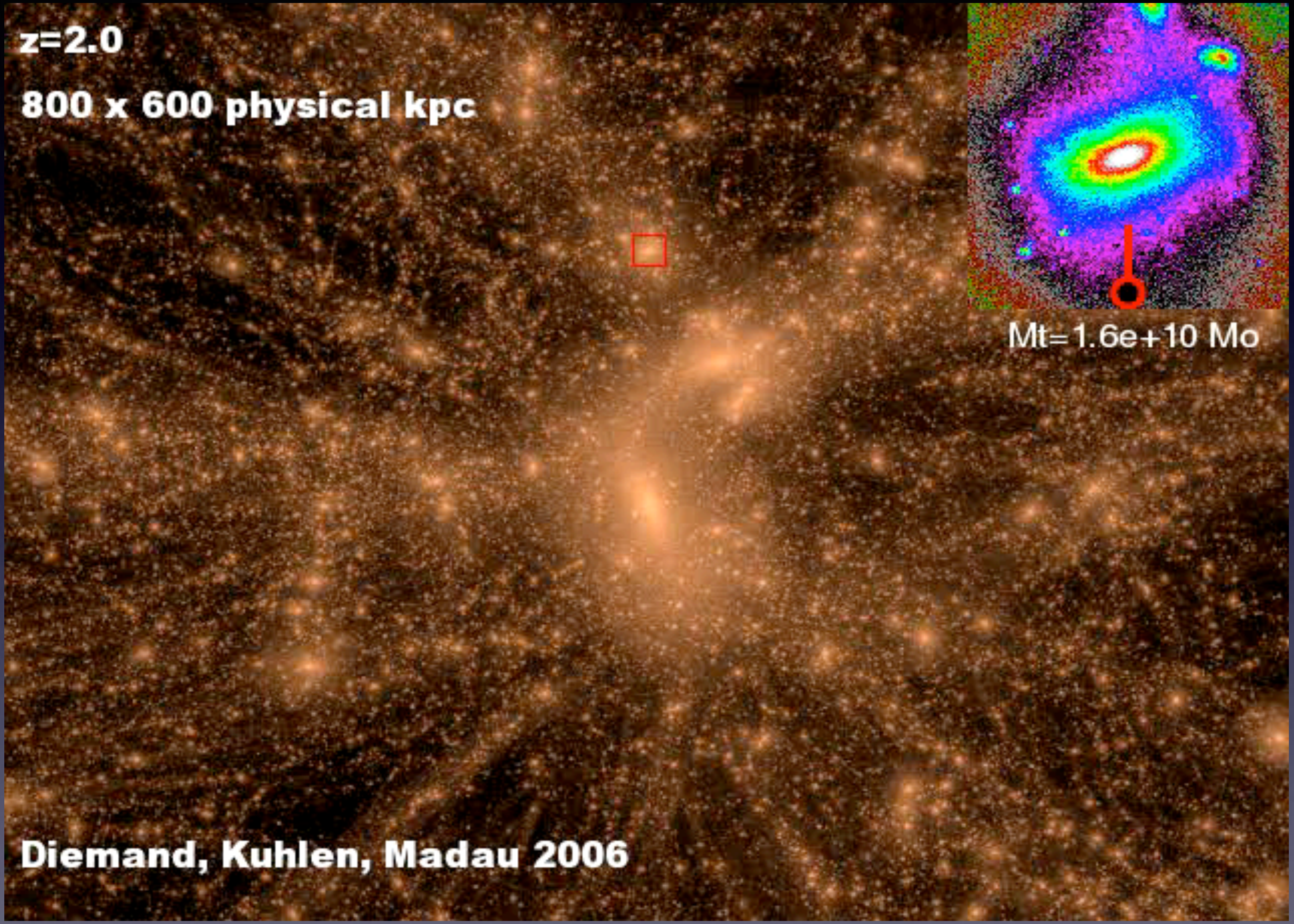
small collapse factors of 12% to 18%
rho ~ r^-2.25 with infinite density caustics

infall caustics



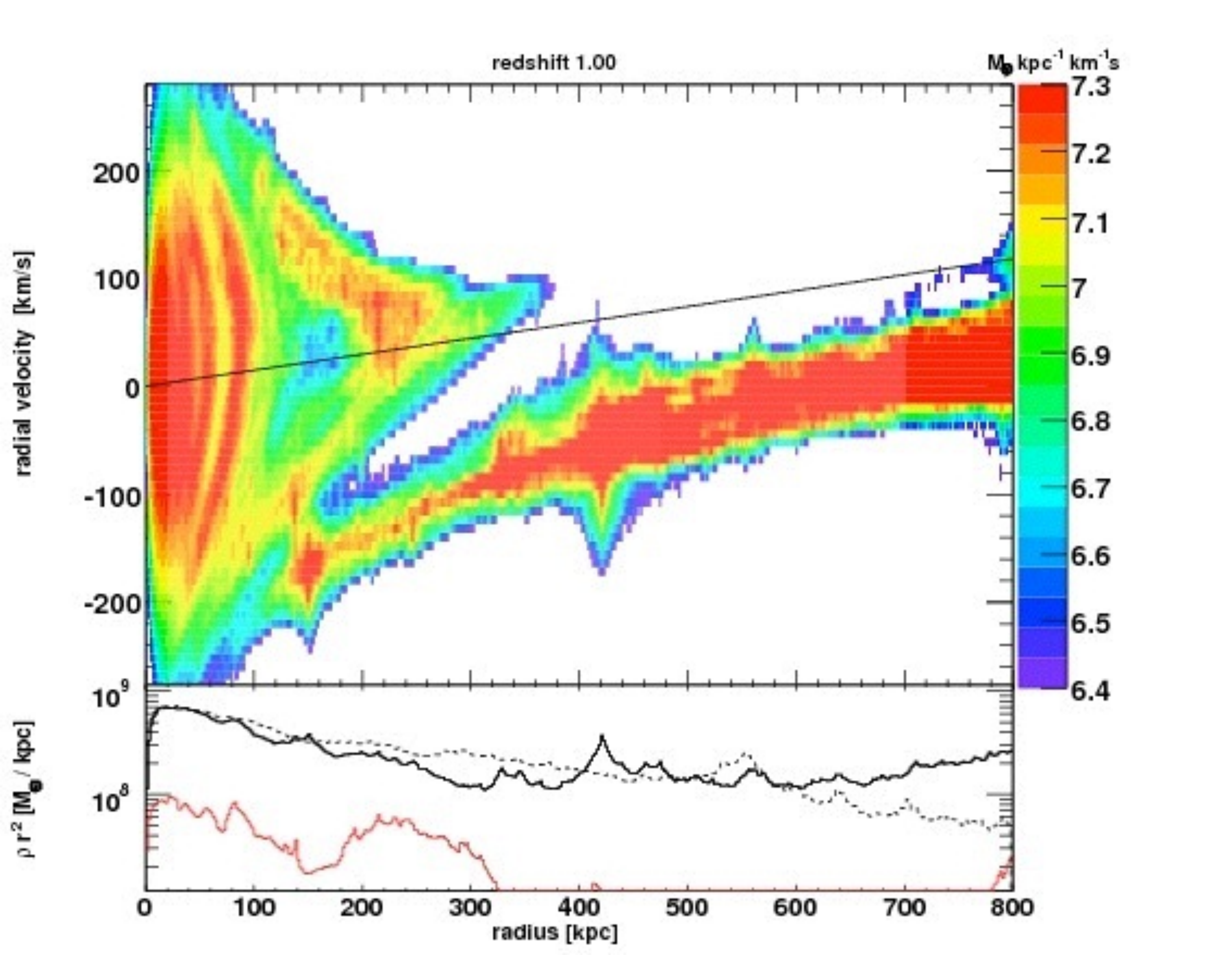
JD, Kuhlen, ApJL 2008

infall caustics



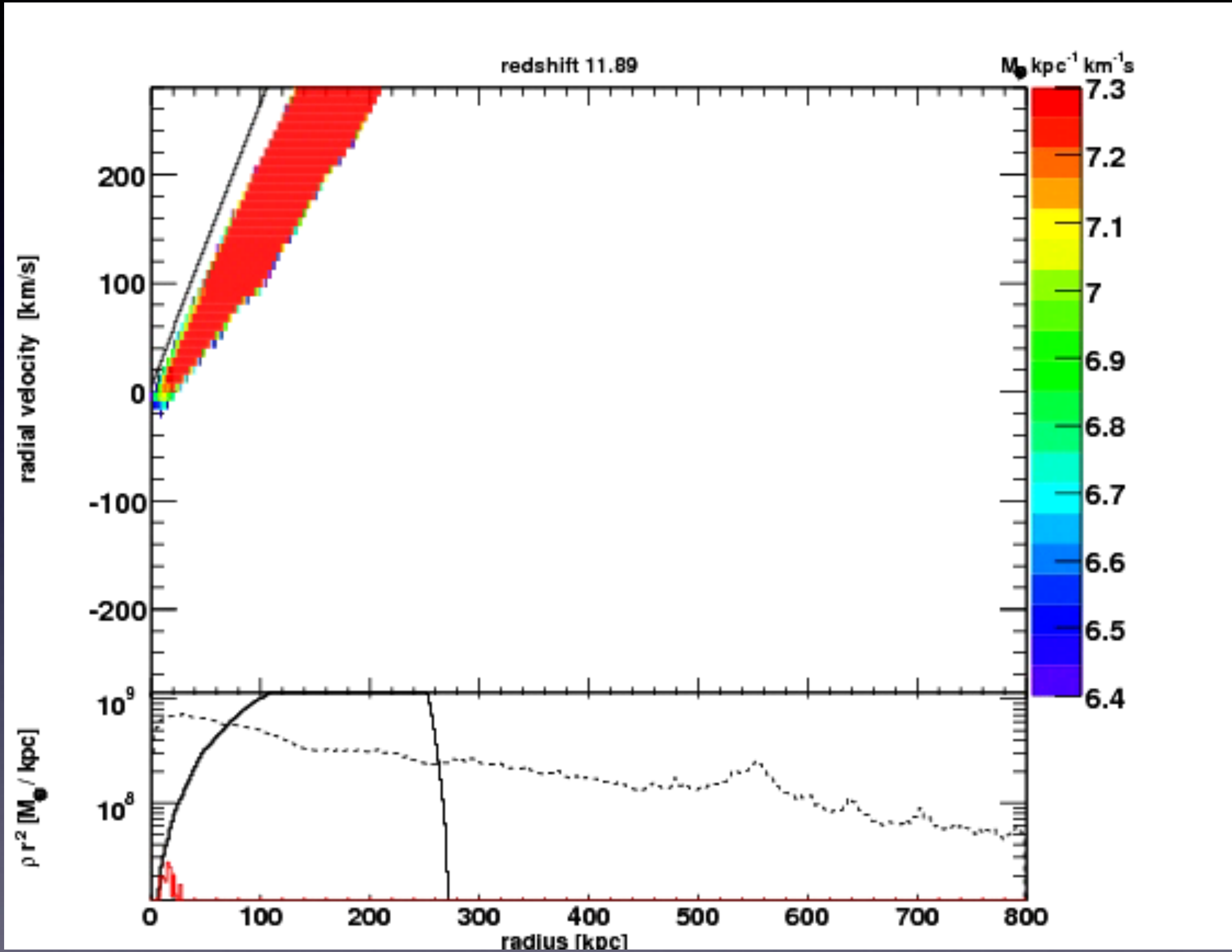
JD, Kuhlen, ApJL 2008

infall caustics

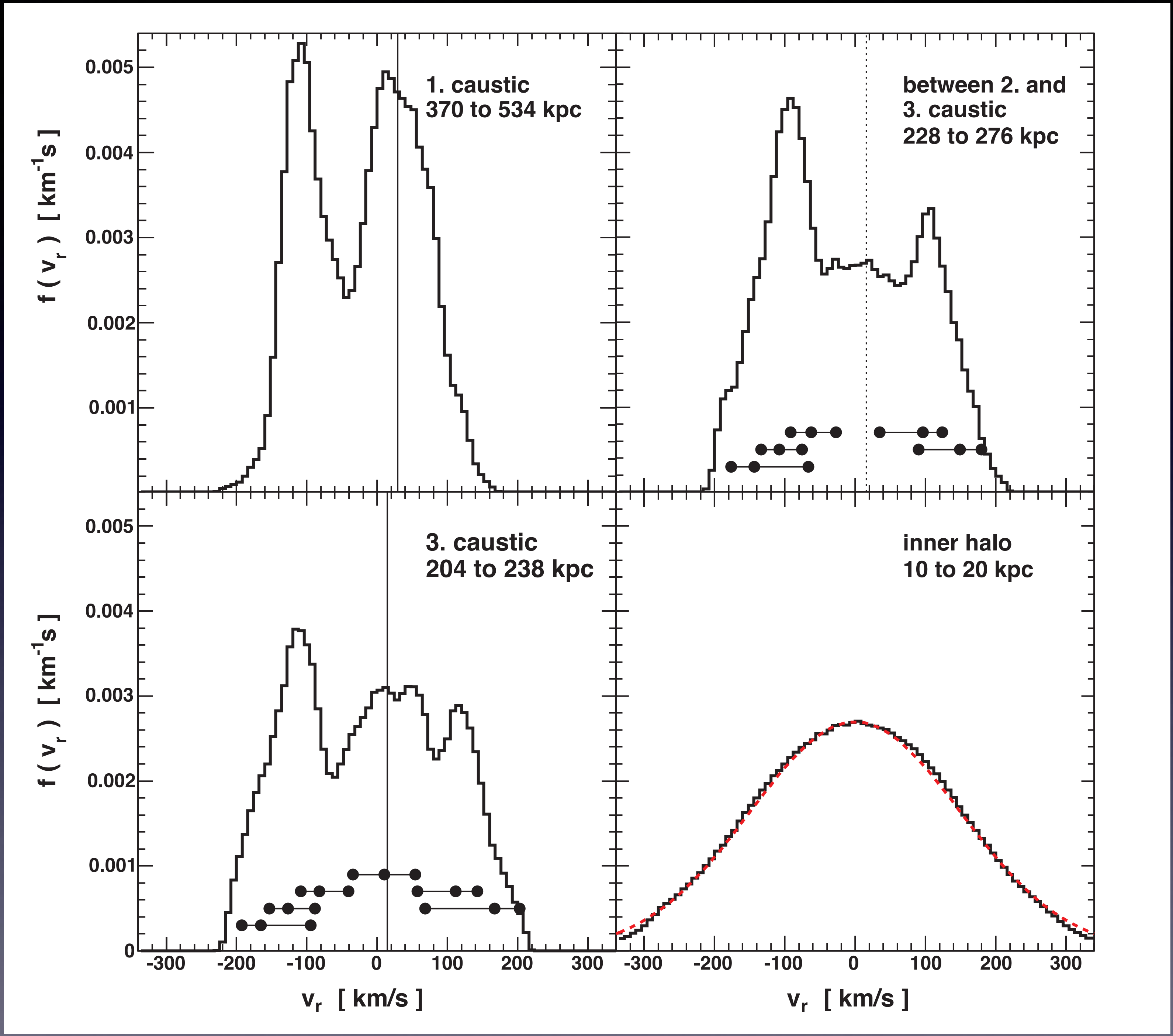


JD, Kuhlen, ApJL 2008

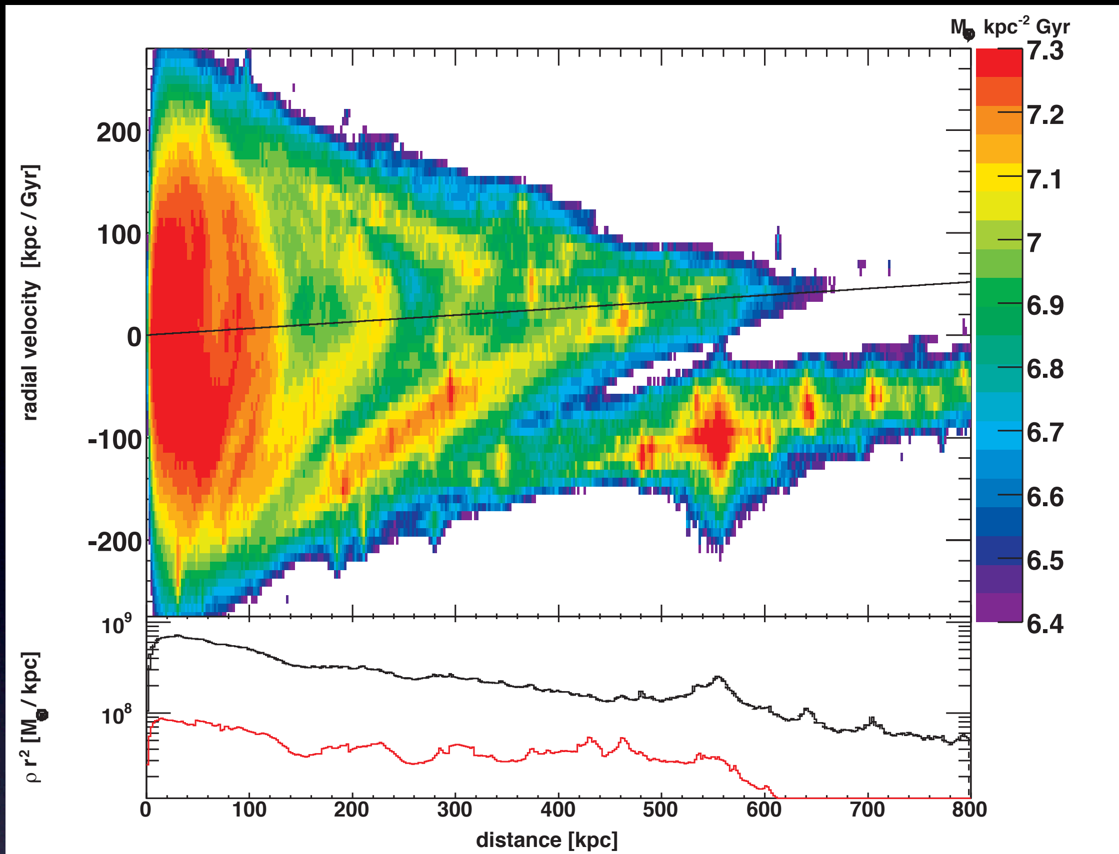
infall caustics



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

$r_{k,\mathrm{med}}$ [kpc]	$r_{k,68\%}$ [kpc]	$\frac{\Delta r_k}{r_{k,\mathrm{med}}}$	$t_{k,\mathrm{med}}$ [kpc]	$t_{k,68\%}$ [kpc]	$\frac{\Delta t_k}{t_{k,\mathrm{med}}}$	$\left(\frac{r_k}{t_k}\right)_{\mathrm{med}}$	$\left(\frac{r_k}{t_k}\right)_{68\%}$	$\left(\frac{r_k}{t_k}\right)_{\mathrm{FGB}}$
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

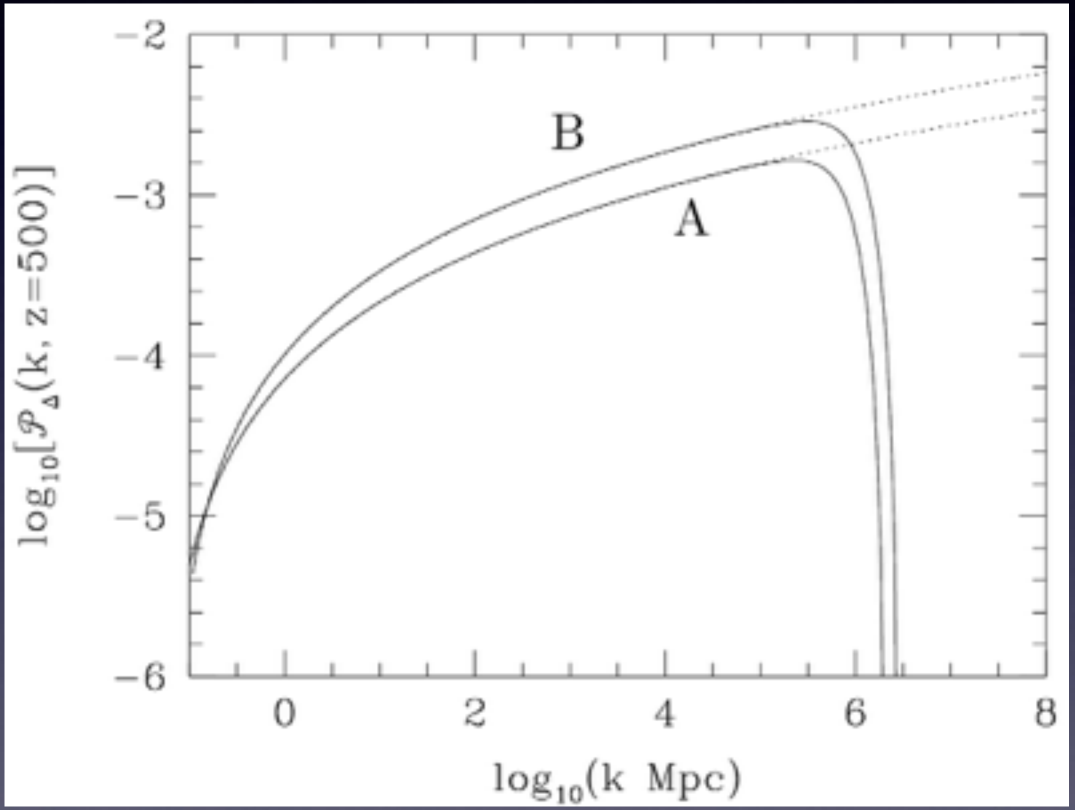
4. microhalos revisited

smallest scale CDM structures

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

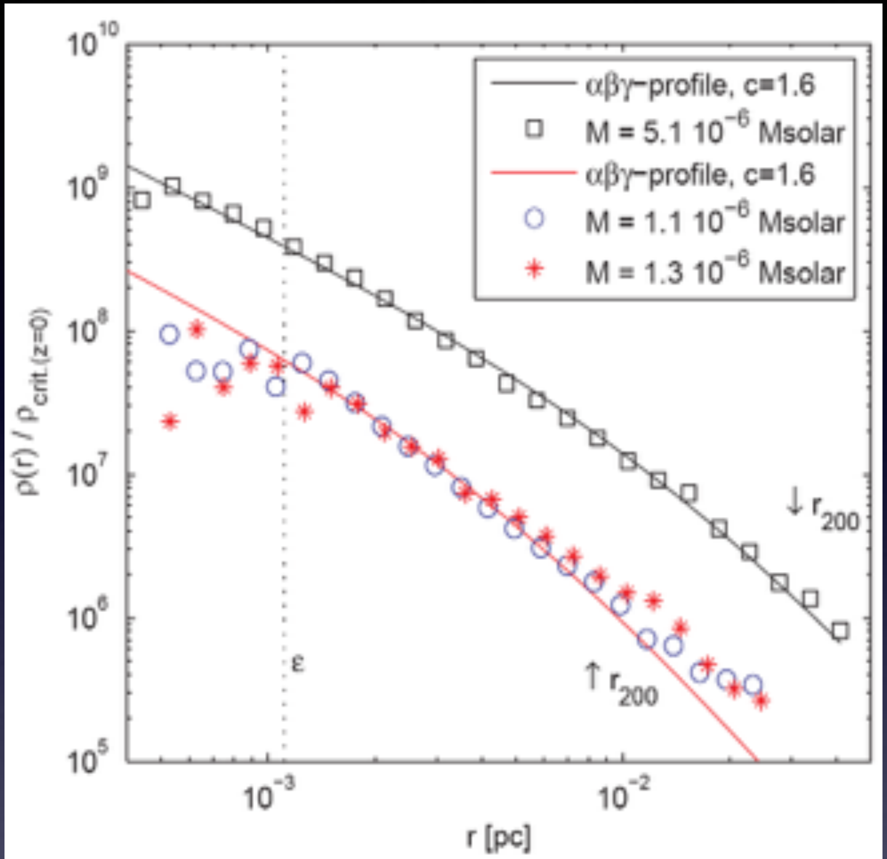
→ small, “micro”-halos should forming around z=40 are the first and smallest CDM structures

from Green, Hoffmann & Schwarz 2003



smallest scale CDM structures

CDM microhalos seem to be about as cuspy as the larger halos that formed in mergers



their concentrations c ~ 3.3 at z=26
evolve into c ~ 90 by z=0
consistent with Bullock et al. 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

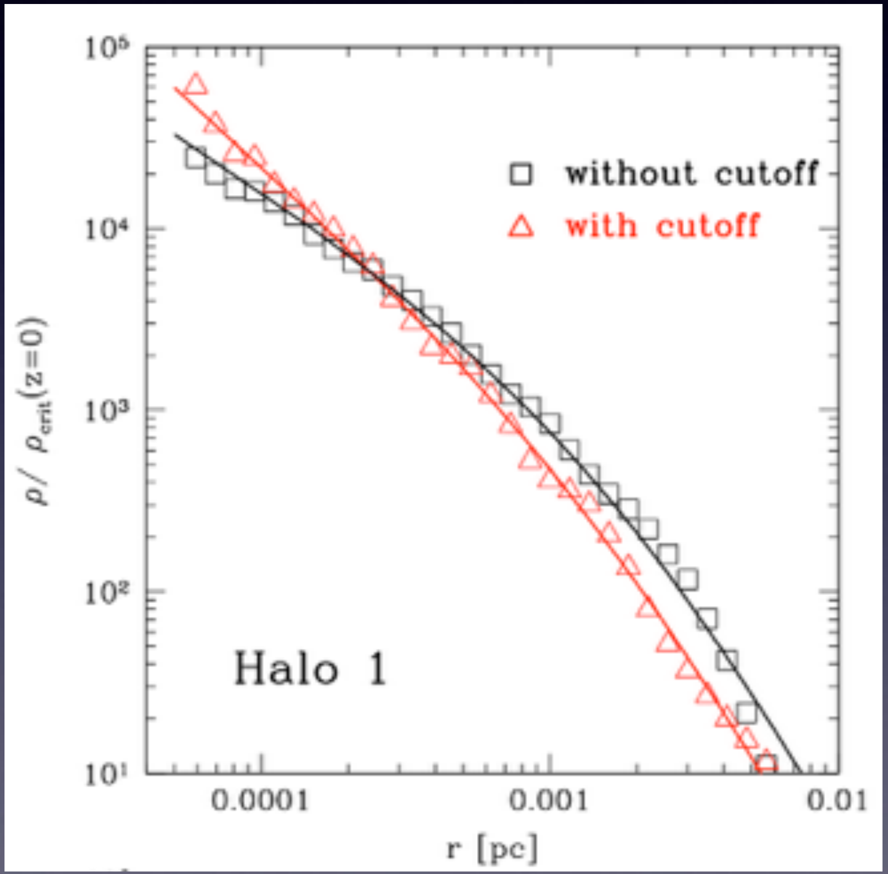
(JD, Moore,Stadel, Nature 2005)

some tidal mass loss and disruption due to encounters with stars (see Goerdt et al. astro-ph/0608495)

microhalo profiles depend on power spectrum

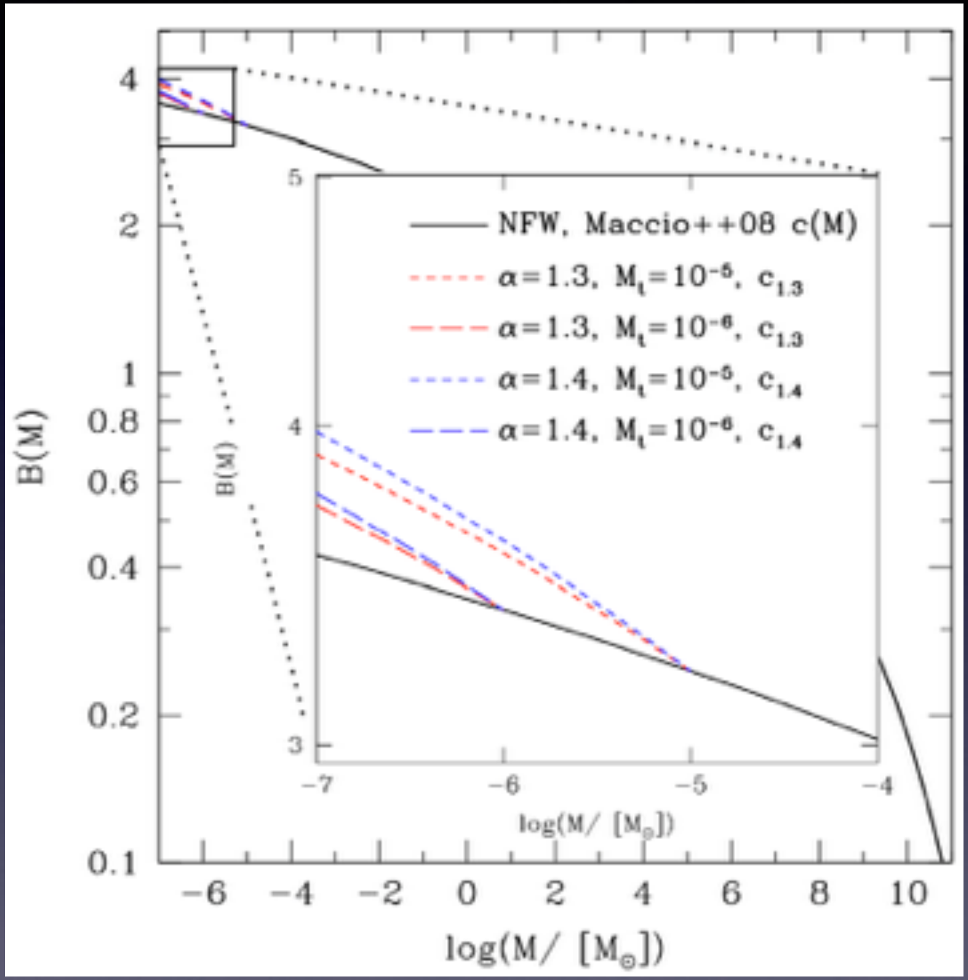
surprising result from Ishiyama et. al, ApJL, 2010:
cutoff leads to steeper profiles!

Ishiyama+, ApJL, 2010



Anderhalden & JD, arXiv:1302.0003

microhalo profiles depend on power spectrum

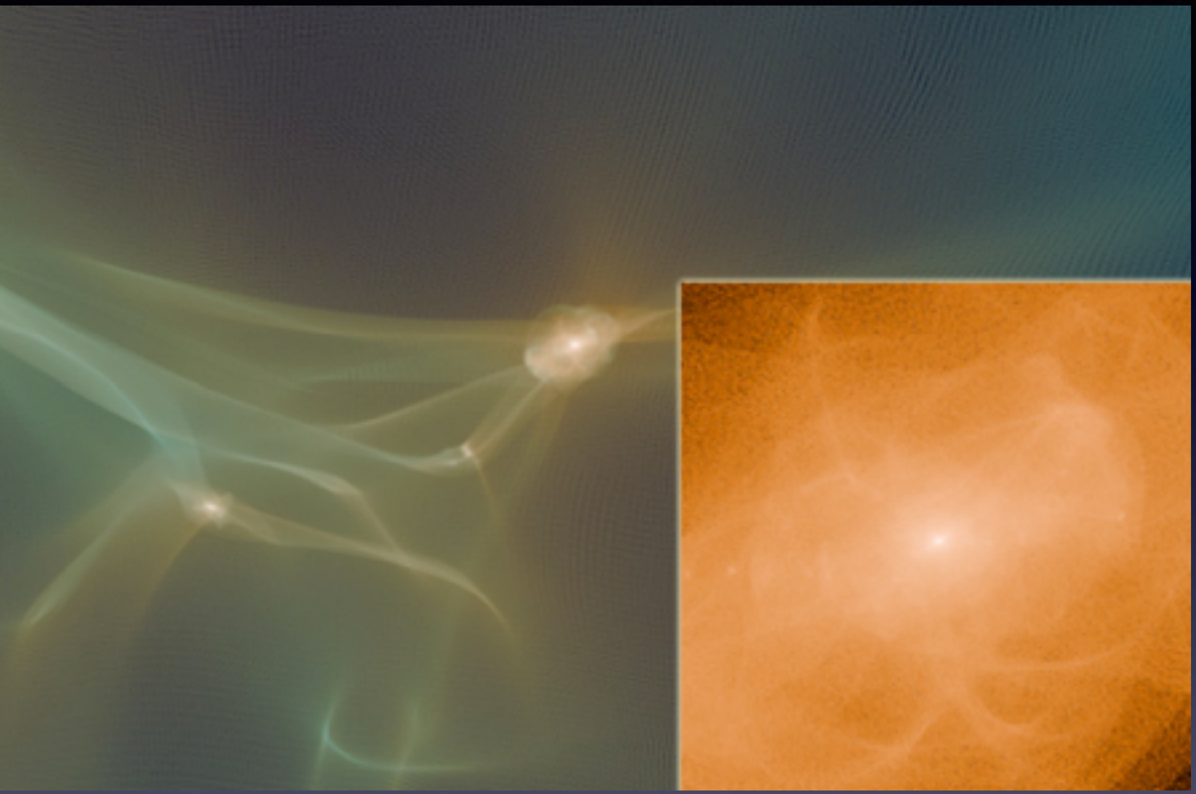


Anderhalden & JD, JCAP 2013

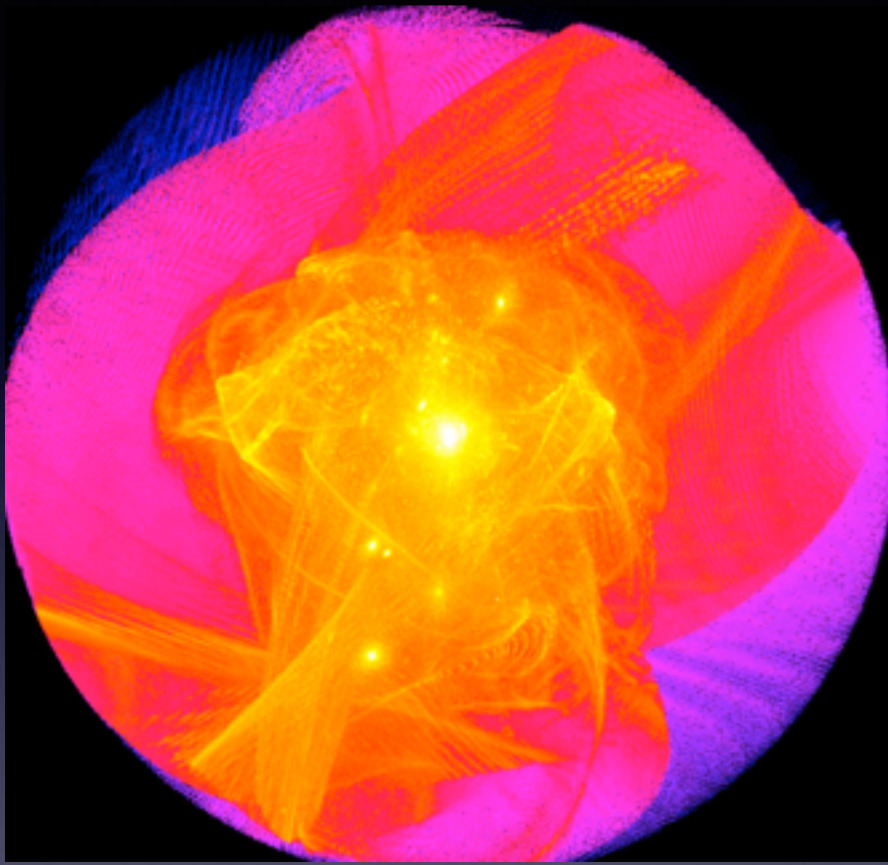
new, steeper microhalo profiles lead to larger boost factors

the effect is quite small: galactic halo boost increases from 3.5 to up to 4.0

high redshift microhalos show clear infall caustics



Ishiyama+, ApJL, 2010



Anderhalden & JD, arXiv:1302.0003

resolved caustics at z=30 increase the halo annihilation signal by 50%.
the effect decreases with time, unclear how much would be left at z=0.

summary of LCDM review

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

• identical density profiles and substructure abundance in the inner regions of field halos and subhalos

• small halos and subhalos contribute significantly to the total DM annihilation signal. Largest contributions per mass decade come form around solar mass scales.

• astrophysical factors in pure CDM annihilation rates are now well constrained (within a factor of two). baryons increase the uncertainty in some regions

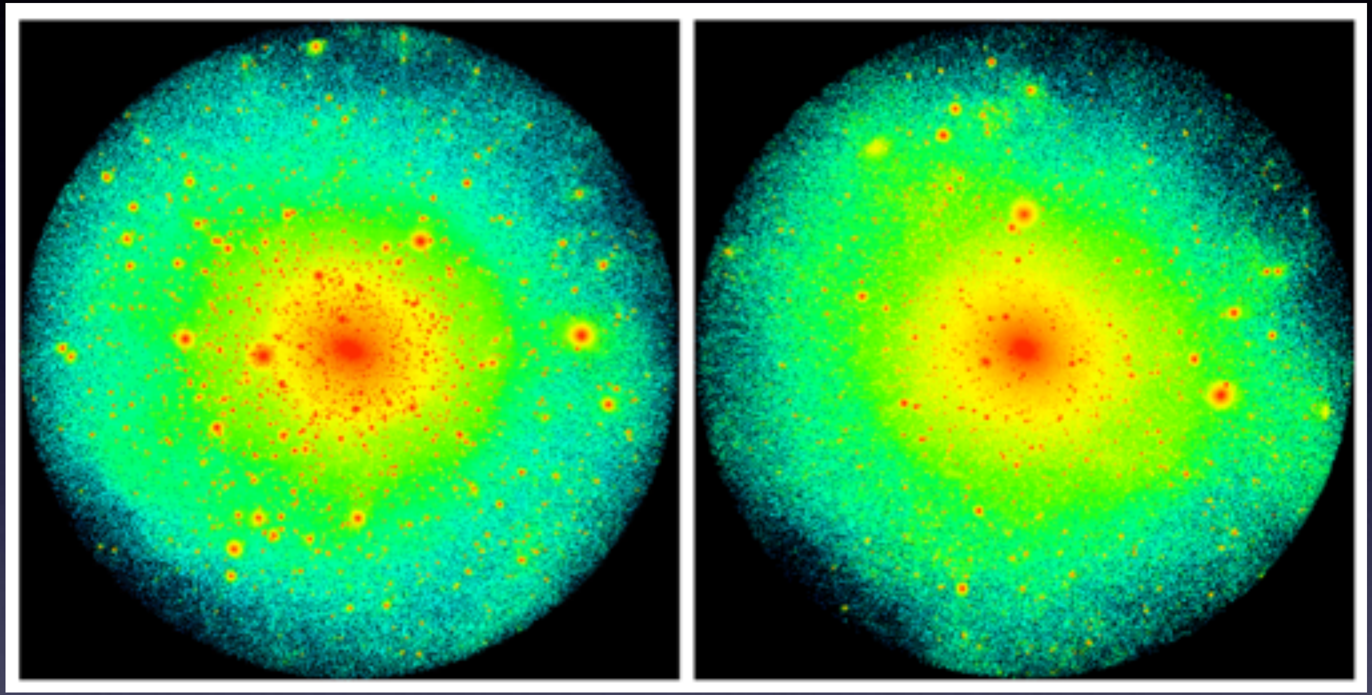
• WIMPs with commonly assumed properties produce annihilation signals in subhalos, which should be detectable by Fermi

• other DM substructures like infall caustics and tidal streams have little effect on direct and indirect DM detection

• microhalos near the cutoff have surprisingly steep inner profiles. this increases galactic halo boost factors by a small amount (up to 15 percent)

Warm Dark Matter and Mixed Dark Matter Models

LCDM



LWDM
m_eff = 2 keV

for details see:
Anderhalden, Schneider, Maccio, JD, Bertone, JCAP 2012/2013
Schneider, Anderhalden, Maccio, JD, MNRAS 2014

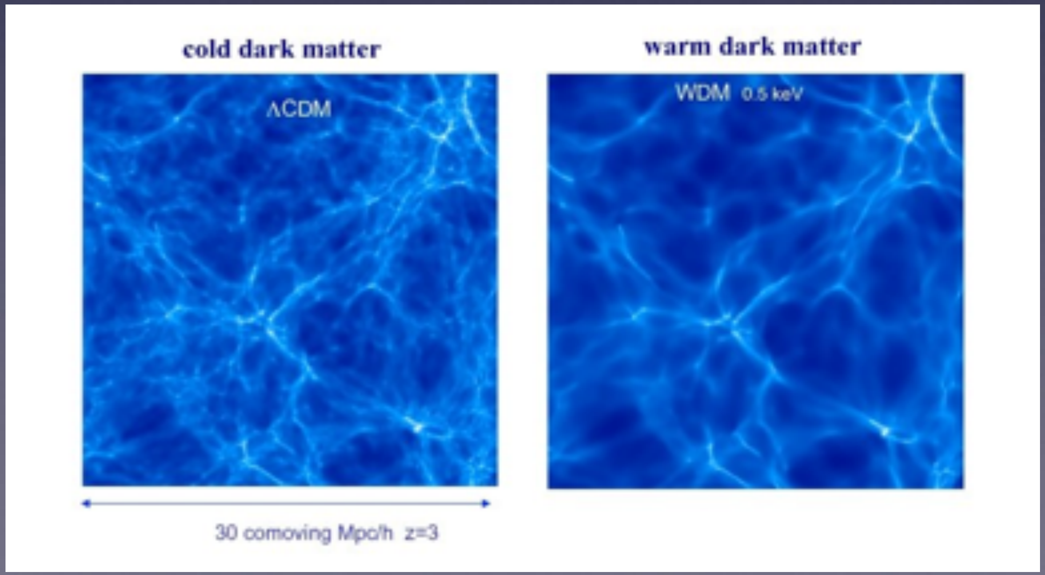
motivation for WDM

- neutrino minimal standard model (νMSM) contains sterile neutrinos with an effective mass of a few keV

- might solve the small scale problems of CDM (e.g. Weinberg+2013):

  - cusp/core problem
  - missing satellites problem
  - too big to fail problem

while maintaining its successes on large scales



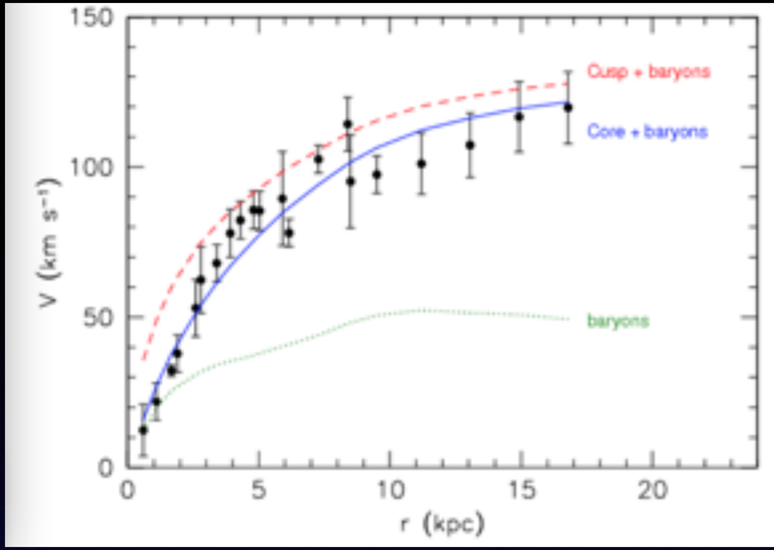
constraints from Lyman-α forest:

$m_{eff} > 2$ keV
Viel et al. 2005, Seljak et al. 2006

$m_{eff} > 3.3$ keV (2σ)
Viel et al. PRD 2013

cusp / core problem

CDM predicts too high DM densities in the inner few kpc of galaxies

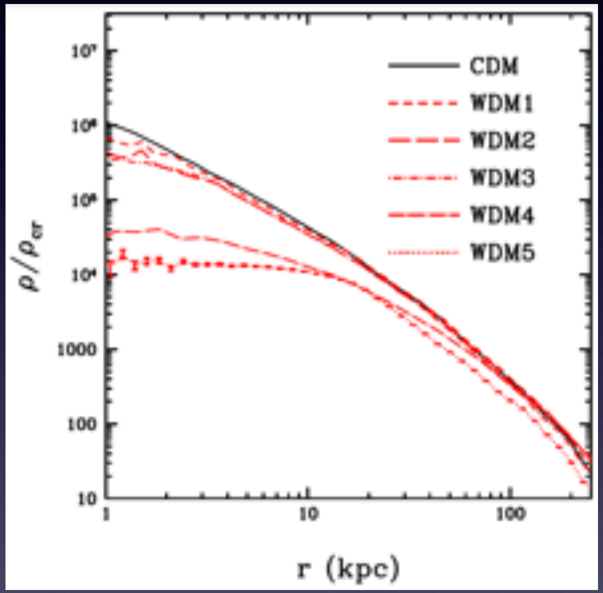


Kuzio de Naray et al. 2008

DM solutions:

needs extreme WDM: m_eff < 0.1 keV ruled out

maybe SIDM?
Rocha et al. 2013
Peter et al. 2013

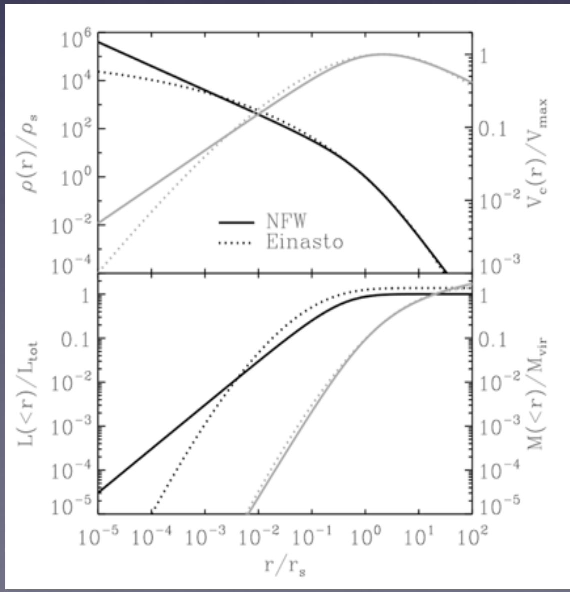


Maccio et al. 2012

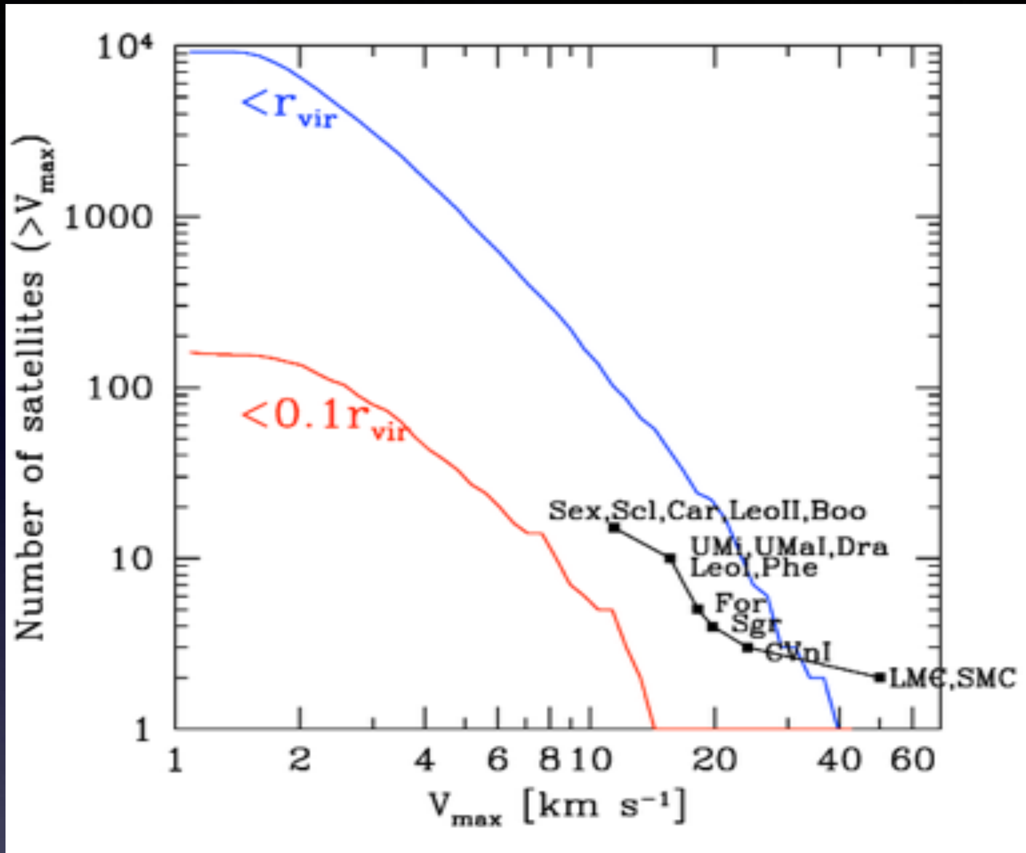
Baryonic solution:

episodic supernova feedback

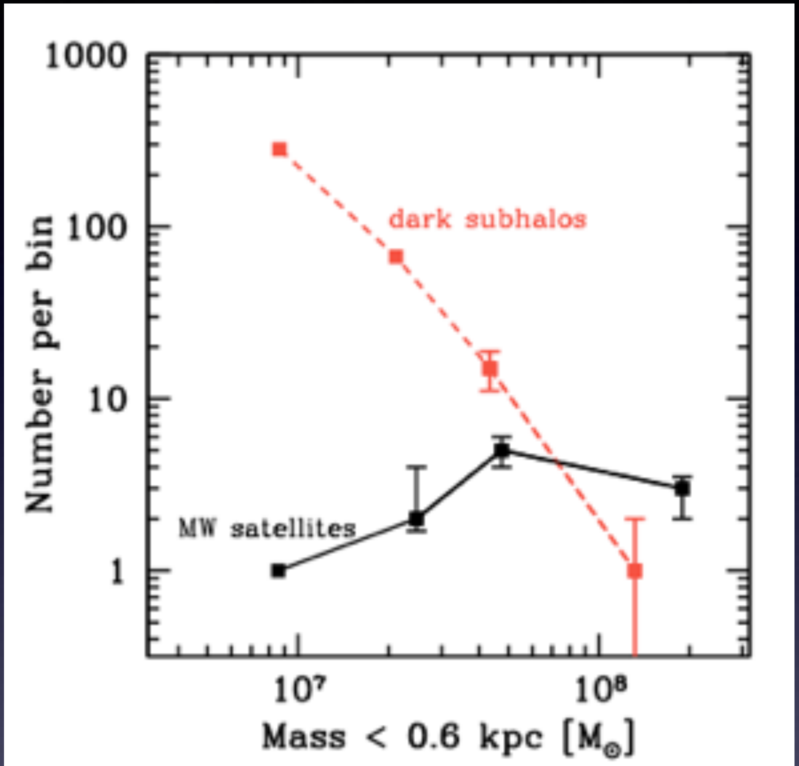
Governato et al. 2012
Teyssier al. 2012



missing satellites problem (Moore+99, Klypin+99)



Madau, JD, Kuhlen 2008



Strigari et al. 2007

the original comparisons assumed $\sqrt{3}\ \sigma^*_{1D} = V_{max}$

this seems to be roughly right

CDM only predicts subhalos, not dwarf galaxies. Luckily, CDM predicts (more than) enough structures to host all satellites (could be up to 1000, Tollerud et al. 2008)

Baryonic solution:

Plausible galaxy formation models roughly reproduce the observed numbers of dwarfs. Many CDM subhalos remain dark (e.g. Governato+2007/2011, Weinberg+2013)

the “too big to fail” problem (Boylan-Kolchin,Bullock,Kaplinhat, 2011/2012)

higher resolution DM simulations and better observational constraints now allow for more detailed comparisons:

dwarf satellite mass within the half light radius is well constrained (Wolf+2009)

cosmological simulations can now resolve the corresponding scales directly

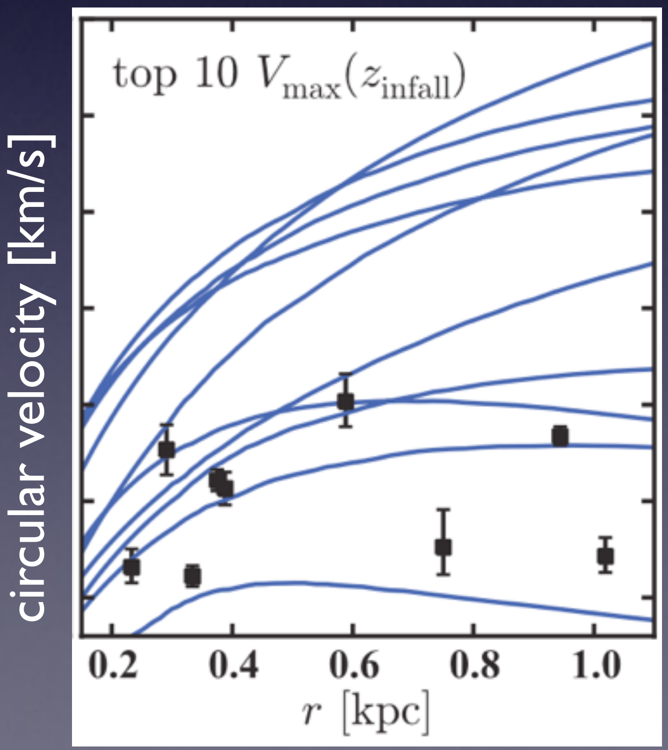
mock observations confirm mass estimates, with small scatter due to subhalo shapes (Rashkov+2012)

most CMD halos have too many dense subhalos

few exceptions (Purcell&Zentner,2012)

and there is some evidence for cores in some of these dwarf galaxies
(Walker & Penarrubia 2012, Amorisco+2013)

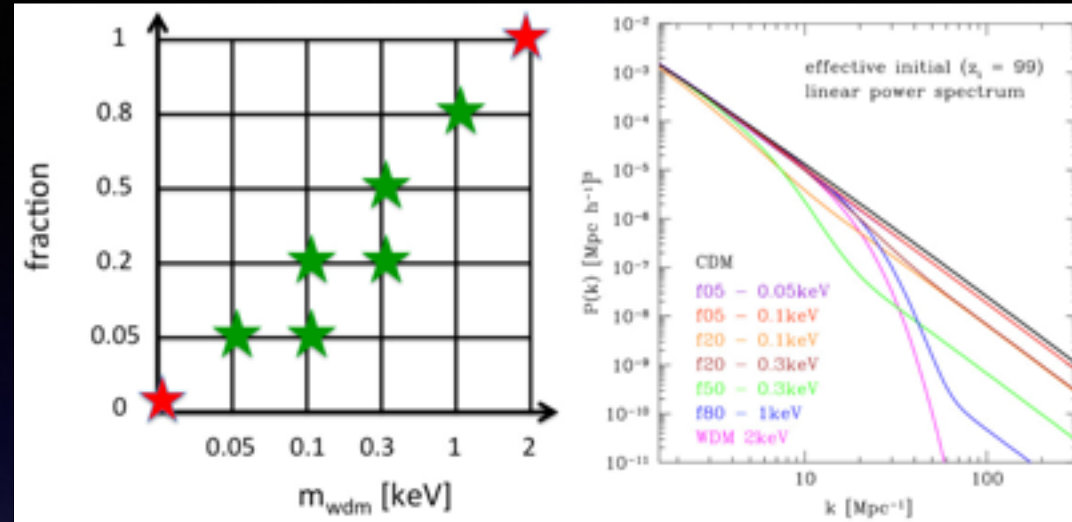
Baryonic solution?
episodic feedback too weak in these small galaxies
(Garrison-Kimmel + 2013)

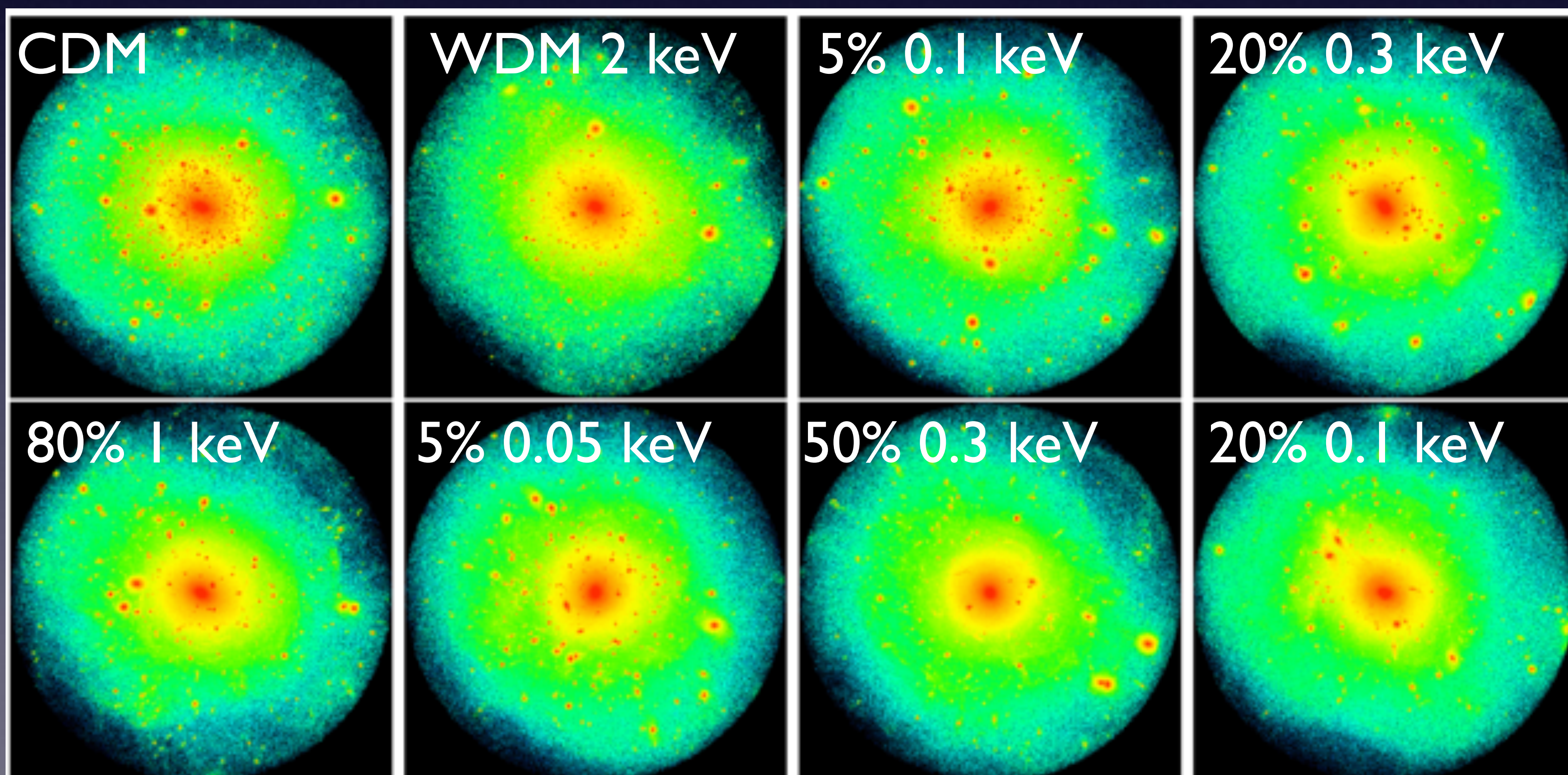


Boylan-Kolchin+2012

WDM and mixed C+WDM simulations

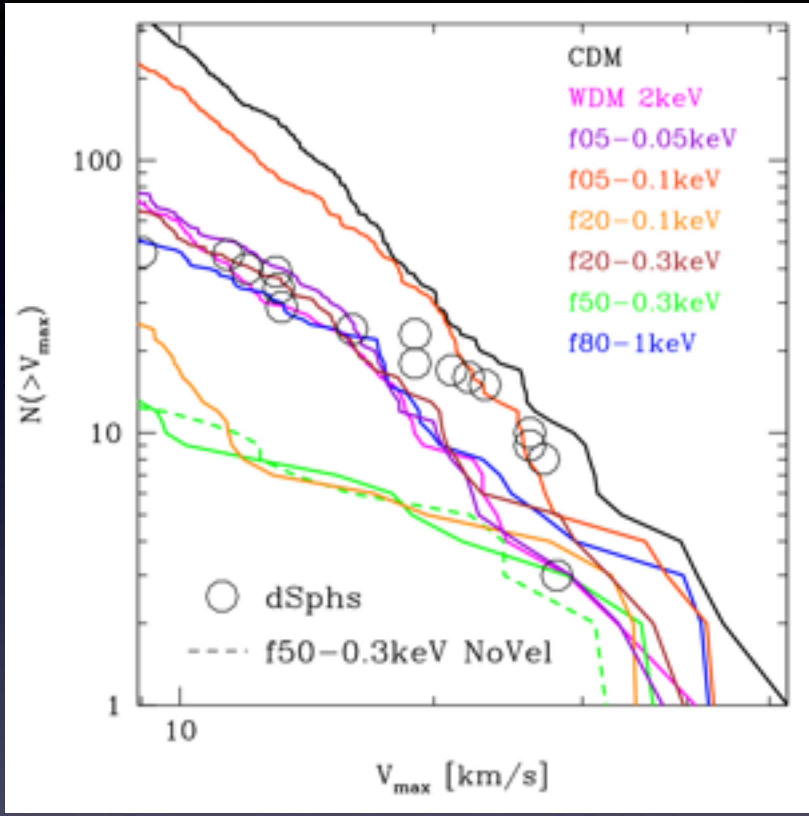
8 simulations
of the same galactic halo
DM model (marginally)
consistent with Lyman-α

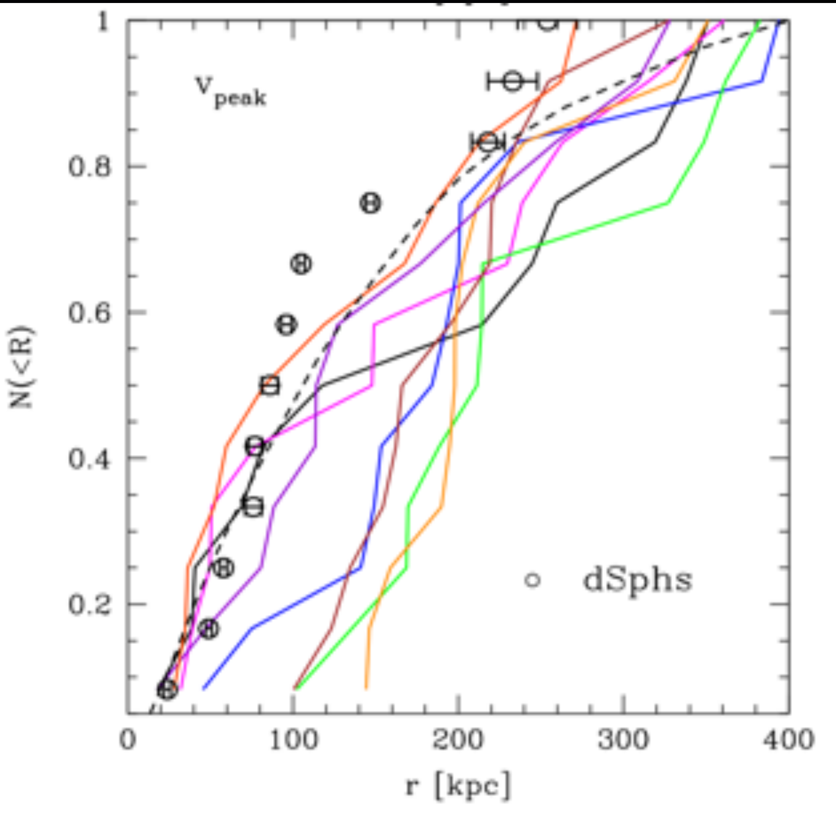




Anderhalden, Schneider, Maccio, JD, Bertone, JCAP 2012/2013

abundance and radial distribution of satellites



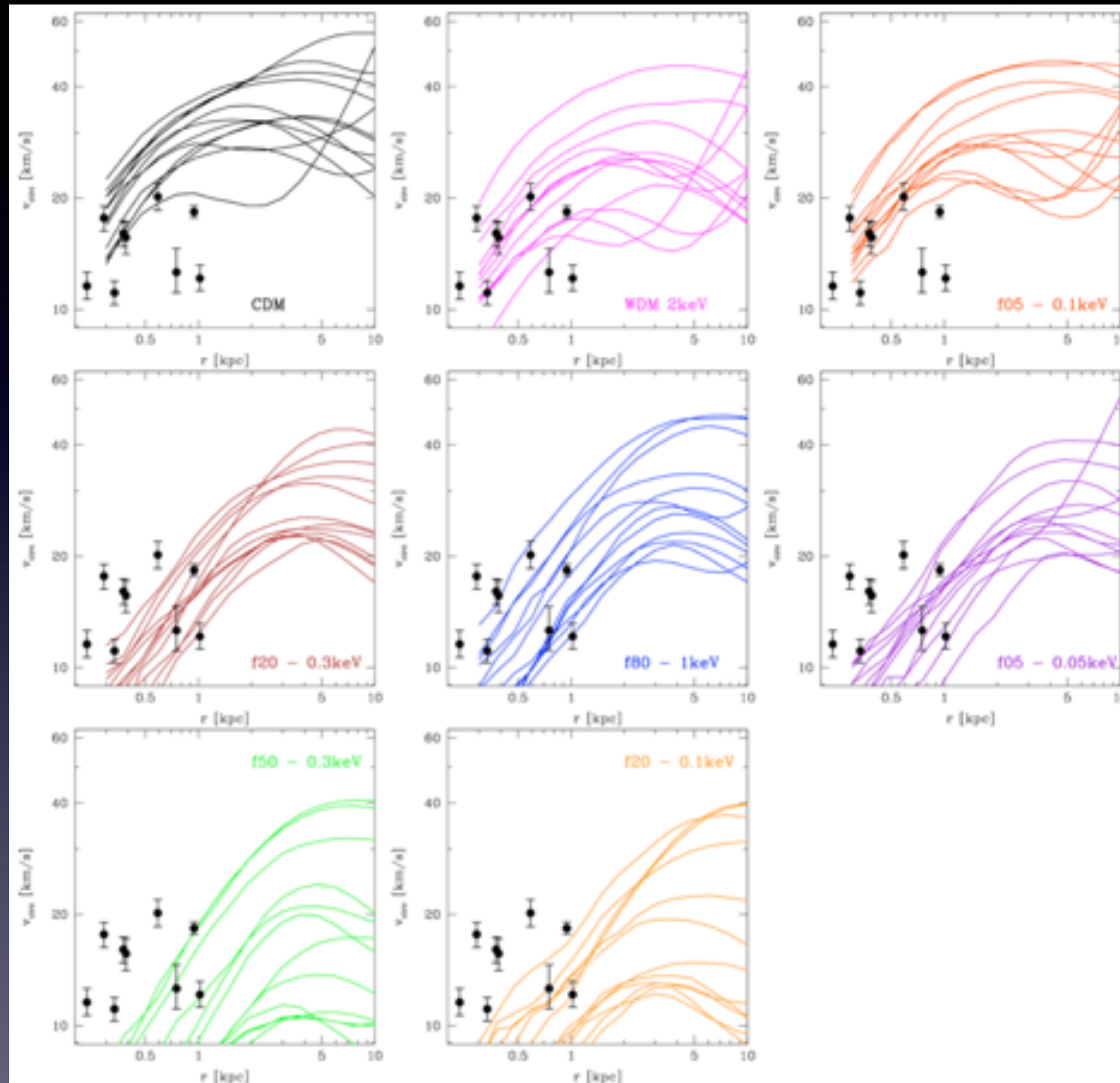


moderate WDM and C+WDM models have enough subhalos, and with a realistic radial distribution

more extreme WDM and C+WDM models contain too few subhalos, and they are found at larger radii than the observed dwarfs (Anderhalden+2013)

(similar WDM results in: Polisensky & Ricotti 2011, Lovell+2011)

the “too big to fail” problem (Boylan-Kolchin,Bullock,Kaplinhat, 2011/2012)



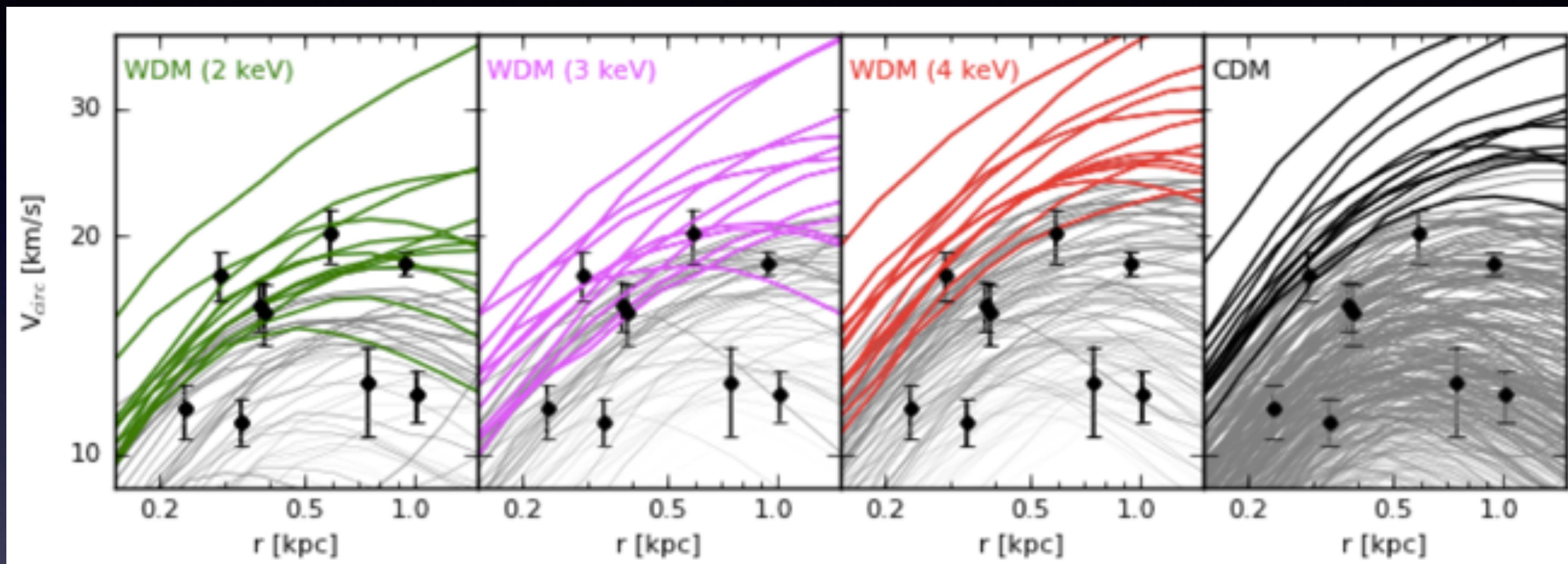
Anderhalden et al. JCAP 2013

some WDM or mixed C+WDM models do solve the problem (Lovell+2011, Anderhalden+2013)

some SIDM models also solve the problem (Vogelsberger+2012, Rocha+2013, Peter+2013)

the “too big to fail” problem (Boylan-Kolchin,Bullock,Kaplinhat, 2011/2012)

Unfortunately WDM models which solve the problem are in tension with the new Lyman-α constraint m > 3.3 keV (Viel+2013):



Warm dark matter does not do better than cold dark matter in solving small-scale inconsistencies

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MNRAS, 2014, see also Polisensky & Ricotti 2014

summary of WDM and C+WDM results

- small scale problems in CDM: cusp/core, missing satellites, too big to fail
- plausible baryonic solutions within CDM exist for the first two
- too big to fail is difficult to resolve with baryonic effects (Garrison-Kimmel+2013)
- WDM cannot solve the cusp/core problem, some SIDM models can
- some WDM, C+WDM and SIDM model can resolve the too big to fail problem
- however, such WDM models are in tension with Lyman-α (Viel+2013)

  (which C+WDM and SIDM are still allowed?)

→ DM distribution quite close to CDM predictions
on all scales probed by the baryons

- still allowed WDM has a similar cutoff scale for baryons and DM structures, which would be quite a coincidence