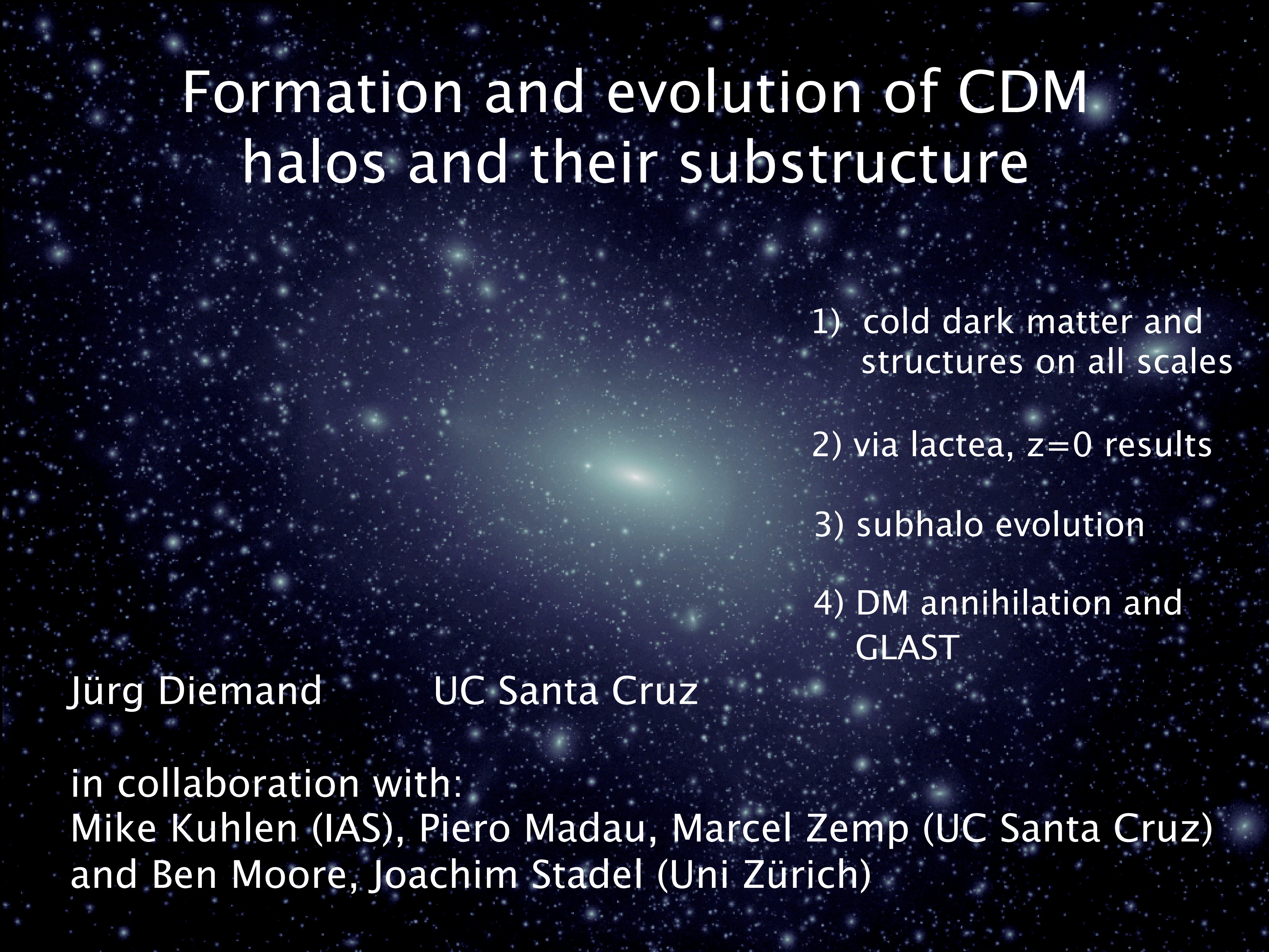


# Formation and evolution of CDM halos and their substructure

1) cold dark matter and structures on all scales

2) via lactea, z=0 results

3) subhalo evolution

4) DM annihilation and GLAST


Jürg Diemand UC Santa Cruz

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

# What is dark matter ?

Evidence for DM:

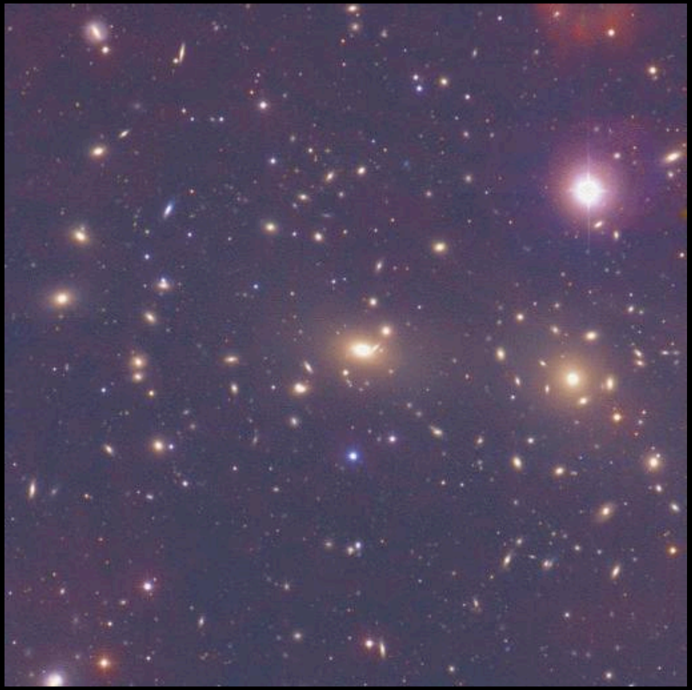
Galaxy cluster dynamics (Fritz Zwicky, 1933)

Coma, Credit: Lopez-Cruz et al

# What is dark matter ?

Evidence for DM:

- Galaxy cluster dynamics (Fritz Zwicky, 1933)
- Spiral galaxy rotation curves
- X-rays from galaxy groups and clusters
- Kinematics of stellar halos
  and globular cluster systems
- Dwarf galaxy velocity dispersions
- Strong and weak lensing
- ...



Coma, Credit:  Lopez-Cruz et al

# What is dark matter ?

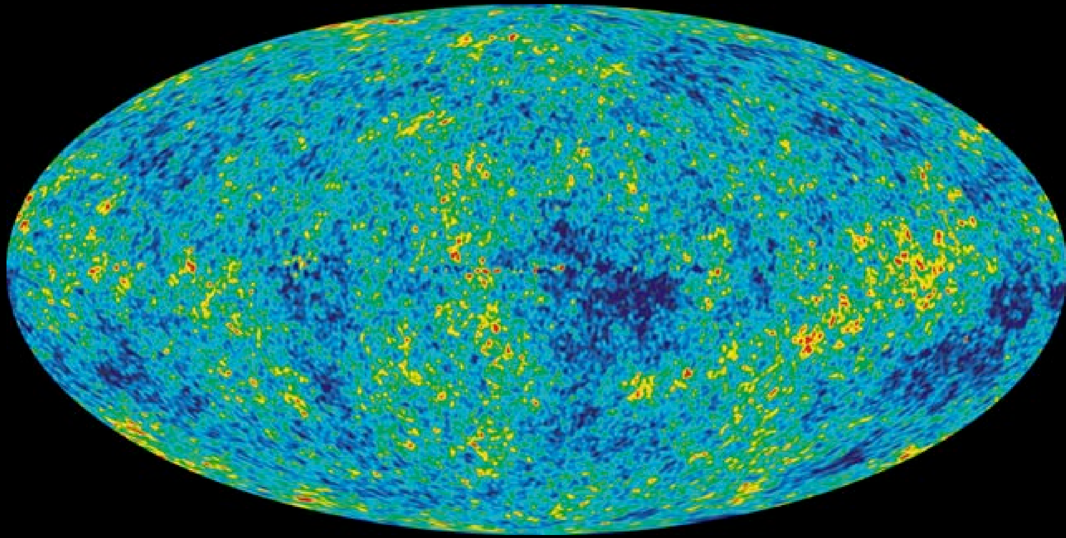
Evidence for DM:
- Galaxy cluster dynamics (Fritz Zwicky, 1933)
- Spiral galaxy rotation curves
- X-rays from galaxy groups and clusters
- Kinematics of stellar halos
  and globular cluster systems
- Dwarf galaxy velocity dispersions
- Strong and weak lensing
- ...

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%)

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



Credit: NASA/WMAP

→ 83% of the clustering matter is some non-baryonic, very weakly interacting, “cold” dark matter

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

# Simulating structure formation

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

- treat all of Omega_m like dark matter, and sample it with N particles
- 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

# Simulating structure formation

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

- treat all of Omega_m like dark matter, and sample it with N particles
- 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:
hydro-dynamical simulations

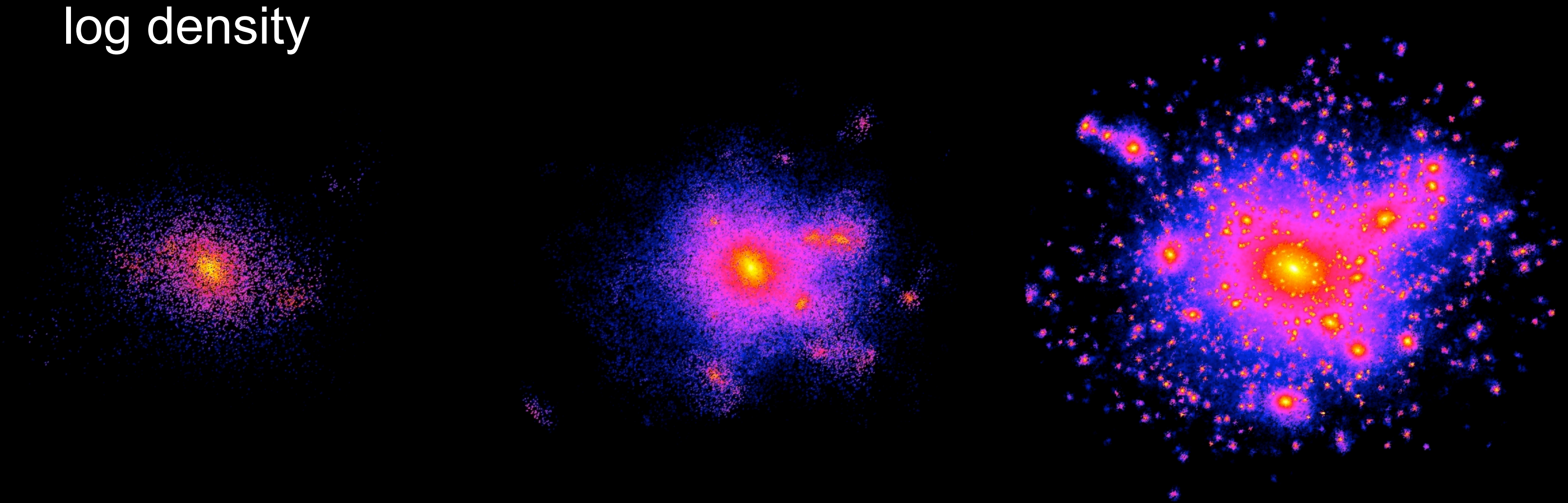
- computationally expensive, resolution relatively low
- hydro is not trivial (SPH and grid codes often disagree, e.g. Agertz etal 2006)
- important physical processes far below the resolved scales (star formation,SN, ... ?)
  implemented through uncertain functions and free parameters

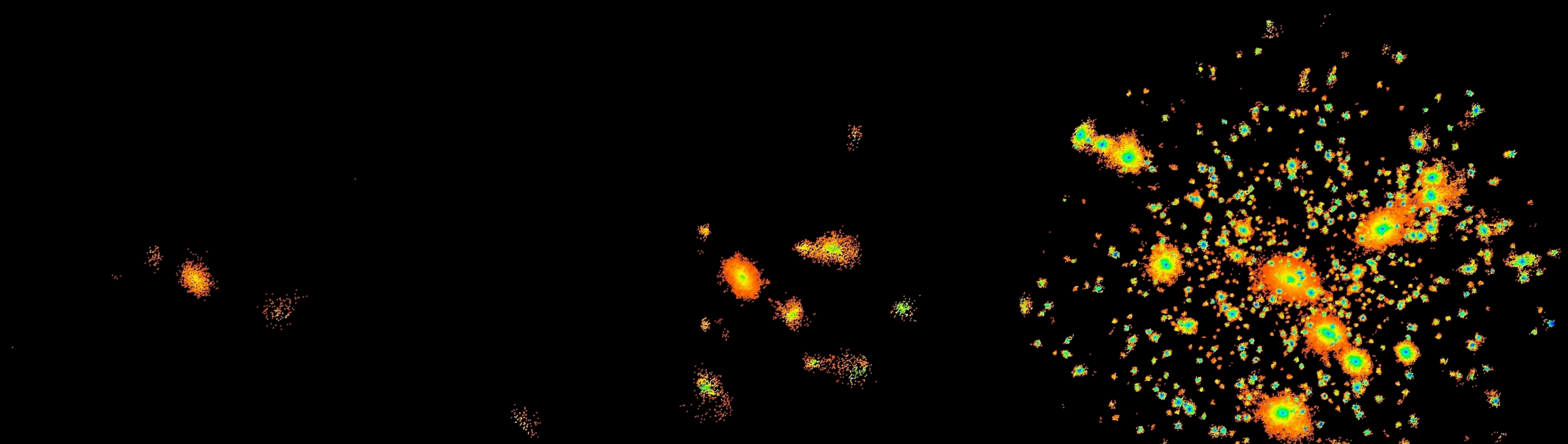
→ approximate solution to the more realistic problem

# Simulating structure formation

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

log density

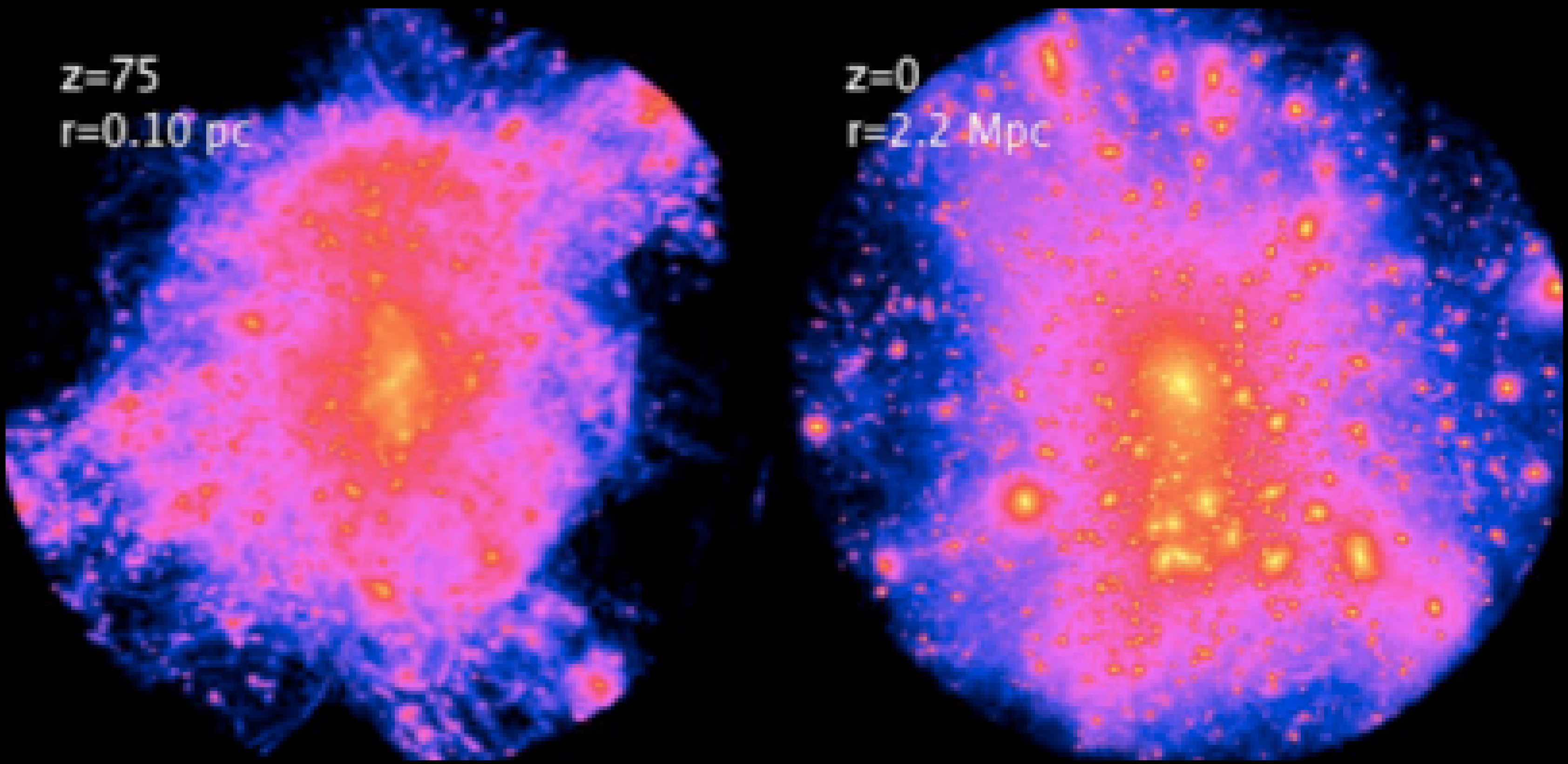




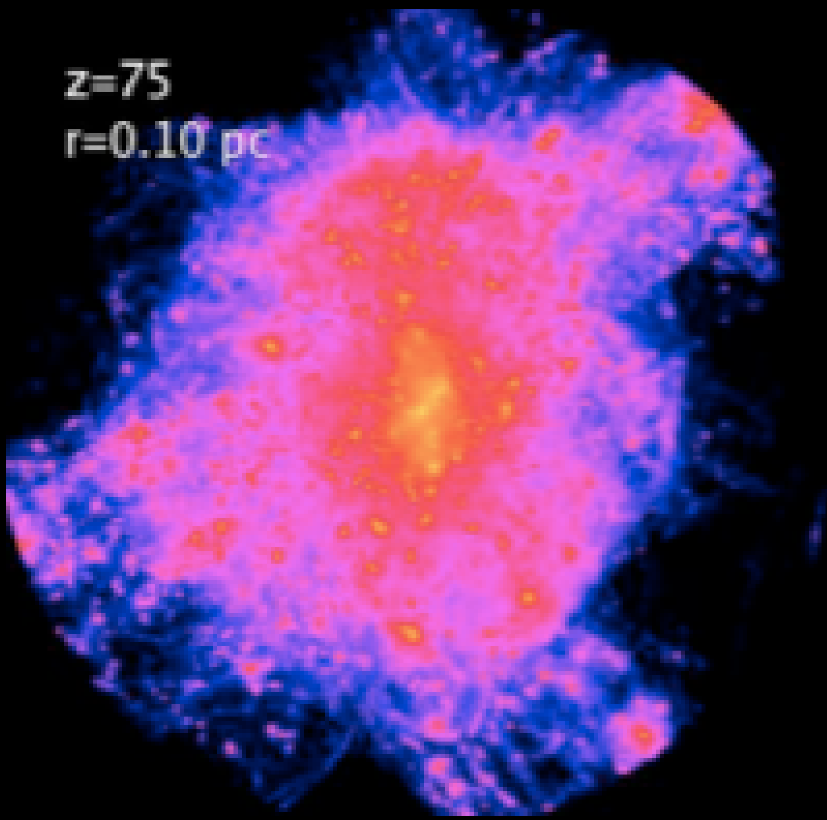
log phase space density

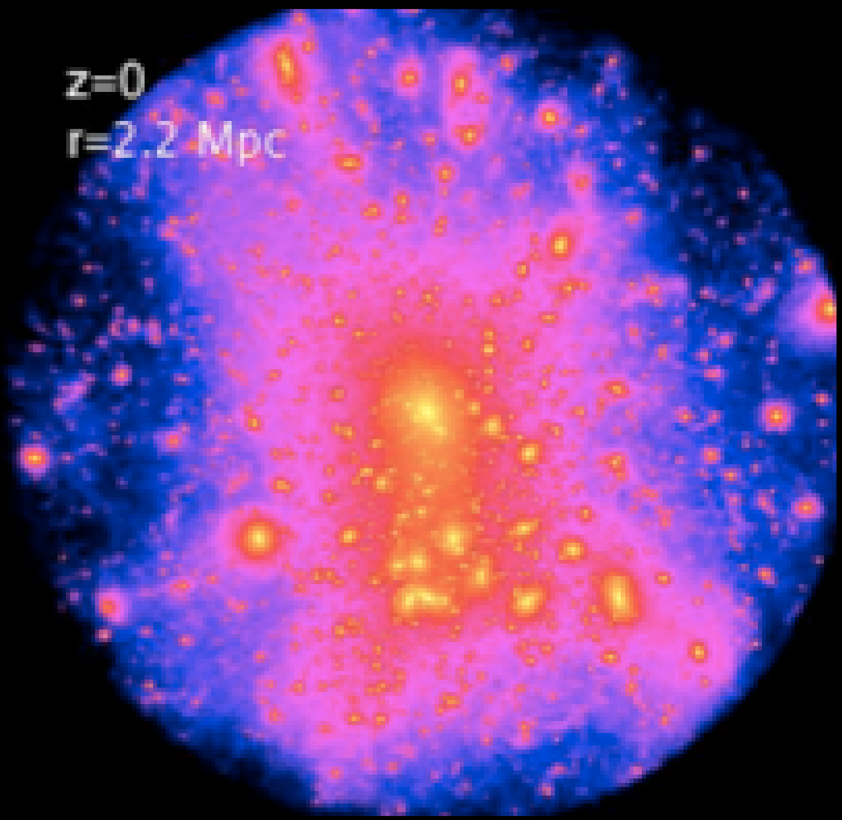
from Ben Moore : www.nbody.net

# CDM forms (sub)structures on many scales



# CDM forms (sub)structures on many scales




M ~ 0.01 Msun  microhalo

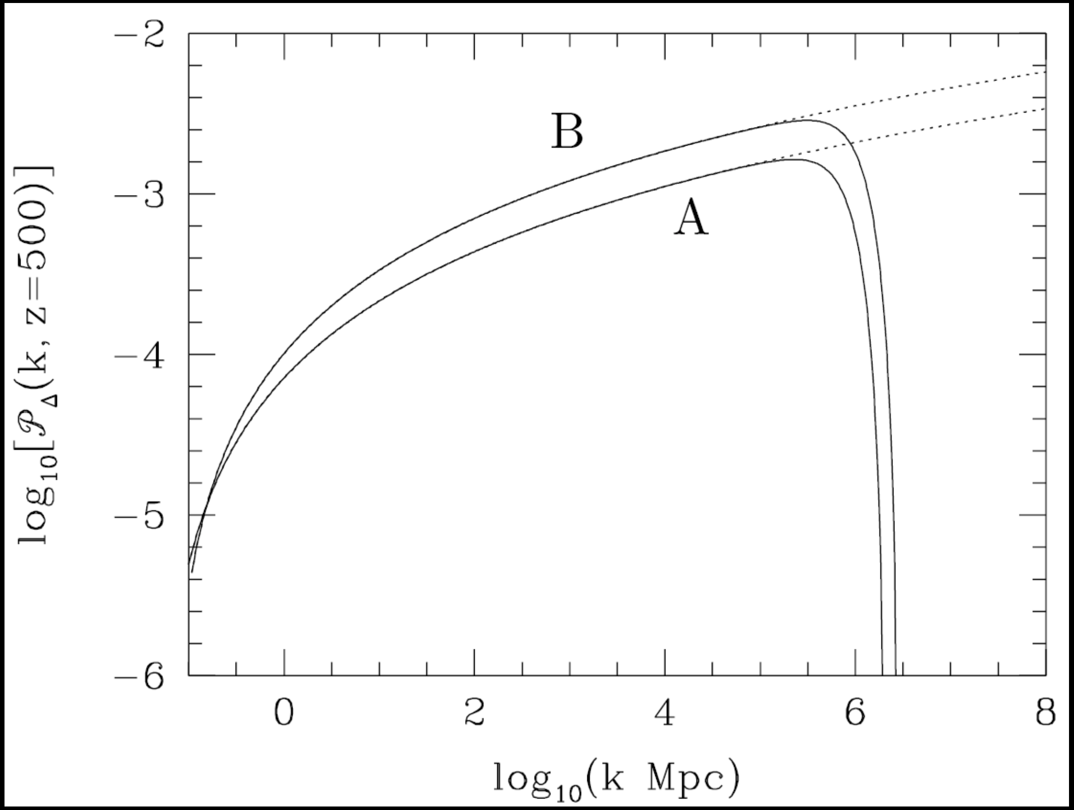
M=6e14 Msun  galaxy cluster

no baryons, dark DM structure, but relevant for DM annihilation signal:
extragalactic background, M31, Draco ... nearby dark subhalos

# smallest scale CDM structures in the field

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

from Green, Hoffmann & Schwarz 2003



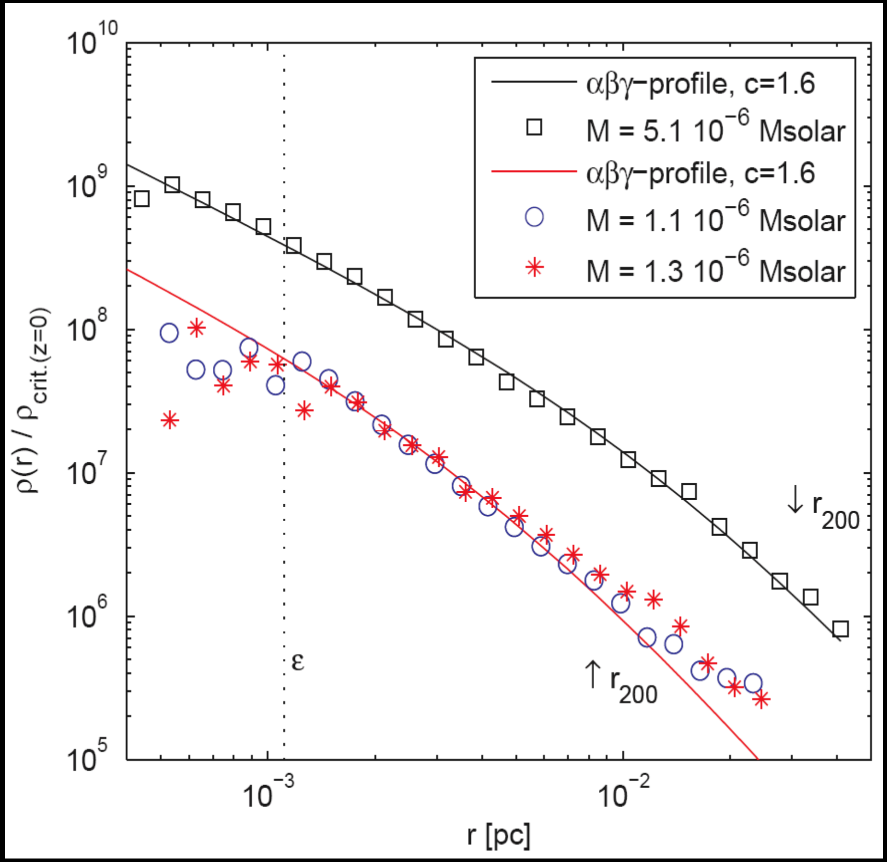

→ small, “micro”-halos should forming around z=40 are the first and smallest CDM structures

# smallest scale CDM structures in the field

CDM microhalos seem to be cuspy

like the larger halos that formed in mergers

they are very concentrated
c~3.3 at z=26
evolves into c~90 by z=0
consistent with Bullock etal model



# smallest scale CDM structures in the field

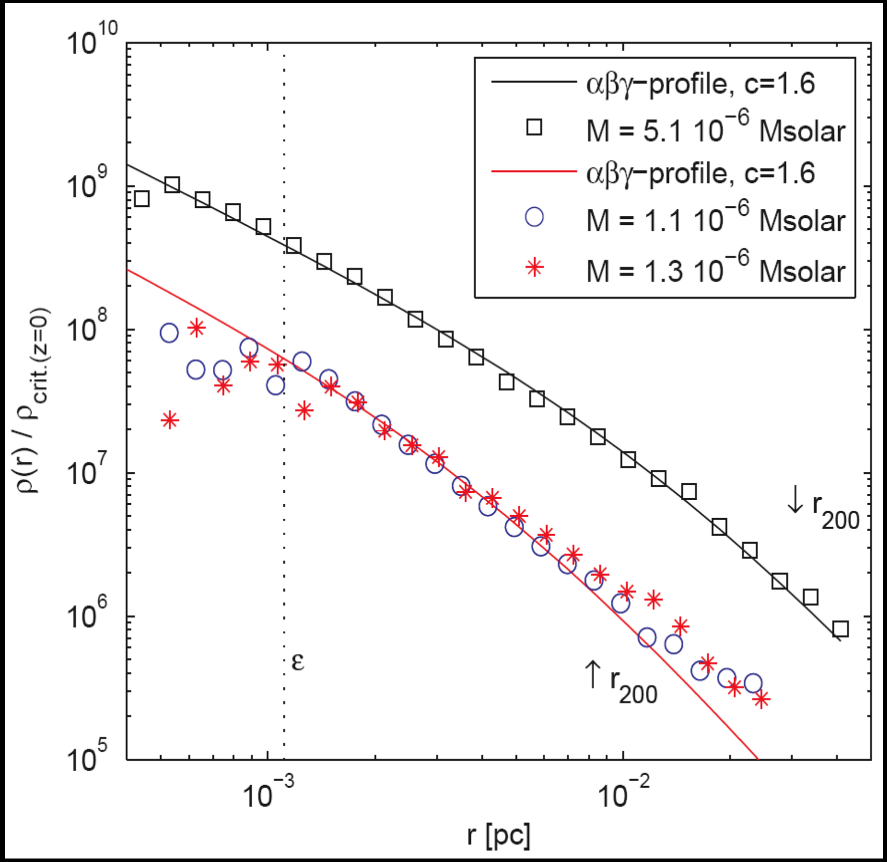
CDM microhalos seem to be cuspy
like the larger halos that formed in mergers

they are very concentrated
c~3.3 at z=26
evolves into c~90 by z=0
consistent with Bullock etal 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 ~ $5 \times 10^{15}$ could be
orbiting in the MW halo today

JD, Moore,Stadel, astro-ph/0501589

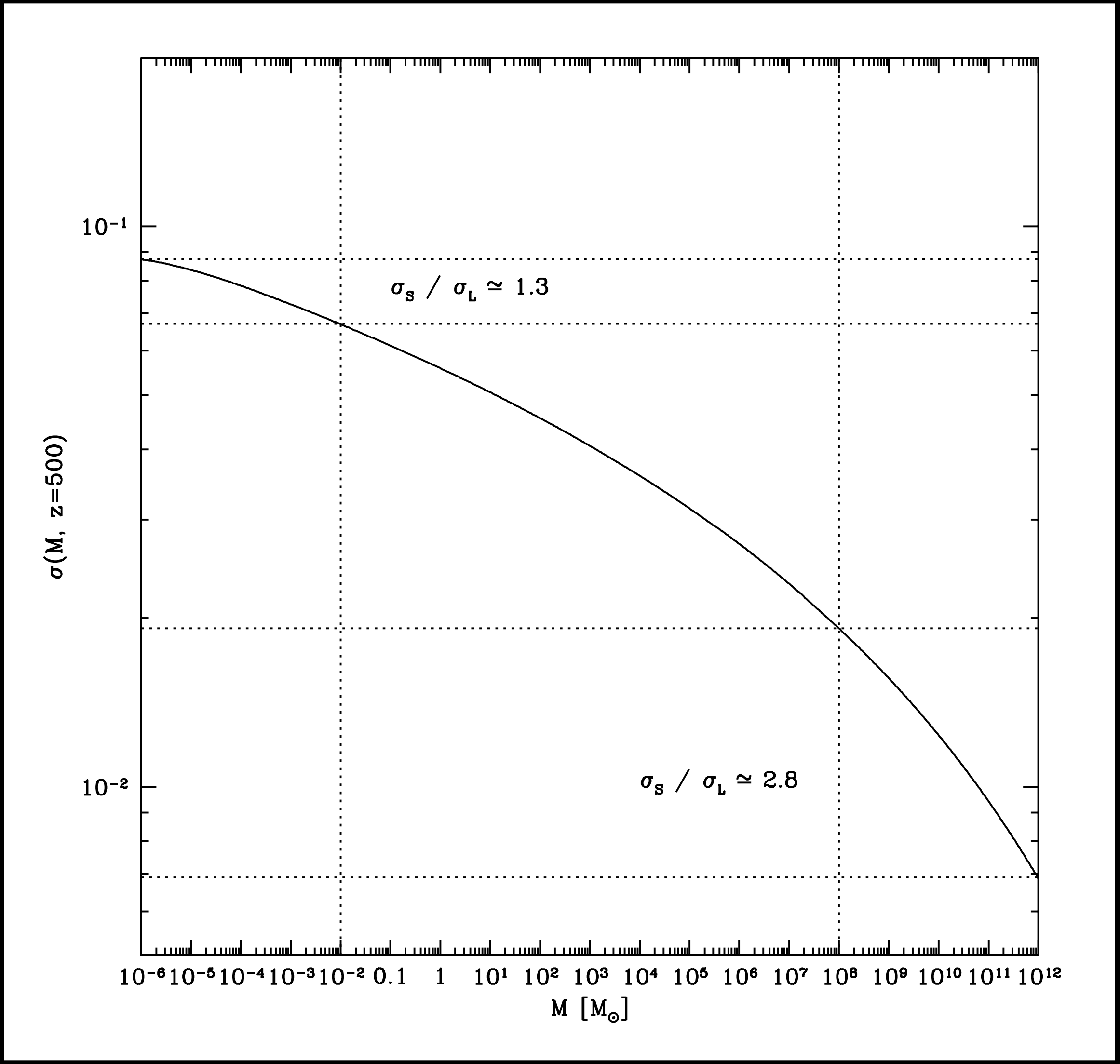



some tidal mass loss and disruption due to
encounters with stars (see Goerdt etal astro-ph/0608495)

# smallest scale CDM substructures

since P(k) ~ $k^{-2.9}$
sigma(M) almost constant on microhalo scales

structures of different mass form almost simultaneous



# smallest scale CDM substructures

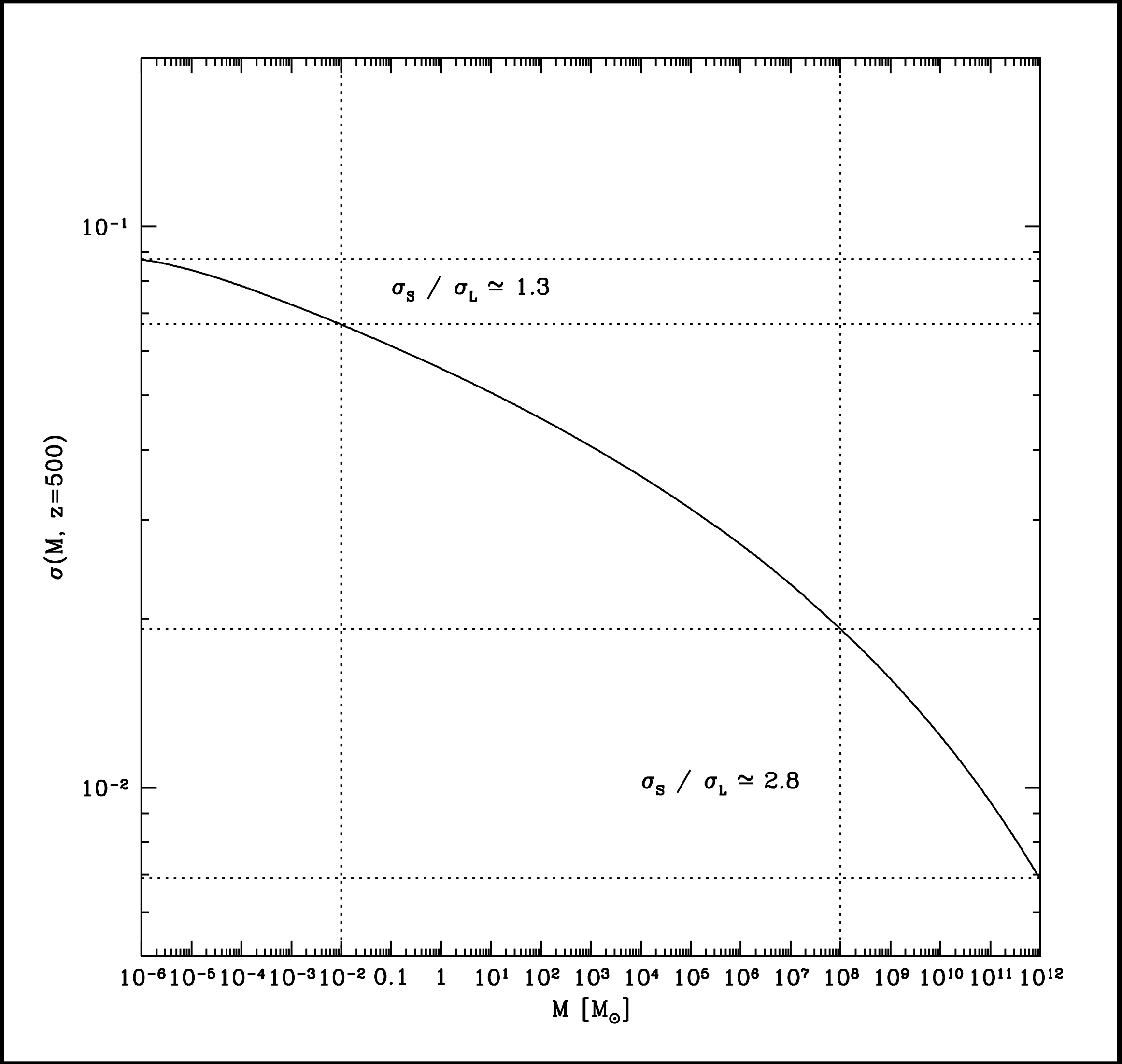
since $P(k) \sim k^{-2.9}$
sigma(M) almost constant on microhalo scales

structures of different mass form almost simultaneous

only true for the average field halo

not true for subhalos, they form on top of a lager perturbation, and therefore earlier

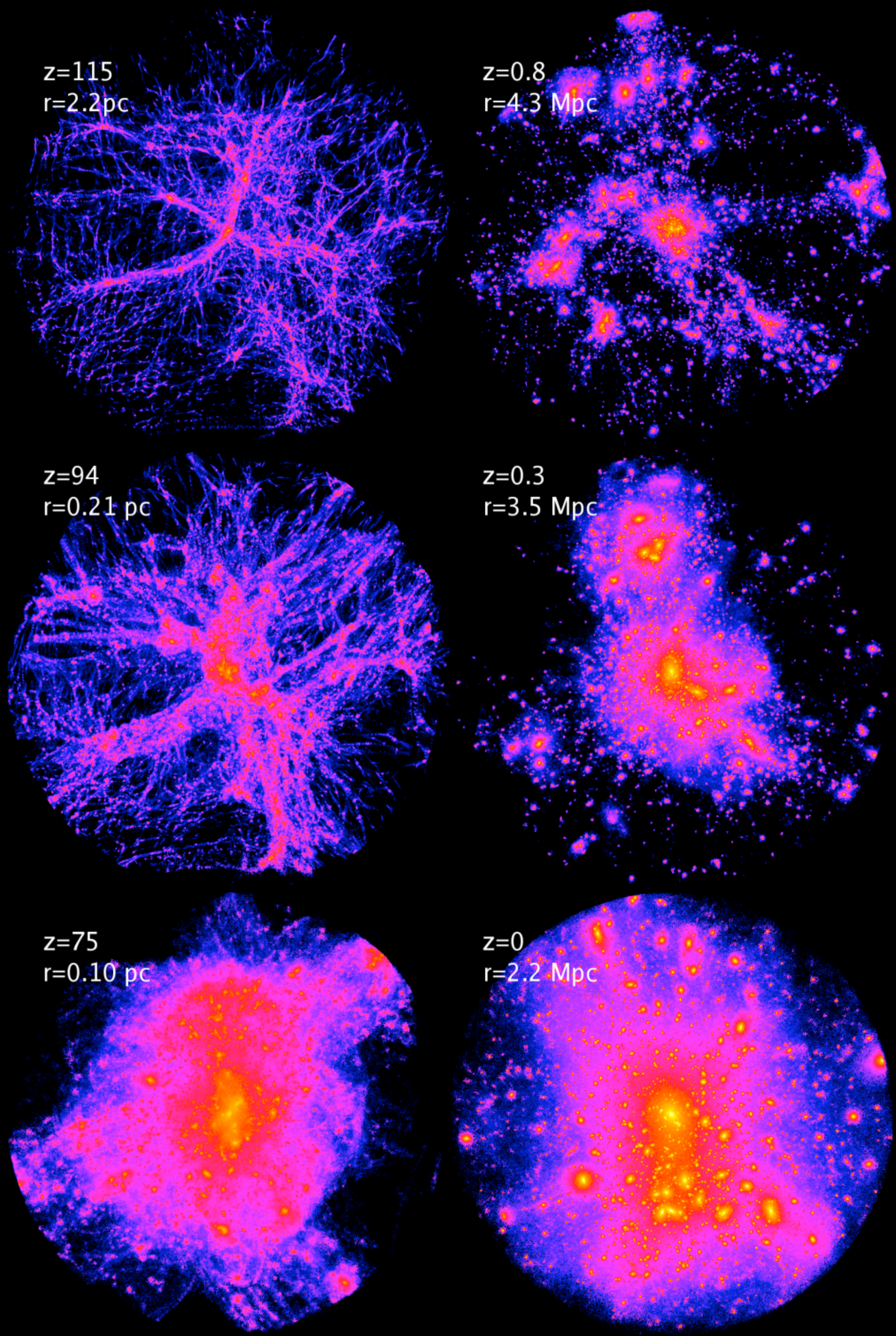
is there enough time for them to virialize and survive accretion into a larger host?



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

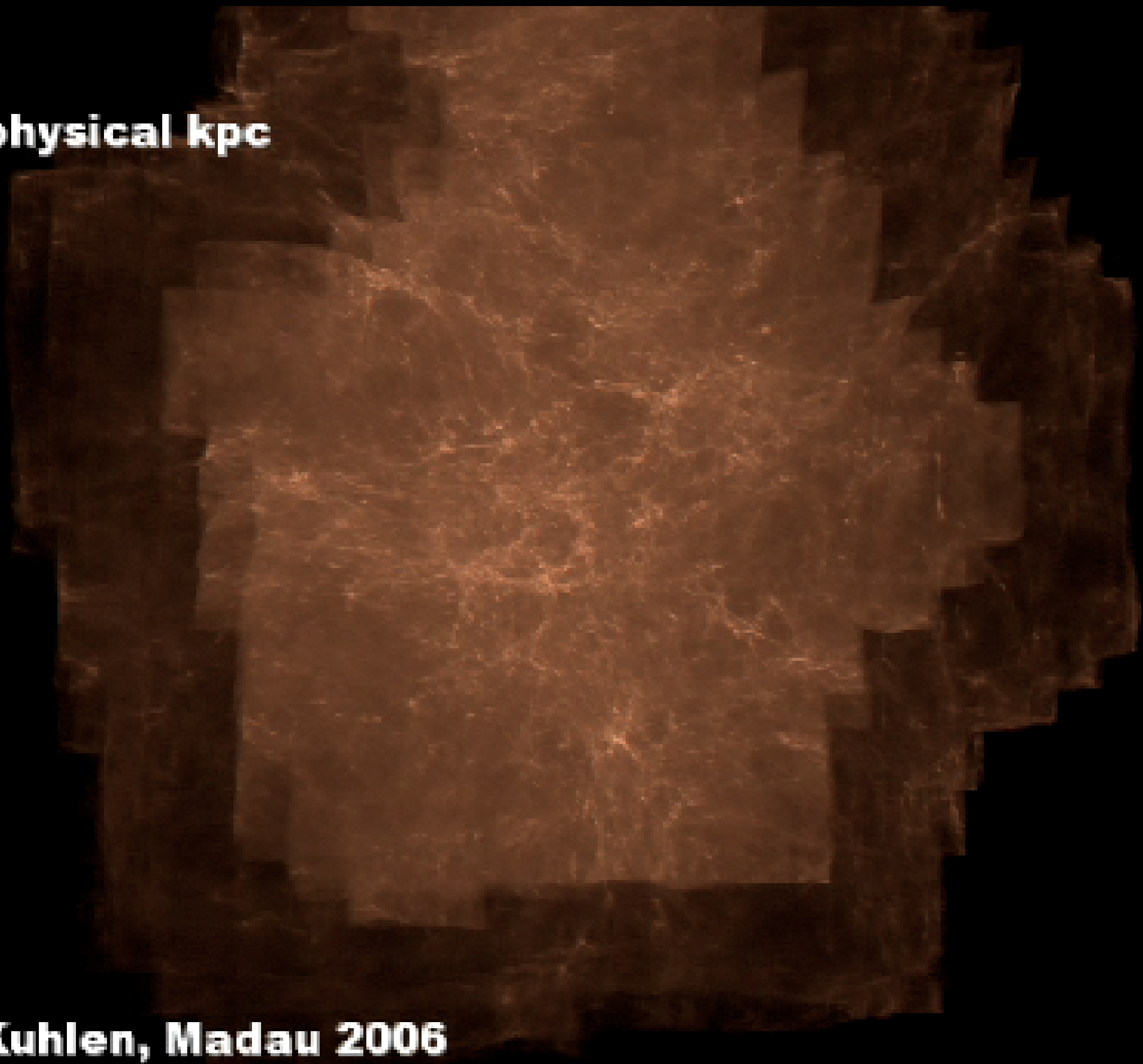
same comoving DM density scale from 10 to $10^6$ times the critical density

in each panel the final $M_{vir}$ ~ 20 million particles are shown

# 2) z=0 results form “via lactea”

## a Milky Way halo simulated with over 200 million particles

- JD, Kuhlen, Madau astro-ph/0611370
- 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

# www.ucolick.org/~diemand/vl

## via lactea

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

main

movies

images

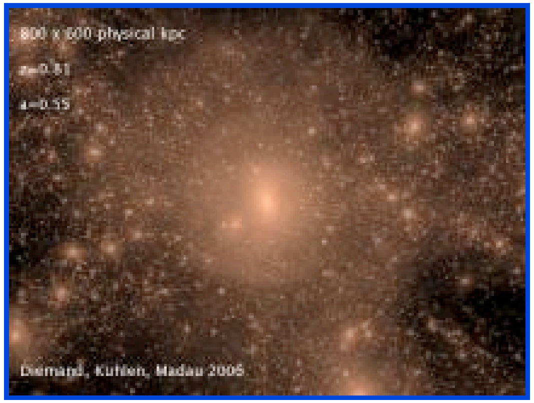
publications

data (full snapshots, subhalo properties, histories etc. will become available in summer 2007)

**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.

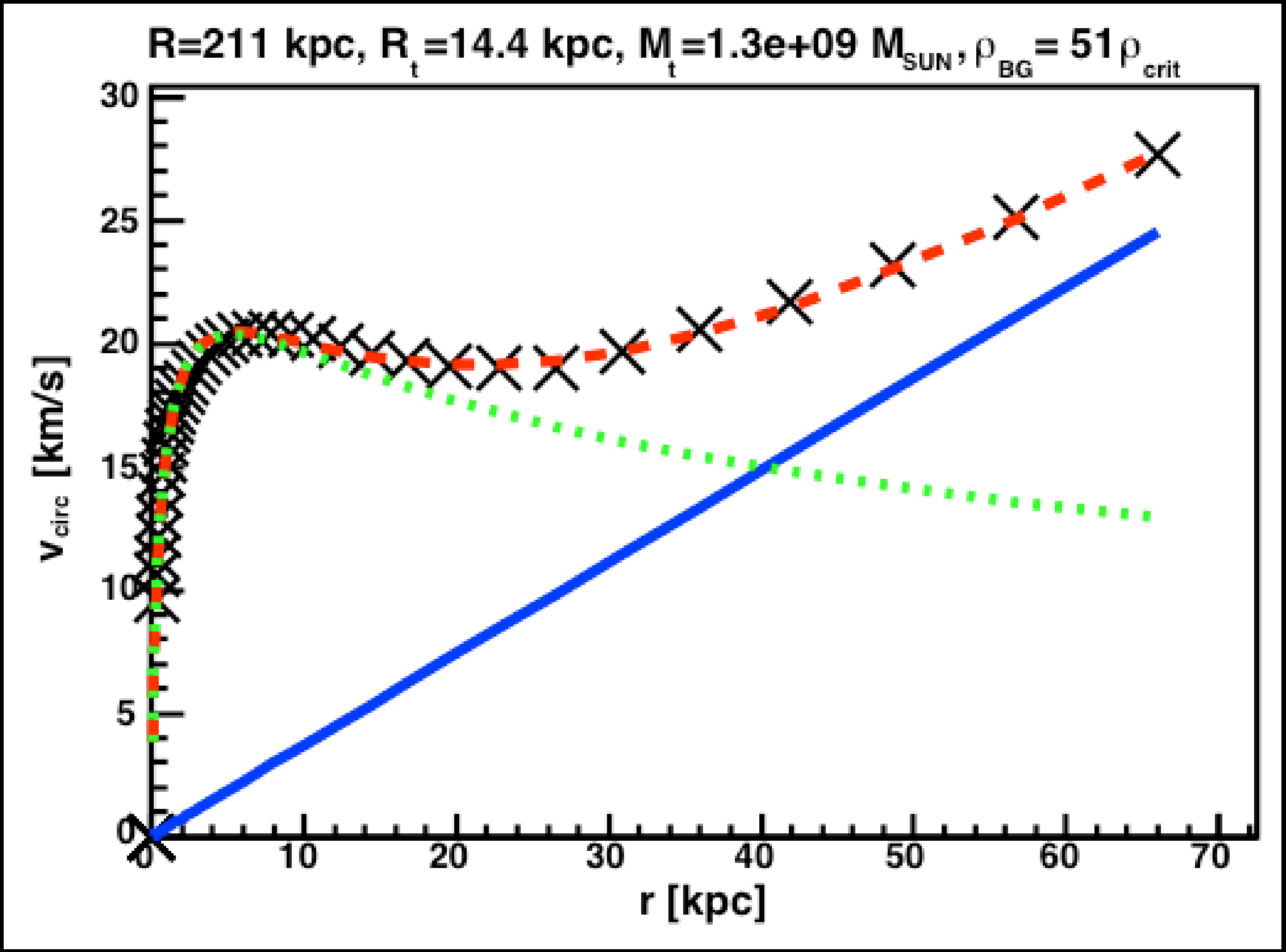
**the formation of the Via Lactea halo**




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

**rotation and zoom into the Via Lactea halo at z=0 (today)**

# subhalo properties: definitions




Vc(r) = sqrt ( G  M(<r) / r)

in spherical bins around
a peak in phase space density

fitted by a constant
background density plus
an NFW subhalo

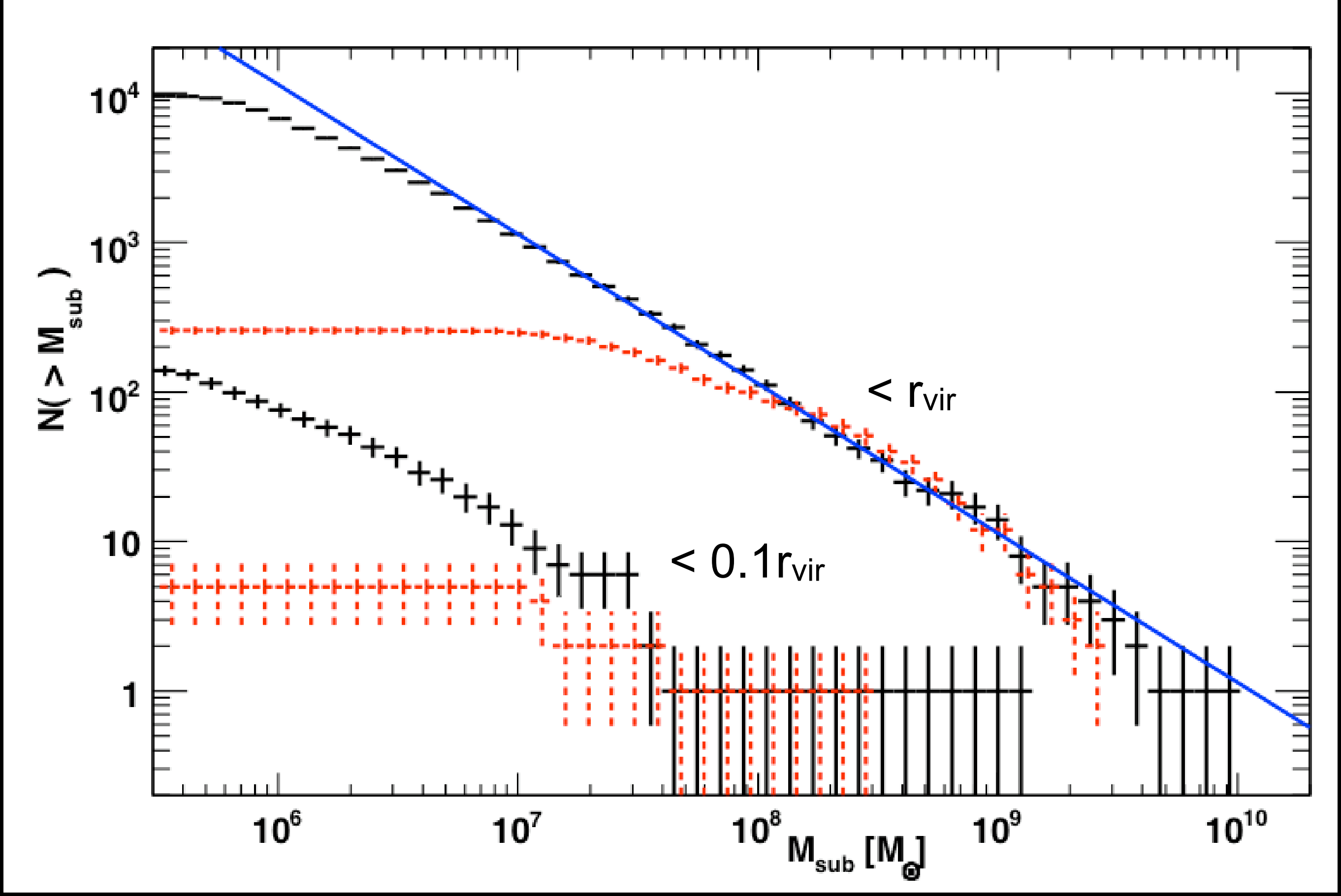
$$\rho(r) = \frac{\rho_s}{r/r_s(1+r/r_s)^2}$$

$$r_{V\max} = 2.163\, r_s.$$

subhalo density (tidal radius) := 2 background density

subhalo tidal mass := total mass(< tidal radius)        ~< bound mass

# subhalo mass functions

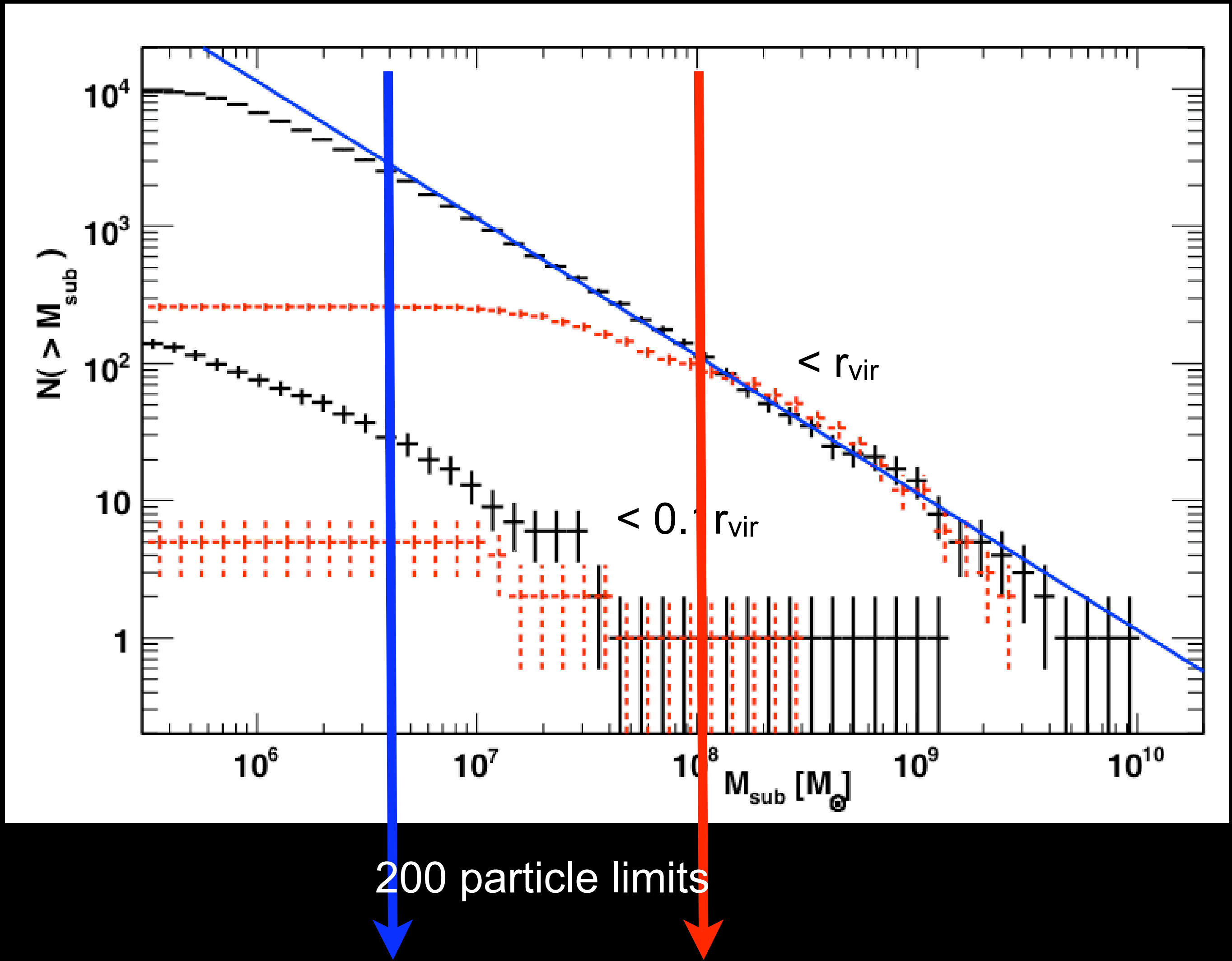



$N(>M) \sim M^{-a}$

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

steeper at high M
due to dynamical friction

# subhalo mass functions




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

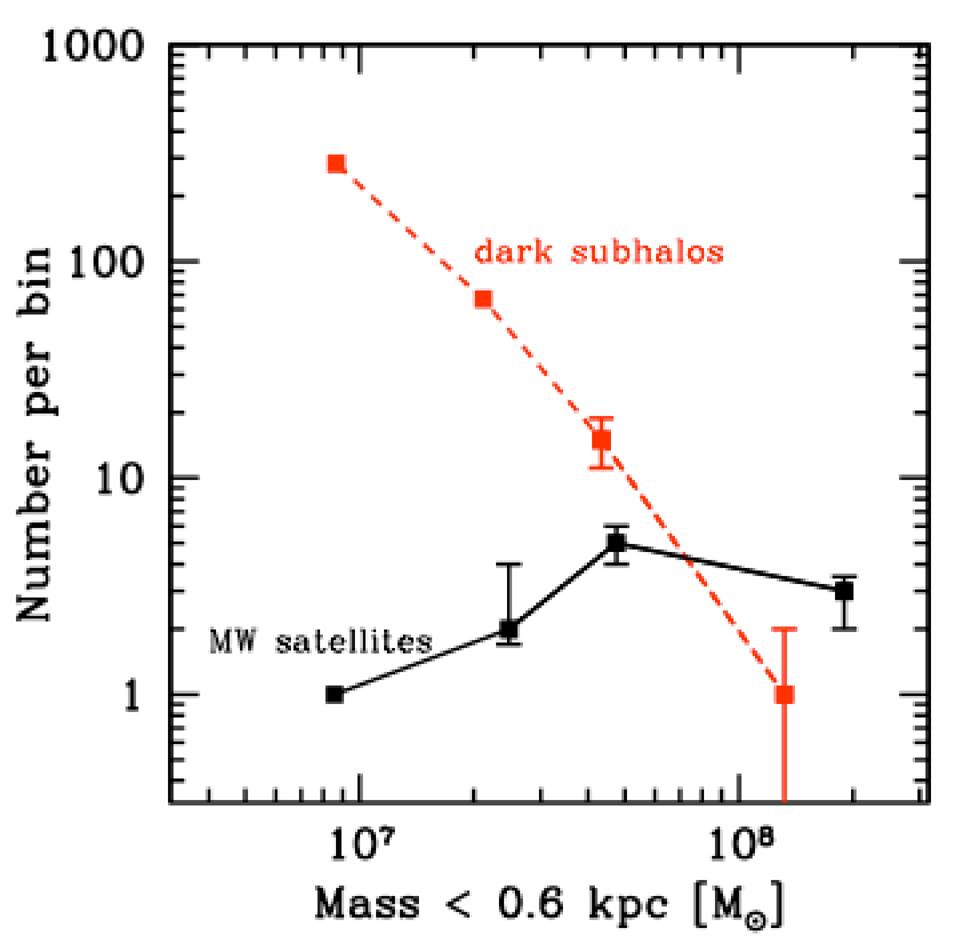
with a between 0.9 and 1.1, depending on mass range used

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

# subhalo abundance vs Milky Way satellite galaxies

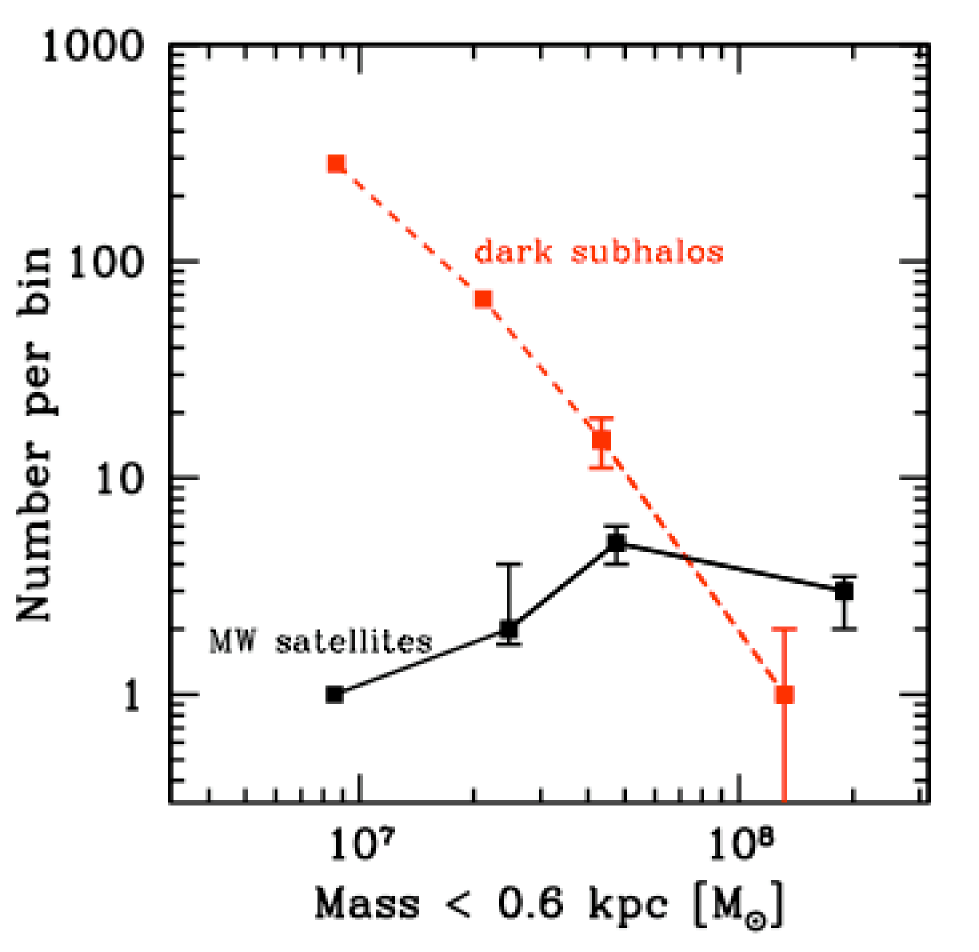



first direct comparison:

mass within 0.6 kpc is now well constrained from stellar kinematics

and this mass is now well resolved in via lactea

# subhalo abundance vs Milky Way satellite galaxies




first direct comparison:

mass within 0.6 kpc is now well constrained from stellar kinematics

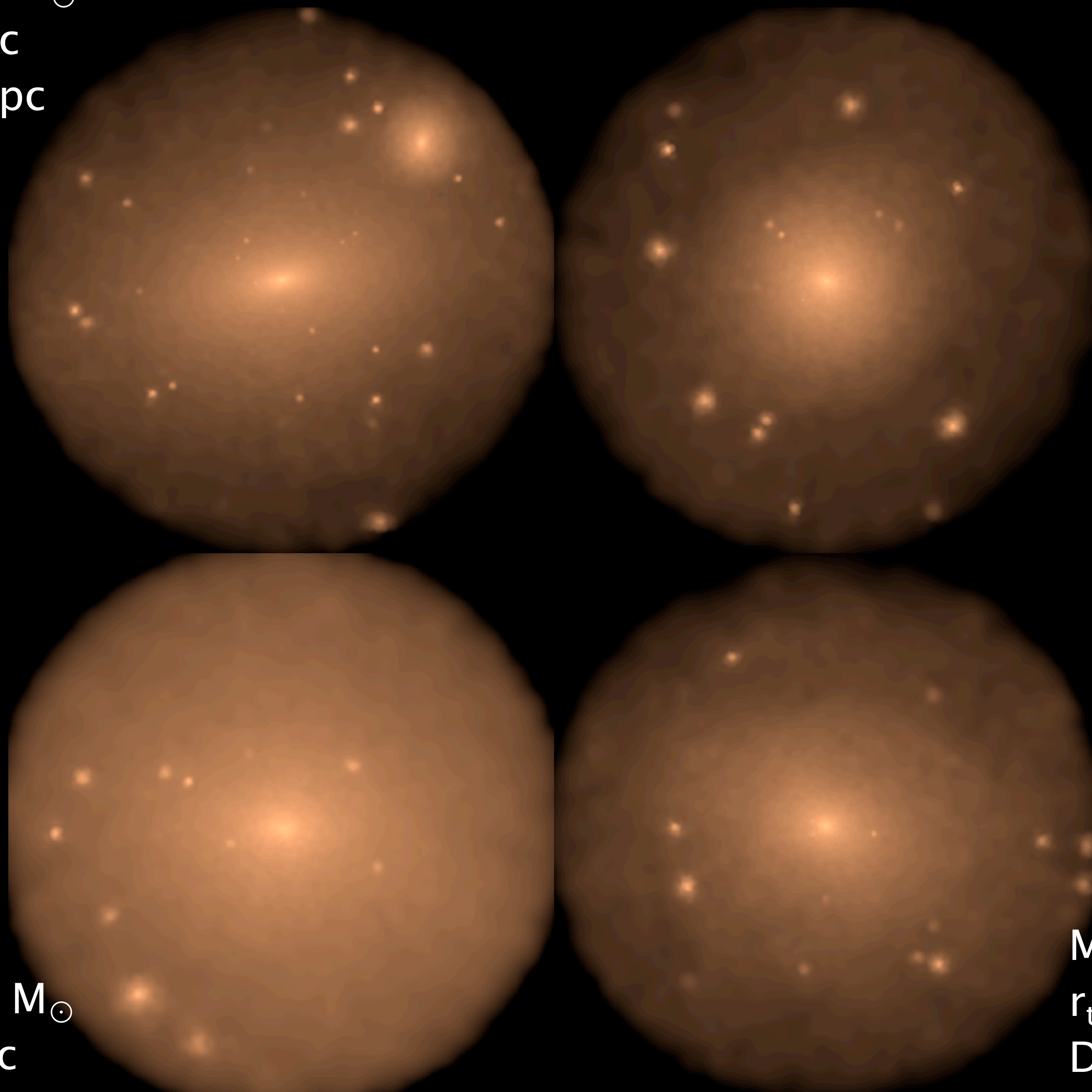
and this mass is now well resolved in via lactea

similar, but more accurate than the classic “missing satellites” figures in Moore etal 1999 and Klypin etal 1999
who assumed sqrt(3) sigma* = Vmax

# 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

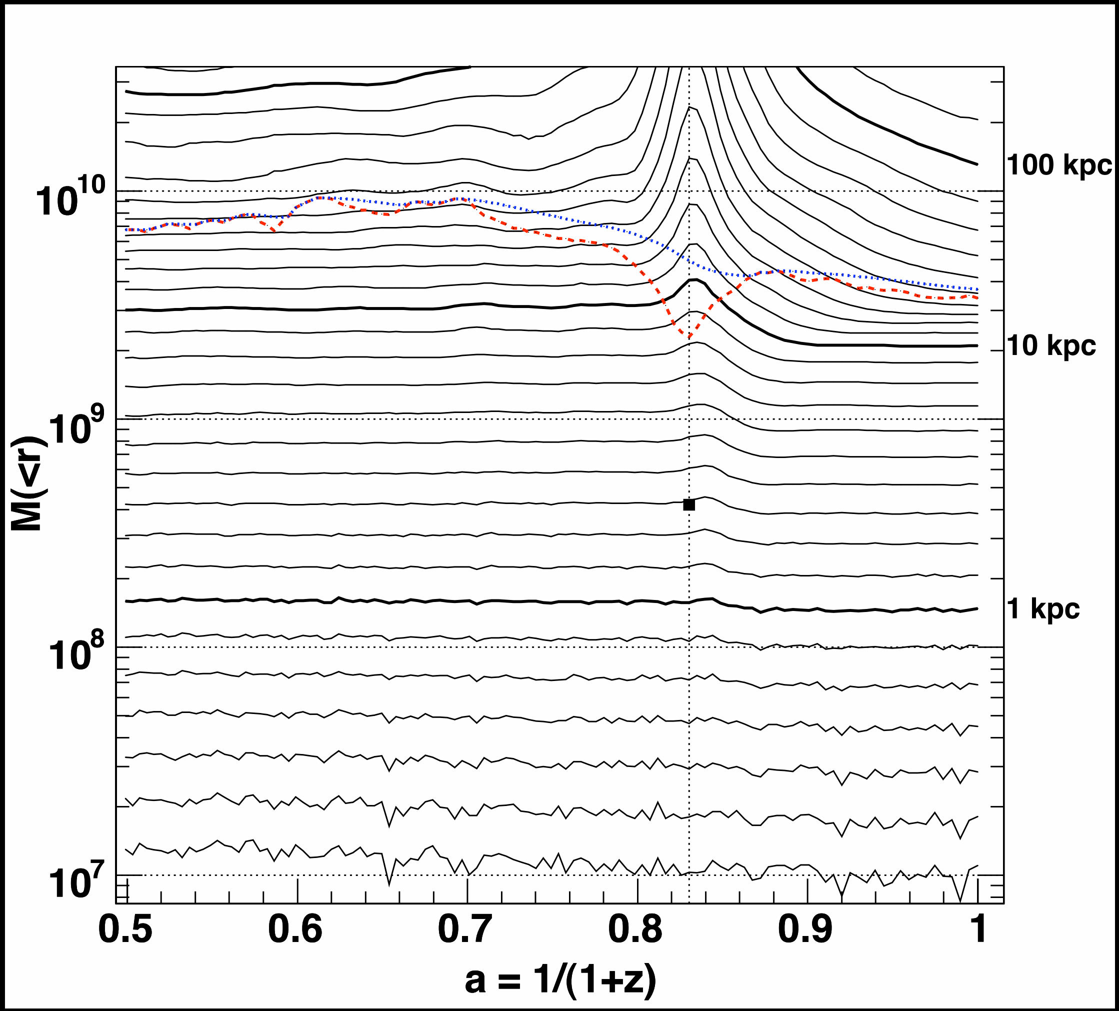


$M_{sub}$=2.4 $10^9$ $M_\odot$
$r_{tidal}$=14.7 kpc
$D_{center}$=185 kpc

$M_{sub}$=3.0 $10^9$ $M_\odot$
$r_{tidal}$=28.0 kpc
$D_{center}$=280 kpc

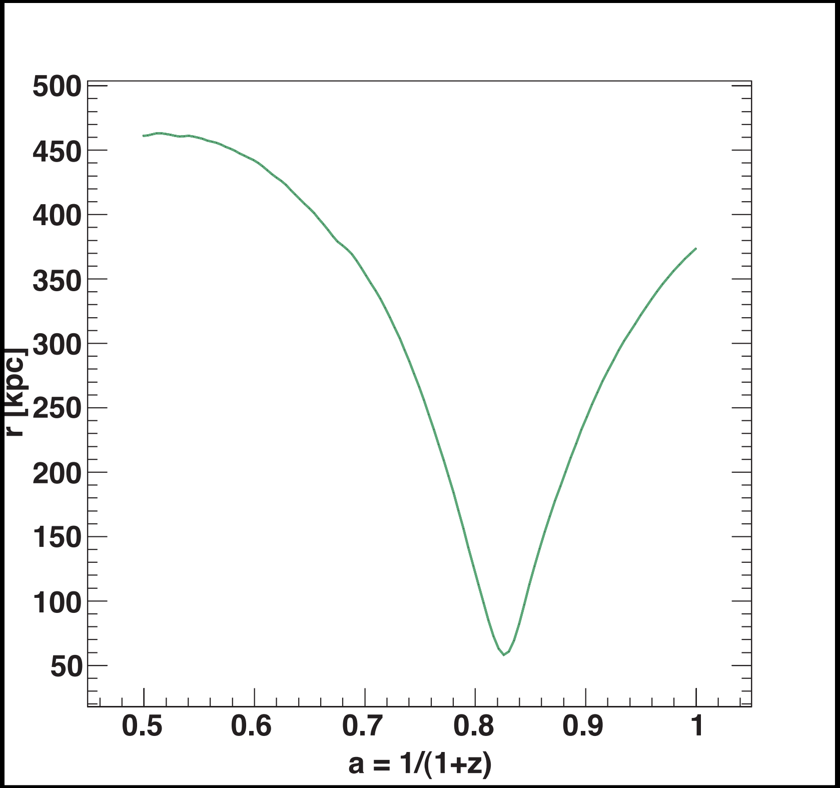
JD, Kuhlen, Madau, astro-ph/0611370

# 3) subhalo evolution




total mass in spheres around subhalo center

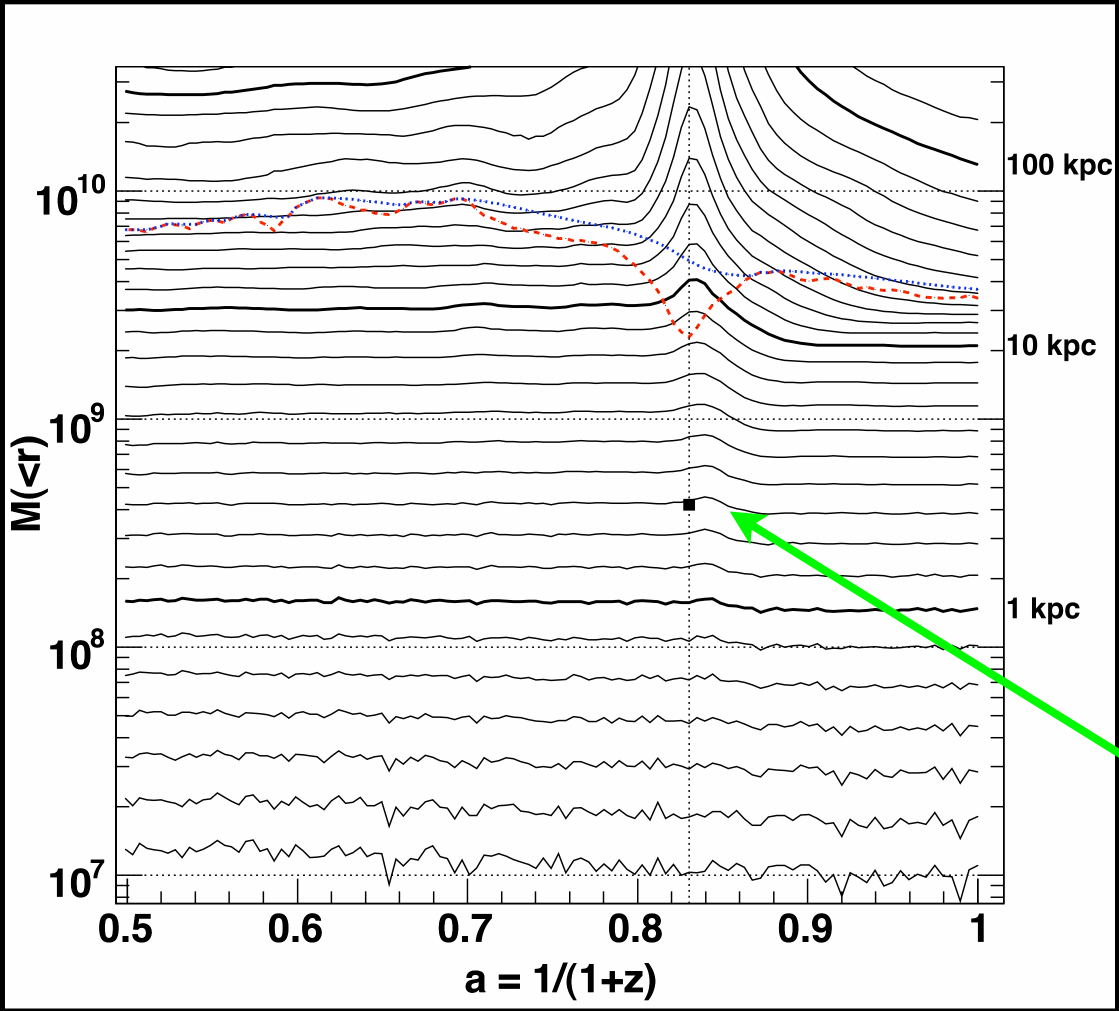
this subhalo has one pericenter passage at 56 kpc




weak, long tidal shock

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

# evolution of subhalo density profiles



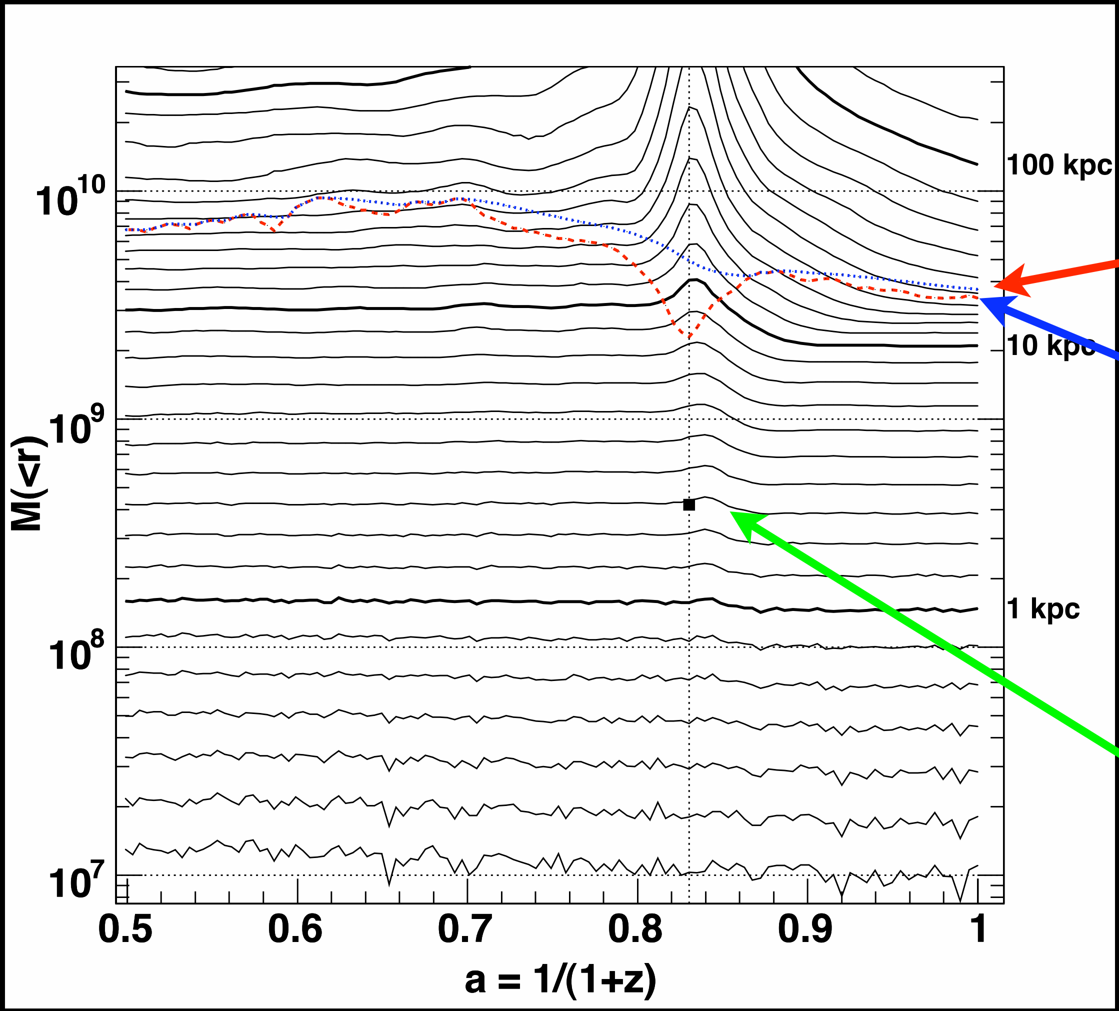

total mass in spheres around subhalo center

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




total mass in spheres around subhalo center

tidal mass, smaller than the bound mass at pericenter

“delayed” tidal mass

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

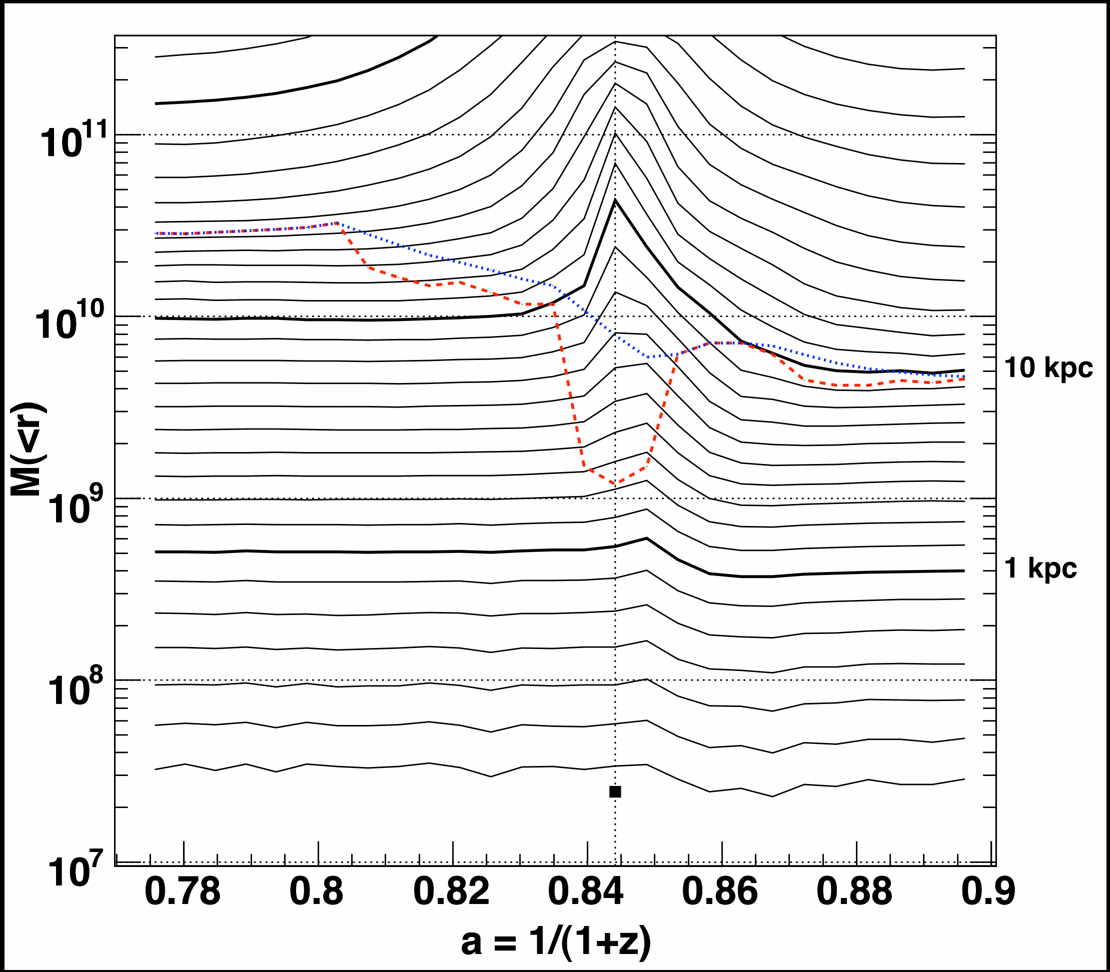
with $T_s = T_{\rm orbit}/6$

shock duration = internal subhalo orbital time

weak, long tidal shock
causes quick compression followed by expansion

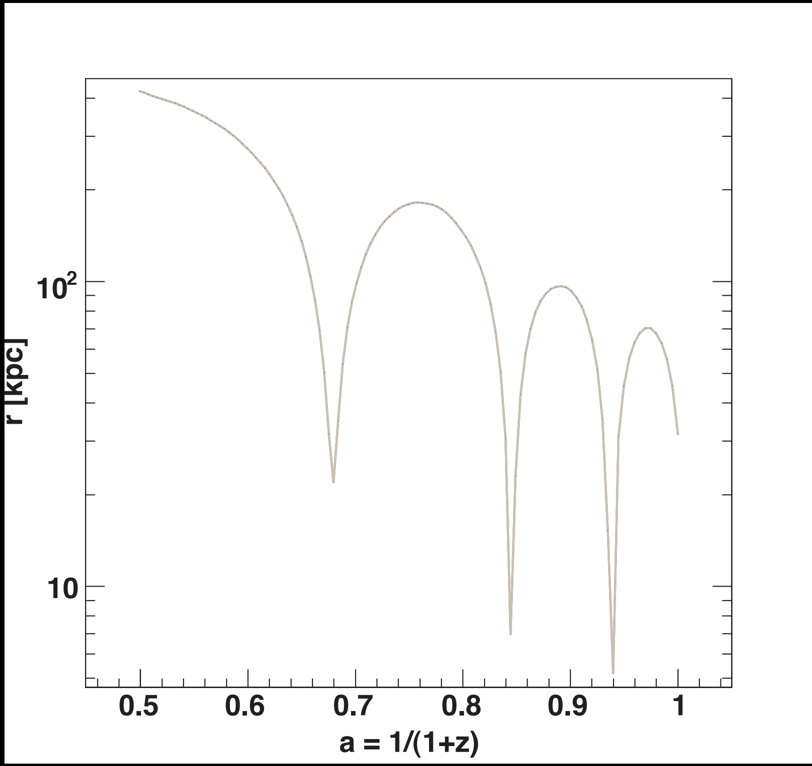
mass loss is larger further out

# evolution of subhalo density profiles

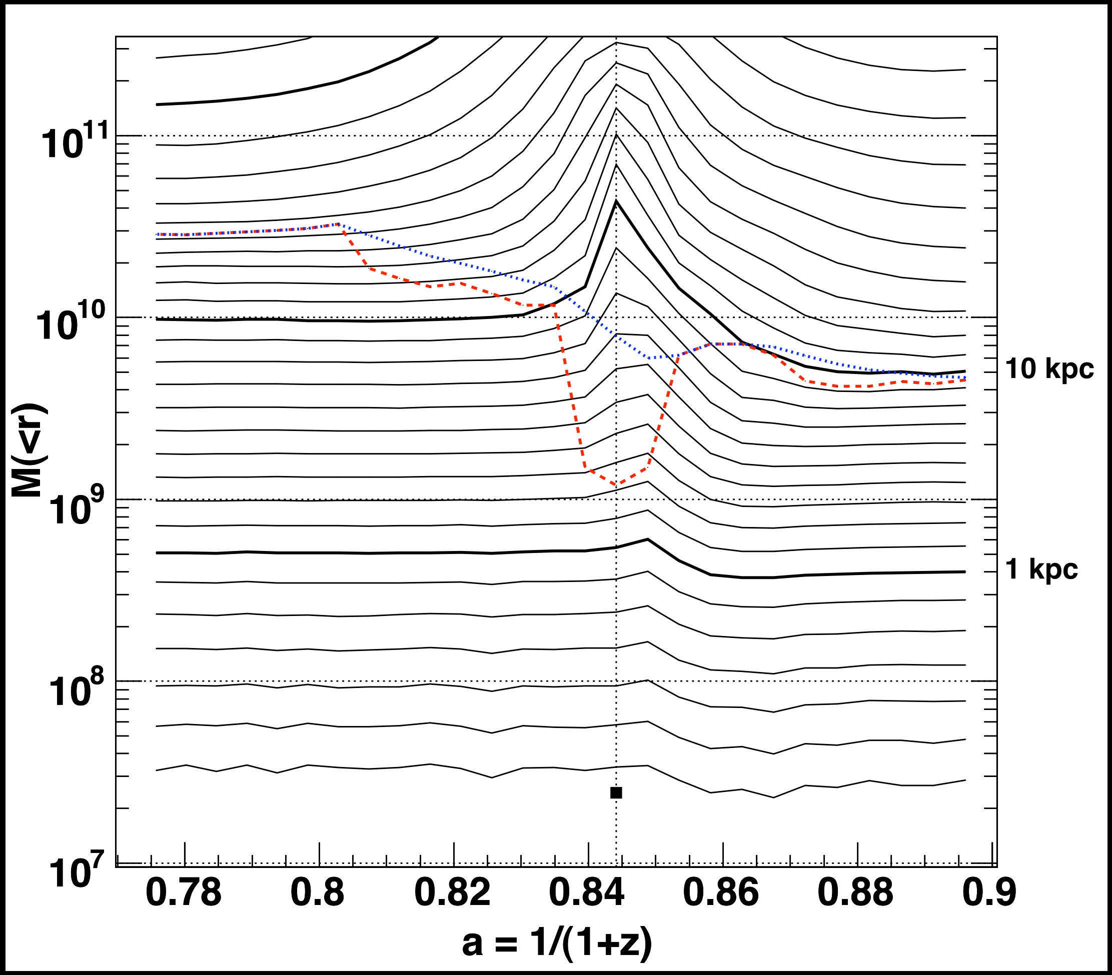



total mass in spheres around subhalo center

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

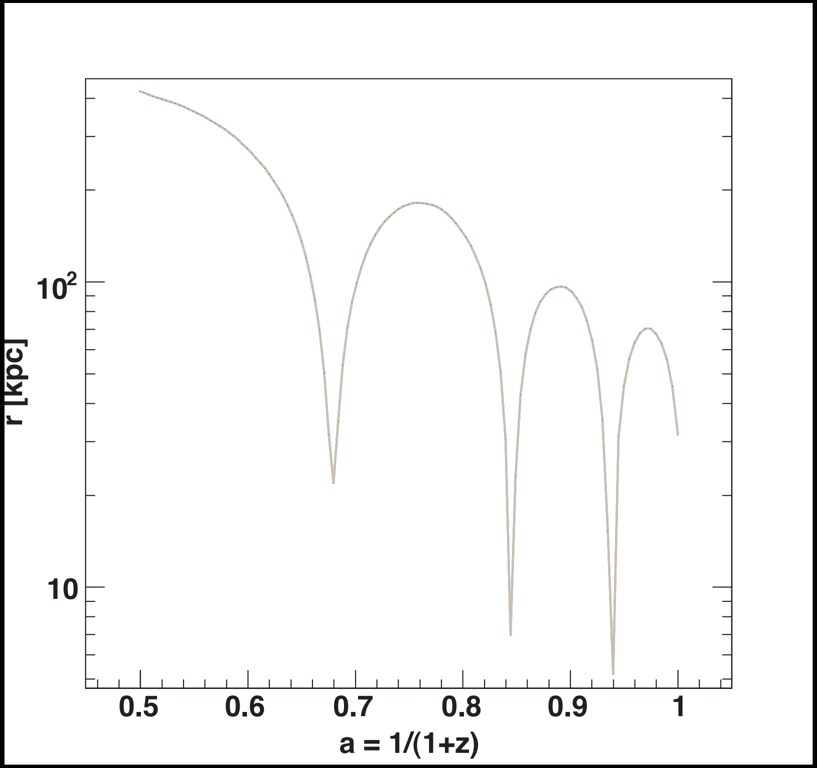


# evolution of subhalo density profiles




total mass in spheres around subhalo center

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)

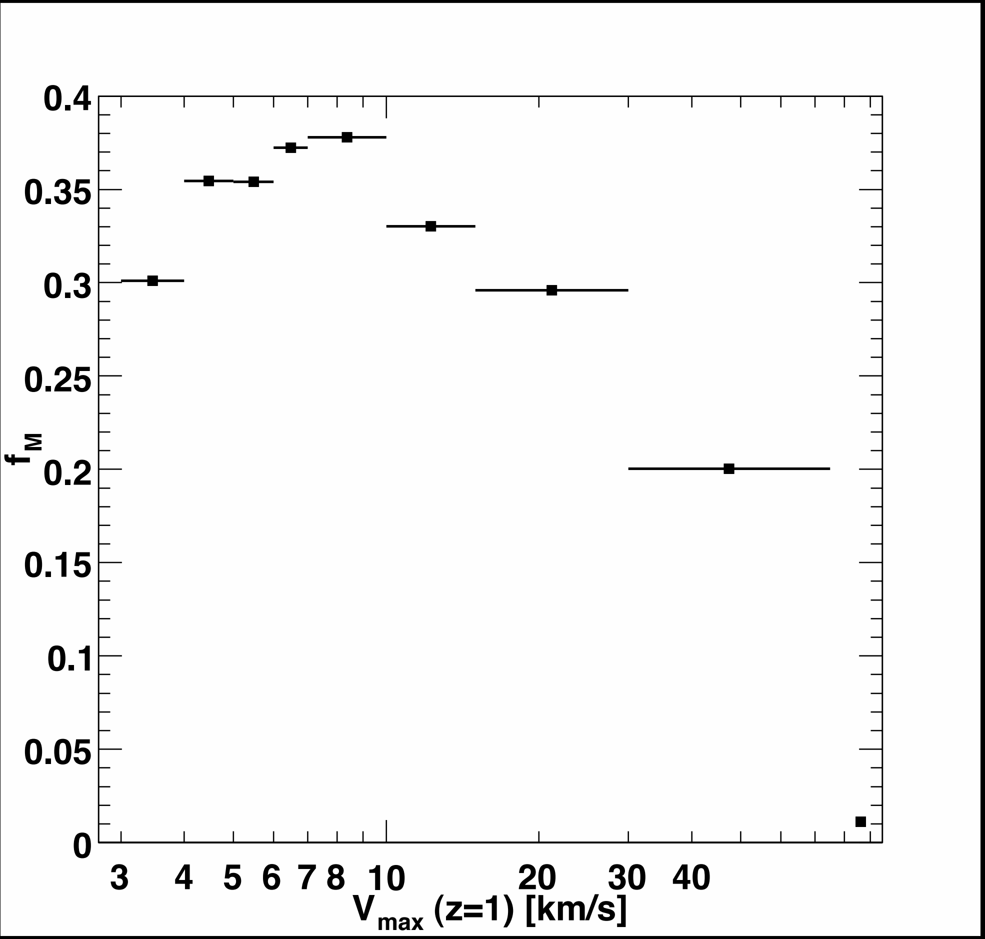
# subhalo survival and merging

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



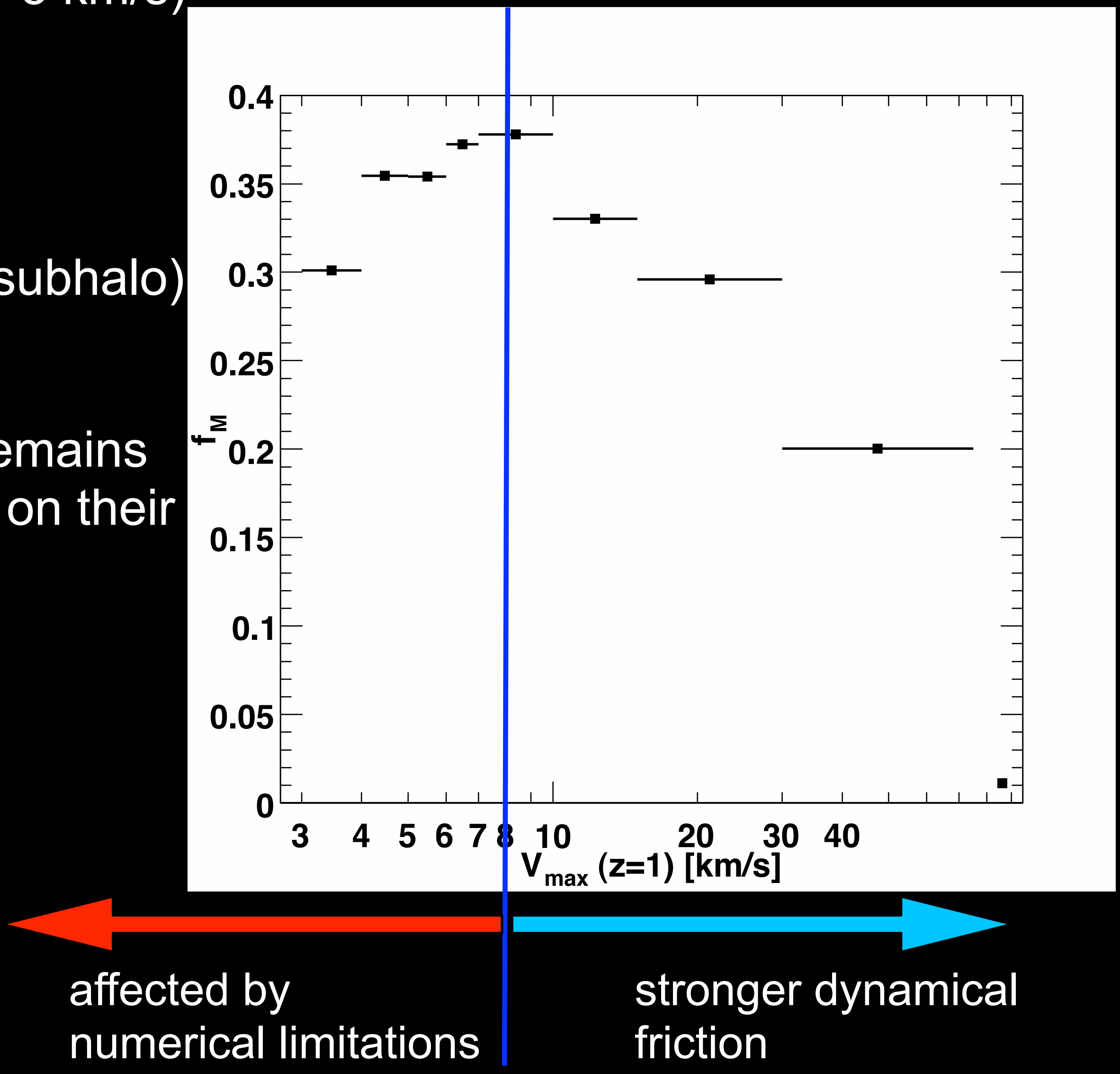
# subhalo survival and merging

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



# possible hosts for Local Group dwarfs

early forming (EF) sample:

the 10 subhalos which had Vmax > 16 km/s at z=10
motivated by reionisation, which might suppress further accretion of gas into small halos (e.g. Bullock etal 2000, Moore etal 2006)

# possible hosts for Local Group dwarfs

early forming (EF) sample:

the 10 subhalos which had Vmax > 16 km/s at z=10
motivated by reionisation, which might suppress further accretion of gas into small halos (e.g. Bullock etal 2000, Moore etal 2006)

largest before accretion (LBA) sample:

the 10 subhalos which had Vmax > 37 km/s at some time
if star formation is always inefficient in small halos

Kravtsov, Gendin & Klypin 2004 model lies in between these two selections

# possible hosts for Local Group dwarfs

early forming (EF) sample:

the 10 subhalos which had Vmax > 16 km/s at z=10
motivated by reionisation, which might suppress further accretion of gas into small halos (e.g. Bullock etal 2000, Moore etal 2006)

largest before accretion (LBA) sample:

the 10 subhalos which had Vmax > 37 km/s at some time
if star formation is always inefficient in small halos

Kravtsov, Gendin & Klypin 2004 model lies in between these two selections

EF and LBA have 6 common objects, out of 10

we show EF sample tracks and only LBA z=0 properties of the LBA sample ...

# possible hosts for Local Group dwarfs

early forming (

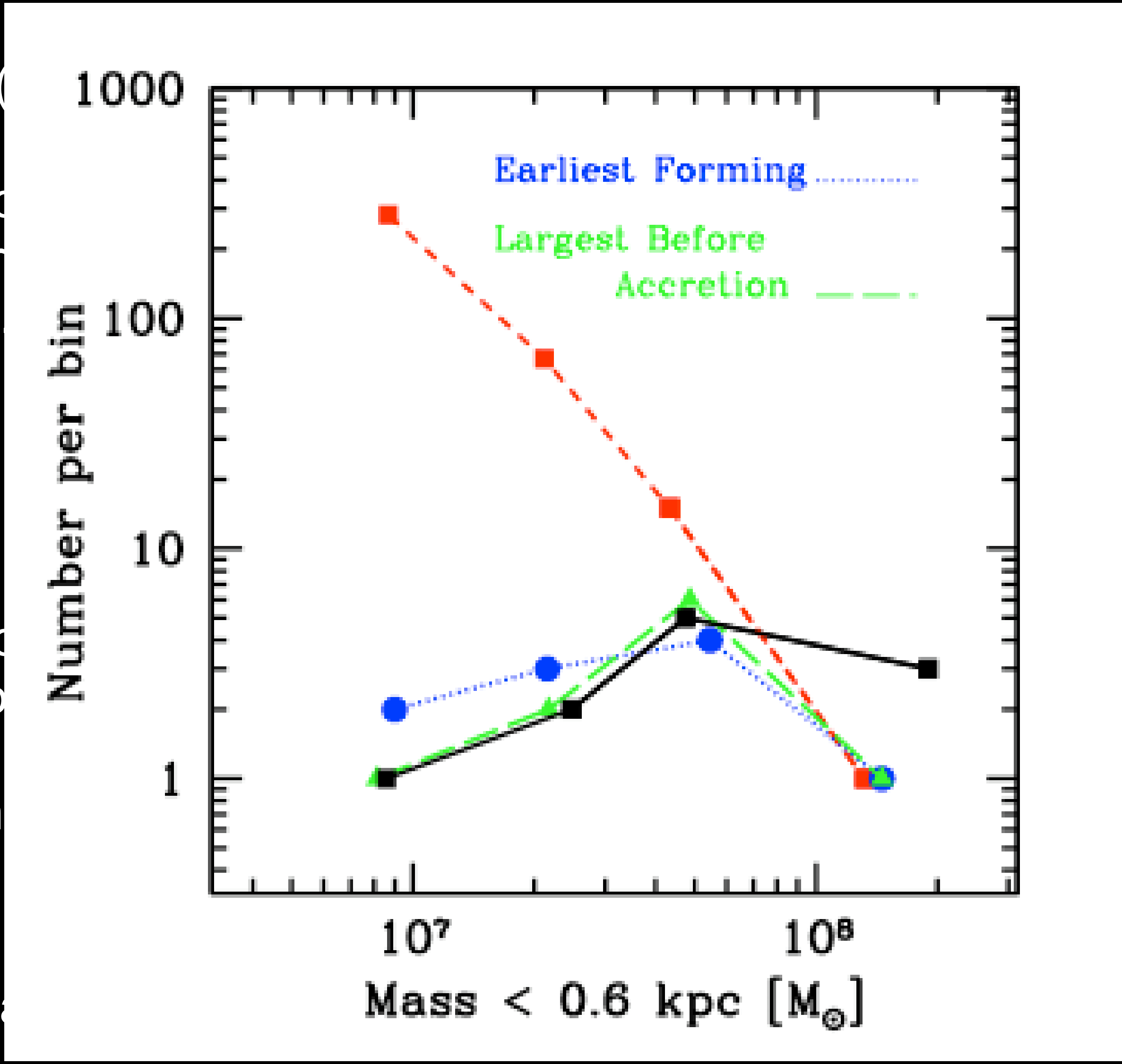
the 10 subhalo
motivated by r … n of gas into
small halos (e.

largest before

the 10 subhalo
if star formatio

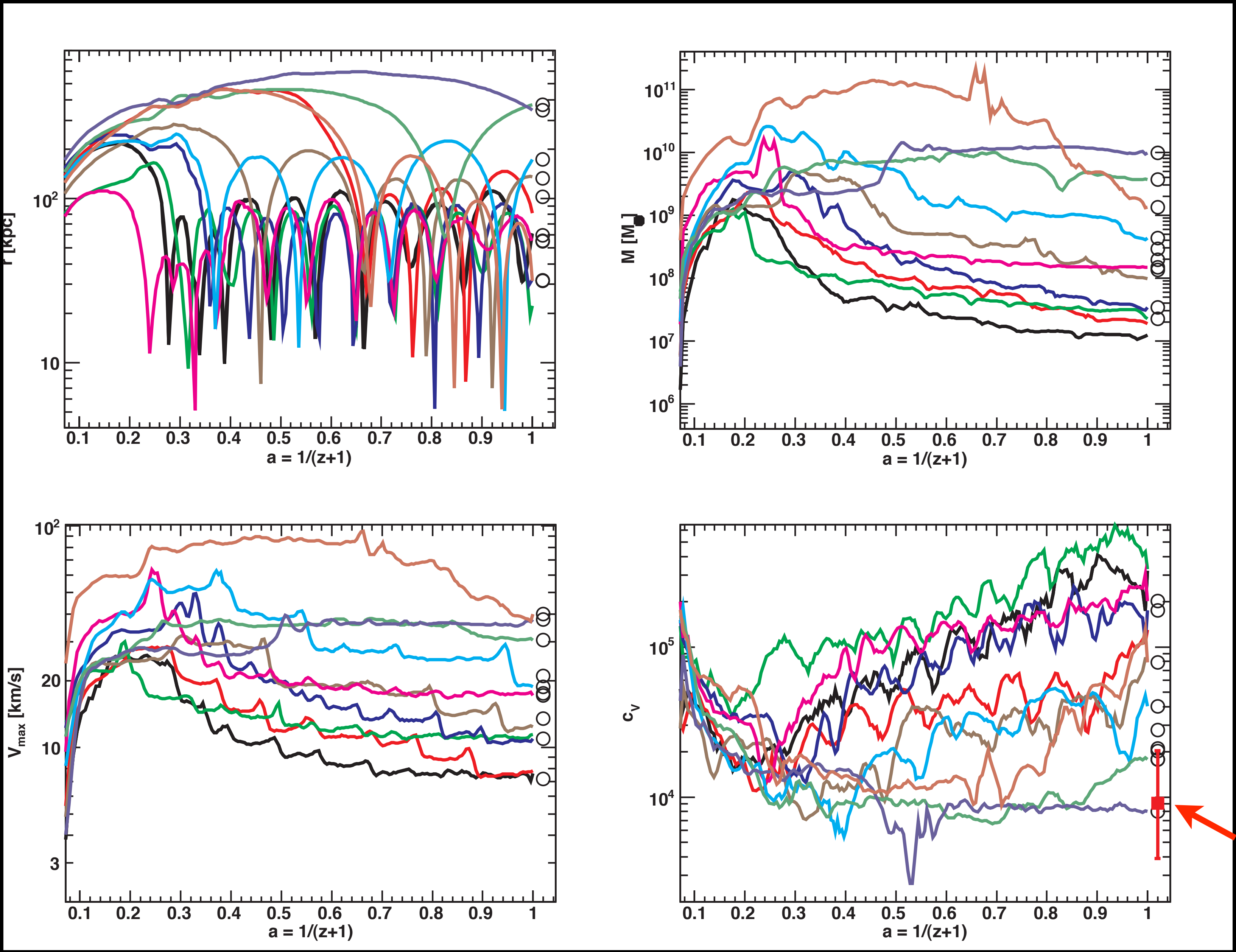
Kravtsov, Gen … selections

EF and LBA h




we show EF sample tracks and only LBA z=0 properties of the LBA sample ...

# possible hosts for Local Group dwarfs




diverse histories:

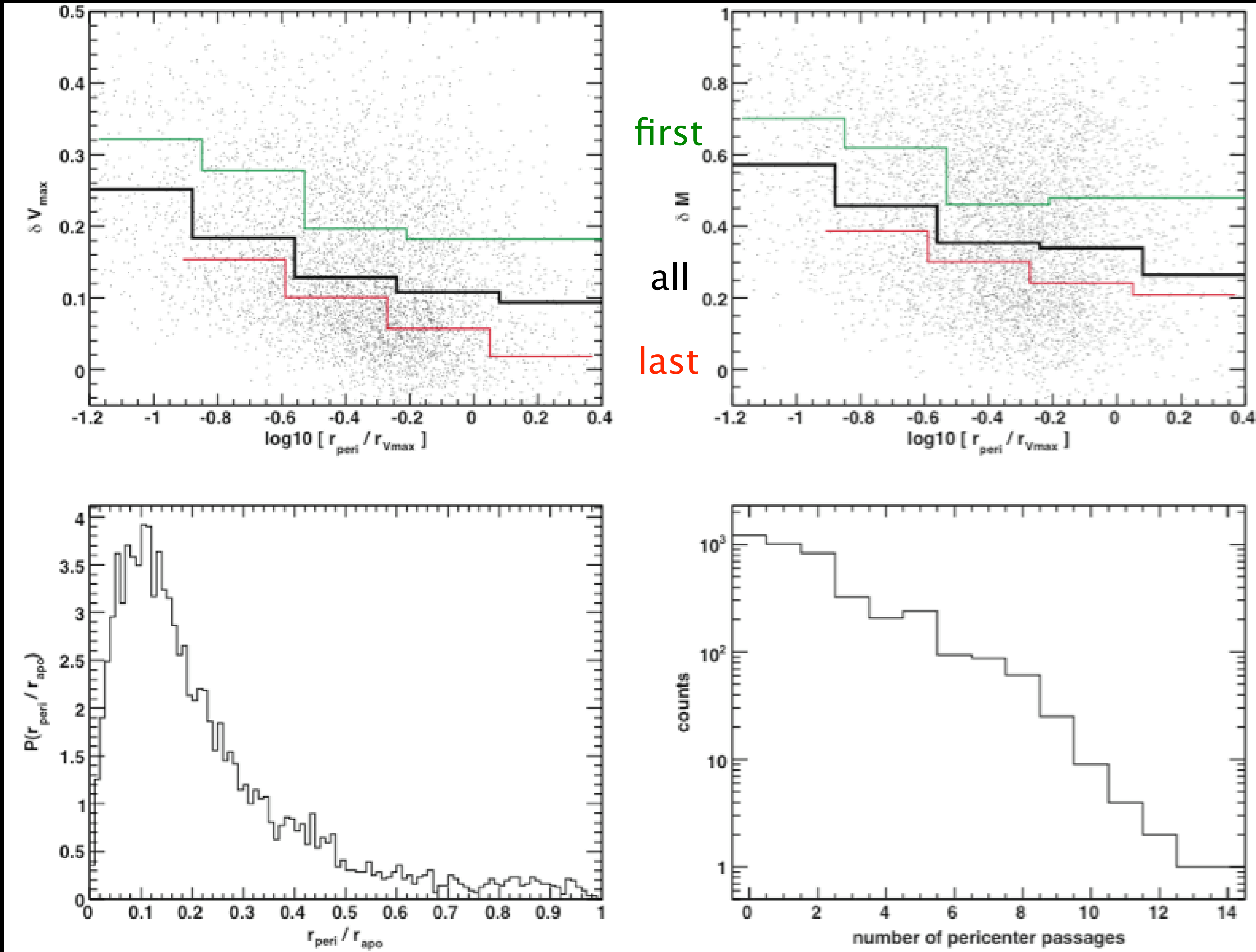
0 to 11 pericenters
inner subhalos tend to have more of them and starting earlier

none to very large mass loss

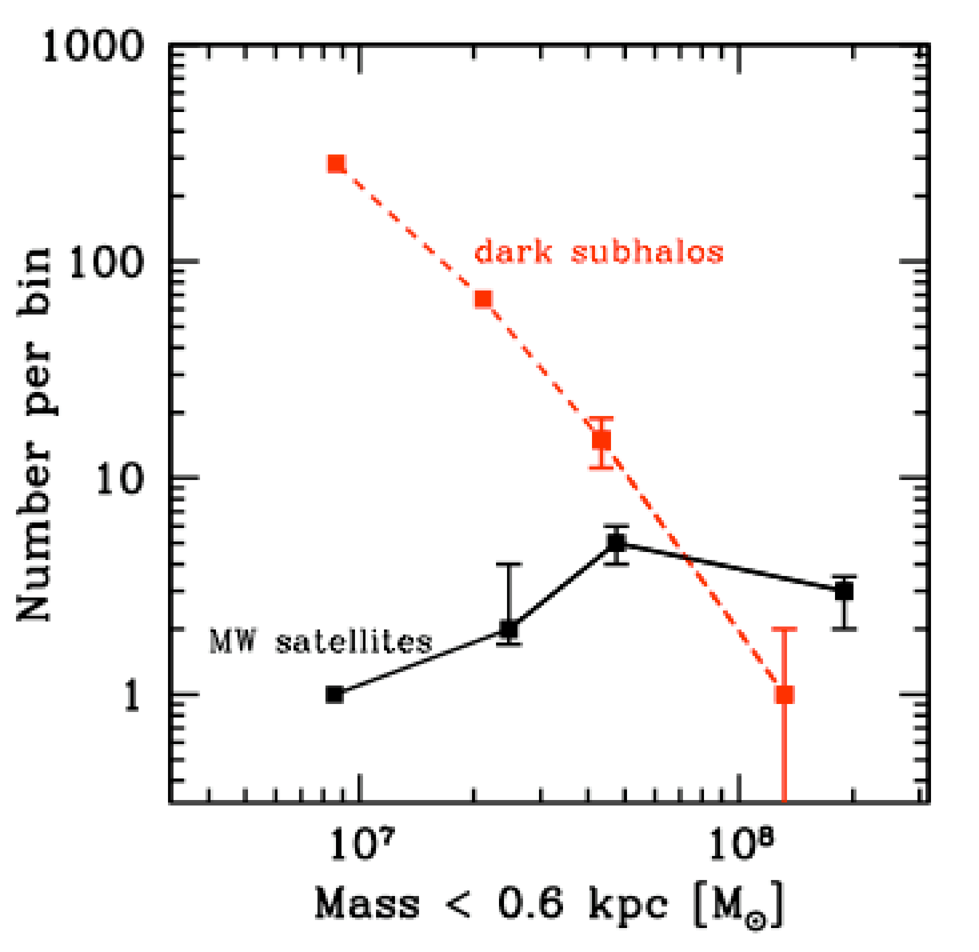
concentrations increase during tidal mass loss

field halo concentrations

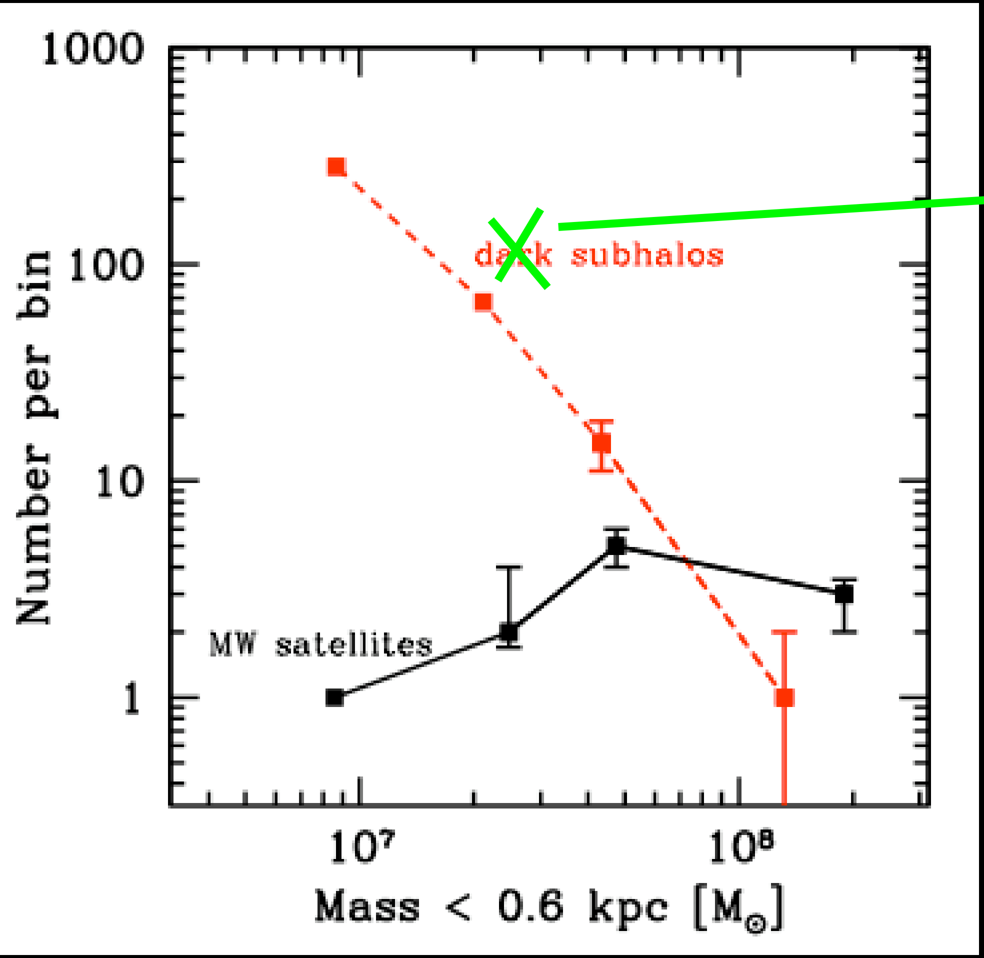
# larger mass loss at first pericenter



# 4) DM annihilation and GLAST



# 4) DM annihilation and GLAST




maybe we just need a different telescope???

glast.gsfc.nasa.gov

see Mike Kuhlen etal, 1st GLAST Symposium 2007, astro-ph/0704.0944

Q: Will GLAST detect $\gamma$-ray photons from dark matter annihilation?
(Bergström et al. 1999; Calcanéo-Roldán & Moore 2000; Stoehr et al. 2003; Taylor & Silk 2003; Tasitsiomi et al. 2004; Koushiappas et al. 2004; Baltz & Wai 2004; etc., etc.)

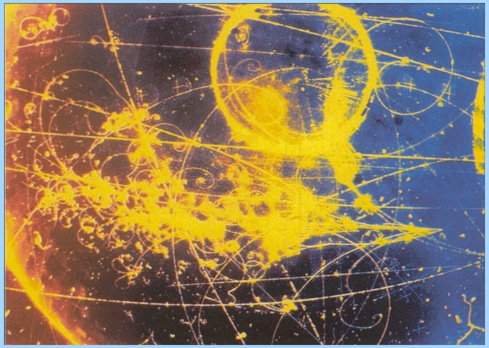
A: It depends. It depends on a lot of things:

1) DM particle properties: type, mass, cross section of particle
2) Backgrounds: extra-galactic and Galactic; how well can we subtract them?
3) DM distribution: how clumpy? subhalo spatial distribution? mass function? Internal density profile?

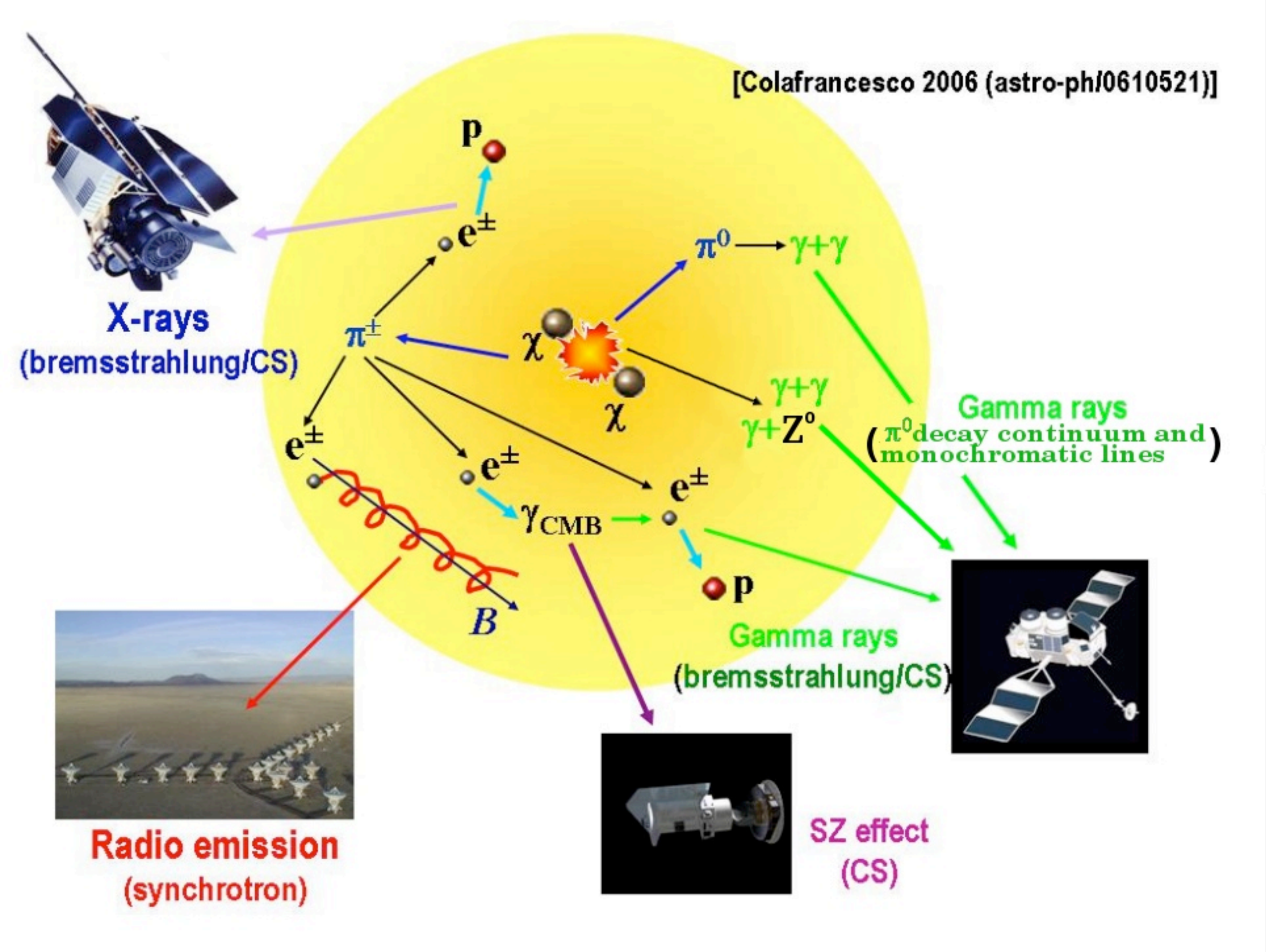
Numerical simulations of DM structure can help address 3).

- Run very high resolution simulation of a Milky Way scale DM halo.
- Run subhalo finder and determine subhalo abundance, distribution, and internal properties.
- Calculate annihilation fluxes and angular sizes, estimate boost factors.
- Pick a particular particle physics model, and create simulated GLAST allsky maps.

# Particle Physics



## DM (WIMP) annihilation signal




Many different DM candidates: axions, WIMPs (neutralino, Kaluza-Klein, ...), etc.

In the following: DM = lightest SUSY particle (neutralino)

$\gamma$'s from neutralino annihilation:

a) $\chi\chi \rightarrow \gamma\gamma$

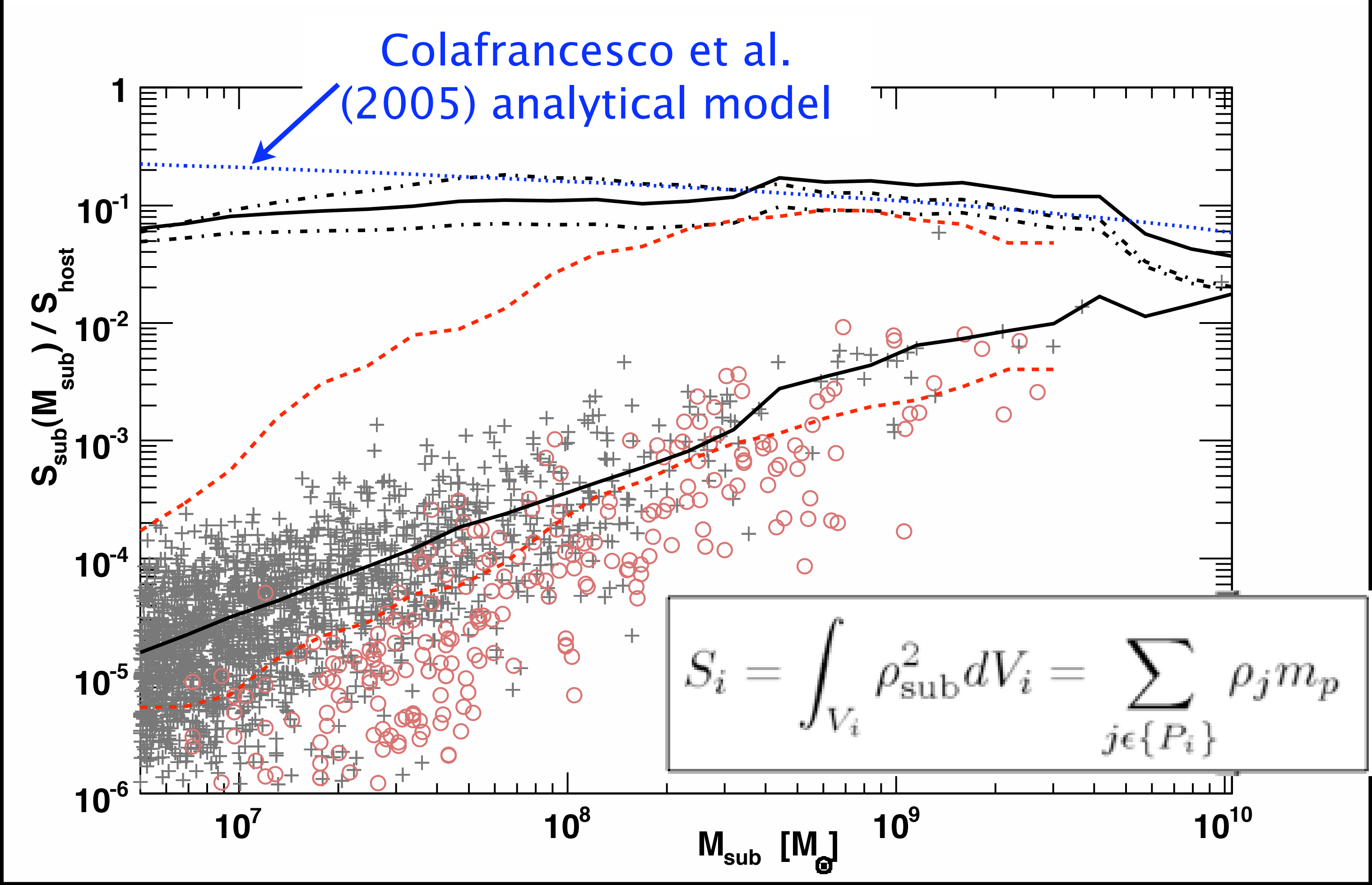
b) $\chi\chi \rightarrow \gamma Z^0$

c) $\chi\chi \rightarrow \{WW, Z^0Z^0, b\bar{b}, t\bar{t}, u\bar{u}\}$

a)+b) spectral line, lower $<\sigma v>$

c) photon continuum from $\pi^0$ decay, higher $<\sigma v>$, more ambiguous signal

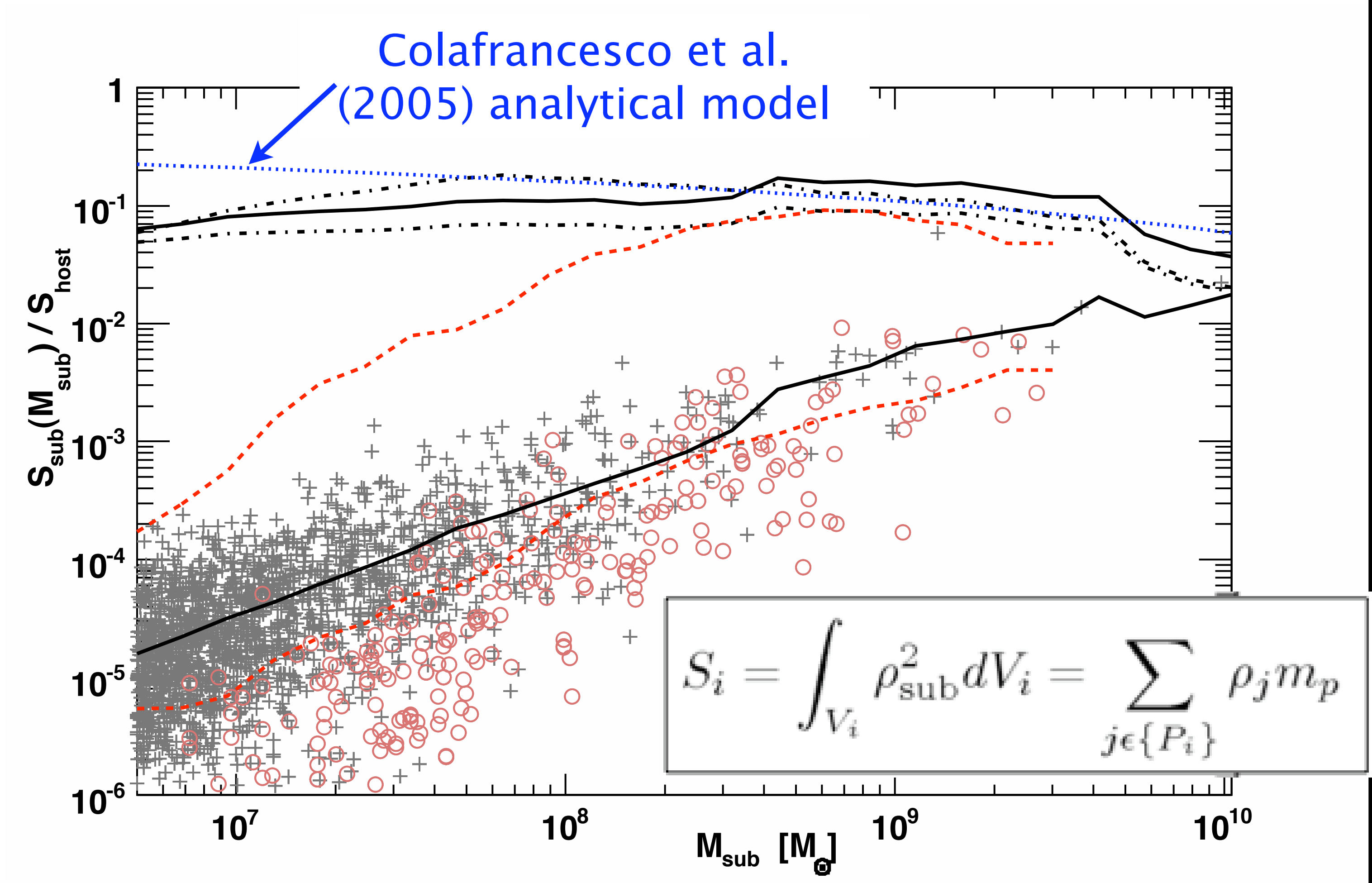
# DM annihilation signal from subhalos




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 yet

# DM annihilation signal from subhalos



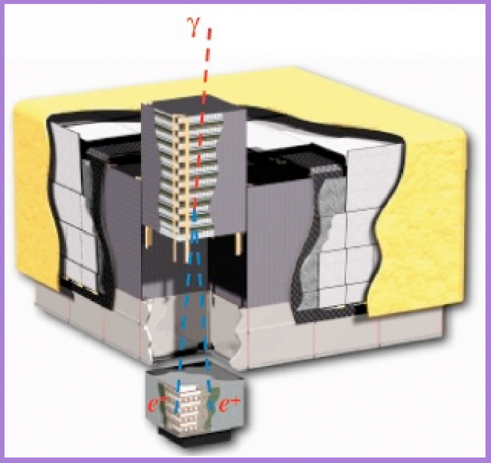

Total signal from subhalos is constant per decade in subhalo mass

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

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

# Detector properties



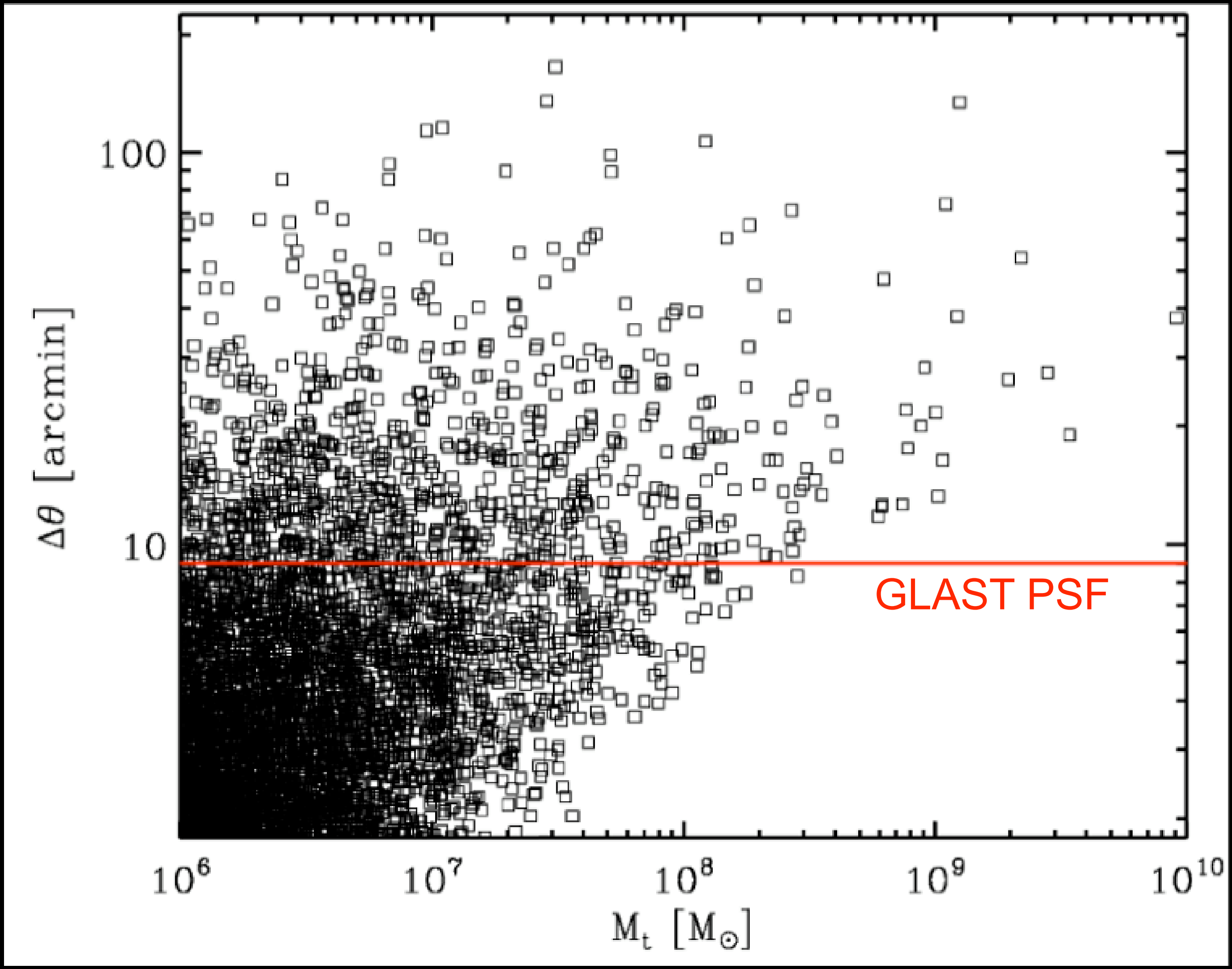



## Science Performance Requirements Summary

From the SRD:

| Parameter | SRD Value | Present Design Value |
|---|---|---|
| Peak Effective Area (in range 1-10 GeV) | >8000 $cm^2$ | 10,000 $cm^2$ at 10 GeV |
| Energy Resolution 100 MeV on-axis | <10% | 9% |
| Energy Resolution 10 GeV on-axis | <10% | 8% |
| Energy Resolution 10-300 GeV on-axis | <20% | <15% |
| Energy Resolution 10-300 GeV off-axis (>60°) | <6% | <4.5% |
| PSF 68% 100 MeV on-axis | <3.5° | 3.37° (front), 4.64° (total) |
| PSF 68% 10 GeV on-axis | <0.15° | 0.086° (front), 0.115° (total) |
| PSF 95/68 ratio | <3 | 2.1 front, 2.6 back (100 MeV) |
| PSF 55°/normal ratio | <1.7 | 1.6 |
| Field of View | >2sr | 2.4 sr |
| Background rejection (E>100 MeV) | <10% diffuse | 6% diffuse (adjustable) |
| Point Source Sensitivity(>100MeV) | $<6\times10^{-9}$ $cm^{-2}s^{-1}$ | $3\times10^{-9}$ $cm^{-2}s^{-1}$ |
| Source Location Determination | <0.5 arcmin | <0.4 arcmin (ignoring BACK info) |
| GRB localization | <10 arcmin | 5 arcmin (ignoring BACK info) |

# angular size vs. mass



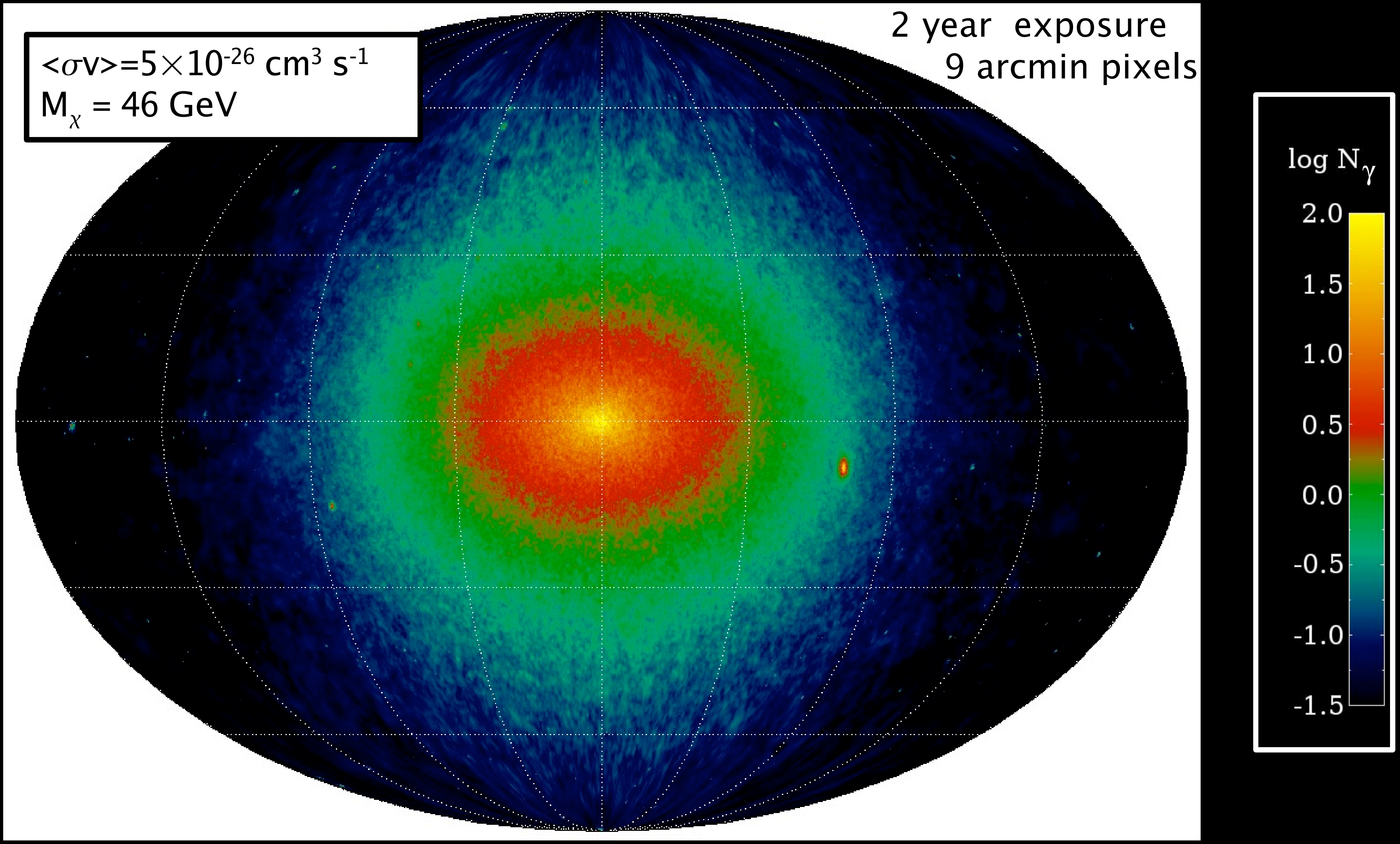

$\Delta\theta$ = angle subtended by twice the subhalo's scale radius $r_s$.

For an NFW profile 90% of the flux originates from within $r_s$.

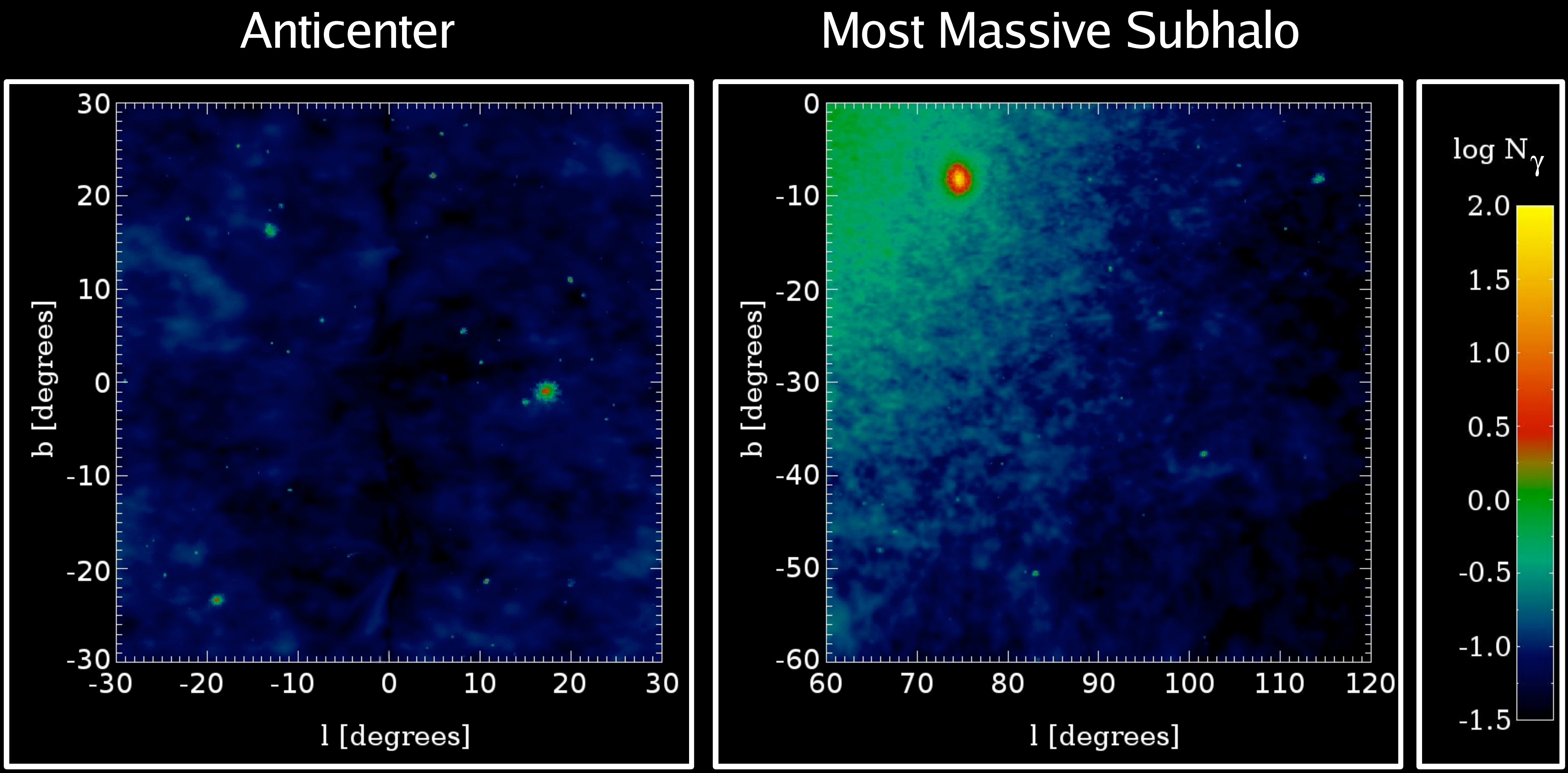
the brightest subhalos would be extended sources for GLAST (PSF 9 arcmin at 10 GeV)

# Simulated Maps

Observer along host halo's **intermediate** ellipsoidal axis

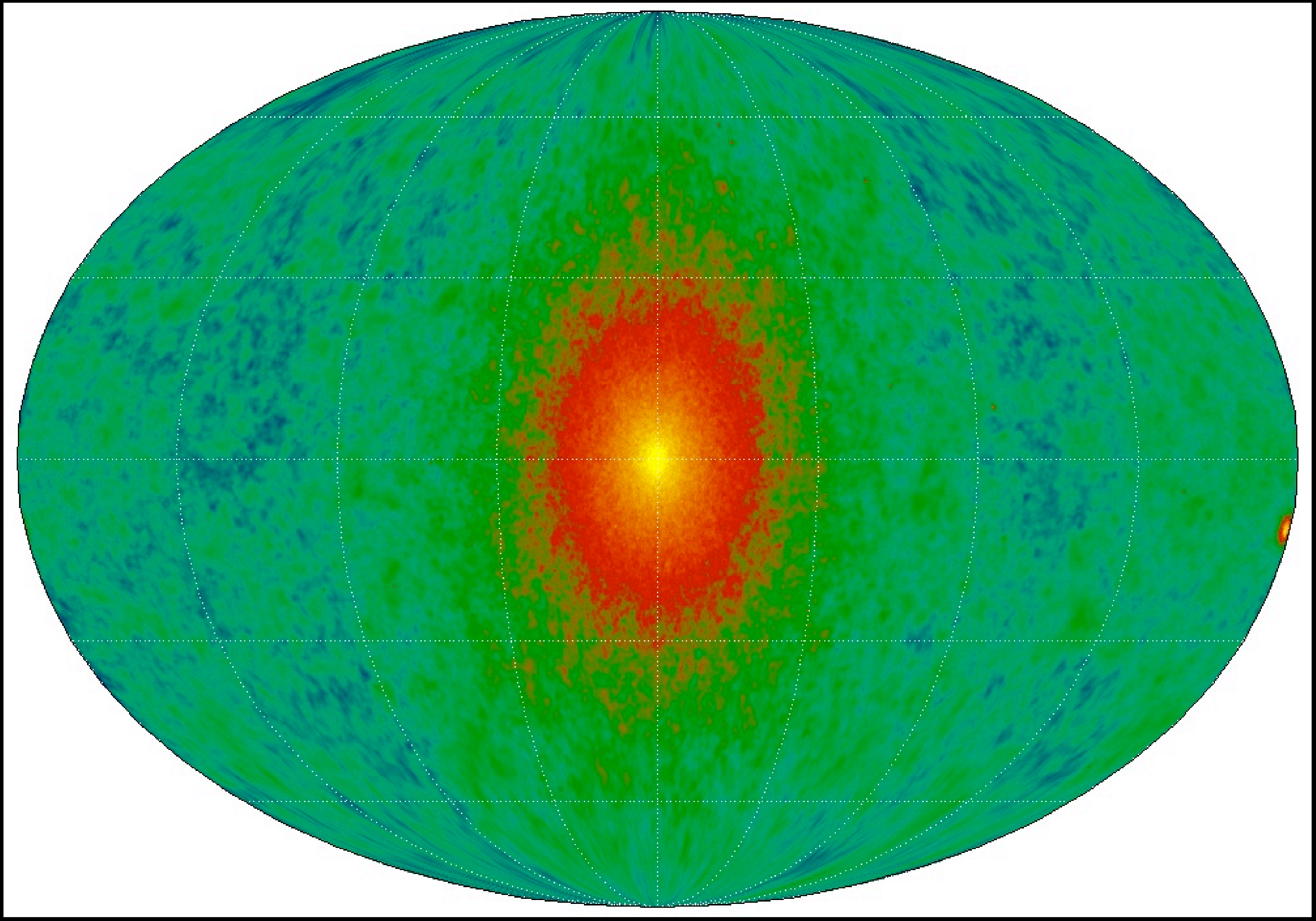


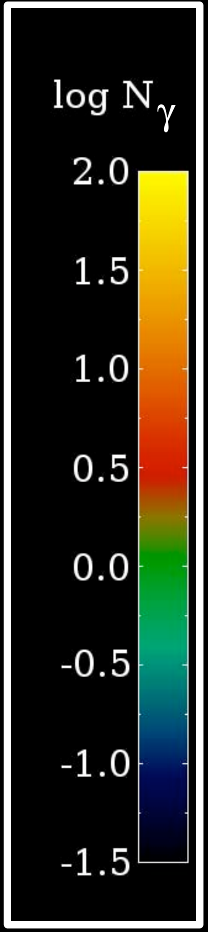
# Simulated Maps



# Simulated Maps

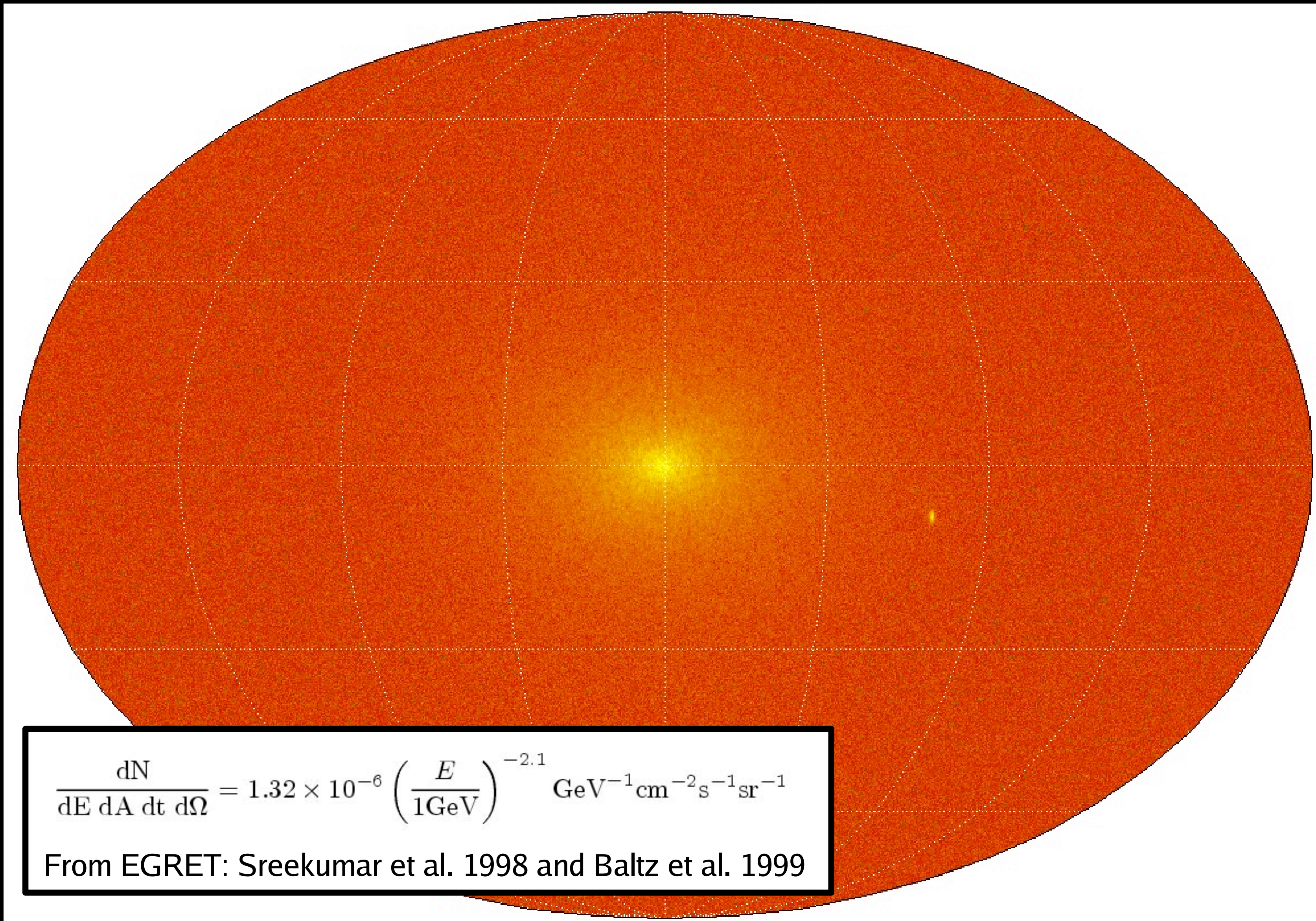
Observer along host halo's **major** ellipsoidal axis

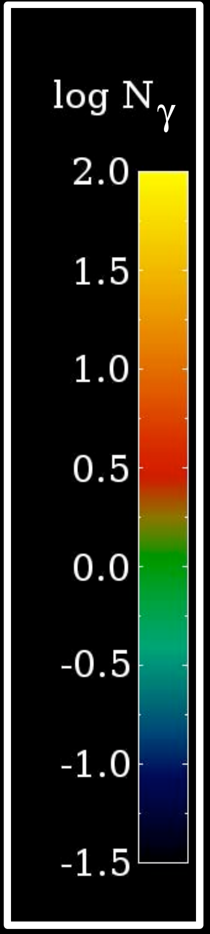




# Simulated Maps

Including a Poisson realization of the extra-galactic background.



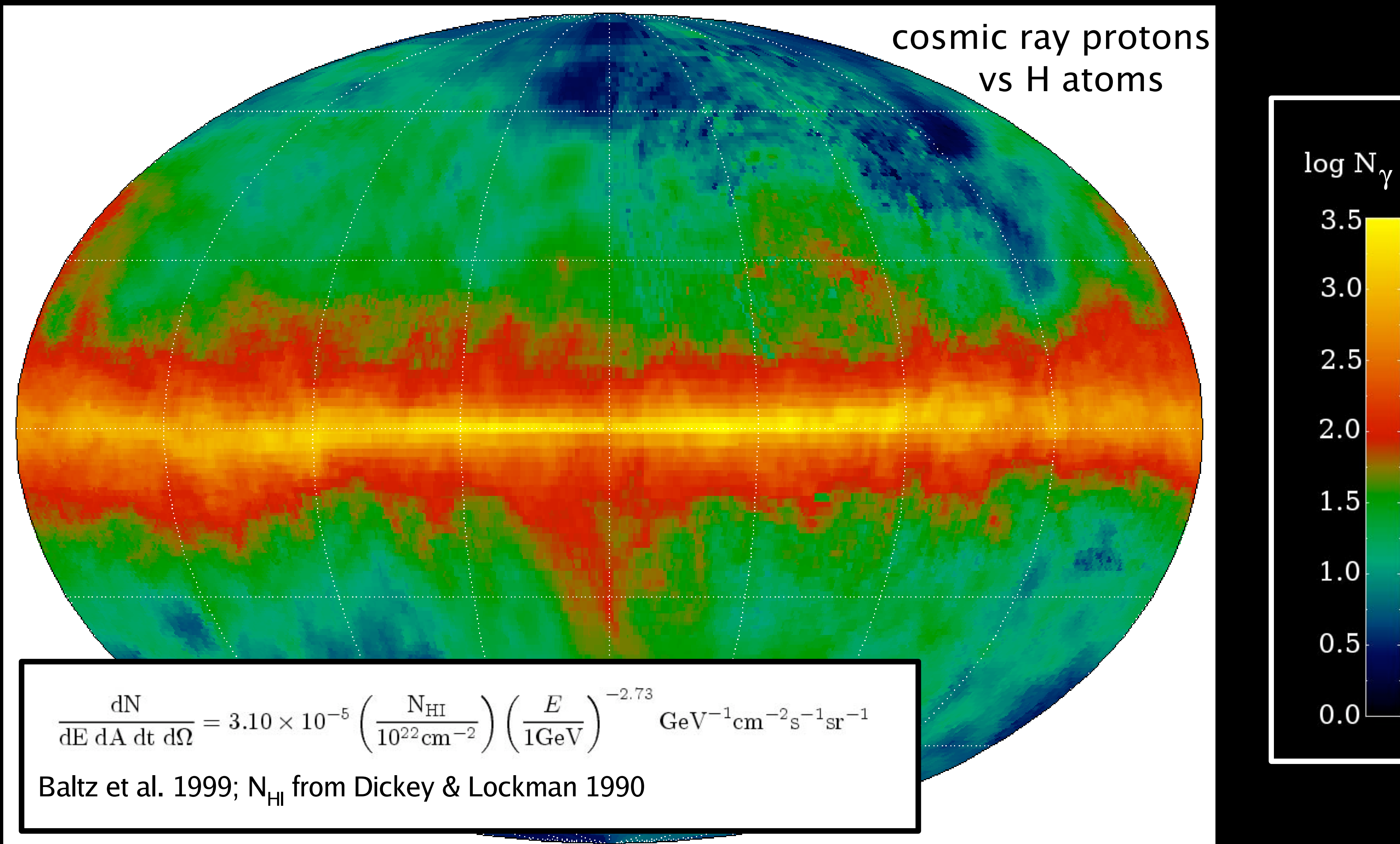



$$\frac{\mathrm{dN}}{\mathrm{dE\ dA\ dt\ d\Omega}} = 1.32 \times 10^{-6} \left(\frac{E}{1\mathrm{GeV}}\right)^{-2.1} \mathrm{GeV}^{-1}\mathrm{cm}^{-2}\mathrm{s}^{-1}\mathrm{sr}^{-1}$$

From EGRET: Sreekumar et al. 1998 and Baltz et al. 1999

# Simulated Maps

The Galactic background ($\propto N_{HI}$) dominates the annihilation signal.

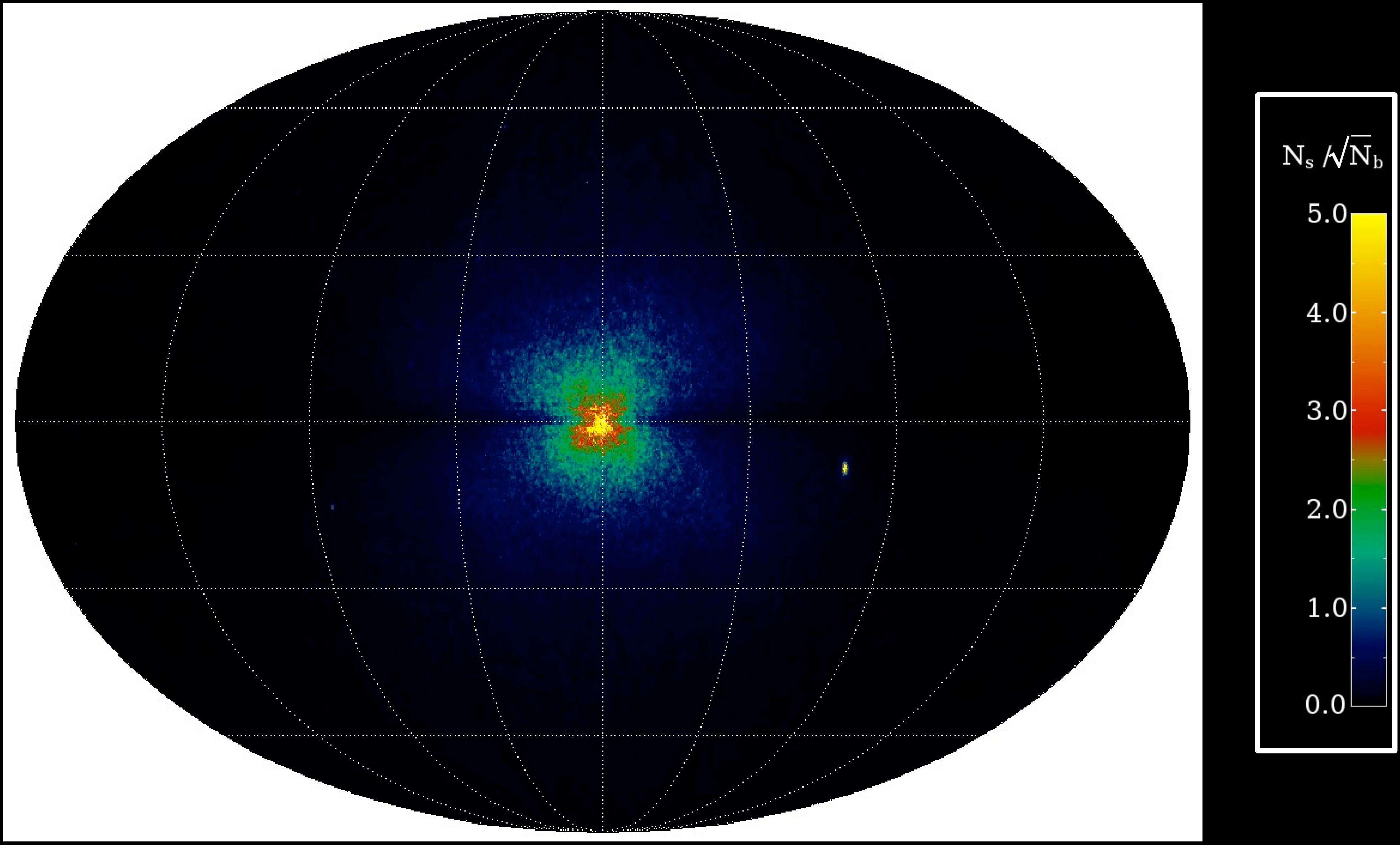



$$\frac{dN}{dE\ dA\ dt\ d\Omega} = 3.10 \times 10^{-5} \left(\frac{N_{HI}}{10^{22} cm^{-2}}\right) \left(\frac{E}{1 GeV}\right)^{-2.73} GeV^{-1} cm^{-2} s^{-1} sr^{-1}$$

Baltz et al. 1999; $N_{HI}$ from Dickey & Lockman 1990

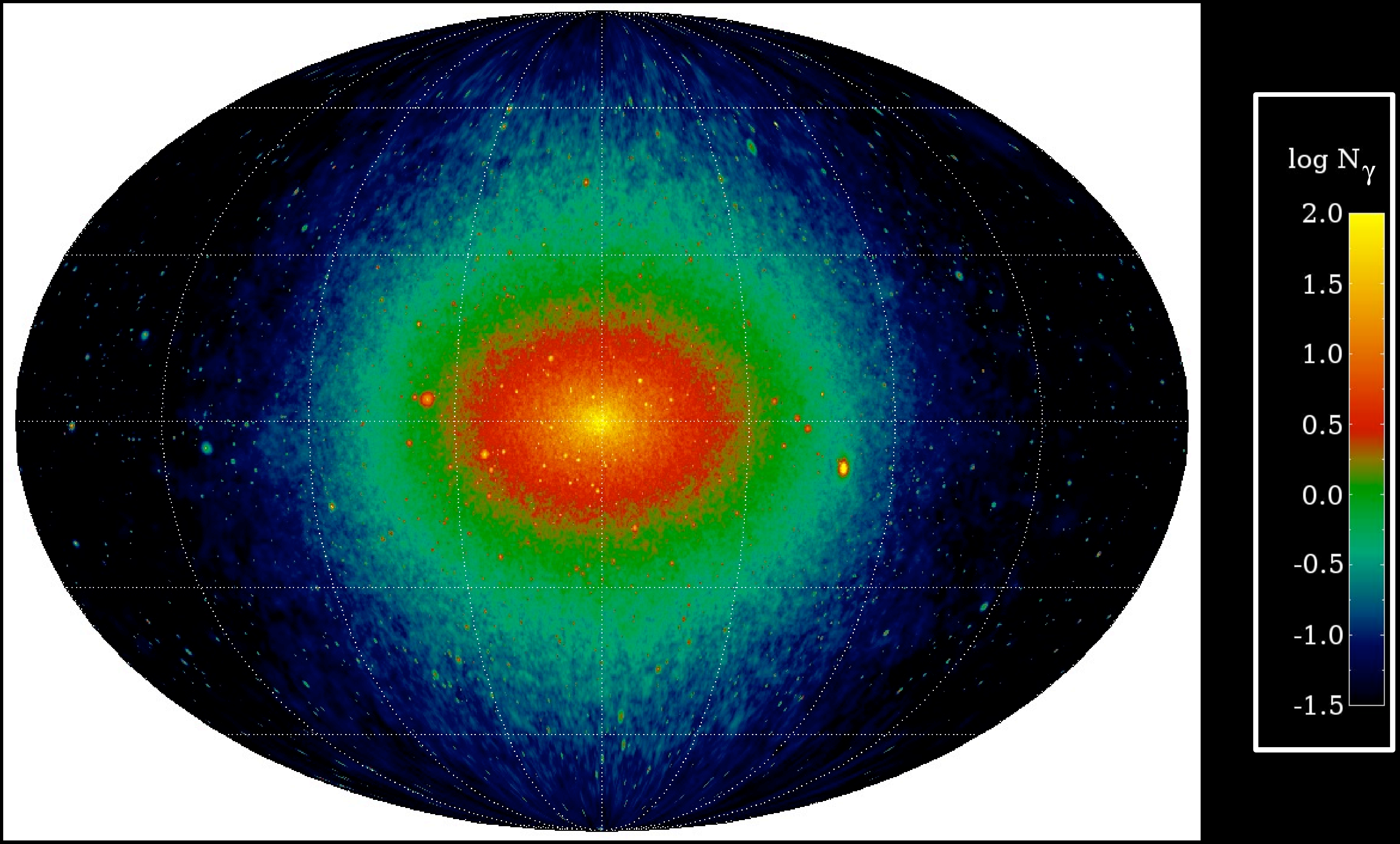
# Simulated Maps

The detection significance exceeds 5 in the Galactic center and in one subhalo.



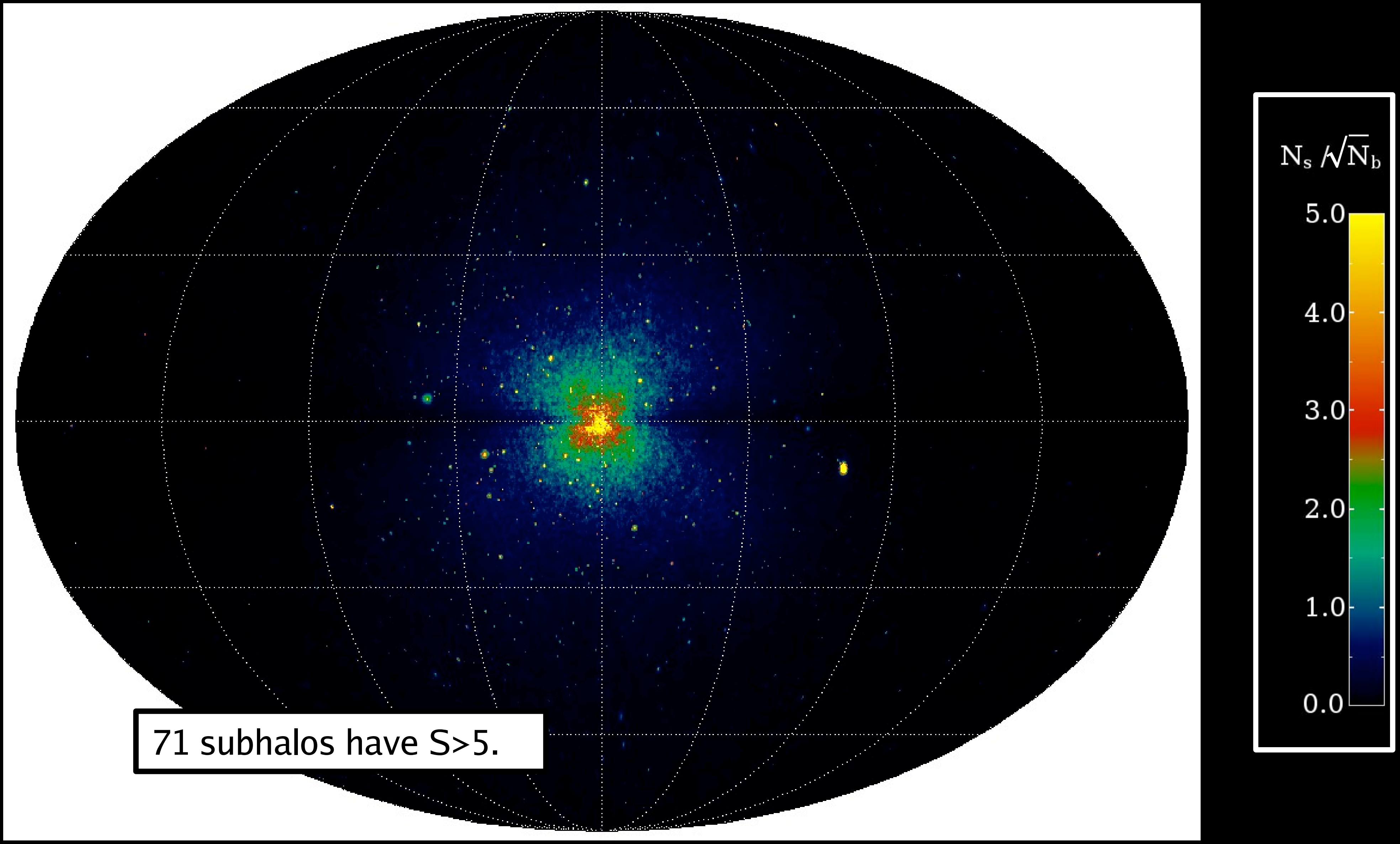
# Simulated Maps

Signal with subhalo boost factor = 10 (strong boost)



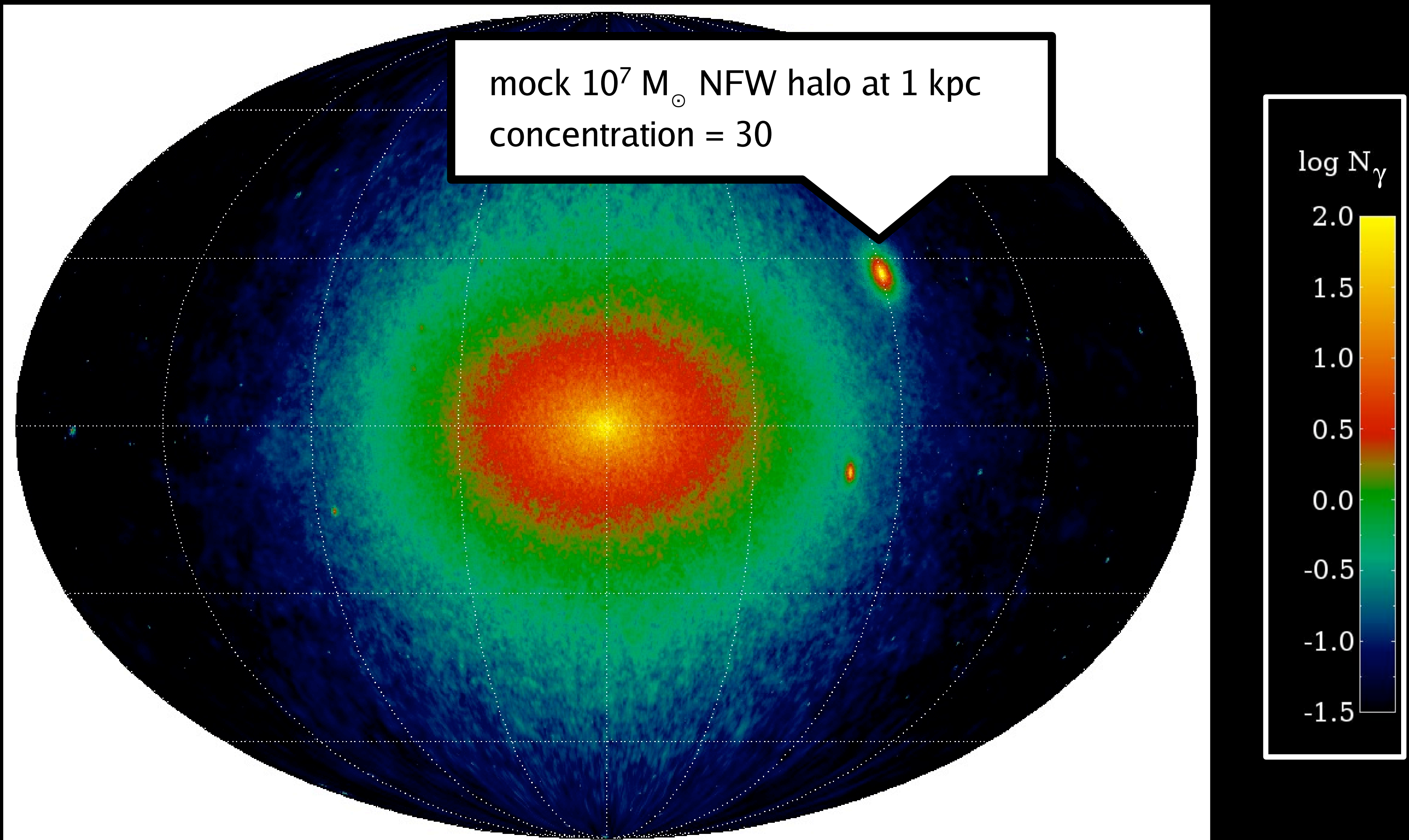
# Simulated Maps

Detection significance with subhalo boost factor = 10 (strong boost)



# Simulated Maps

What if we happen to be sitting close to a dark halo?



# summary

CDM has structures and substructures on a wide range of scales

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

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

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

with an optimistic cross section and particle mass GLAST could detect the glactic center and some (massive and/or nearby) subhalos

# summary

CDM has structures and substructures on a wide range of scales

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

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

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

with an optimistic cross section and particle mass GLAST could detect the glactic center and some (massive and/or nearby) subhalos

# future work

higher resolution runs on INCITE (DOE), NASA and local (Plejades) supercomputers using improved time steps based on dynamical times (Zemp etal2006)

cosmological gamma ray background from DM annihilation (+ absorption by the EBL)

phase space distribution of DM in the solar neighborhood