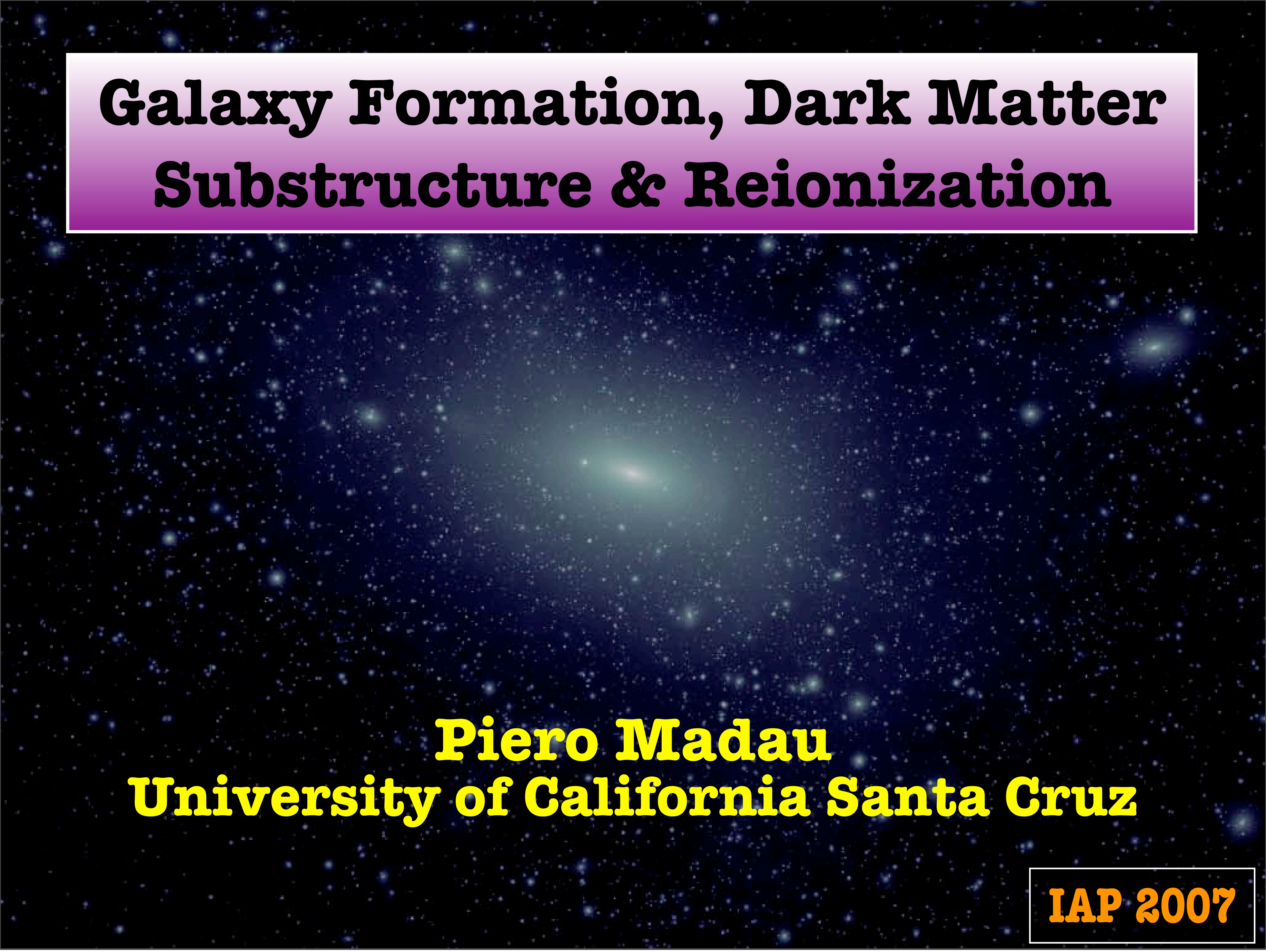

Galaxy Formation, Dark Matter Substructure & Reionization

Piero Madau
University of California Santa Cruz

IAP 2007

Galaxy Formation, Dark Matter Substructure & Reionization

- CDM substructure on small scales
- "Via Lactea" Nbody simulation
- Subhalo population of MW
- "Missing satellite problem"
- DM annihilation and GLAST

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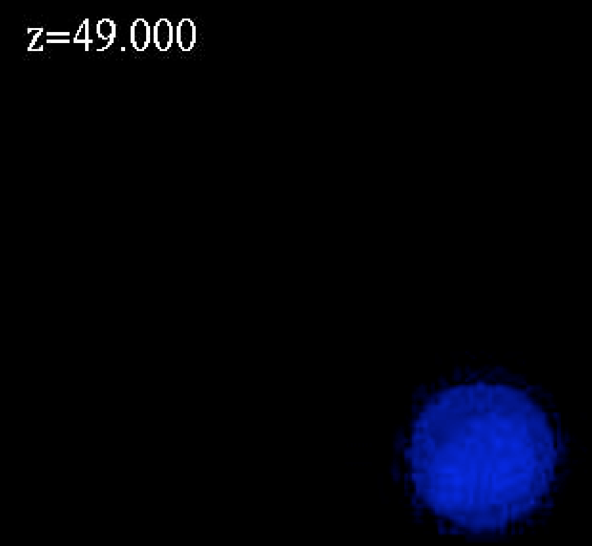
Halo substructure

In the standard paradigm of cosmological structure formation (ΛCDM) galaxies form hierarchically, with low-mass objects (“**halos**") collapsing earlier and merging to form larger and larger systems over time. **Halos collapsing at high redshift,** when the universe is very dense, have central densities that are correspondingly high.



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When these halos merge into larger hosts, their high densities allow them to resist the strong **tidal forces** that acts to destroy them.

Nbody simulations show that gravitational interactions unbind most of the mass associated with the merged progenitors, but it is expected a significant fraction of these small halos will survive the hierarchical process as distinct substructure.

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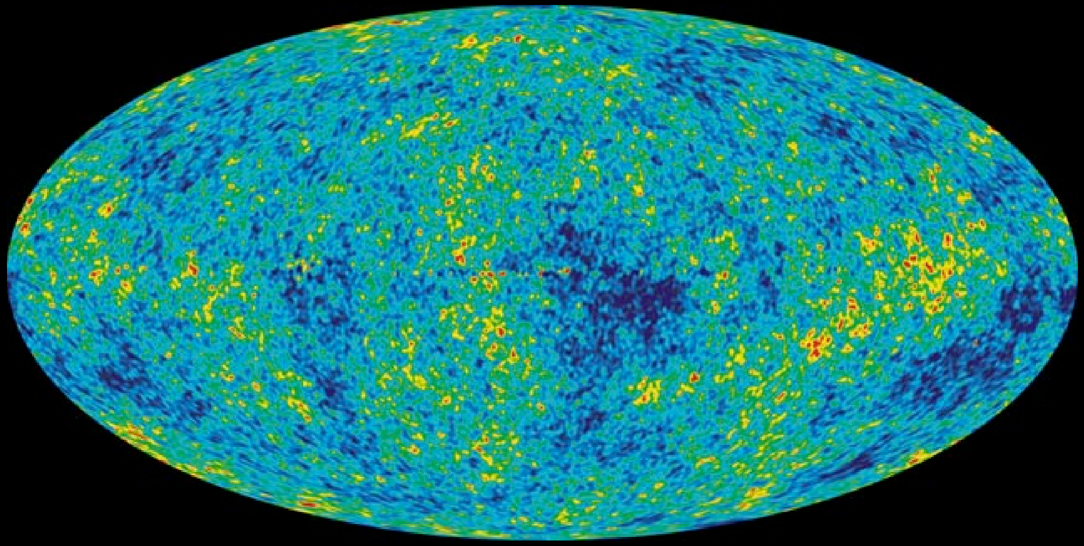
It is therefore a clear, unique prediction of ΛCDM that galaxies are embedded in massive, extended dark matter halos teeming with self-bound substructure or "subhalos". High resolution Nbody simulations have confirmed that CDM halos both on cluster and galaxy scales are not smooth but are clumpy on all resolved mass scales.

What WIMP makes up the DM?



CMB, LSS, SN Ia, BBN ➪ ΛCDM

WMAP-3yr (alone, flat prior): $\Omega_m=0.238$, $\Omega_b=0.042$
➪ 83% of the matter content of the universe is some non-baryonic, very weakly interacting cold particle

DM is “cold” or “not very warm”: Lyα forest, early reionization

We do not know what is, but we can still simulate its clustering properties under gravity...

Simulating CDM halos

collisionless (“pure N-body”, DM only) simulations

- assume all Ω_m is WIMP, and sample it with N particles
- bad approximation in the center of galaxies where baryons dominate
- simple physics: just gravity
- allows high resolution
- no free parameters (ICs known from CMB)

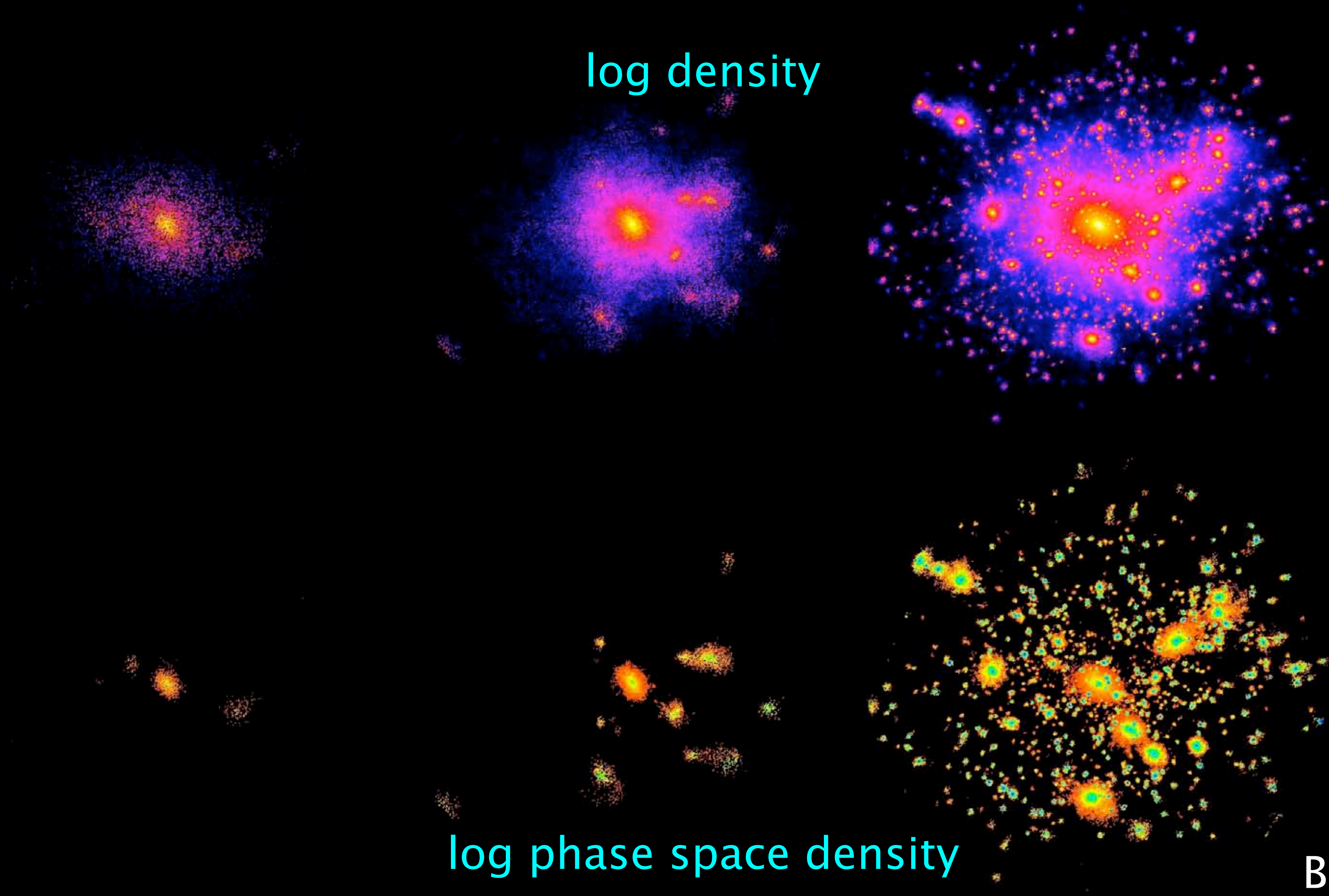
⇨ accurate solution to an idealized problem

hydrodynamical simulations

- computationally expensive, relatively low resolution (use AMR)
- hydro is complicated (SPH and grid codes often disagrees, see e.g. Agertz et al. 2006)
- important physical processes typically act on scales far below resolution (SF, SNe, etc) and are implemented through uncertain functions and free parameters

⇨ approximate solution to a more realistic problem

A brief history of Nbody simulations of CDM halos



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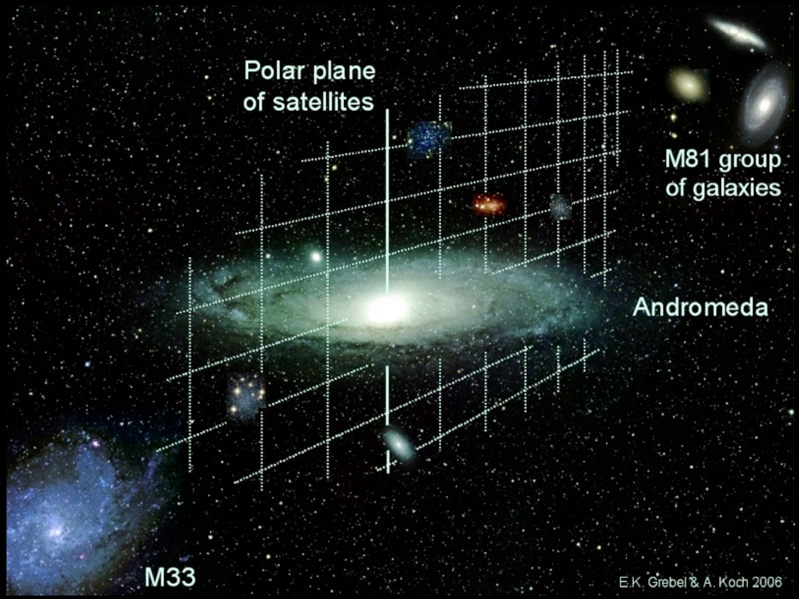
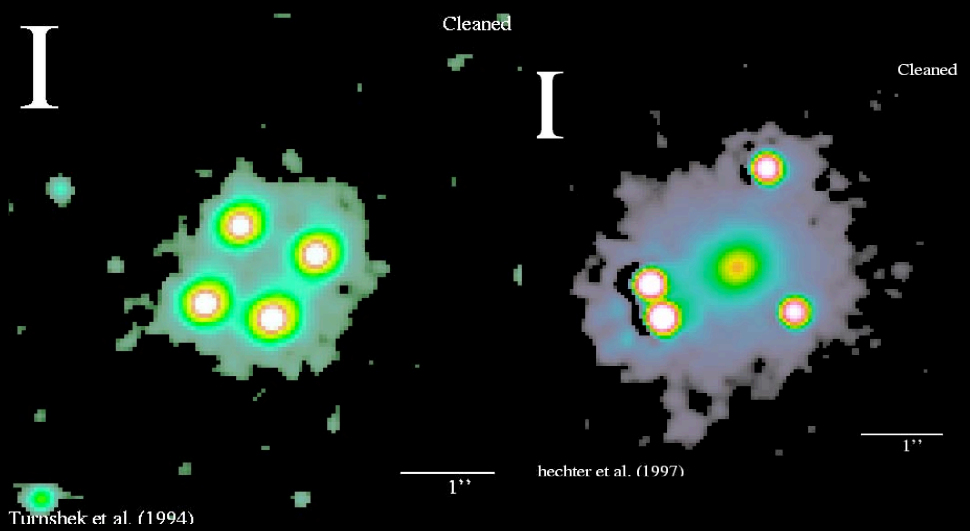
ability of subhalos to survive as substructure within the host is particularly sensitive to resolution issues

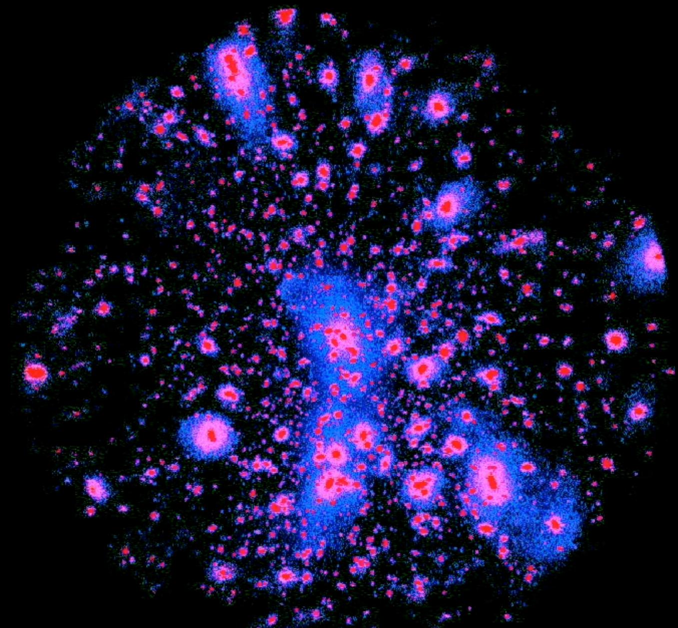
Observational probes of substructure

1. Satellite Galaxies of MW: the most massive DM subhalos are predicted to be associated with luminous dSph satellites. The amount and spatial distribution of satellites around the MW provide then unique information and clues on the galaxy assembly process. N.B. Most dark matter subhalos appear to have no optically luminous counterparts in the Local Group ("missing satellite problem" Moore +99; Klypin+99).



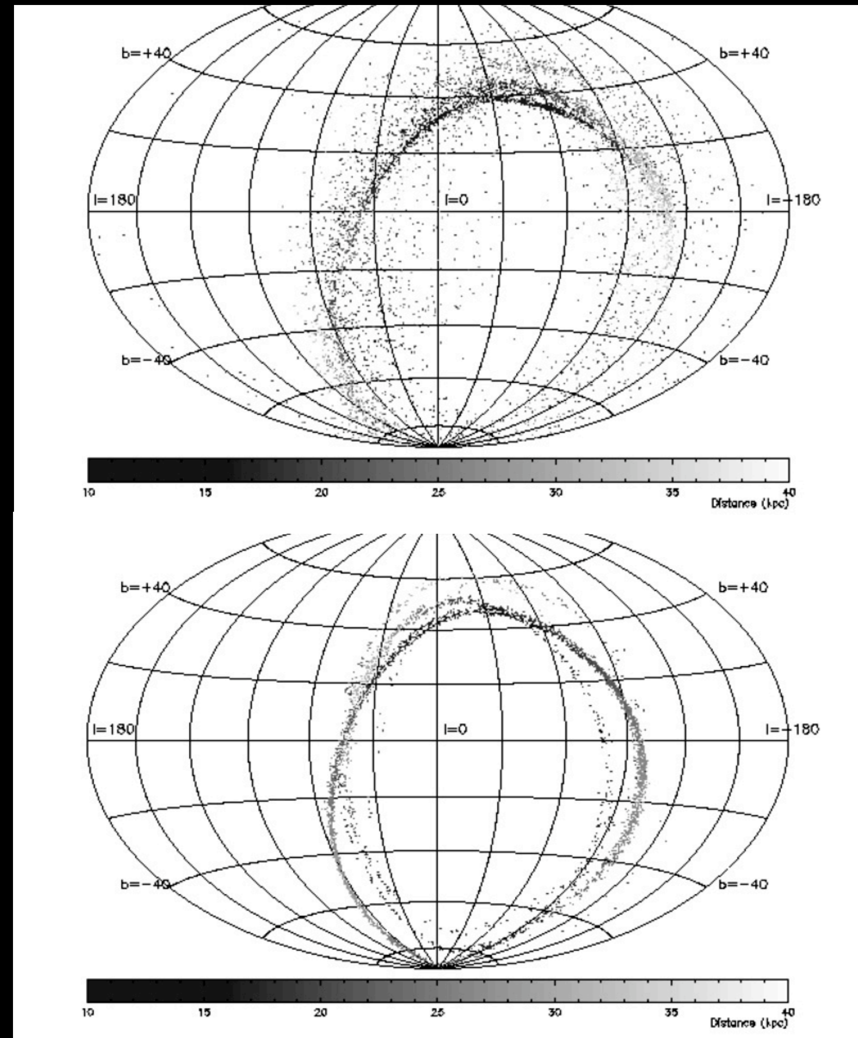
2. Gravitational Lensing: galaxy substructure may explain the flux ratio anomalies observed in multiply-imaged lensed QSOs (Metcalf & PM 01; Chiba 02; Dalal & Kochanek 02). Effect is sensitive to subhalo surface mass density in the inner 5-10 kpc.





phase-space density ρ/σ^3 z=0 cluster

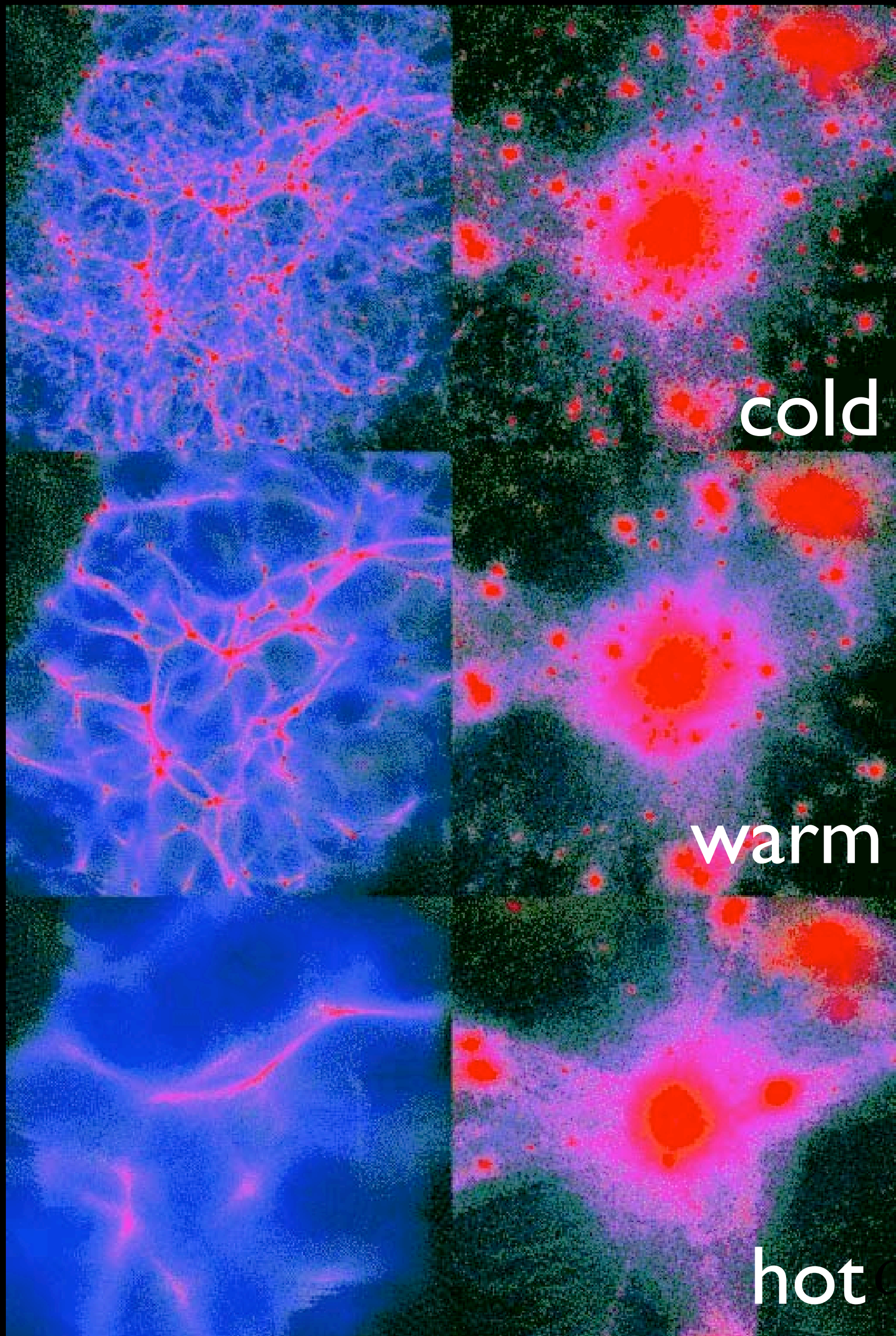
3. Dark Matter Annihilation: because of their high phase-space densities, subhalos may be detectable via γ-rays from DM particle annihilation in their cores (Bergstrom et al. 1999; Calcaneo-Roldan & Moore 2000; Stoehr et al. 2003; Colafrancesco, Profumo, & Ullio 2005; Diemand, Kuhlen, & Madau 2006): γ-ray luminosity $\propto \int \rho^2 dV$. (GLAST, VERITAS).

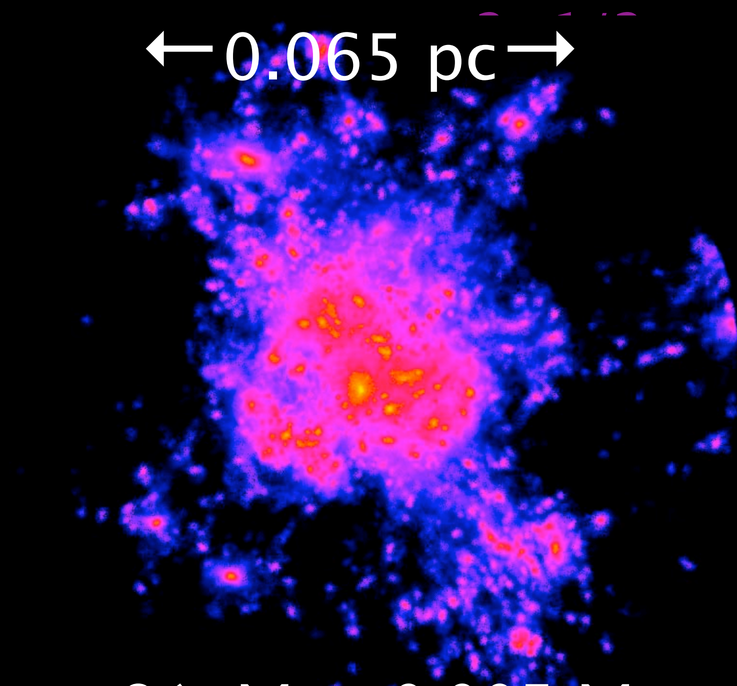


4. Tidal streams: presence of a population of CDM clumps alters the phase-space structure of a globular cluster tidal stream (Ibata+ 02). If the global Galactic potential is nearly spherical, this corresponds to a broadening of the stream from a thin great-circle stream into a wide band on the sky. (GC streams detectable by GAIA)

a galaxy cluster

Most like it cold

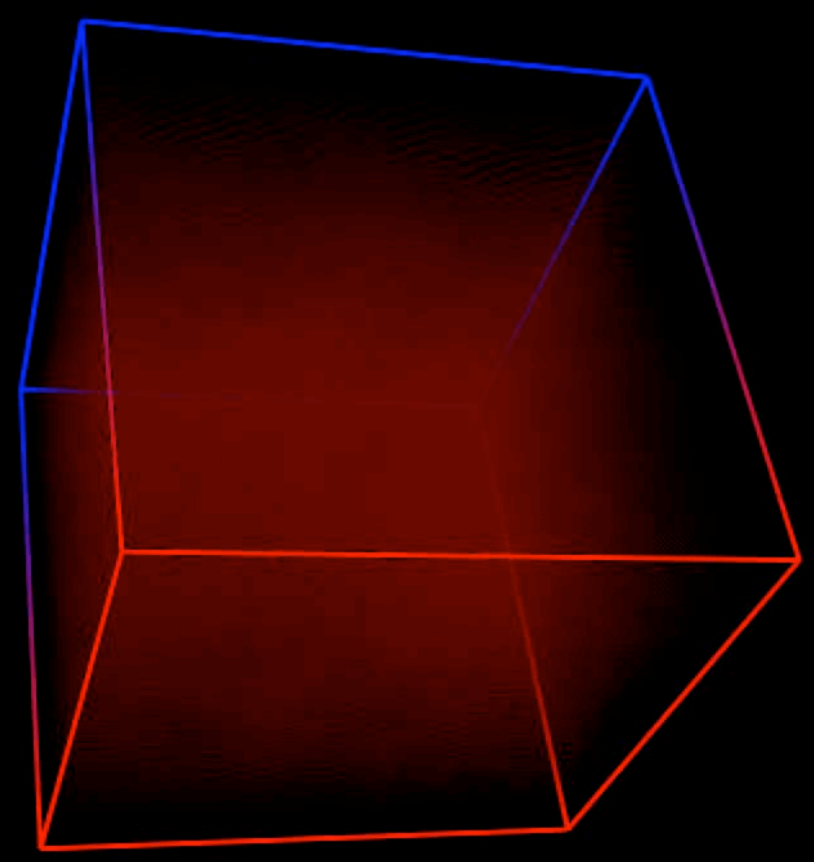


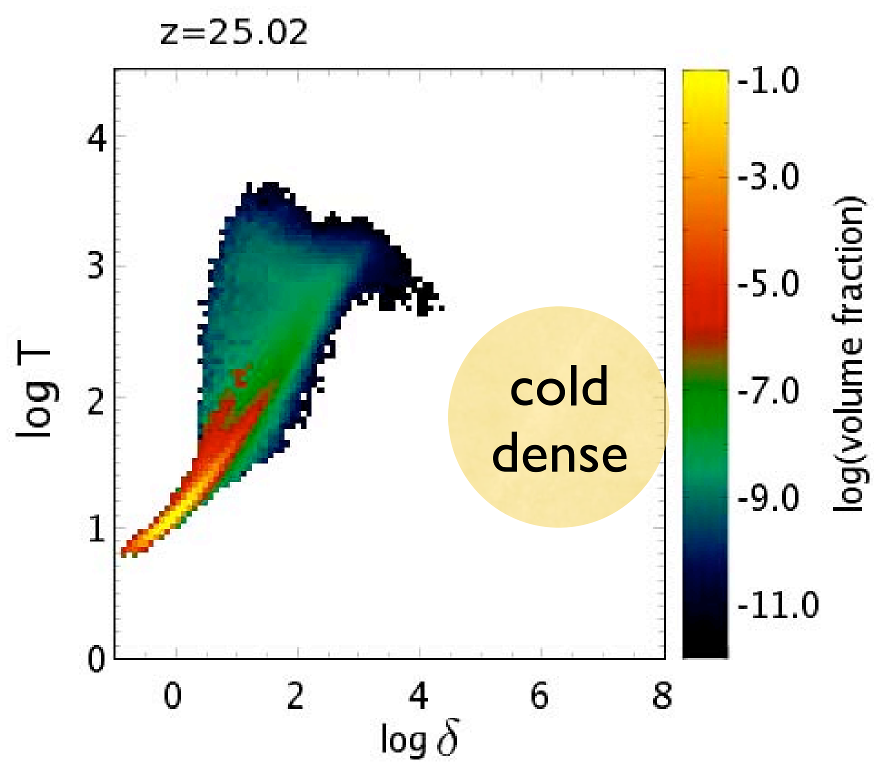


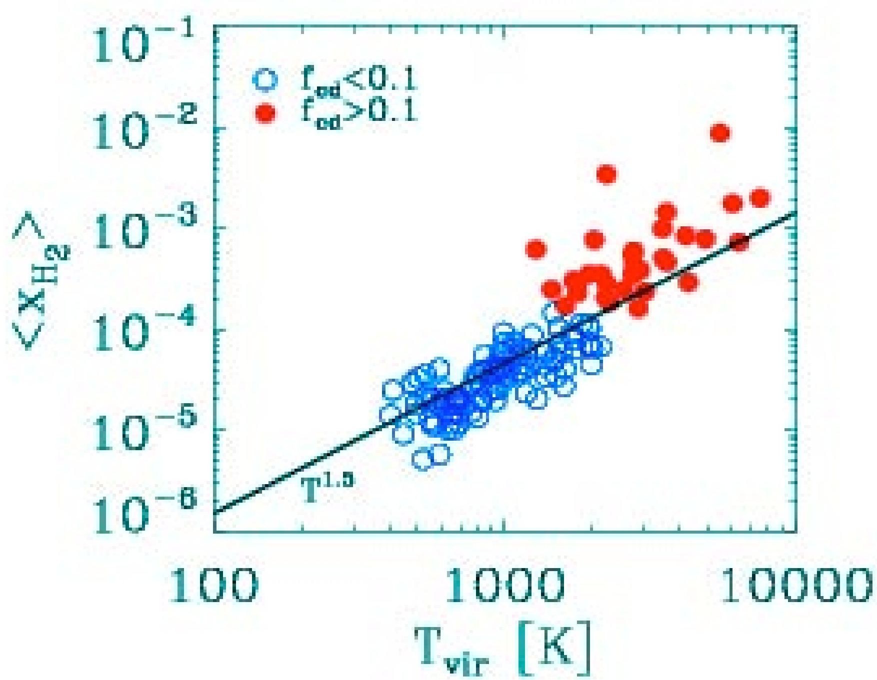
z=86 M_{vir}=0.005 $M_\odot$

minimum scale for the gravitational aggregation of collisionless CDM~ $M_\oplus$

From dark halos to first galaxies

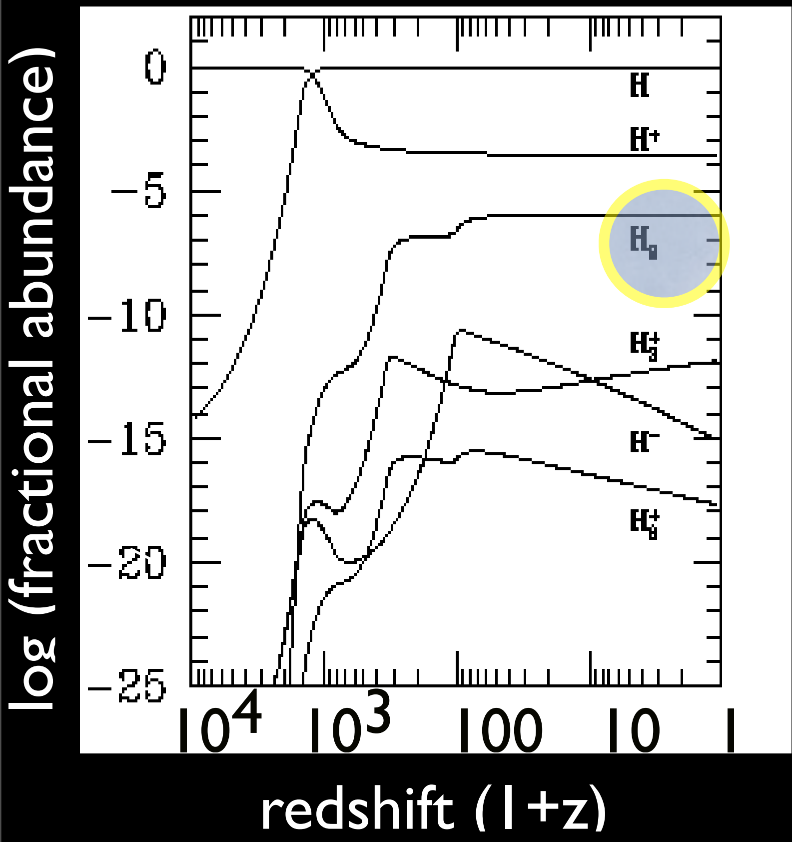






Kuhlen & PM 05

H_2 cooling and reionization



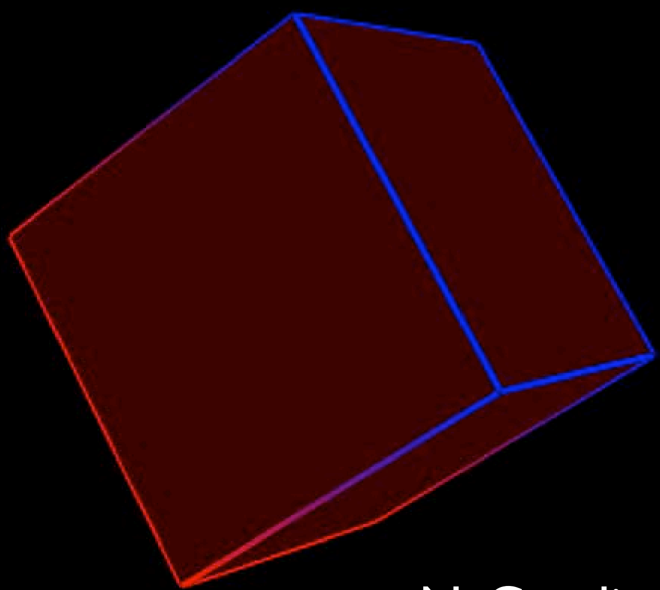
free electrons serve as catalysts for the formation of H_2 through the negative ion H^-

$$H + e^- \leftrightarrow H^- + \gamma.$$

$$H^- + H \leftrightarrow H_2 + e^-$$

H_2 is the main source of cooling in the first generation of gravitationally bound gas clouds

$x_{H2}(IGM) \sim 10^{-6} \Rightarrow t_{cool} >> H^{-1}$



N. Gnedin

Where are the hosts of the first stars today?

"VIA LACTEA": the highest-resolution DM simulation of a Milky Way-sized halo

Largest DM simulation to date at these scales. 320,000 cpu hours (36.5 cpu yrs) 213,217,920 high res particles embedded in a periodic 90 Mpc box sampled at lower resolution to account for tidal field.

M_{halo}=1.8e12 $M_\odot$
r_{200}=390 kpc
softening=90 pc
m_p=2e4 $M_\odot$

time resolution: adaptive timesteps as short as 68,500yr=Hubble time/200,000

WMAP 3-year cosmology:

Ω_M=0.238, Ω_Λ=0.762, h=0.73, n=0.951, σ_8=0.74

First simulation to resolve building blocks of galaxy formation down to the present epoch

by Juerg Diemand, Michael Kuhlen, and PM

via lactea 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

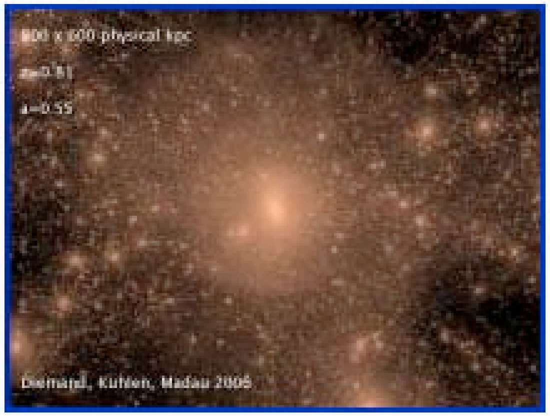
publications

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

movies

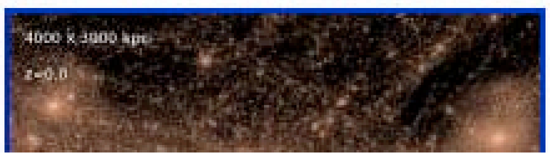
These animations show the projected dark matter density-square maps of the simulated Milky Way-size halo Via Lactea. The logarithmic color scale covers the same 20 decades in projected density-square in physical units in each frame. All movies are encoded in MPEG format and some are available in different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

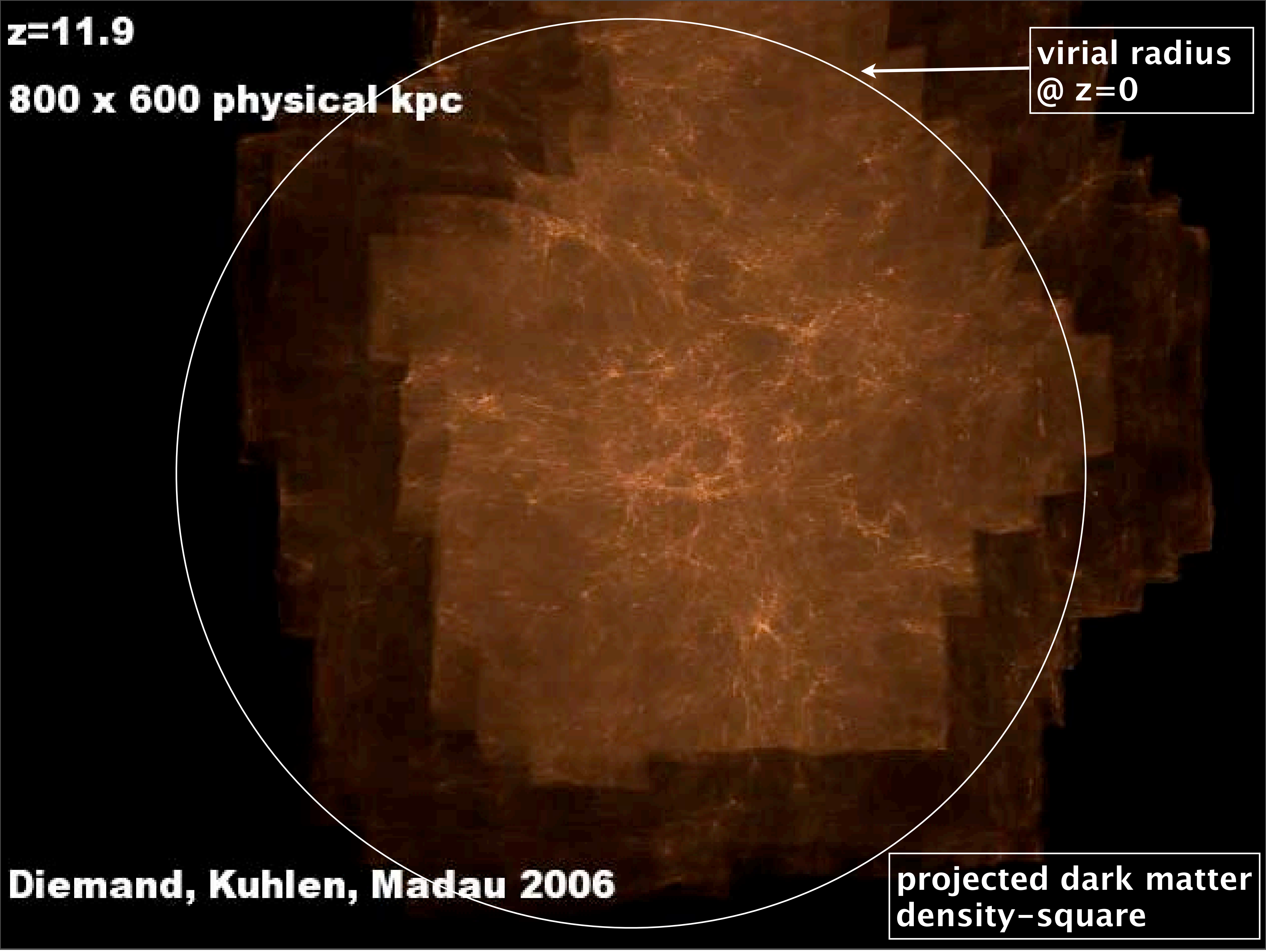
the formation of the Via Lactea halo



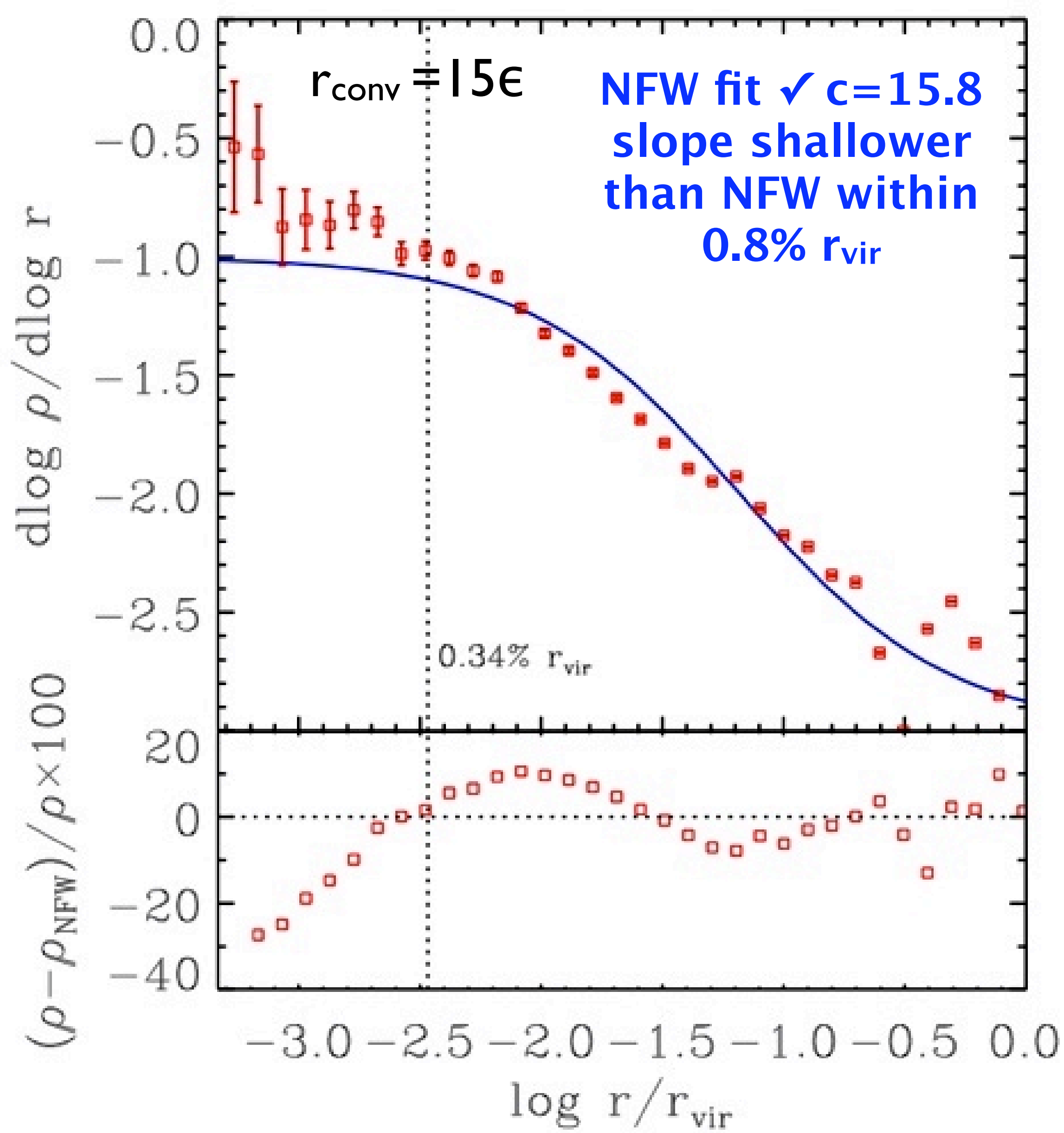
- entire formation history (z=12 to 0): high quality (218MB)
  smaller frames, quality: high(55MB) medium(11MB) low(4.7MB)
- entire formation history, plus rotation and zoom at z=0:
  quality: high(433MB) medium(72MB)
- early, active phase of merging and mass assembly (z=12 to 1.3): (81MB)
- late, passive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

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




z=11.9
800 x 600 physical kpc
virial radius
@ z=0
Diemand, Kuhlen, Madau 2006
projected dark matter
density-square

Logarithmic slope of density profile

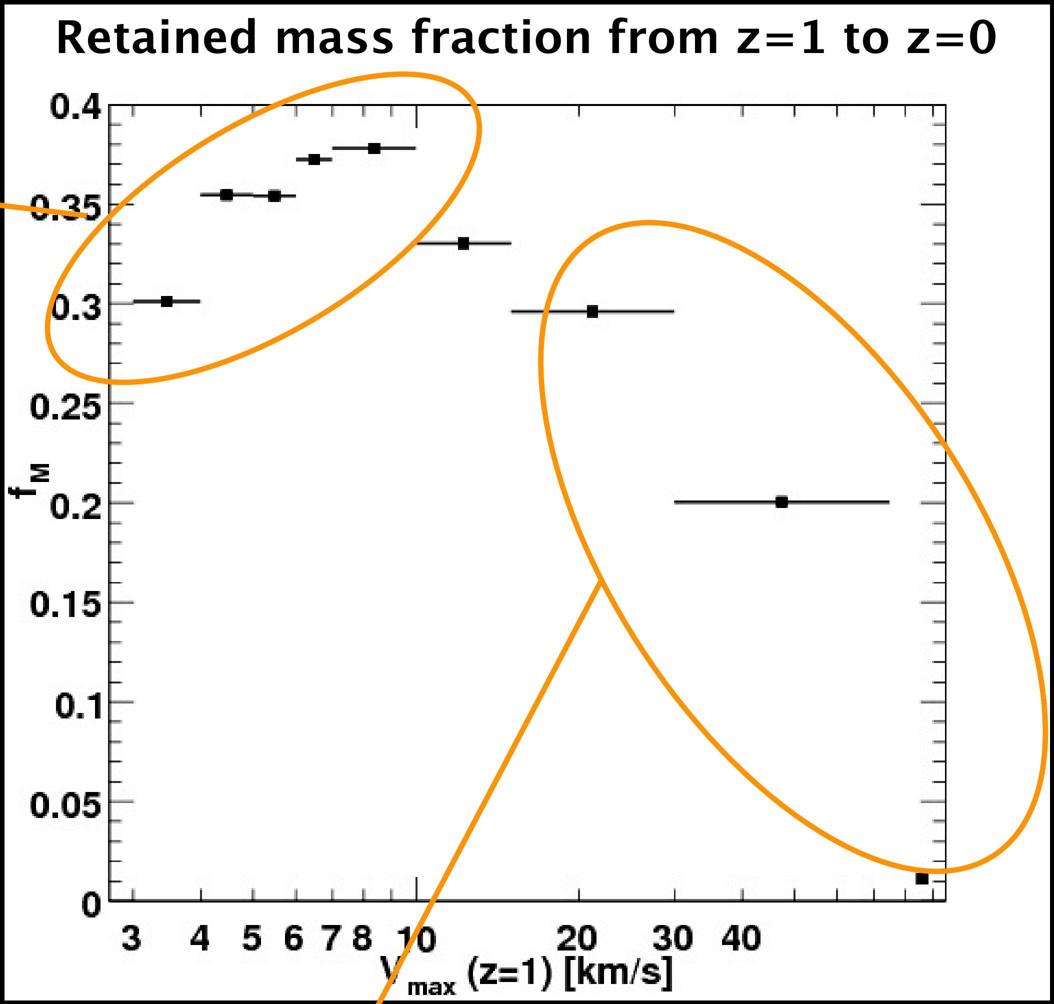



z=0.0 low resolution
3e6 vs 85e6 particles
80 kpc


z=0.0
3e6 vs 85e6 particles
80 kpc

Tidal mass losses

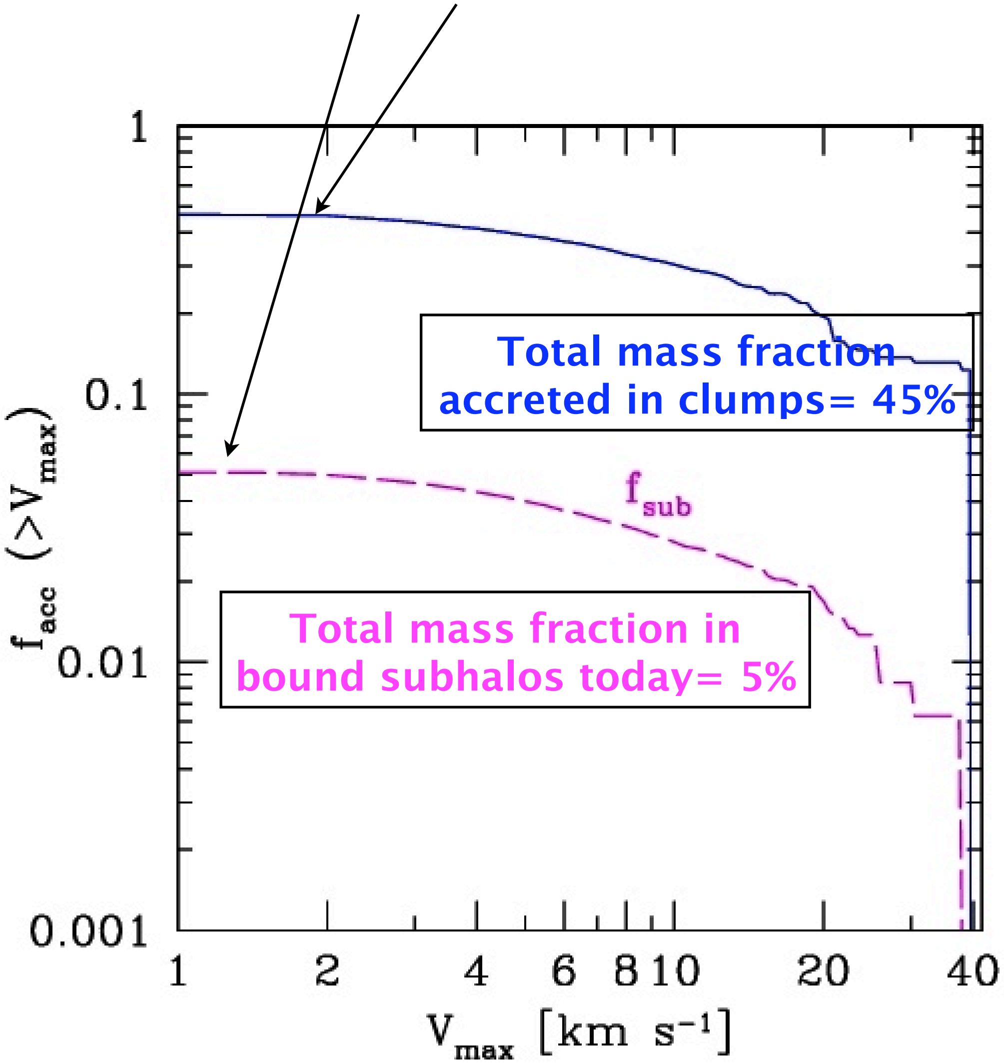
smallest systems suffer from artificially large mass loss due to finite numerical resolutions



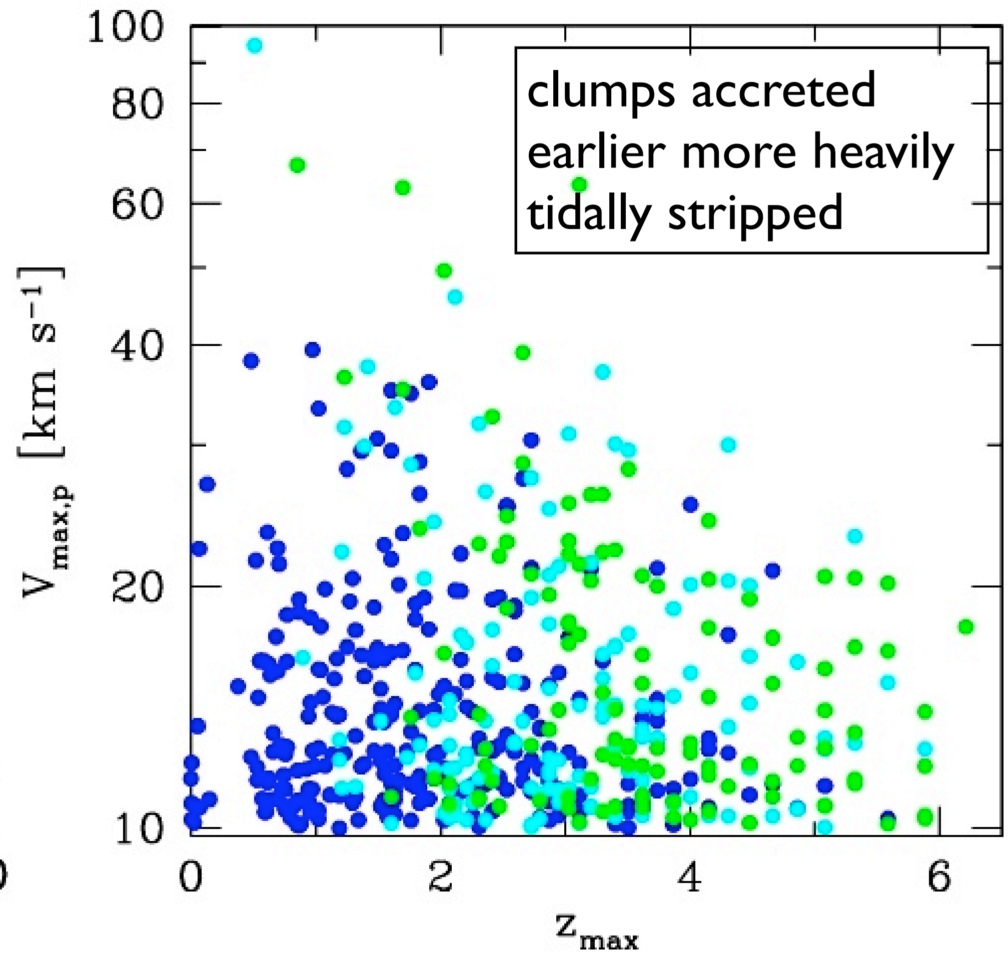
97% of the z=1 well resolved subhalos have a surviving bound remnant at z=0

the retained mass fraction is larger for initially lighter subhalos

largest subhalos sink towards the center due to dynamical friction and retain a small fraction of their initial mass numerical resolution



all 510 subhalos that reached $V_{max,p} > 10$ km/s at z_{max}



color coding: different ranges of V_{max} today

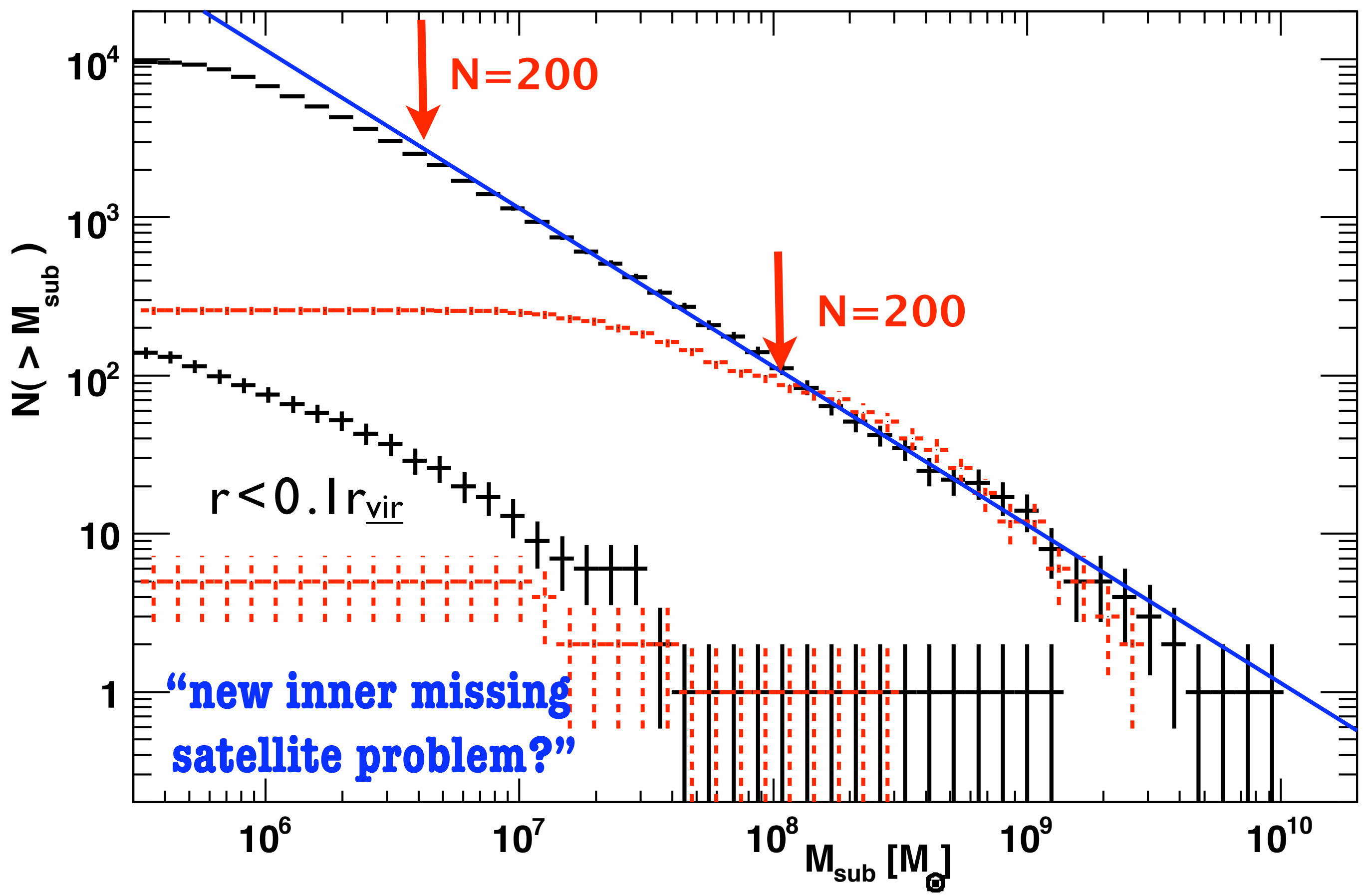
$V_{max} < V_{max,p}/2$

$V_{max,p}/3 < V_{max} < V_{max,p}/2$

$V_{max} < V_{max,p}/3$

Subhalo mass function

6100 subhalos within r_{200} above $10^6\,M_\odot$

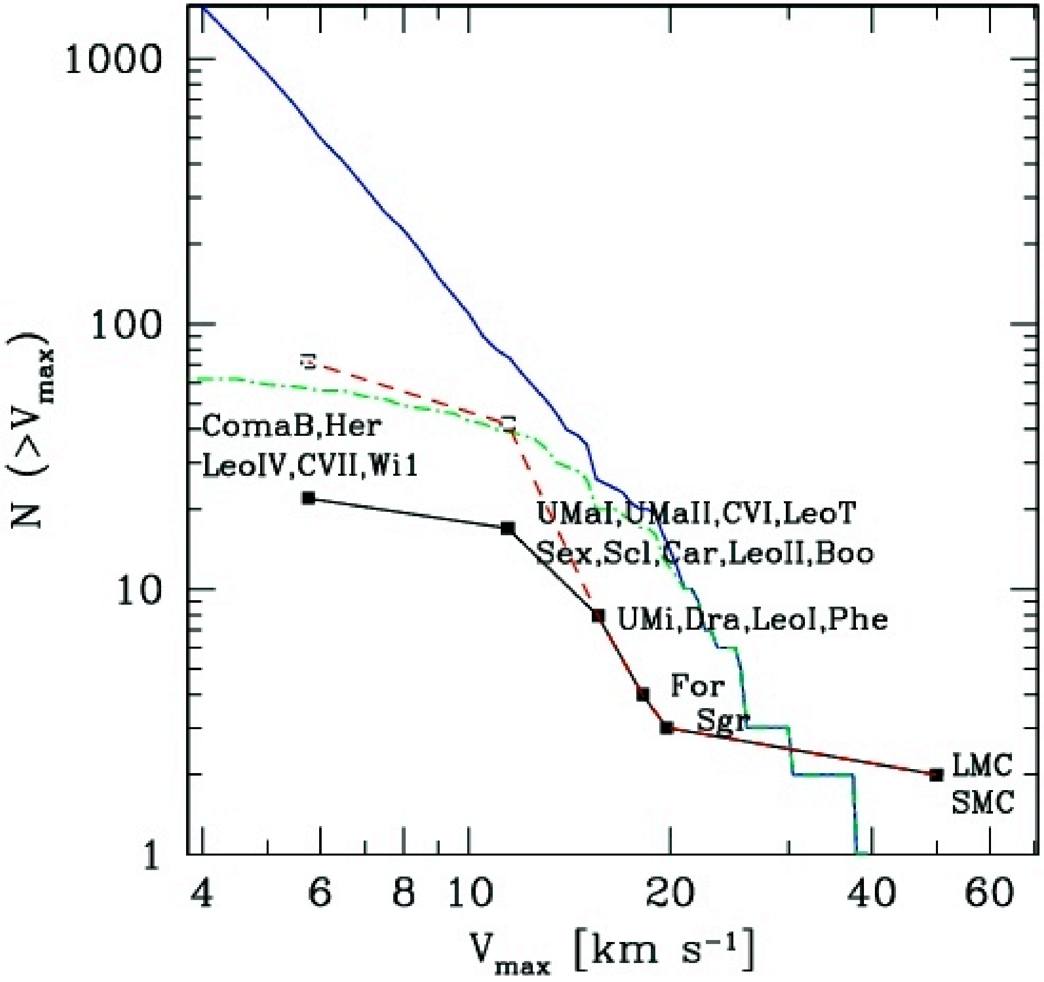


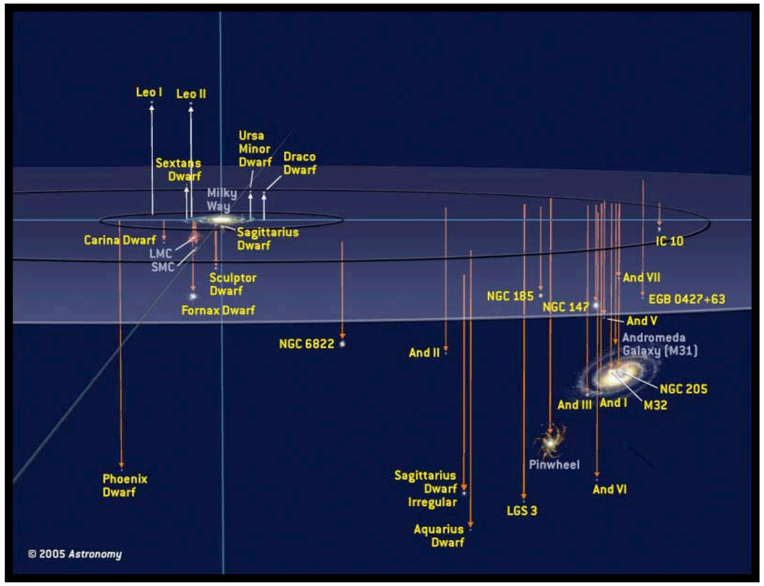
$N(>M_{sub}) \propto 1/M_{sub}$

mf steeper at high M due to dynamical friction/tidal mass losses

shallower at low M due to numerical limitations

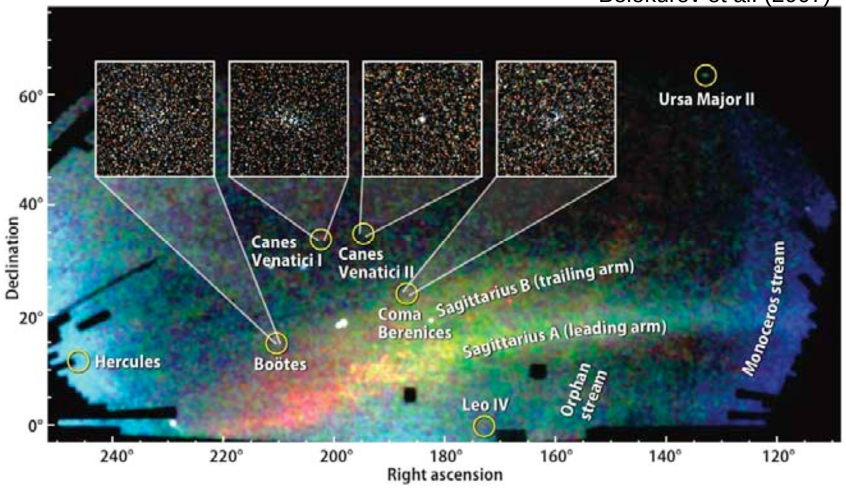
The substructure problem





SDSS is still discovering more dwarfs.

Belokurov et al. (2007)



NB comparsion traditionally assumes $\sqrt{3}\sigma_* = V_{max}$. Dark halos extend well beyond the stellar radius of a satellite ⇨ stellar kinematics alone provide only a lower limit on the halo V_{max} value.

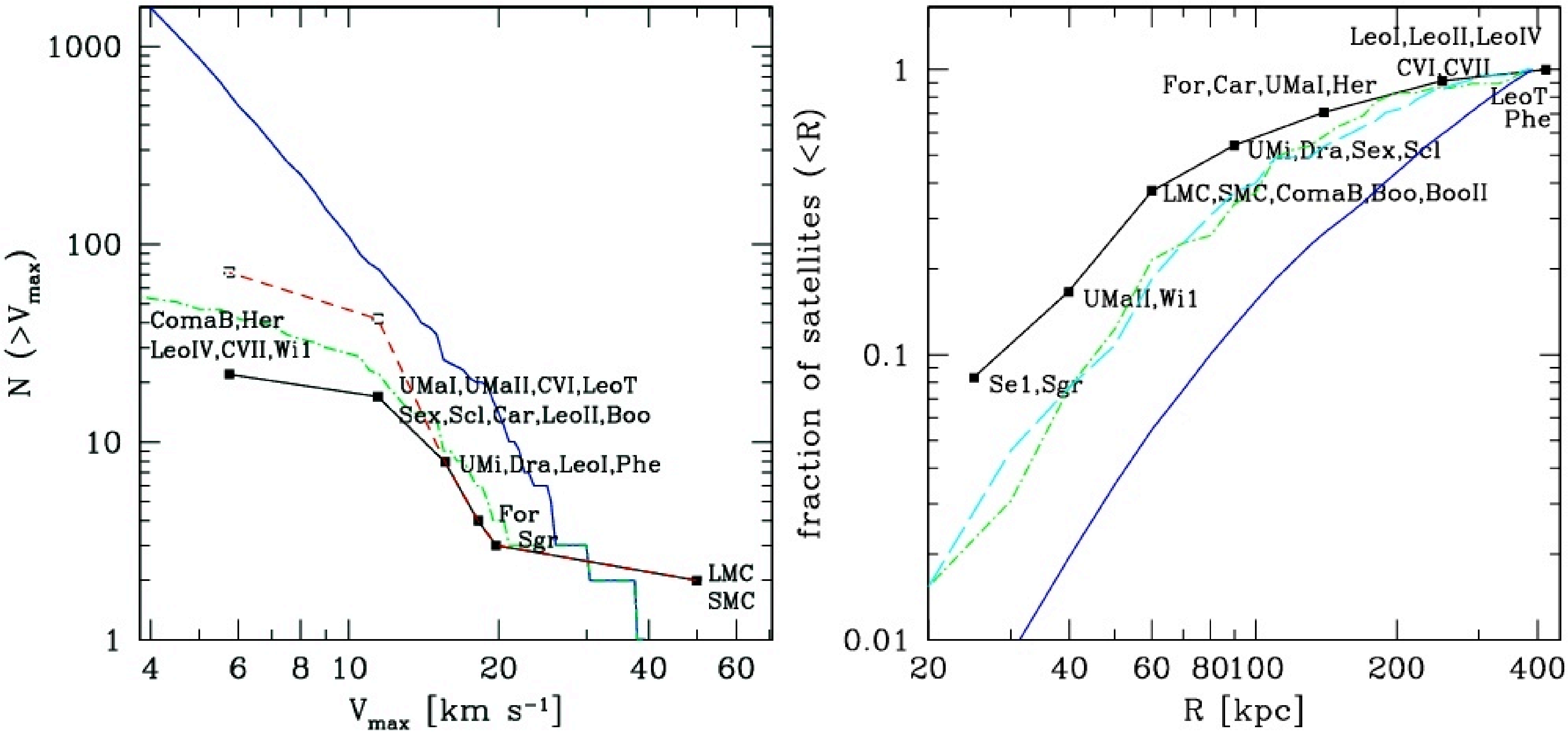
Are there many more ultra-faint Milky Way companions waiting to be discovered below μ_V=27-28 mag arcsec^{-2}?

Via Lactea predicts 1000 satellites with $M_{sub}>10^7\ M_\odot$ (> Leo T, Leo IV, Coma B, CVII)

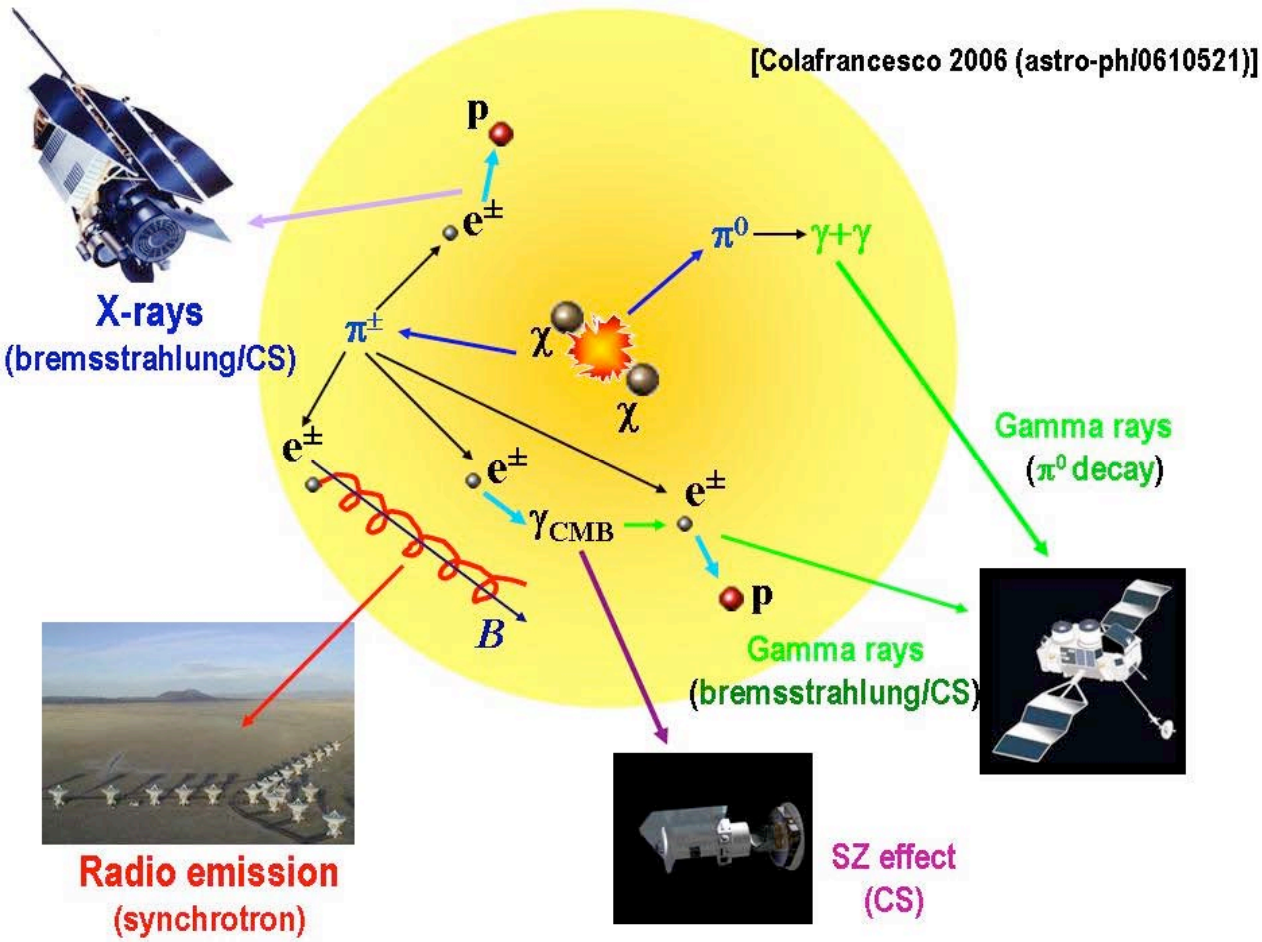
Leo T (Irwin et al. 2007)
M(H I)$>10^5\ M_\odot$ and $L>10^{3-4}\ L_\odot$

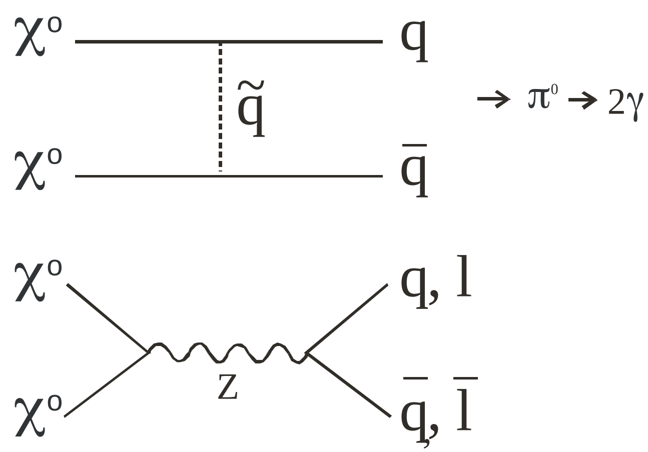
Need a very efficient feedback mechanism quenching SF for $V_{max}<20$ km/s (today)
$V_{max,p}<35$ km/s (past)

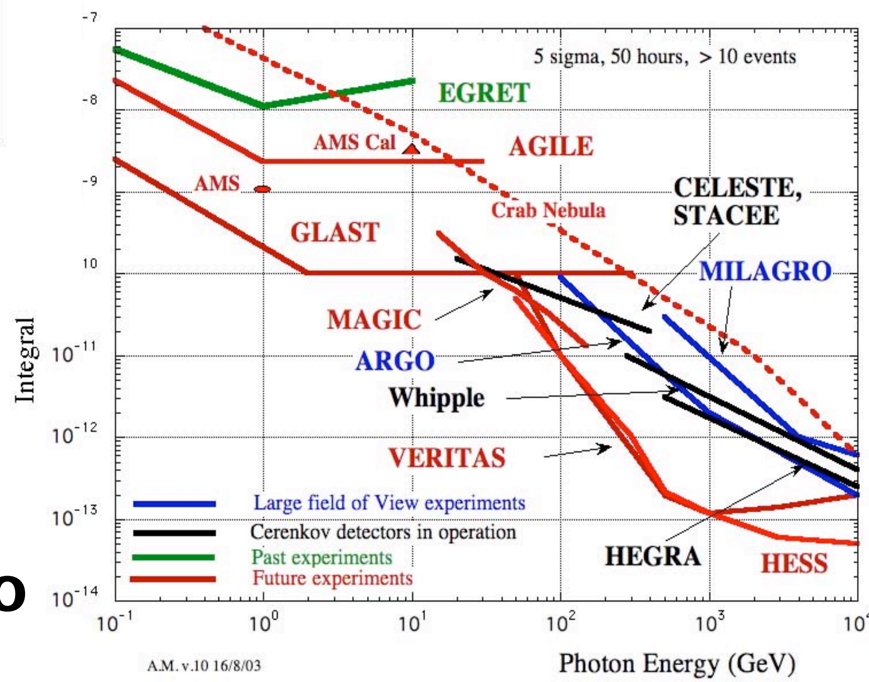
Radial distribution of subhalos



DM not so dark?







Minimal Supersymmetric Extension of Standard Model favors neutralino as main DM constituent

Annihilation flux for a distant spherically symmetric system of radius r_{vir}:

annihilation cross-section x thermal velocity

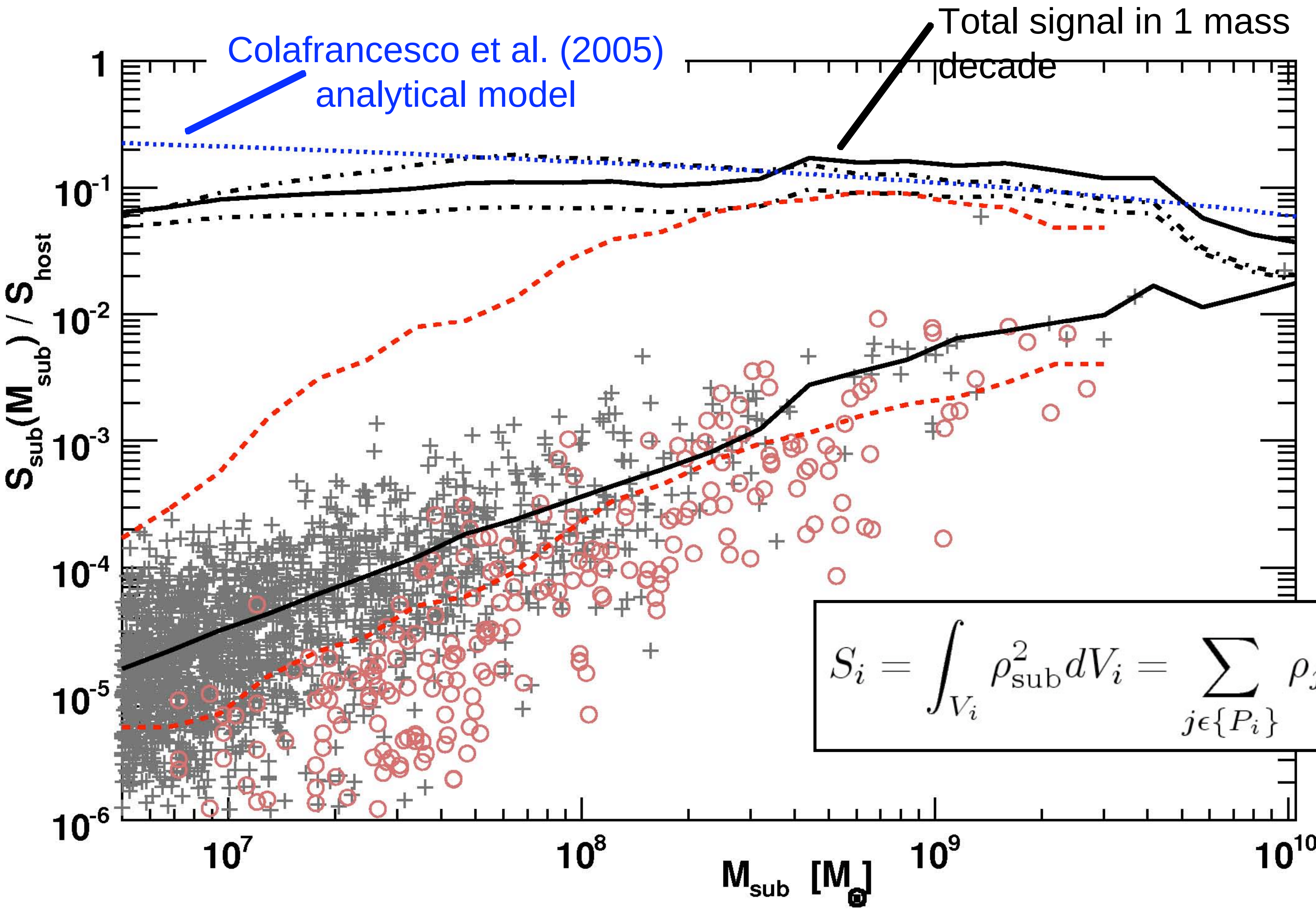
γ-photons produced per annihilation

$$F = \frac{N_\gamma \langle \sigma v \rangle}{2\, d^2 m_\chi^2} \int_0^{r_{\rm vir}} \rho_{DM}^2(r) r^2 dr$$

mass of DM particle

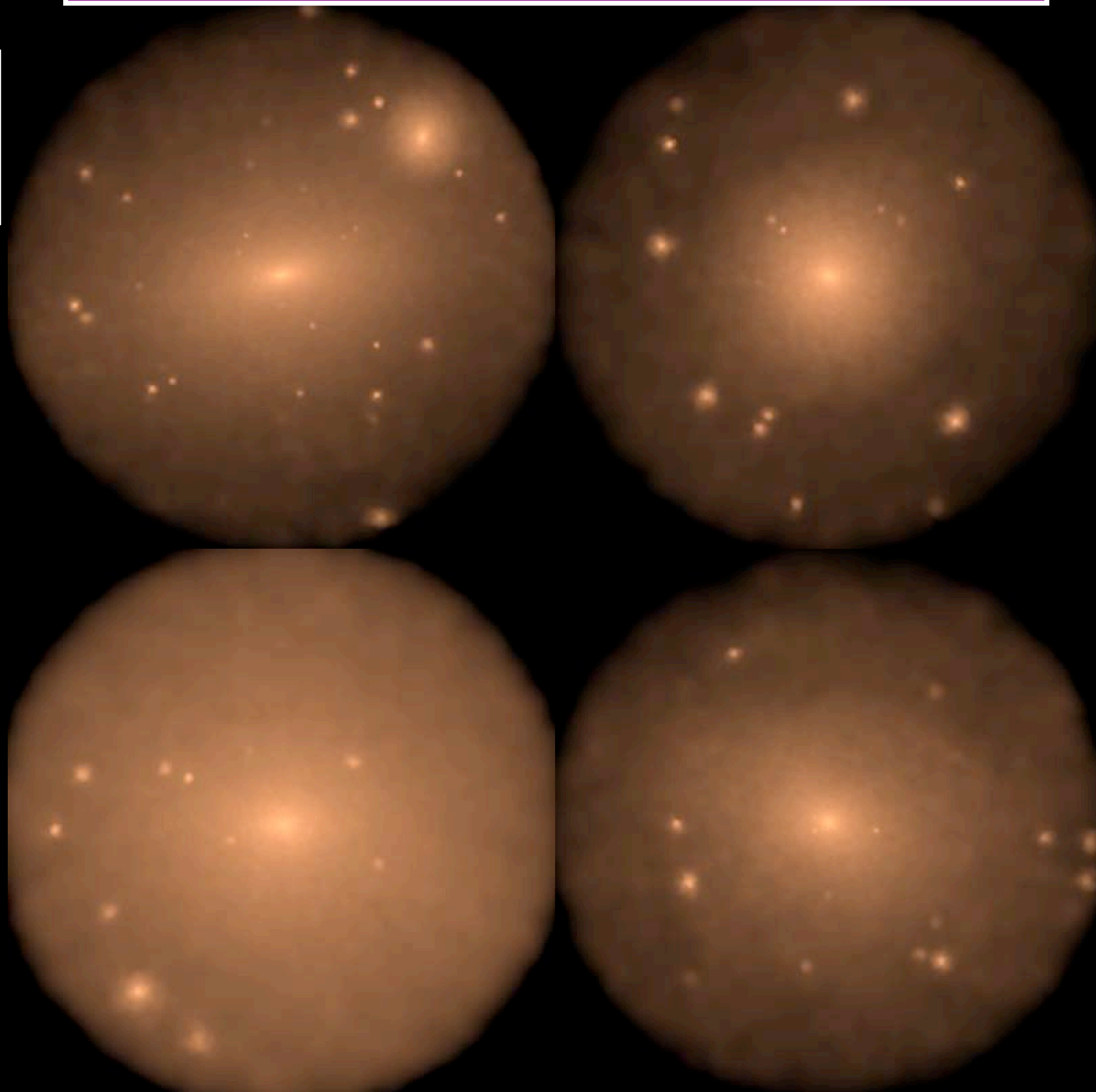
The density squared weighting of the integrand results in most of the flux in dark DM halos being produced by a small fraction of their mass in the densest regions: (1) galactic center and (2) halo substructure

subhalo annihilation luminosity vs. M_{sub}



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

Sub-subhalos resolved in most massive satellites!



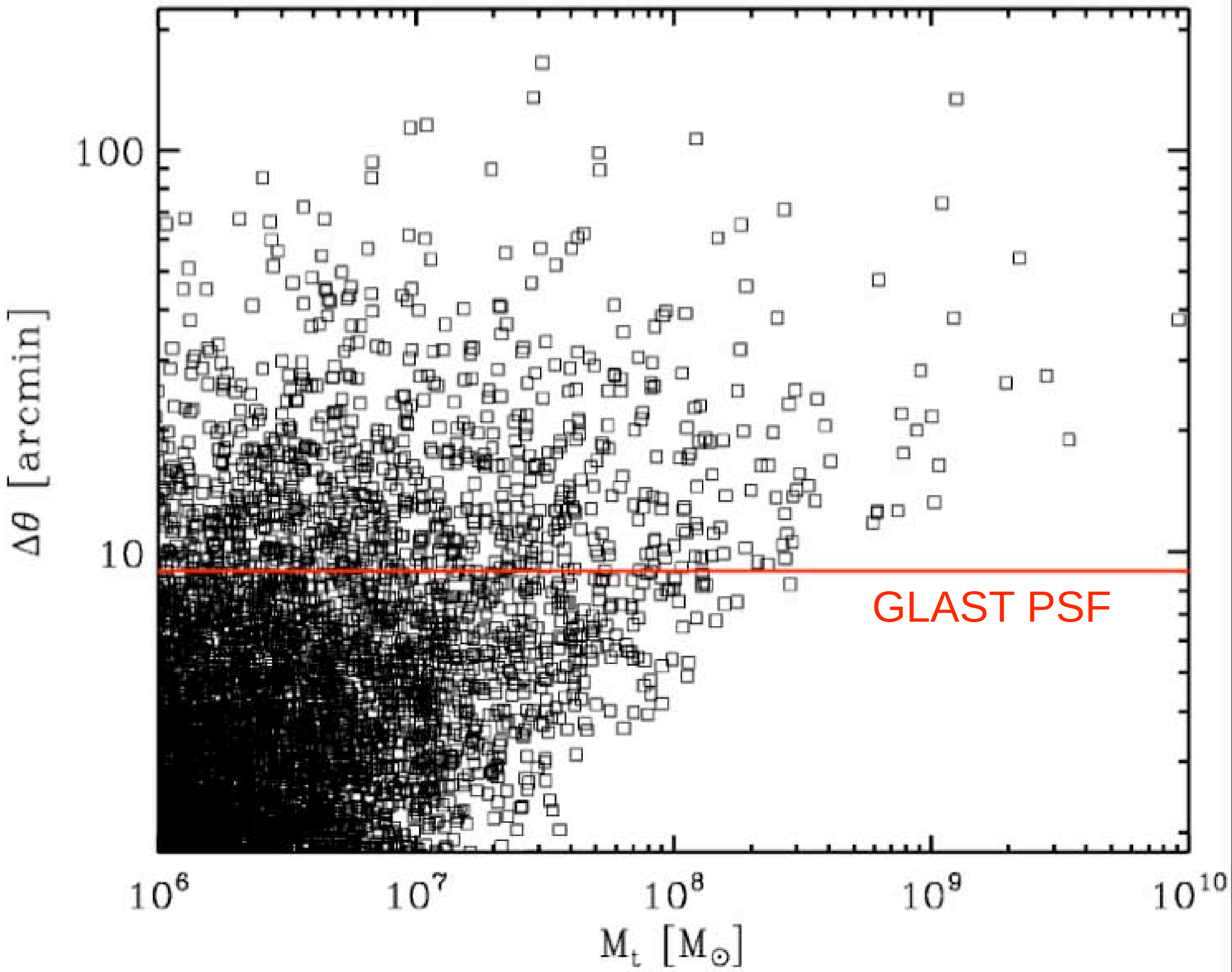
$M_{sub} = 9.8e9\ M_\odot$
r_t=40.1 kpc
D=345 kpc

$M_{sub} = 3.7e9\ M_\odot$
r_t=33.4 kpc
D=374 kpc

$M_{sub} = 3.0e9\ M_\odot$
r_t=28kpc
D=280 kpc

$M_{sub} = 2.4e9\ M_\odot$
r_t=14.7 kpc
D=185 kpc

subhalo density (tidal radius) = 2 background density
subhalo tidal mass = total mass (< tidal radius) ≤bound mass

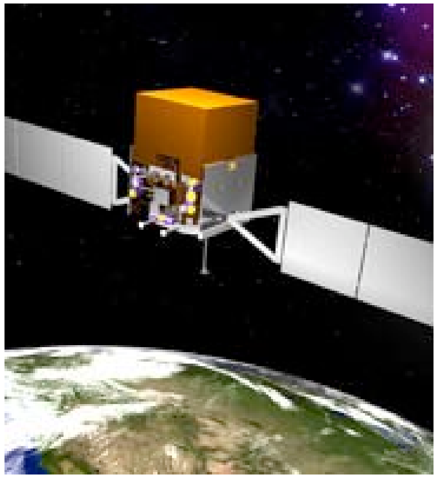


$\Delta\theta$ = angle subtended by twice the subhalo's scale radius r_s.

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

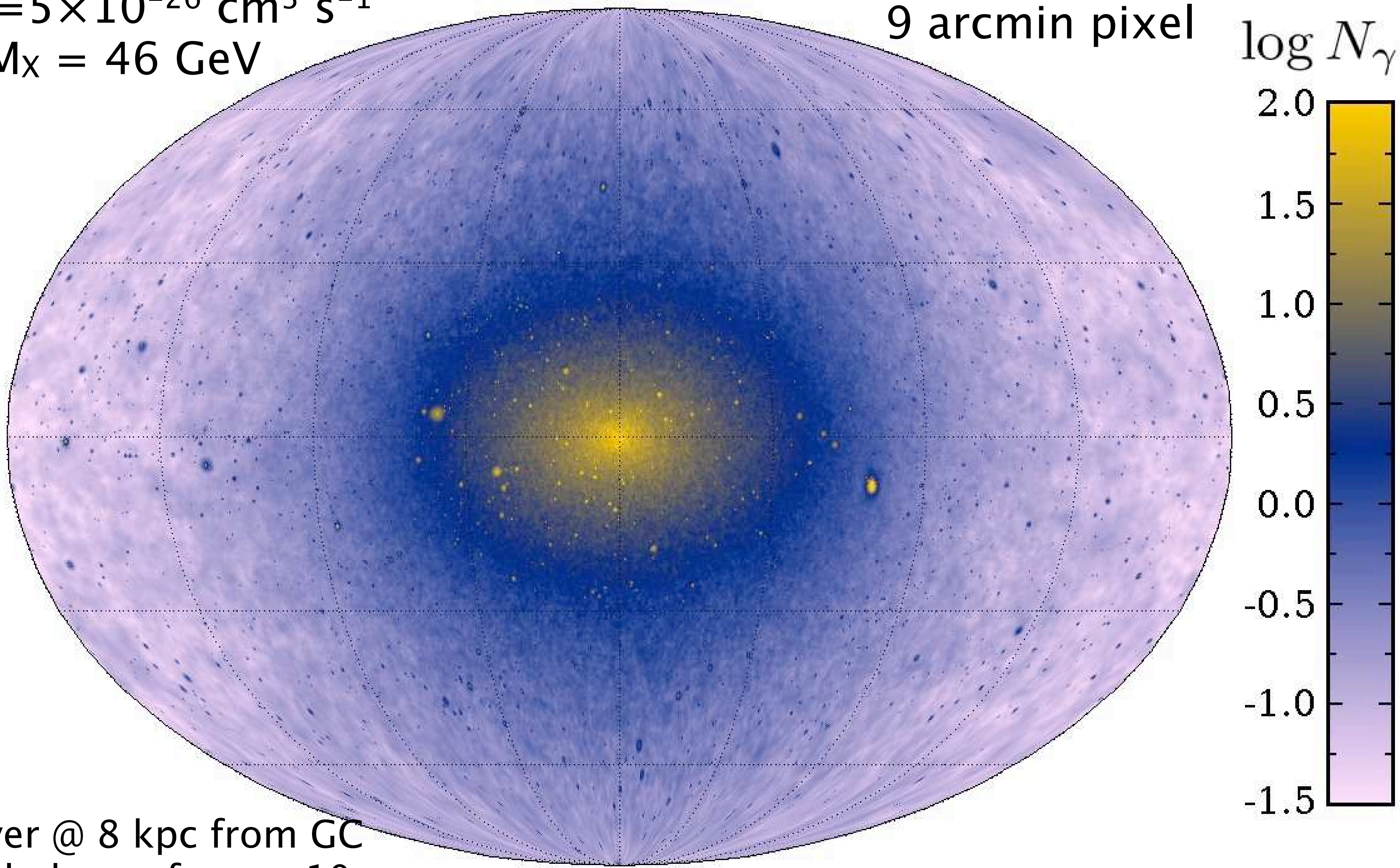
the brightest subhalos would be extended sources for **GLAST** (PSF 9 arcmin at 10 GeV)

GLAST allsky map of neutralino DM annihilation



$<\sigma v> = 5\times10^{-26}$ cm^3 s^{-1}
M_X = 46 GeV

2-year exposure
9 arcmin pixel



observer @ 8 kpc from GC
subhalo boost factor=10

Conclusions

- The highest-resolution simulation to date of the CDM halo of the Milky Way predicts the existence of more than 2,000 bound subhalos with $M_{sub} > 4 \times 10^6 M_\odot$, distributed approximately with equal mass per decade of mass (a similar steeply rising subhalo mass function is also present at redshift z=0.5 in an elliptical-sized halo simulated with comparable resolution).

- the fraction of Via Lactea mass brought in by subhalos that have a surviving bound remnant today within r_{200} is 45%. About 10% of the material they brought in remains in self-bound identifiable substructure at the present-epoch.

- because of tidal mass loss, the number of massive Galactic subhalos that reached a peak circular velocity of $V_{max} > 10$ km/s throughout their lifetime exceeds 500, 5 times larger than their present-day abundance and more than twenty times larger than the current (incomplete) tally of observed dwarf satellites of the Milky. Any mechanism that suppresses star formation in small halos must start acting early, at redshift z>3.

• unless the circular velocity profiles of Galactic satellites peak at values significantly higher that expected from the stellar line-of-sight velocity dispersion, only 1 out of 5 subhalos with V_{max}>20 km/s today must be housing a luminous Milky Way dwarf.

• nearly 600 halos with masses greater than $10^7\ M_\odot$ are found today in the "field" between 400 and 600 kpc i.e. small dark matter clumps appear to be relatively inefficient at forming stars even well beyond the virial radius.

Coming next: "Super Via Lactea", a 10^9 DM particle simulation (DOE INCITE, 1.5 M cpu h)


THE END