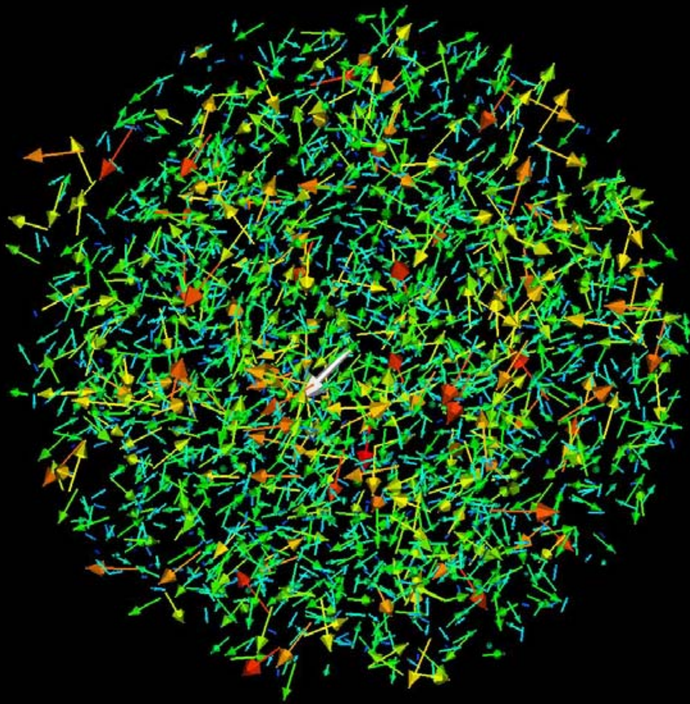
The Structure of Cold Dark Matter Haloes

Recent Insights from High Resolution Simulations



Marcel Zemp (UM)

with Jürg Diemand (UZH), Mike Kuhlen (UCB), Piero Madau (UCSC), Ben Moore (UZH), Doug Potter (UZH), Joachim Stadel (UZH) & Larry Widrow (QU)

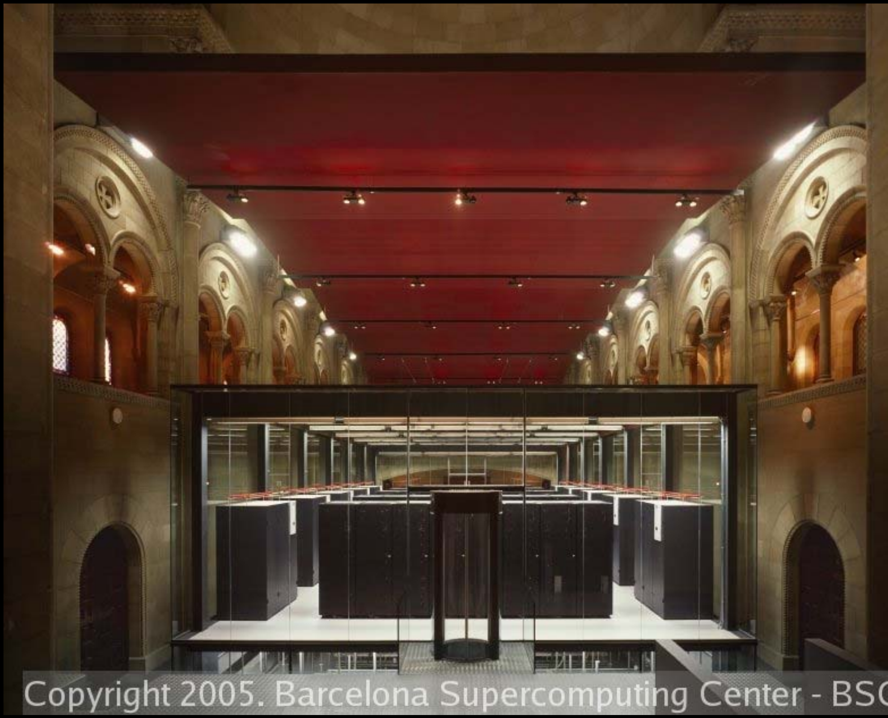
Dark Stars Workshop
Ann Arbor, 10. November 2009

Via Lactea II & GHALO

- Formation of Milky Way size cold dark matter structure in a cosmological framework $\Rightarrow$ no baryons
- WMAP 3-year cosmology
- Via Lactea II was running under INCITE program of DOE
- Via Lactea II one of 10 breakthroughs of 2008 in scientific computing selected by DOE

Supercomputers

Via Lactea II on
Jaguar at ORNL
1×10^6 CPUh



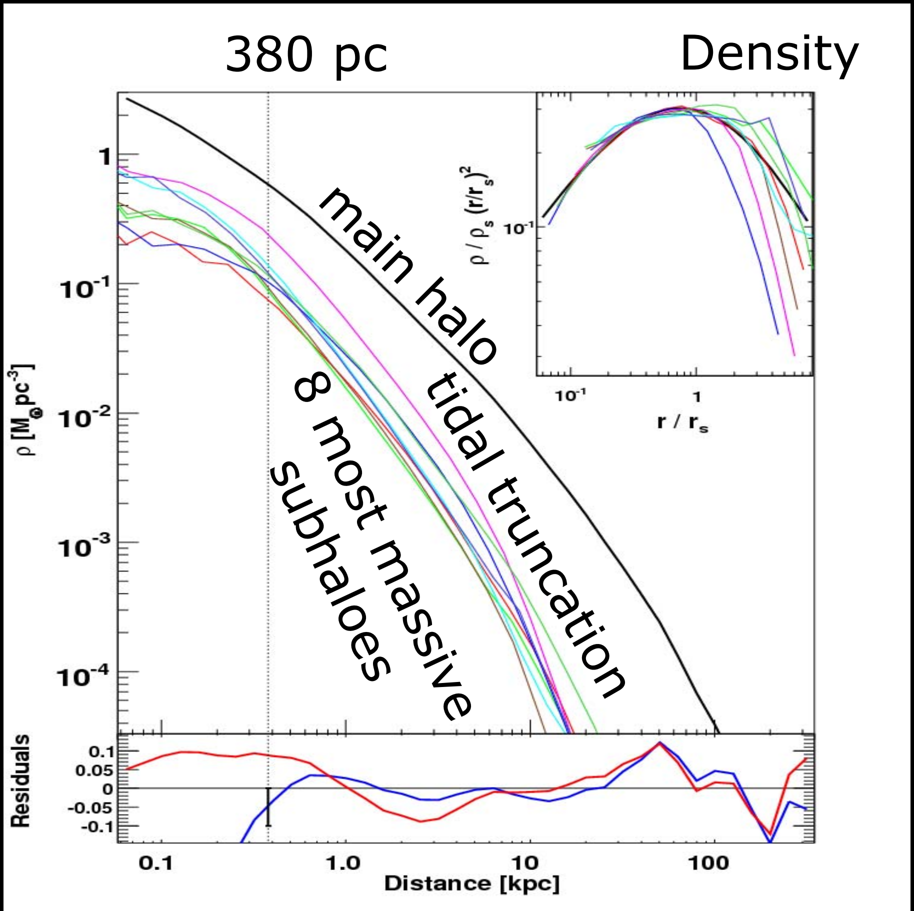
GHALO on
MareNostrum at BSC
2×10^6 CPUh

Basic Properties

	Via Lactea II	GHALO
M_{200b} [Mo]	1.92×10^{12}	1.27×10^{12}
r_{200b} [kpc]	402	349
$v_{circ,max}$ [km s^{-1}]	201	153
M_p [Mo]	4100	994
N_{200b}	4.68×10^{8}	1.27×10^{9}
$N_{tot,hr}$	1.1×10^{9}	2.1×10^{9}

Density Profile I

Nature, 2008, 454, 735

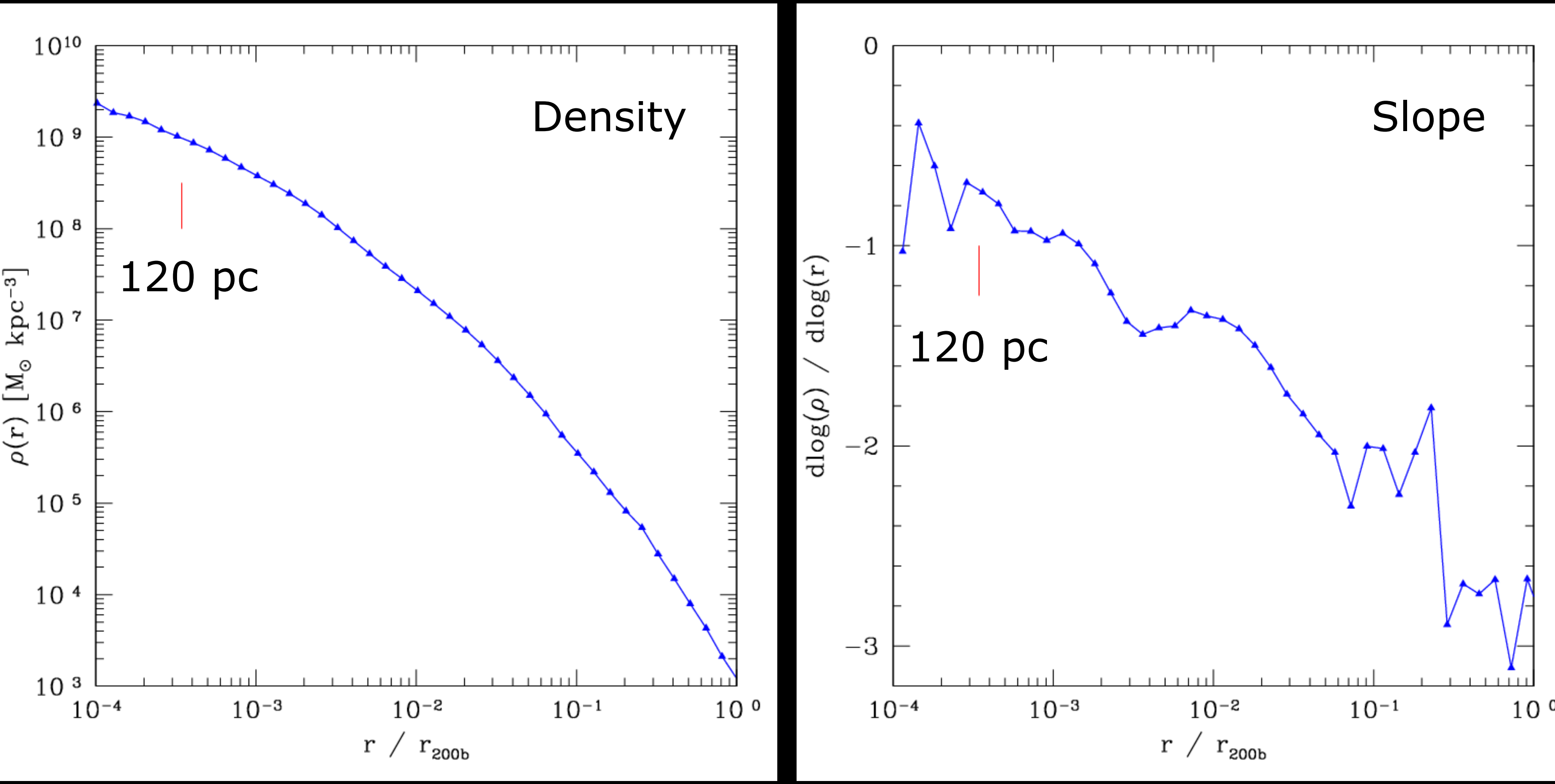


Best fit:
γ = 1.24

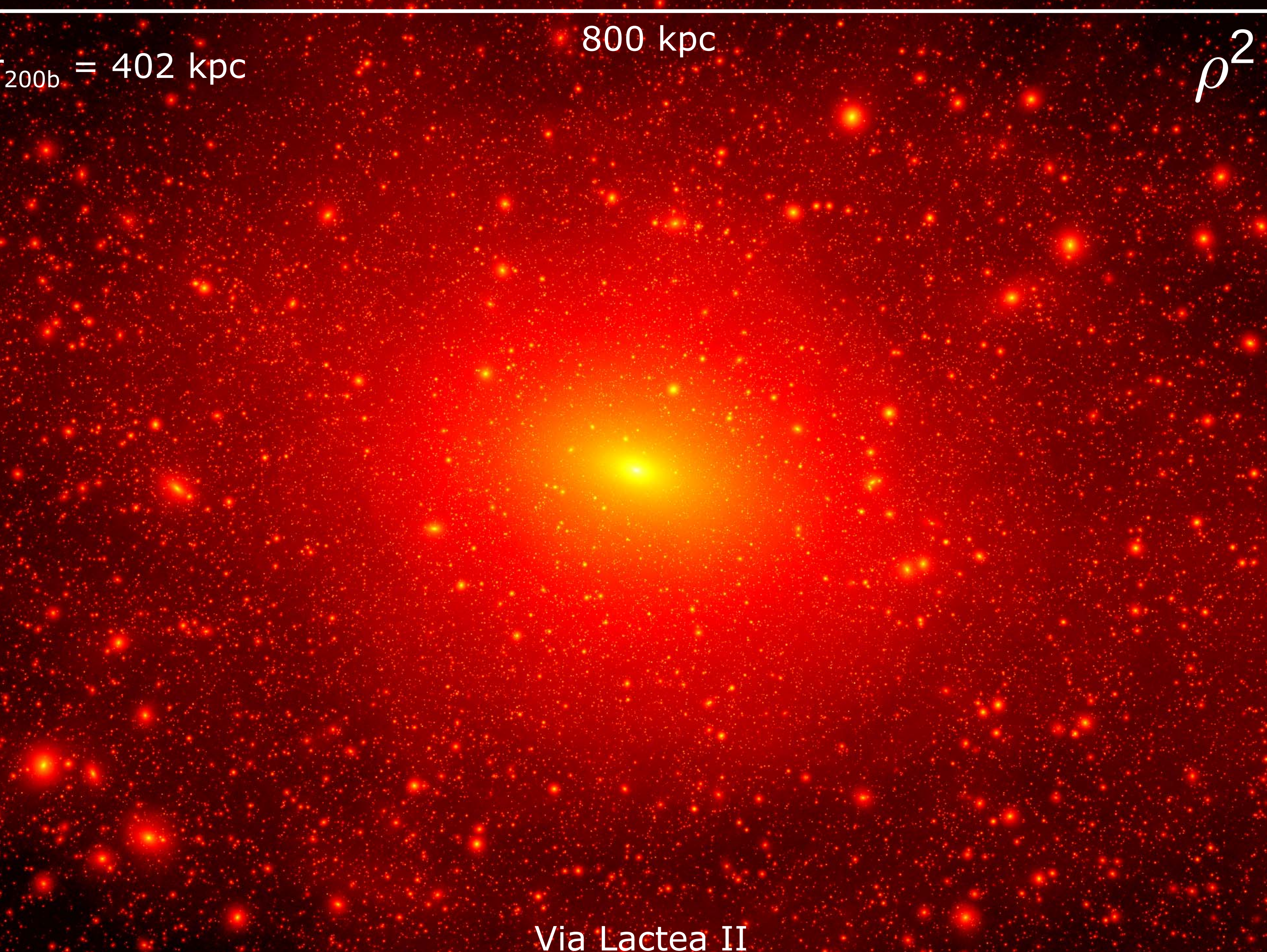
Via Lactea II: $\rho_{\mathrm{GNFW}}(r) = \rho_s (r/r_s)^{-\gamma} (1 + r/r_s)^{-3+\gamma}$

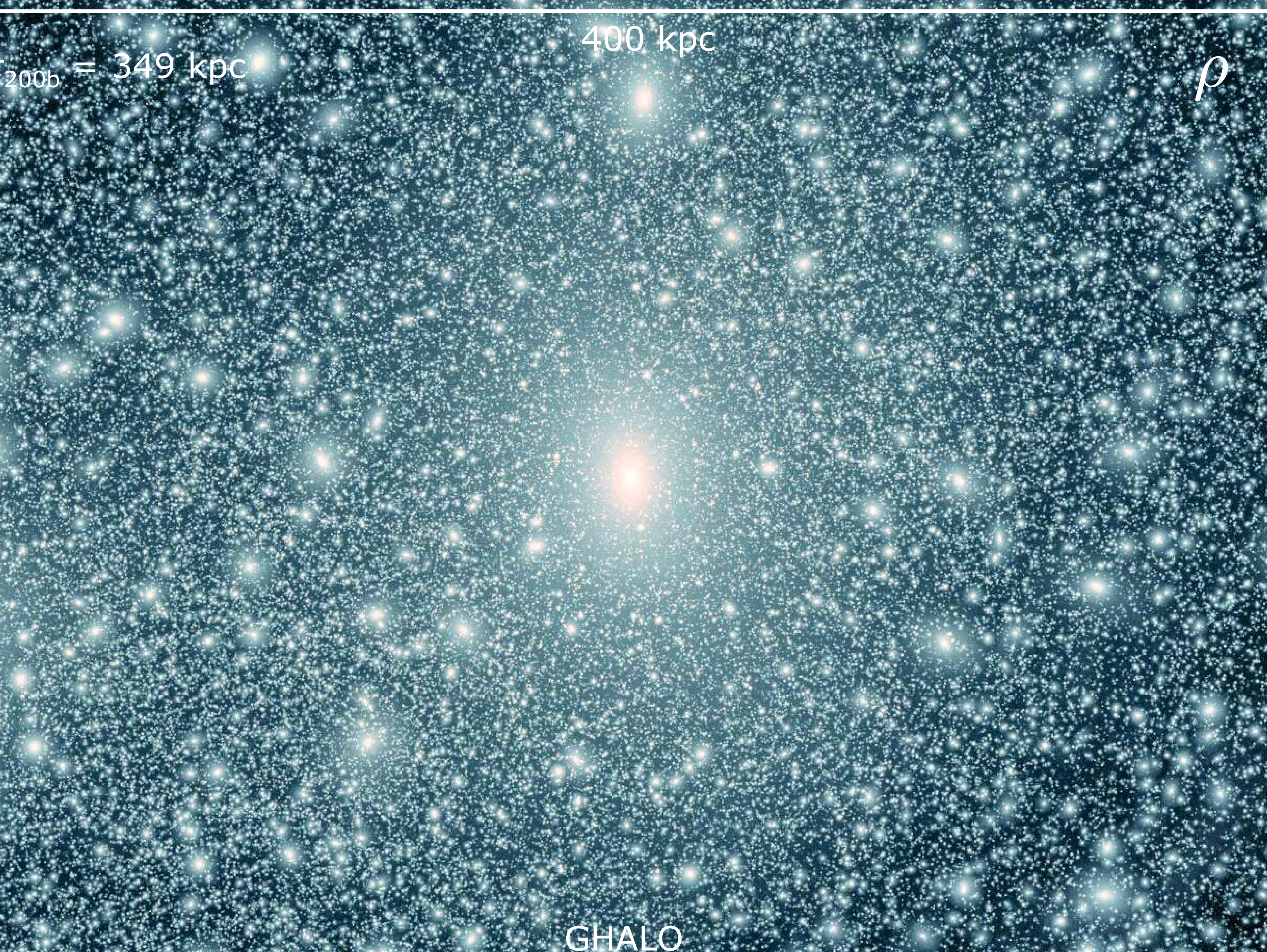
Density Profile II

MPLA, 2009, 24, 2291



GHALO: $\rho_{SM}(r) = \rho_0 \exp(-\lambda[\ln(1 + r/R_\lambda)]^2)$


800 kpc
r_{200b} = 402 kpc
ρ^2
Via Lactea II

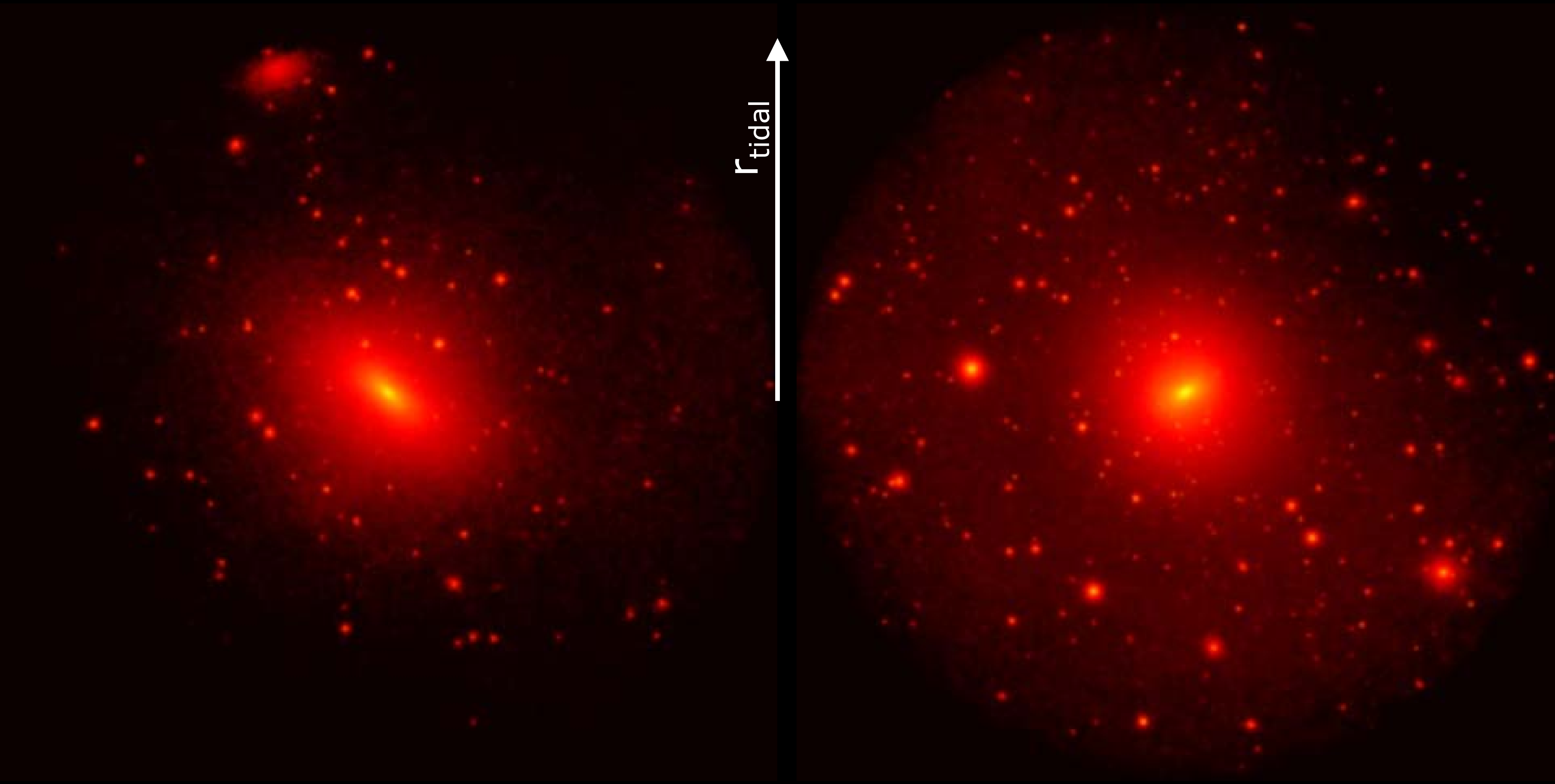


400 kpc
200b = 349 kpc
ρ
GHALO

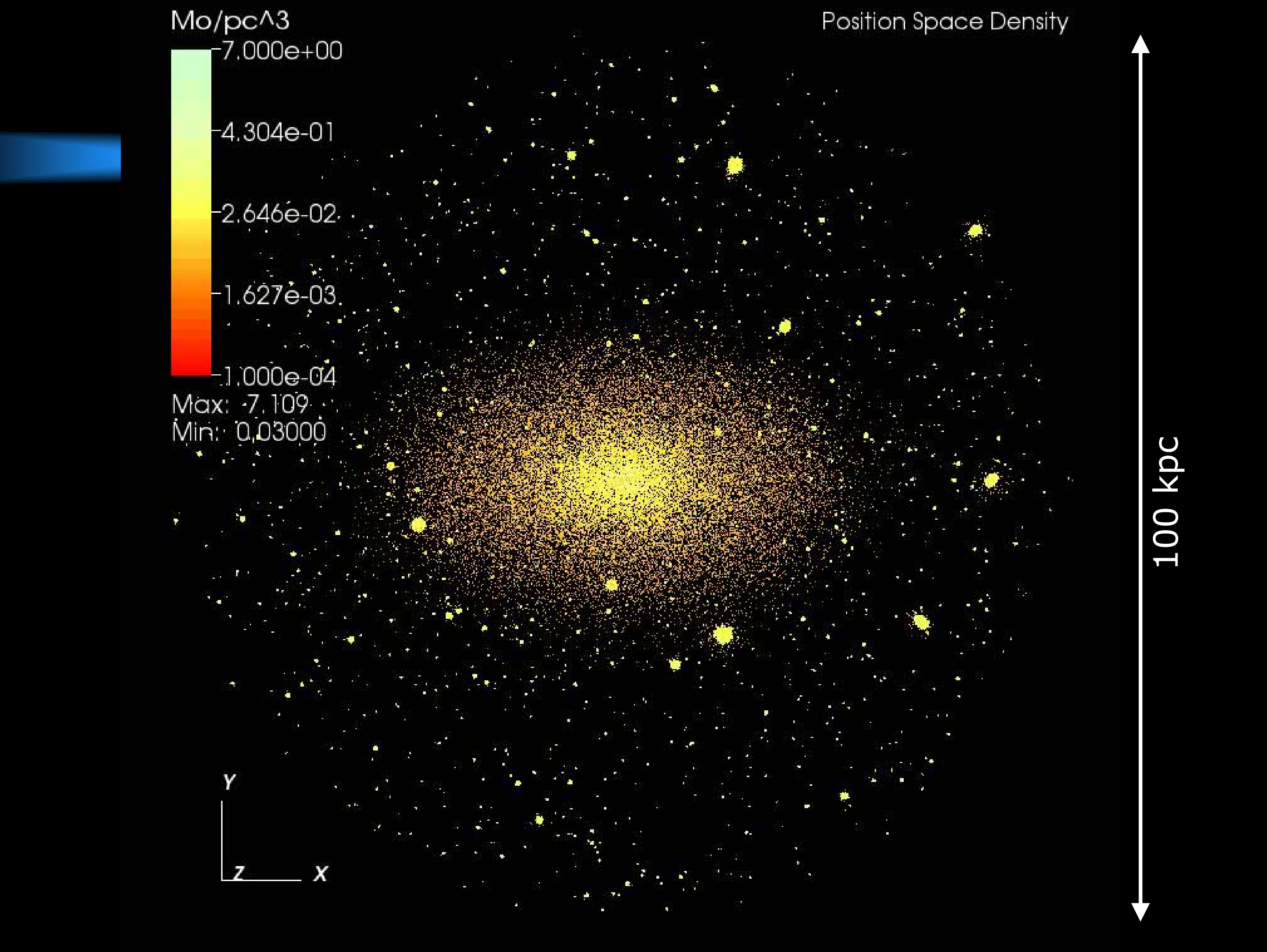
Via Lactea II Subhaloes

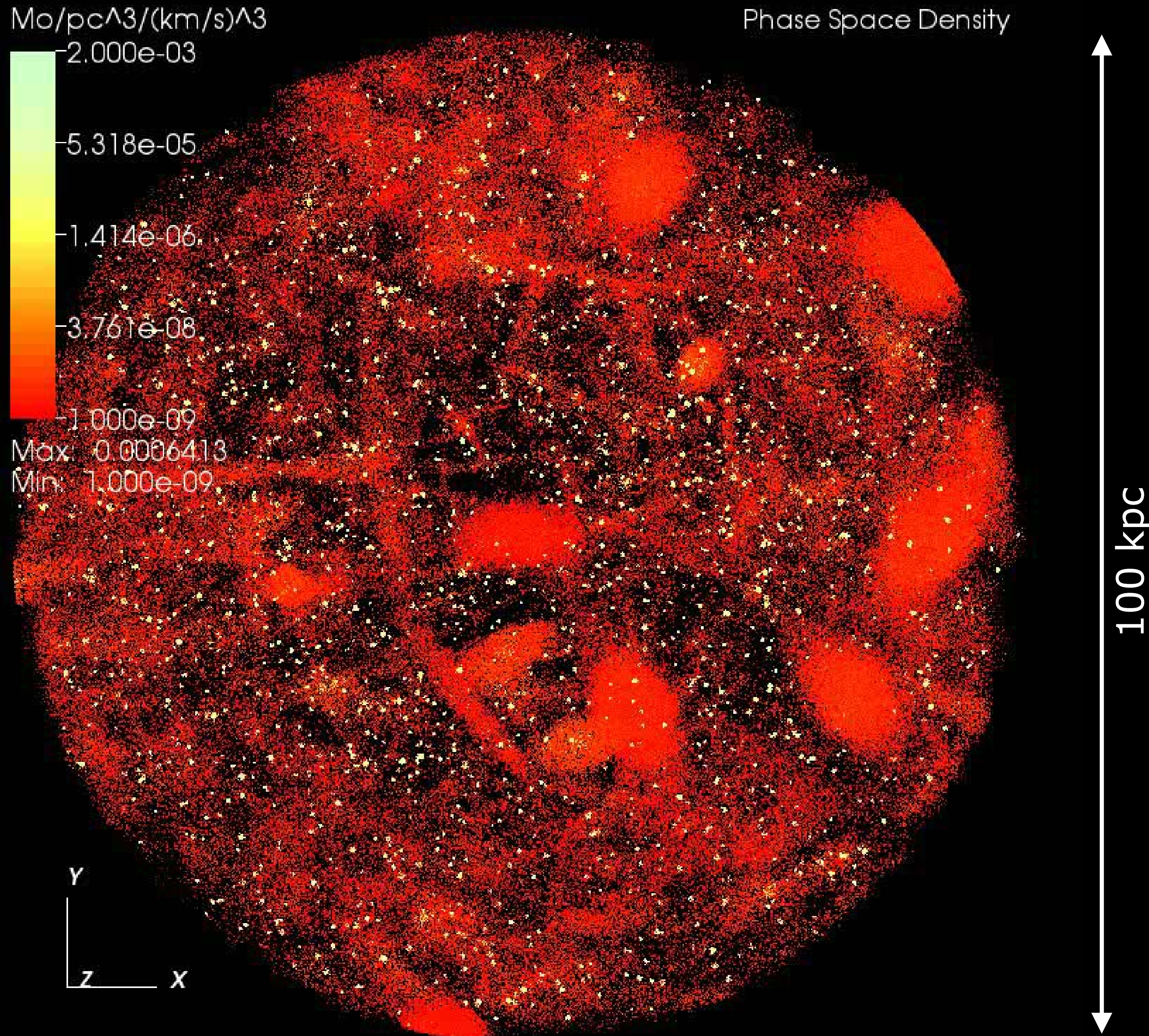
- 40000 subhaloes within 400 kpc
- 2000 subhaloes within 50 kpc
- 20 subhaloes within 8 kpc
- Subhaloes locally at 8 kpc that looked smooth in previous simulations
- Subhaloes within subhaloes
  $\Rightarrow$ Subsubhaloes $\Rightarrow$ Sub^{2}haloes
  $\Rightarrow$ Sub^{n}haloes

Sub²haloes



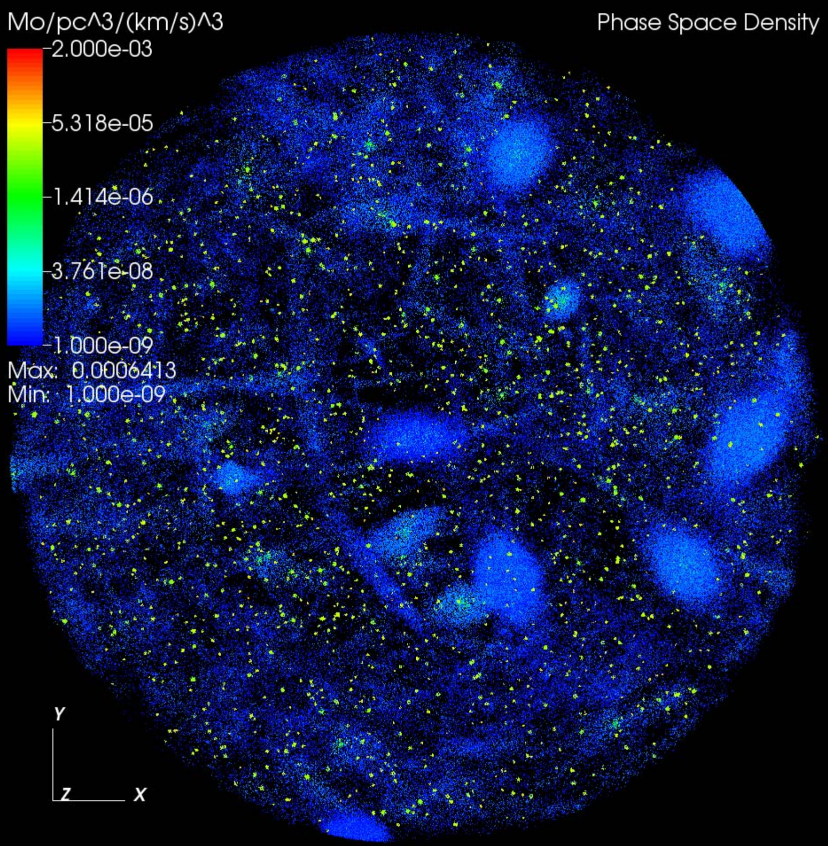
$M_{tidal} = 1.97 \times 10^9$ Mo $M_{tidal} = 5.09 \times 10^9$ Mo


Mo/pc^3
7.000e+00
4.304e-01
2.646e-02
1.627e-03
1.000e-04
Max: 7.109
Min: 0.03000
Position Space Density
Y
Z
X
100 kpc

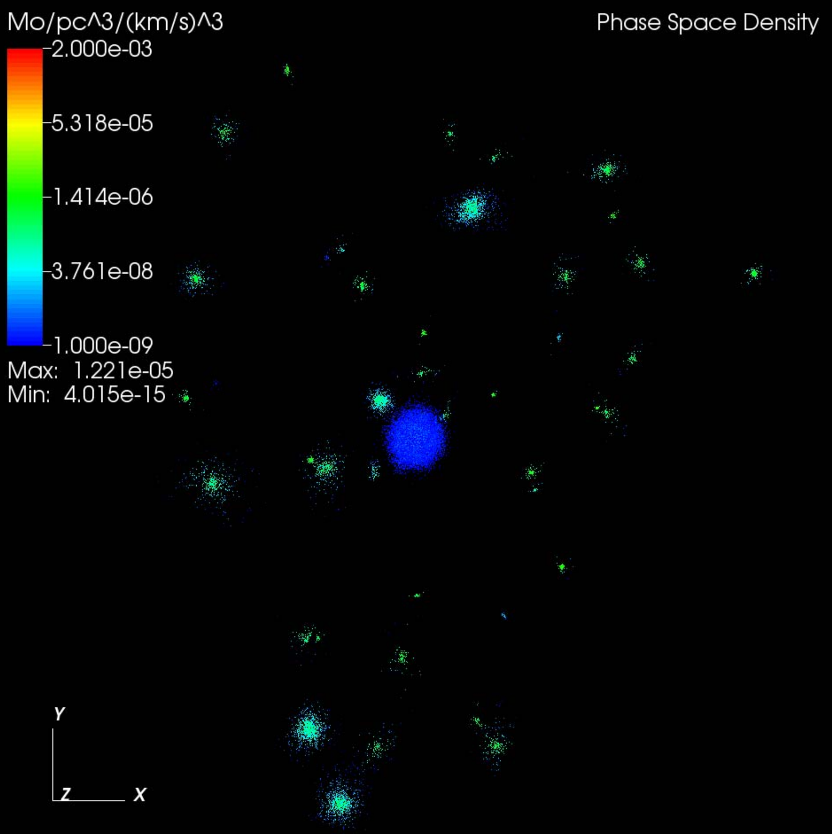

Mo/pc^3/(km/s)^3
Phase Space Density
2.000e-03
5.318e-05
1.414e-06
3.761e-08
1.000e-09
Max: 0.0006413
Min: 1.000e-09
Y
Z
X
100 kpc

Resolution: VL2 vs. VL2m

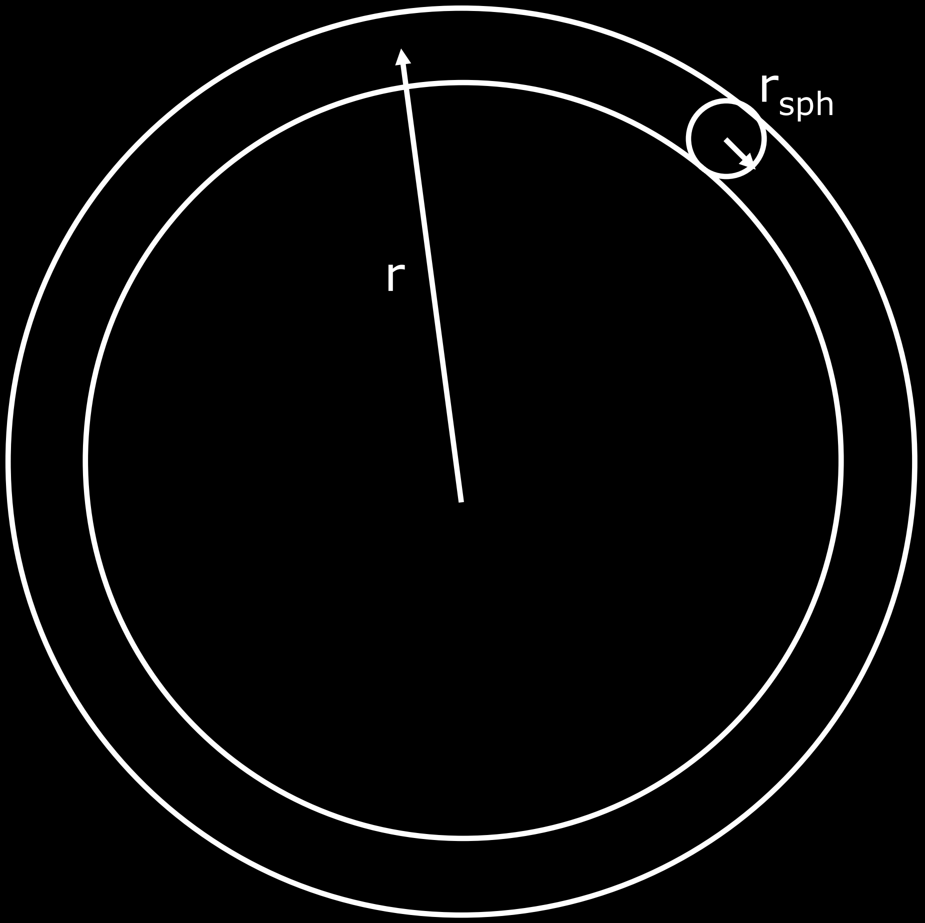
m_p



$64 \times m_p$



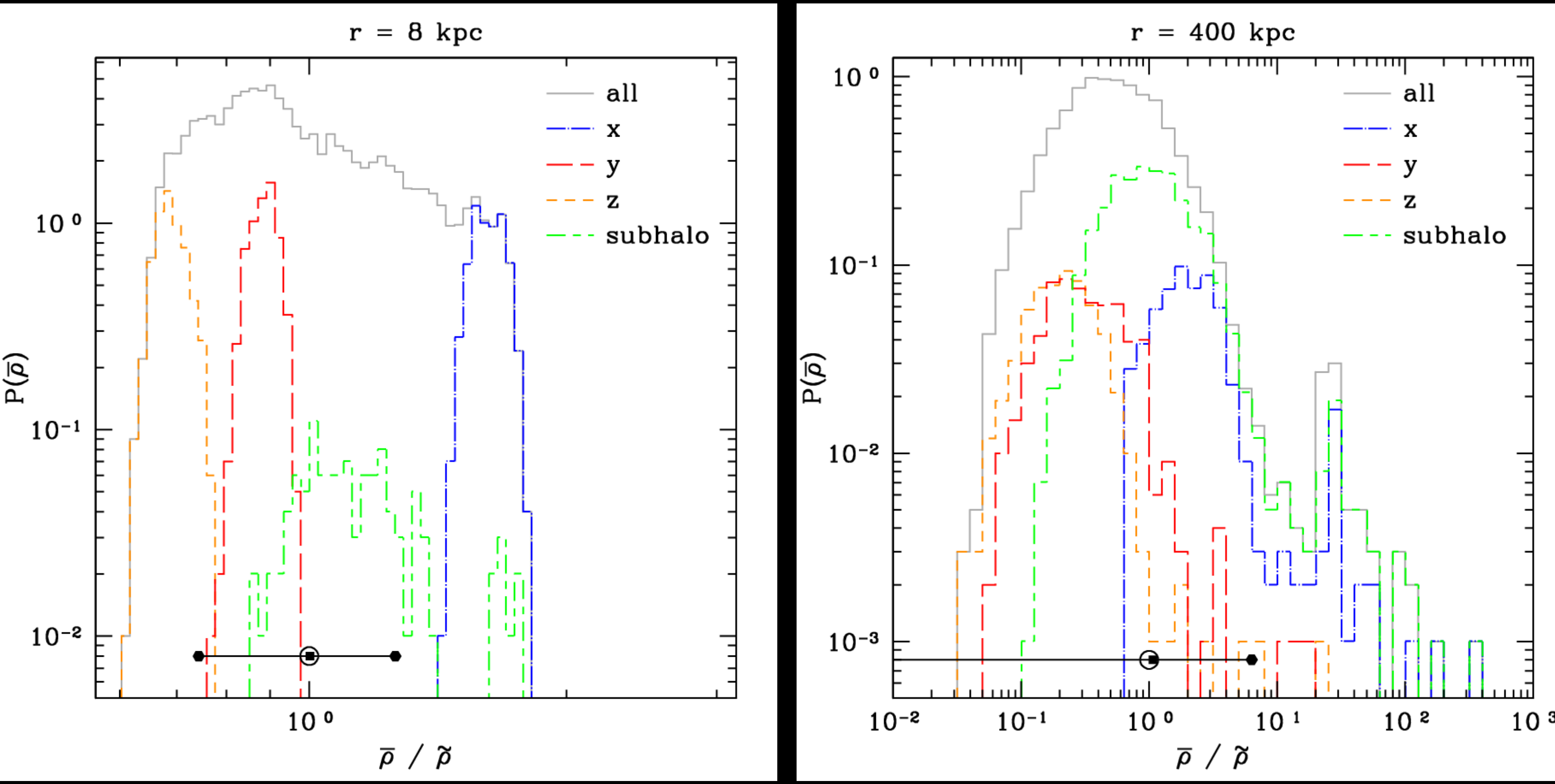
Local Properties: Procedure



- Cut out spheres that contain $O(10^3)$ particles
- Calculate density, mean velocity, dispersion tensor etc.

Local Densities I

MNRAS, 2009, 394, 641



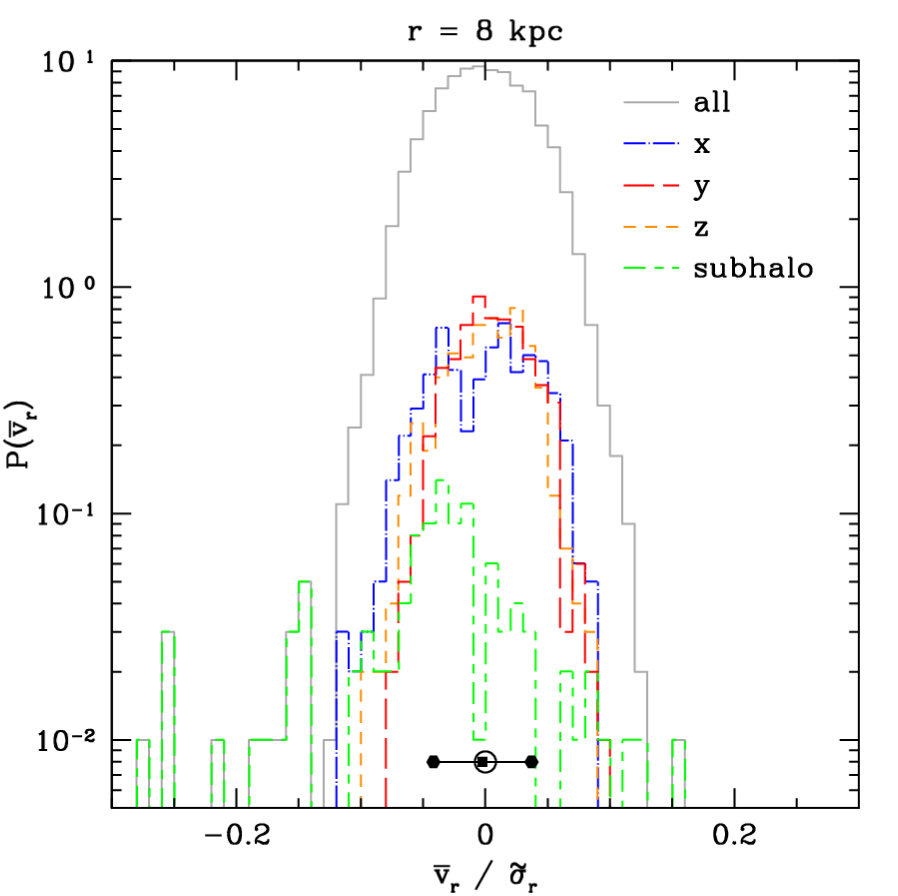
$\tilde{\rho} = 1.059 \times 10^{-2}\ M_{\odot}\ pc^{-3}$ $\tilde{\rho} = 1.094 \times 10^{-6}\ M_{\odot}\ pc^{-3}$

Local Densities II

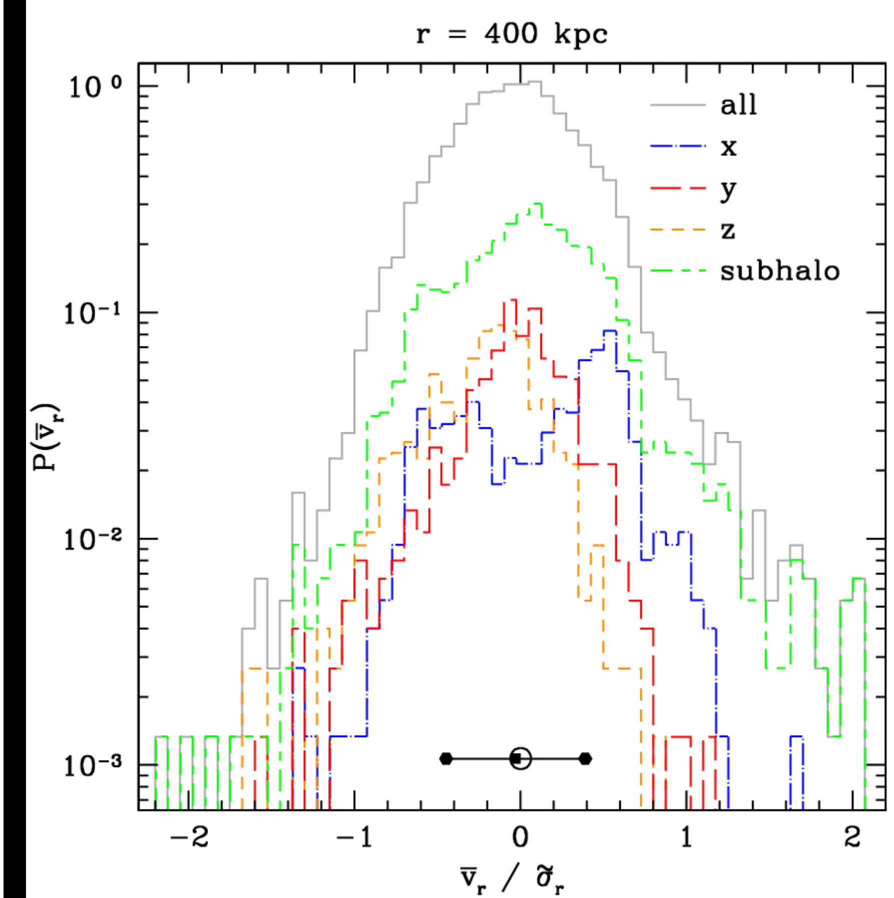
- Gini coefficient measures inequality
  8 kpc: $G(\overline{\rho}) = 0.14$
  400 kpc: $G(\overline{\rho}) = 0.62$
  USA: G(USD) = 0.47 (2006)
- Holes in the dark matter distribution
  $\Rightarrow$ 2% of spheres at 400 kpc with radius $r_{sph}/4$ which normally contain ca. 20 particles are empty!

Local Mean Velocities

MNRAS, 2009, 394, 641



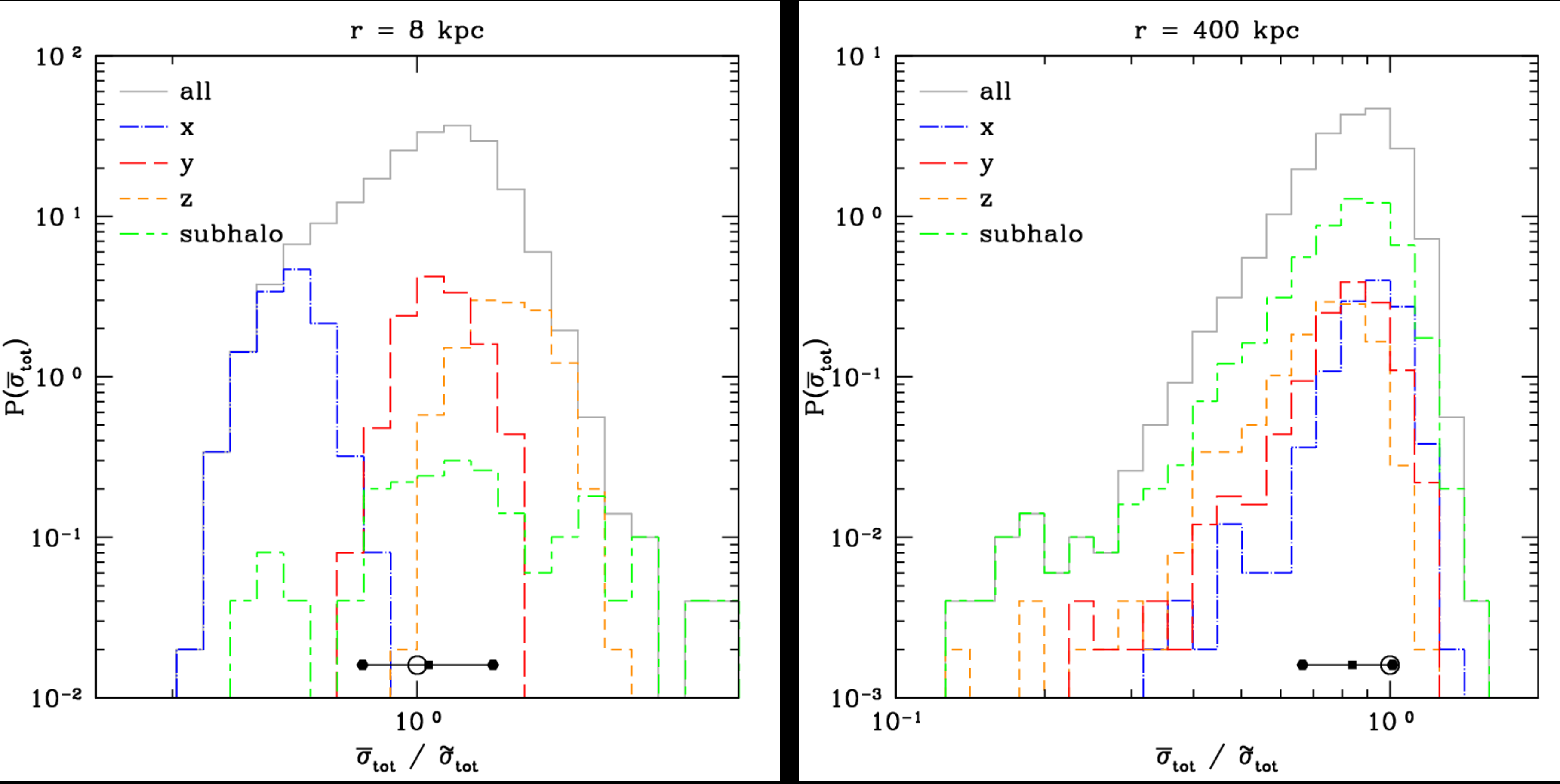
$\tilde{\sigma}_r$ = 144.1 km s^{-1}



$\tilde{\sigma}_r$ = 73.03 km s^{-1}

Local Velocity Dispersions

MNRAS, 2009, 394, 641

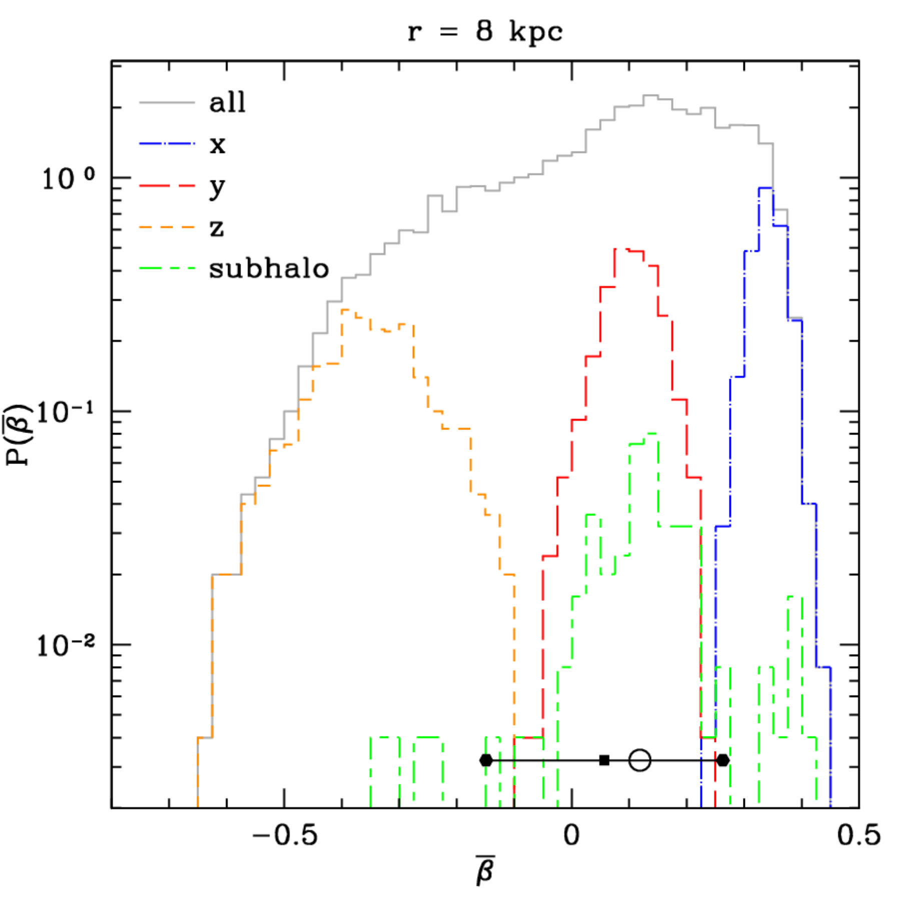


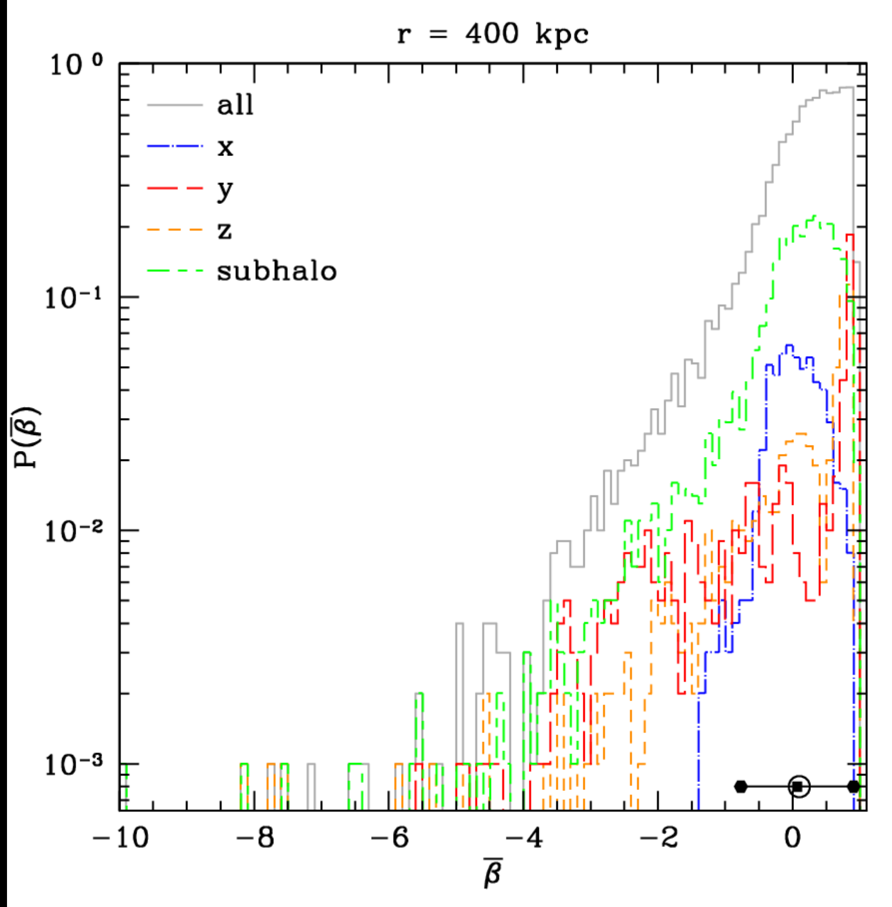
$\tilde{\sigma}_{tot}$ = 239.5 km s^{-1}

$\tilde{\sigma}_{tot}$ = 122.2 km s^{-1}

Local Velocity Anisotropy

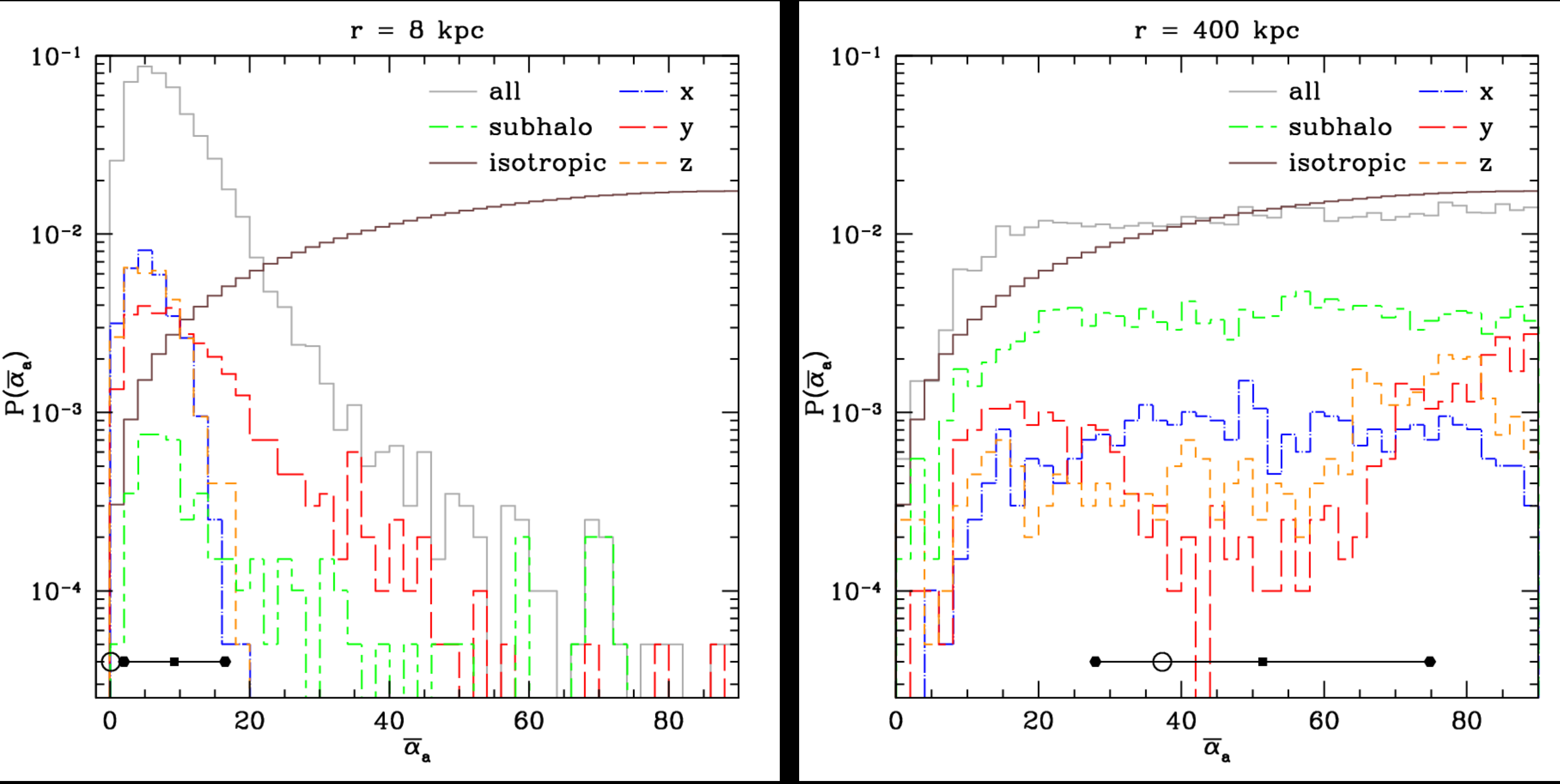
MNRAS, 2009, 394, 641





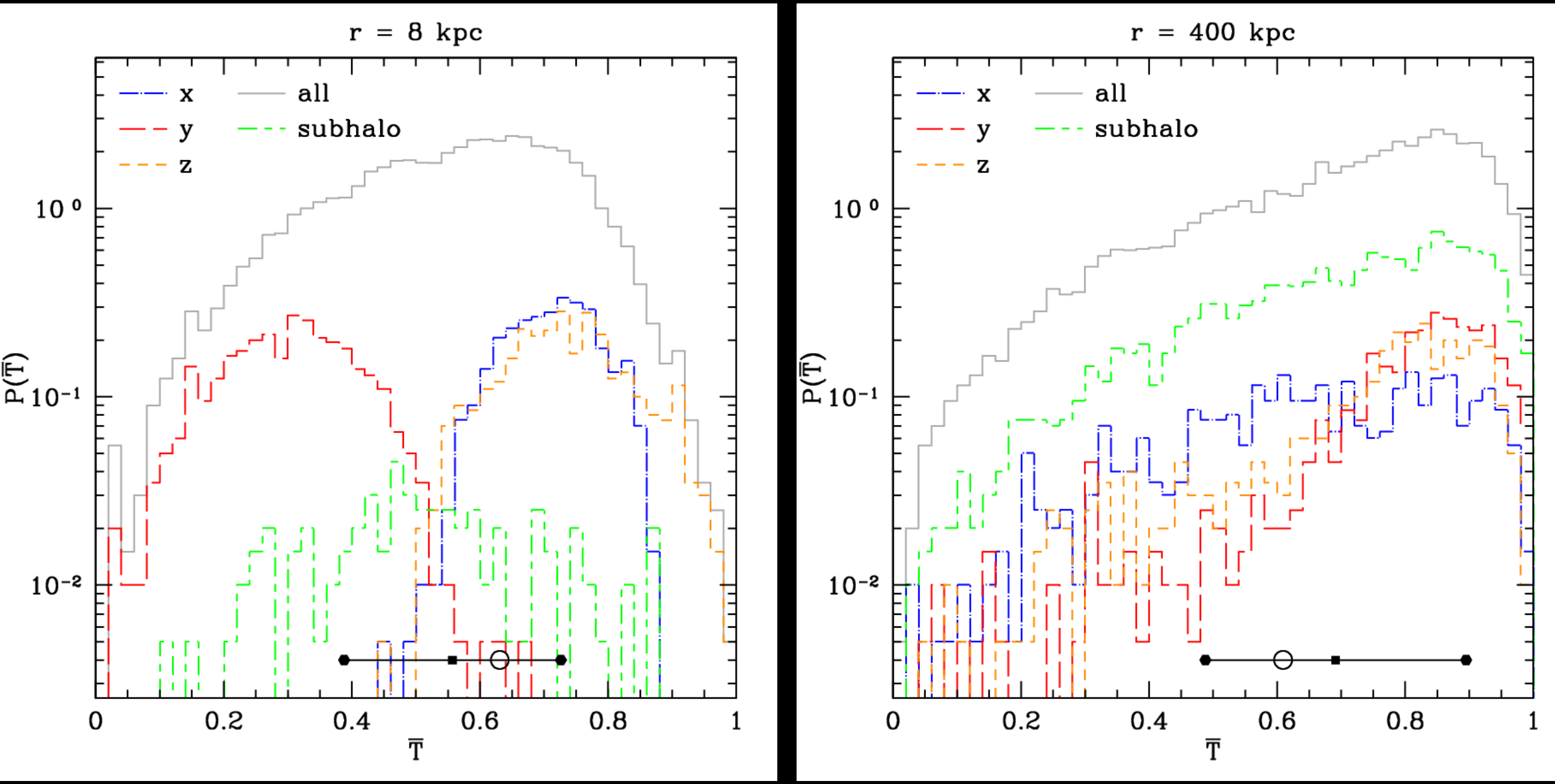
VD Ellipsoid Orientation

MNRAS, 2009, 394, 641



VD Ellipsoid Shape

MNRAS, 2009, 394, 641



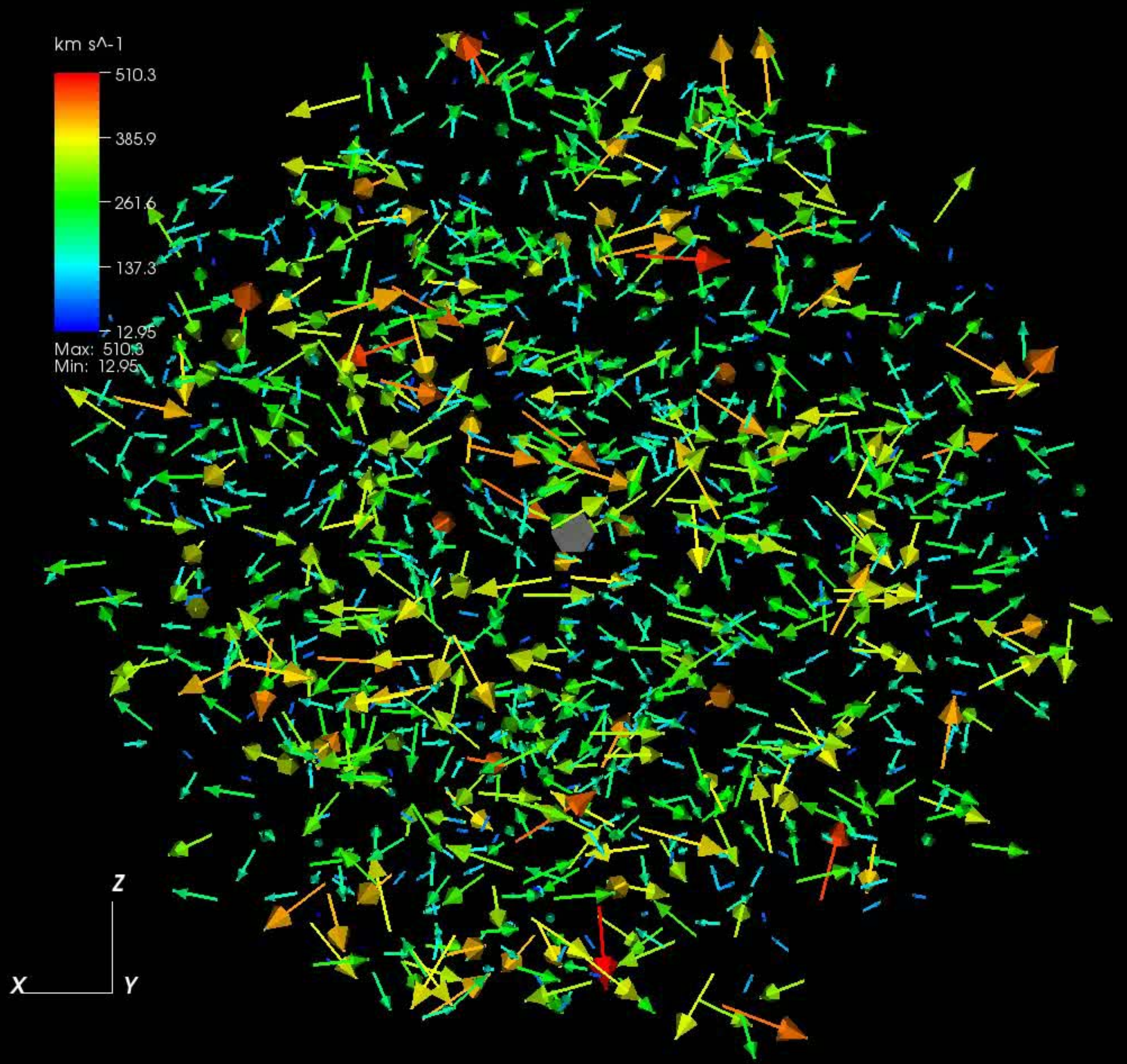
oblate triaxial prolate oblate triaxial prolate

Position Space @ 8 kpc

r = (0,8,0) kpc
d = 1 kpc

MNRAS, 2009, 394, 641

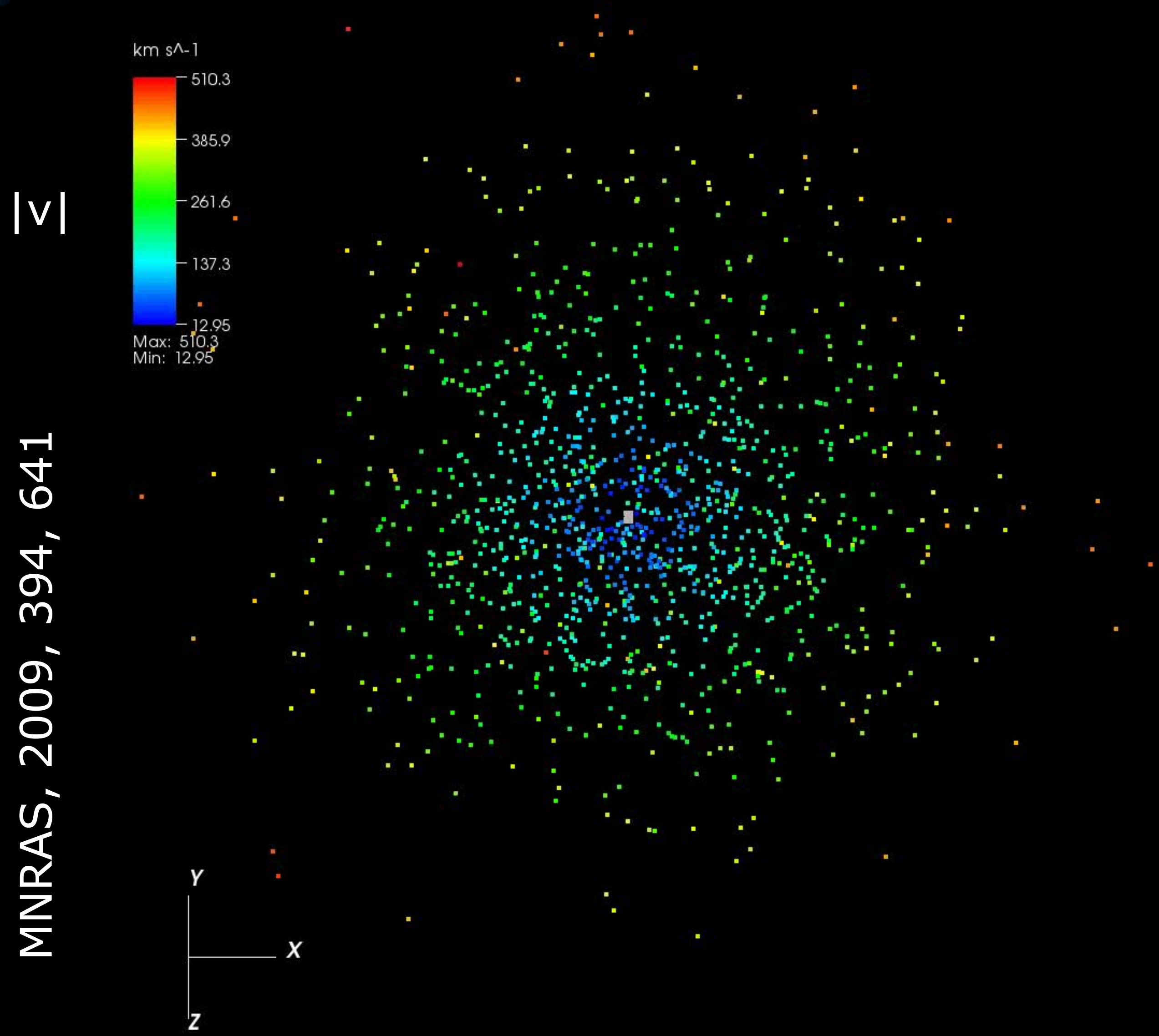
|v|



Velocity Space @ 8 kpc

r = (0,8,0) kpc
d = 1 kpc

MNRAS, 2009, 394, 641

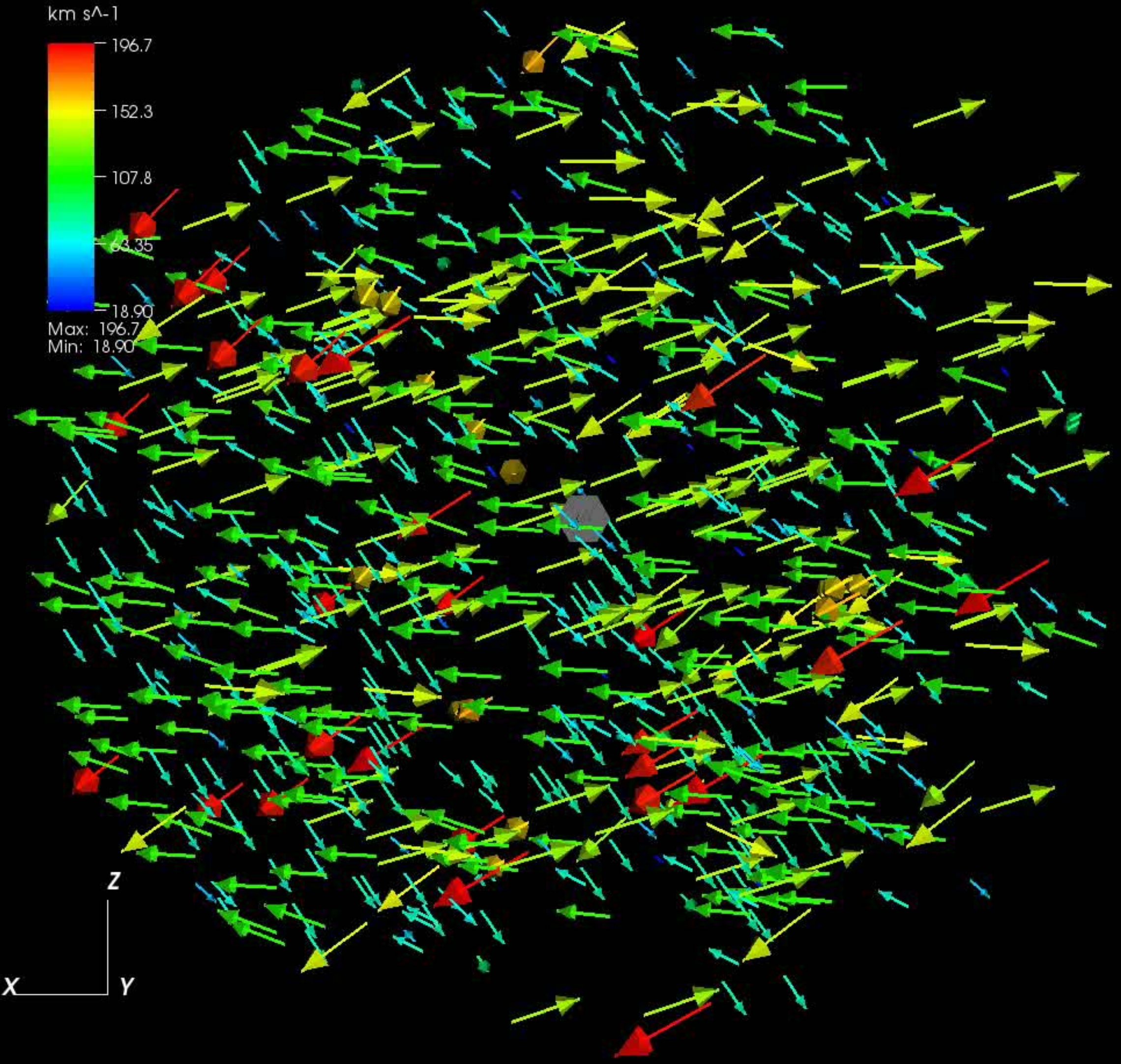


Position Space @ 400 kpc

|v|

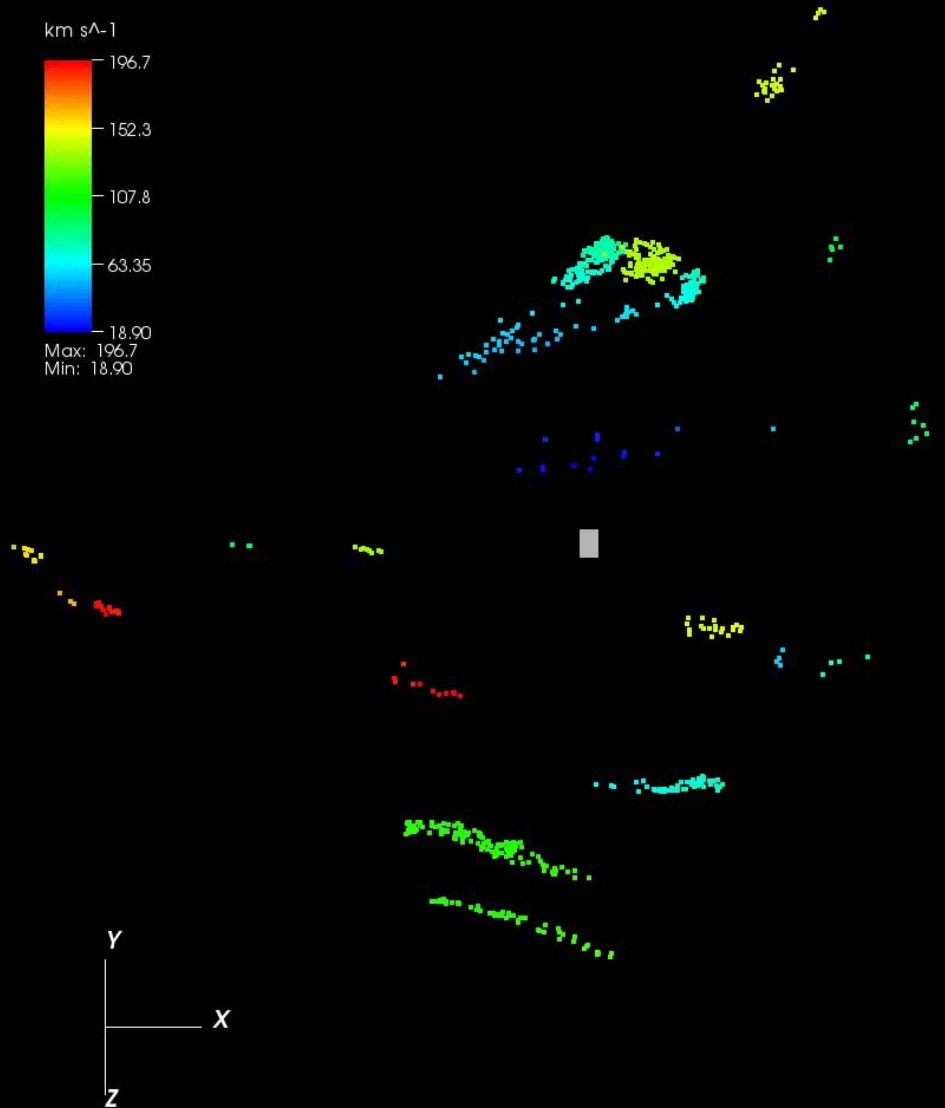
r = (0,400,0) kpc
d = 21.4 kpc

MNRAS, 2009, 394, 641



Velocity Space @ 400 kpc

|v|



r = (0,400,0) kpc
d = 21.4 kpc

MNRAS, 2009, 394, 641

Annihilation Luminosity

- Annihilation is a two-body process

$$\mathcal{L} \equiv \int \rho^2 \mathrm{d}V$$

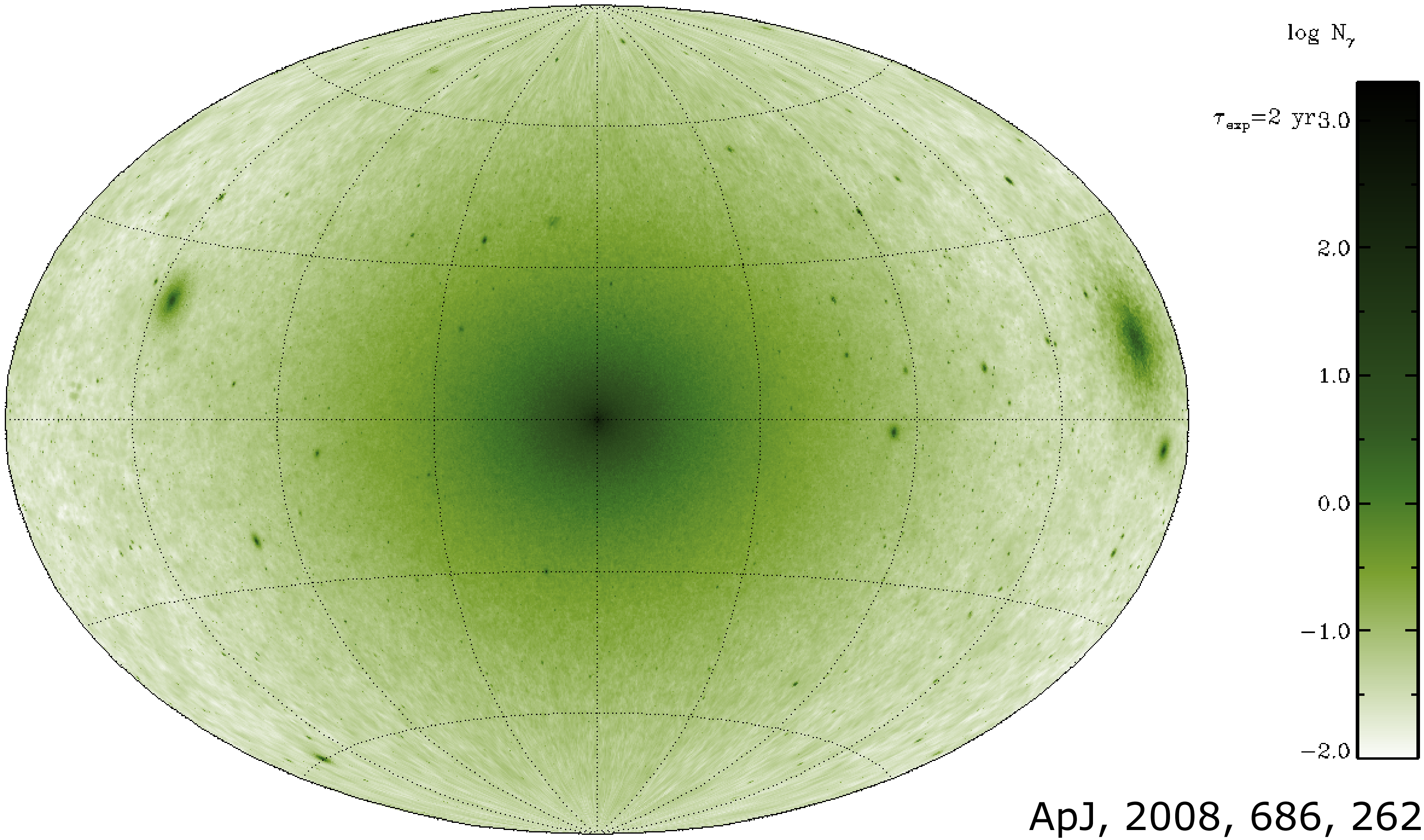
- For cusped profiles

$$\mathcal{L} \propto r_\mathrm{s}^3 \rho_\mathrm{s}^2 \propto V_\mathrm{max}^3 \sqrt{c_V}$$

- Luminosity is concentrated

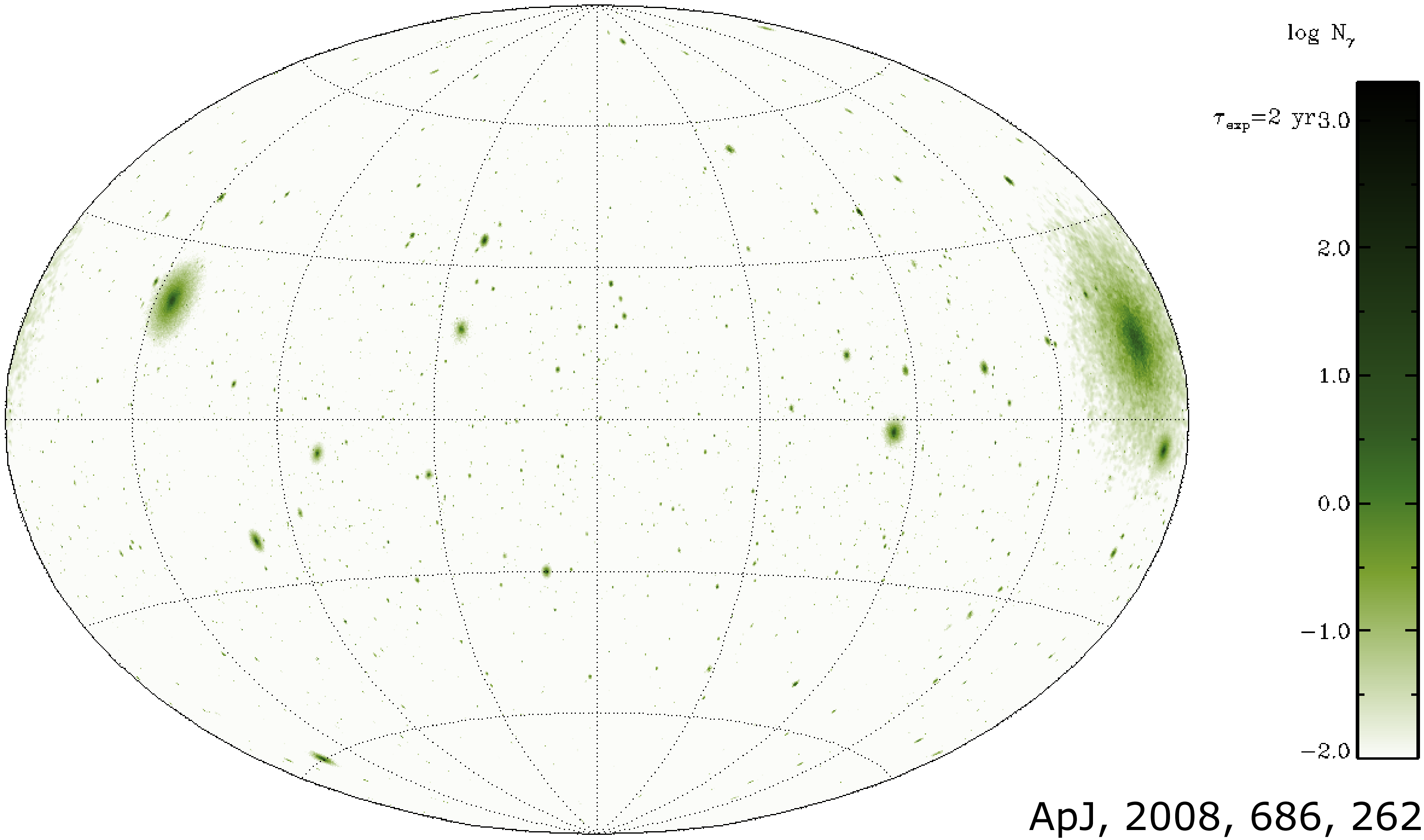
$$\mathcal{L}(r_\mathrm{s})/\mathcal{L}_\mathrm{tot} \sim 90\%$$

Total Annihilation Signal



ApJ, 2008, 686, 262

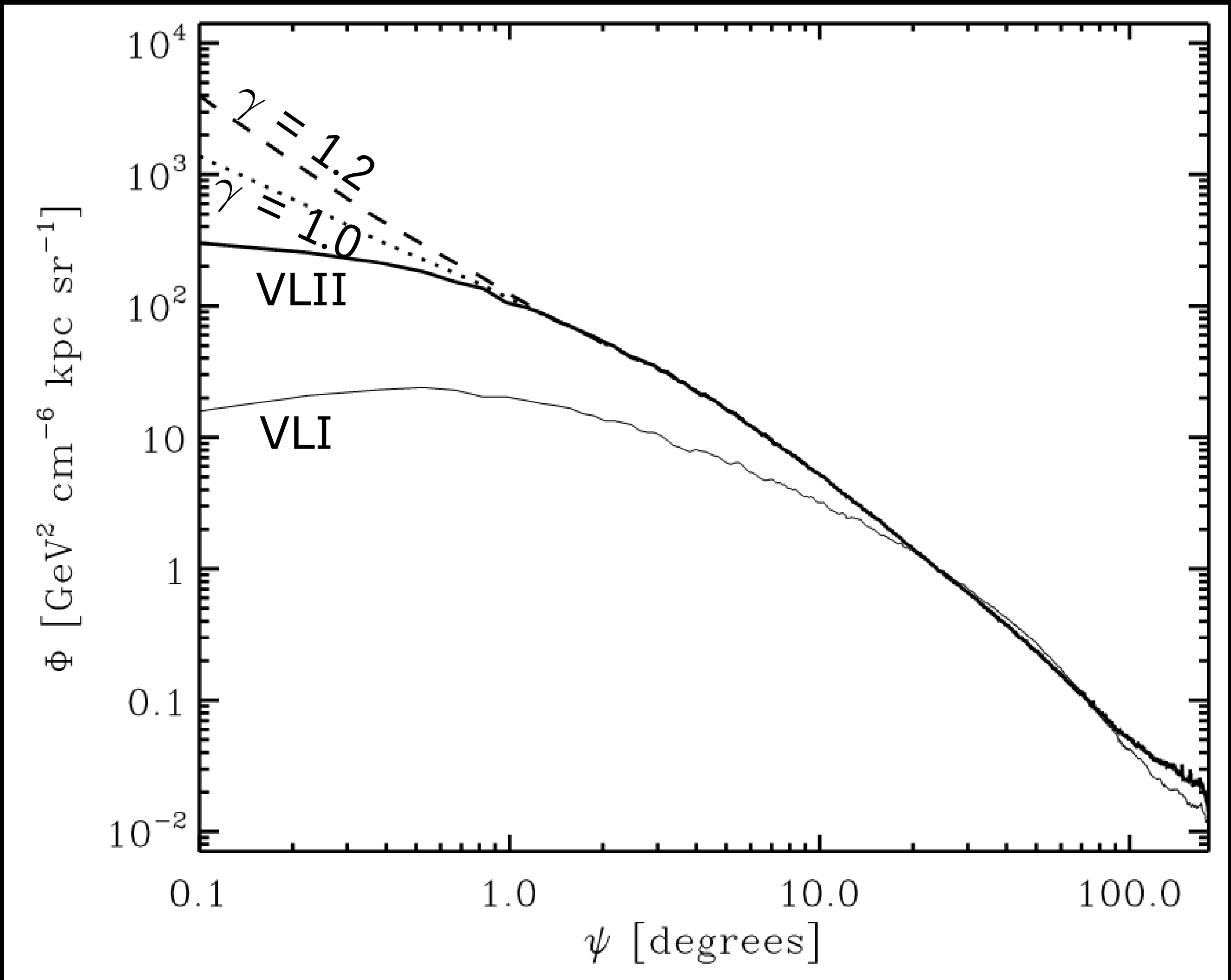
Subhalo Annihilation Signal



ApJ, 2008, 686, 262

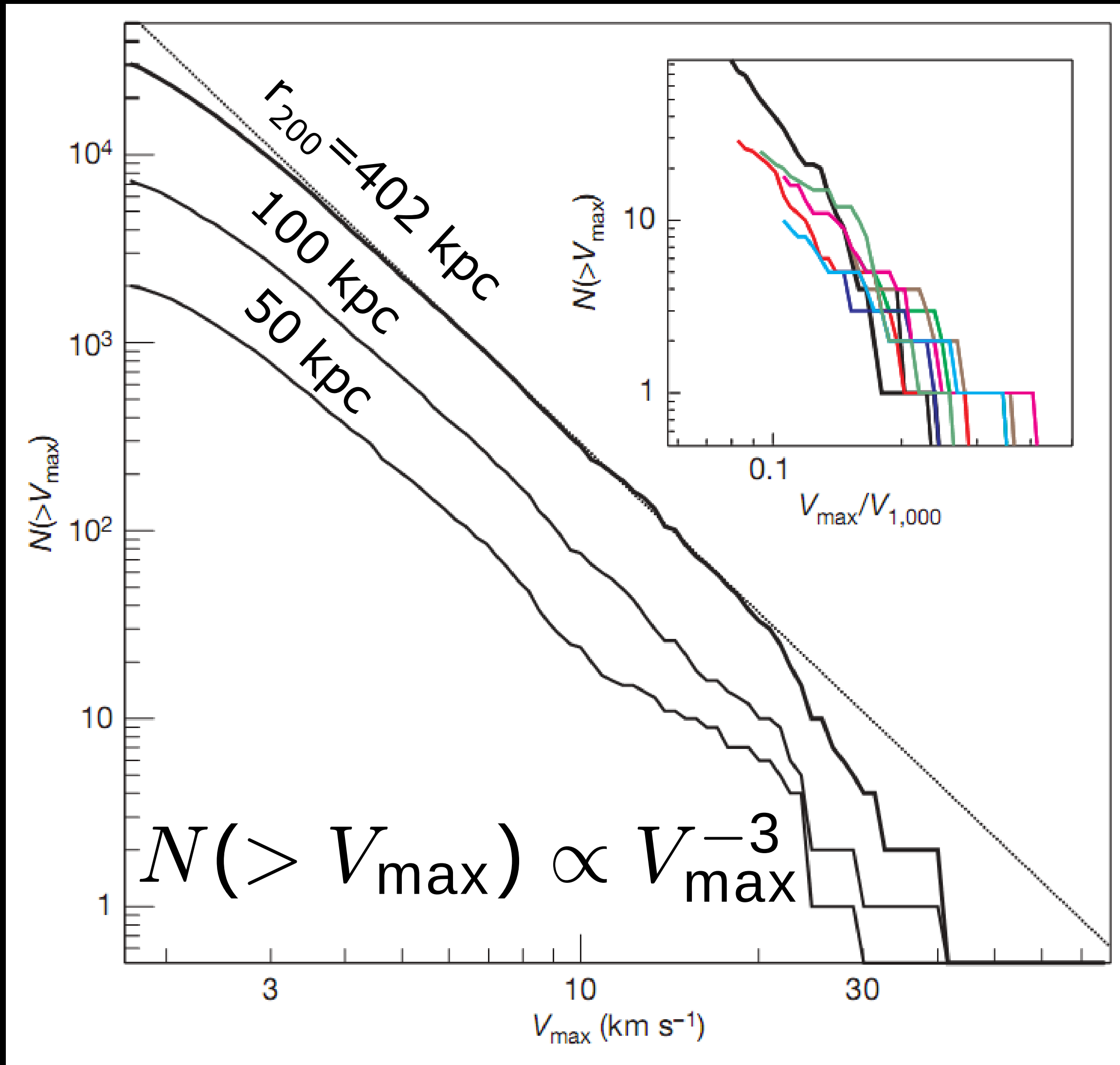
Central Flux Corrections

ApJ, 2008, 686, 262

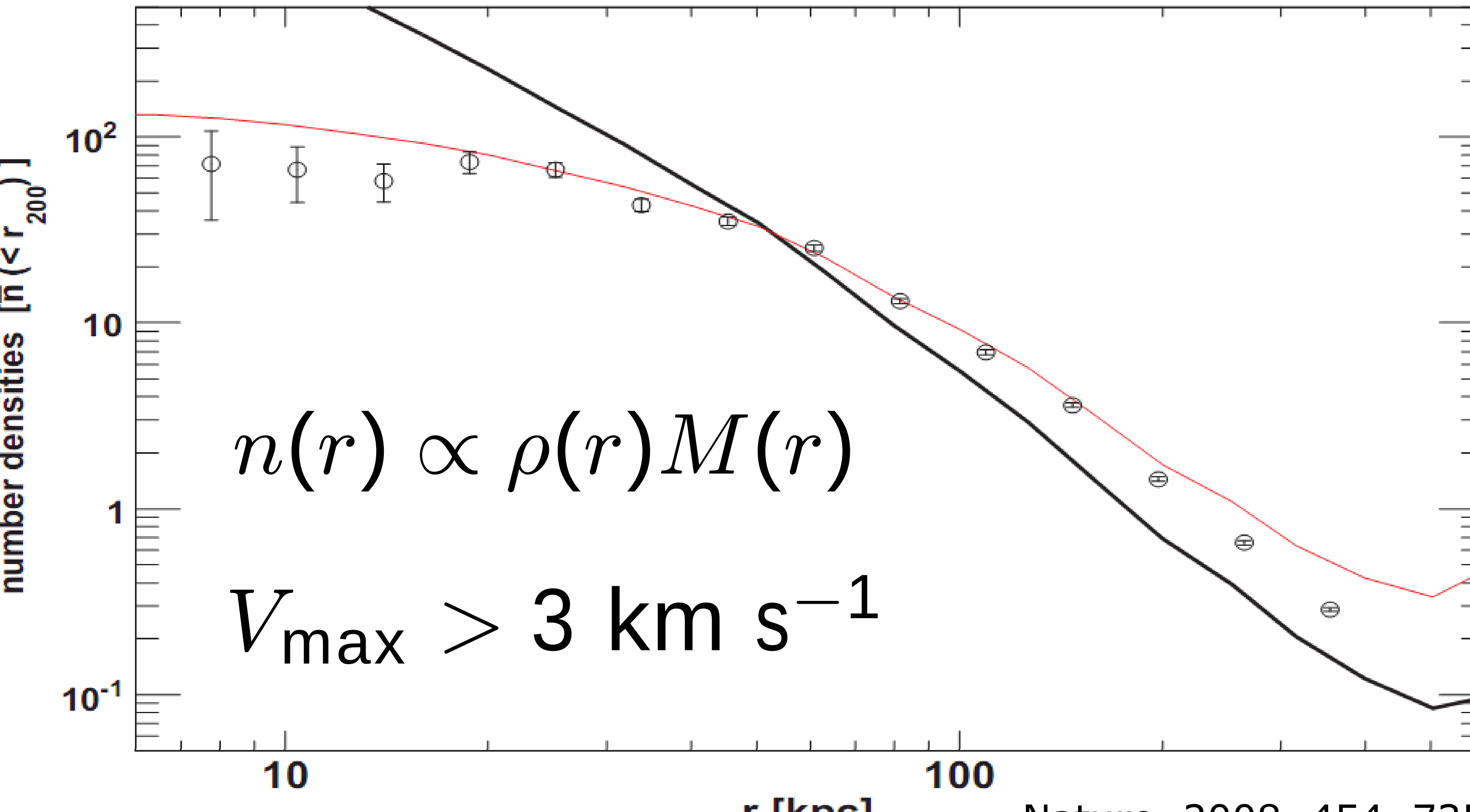


Sub^{n}halo Abundance

Nature, 2008, 454, 735



Subhalo Spatial Distribution

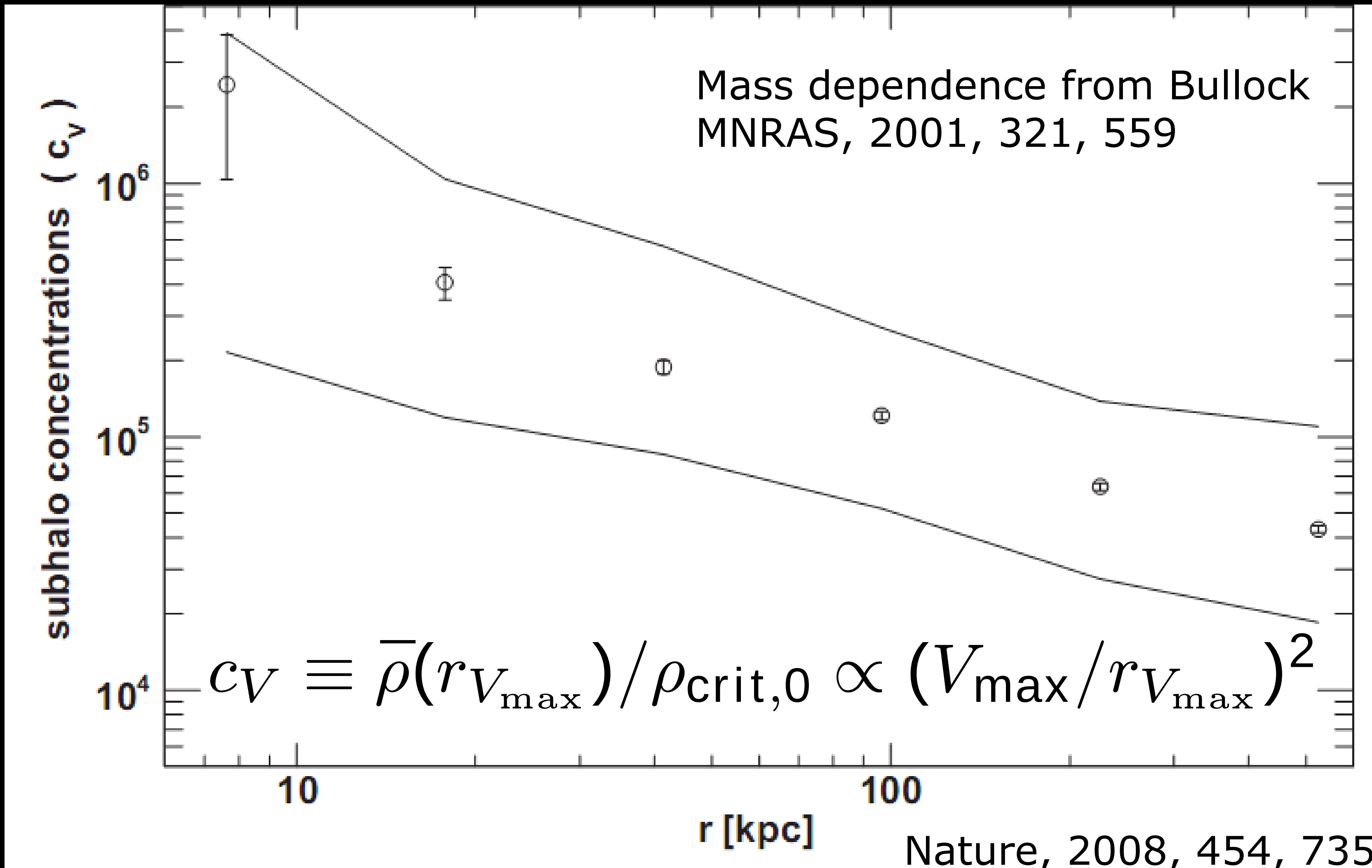


$$n(r) \propto \rho(r) M(r)$$

$$V_{\mathrm{max}} > 3 \text{ km s}^{-1}$$

Nature, 2008, 454, 735

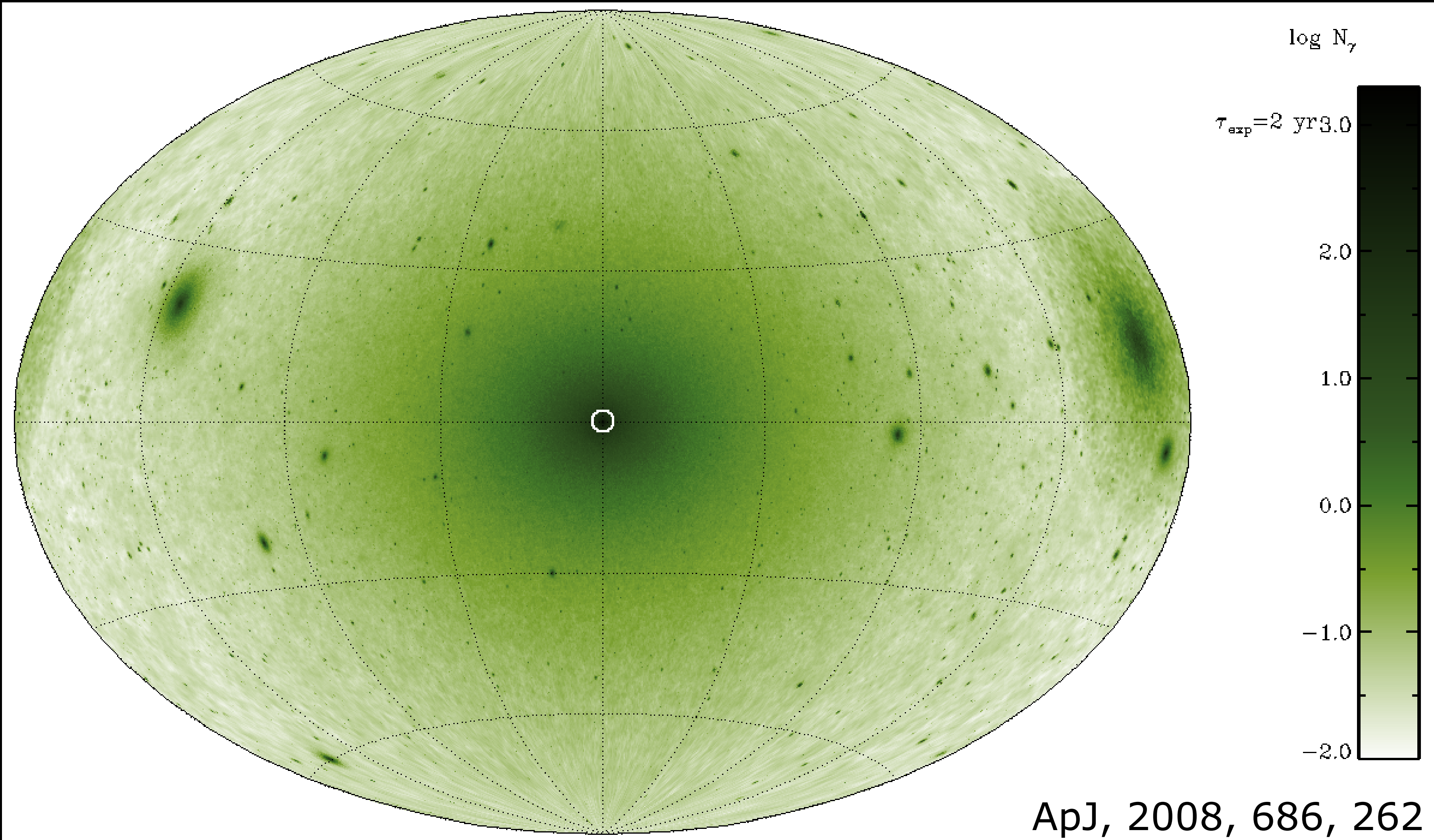
Subhalo Concentrations



Boost Factor

- Small subhaloes contribute more than large ones
- Total resolved subhalo contribution is 97% of host halo in Via Lactea II
  $\Rightarrow$ boost factor B = 1.97
- Extrapolation to smaller masses can lead to B = O(10)
- Tidal debris $\Rightarrow$ B = O(1)

Corrected Total Signal

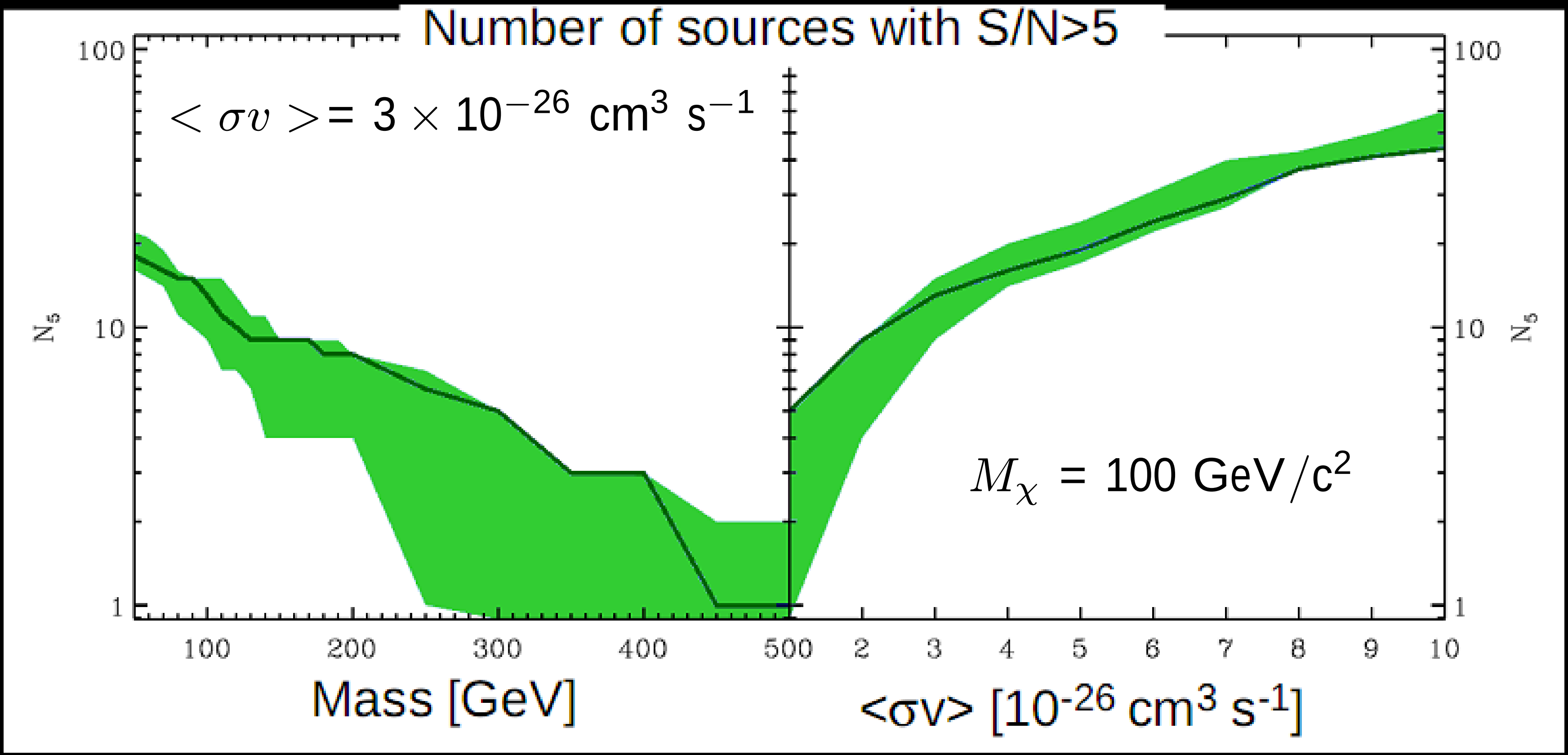


ApJ, 2008, 686, 262

Diffuse Background

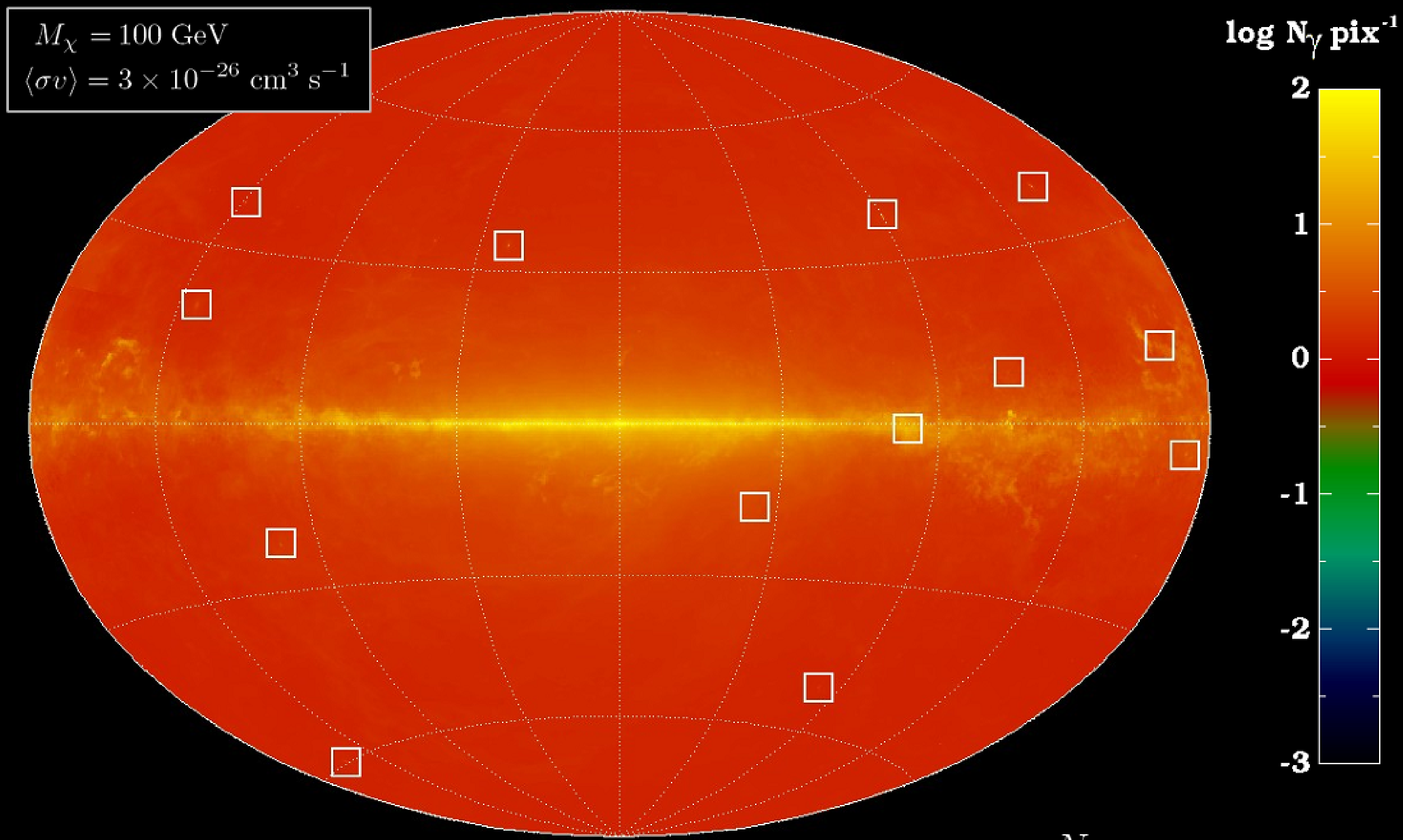
- Isotropic extragalactic component
  $\Rightarrow$ measured by EGRET
- Galactic component
  $\Rightarrow$ modelled with GALPROP
- Undetectable subhaloes and smooth host halo
  $\Rightarrow$ modelled from simulation
- Detector sensibility
- Calculate Signal-to-Noise

Detectable Subhaloes



ApJ, 2008, 686, 262

Signal-to-Noise



We calculate a signal-to-noise ratio for every subhalo: $S/N = \frac{N_s}{\sqrt{N_s + N_b}}$

Summary I

- Density profile becomes flatter than NFW $\Rightarrow$ slope -0.8 @ 0.05 % r_{vir}
- DM haloes have a lot of structure: $\Rightarrow$ sub^nhaloes, streams and voids
- Velocity space is not smooth
- Generally grainy structure in phase space $\Rightarrow$ the distribution function is not smooth!

Summary II

- a few subhaloes should be detectable
- 95 % are extended sources
  $\Rightarrow$ discrimination against pointlike sources like pulsars
- Distribution on sky is consistent with isotropy
- High S/N $\Rightarrow$ massive subhaloes with median $V_{max} = 24$ km s^{-1}
- D ~ 10 – 100 kpc

Summary III

- Locally (@ 8 kpc) numerically limited
- Missing baryonic physics
- Important for understanding DM detection experiments and stellar streams embedded within DM streams


1600 kpc
Via lactea II
Diemand Kuhlen Madau Zemp Moore Potter Stadel 2008