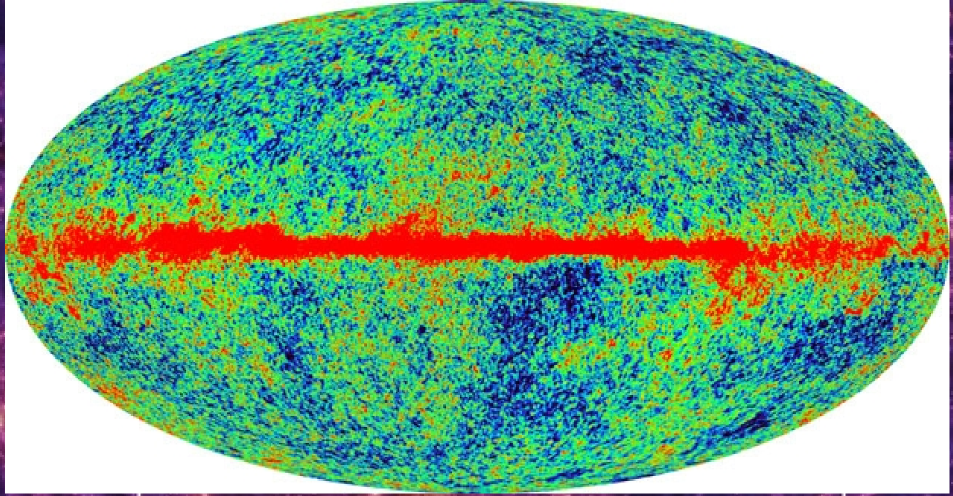


DM Workshop
Fermilab
May 2007

Simulations of the Dark Matter Distribution

Simon White
Max Planck Institute for Astrophysics

- Quasilinear DM distribution
  - -- Large-scale gravitational lensing
  - -- Ly α forest
  - -- high redshift 21 cm distribution

Nature of DM
neutrino contrib'n
primordial *n*

- Nonlinear DM distribution in our Galaxy
  - -- Radial mass distribution in the Milky Way
  - -- Substructures
  - -- structure on the scale of DM detectors

Nature of DM
annihil'n signature
direct detect signal

- DM distribution around groups and clusters
  - -- radial distribution
  - -- flattening
  - -- structure of substructures

Nature of DM
Interaction with baryons

Many people are enthusiastic about Dark Matter!

ΛCDM galaxy halos (without galaxies!)

- Halos extend to ~10 times the 'visible' radius of galaxies and contain ~10 times the mass in the visible regions

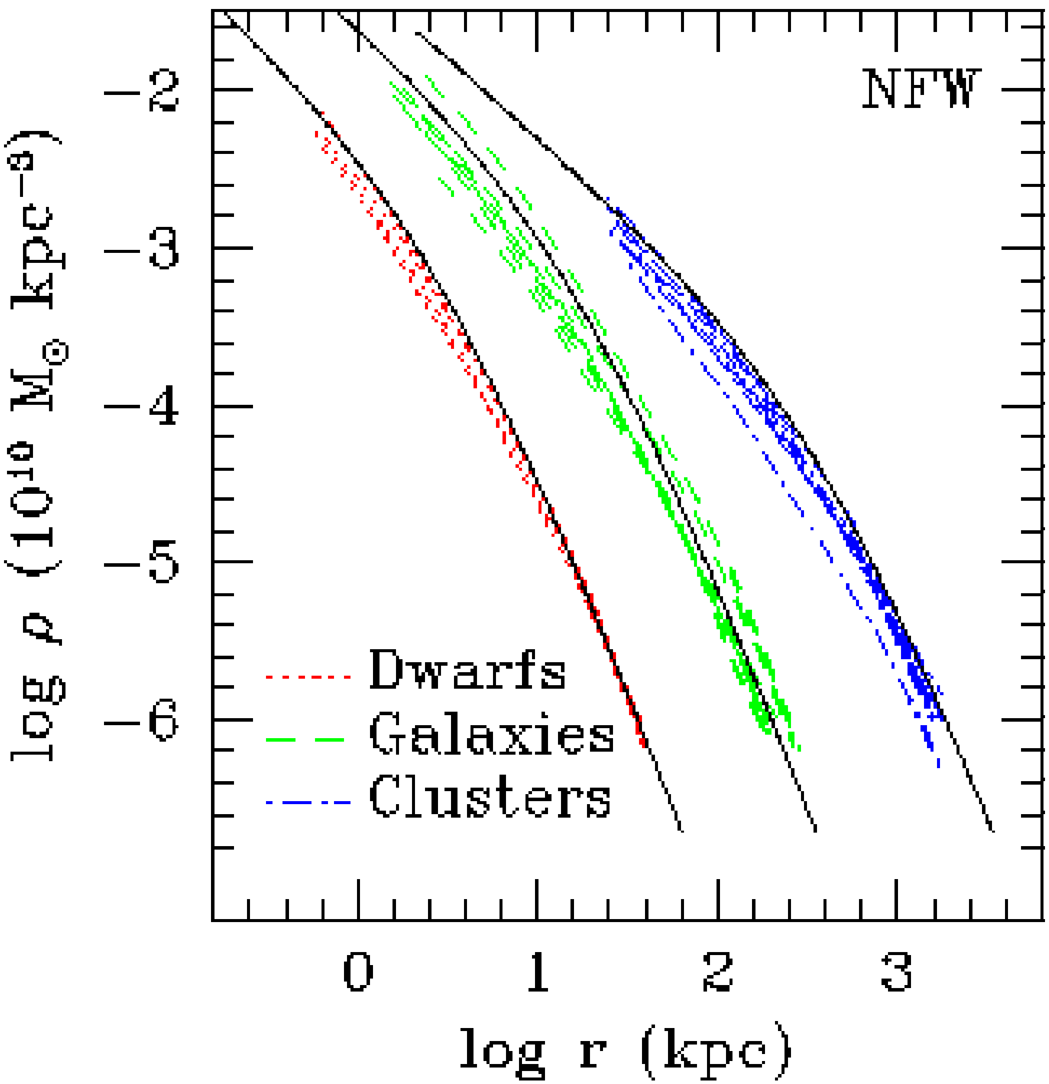
- Equidensity surfaces approximate triaxial ellipsoids
  -- more prolate than oblate
  -- axial ratios greater than two are common

- "Cuspy" density profiles with outwardly increasing slopes
  -- $d \ln \varrho / d \ln r = \gamma$ with $\gamma < -2.5$ at large r
  $\gamma > -1.2$ at small r

- Substantial numbers of self-bound substructures containing ~10% of the mass and with $d N / d M \sim M^{-1.8}$

→ Most substructure mass is in the most massive subhaloes

Density profiles of dark matter halos



The average dark matter density of a dark halo depends on distance from halo centre in a very similar way in halos of all masses at all times

-- a universal profile shape --

$$\rho(r)/\langle\rho\rangle \approx \delta\, r_s / r(1 + r/r_s)^2$$

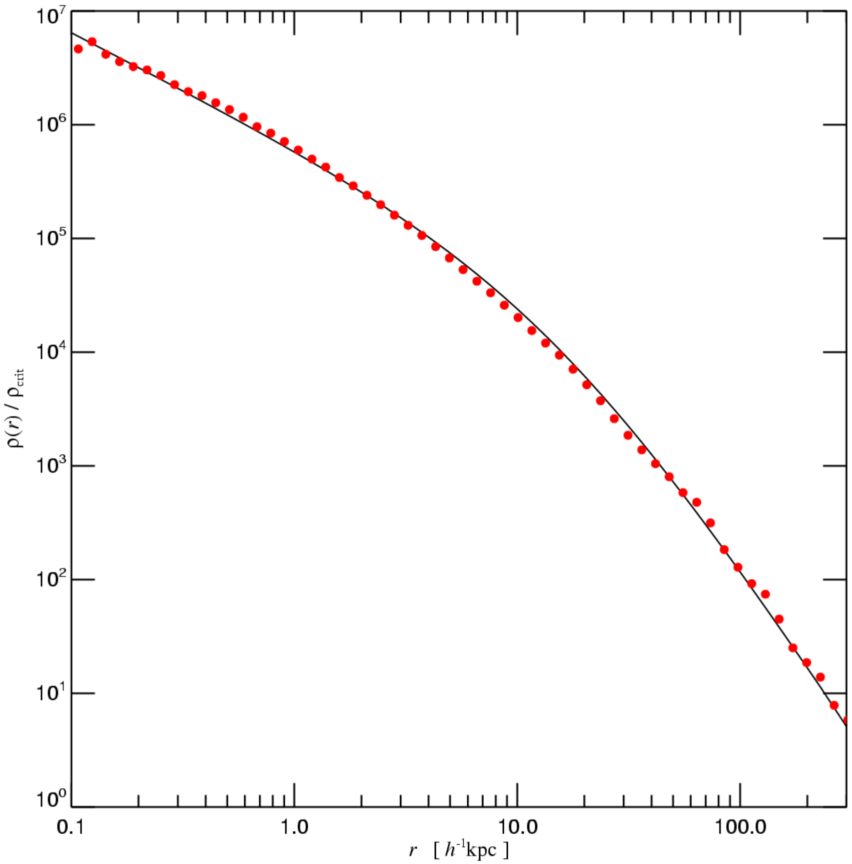
More massive halos and halos that form earlier have higher densities (bigger δ)

A high-resolution Milky Way halo

600 kpc

Navarro et al 2006

$N_{200} \sim 3 \times 10^7$

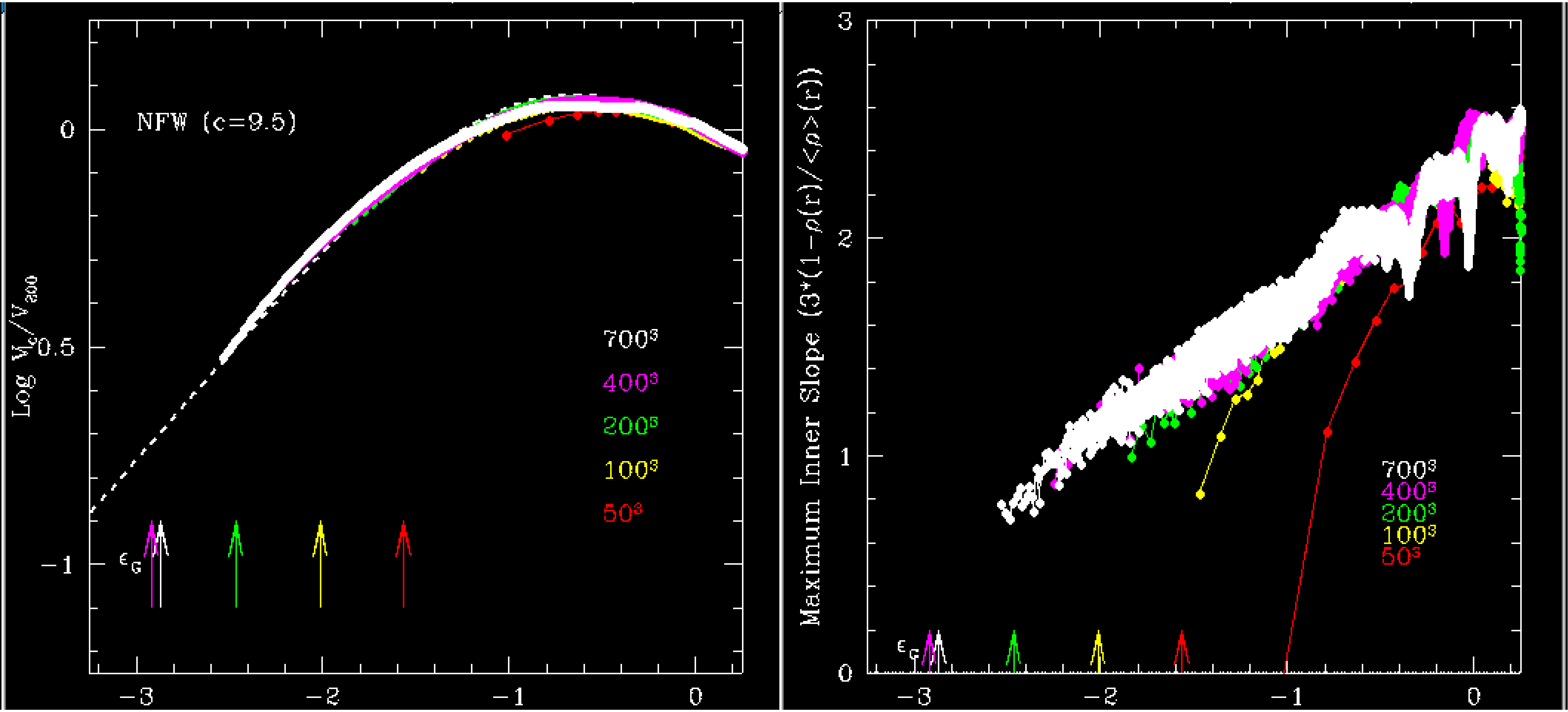


Convergence tests on density profile shape

Navarro et al 2006

DM profiles are converged to a few hundred parsecs

The inner asymptotic slope must be shallower than – 0.9



Dark Matter Annihilation

For certain kinds of Dark Matter particles

---Self-annihilation is possible
---Annihilation products will typically include γ-rays

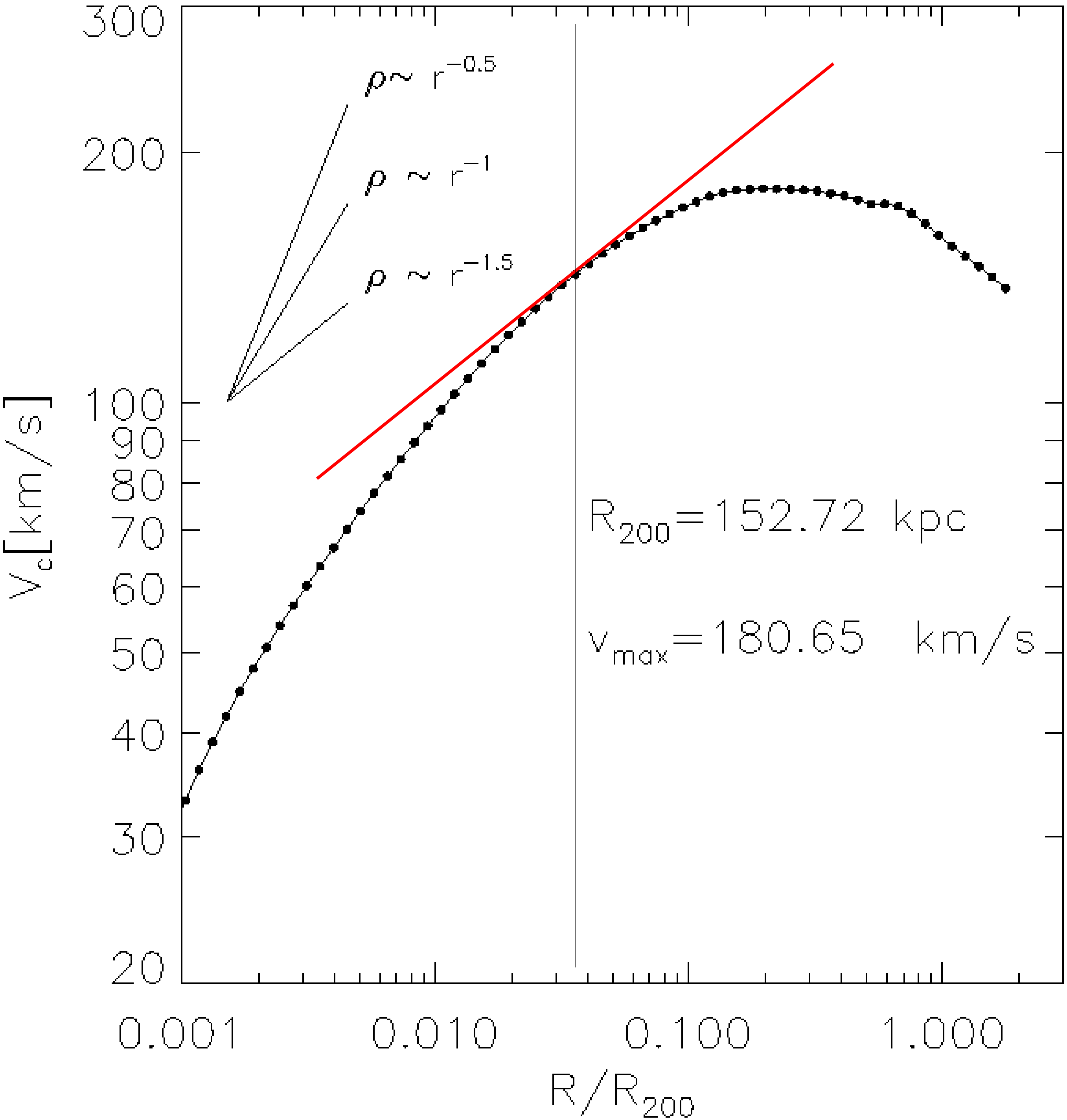
The luminosity density of annihilation emission is

$$\mathscr{L}(\mathbf{x}) \propto n_{\mathrm{DM}}(\mathbf{x})^2 \langle \sigma \, \mathrm{v} \rangle$$

Thus the γ-ray luminosity of an object is

$$L \propto \langle \sigma \, \mathrm{v} \rangle \int \rho^2 \, \mathrm{dV} \propto \langle \sigma \, \mathrm{v} \rangle \int \rho^2 r^2 \, \mathrm{d}r$$

→ critical density exponent for convergence is $\rho \propto r^{-1.5}$



- N_{200} =2.23 x 10^8
- Inner slope > -1
- Annihilation mainly from region where $\gamma \sim -1.5$ R ~ 5 kpc
- Baryonic effects will increase the DM density and thus the emission
- Central BH may cause substantial additional effect

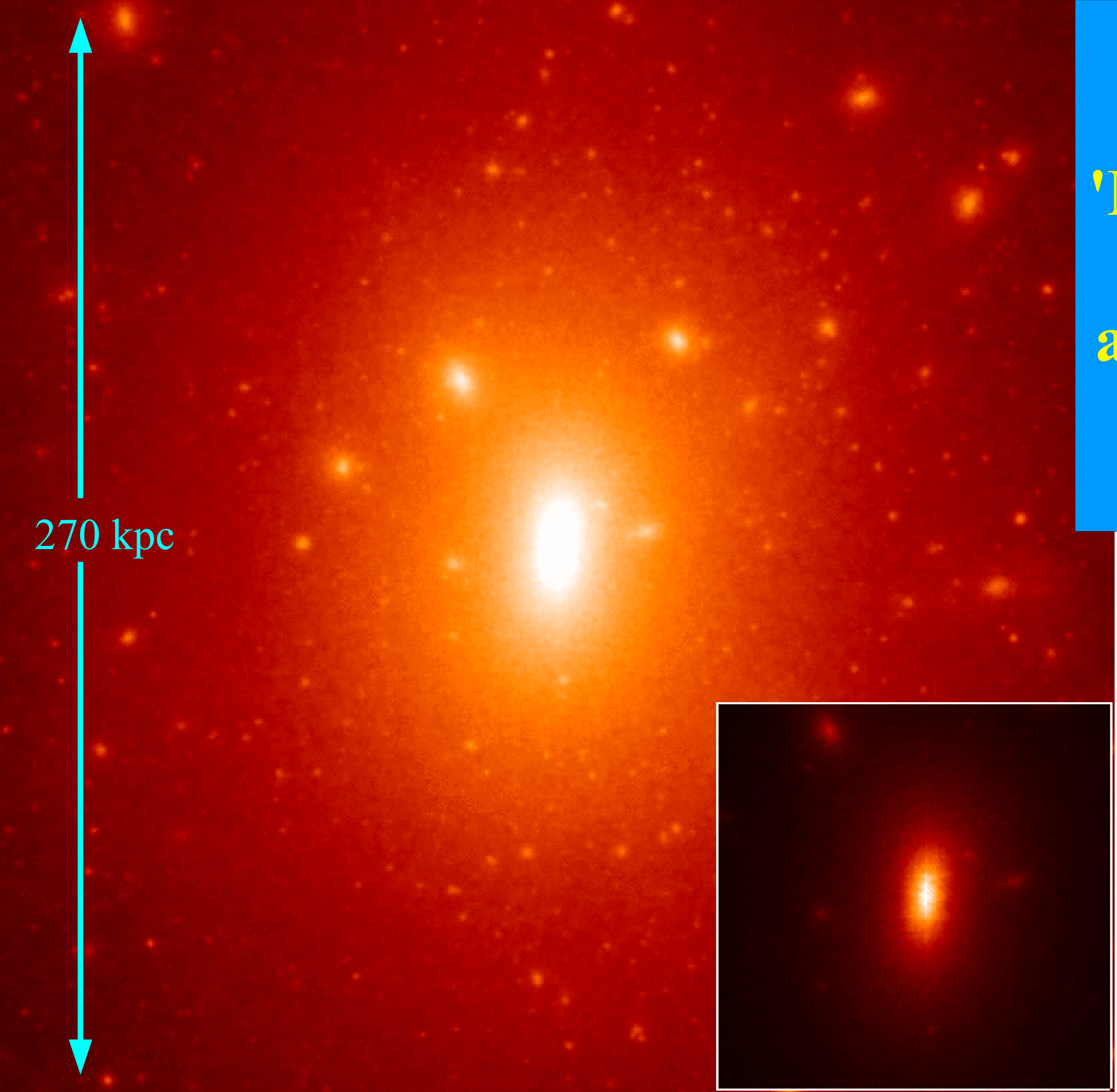


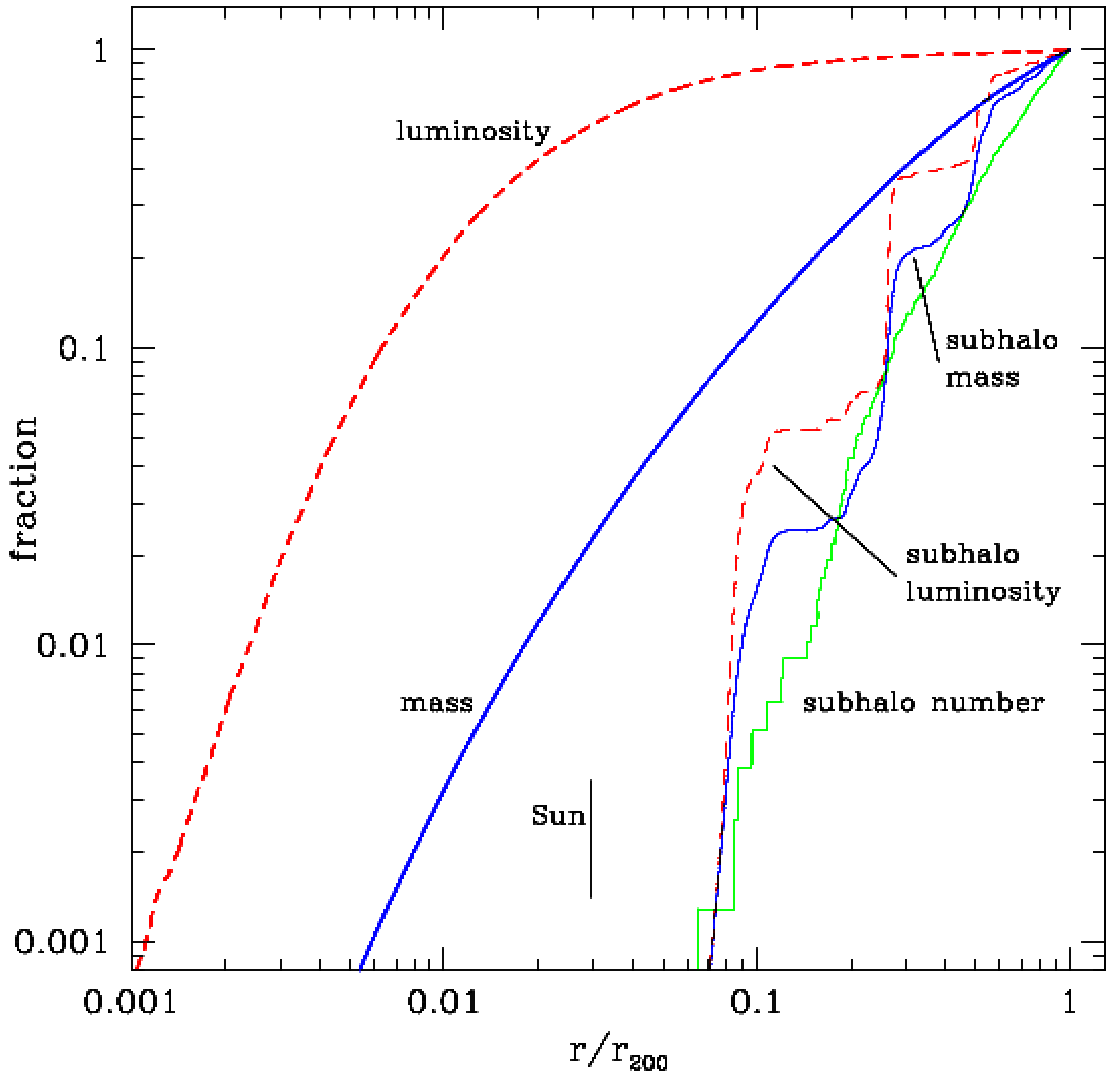
Image of a 'Milky Way' halo in annihilation radiation

Stoehr et al 2003

$$S(\boldsymbol{\theta}) \propto \int \rho^2 \, dl$$

Cumulative radial distributions of mass and light

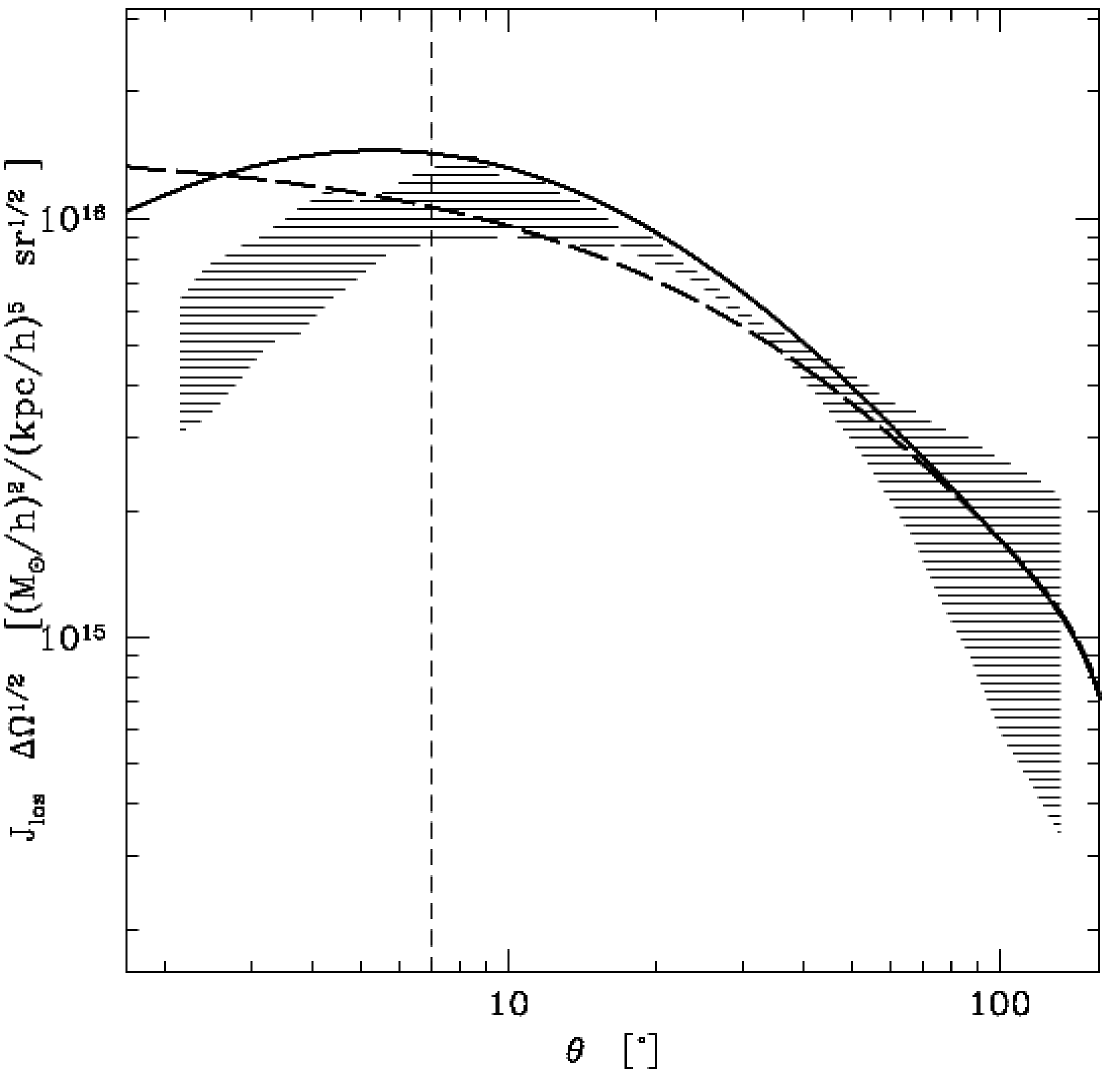
Stoehr et al 2003



- Half mass/light radii of the diffuse halo component are 90 kpc and 7 kpc
- Half mass/light radii of the subhalo component are both 130 kpc
- Total light from subhalo component is 25% that from the diffuse component
- The Sun is *much* closer to the peak of the diffuse emissivity than to a subhalo

→ Observed flux dominated by diffuse emission from inner Galaxy

Signal-to-noise of the simulated Milky Way as seen from the Sun's position

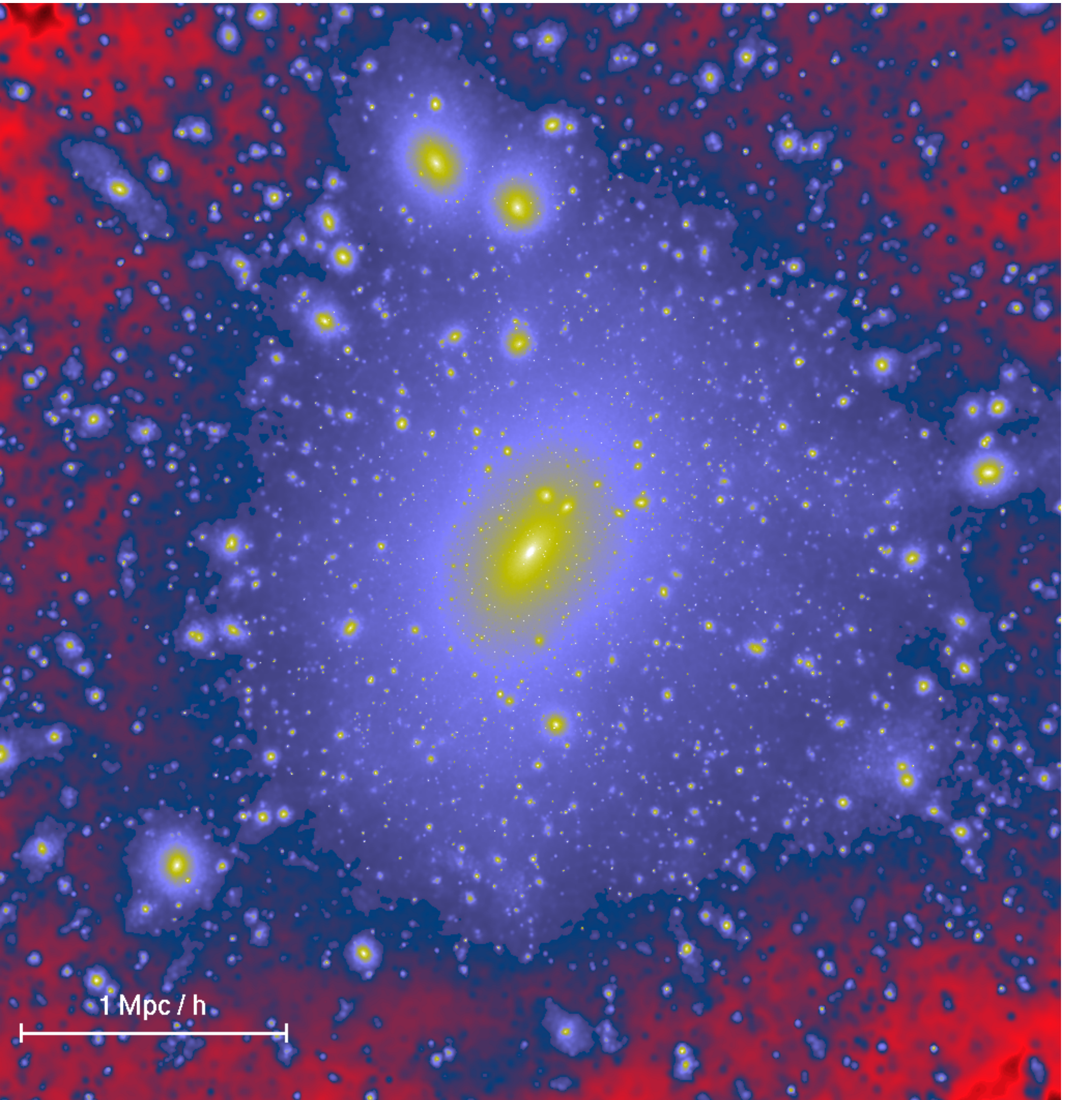


Stoehr et al 2003

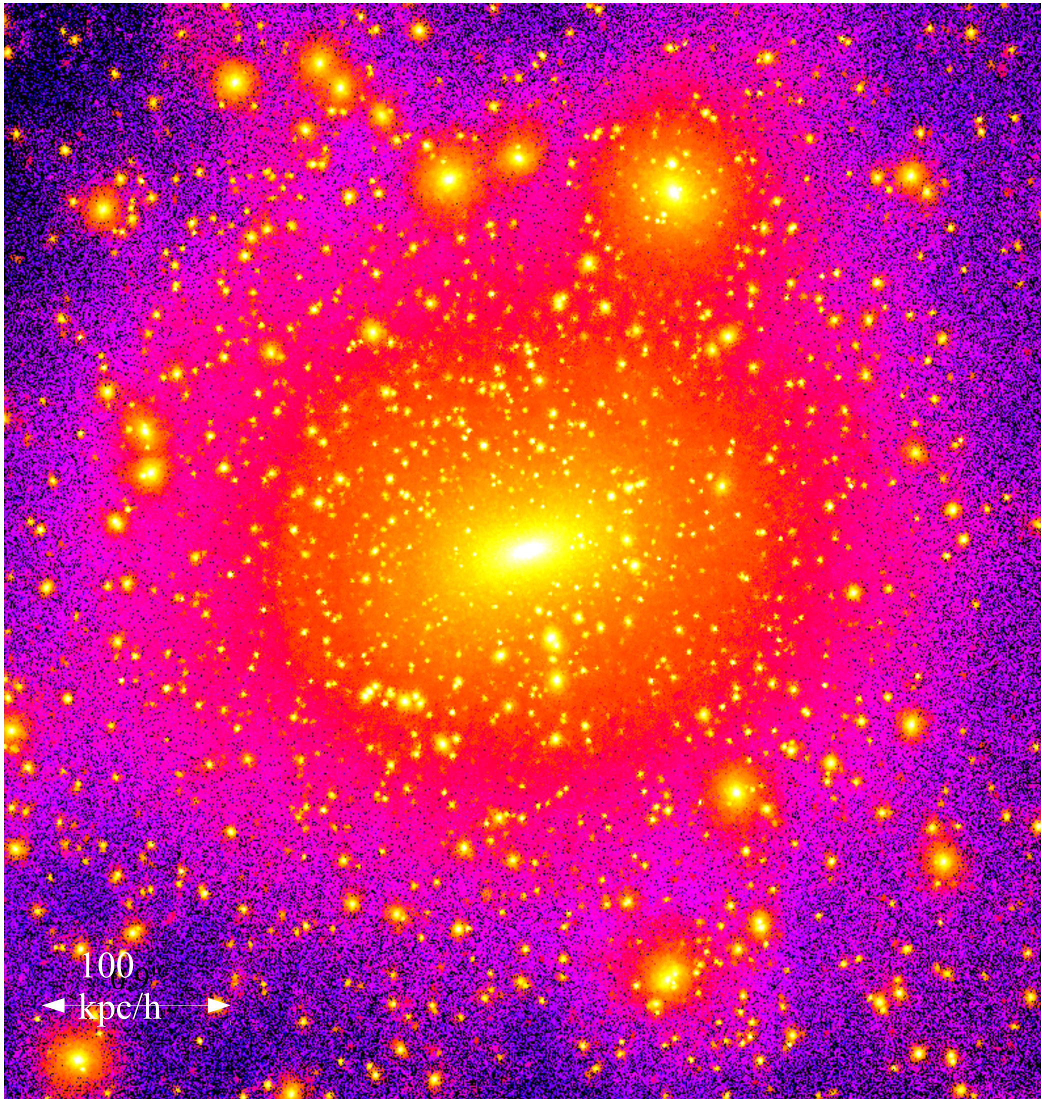
- Hatched area is scatter in circularly averaged signal-to-noise profiles for *wide beam* observation of 8 artificial skies assuming *uniform* background
- Heavy lines from analytic fits to the density profile
- Best S/N is achieved about at a radius of 10 degrees
- At this radius simulation is secure and backgr'd is *lower* than nearer the centre

Small-scale structure in ΛCDM halos

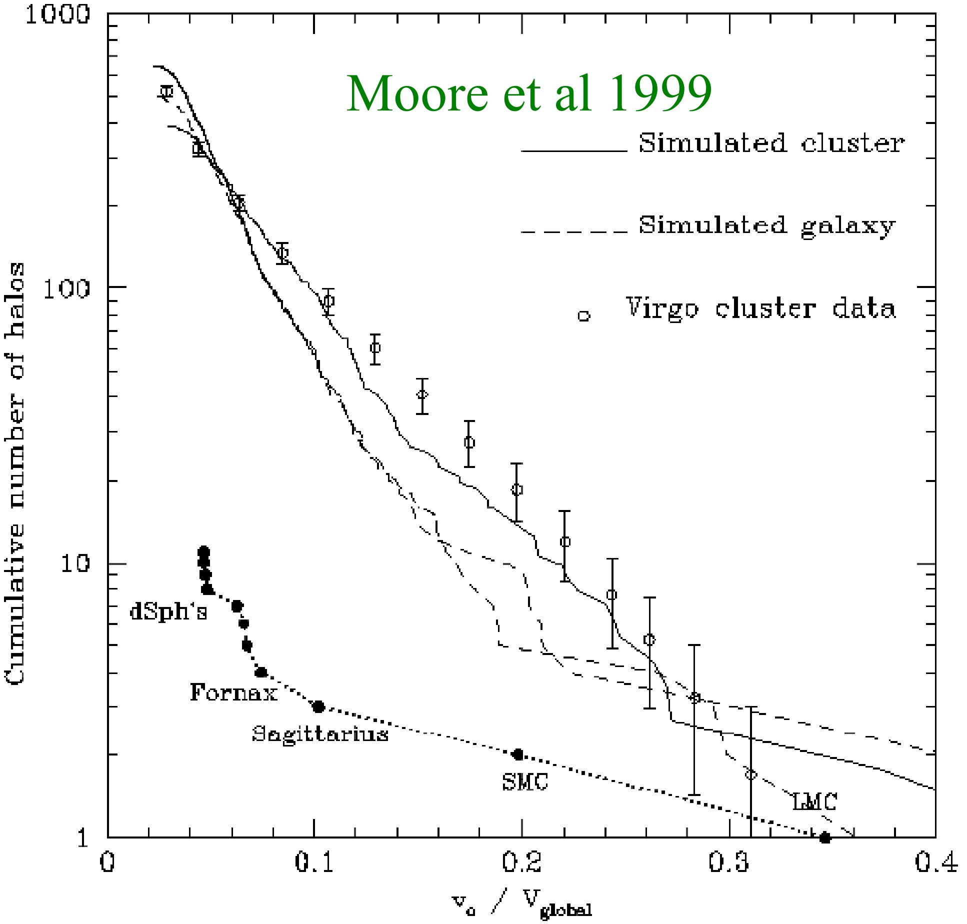
A rich galaxy cluster halo
Springel et al 2001

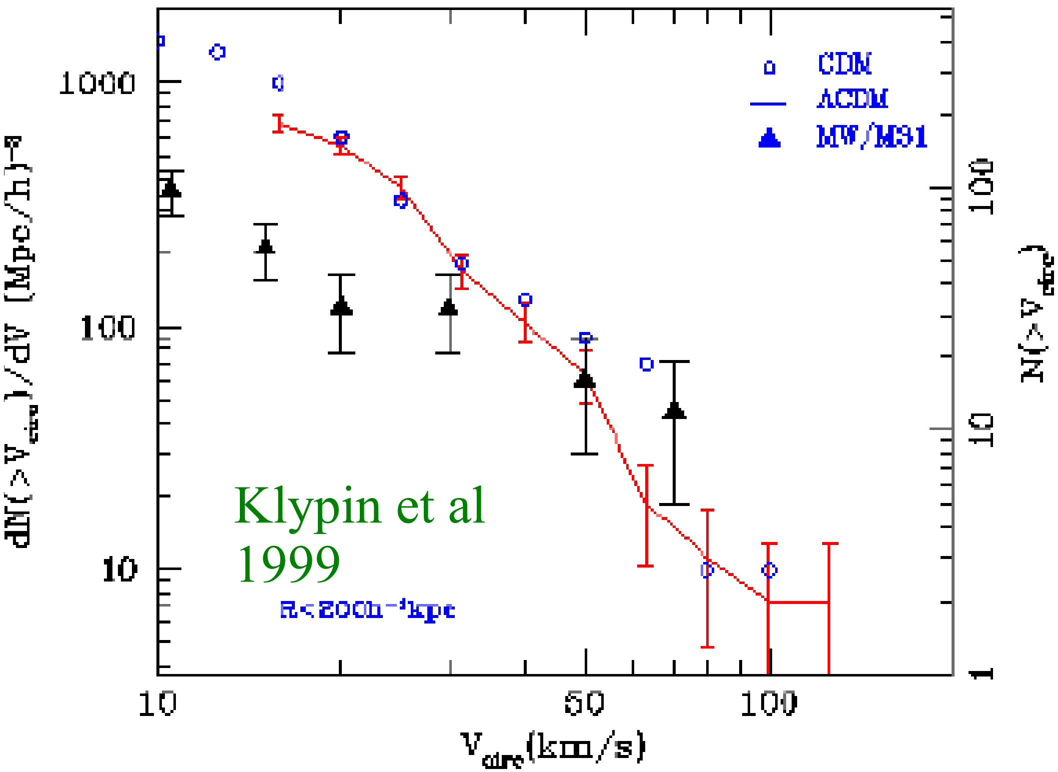


A 'Milky Way' halo
Power et al 2002



Is the kinematics of the Milky Way's satellites inconsistent with ΛCDM substructure?

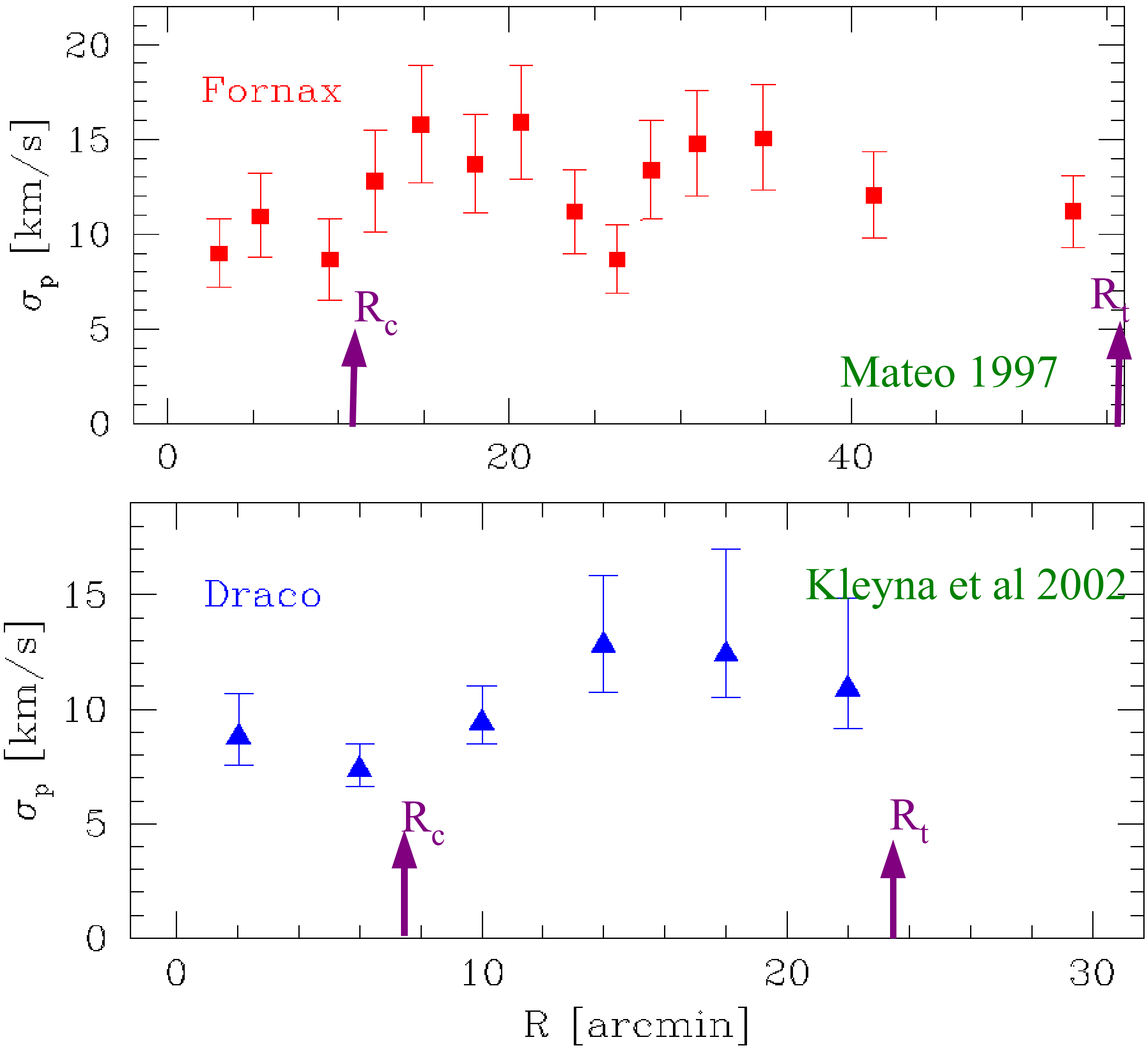




- Number of observed satellites was ***claimed*** to be ~1/30 the number of ΛCDM satellites with the same max. circular velocity $V_c = (GM/r)^{1/2}$
- But the MW data are plotted at the ***incorrect*** values of V_c for this test!

Stoehr et al 2002

Dark Matter within Satellites



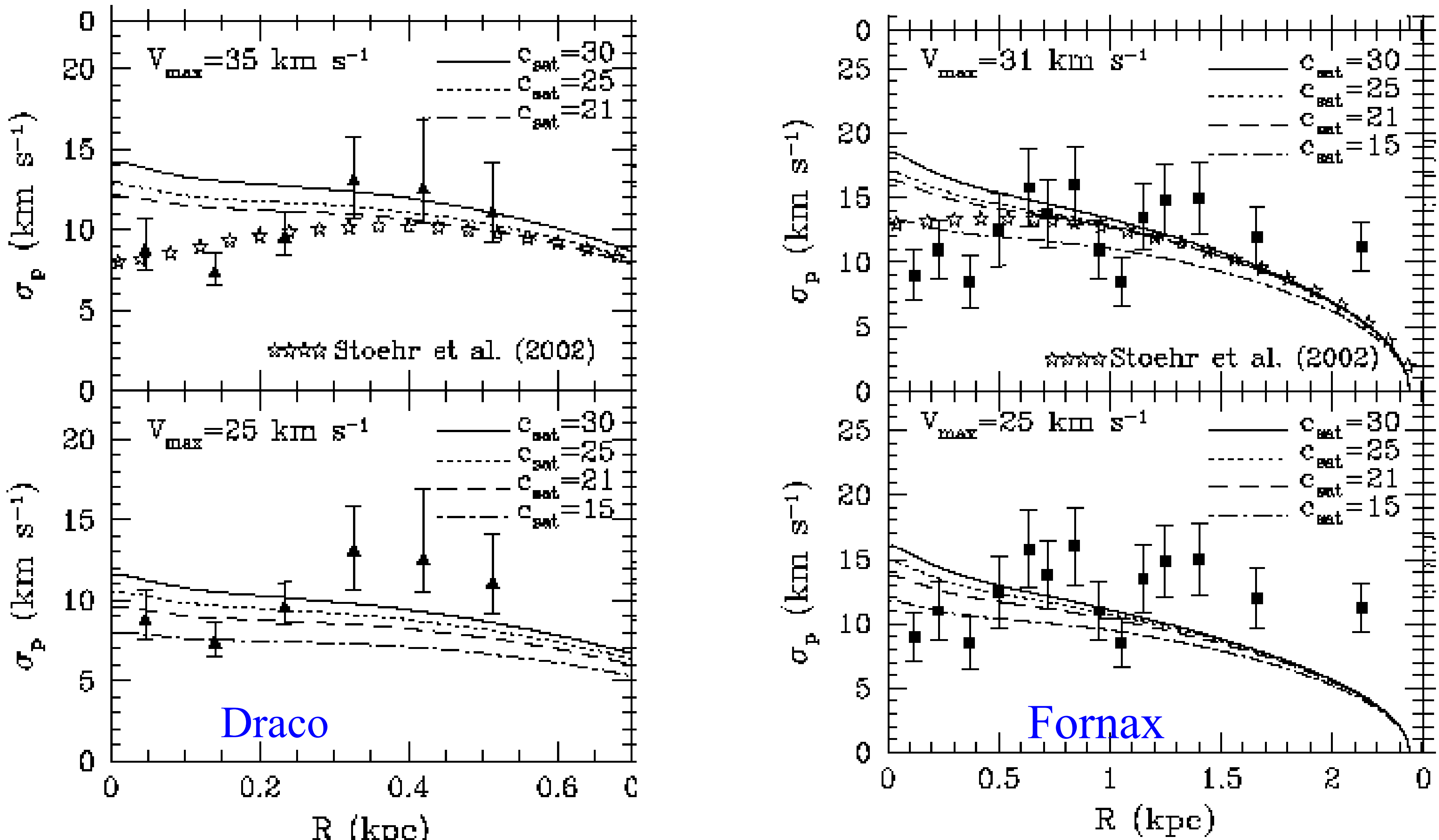
- Flat stellar velocity dispersion out to the tidal radius
  → *rising* V_c curve
- Extended DM halos?
- High DM phase density? ~~*WDM*~~ ?
- $V_{c,max} \gtrsim$ 25 km/s ?
- Critical observation: extratidal stars?

DENSITY PROFILES OF COLD DARK MATTER SUBSTRUCTURE: IMPLICATIONS FOR THE MISSING-SATELLITES PROBLEM

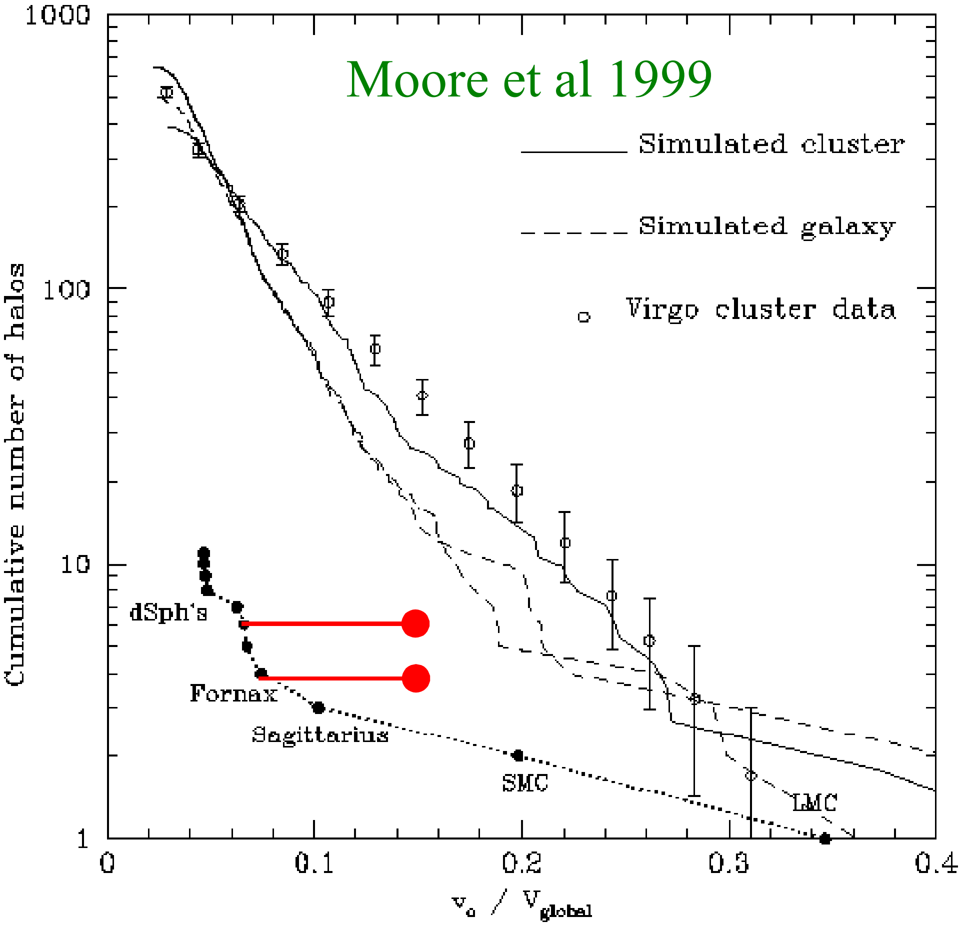
2004 (ApJ)

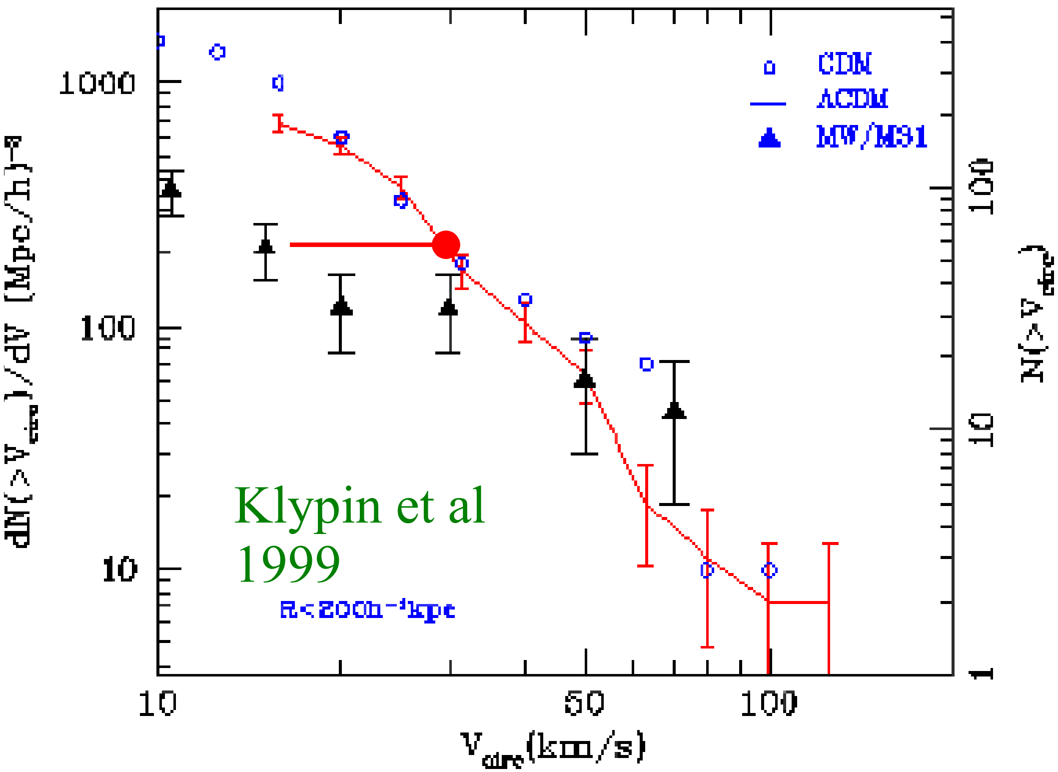
STELIOS KAZANTZIDIS[1], LUCIO MAYER, CHIARA MASTROPIETRO, JÜRG DIEMAND, JOACHIM STADEL, AND BEN MOORE

Motivated by the structure of our stripped satellites, we compare the predicted velocity dispersion profiles of Fornax and Draco to observations, assuming that they are embedded in CDM halos. We demonstrate that models with isotropic and tangentially anisotropic velocity distributions for the stellar component fit the data only if the surrounding dark matter halos have maximum circular velocities in the range $20 - 35\ \mathrm{km\,s^{-1}}$.

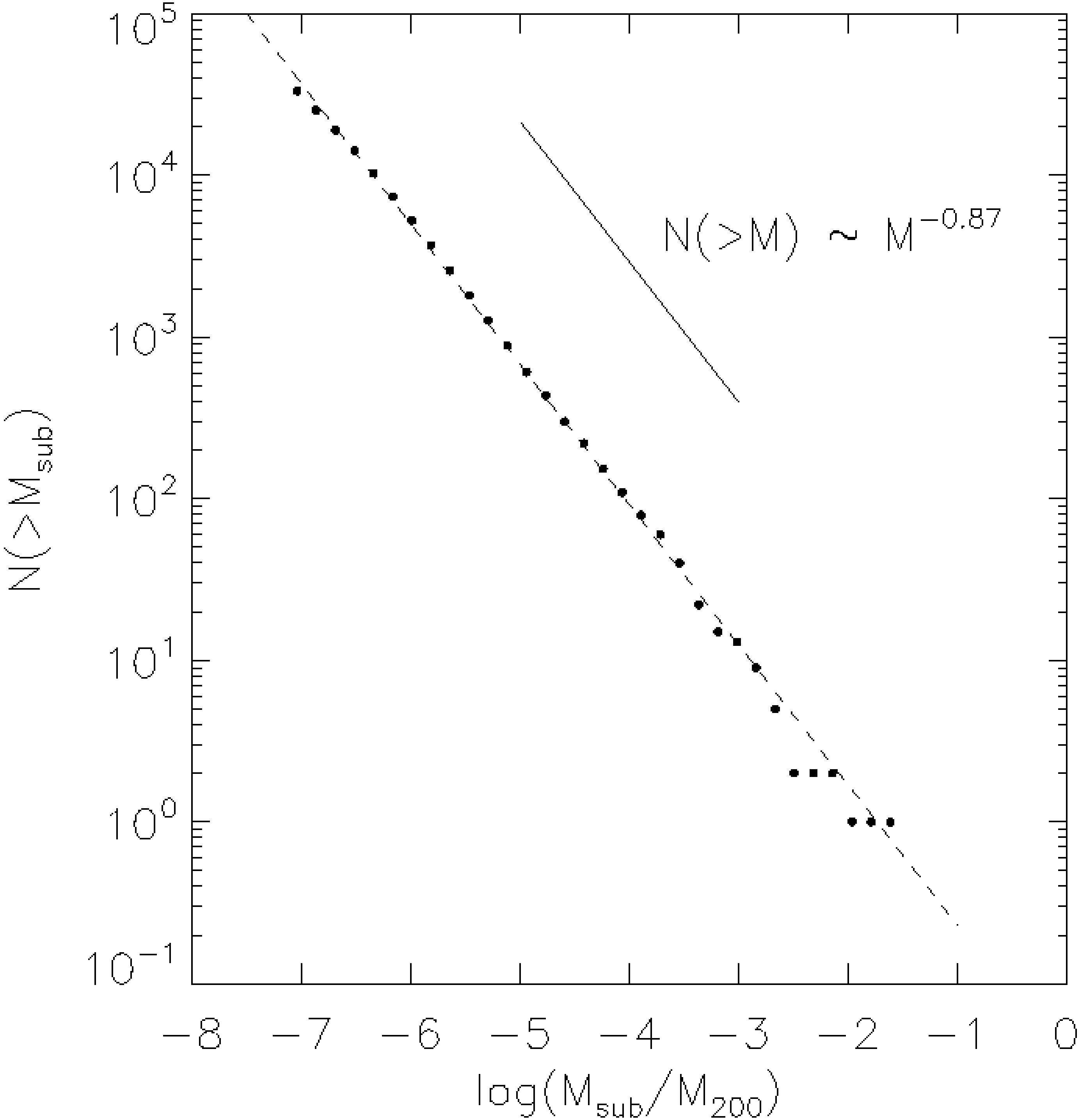


Inconsistency with observed satellite kinematics?

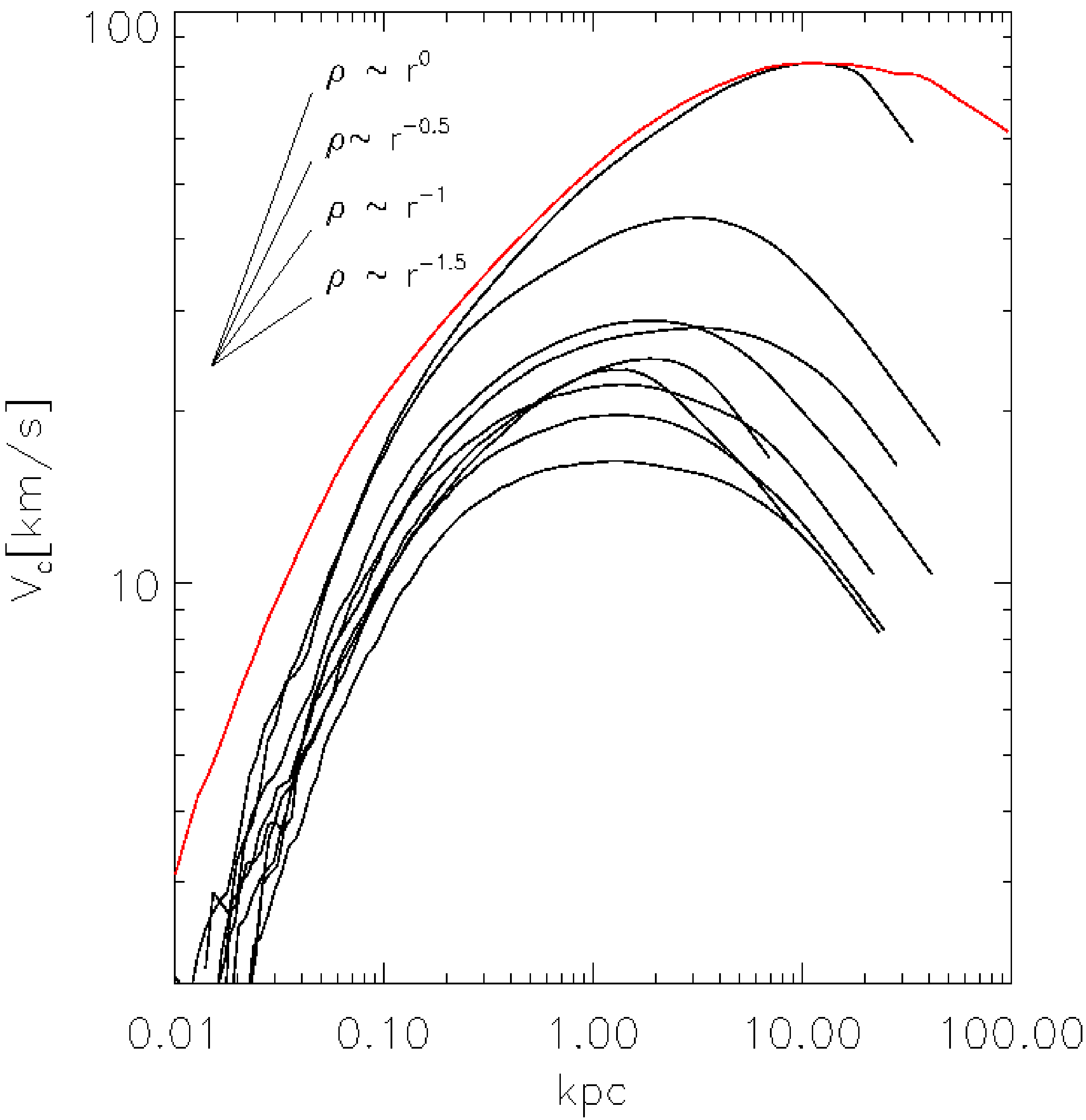




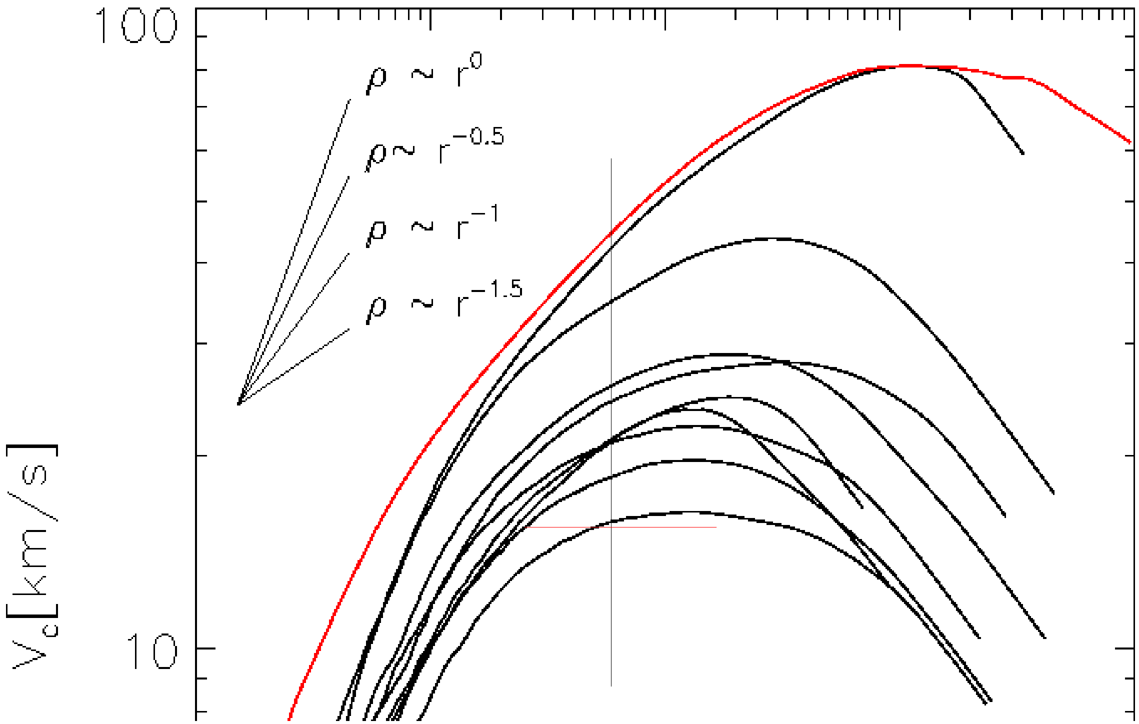
- Inconsistency is much less dramatic when one uses the *limiting* circular velocity inferred from the velocity dispersion profiles
- The *maximum* of the DM circular velocity profile may be outside the visible galaxy and still larger (plots show shift to V_{max} = 30 km/s)

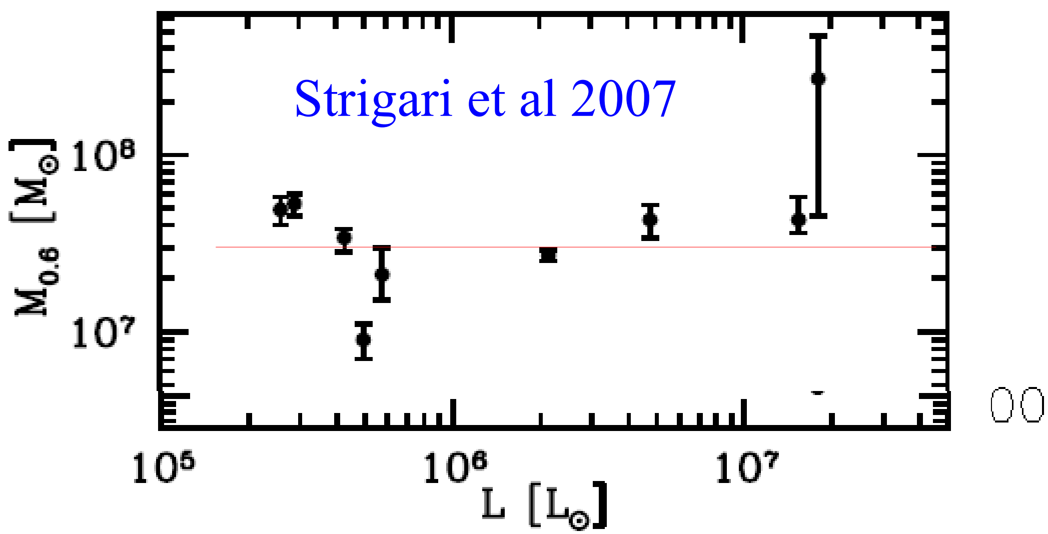


- $N_{200} = 2.23 \times 10^8$
- >30,000 subhalos
- 8% of mass within R_{200} in subhalos
- Total subhalo mass (weakly) convergent as $m_{sub} \rightarrow 0$



- Circular velocity curves for 9 of the 30 most massive subhalos
- The 'main halo' curve is scaled to the (r_m,V_m) of largest subhalo
- The maximum circular velocities are at radii outside observed satellites
- Shape inside r_m is similar to that of main halo
- Inner core *still* not well enough resolved to predict total annihilation radiation





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All but one of 11 well observed satellites could be in these subhalos

ΛCDM on the scale of a DM detector

Helmi & White 1999, Vogelsberger & White 2007

For effectively collisionless DM: $\frac{D}{Dt} f(\mathbf{x}, \mathbf{v}, t) = 0$

i.e. phase-space density preserved along orbit of each particle

Initial phase-space density is effectively 3-dimensional

→ current DM distribution is a superposition of 3-d "sheets" in local ($\mathbf{x}, \mathbf{v}$) space near the Sun

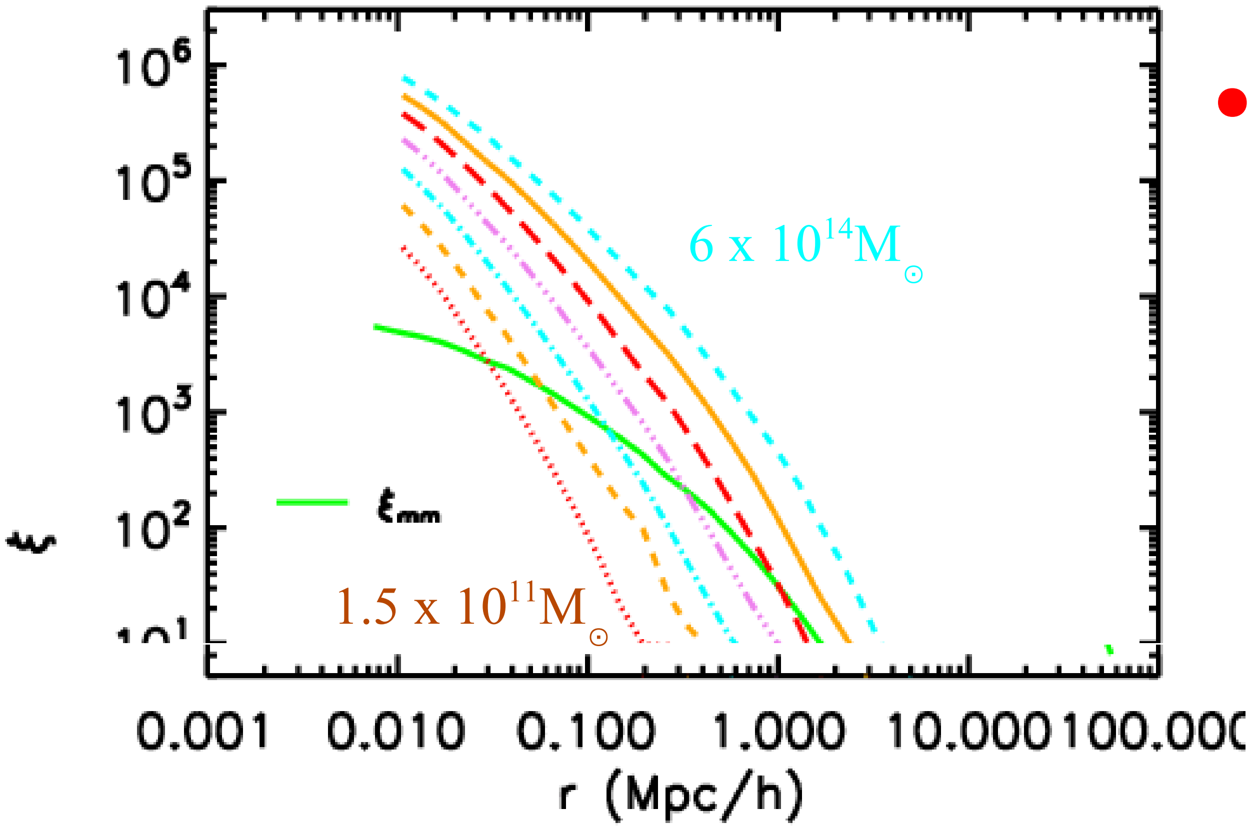
3-d density of each sheet decreases with time as $\sim (1 + t / t_{orb})^{-3}$

→ up to 10^5 sheets near the Sun

→ a Schwarzschild-like distribution
weak caustics

Density profile shapes at large radii

Hayashi et al 2007



- Mean density profiles of halos of given M_{200} are well fit down to overdensities of 10 by the fitting formula of Navarro et al (2004)

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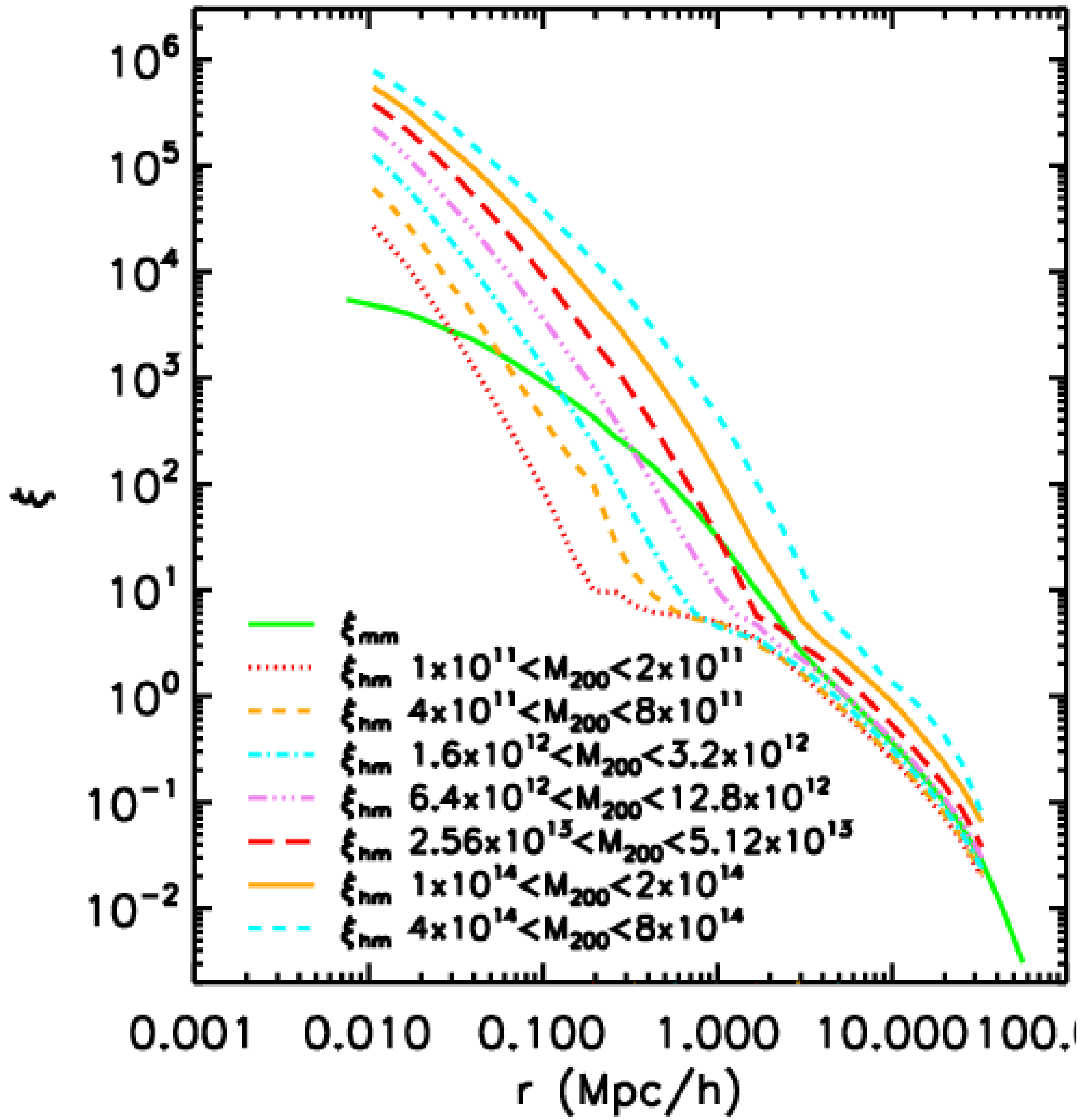

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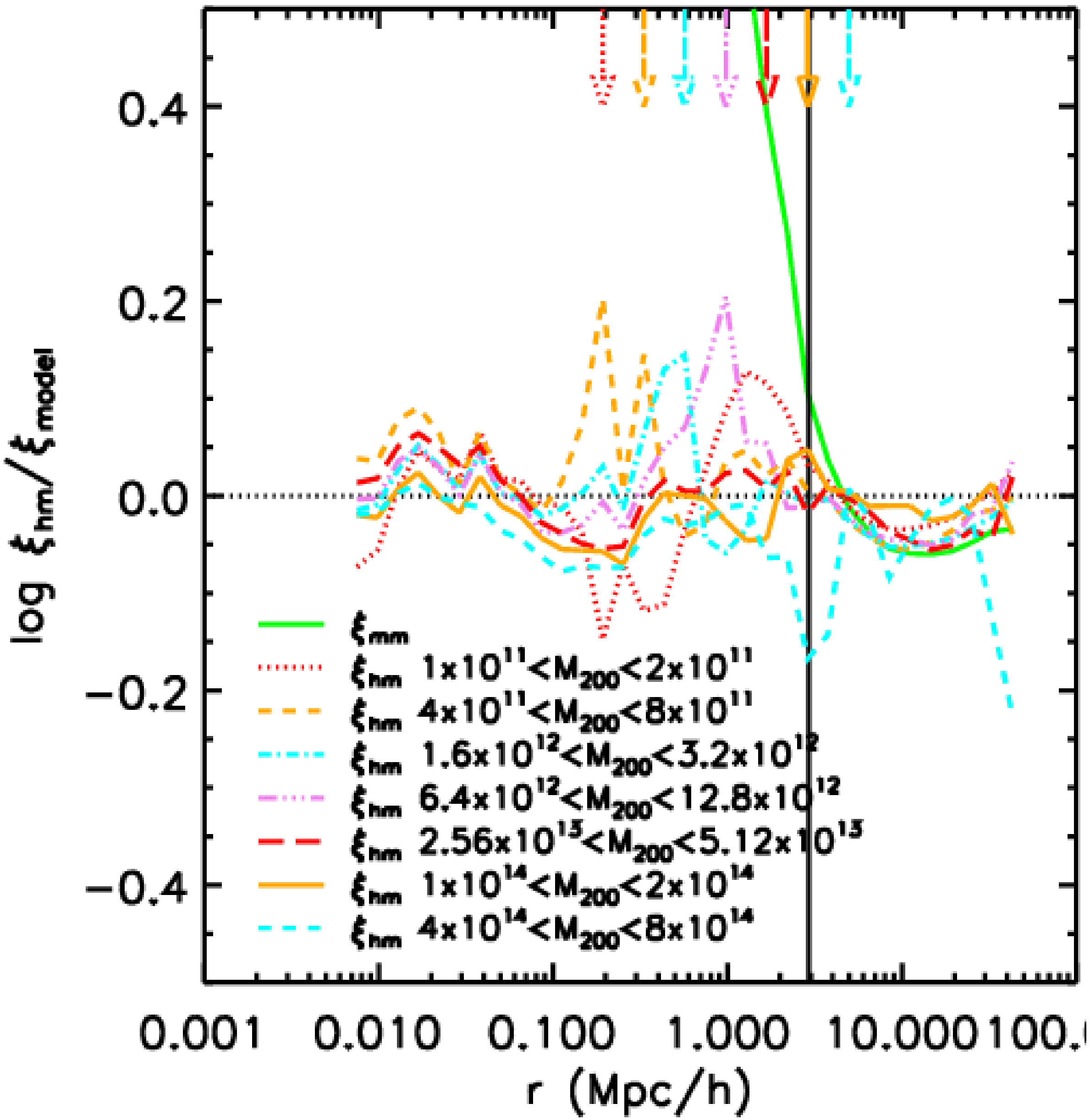

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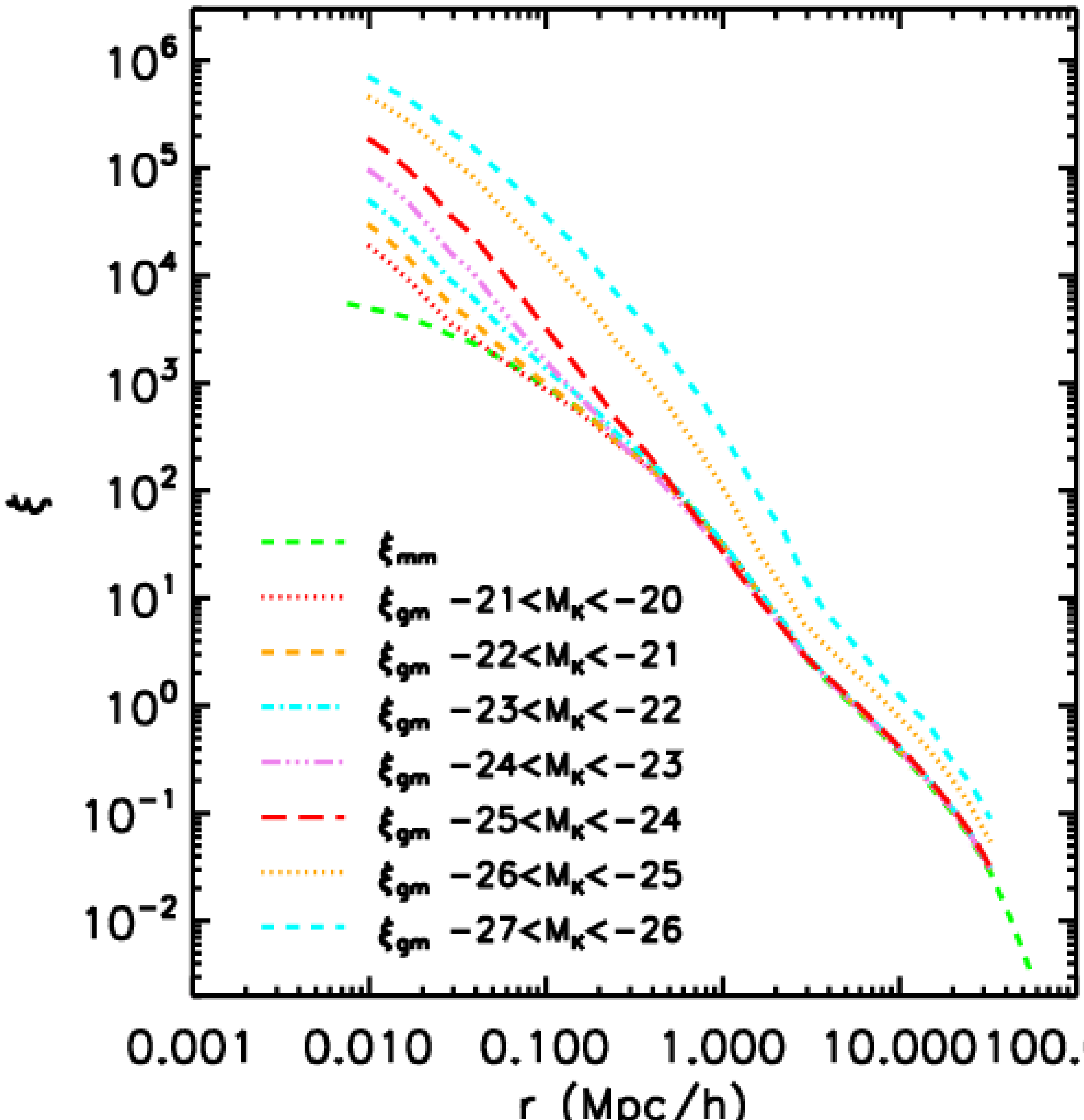
Galaxy-mass cross-correlations to large radii

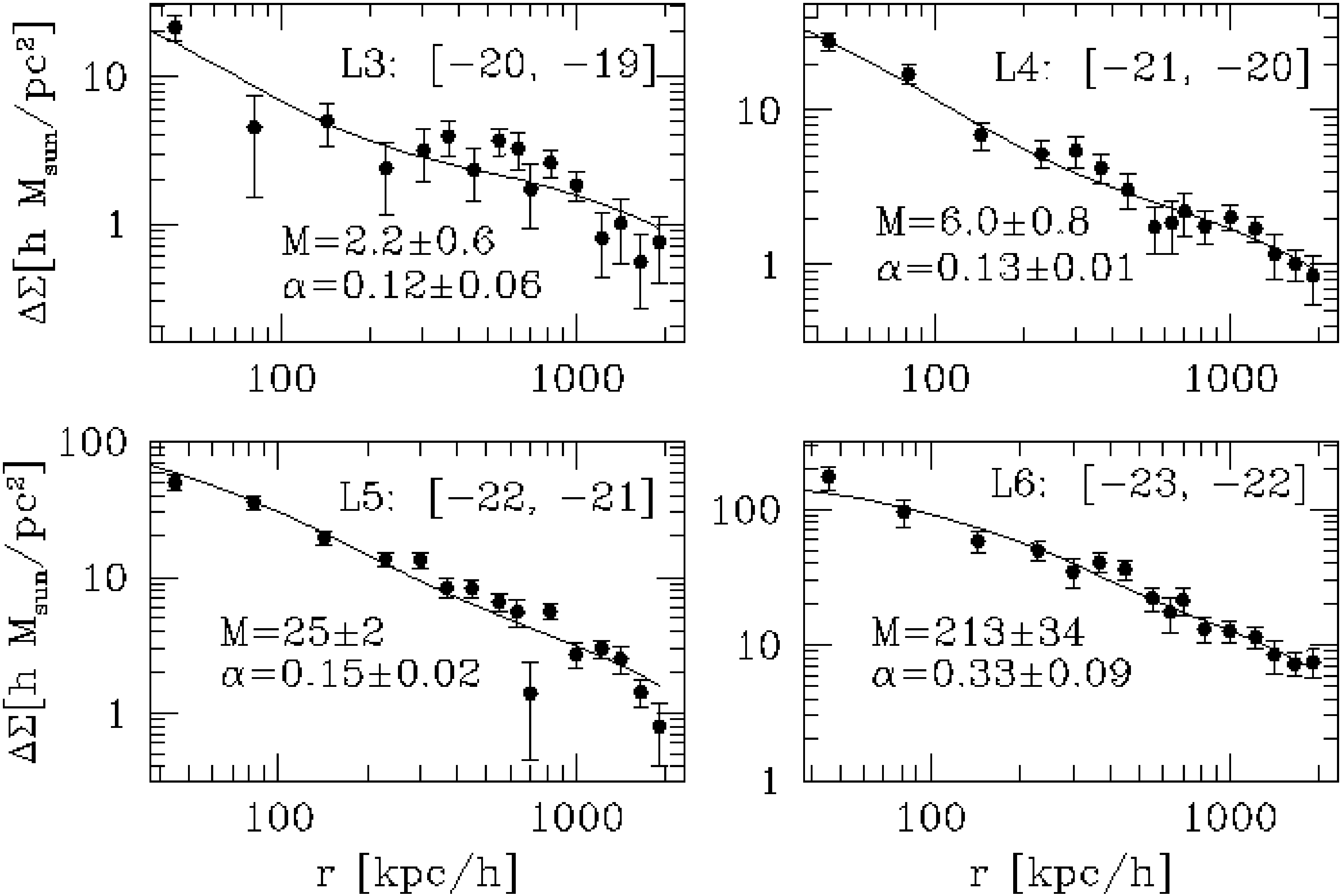
Hayashi et al 2007

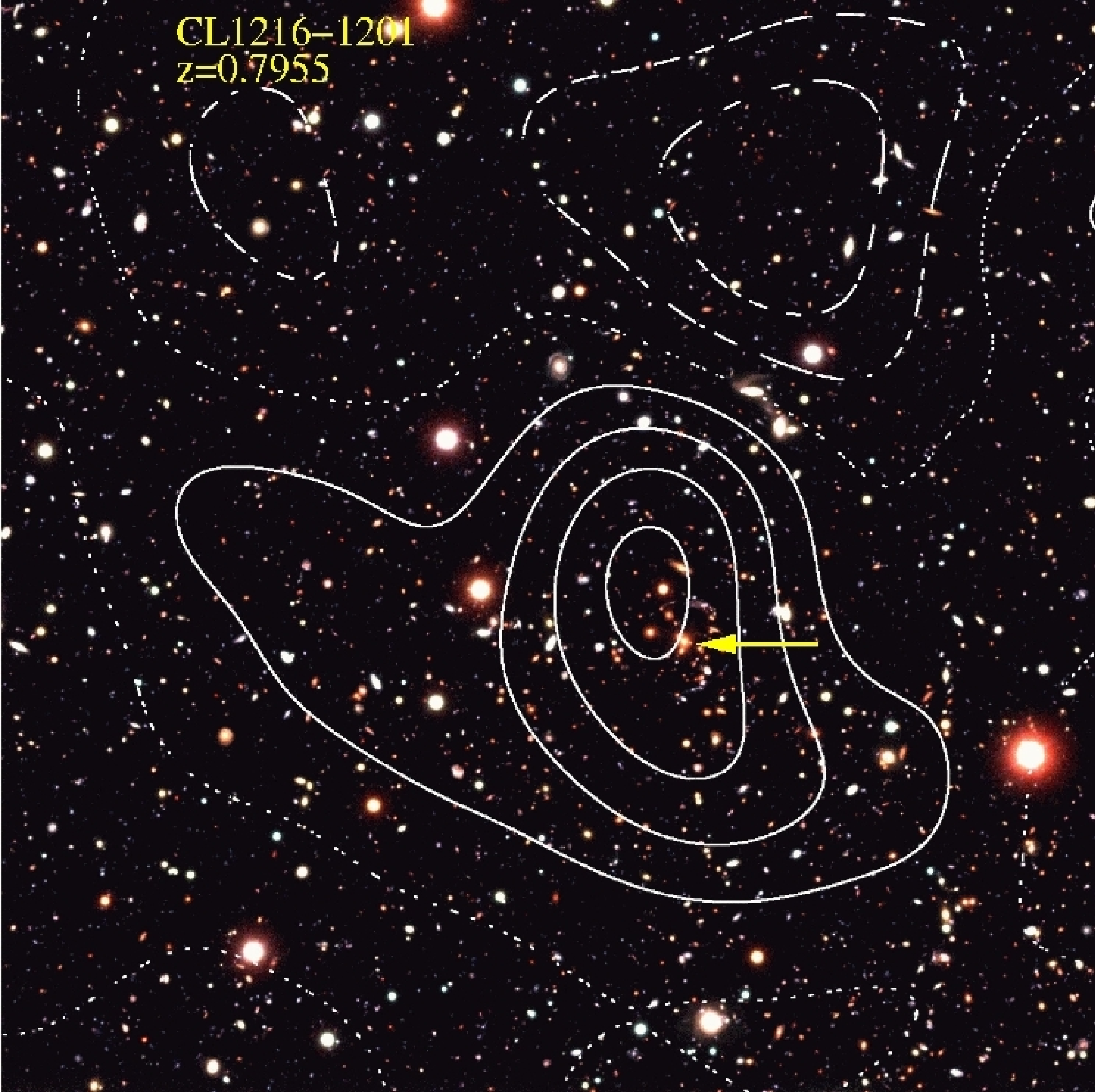


- Galaxy mass cross-correlations are directly measurable through galaxy-galaxy lensing
- They can be predicted from an HOD model and mean halo mass profiles
- Here they are predicted with the Croton et al gal. formation simulation
- On large scale they follow the *nonlinear* ξ_{mm}

Weak lensing measures of halo mass profiles

Seljak et al 2004: from SDSS



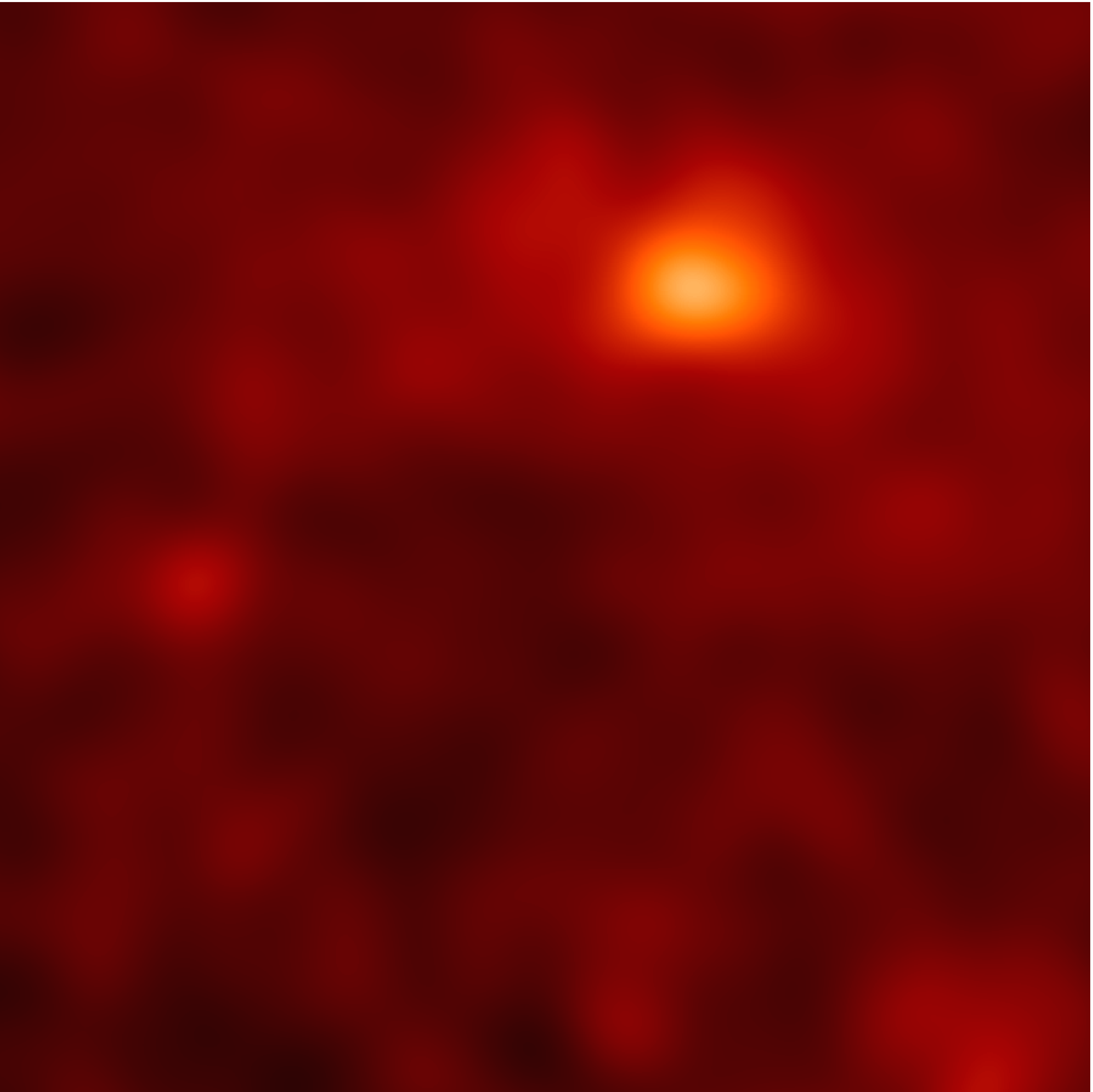


Clowe et al 2006

High redshift with strong lensing

σ_{clus}=1034±46

from measured redshifts



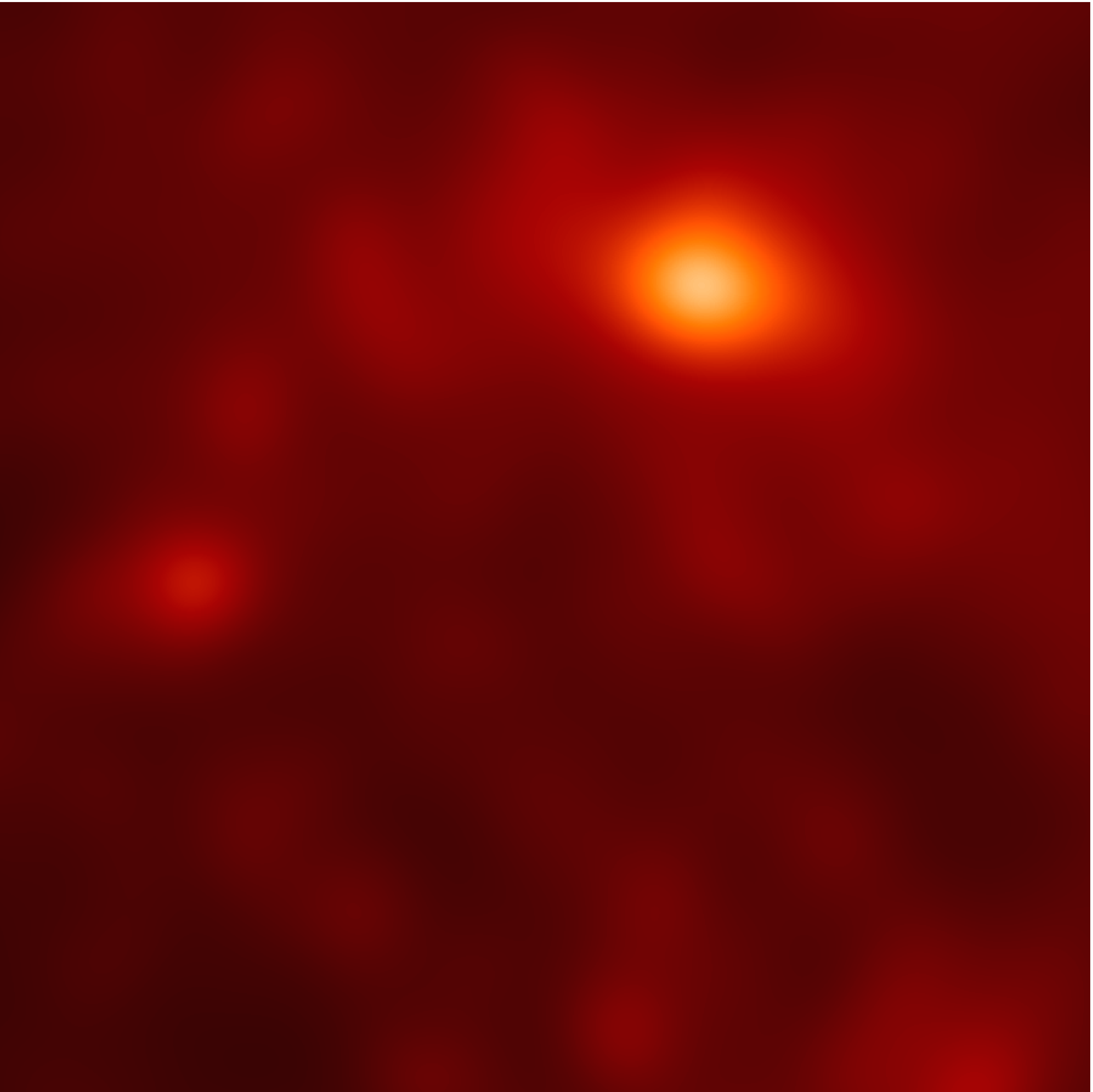
15 arcmin square

$\bar{z}_{source} = 1.2$

$\theta_{res} = 30''$

100 gals/
squ.arcmin

reconstruction
noise *in*cluded



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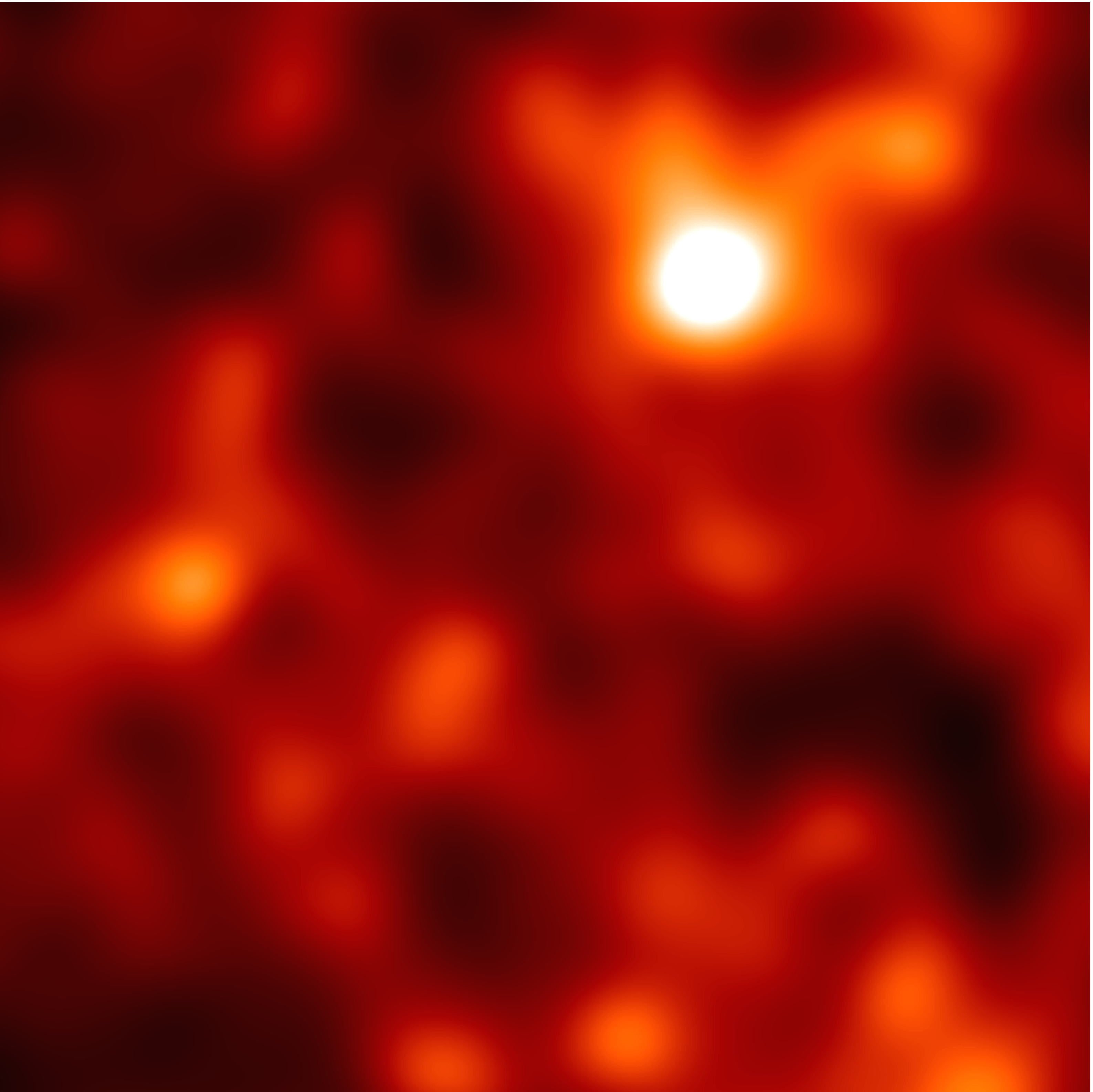

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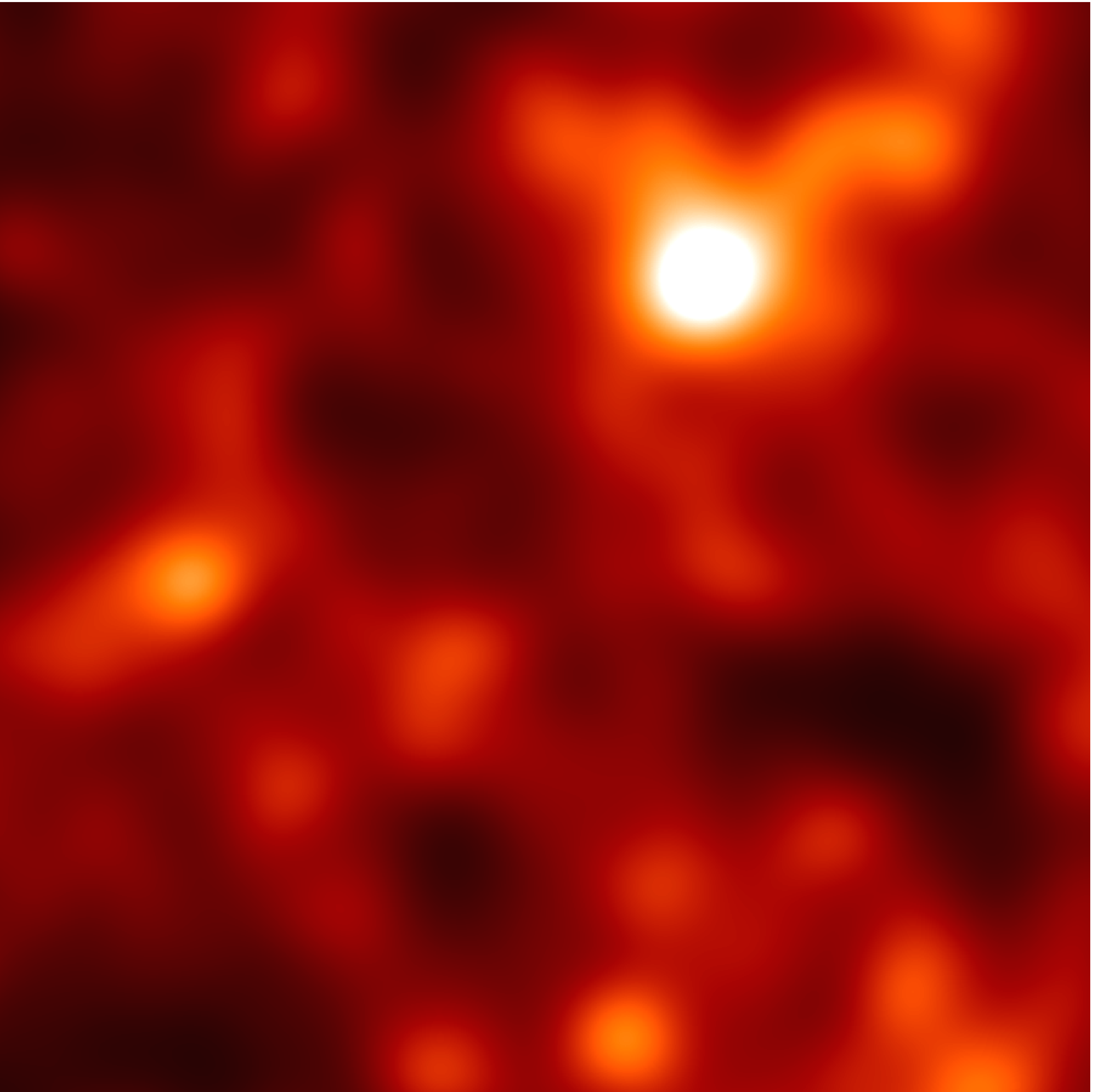
SKA 21cm survey

reconstruction noise *in*cluded



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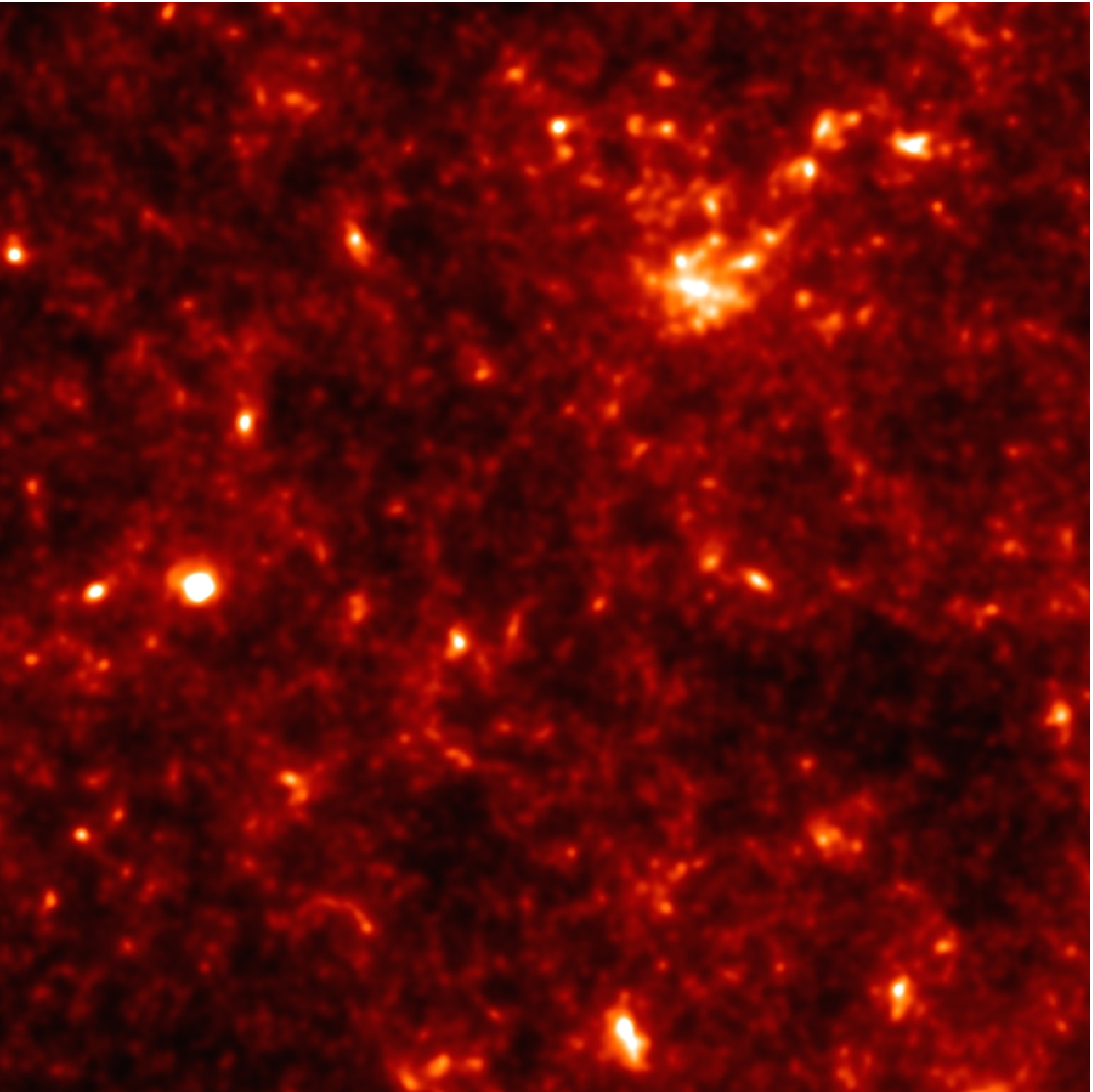

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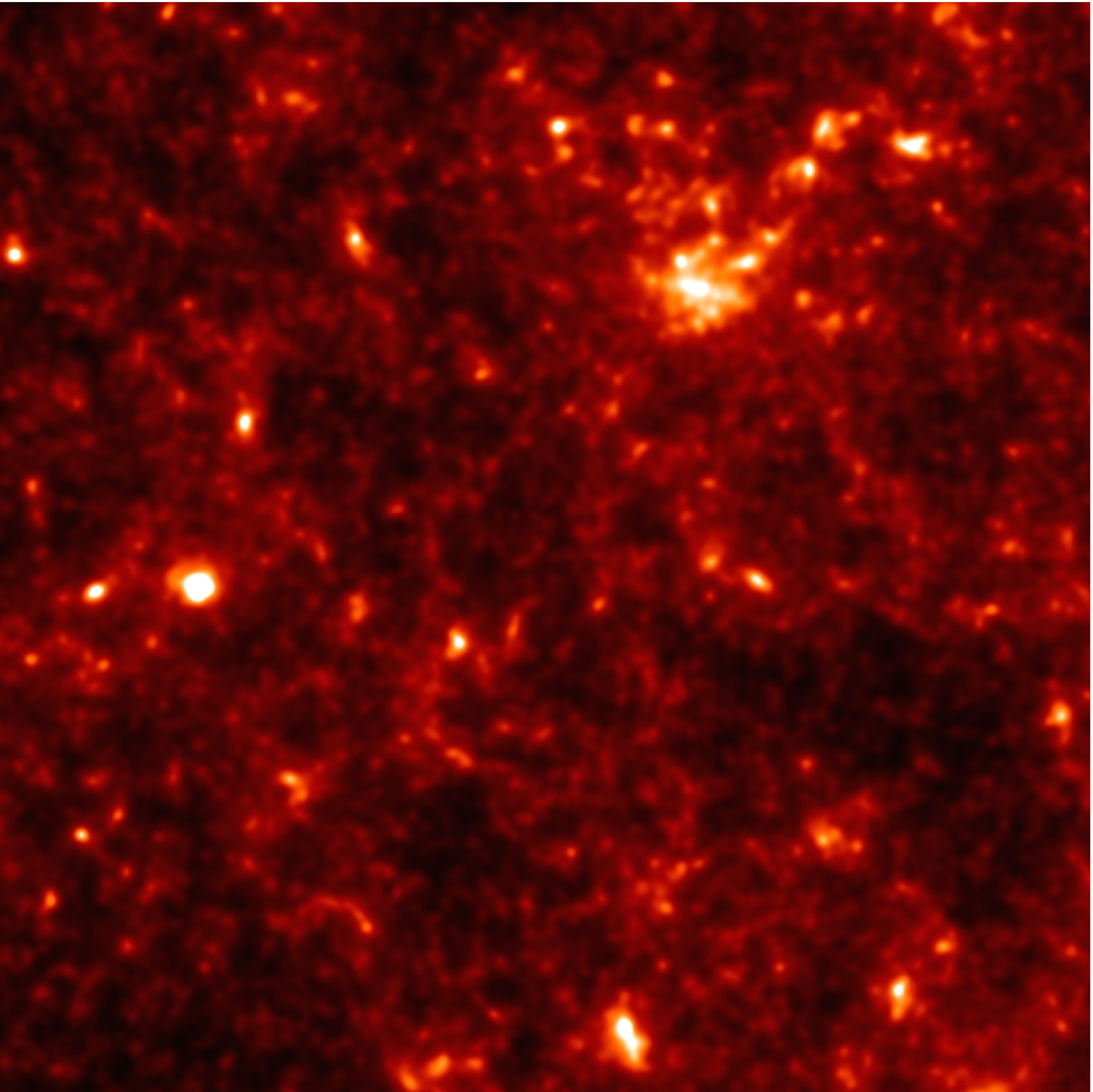
"super"-SKA
21cm survey

reconstruction
noise *in*cluded



15 arcmin square

$z_{source} = 15$

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"super"-SKA
21cm survey

reconstruction
noise *ex*cluded

CONCLUSIONS

- The observed properties of Galactic satellites are not in conflict with the substructure predicted in CDM models → astrophysics!
- Dark matter should be smoothly distributed on small scales with a Schwarzschild-like (multivariate gaussian) velocity distribution
- Substructures and caustics should be subdominant sources of annihilation radiation
- Annihilation radiation should be most easily detected over a large area $\sim 10^{o}$ away from the Galactic Centre and at high latitude
- Galaxy-galaxy lensing can (by stacking signal) detect the mean shapes and profiles predicted for DM halos
- Lensing of 21cm from prerecombination HI could image the DM distribution over the whole sky with high fidelity and resolution