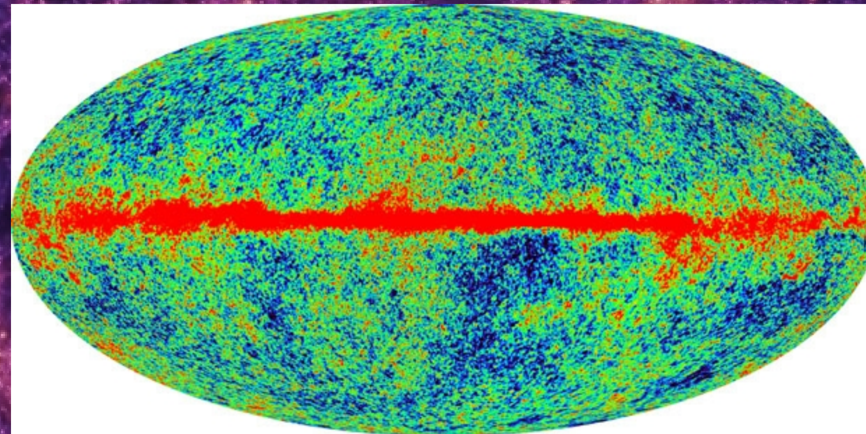
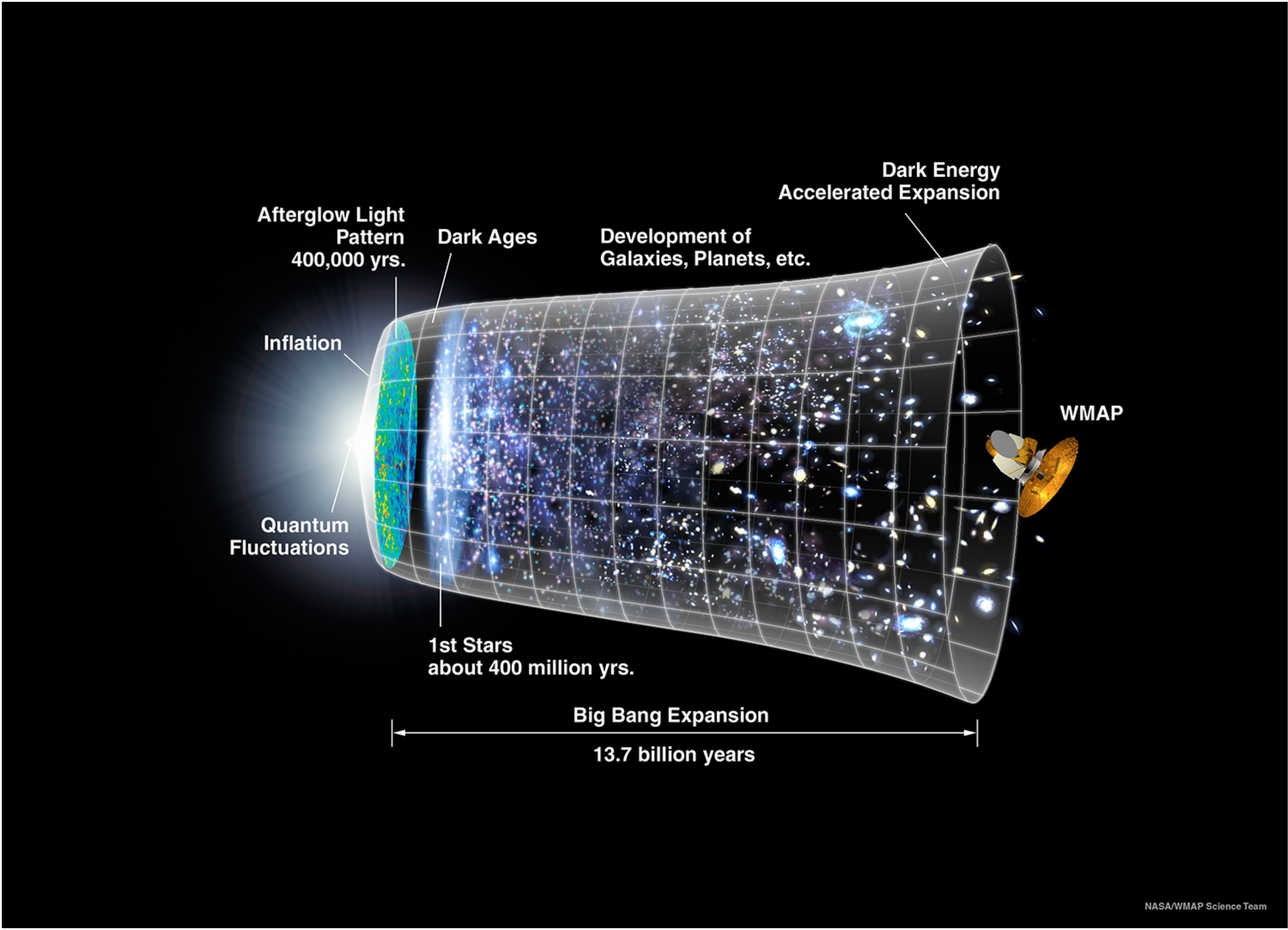


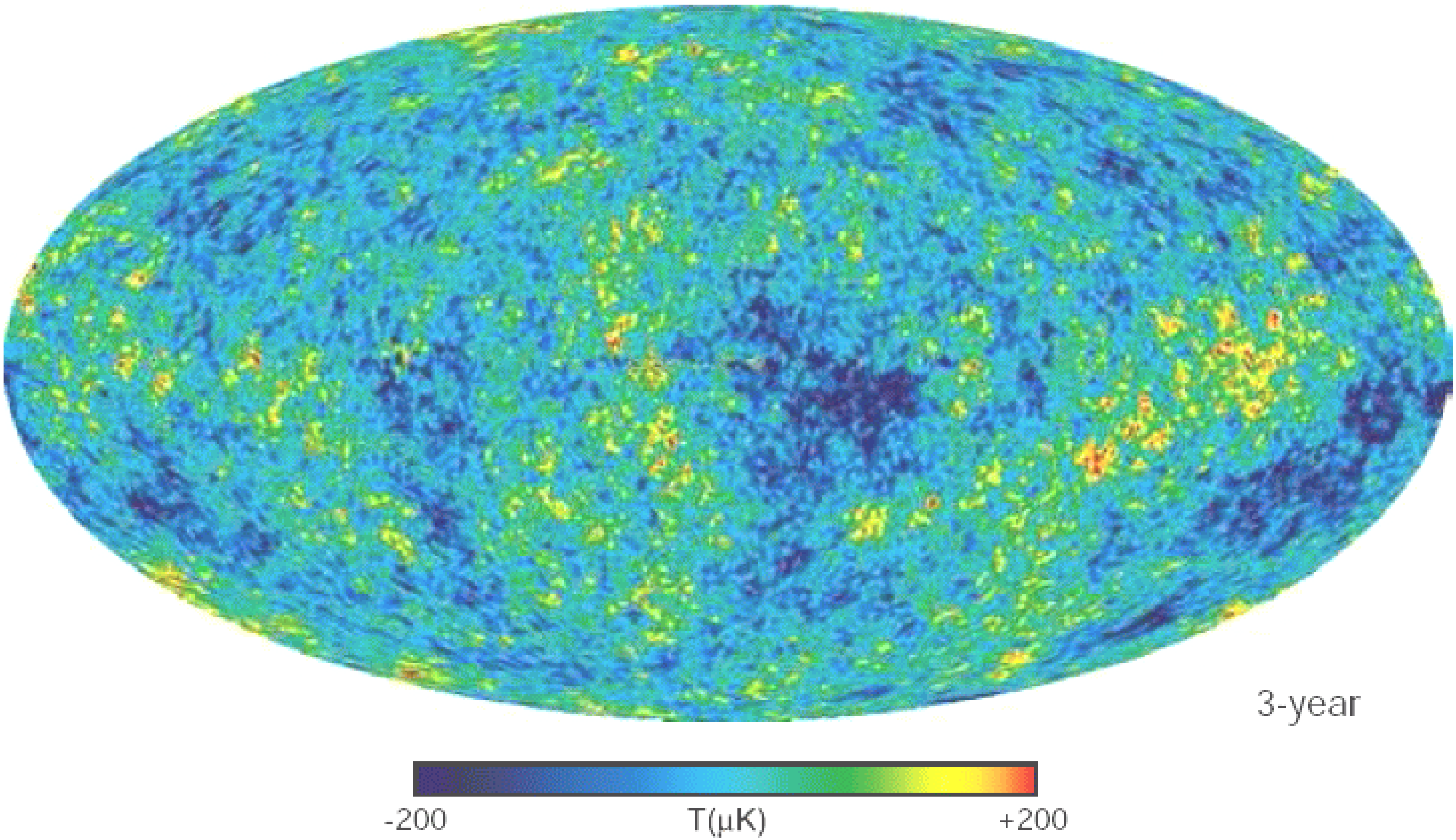
Structure formation in the Universe,
Chamonix,
May 2007

Structure formation in the concordance cosmology

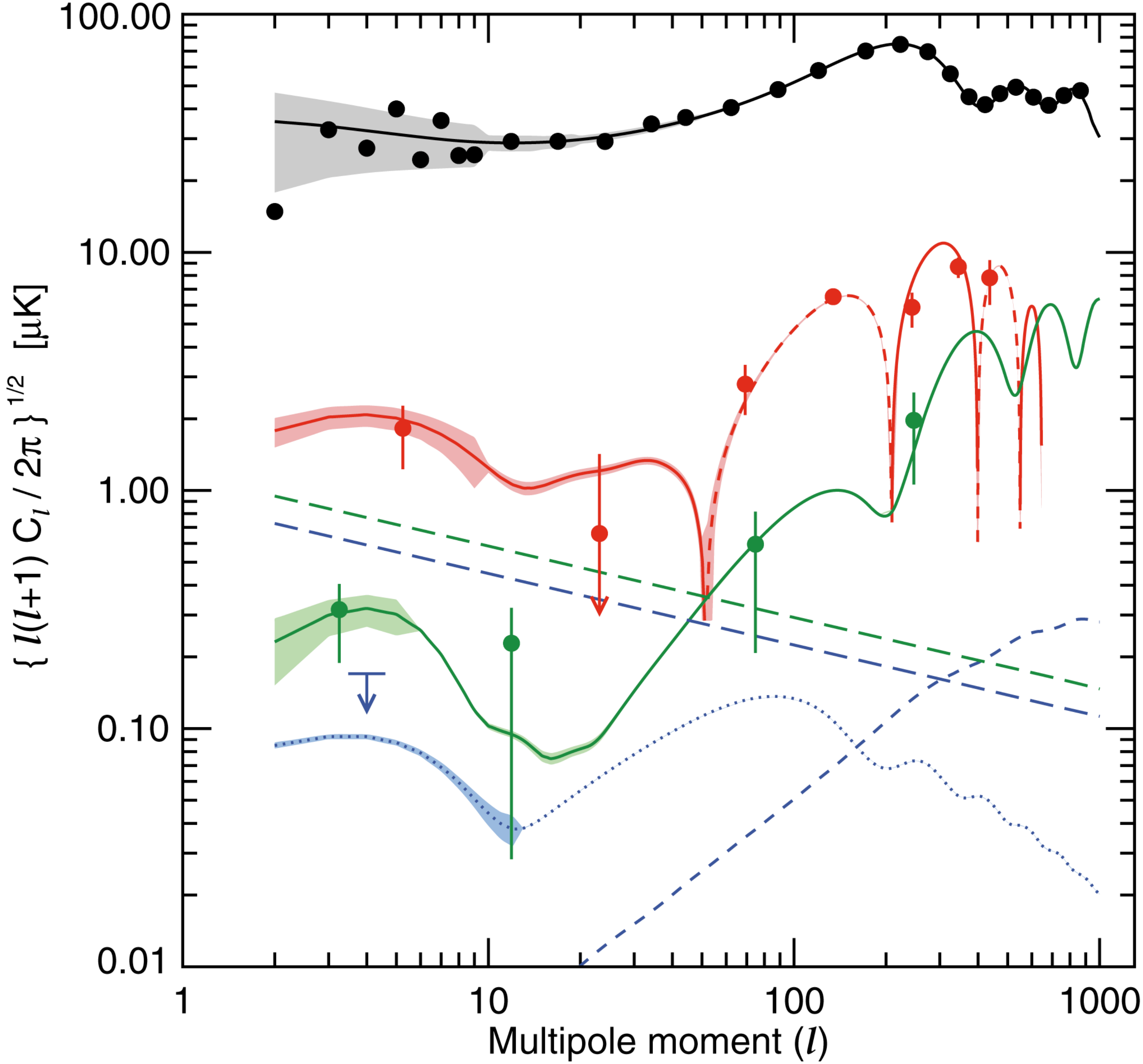
Simon White
Max Planck Institute for Astrophysics


Afterglow Light
Pattern
400,000 yrs.
Dark Ages
Development of
Galaxies, Planets, etc.
Dark Energy
Accelerated Expansion
Inflation
WMAP
Quantum
Fluctuations
1st Stars
about 400 million yrs.
Big Bang Expansion
13.7 billion years
NASA/WMAP Science Team

WMAP3 team

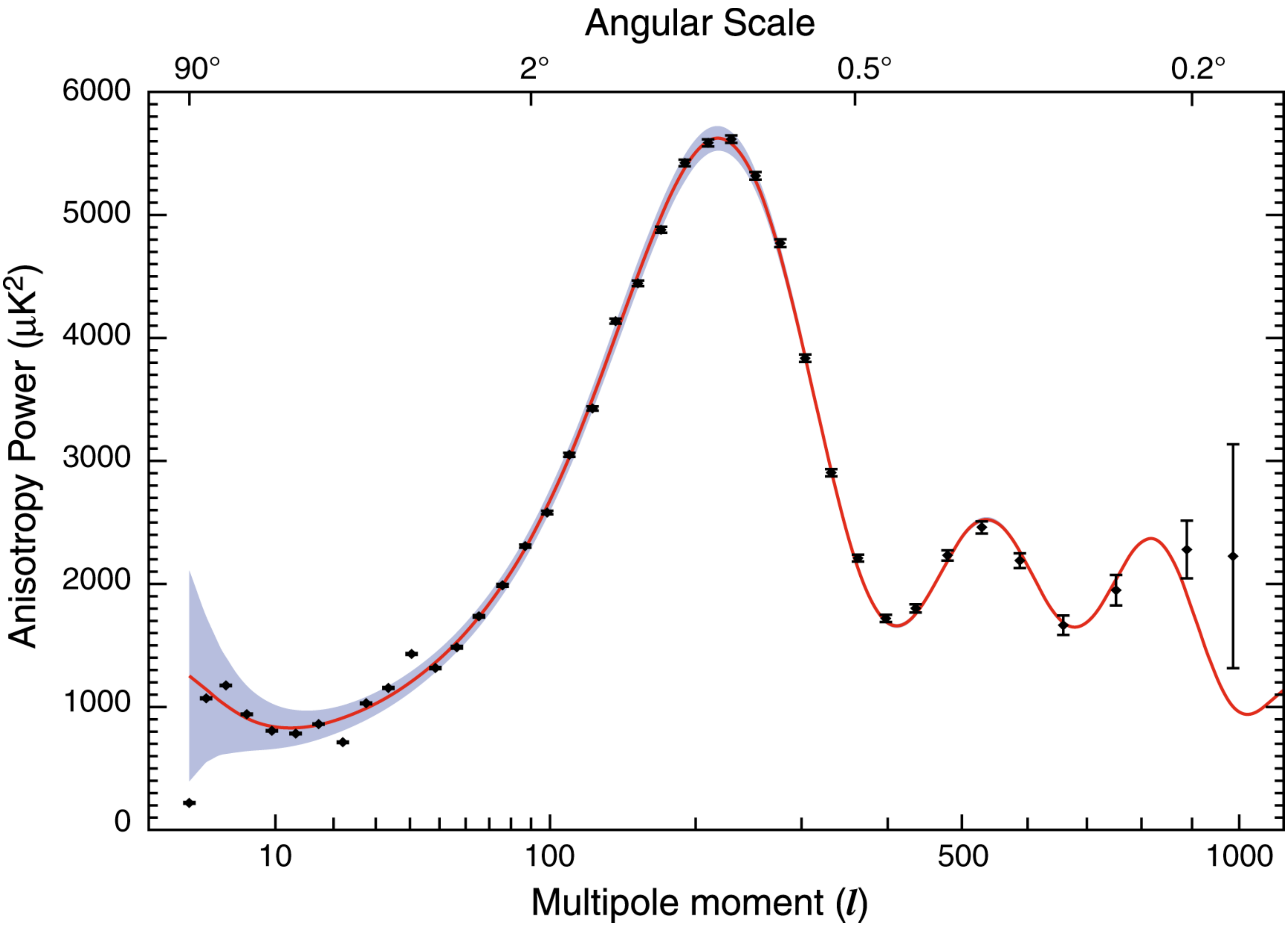


WMAP3 team



100.00
10.00
1.00
0.10
0.01
{ $l(l+1)$ C_l / 2π } $^{1/2}$ [μK]
1
10
100
1000
Multipole moment (l)

WMAP3 team



Angular Scale
90°
2°
0.5°
0.2°
6000
5000
4000
3000
2000
1000
0
Anisotropy Power (μK²)
10
100
500
1000
Multipole moment (l)

WMAP3 team

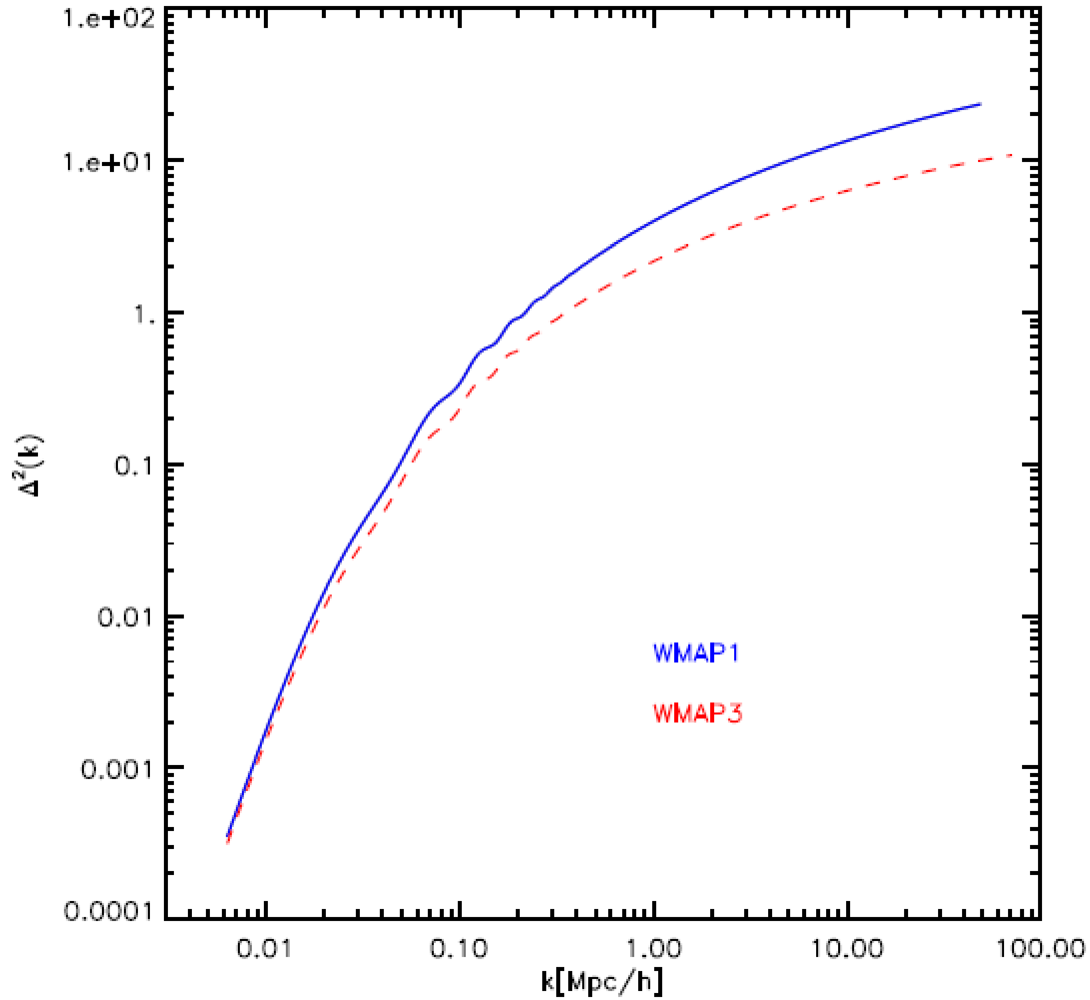
Parameter	First Year Mean	WMAPext Mean	Three Year Mean
$100\Omega_b h^2$	$2.38^{+0.13}_{-0.12}$	$2.32^{+0.12}_{-0.11}$	2.23 ± 0.08
$\Omega_m h^2$	$0.144^{+0.016}_{-0.016}$	$0.134^{+0.006}_{-0.006}$	0.126 ± 0.009
H_0	72^{+5}_{-5}	73^{+3}_{-3}	74^{+3}_{-3}
τ	$0.17^{+0.08}_{-0.07}$	$0.15^{+0.07}_{-0.07}$	0.093 ± 0.029
n_s	$0.99^{+0.04}_{-0.04}$	$0.98^{+0.03}_{-0.03}$	0.961 ± 0.017
Ω_m	$0.29^{+0.07}_{-0.07}$	$0.25^{+0.03}_{-0.03}$	0.234 ± 0.035
σ_8	$0.92^{+0.1}_{-0.1}$	$0.84^{+0.06}_{-0.06}$	0.76 ± 0.05

In just 2 years the Universe:

- Got ionized later (z ~ 10 rather than z ~ 15)
- Lost weight
- Got smoother, particularly on small scales

Linear matter power spectra for WMAP1/WMAP3

$k^3\,P(k)$



- On large scales the matter power spectra agree
- On small scales WMAP3 power is lower by > a factor of 2
  → significantly later formation of the first objects

The growth of Dark Matter structures

- Dark matter is: "uniform" on the largest scales,
  "filamentary" on intermediate scales ,
  "clumpy" on small scales

- Large-scale cosmic web grows by infall into and then flow along the filaments

- Halos grow by inhomogeneous infall and merging at the nodes of the cosmic web

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

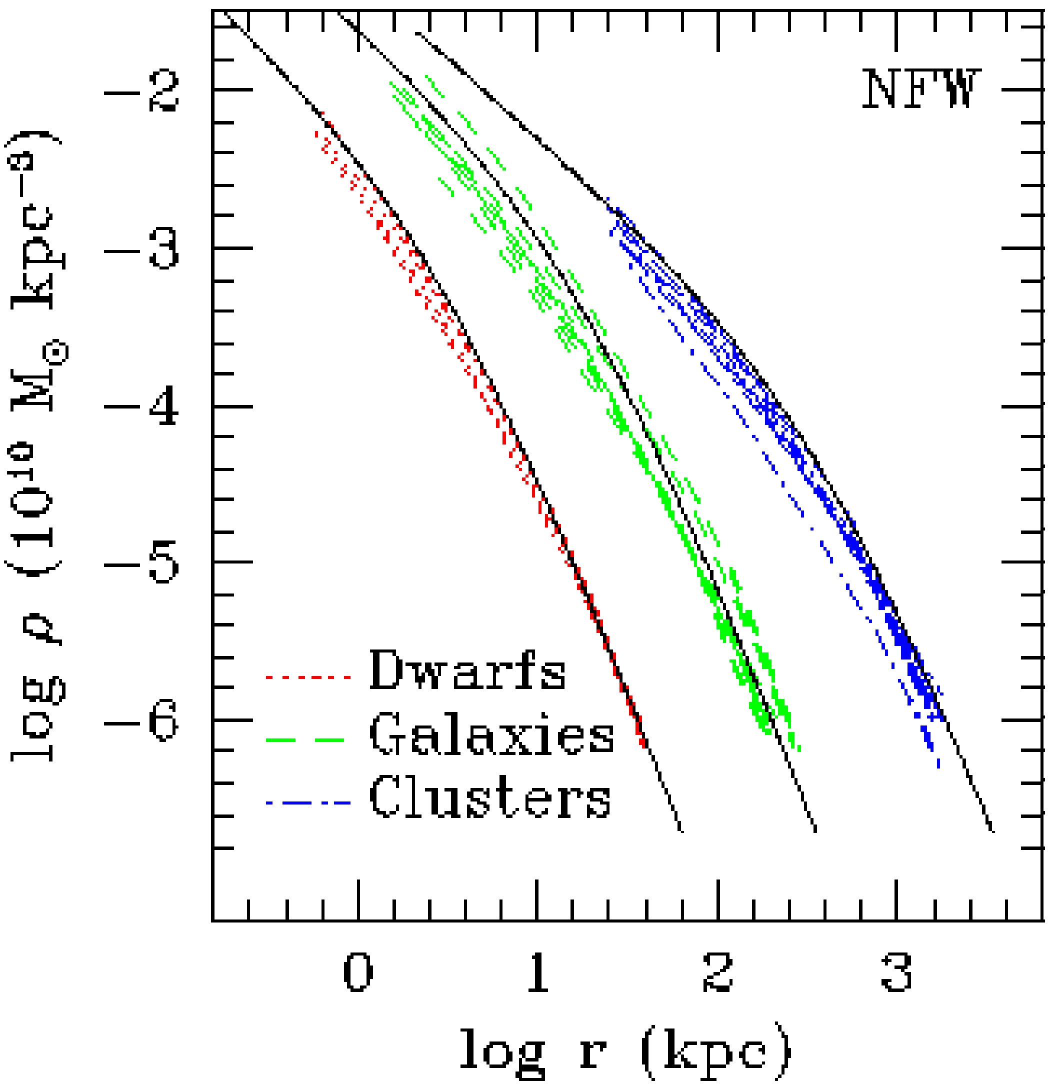
- Equidensity surfaces approximate triaxial ellipsoids
  -- more prolate than oblate
  -- axial ratios greater than two are common

- "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)

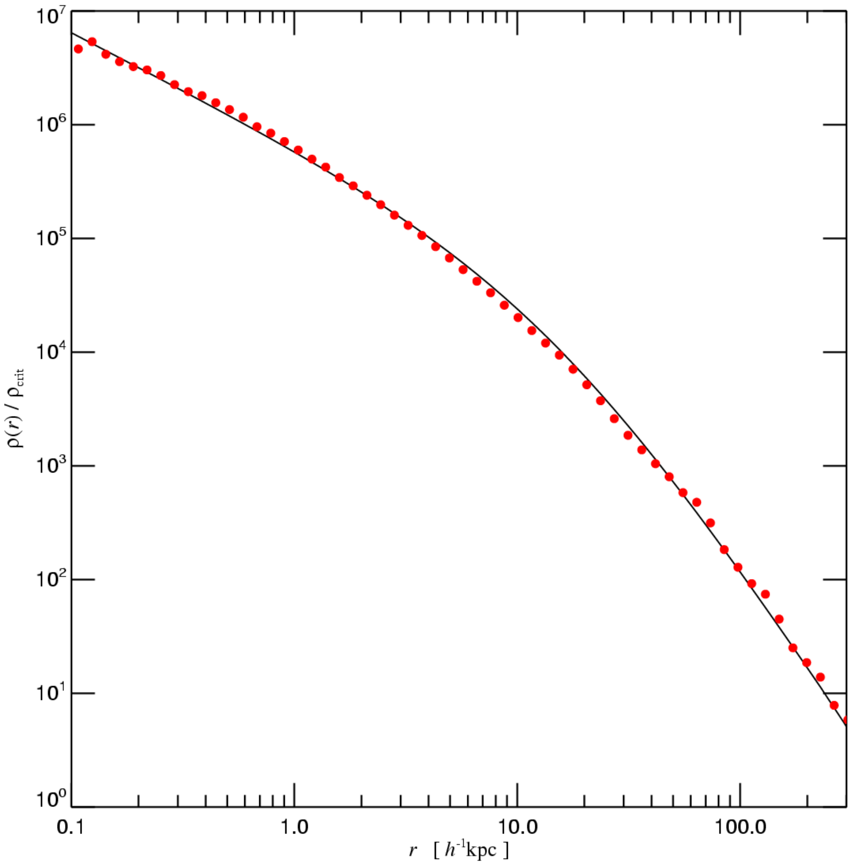
Navarro et al 1996

A high-resolution Milky Way halo

600 kpc

Navarro et al 2006

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

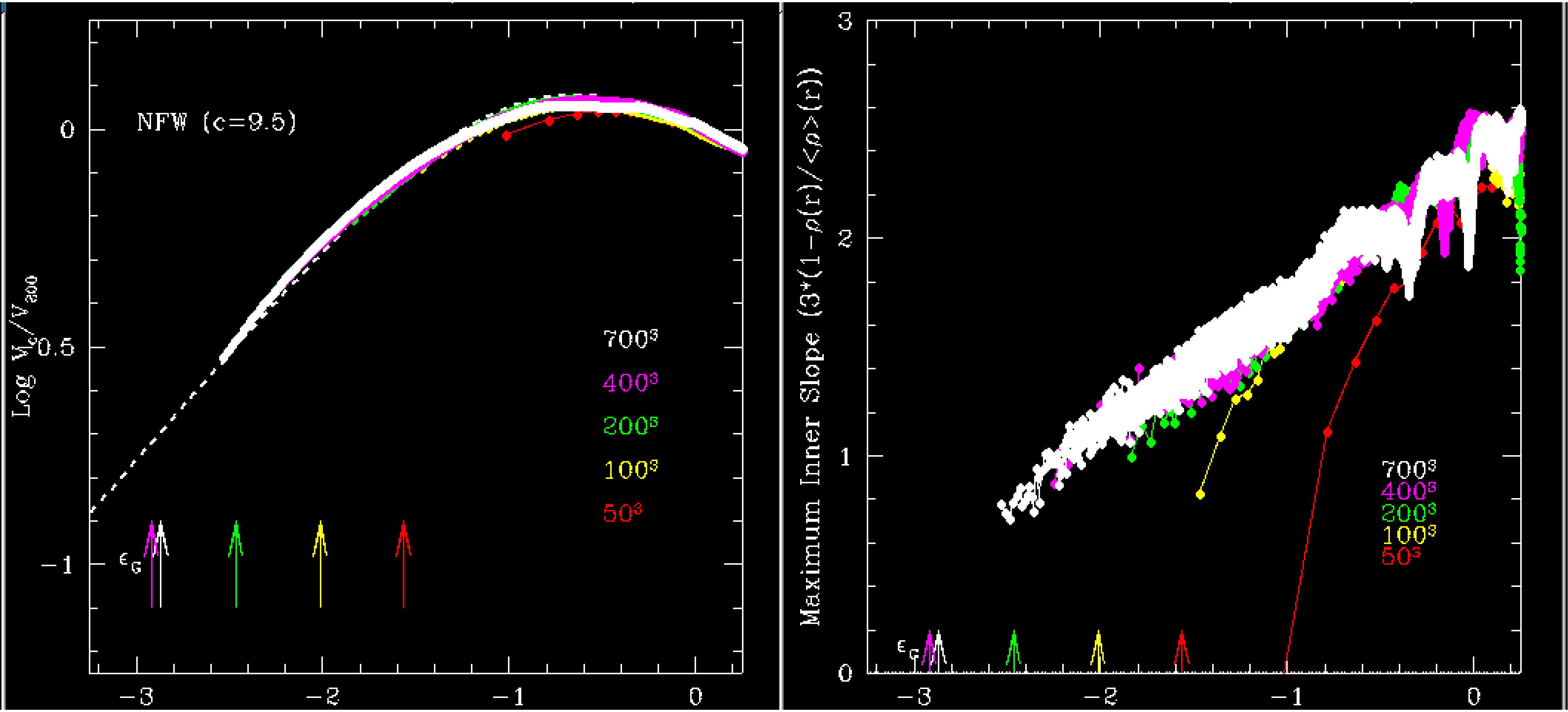


Convergence tests on density profile shape

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

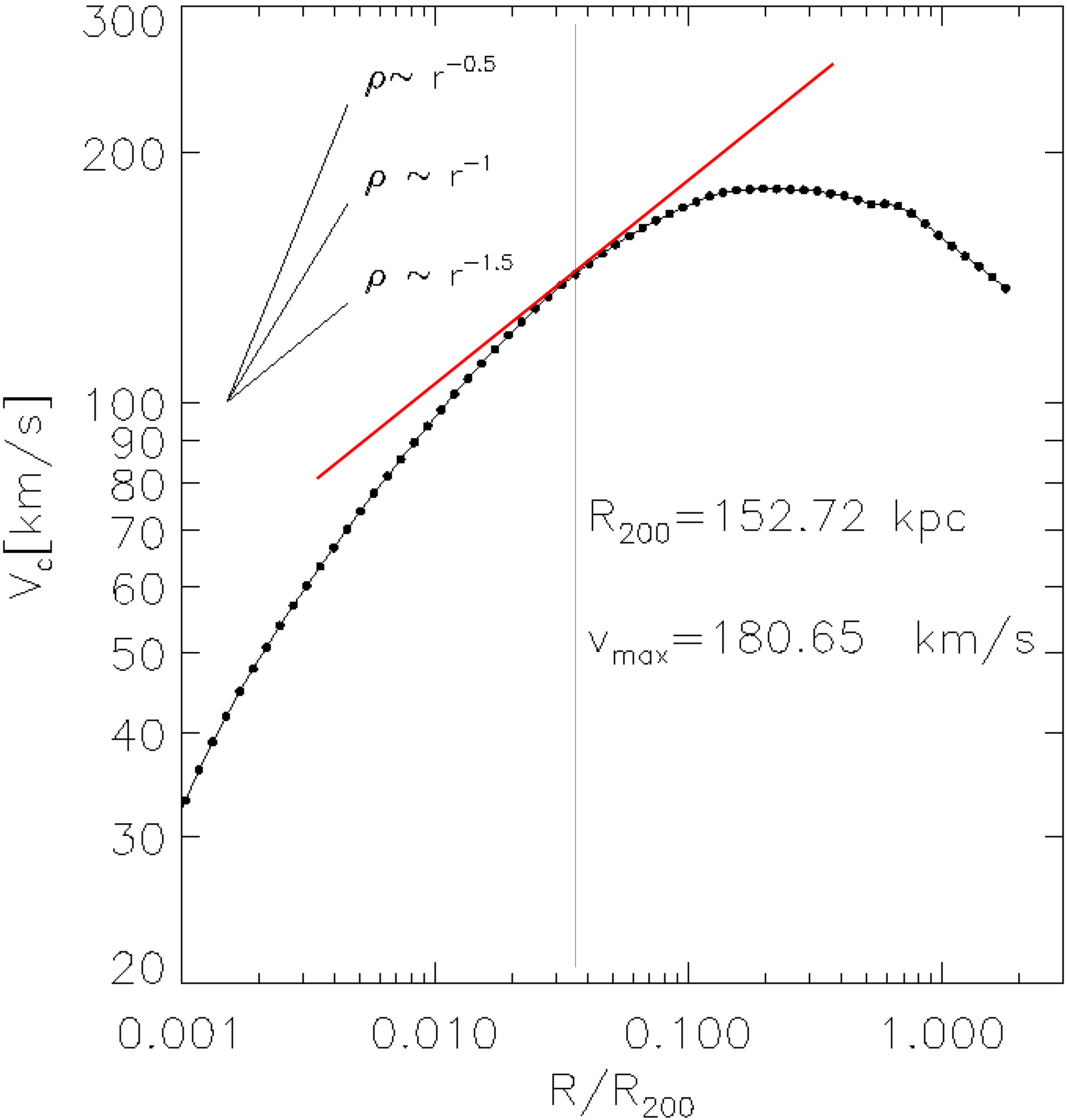
The luminosity density of annihilation emission is

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

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

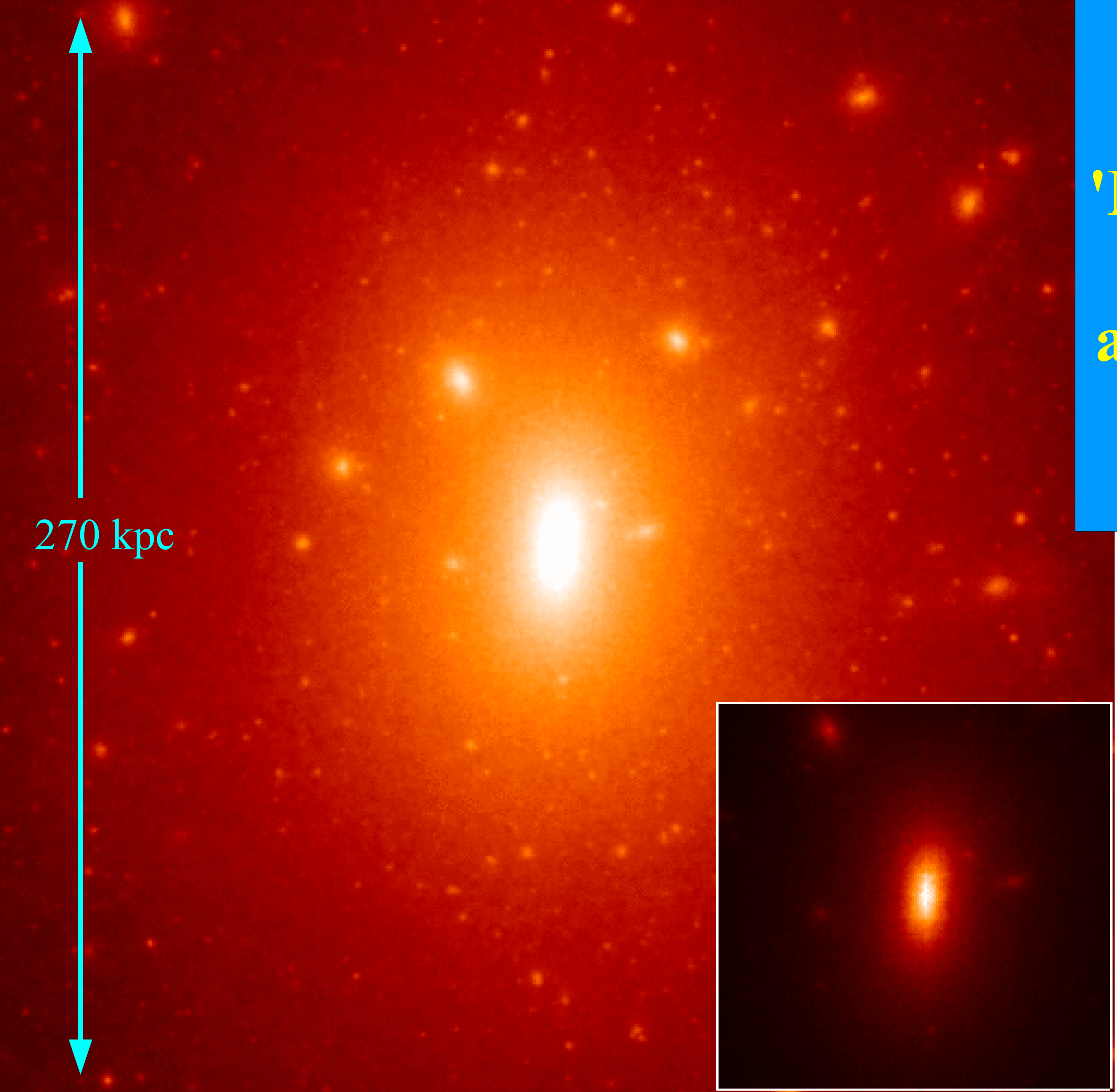
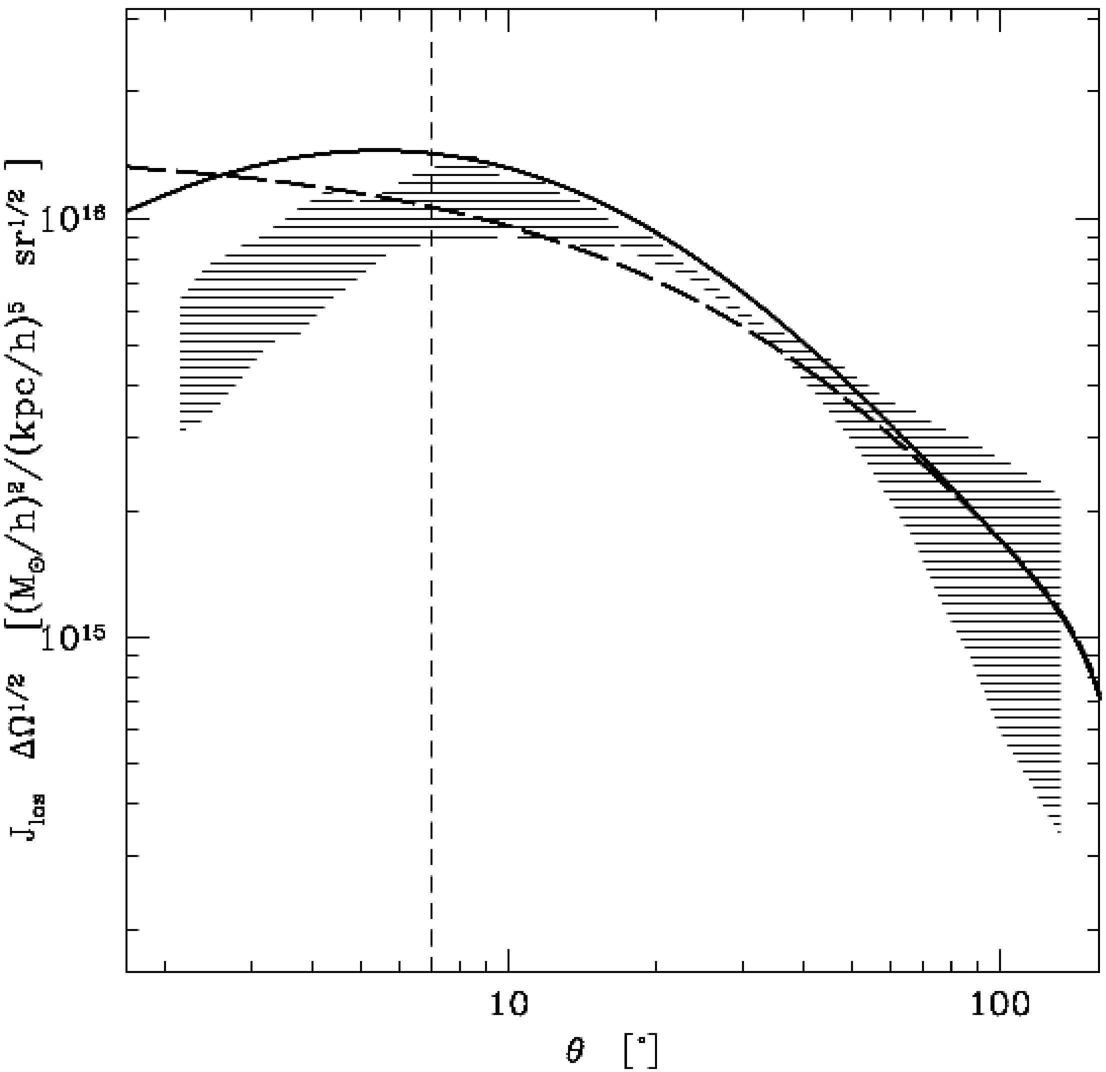


Image of a 'Milky Way' halo in annihilation radiation

Stoehr et al 2003

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

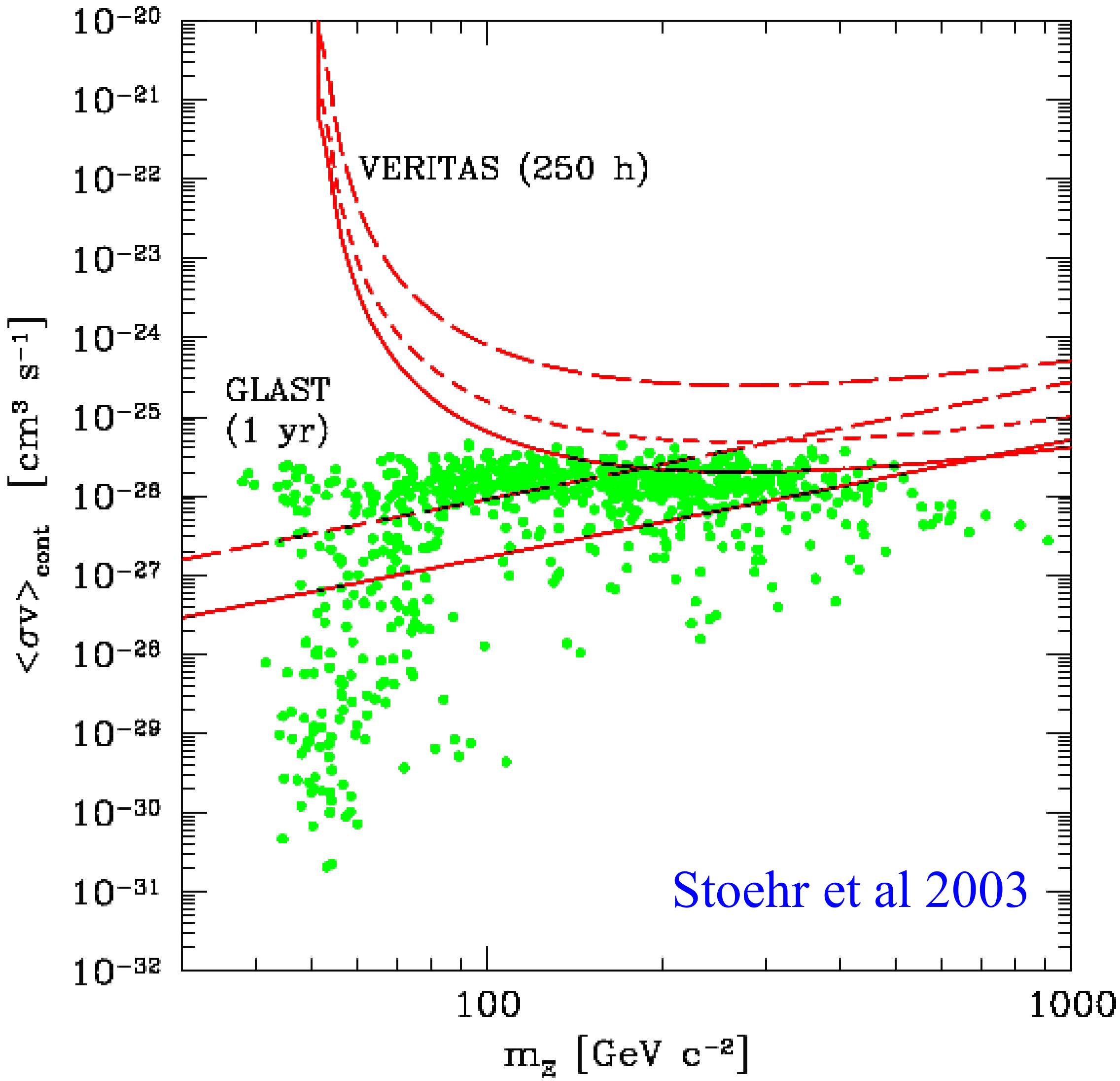
Signal-to-noise of the simulated Milky Way as seen from the Sun's position



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

Could GLAST or VERITAS see the Signal?

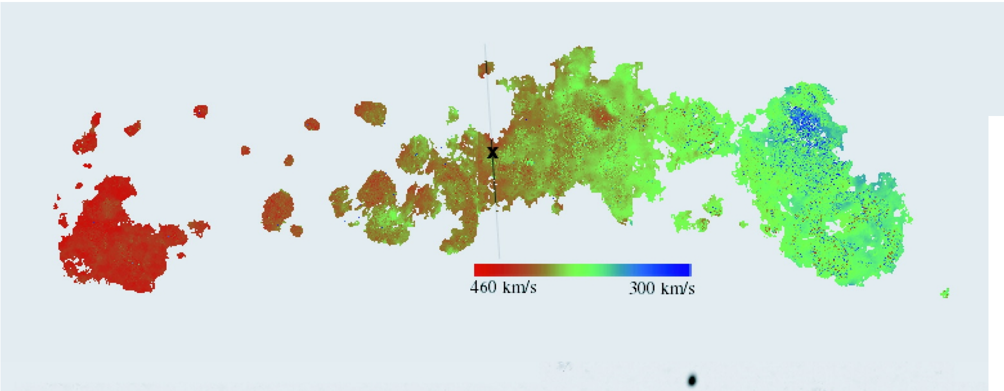


Possible MSSM params from Darksusy

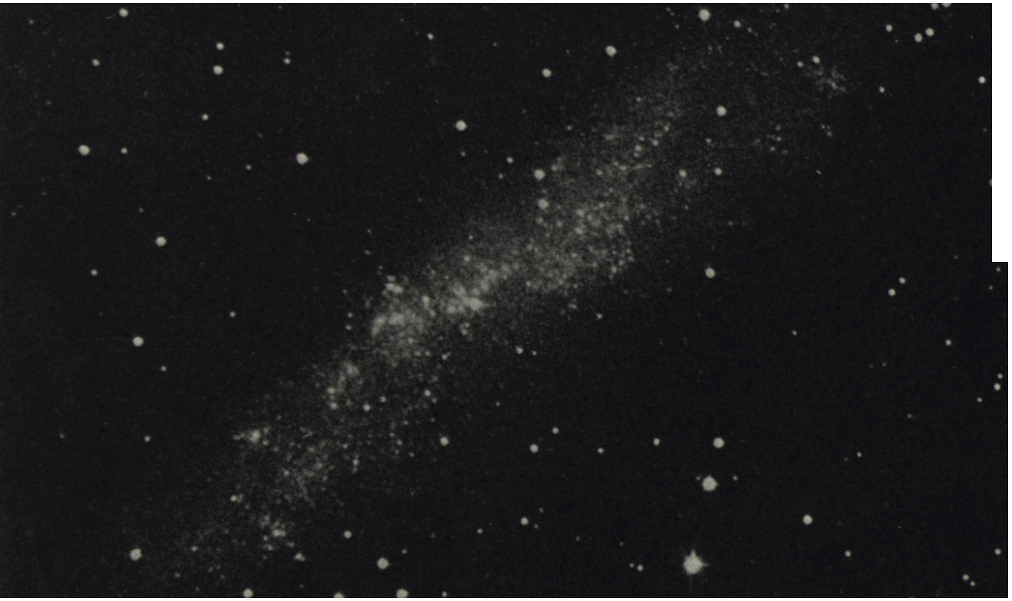
- For VERITAS (a Cerenkov detector with 1.75° FOV) the detectability of the G.C. depends on poorly resolved regions of the simulation and is marginal

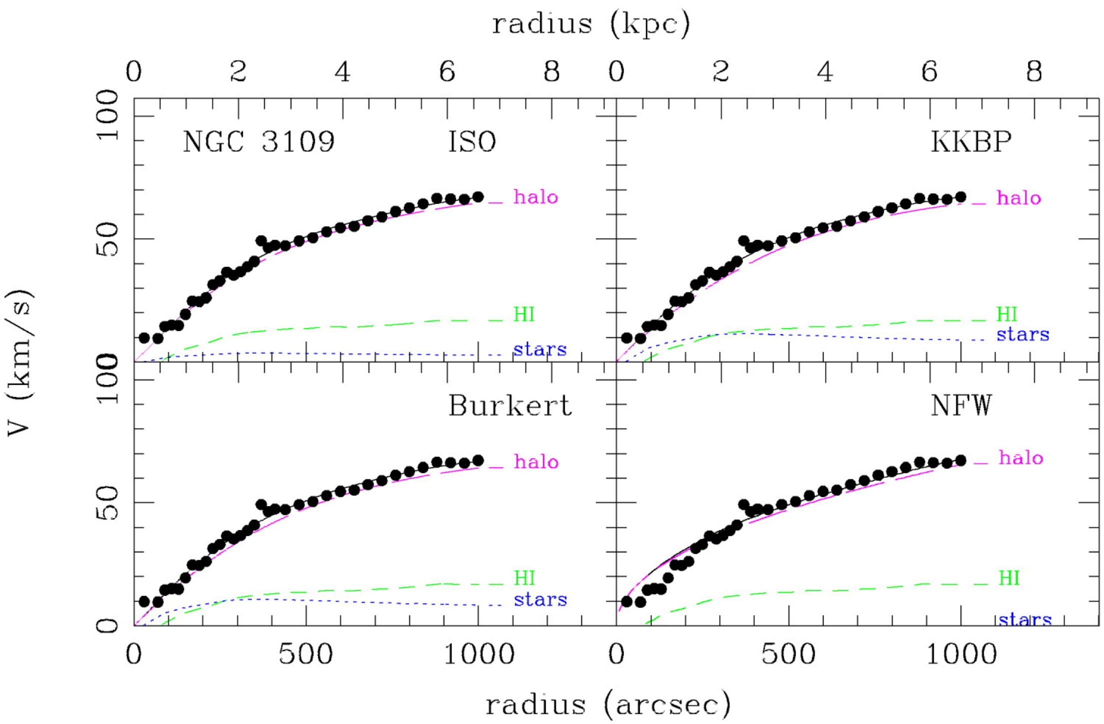
- For GLAST (a satellite with 3 sterad. FOV) detection should be possible 20° to 30° from the G.C. in a very long integration and for most MSSM param's. This does *not* depend on poorly resolved regions of the simulation

Dwarf galaxy rotation curves still don't fit well



Blais-Ouellette, Amram & Carignan 2001

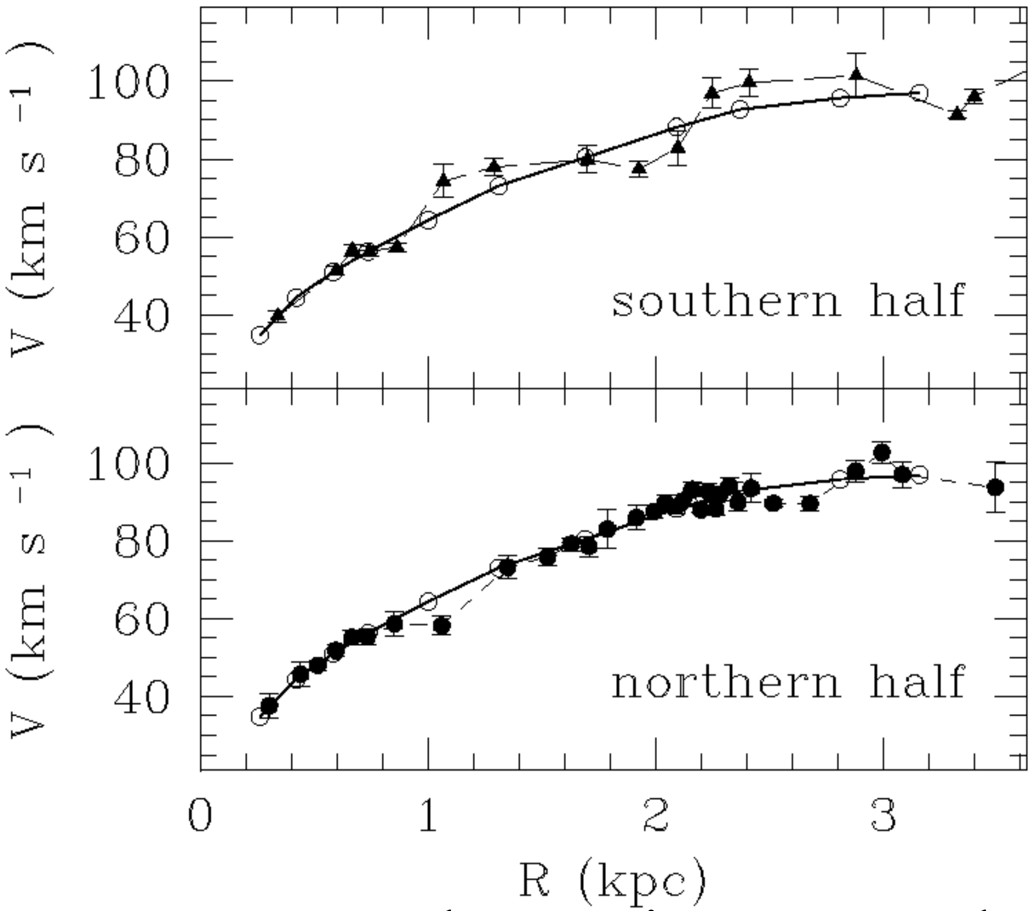


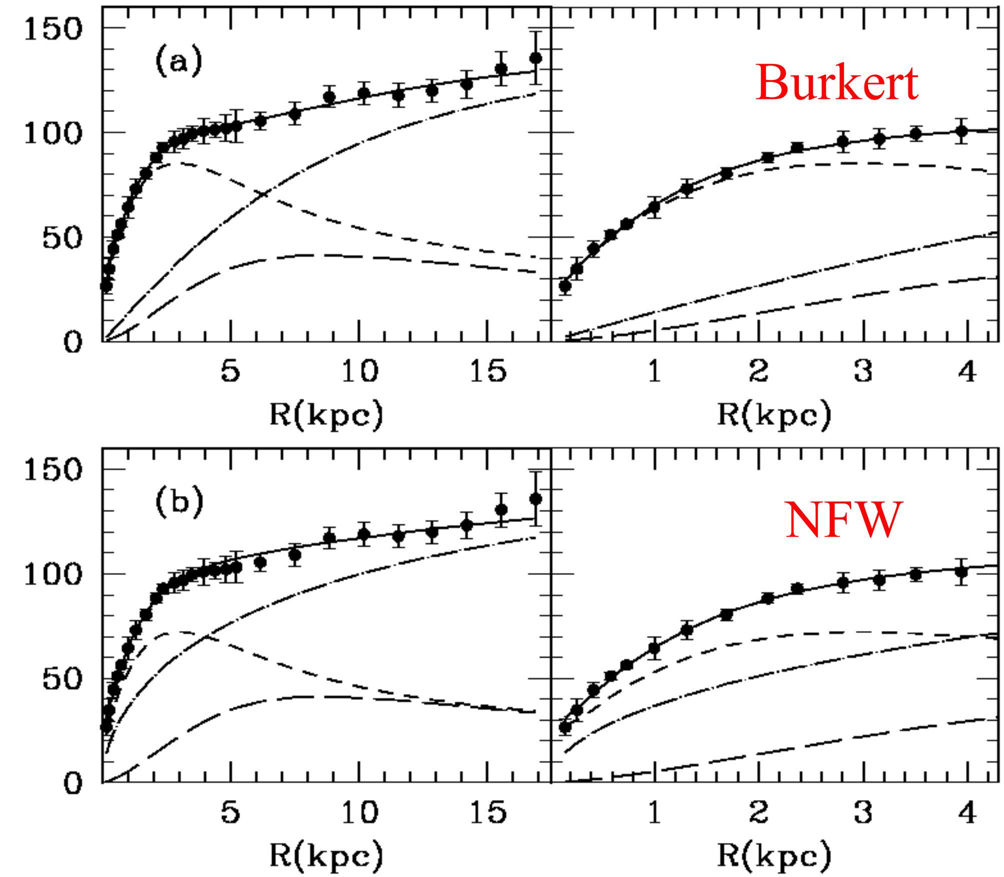


- Effects of galaxy formation?
- Non-circular motions, warps, bars, triaxial halos?

The rotation curve of M33

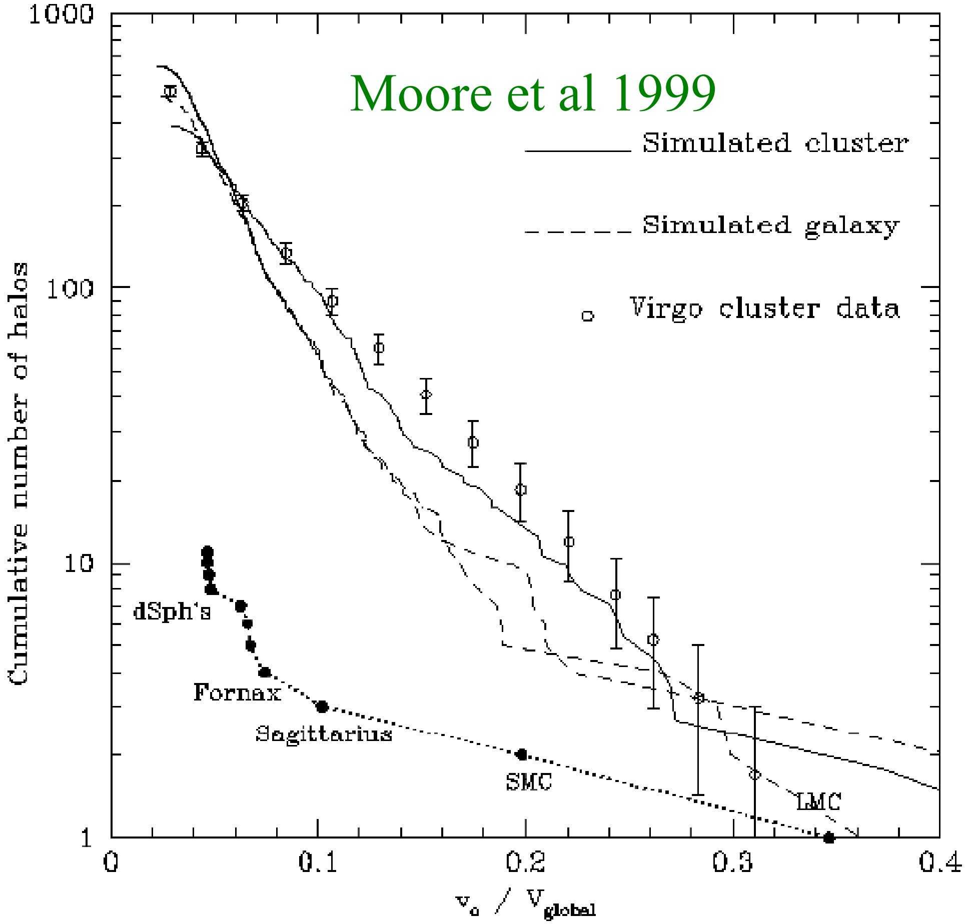
Corbelli 2003

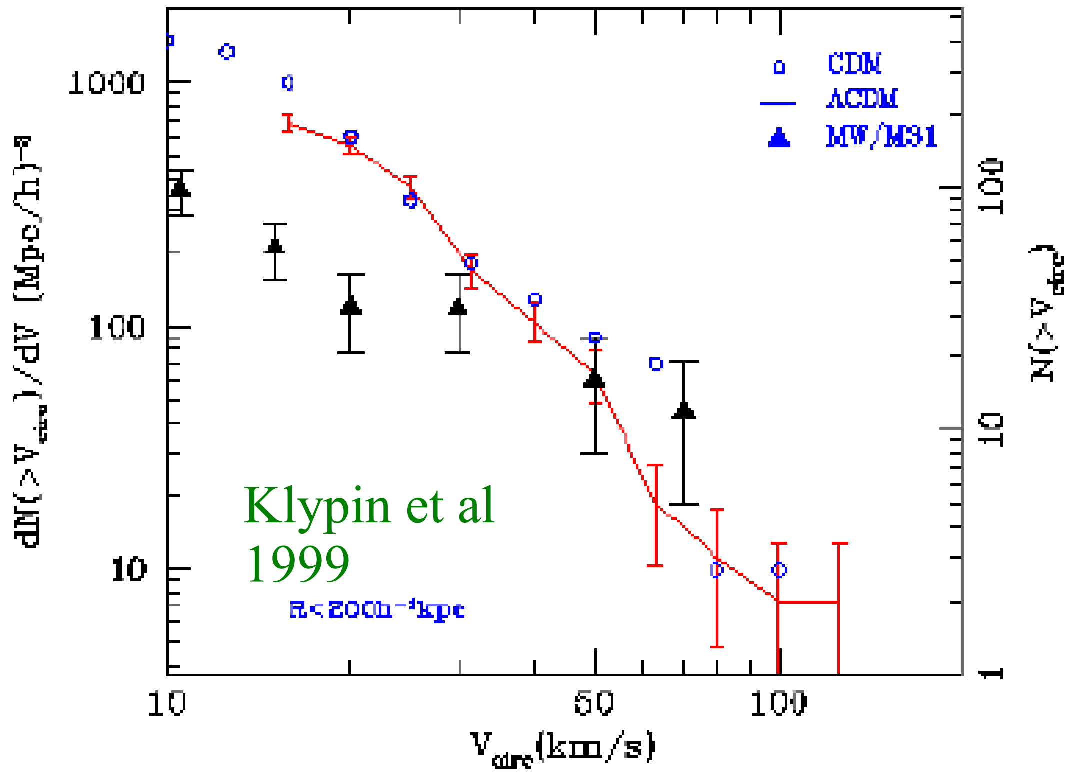




- Fluctuations around mean curve are up to 10 km/s
- Galaxy is strongly DM-dominated at large r
- NFW fit is quite acceptable though concentration is slightly low for ΛCDM

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

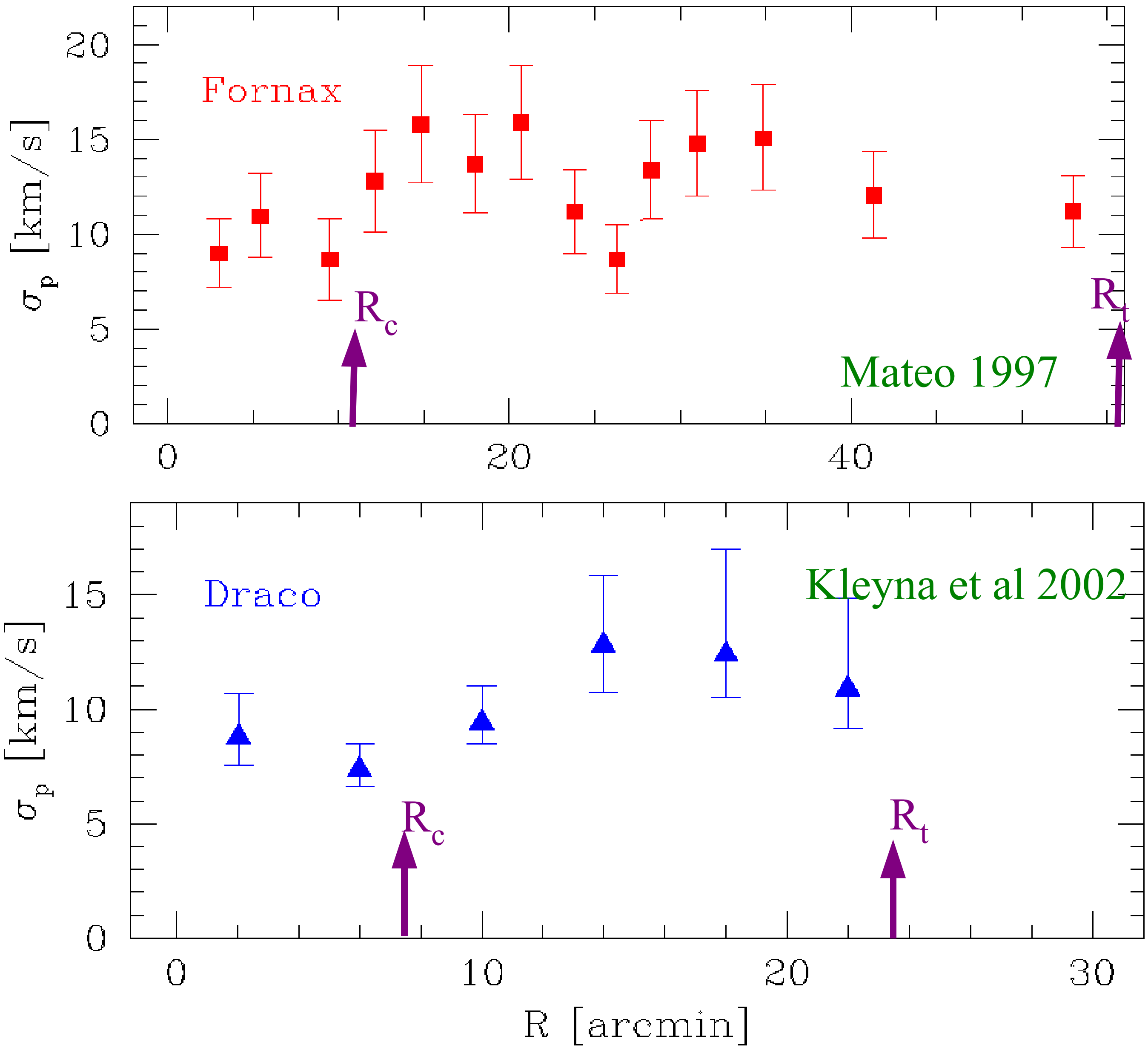




- Number of observed satellites appears to be ~1/30 the number of ΛCDM satellites with the same max. circular velocity $V_c = (GM/r)^{1/2}$
- But the MW data are plotted at the incorrect values of V_c for this test!

Stoehr et al 2002

Dark Matter within Satellites



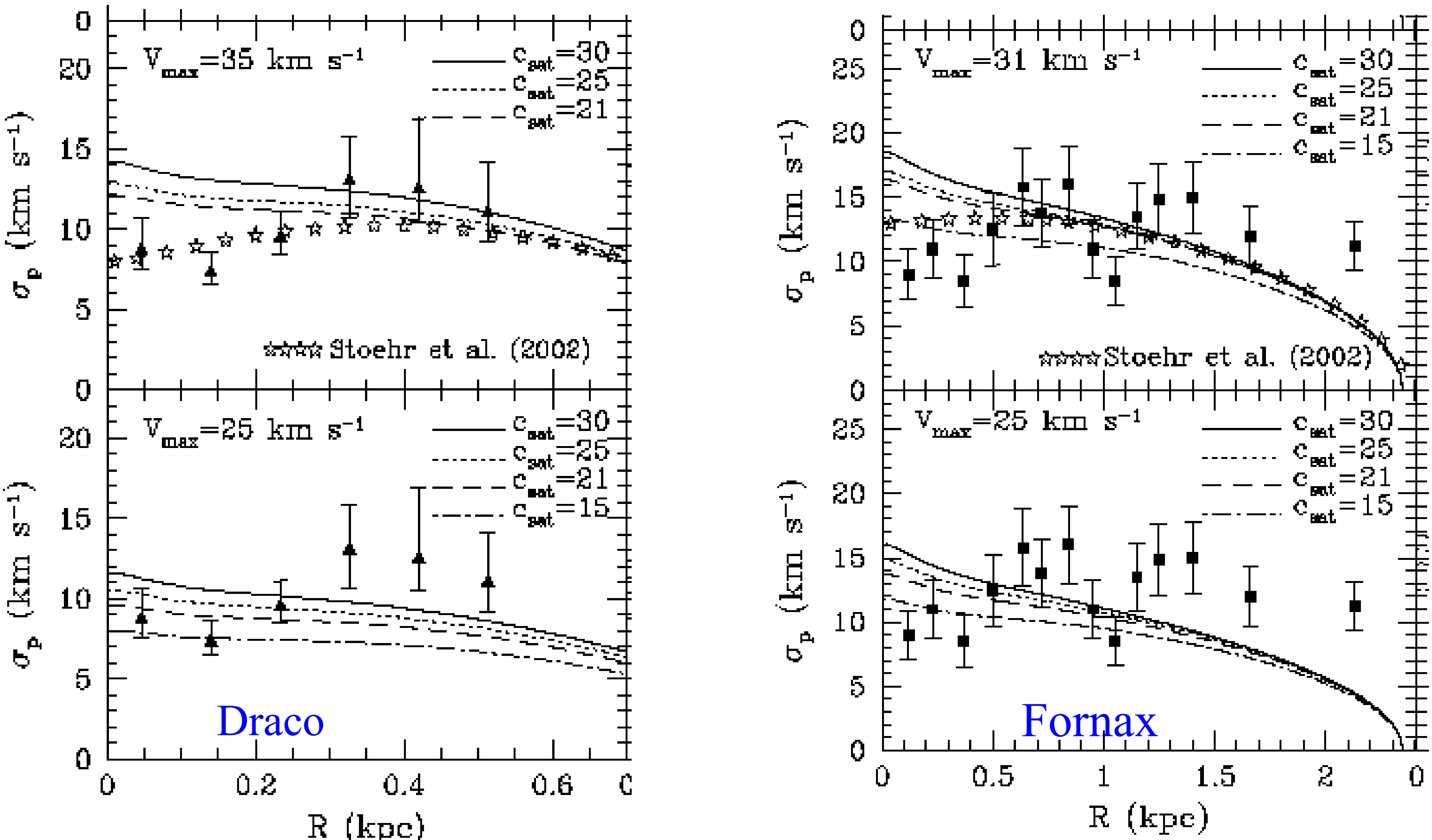
- Flat stellar velocity dispersion out to the tidal radius
  → *rising* V_c curve
- Extended DM halos?
- High DM phase density? ~~*WDM*~~ ?
- $V_{c,max} \gtrsim$ 25 km/s ?
- Critical observation: extratidal stars?

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

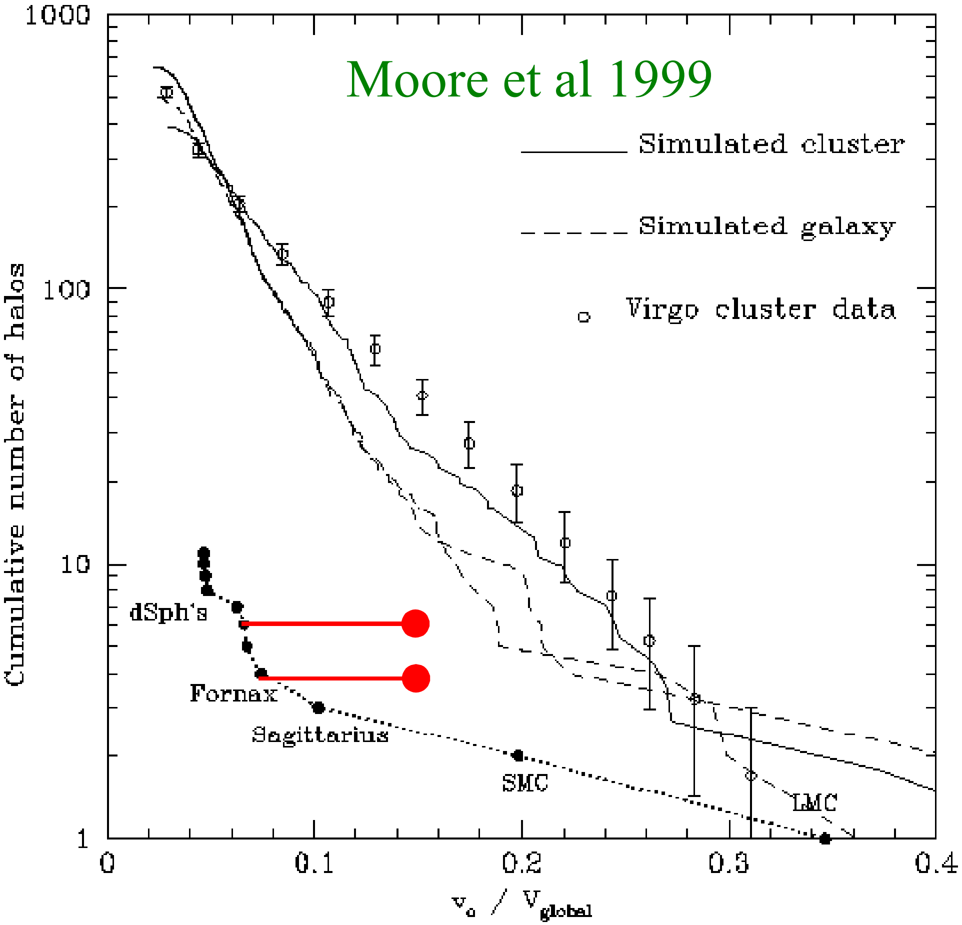
2004 (ApJ)

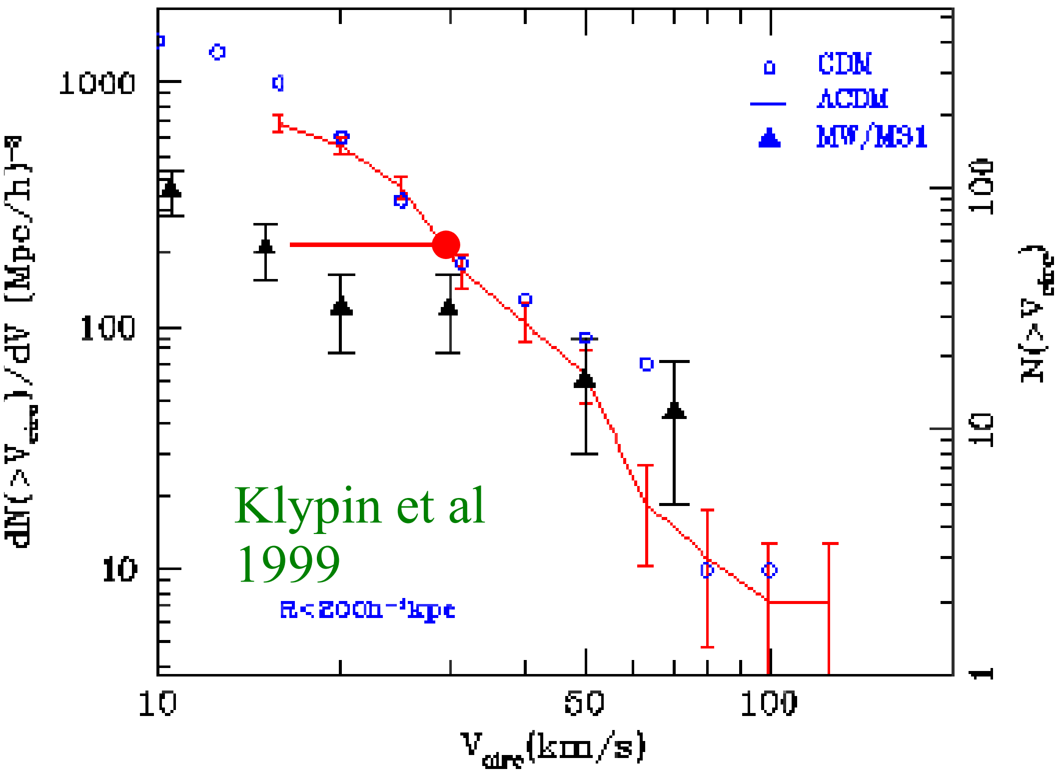
Stelios Kazantzidis[1], Lucio Mayer, Chiara Mastropietro, Jürg Diemand, Joachim Stadel, and Ben Moore

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 $20 - 35\ \mathrm{km s}^{-1}$.

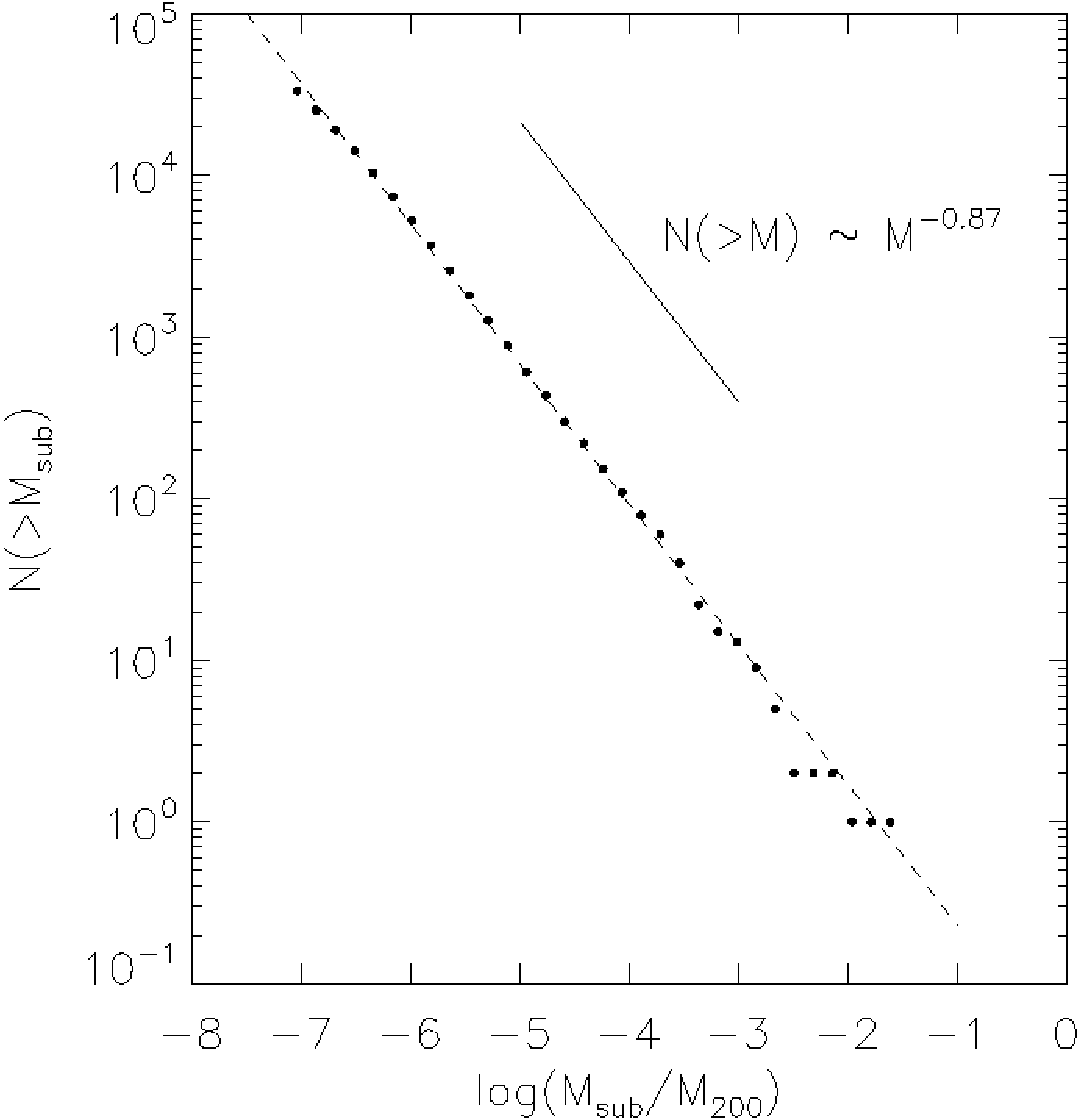


Inconsistency with observed satellite kinematics?

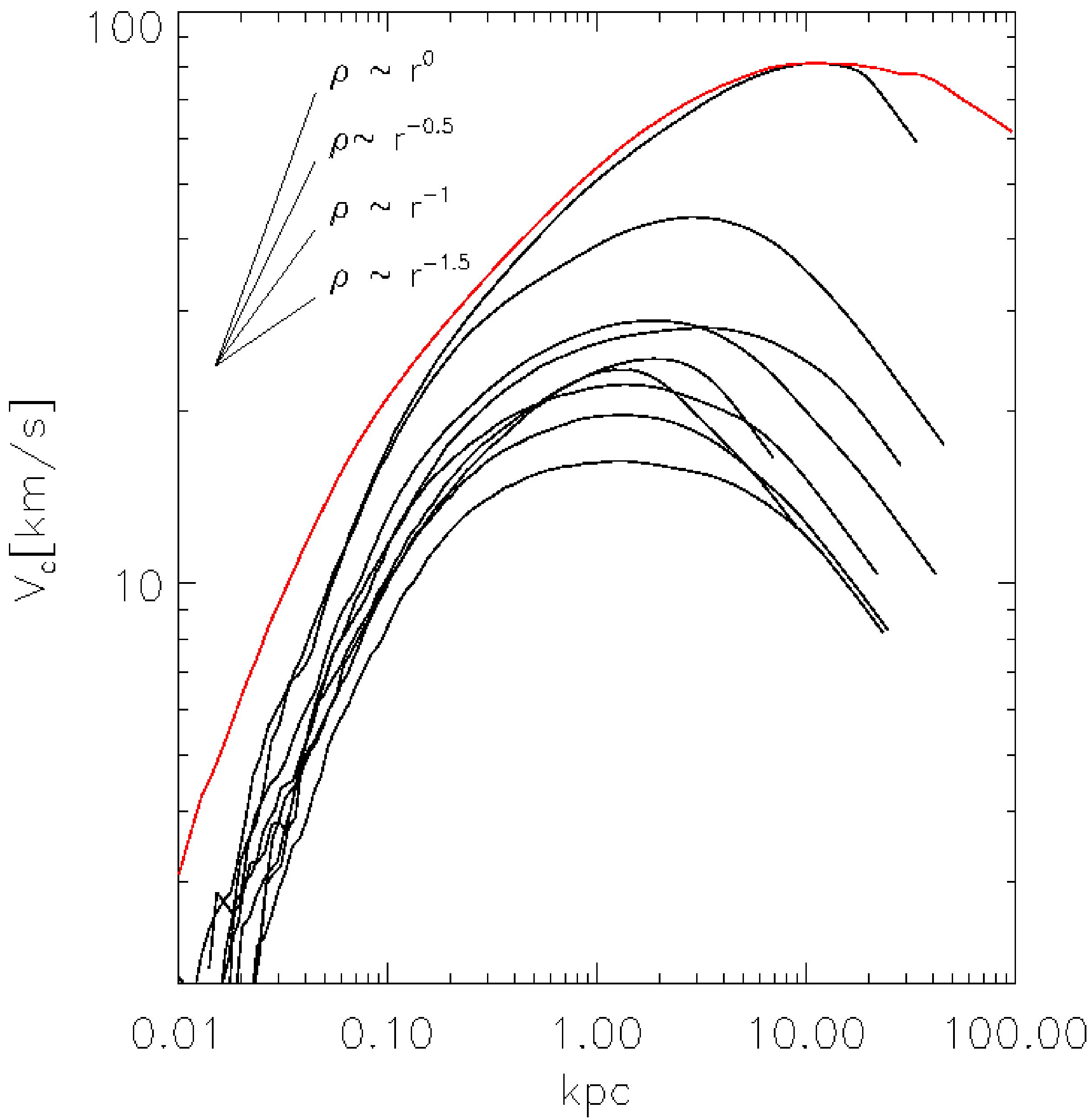




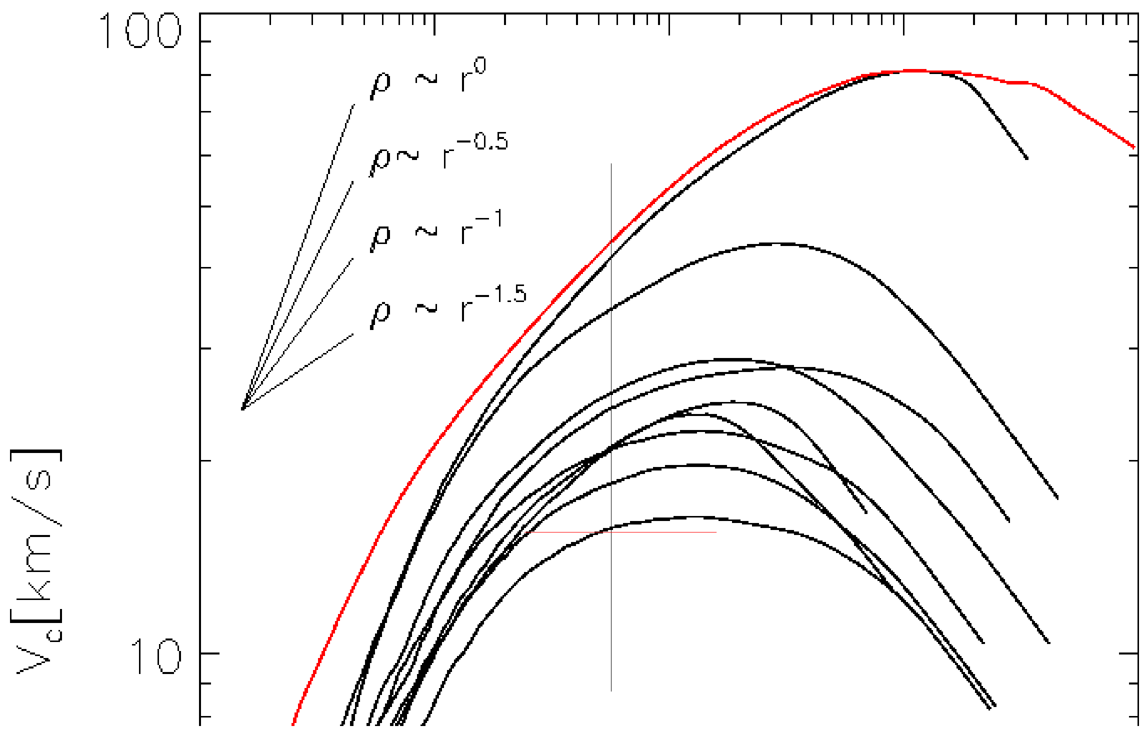
- Inconsistency is much less dramatic when one uses the *limiting* circular velocity inferred from the velocity dispersion profiles
- The *maximum* of the DM circular velocity profile may be outside the visible galaxy and still larger (plots show shift to V_{max} = 30 km/s)

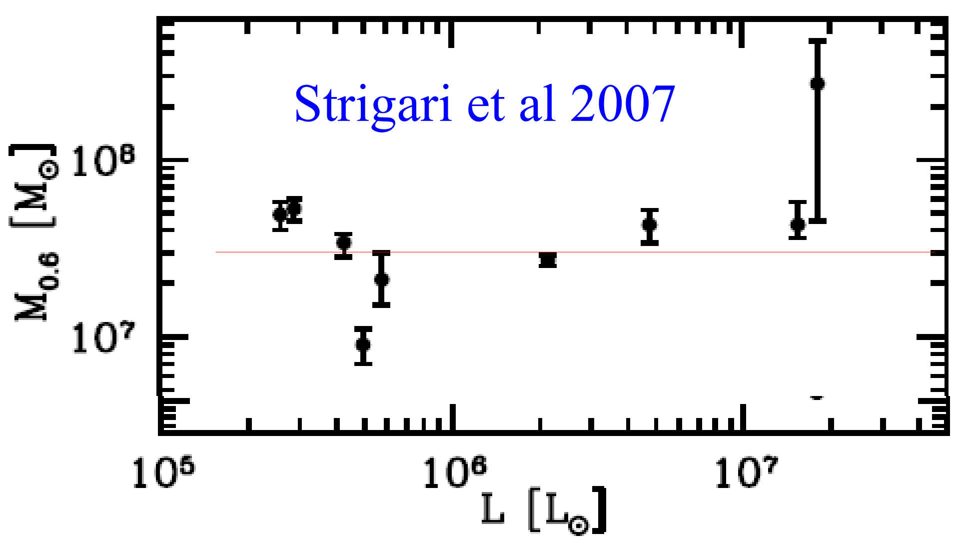


- $N_{200} = 2.23 \times 10^8$
- >30,000 subhalos
- 8% of mass within R_{200} in subhalos
- Total subhalo mass (weakly) convergent as $m_{sub} \to 0$



- 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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- The maximum circular velocities are at radii outside observed satellites
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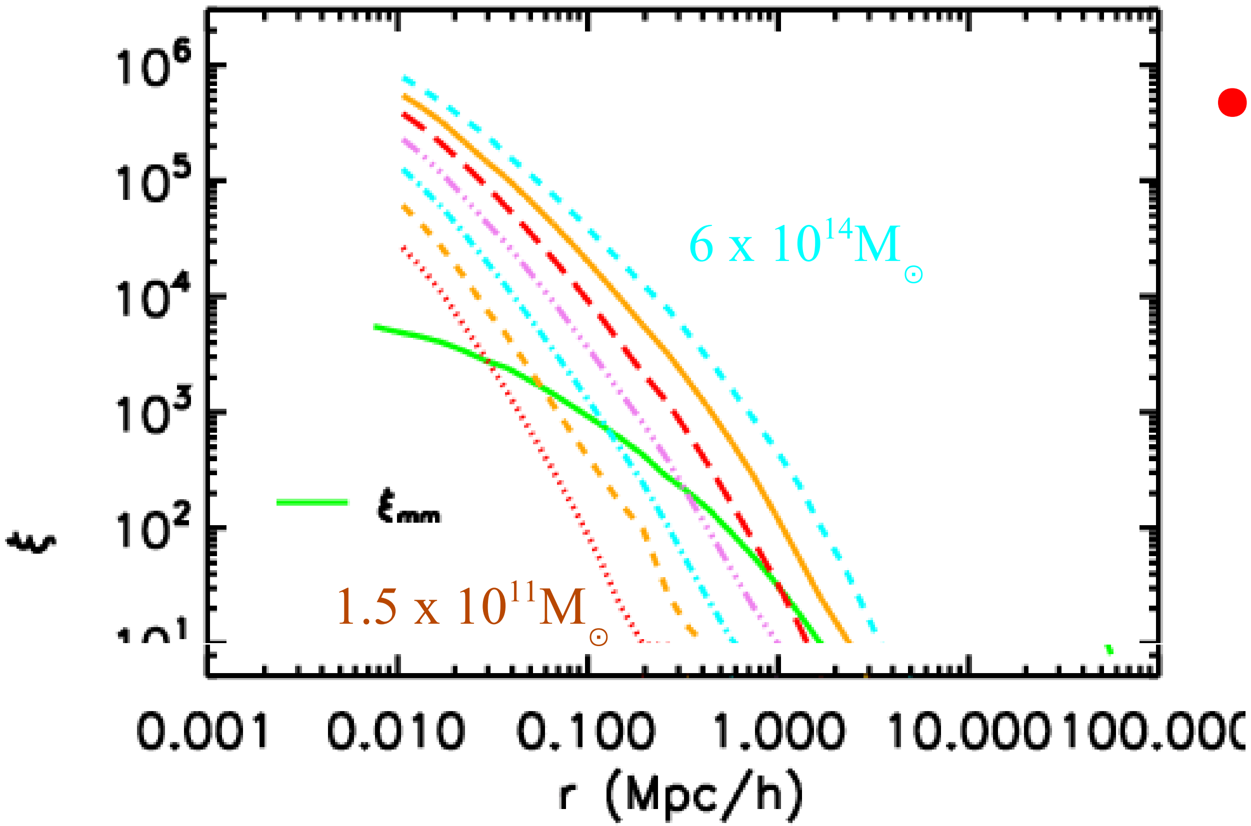
- Inner core *still* not well enough resolved to predict total annihilation radiation

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

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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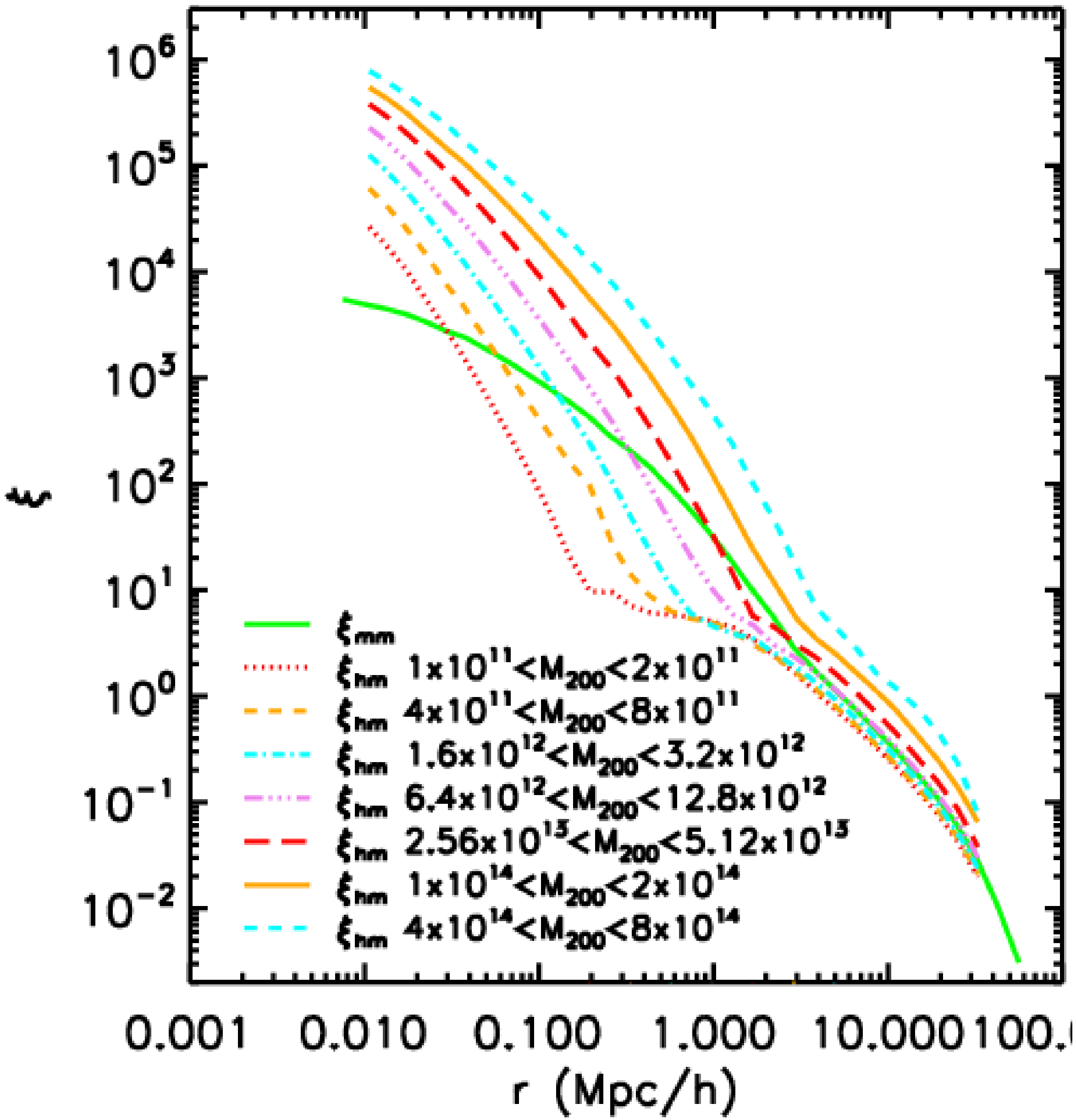

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- At lower overdensities they are well fit by the *linear* mass correlation function with bias from Sheth, Mo, Tormen (2001)

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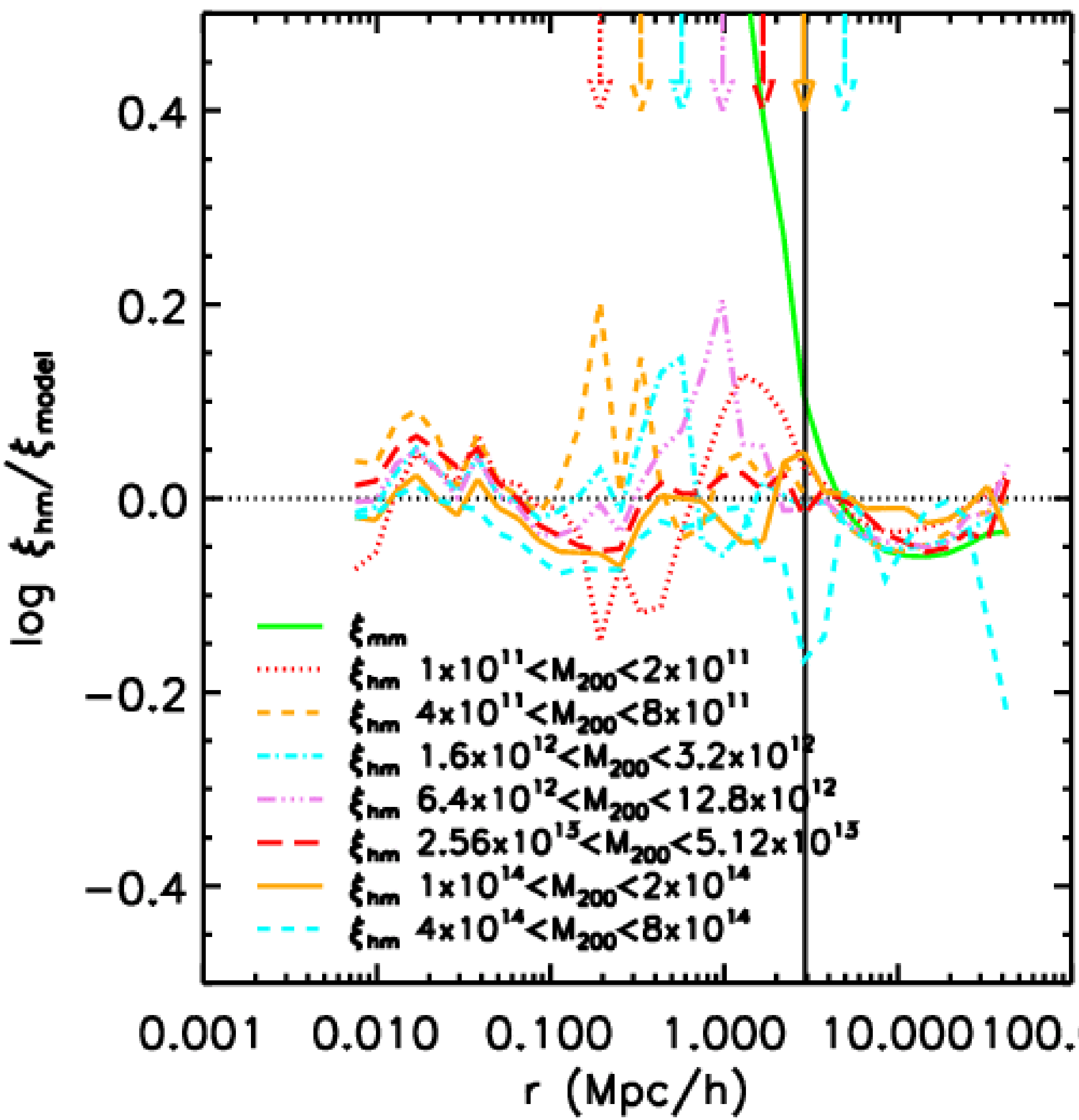
Hayashi et al 2007



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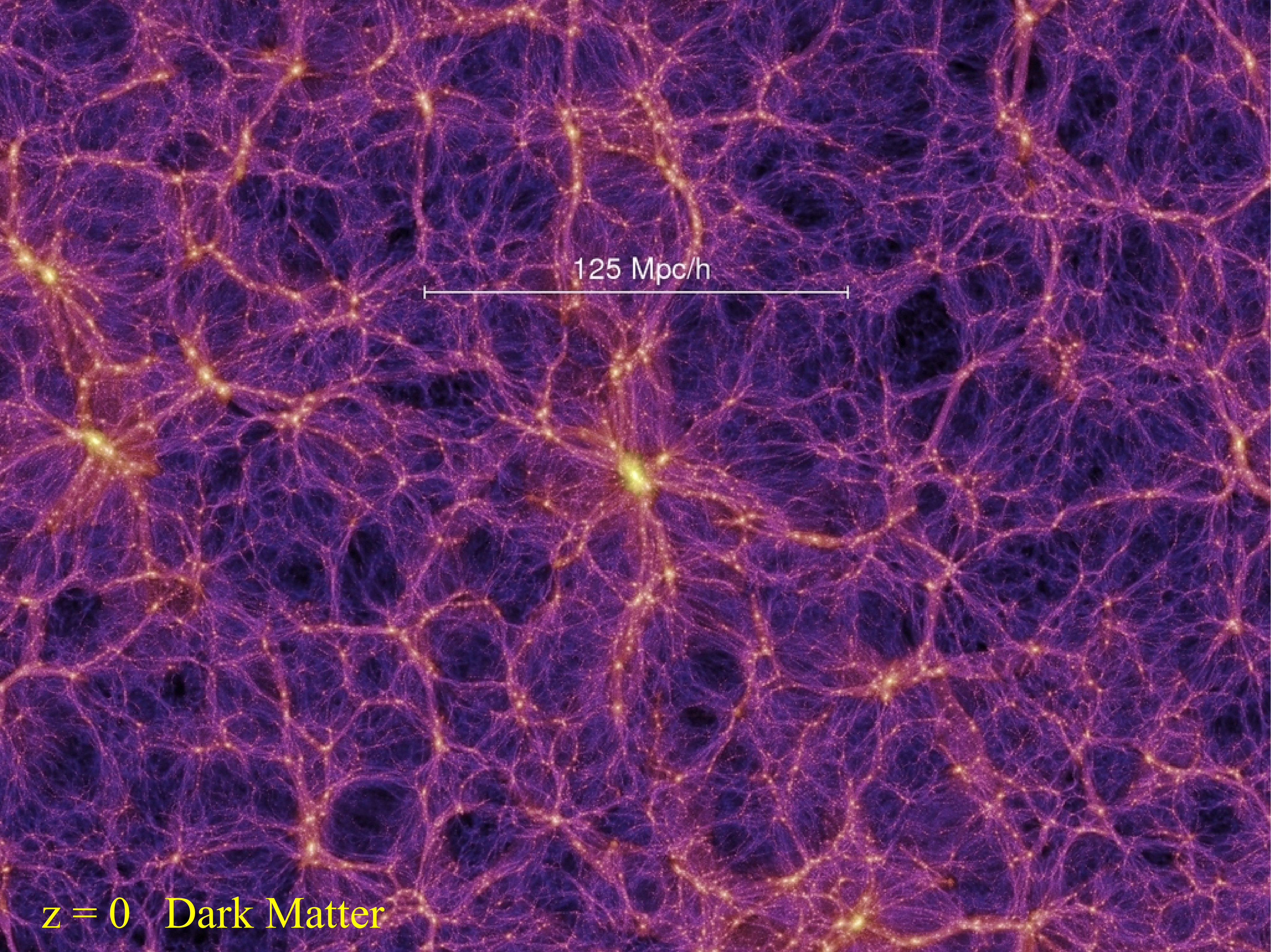
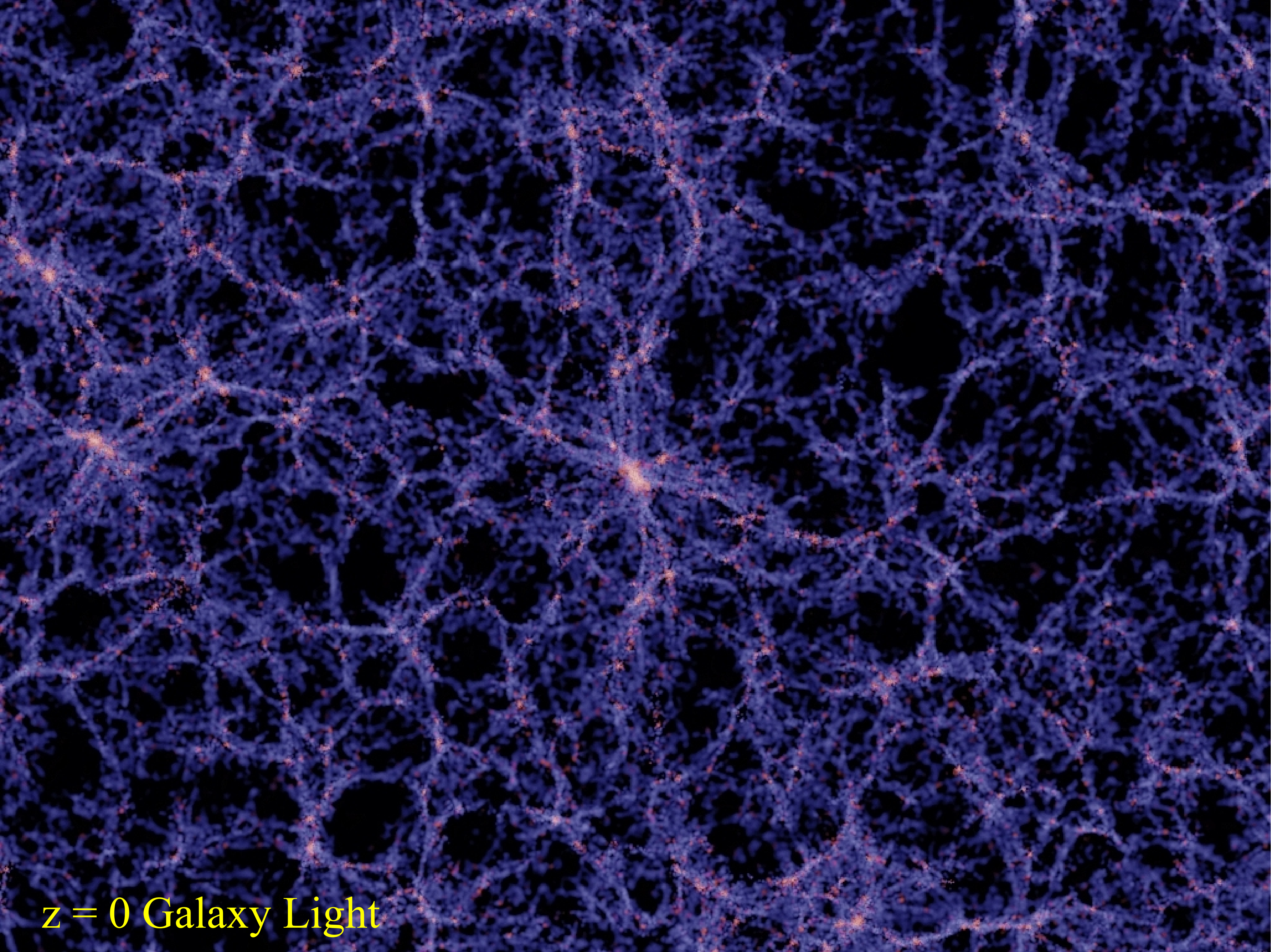
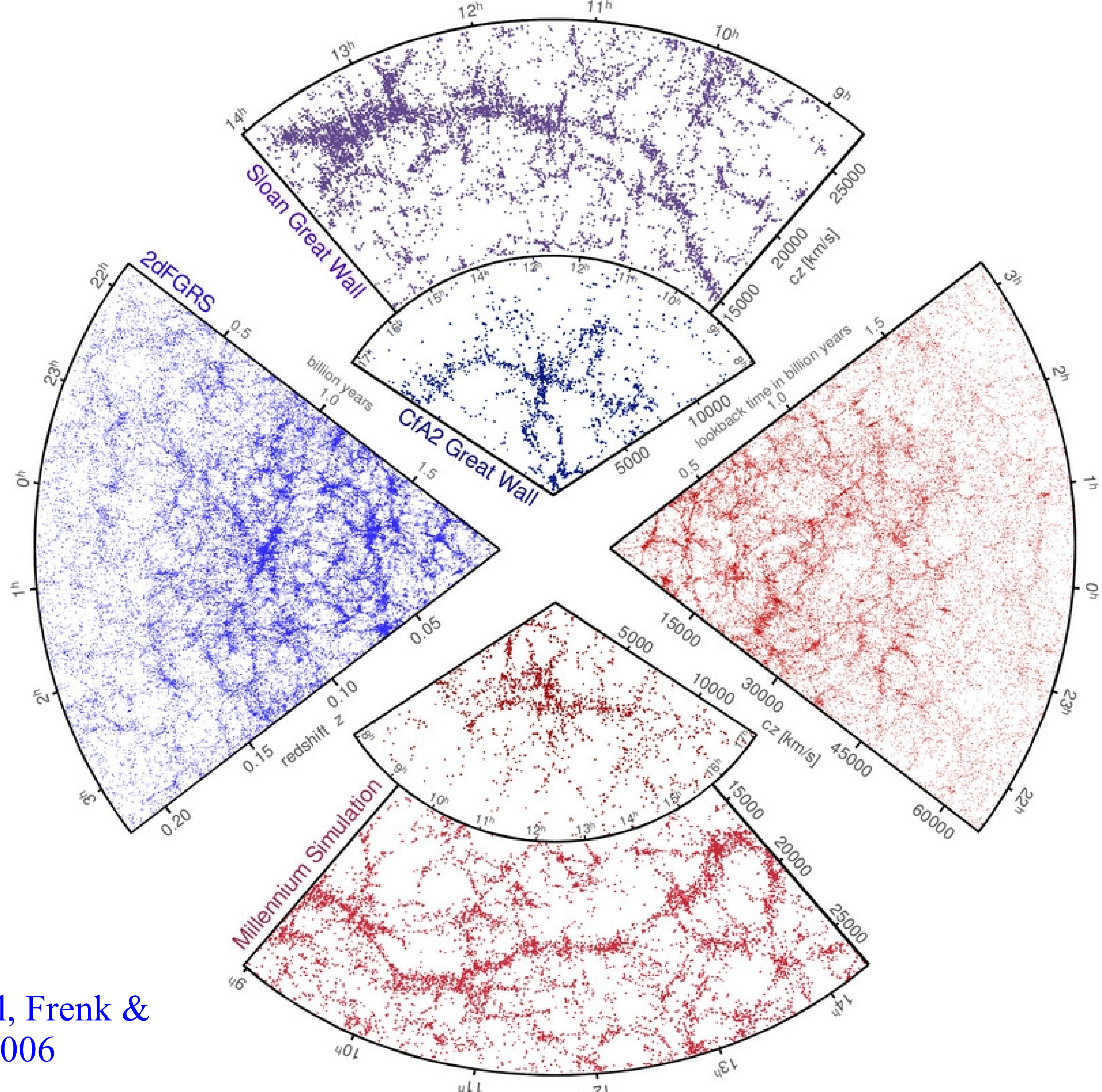

125 Mpc/h
z = 0 Dark Matter

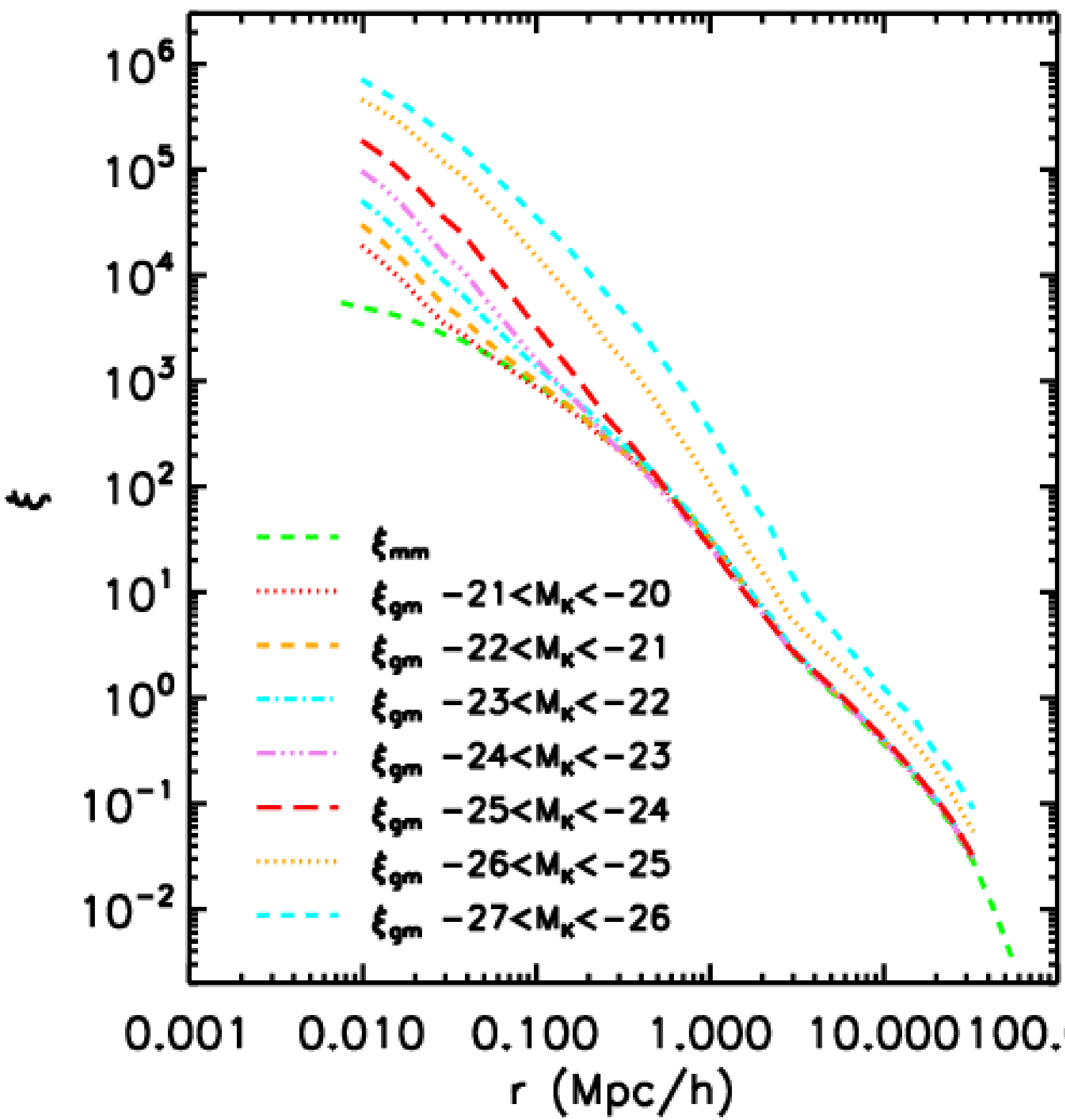

z = 0 Galaxy Light



Springel, Frenk &
White 2006

Galaxy-mass cross-correlations to large radii

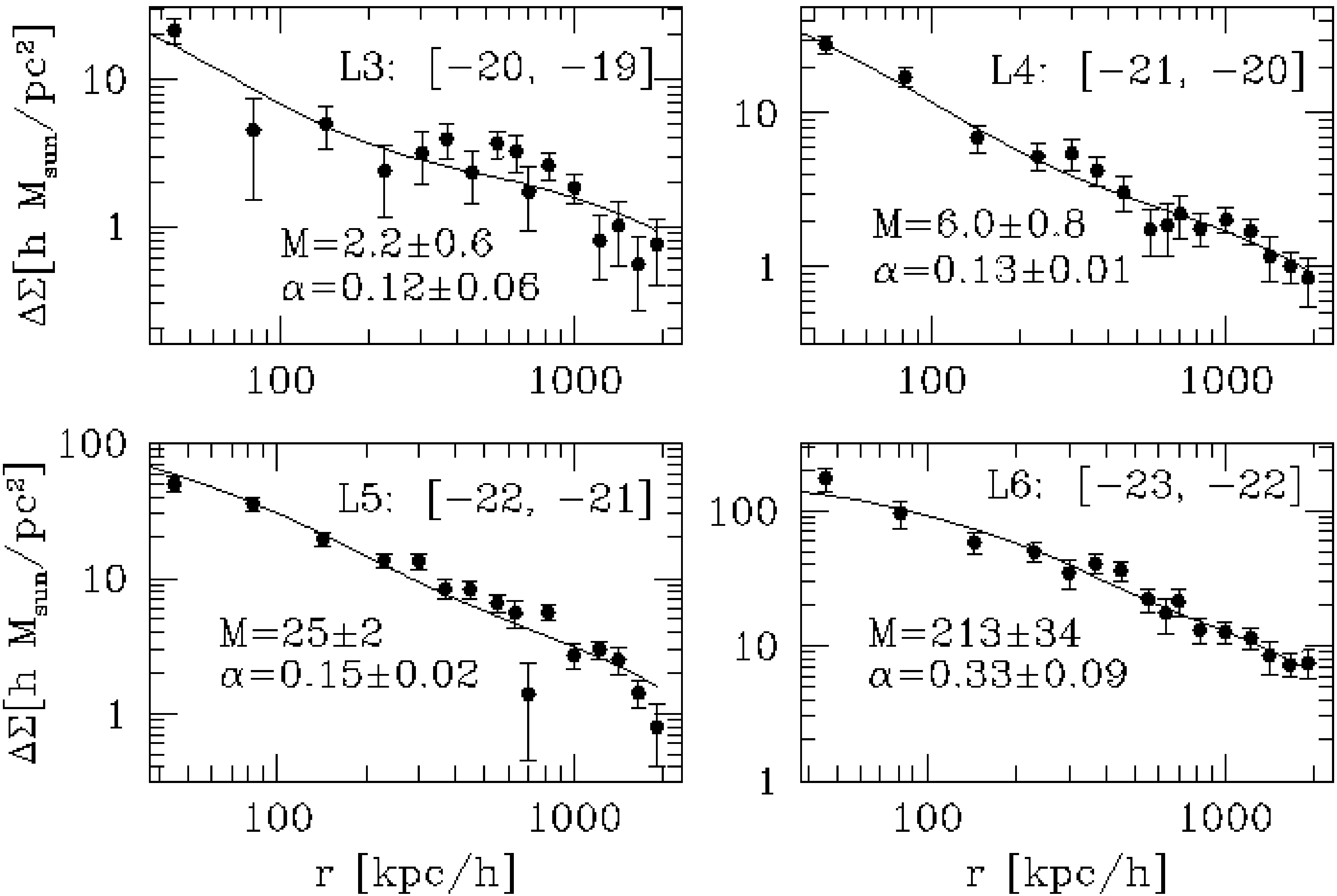
Hayashi et al 2007

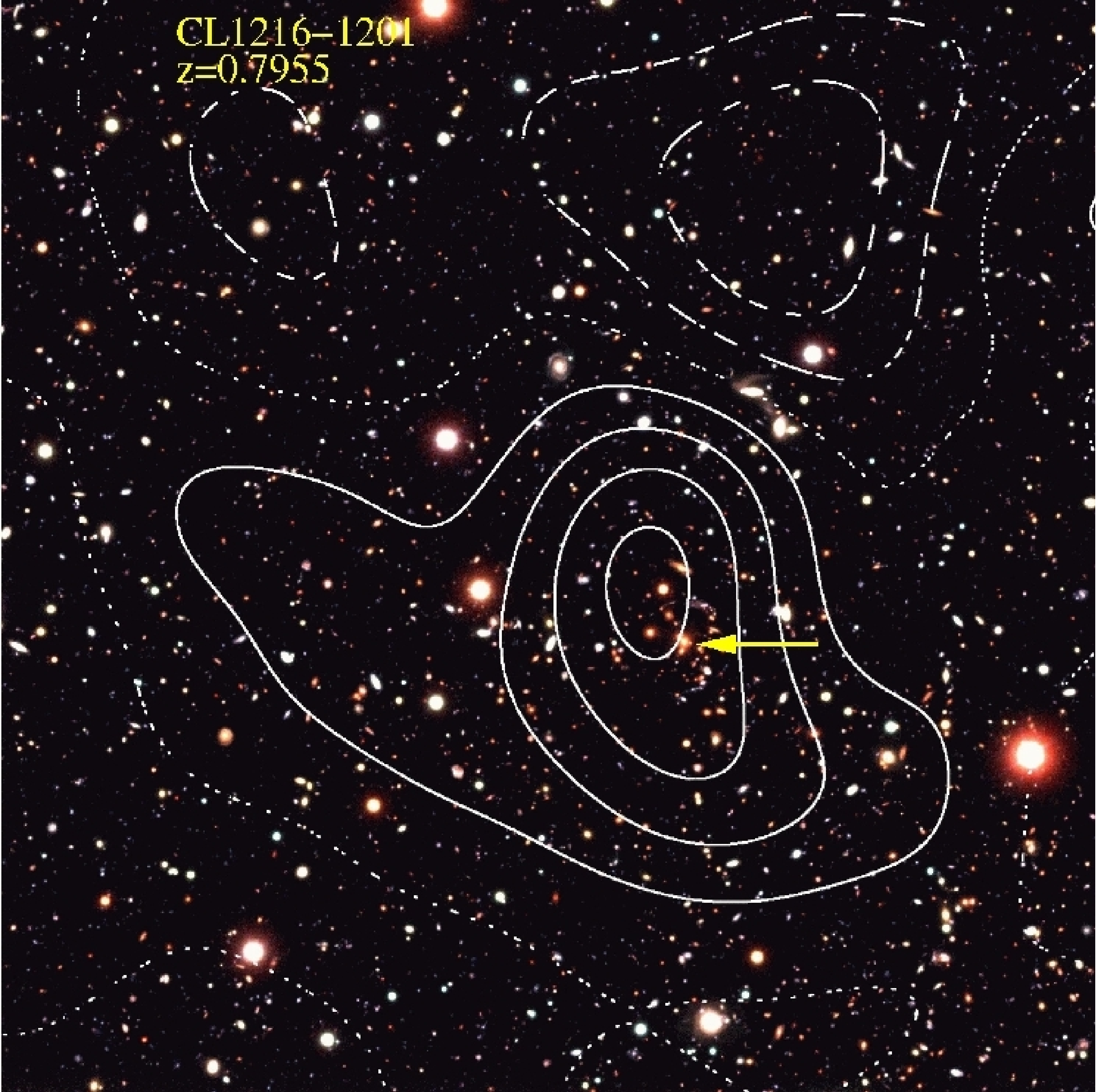


- Galaxy mass cross-correlations are directly measurable through galaxy-galaxy lensing
- They can be predicted from an HOD model and mean halo mass profiles
- Here they are predicted with the Croton et al gal. formation simulation
- On large scale they follow the *nonlinear* ξ_{mm}

Weak lensing measures of halo mass profiles

Seljak et al 2004: from SDSS



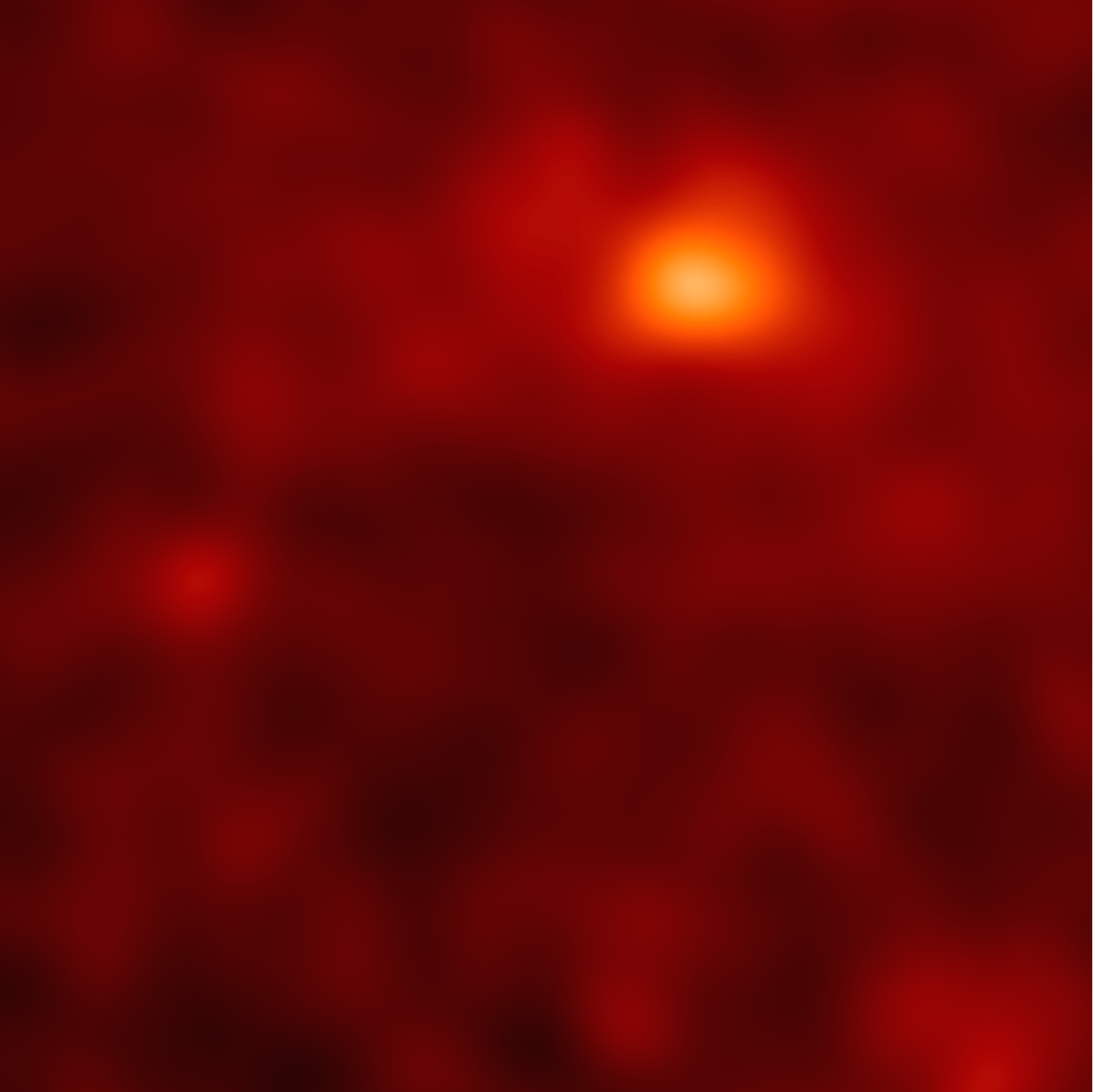


Clowe et al 2006

High redshift with strong lensing

σ_{clus}=1034±46

from measured redshifts



15 arcmin square

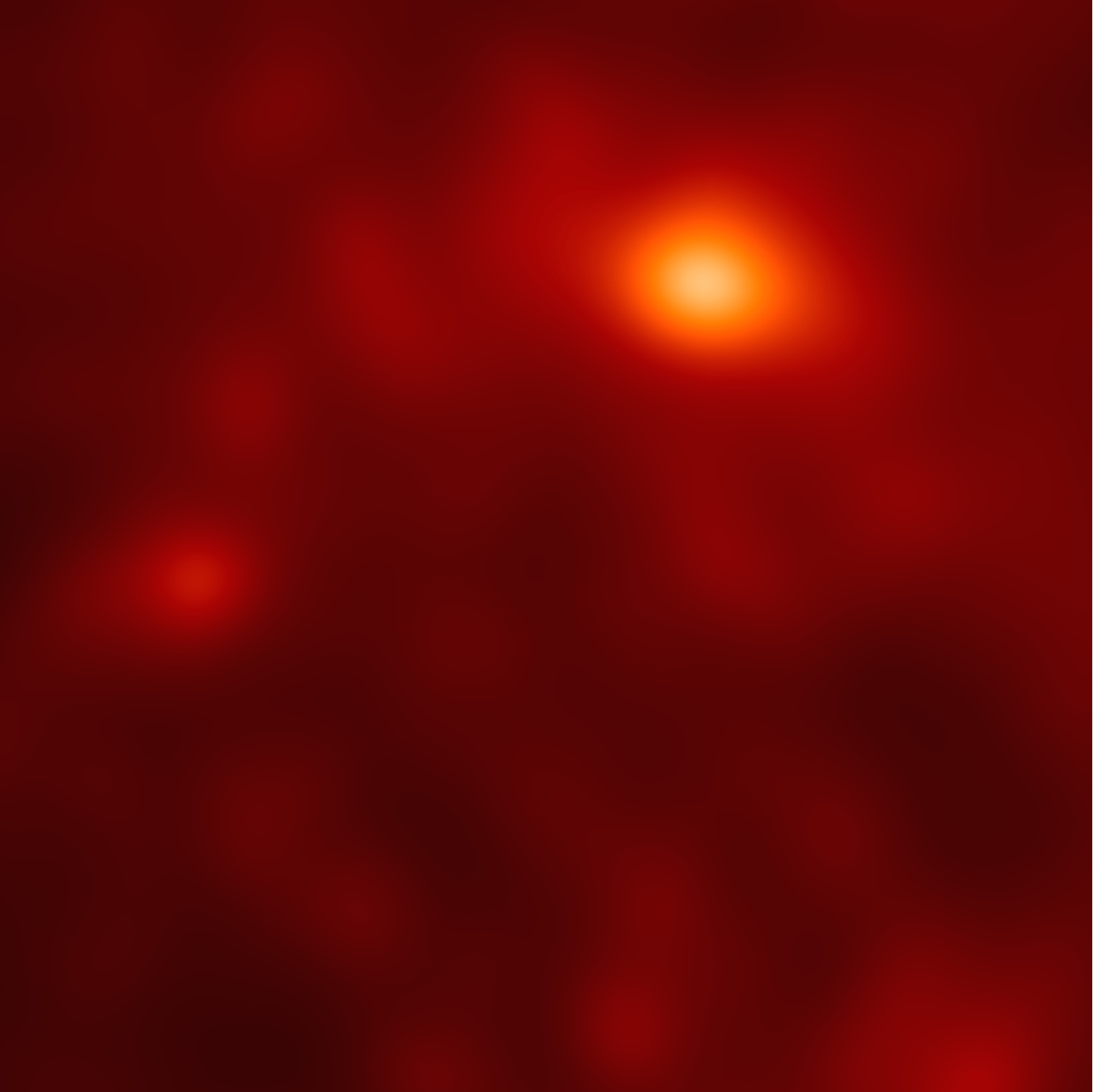
$\overline{z}_{source} = 1.2$

$\theta_{res} = 30''$

100 gals/
squ.arcmin

reconstruction
noise *in*cluded

Hilbert, Metcalf
& White 2007



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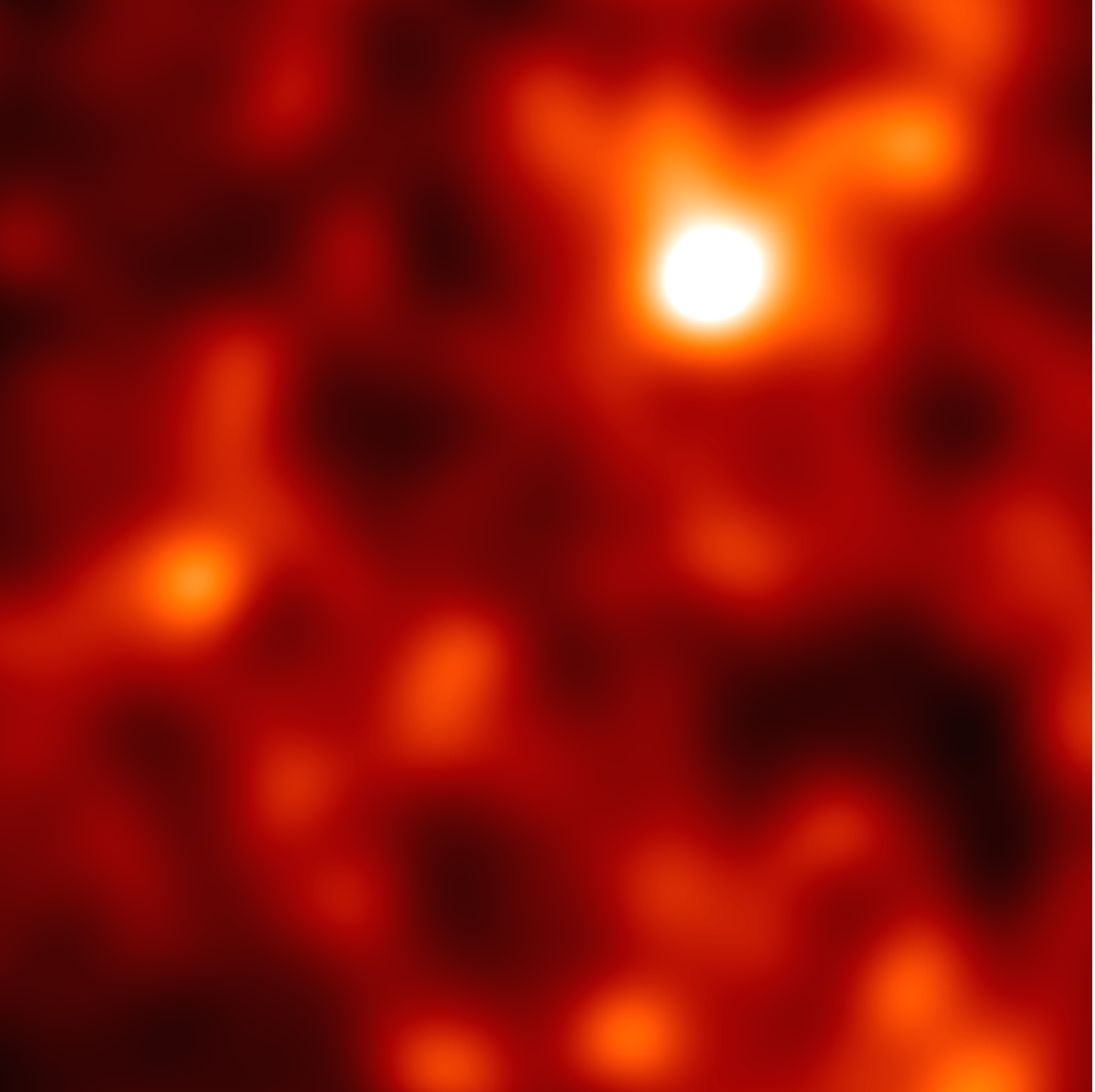

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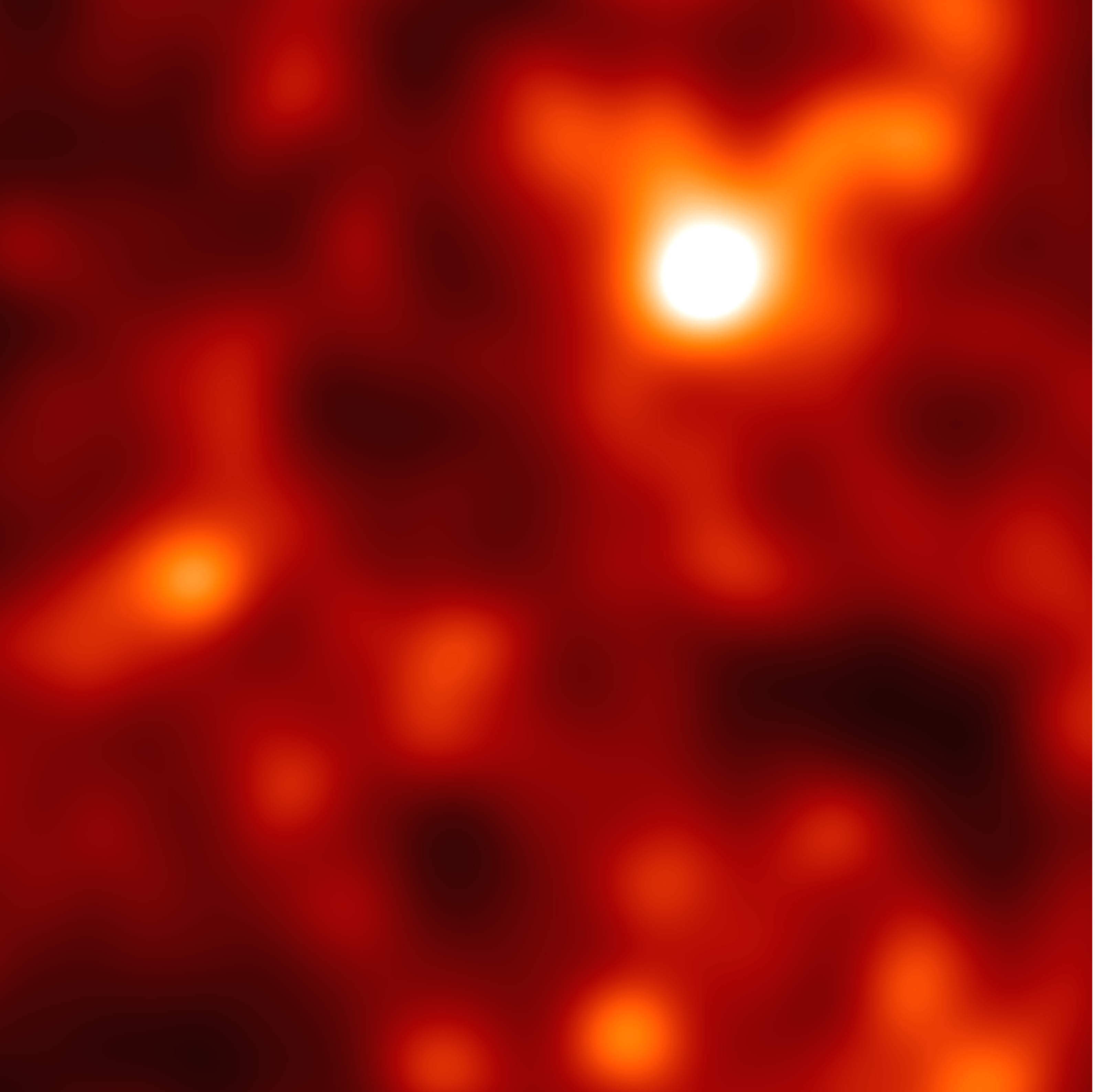
$\theta_{res} = 30''$

SKA 21cm survey

reconstruction noise *in*cluded

Hilbert, Metcalf & White 2007



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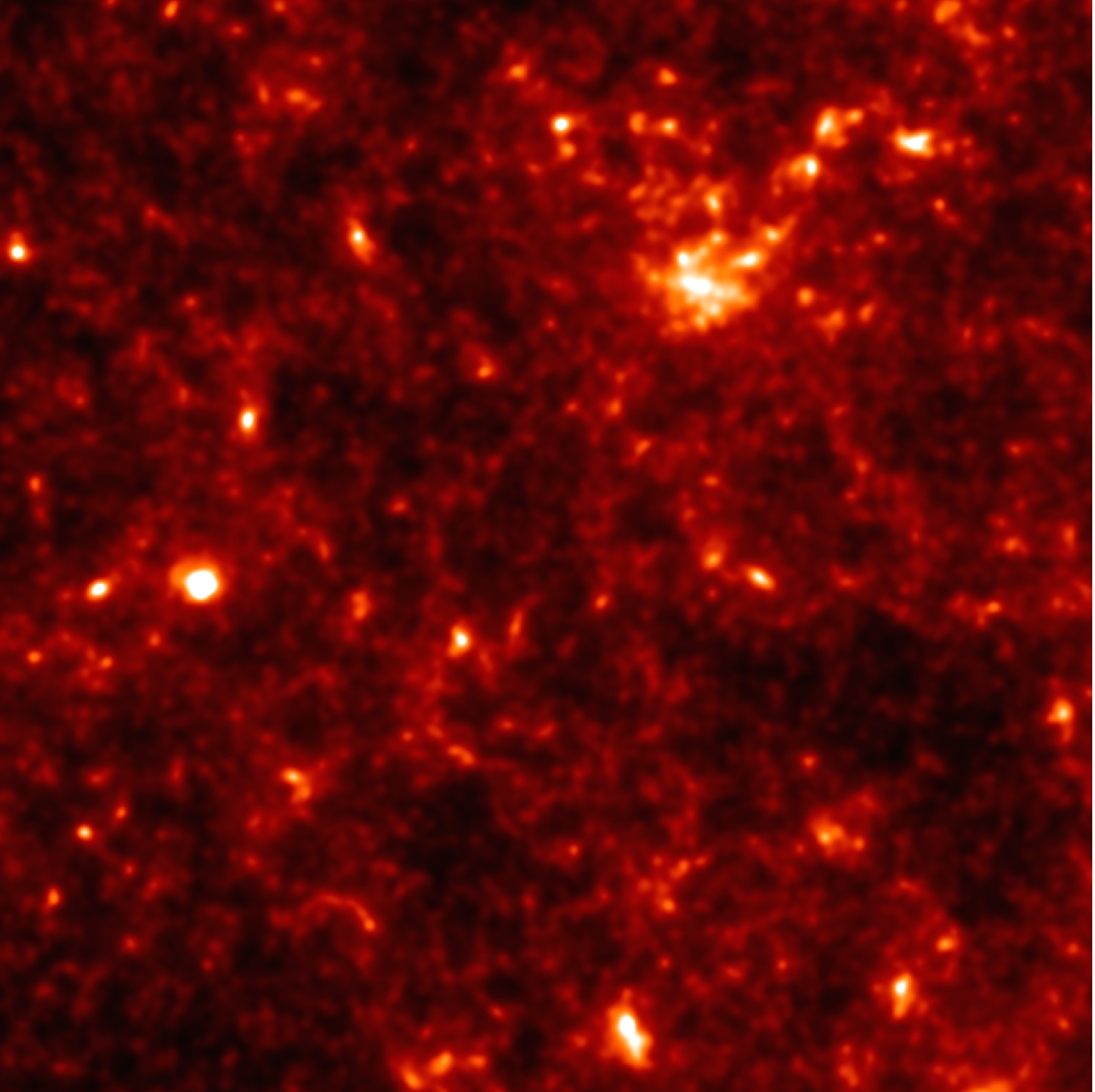
SKA 21cm survey

reconstruction noise *ex*cluded

Hilbert, Metcalf & White 2007



15 arcmin square

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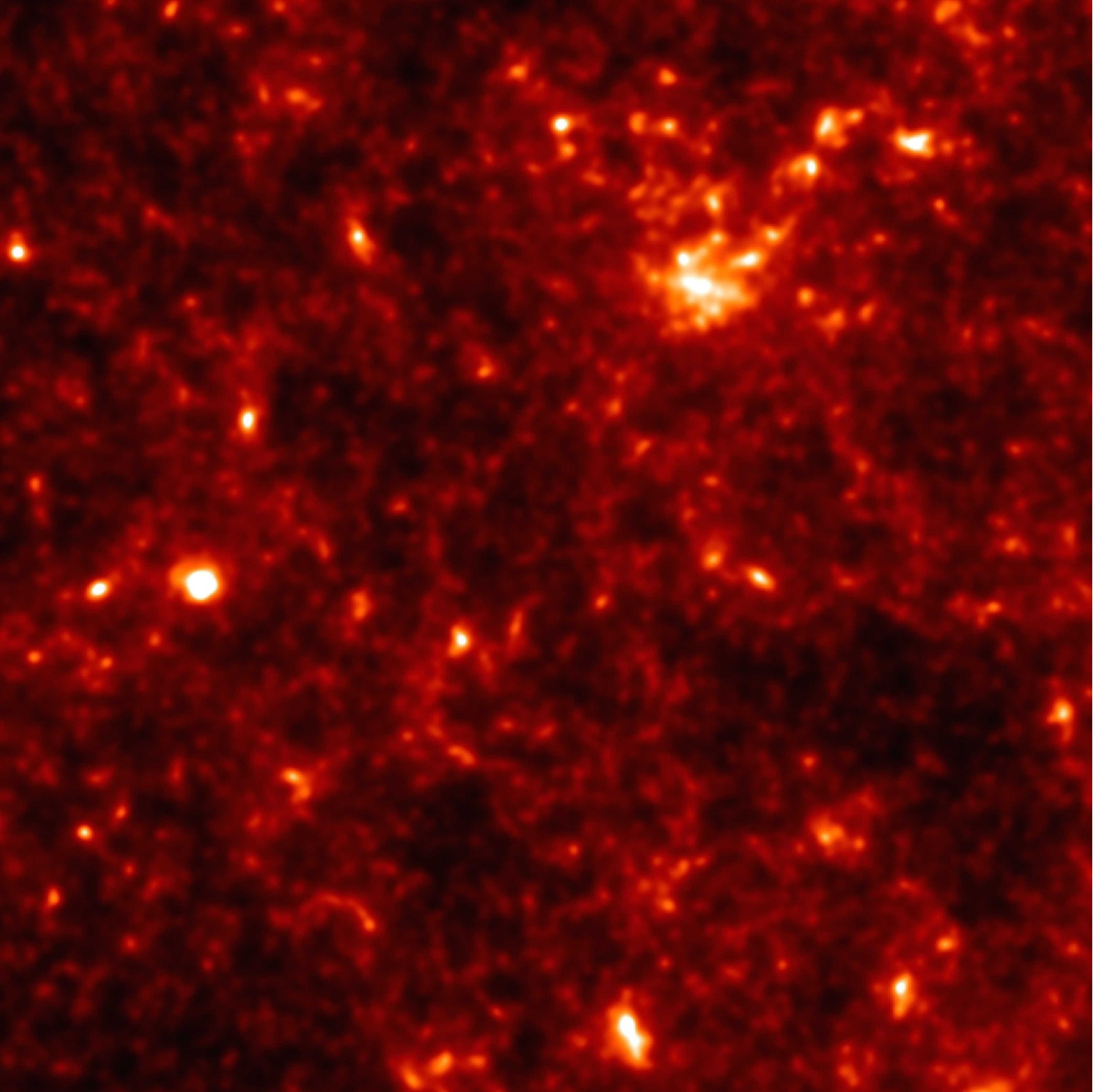
"super"-SKA
21cm survey

reconstruction
noise *in*cluded

Hilbert, Metcalf
& White 2007



15 arcmin square

$z_{source} = 15$

$\theta_{res} = 30''$

"super"-SKA
21cm survey

reconstruction
noise *ex*cluded

Hilbert, Metcalf
& White 2007

CONCLUSIONS

- The WMAP3 parameters result in later formation of the first structures than for WMAP1
- Improving simulations of the formation of DM structure in ΛCDM continue to be consistent with most observations (but dwarf galaxy rotation curves are still a problem)
- The observed properties of Galactic satellites are not in conflict with the substructure predicted in CDM models $\longrightarrow$ astrophysics!
- Annihilation radiation may be first detected by GLAST over a large area $\sim 10^{\circ}$ away from the Galactic Centre and at high latitude
- Galaxy-galaxy lensing can (by stacking signal) detect the <u>mean</u> 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