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Dark Matter in Galaxies: a theoretical overview

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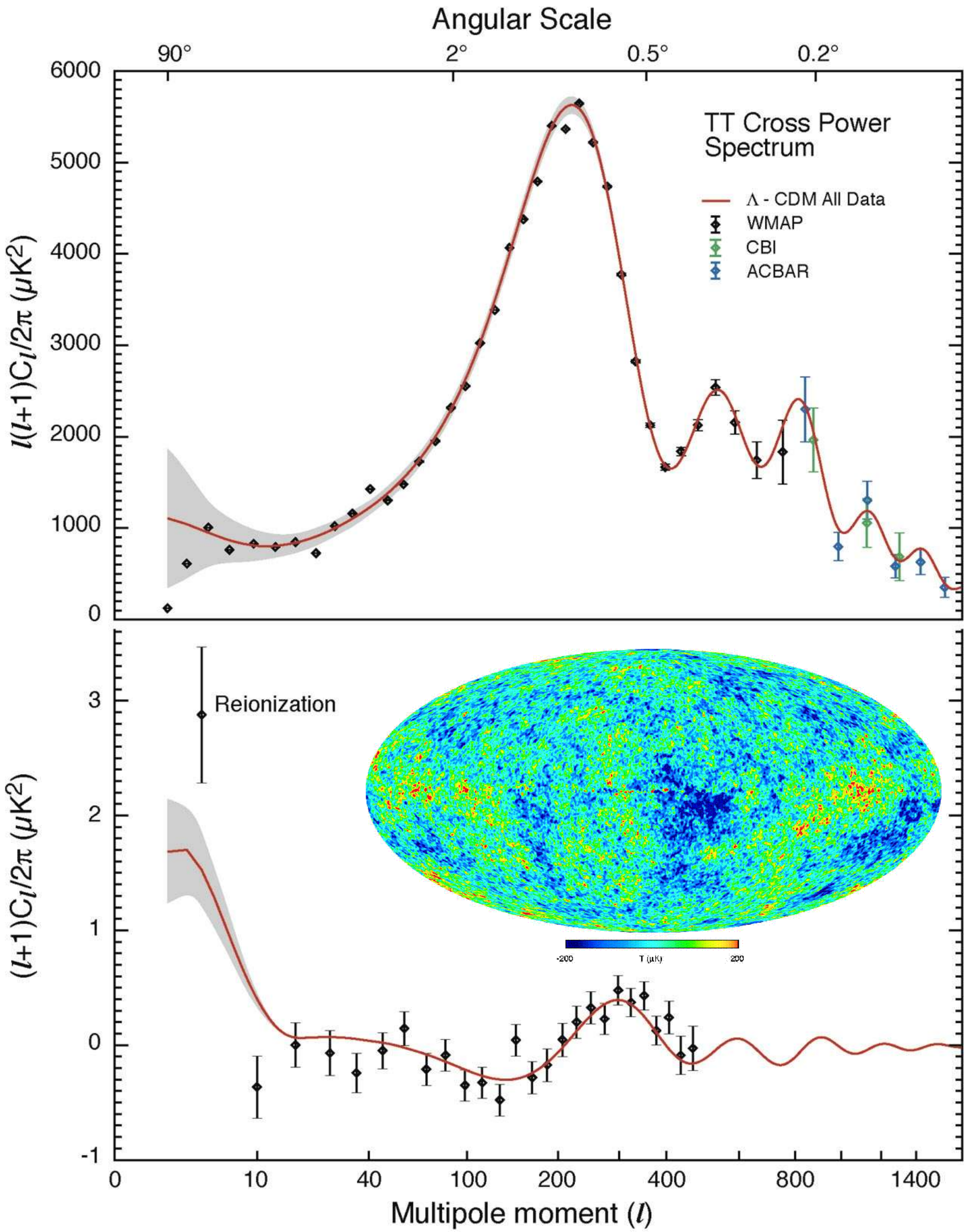


The Emergence of the Cosmic Initial Conditions

- $> 10^5$ independent $\sim 5\ \sigma$ measurements of T are fit by an *a priori* model with 6 (physical) parameters
- Best ΛCDM model has:

  (Bennett et al 2003)

  $t_o = 13.7 \pm 0.2$ Gyr

  $h = 0.71 \pm 0.03$ $\quad \sigma_8 = 0.84 \pm 0.04$

  $\Omega_t = 1.02 \pm 0.02$ $\quad \Omega_m = 0.27 \pm 0.04$

  $\Omega_b = 0.044 \pm 0.004$

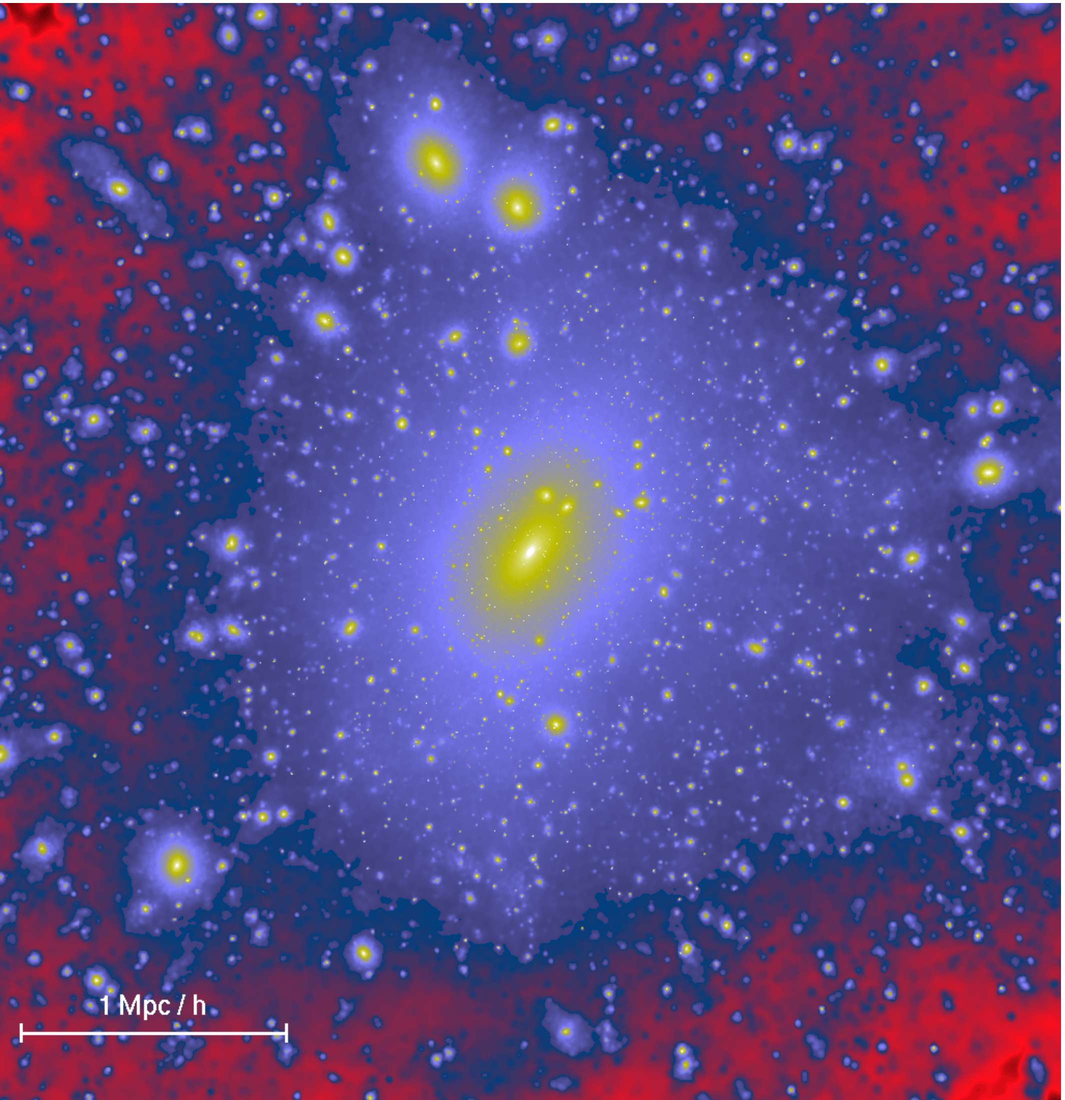
  $\tau_e = 0.17 \pm 0.07$

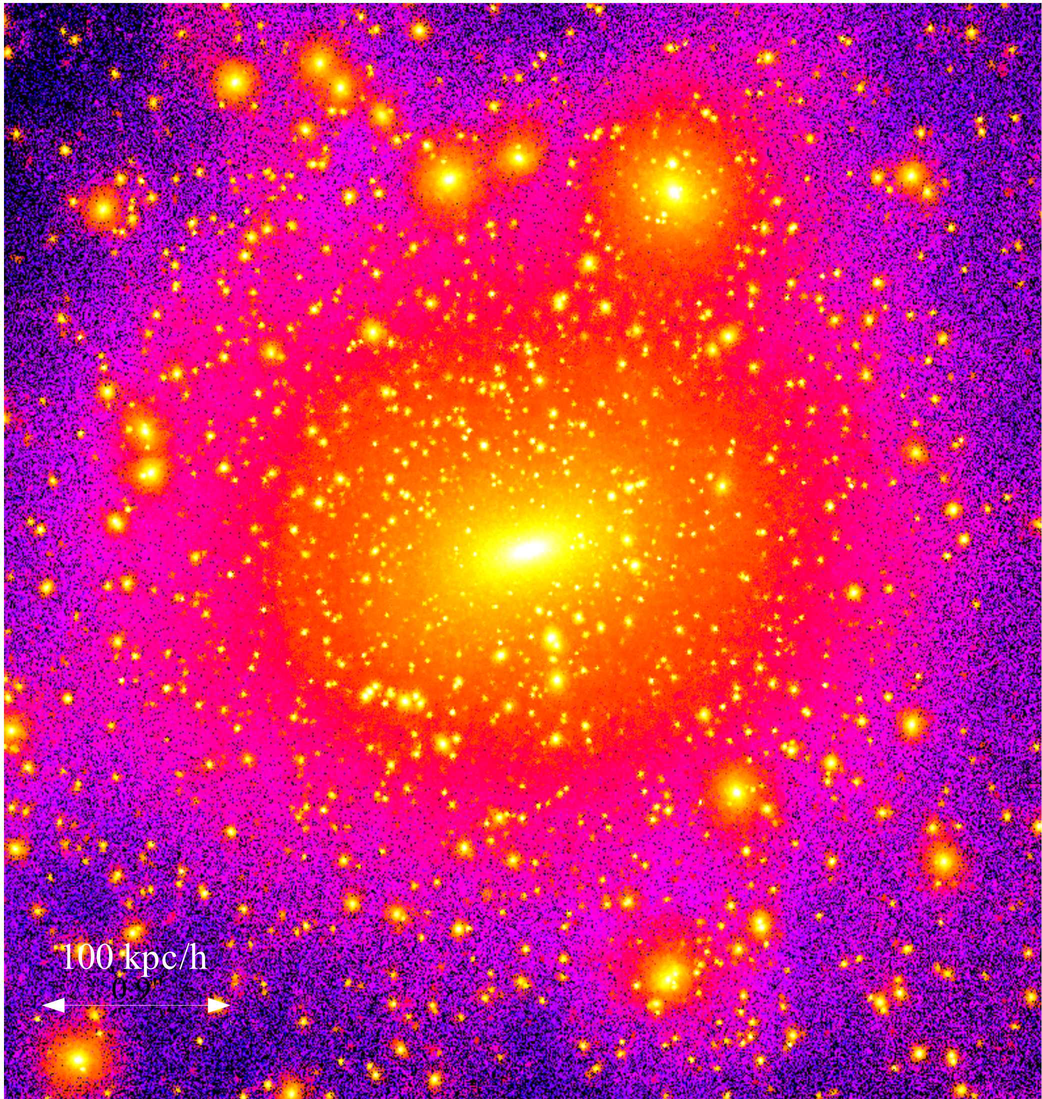
- Parameters in excellent agreement with other data

Small-scale structure in ΛCDM halos

A rich galaxy cluster halo
Springel et al 2001

A 'Milky Way' halo
Power et al 2002

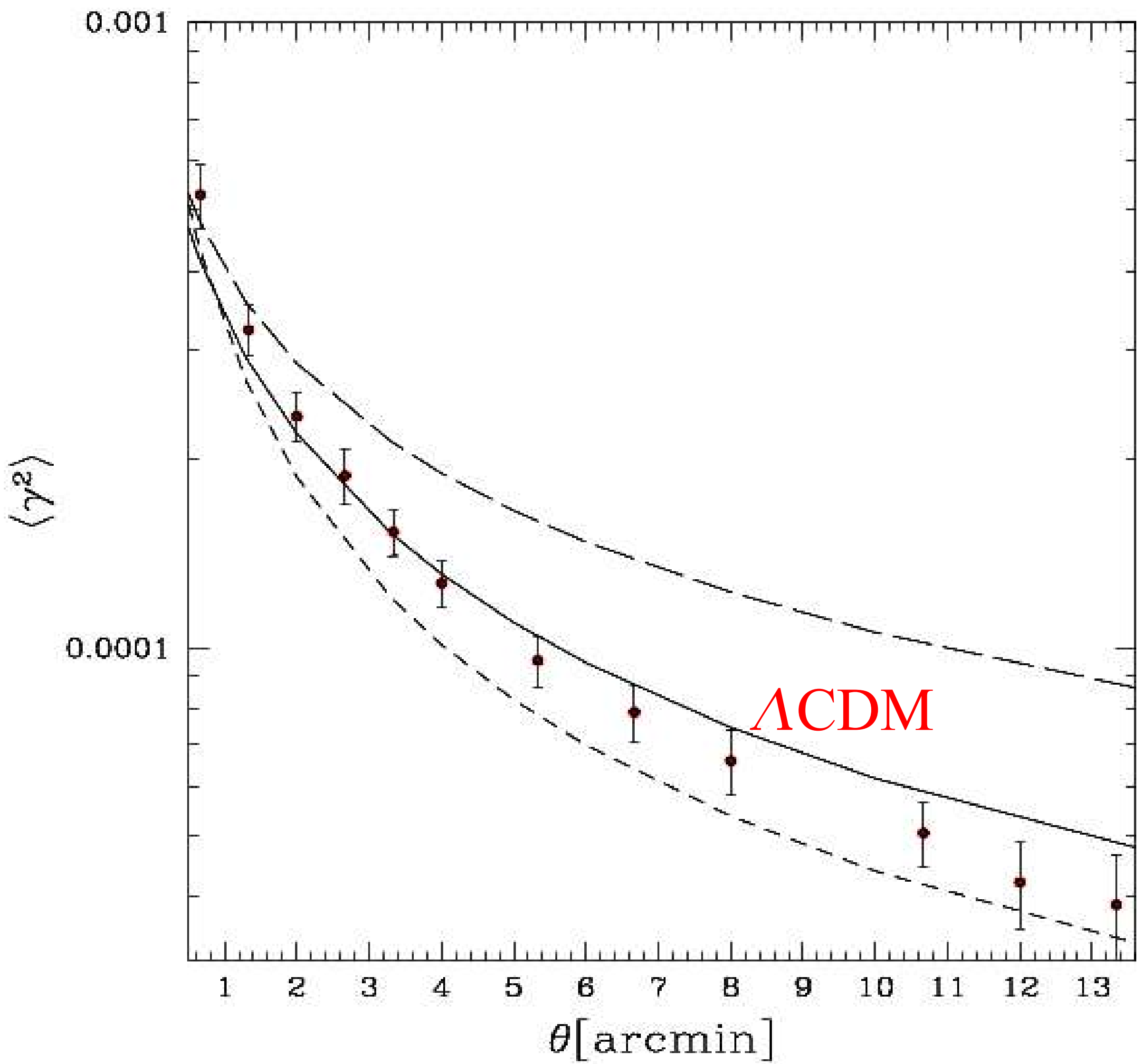




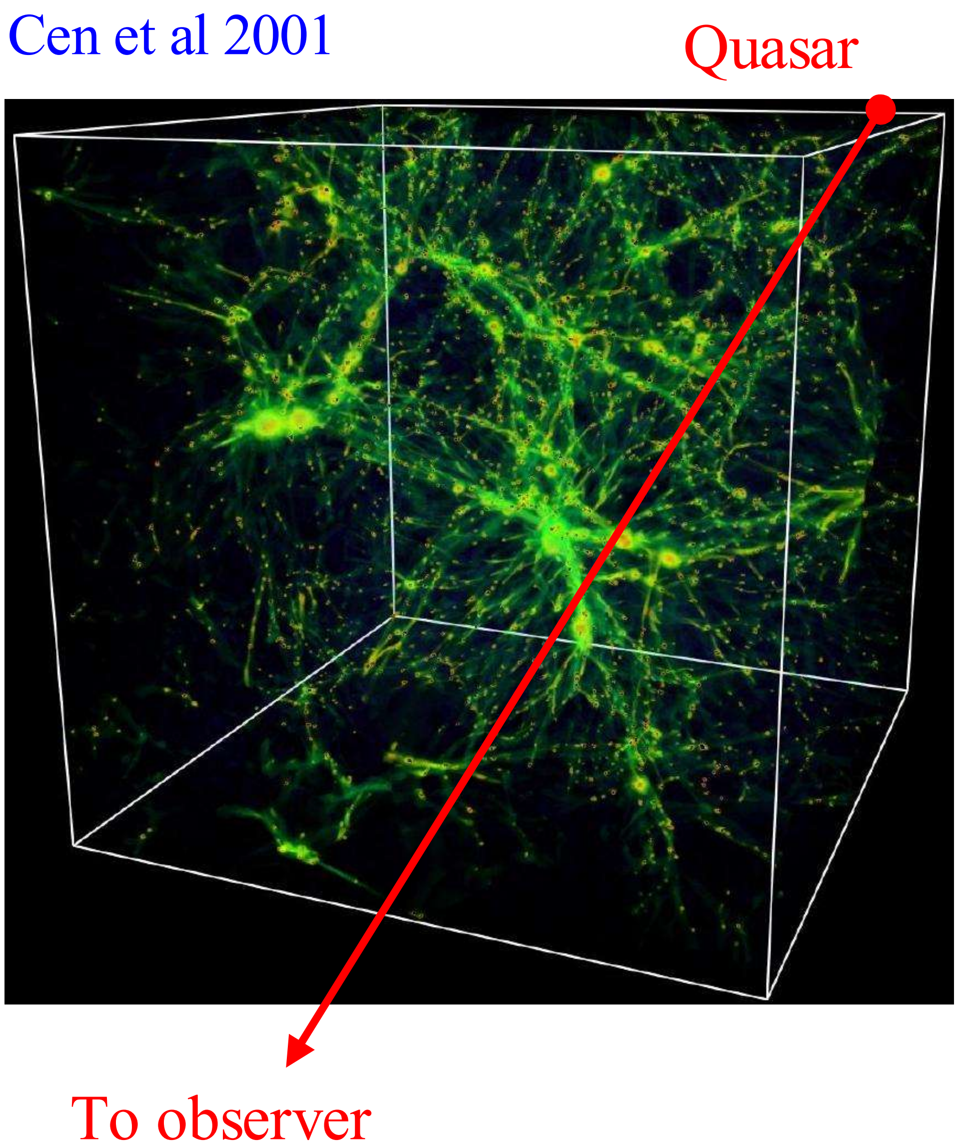
A measurement of dark matter clustering

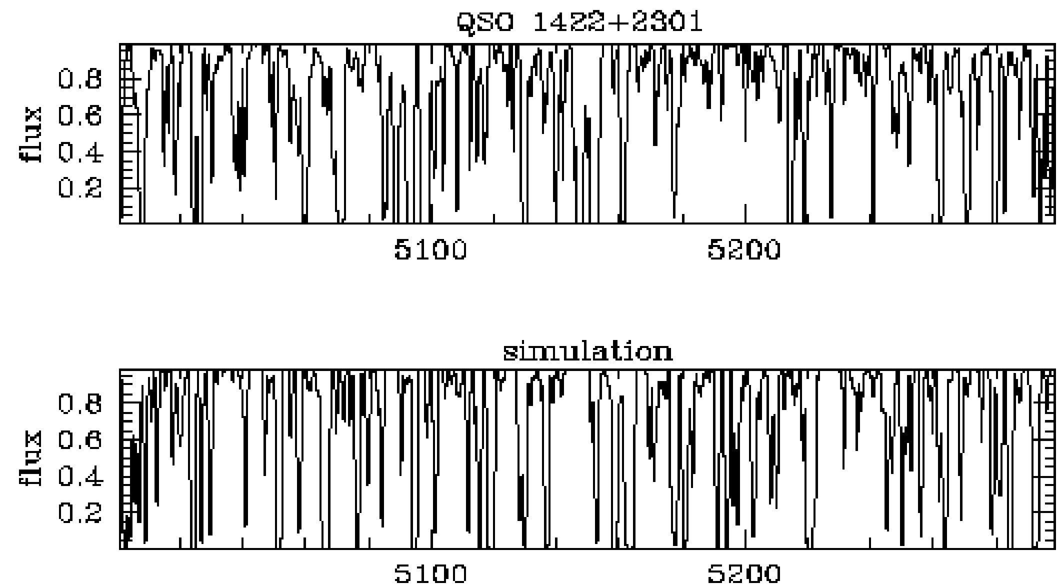
Van Waerbeke et al 2001

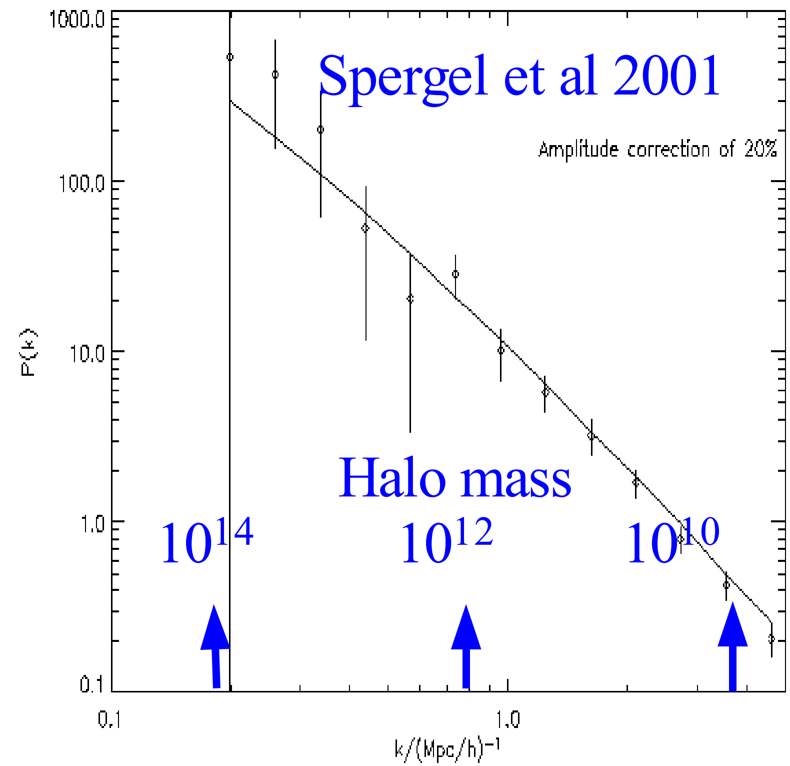
- $<\gamma^2>$ is the mean square gravitational shear of background galaxy images within circles of radius ϑ.
- It is proportional to the mean square lensing mass within these circles
- On scales of a few arcmin the signal is dominated by *nonlinear* DM clustering, i.e. by the dark halos of galaxies and galaxy groups



Structure in the intergalactic medium







Small-scale structure in ΛCDM halos

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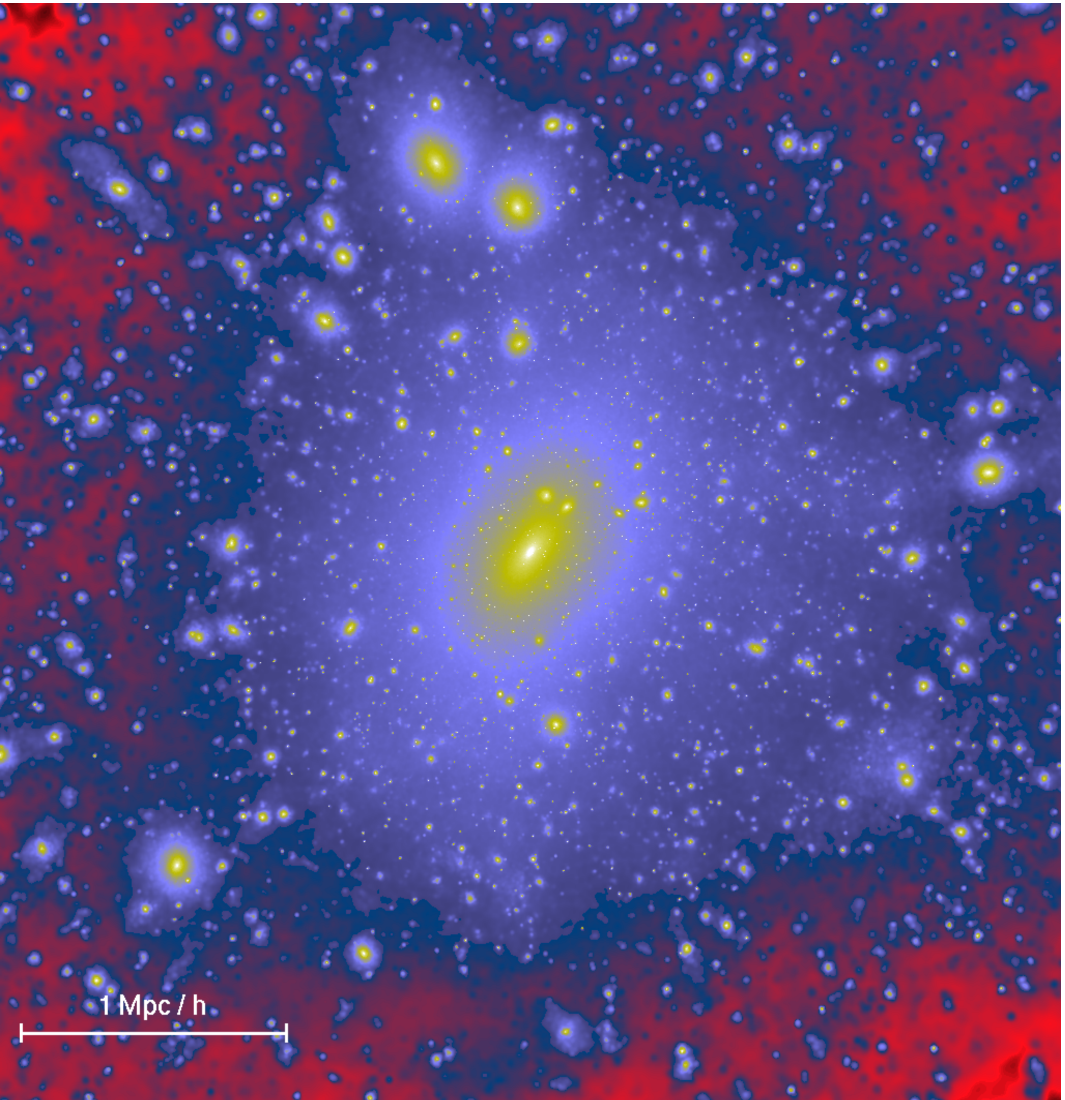

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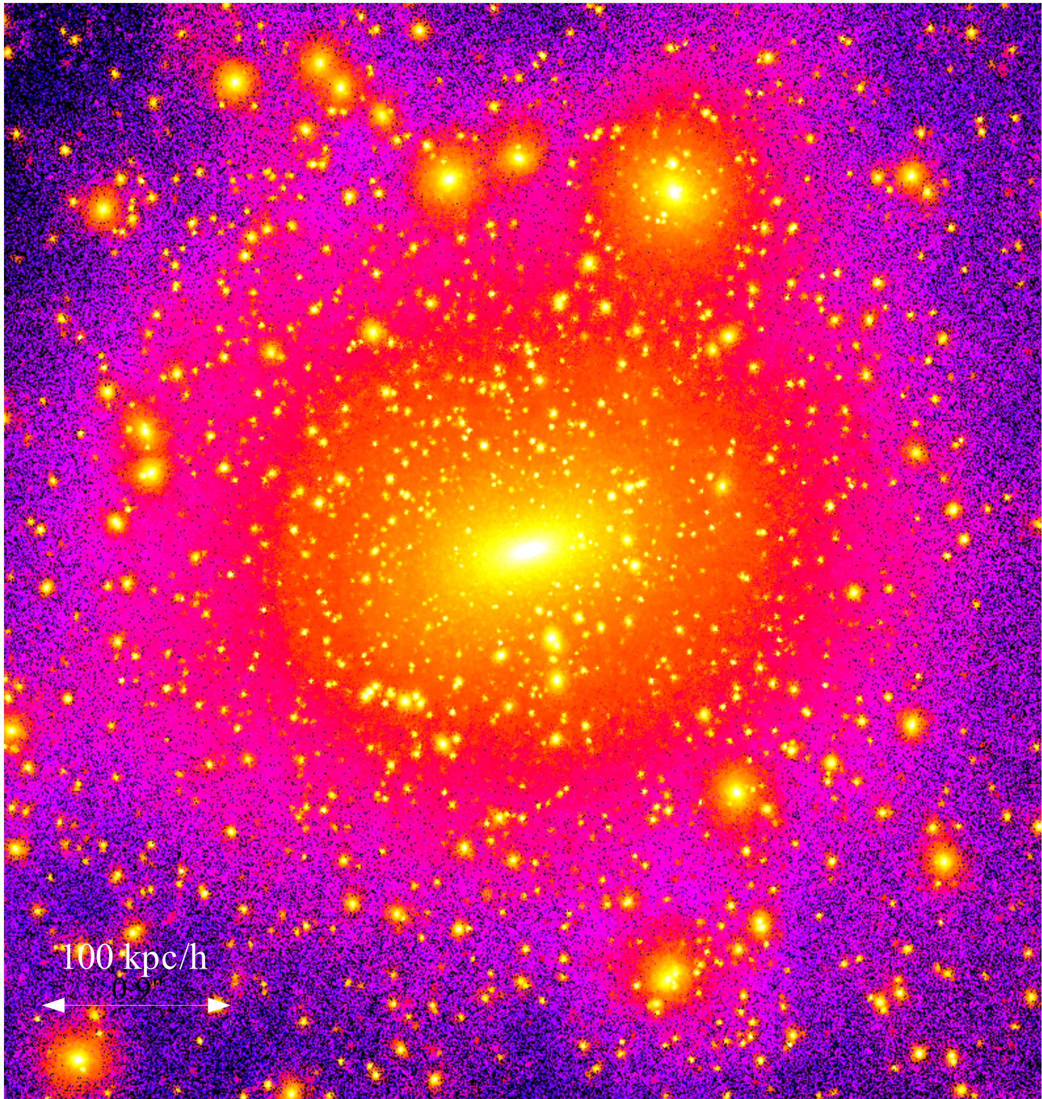
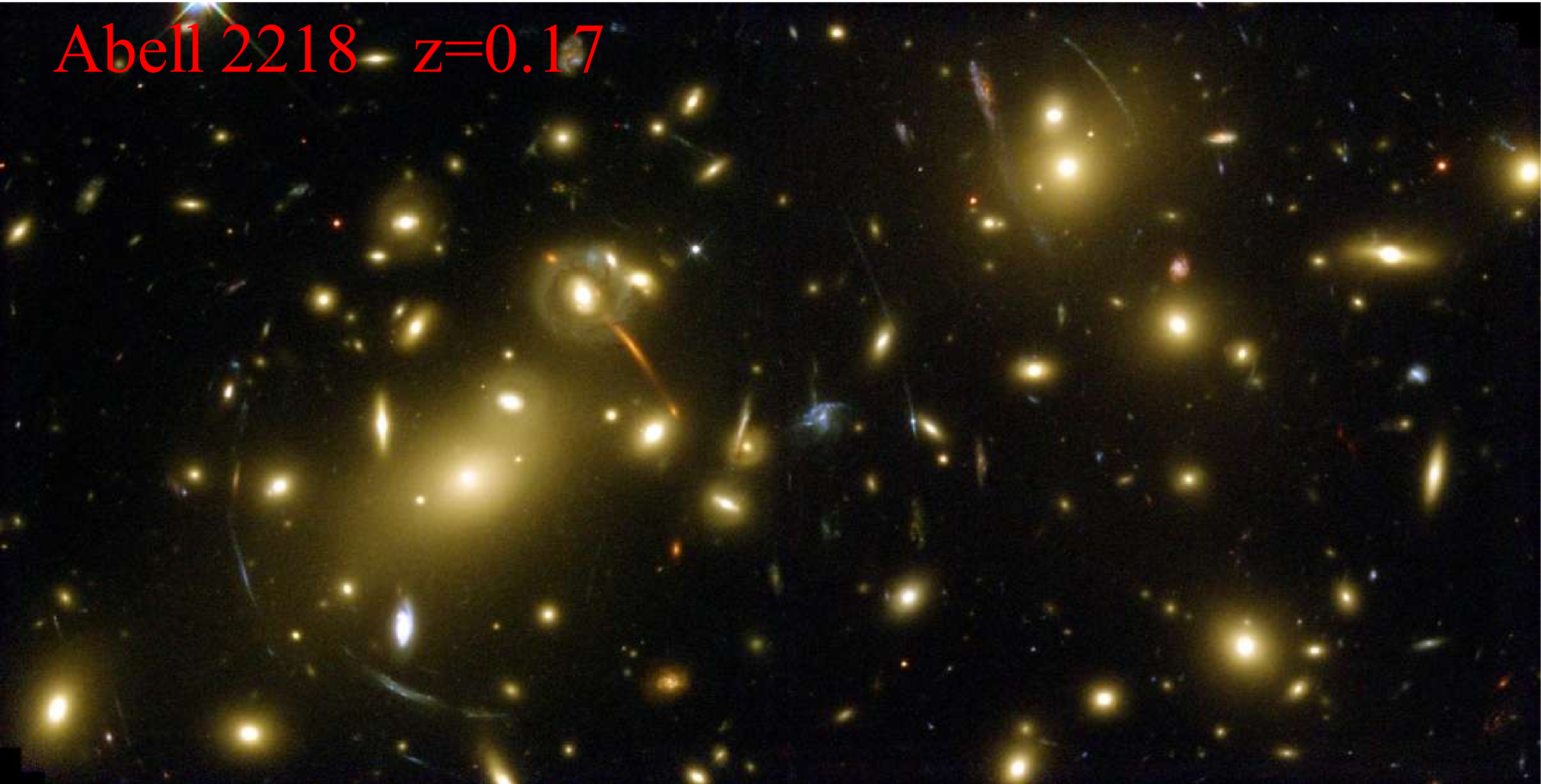


Gravitational lensing by a galaxy cluster

Both strong lensing and X-ray data indicate that many/most clusters have compact cores or cusps and an NFW-like density structure



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 $d N / d M \sim M^{-1.8}$

Tests for the extent of dark halos

- Motions of satellite galaxies (Zaritsky et al 1993, 1996; McKay et al 2002, Prada et al 2003 (SDSS); Norberg et al 2003 (2dF))
- 'Galaxy-galaxy' lensing (McKay et al 2002 (SDSS); Hoekstra, this meeting)
- Shapes and kinematics of streams (Majewski, this meeting)

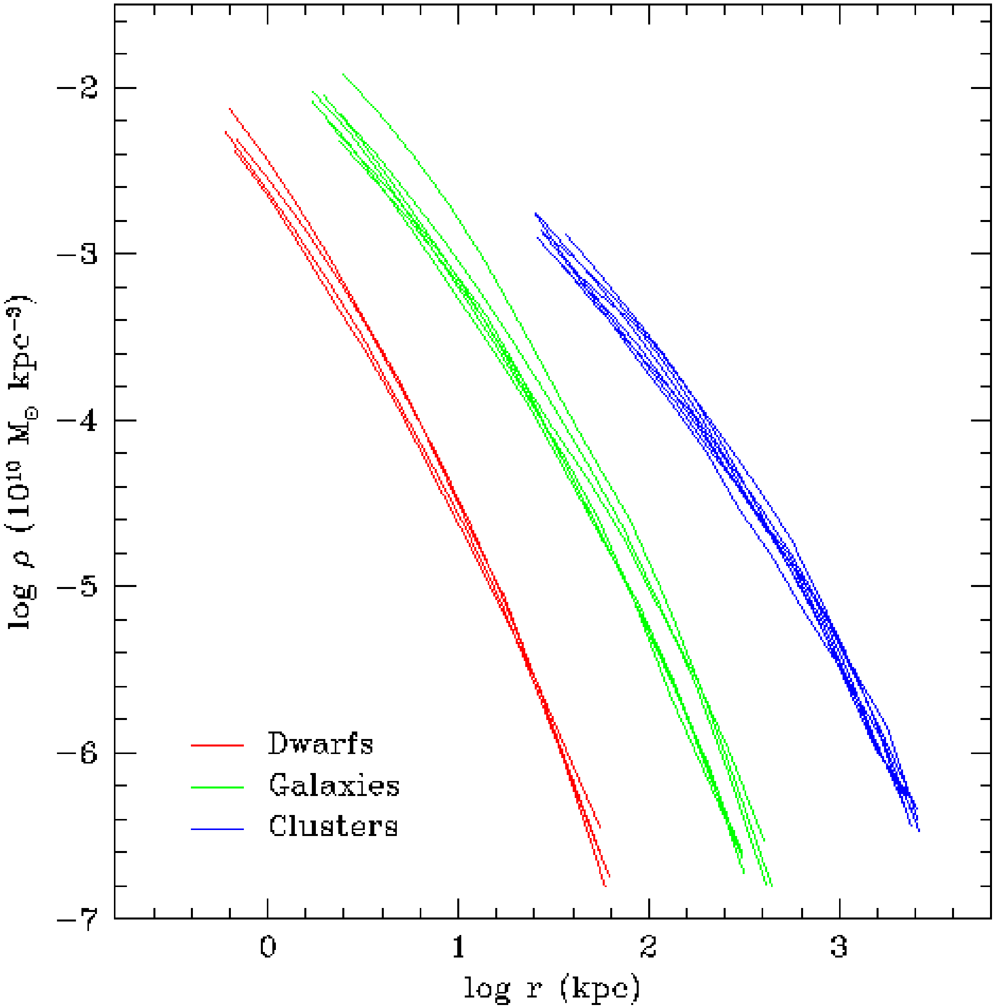
Tests for the shape of dark halos

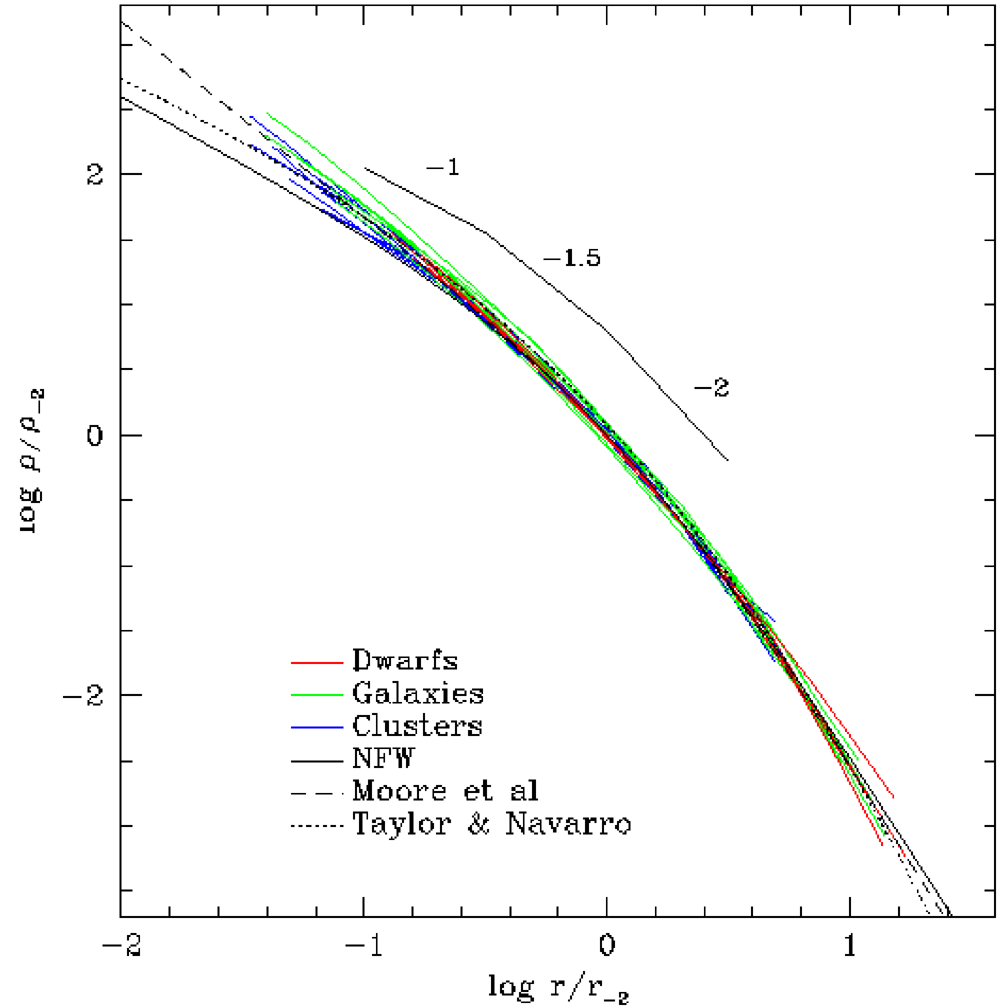
- 'Galaxy-galaxy' lensing (Hoekstra, this meeting)
- Polar ring shapes and kinematics (Sackett, Iodici, this meeting)
- Sagittarius stream kinematics (Ibata et al 2002, Spergel et al)

Explanations for the core/satellite "crises"

- The dark matter is warm
- The dark matter has a finite self-scattering cross-section
- The primordial density power spectrum has a break
- There is no dark matter -- gravity needs modifying
- Only 10% of sub-halos contain stars
- The comparison of models and data is incorrect

Profiles from high-resolution simulations

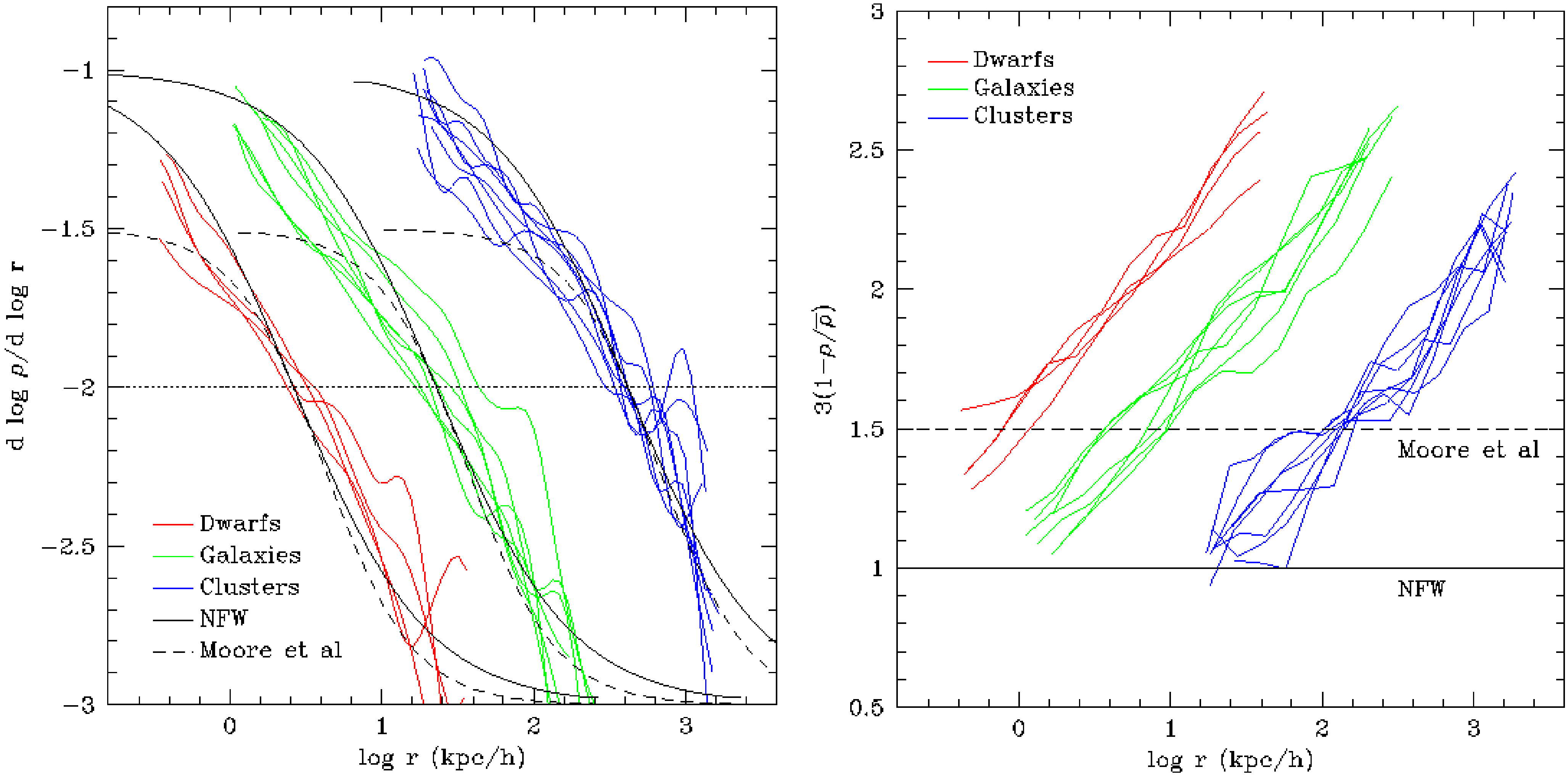




Hayashi, Navarro et al 2003

$N_{200} > 10^6$, $\epsilon \sim 0.002\ R_{200}$, convergence tested at all plotted points

Profile slopes



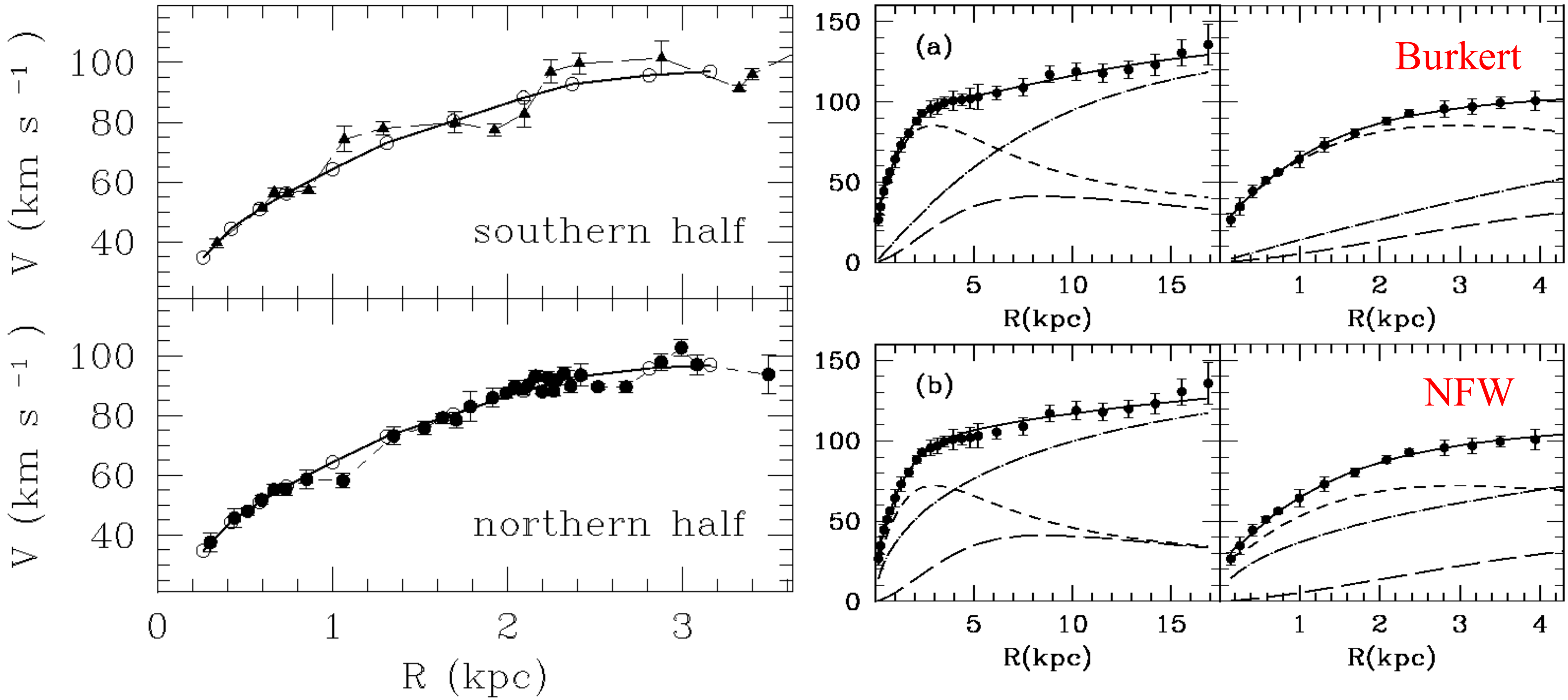
Hayashi, Navarro et al 2003

Local slope of density profile

Upper limit on asymptotic inner slope

The rotation curve of M33

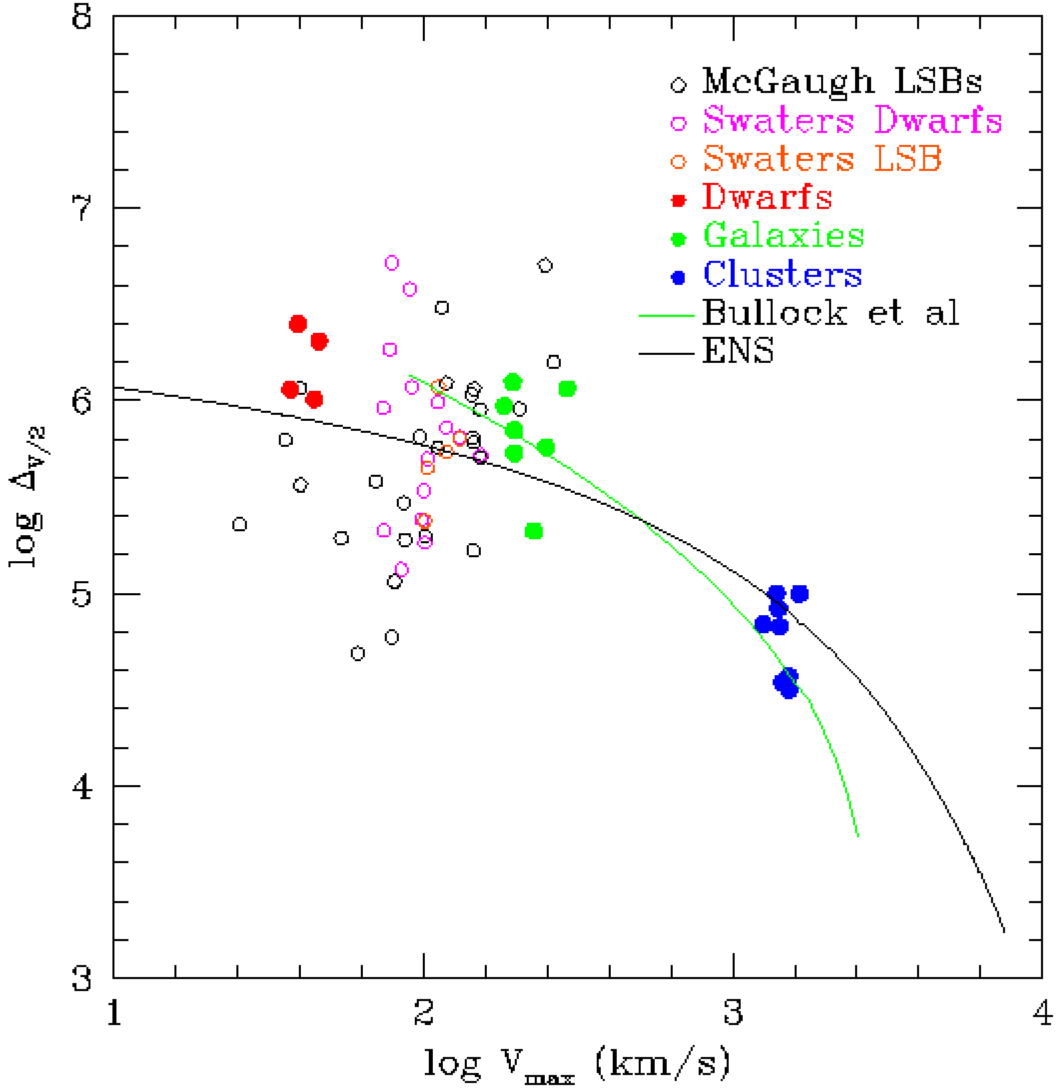
Corbelli 2003



- 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

Comparison to observed dwarf and LSB galaxies

Hayashi, Navarro et al 2003



- V_{max} is maximum of observed rotation curve or of halo circular velocity curve
- $\Delta_{V/2}$ is the density contrast relative to the critical density within the point where V_{rot} first reaches $V_{max}/2$

Is the observed $V_{rot}(r)$ really $(G\ M(r)/r)^{1/2}$?

- Noncircular streaming motions -- bars, triaxial halos?
- Chaotic motions -- turbulence, outflows?
- Warps?
- Beam smearing?
- Incomplete coverage of galaxy by emitting gas?
- Slit misalignment?

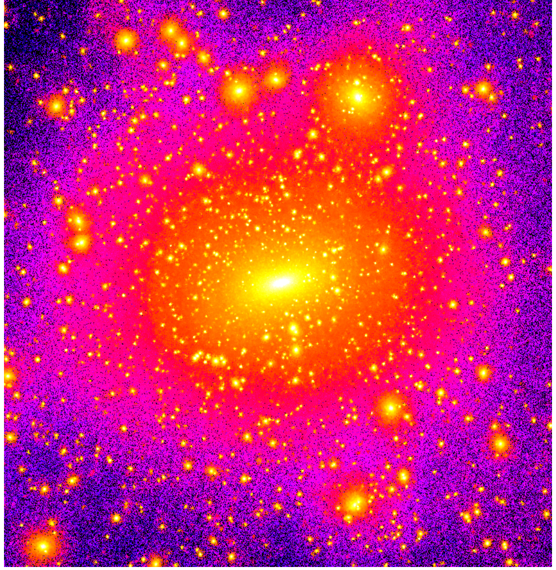
Does $\rho_{DM}(r)$ reflect the 'pregalactic' prediction?

- 'Adiabatic' compression as galaxy accumulates
- Re-expansion due to rapid (baryonic) mass loss
- Removal of central cusp by a bar
- Removal of central cusp by tidal effects

Other problems with massive, cuspy halos?

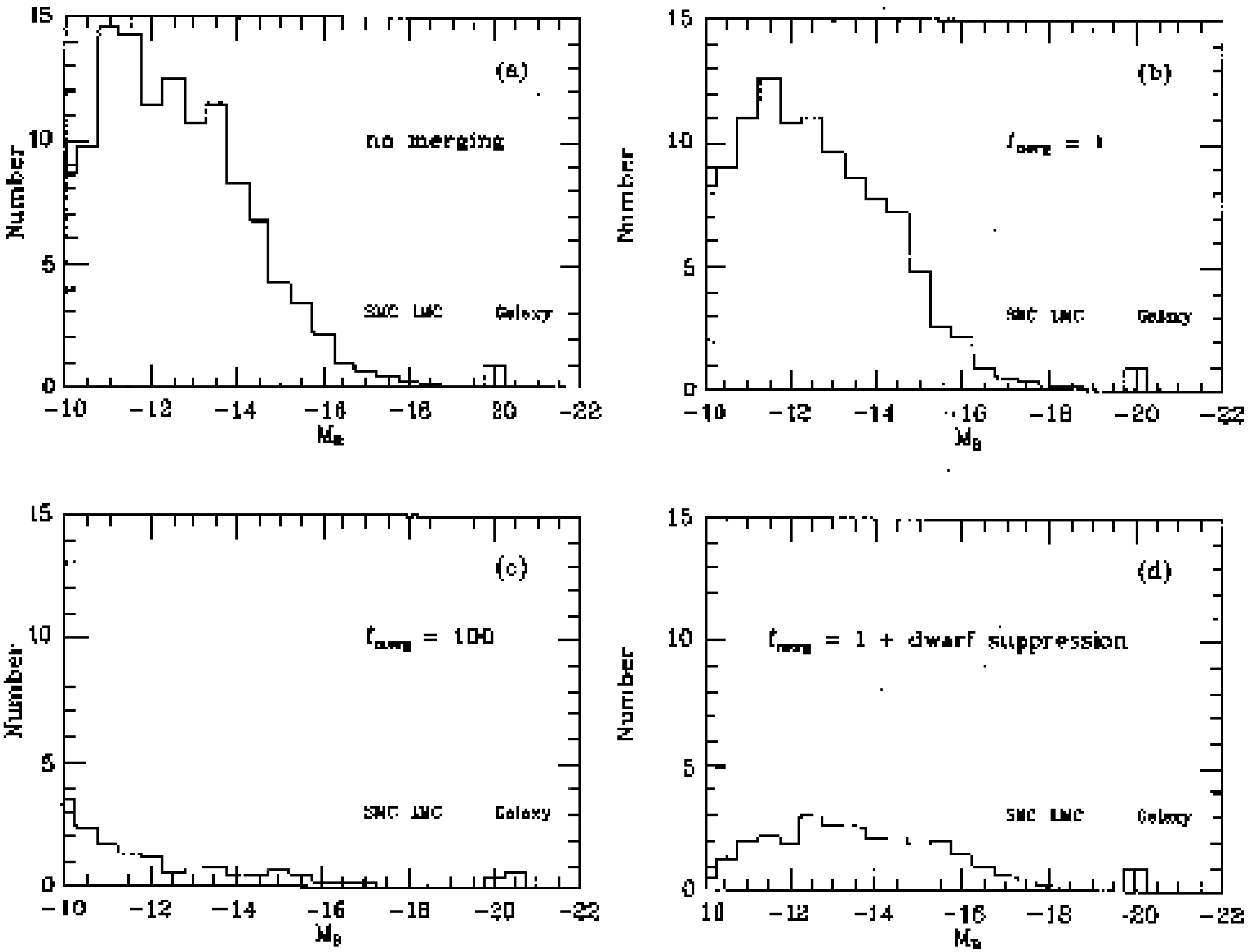
- Observed components account for most/all of the dynamically required mass in some systems
  - --- Milky Way (bulge microlensing)
  - --- barred galaxies (bar M/L from streaming motions)
  - --- massive spirals (disk M/L from spiral-driven motions)

- Concentrated and massive halos can slow the pattern speed of bars to well below the observed values



Too many satellites for CDM?

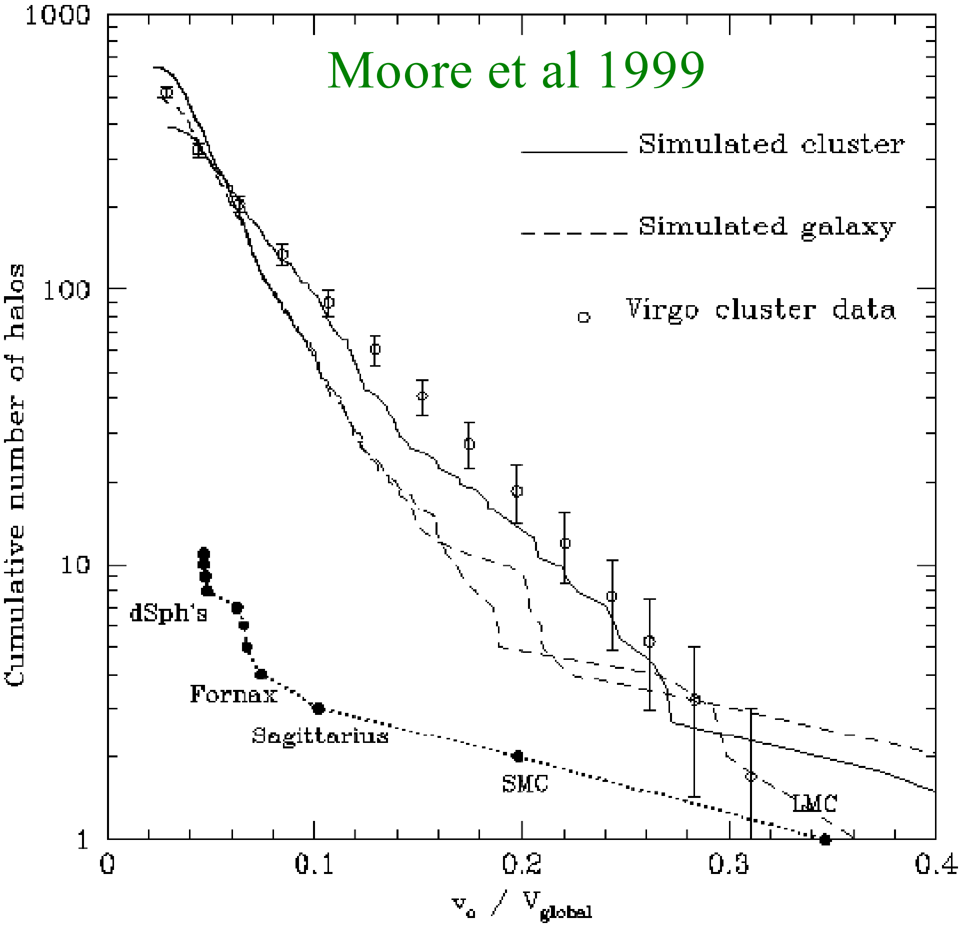
Kauffmann, Guiderdoni, White 1993

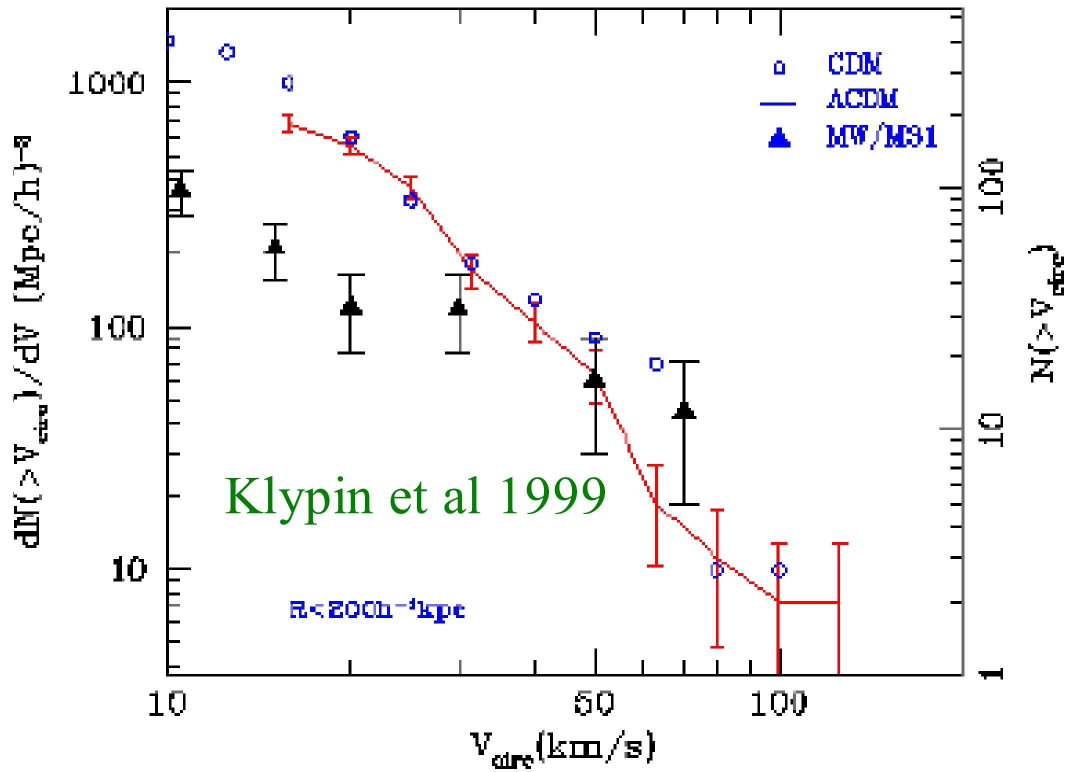


- In hierarchical models like CDM the Milky Way's halo formed out of many smaller halos
- If all progenitors made stars with *reasonable* efficiency too many satellites result
- Star formation must be strongly suppressed in low mass progenitors

Reionisation effects?

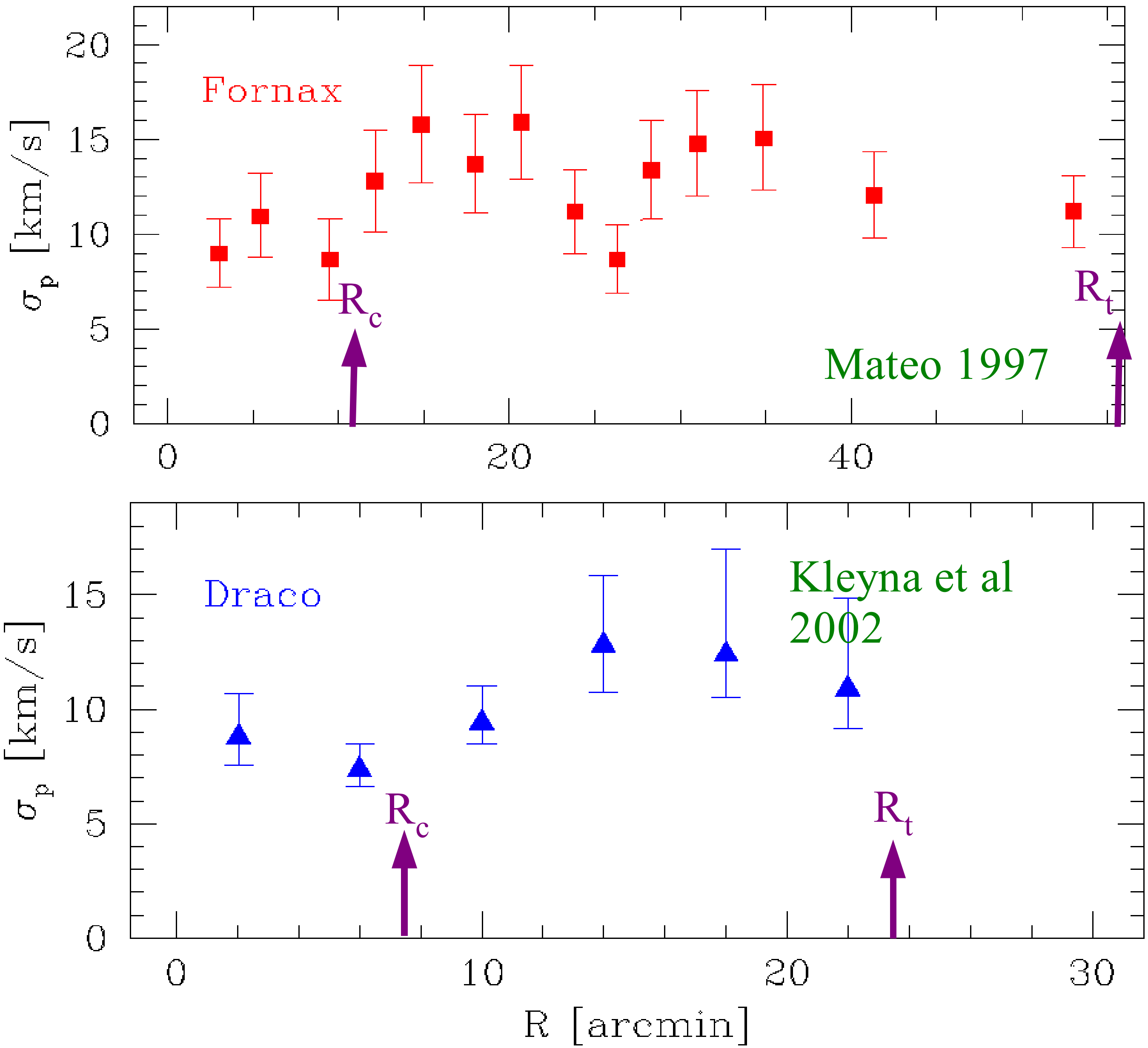
Inconsistency with observed satellite kinematics?





- The number of observed satellites with circular velocity $V = (GM/r)^{1/2}$ (inferred from the observed velocity dispersion) exceeding 10 km/s is at least 10 times smaller than the number expected in a ΛCDM halo

Dark Matter within Satellites

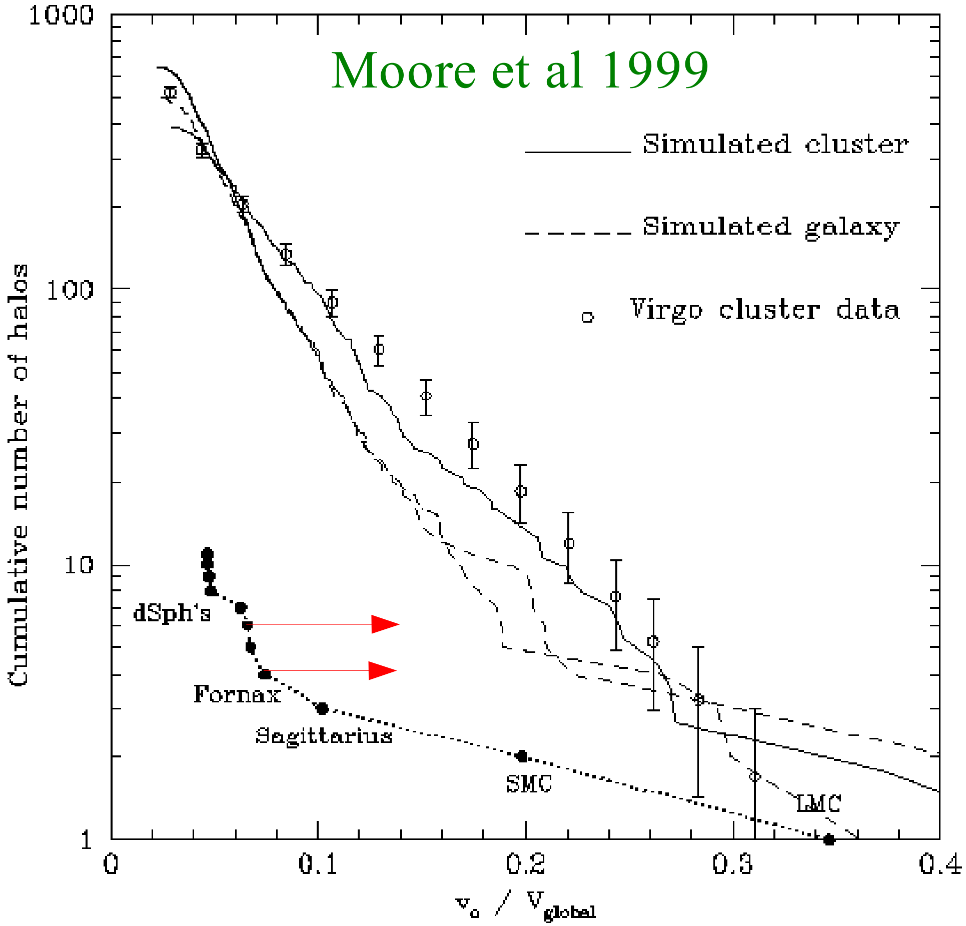


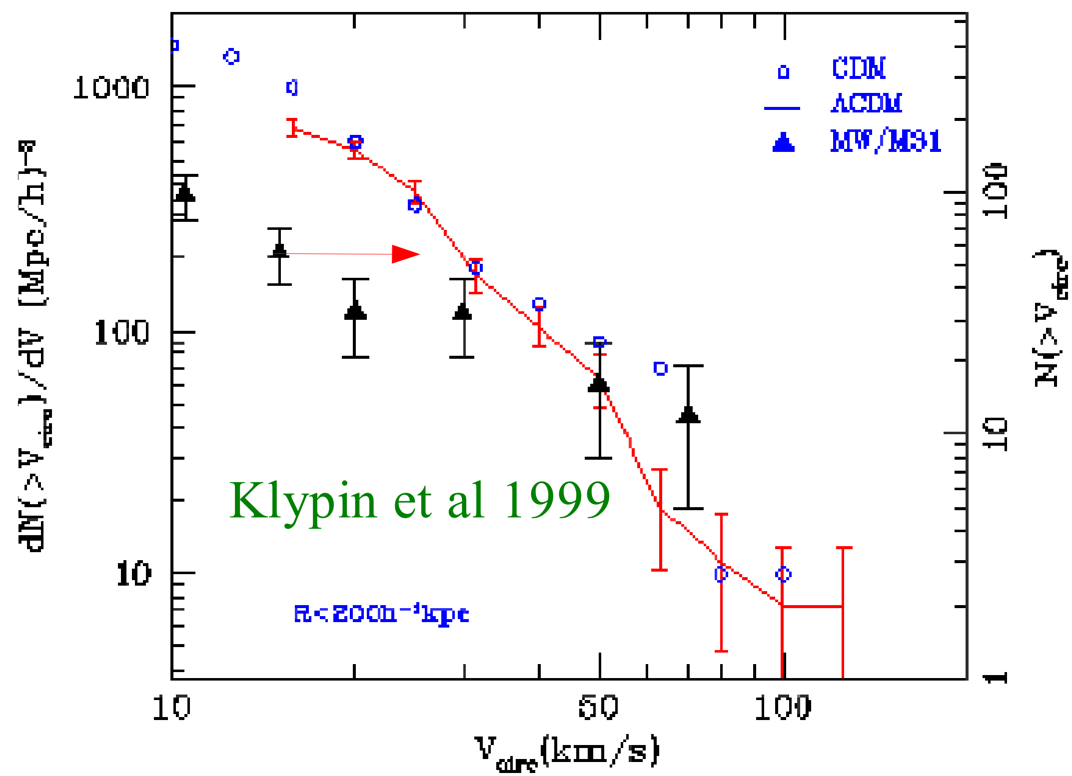
- Flat stellar velocity dispersion out to the tidal radius

  $\longrightarrow$ *rising* V_c curve

- Extended DM halos?
- High DM phase density? ~~*WDM*~~ ?
- $V_{c,max} \gtrsim$ 25 km/s ?
- Critical observation: extratidal stars?

Inconsistency with observed satellite kinematics?

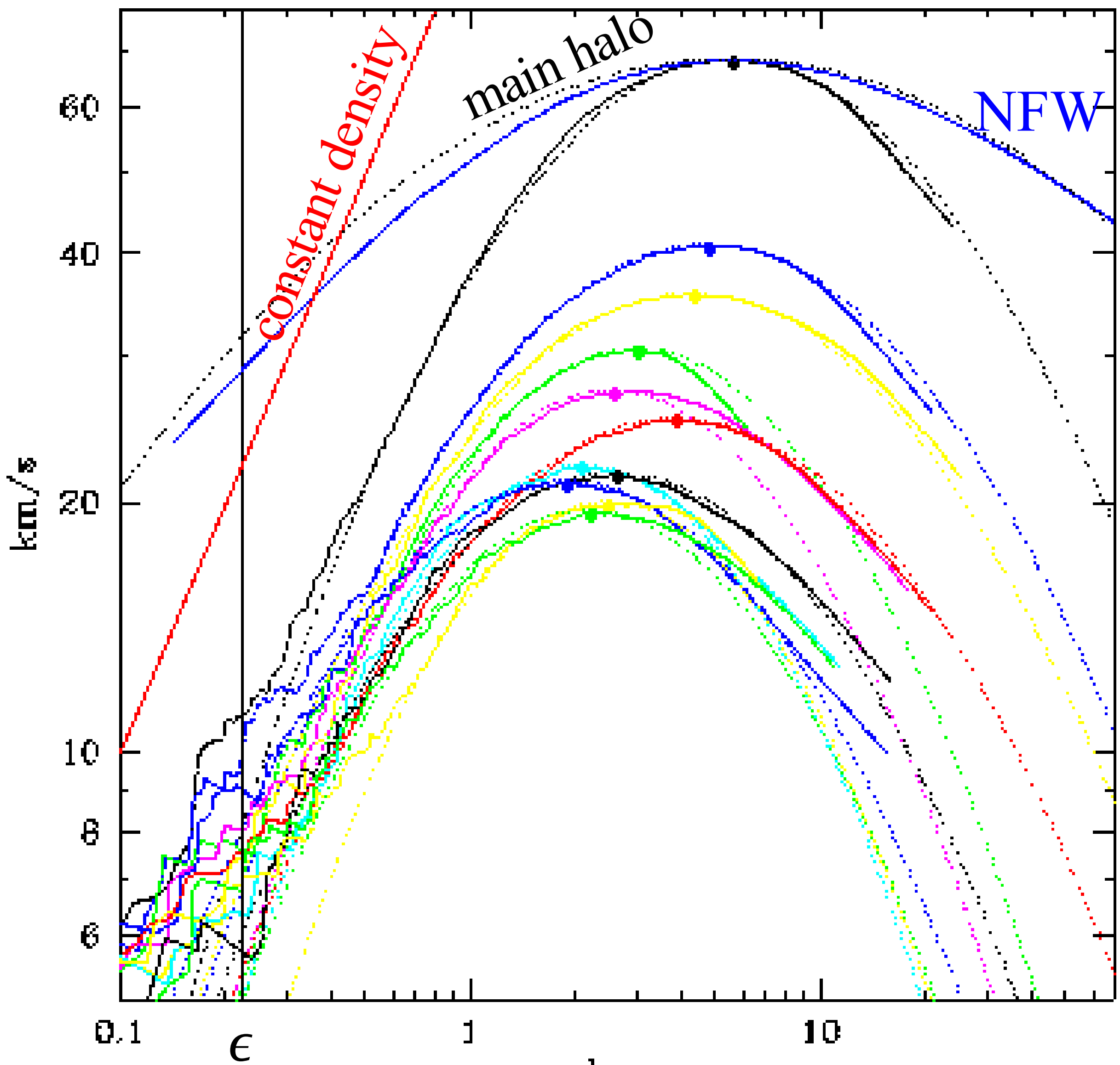




- Inconsistency is much less dramatic when one uses the *limiting* circular velocity inferred from the velocity dispersion profiles
- The *maximum* of the DM circular velocity profile could be outside the visible galaxy and still larger

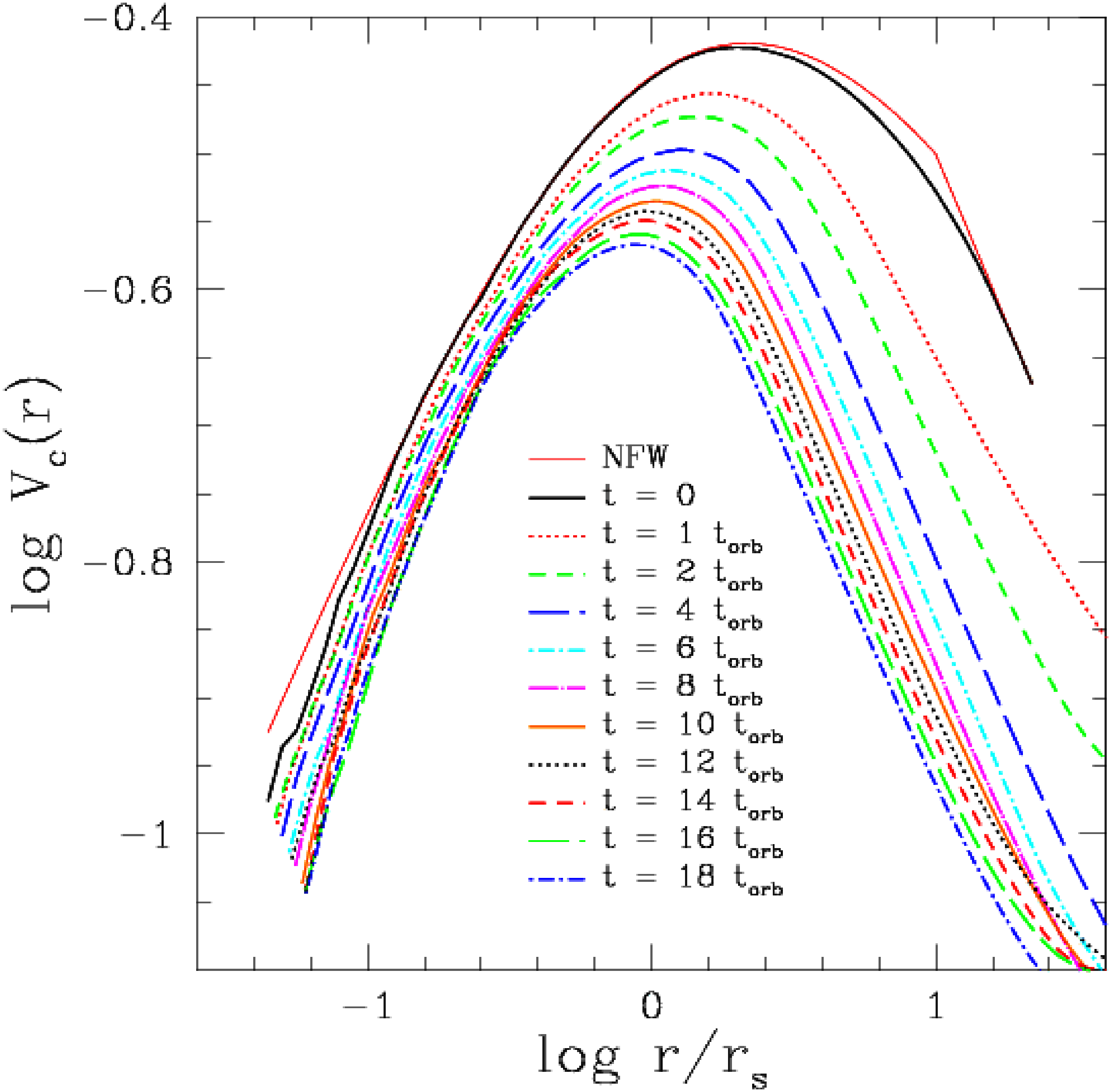
Satellite circular velocity curves

Stoehr et al 2003



- Circular velocity curves for 11 of the 30 most massive subhalos in a 10^7 particle 'Milky Way' halo
- The NFW and 'main halo' curves are scaled to the (r_m,V_m) of largest subhalo
- All curves are narrower than NFW or 'main halo'
- Many profiles approach a constant density core in their inner regions
- ***The MOST MASSIVE of these potentials could host the observed satellites***

High resolution simulations of subhalo stripping



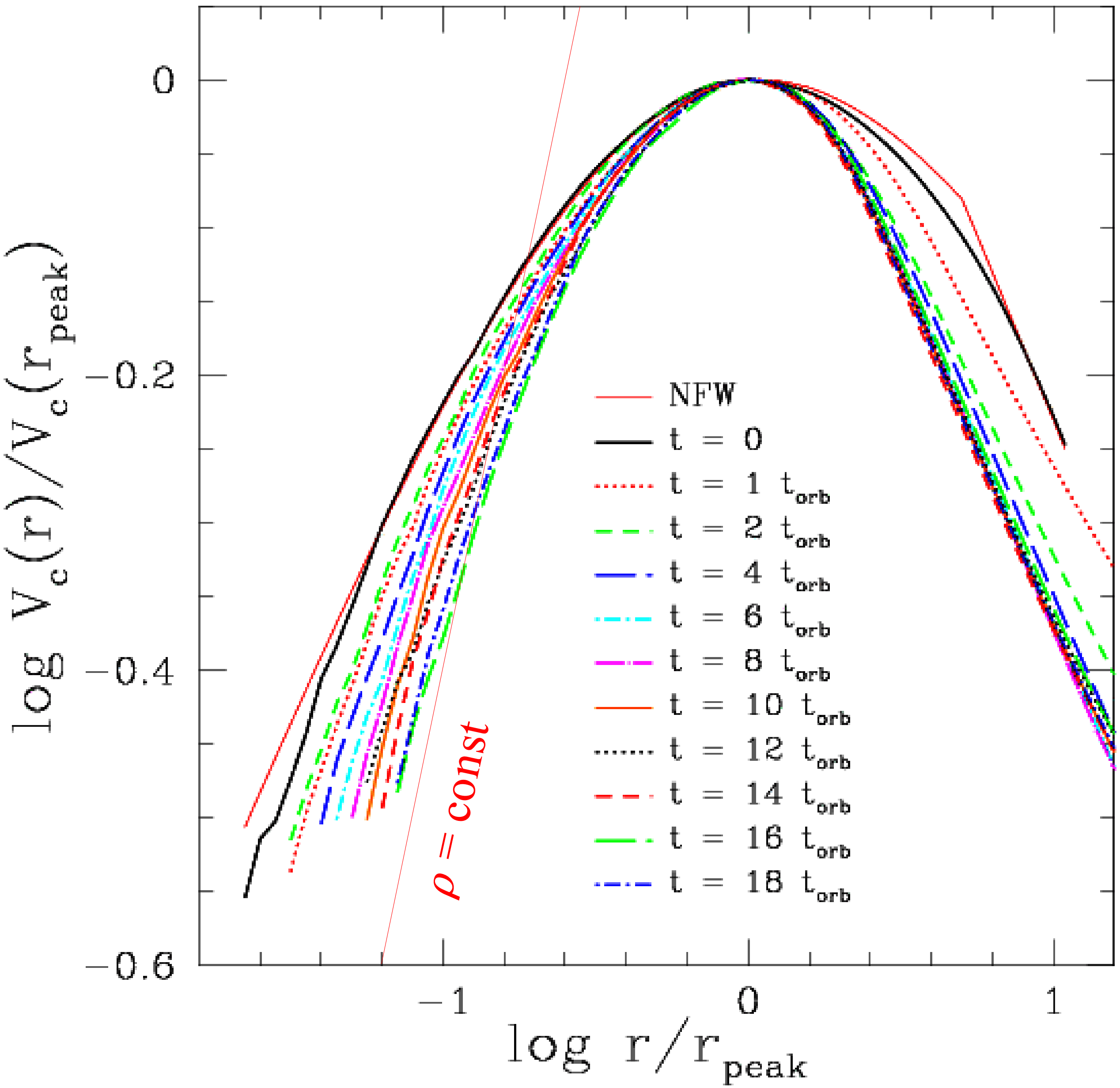
Hayashi et al 2003

Tidal stripping of an equilibrium NFW subhalo with N ~ 400,000 falling into a rigid NFW Milky Way.

R_{apo}=10 R_s R_{peri}= 3 R_s

Note that the amplitude of the $V_c(r)$ curve drops even in the inner regions

High resolution simulations of subhalo stripping



Hayashi et al 2003

Tidal stripping of a single NFW subhalo with N ~ 400,000 falling into a rigid NFW Milky Way

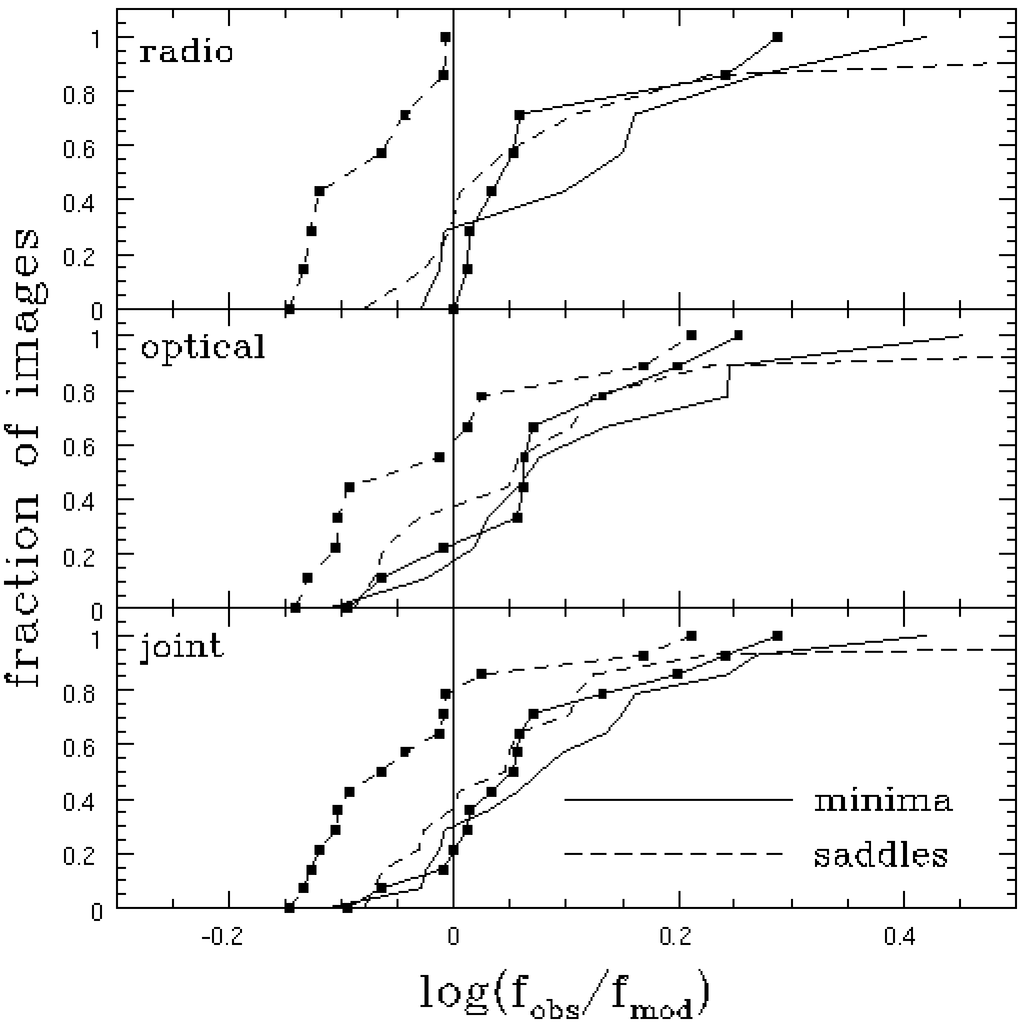
Note the steepening of the inner $V_c(r)$ curve

Effects of CDM substructure

- Dynamical heating of Galactic substructures
  - -- the disk? globular clusters? halo streams?
  - -- effects dominated by most massive objects -- LMC, SMC
- Differential image magnification in multiply imaged QSOs
  - -- dominant substructures have lensing scale smaller than image separation but larger than image size
    - $\longrightarrow$ intermediate masses
- Relation to high-velocity clouds?
- Visible in annihilation radiation at γ frequencies?

Detection of ΛCDM substructure?

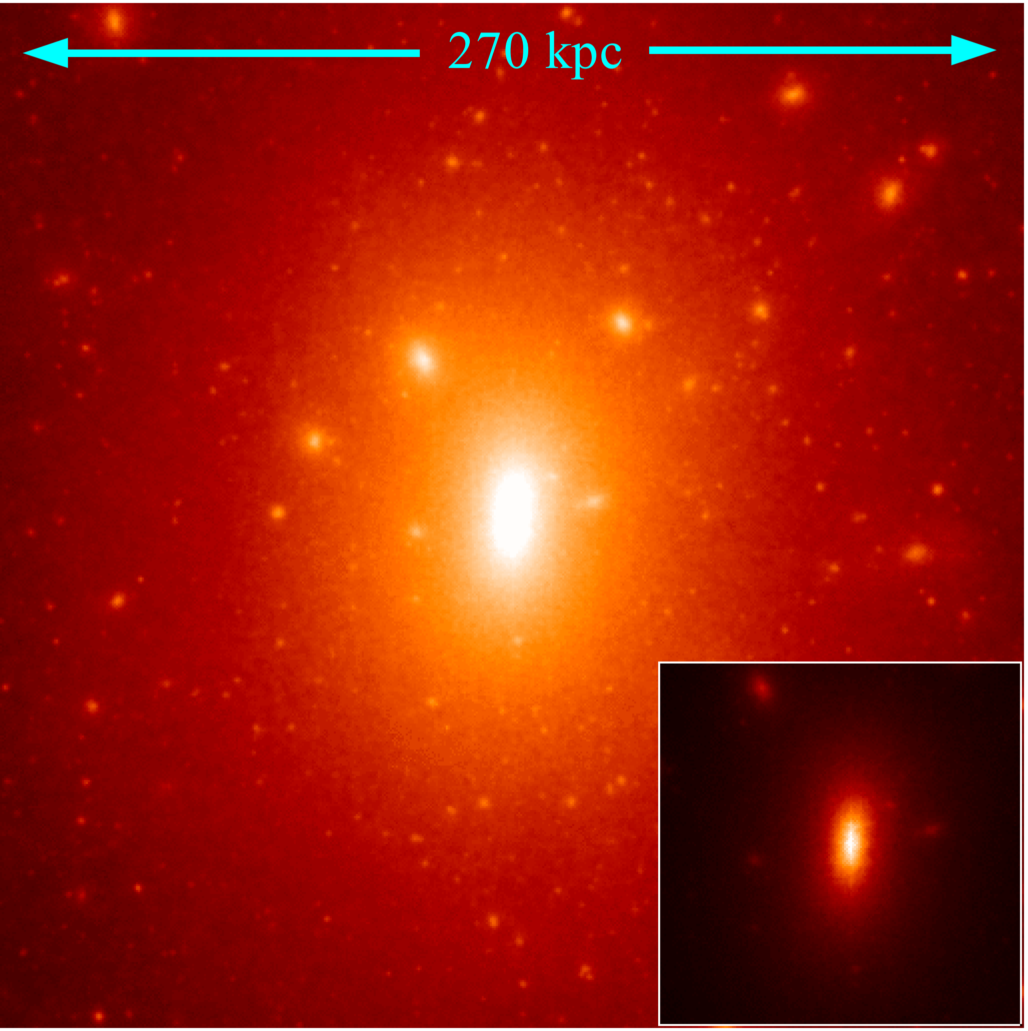
Dalal & Kochanek 2003
Mao, this meeting



- In 4-image lensed quasars, the image *geometry* allows image classification into minima/saddles and brighter/fainter of each type
- Smooth lens models which fit the image positions usually *fail* to fit their relative brightness
- The brightest saddle image is preferentially dimmed, as expected for perturbation by fine structure
- This *cannot* be due to propagation effects, e.g. in the ISM of the lens
- It *cannot* be due to microlensing as radio images are too big
- 5 - 10% of lens mass must be in substructure

γ-rays from the annihilation of DM particles

Stoehr et al 2003



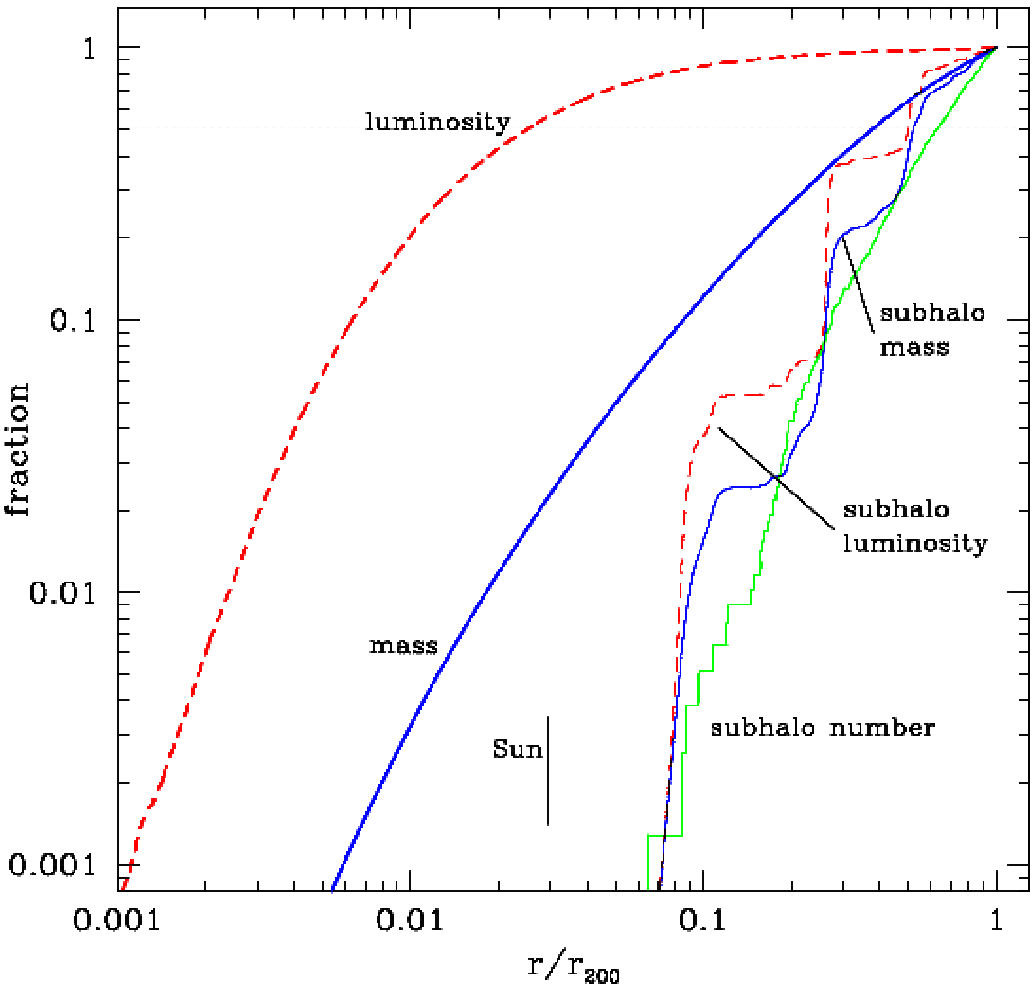
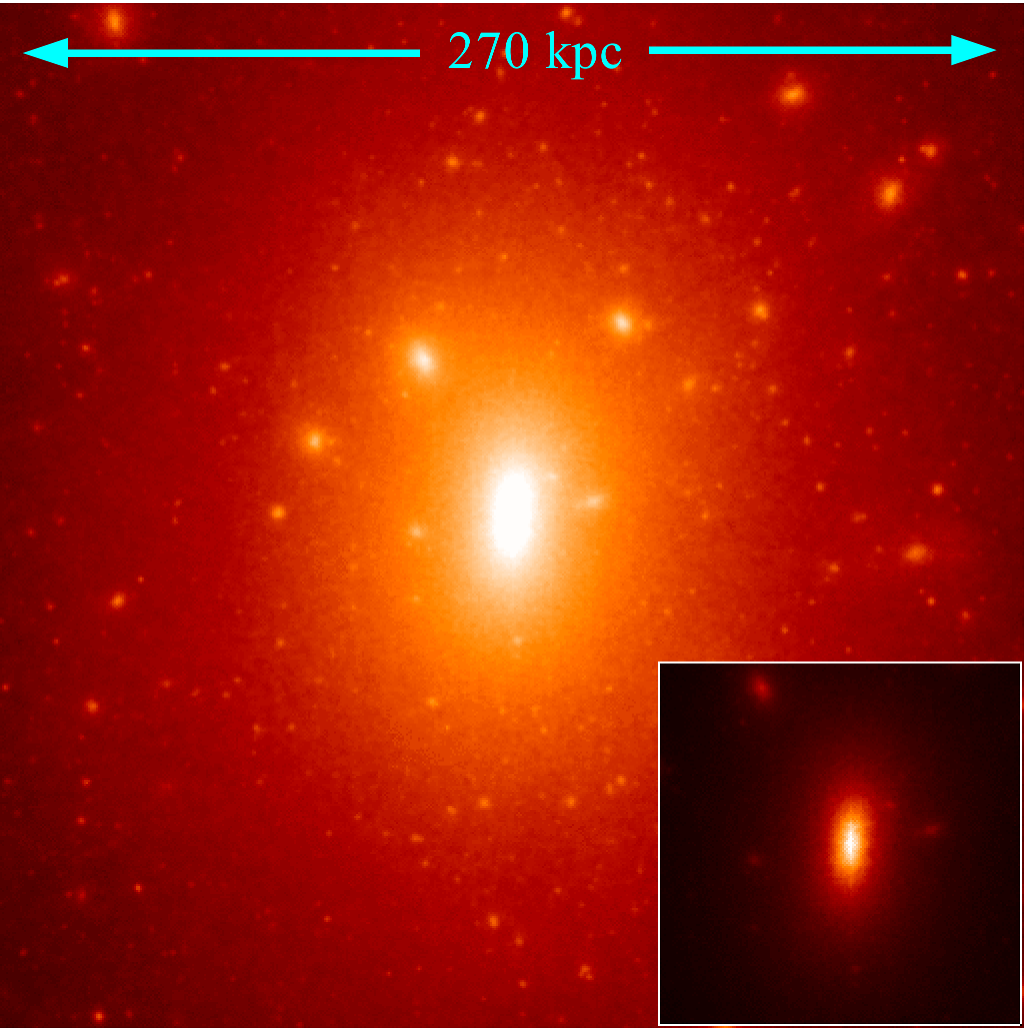


Image of a 'Milky Way' halo in annihilation radiation

Distributions of mass and of smooth and subhalo luminosity

γ-rays from the annihilation of DM particles

Stoehr et al 2003



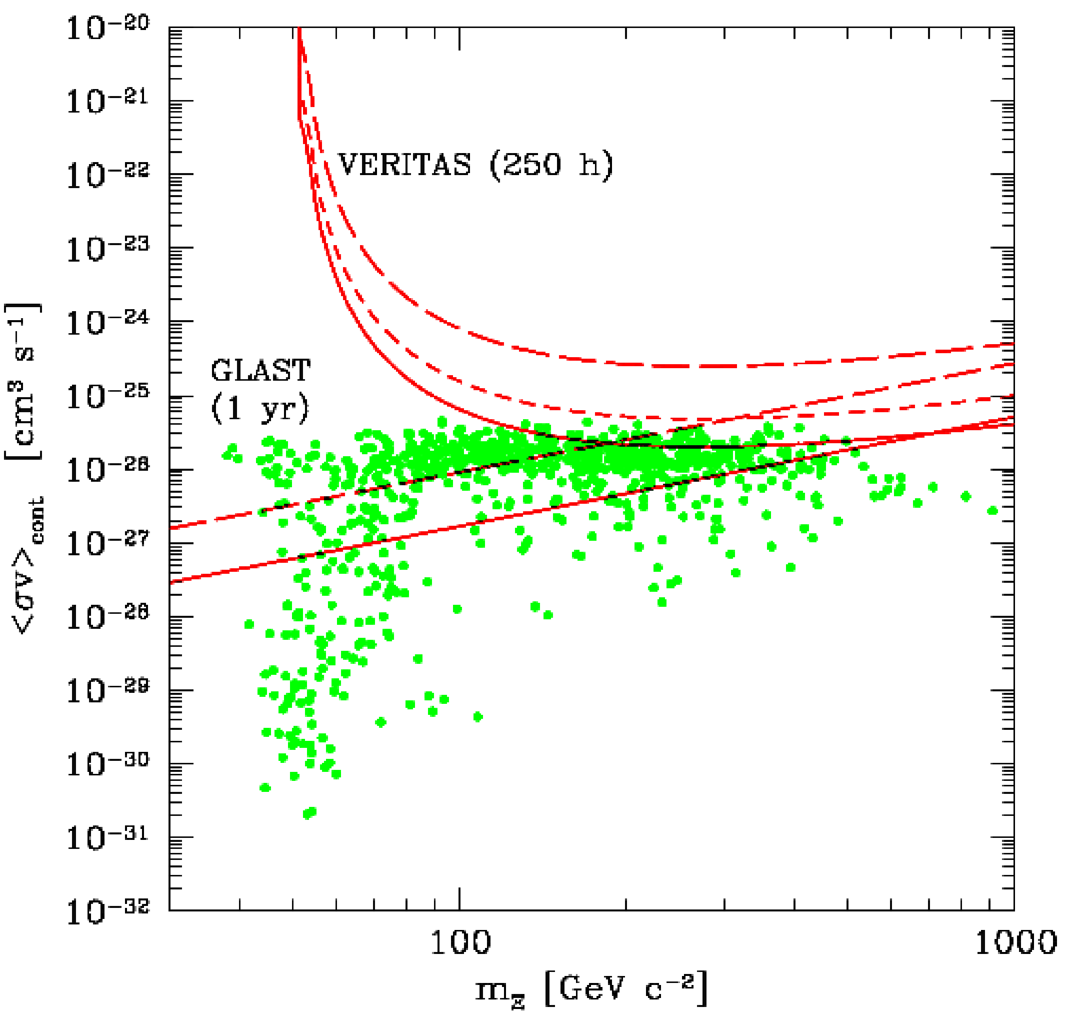


Image of a 'Milky Way' halo in annihilation radiation

Detection limits for minimal supersymmetric DM models