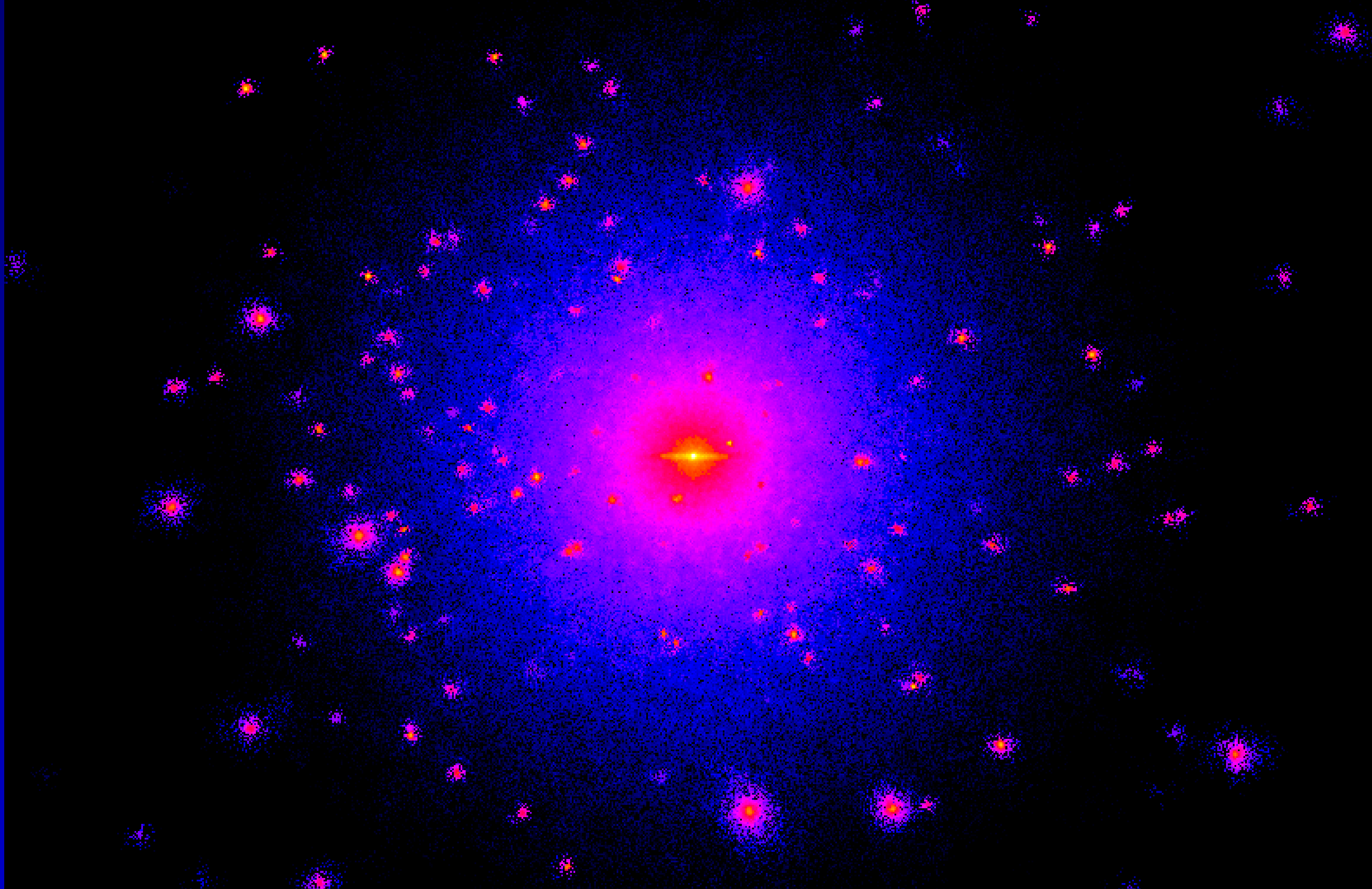
Dark and Luminous Galactic Halos

Julio F. Navarro



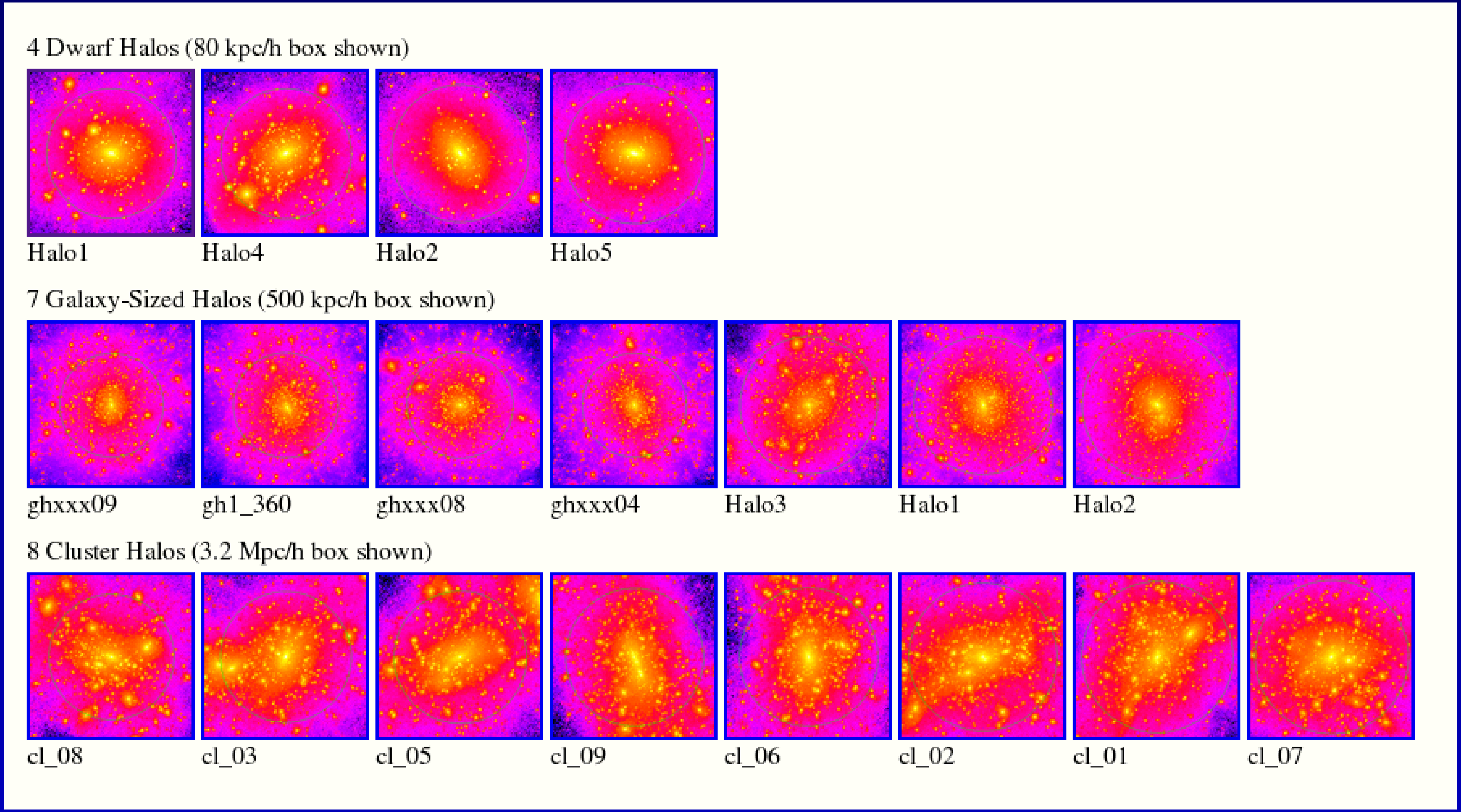
Font and Navarro 2001

The Milky Way and its Dark Matter Halo

The Plan

- Short review (and new results) on the **structure** of Cold Dark Matter Halos
  - Central cusp
  - Halo shapes and LSB rotation curves
  - Galaxy-induced halo transformations
- Luminous (Stellar) Halos
  - Structure and application to observations

Dwarf, Galaxy, and Cluster Halos



- Virial velocities range from 30 km/s to 1500 km/s
- Each halo has ~10^6 particles within the virial radius and is resolved down to $r_{conv} \simeq 0.01\, r_{vir}$

Hayashi et al 2004

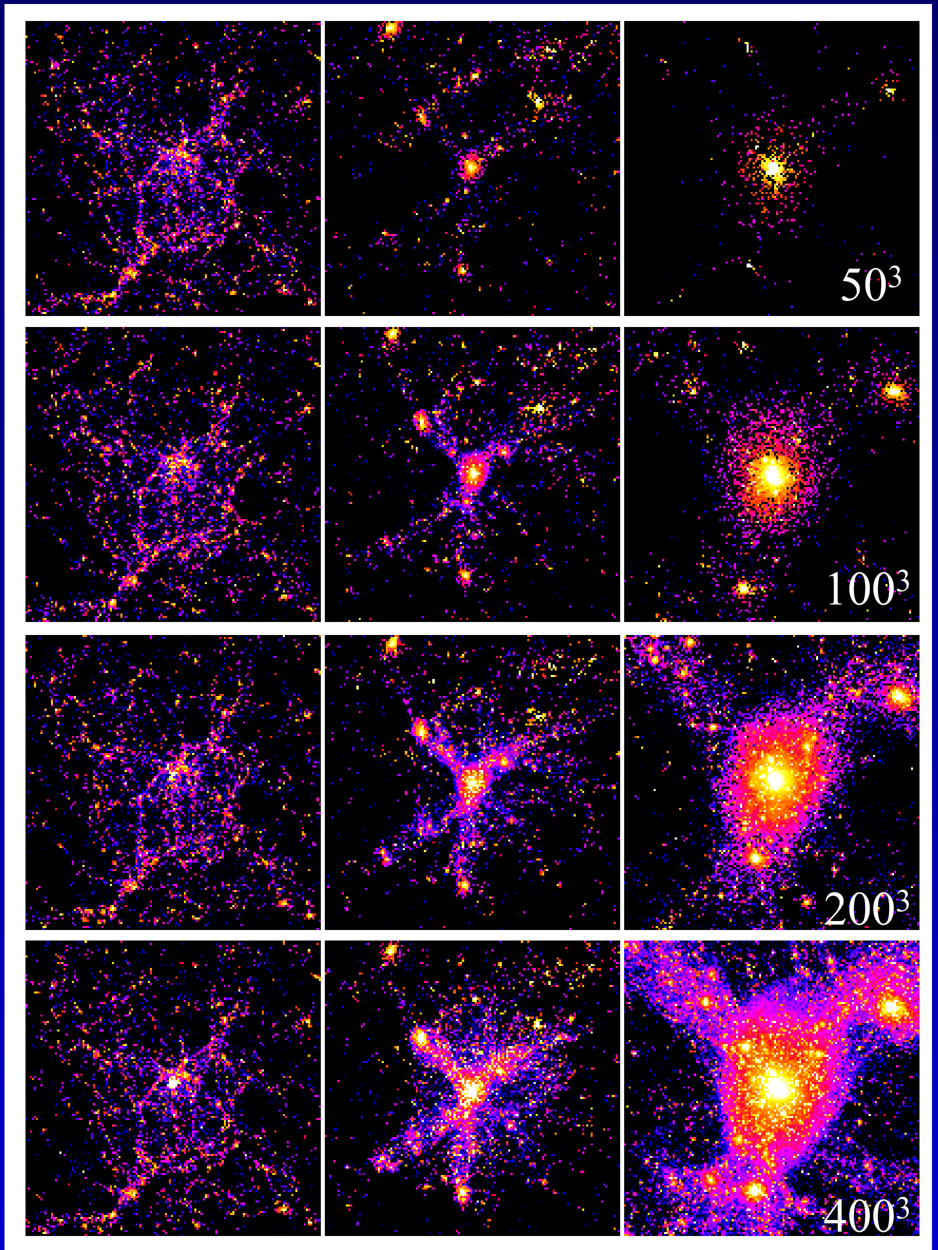
The Quest for a Billion-Particle Dark Matter Halo

Science Case:

The Structure of Substructure:

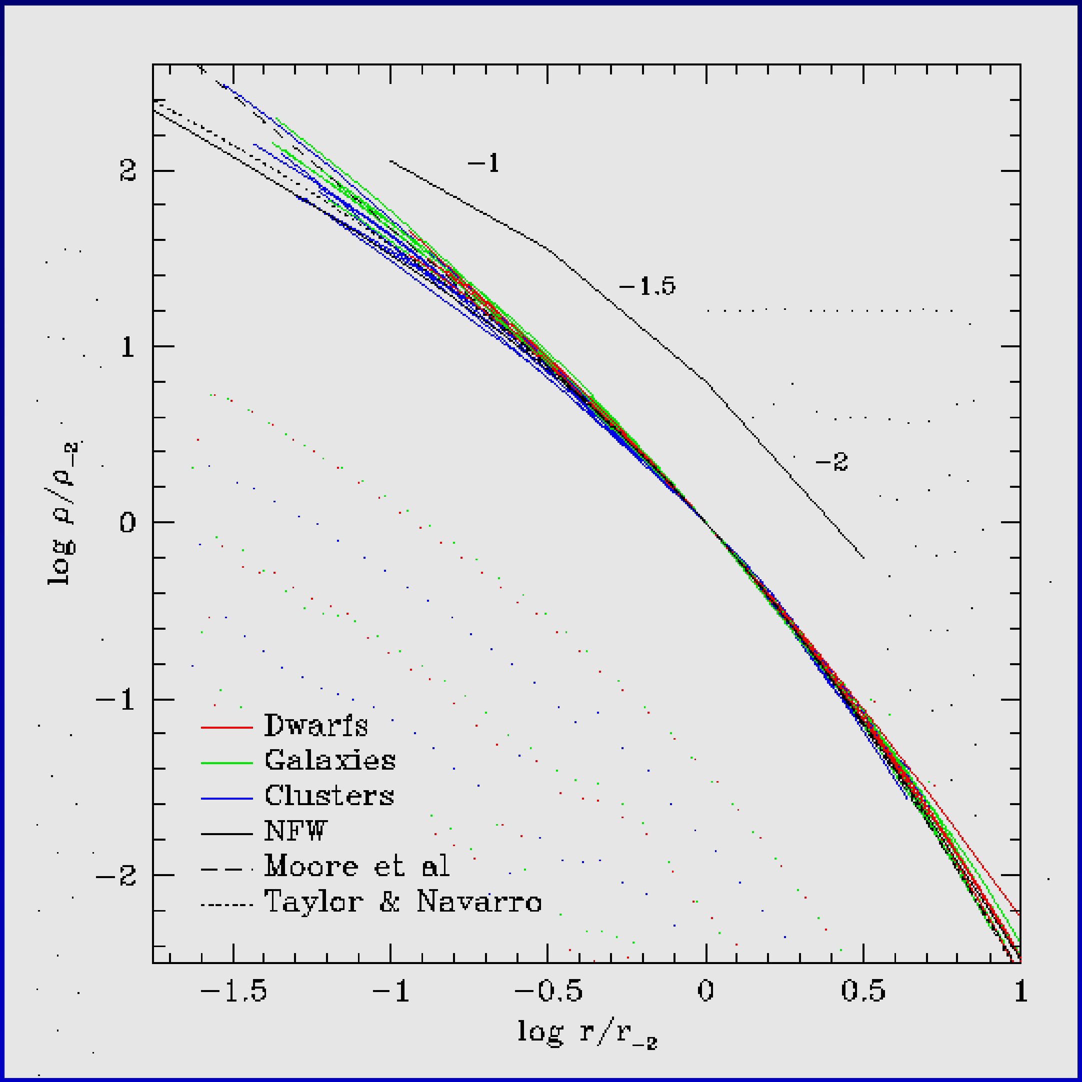
- what is the spatial distribution and kinematics of substructure? (lensing flux anomaly, etc)
- what is the density profile of dSph halos?

- The phase-space distribution of DM particles
- The Structure of the Central Cusp
  - Is the cusp well represented by a power-law and what is its slope? (rotation curves, etc)
  - what is $\int\langle\rho^2\rangle/\langle\rho\rangle^2$? (annihilation flux, etc)
- A semi-analytic model of the Milky Way: from the detailed structure of disk/bulge/halo to the origin of the faintest galaxies in the universe



The Central Cusp

The Universal Mass Profile of ΛCDM halos



Scaled Density

Scaled Radius

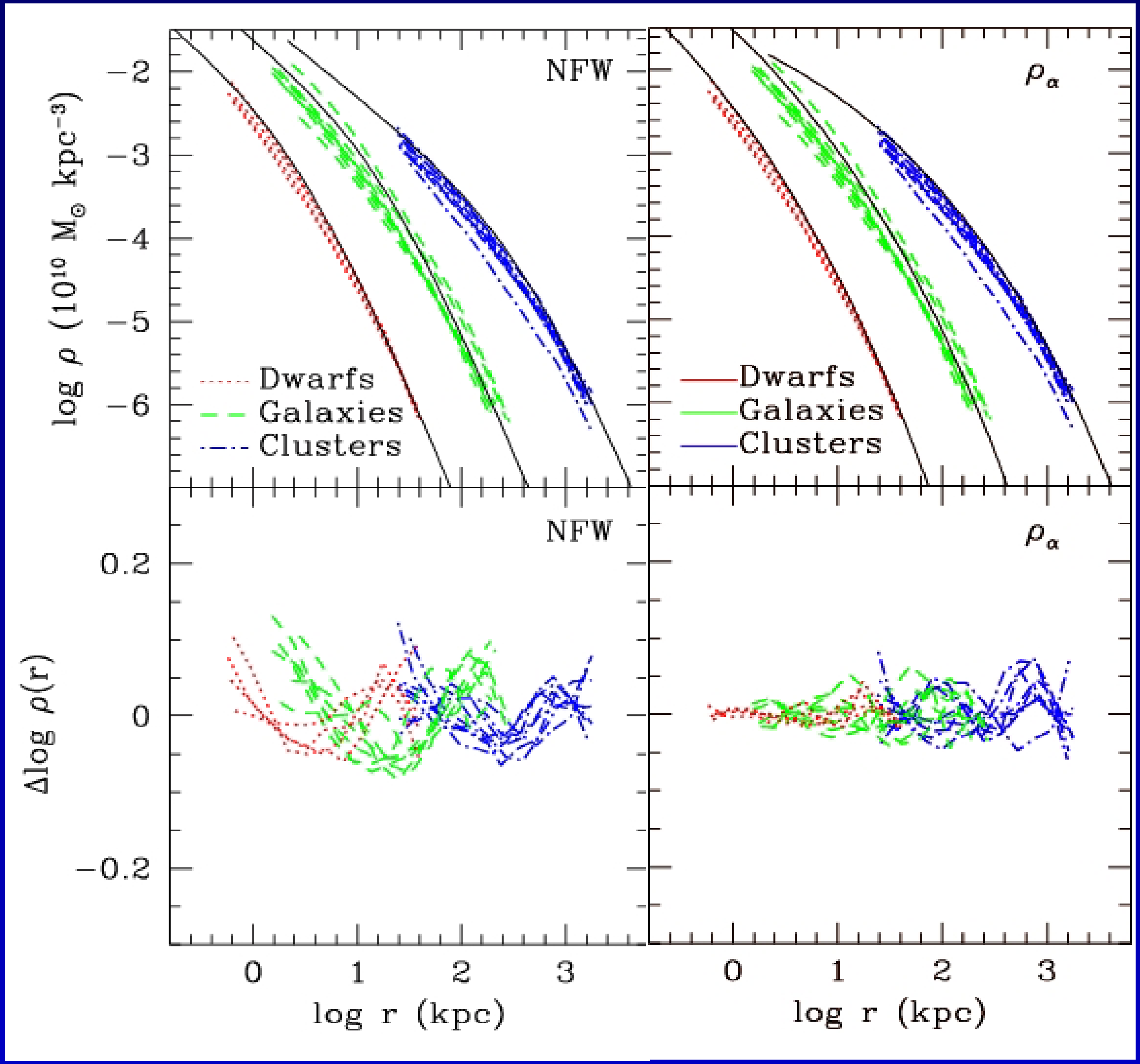
- Properly scaled, all halos look alike: CDM halo structure appears to be approximately "universal"
- Usually characterized by a "concentration" parameter: $c = r_{vir}/r_{-2}$

Navarro et al 2004

An improved fitting formula

Density

residuals



Radius

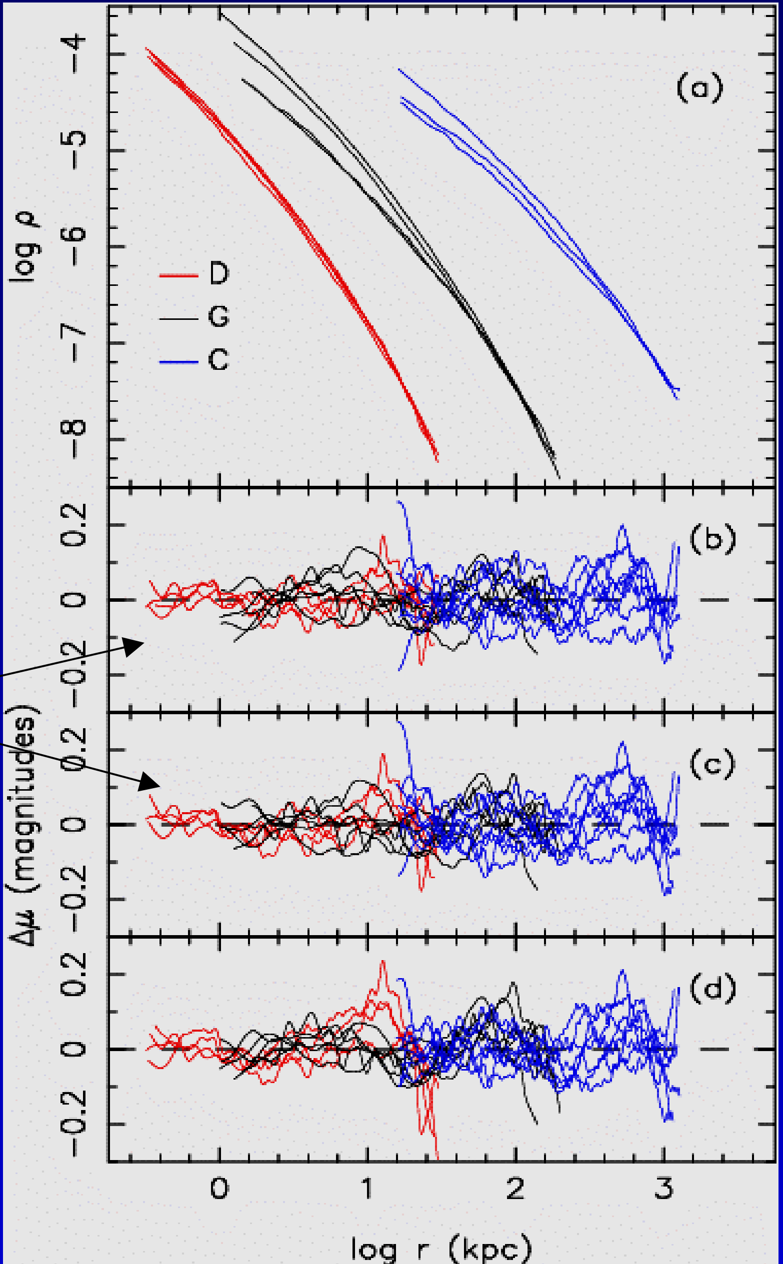
A law where the logarithmic slope of the density profile is a simple power-law of radius fits the dark halos to better than 5% at all radii.

$$\frac{d \log \rho_\alpha}{d \log r} = -2\left(\frac{r}{r_{-2}}\right)^{\alpha}$$

Remarkably, this is the same radial behaviour (a Sersic law) of the stellar distribution in elliptical galaxies!

Navarro et al 2004

Density Profiles of CDM Halos



Residuals:

Sersic-law like profiles (no cusp)

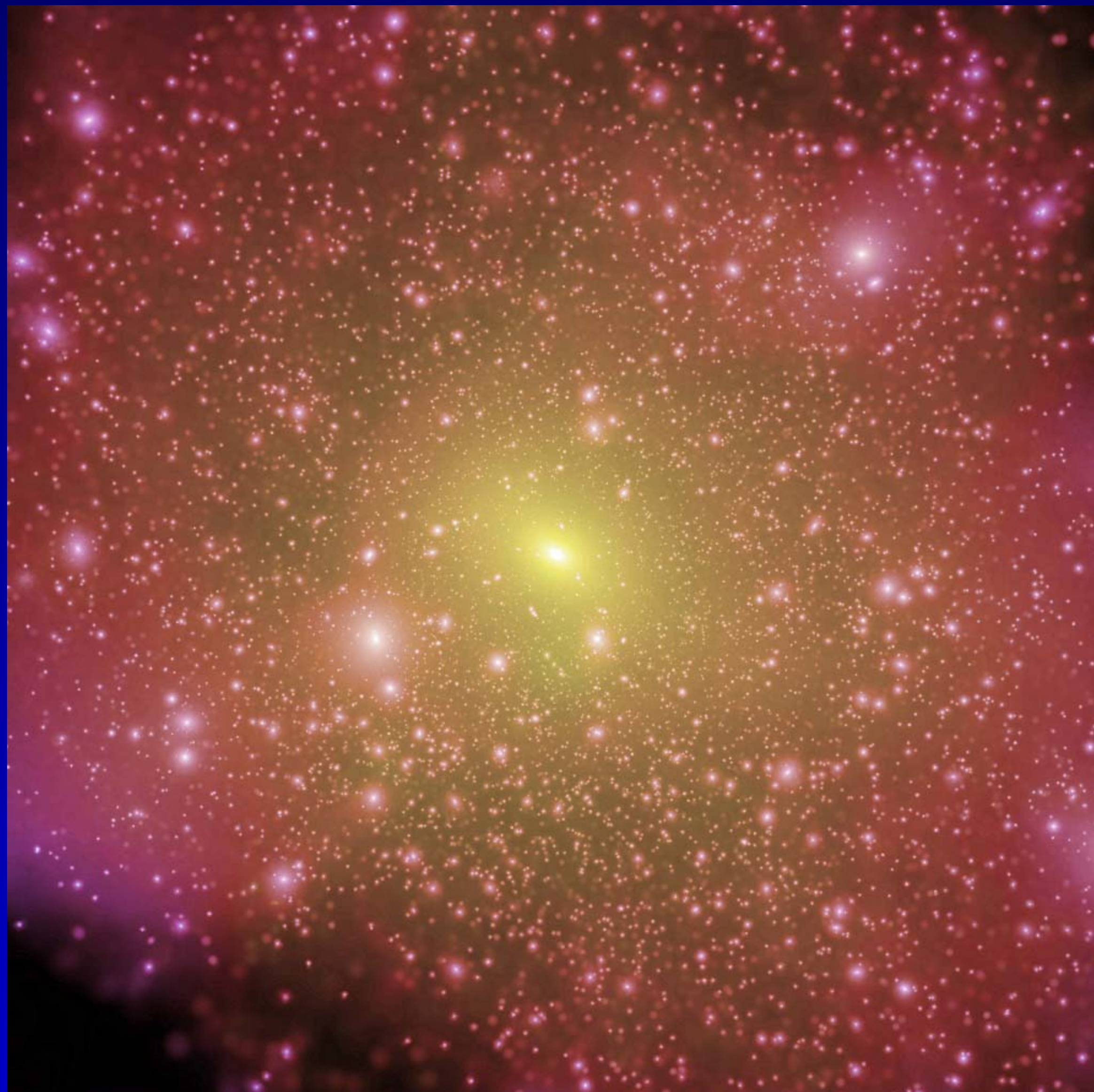
Power-law cusp

•Fits with a core or with a power-law inner slope $\rho \sim r^{-\gamma}$ **($r \rightarrow 0$)** provide equally good fits to the data, so situation is unclear.

Merritt, Navarro et al 2005

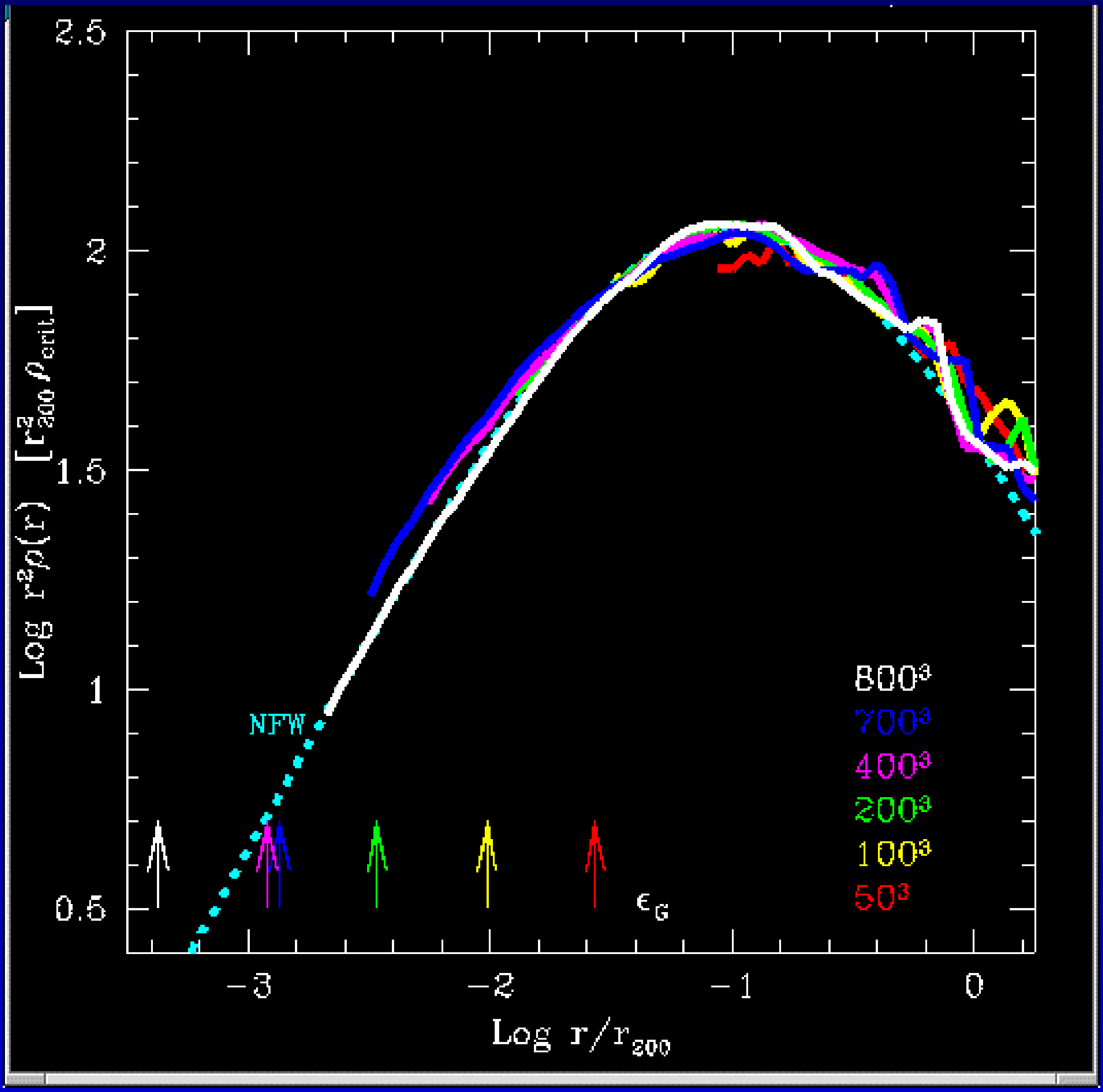
A 45-million particle CDM halo

500 kpc



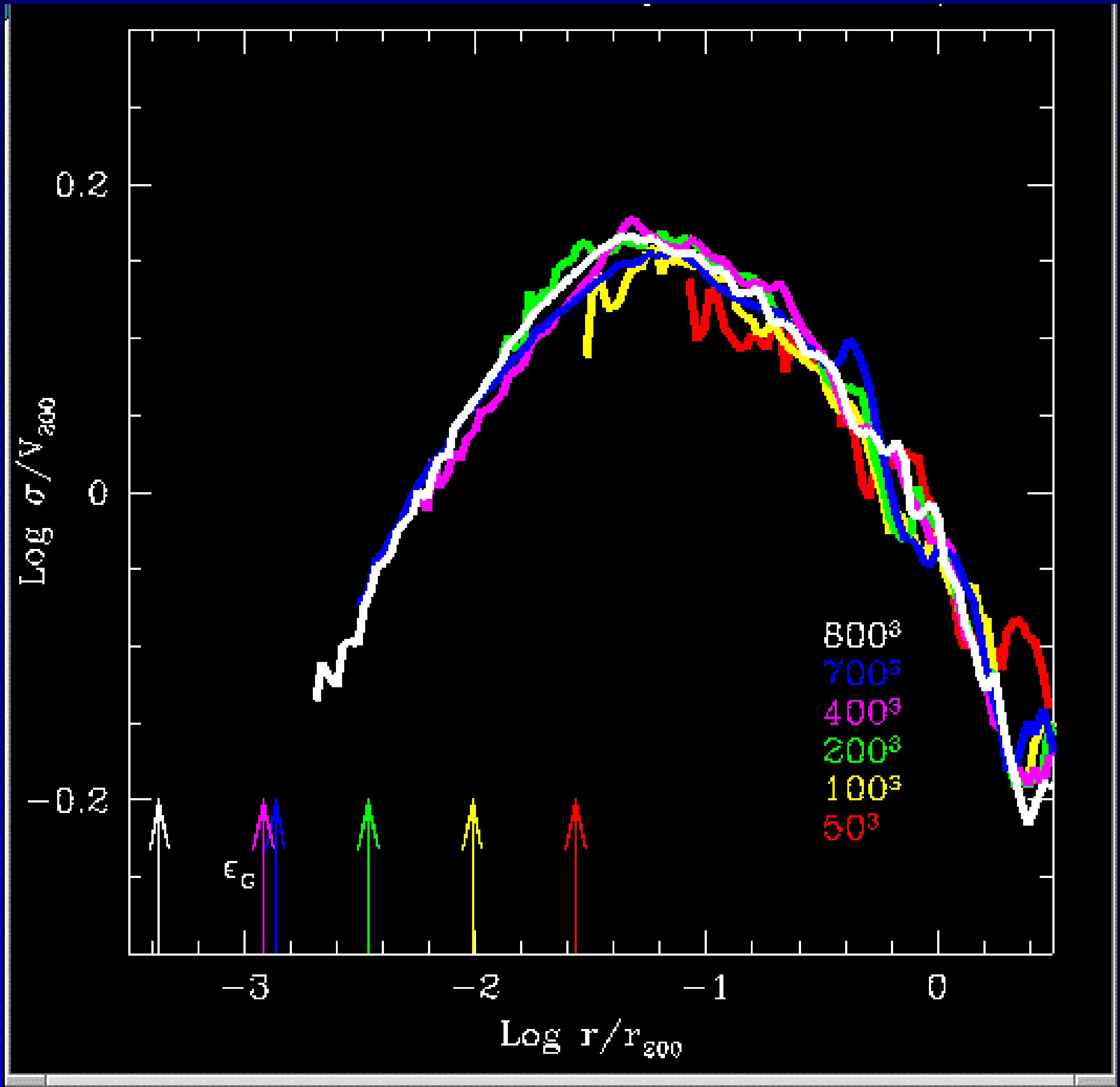
The largest halo simulation in our series so far

Density Profile



Density profile and best-fit NFW profile

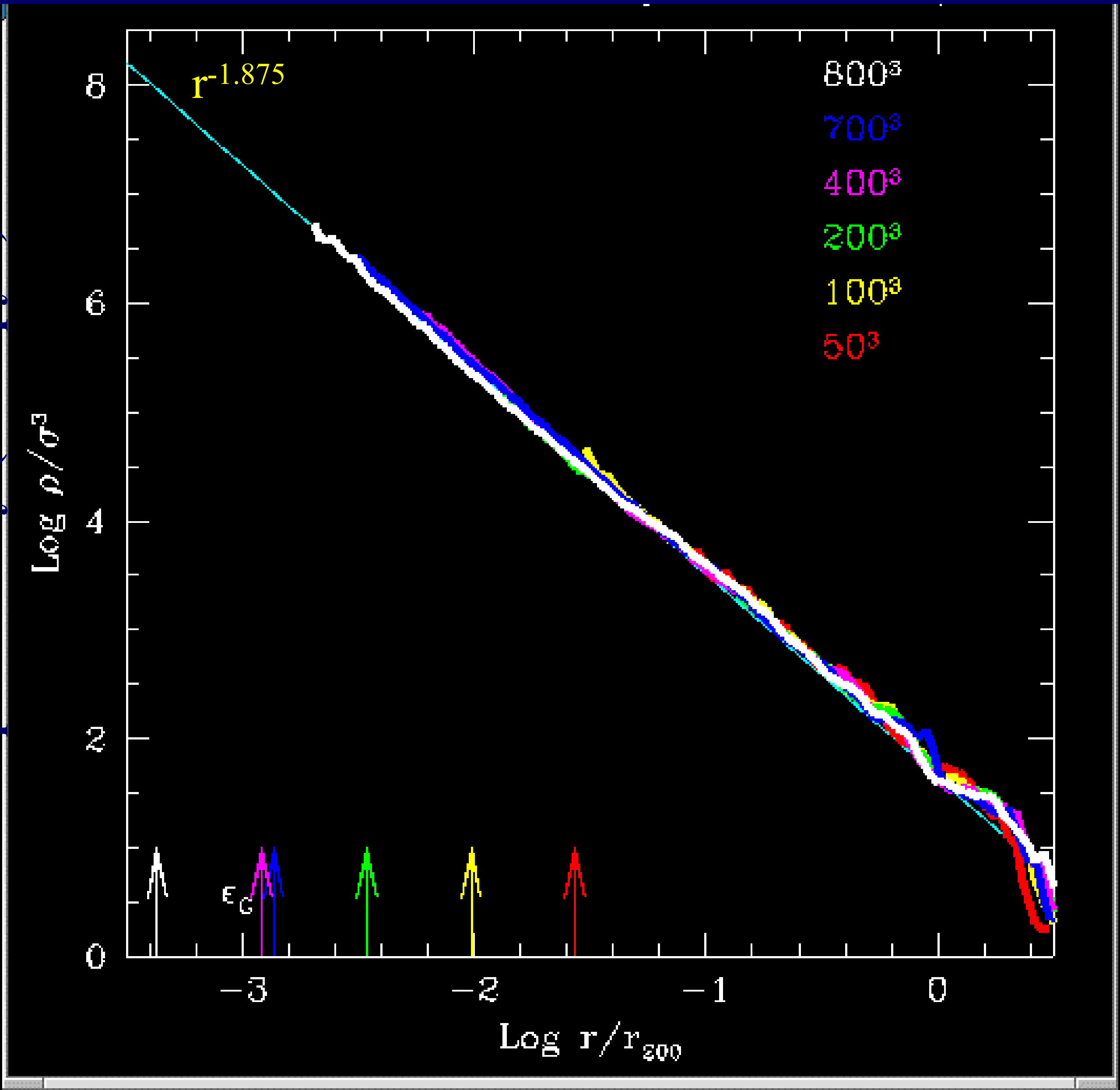
Velocity Dispersion Profile of a CDM Halo



Velocity dispersion profile for our series, including smaller test cases, plotted down to the converged radius.

“Phase-Space Density” Profile

Phase-space density (’entropy’-1)

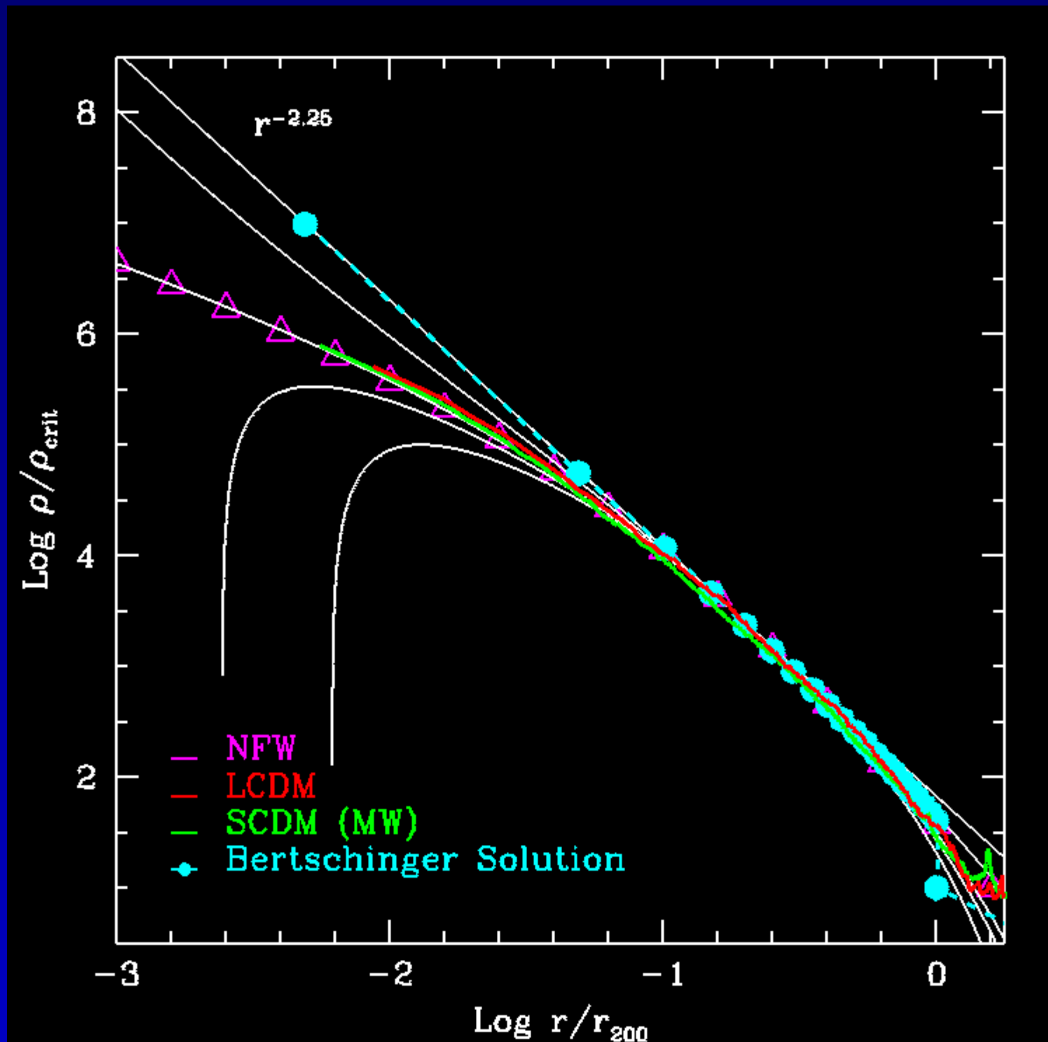


Phase-space density profile for our series, including smaller test cases, plotted down to the converged radius.

Note the remarkable power-law behaviour of this quantity, with slope identical to Bertschinger’s self-similar secondary infall solution.

‘Hydrostatic’ Isotropic Solutions to Power-Law Phase Space Density Profiles

Density



Radius

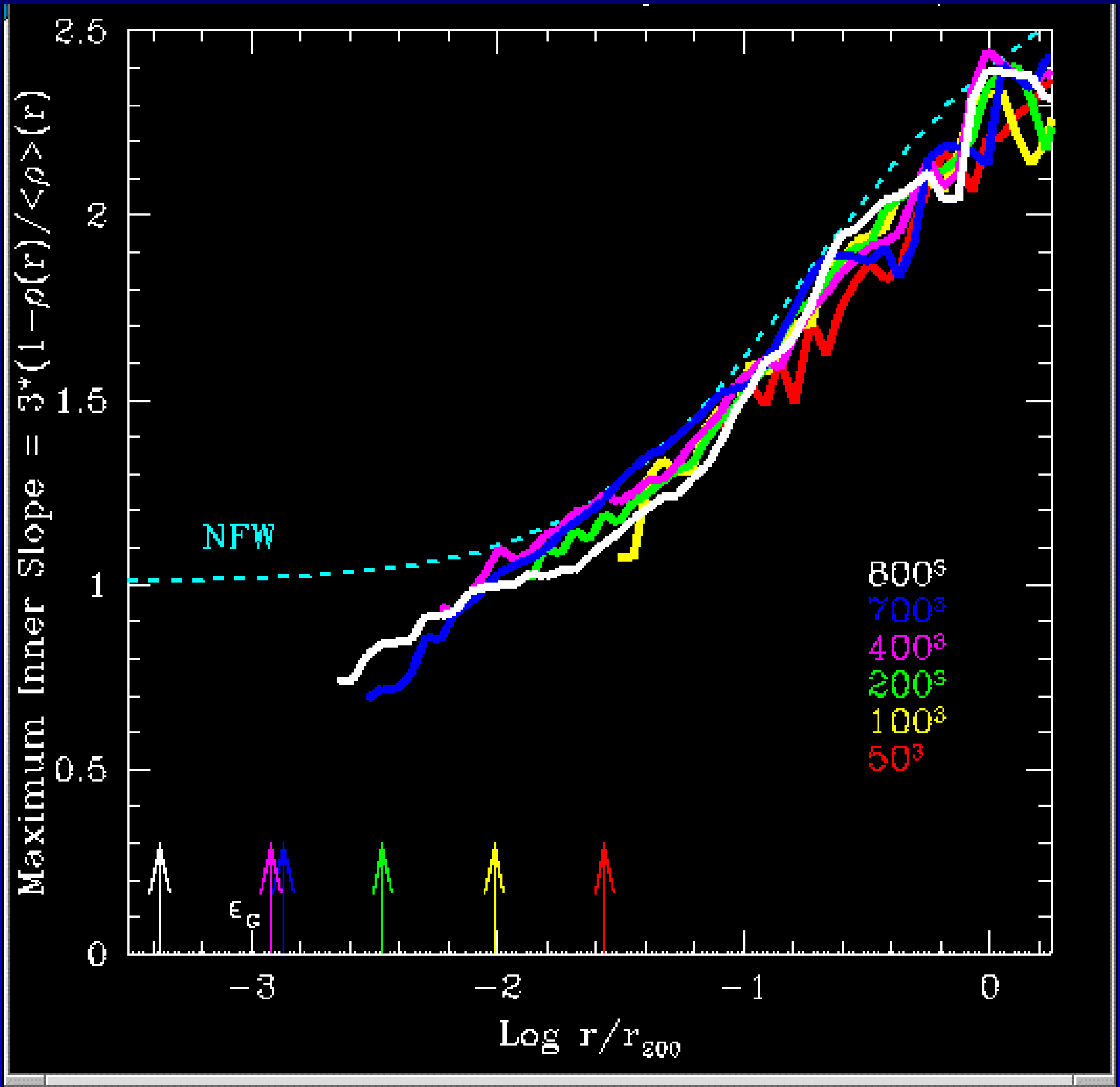
Depending on the local ‘pressure’, there is a family of solutions ranging from a power law to a profile resembling that of CDM halos, which corresponds to the ‘critical’ case beyond which solutions are unphysical.

Example: the singular isothermal sphere ($\rho \sim r^{-2}$, σ^2=const.) may be recovered from Jeans’ equation and the power-law entropy constraint if the (isotropic) velocity dispersion is $2\sigma^2 = GM(r)/r$. As σ^2 is decreased, a family of solutions is generated.

CDM density profiles appear to correspond to the minimum ‘pressure’ compatible with the radial entropy stratification of the spherical collapse model. Innermost (asymptotic slope in this case is -0.75.

Taylor and Navarro 2001

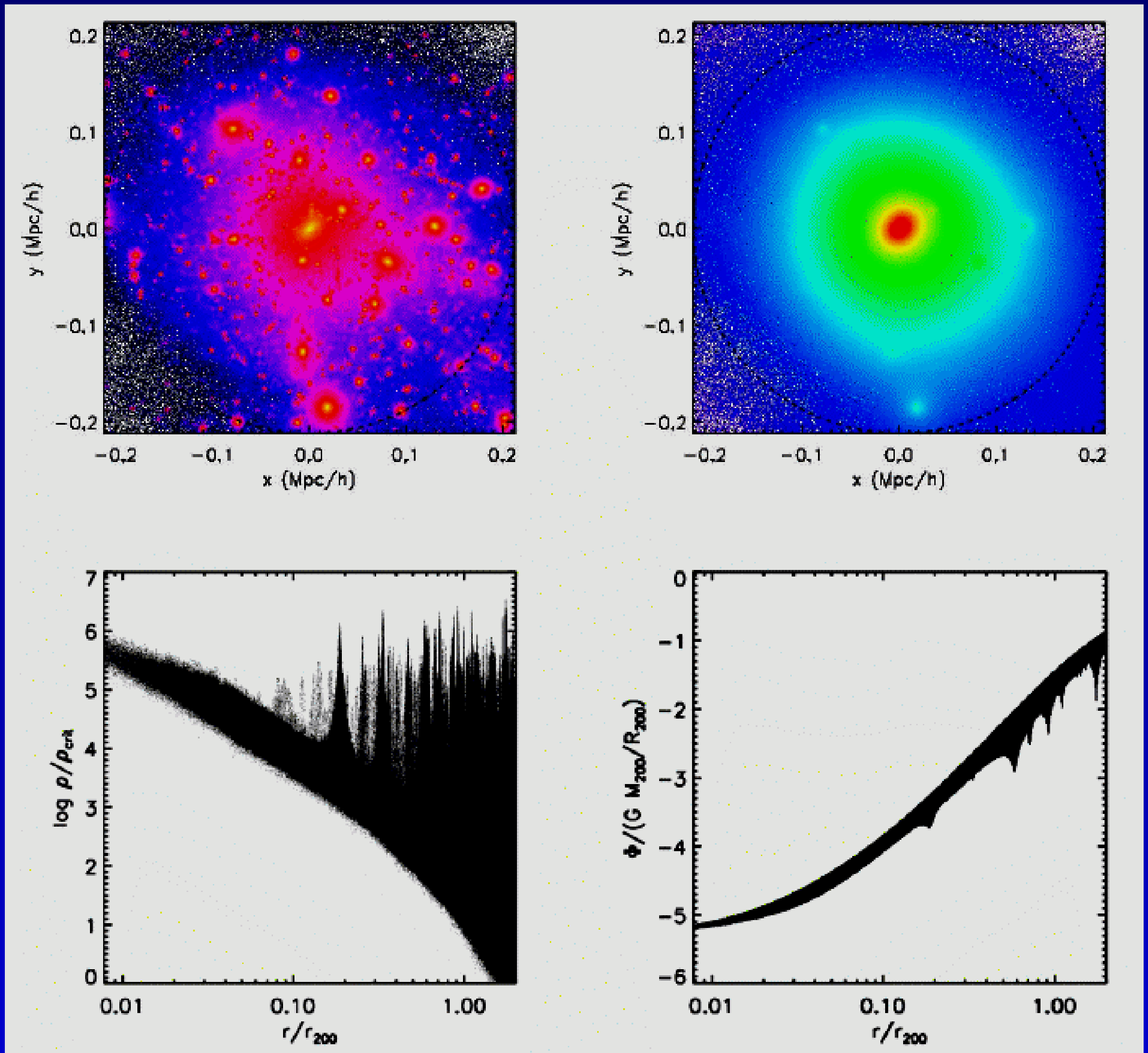
Maximum Innermost Slope of Central Cusp



- No obvious convergence to a power-law inner profile.
- Central cusp must be quite shallow: shallower than r^{-1} but not inconsistent with $r^{-0.75}$

The Shapes of Galactic Halos and LSB rotation curves

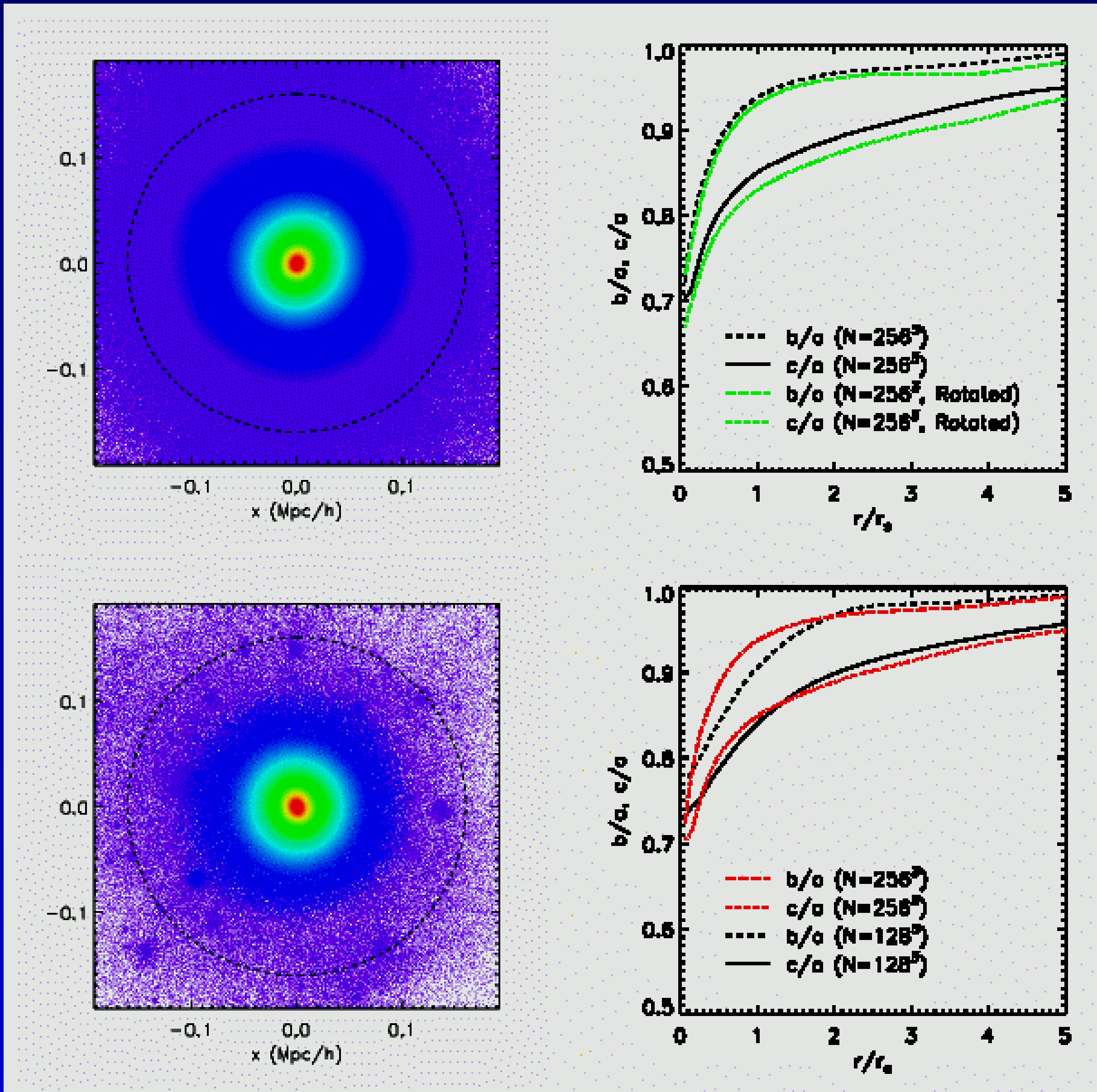
Halo shapes: density vs potential



- Shapes are much easier to measure using gravitational potential rather than density

Hayashi et al 2006

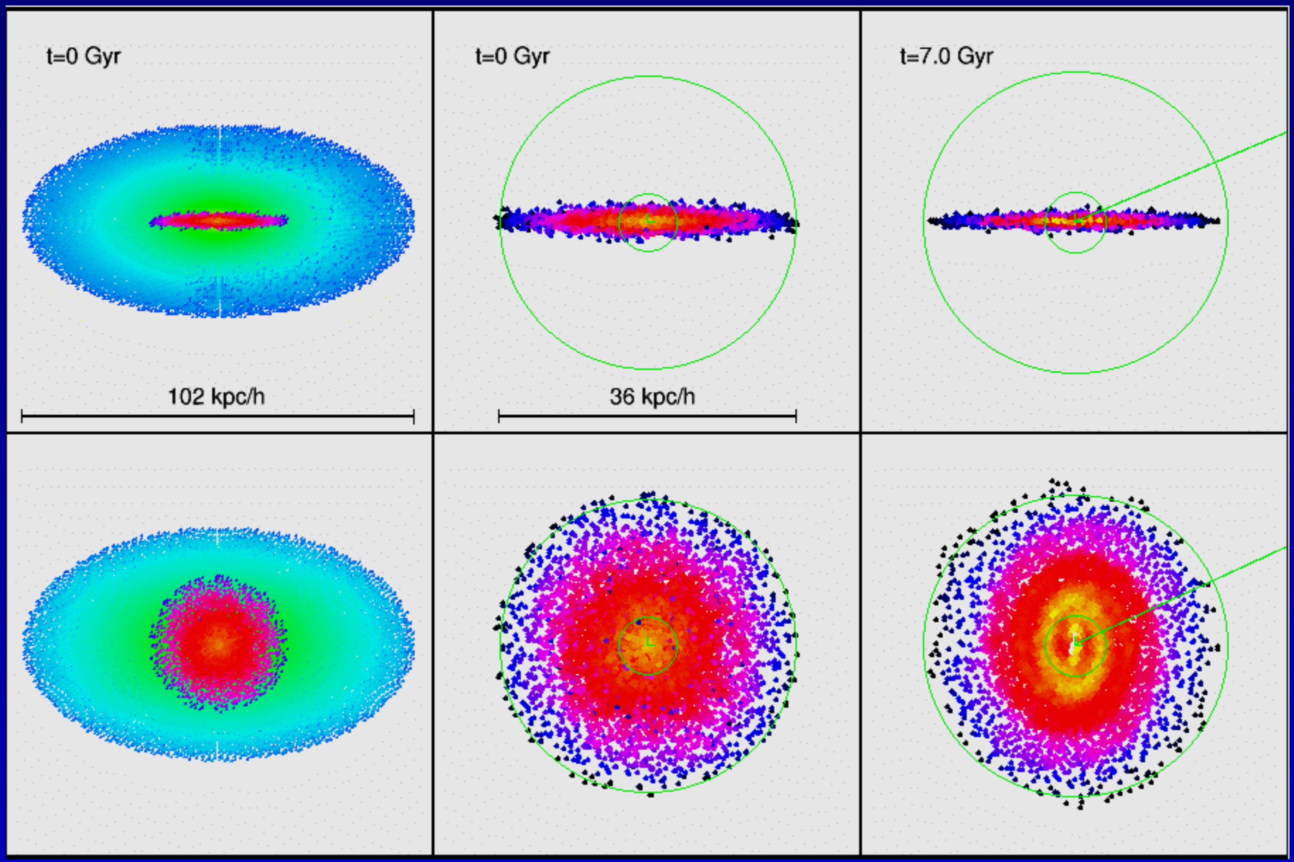
Radial Dependence of Halo Shape



- Halos become more aspherical towards the center, with a strong tendency to become prolate, in density and potential

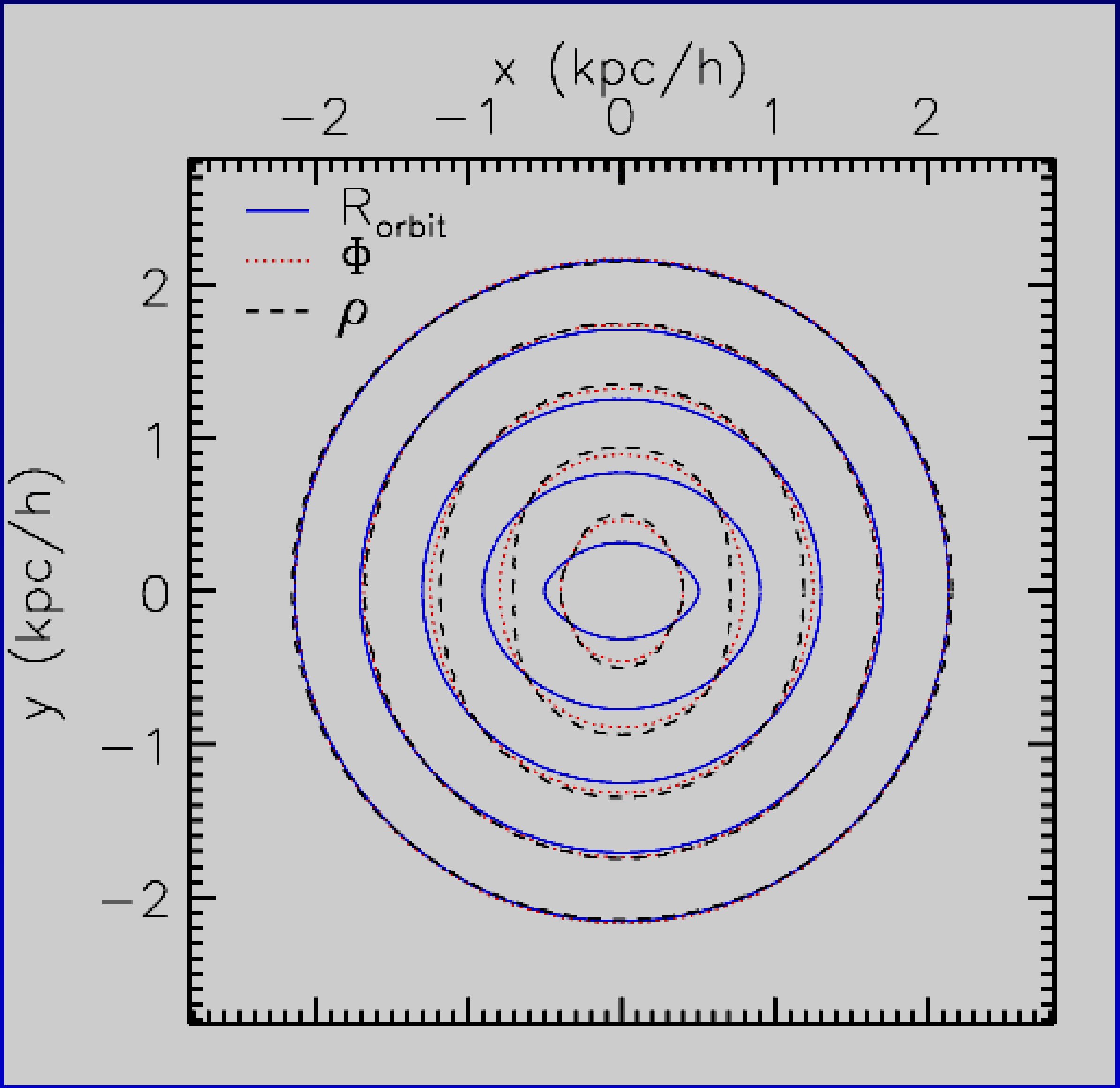
- Angular momentum tends to be perpendicular to major axis

Signatures of Halo Triaxiality: Elliptical Orbits



For disks situated in the symmetry plane of a triaxial halo, closed loop orbits may be to first order approximated by ellipses

Orbits in an m=2 perturbed NFW halo



For a perturbed potential of the form:

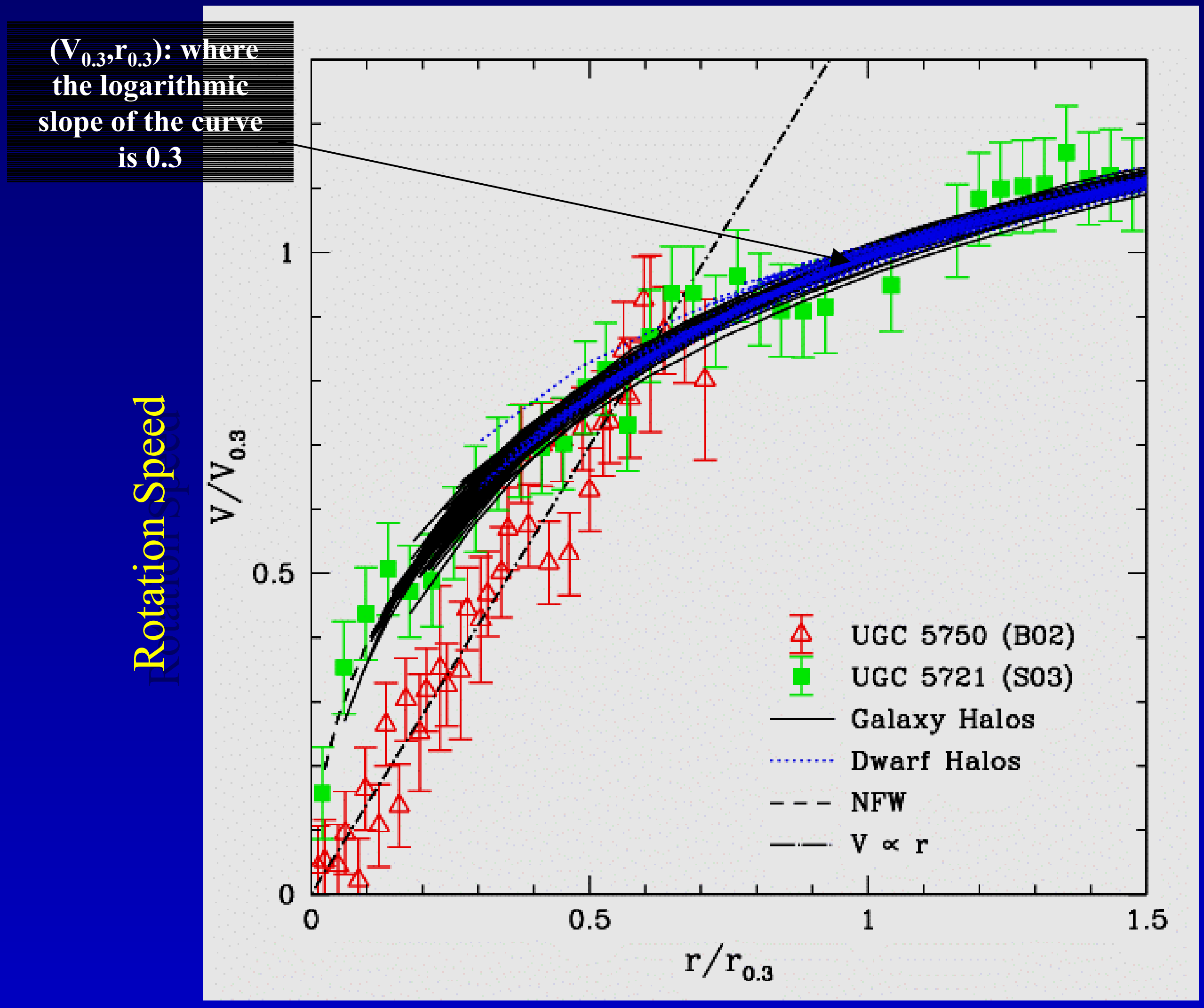
$$\Phi(r) = (1+f\cos 2\theta)\,\Phi_{NFW}(r),$$
$$(f \ll 1)$$

The ellipticity of the orbit is given by:

$$\varepsilon(r) \sim f\,(v_{esc}^2/v_c^2 - 1)$$

which increases toward the center for an NFW potential, so that large deviations from circularity may be obtained with small perturbations.

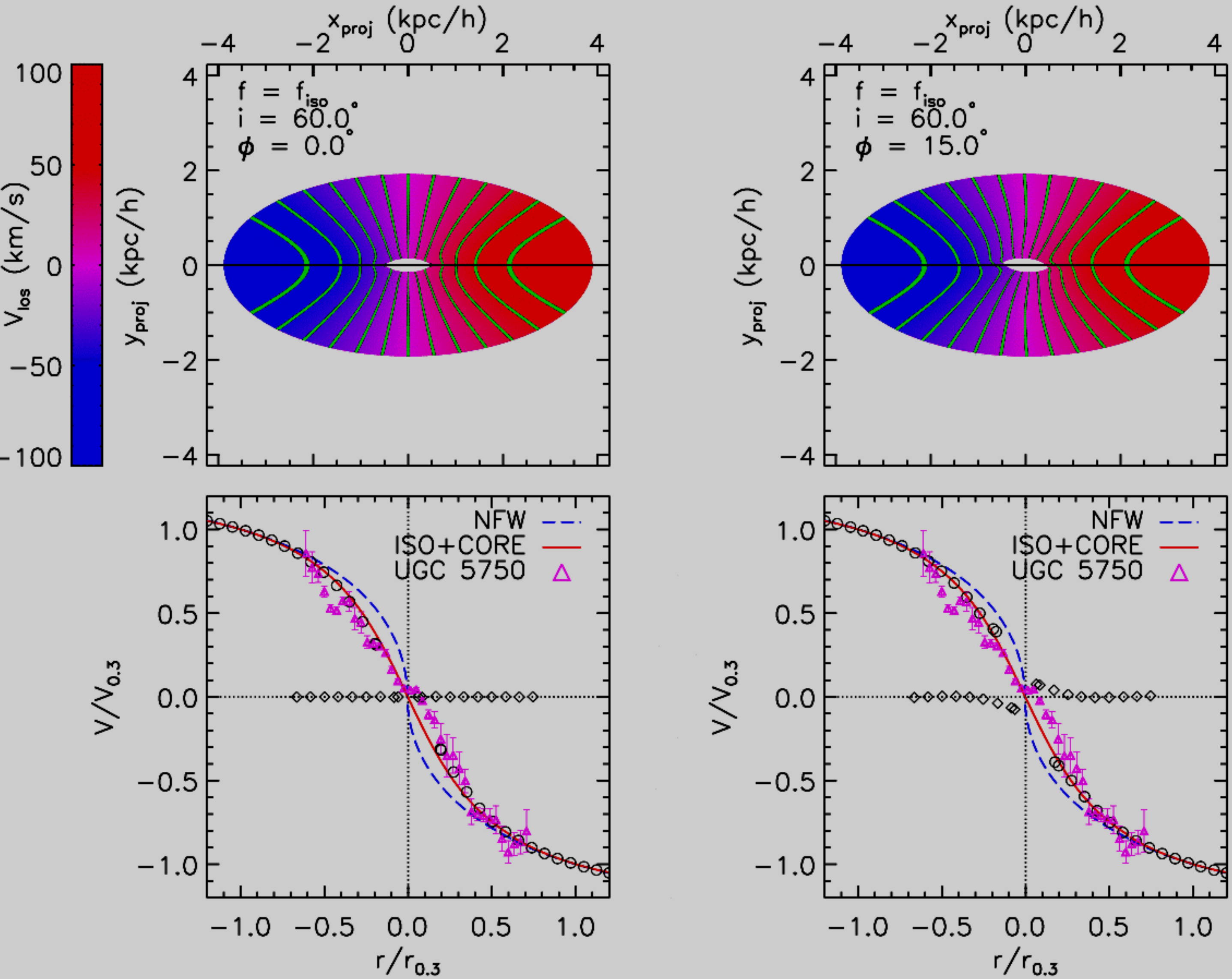
Scaled LSB rotation curves



- Most LSB rotation curves are reasonably well fitted by CDM halos
- The rest are like UGC5750, shown in the figure

Hayashi et al 2003

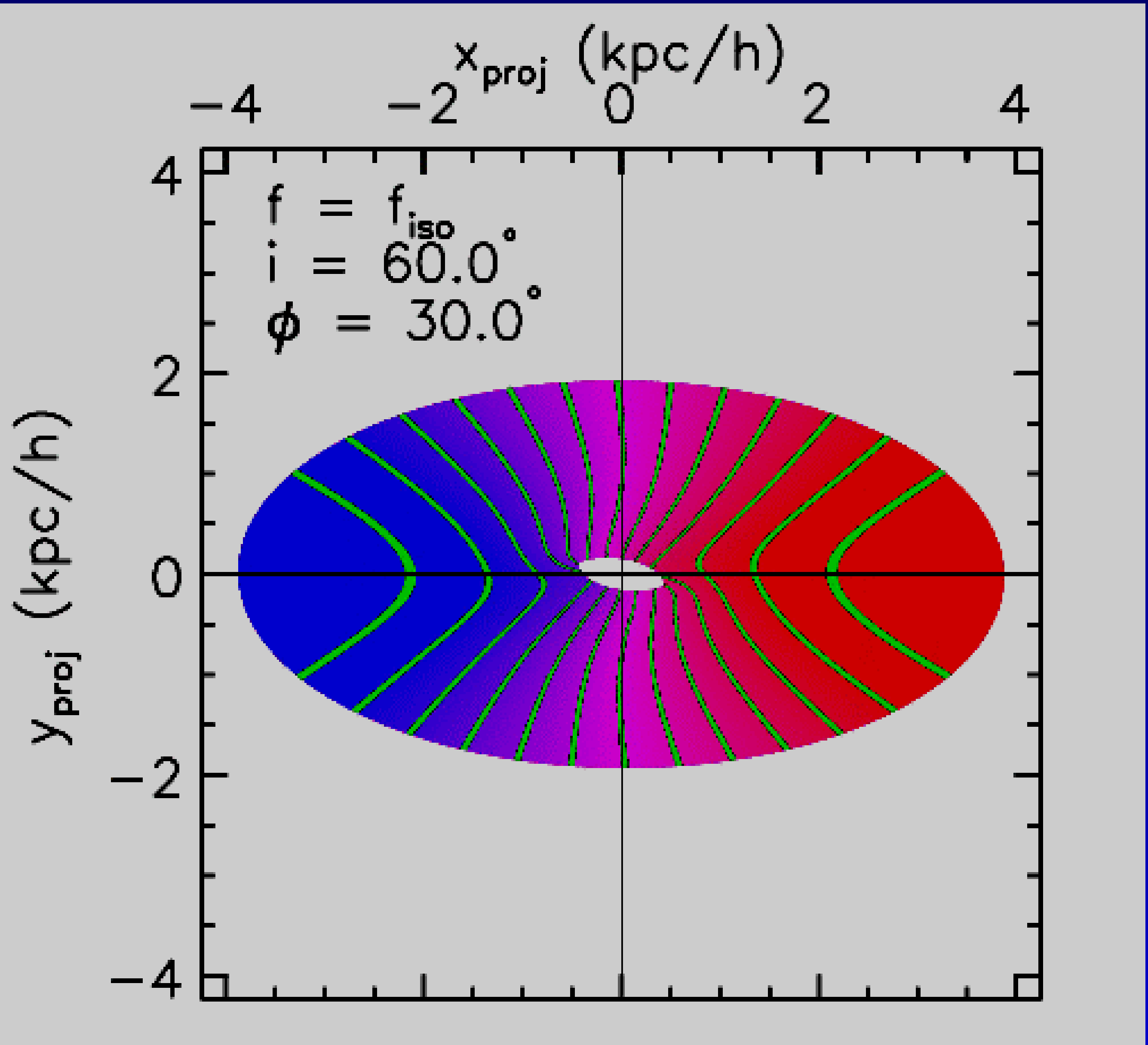
Long-slit rotation curves



- Along the long axis of symmetry of the orbits, the line-of-sight velocities are gradually reduced toward the center (relative to circular) so that the rotation curve looks “solid-body”, mimicking the presence of a constant-density core.

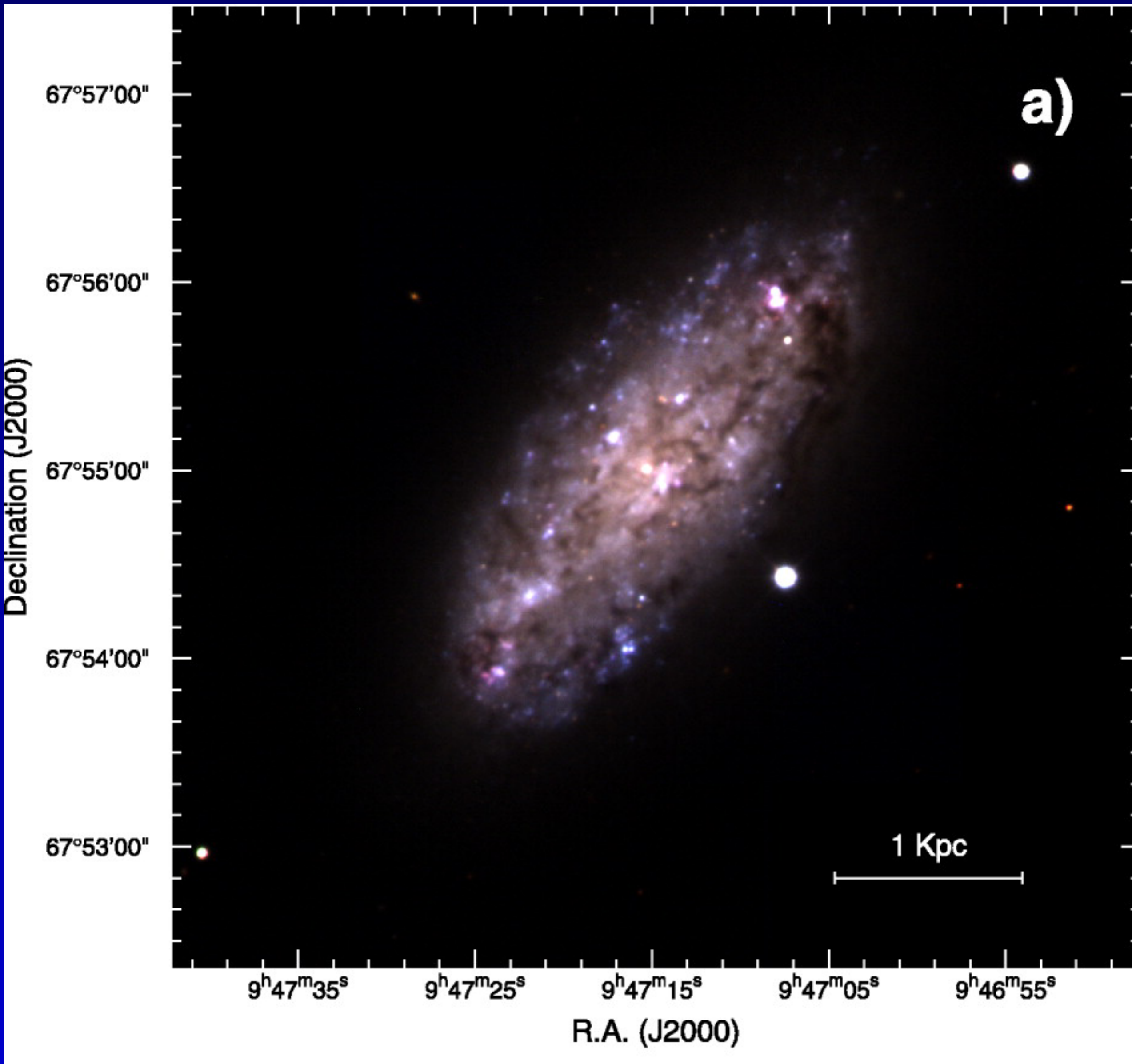
- For this configuration, the velocity field is symmetric and orbits are indistinguishable from circular.

The imprint of halo triaxiality on disk velocity fields



- Lines of constant speed are asymmetric, and show characteristic “kinks”.
- Iso-velocity contours are (anti)symmetric in diagonally opposite quadrants, but differ in contiguous ones.
- The effect becomes gradually more pronounced toward the centre.

LSBs with 2D Velocity Field Data: NGC 2976

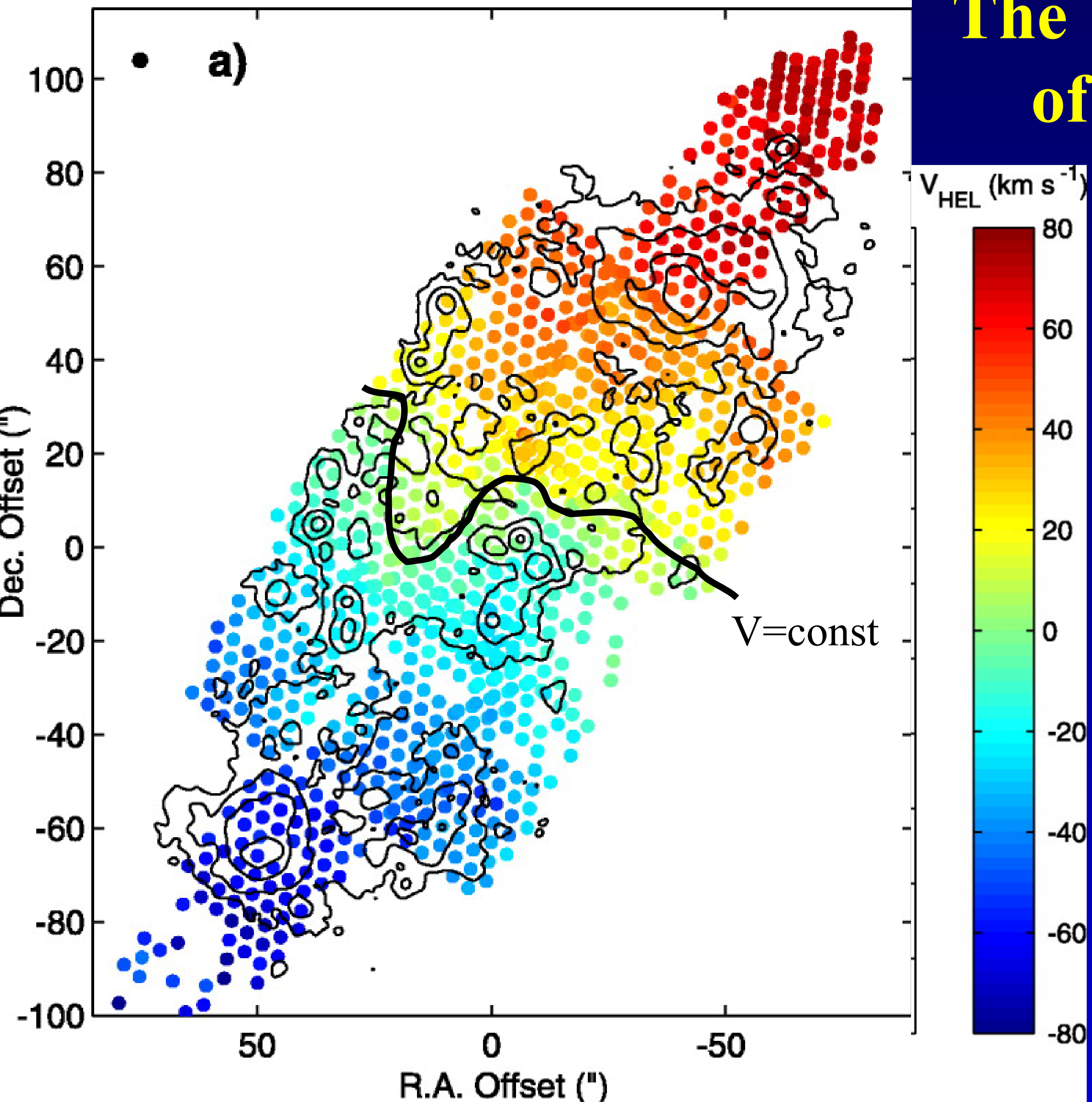


NGC 2976:
an LSB disk without obvious bulge or bar components.

"…independent of any assumptions about the stellar disk or the functional form of the density profile, NGC 2976 does not contain a cuspy dark matter halo"

Simon et al 2004

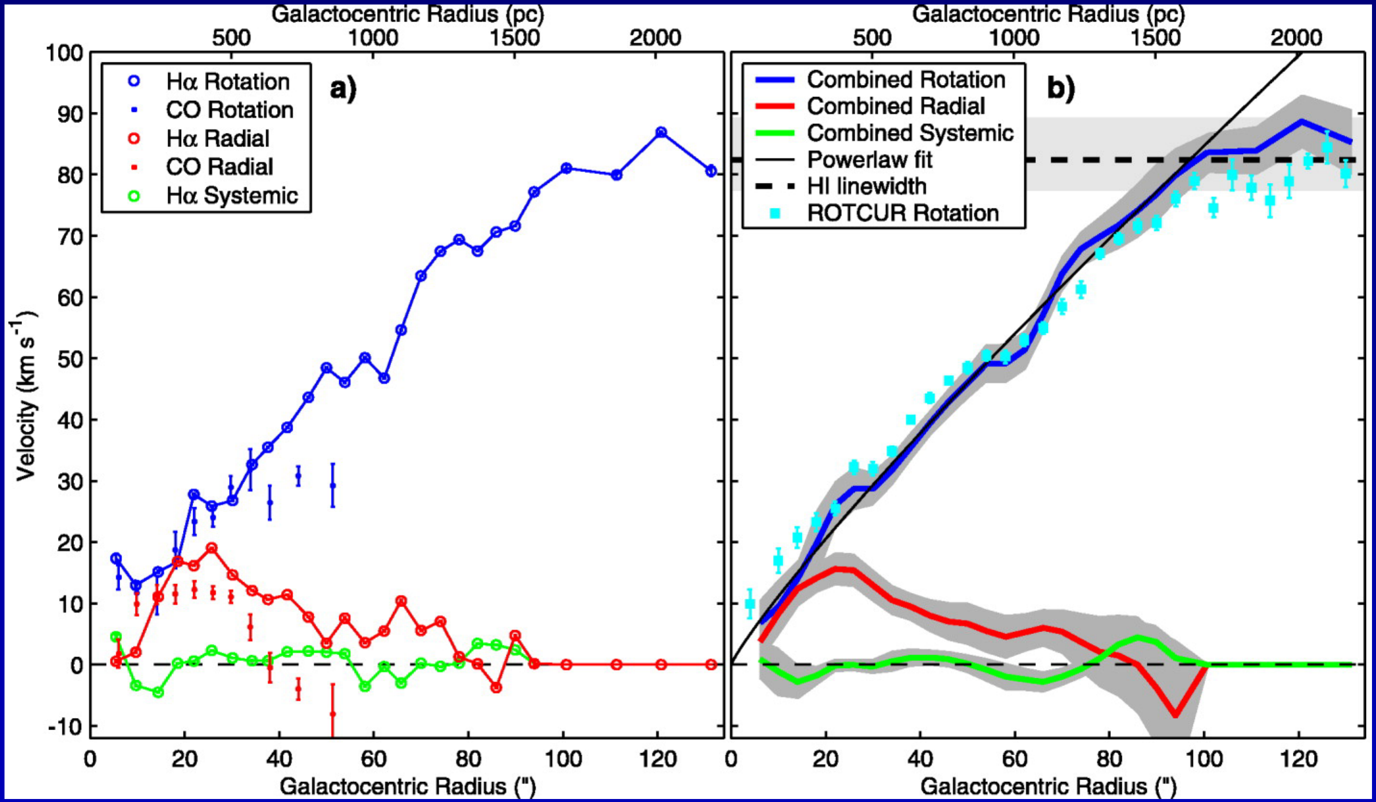
The Velocity Field of NGC 2976



Velocity field is quite asymmetric, with "kinks" similar to those seen in projection for disks in triaxial halos.

Simon et al 2004

Modeling of 2D Velocity Field Data: NGC 2976

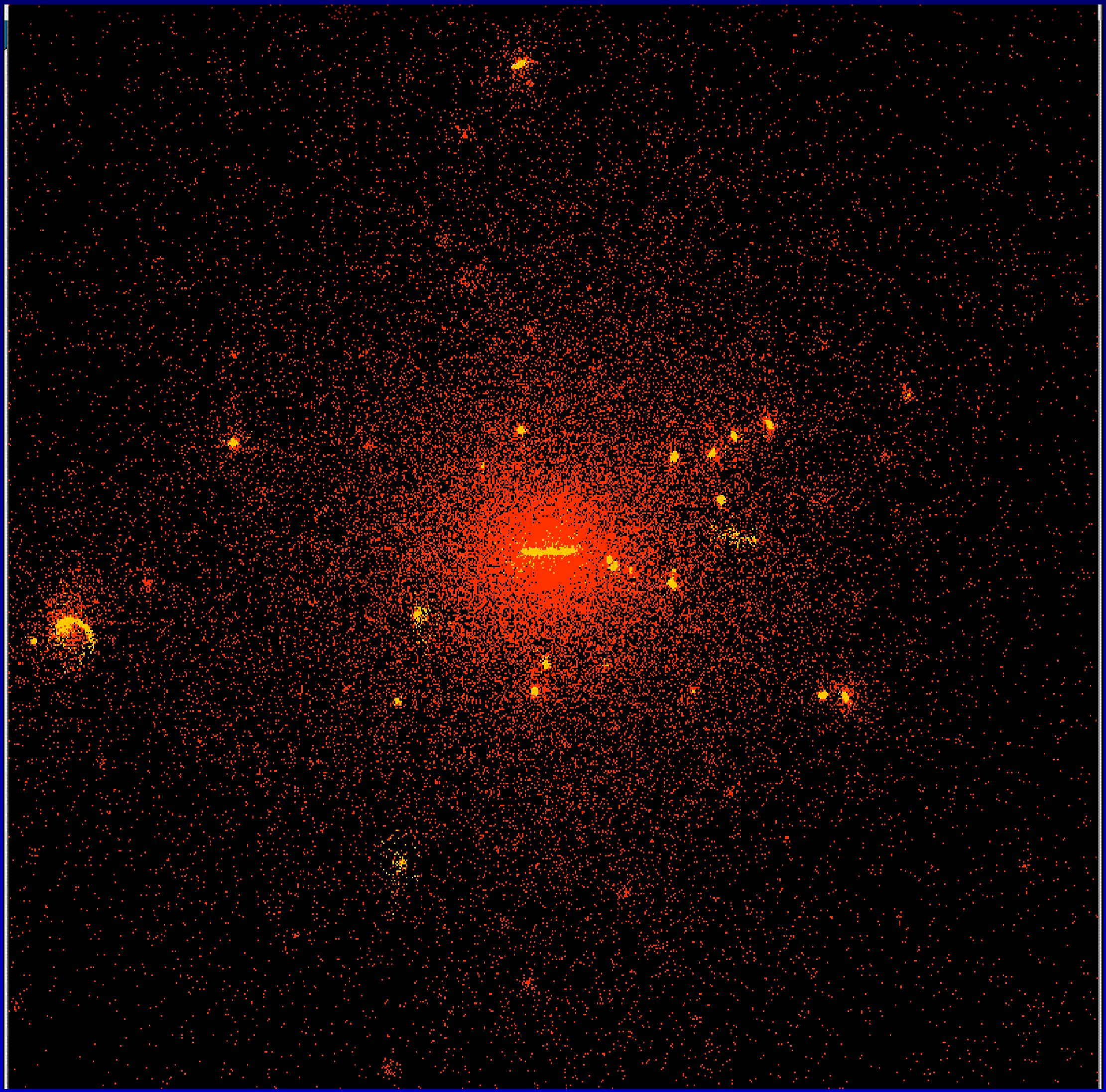


Simon et al (2004) choose to model such deviations by tilted concentric rings with rotation, as well as “radial” (i.e. expansion or contraction) velocities.

Good fits are obtained, but this treatment may mask the presence of elliptical motions and may hide a cusp.

Simon et al 2004

Galaxy-Induced Transformations of Cold Dark Matter Halos



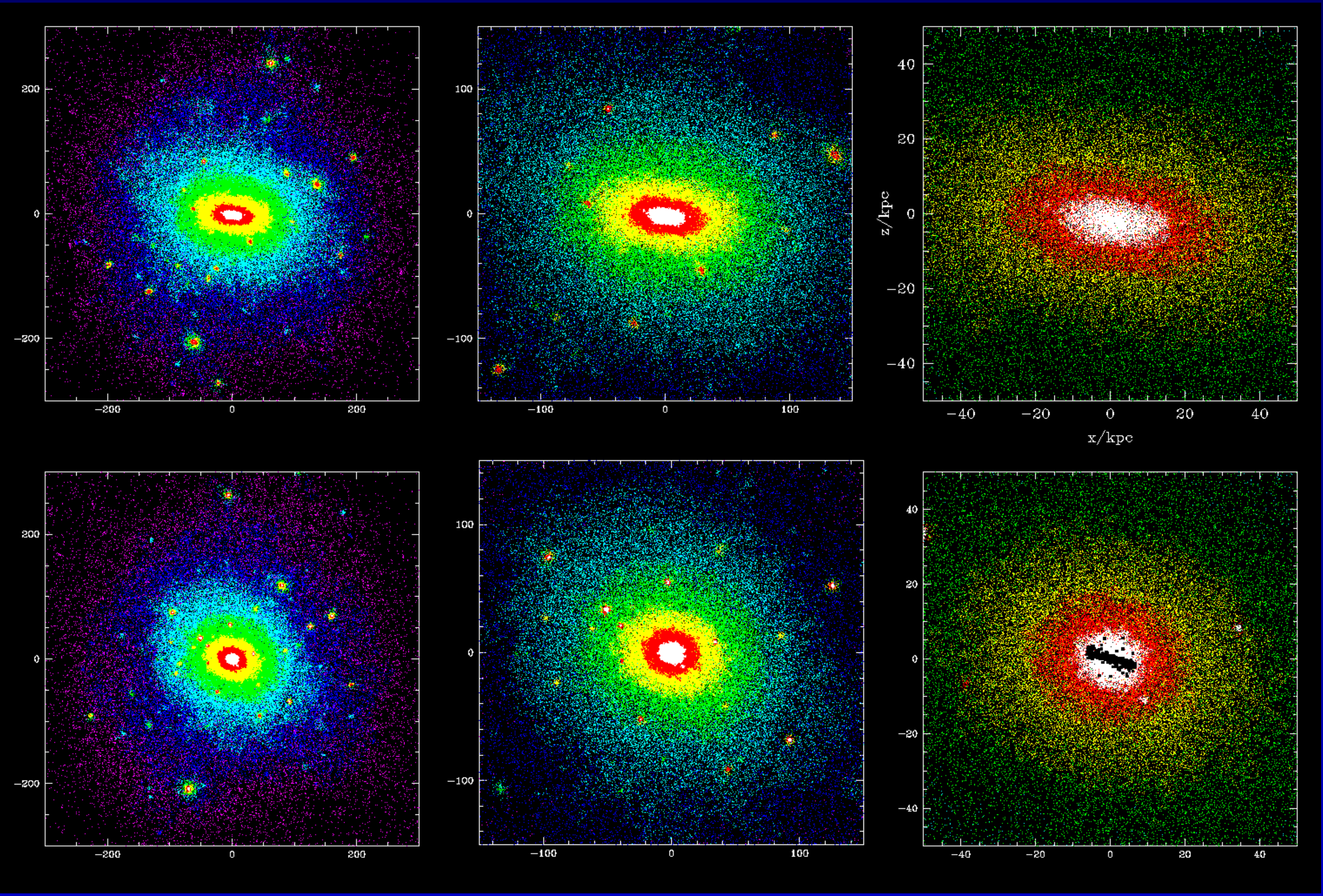
- Set of simulations including only the effects of radiative cooling and of an UV background.

- A total of 13 simulations of ~200 km/s halos with a reasonably “quiet” aseembly history, i.e. no major mergers since z=2.

- Disks and satellites are well resolved; typically N_{disk}~50,000

Yellow=cold gas
Red=dark matter

Changes in Shape: Density

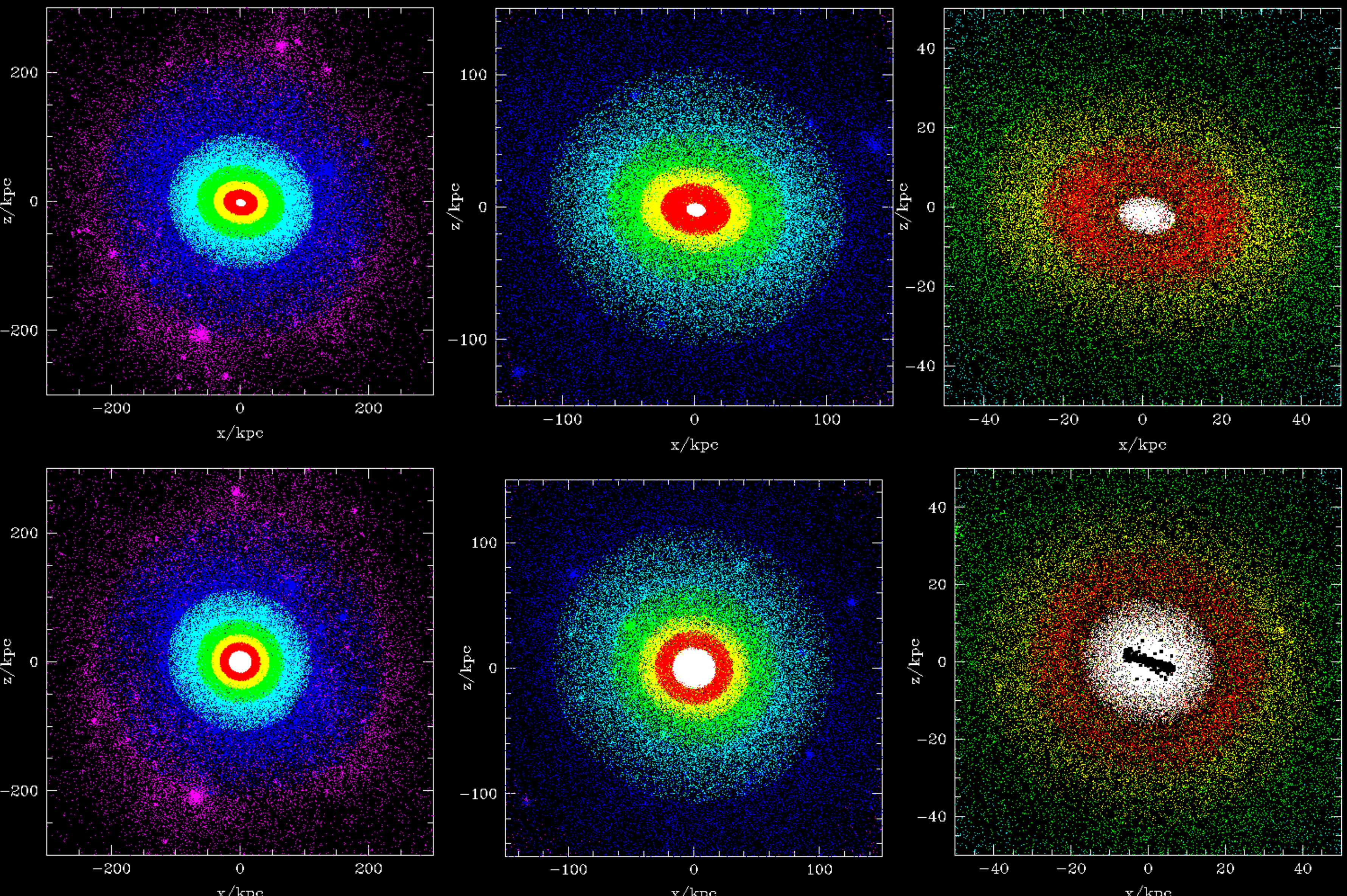


Dark Matter only

Dark Matter + Baryons

Zoom: x1 x2 x4

Changes in Shape: Potential



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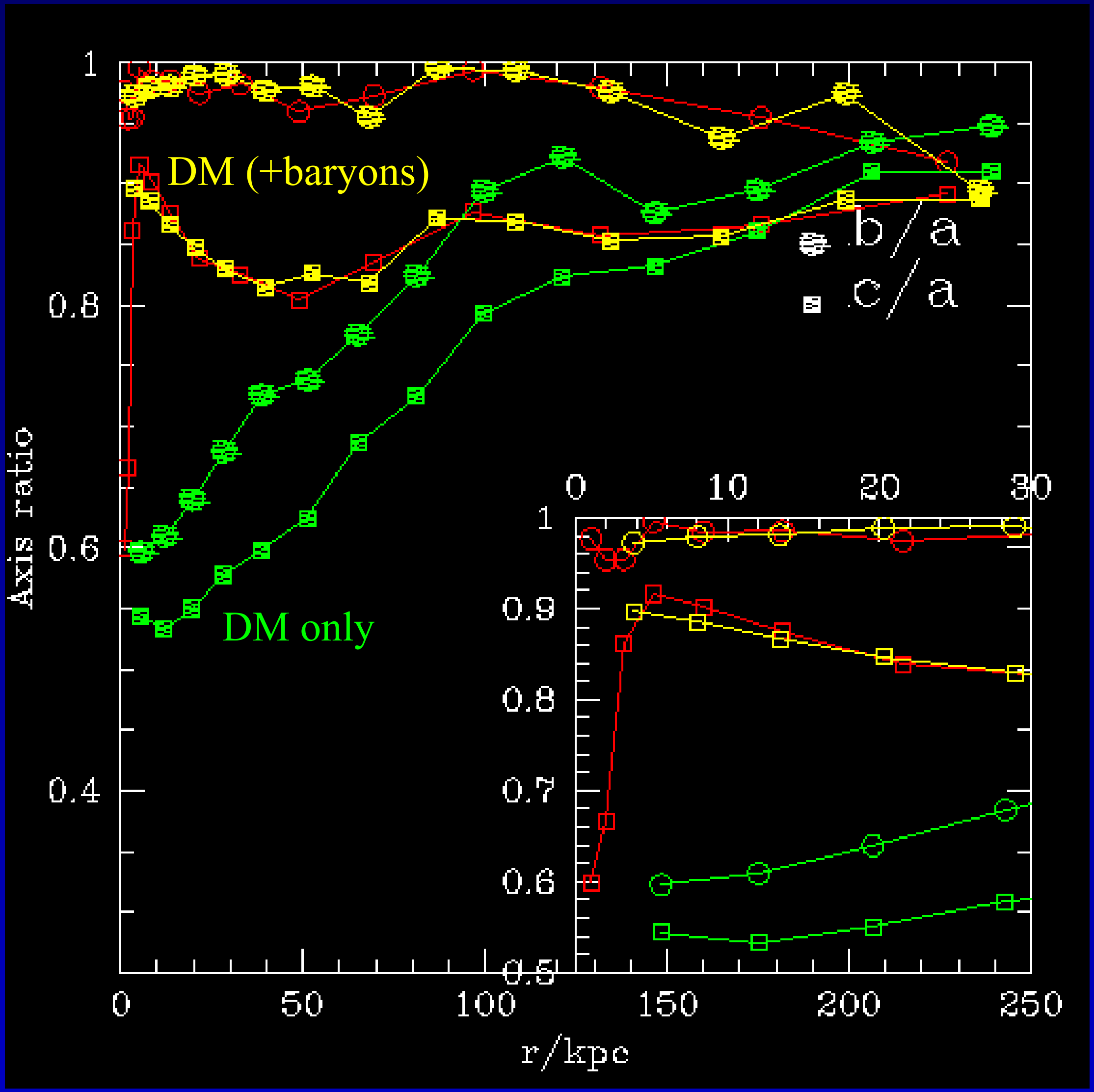
Changes in Shape: Potential

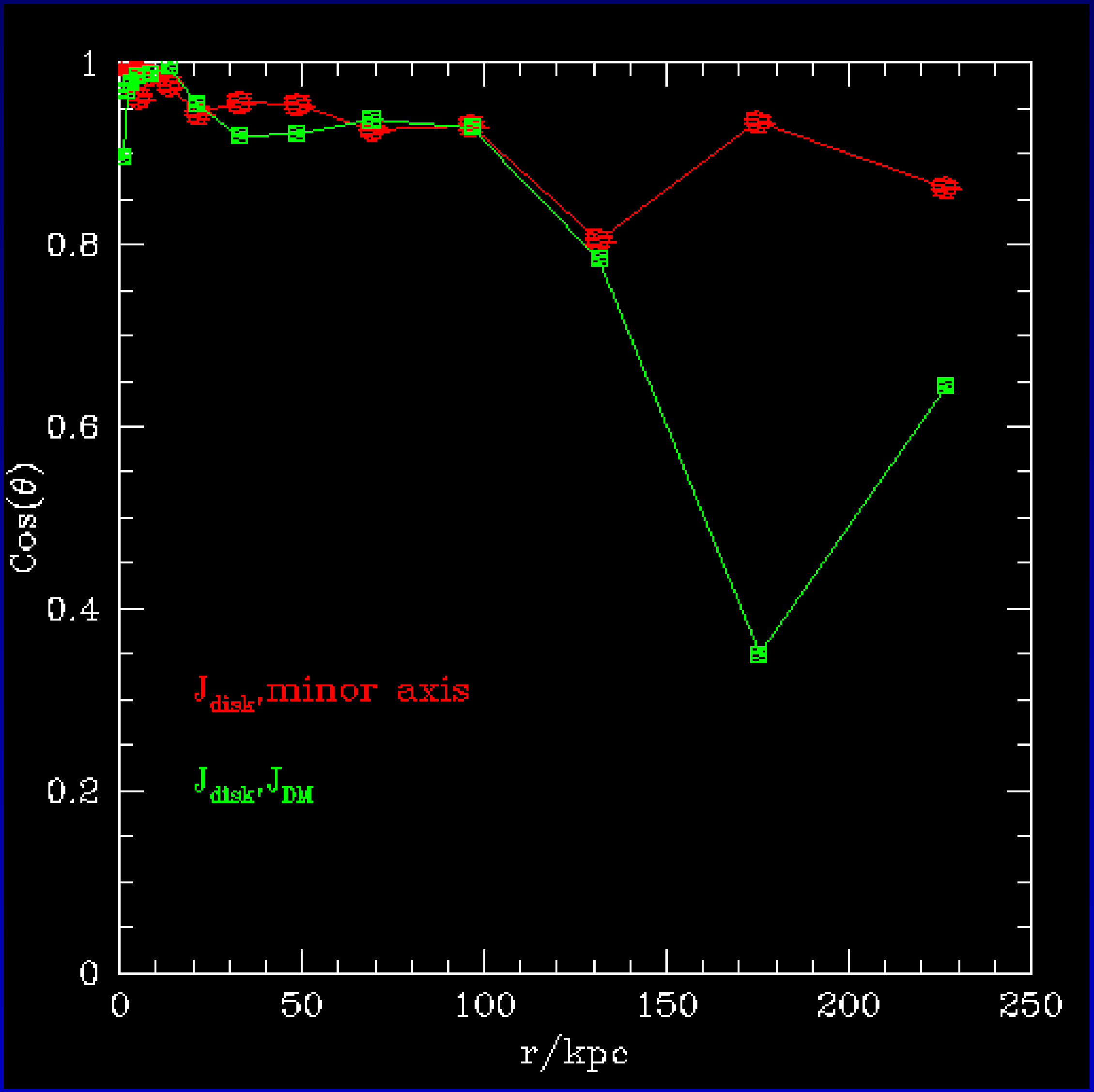


Radius

- Dark halo becomes much more spherical as a result of the assembly of the galaxy
- Nearly prolate halos may become oblate, an effect that extends well beyond the luminous galaxy
- Minor axis roughly coincides with the rotation axis of the disk
- Disk angular momentum is well aligned with that of the halo.

Alignment between Disk and Dark Matter

Θ=angle between J_{disk} and minor axis (or J_{DM})



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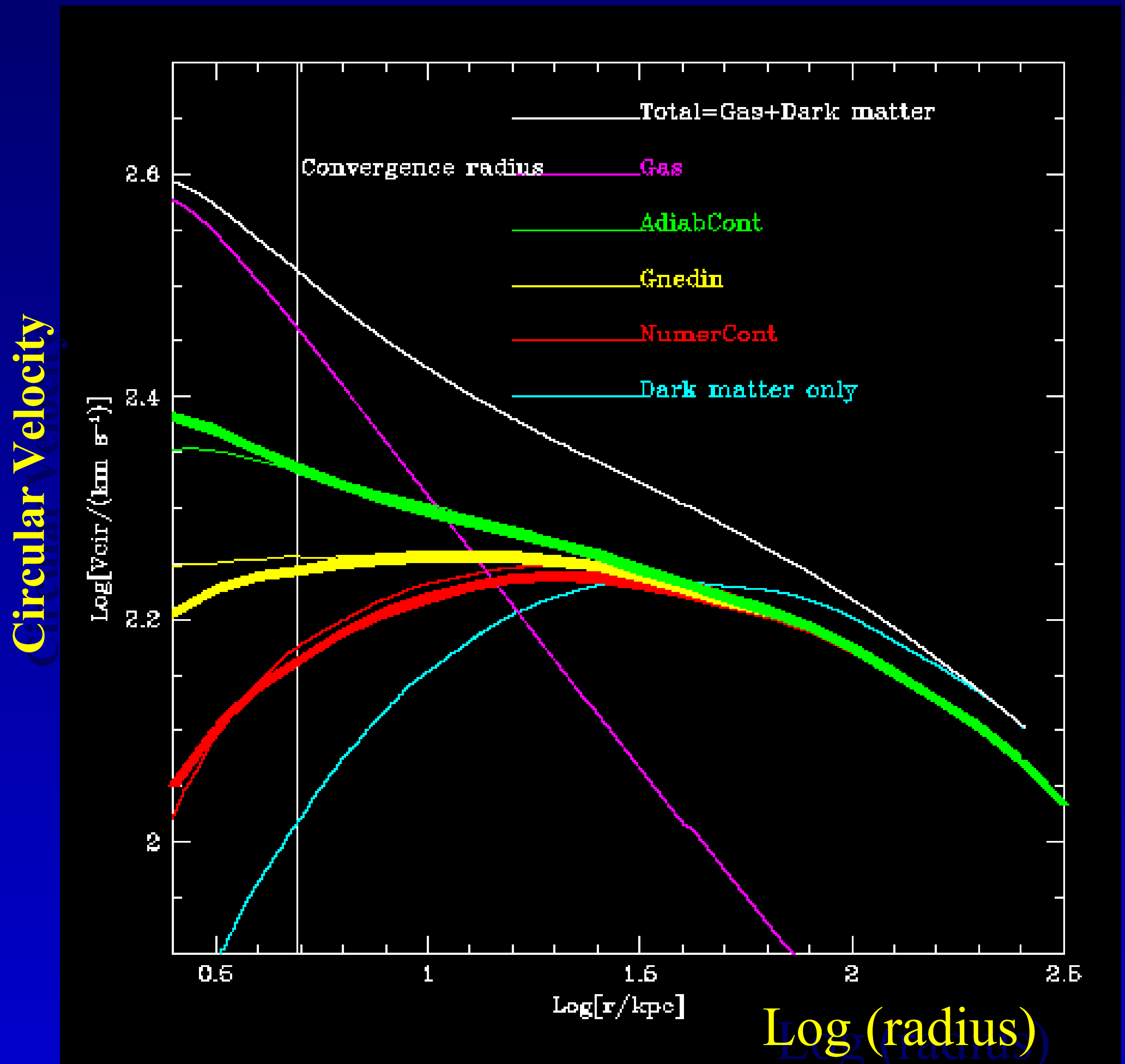
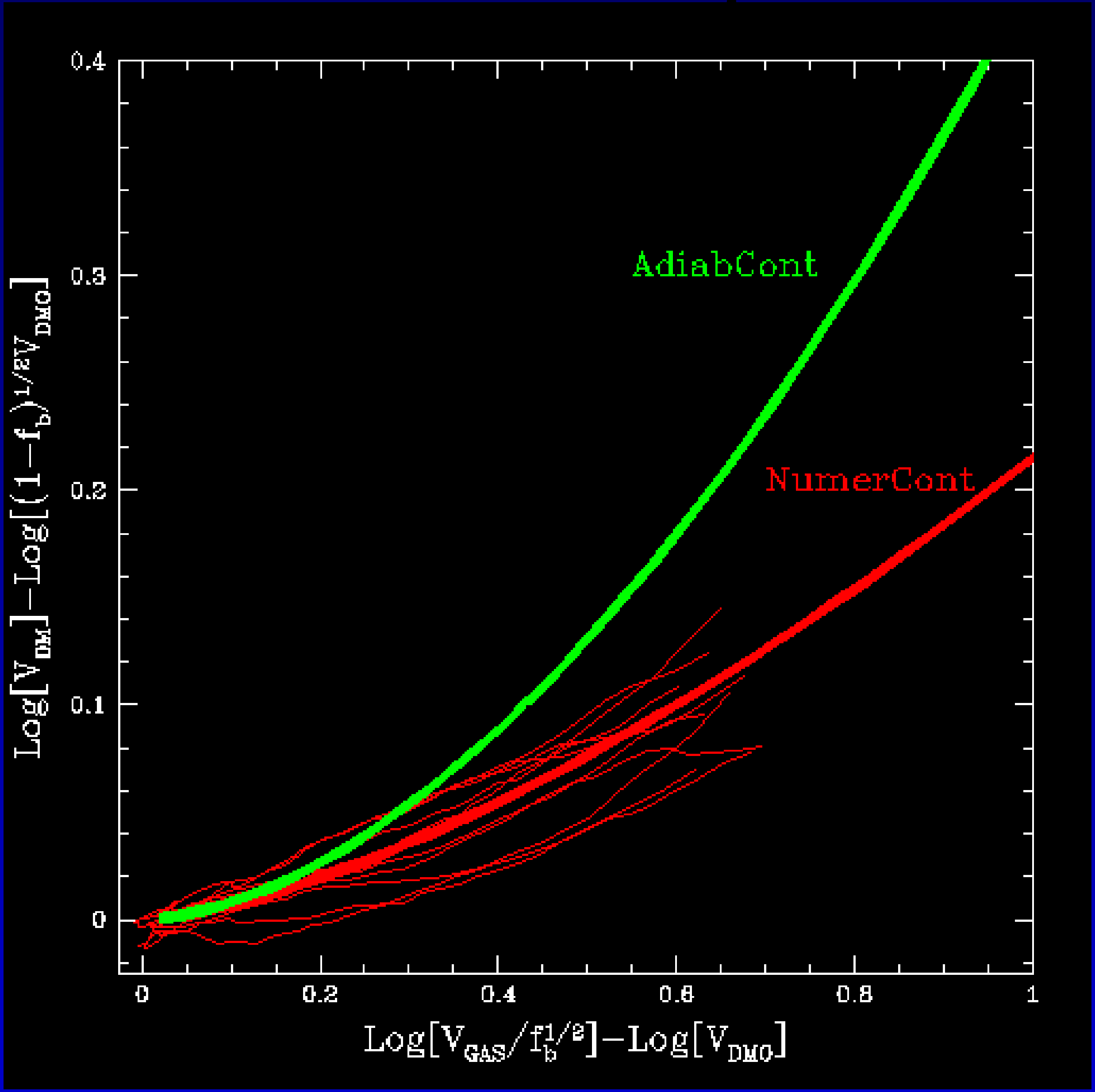
Changes in Dark Mass Profile



•The dark matter responds to the assembly of the galaxy by becoming more centrally concentrated.

•The response, however, is weaker than expected from simple models based on adiabatic invariant approximations.

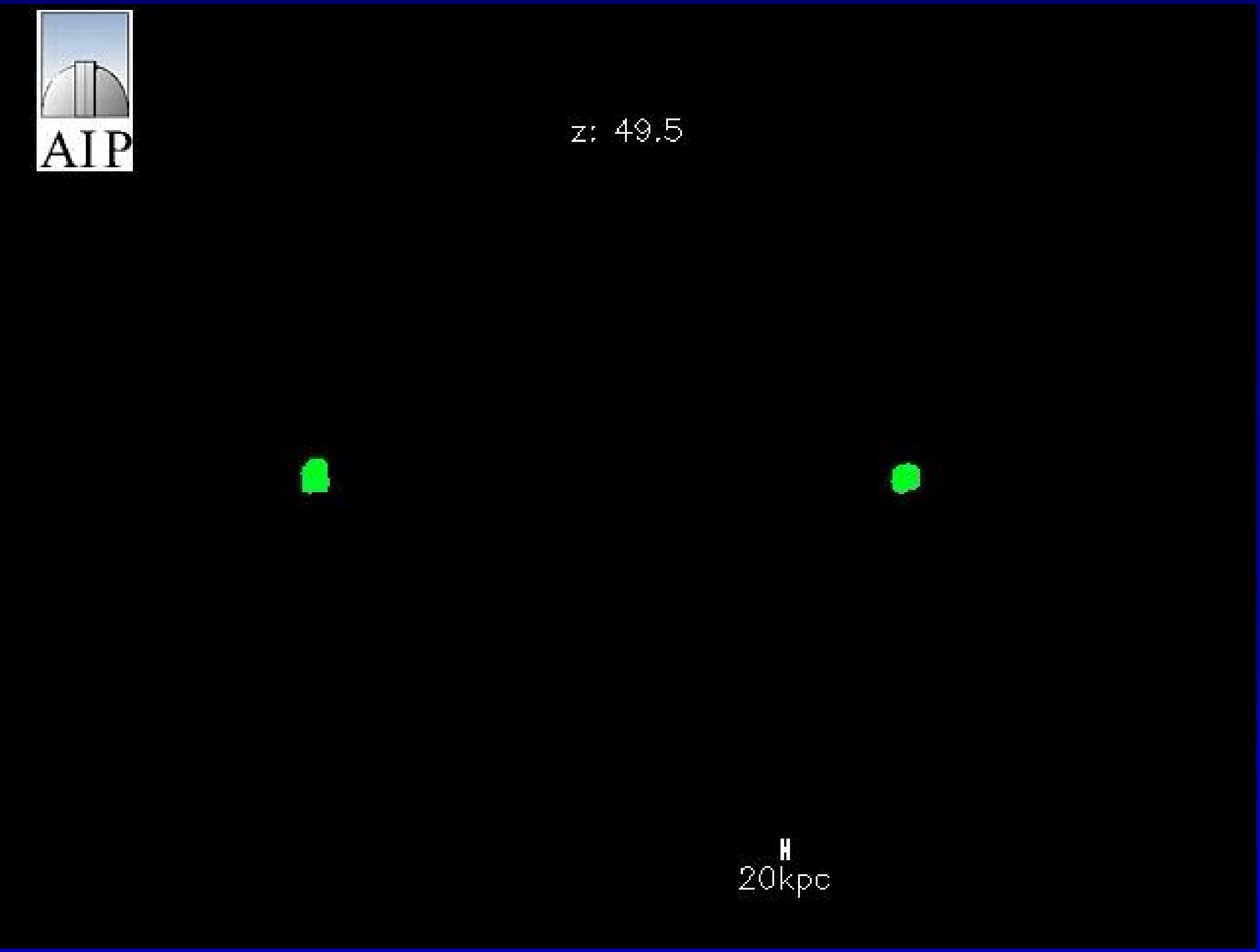
Halo Contraction in Response to Galaxy Assembly



The halo response is weaker than expected from the traditional adiabatic contraction formula.

This has interesting implications for reconciling the Tully-Fisher relation with the abundance of galaxy-sized LCDM halos

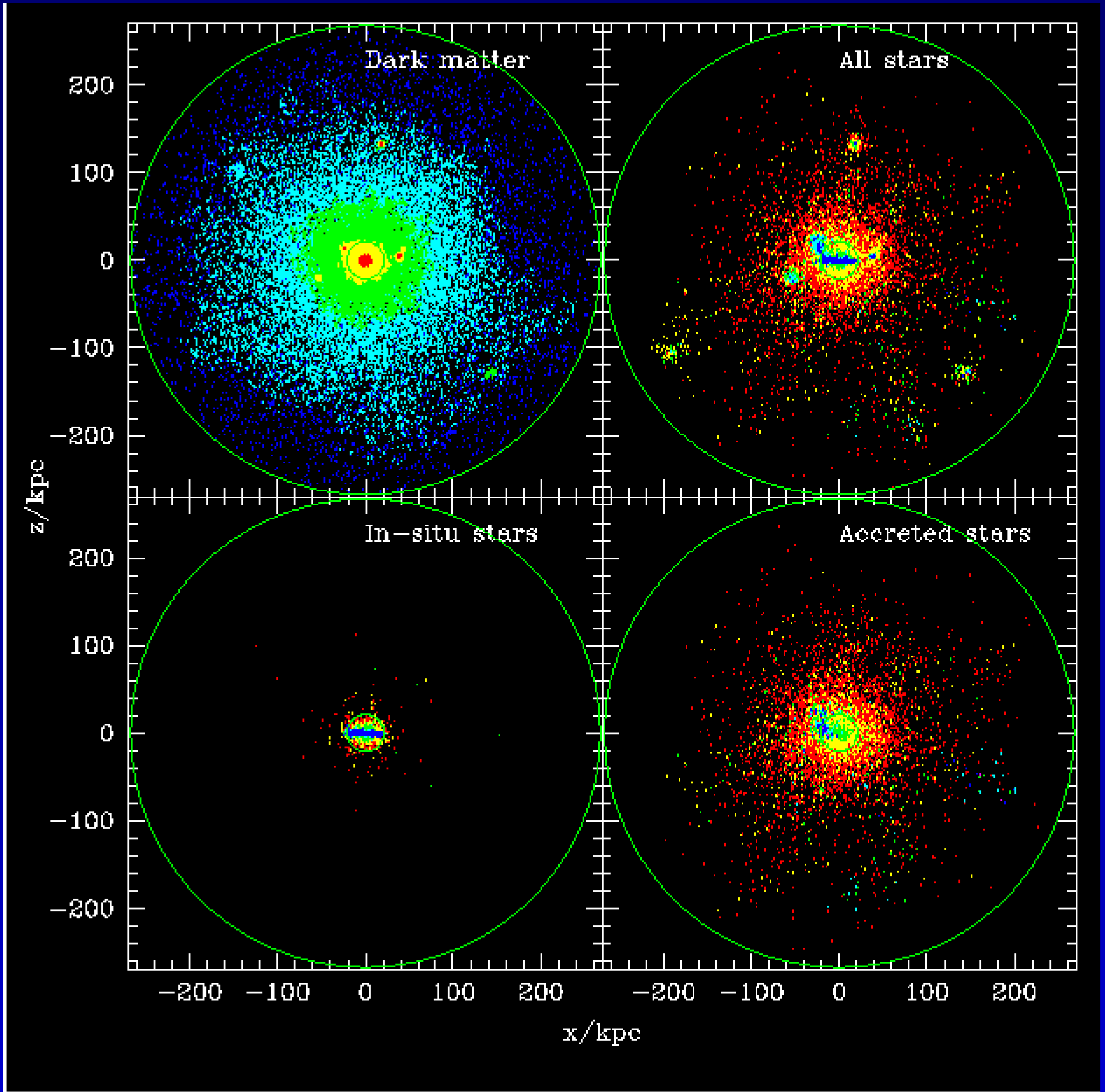
Luminous Halos around Galaxies



The majority of galaxies assembled in a CDM-dominated universe have gone through a period of intense merging activity.

Steinmetz & Navarro 2000

Stars Beyond Galaxies: Luminous Halos Around Galaxies

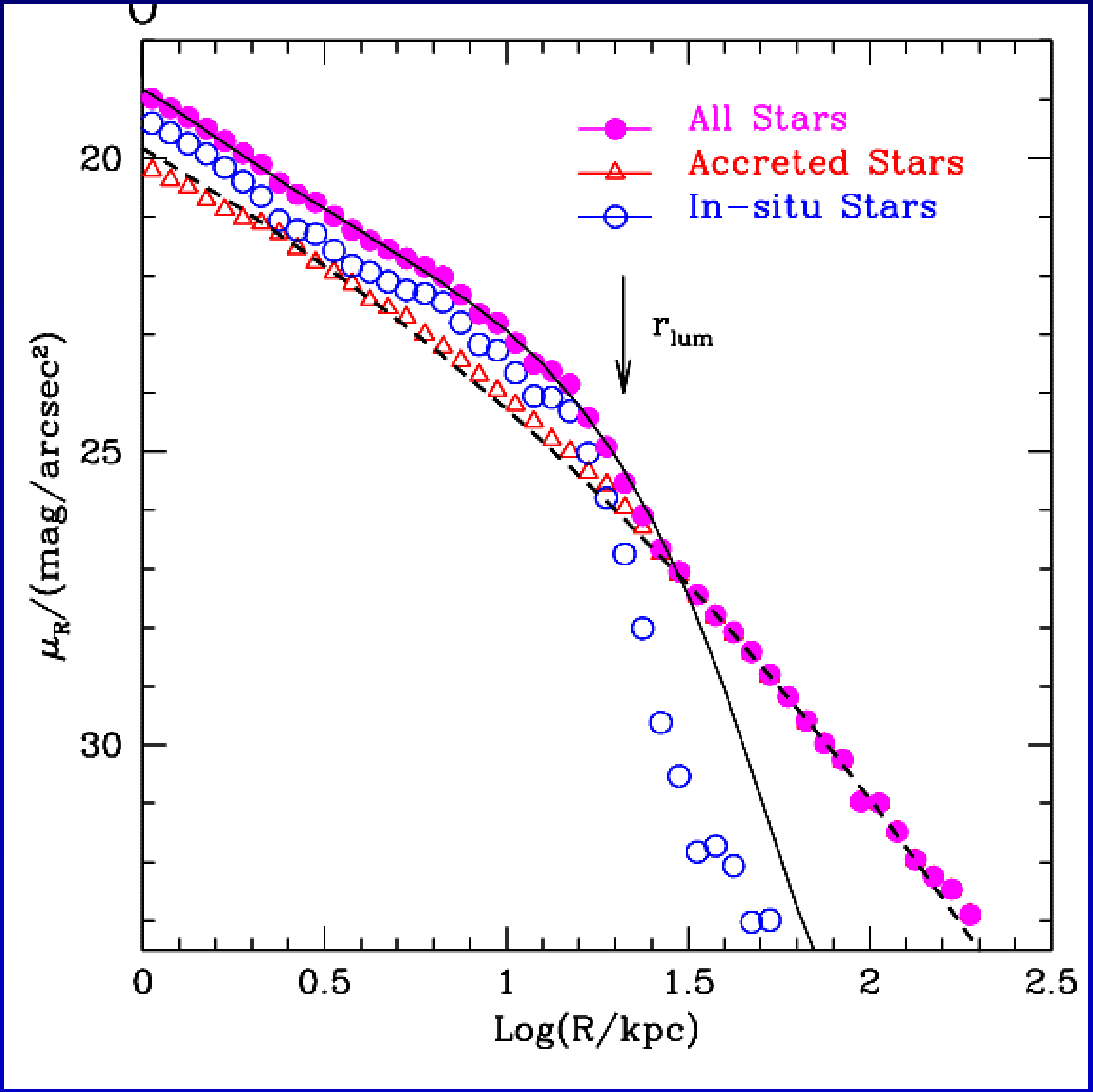


Essentially all stars beyond the traditional luminous radius of a galaxy (and not in satellites) originate in past accretion events

The outer luminous halo of a galaxy holds important clues to the merging history of a galaxy

Abadi, Navarro & Steinmetz 2005

The Outer Surface Brightness Profile of Galaxies



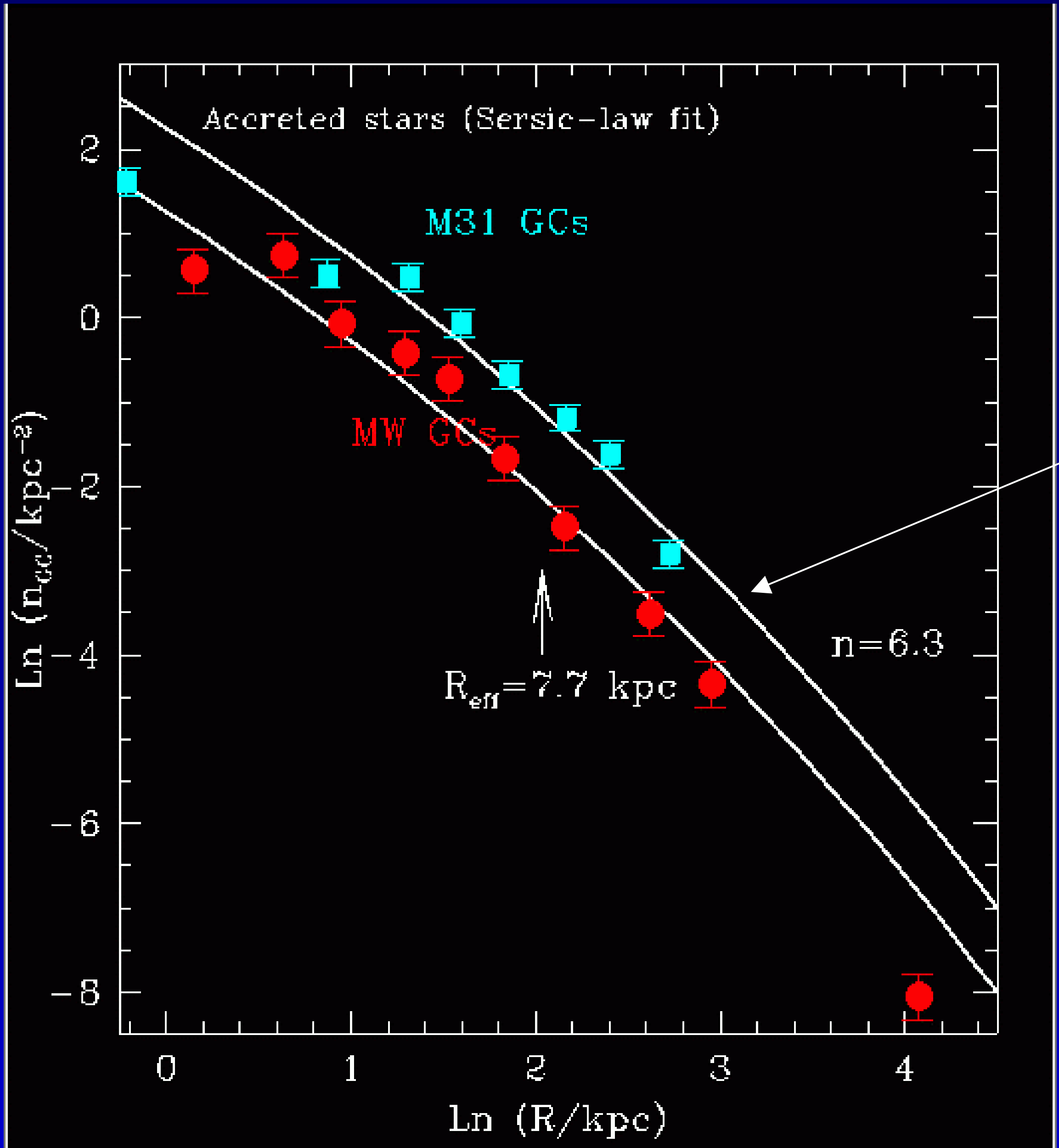
•Outer halos appear as an "excess" of light over extrapolations of the inner surface brightness profile of a galaxy.

•The outer halo is well approximated by a Sersic law

•The same law describes very well the profile of all accreted stars

Abadi, Navarro & Steinmetz 2005

Globular clusters: Tracers of accreted stars?

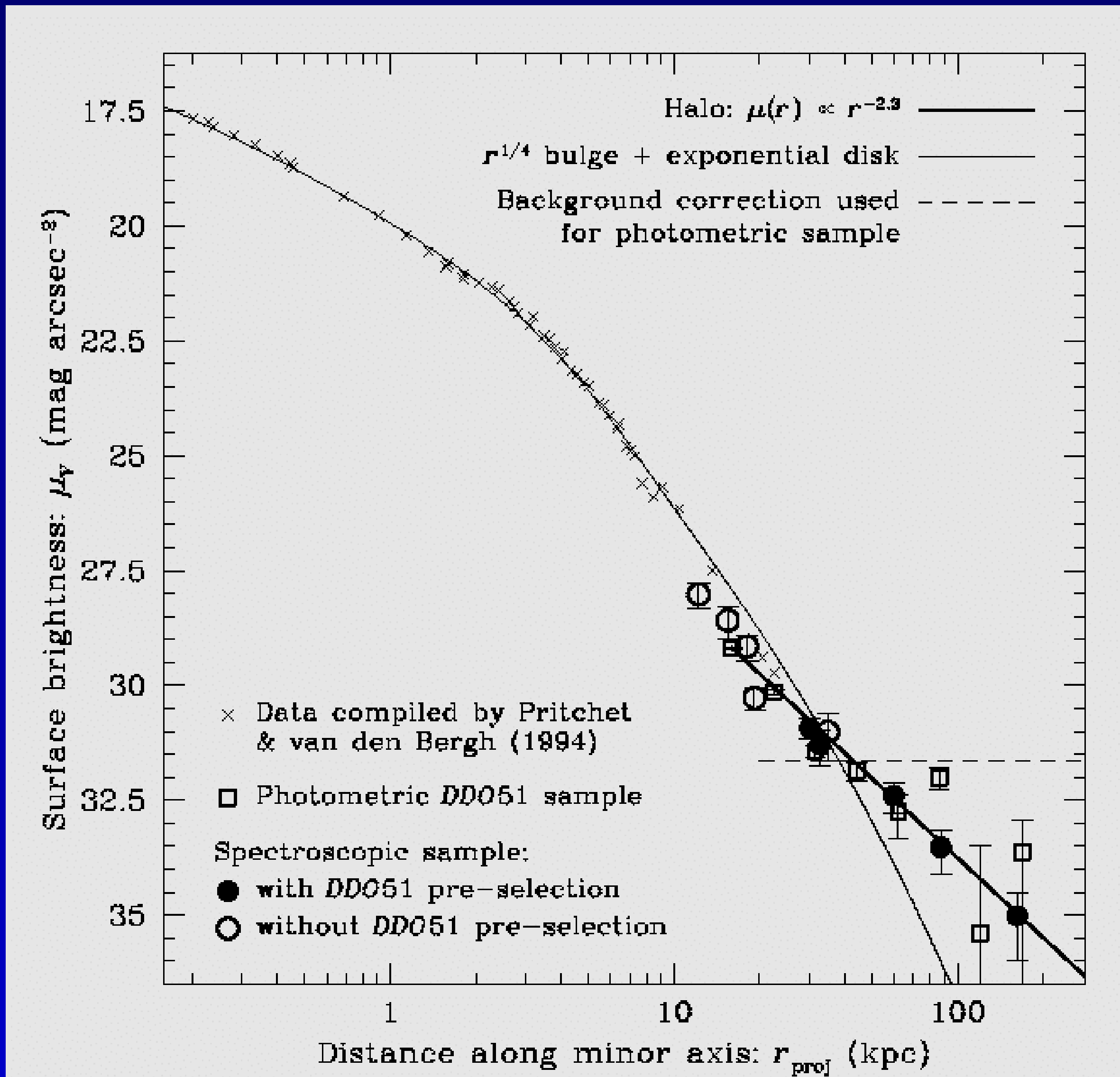


- The number density profile of globular clusters around M31 and the Milky Way is consistent with the density profile of accreted stars in our simulations.
- Curves in the figure are *not* fits, they just show a Sersic law with parameters of the accreted stars.
- Majority of GCs might be relicts of accretion events? (Searle & Zinn 1978)

Abadi, Navarro & Steinmetz 2005

The Outer Surface Brightness Profile of M31

Surface Brightness

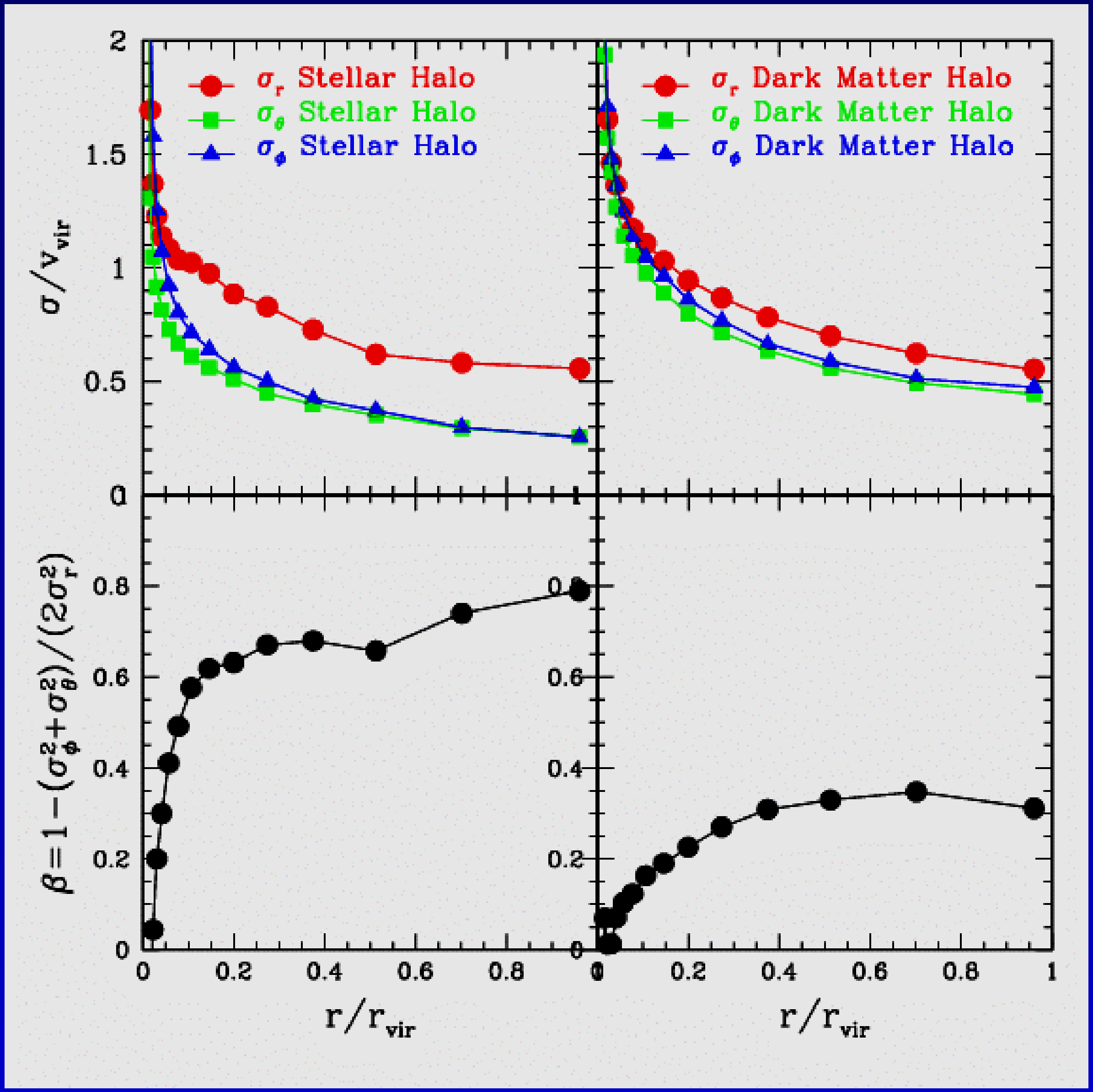


Such outer halos have been detected around edge-on, isolated spirals (Zibetti et al 2004) and M31 (see also Irwin et al 2005)

- The outer spheroid may be used to estimate the total number of accreted stars in a galaxy!

Guhatakurta et al 2005

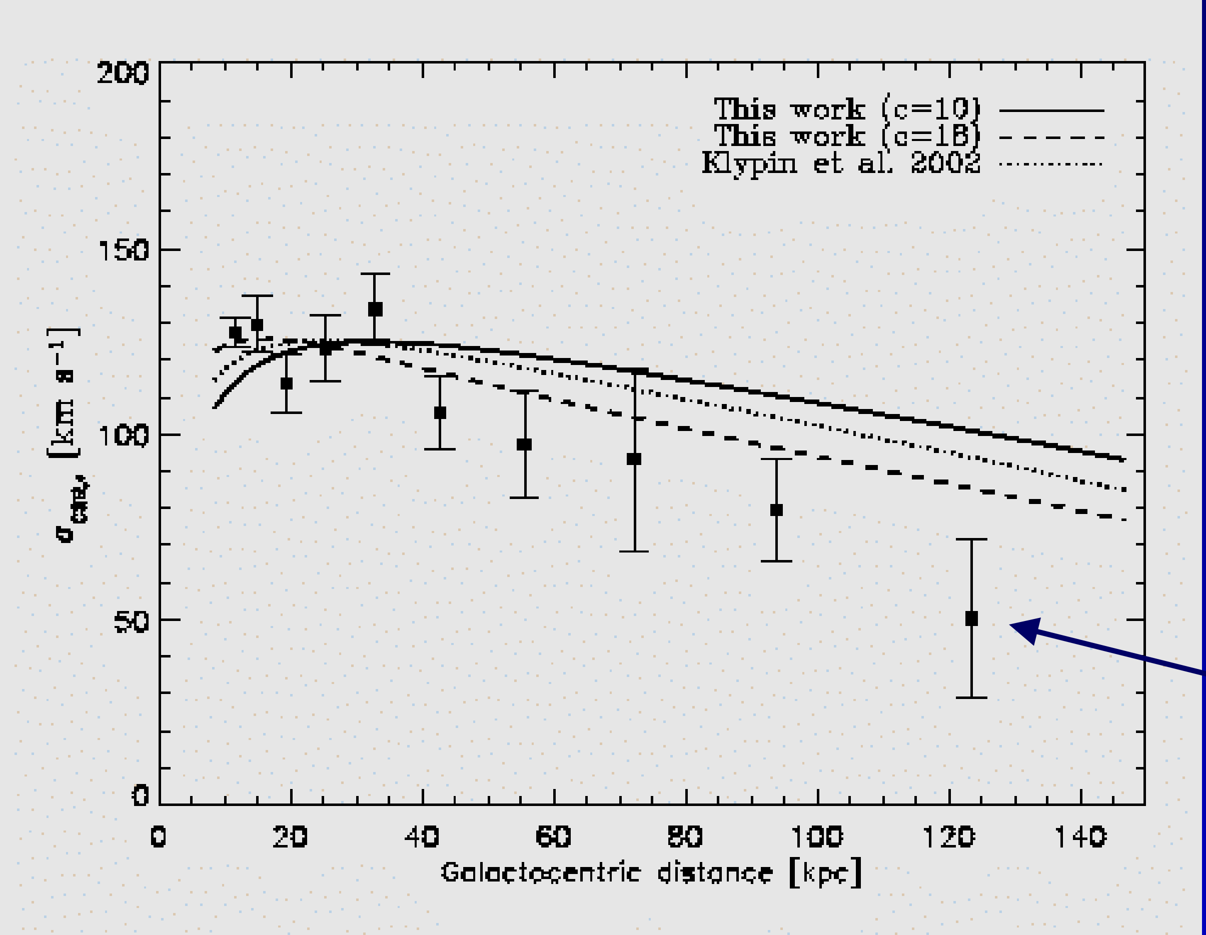
The Dynamics of Luminous Halos



The velocity dispersion tensor of stars in the outer halo is remarkably anisotropic: $\sigma_r^2 \sim 4\,\sigma_t^2$

Abadi, Navarro & Steinmetz 2005

The Dynamics of the Milky Way's Luminous Halo

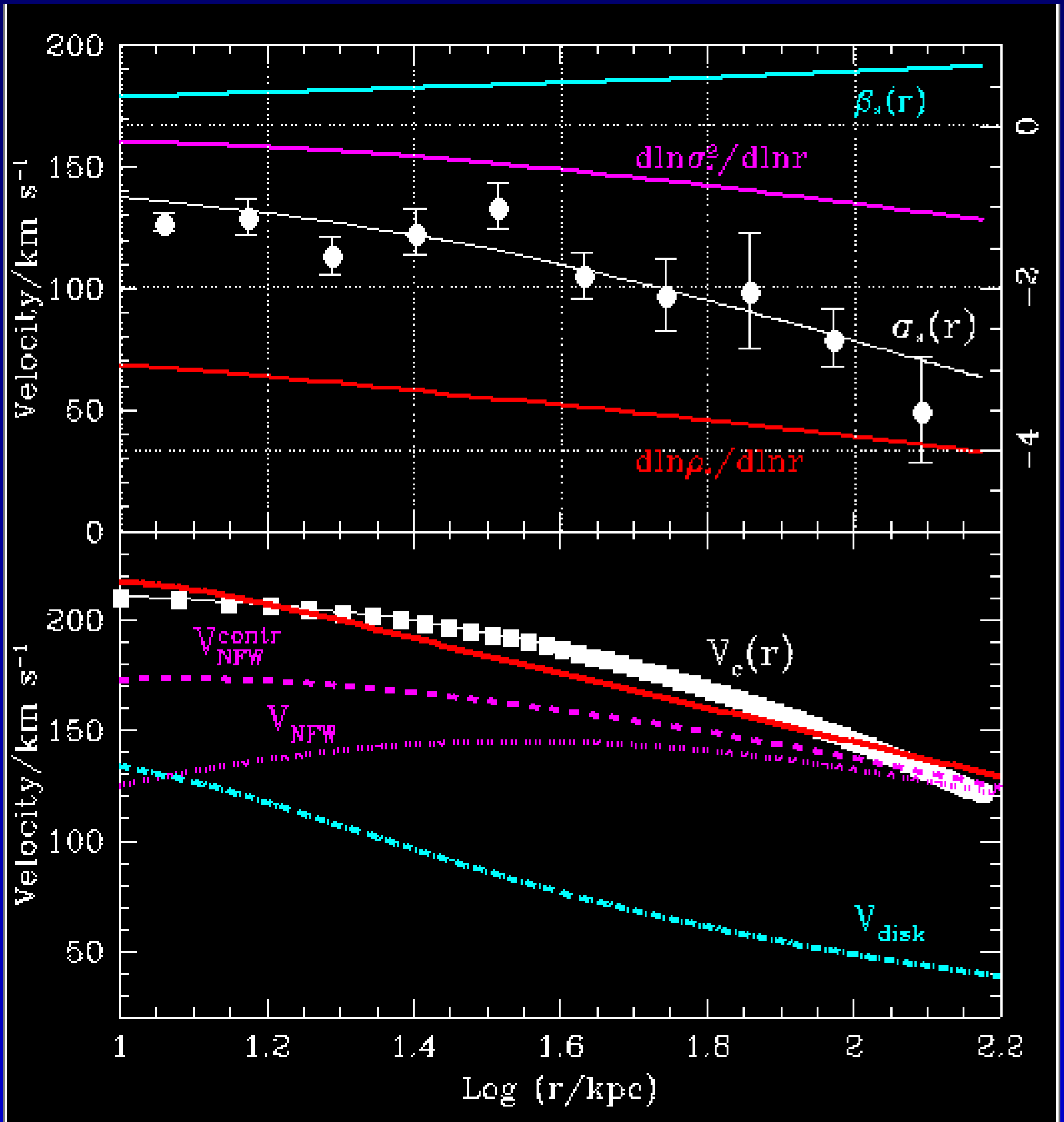


The velocity dispersion of halo tracers drops significantly in the outer regions of the Milky Way.

Traditional modeling of such data favors truncated dark matter halos

Battaglia et al 2005

The Mass of the Milky Way



- Combining our model for stellar halo with these data suggests that circular velocity of the Milky Way drops in the outer regions (V_{vir} ~ 110 km/s)

- The Milky Way halo might be much less massive than commonly assumed!
- ($7\text{-}8 \times 10^{11} M_{sun}$)

- How can we test this?➔ Escape velocity

Abadi, Navarro & Steinmetz 2005

The End