The Small Scale Structure of Cold Dark Matter

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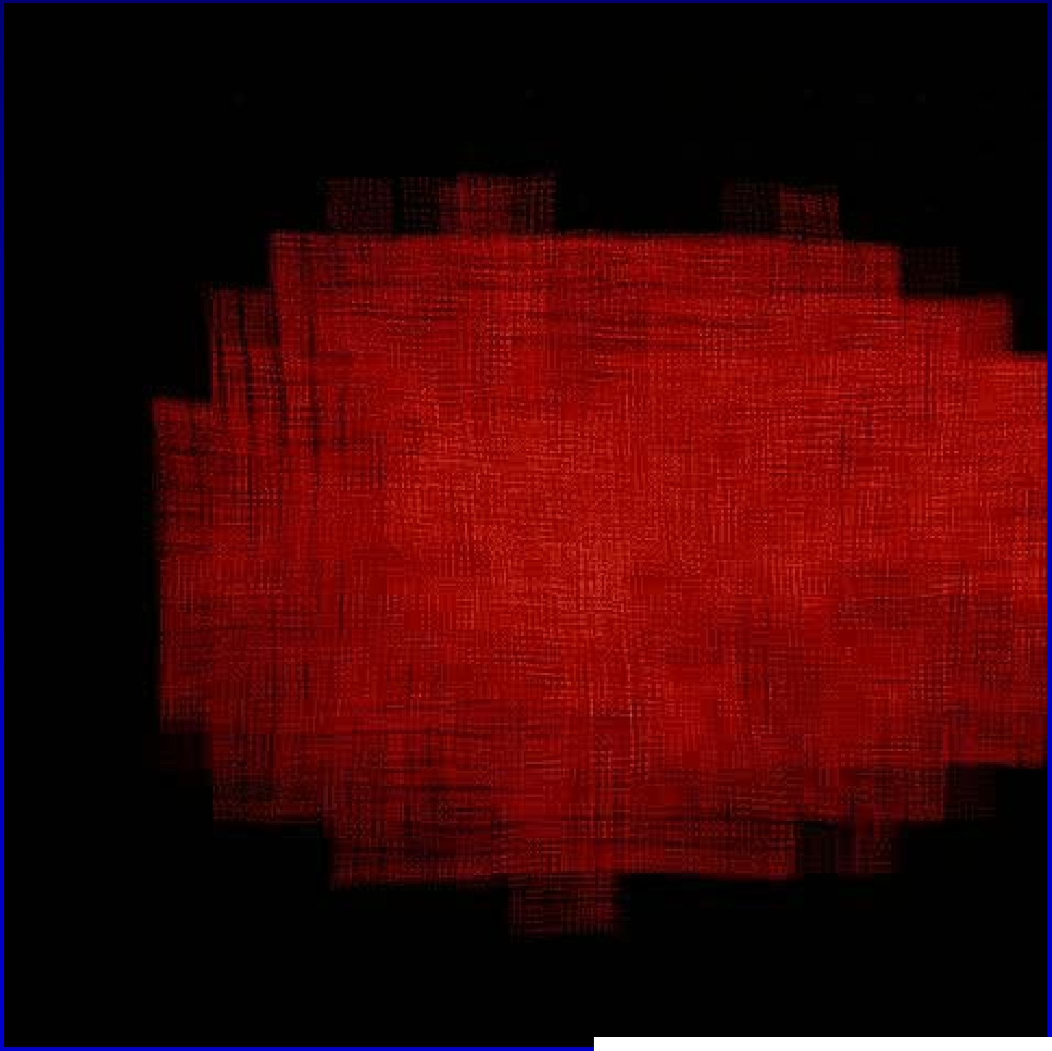
UVic

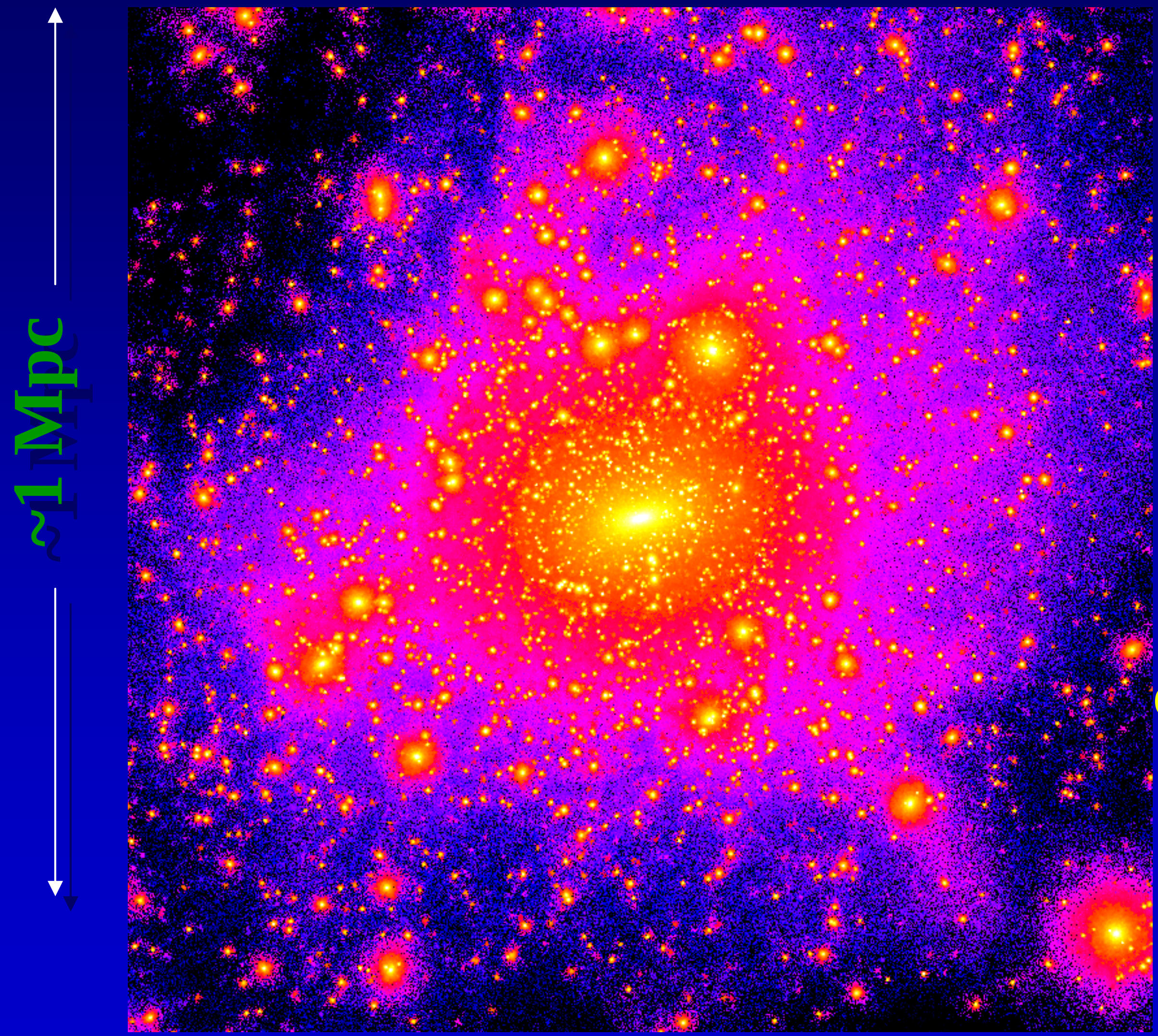
NSERC CRSNG

CIAR



The assembly of a LCDM halo

Dark Matter Halos:
The Hosts of Galaxy Systems in CDM Universes



Dark Matter only

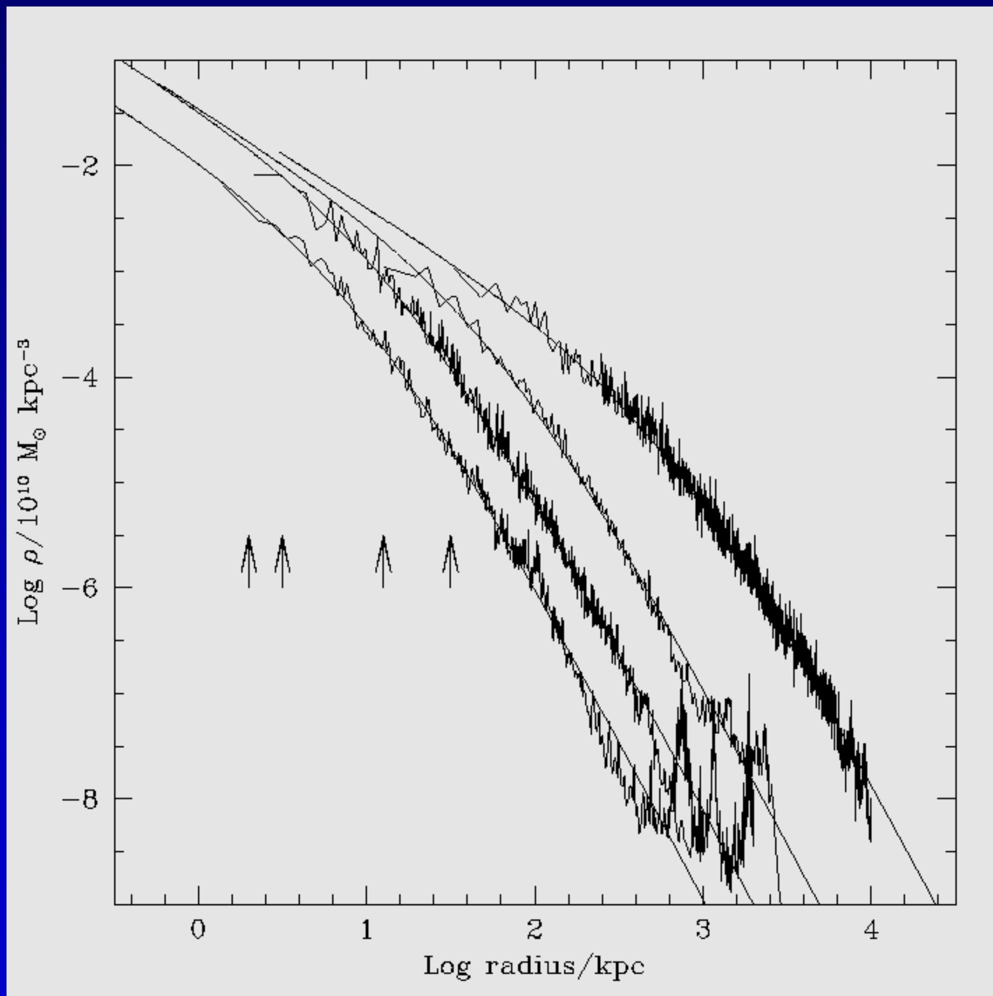
- Structure is formed from the bottom-up (i.e. small, dense halos collapse first)
- A substantial fraction of the mass is accreted through mergers.
- A significant amount of substructure remains in the halo at z~0.

The Structure of CDM halos

- CDM mass profiles are "universal":
  - their shape is independent of mass and cosmological parameters.
- CDM density profiles are "cuspy"
  - density increases inward down to the innermost resolved radius. No clear evidence for an asymptotic power-law behaviour near the center.
- CDM halos are "triaxial":
  - Substantial deviations from spherical symmetry are common, with inertia axial ratios often as high as b/a~0.75, c/a~0.5.
- CDM halos are "clumpy":
  - Roughly 10% of the mass is in the form of self-bound clumps; the cores of accreted satellites that have so far survived full tidal disruption.

Mass Profile of Cold Dark Matter halos

Density



Radius

- Density profiles clearly differ from power laws
- The profile is shallower than isothermal near the center
- There is no obvious density 'plateau' or 'core' near the center

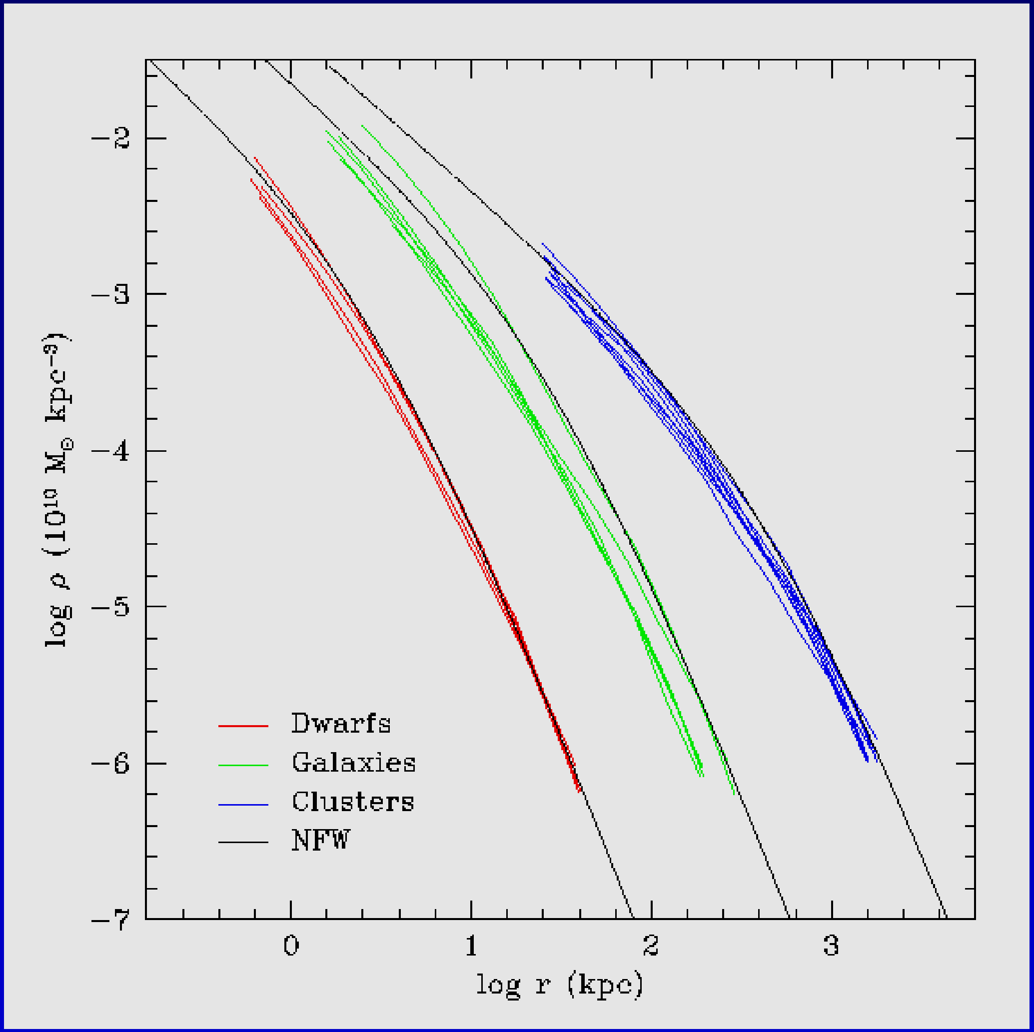
- Mass profiles of dark halos are independent of halo mass and cosmological parameters (Navarro, Frenk & White 1996, 1997)

- There has been some controversy about the inner mass slope, but now most simulators tend to agree (see Navarro et al 2004, Diemand et al 2004, Fukushige et al 2004)

$$\frac{\rho(r)}{\rho_{crit}} = \frac{\delta_c}{(r/r_s)(1+r/r_s)^2}$$

Navarro, Frenk & White 1996, 1997

Mass Profiles of ΛCDM halos



Density

Radius

- Simulations spanning ~6 decades in halo mass, from dwarf galaxies (V_c~ 50 km/s) to galaxy clusters (V_c~1000 km/s)

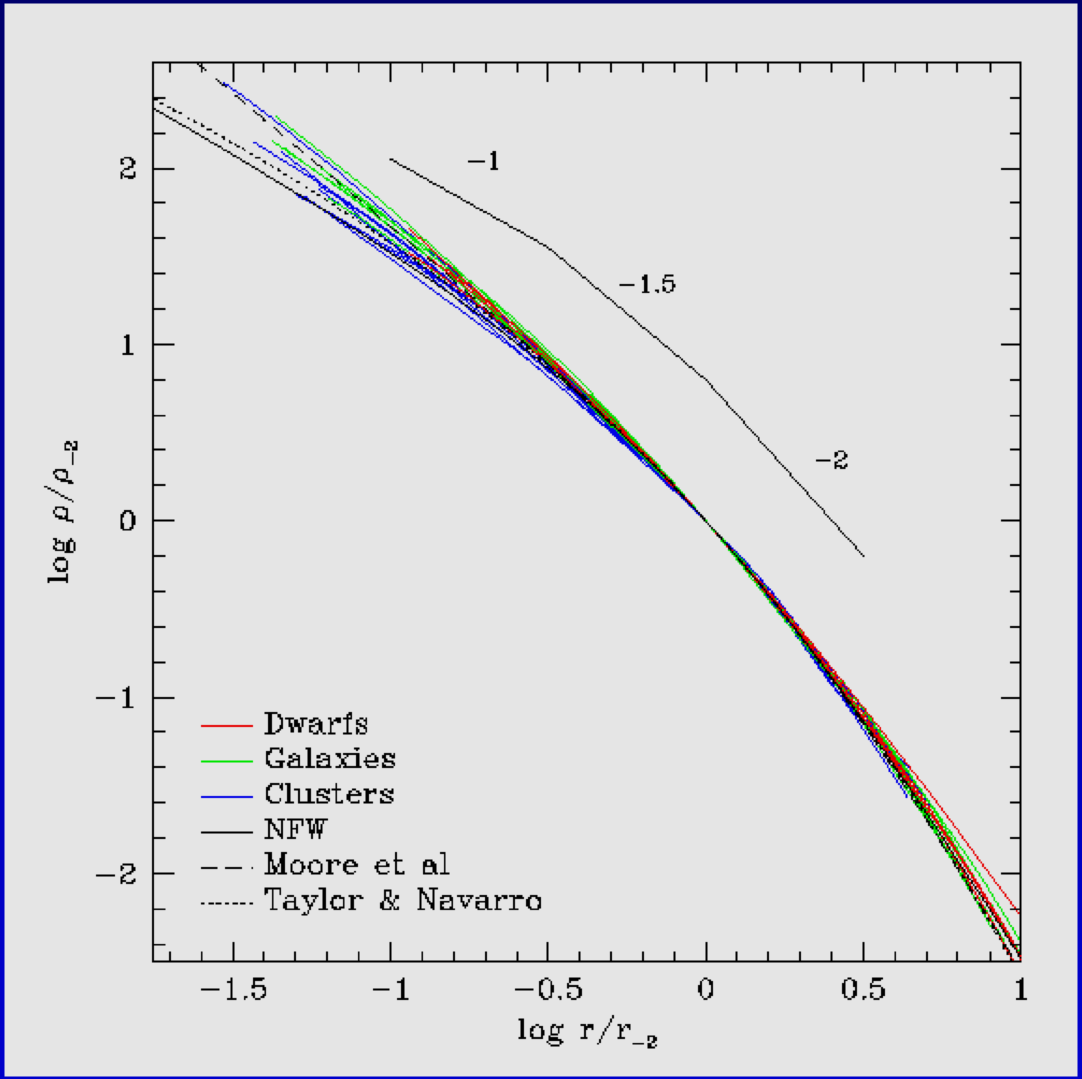
- Each simulation has of order a million particles within the virial radius (compare this with 10^4 for NFW)

- Well understood role of numerical effects through extensive convergence studies

Navarro et al 2004

The Universal Mass Profile of ΛCDM halos

Scaled Density



Scaled Radius

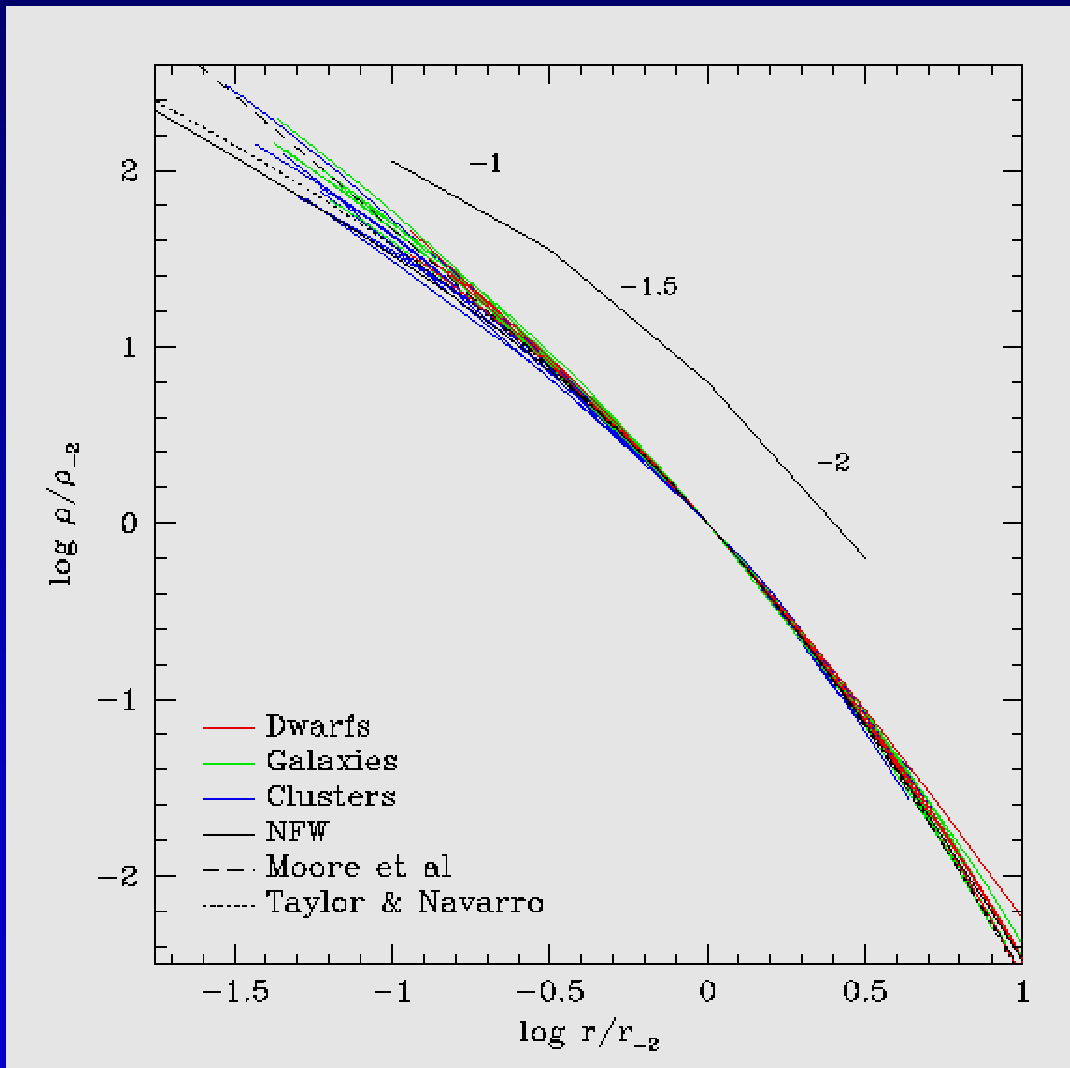
Properly scaled, all halos look alike: CDM halo structure appears to be approximately “universal”

Navarro et al 2004

The Central Cusp

The Universal Mass Profile of ΛCDM halos

Scaled Density



Scaled Radius

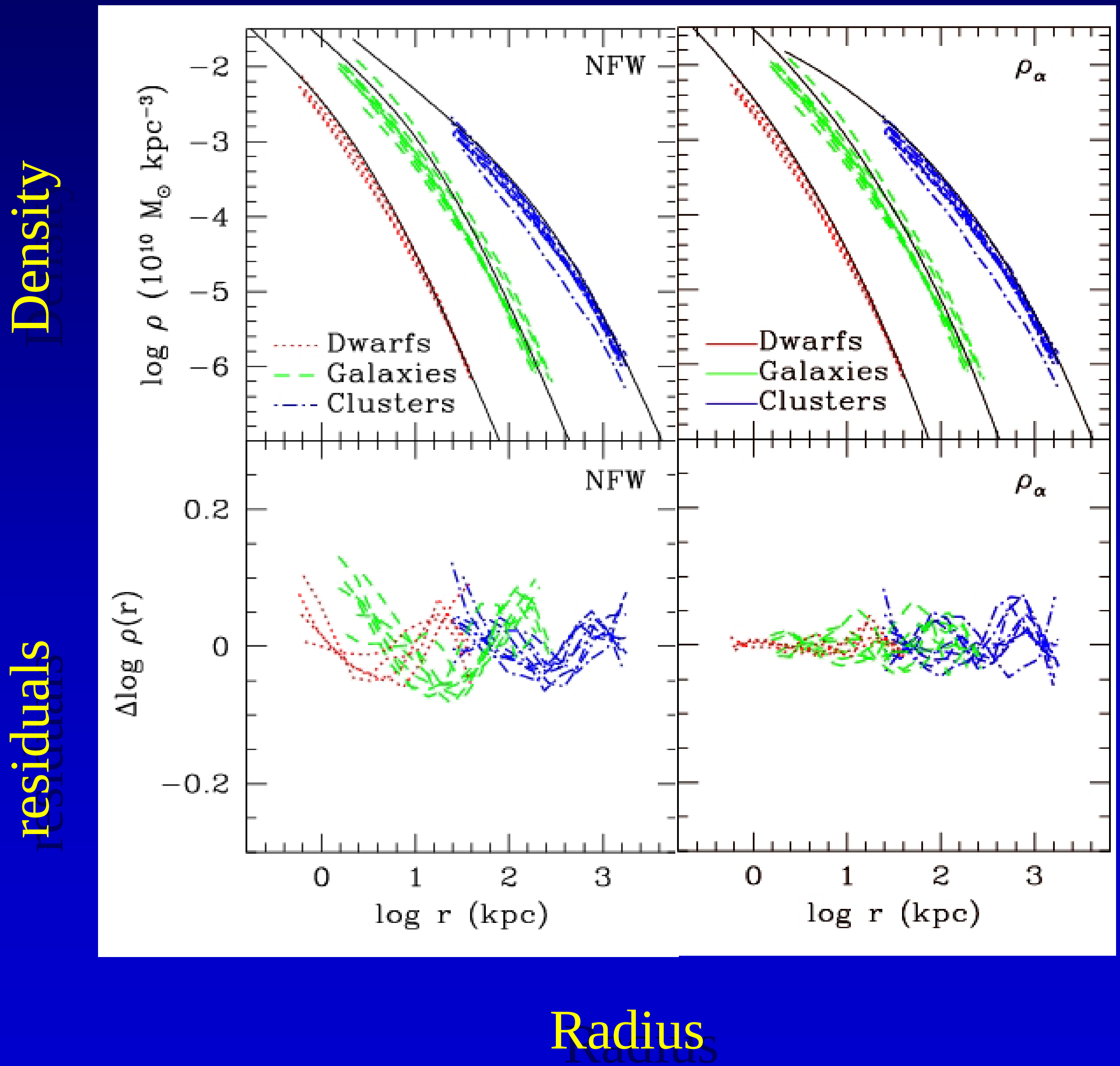
- Properly scaled, the structure of CDM halos appears to be approximately "universal"

- However, there is some genuine dispersion in profile shapes.

- Usually characterized by a "concentration" parameter: $c=r_{vir}/r_{-2}$

Navarro et al 2004

An improved fitting formula



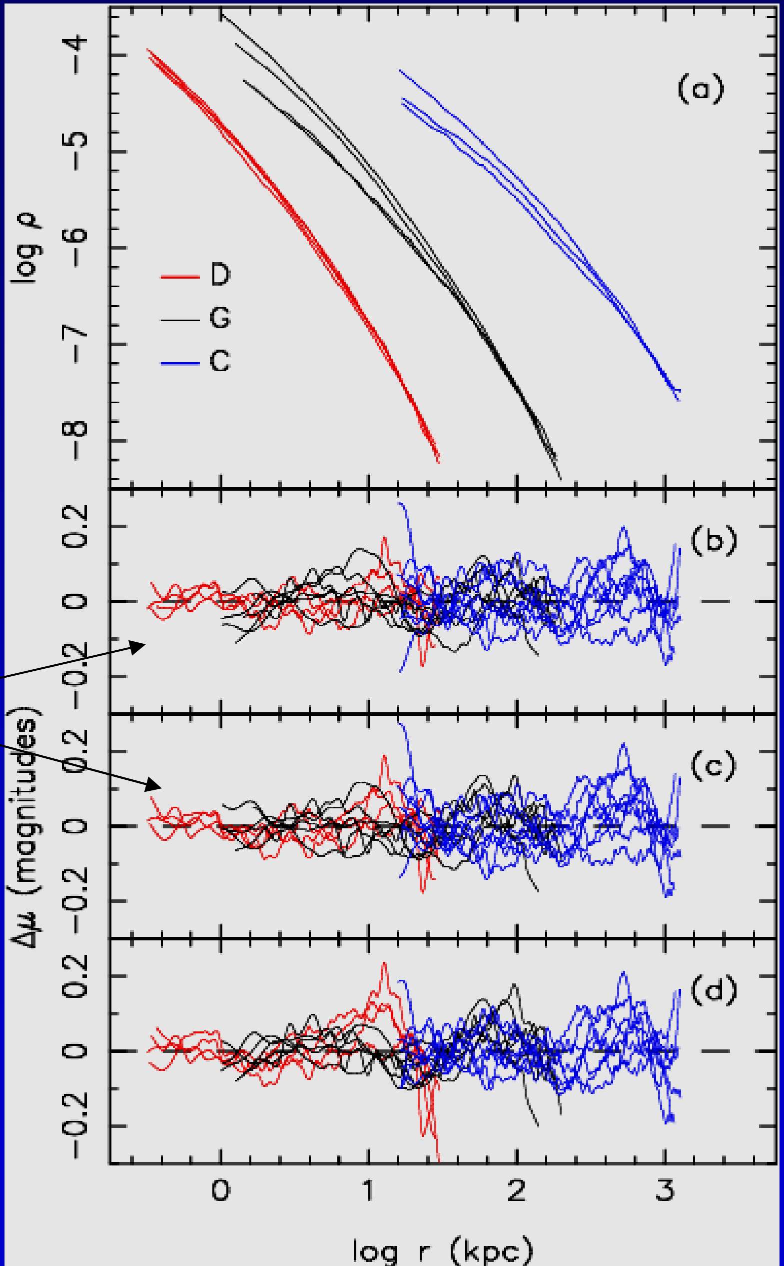
A law where the logarithmic slope of the density profile is a simple power-law of radius fits the dark halos to better than 5% at all radii.

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

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:

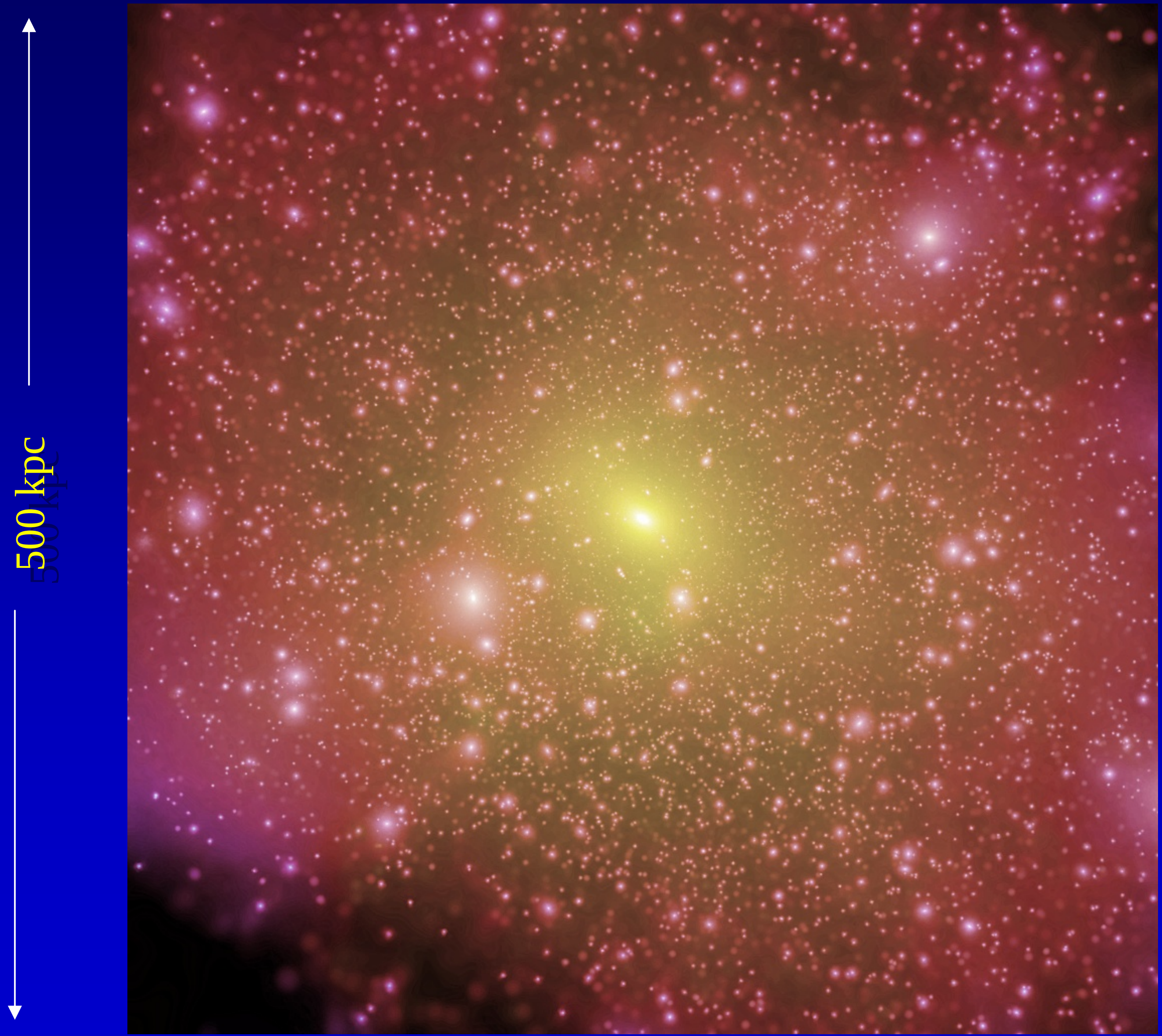
Sersic-law like profiles (no cusp)

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

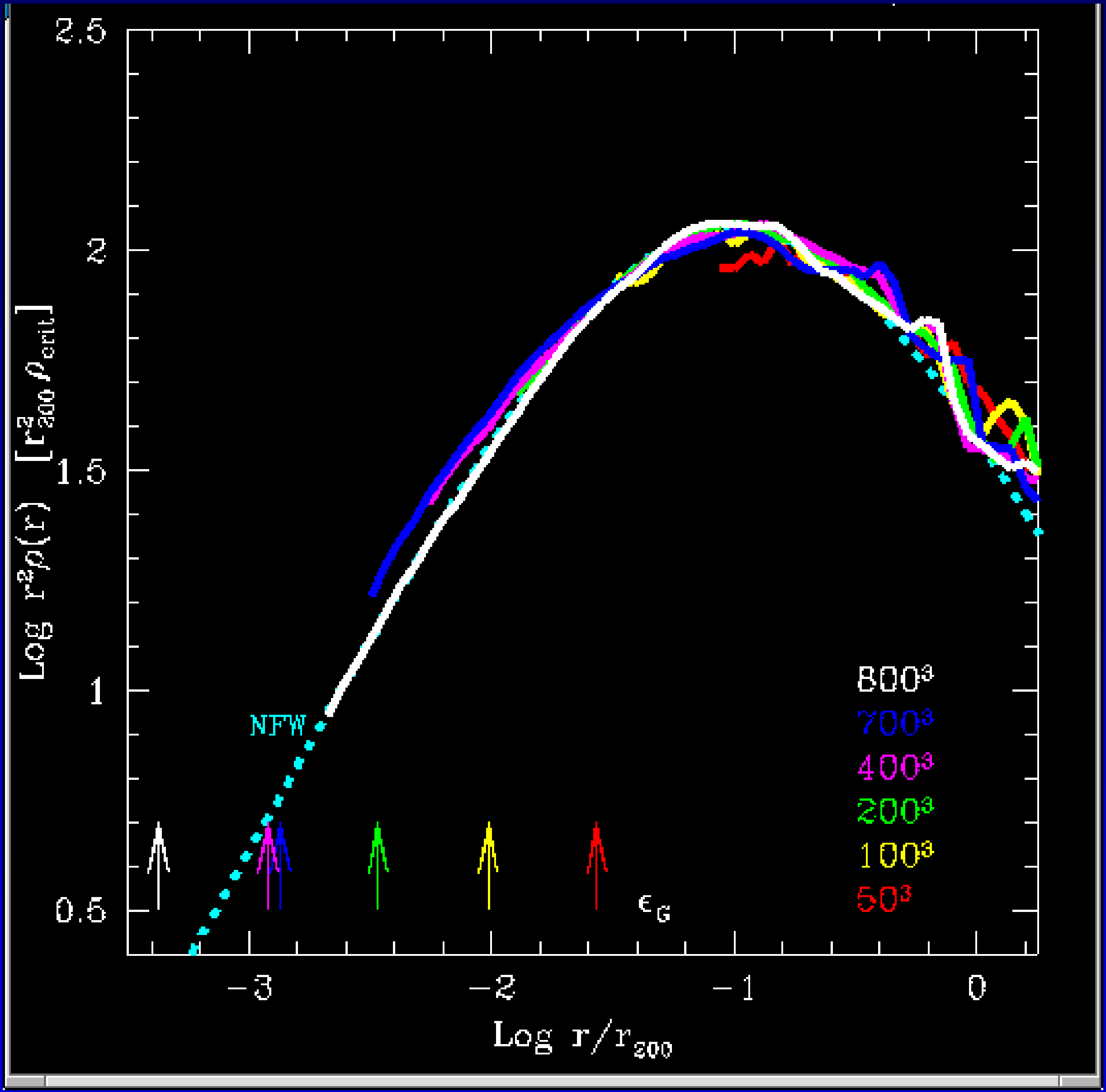
A 200-million particle CDM halo



The largest halo simulation in our series so far

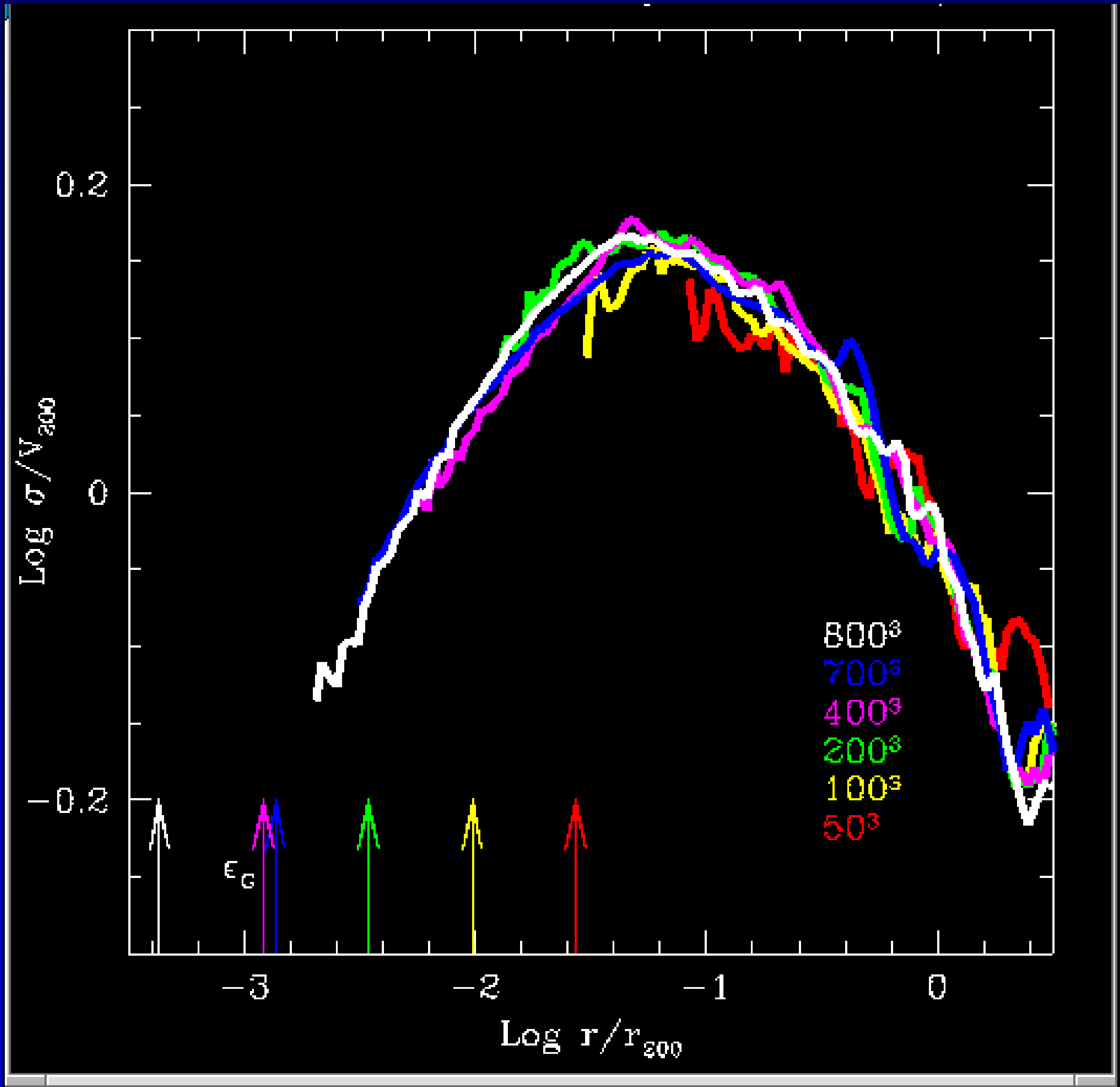
Play Movie

Density Profile



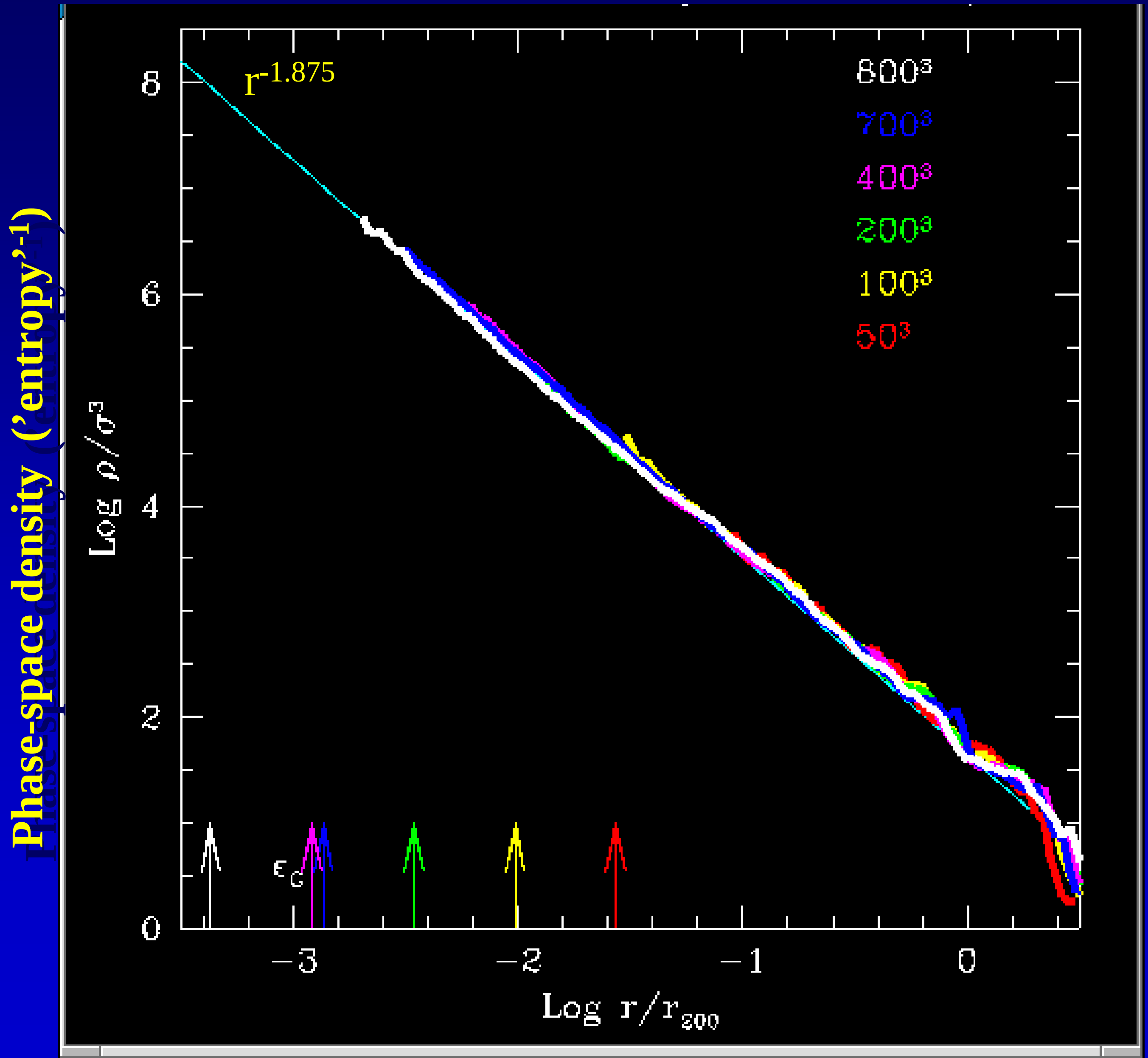
Density profile and best-fit NFW profile

Velocity Dispersion Profile of a CDM Halo



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

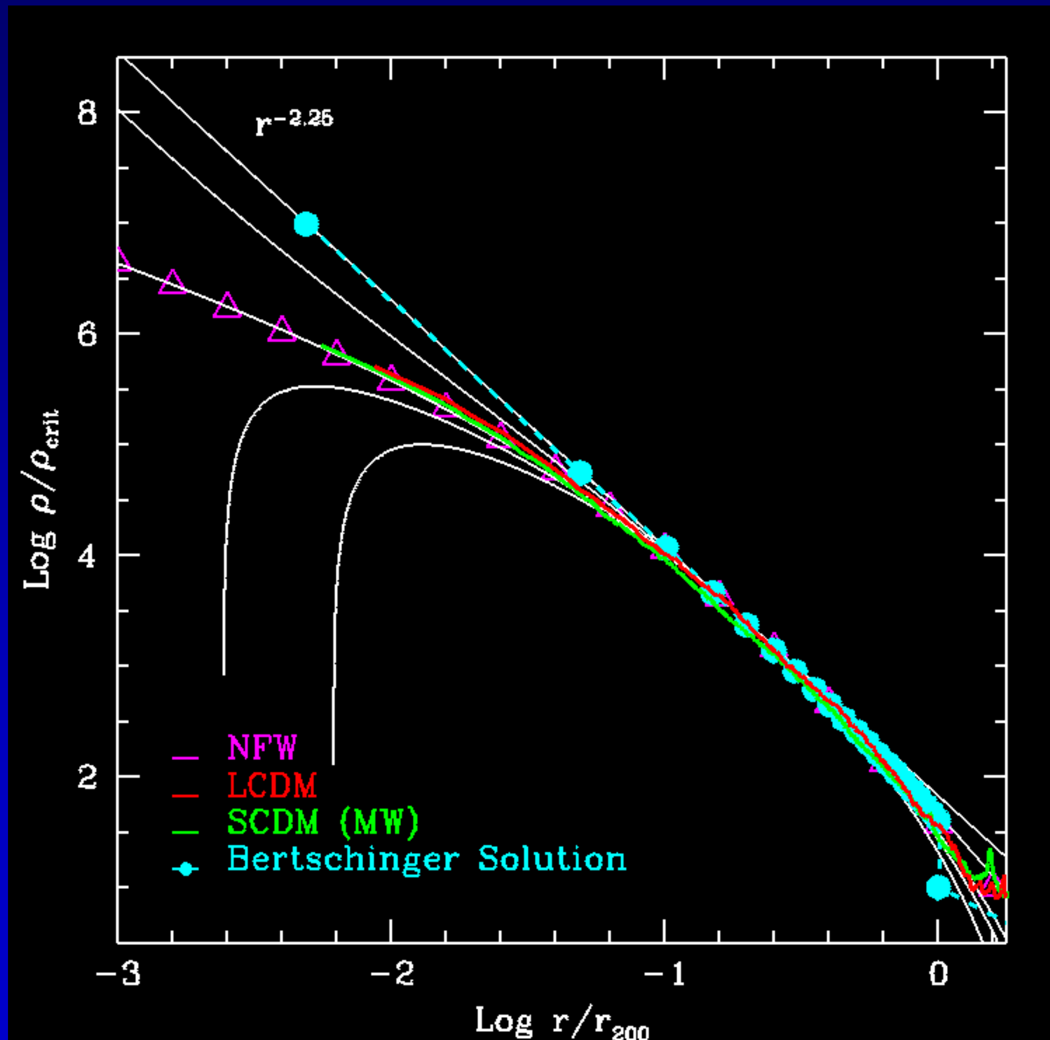
“Phase-Space Density” Profile



Phase-space density 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.

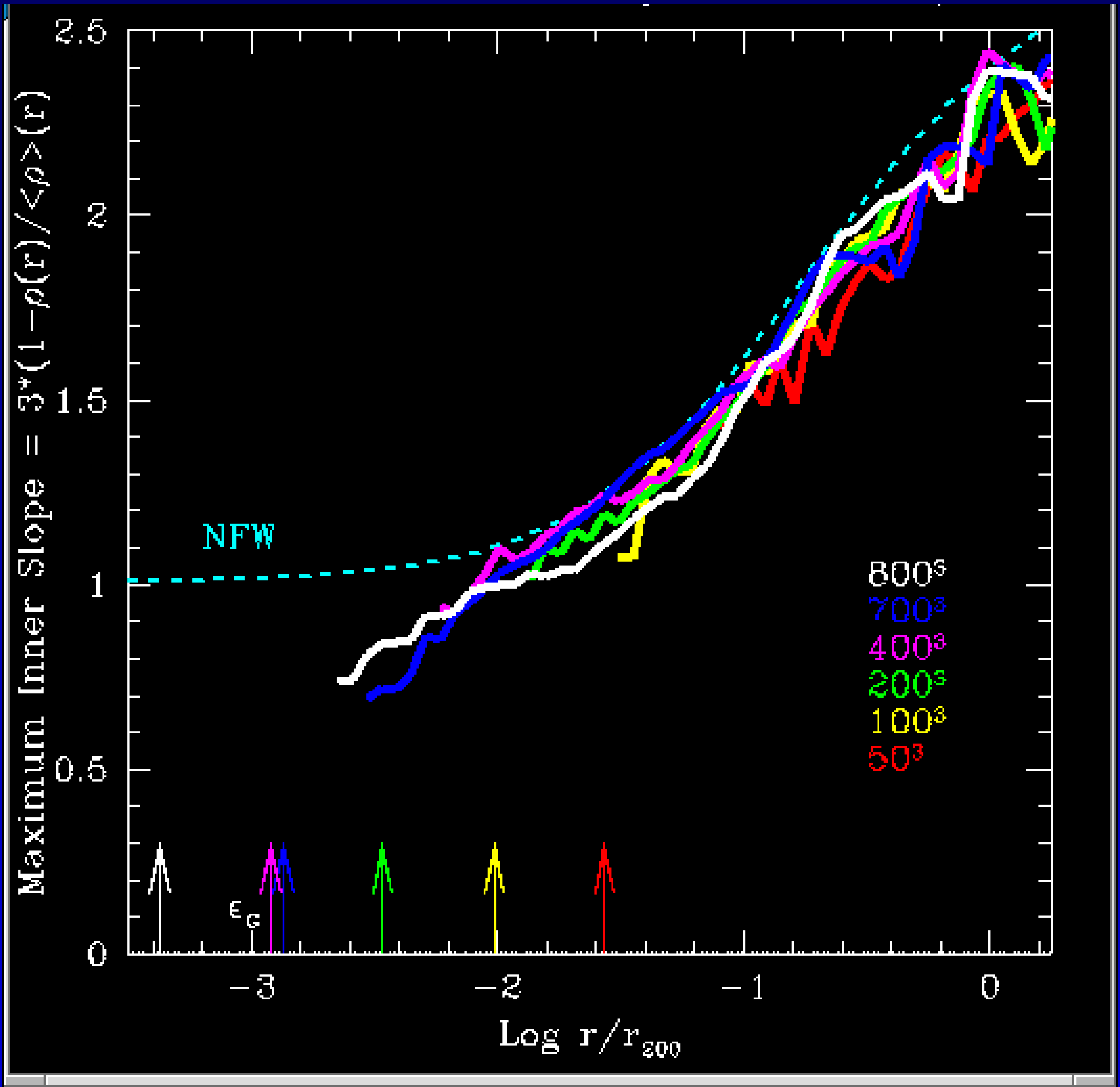
CDM density profiles appear to correspond to the minimum ‘pressure’ compatible with the radial entropy stratification of the spherical collapse model.

Example: the singular isothermal sphere ($\rho \sim r^{-2}$, σ=const.) may be recovered from Jeans’ equation and 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.

Innermost (asymptotic) slope in this case is -0.75

Taylor and Navarro 2001

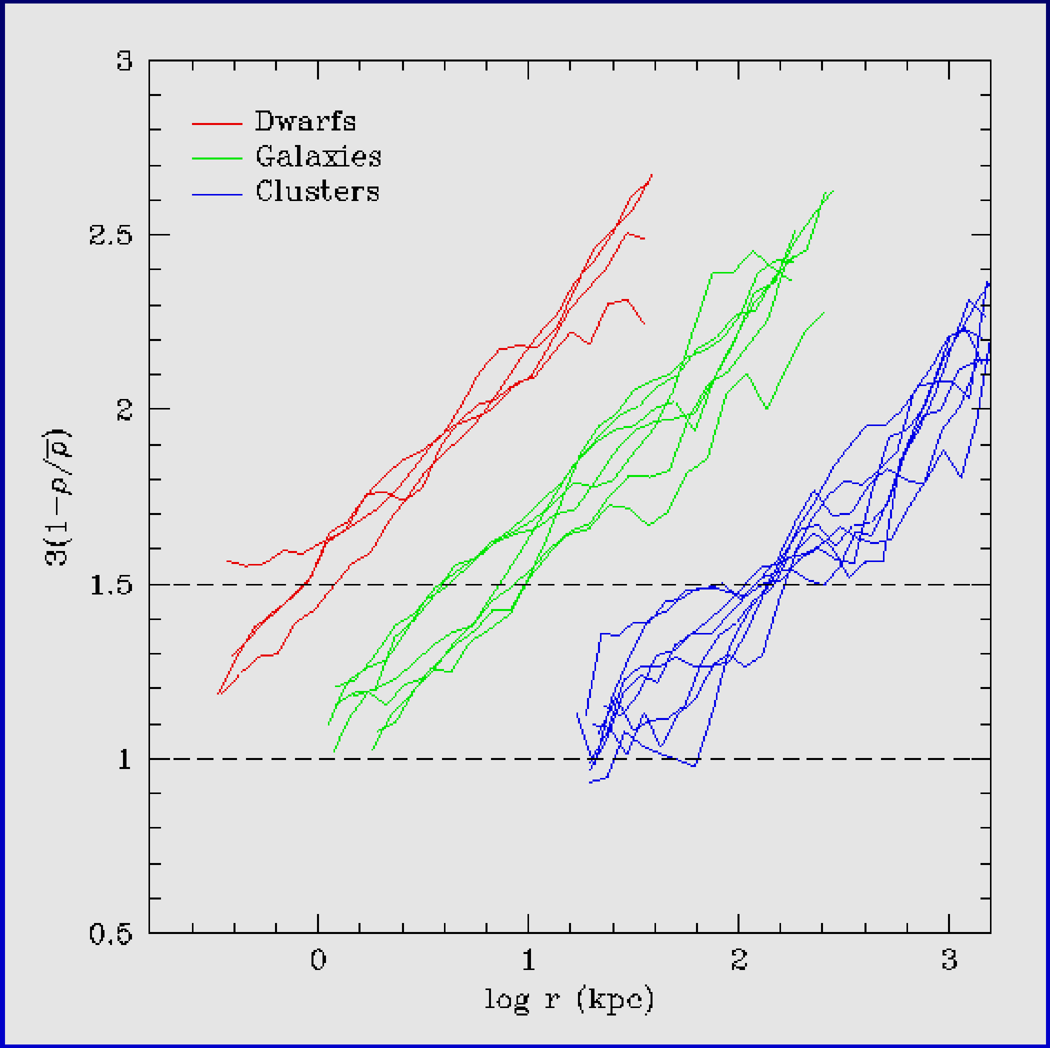
Maximum Innermost Slope of Central Cusp



- 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 Inner Cusp of CDM Halos

Maximum Asymptotic Inner Slope



Radius

- The total mass enclosed within a given radius is robustly measured in the simulations.
- Combined with the local density, it may be used to derive an upper limit to the inner asymptotic logarithmic slope
- There is not enough mass in the inner regions to sustain a power-law profile as steep as $\rho \sim r^{-1.5}$

Navarro et al 2004

Dark Matter annihilation

- If dark matter particle is Majorana, it may self-annihilate in high density regions and give rise to a detectable signal

$$F = \frac{N_\gamma \langle \sigma v \rangle}{2 m_{\rm DM}^2} \int_V \frac{\rho_{\rm DM}^2(\mathbf{x})}{4\pi d^2(\mathbf{x})}\, {\rm d}^3 x,$$

$$F = \frac{N_\gamma \langle \sigma v \rangle}{2 d^2 m_{\rm DM}^2} \int_0^{r_{200}} \rho_{\rm DM}^2(r) r^2 \, {\rm d}r,$$

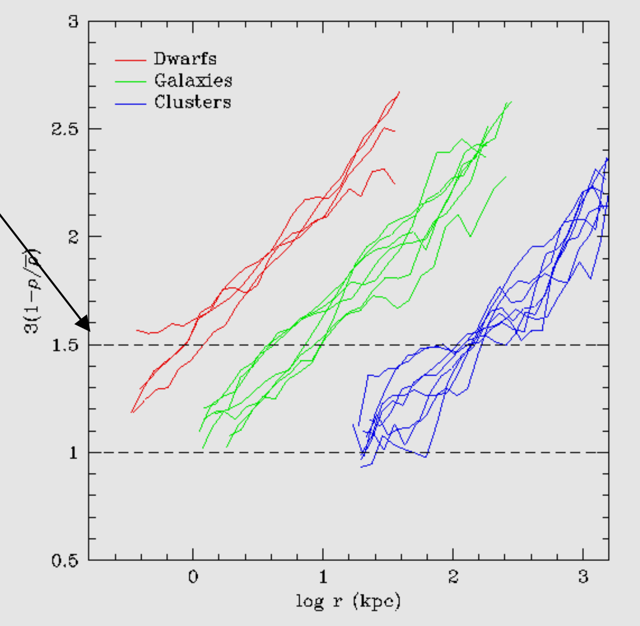
➔ this collision-driven process is highly dependent on the central properties of the halo

➔ for a smooth halo, most of the flux will come from the region where $\rho \sim r^{-1.5}$ (indeed, it formally diverges for cusps this steep)

➔ for galactic halos, this happens at moderately large radius (~3-5 kpc)

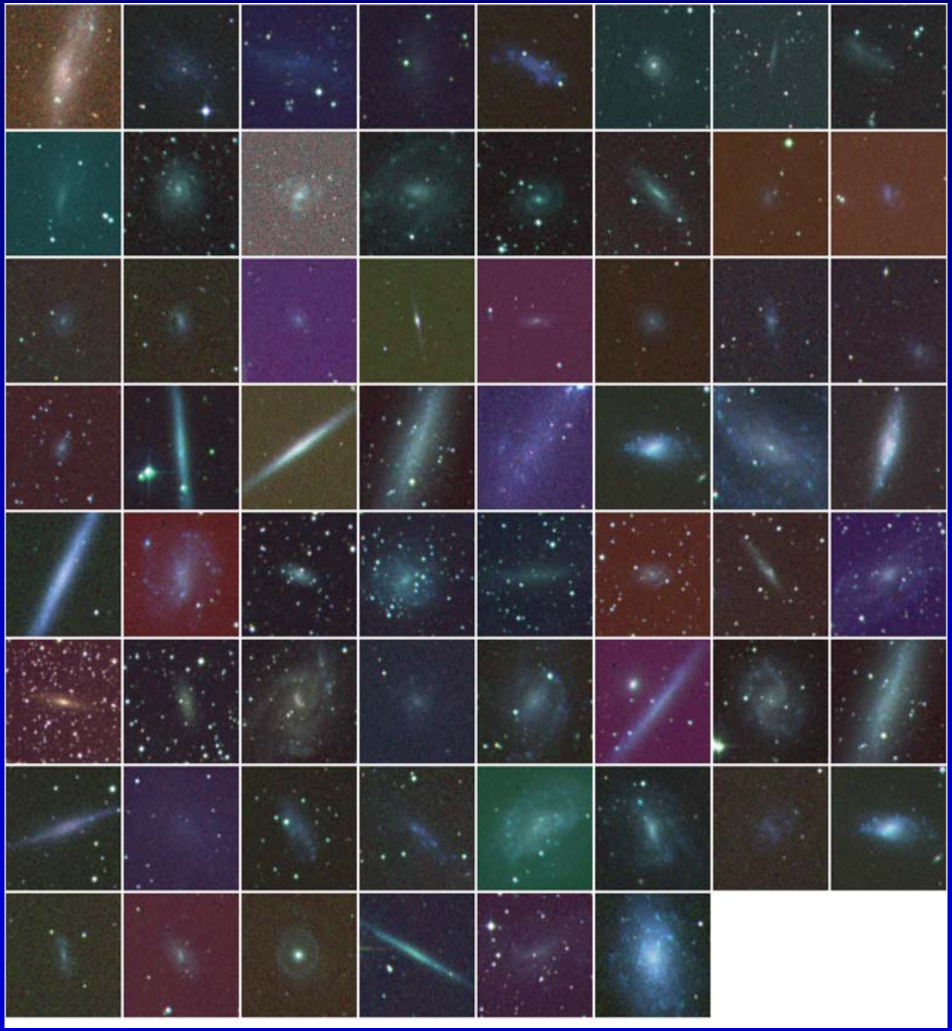
➔ This implies that annihilation signal is predicted be extended, and not point-like

➔ It should have a sharp upper energy cutoff: the rest-mass energy of the particle



The Shapes of Galactic Halos and LSB rotation curves

Cusps versus Cores: The Rotation Curves of Low Surface Brightness Galaxies

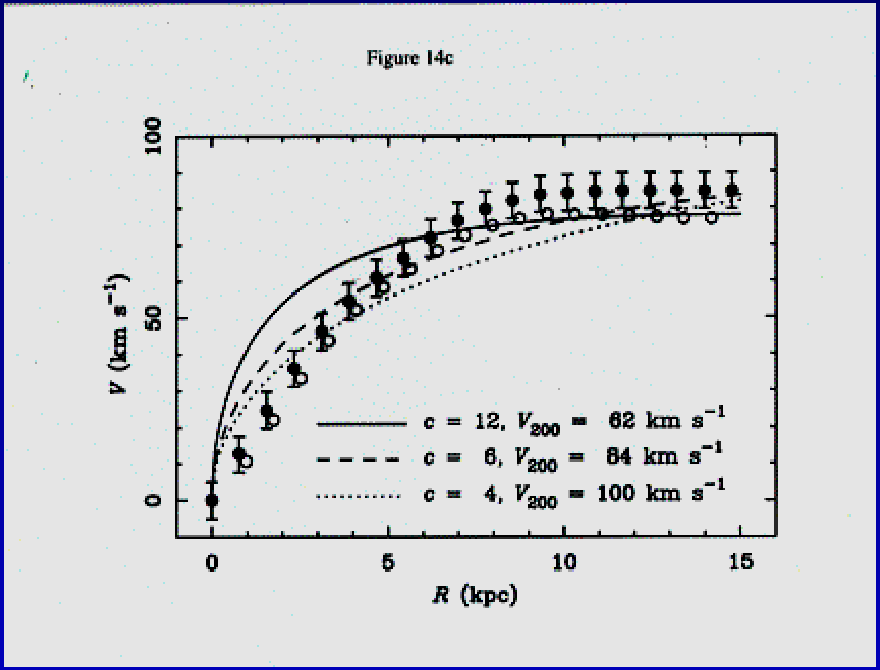


- Compare dwarf- and galaxy-sized halo circular velocity (V_C) profiles with rotation curves of dark matter-dominated LSB galaxies
- Rotation curve datasets of
de Blok et al (2001) (B01),
de Blok & Bosma (2002) (B02),
and Swaters et al (2003) (S03)
- Peak velocities range from 25 km/s to 270 km/s

LSB rotation curves and CDM halos

•The shape of some LSB galaxy rotation curves is inconsistent with the circular velocity curves of CDM halos.

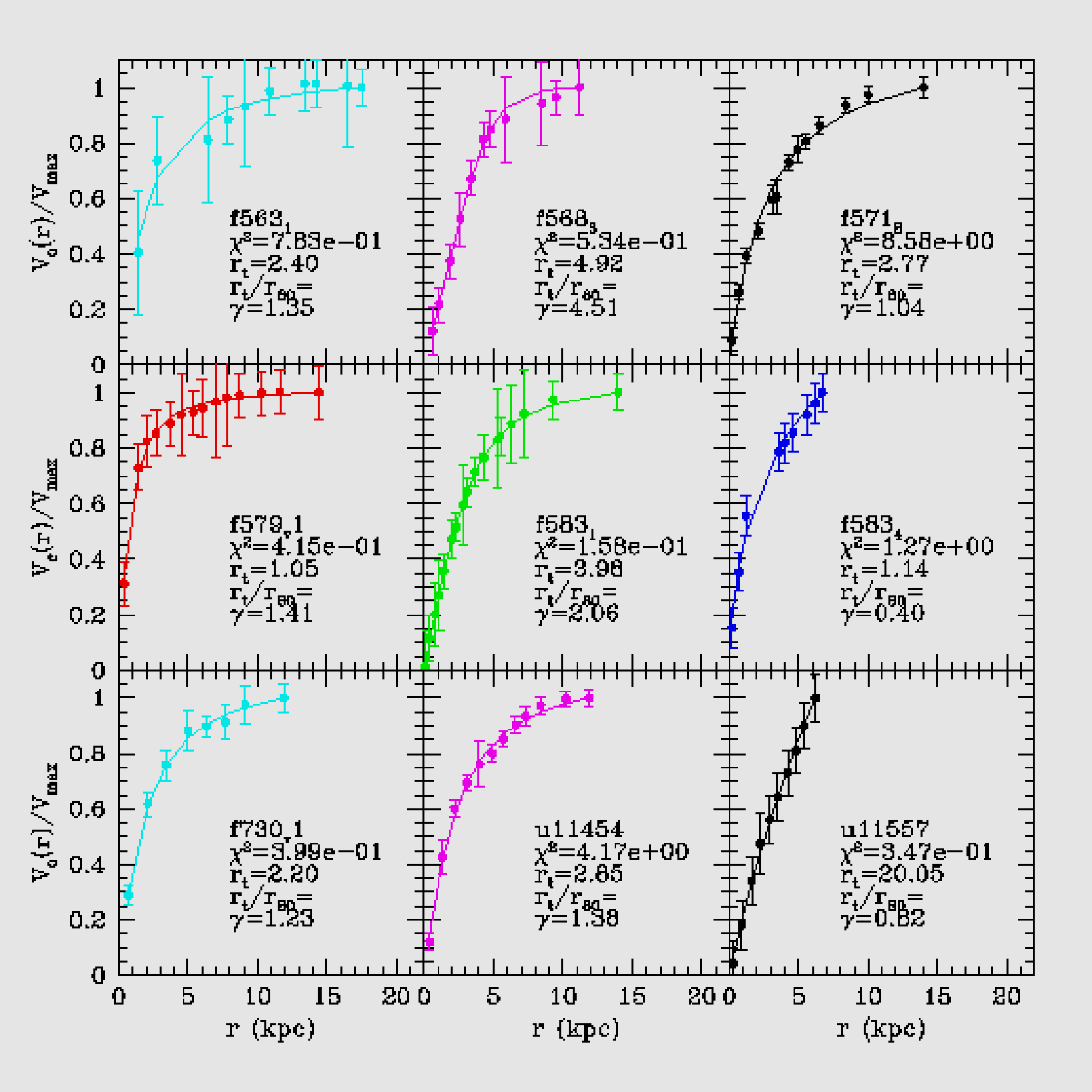
•Strictly, the disagreement is between gas rotation speeds and halo circular velocities. These two may be different if halo is not spherical, or if velocity dispersion of the gas is important, etc.



McGaugh & de Block 1998
see also Moore 1994
Flores & Primack 1994

LSB rotation curves (McGaugh et al sample)

Rotation Speed

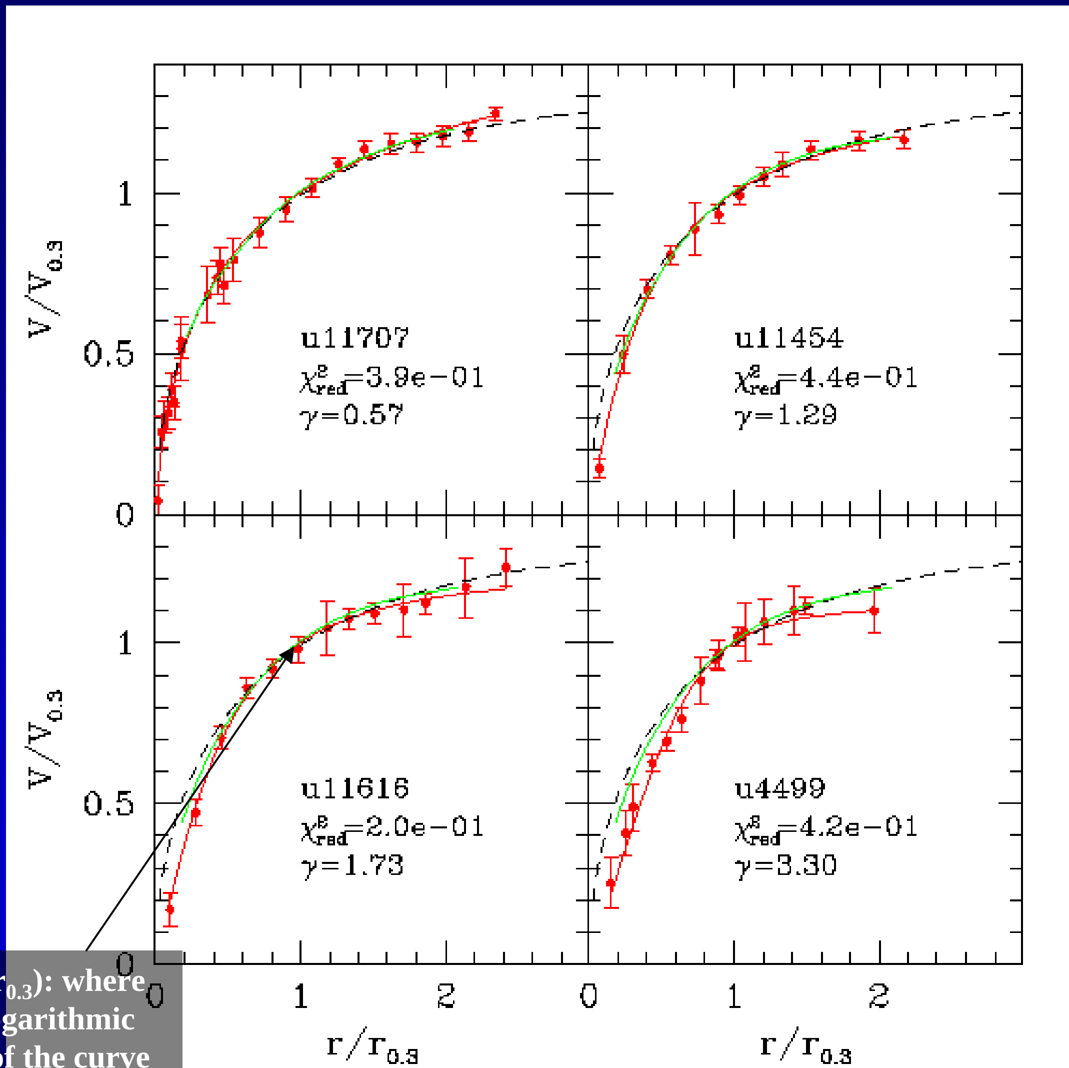


Radius

- The shape of the rotation curves varies significantly from galaxy to galaxy
- Let us characterize them with a simple formula: $V_c(r)=V_0\,(1+(r/r_t)^{-\gamma})^{-1/\gamma}$
- The parameter γ is a good indicator of the shape of the rotation curve

Hayashi et al 2003

Scaled LSB rotation curves: a representative sample



Rotation Speed

Radius

($V_{0.3}$,$r_{0.3}$): where the logarithmic slope of the curve is 0.3

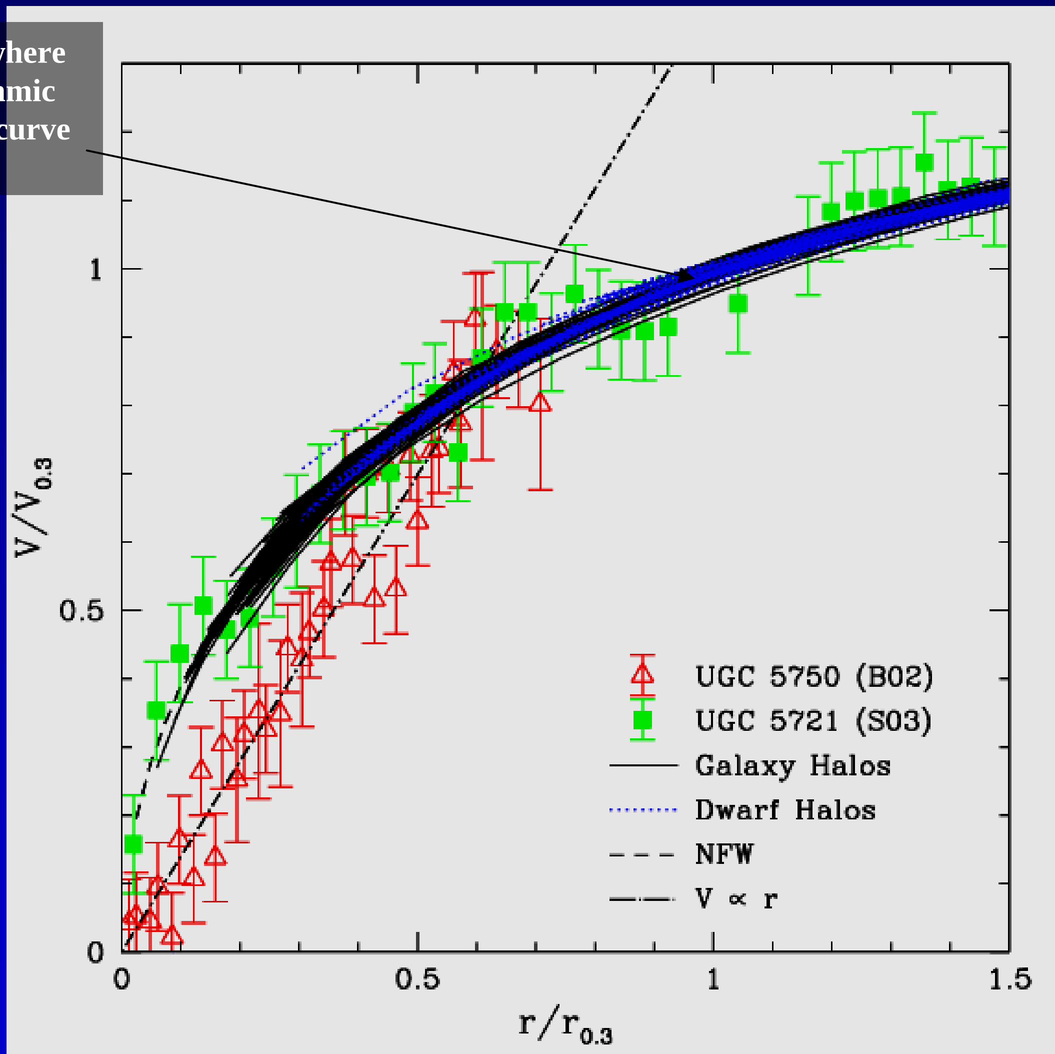
- About 3/4 of LSB rotation curves have **0.5<γ<2** (these are reasonably well fitted by CDM halos)
- The rest have **γ>>2** (in disagreement with CDM halos)

Hayashi et al 2003

Scaled LSB rotation curves

($V_{0.3}$,$r_{0.3}$): where the logarithmic slope of the curve is 0.3

Rotation Speed

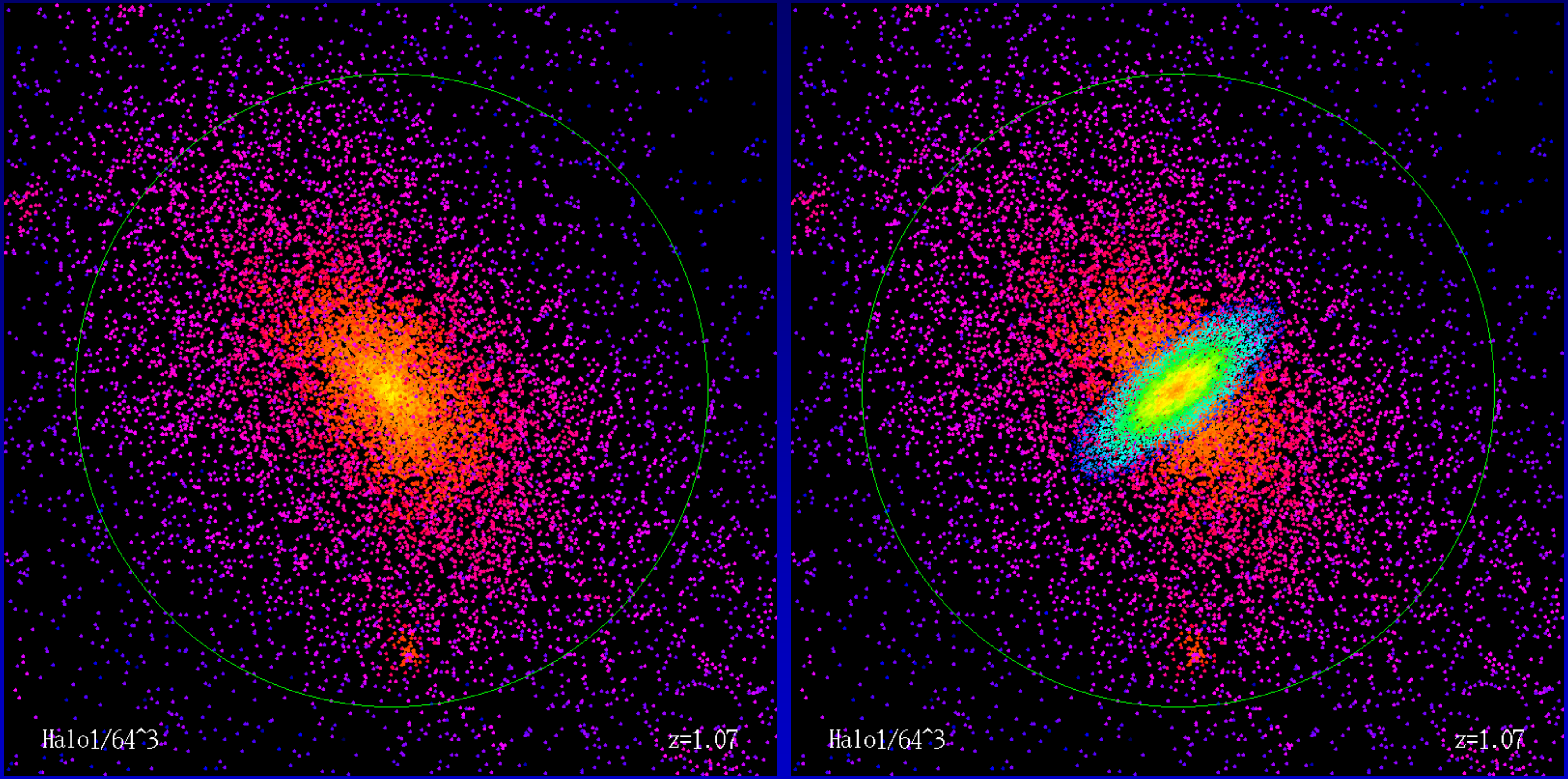


Radius

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

Hayashi et al 2003

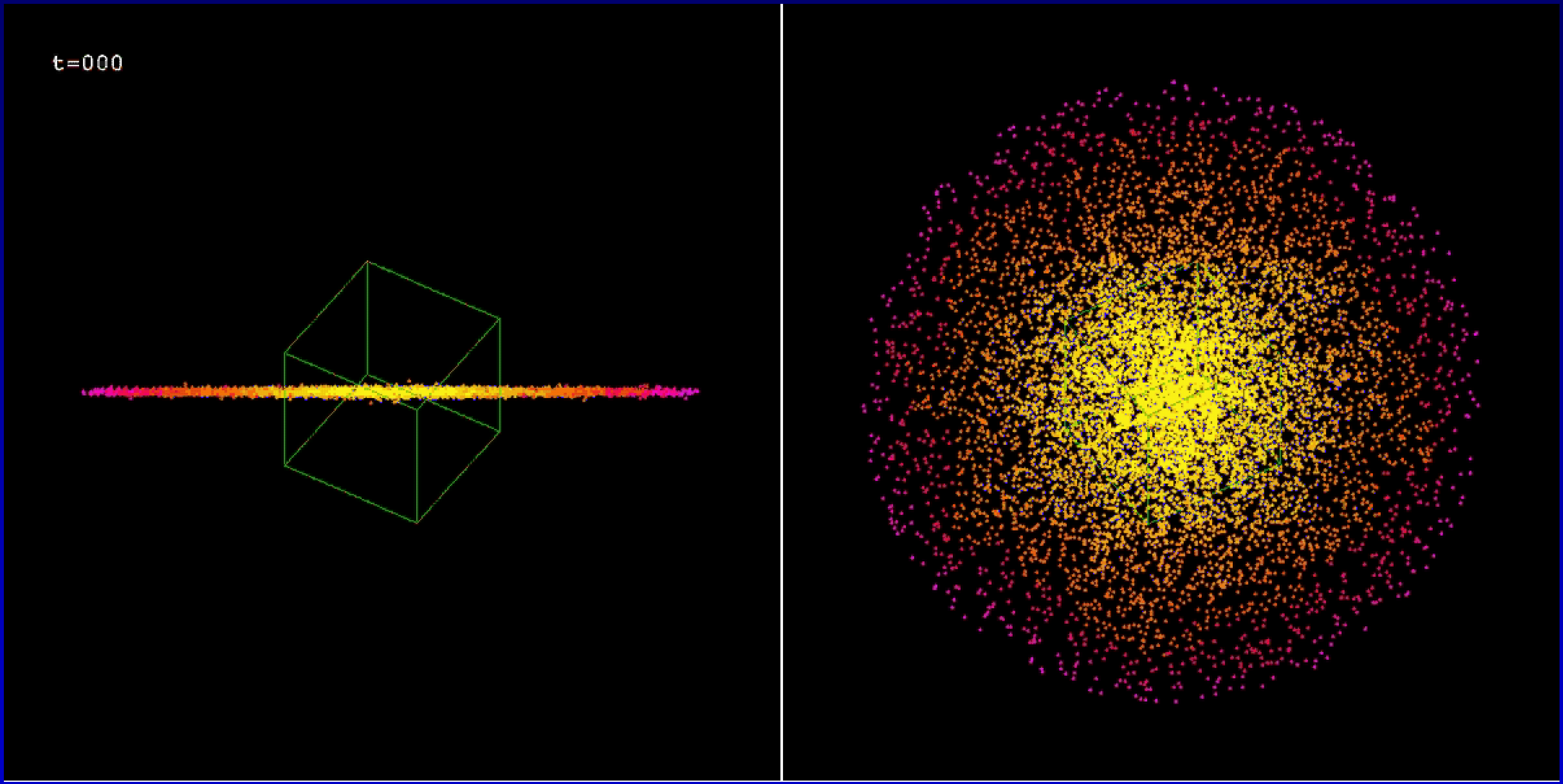
Disks in realistic dark matter halos



•Massless isothermal gaseous disk in the DM halo potential tracks the closed orbits within this non-spherical potential

Hayashi et al 2004

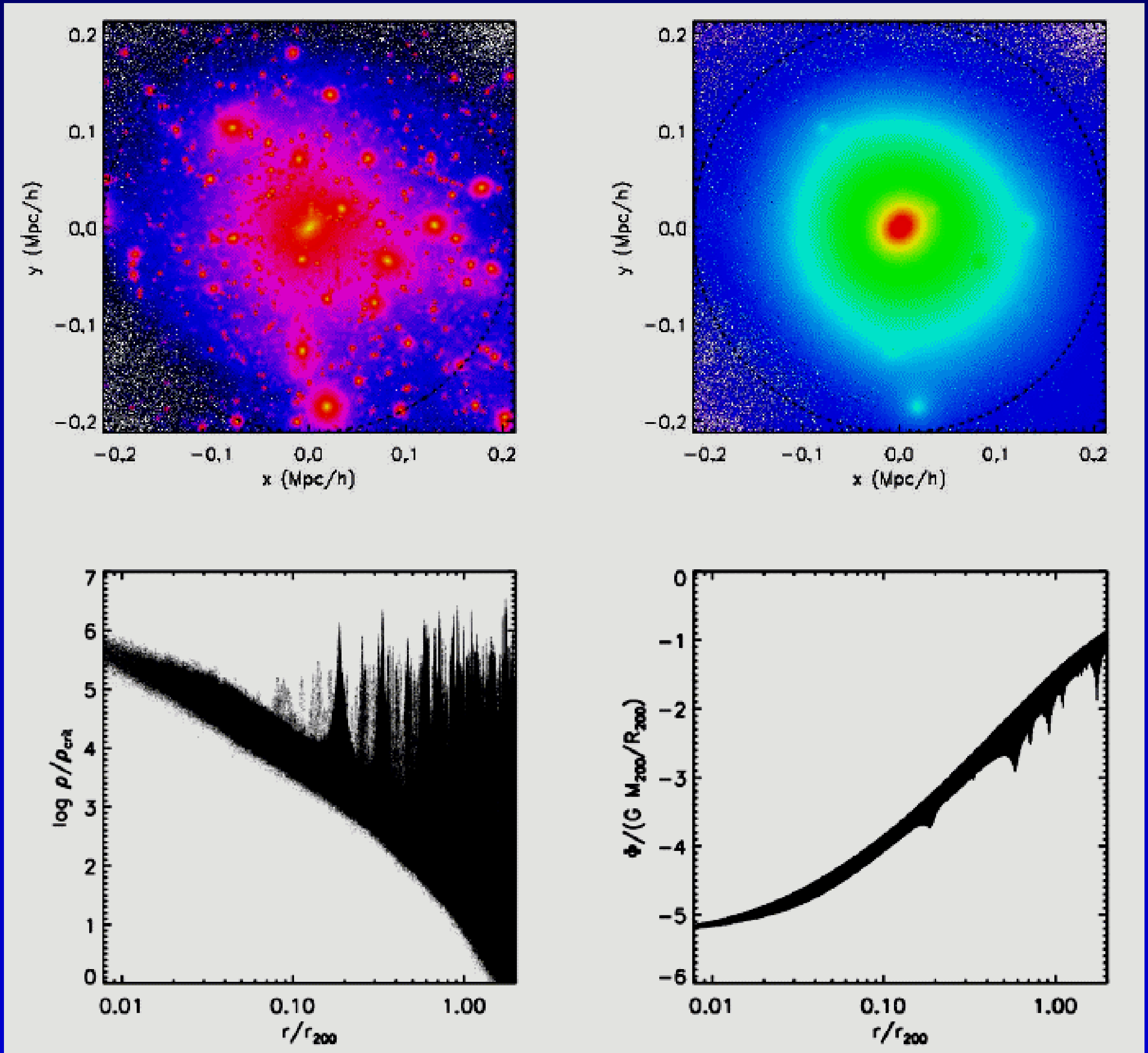
Disks in realistic dark matter halos



- Massless isothermal gaseous disk in the DM halo potential

Hayashi et al 2004

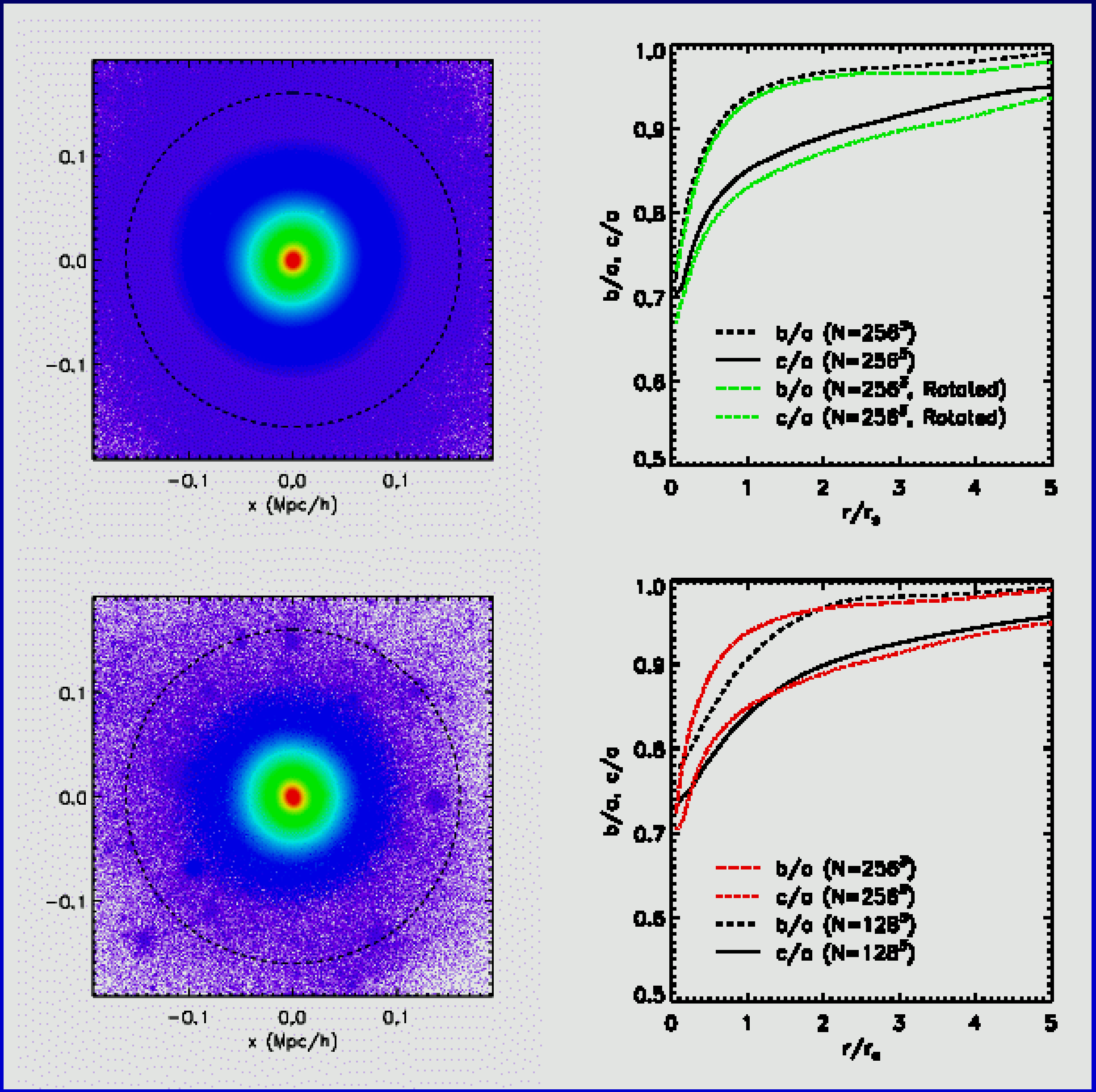
Halo shapes: density vs potential



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

Hayashi et al 2006

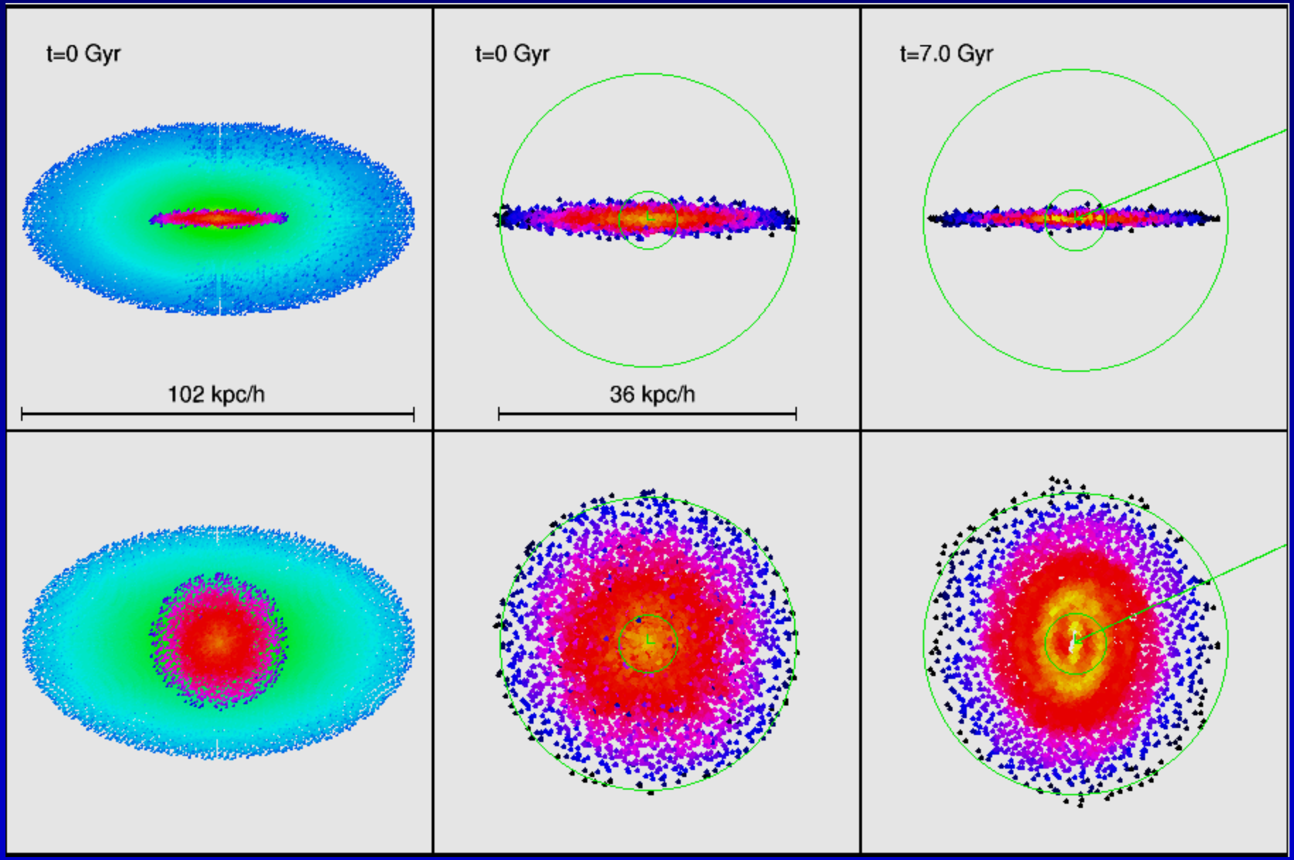
Radial Dependence of Halo Shape



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

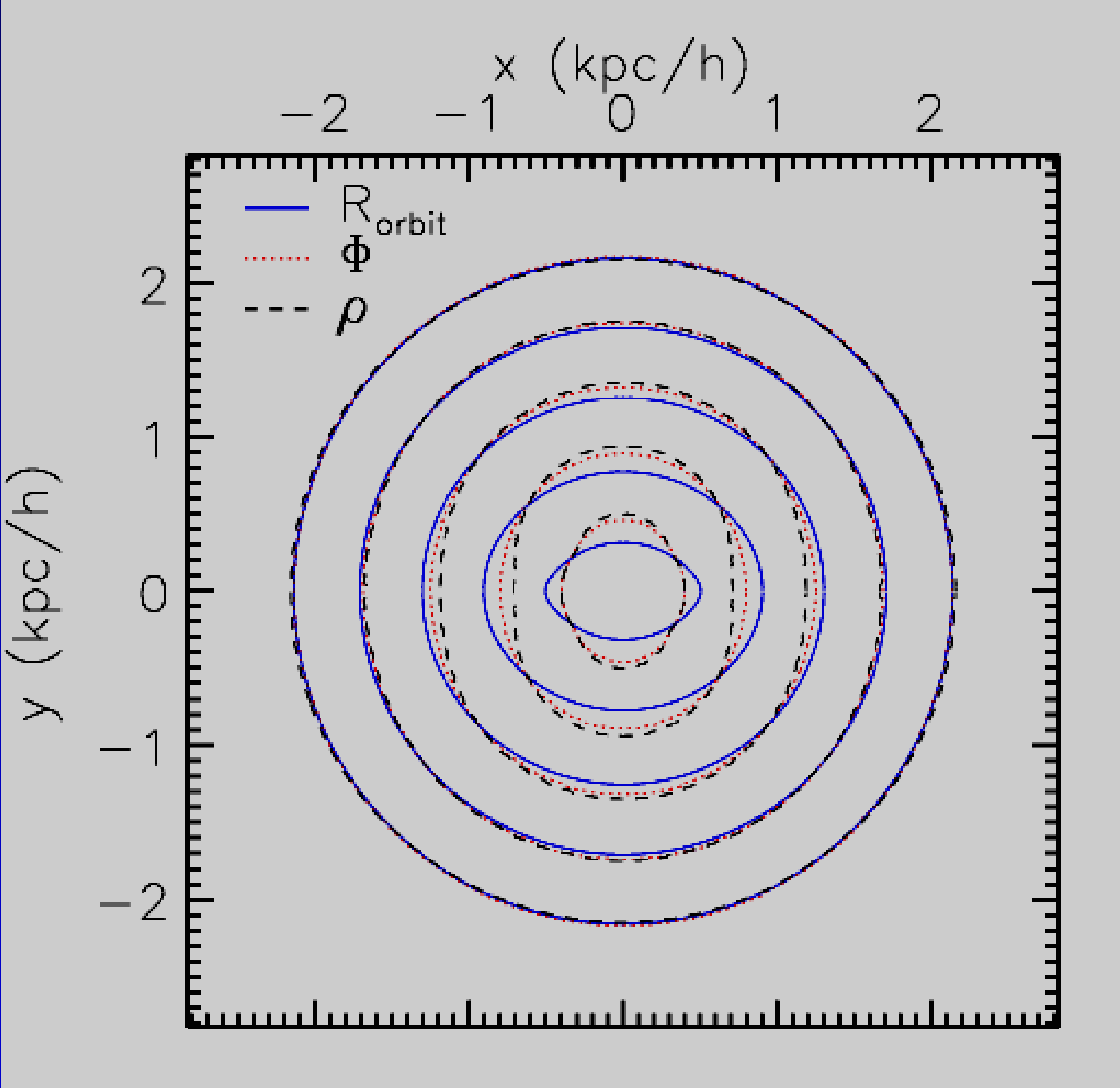
- Angular momentum tends to be perpendicular to major axis

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:

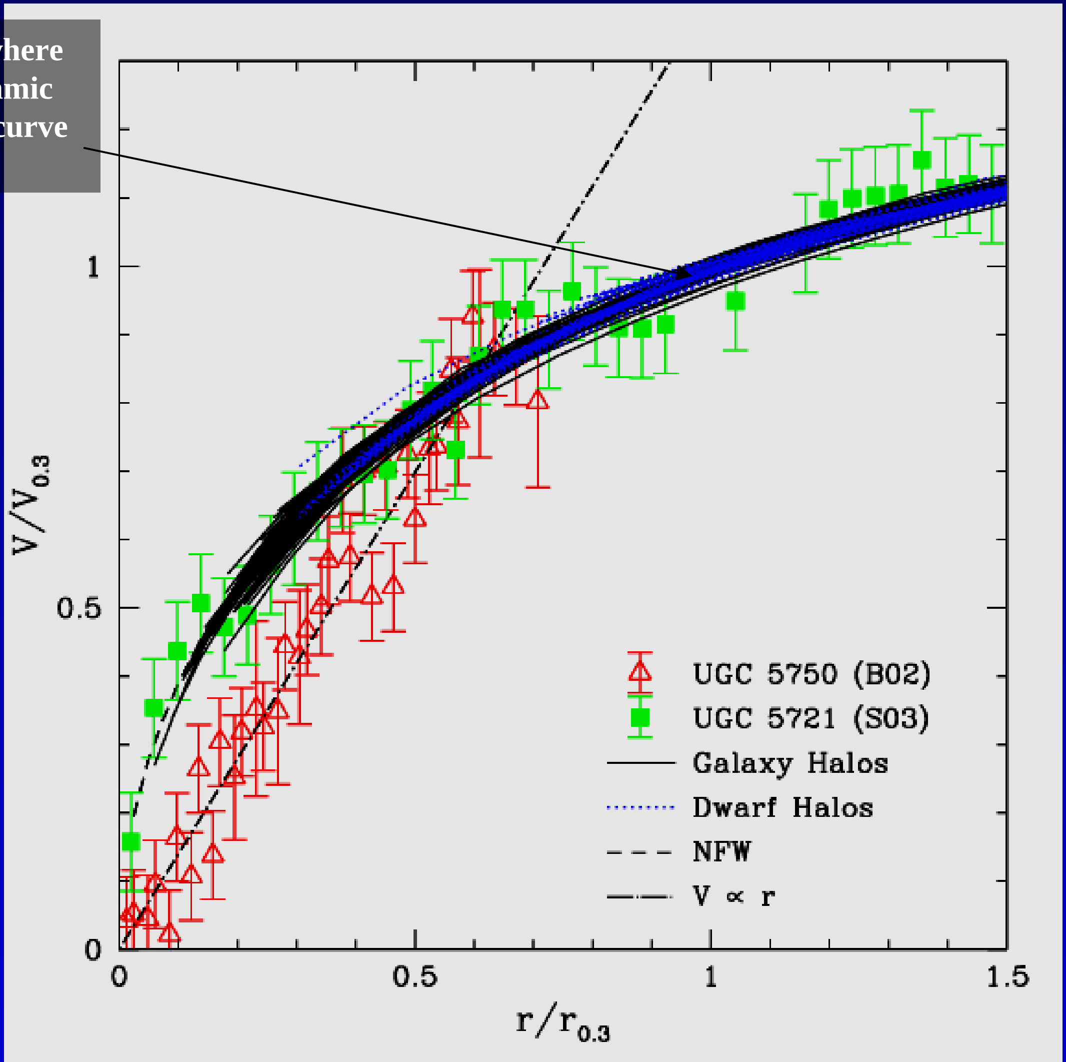
$$\varepsilon(r) \sim f\, (v_{esc}^2 / v_c^2 - 1)$$

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

($V_{0.3}$,$r_{0.3}$): where the logarithmic slope of the curve is 0.3

Rotation Speed

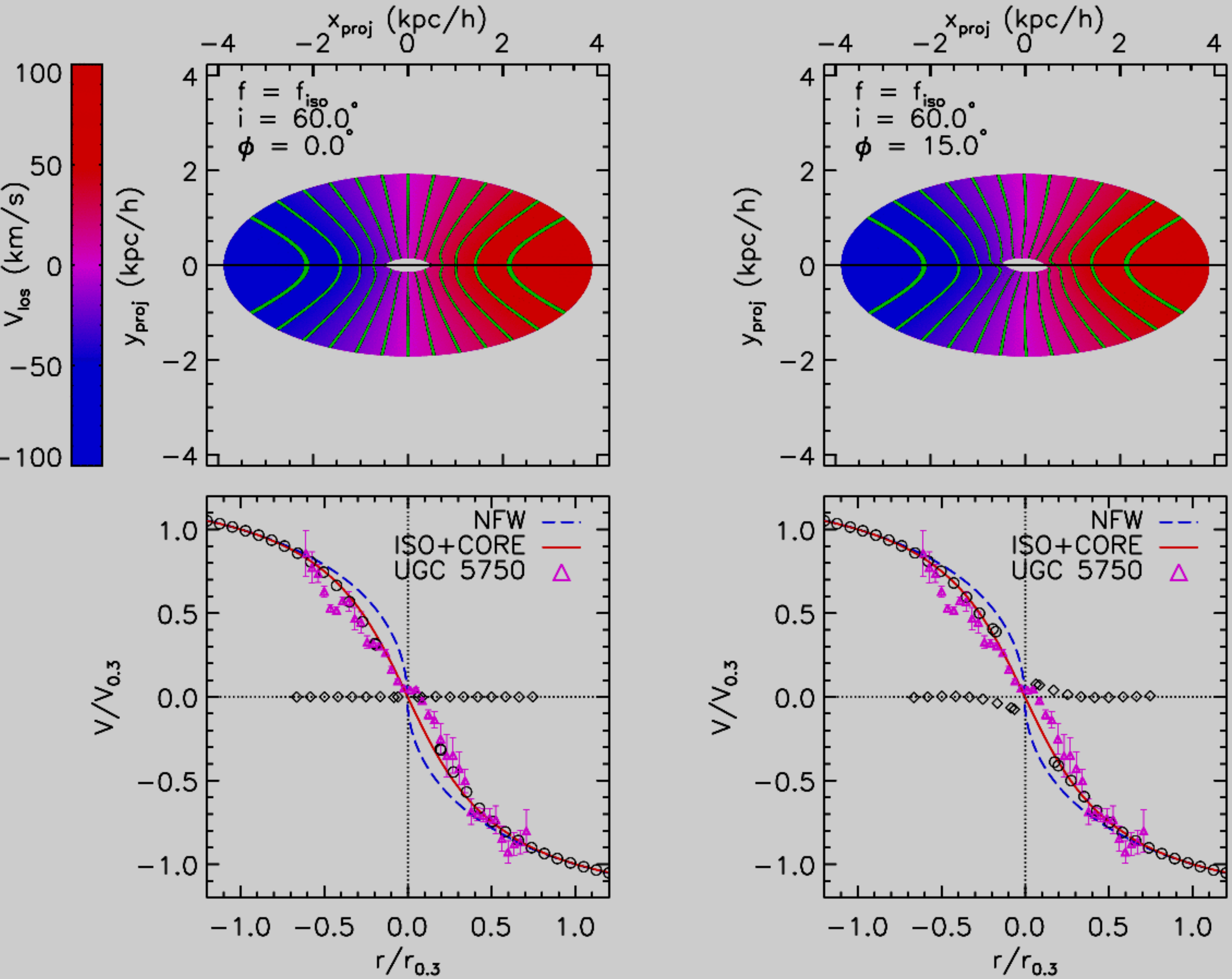


Radius

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

Hayashi et al 2003

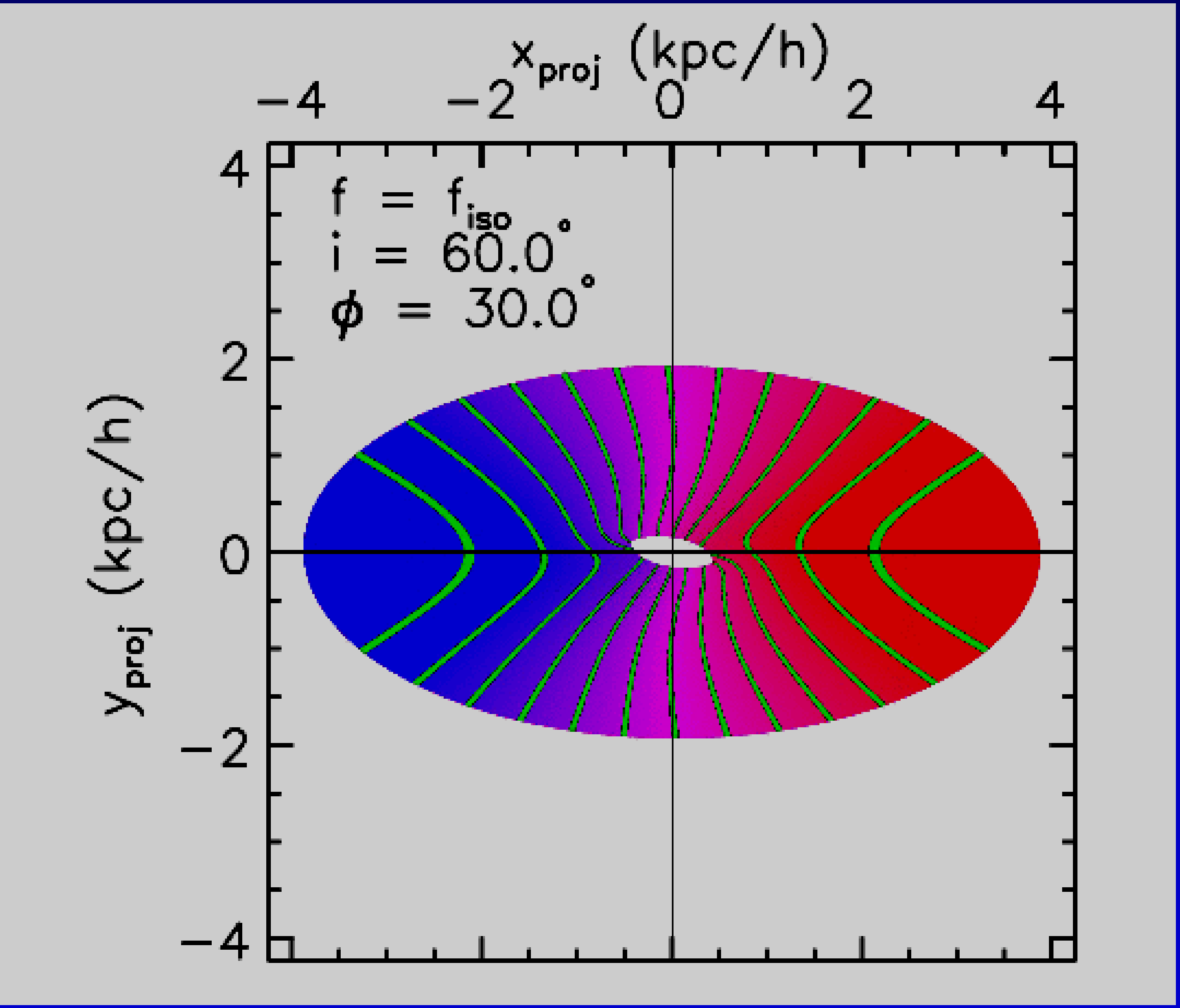
Long-slit rotation curves



- 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.

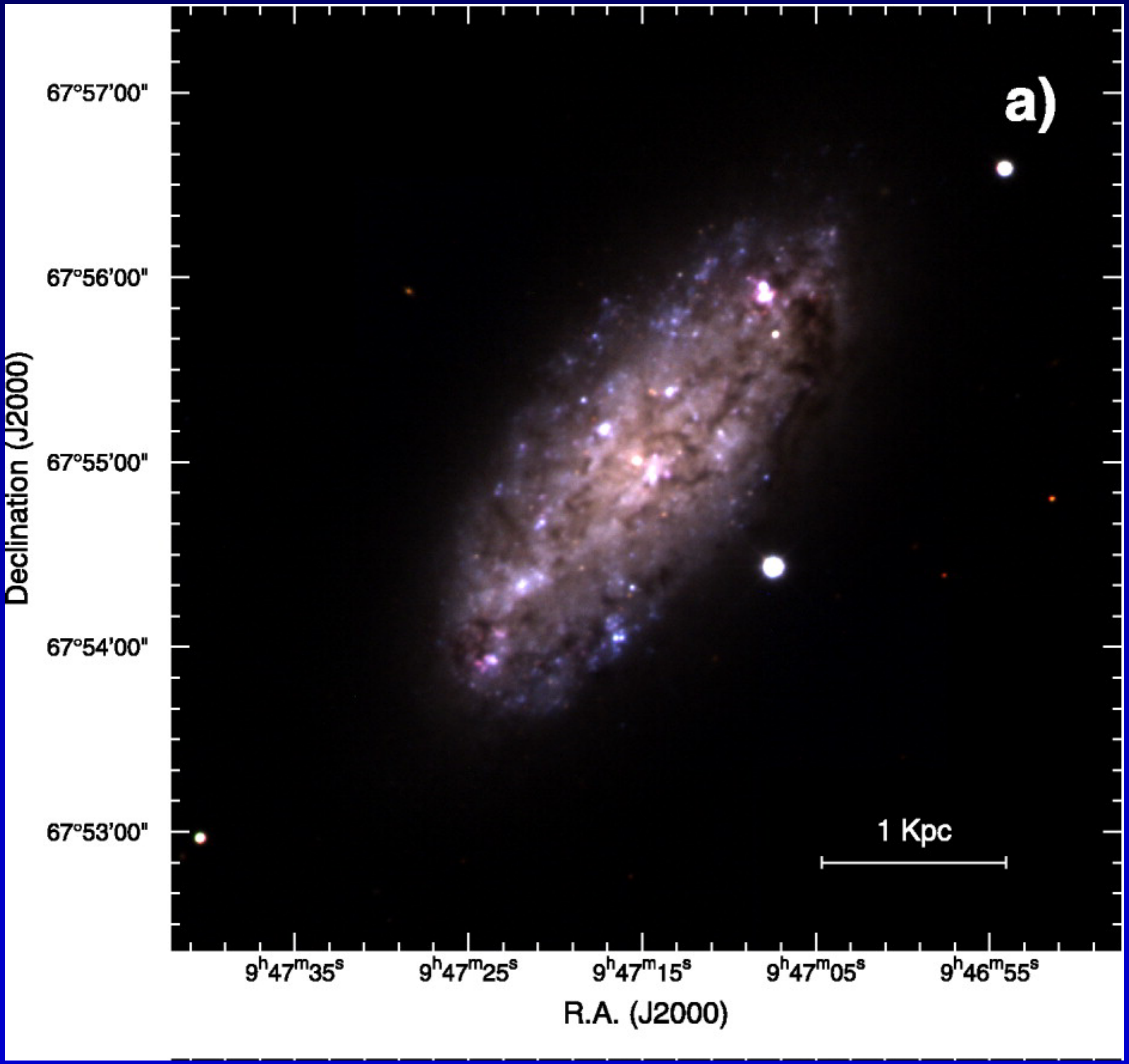
- For this configuration, the velocity field is symmetric and orbits are indistinguishable from circular.

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

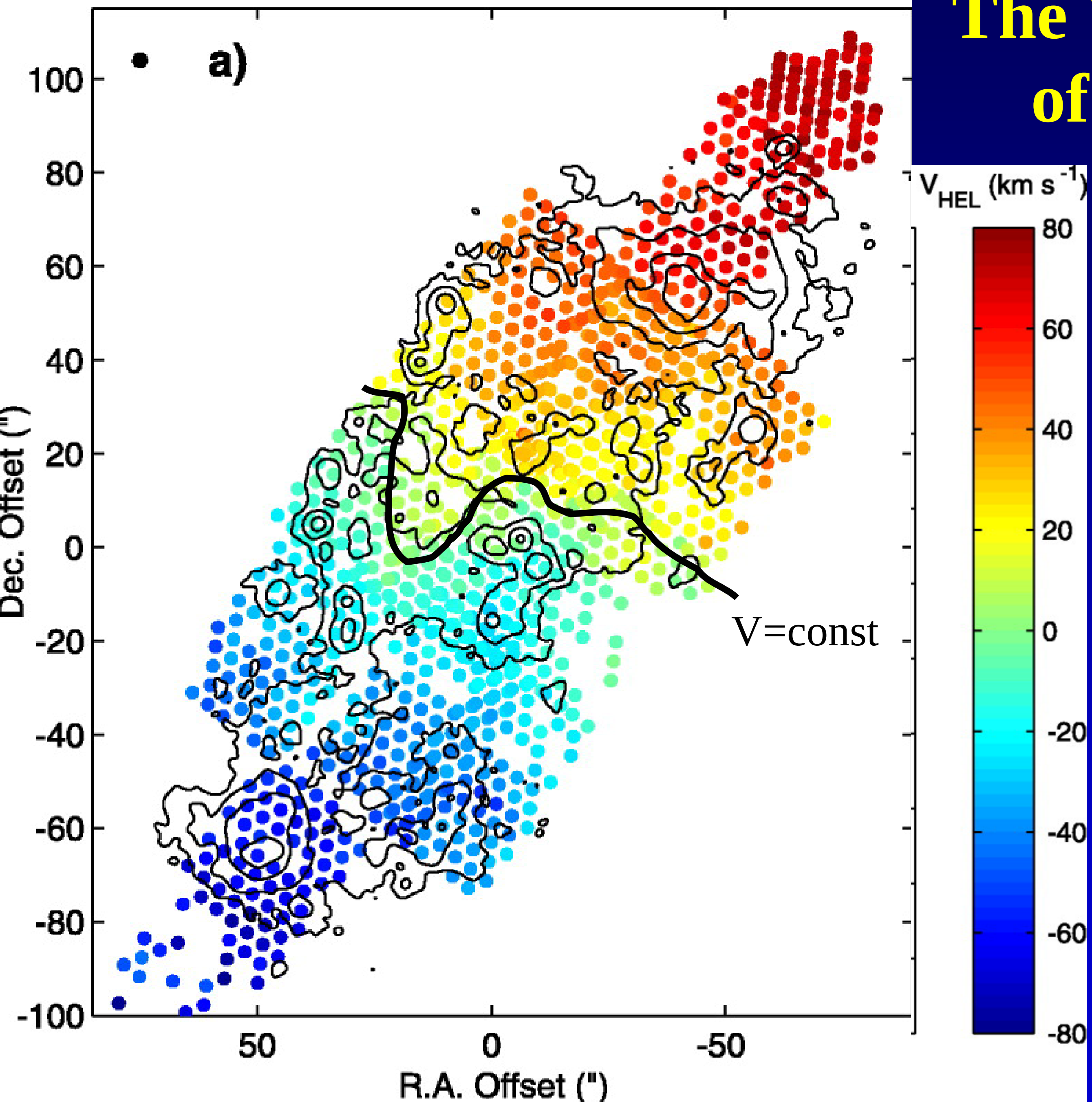


NGC 2976:
an LSB disk without obvious bulge or bar components.

"…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

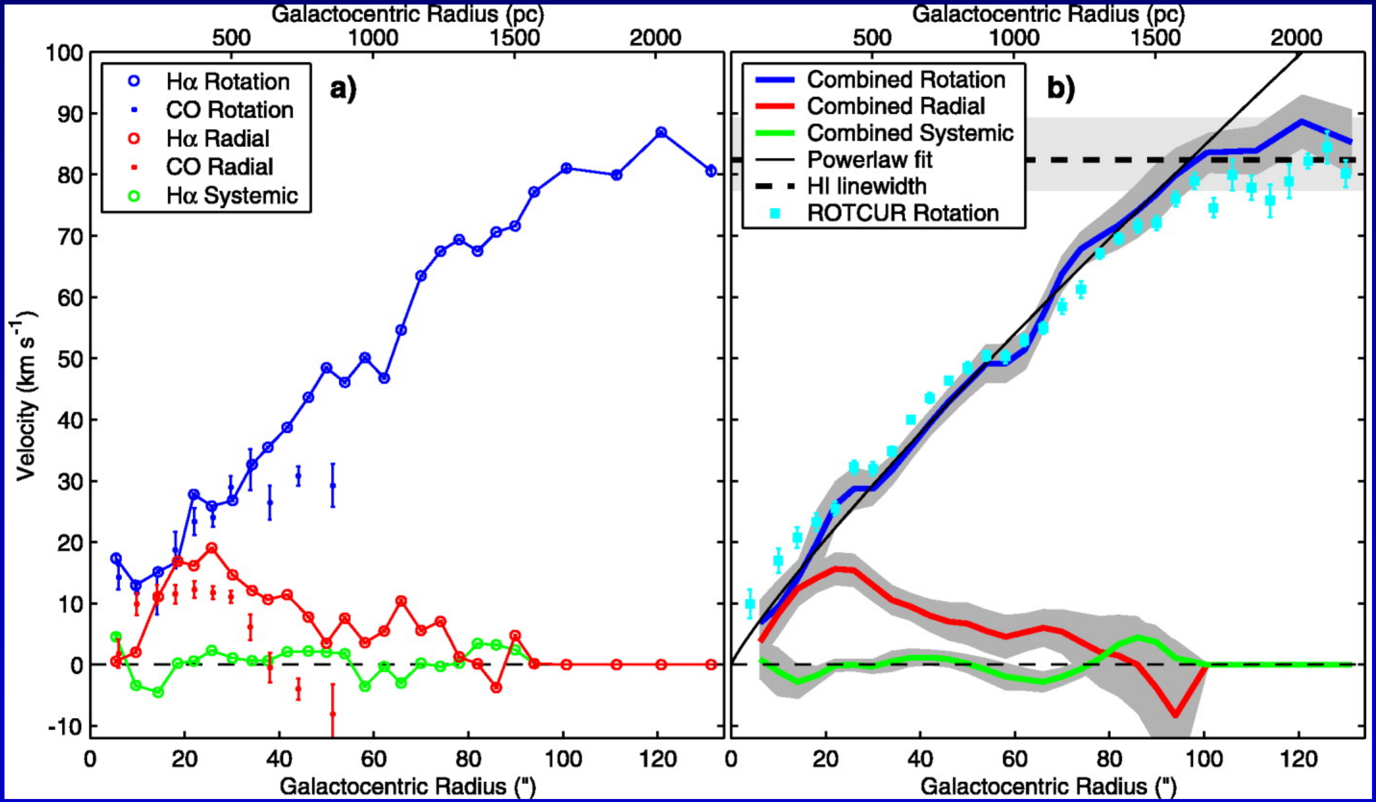
The Velocity Field of NGC 2976



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

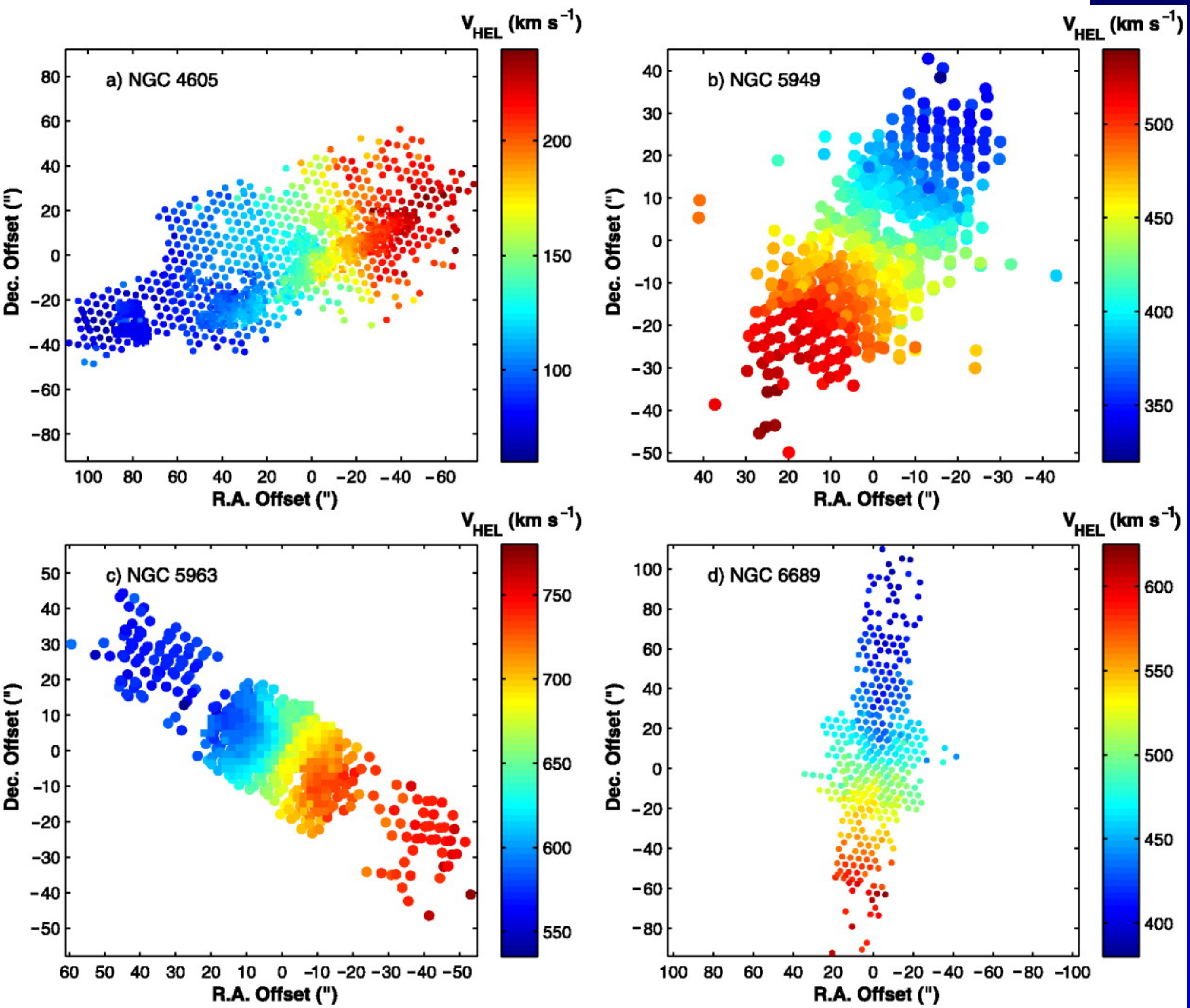


Simon et al (2004) choose to model such deviations by tilted concentric rings with rotation, as well as "radial" (i.e. expansion or contraction) velocities.

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

Simon et al 2004

Other LSBs with 2D velocity data



•Inner regions of halos surrounding dwarfs show a variety of behaviors: some are consistent with cusps, others are not.

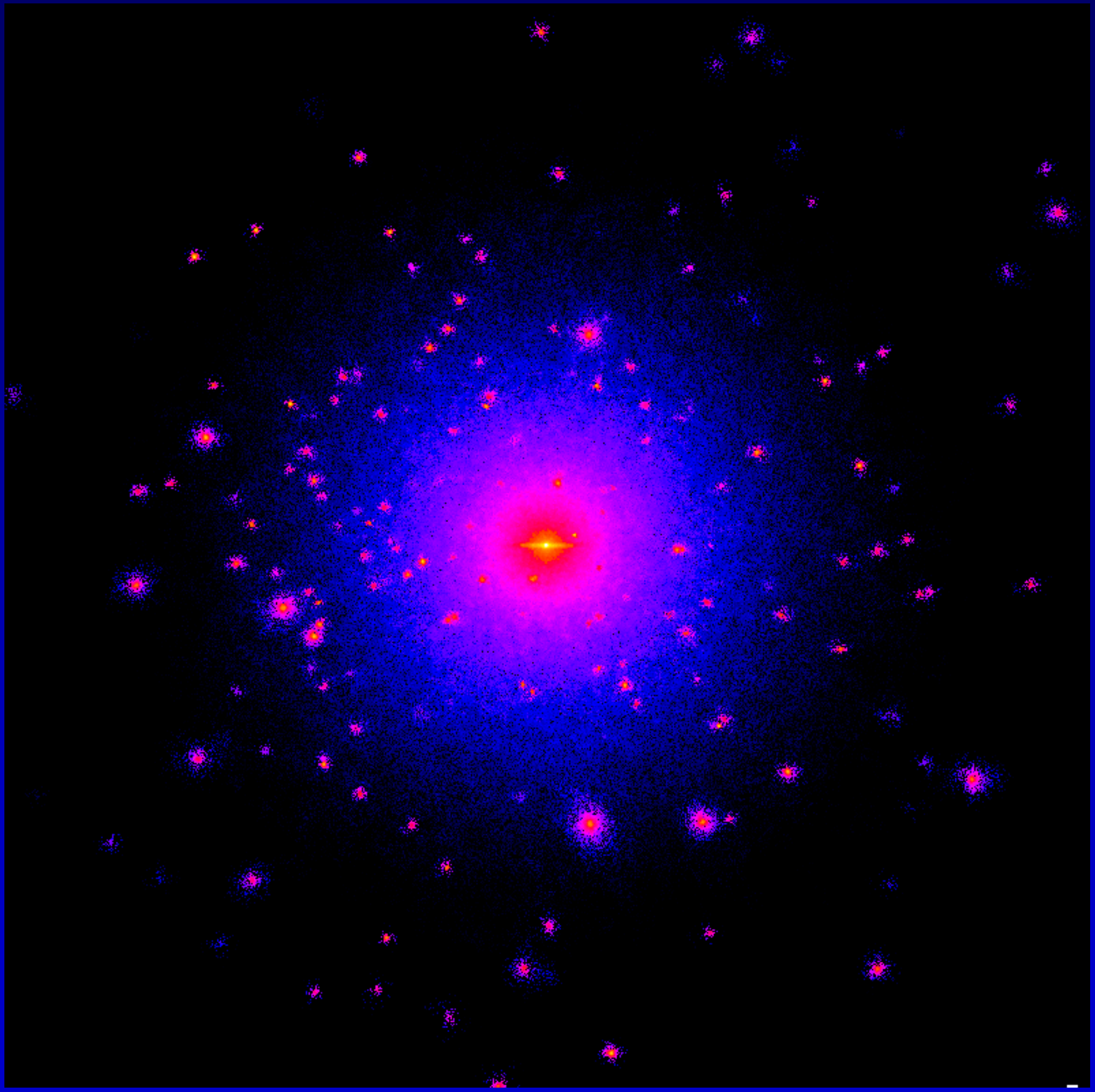
•Asymmetries in the velocity fields ("radial motions") are common

•Could this reflect various orientations of disks within halos of different triaxiality?

Simon et al 2005

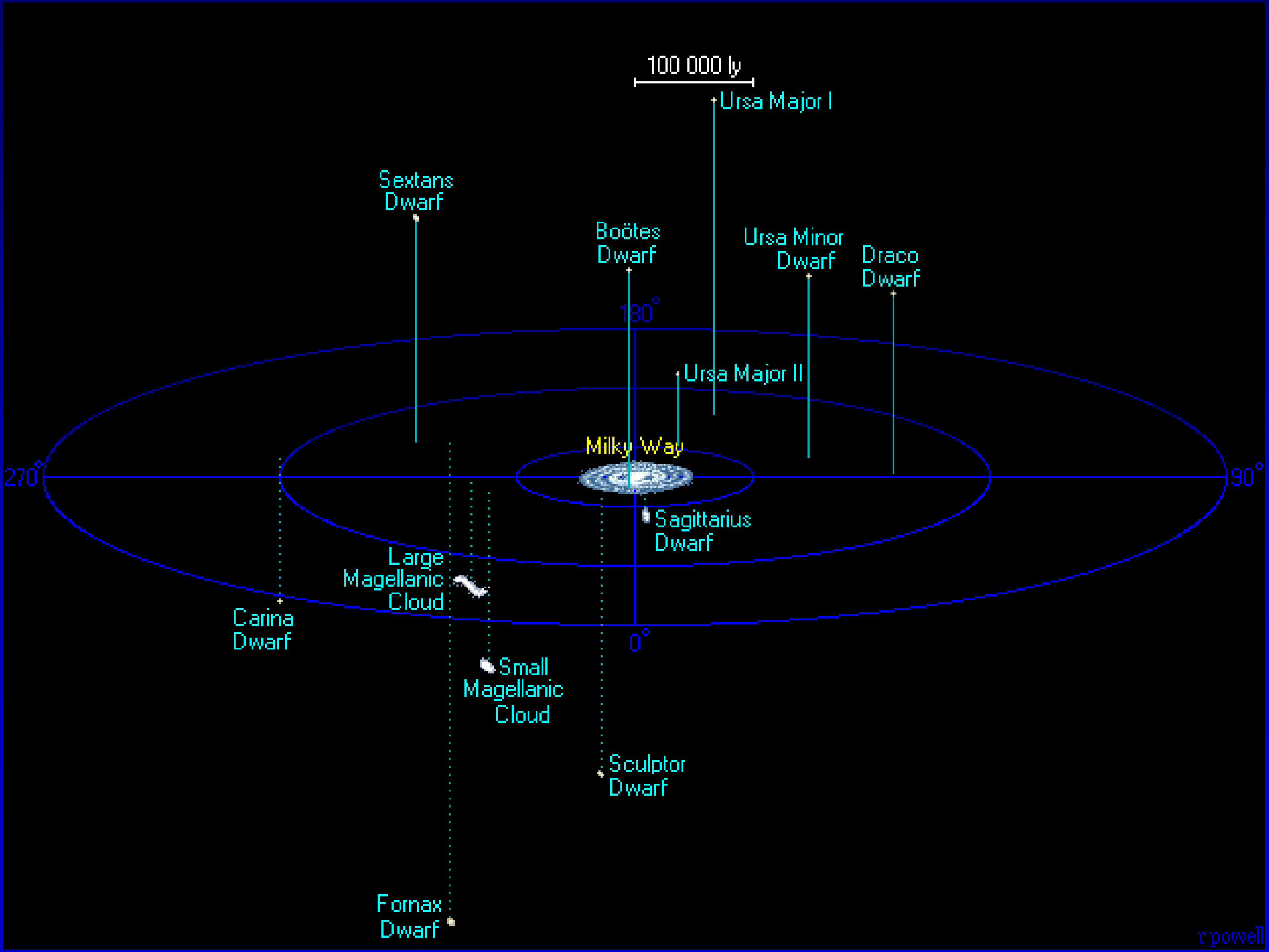
Dark Halo Substructure and Milky Way Satellites

Dark Matter in the Milky Way

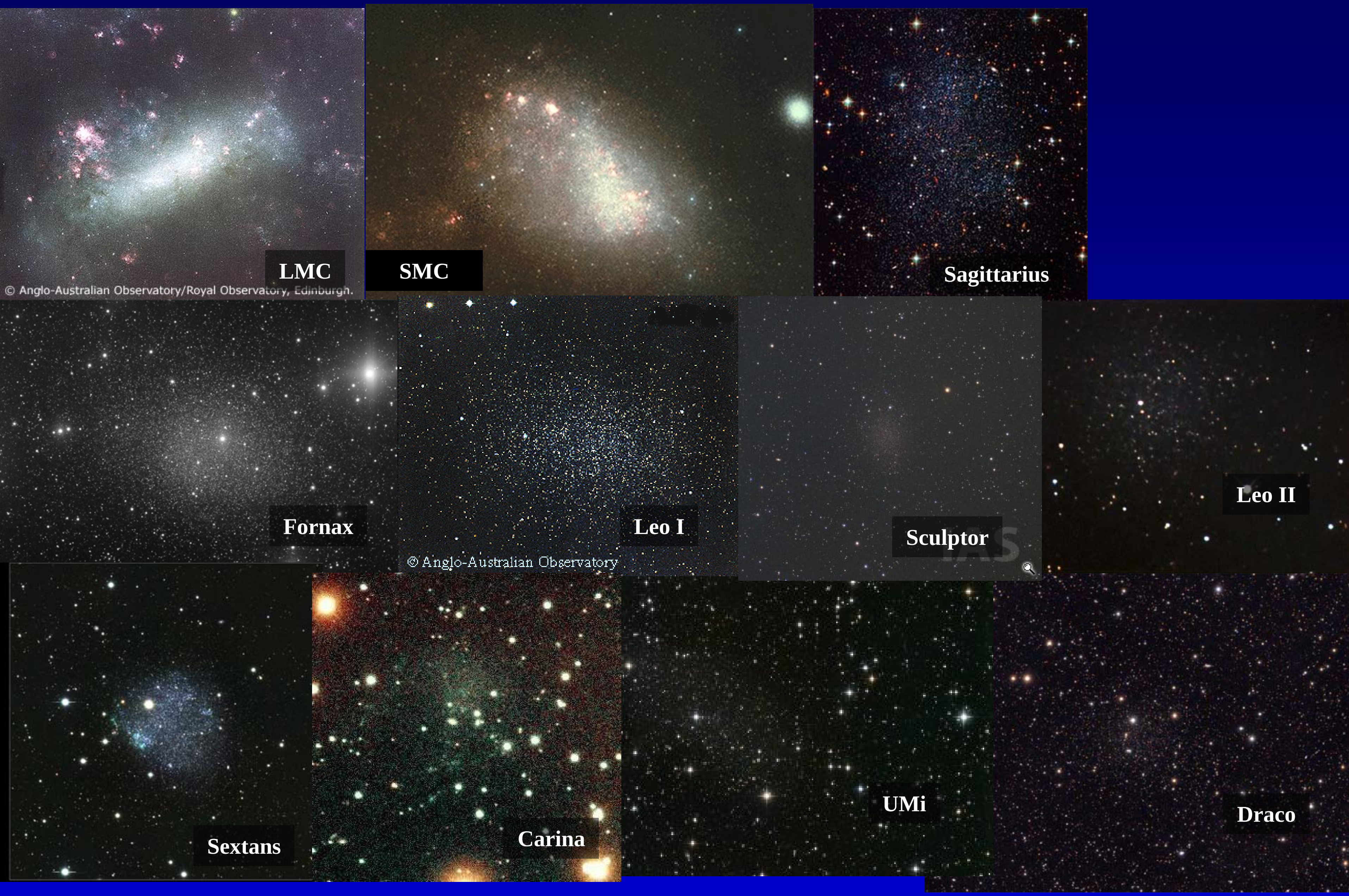


The Milky Way galaxy, as seen with "dark matter-sensitive" eyes. The luminous disk-like component of the galaxy is the small yellowish object at the center. It is surrounded by a Cold Dark Matter halo that extends twenty times as far as its luminous radius and is punctuated by hundreds of "dark clumps"—the remnants of past violent merger and accretion events that characterize the formation of our Galaxy. (Credit: Andreea Font and Julio Navarro)

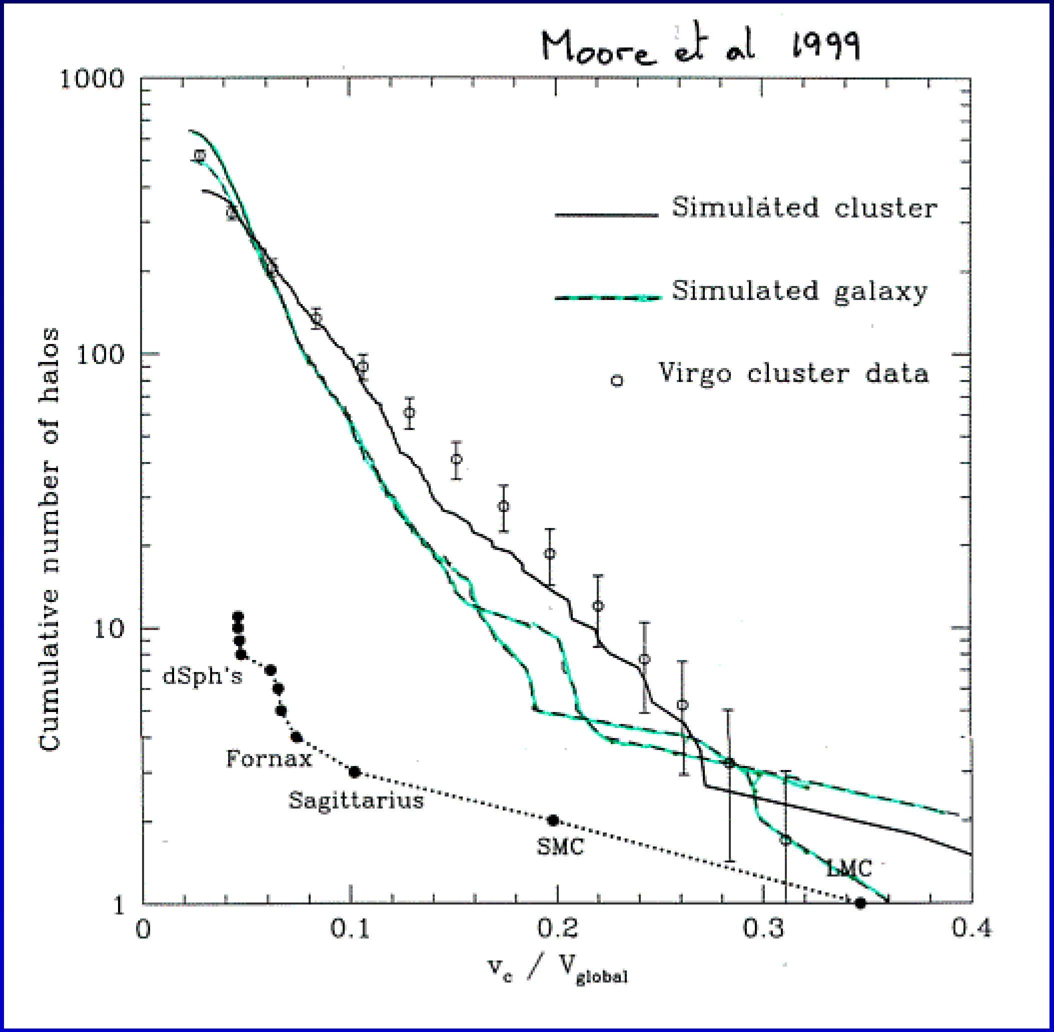
A Map of our Solar Neighbourhood



The Milky Way Satellite Gallery



Substructure and the abundance of Milky Way satellites



Cumulative Number

Circular Velocity

Low mass halos outnumber known satellites by a large factor!

Two questions:

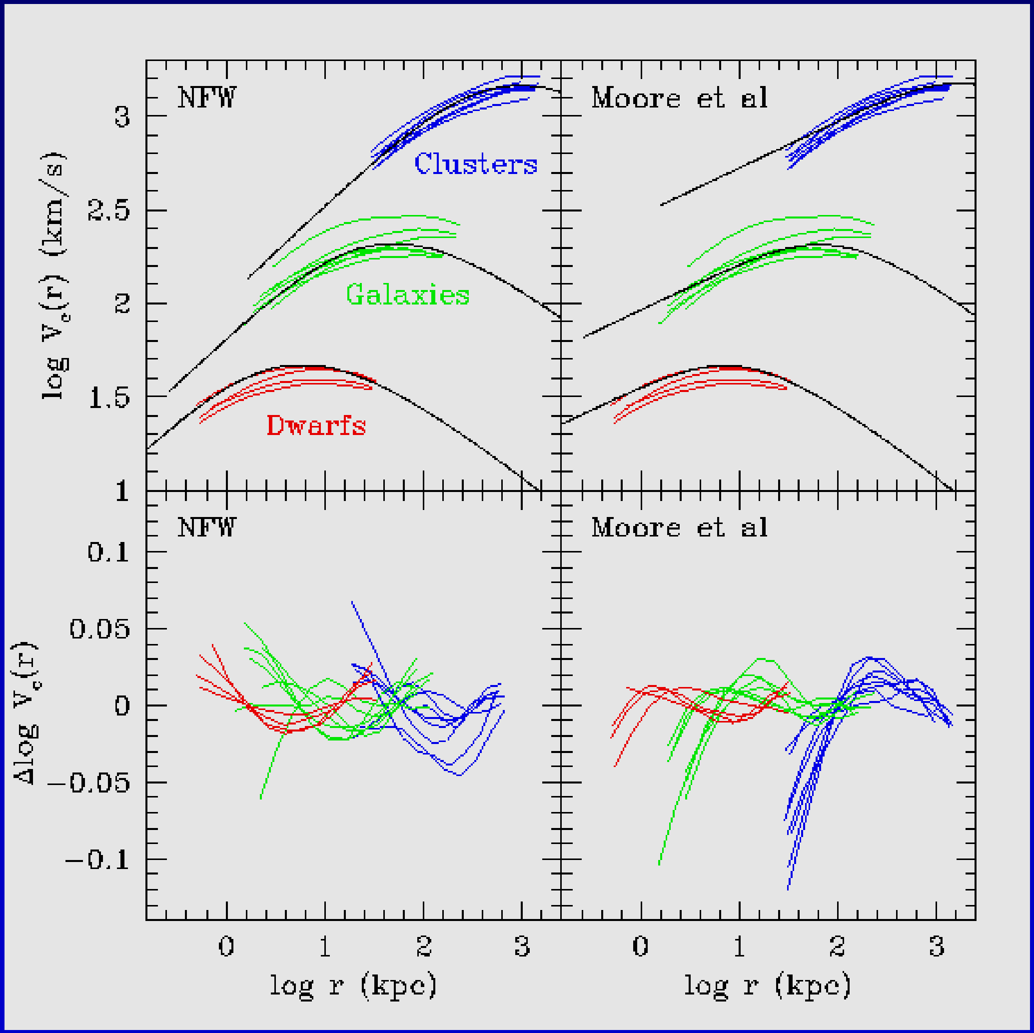
Are surveys of nearby satellites complete?

What is the circular velocity associated with each satellite?

CDM halo circular velocity profiles

Circular Velocity

residuals



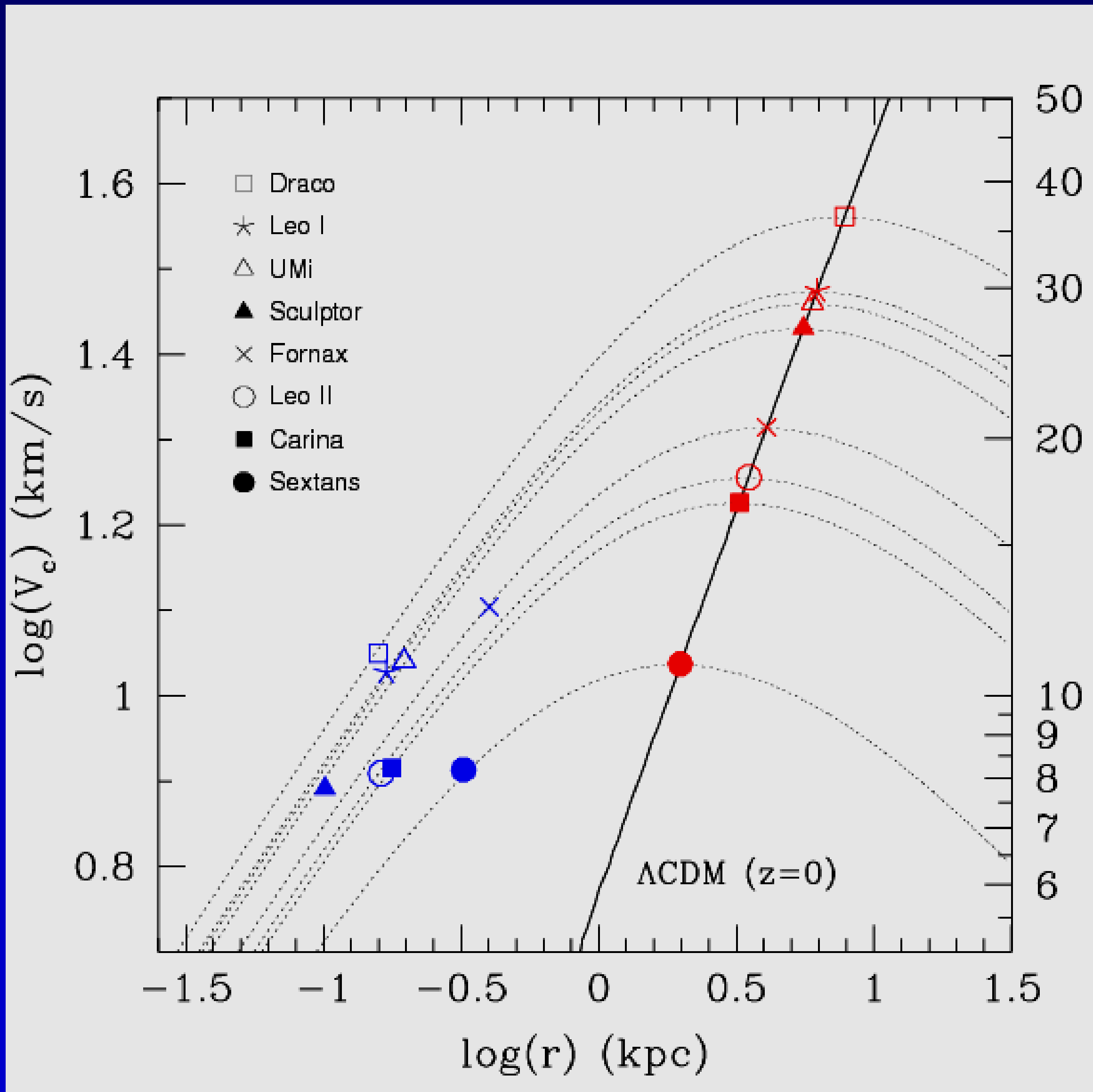
Radius

CDM halos are shallower than isothermal near the center, which implies that their circular velocity increases outwards.

The higher the density at a fixed physical radius, the more massive the halo.

The circular velocity profiles of dSphs

Circular Velocity

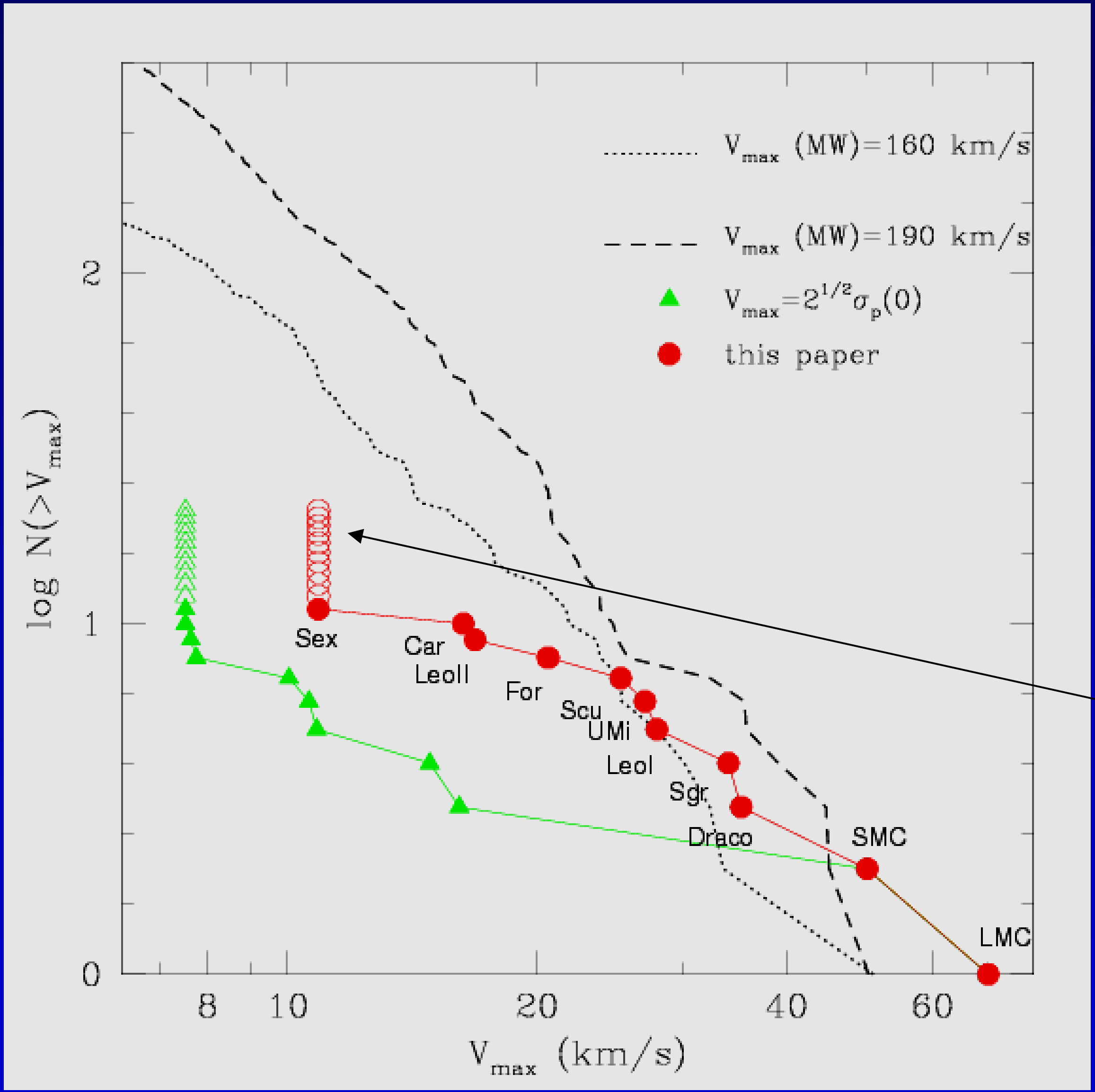


Radius

The mass within the luminous radius places strong constraints on the peak circular velocity of its surrounding halo.

Penarrubia et al 2007

The satellite “crisis” revisited



Number of satellites

Halo peak circular velocity

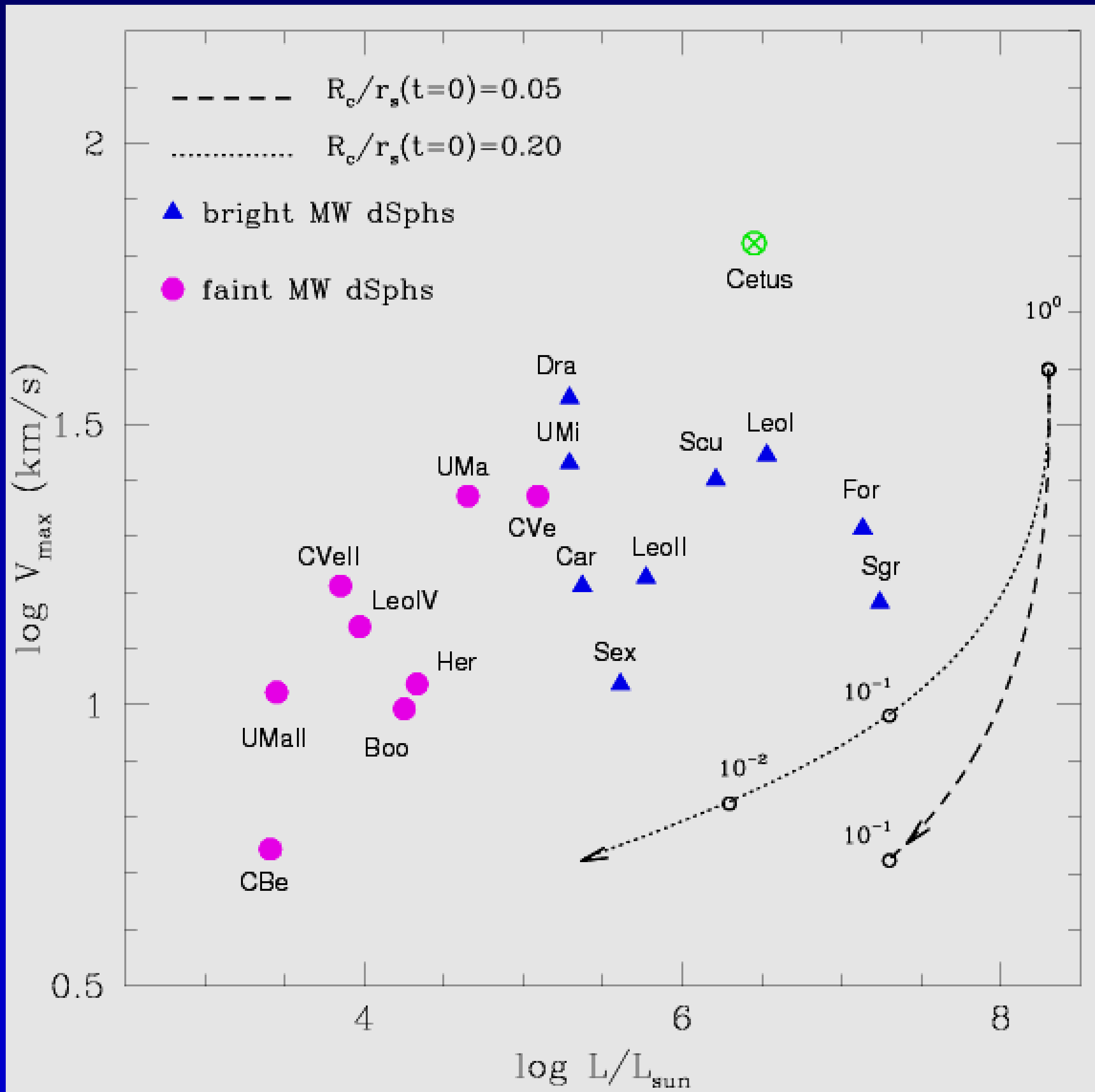
There seems to be good agreement between the number of satellites and the abundance of massive substructure halos.

Newly discovered dwarfs---”predicted” by CDM! (no dynamical data yet)

Penarrubia et al 2007

The halo properties of dSph galaxies

Peak Circular Velocity

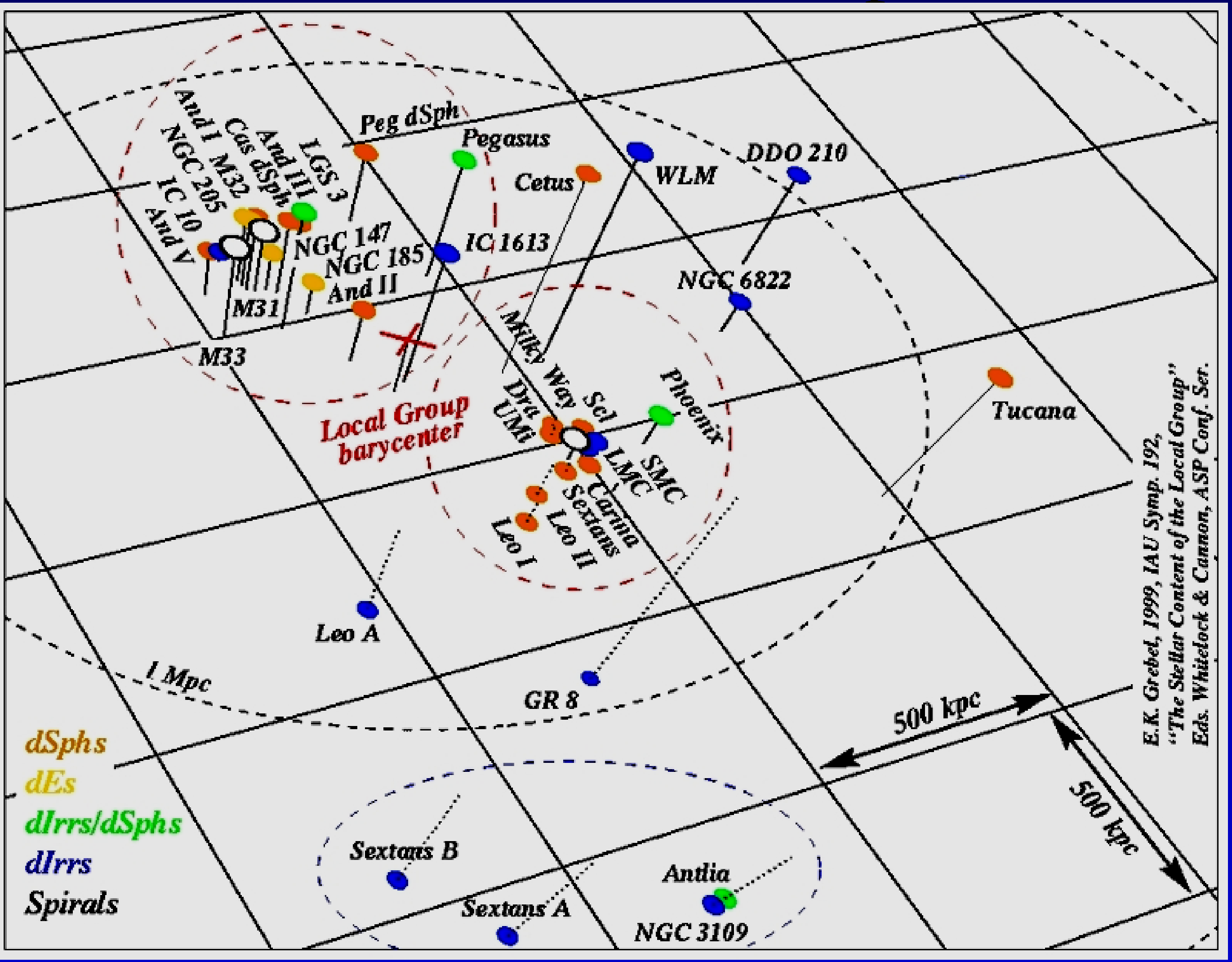


Luminosity

Most dSphs, despite the broad range in luminosity, seem to inhabit very similar halos

Penarrubia et al 2007

Local Group Satellites

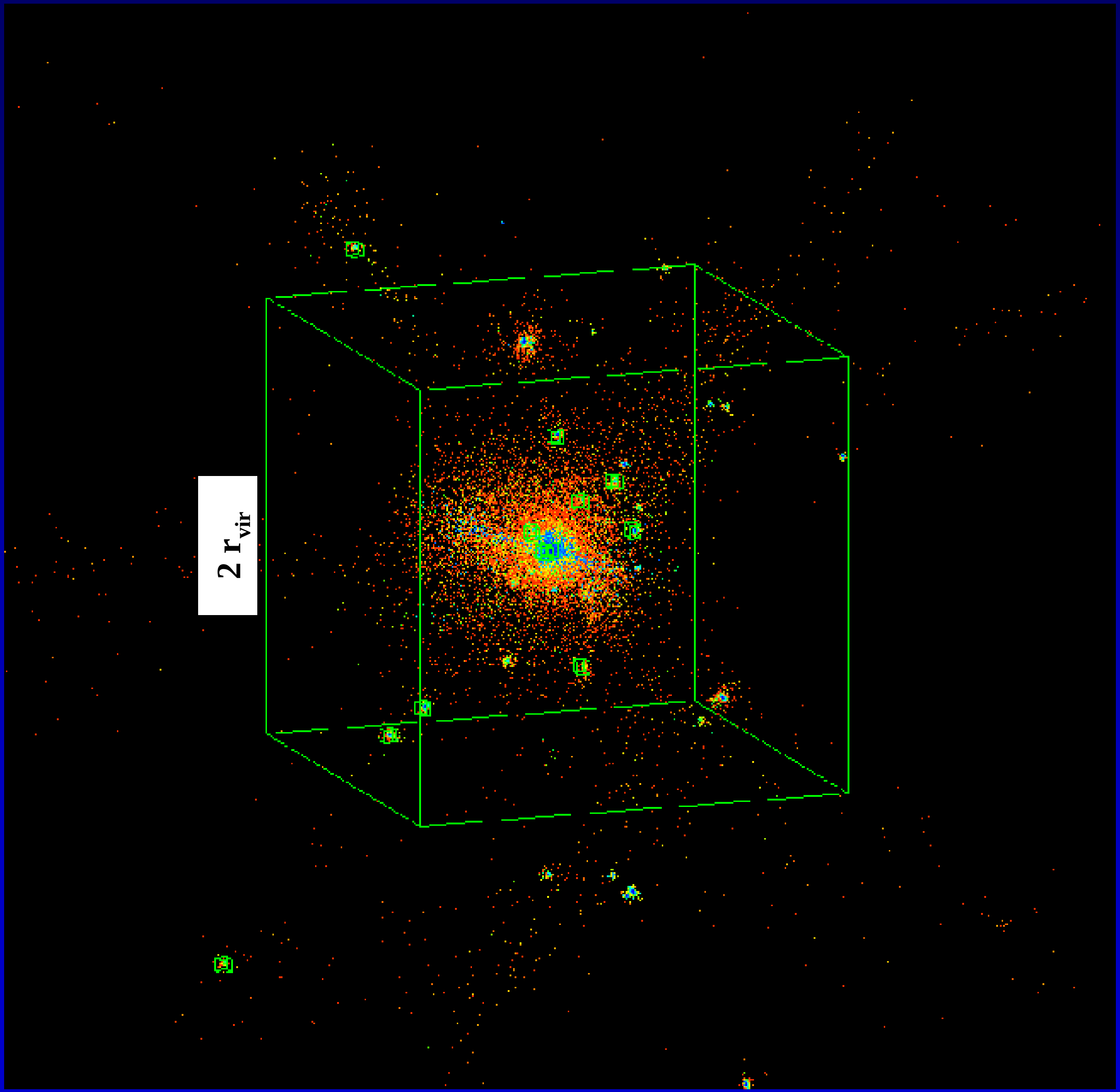


Local Group satellites show a number of dynamical and morphological oddities:

- Leo I and other dynamical rogues
- Planes?
- Anisotropy about M31
- Isolated dSphs

Grebel et al 1999

Satellites “associated” with the primary

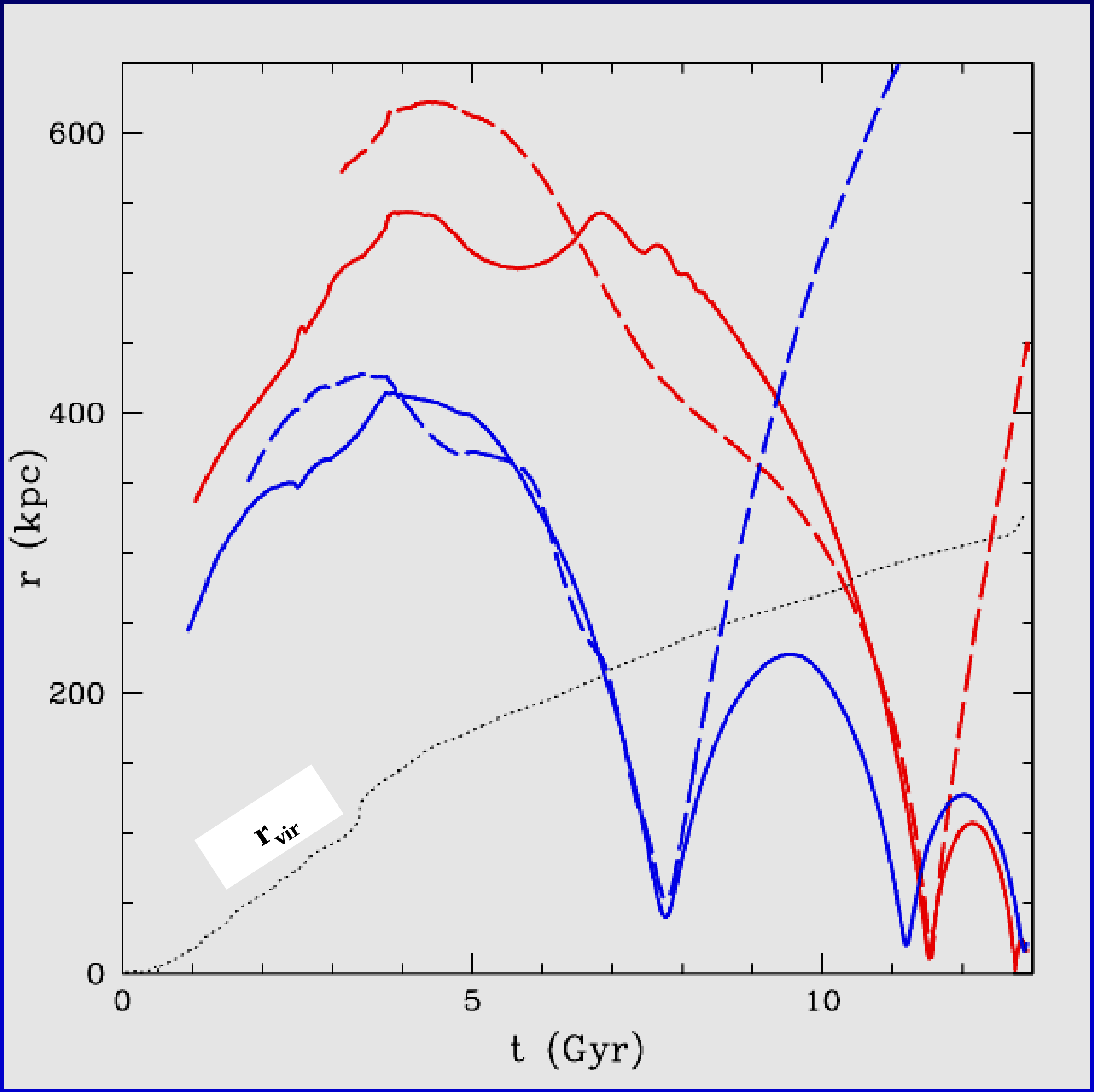


Satellites “associated” with the primary (i.e., those that have in the past been within the primary’s virial radius) are surrounded with boxes.

Note the few outliers on orbits that take them well beyond the virial radius of the host.

Sales et al 2007

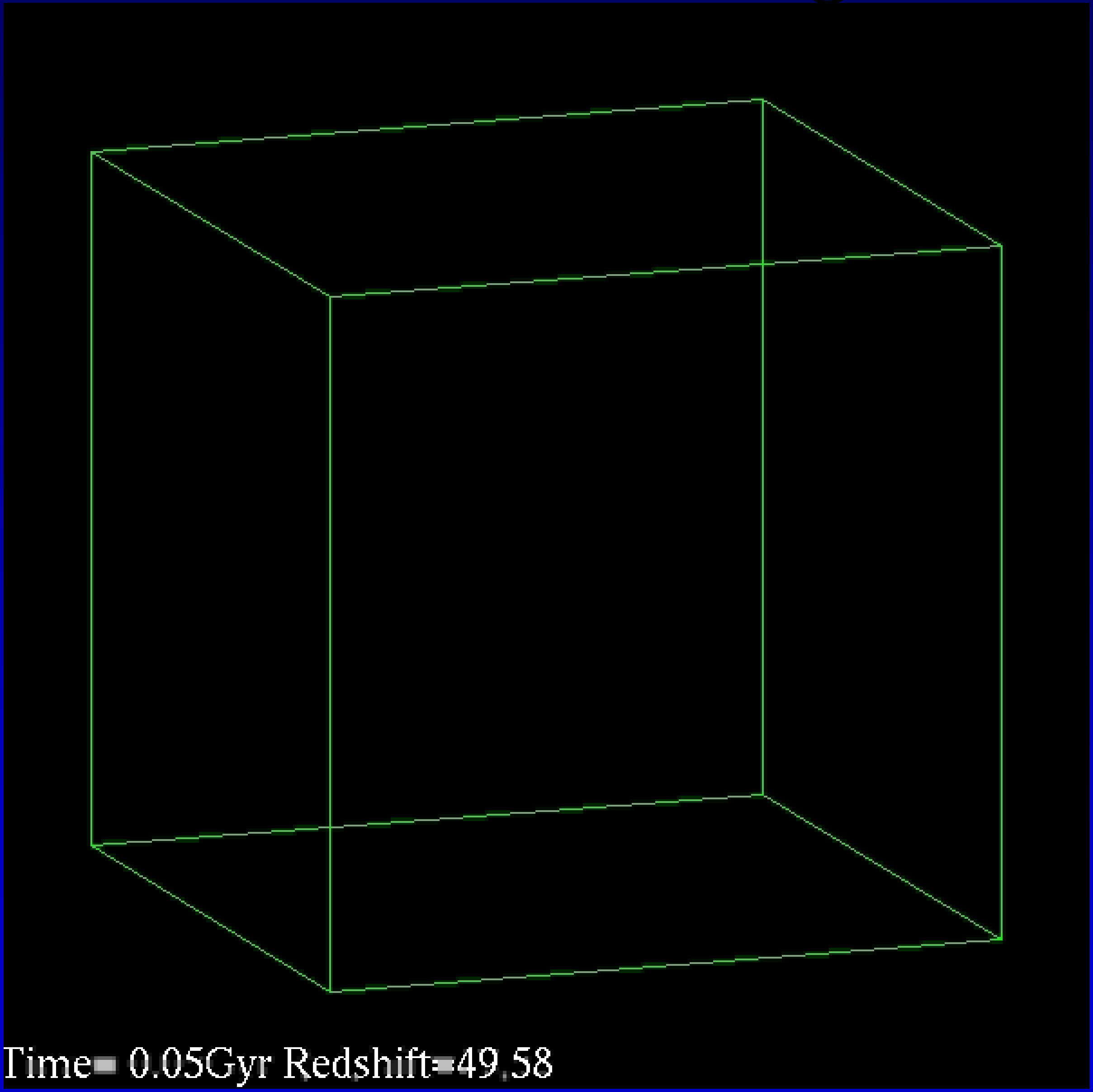
Satellites on Extreme Orbits: a Natural Consequence of Hierarchical Clustering



"Ejected" satellites come in pairs or multiple systems.

Sales et al 2007

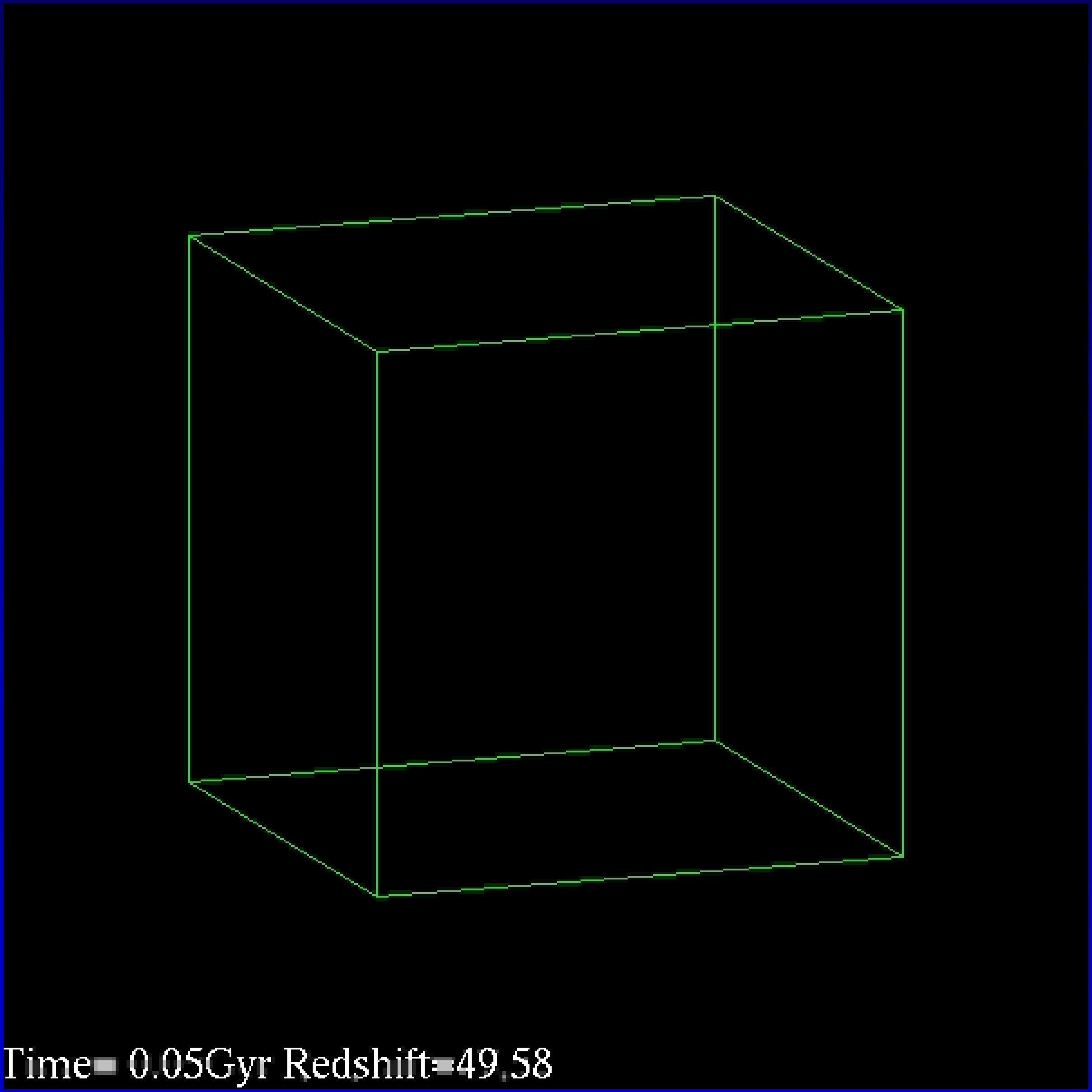
Cosmic Ménage à Trois



Multiple-body interactions during first pericentric approach lead some (low-mass) satellites to gain orbital energy and to be ejected from the system on highly energetic orbits.

Sales et al 2007

Cosmic Ménage à Trois



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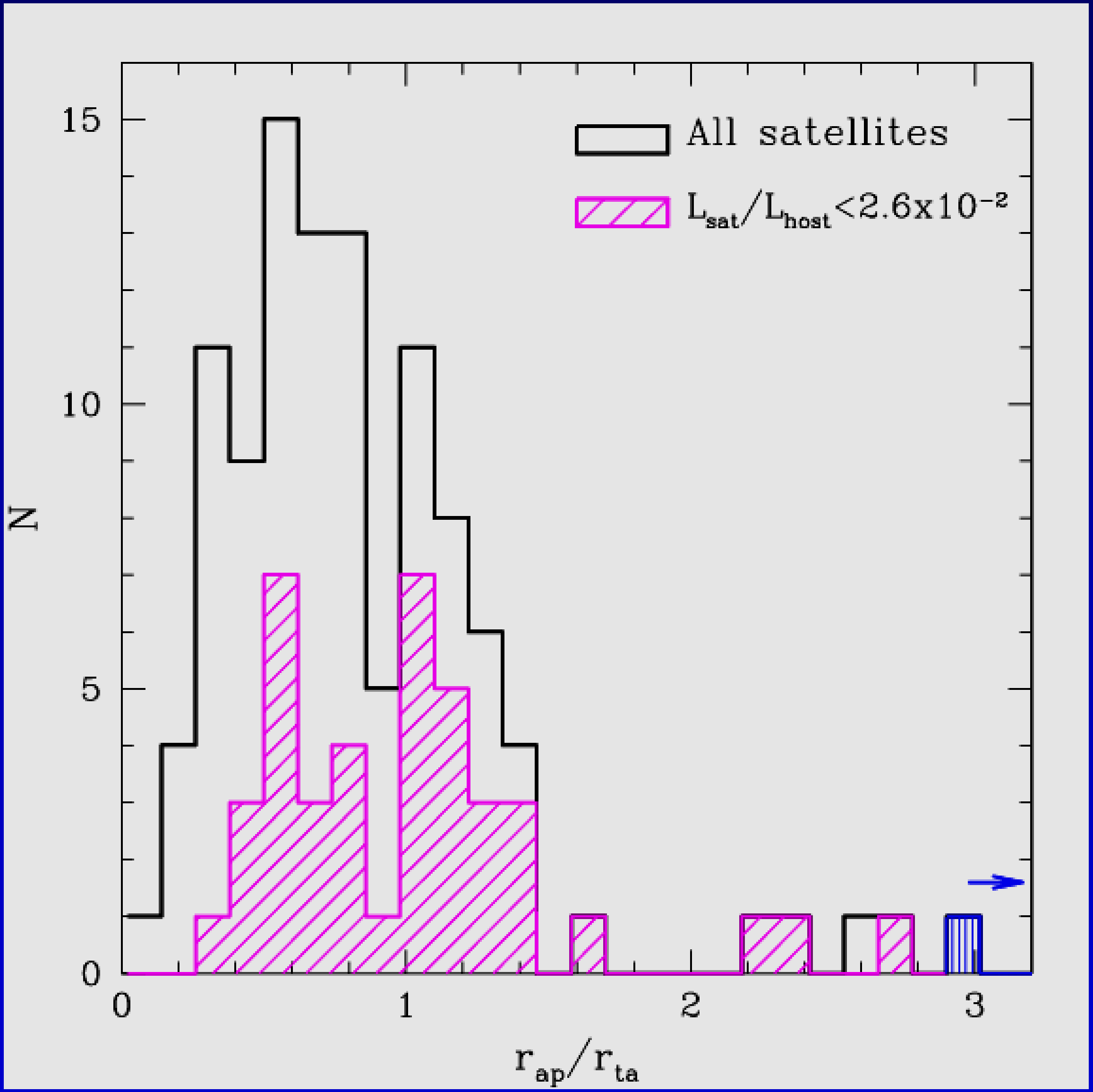
Sales et al 2007

Satellites on Extreme Orbits



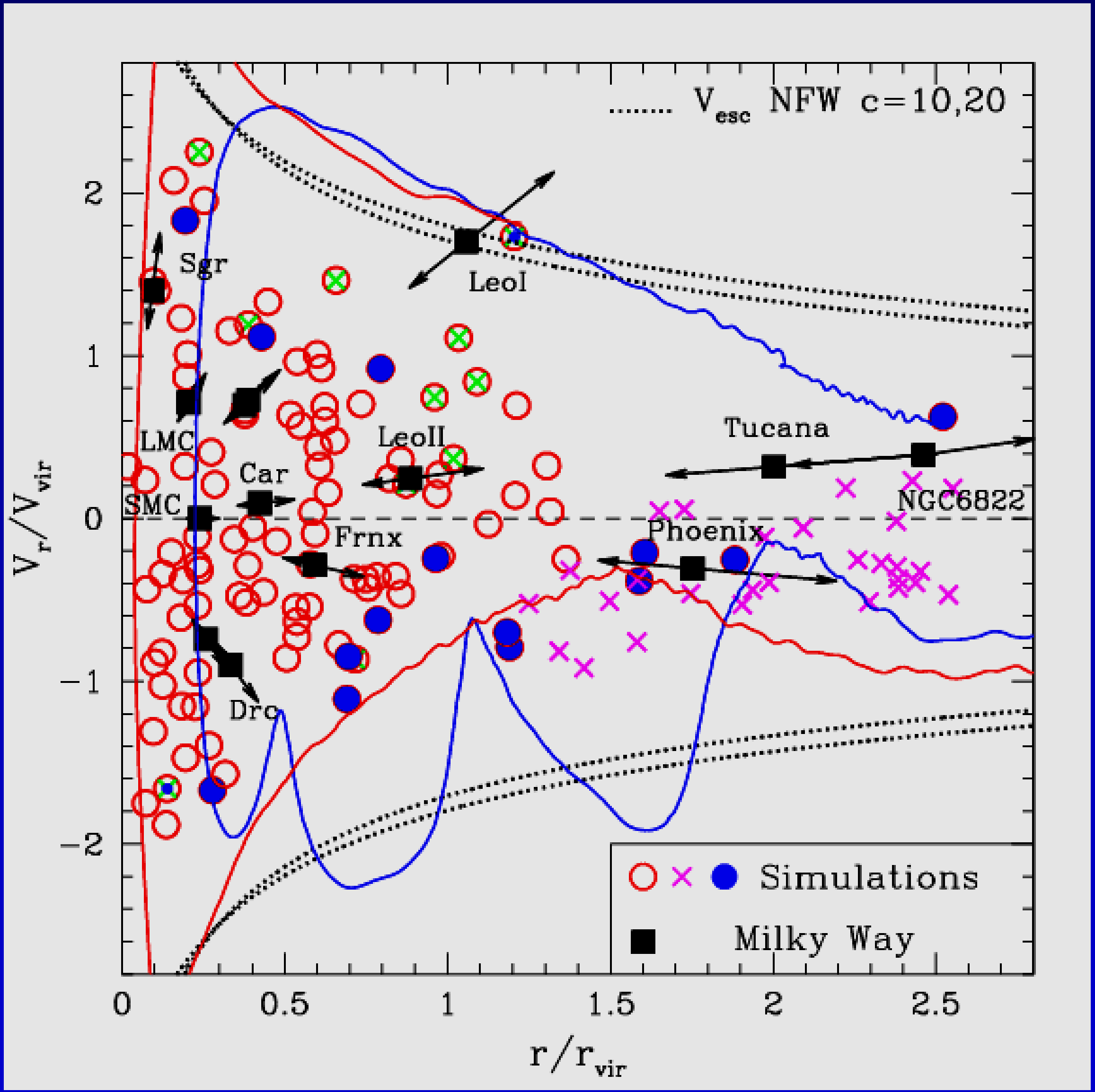
Multiple-body interactions seem to happen quite frequently.

A full 1/3 of surviving satellites are at present on orbits with apocentric distance that exceeds their turnaround radius.

Apocenter/turnaround radius

Sales et al 2007

Application to the Milky Way



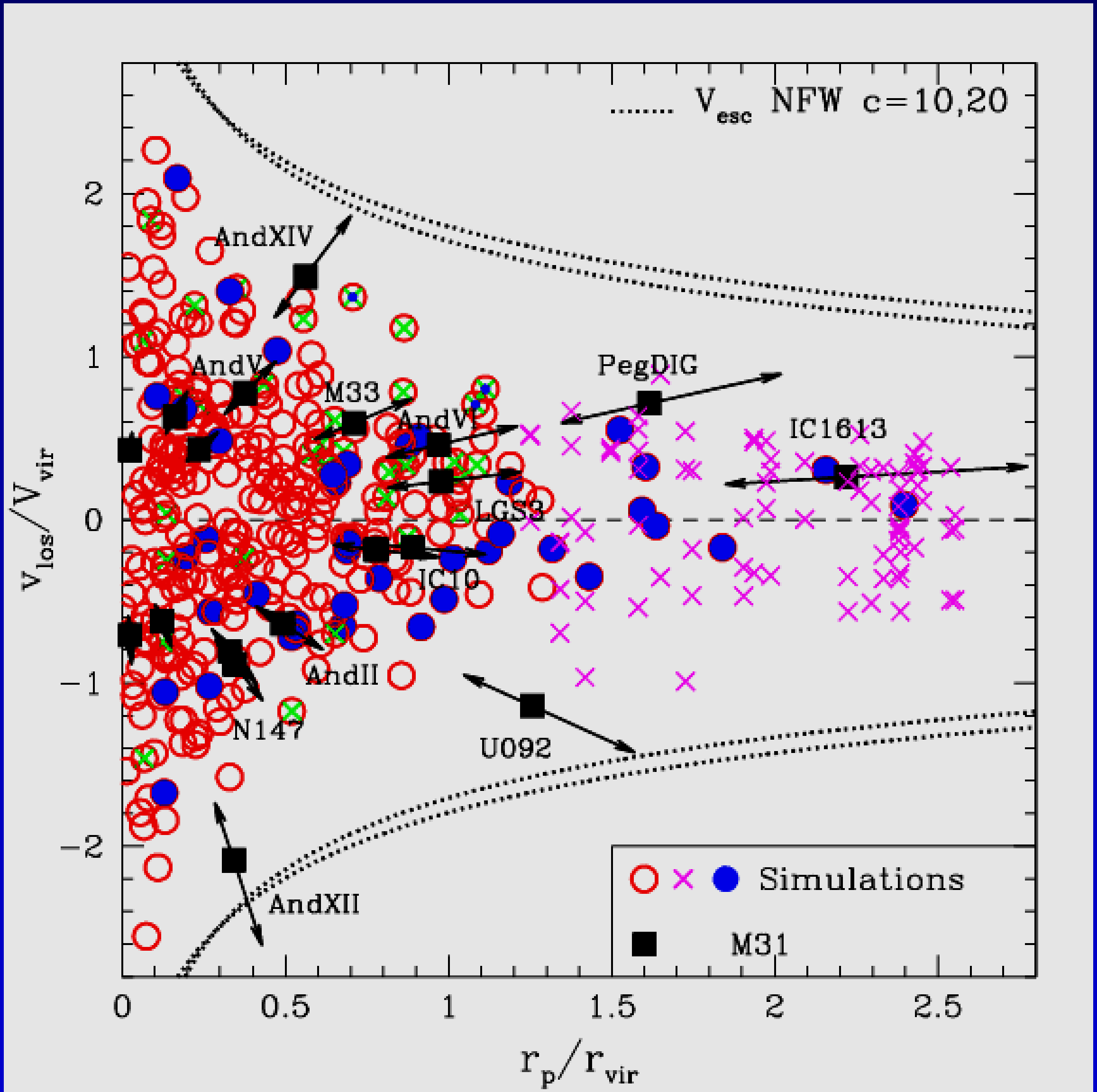
Using the velocity dispersion of satellites to estimate the Milky Way halo mass leads to a virial velocity of ~100-120 km/s.

Satellites like Leo I are barely bound to such potential: a possible ejected satellite?

Note that Tucana, another dSph in an odd orbit may have originated in the same way…

Sales et al 2007

Rogue Satellites around M31



The same process may explain some of the kinematical outliers recently found around M31.

M33 the culprit?

Sales et al 2007

Summary and Conclusions

- ΛCDM halo density profiles:
  - roughly independent of mass
  - shallower near the center: inner asymptotic slopes significantly shallower than –1.5
  - Inferred circular velocity profiles consistent with most LSB galaxies except for a few.
  - theoretical predictions that take into account the effects of halo triaxiality, finite thickness, and finite velocity dispersion of gaseous disks may easily explain this the difference.
- Evidence that CDM halos have ‘too much structure’ on small scales remains unconvincing.
  - Abundance of observed satellites consistent with predicted abundance of massive substructure satellites
  - Satellites on extreme orbits: proof of hierarchical assembly.

The End