THE STRUCTURE OF COLD DARK MATTER HALOS

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2097 citations to NFW paper to date

Highlights of the Paper

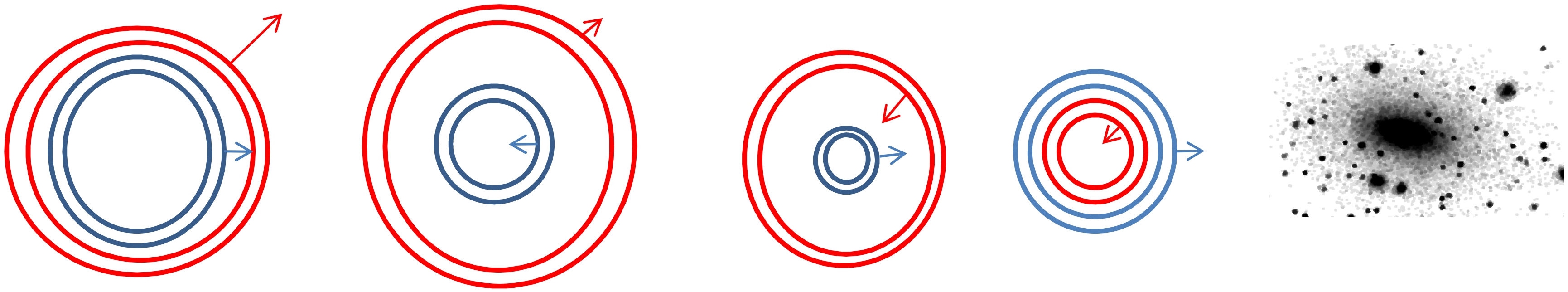
- N-body simulation to study DM halos in CDM cosmology.
- A universal profile fits halos ranging from those of dwarf galaxies to rich galaxy clusters.
- Possible shortcomings:
  - Cusp in the center
  - Prediction of more halos than observed galaxies

Outline

- Description of DM halo formation
- NFW numerical simulation
- Results
- Summary

DM Halos: Virialization of DM Particles

- Weakly Interacting Massive Particles (WIMPs) are the believed candidates for DM particles.
- WIMPs interact with baryons only through gravitational force.
- The gravitational interactions between WIMPs result in collapsing, mixing, relaxation, and settling into an equilibrium configuration.



Initial Hubble flow

Collapsing,
Inner shells reach
The center earlier

Inner shells
cross the center
and move outward

Shell crossing,
relaxation

Virialization,
DM halo

NFW Numerical Simulation

- Simulation of 19 systems ranging from dwarf galaxies to rich clusters.
- Standard CDM, $\Omega_m = 1$.
- P^3M code (Particle-particle-particle-mesh)
- 262,144 particles in periodic boxes of 360 and 30 Mpc
- Virial radius = r_{200}
- Gravitational softening 1% of r_{200}

Simulation Result : NFW Profile

- A universal profile (NFW)

$$\boldsymbol{\rho (r) \propto 1 / (r/r_s) [1 + (r/r_s)]^2}$$

$$\rho (r) \propto r^{-1} \text{ for } r << r_s$$
$$\rho (r) \propto r^{-3} \text{ for } r >> r_s$$

- In Comparison with other profiles
  - Isothermal
    $\rho (r) \propto 1 / r^2$, constant circular velocity
  - Core-Isothermal
    $\rho (r) \propto 1 / [1 + (r/r_s)^2]$

Density Profile and Circular Velocity

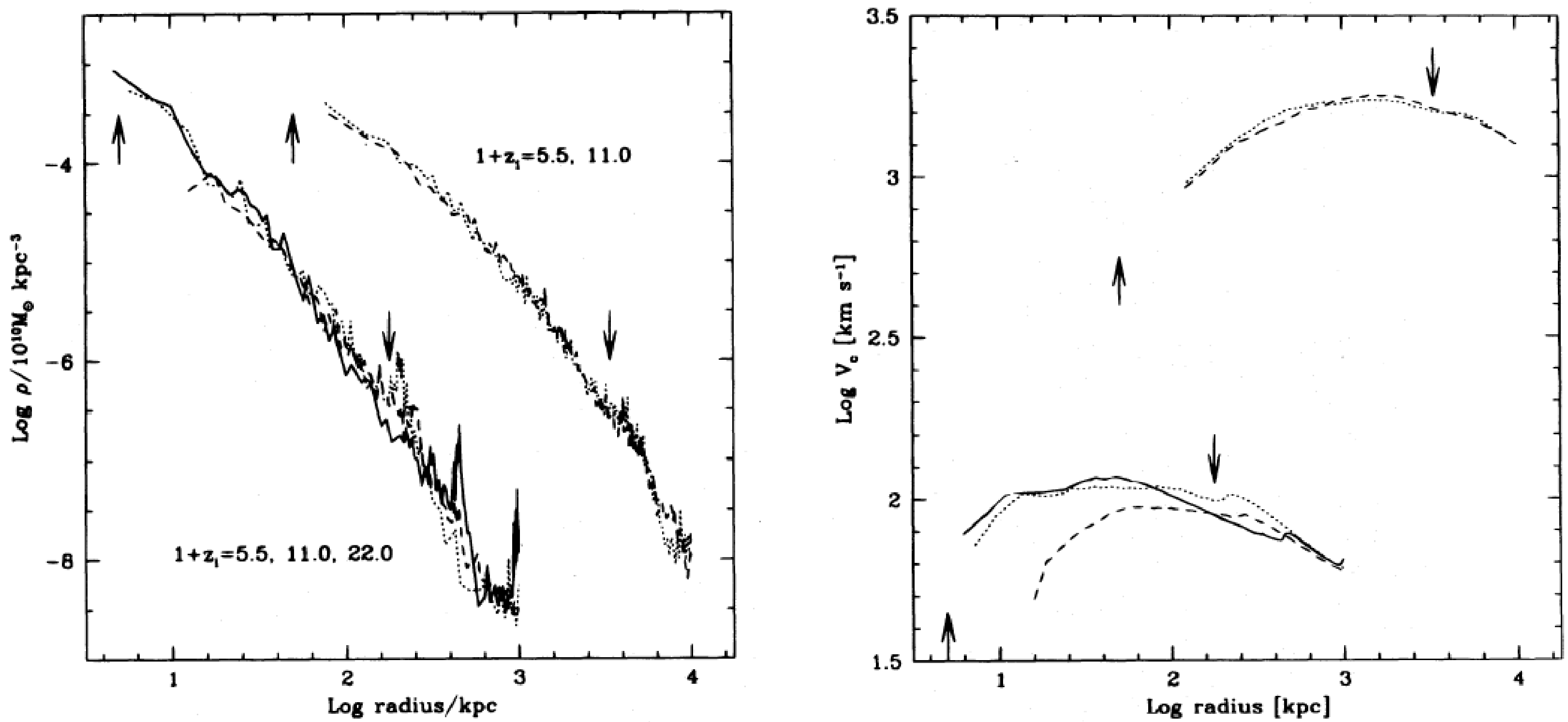


FIG. 1*a* FIG. 1*b*

FIG. 1.—(*a*) Effects of varying the initial redshift on the density profile of simulated halos. The masses of the two halos shown are $\sim 10^{11}$ and $\sim 10^{15}\, M_{\odot}$. The gravitational softening and the virial radius are indicated with upward- and downward-pointing arrows, respectively. Solid, dotted, and dashed lines correspond to $1 + z_i = 22.0$, 11.0, and 5.5, respectively. (*b*) Circular velocity profiles for the halos shown in (*a*). Arrows are also as in (*a*). For $1 + z_i = 5.5$, the circular velocity near the center of the small halo is substantially underestimated. For larger z_i, the models converge to a unique profile.

Similar halo profiles for dwarf galaxies ($10^{11}\ M_{\odot}$) and clusters ($10^{15}\ M_{\odot}$). The profiles are insensitive to initial simulation redshifts, $1+z_i$ = 5.5 or 11.

Scaled Density Profile

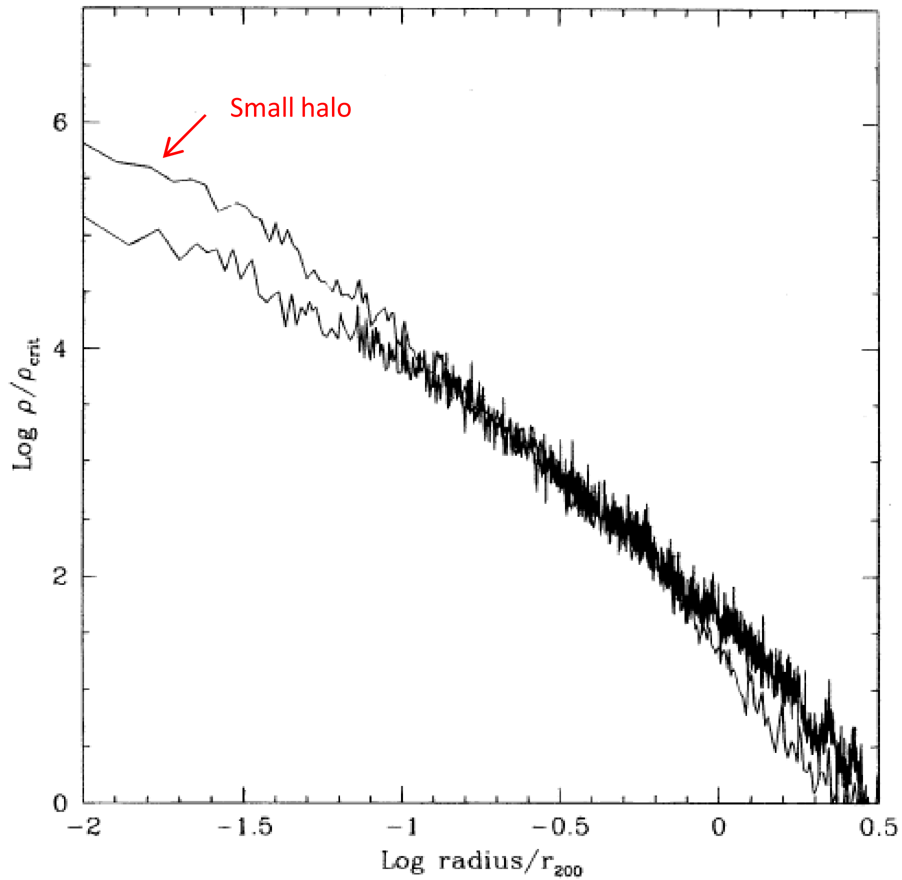


FIG. 4.—Scaled density profiles of the most and least massive halos shown in Fig. 3. The large halo is less centrally concentrated than the less massive system.

Large halos are less concentrated than the smaller halos.

Halo Contribution Is Less Important in Bright Galaxies

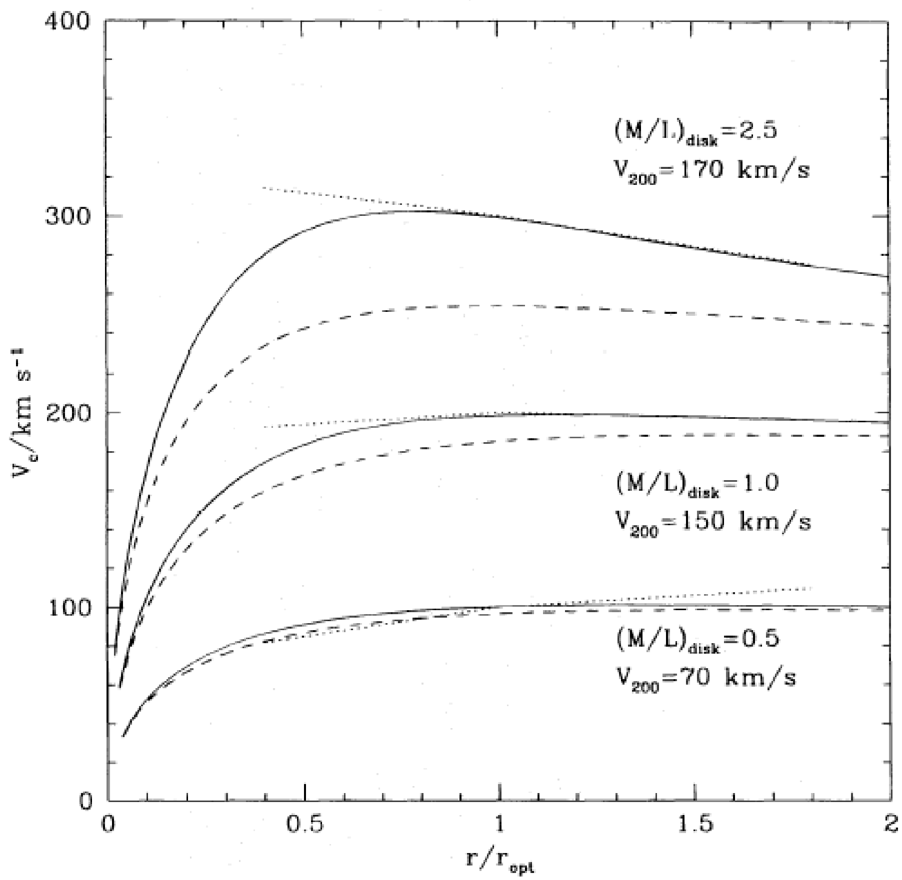


FIG. 11.—Rotation curves of disk + halo systems (*solid lines*) with parameters chosen to match the observational data of Persic & Salucci (1995) (*dotted lines*). The dashed lines indicate the contribution of the dark halo. Note that the disk mass-to-light ratio increases as a function of mass and that the halo contribution is less important in bright galaxies.

Rotation Curves of Dwarf Galaxies

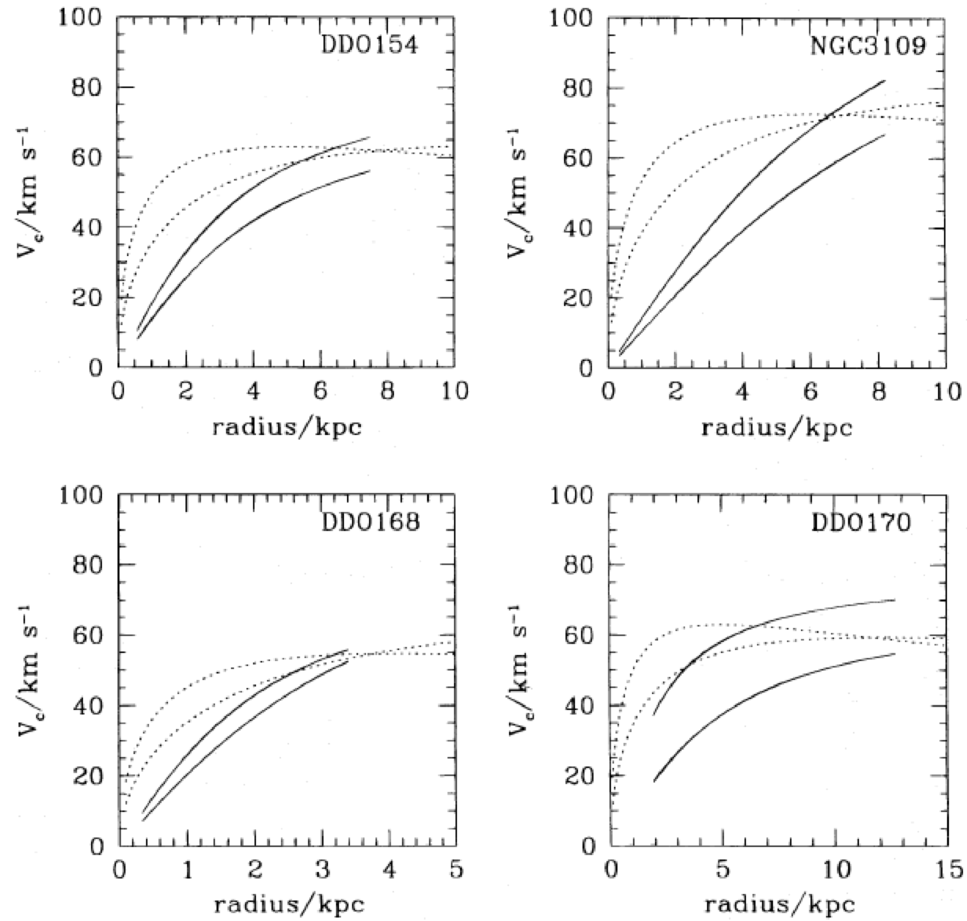


FIG. 12.—Circular velocities of CDM halos (*dotted lines*) compared with the halo contribution to the rotation curve of four dwarf galaxies (*solid lines*). The solid lines encompass the likely contribution of the halo and correspond to the "maximal" and "minimal" disk hypotheses. CDM halos seem to be significantly more concentrated than allowed by observations.

Rotation curves of dwarf galaxies do not match circular velocities of CDM halos at the center (core instead of cusp at the center).

Galaxy Cluster DM Halo Profile

Ideal gas law

$$p(r) \propto \rho_g(r)\, T(r)$$

Hydrostatic equilibrium

$$\frac{d\,p(r)}{d\,r} \propto -\frac{M(<r)\,\rho_g(r)}{r^2}$$

Total mass

$$M(<r) = f(\rho_g, T)$$

DM halo profile can be obtained from the X-ray data of the gas

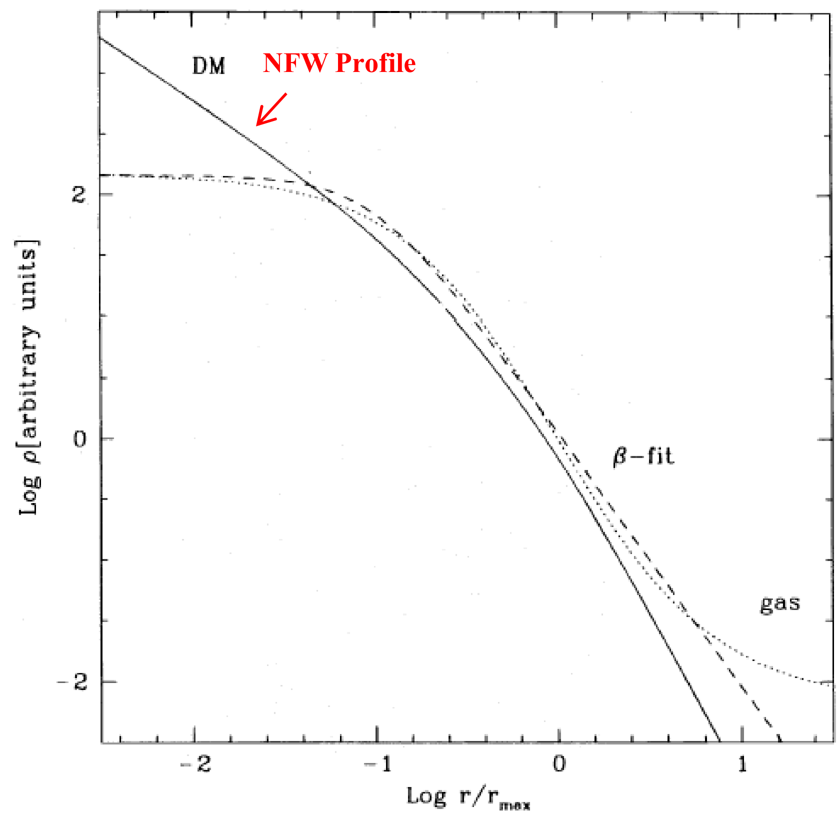


FIG. 14.—Density profile of an isothermal gas (*dotted line*) in hydrostatic equilibrium within a CDM halo whose structure is given by eq. (3) (*solid line*). The dashed line indicates a fit using the β model. The parameters $r_c = 0.1 r_{max}$ and $\beta = 0.7$ give an excellent β-model fit to the gas profile.

NFW provides good fits to galaxy cluster DM halos

Recent Data confirm Cluster NFW Profile

Question 1: Does the NFW model provide a statistically acceptable description of the total mass (dark+luminous matter) profiles in the clusters?

$$\rho(r) = \frac{\rho_0}{(\frac{r}{r_s})(1 + \frac{r}{r_s})^2}$$

Result 1: **YES! The NFW provides a good description of the data (32/34).**

Schmidt & Allen 2007, MNRAS 379, 209

Question 2: Can a singular, isothermal (SI) density profile provide a statistically acceptable description of the total mass profiles in the clusters?

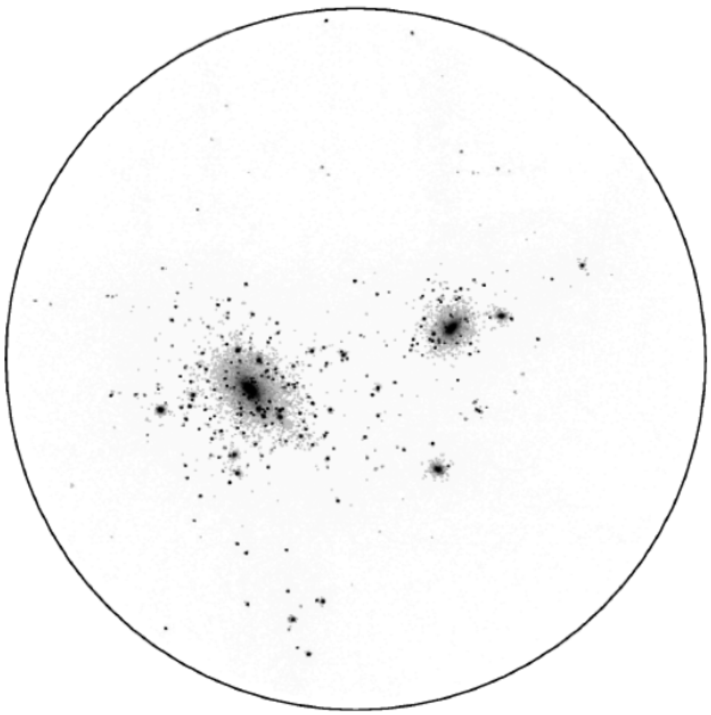
$$\rho(r) = A/r^2$$

Result 2: **NO! The SI model is completely rejected in almost every case (32/34)**

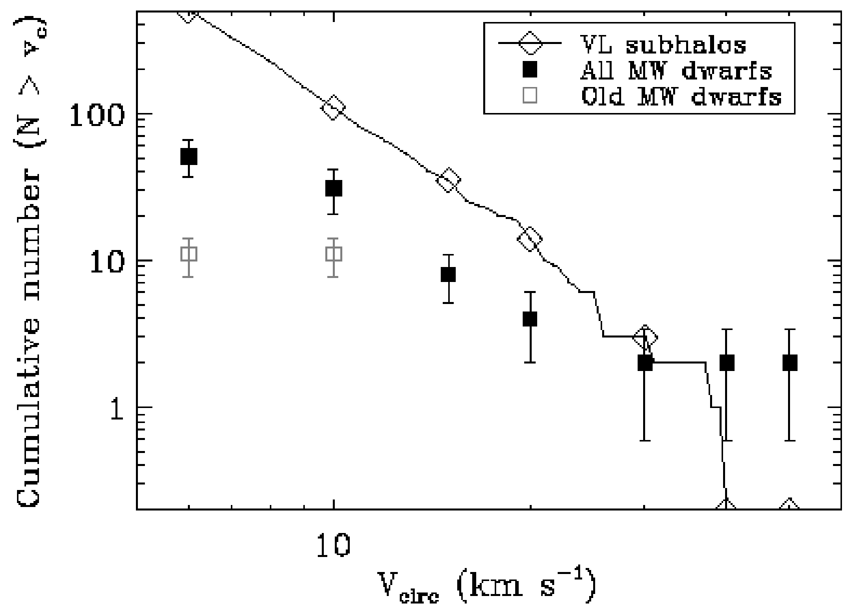
S. Allen, SSI 2007

Possible Shortcoming

Prediction of more DM halos than observed galaxies



Klypin et al. 1999, ApJ,522,82



Simon & Geha, 2007, ApJ, 670, 313

Recent discoveries of ultra-faint MW satellite galaxies suggest this might not be a problem.

Possible Shortcoming

Prediction of cusp in the center of DM halos

- Recent observations of nearby galaxies indicate a core dominated profile is clearly preferred over a NFW cusp type halo for many low-mass disk galaxies.
- The observations favor a Kpc-size core of roughly constant density DM at the center of low-mass disk galaxies

Recent observations confirm that a cusp type halo is inconsistent with the core of low-mass galaxies.

Primack 2009

Summary

- N-body simulation to study DM halos in CDM cosmology.
- A universal profile fits halos ranging from those of dwarf galaxies to rich galaxy clusters.

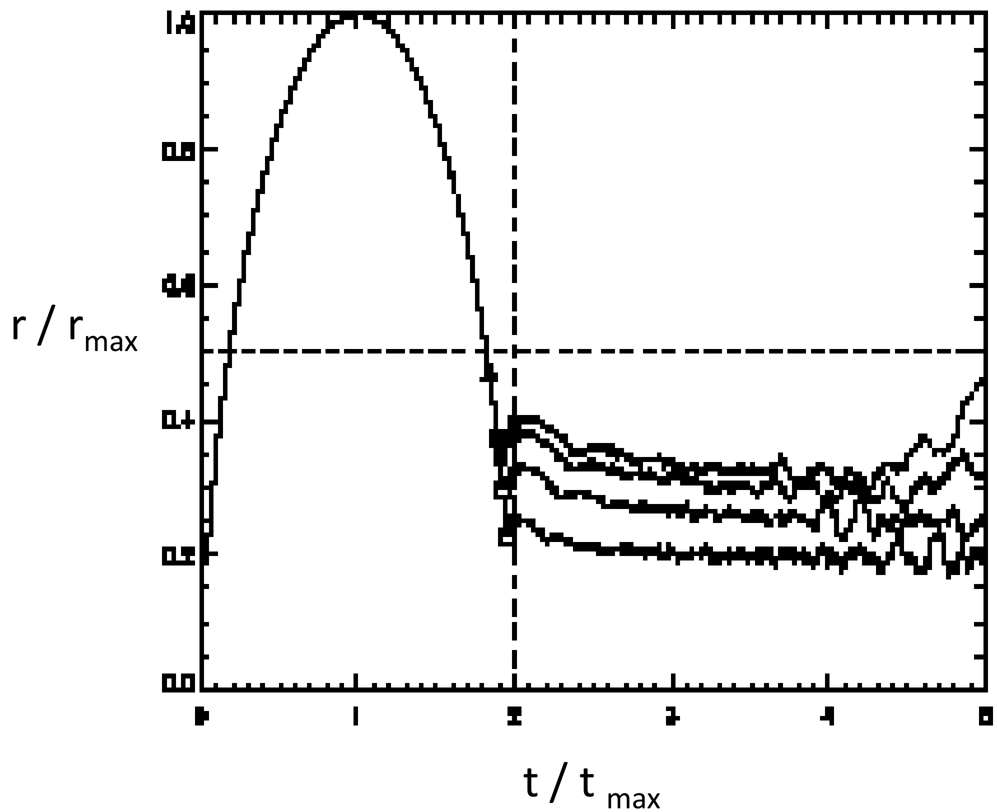
$$\rho\,(r) \propto 1\,/(r/r_s)\,[1 + (r/r_s)]^2$$

- Possible shortcomings:
  - Cusp in the center
  - Prediction of more halos than observed galaxies (might not be a problem now)

WIMP assumption provides a good match to observed DM halo profiles. Strong evidence for DM instead of other alternatives.

Backup Slides

Evolution of the Halo : Effect of Shell-Crossing



Sanchez-Conde et al. 2007, MNRAS, 378,339