Structure of Dark Matter Halos from Hierarchical Clustering

Toshiyuki Fukushige(Univ. of Tokyo)

Internal Structure of Dark Matter Halo

Initial Density Fluctuation (predicted by cosmology)

$\downarrow$

$\downarrow$ Cosmological Collisionless Collapse

$\downarrow$ Hierarchical Clustering

$\downarrow$

Dark Matter Halo (+ Satellites)

by Cosmological N-body Simulation

(animation)

Cusp/Core Problem

(Theoretical Prediction:) CDM cosmological simulation

by Navarro, Frenk, White (1996, 1997)

NFW Universal Density Profile ($\alpha = 1$)

$$\boldsymbol{\rho} \propto \frac{\mathbf{1}}{(\boldsymbol{r}/\boldsymbol{r}_0)^{\boldsymbol{\alpha}}(\mathbf{1} + \boldsymbol{r}/\boldsymbol{r}_0)^{\mathbf{3}-\boldsymbol{\alpha}}}$$

"Cusp"

$\Updownarrow$

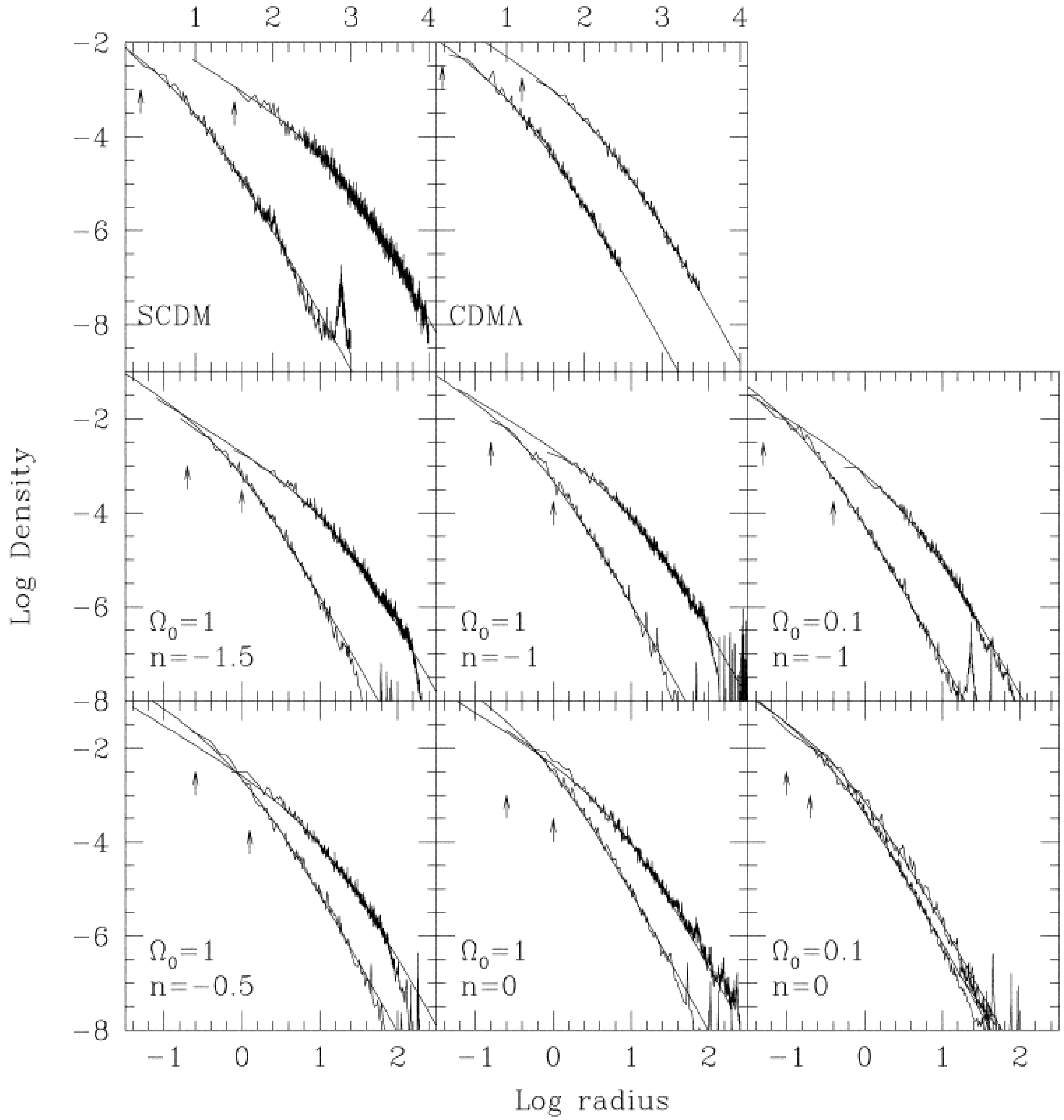
Observation: Density Profile from Rotation Curve

of Low Surface Brightness (LSB) Galaxies

(Flores, Primack 1994, Moore 1994)

"Core"

NFW Universal Profile (NFW 1997)



independent of halo mass, initial density fluctuation spectrum, and values of the cosmological parameters

Dubinski and Cerlberg (1991)

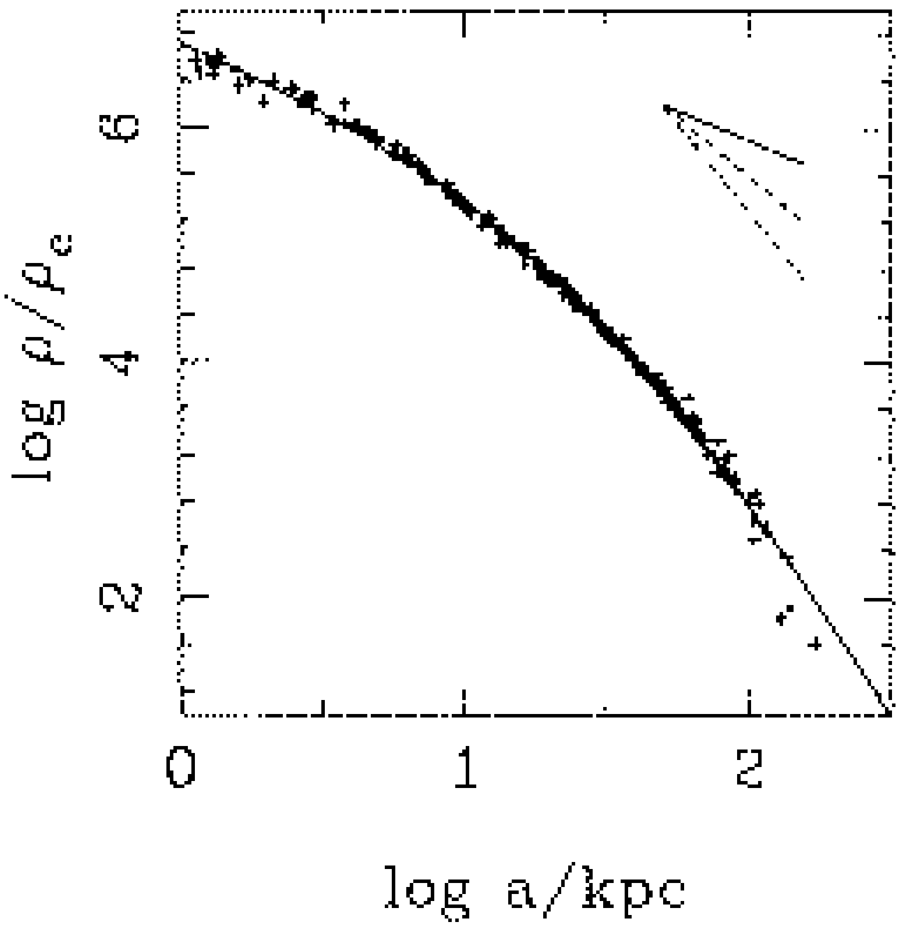
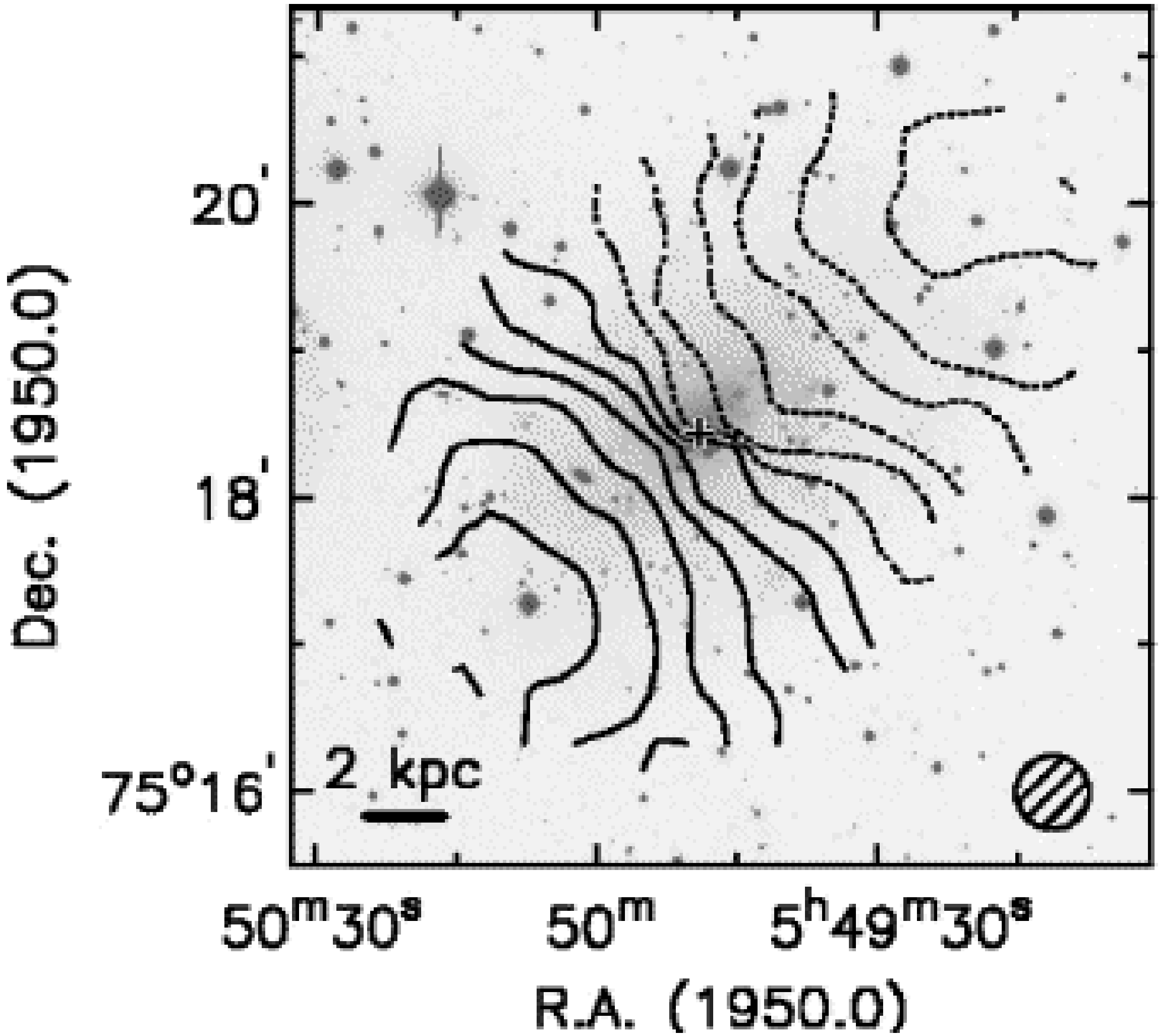


FIG. 2.—Density profiles of dark halos. Density is in units of the critical density ρ_c, and the elliptical radius a is in kpc. Thirteen points were used for the two-parameter fit of Hernquist's profile for each of the 14 halos. Each set of points has been renormalized to the fiducial Hernquist profile, with $r_s = 28$ kpc and $M_s = 2.1 \times 10^{12}\ M_\odot$ represented by the solid line. The lines in the upper right-hand corner present power-law slopes of −1, −2, and −3, respectively.

LSB Galaxy

ex. DDO39 (Swaters et al. 2003)



LSB Galaxy Rotation Curve

from Flores and Primack (1994)

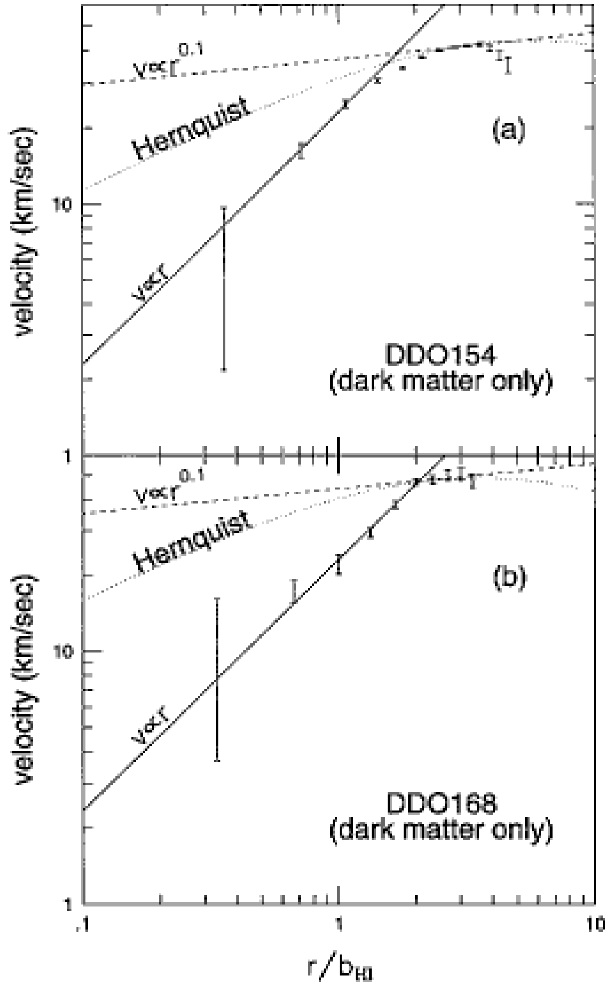
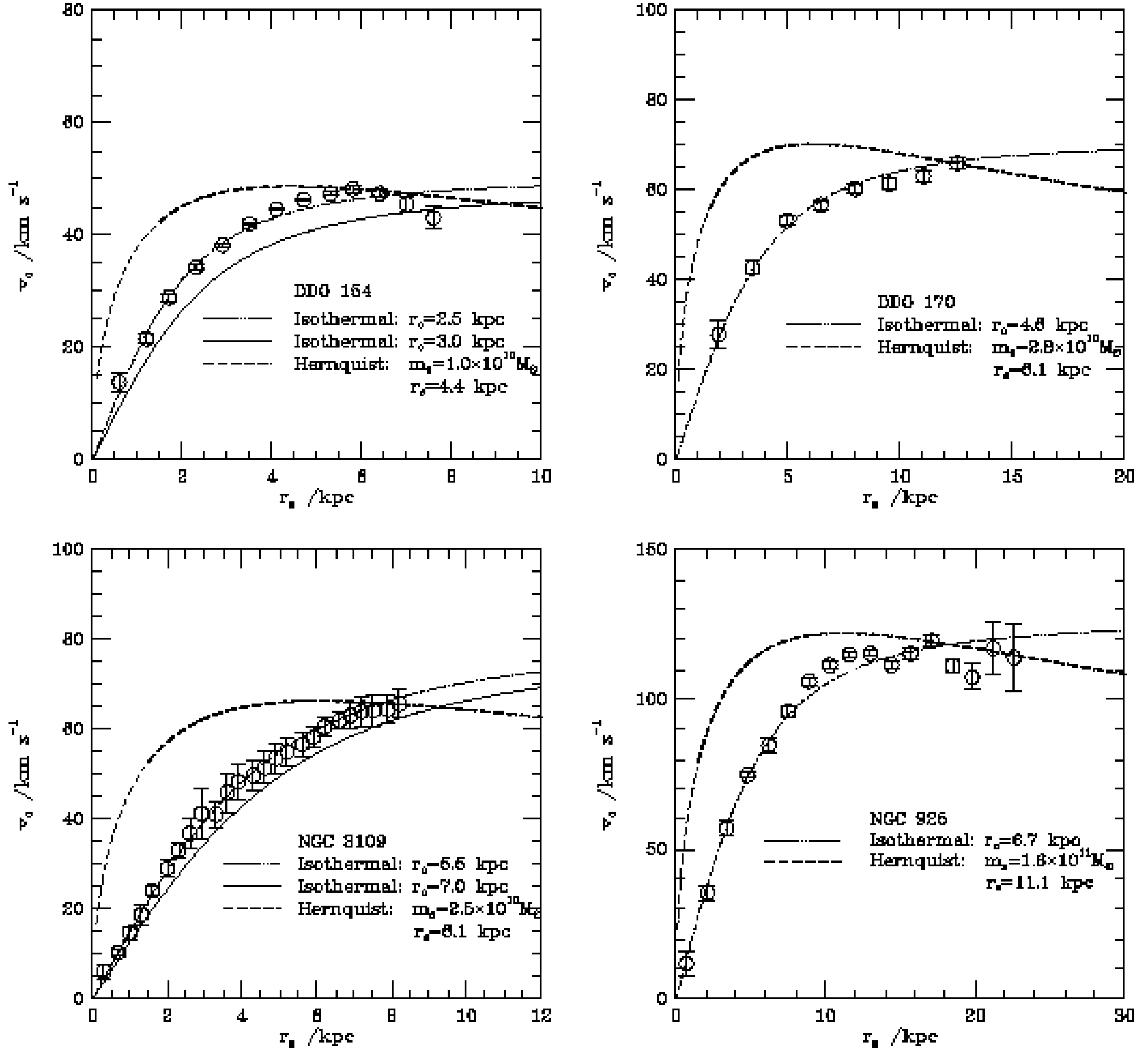


FIG. 1.—DM contribution to the circular velocity about the center of (*a*) DDO 154, and (*b*) DDO 168, both as a function of distance from the center in units of the H I–disk scale length. The circular velocity plotted was obtained by subtraction from the data of the contribution due to the two luminous matter components (see text). The lines show the radial behavior expected if the dark matter had a Hernquist (*dotted line*), $r^{-1.8}$ (*dashed line*), or constant (*solid line*) density profile.

LSB Galaxy Rotation Curve (continued)

from Moore (1994)



Cusp/Core Problem

(Theoretical Prediction:) CDM cosmological simulation

by Navarro, Frenk, White (1996, 1997)

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$$\rho \propto \frac{1}{(r/r_0)^{\alpha}(1 + r/r_0)^{3-\alpha}}$$

"Cusp"

$\Updownarrow$

Observation: Density Profile from Rotation Curve

of Low Surface Brightness (LSB) Galaxies

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Right ????

$\Updownarrow$

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of Low Surface Brightness (LSB) Galaxies

"Core"

Reliable ????

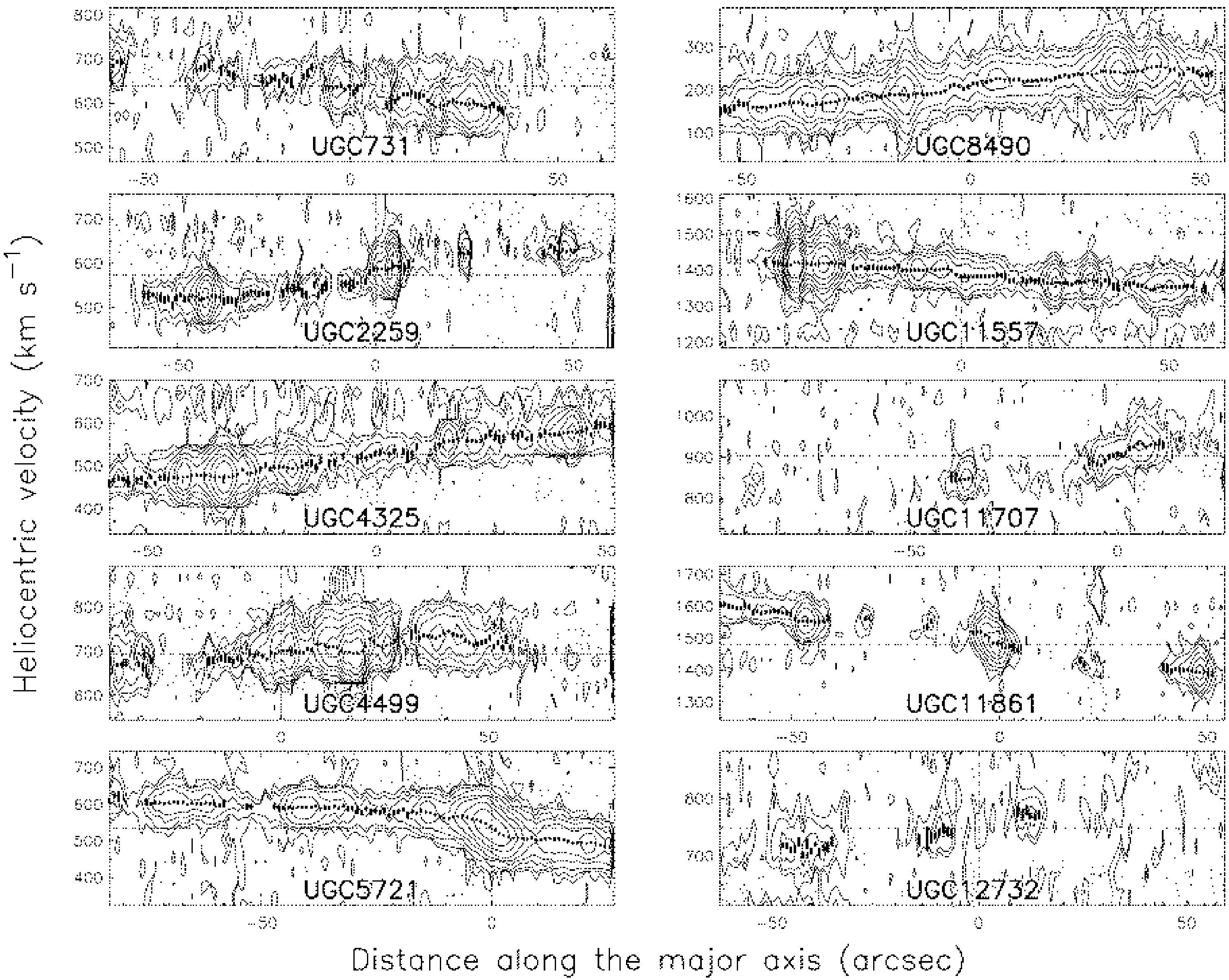
Reliability of LSB Galaxy Rotation Curve Observation

Early Suspicion on Observation

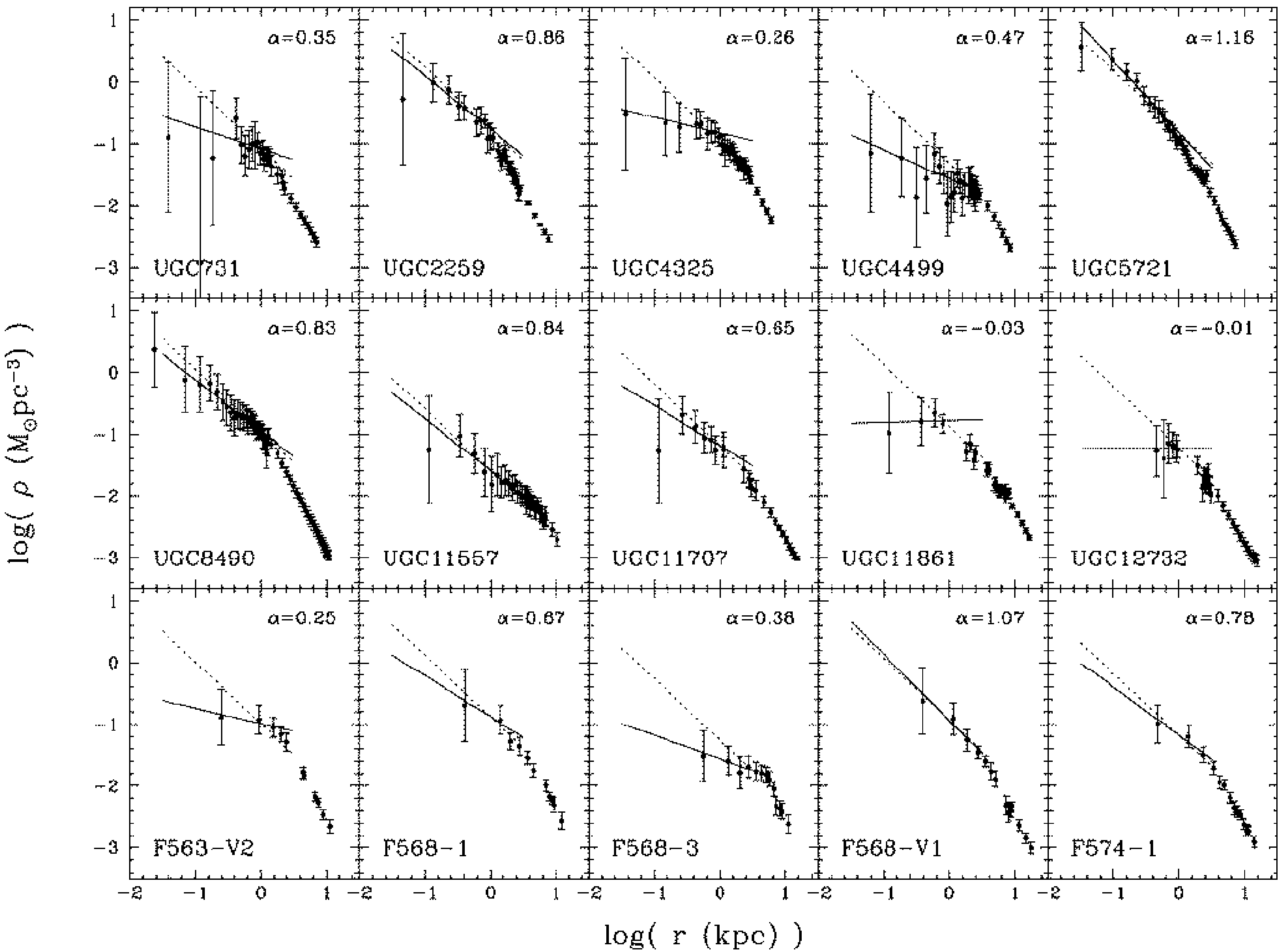
- Beam smearing
- Pointing error
- Small sample
- Duty sample
- Inconsistency among observers
- etc..

de Blok (2003): These problems no more exist.
Data prefer soft cores ($0 < \alpha < 1$)

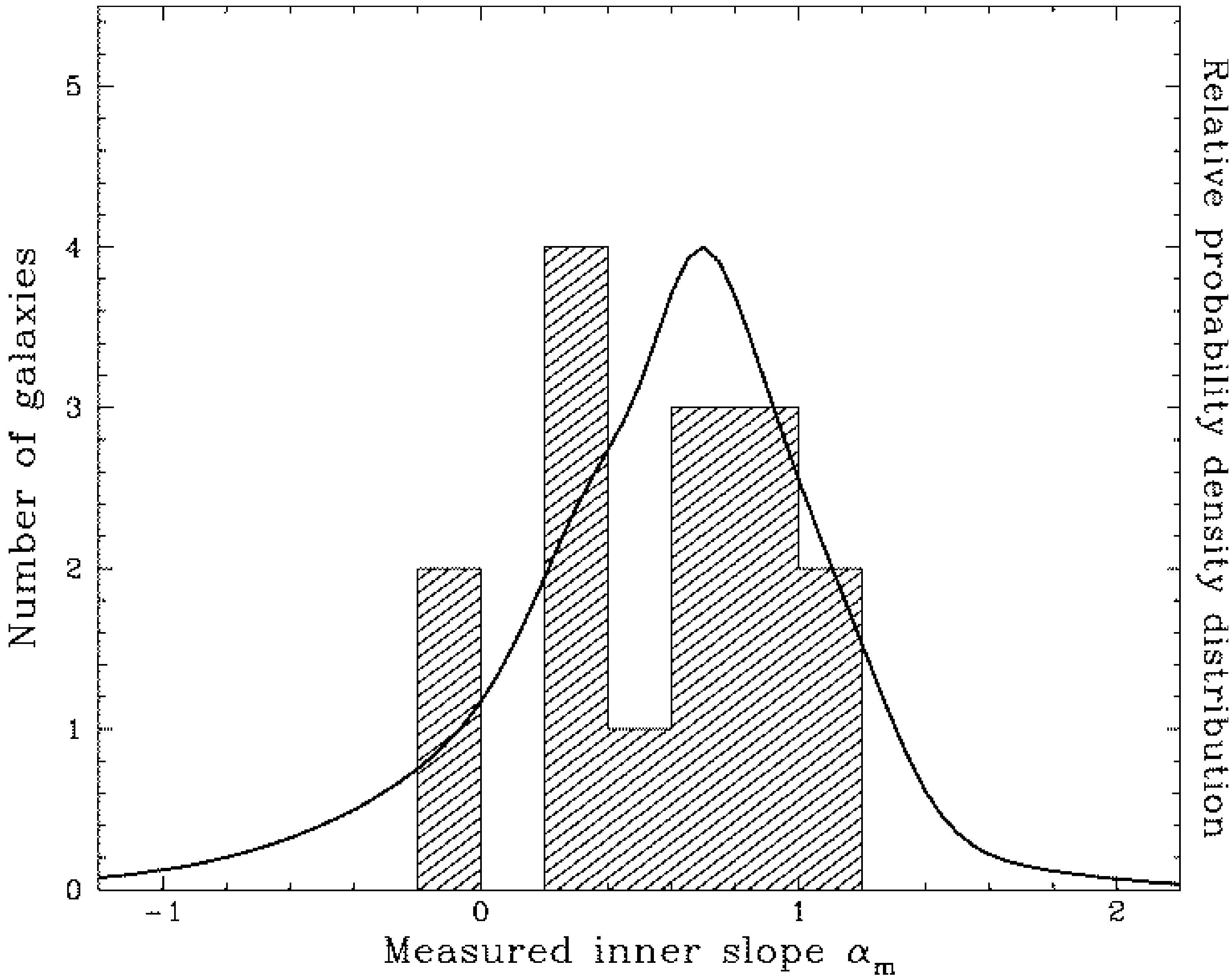
Swaters et al. (2003)



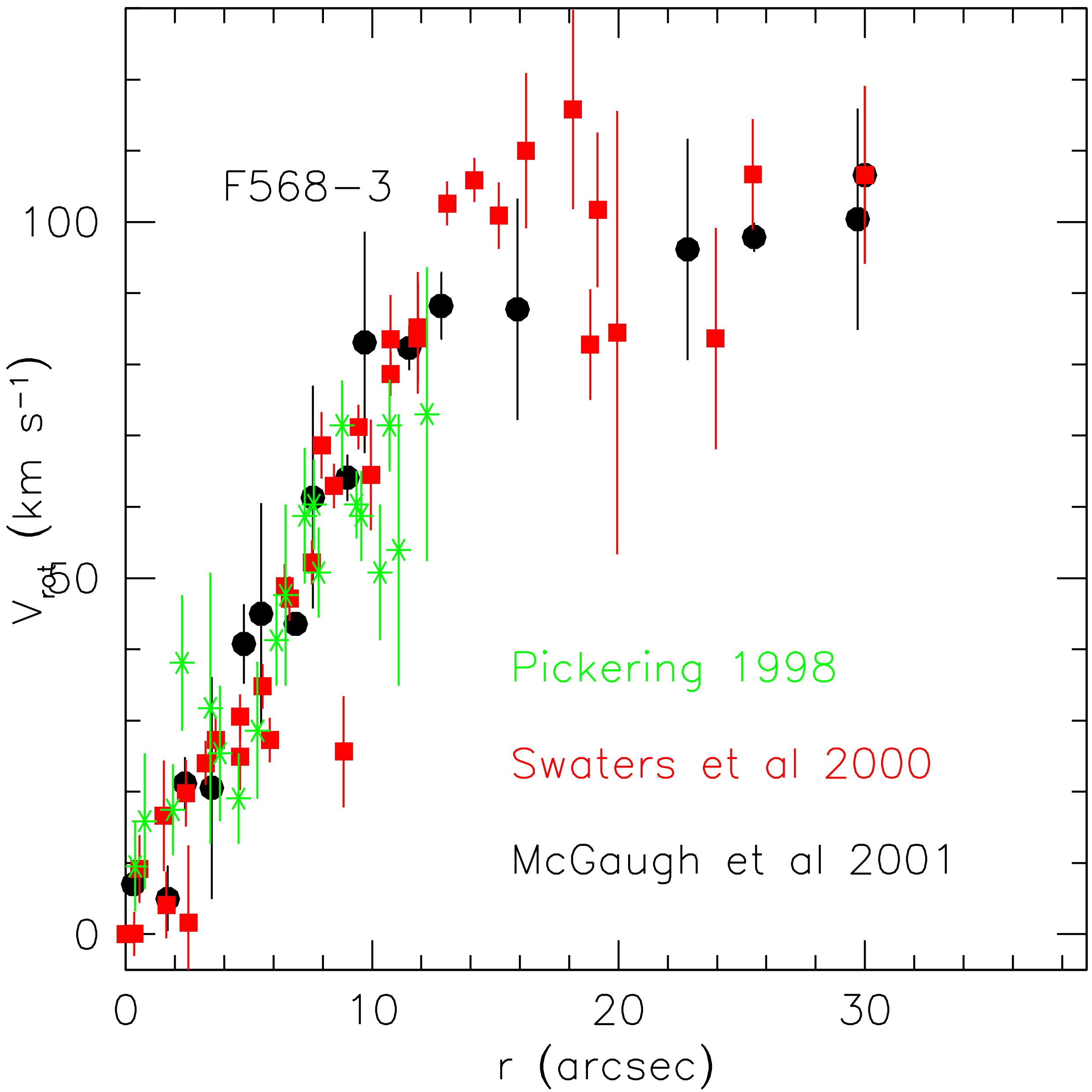
Swaters et al. (2003) (continued)



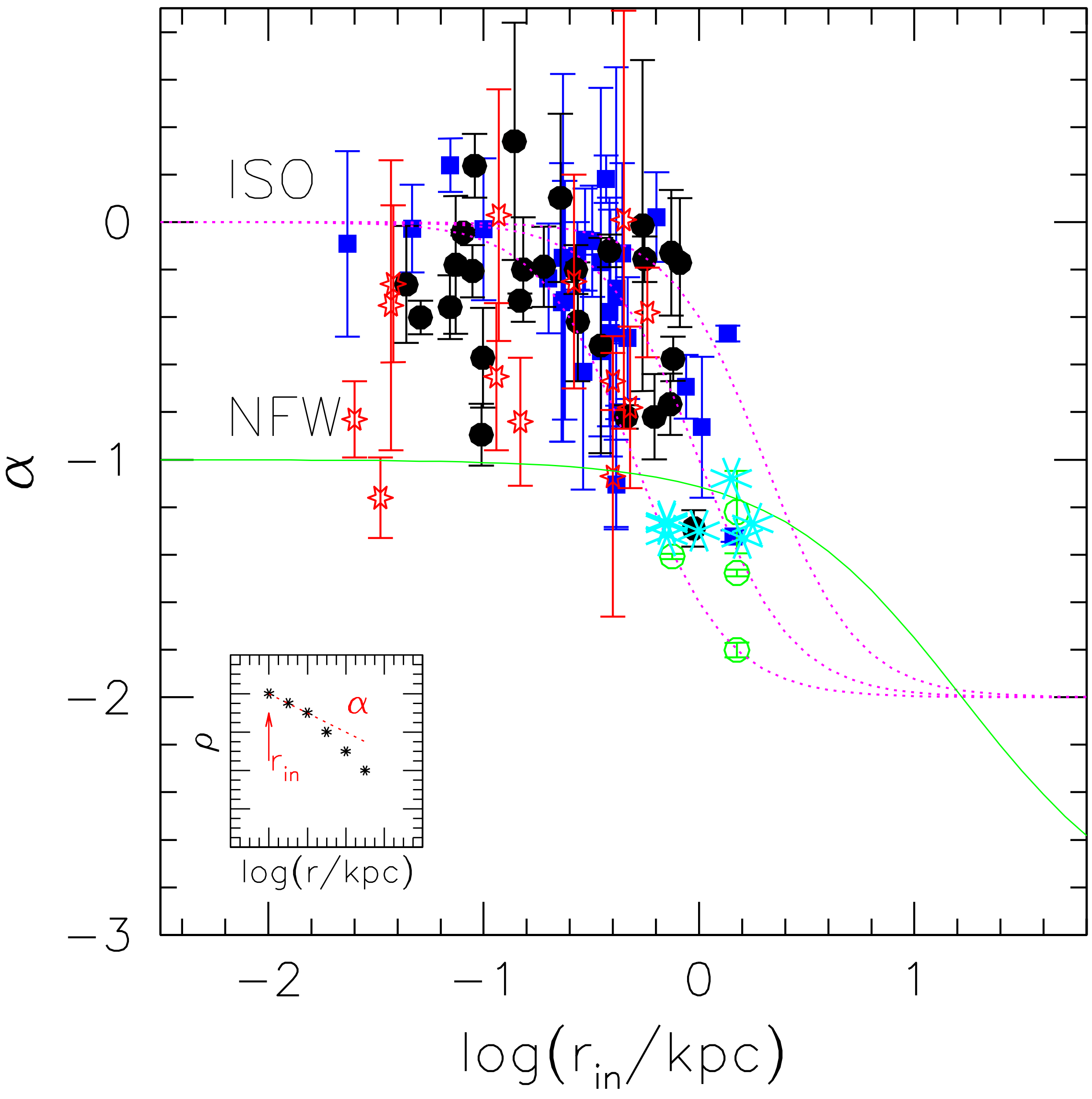
Swaters et al. (2003) (continued)



de Blok (2003)


F568-3
Pickering 1998
Swaters et al 2000
McGaugh et al 2001
0
50
100
0
10
20
30
V_{rot} (km s^{-1})
r (arcsec)

de Blok (2003) (continued)



Validity of NFW's Prediction

- Final Product of Non-Linear Structure Formation
- Universal? or Initial Condition Dependence?
- From Simulation, No Theory nor Modeling
- Alternative Dark Matter
- Reliability of Their Simulation
  - Reliable?
  - Validity Range

Trials for Theory or Modeling

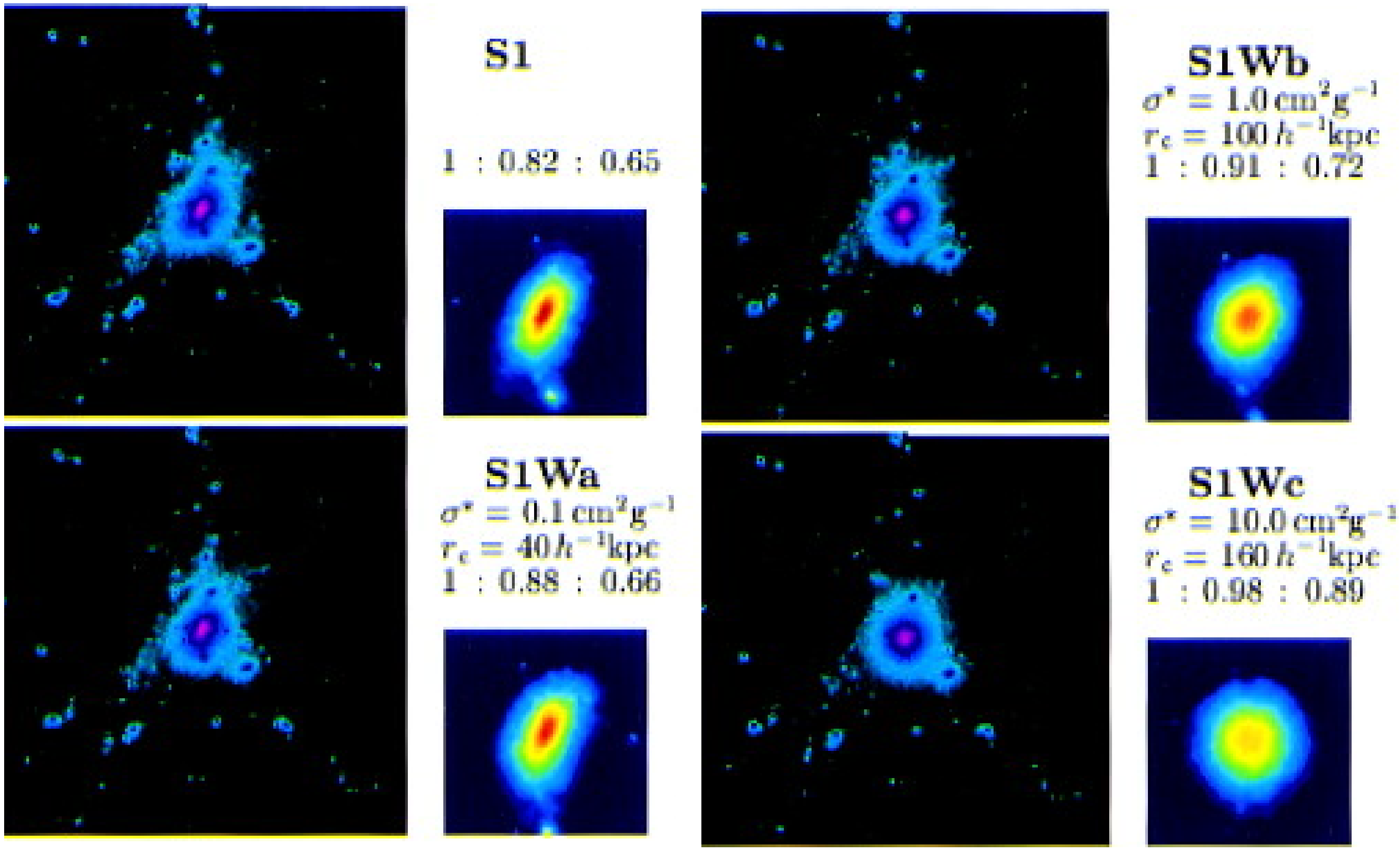
Evans, Collet (1997)
Syer, White (1998)
Avila-Reese, Firmani, Hernandez (1998)
Nusser, Sheth (1999)
Kull (1999)
Heriksen, Widrow (1999)
Yano, Gouda (1999)
Subramanian, Cen, Ostriker (2000)
Lokas (2000)
Bullock et al. (2001)
Taylor, Navarro (2001)
etc.

No Successful Explanation for Universal Profile

Alternative Dark Matter Model

ex. Self-Interacting Dark Matter (Spergel, Steinhardt 2000)

Yoshida et al. (2000)



Small cross section to explain core and roundness of galaxies cluster.

$\Updownarrow$

Large cross section to explain core of dwarf LSB galaxy.

Reliability of Simulation

Claim from Higher Resolution Simulation
$[N \sim 10^6, r_{\rm lim} \sim 0.01 r_{\rm v}$(~ 30kpc for cluster, 1kpc for galaxy)]

- Fukushige, Makino (1997, 2001, 2003)
- Moore et al. (1998, 1999), Ghigna et al. (2000)

  Universal, but $\alpha = 1.5$

- Jing, Suto (2000)

  Not universal: galaxy to cluster : $\alpha =$ 1.5 to 1.1

- Navarro (2001), Klypin (2001)

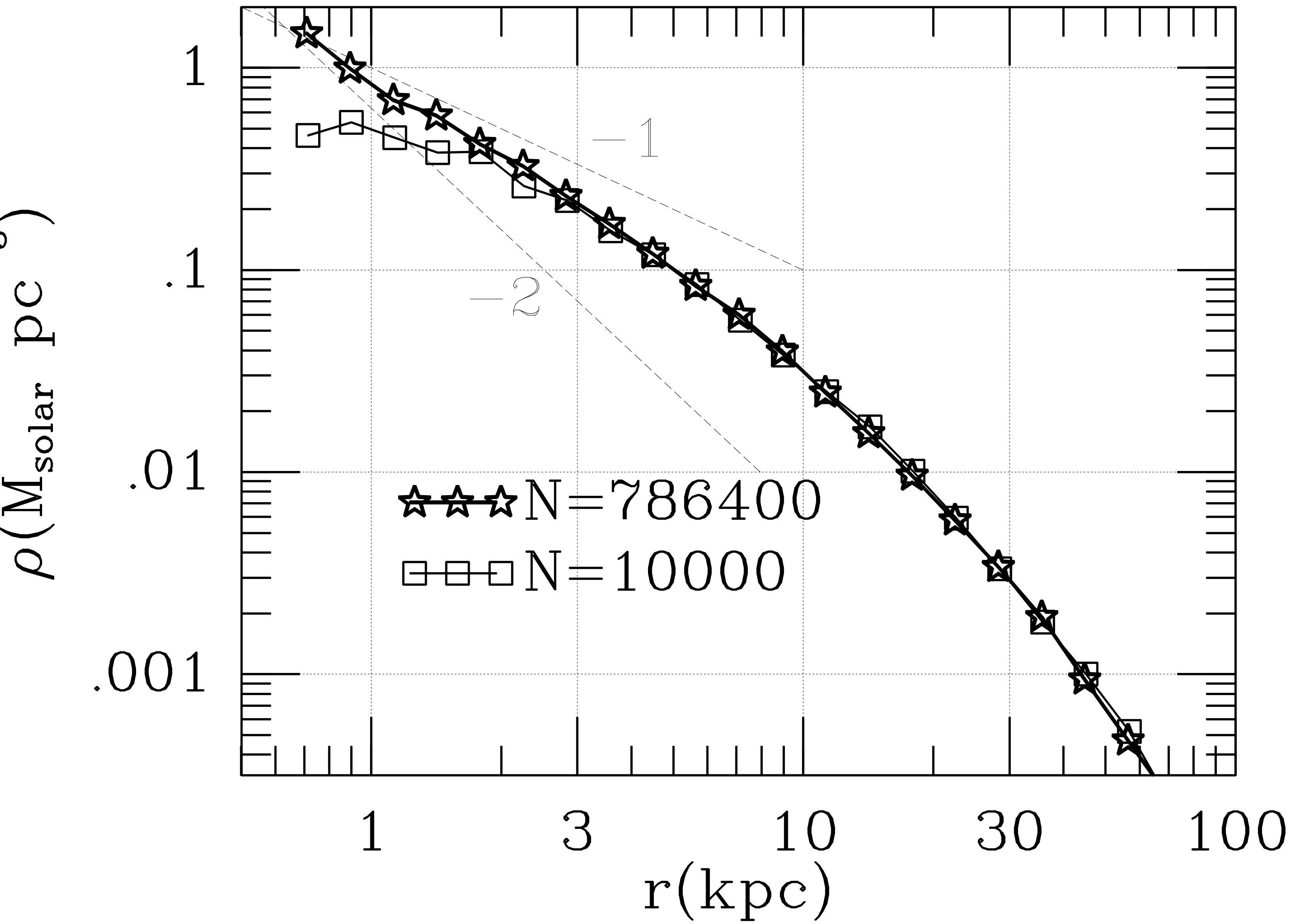
  Still can fit by NFW model with small r_0

  Inner slope shallower than -1.5

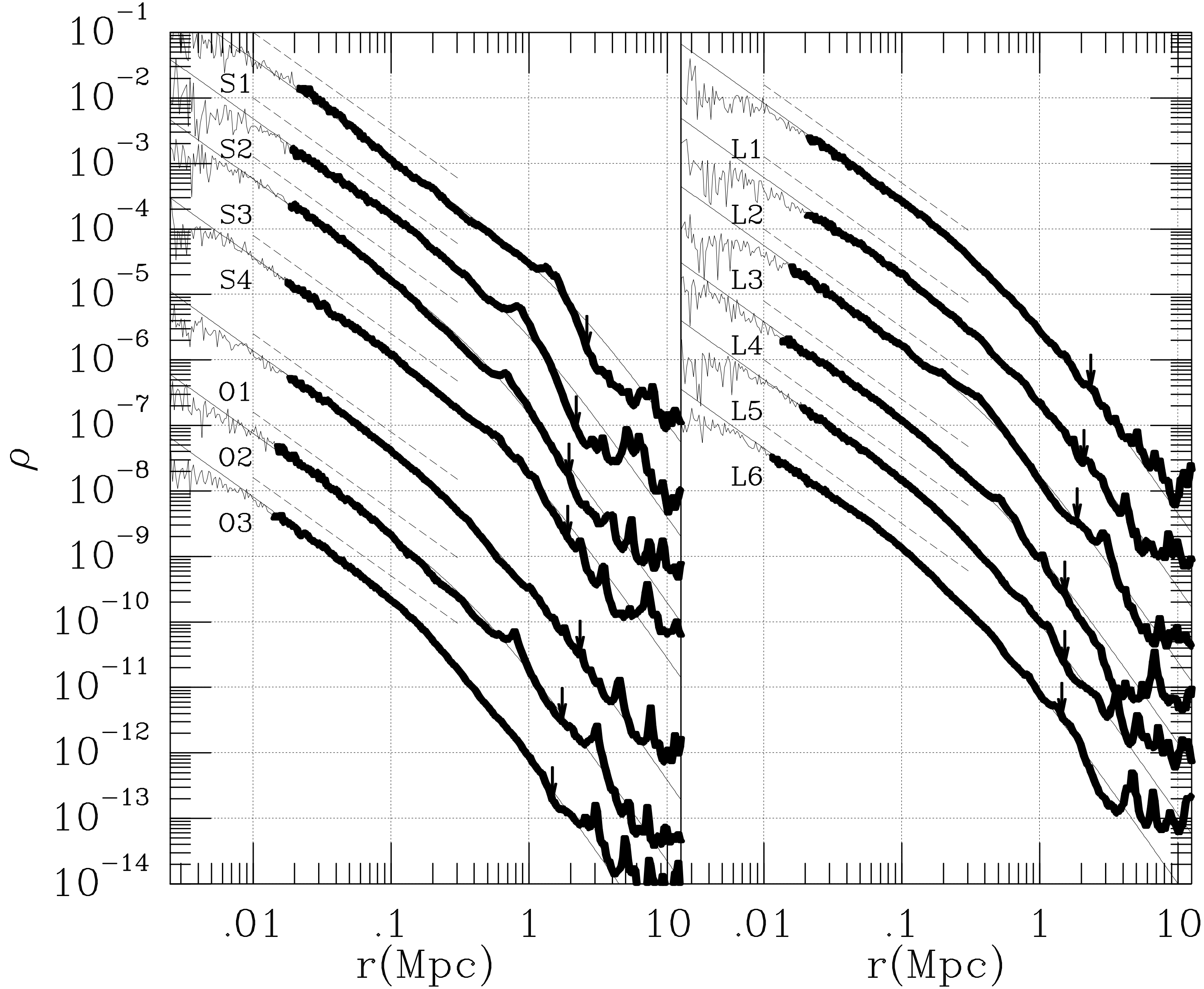
- Power et al. (2003)

  $\alpha = 1.2$

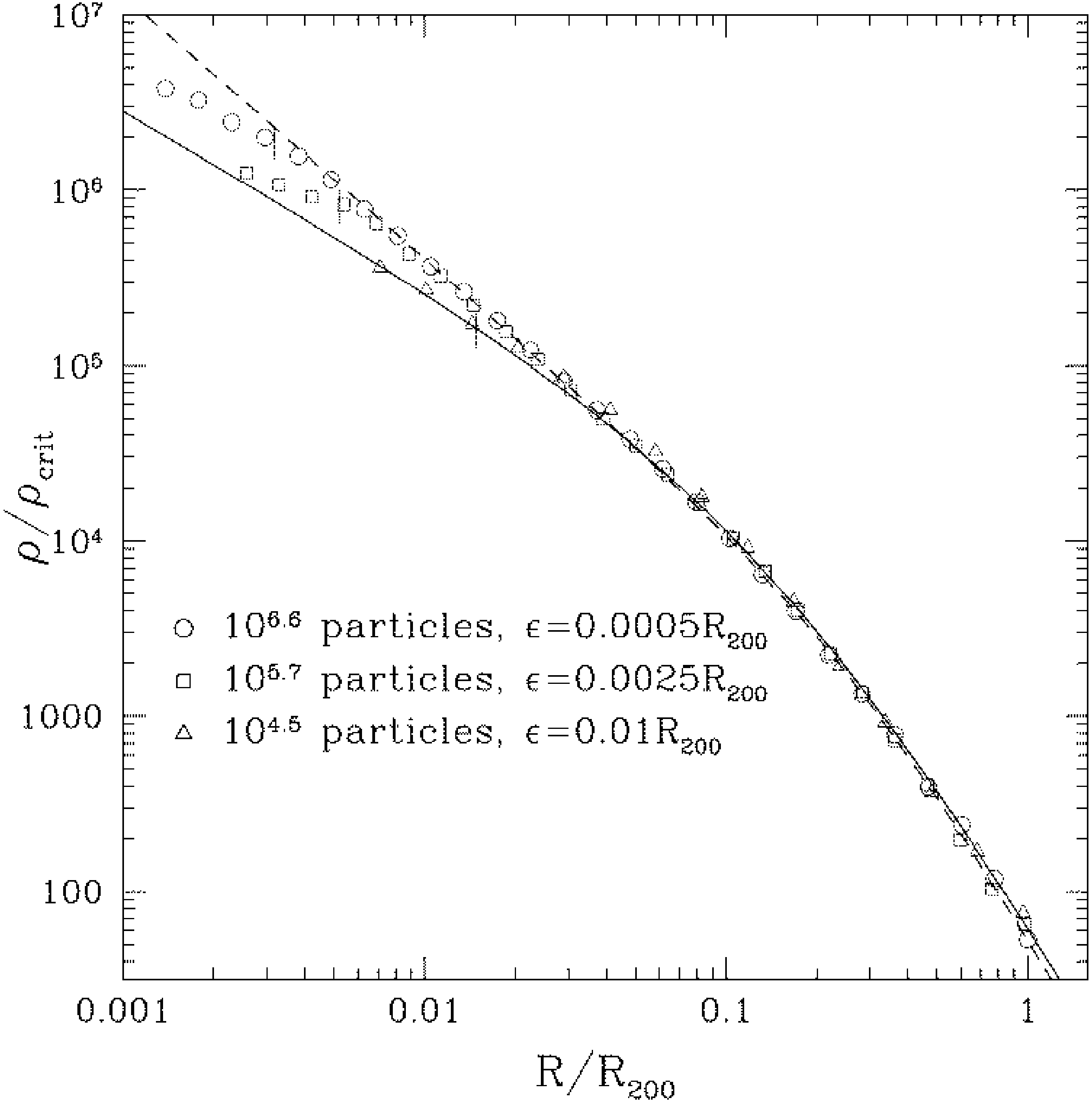
Fukushige, Makino (1997)



Fukushige, Makino (2003)



Ghigna et al. (2000)



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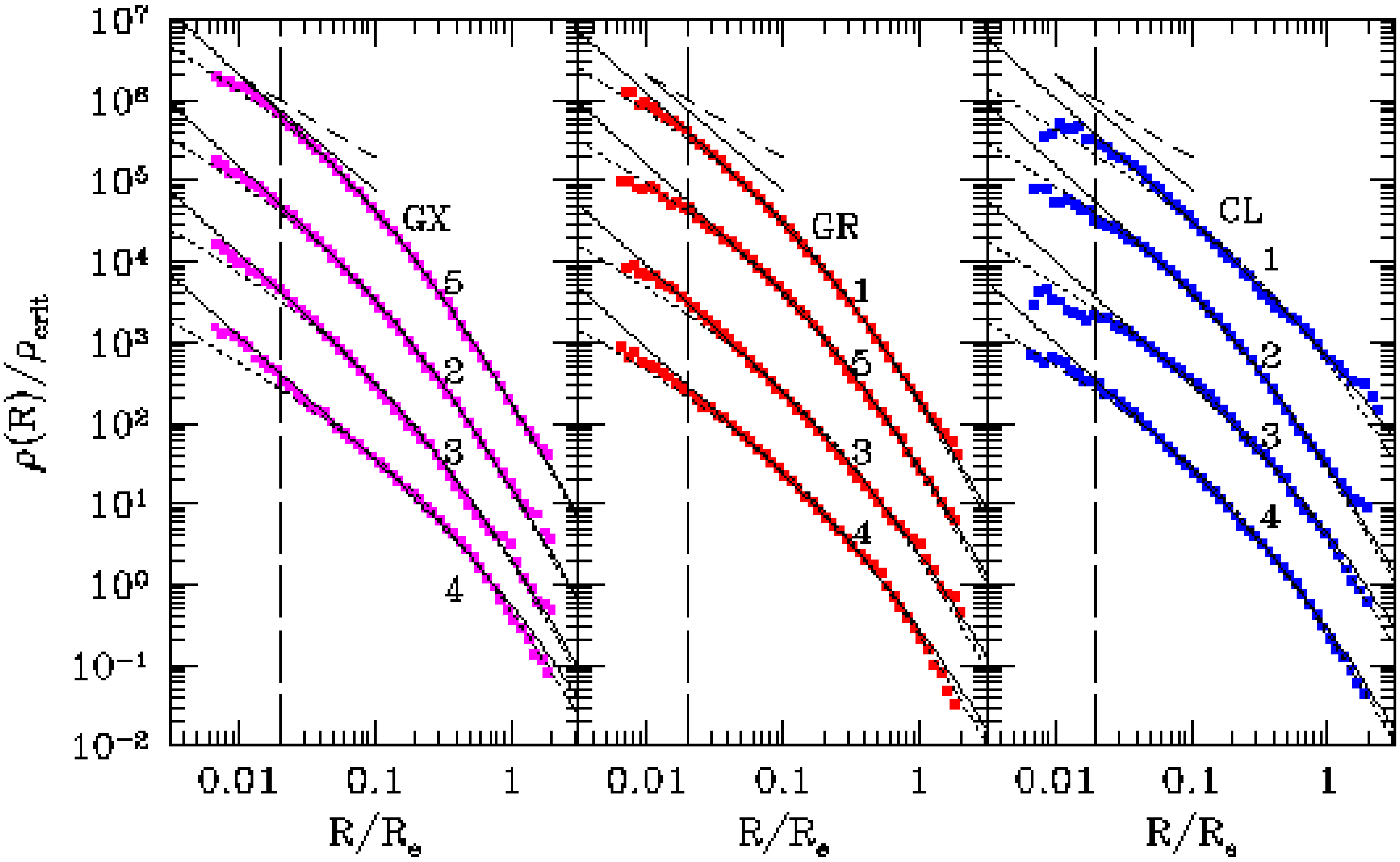
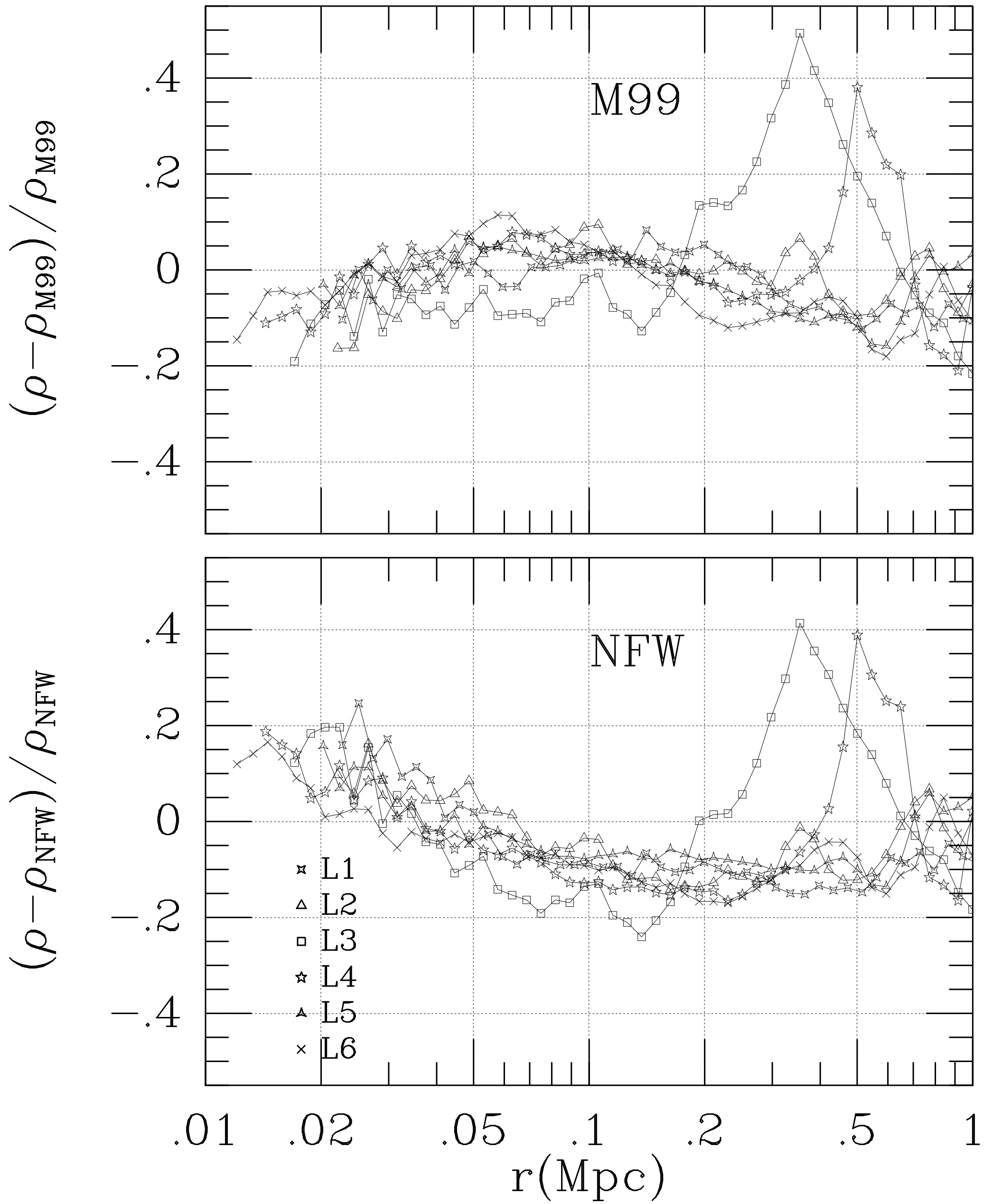


Fitting to M99 and NFW profile

from Fukushige, Makino (2003)



Why so difficult to obtain correct results?

Central cusp $\rightarrow$ High ρ

Many Sources of Numerical Error !!!

– Small N (Two-body relaxation)

– Large Stepsize in Time Integration

– Large Softening length

– Low Force Accuracy

– Small Initial Redshift, etc....

All Make Cusp Smoothed Artificially

Smoothing of Cusp in Small N Simulations

Smoothing by two-body relaxation

— Gravothermal expansion

Evolution by two-body relaxation depends on dv^2/dr

If $dv^2/dr < 0$ (ex. King model) : Contraction

If $dv^2/dr = 0$ (Isothermal) : Depend on initial perturbation

If $dv^2/dr > 0$ (ex. NFW, Hernquist model) : Expansion

Gravothermal Evolution

– Hachisu, Nakada, Nomoto, Sugimoto (1978) : Isothermal Gas Sphere

– Quinlan (1996): Hernquist Model

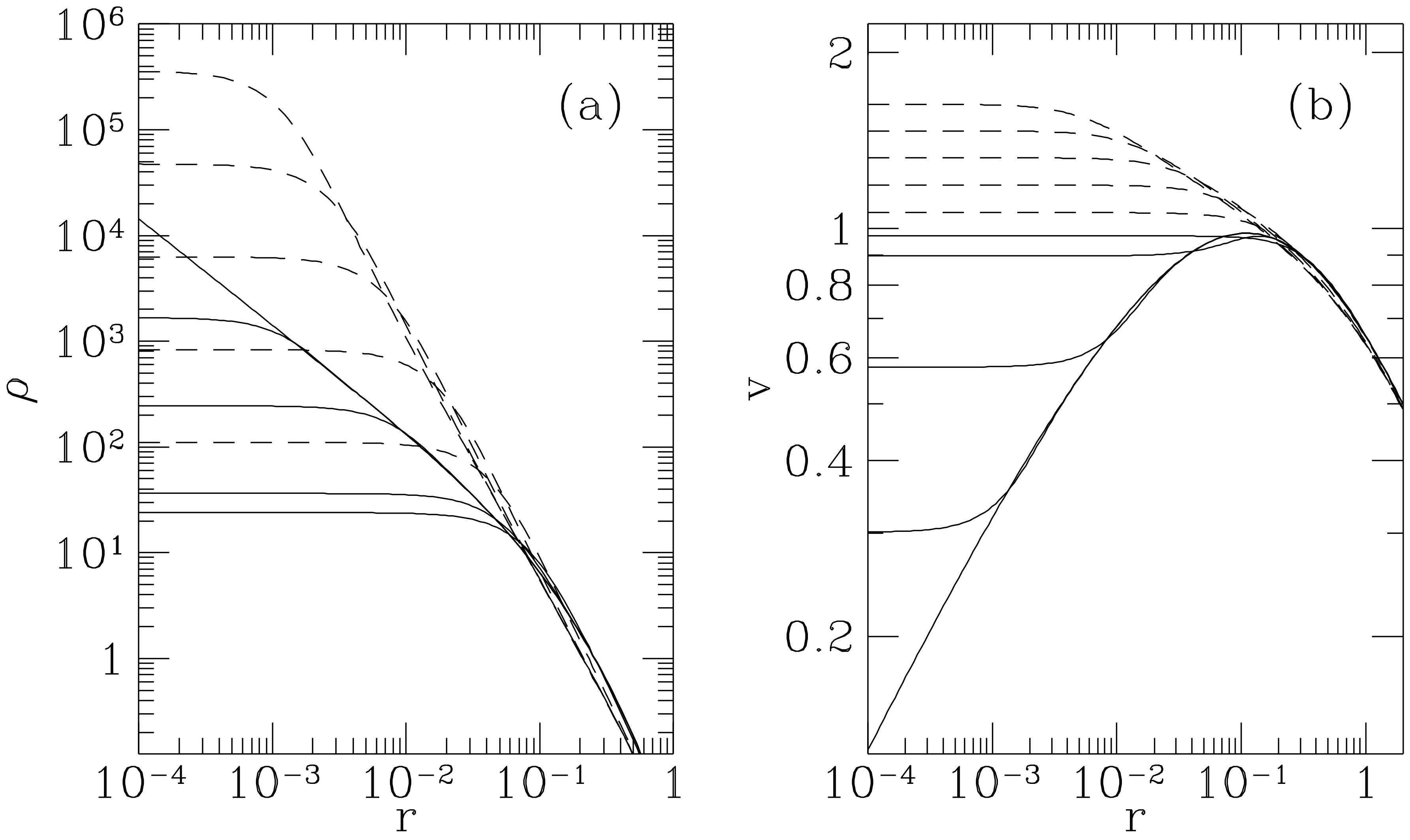
– Endo, Fukushige, Makino (1997): Isothermal N-body Model

– Moore et al. (1998): Halo Simulations

– Hayashi et al. (2003): Idealized Subhalo Simulations

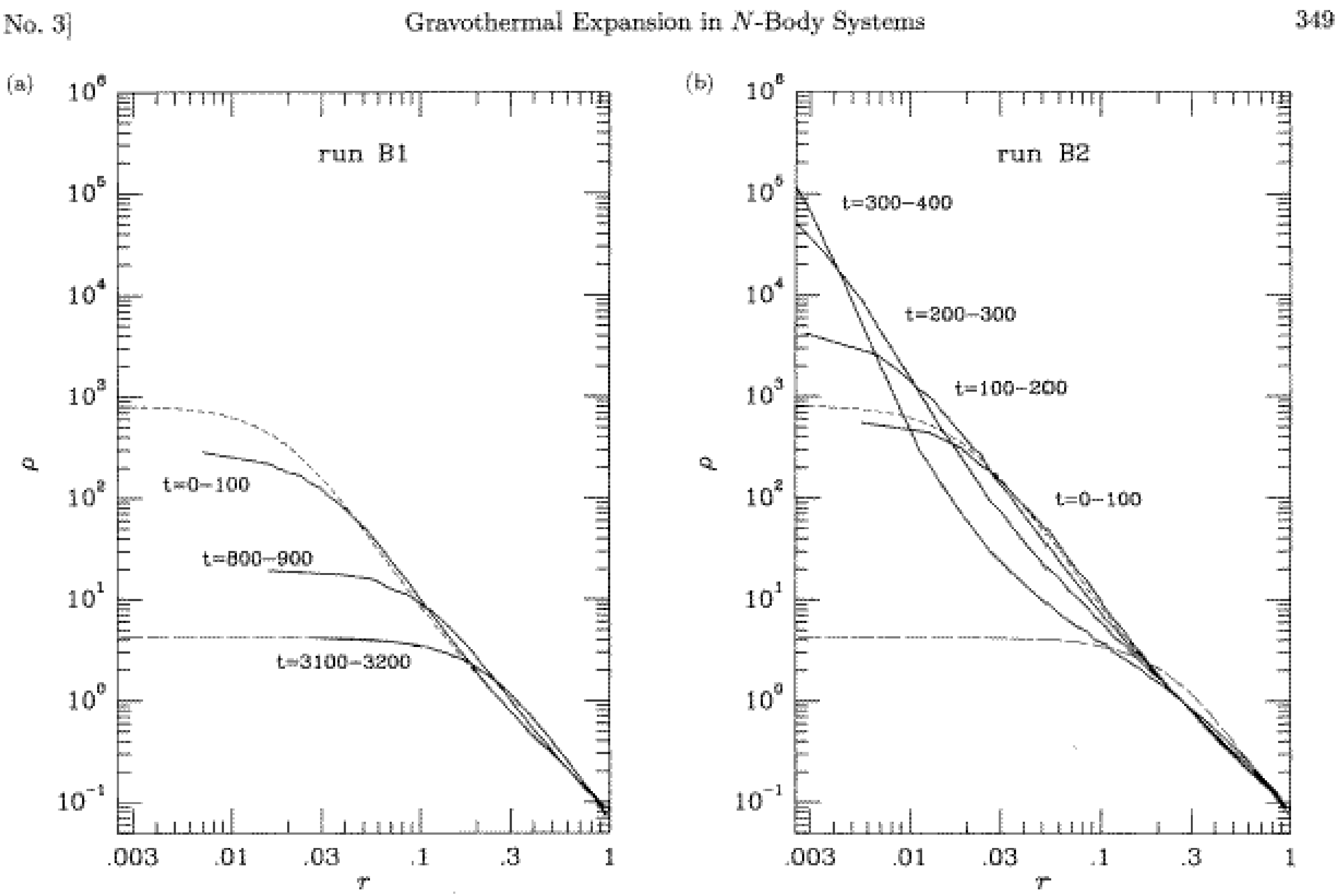
Gravothermal Expansion in Hernquist Model

(Quinlan 1996)



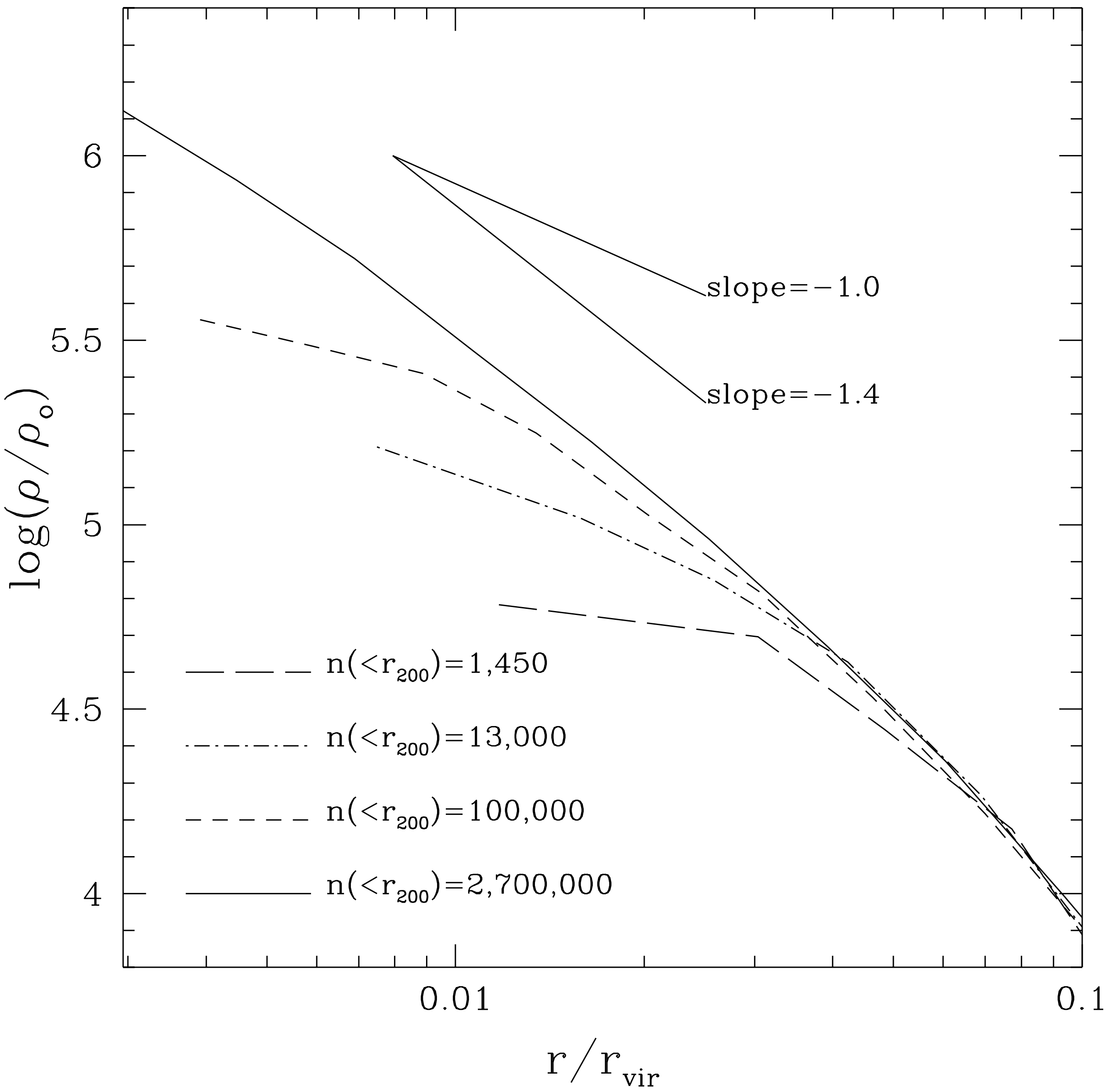
Evolution of Isothermal Sphere

(Endo, Fukushige, Makino 1997)



Gravothermal Expansion in Halo Simulations

(Moore et al. 1998)



True Profile vs. Numerical Smoothing

Accuracy Criteria (Fukushige, Makino 2001)

If the following criteria are satisfied,
the density at r is OK. (experimentally obtained)

- Two-body Relaxation: $t_{\rm rel}(r)/t > 3$

$$t_{\rm rel}(r) = \frac{0.065 v(r)^3}{m\rho(r)\ln(1/\varepsilon)}, \qquad t\text{: simulation span}$$

- Time Integration : $t_{\rm dyn}(r)/\Delta t > 40$

$$t_{\rm dyn} = \frac{1}{\sqrt{G\bar{\rho}(r)}}, \qquad \Delta t\text{: time step size}$$

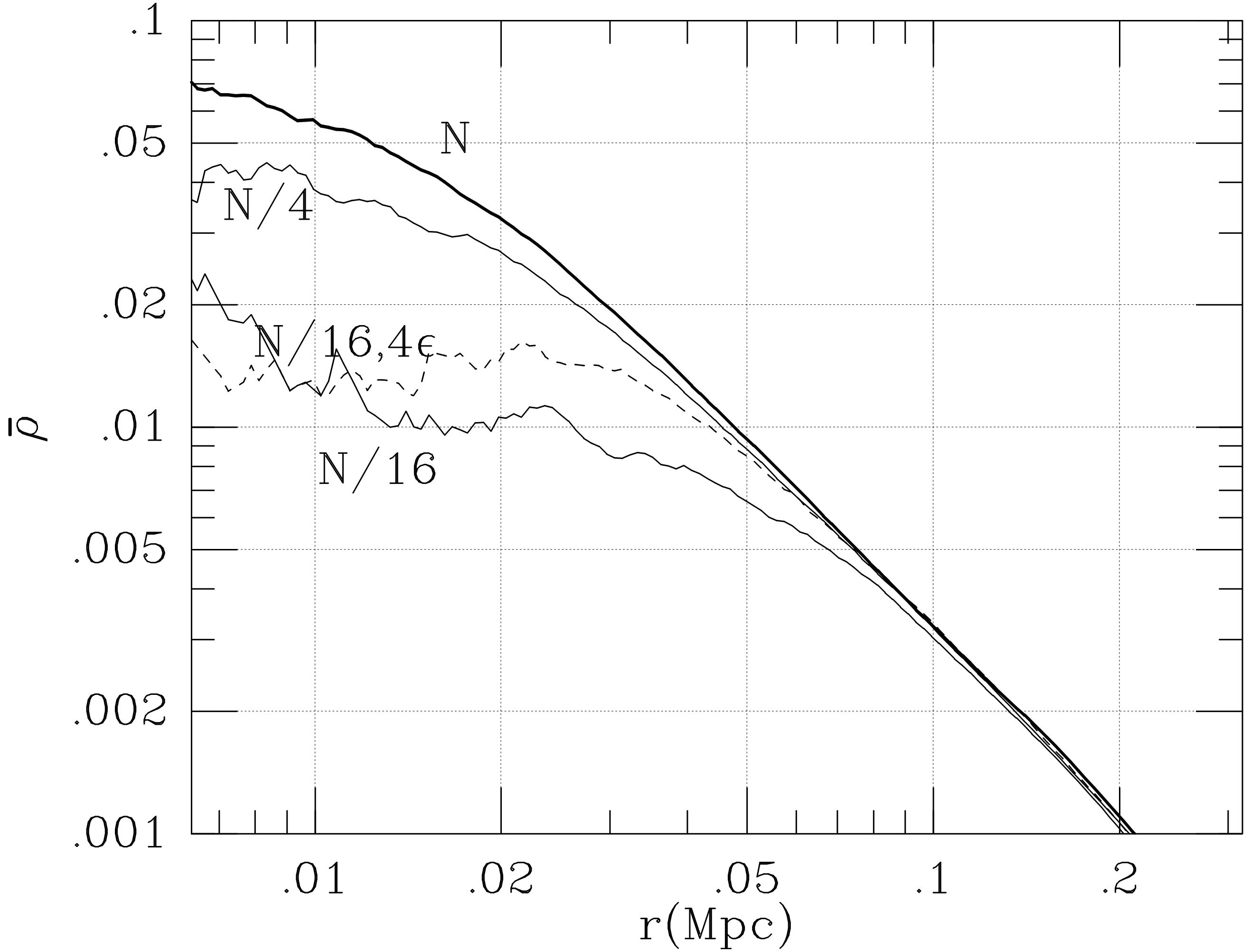
- Potential Softening: $r > 3\varepsilon$

  ε: softening length

Similar Accuracy Criteria (Power et al. 2003)

Accuracy Criterion on Two-body Relaxation

Smoothing Due to Two-Body Relaxation
(Gravothermal Expansion)



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  $\alpha = 1.2$

Our New simulations (Fukushige, Kawai, Makino 2003)

Simulation Model

- Cluster-Sized Halos
- 2 Cold Dark Matter Models (Standard, Lambda)
- 8 halos (4 SCDM, 4 LCDM)
- "Re-Simulation" technique + External Tidal Field

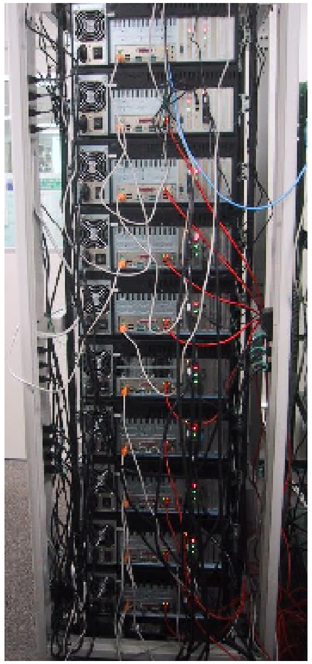
Model	Run	$M_{vir}(M_\odot)$	$N_{vir}(\times 10^6)$
SCDM	S1	1.6×10^{15}	29.2
	S2	1.2×10^{15}	31.2
	S3	1.2×10^{15}	4.5
	S4	4.5×10^{15}	6.9
LCDM	L1	9.6×10^{14}	25.2
	L2	7.0×10^{14}	26.0
	L3	6.5×10^{14}	7.2
	L4	4.5×10^{14}	7.8

Code and Hardware

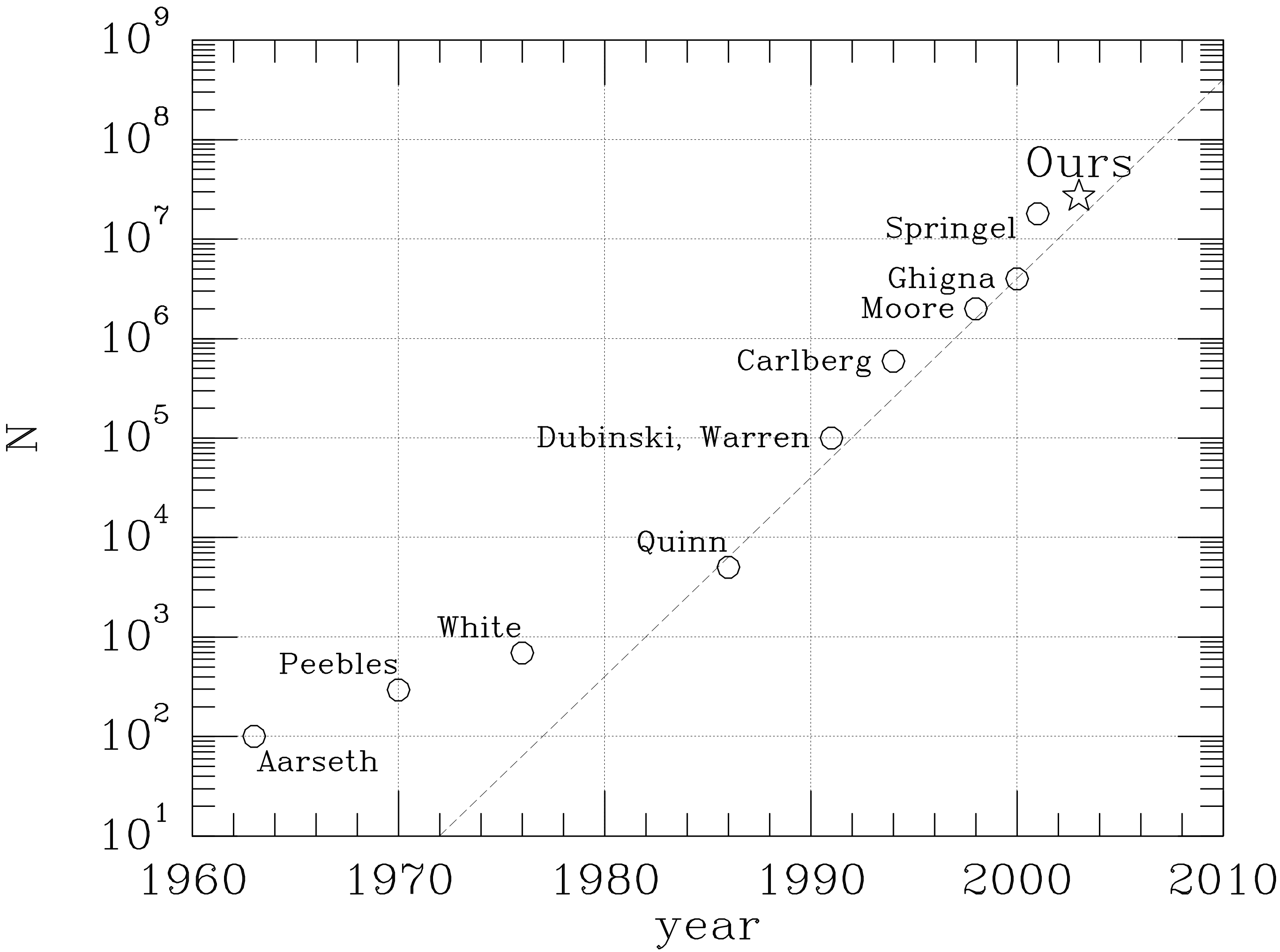
Parallel Treecode (by A. Kawai)

Test and Initial Condition: NAO ADAC

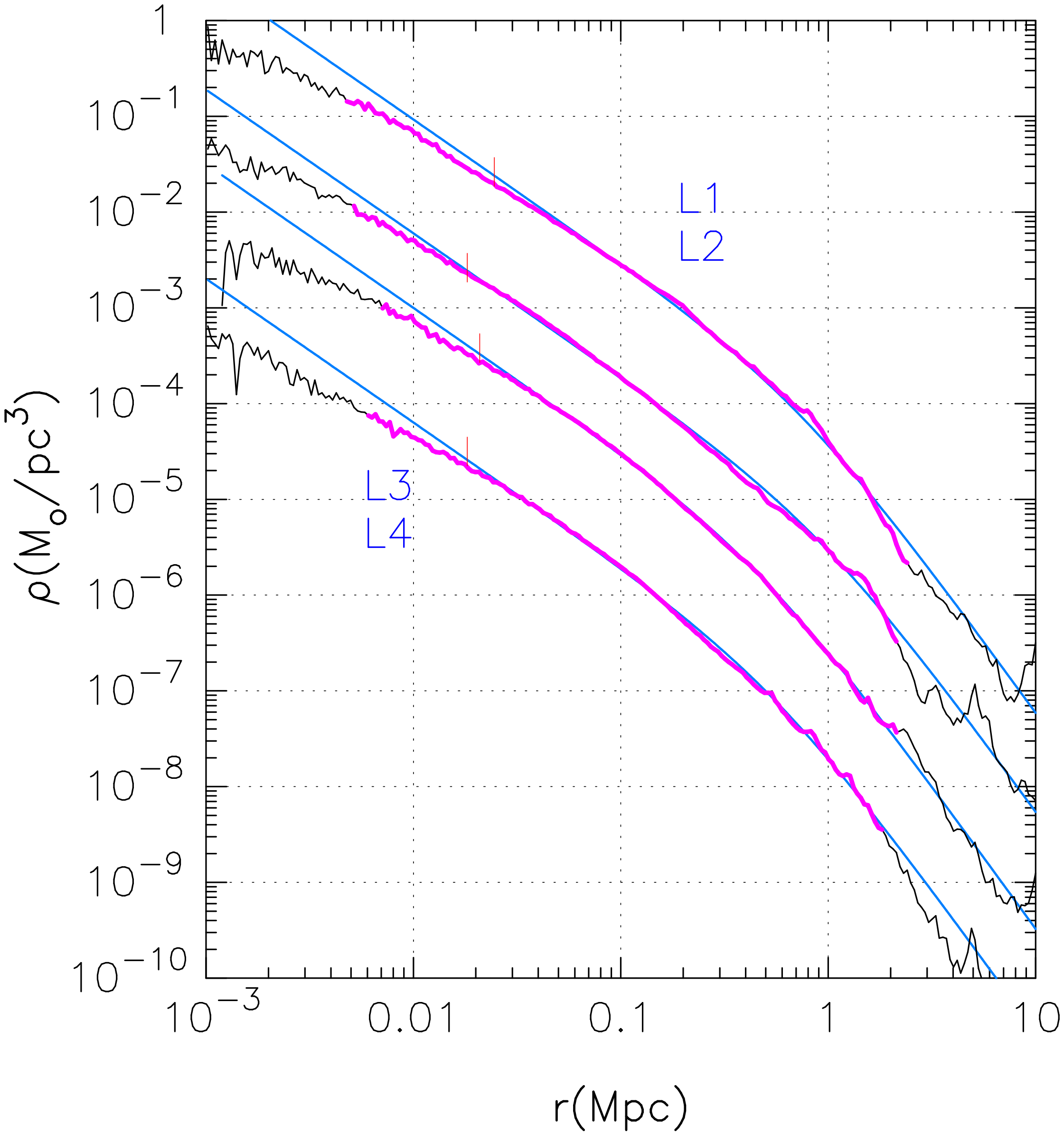
Simulations: 8 node GRAPE-5 cluster in Univ. of Tokyo
and 8 node MDGRAPE-2 cluster in RIKEN



History of N in dark matter simulations [modified from Moore (2000)]



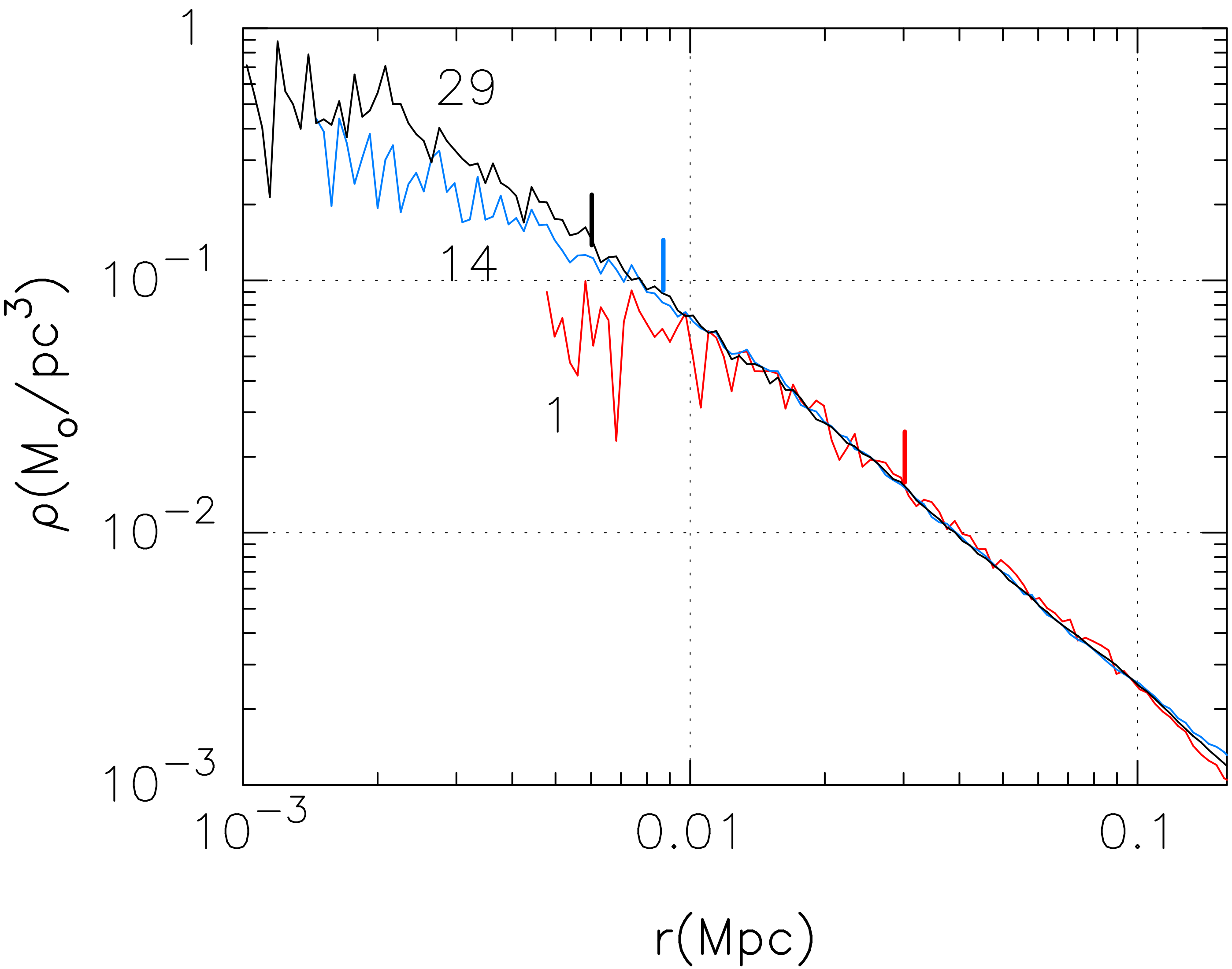
Density Profile (LCDM)



Magenta: Reliable at $r < r_{\rm vir}$ (FM2001)

Blue: Moore et al. (1999)'s profile Red: 1% virial radius

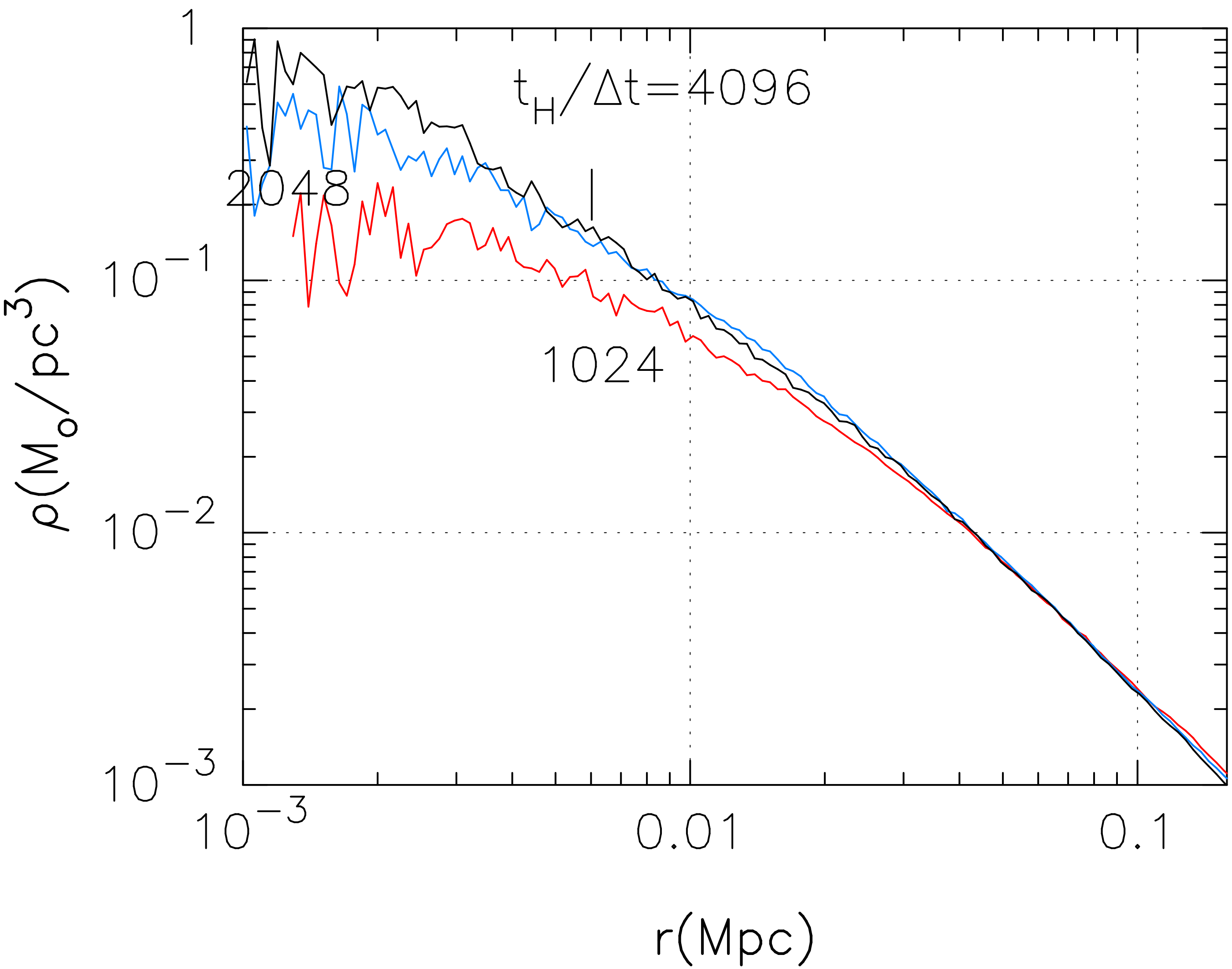
Convergence Test (Two-body Relaxation)



Black: N_v = 29M, Blue: 14M, Red: 1M

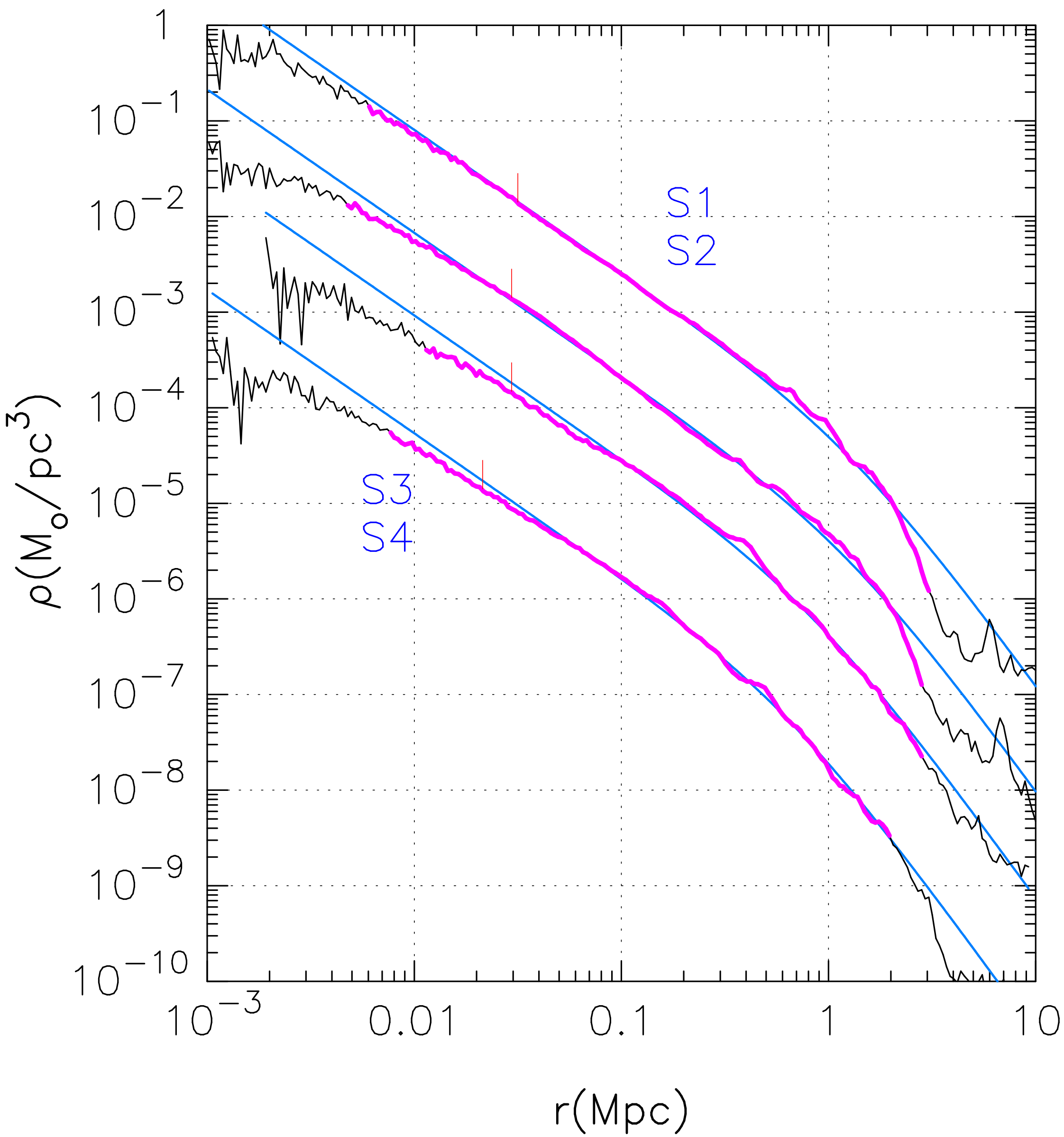
Bar: Reliability Limit

Convergence Test (Timestep Size)



Bar: Reliability limit from two-body relaxation

Density Profile (SCDM)



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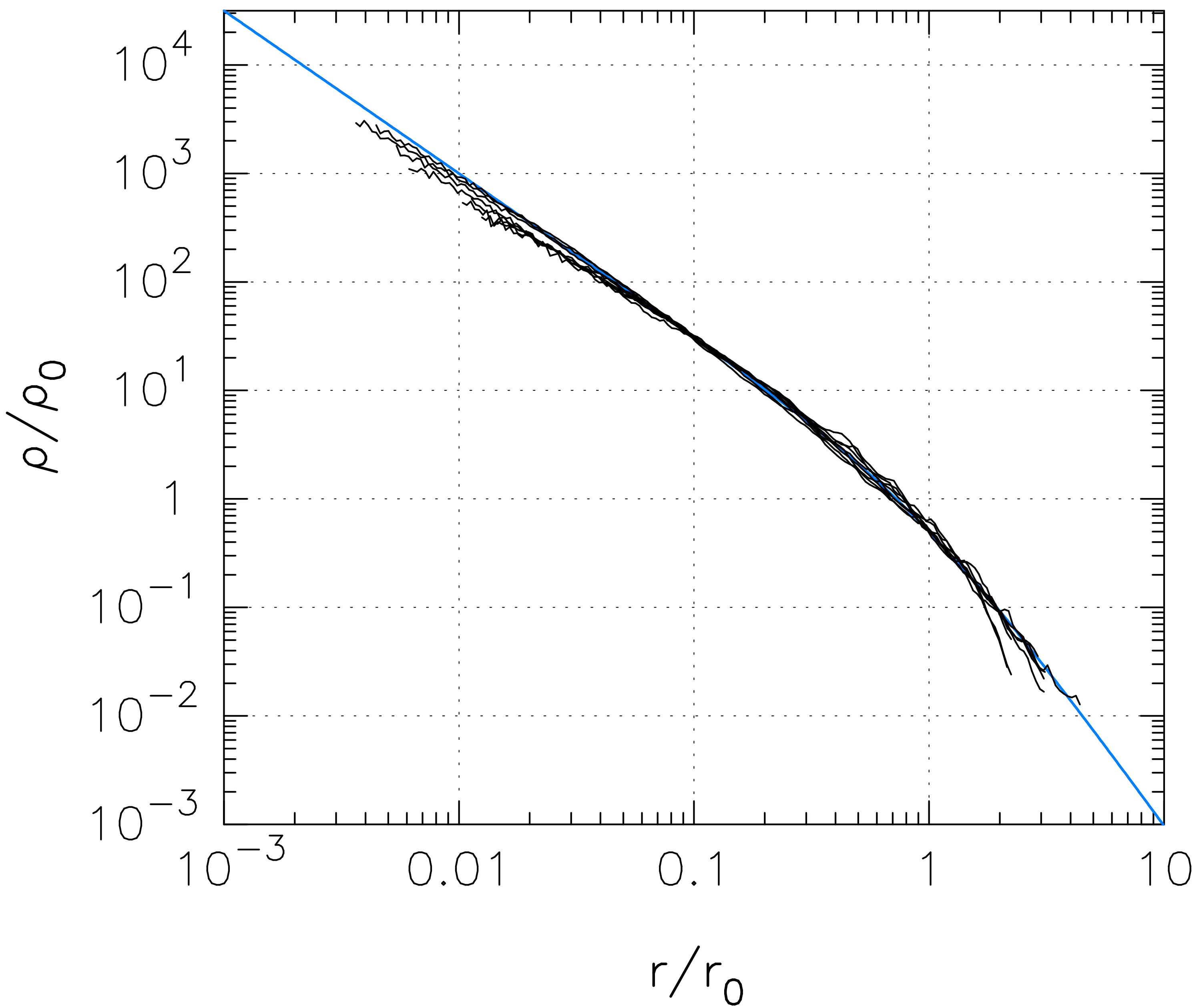
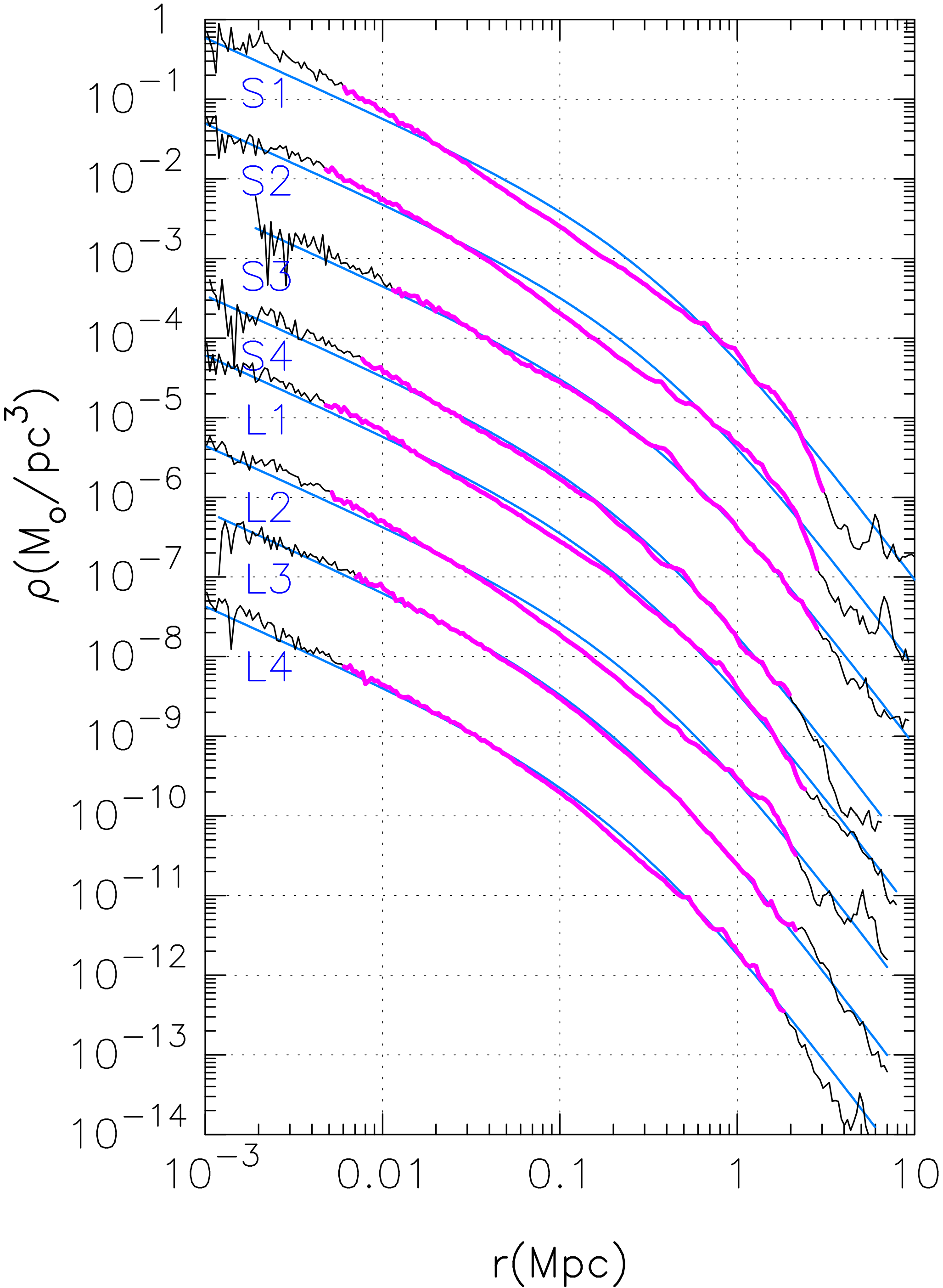
Density Profile (all)

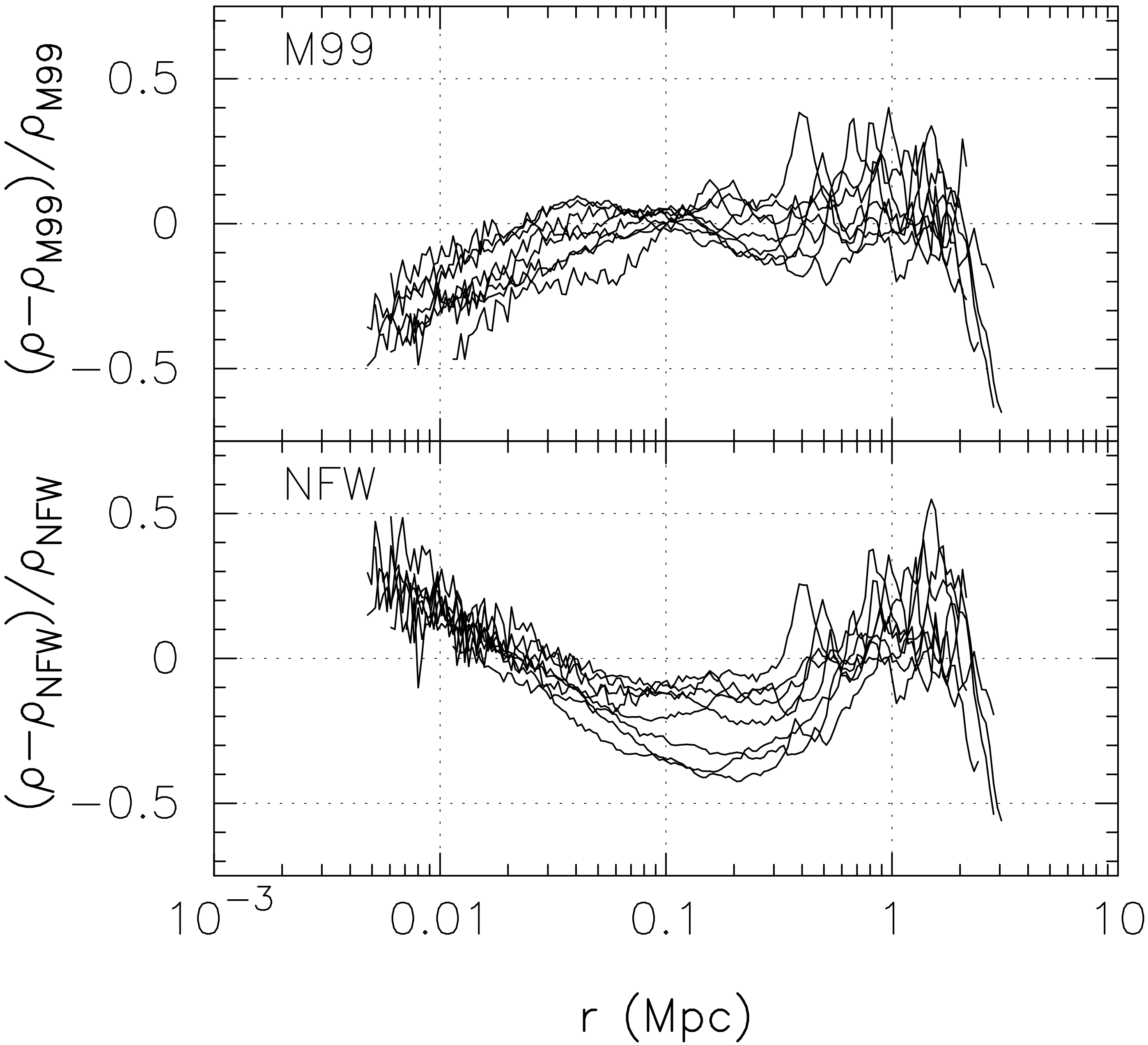


Blue: Moore et al. (1999)'s profile

Fitting to NFW Profile



Fitting to M99 and NFW Profiles (Residual)



Different Fitting Profiles

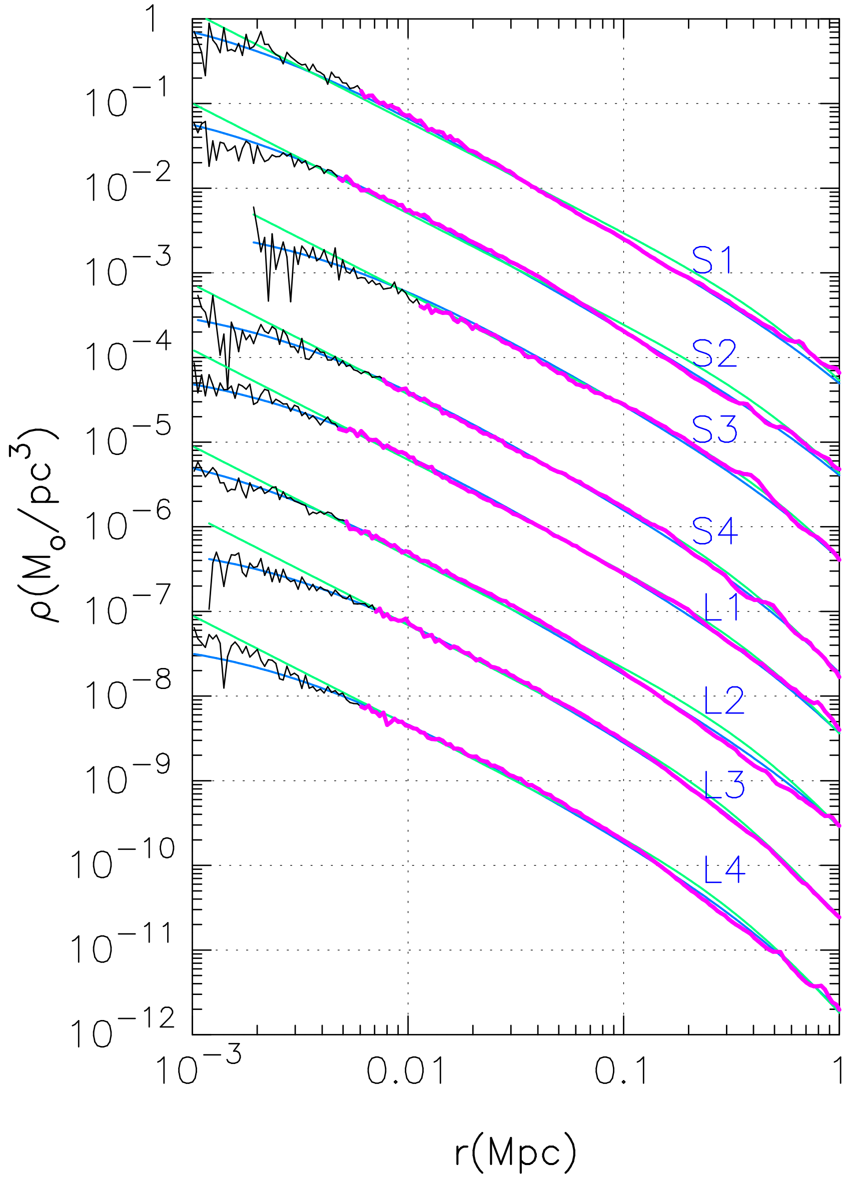
Fitting (1) : α=1.3

Fitting (2) : Interpolation Formula of M99 profile and Flat Core

$$\rho = \frac{\rho_0}{C_0 \left[1 + (r/r_c)\right]^{1.5} \left[1 + (r/r_0)^{1.5}\right]}$$

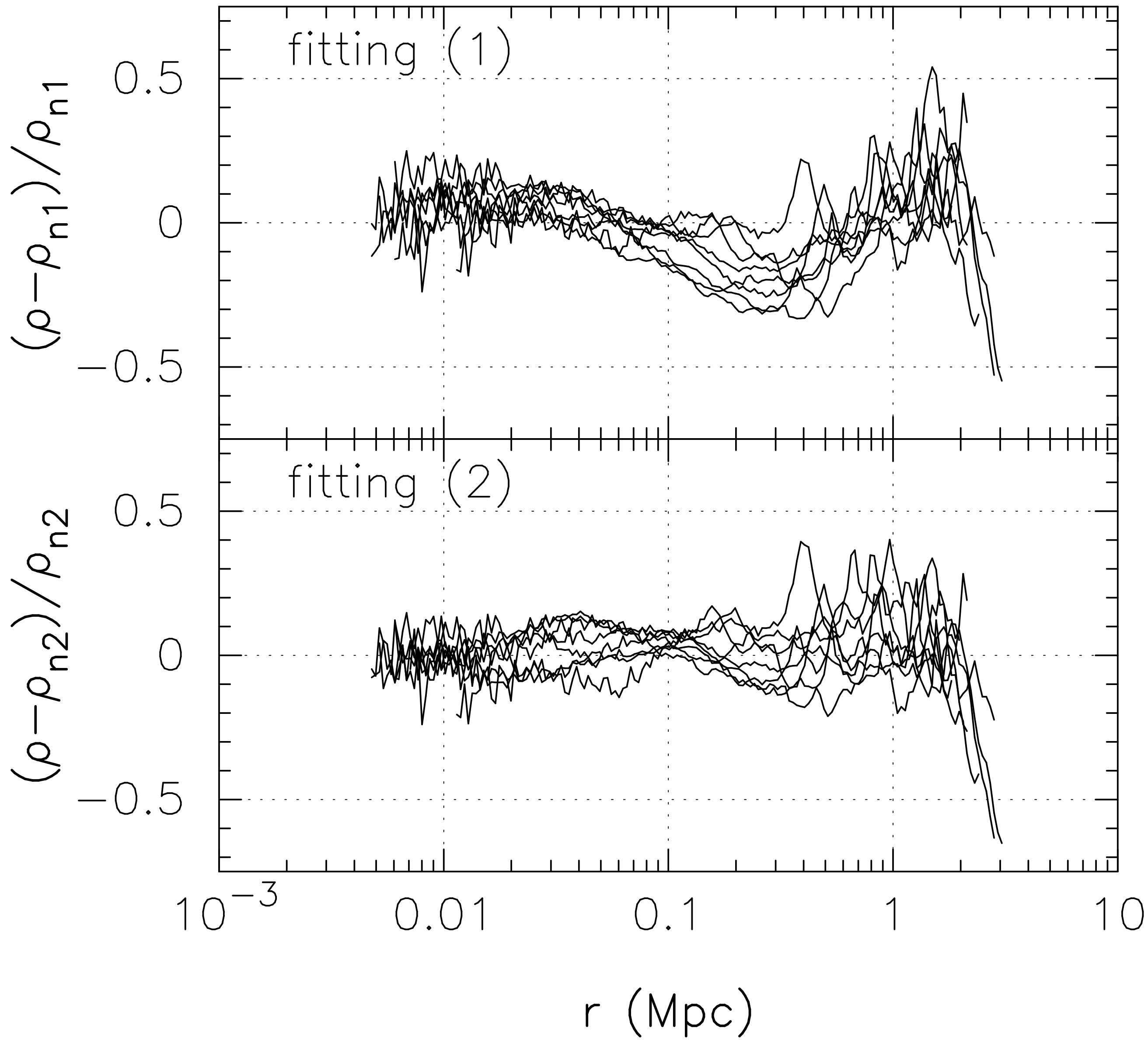
where $C_0 = \left[1 + (r_0/r_c)\right]^{1.5}$

Different Fitting Profile (Continued)



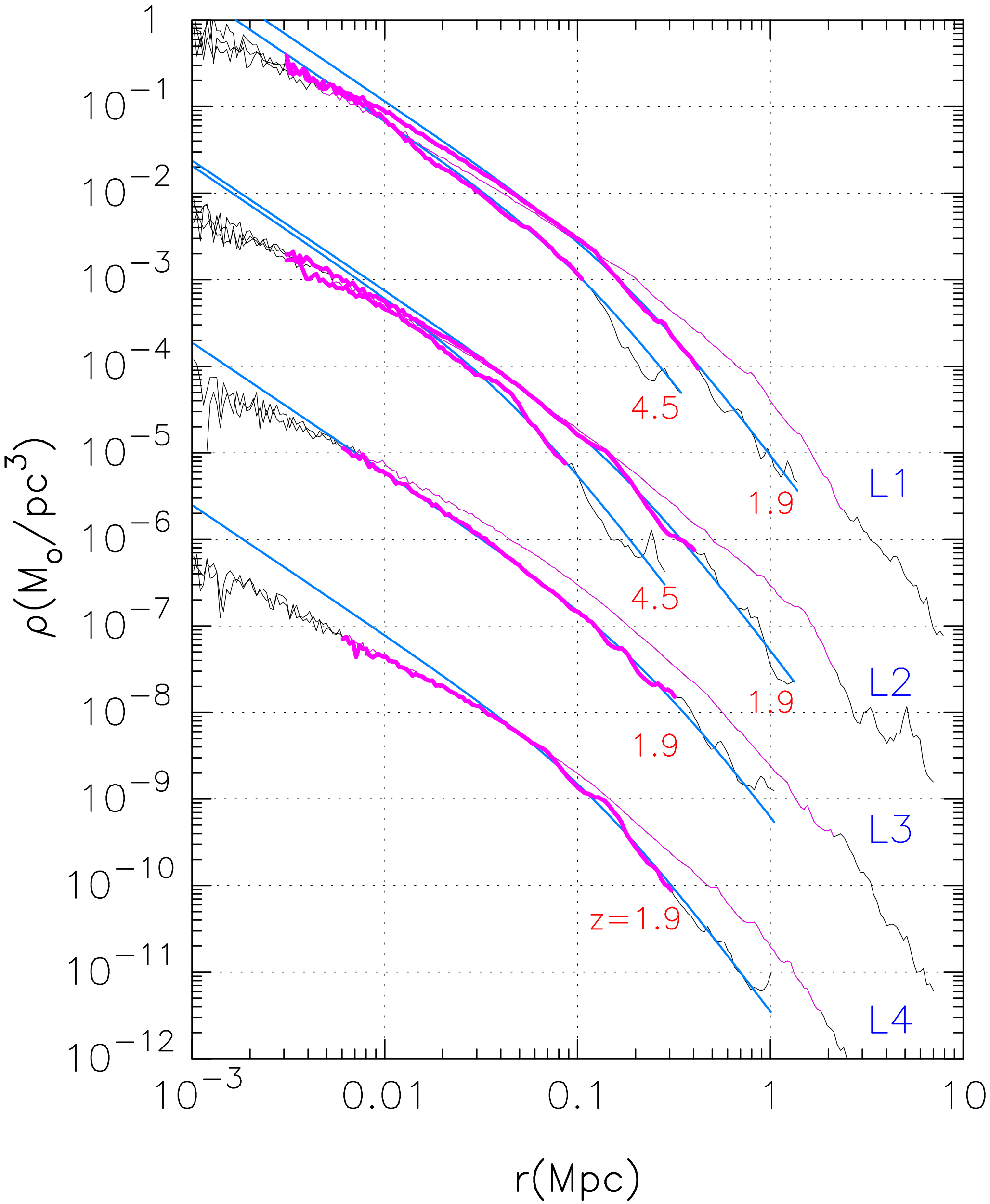
Green: Fitting (1) Blue: Fitting (2)

Different Fitting Profile (Residual)



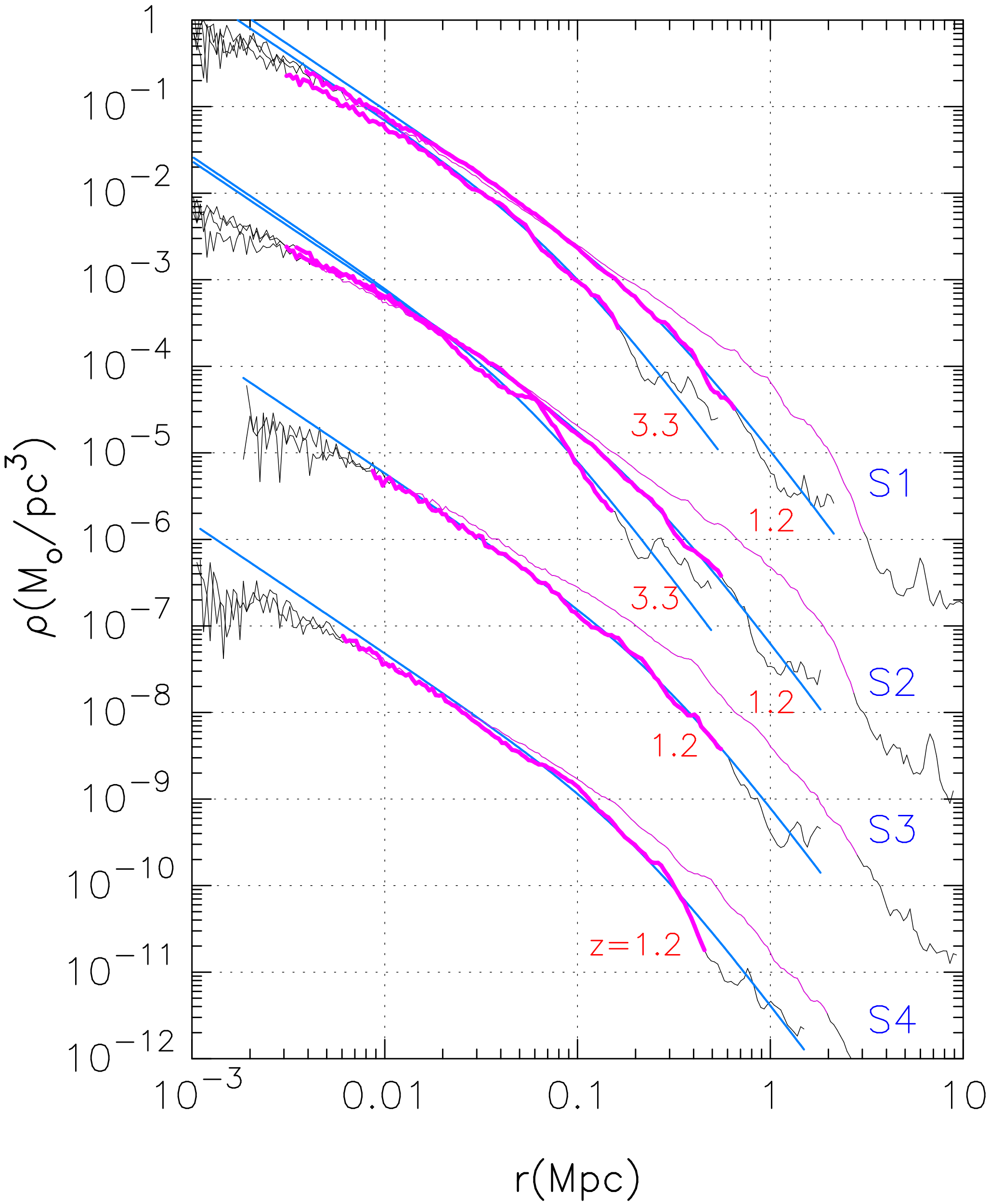
Fitting (1): $\alpha = 1.3$, Fitting (2): Interpolation formula

Evolution (LCDM)



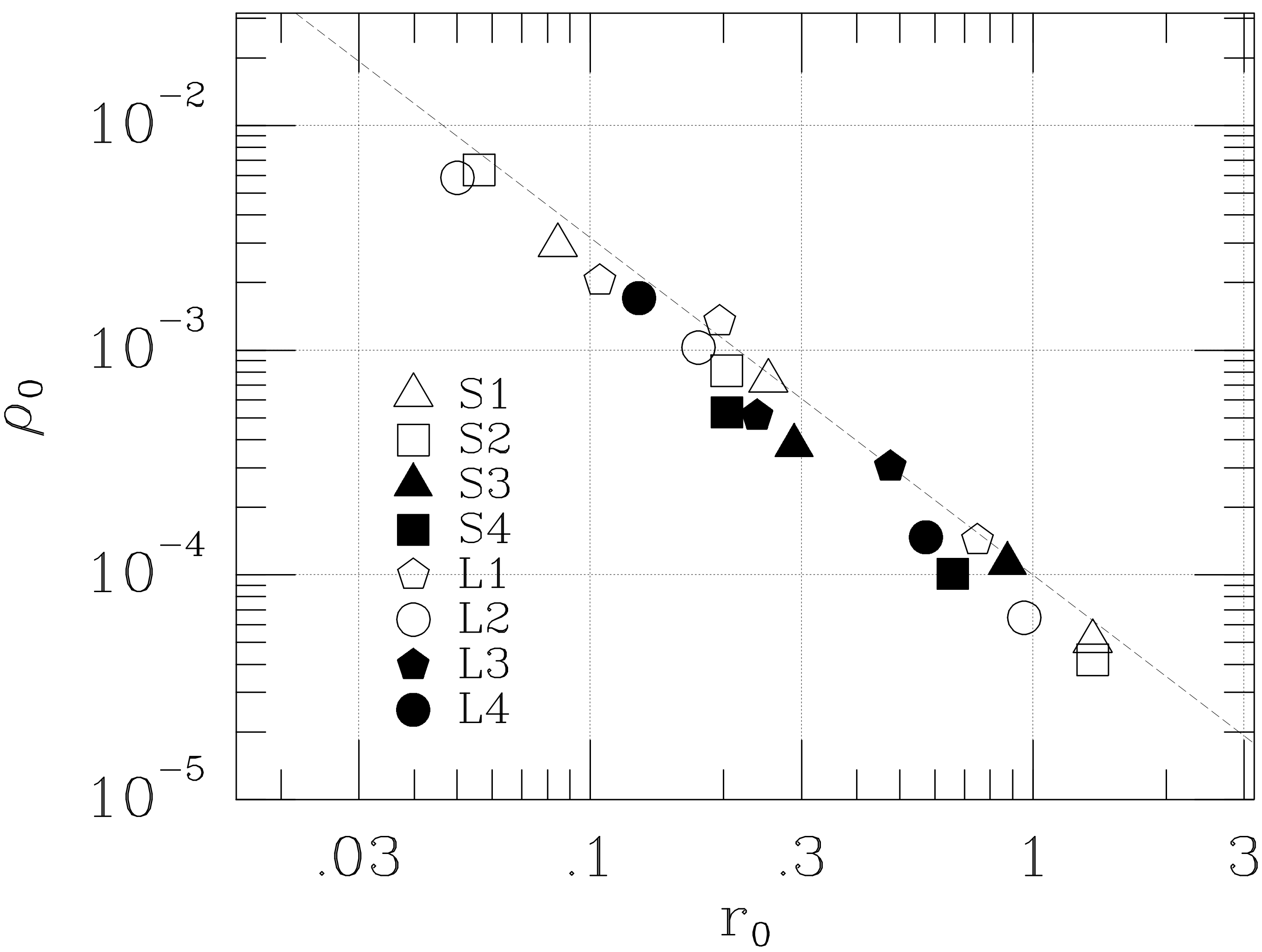
Blue: M99 profile

Evolution (SCDM)



Blue: M99 profile

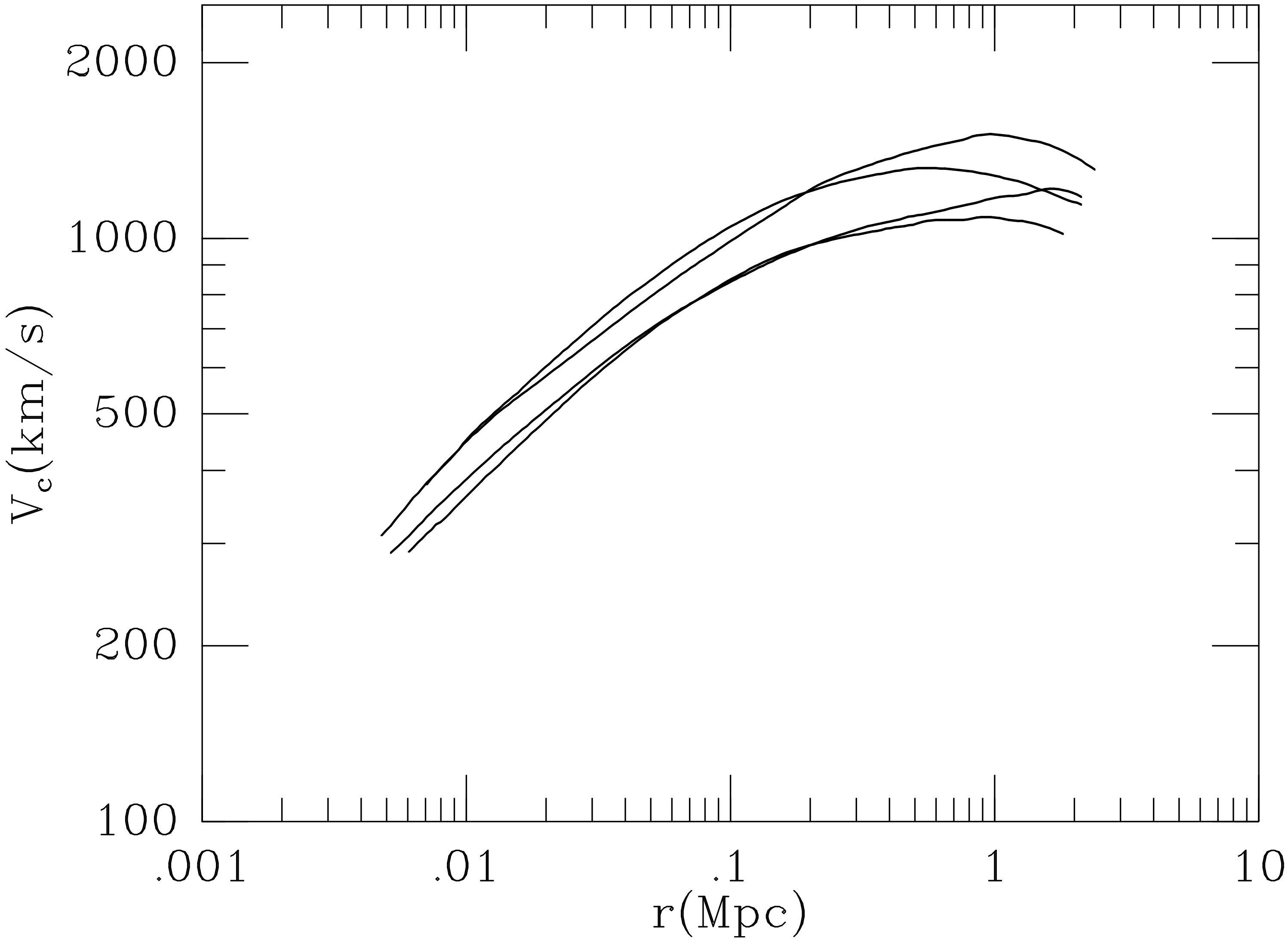
Relation between Scaling Densities and Radii



in $M_\odot/\mathrm{pc}^3$ (ρ_0) and Mpc (r_0)

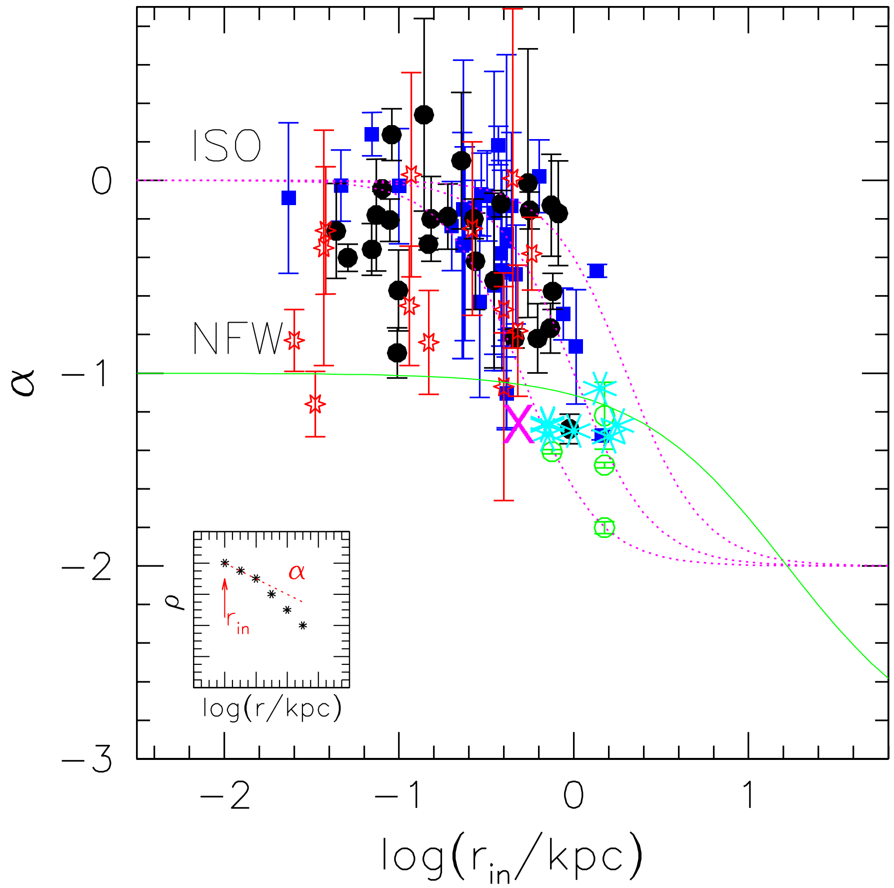
Extrapolation Our Results to LSB Dwarf Scale

Rotation Curve Profile (Accumulative Mass profile) of LCDM runs



Extrapolation Our Results to LSB Dwarf Scale (continued)

$V_{\rm c,max} \sim$ 5 – 10 kpc $\quad \rightarrow r_{\rm lim} \sim 0.5$kpc, $\alpha \sim 1.3$



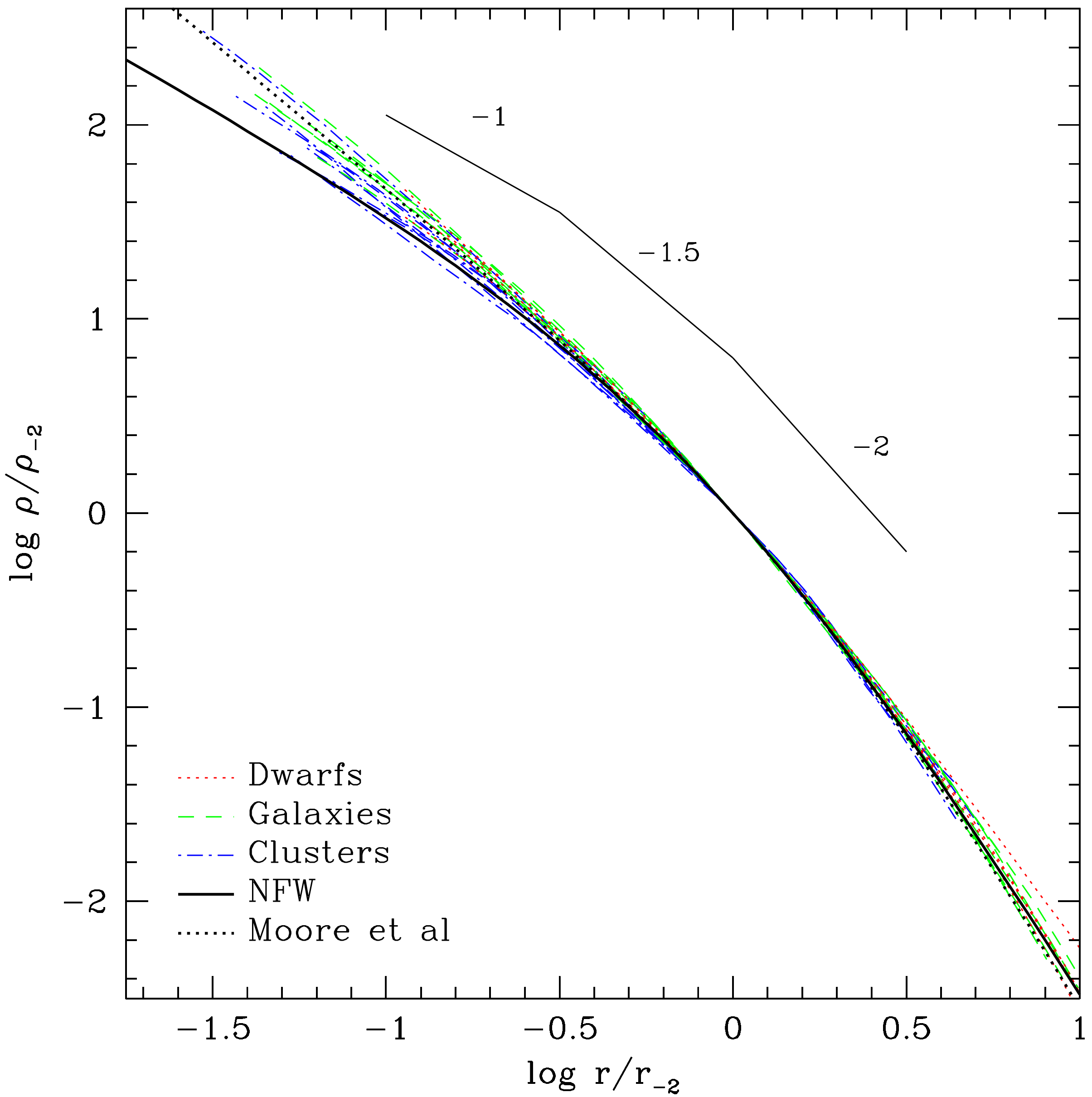
Summary of Our Simulations

8 Cluster-Sized CDM Halos Simulation:

- The slope of inner cusp within $0.01 r_{\rm v}$ is shallower than -1.5.
- Good agreement with M99 profile at $r > 0.01 r_{\rm v}$.
- The result can be fitted to $\alpha = 1.3$ or the interpolation formula

New simulations of Navarro's Group (2003)

$N \sim 10^6$, $1 < \alpha < 1.5$



Status Summary of Cusp/Core Problem

- Observers say that data are reliable and prefer soft core ($0 < \alpha < 1$)
- Cosmological simulations indicate the cusp ($1.0 < \alpha < 1.5$), but not completely confirmed in the dwarf LSB scale.
- No theory nor physics
- Those are under the minimum disc assumption (e.g. enough consideration for baryon)