Cosmological implications of density profiles of dark matter halos

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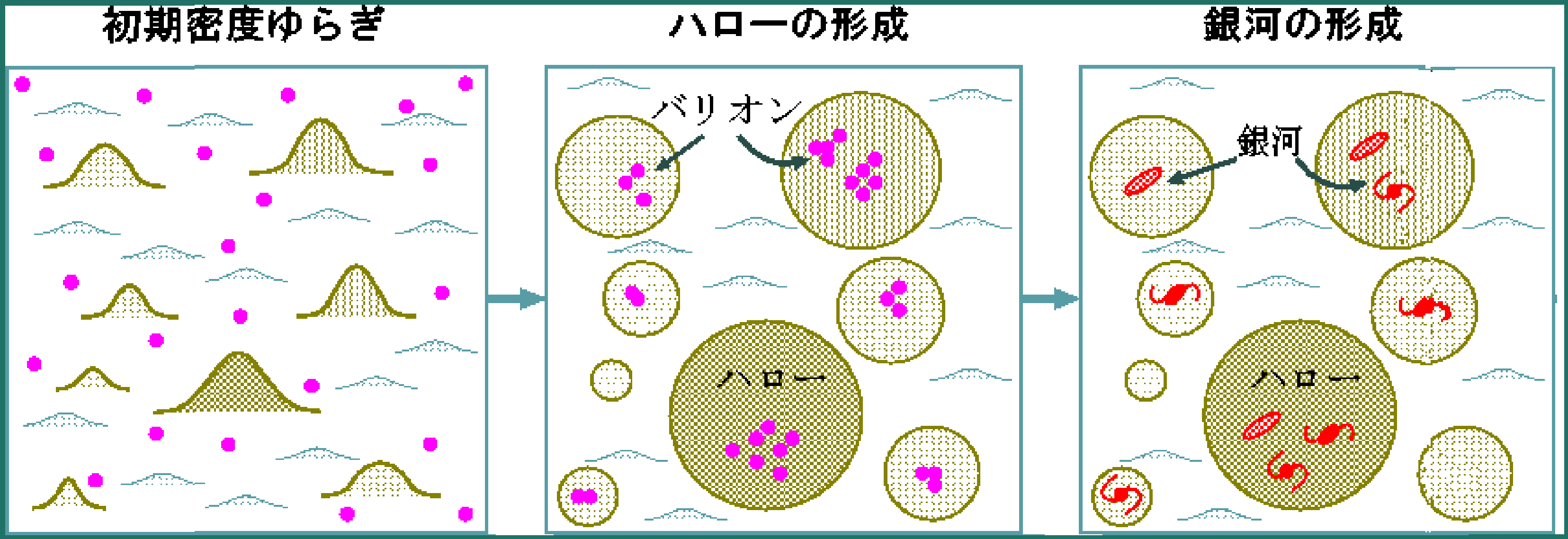
Why dark matter halos ?

- ***Self-gravitating virialized objects***
- ***Sites for galaxies and clusters***
  - radiative cooling of baryonic gas
  - energy and angular momentum transfer
  - star formation and supernova heating
- More directly related to cosmological initial conditions (easier to predict/model theoretically) than complicated astronomical objects

Gravitational instability picture



gravitational evolution

gas cooling
radiative processes
star formation…

Formation of dark halos (=self-gravitating systems of dark matter) is the most fundamental process in cosmological structure formation

Why density profiles of dark halos ?

- **Theoretical interest:** ***what is the final state of the cosmological self-gravitating system ?***
  - forget cosmological initial conditions?
  - keep the memory of initial conditions somehow?
- **Practical importance:** ***testable predictions for galaxies and clusters***

  can distinguish the underlying cosmological model through comparison with observations (i.e.,galactic rotation curve, gravitational lensing, X-ray/SZ observation)

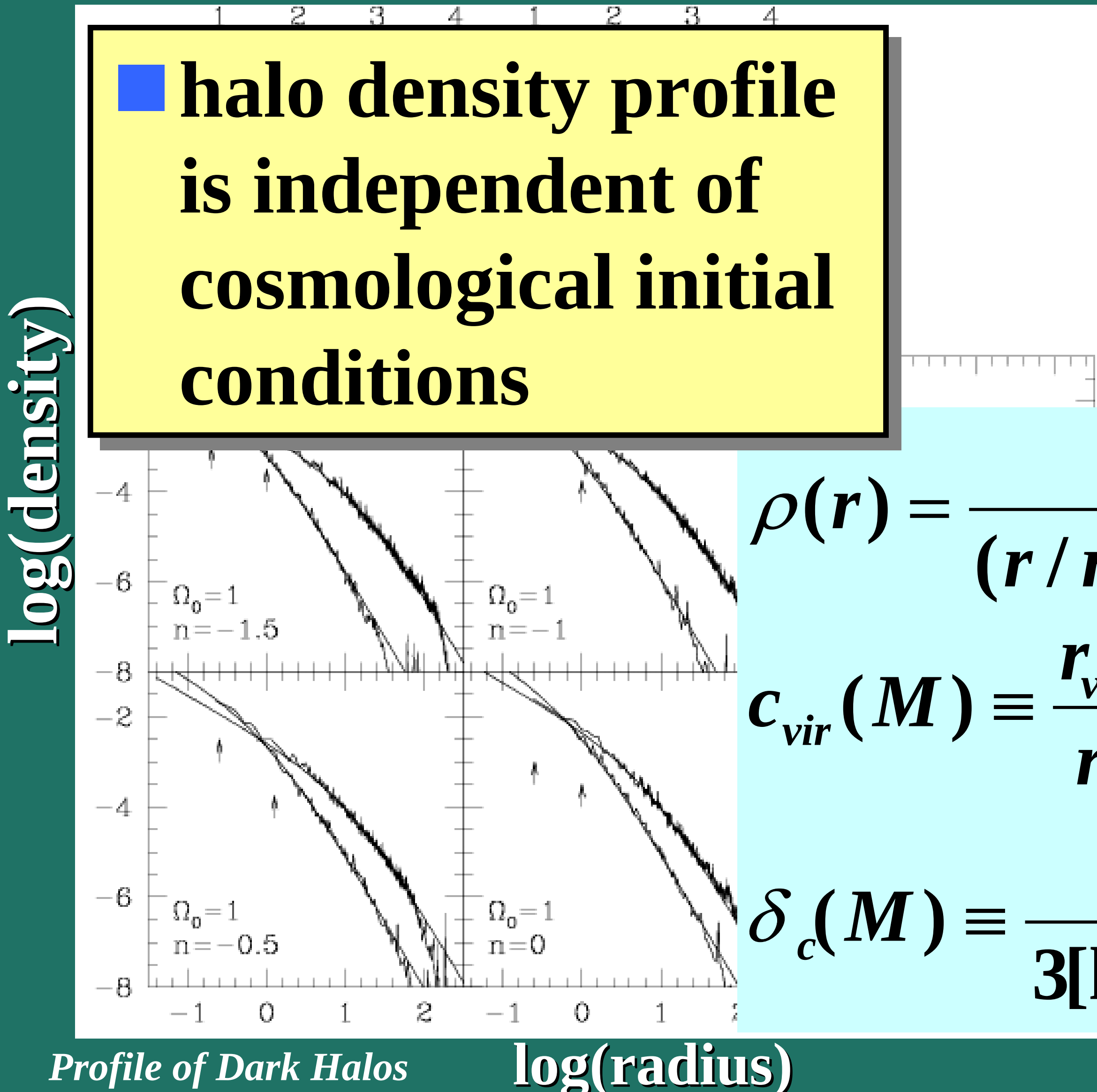
Brief history before NFW

- **1970: Peebles; N-body simulation (N=300).**
- **1977: Gott; secondary infall model $\rho \propto r^{-9/4}$.**
- **1985: Hoffman & Shaham; predict that density profile around density peaks is $\rho \propto r^{-3(n+3)/(n+4)}$.**
- **1986: Quinn, Salmon & Zurek; N-body simulations (N∼10000), confirmed $\rho \propto r^{-3(n+3)/(n+4)}$.**
- **1988: Frenk, White, Davis & Efstathiou;N-body simulations ($N=32^3$), showed that CDM model can reproduce the flat rotation curve out to 100kpc.**
- **1990: Hernquist; proposed an analytic model with a central cusp for elliptical galaxies $\rho \propto r^{-1}(r+r_s)^{-3}$.**

NFW universal density profile

- **halo density profile is independent of cosmological initial conditions**

Navarro, Frenk & White (1997)



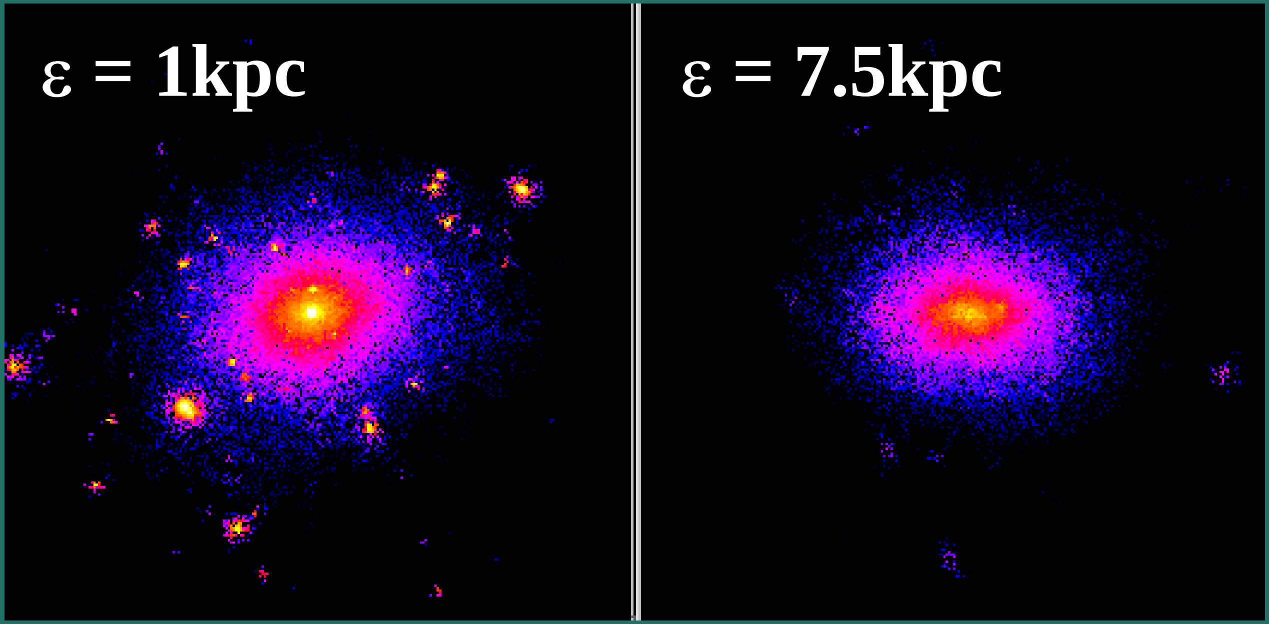
$$\rho(r)=\frac{\delta_c\rho_{crit}}{(r/r_s)(1+r/r_s)^2}$$

$$c_{vir}(M)\equiv\frac{r_{vir}(M)}{r_s(M)}$$

$$\delta_c(M)\equiv\frac{\Delta_{vir}\Omega_0 c^3}{3[\ln(1+c)-c/(1+c)]}$$

Importance of high-resolution simulations

- low mass/force resolutions
  ⇒ shallower potential than real
  ⇒ artificial disruption/overmerging
  (especially serious for small systems)

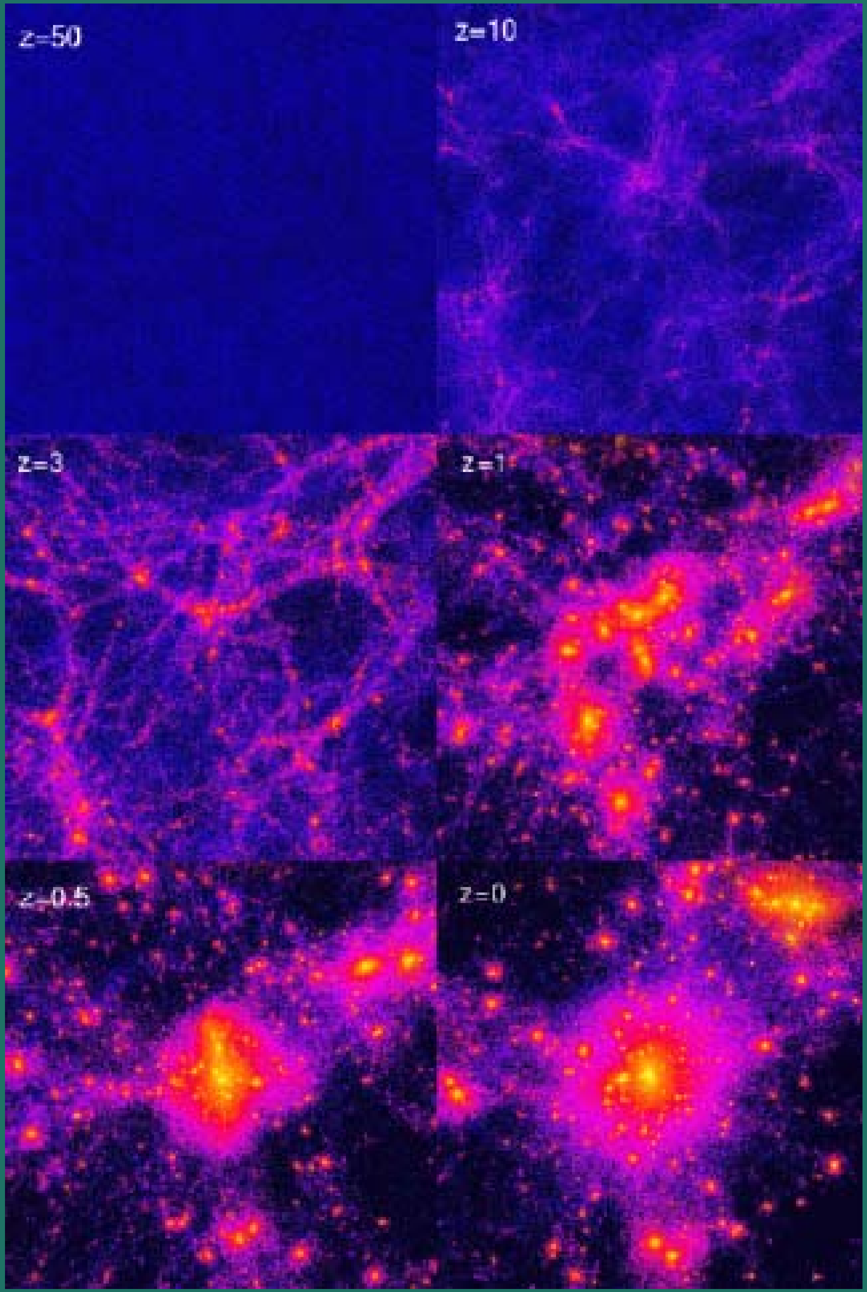


central 500kpc region of a simulated halo in SCDM

Moore (2001)

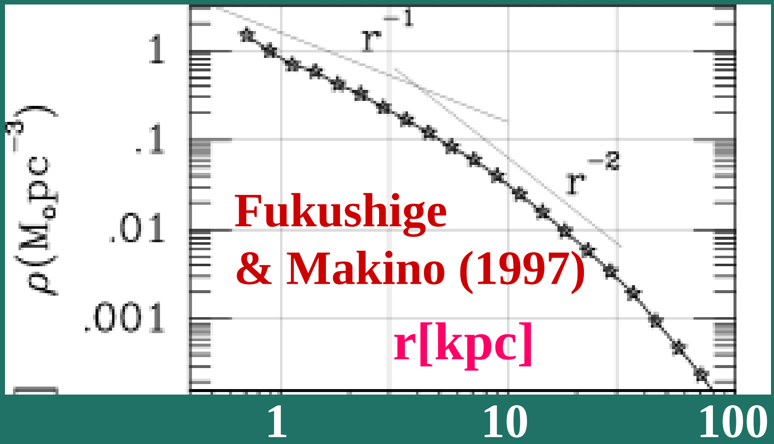
Simulated halos in higher resolution

Yoshida et al. (2000)

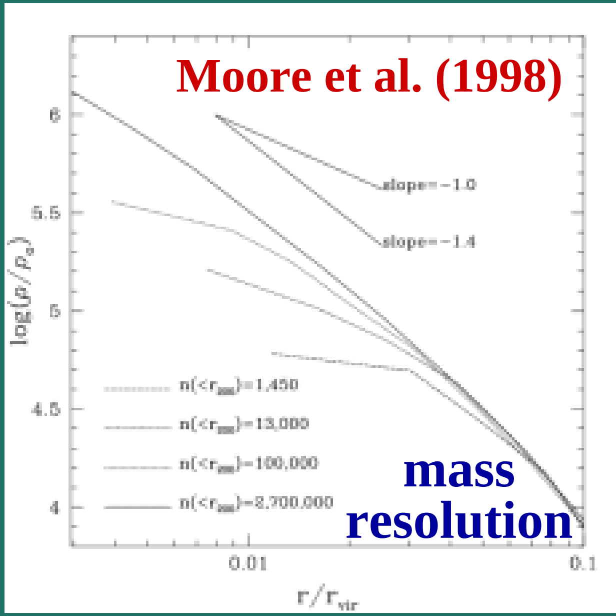


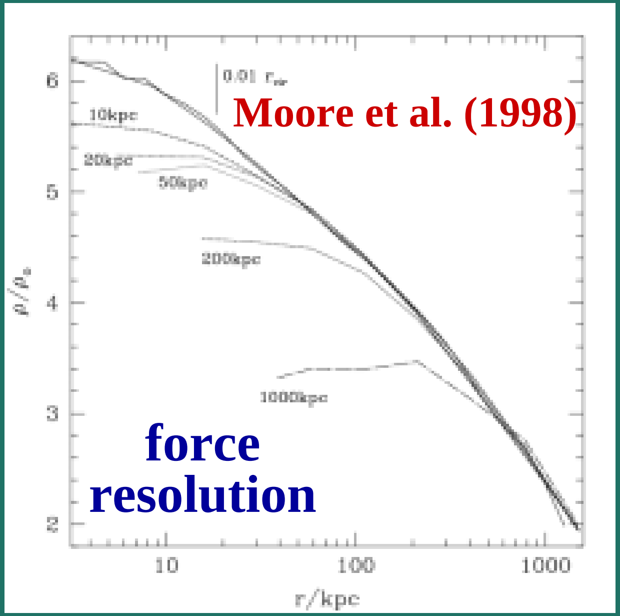
Moore (2001)

Profiles in higher-resolution simulations



- inner slope in higher-resolution simulations is steeper (~ –1.5) than the NFW value (–1.0)

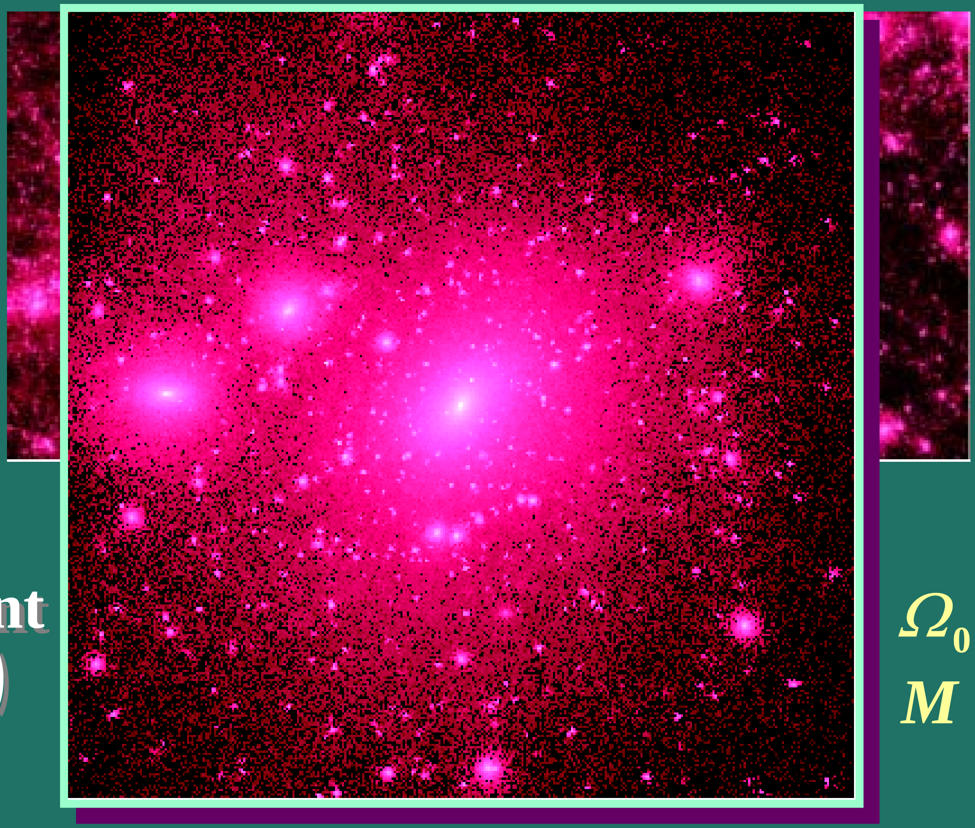




Simulated galactic halo

- Formation of galactic halos in cold dark matter model

present (z=0)



z=1

$\Omega_0 = 0.3, \lambda_0 = 0.7, h = 0.7$

$M = 5 \times 10^{12} h^{-1} M_{sun}$

(Jing & Suto 2000)

Simulated cluster halo

- Formation of clusters in cold dark matter model

present
(z=0)

z=1.0

$\Omega_0 = 0.3,\ \lambda_0 = 0.7,\ h = 0.7$

$M = 3 \times 10^{14} h^{-1} M_{sun}$

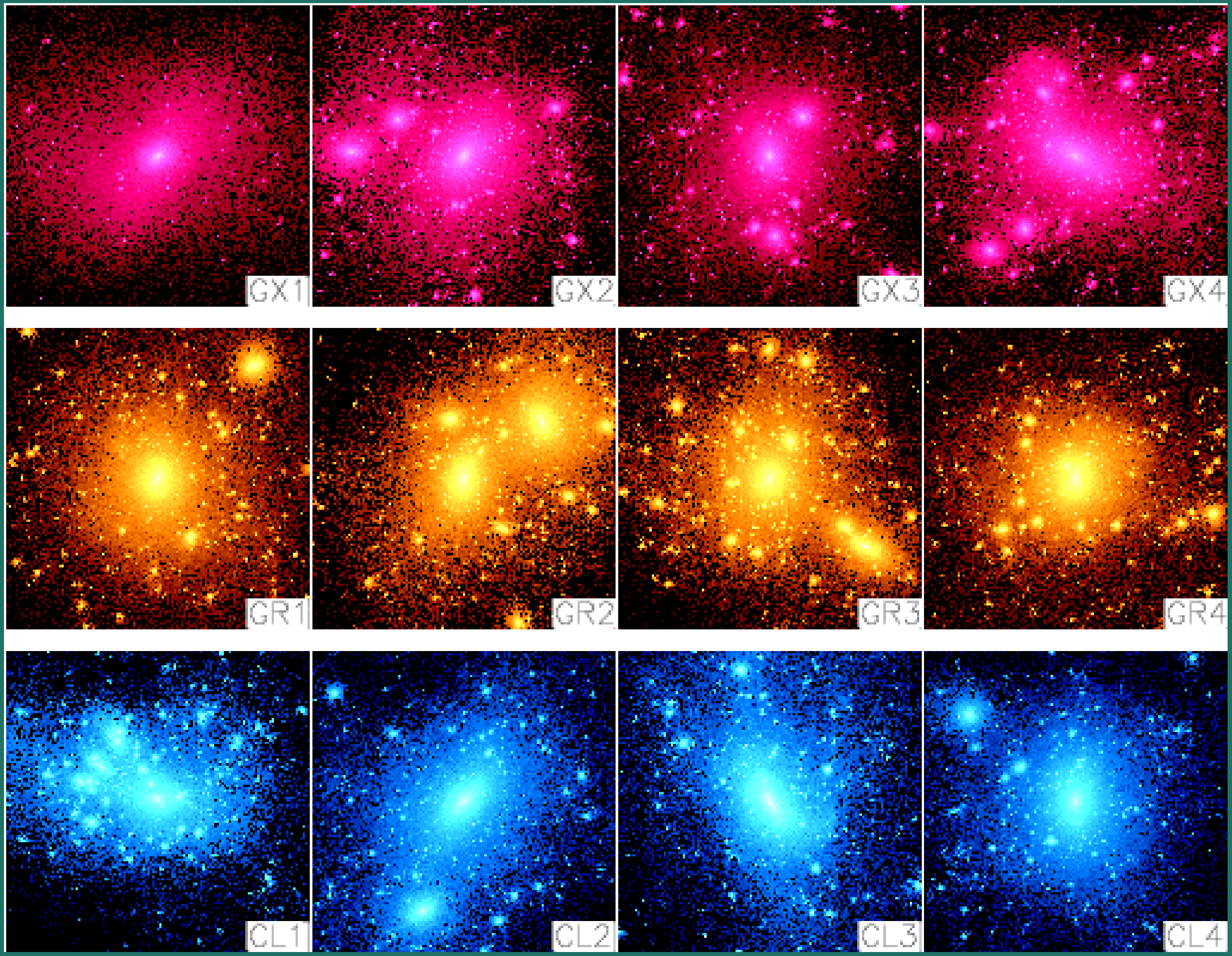
(Jing & Suto 2000)

Density profiles of our halos

galaxies
~ $5x10^{12}M_{sun}$

groups
~ $5x10^{13}M_{sun}$

clusters
~ $3x10^{14}M_{sun}$



Jing & Suto (2000)

Evolution of halo density profiles

galaxies
~ $5x10^{12}M_{sun}$

groups
~ $5x10^{13}M_{sun}$

clusters
~ $3x10^{14}M_{sun}$

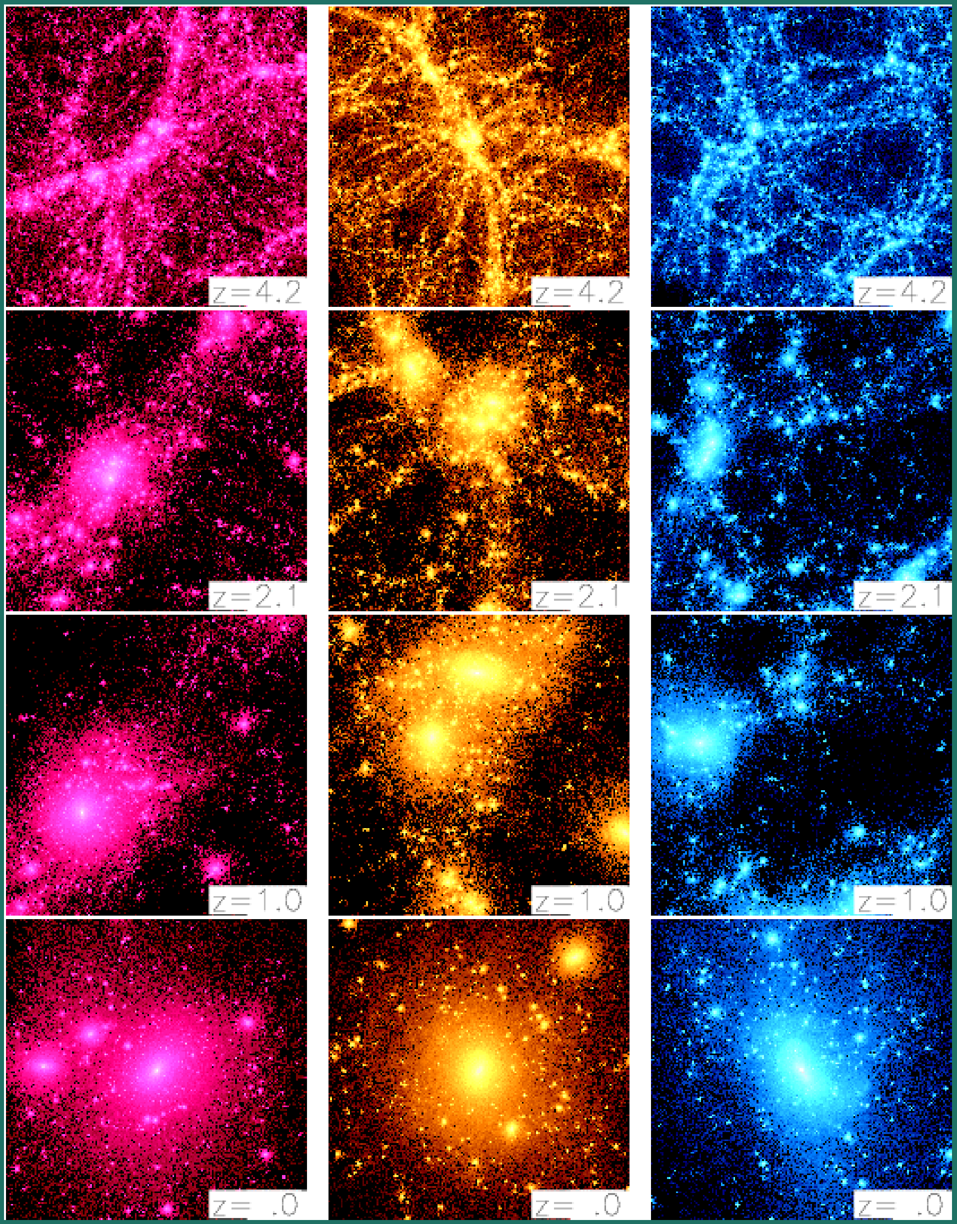
Jing & Suto (2000)

z=4.2

z=2.1

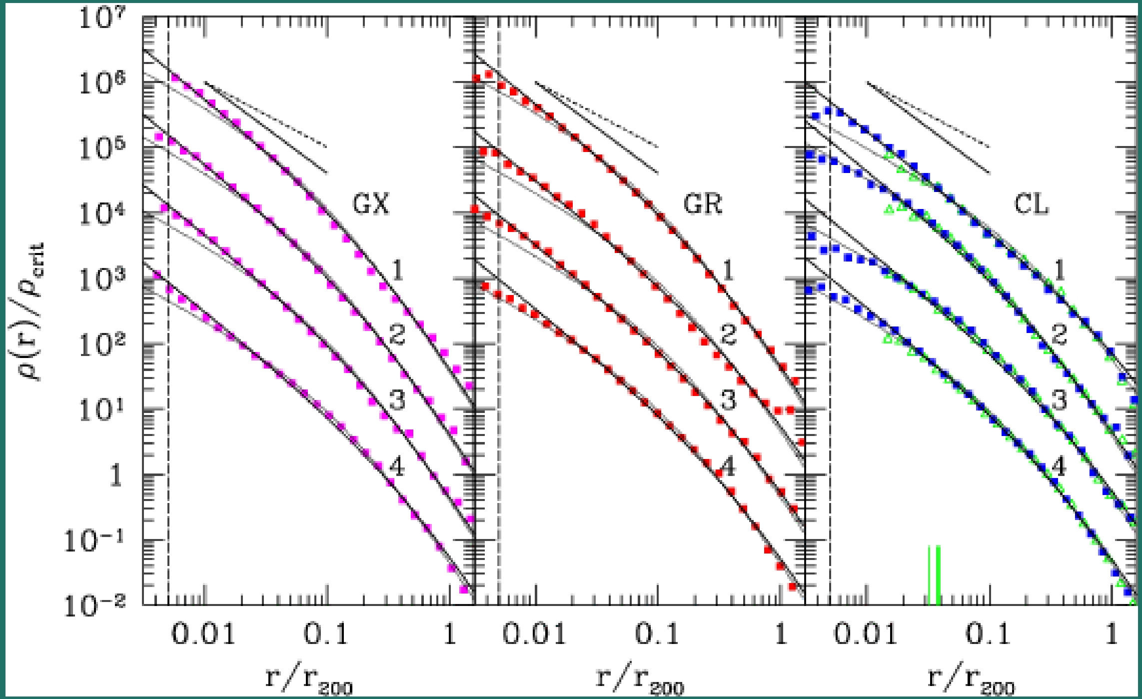
z=1.0

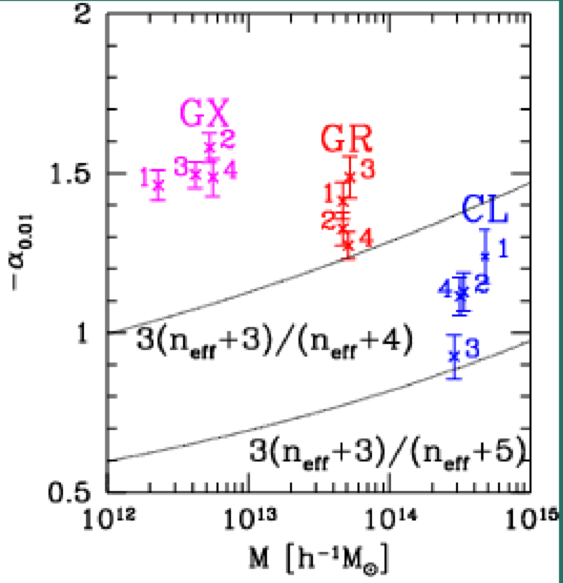
z=0



Mass dependence of halo profiles

- Inner slope of the profile is dependent on the mass of halos ($\alpha = -1.2 \sim -1.5$) ?





Jing & Suto (2000)

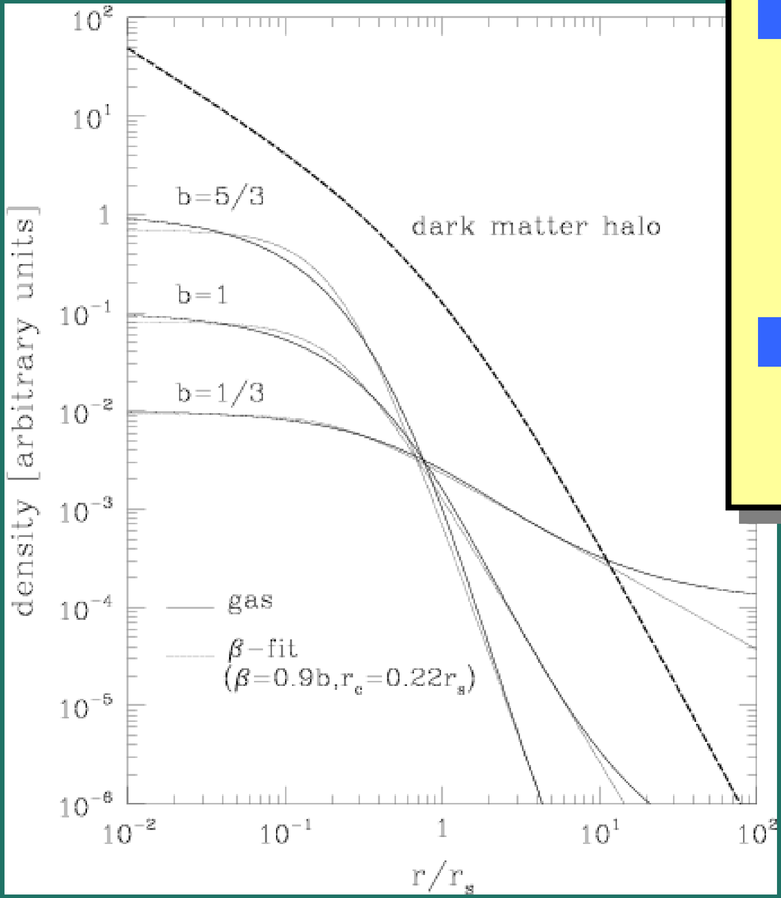
Summary of theoretical results

- ***Simulations***
  - Profiles of dark matter halos seem to be fairly universal (at least approximately)
  - Shape of halo profiles is independent of the cosmological initial conditions
  - Cusp rather than core in the central region
- ***Theoretical models***
  - The presence of cusp is consistent.
  - Inner slope is expected to depend on the primordial spectrum of fluctuations in general.

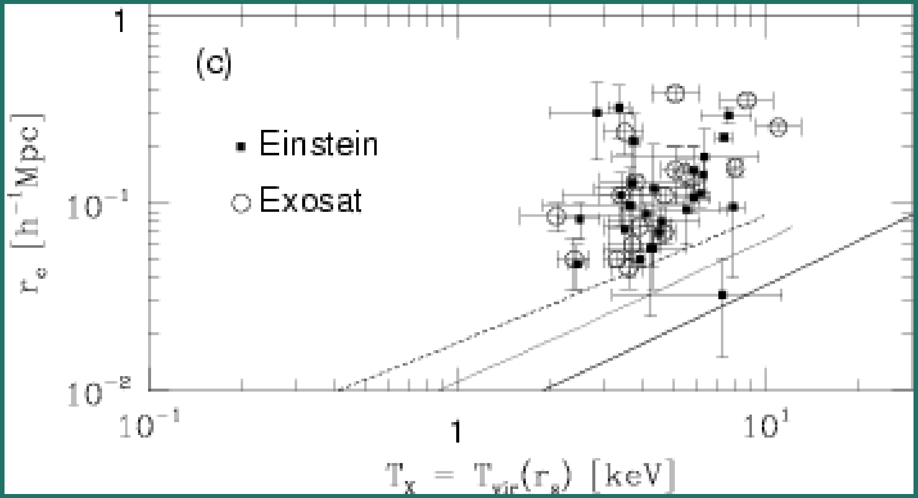
⇒ **needs observational confrontation**

X-ray gas profiles of clusters

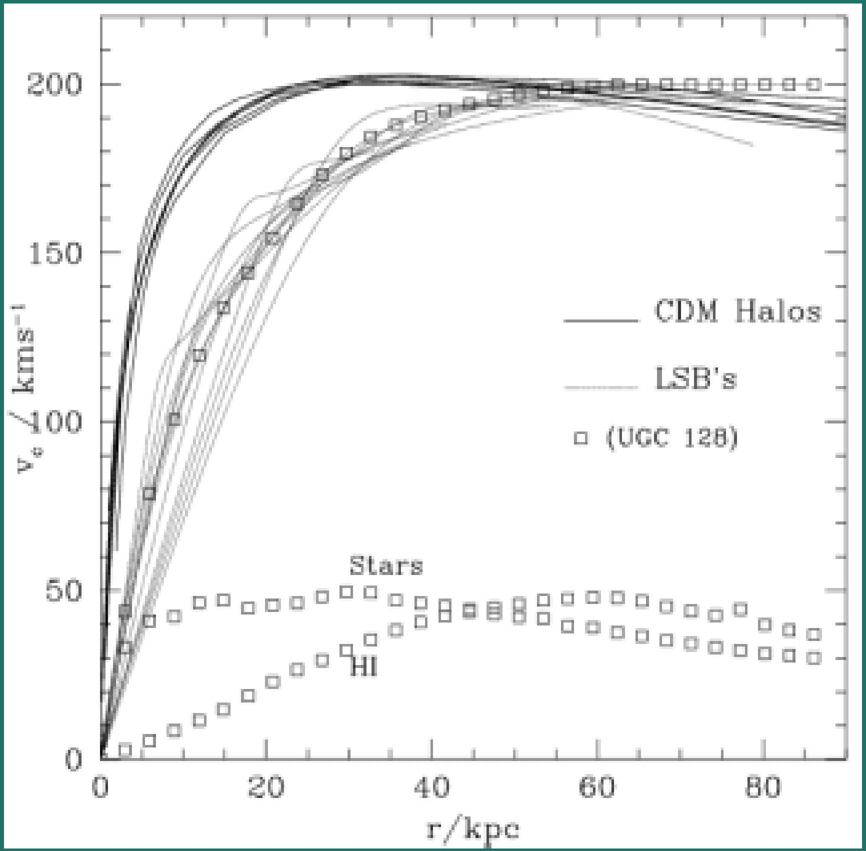
- isothermal gas profile in NFW potential is close to the isothermal β model
- predicted core radius is smaller than those observed



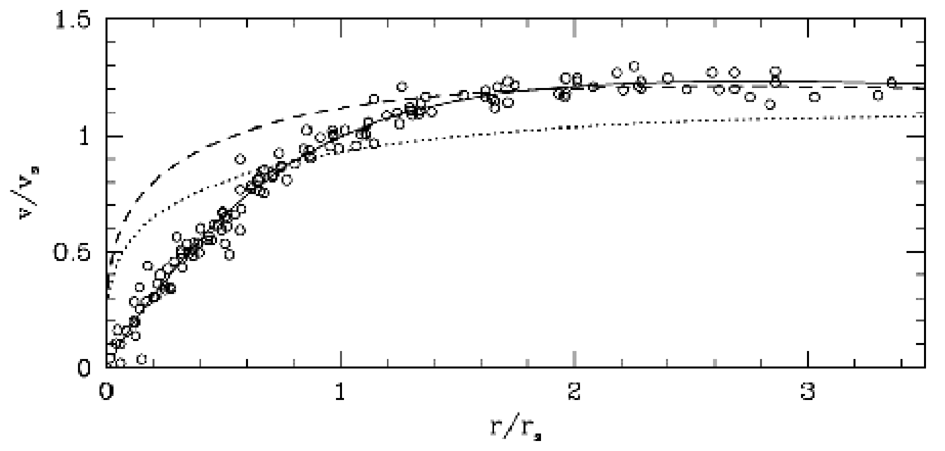
Makino, Sasaki & Suto (1998)



Rotation curves of DM dominated galaxies



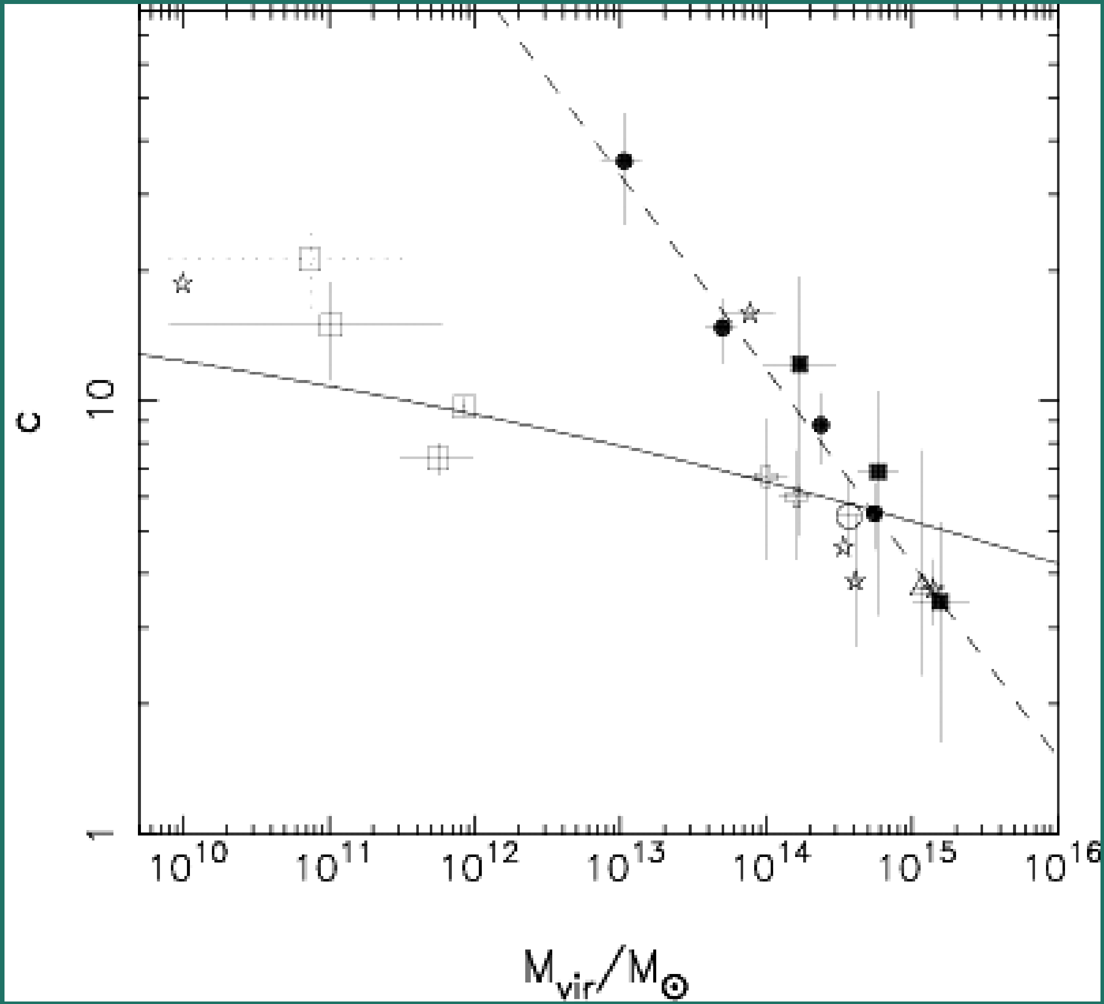
Moore et al. (1999)



- dwarf spirals to giant low surface brightness galaxies indicate the central cores

  ⇒ inconsistent with the CDM simulations

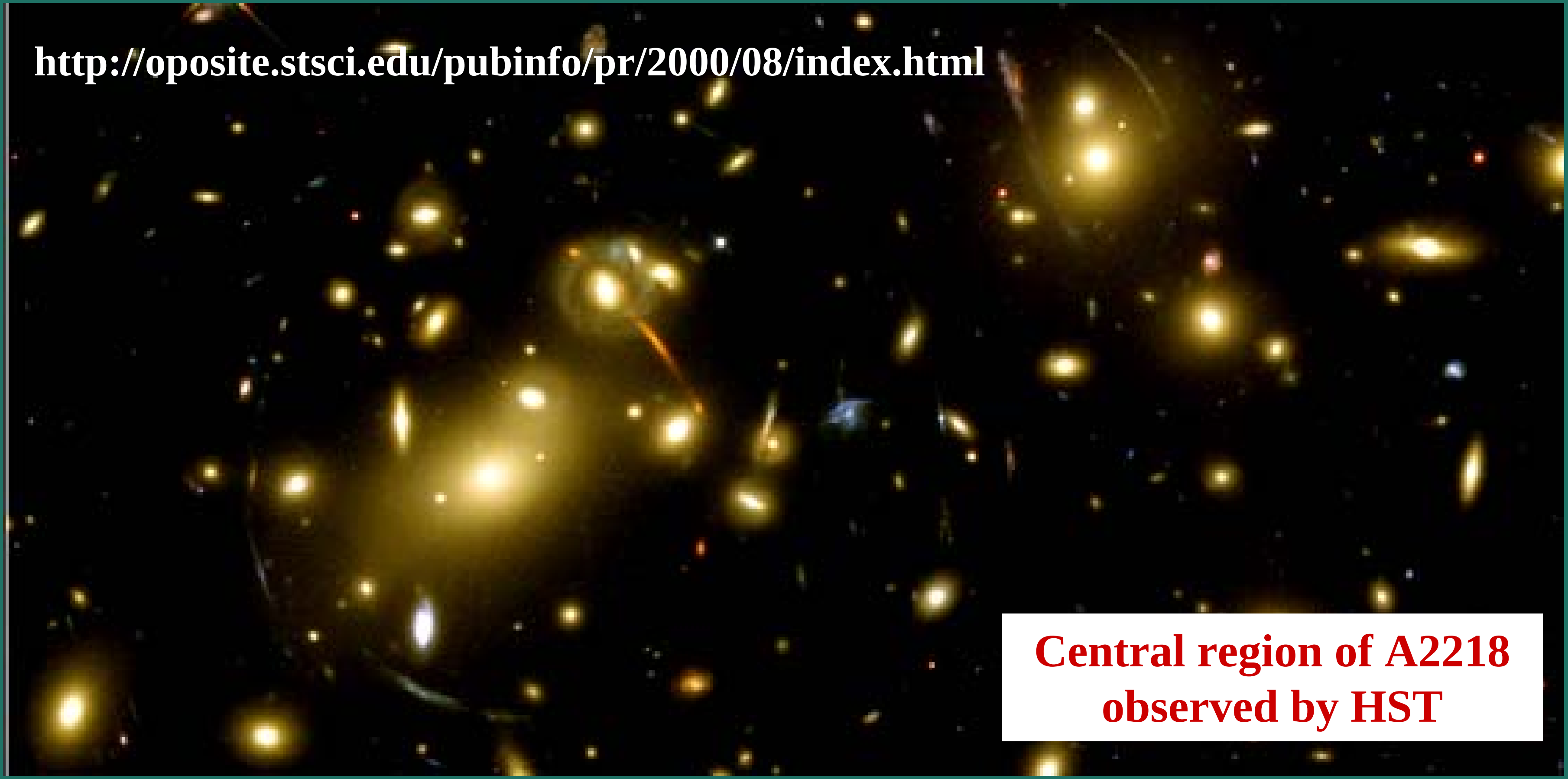
Observed profile parameters for halos



- Roughly consistent with simulations

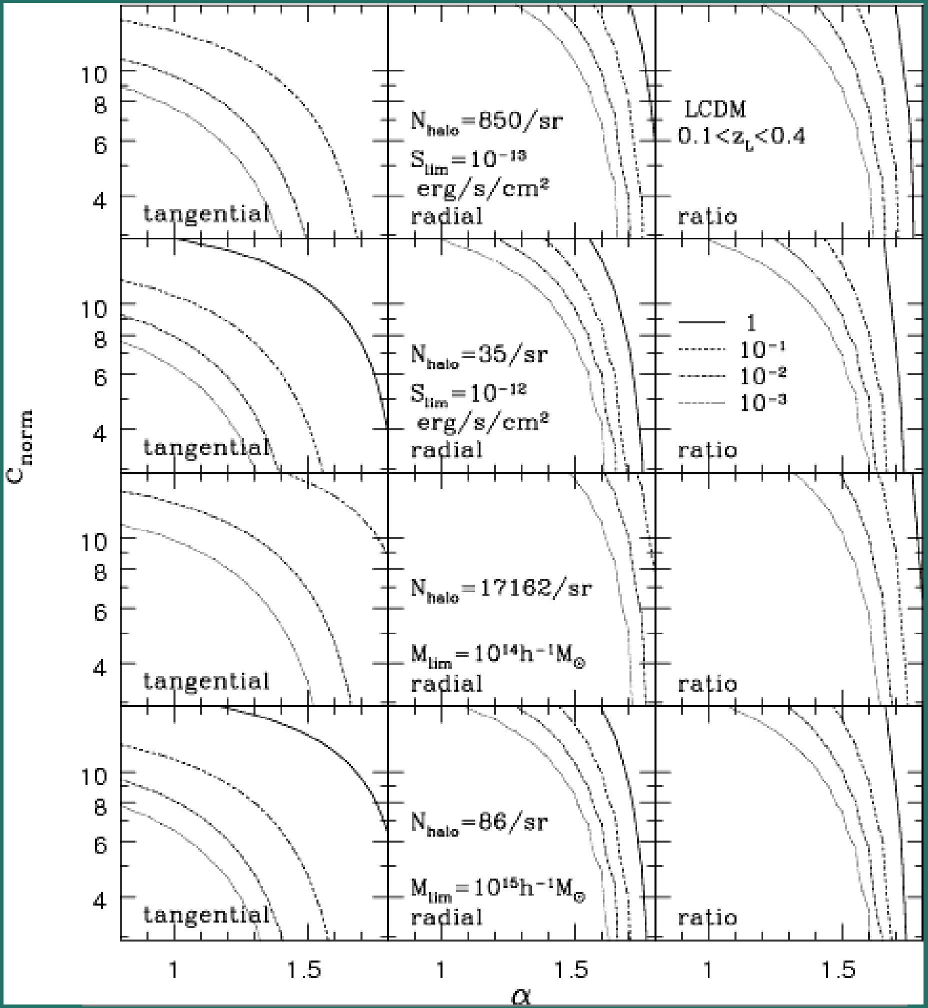
Cheng & Wu (2001)

Gravitational lensing: A2218



Arc statistics of gravitational lensing

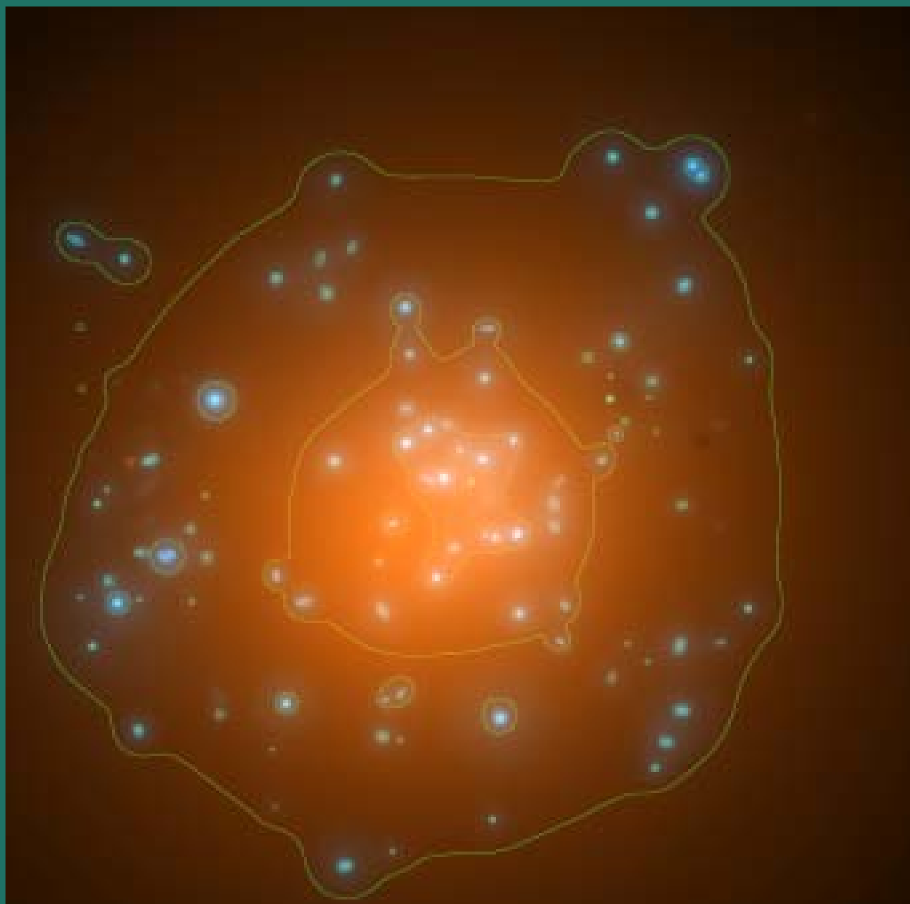
Observed high-frequency of radial arcs favors the steep central cusp in massive halos as indeed suggested by simulations (Molikawa & Hattori 2001; Oguri, Taruya & Suto 2001)

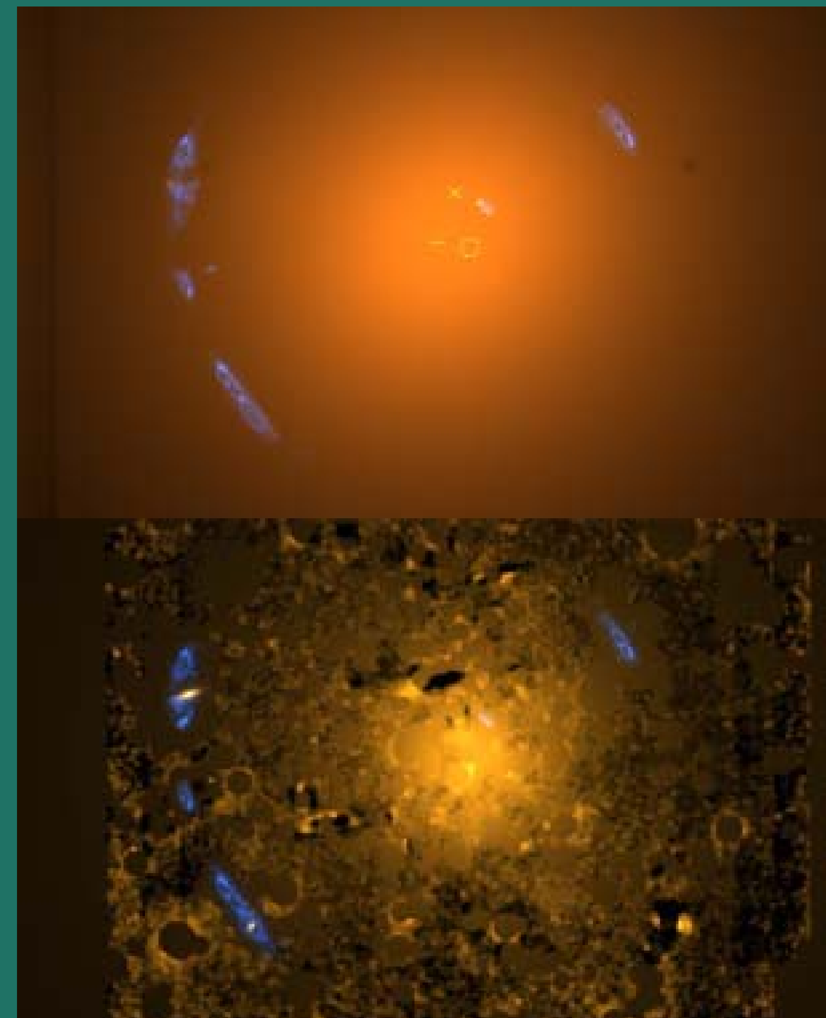


Oguri, Taruya & Suto (2001)

Gravitational lensing of CL0024+1654

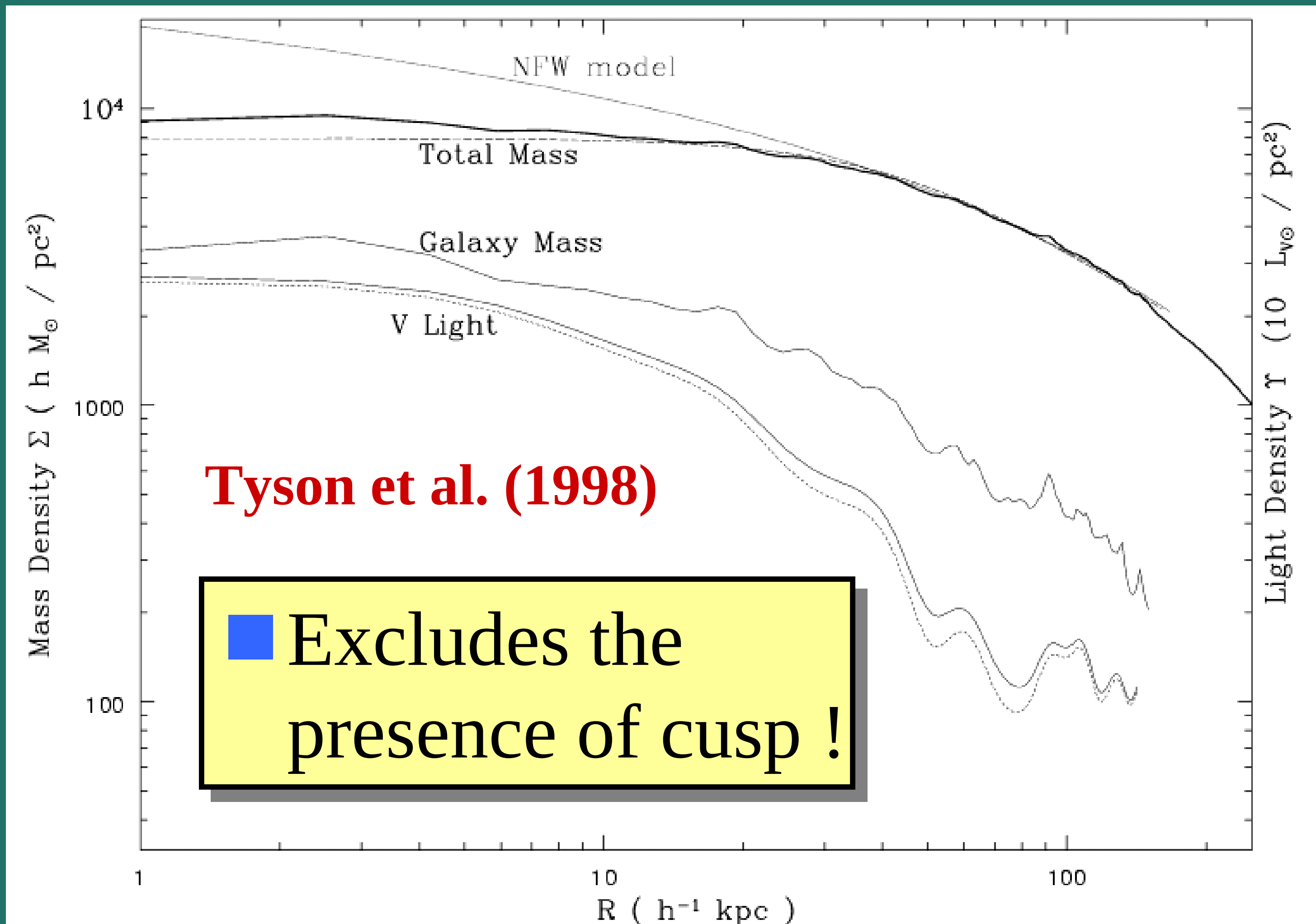
reconstructed mass distribution





Tyson et al. (1998)

Reconstructed mass profile of CL0024+1654



Tyson et al. (1998)

- Excludes the presence of cusp !

Implications: problems with cold dark matter ?

- ***Observations favor the presence of core rather than cusp.***
  - Rotation curves of low-surface brightness galaxies
  - Cluster mass profile from gravitational lensing
  - still controversial, but ...
- ***Cold dark matter is really collisionless ?***

  Self-interacting dark matter
  (Spergel & Steinhardt 1999)

Self-interacting dark matter

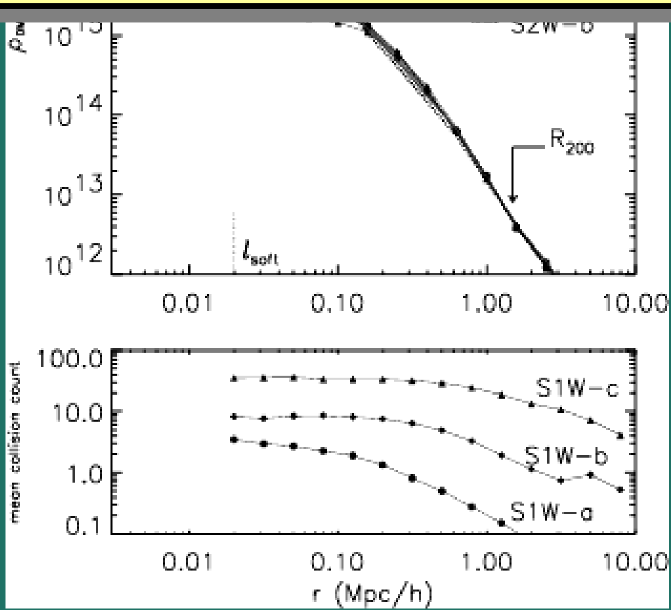
- ***Collisionless dark matter***
  - reproduces nicely the observed large-scale structure of the universe ($r \gg 1$Mpc)
  - **problems on smaller scales ($r<1$Mpc)**

    LSB rotation curves, soft core in CL0024+1624, prediction of a factor of ten more subhalos than observed in the Local Group
- Required scattering cross section

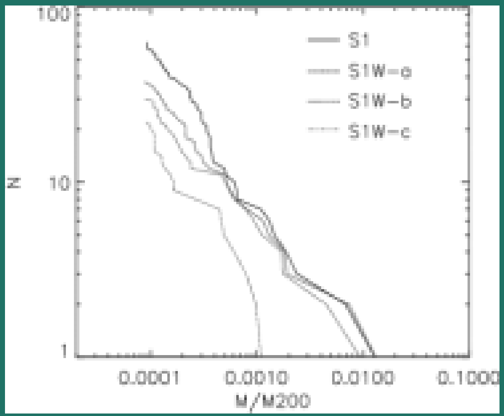
$$\boldsymbol{(mn)\frac{\sigma}{m}\ell = 1 \quad \Rightarrow \quad \frac{\sigma}{m} = 2\mathrm{cm}^2/\mathrm{g}\left(\frac{10^4\rho_{\mathrm{crit}}}{\rho_{\mathrm{center,cl}}}\right)\left(\frac{1\mathrm{Mpc}}{\ell}\right)}$$

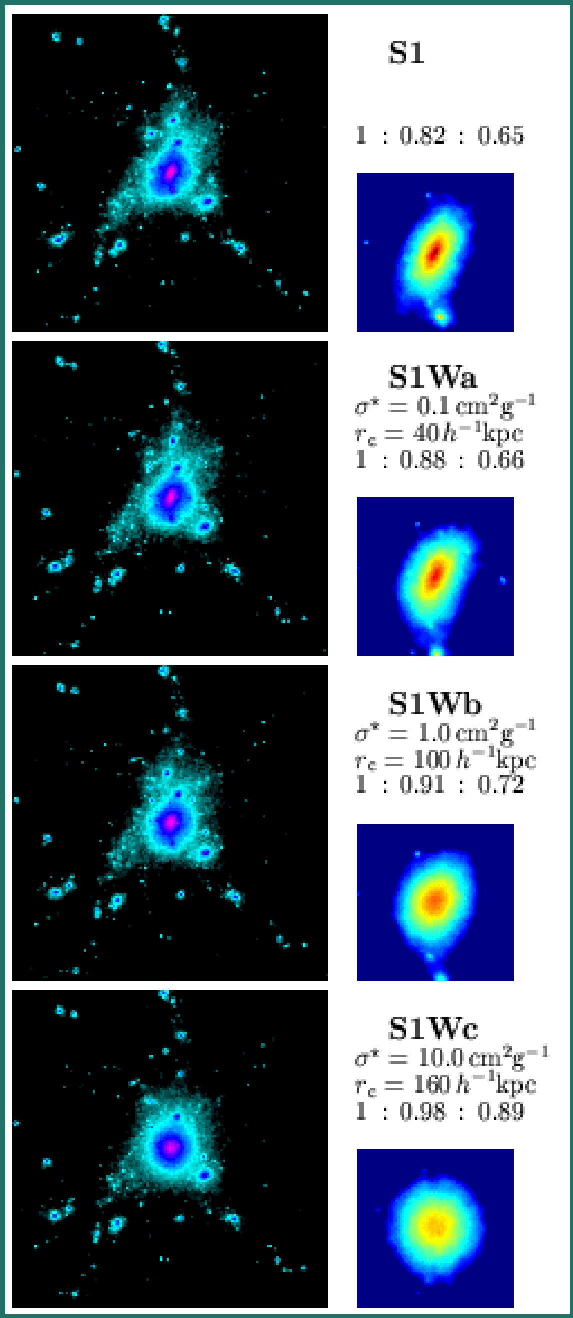
Collisional Dark Matter

- σ→∞ (fluid limit), steeper cusp !
- $\sigma/m \sim 1\ \mathrm{cm}^2/\mathrm{g}$ ⇒ no cusp, rather forms a central core, but the resulting halos are too spherical…



Yoshida et al. (2000)





Conclusions

- ***The situation is confusing at best.***
  - Numerical simulations for collisionless dark matter consistently suggest the formation of a central cusp ($\propto r^{-1.5}$) rather than a core.
  - No convincing theoretical model yet which accounts for the universality of the shape of the profile.
  - Observations indicate a relatively flat core rather than a cusp.
  - Collisional dark matter with an appropriate cross section can erase the central cusp but result in too spherical halos.
- ***More work remains to be done.***