Density profiles and clustering of dark matter halos and clusters of galaxies

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Matter and Energy in Clusters of Galaxies
星系團的物質與能量

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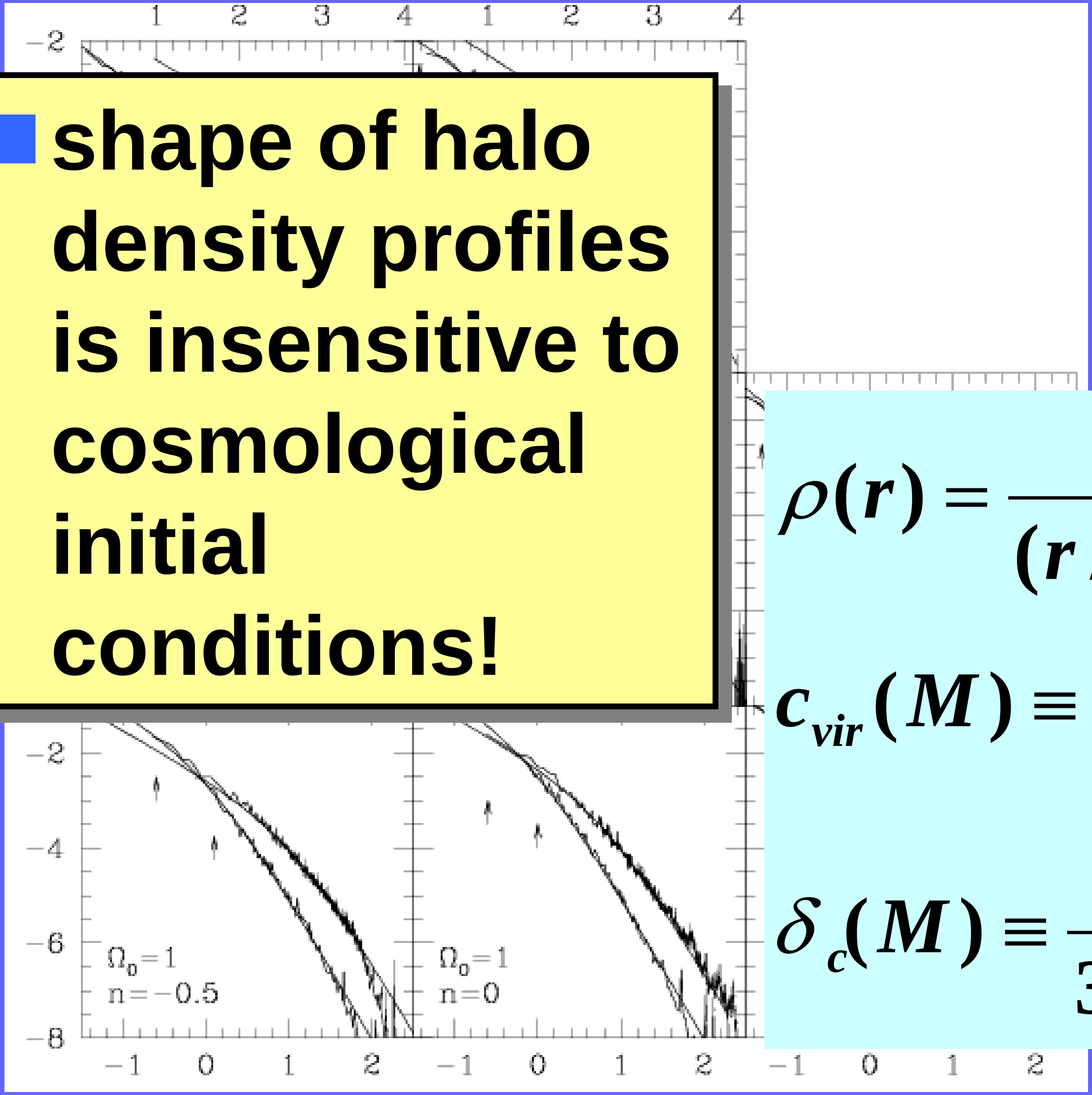
Why density profiles of dark halos ?

- **Theoretical interest:** *what is the final state of the cosmological self-gravitating system ?*
  - forget cosmological initial conditions?
  - keep initial memory somehow?
- **Practical importance:** *testing cosmology and/or nature of dark matter*
  - galactic rotation curve, gravitational lensing, X-ray/SZ observations of clusters

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$\sim$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 $\rho \propto r^{-1}(r+r_s)^{-3}$.
- **1996:** **Navarro, Frenk & White**; universal density profile for dark matter halos.

NFW universal density profile



- **shape of halo density profiles is insensitive to cosmological initial conditions!**

Navarro, Frenk & White (1997)

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

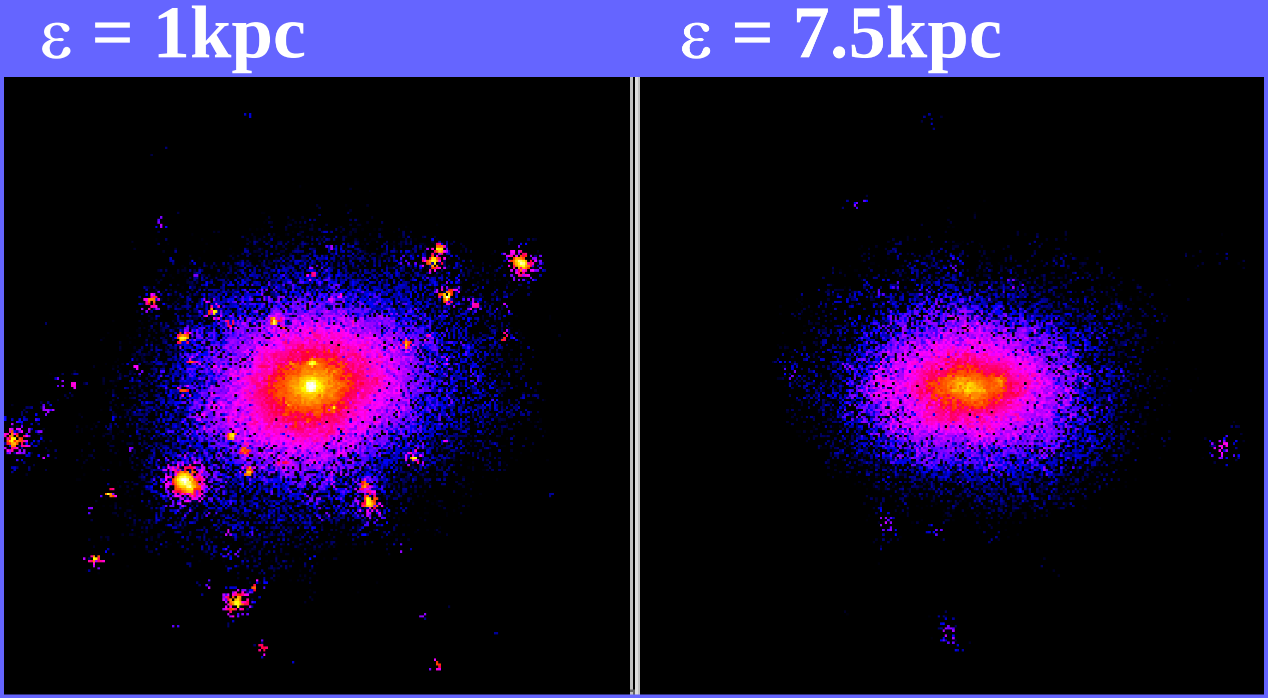
$$c_{vir}(M) \equiv \frac{r_{vir}(M)}{r_s(M)}$$ concentration parameter

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

Importance of high-resolution simulations

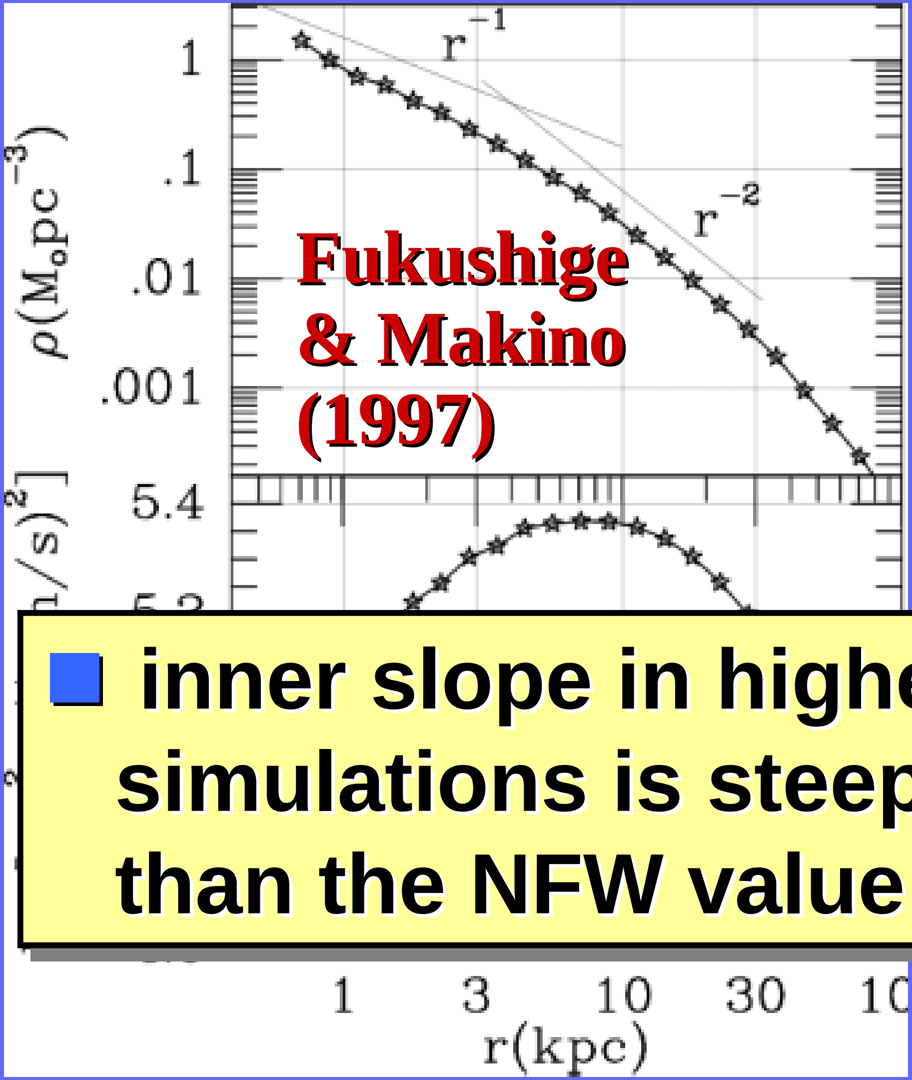
- low mass/force resolutions
  ⇒ shallower potential than real
  ⇒ artificial disruption/overmerging
  (especially serious for small systems)

Moore (2001)

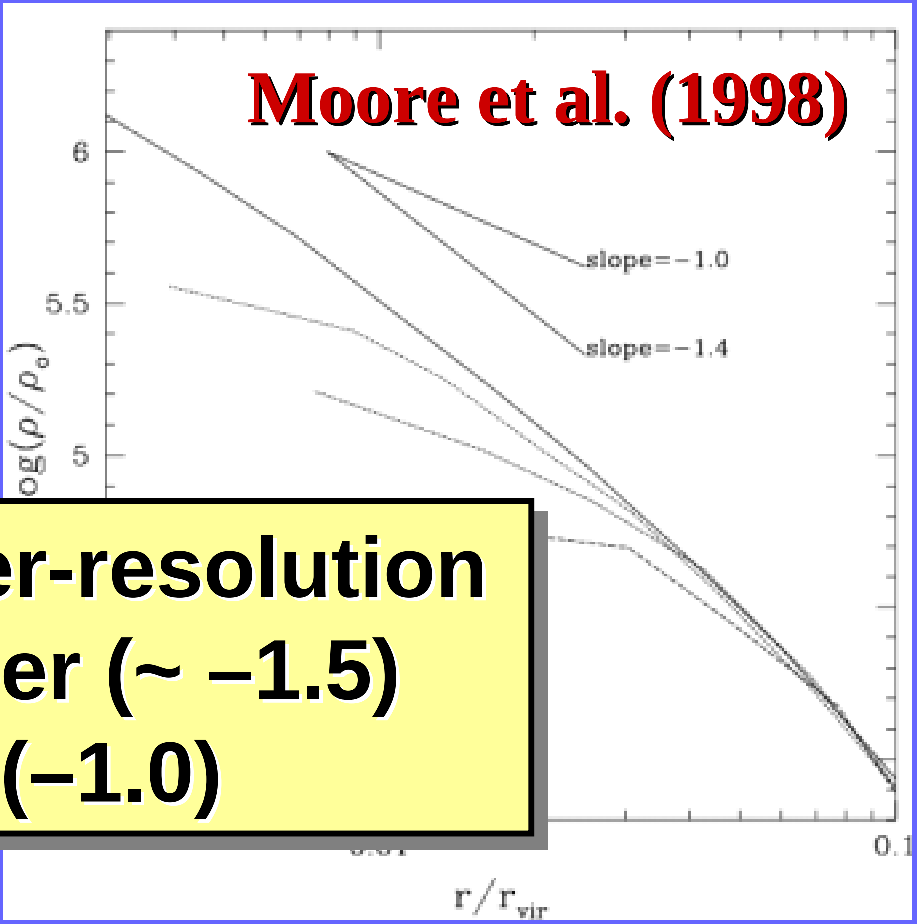


central 500kpc region of a simulated halo in SCDM

Profiles in higher-resolution simulations



Fukushige & Makino (1997)



Moore et al. (1998)

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

Origin of the universal density profiles ?

- **1977:** Davis & Peebles; stable clustering solution of 2pt correlation function
  $\xi \propto r^{-3(n+3)/(n+5)}$
- **1977:** Gott; secondary infall model
  $\rho \propto r^{-9/4}$
- **1985:** Hoffman & Shaham; mass profile around density peaks $\rho \propto r^{-3(n+3)/(n+4)}$
- **1997:** Syer & White; dynamical friction of satellites halos $\rho \propto r^{-3(n+3)/(n+5)}$

Gallery of high-resolution simulated halos

galaxies

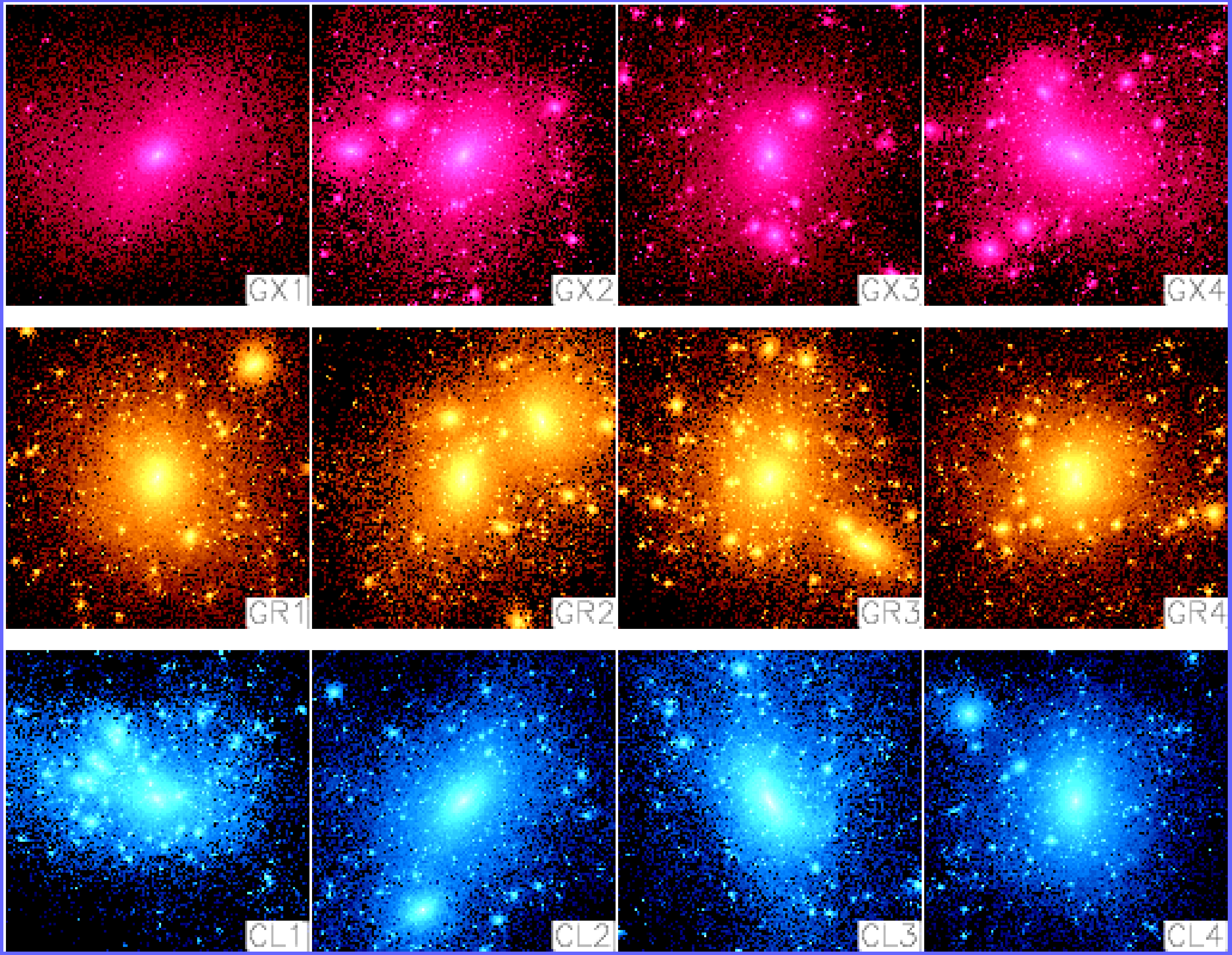
~ $5\text{x}10^{12}M_{sun}$

groups

~ $5\text{x}10^{13}M_{sun}$

clusters

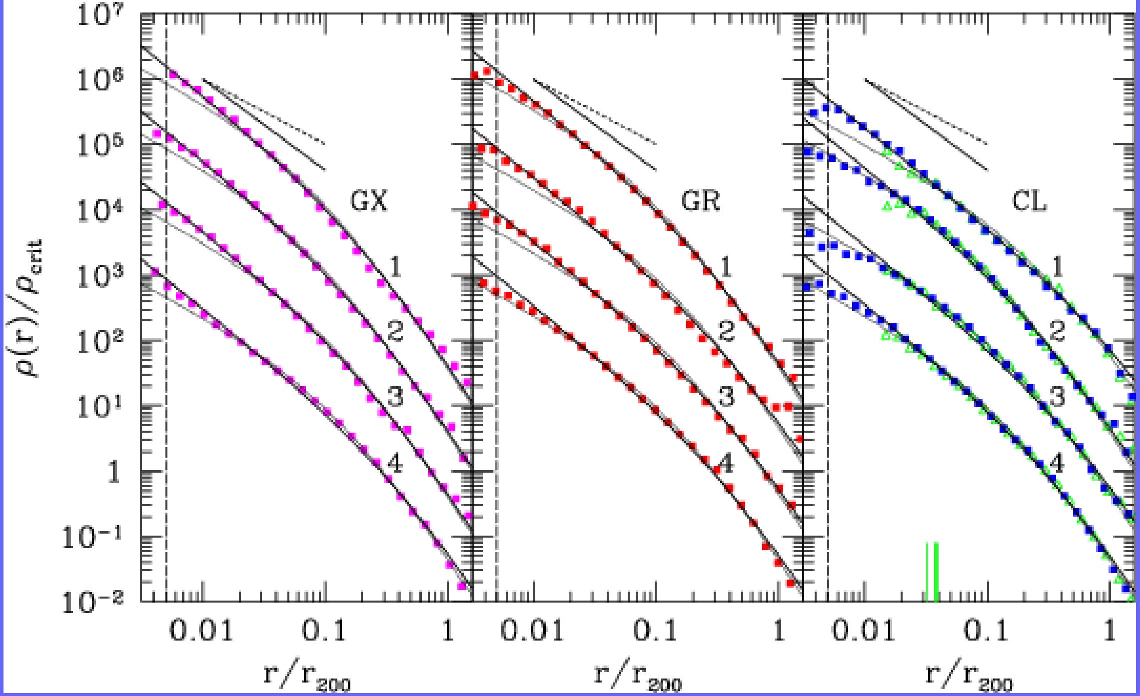
~ $3\text{x}10^{14}M_{sun}$

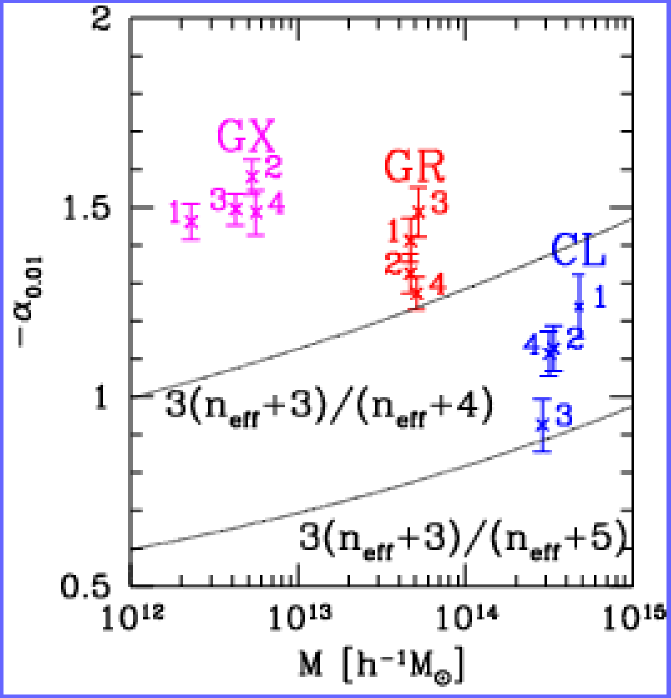


Jing & Suto (2000)

Weak mass-dependence of halo profiles ?

- Inner slope of the profile (**α** = -1.2〜-1.5) is weakly dependent on the halo mass ?





Jing & Suto (2000), *but see also Fukushige & Makino (2001)*

Summary of simulation and theory

Simulations

- Density profiles of dark halos are fairly universal (at least approximately), and are insensitive to the cosmological initial conditions
- Cusp rather than core in the central region

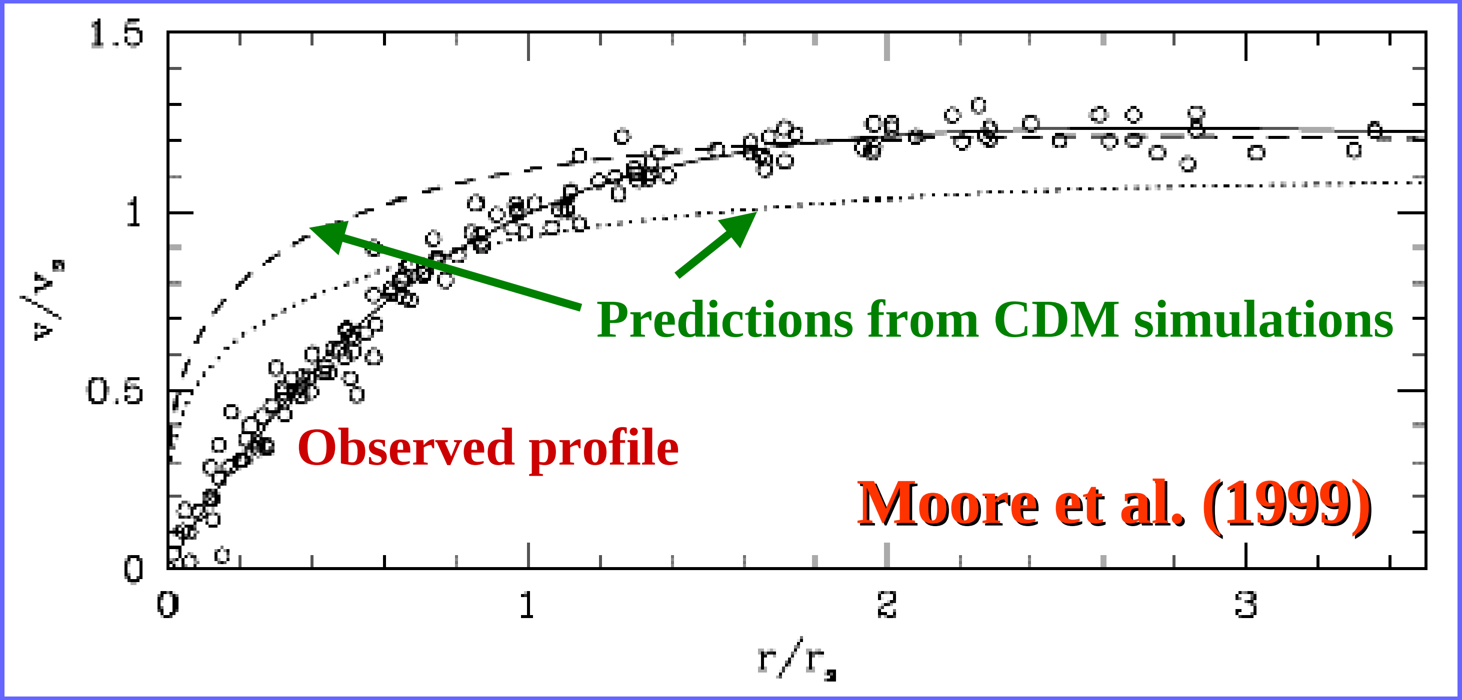
$$\rho(r) = \frac{\delta_c \rho_{crit}}{(r/r_s)^{\alpha}(1+r/r_s)^{3-\alpha}} \quad \alpha \approx 1.5$$

Theoretical models

- Either core or cusp is acceptable.
- Inner slope is generally expected to depend on the primordial spectrum of fluctuations.

⇒ ***needs observational confrontation***

Rotation curves of DM dominated galaxies



- dwarf spirals to giant low surface brightness galaxies indicate the central cores rather than cusps !

⇒ inconsistent with CDM simulations

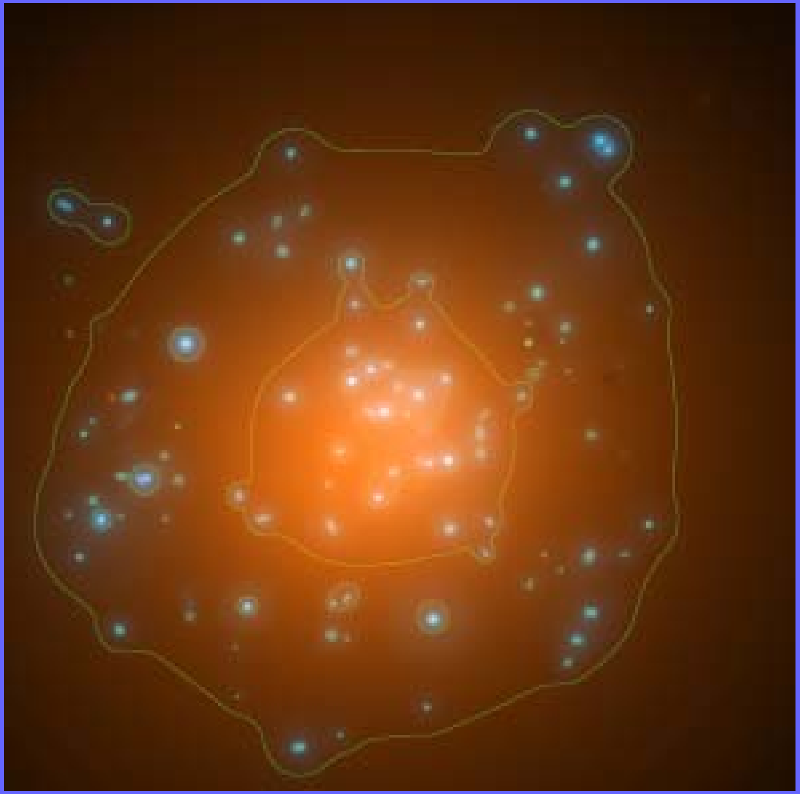
(Moore et al. 1999; de Blok et al. 2000; Salucci & Burkert 2000)

Gravitational lensing of CL0024+1654

HST image

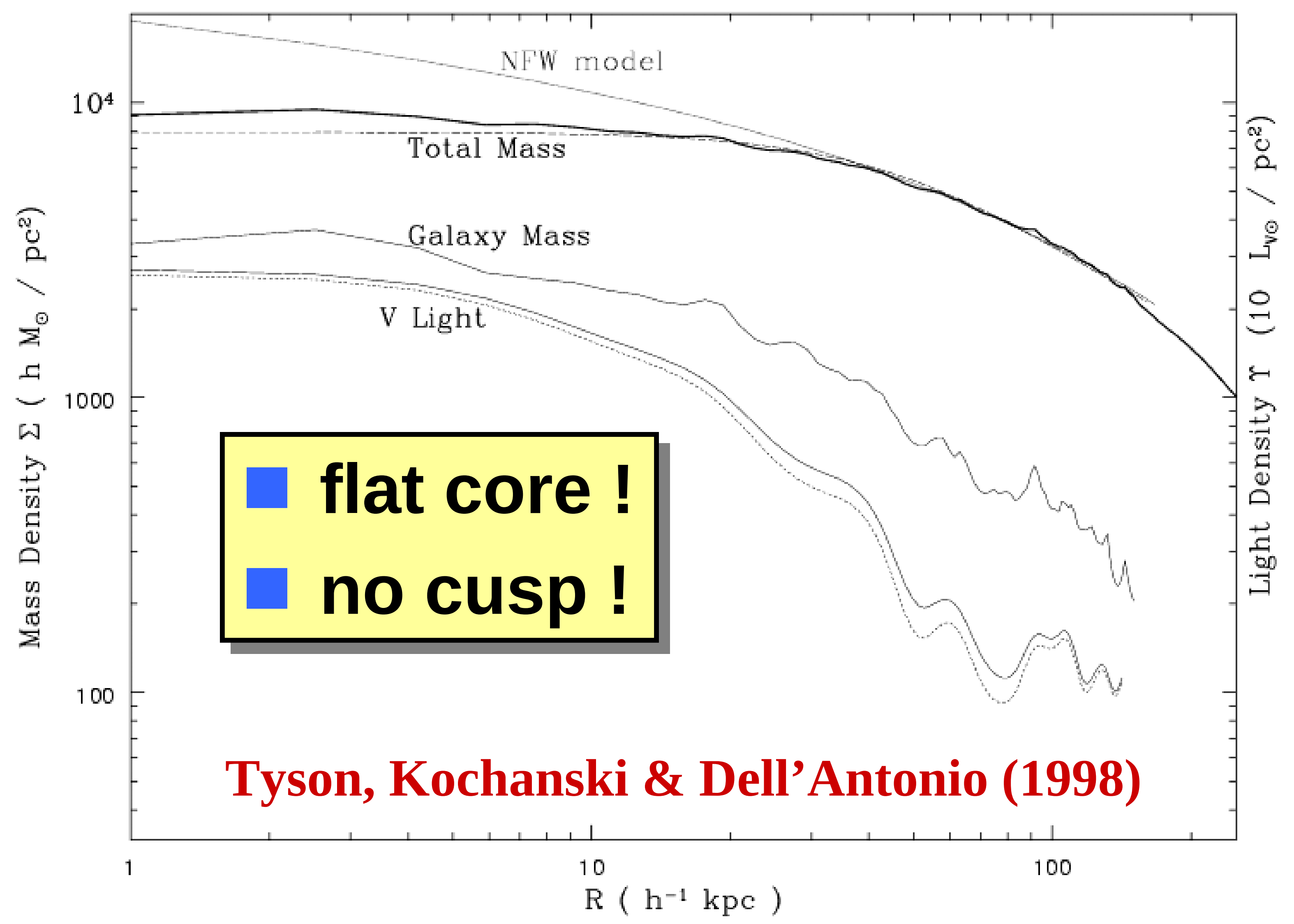
Z=0.39, $L_X = 5 \times 10^{43}\ h^{-2}$ erg/s

reconstructed mass distribution (with 512 parameters)



Tyson, Kochanski & Dell'Antonio (1998)

Reconstructed mass profile of CL0024+1654



- **flat core !**
- **no cusp !**

Tyson, Kochanski & Dell’Antonio (1998)

Crisis of 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)
- ***Other hydrodynamical/radiative processes ?***
  - Supernova feedback
  - Bar-driven core formation (Weinberg & Katz 2001)
  - ...

Self-interacting dark matter ?

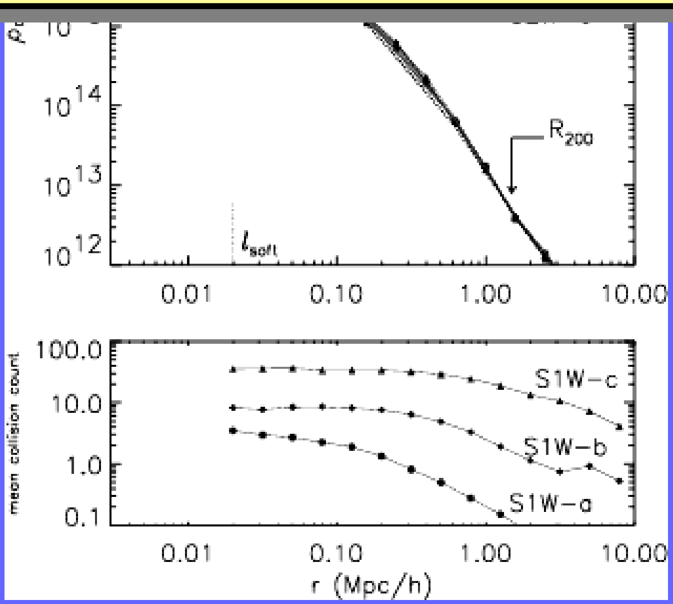
- ***Collisionless dark matter***
  - reproduces nicely the observed large-scale structure of the universe ($r \gg 1$Mpc)
  - **problems on smaller scales ($r<1$Mpc)**

    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

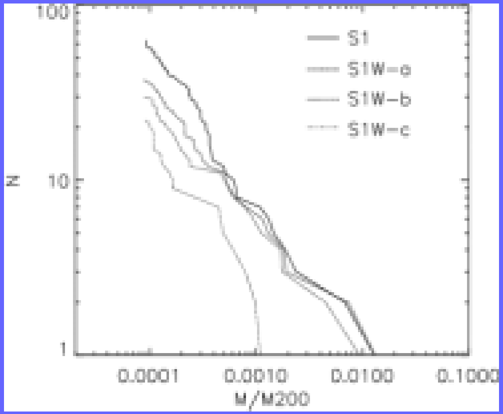
$$(mn)\frac{\sigma}{m}\ell = 1 \quad \Rightarrow \quad \frac{\sigma}{m} = 2\mathrm{cm}^2/\mathrm{g}\left(\frac{10^4\rho_{\mathrm{crit}}}{\rho_{\mathrm{center,cl}}}\right)\left(\frac{1\mathrm{Mpc}}{\ell}\right)$$

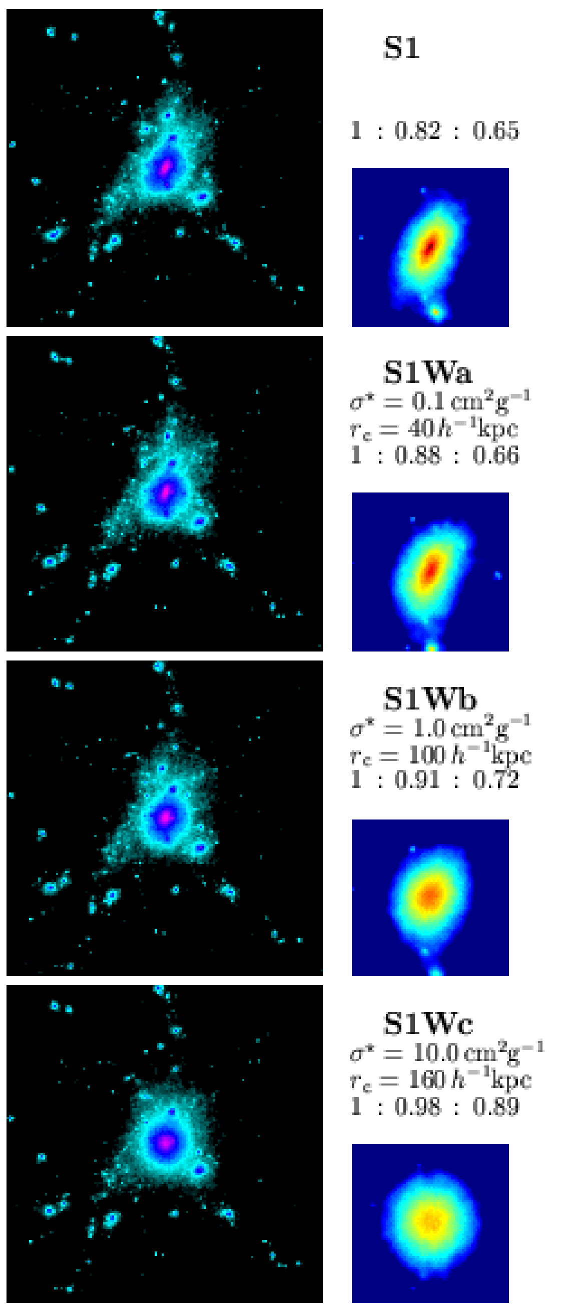
Collisional Dark Matter

- $\sigma \to \infty$ (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)





Constraining halo central density profiles with gravitational lensing

- ***Statistics of QSO multiple images***

  (Wyithe, Turner & Spergel 2001; Keeton & Madau 2001; Li & Ostriker 2001; Takahashi & Chiba 2001)

- ***Arc statistics of clusters of galaxies***

  (Bartelmann et al. 1998; Molikawa & Hattori 2001; Oguri, Taruya + YS 2001)

- ***Time-delay statistics of QSO multiple images***

  (Oguri, Taruya, YS + Turner 2002)

$\Rightarrow$ *generally favor a steep cusp* ($\alpha \sim -1.5$)

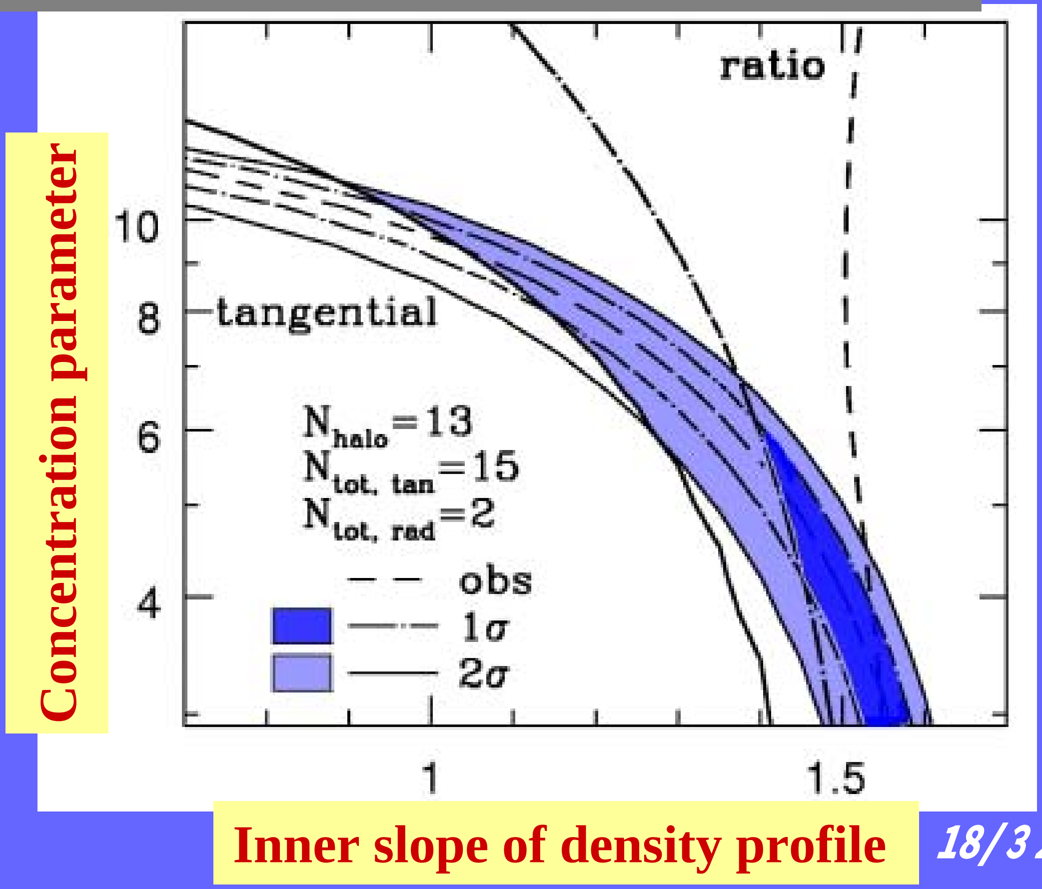
Constraints from the existing arc samples

- **tentative application to 13 galaxy clusters with $S_X>10^{-12}$ erg/s/cm^2 and $0.1<z_L<0.4$**
  $\Rightarrow$ $N_{tot,\,tan}=15$, $N_{tot,\,rad}=2$ (Luppino et al. 1999)

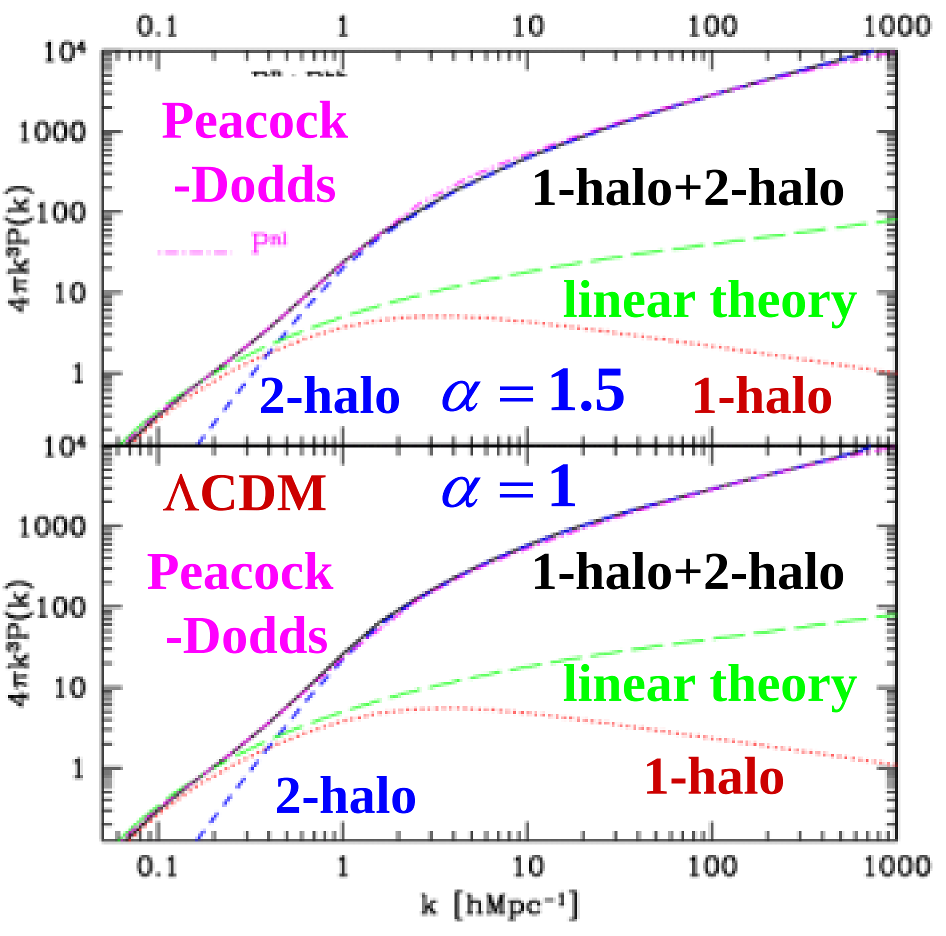
Observed high-frequency of radial arcs favors the steep central cusp in massive halos as indeed suggested by CDM simulations

(Molikawa & Hattori 2001)

Oguri et al. (2001)



From density profiles to clustering of dark matter: dark matter halo approach

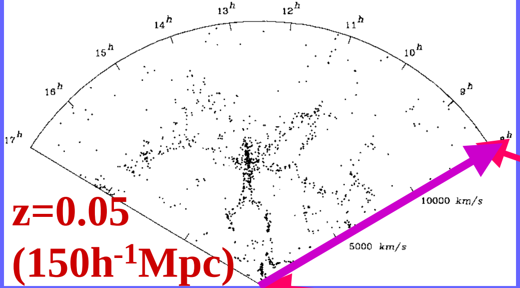


Seljak (2000)

- Accurate modeling of nonlinear clustering of dark matter
  - interpolation of linear theory and stable solution using N-body data (e.g., Hamilton et al. 1991; Peacock & Dodds 1996)
  - dark matter halo approach: pairs of particles (in a single halo + in two different halo) weighted over the halo mass function (e.g., McClelland & Silk 1977; Seljak 2000; Ma & Fry 2000)
- **Both results agree well when adopting the halo profiles from N-body simulations**

Clustering of luminous objects on the light-cone

1986

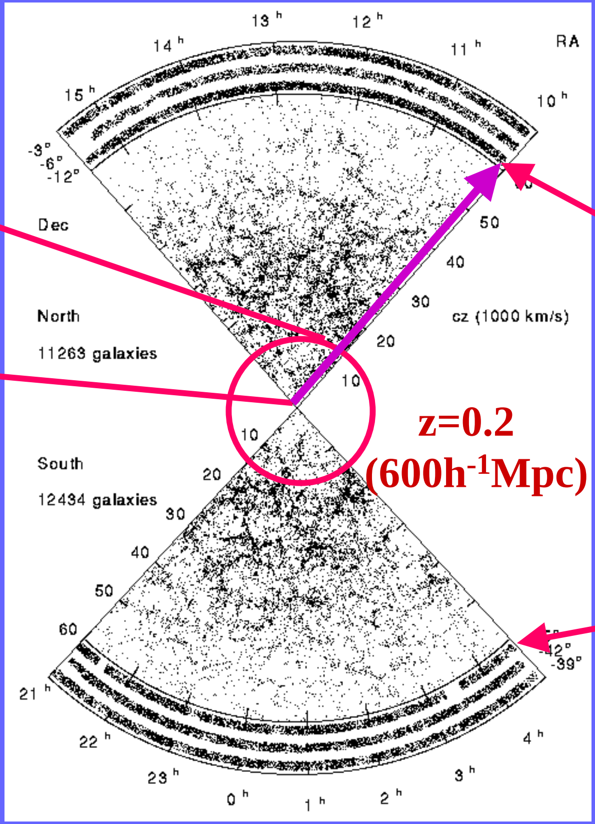


z=0.05

(150h^{-1}Mpc)

CfA redshift survey:
de Lapparent et al.(1986)

1996

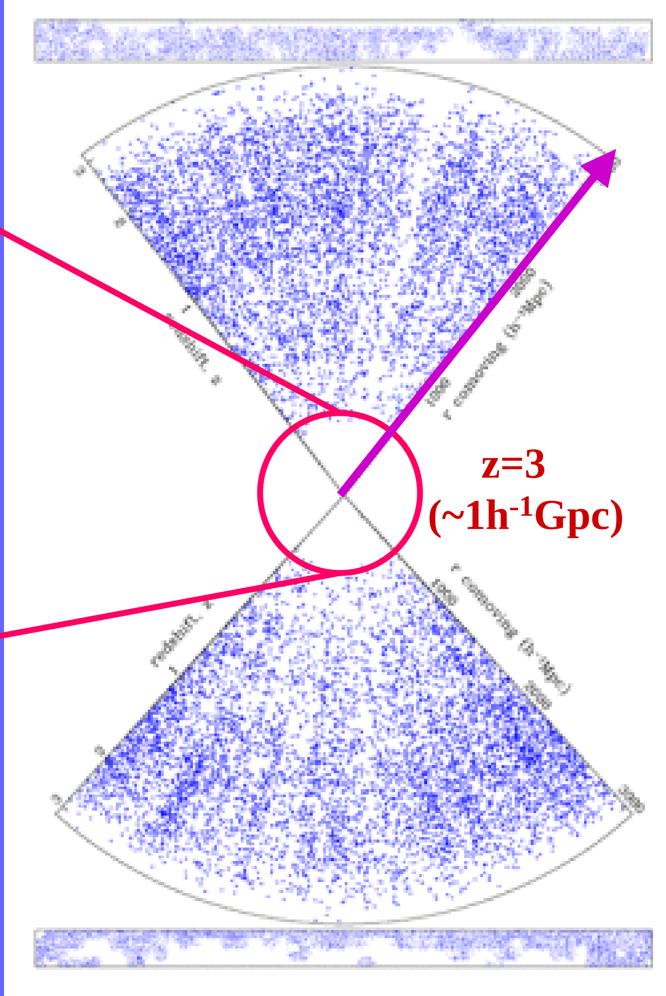


z=0.2

(600h^{-1}Mpc)

Las Campanas redshift survey:
Schectman et al. (1996)

2001



z=3

(~1h^{-1}Gpc)

2dF QSO survey: Shanks et al. (2001)

- ***Evolution along the light-cone is essential even in the current surveys !***

Predicting the clustering of dark matter on the light-cone

- ***redshift-space distortion***

$$\xi(r;z) = \frac{1}{2\pi^2}\int_0^\infty k^2 dk\, \underline{P_{nl}^R(k,z)}\, \underline{f(k,\beta,\sigma_{\mathrm{1D,vel}})}\,\frac{\sin kr}{kr}$$

gravitational nonlinear evolution

linear and nonlinear redshift-space distortion

- ***average over the light-cone***

$$\xi^{LC}(r) = \frac{\displaystyle\int_{z_{\min}}^{z_{\max}} dz\,\xi(r;z)[\phi(z)n(z)]^2 \frac{dV_c}{dz}}{\displaystyle\int_{z_{\min}}^{z_{\max}} dz[\phi(z)n(z)]^2 \frac{dV_c}{dz}}$$

comoving volume element

selection function

mean number density

Yamamoto & Suto (1998) ; Hamana, Colombi & Suto (2001)

Phenomenological model for scale- and mass-dependent ***halo*** biasing

- ***mass-dependence (Jing1998; Sheth & Tormen 1999) + scale-dependence (Taruya & Suto 2000)***

$$b_{halo}(M,R,z) = b_{\mathrm{ST}}(M,z)[1+b_{\mathrm{ST}}(M,z)\sigma_{\mathrm{mass}}(R,z)]^{0.15}$$

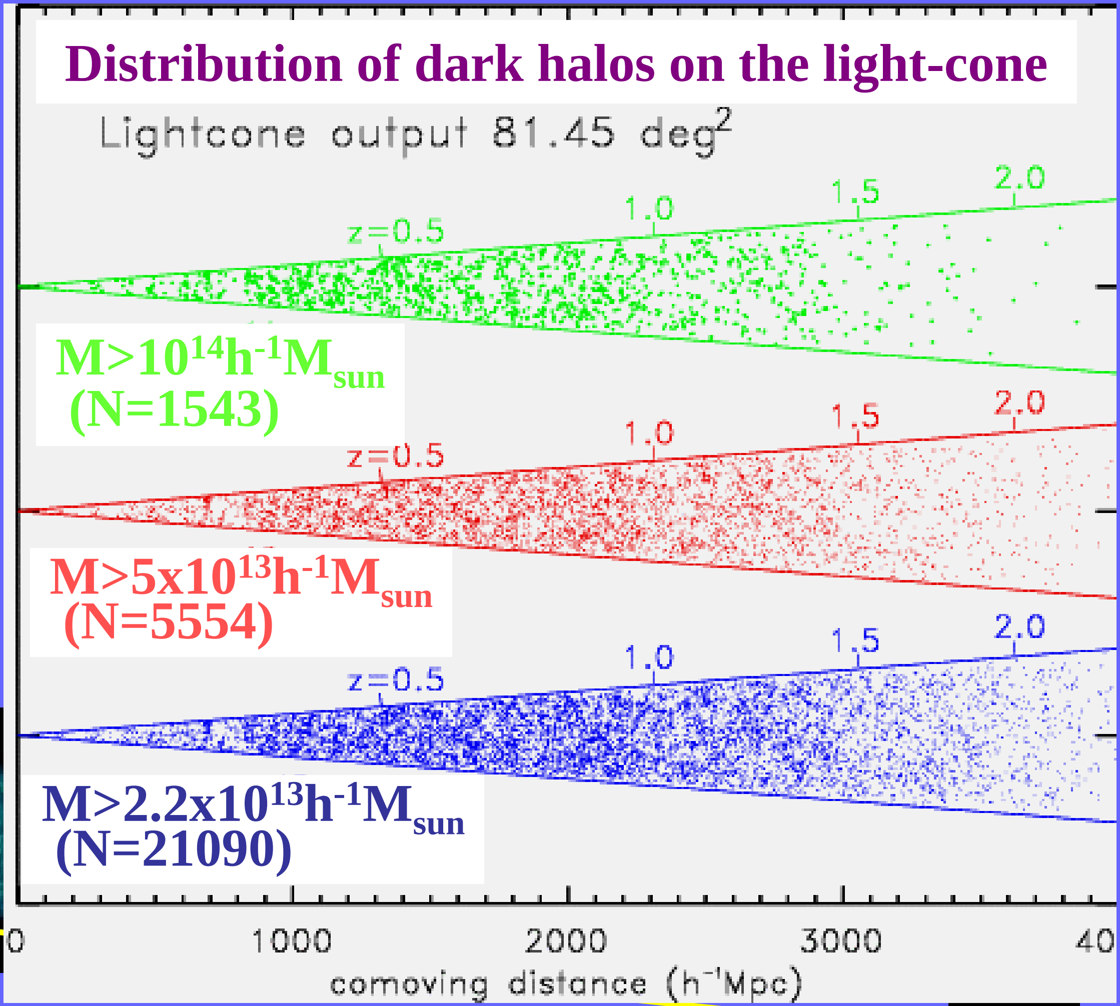
$$\xi_{halo}(M,R,z) = b^{2}_{halo}(M,R,z)\,\xi_{\mathrm{mass}}(R,z)$$

- ***average over the light-cone***

$$\xi^{LC}_{halo}(>M,r) = \frac{\displaystyle\int_{z_{\min}}^{z_{\max}} dz \int_{M}^{\infty} dM\,\xi_{halo}(M,R,z)\,n^{2}_{\mathrm{ST}}(M,z)\frac{dV_c}{dz}}{\displaystyle\int_{z_{\min}}^{z_{\max}} dz \int_{M}^{\infty} dM\; n^{2}_{\mathrm{ST}}(M,z)\frac{dV_c}{dz}}$$

Hamana, Yoshida, Suto & Evrard; ApJ 561(2001)L143 http://www.physics.isa.umich.edu /hubble-volume/ lightcones.htm

Light-cone output from the Hubble volume Λ simulation

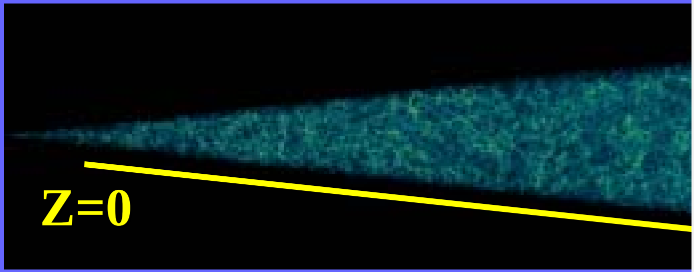


Distribution of dark halos on the light-cone

$M>10^{14}h^{-1}M_{sun}$ (N=1543)

$M>5\times10^{13}h^{-1}M_{sun}$ (N=5554)

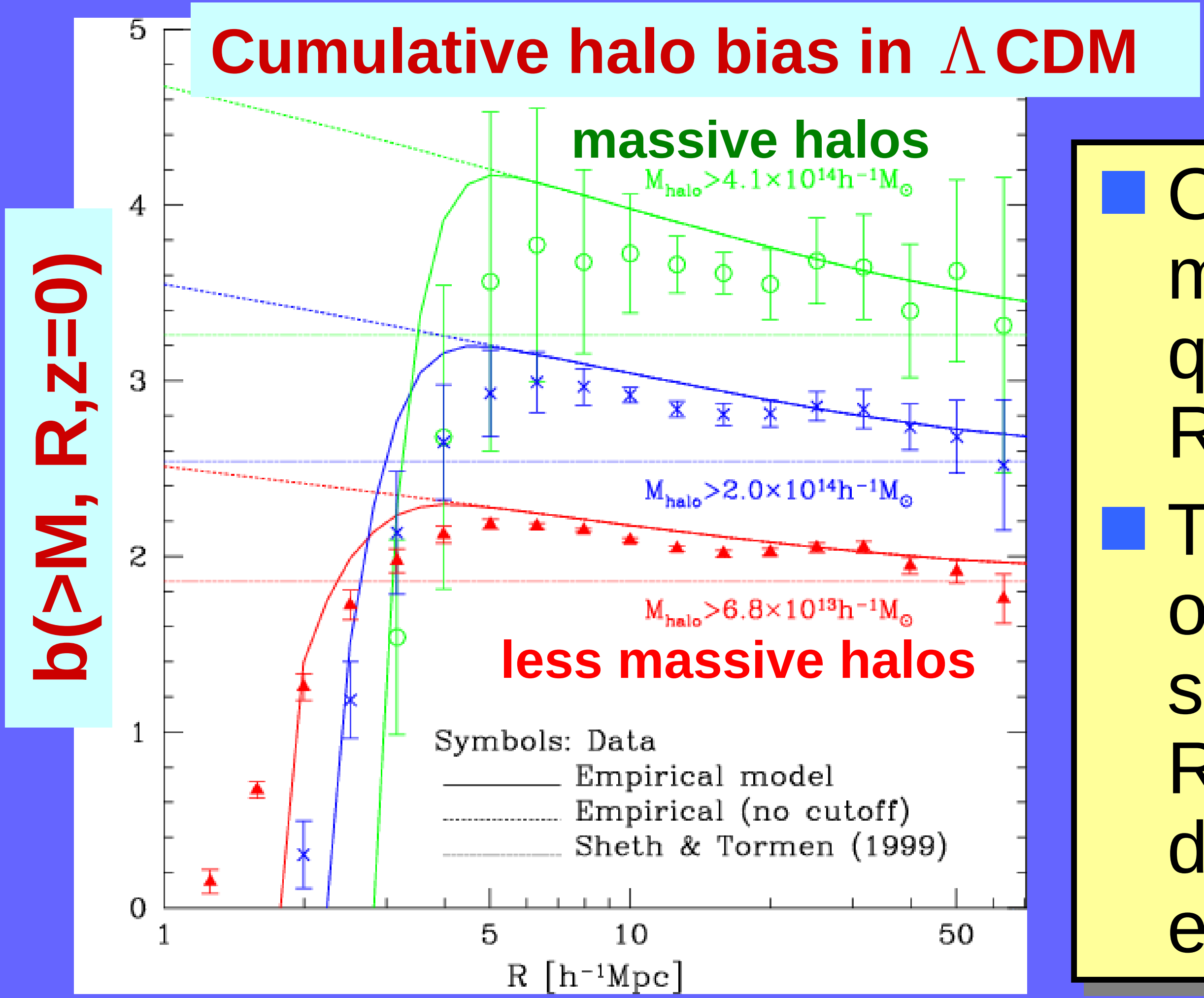
$M>2.2\times10^{13}h^{-1}M_{sun}$ (N=21090)



Z=0

Hamana, Yoshida, Suto & Evrard (2001)

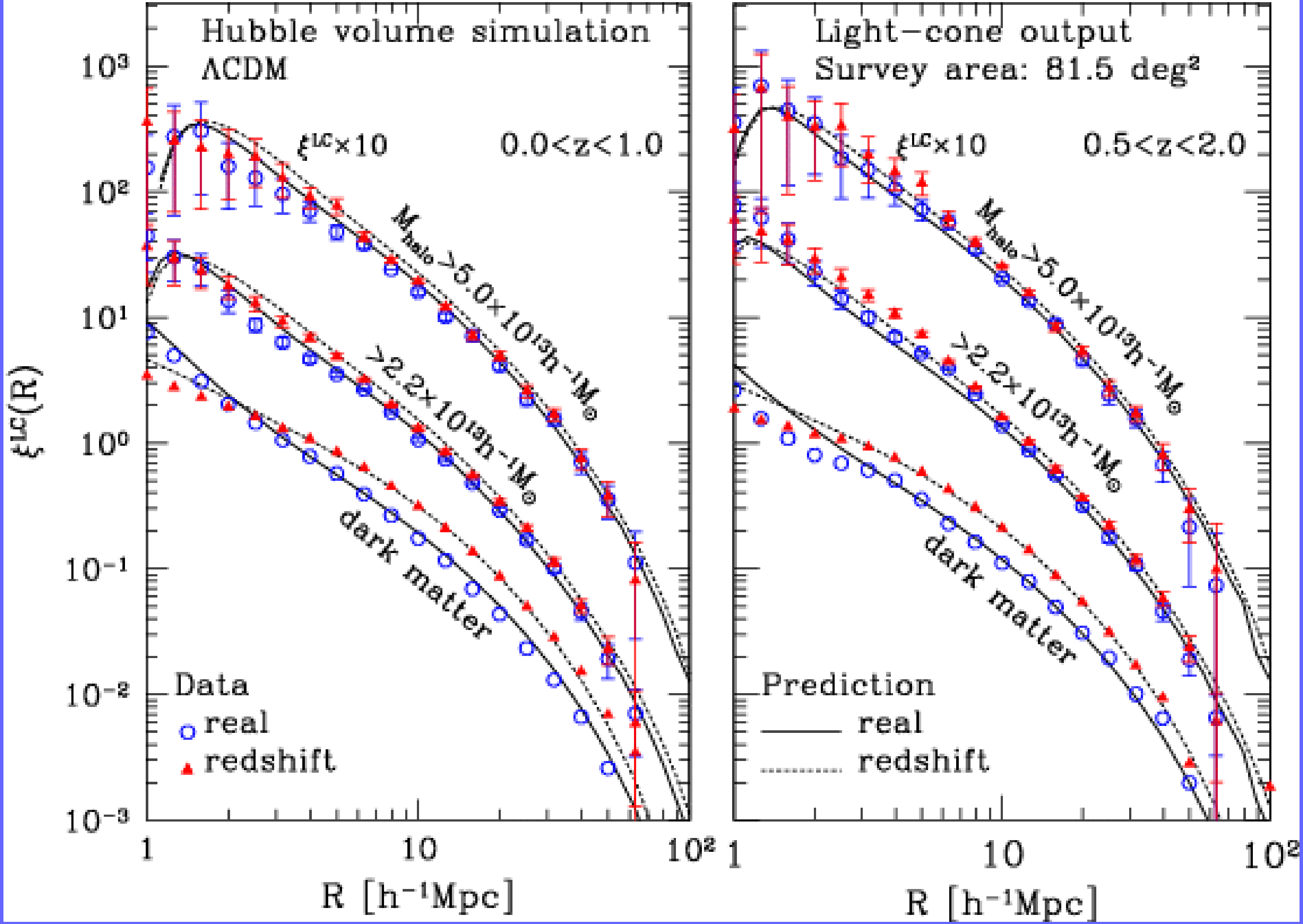
Calibrating the halo biasing model with the Hubble volume simulation at z=0



Hamana et al. (2001)

- Our halo bias model works quite well at $R>20h^{-1}$Mpc.
- The suppression of biasing in simulation at $R<5h^{-1}$Mpc is due to the halo exclusion effect.

Correlation functions of halos on the light-cone



Hamana et al. (2001)

Summary of the current results

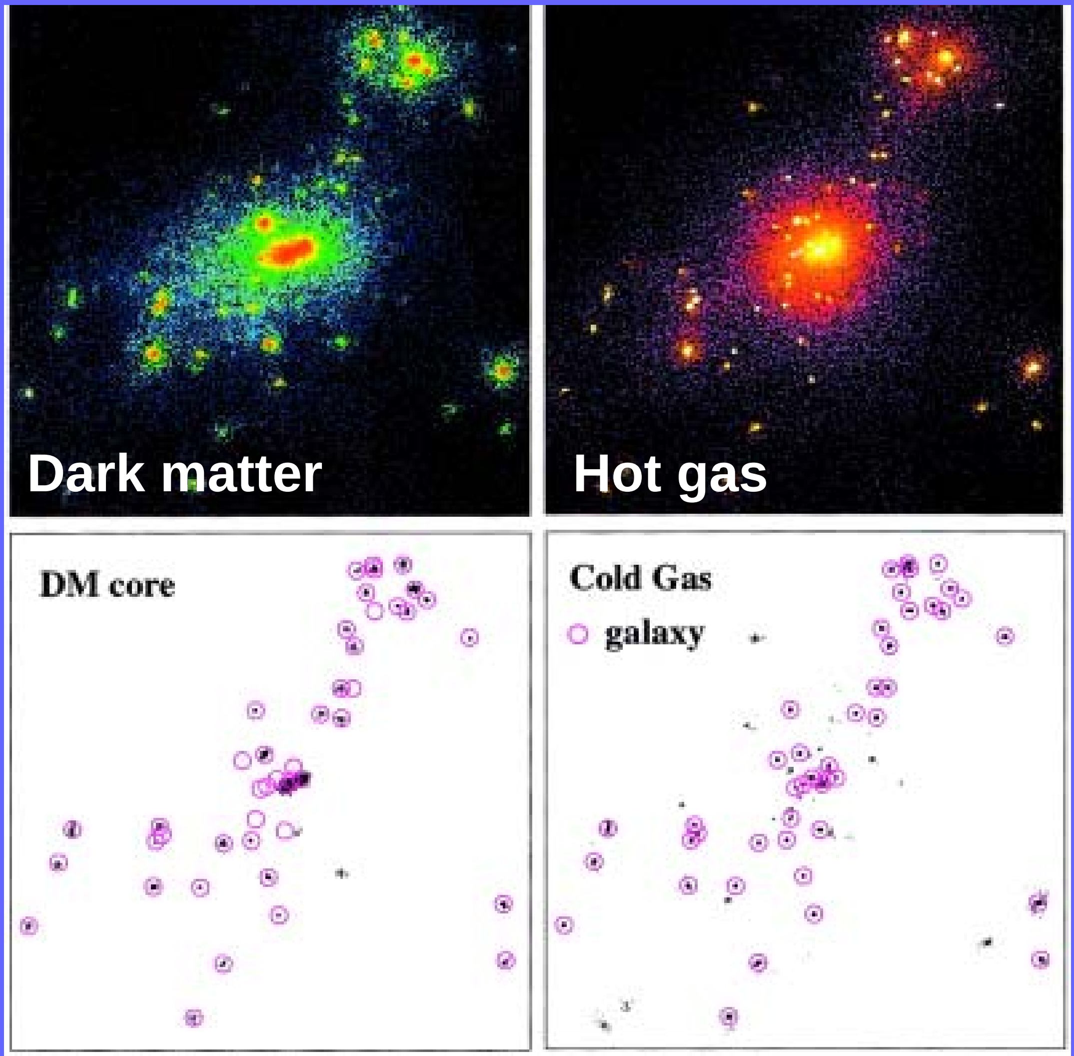
- ***Halo density profiles: still controversial***
  - LSB/dwarf galaxies, CL0024-1654: a flat core
  - N-body simulations, gravitational lensing : a cusp
  - Needs further work from different aspects
- ***Halo clustering: a phenomenologically successful model on the light-cone***
  - gravitational nonlinear evolution
  - redshift-space distortion
  - mass-, time-, and scale-dependent bias
  - selection function
  - evolution in the survey volume itself

An incomplete list of unresolved issues

- ***Halo density profile:***
  - physical explanation of the central cusp
  - characterizing the degree of non-sphericity
- ***From dark halos to visible objects:***
  - halo mass -- cluster gas temperature relation
  - non-gravitational effects inside dark halos (cooling, star/galaxy formation, preheating, supernova feedback, etc.)
- ***Clustering:***
  - predicting the clustering of X-ray/SZ clusters, QSOs, and massive halaxies at high-z on the light-cone.
  - developing the higher-order clustering statistics using the dark halo approach

Relation between dark halos and clusters

A cluster-size halo ($8 \times 10^{14} M_{sun}$ at $z=0$)

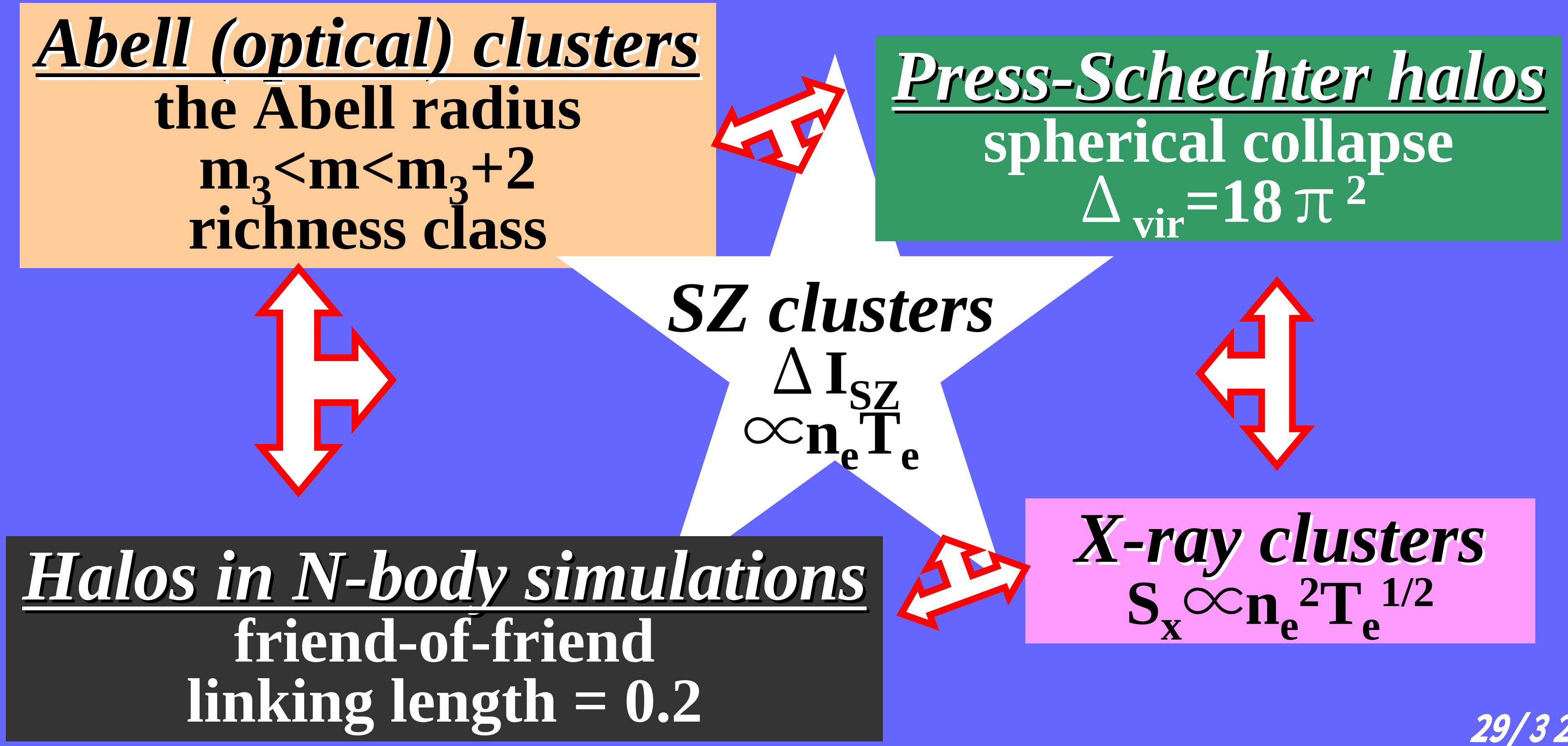


- Globally similar distribution, but their precise relation is unclear because definitions of clusters (especially at high z) are very ambiguous.

SPH simulations in LCDM:
$75 \times 75 \times 15\ h^{-3}\mathrm{Mpc}^3$
(Yoshikawa, Taruya, Jing & Suto 2001)

From dark halos to galaxy clusters ?

- Definitely they are closely related, but the exact one-to-one correspondence is unlikely....



Abell (optical) clusters

the Abell radius

$m_3 < m < m_3 + 2$

richness class

Press-Schechter halos

spherical collapse

$\Delta_{vir} = 18\pi^2$

SZ clusters

$\Delta I_{SZ} \propto n_e T_e$

X-ray clusters

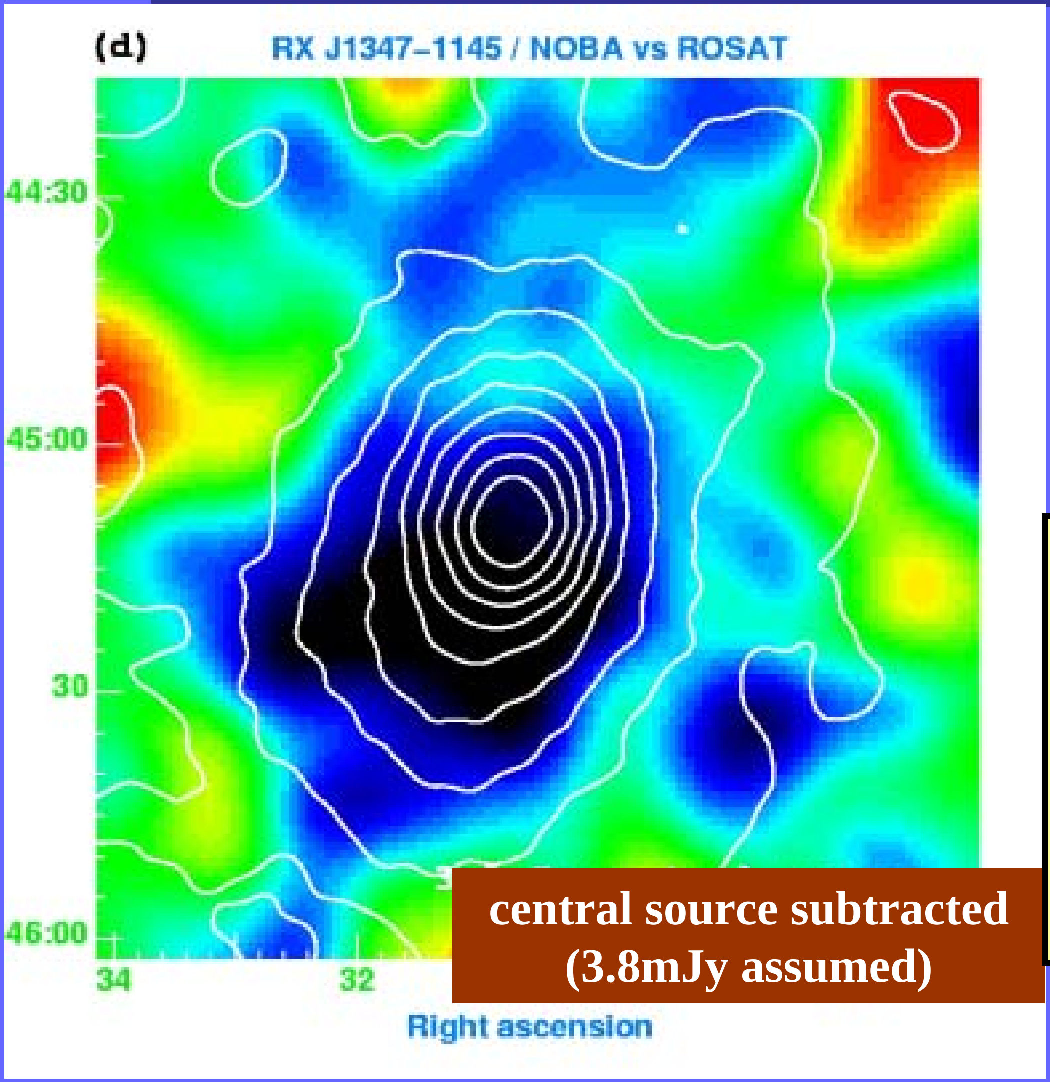
$S_x \propto n_e^2 T_e^{1/2}$

Halos in N-body simulations

friend-of-friend

linking length = 0.2

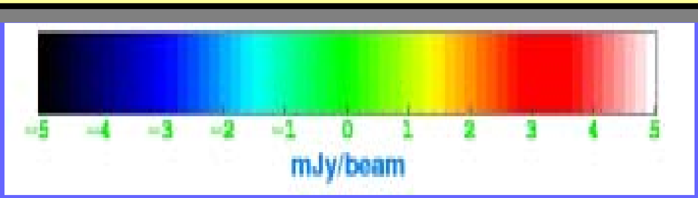
An example; substructure of RXJ1347-1145 (z=0.45) detected via SZ map at 150 GHz



central source subtracted (3.8mJy assumed)

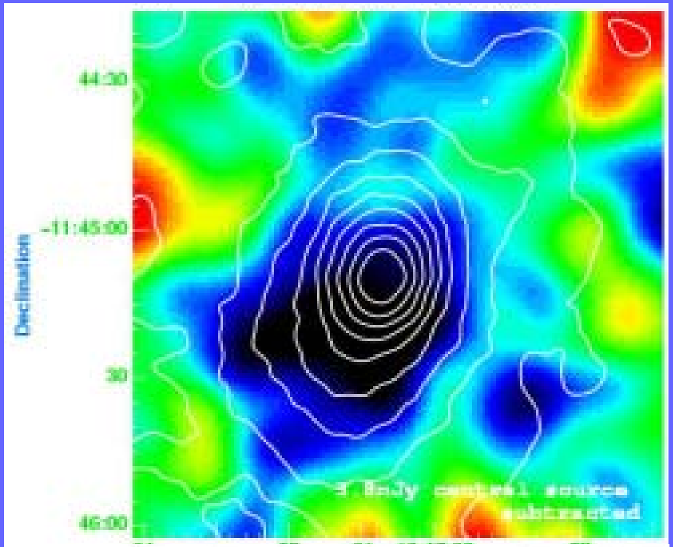
150GHz with NOBA (Nobeyama Bolometer Array) at Nobeyama 45m telescope
in March, April, 1999
and February 2000
$\sigma_{\rm FWHM}$=13"

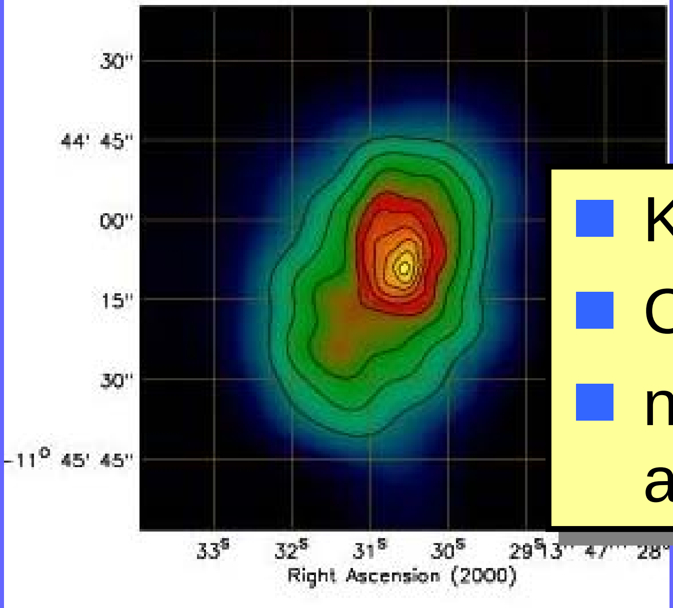
- Globally similar morphology to the X-ray image
- Substructure in the South-East direction

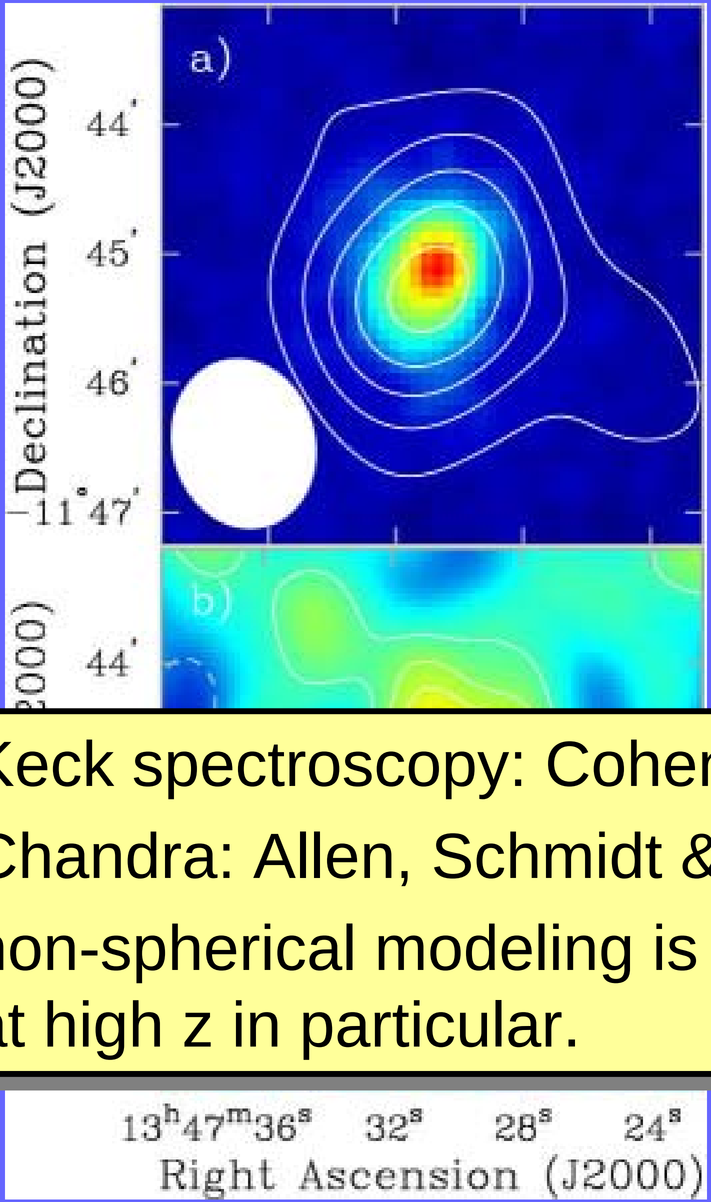


Komatsu et al. PASJ 53(2001)57

Confirmed by Chandra and BIMA observations







RXJ1347-1145

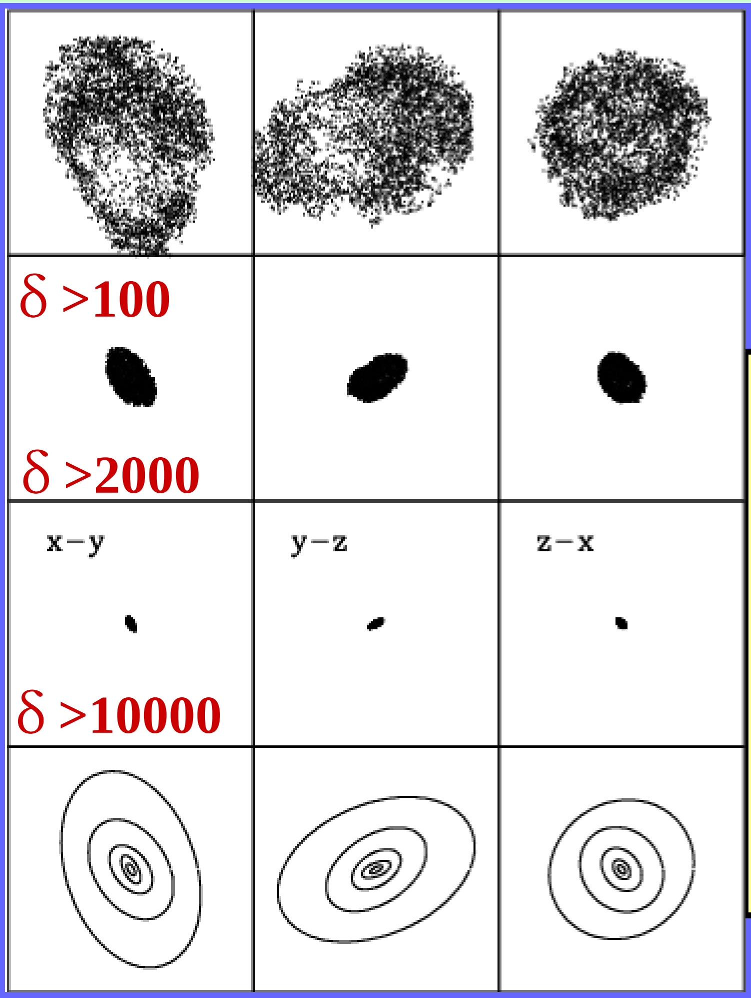
BIMA@30GHz
63”x80” beam
(10.3mJy point
source removed)

Carlstrom et al.
(2001)

- Keck spectroscopy: Cohen & Kneib (2002)
- Chandra: Allen, Schmidt & Fabian (2002)
- non-spherical modeling is crucial, perhaps at high z in particular.

Triaxial model for dark halos

Isodensity of a cluster-scale halo



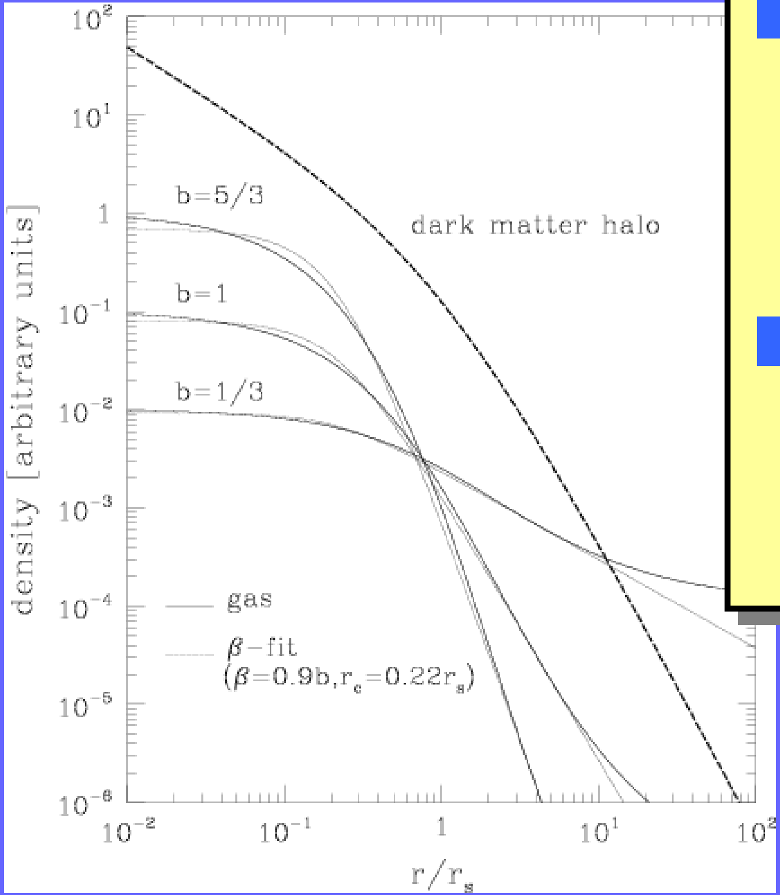
$$\rho(R) = \frac{\delta_c \rho_{crit}}{(R/R_s)^{\alpha}(1+R/R_s)^{3-\alpha}}$$

$$R^2(\rho) \equiv \frac{X^2}{a^2(\rho)} + \frac{Y^2}{b^2(\rho)} + \frac{Z^2}{c^2(\rho)}$$

Jing & Suto (2002) ApJ, August issue

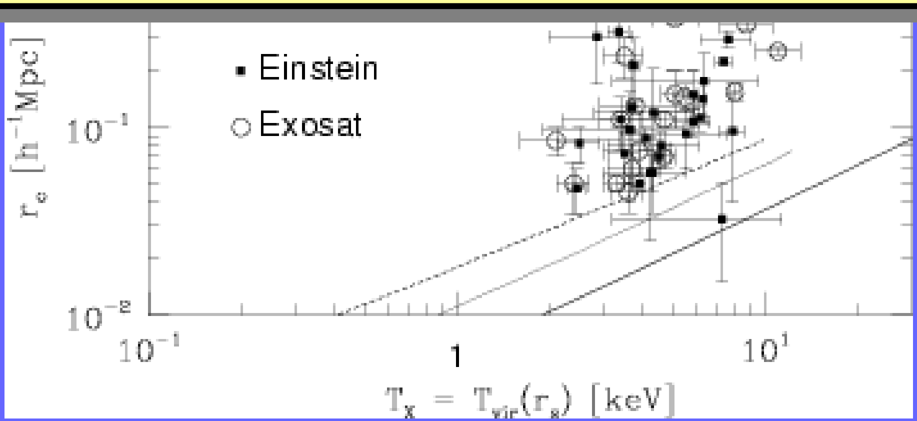
- Non-spherical description is becoming crucial in properly interpreting recent high-angular resolution data of the weak/strong lensing, X-ray/SZ cluster observations

X-ray gas profiles of clusters



Makino, Sasaki & Suto (1998)

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



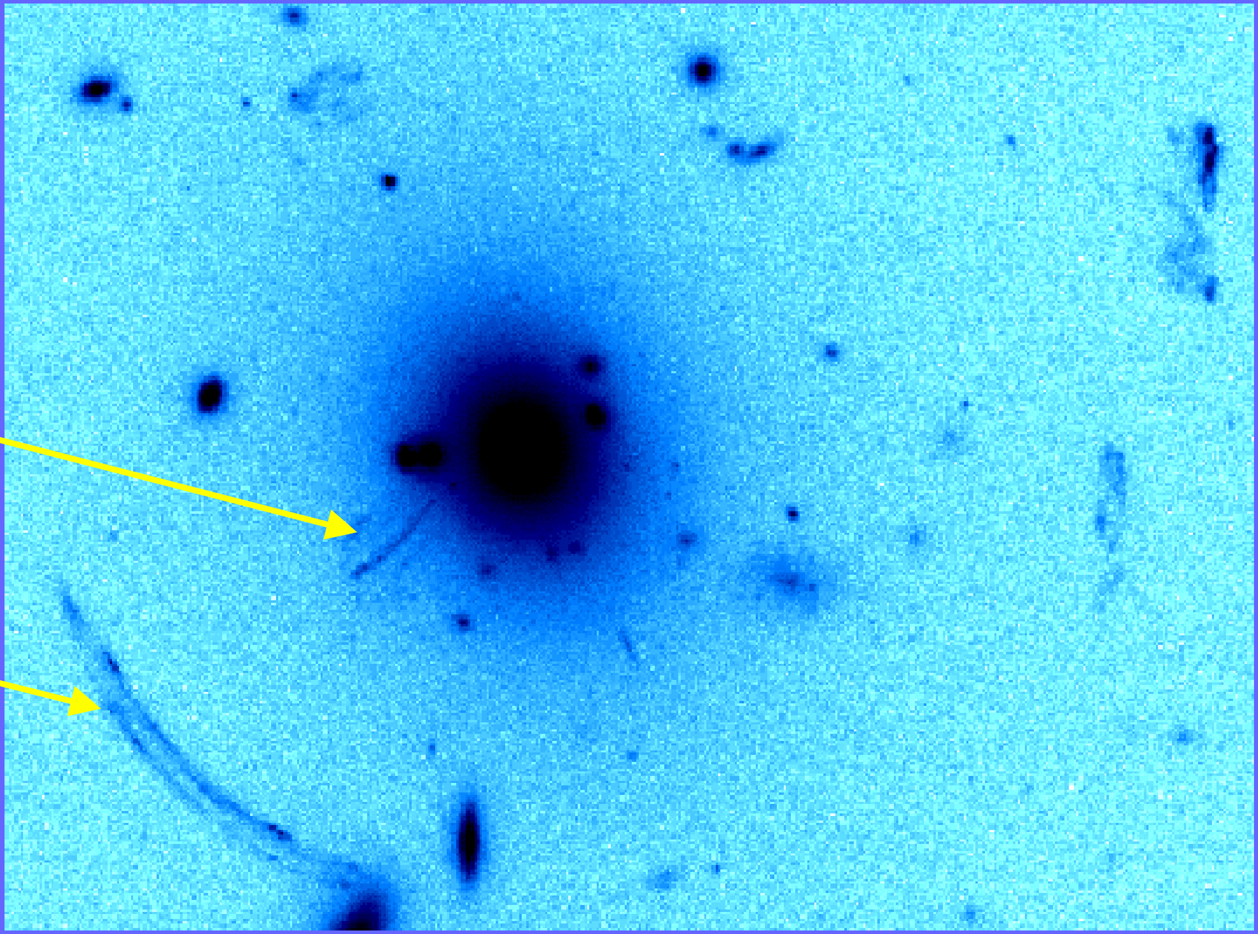
Tangential and radial arcs

MS2137-2353

(z=0.313)

Radial arc

Tangential arc

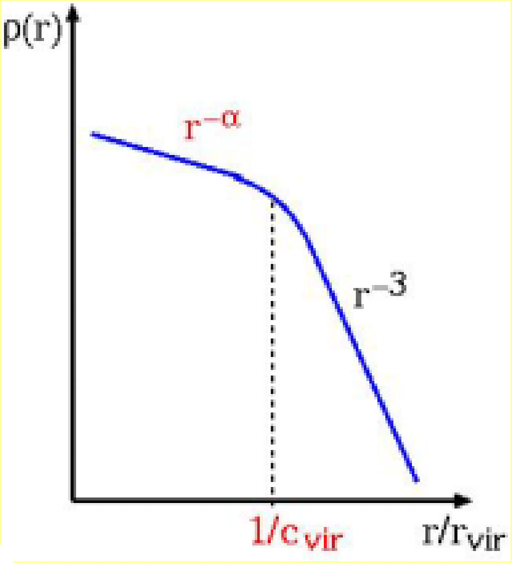


Hammer et al. (1997)

Model for halo density profile

- ***Halo density profile***

$$\rho(r) = \frac{\rho_{\rm crit}\delta_{\rm c}}{(r/r_{\rm s})^{\alpha}(1+r/r_{\rm s})^{3-\alpha}}$$



- ***Concentration parameter***

$$c_{\rm vir}(M,z) = \frac{r_{\rm vir}(M,z)}{r_{\rm s}(M,z)}$$

$$c_{\rm vir}(M,z) = c_{\rm norm}\frac{2-\alpha}{1+z}\left(\frac{M_{\rm vir}}{10^{14}h^{-1}M_{\odot}}\right)^{-0.13}$$

- ***Log-normal distribution for scatter in $c_{\rm norm}$***

$\Delta(\log c_{\rm vir})=0.18$ (Bullock et al. 2001; Jing 2000)

- ***Free parameters: $c_{\rm norm}$ and α***

Expected number of arcs

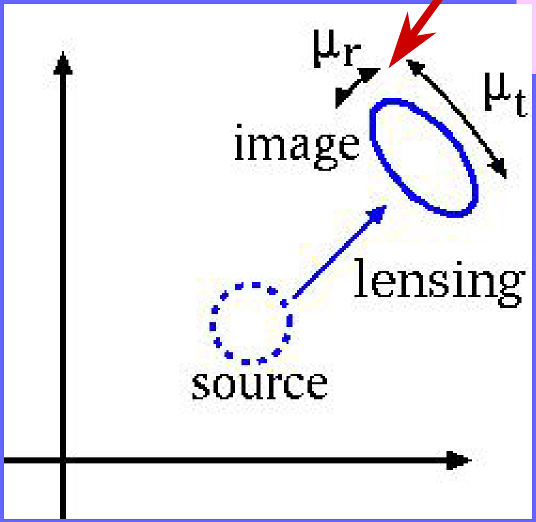
Number of arcs per unit solid angle

$$N_{\rm tot} = \int_{z_{\rm L,min}}^{z_{\rm L,max}} dz_{\rm L} \int_{M_{\rm min}(z_{\rm L})}^{\infty} dM\, \boxed{N(M, z_{\rm L})}\, \underline{n_{\rm PS}(M, z_{\rm L})}(1+z_{\rm L})^3 4\pi D_{\rm OL}^2 \frac{c\,dt}{dz_{\rm L}}$$

halo mass function (lens objects)

Number of arcs per given halo

$$\boxed{N(M, z_{\rm L})} = \int_{z_{\rm L}}^{z_{\rm S,max}} dz_{\rm S}\, \underline{\sigma(M, z_{\rm L}, z_{\rm S})} \frac{c\,dt}{dz_{\rm S}}(1+z_{\rm S})^3 \int_{L_{\rm min}}^{\infty} dL\, \underline{n_{\rm g}(L, z_{\rm S})}$$

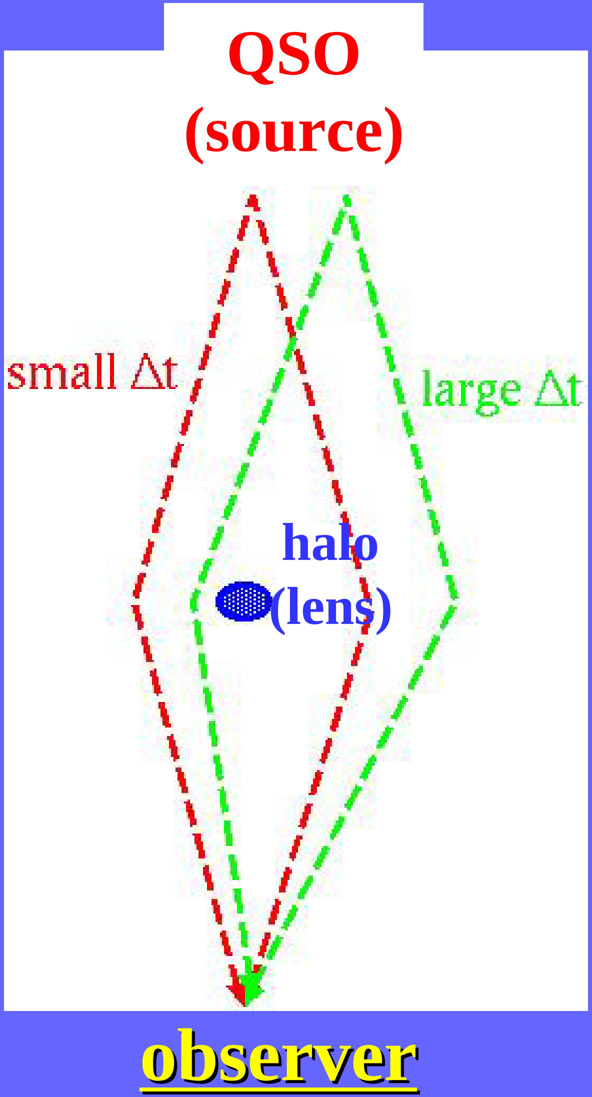


Cross section of arc formation in a given halo

Galaxy luminosity function (sources)

Oguri, Taruya & Suto (2001)

Time-delay in QSO multiple images to probe the halo density profile



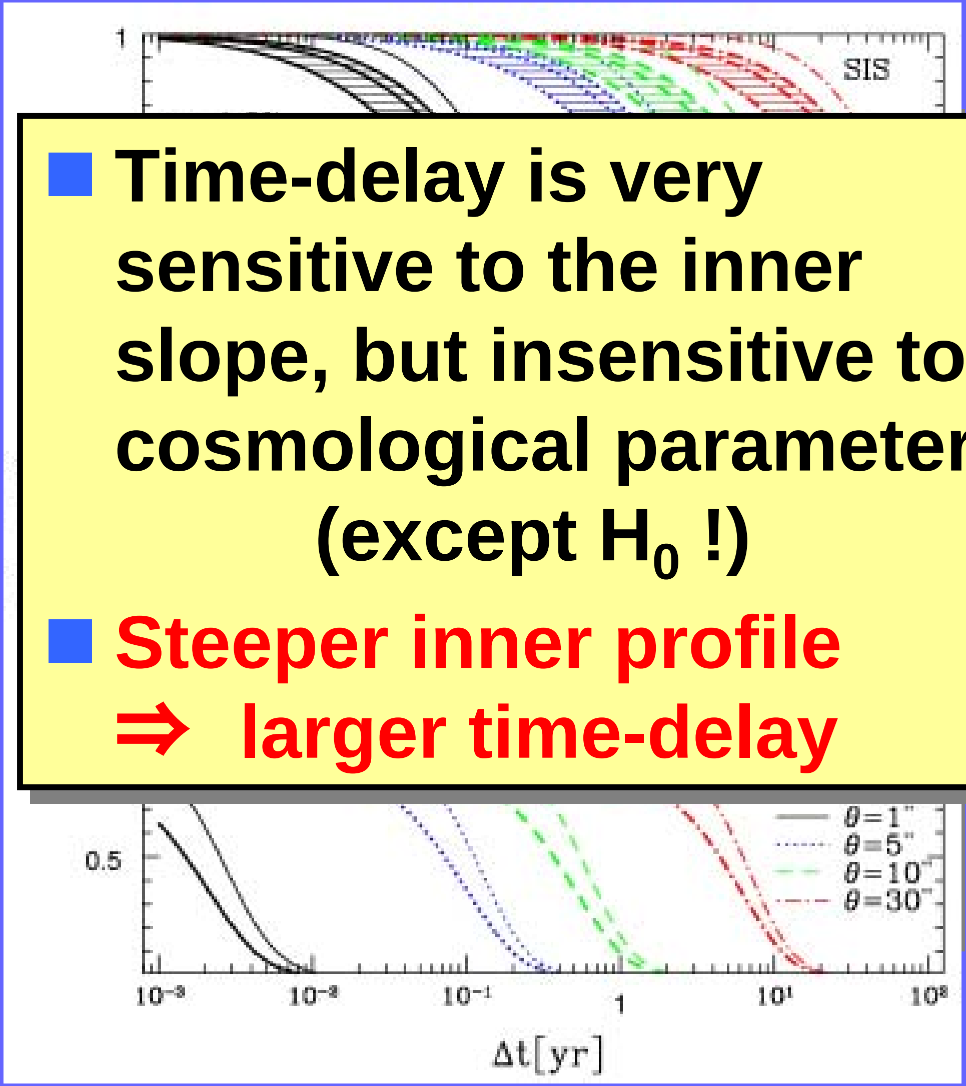
QSO (source)

small Δt

large Δt

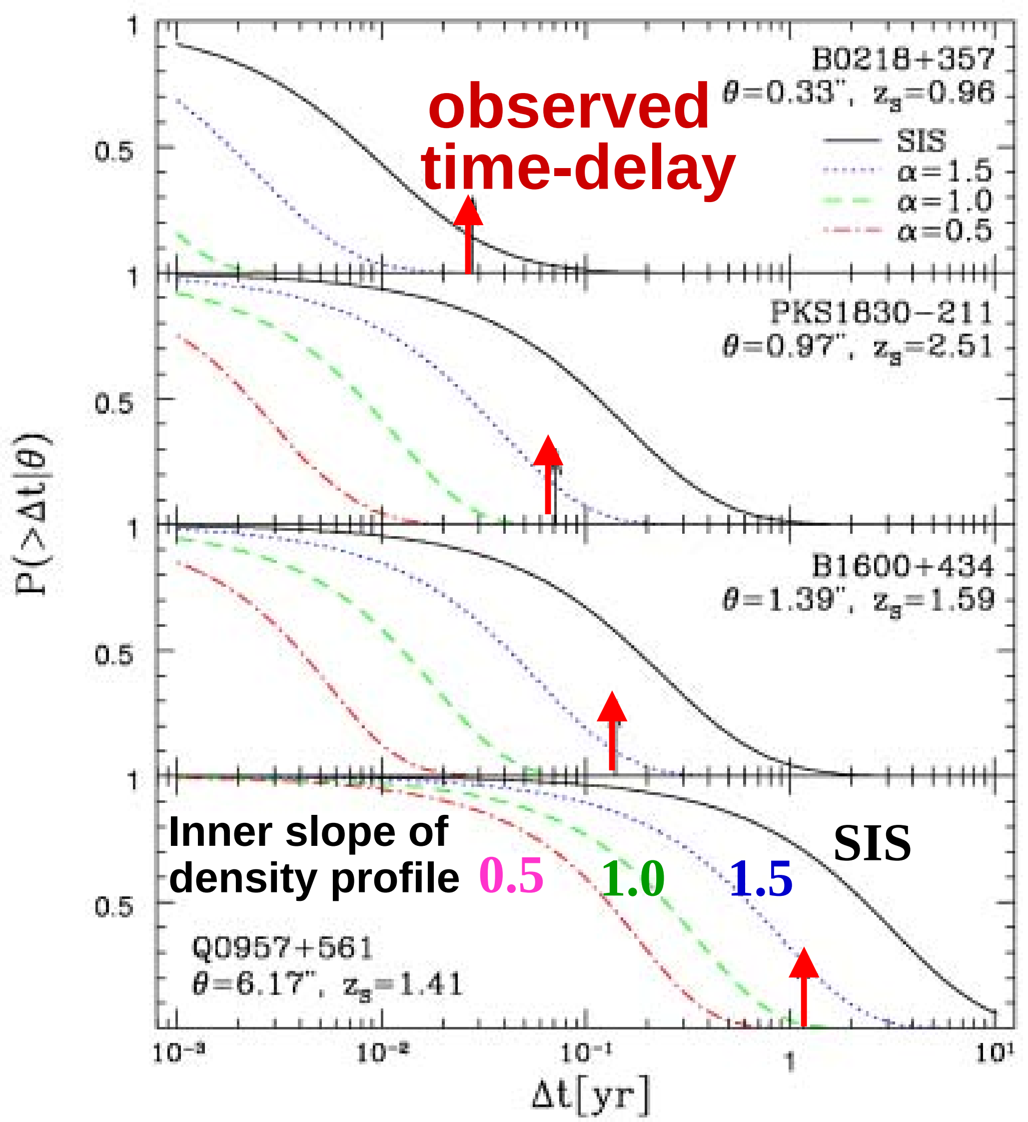
halo (lens)

observer



- **Time-delay is very sensitive to the inner slope, but insensitive to cosmological parameters (except H_0 !)**
- **Steeper inner profile ⇒ larger time-delay**

Tentative applications to 4 lens systems

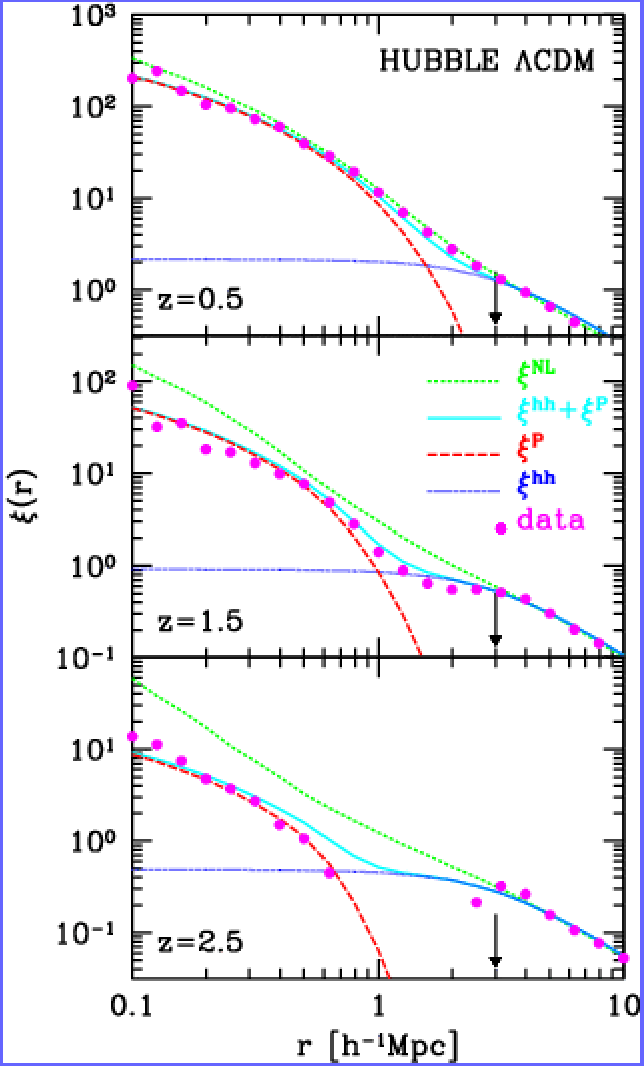

observed time-delay

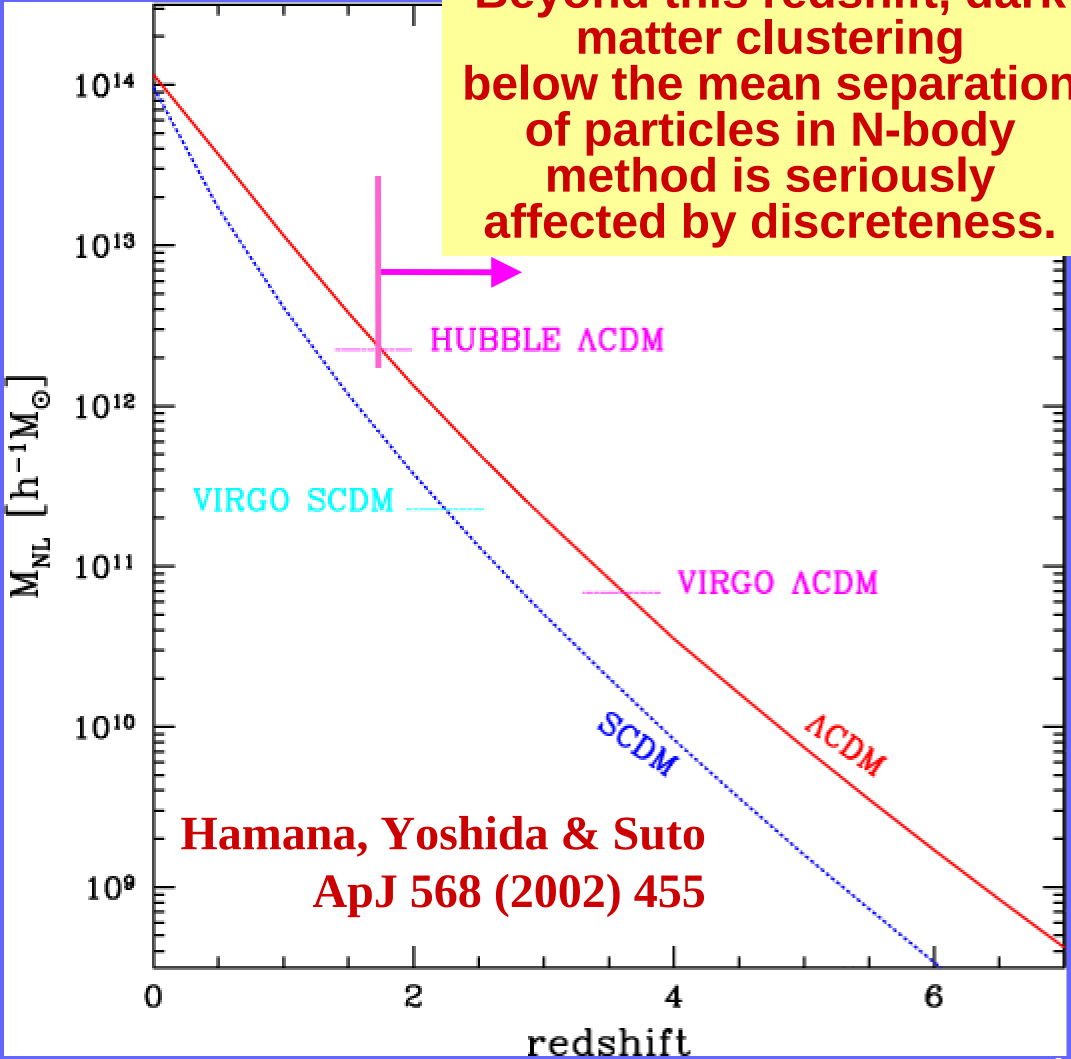
Inner slope of density profile **0.5** **1.0** **1.5** **SIS**

- **Observed time-delay is consistent with predicted time-delay probability when the density profile has a steep cusp $\propto r^{-1.5}$**

Oguri et al. 2002

Evaluating the particle discreteness effect using dark halo approach to clustering





Beyond this redshift, dark matter clustering below the mean separation of particles in N-body method is seriously affected by discreteness.

Hamana, Yoshida & Suto
ApJ 568 (2002) 455