Clustering and density profile of dark matter halos

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New Trends in Theoretical and Observational Cosmology

Why dark matter halos ?

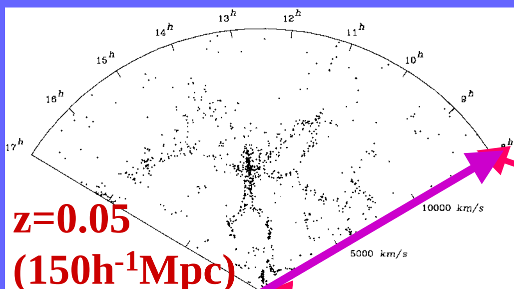
- ***Self-gravitating virialized objects***
- ***Sites for galaxies and clusters***
  - radiative cooling of baryonic gas
  - energy and angular momentum transfer
  - star formation and supernova heating
- ***More directly related*** to cosmological initial conditions than other small-scale objects
- ***Easier to predict/model*** theoretically since gravity dominates

Topics in this talk include …

- ***Clustering:***
  - **dark matter** clustering on the light-cone
    (Yamamoto + YS 1998)
  - Comparison with **simulations** on the light-cone
    (Hamana, Colombi + YS 2000)
  - Morphology-dependent **galaxy** bias from SDSS data
    (Kayo, Nakamura, Fukugita + YS for SDSS collaboration)
  - **halo** clustering on the light-cone
    (Hamana, Yoshida, YS + Evrard 2001)
- ***Density profile:***
  - High-resolution N-body simulation (Jing+YS 2000)
  - Implications from the **gravitational arc statistics**
    (Oguri, Taruya + YS 2001)
  - Possible constraints from **time-delay statistics**
    (Oguri, Taruya, YS + Turner 2001)
- ***Halo density profile to dark matter clustering:***
  (Hamana, Yoshida + YS 2001)

Clustering on the light-cone

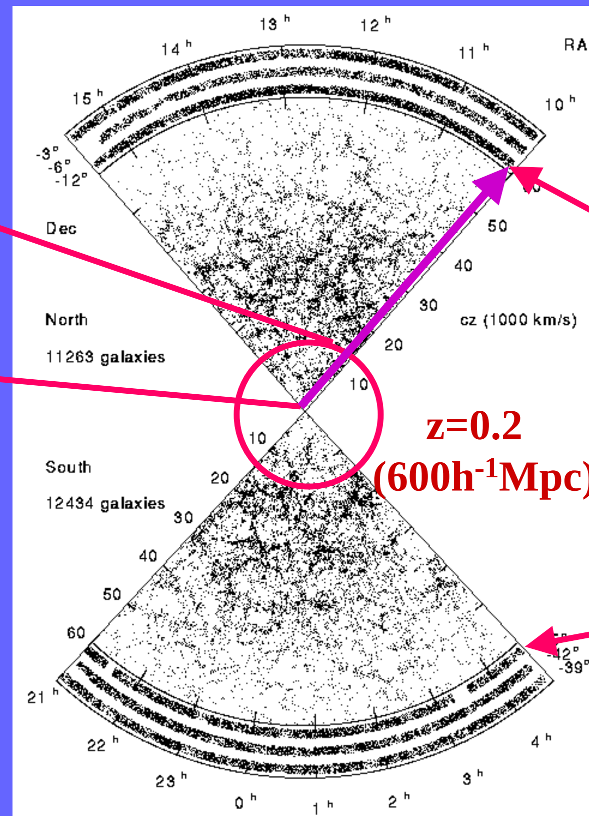
1986



z=0.05 ($150h^{-1}$Mpc)

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

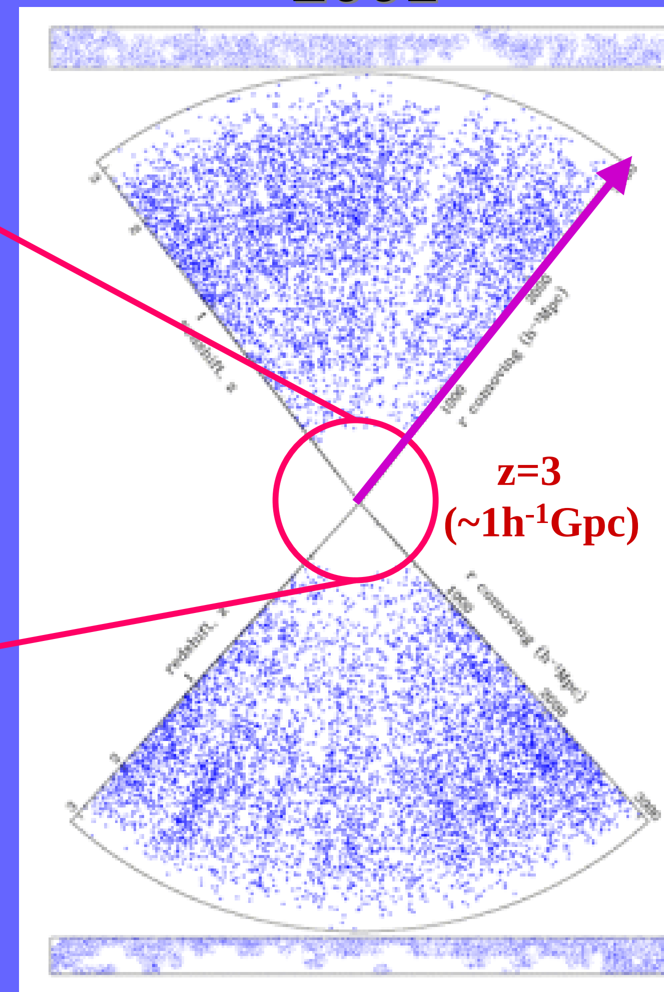
1996



z=0.2 ($600h^{-1}$Mpc)

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

2001



z=3 ($\sim 1h^{-1}$Gpc)

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

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

Cosmological light-cone effects

- ***linear and nonlinear gravitational evolution***
- ***redshift-space distortion due to peculiar velocity***
  - linear distortion (the Kaiser effect)
  - nonlinear distortion (finger-of-god effect)
- ***evolution of objects on the light-cone***
  - number density and luminosity evolution
  - object-dependent spatial bias relative to mass
- ***observational selection function***
  - magnitude-limit and luminosity function
  - shape of the survey boundary

Matsubara, Suto & Szapudi (1997); Matarrese et al. (1997)
Yamamoto & Suto (1998); Suto, Magira, Jing, Matsubara & Yamamoto (1999)

Predicting the clustering on the light-cone

- ***redshift-space distortion***

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

gravitational nonlinear evolution

linear and nonlinear redshift-space distortion

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

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

comoving volume element

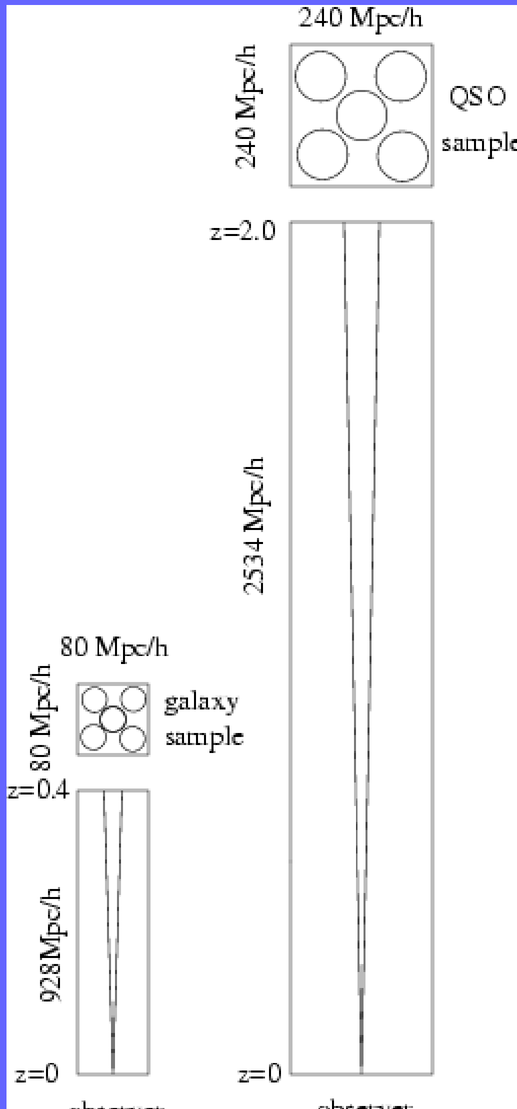
selection function

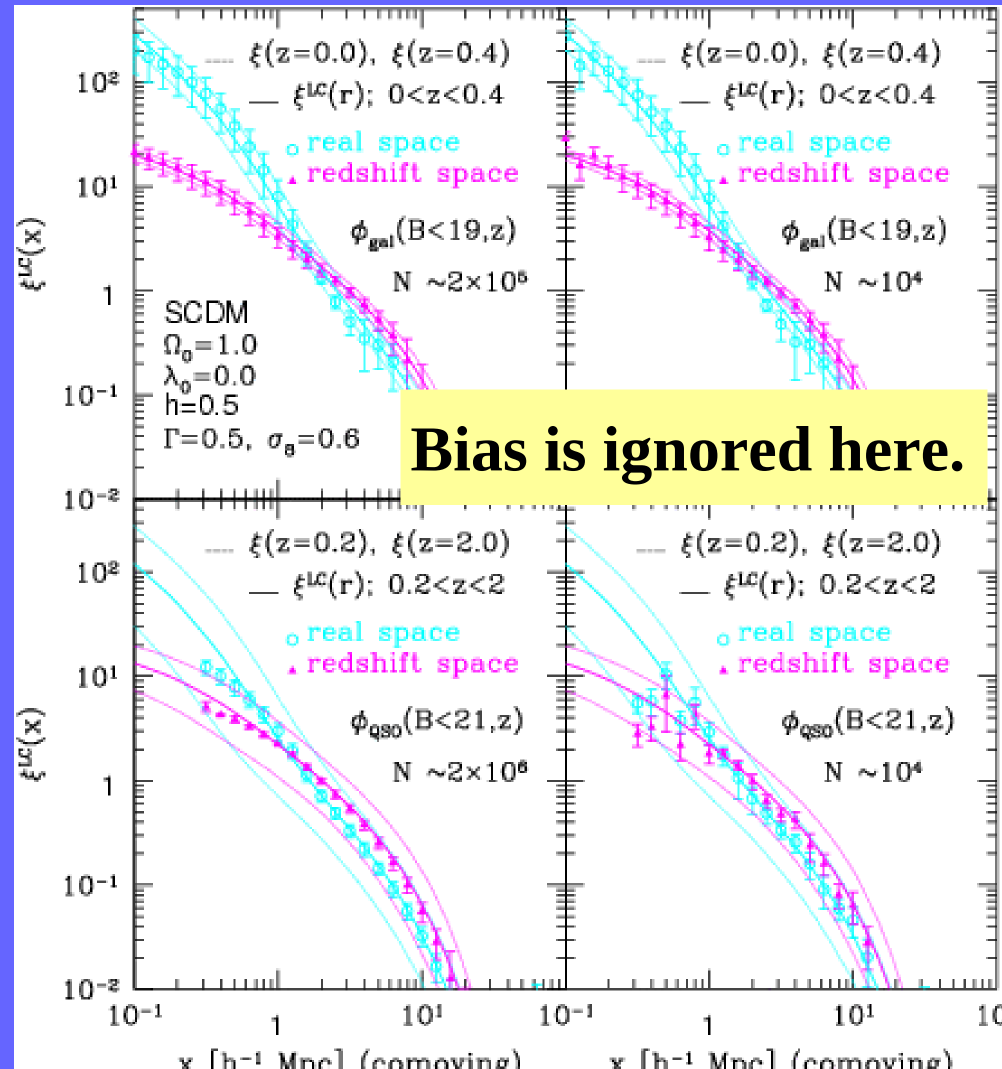
mean number density

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

Correlation functions of ***dark matter*** on the light-cone

Dark matter particle distribution on the light-cone from N-body simulations

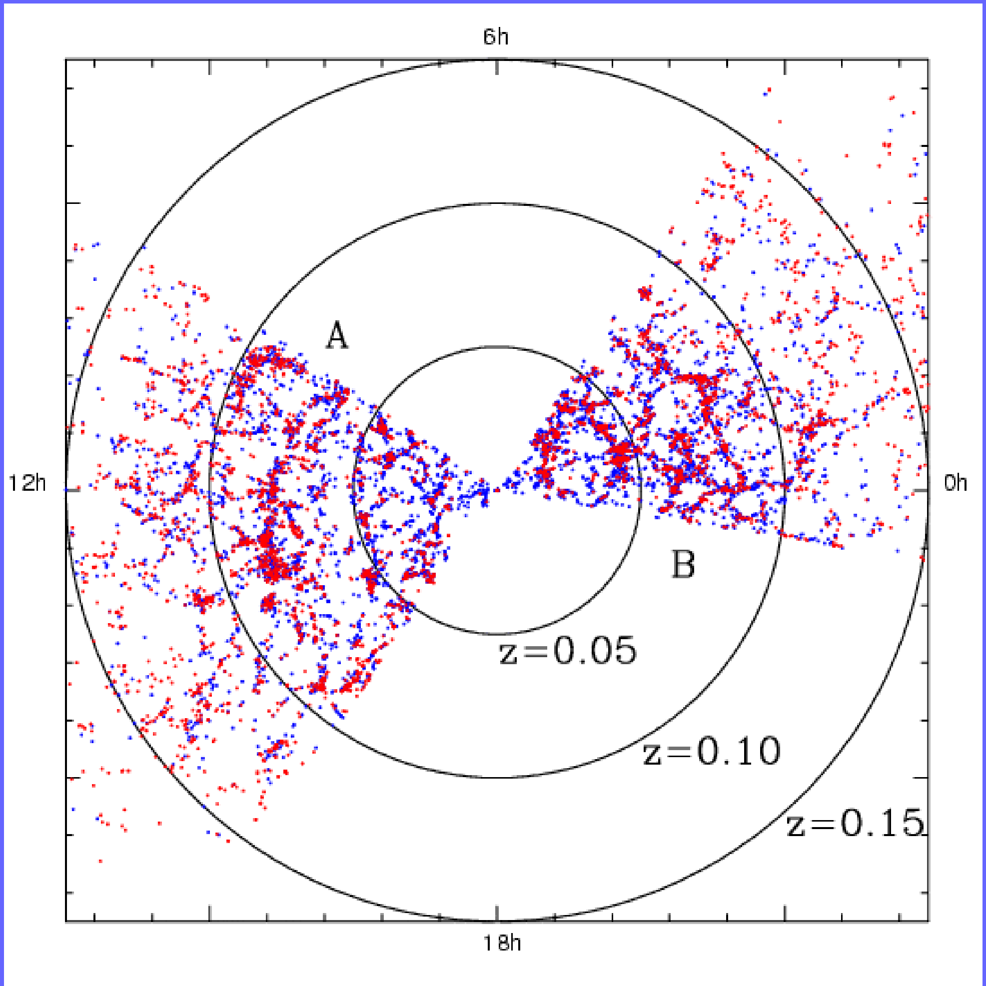




Bias is ignored here.

Hamana, Colombi & Suto (2001)

Slices from SDSS spectroscopic galaxy samples



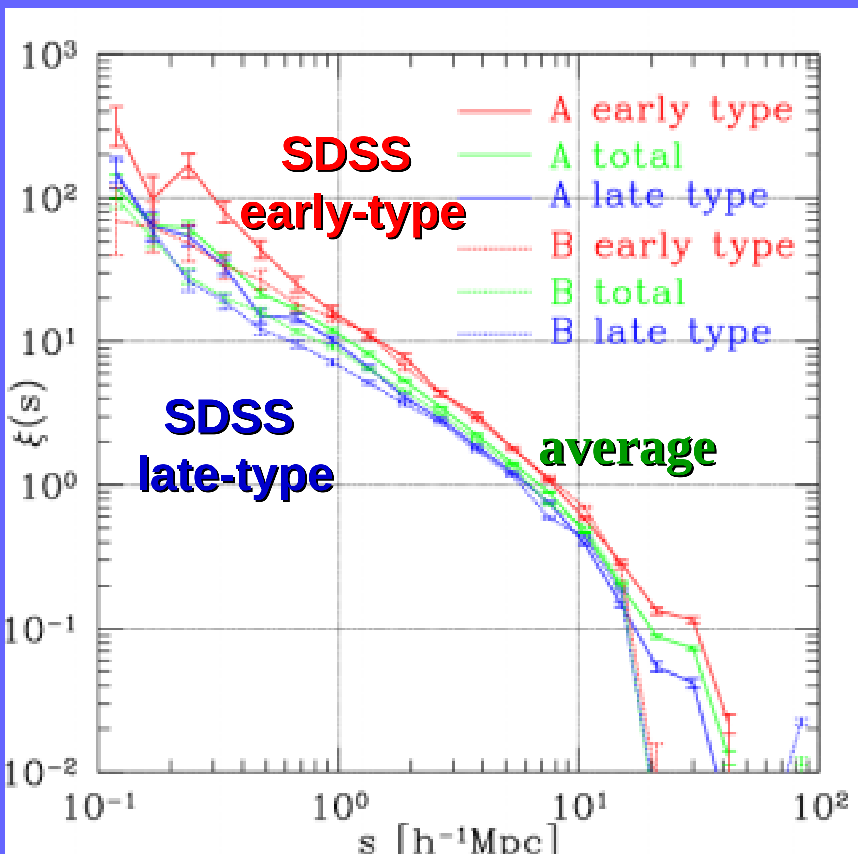
Clustering of galaxies on the light-cone !
(although the light-cone effect is not important)

- 9971 galaxies (r'<17) in SDSS EDR (Early Data Release)
- Classification of "early" and "late"-types using the concentration index (Doi, Fukugita & Okamura 1993) by Nakamura, Fukugita et al. (2001)

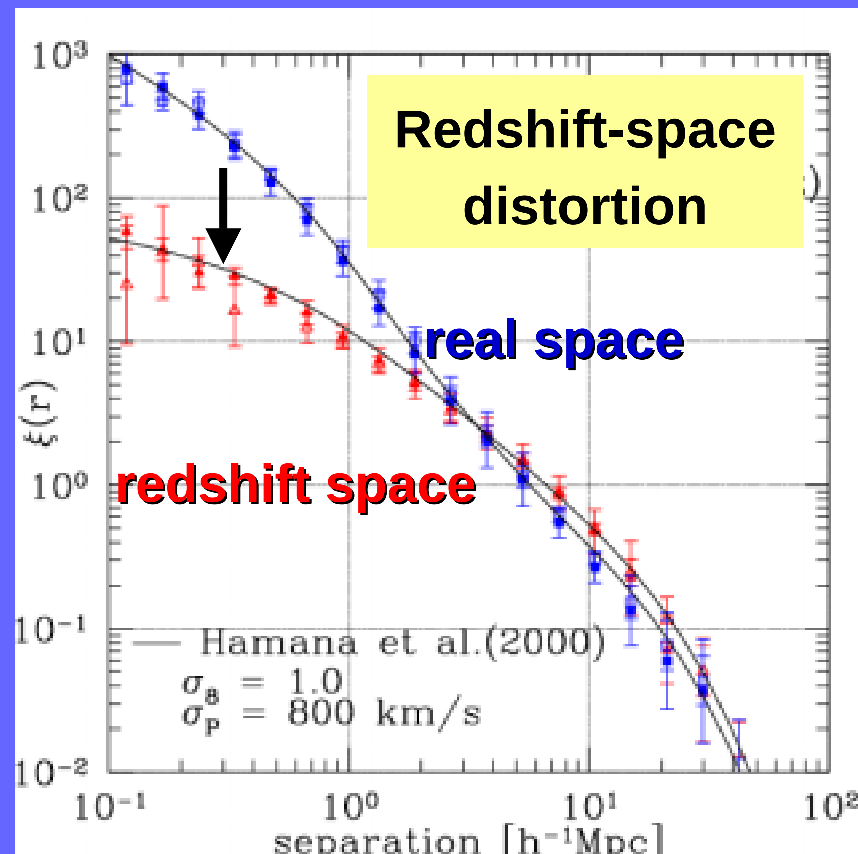
slice	A	B
early	2151	1612
late	3145	3063
total	5296	4675

Sample-variance of ξ(s)

Morphology dependent correlation functions of SDSS galaxies



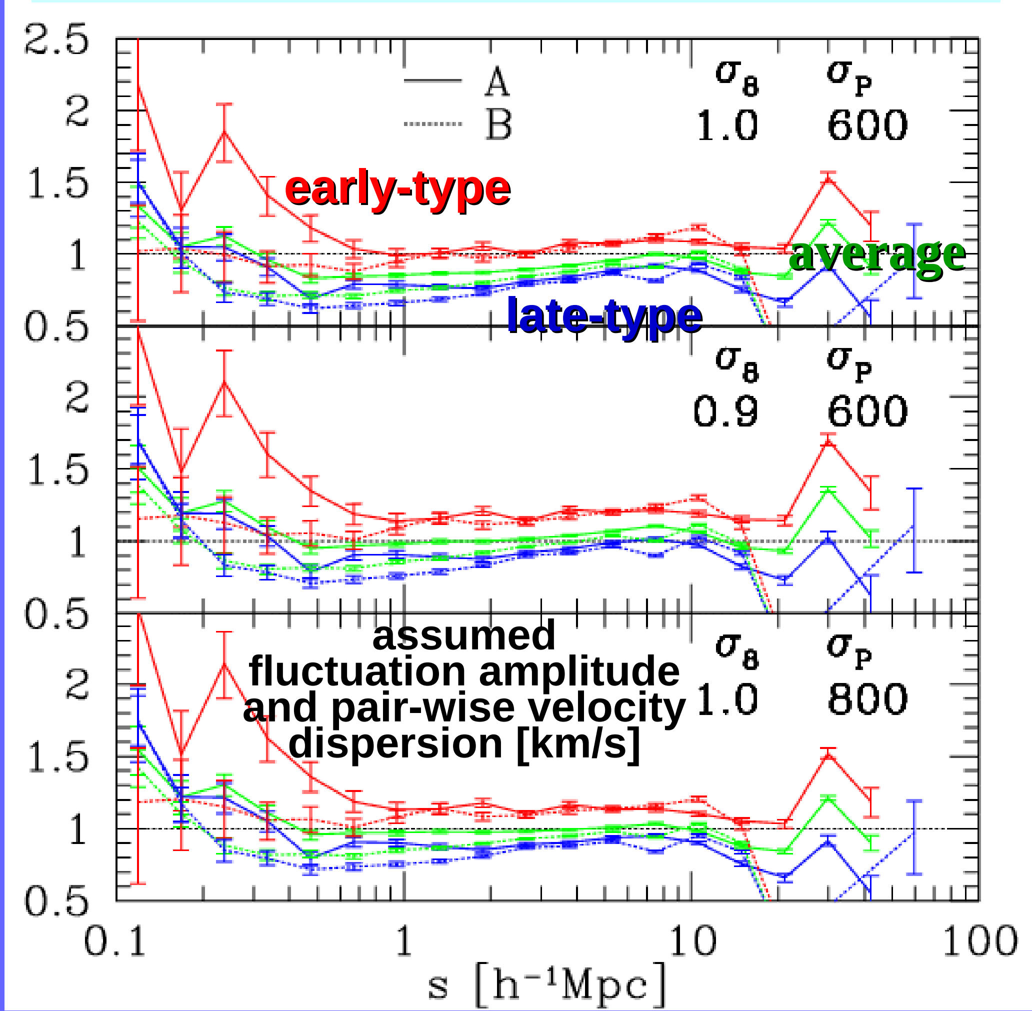
N-body Mock samples and the model predictions



Kayo, Nakamura, Fukugita, YS et al. in preparation

Morphology-dependent galaxy bias from SDSS data

$$b(s) \equiv \sqrt{\xi(s; galaxies) / \xi(s; \Lambda CDM)}$$

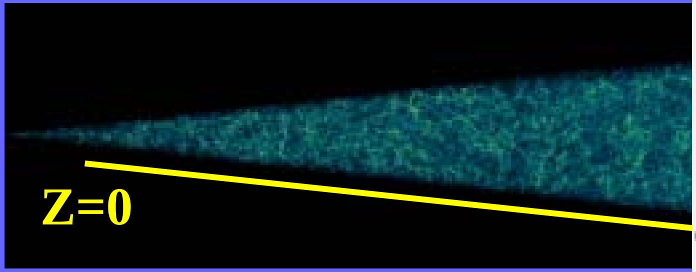


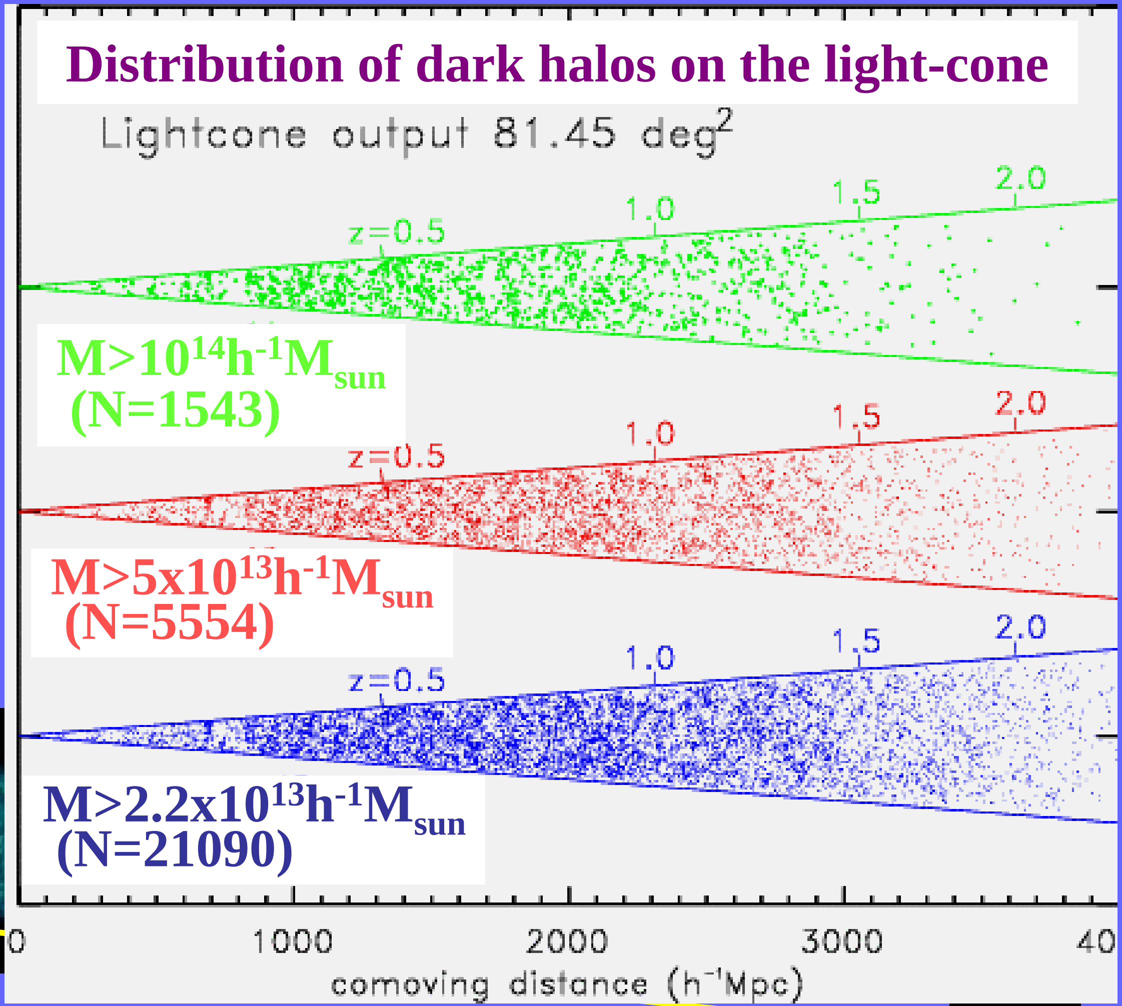
Kayo et al. , in preparation

- ΛCDM (+ σ_8, σ_p) assumed.
- Big sample-variance at s < 1h^{-1}Mpc, but clear morphology dependence on clustering amplitude.
- "early"-types are positively biased relative to mass, while "late"-types are anti-biased.
- For s> 1h^{-1}Mpc, galaxy bias is fairly scale-independent.

http://www.physics.isa.umich.edu/hubble-volume/ lightcones.htm

Light-cone output from the Hubble volume Λ simulation





Hamana, Yoshida, Suto & Evrard (2001)

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

- ***mass-dependence** (Jing1998;Sheth & Tormen 1999) **+ scale-dependence** (Taruya & Suto 2000) **in halo biasing** (cf., Yoshikawa et al. 2001; poster #63)*

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

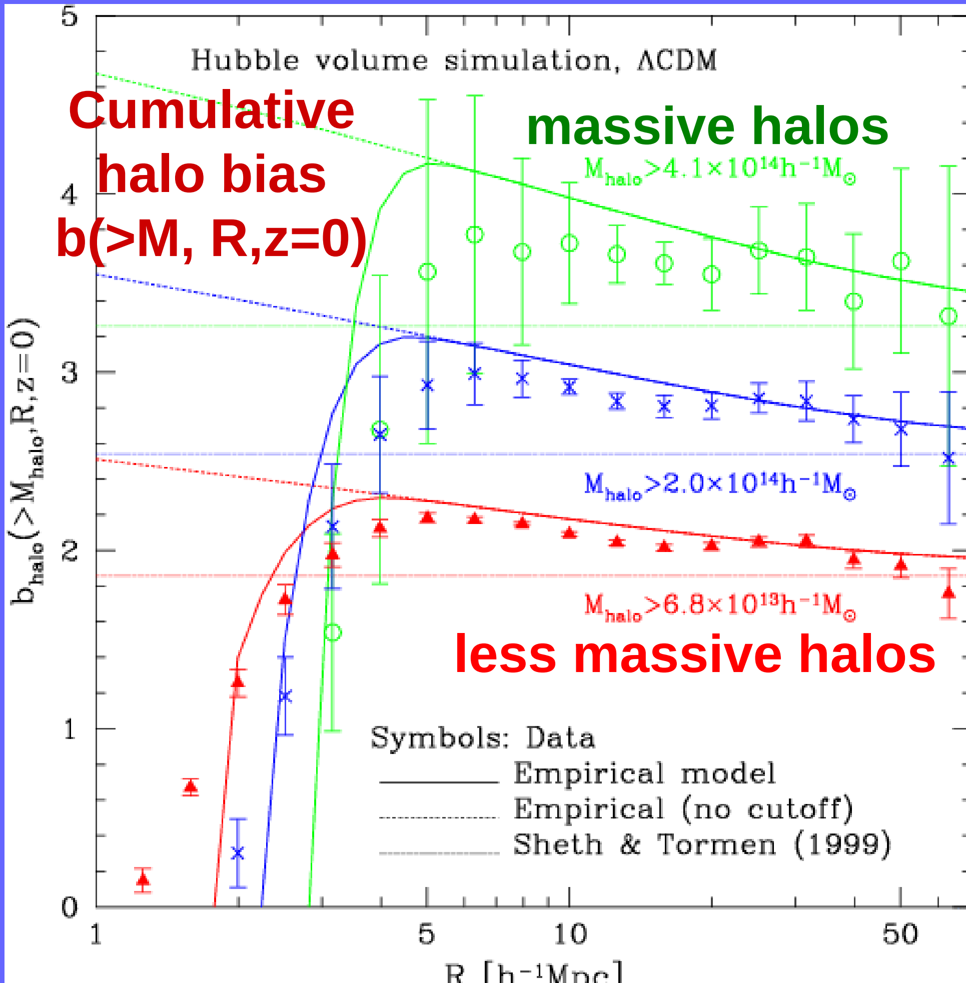
$$\xi_{halo}(M,R,z) = b_{halo}^2(M,R,z)\,\xi_{\mathrm{mass}}(R,z)$$

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

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

Hamana et al. (2001)

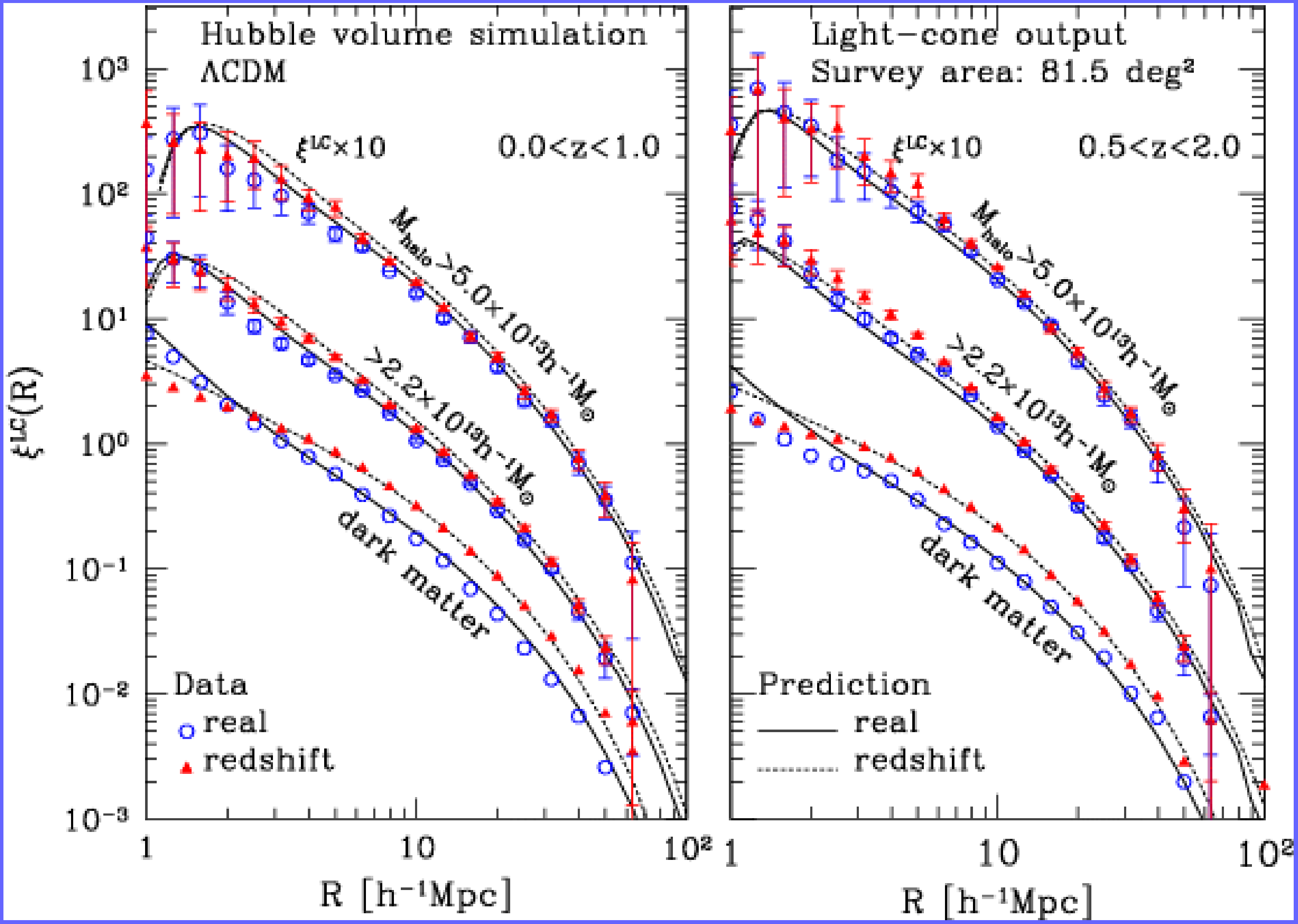
Calibrating the halo biasing model with the Hubble volume simulation at z=0



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.
- For massive halos, our model underestimates the measured biasing by <10% at $5h^{-1}\text{Mpc}<R<20h^{-1}$Mpc, which would be less than other possible systematic errors.

Correlation functions of halos on the light-cone



Hamana et al. (2001)

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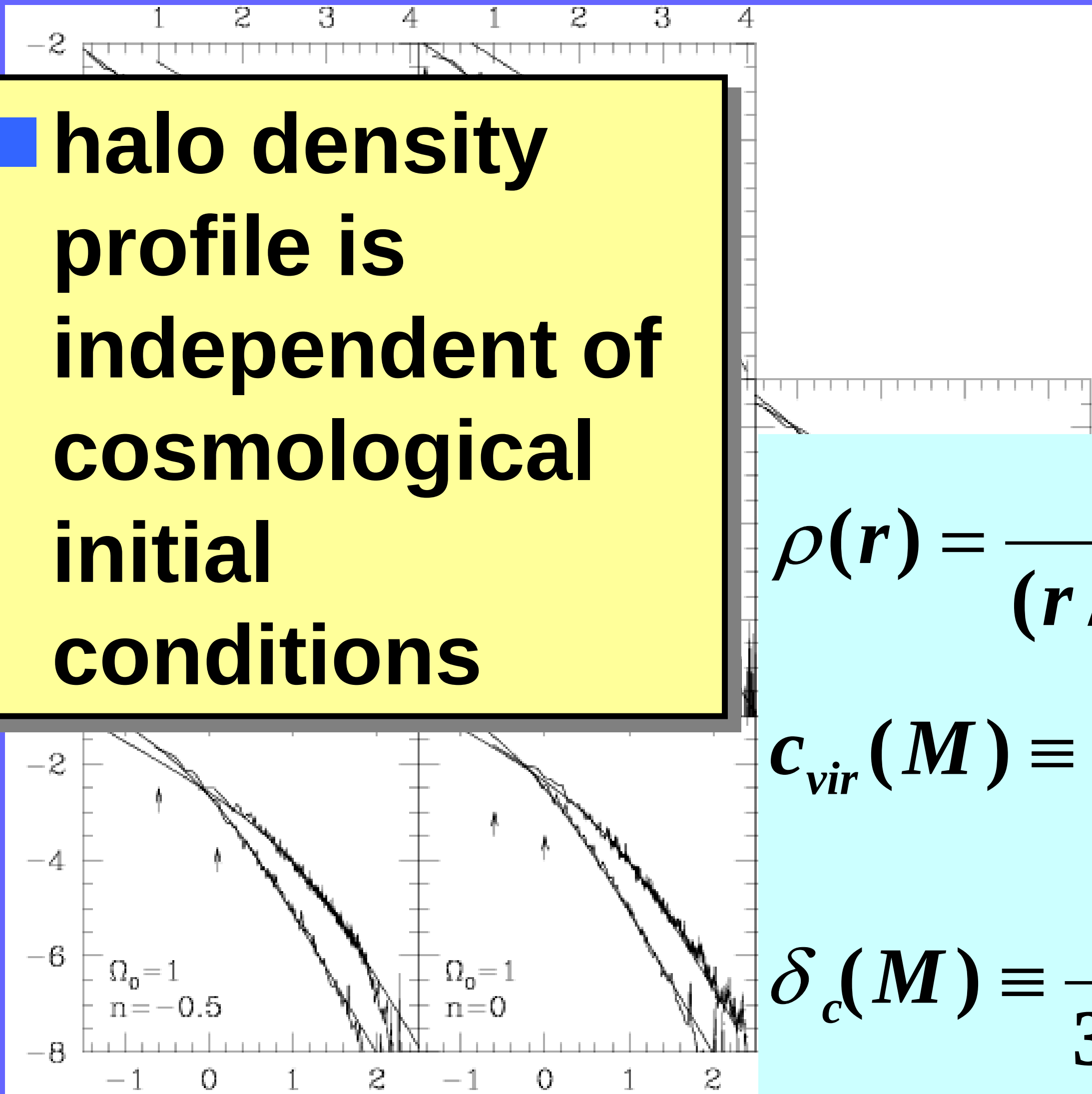
  - High-resolution N-body simulation (Jing+YS 2000)
  - Implications from the **gravitational arc statistics**
    (Oguri, Taruya + YS 2001)
  - Possible constraints from **time-delay statistics**
    (Oguri, Taruya, YS + Turner 2001)
- ***Halo density profile to dark matter clustering:***
  (Hamana, Yoshida + YS 2001)

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:** *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)

NFW universal density profile



log(radius)

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

Navarro, Frenk & White (1997)

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

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

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

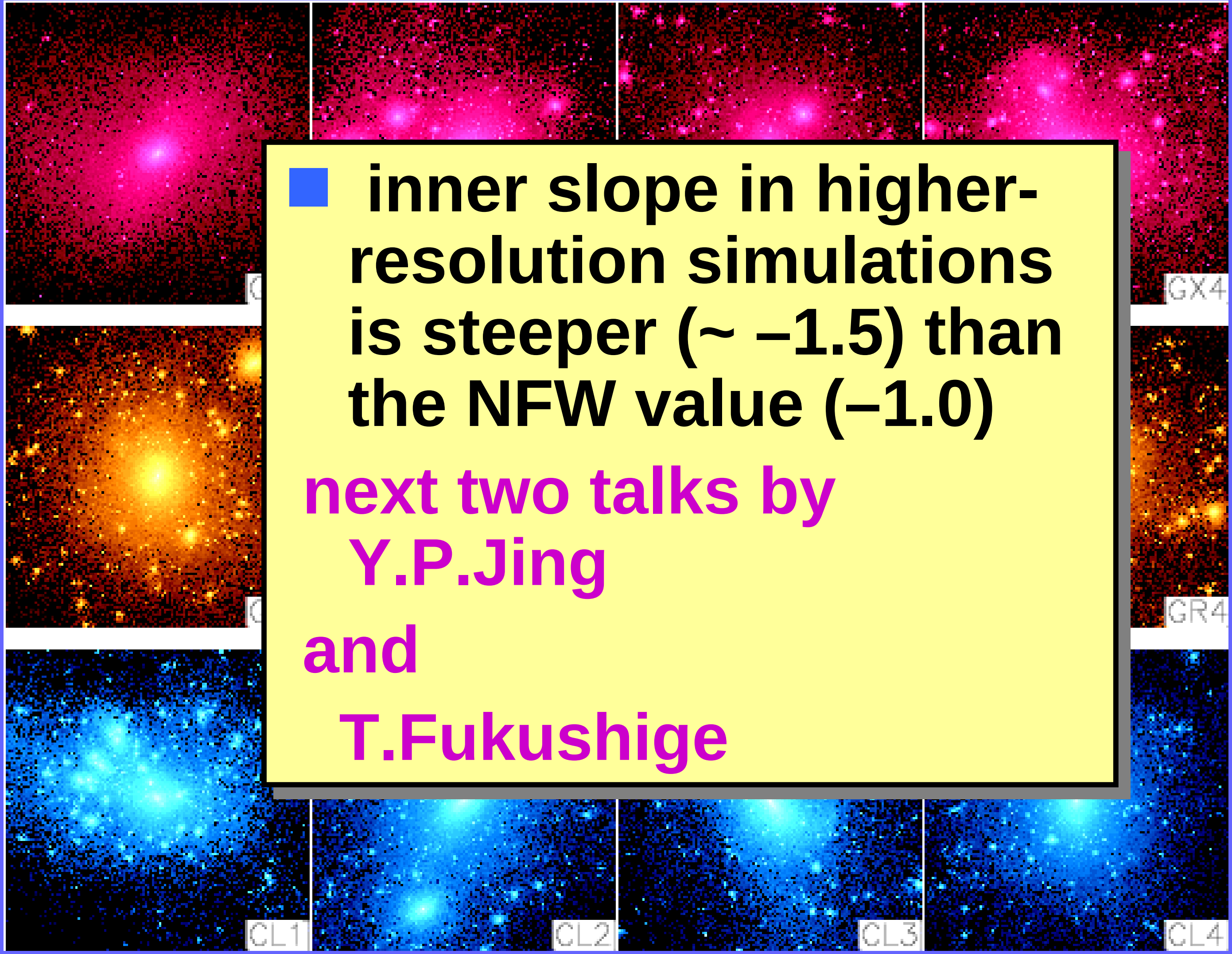
Halo profiles in higher-resolution N-body simulations

galaxies
~ $5\times10^{12} M_{sun}$

groups
~ $5\times10^{13} M_{sun}$

clusters
~ $3\times10^{14} M_{sun}$

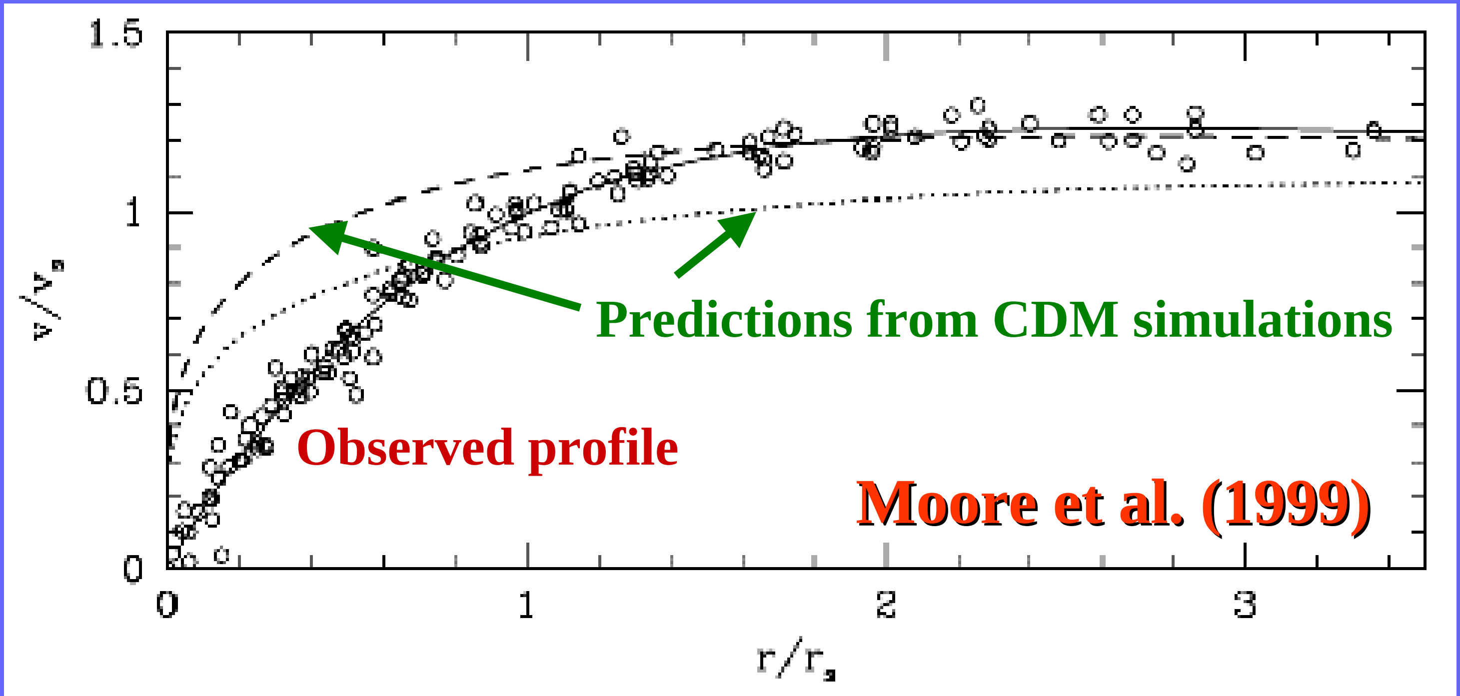
Jing & Suto (2000)



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

next two talks by
Y.P.Jing
and
T.Fukushige

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

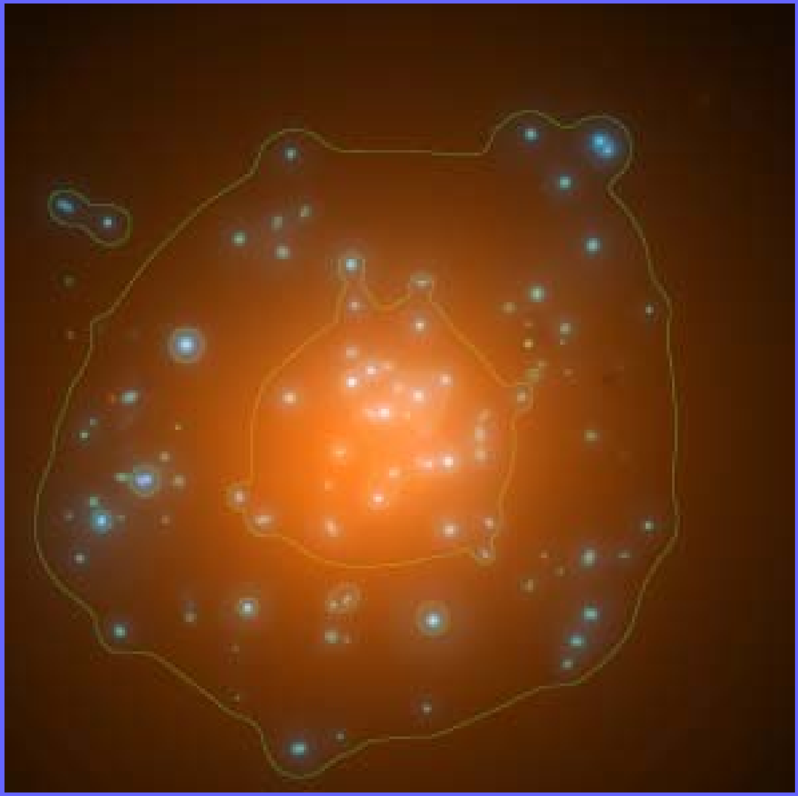
(Moore et al. 1999; de Blok et al. 2000; Salucci & Burkert 2000)

Gravitational lensing of CL0024+1654

HST image

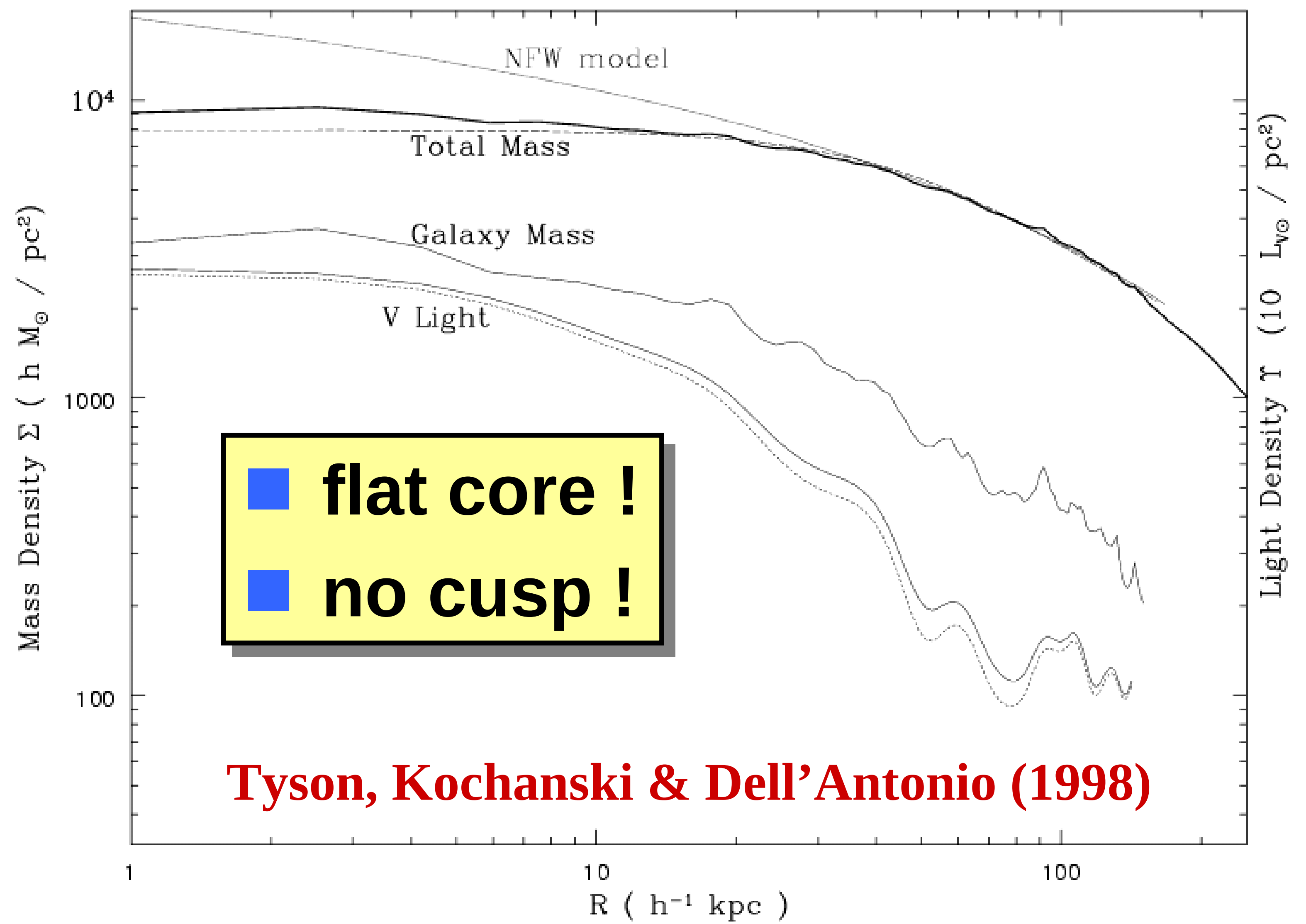
Z=0.39, $L_X = 5\times10^{43}\ h^{-2}$ erg/s

reconstructed mass distribution (with 512 parameters)



Tyson, Kochanski & Dell'Antonio (1998)

Reconstructed mass profile of CL0024+1654



Tyson, Kochanski & Dell'Antonio (1998)

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)

- ***Bar-driven core formation ?***

(Weinberg & Katz 2001)

Constraining halo central density profiles with gravitational lensing

- ***Number statistics of QSO multiple images***

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

- ***Arc statistics***

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

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

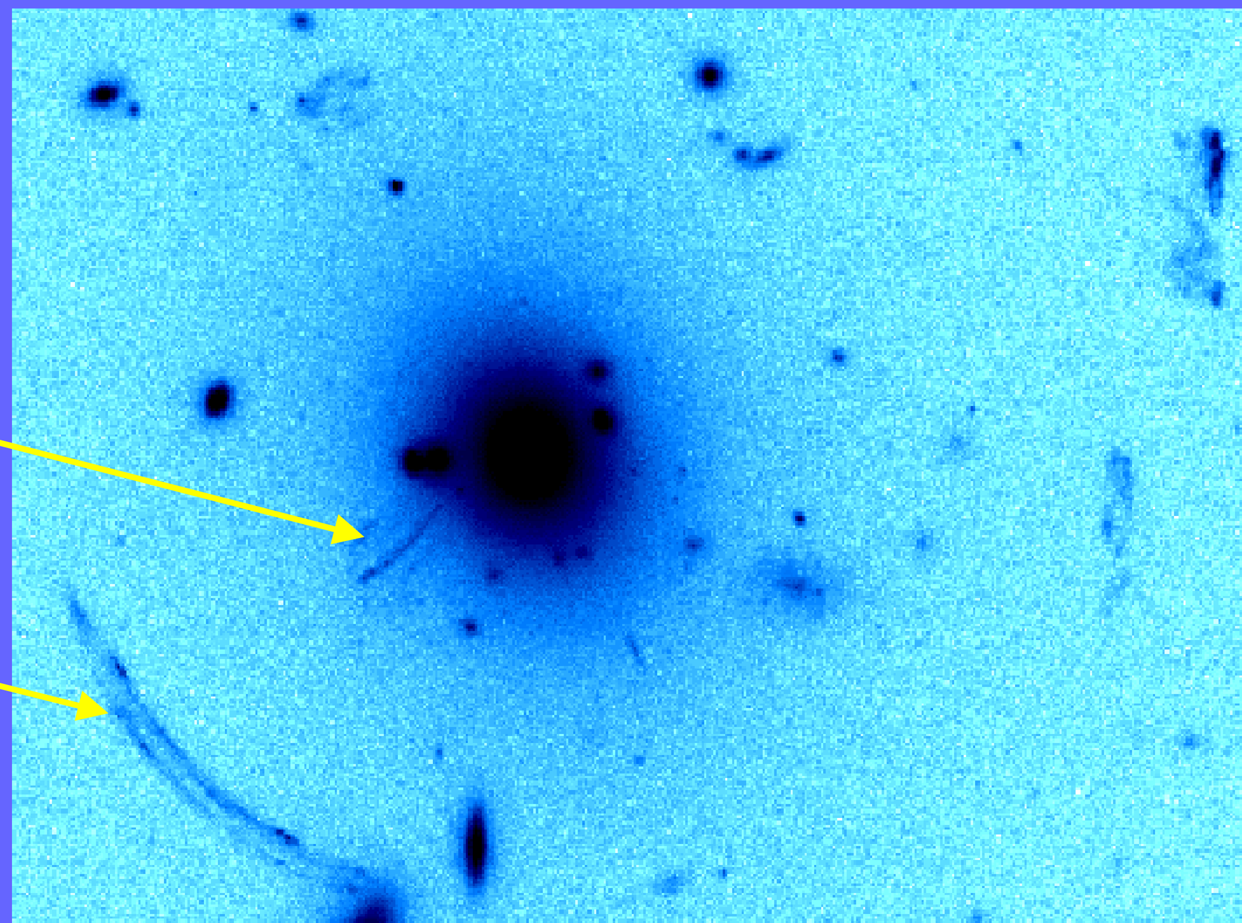
  (Oguri, Taruya, YS + E.L.Turner 2001)

Tangential and radial arcs

MS2137-2353
(z=0.313)

Radial arc

Tangential arc

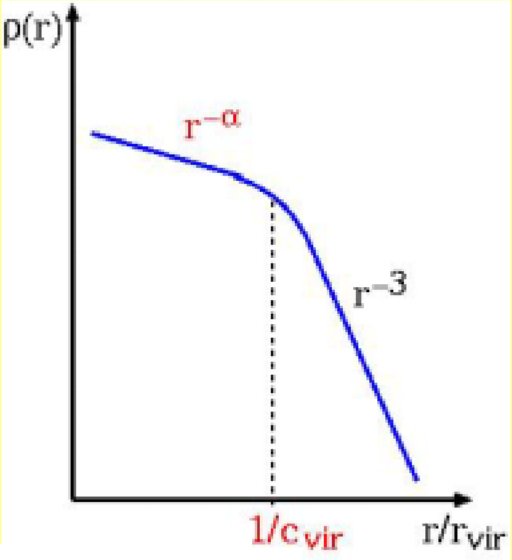


Hammer et al. (1997)

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_{norm}***

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

- ***Free parameters: c_{norm} and α***

Expected number of arcs

Number of arcs per unit solid angle

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

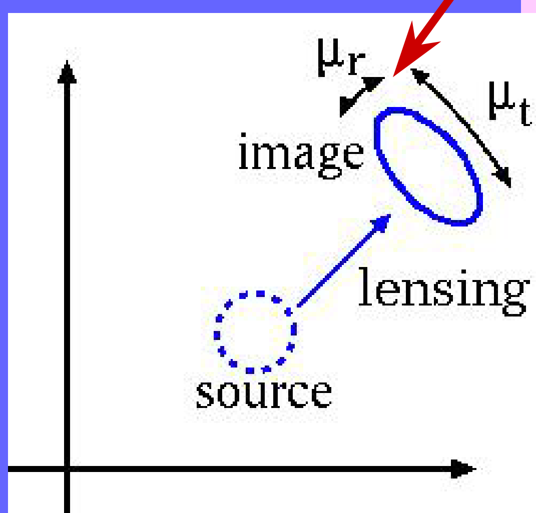
halo mass function (lens objects)

Number of arcs per given halo

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

Cross section of arc formation in a given halo

Galaxy luminosity function (sources)

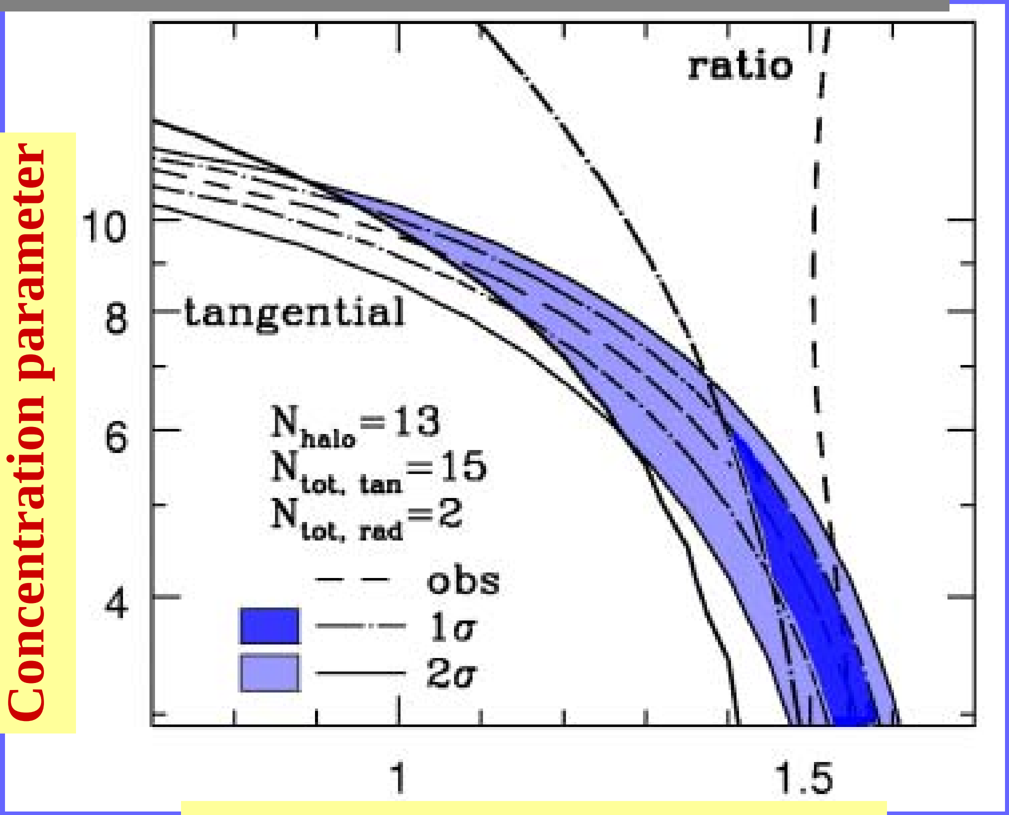


Oguri, Taruya & Suto (2001)

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)

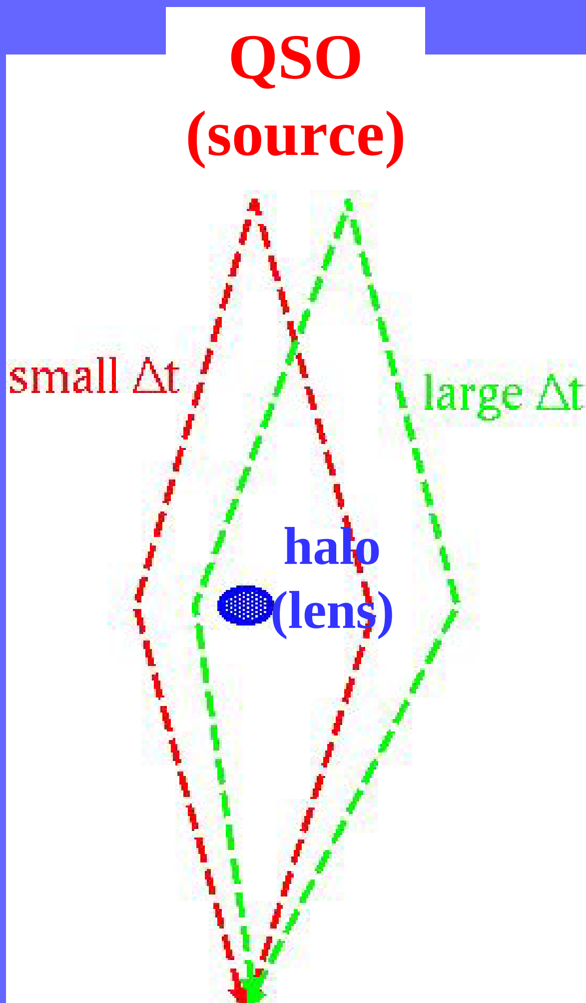


Concentration parameter

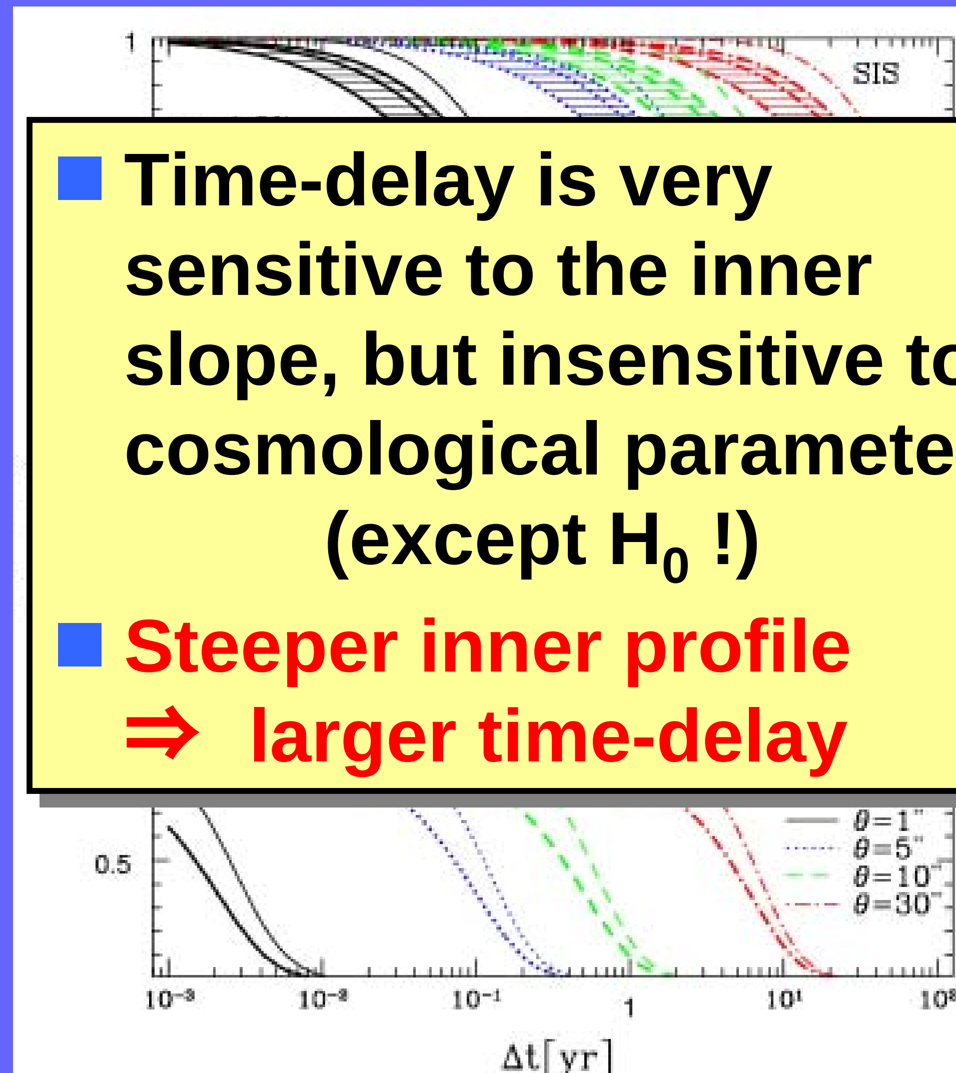
Inner slope of density profile

Oguri et al. (2001)

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

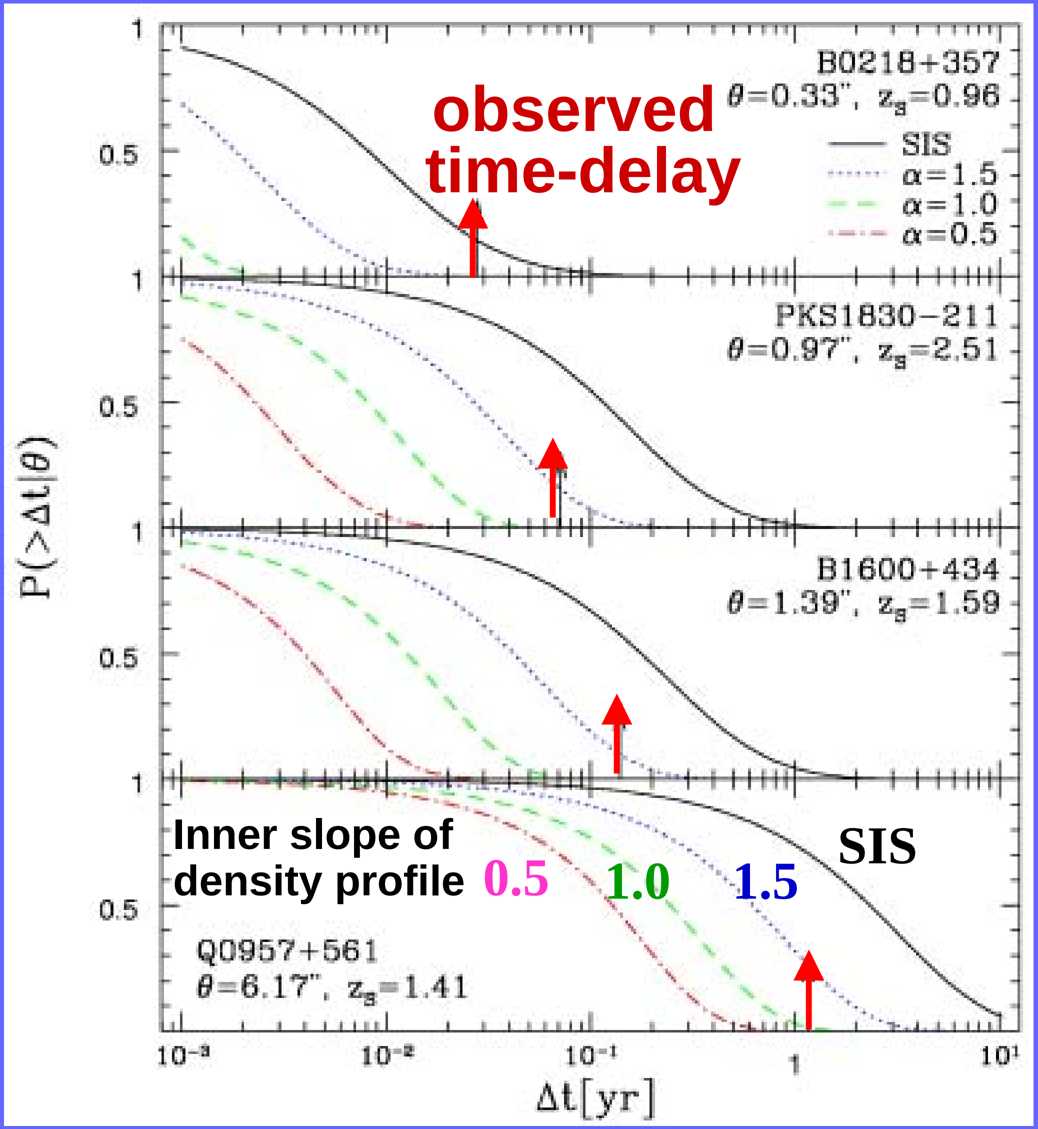


observer



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

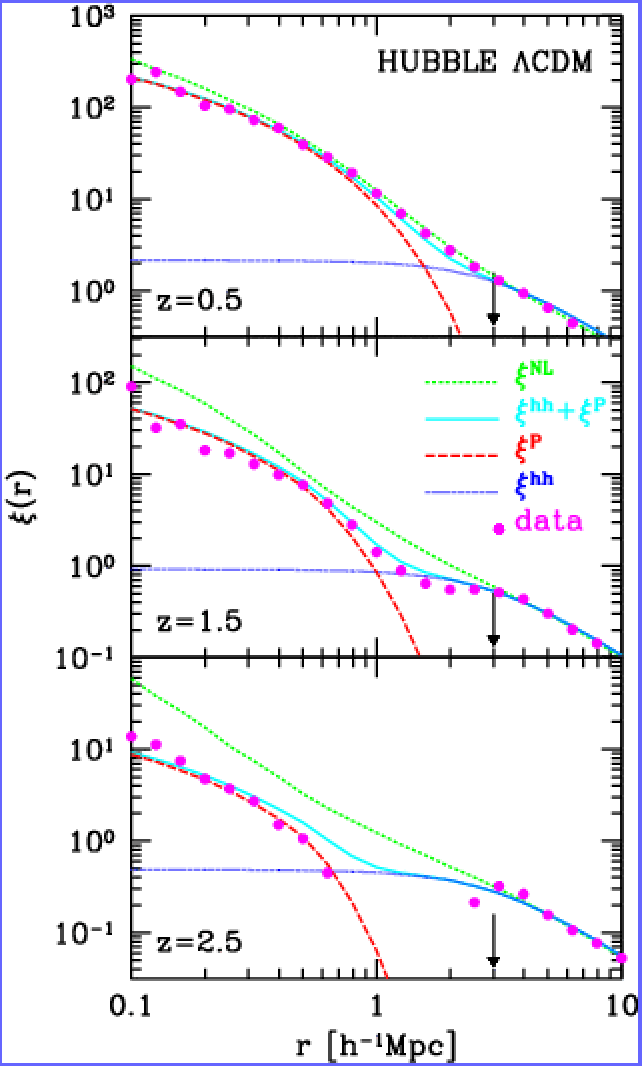
Tentative applications to 4 lens systems

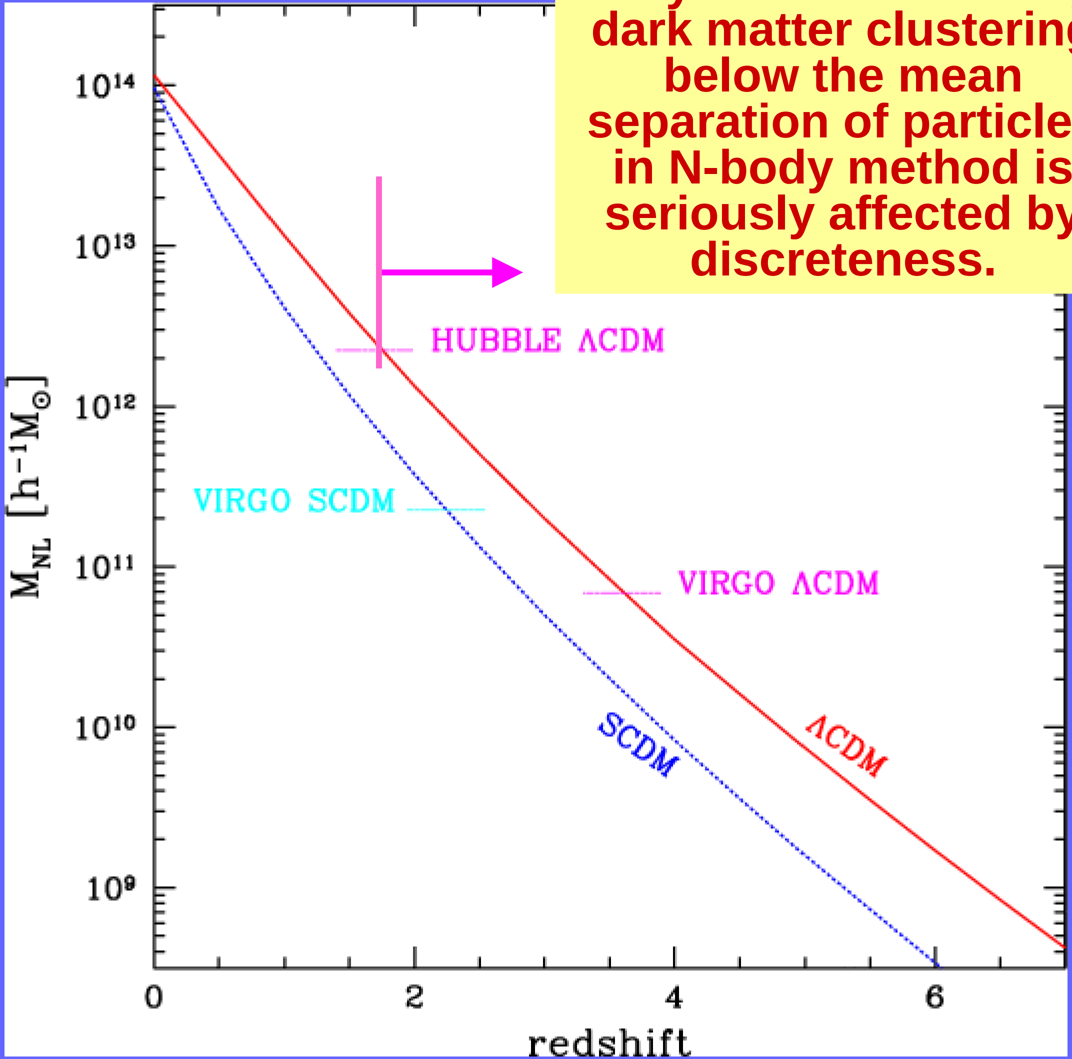


- **Observed time-delay is consistent with predicted time-delay probability when the density profile has a steep cusp $\propto r^{-1.5}$**

Oguri et al. 2001; see poster #33

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.

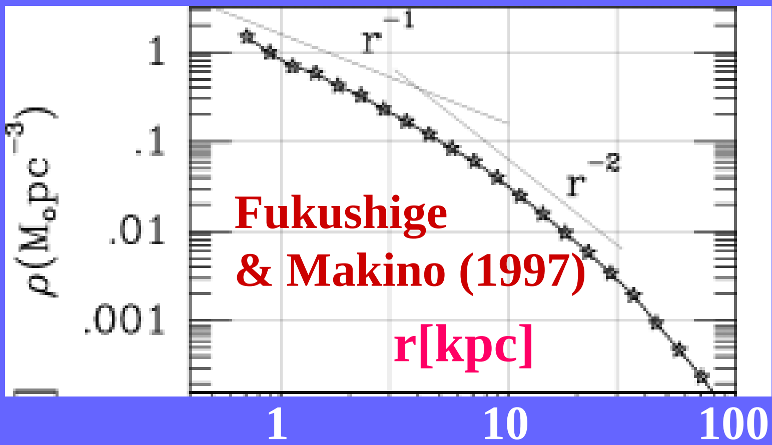
Conclusions

- ***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
- ***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

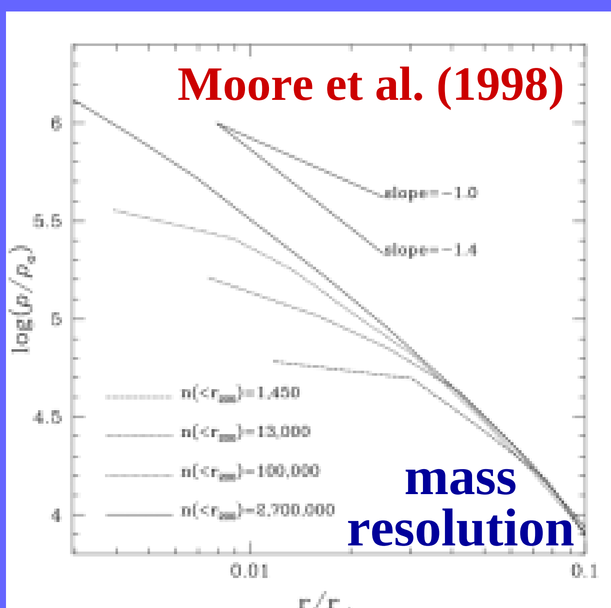
Brief history before NFW

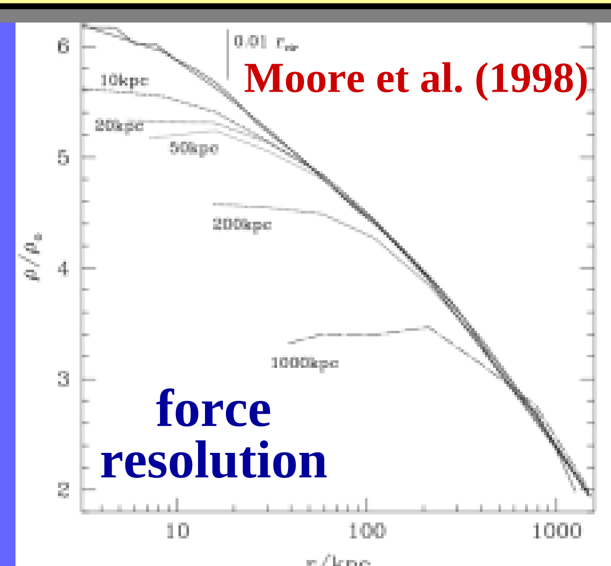
- **1970:** Peebles; N-body simulation (N=300).
- **1977:** Gott; secondary infall model $\rho \propto r^{-9/4}$.
- **1985:** Hoffman & Shaham; predict that density profile around density peaks is $\rho \propto r^{-3(n+3)/(n+4)}$.
- **1986:** Quinn, Salmon & Zurek; N-body simulations (N～10000), confirmed $\rho \propto r^{-3(n+3)/(n+4)}$.
- **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 $\rho \propto r^{-1}(r+r_s)^{-3}$.

Profiles in higher-resolution simulations

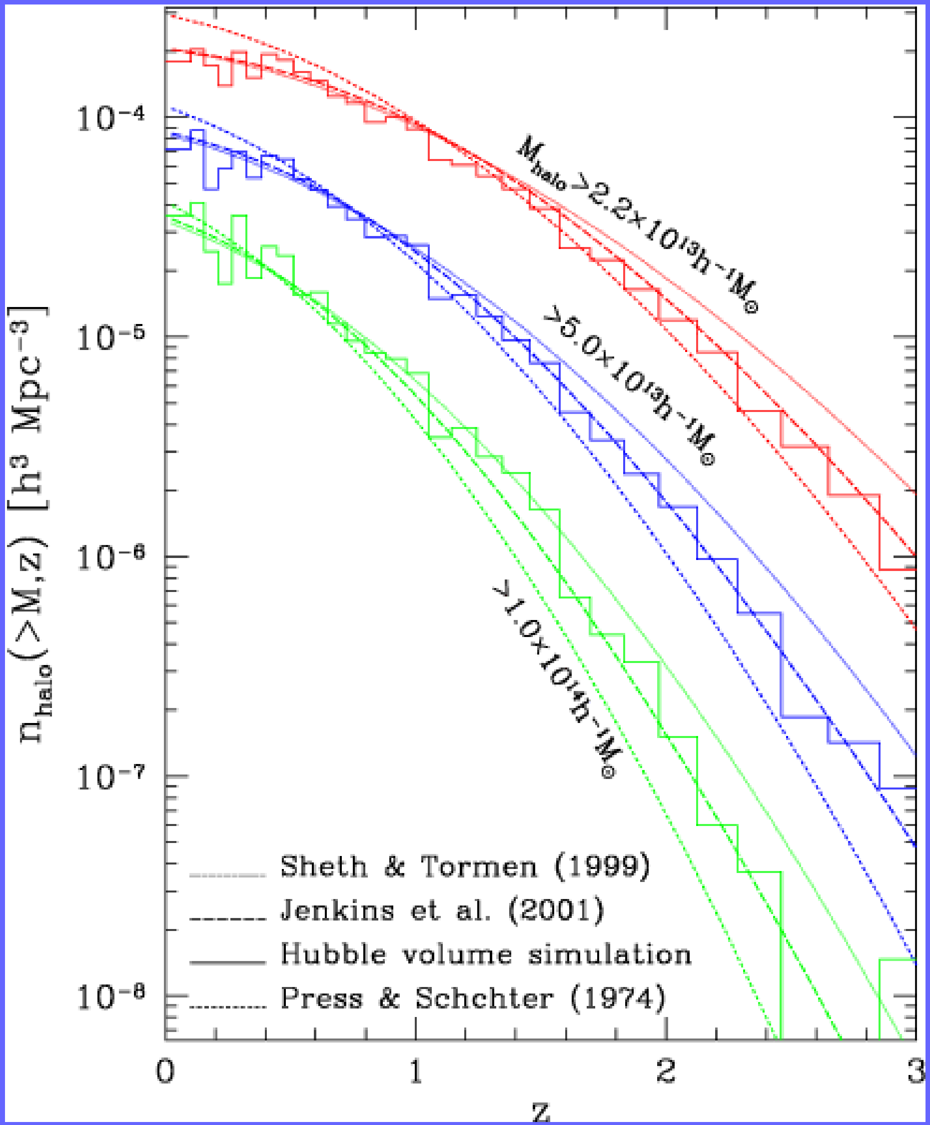


- inner slope in higher-resolution simulations is steeper (~ –1.5) than the NFW value (–1.0)





Mass function of dark halos



- The Press-Schechter mass function underpredicts, while an empirical correction by Sheth & Tormen (1999) overpredicts, the Hubble volume simulation data at high mass (Jenkins et al. 2001).

Hamana, Yoshida, Suto & Evrard (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

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

Halos in N-body simulations

friend-of-friend

linking length = 0.2

X-ray clusters

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