The distribution of dark matter around galaxies : Mean surface density profile and outer structure

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@IDM2010, Montpellier / Ref. : Masaki, Yoshida & Fukugita (2010) in prep.

Gravitational lensing

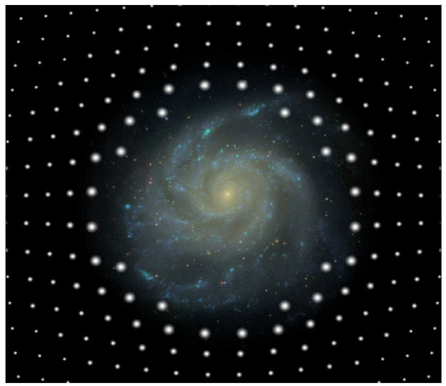
- Lensing is a powerful method to probe how matter is distributed around galaxies.
- Two probes :

Shear of galaxy image

$$\gamma_t(R) = \frac{\bar{\Sigma}(< R) - \Sigma(R)}{\Sigma_{\rm crit}} = \frac{\Delta\Sigma(R)}{\Sigma_{\rm crit}}$$

Magnification of quasar flux

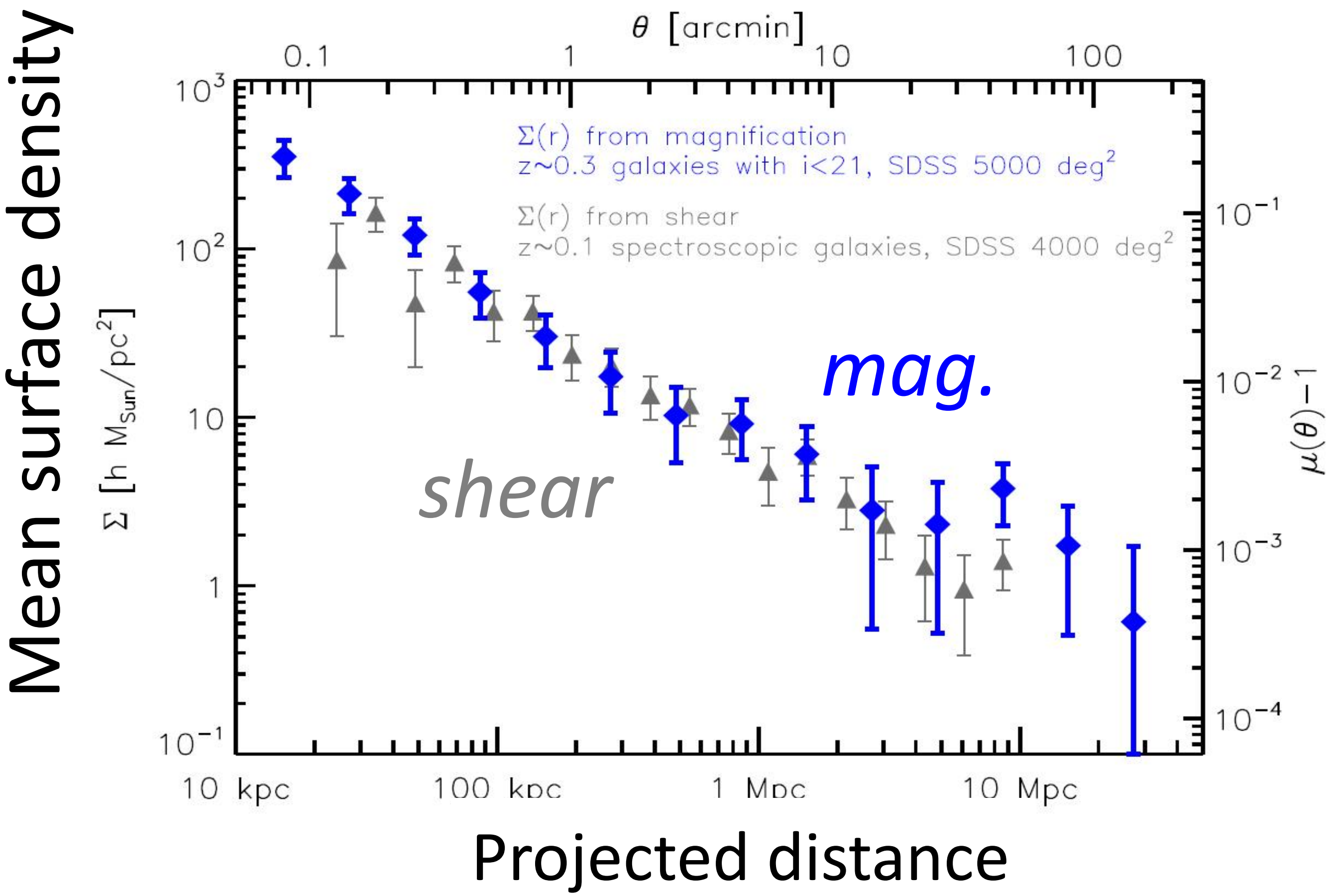
$$\mu(R) = 1 + 2\frac{\Sigma(R)}{\Sigma_{\rm crit}}$$



- Σ : projection of spatial density profile

Gravitational lensing

- Recent analyses of SDSS data by Sheldon et al. '04 - shear, Ménard et al. '10 - magnification



- *Two features :*
  * The observed surface density profile can be described by a single power-law ~ $R^{-0.8}$
  → Inconsistent with NFW profile (~ R^{-2} at large R)?

  * The power law form continues to ~*10Mpc/h*
  → Galaxies have a very extended halo well beyond the typical virial radius (~*100kpc/h*) ? How much mass is associated with the galaxies ?

Aims

- Using *N*-body simulations of the ΛCDM cosmology,

  - Test the model against the observed surface density profile around SDSS galaxies reported by Ménard et al. (2010).

  - Study the amount of dark matter associated with halos experimentally.

"How and where is the mass distributed?"

N-body simulation

N-body simulation details

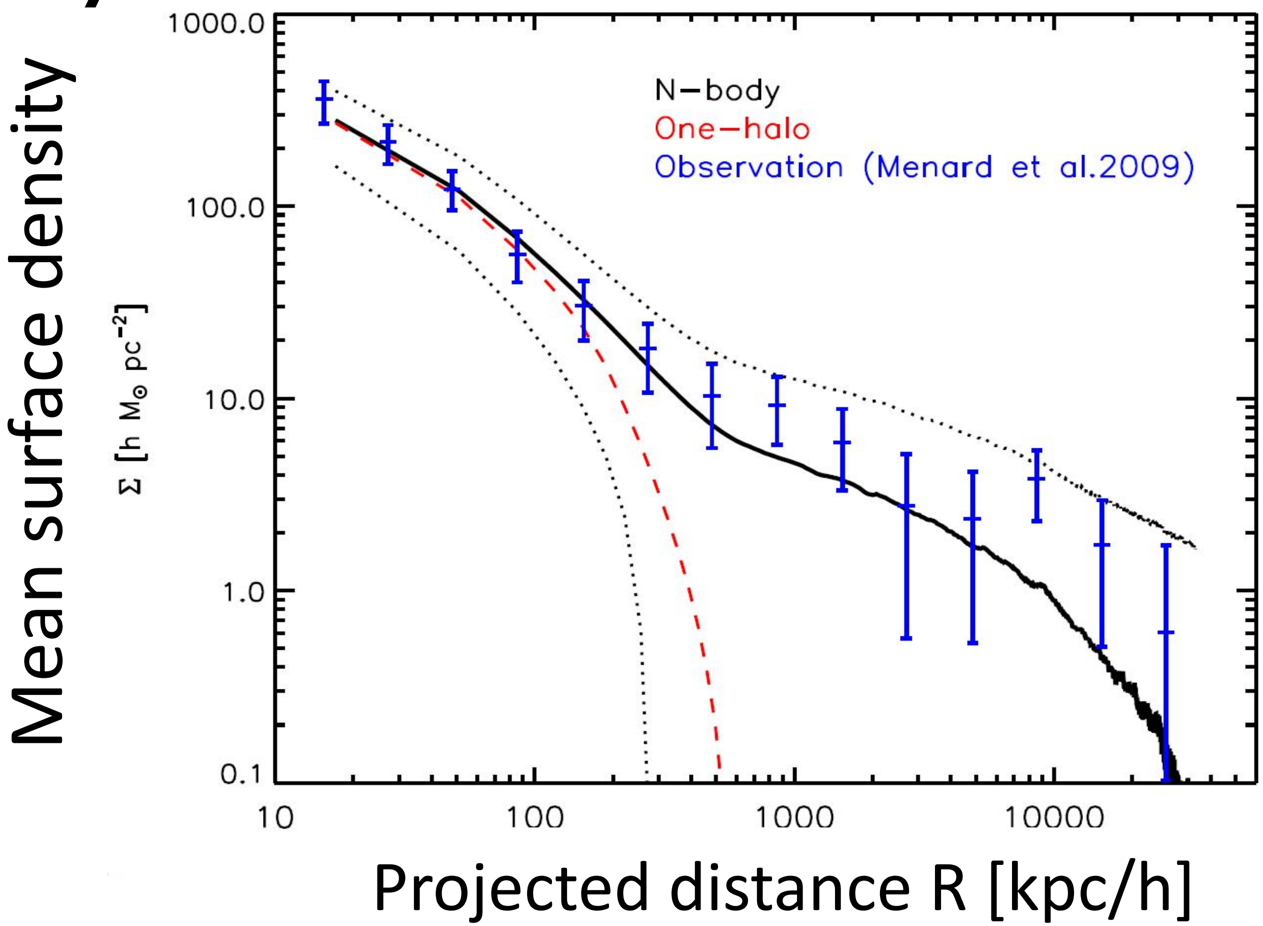
- Cosmological params. : *WMAP 5-yr*
- Initial condition : 2nd order lagrangian perturbation theory, rather than the standard ZA.
- Numerical params. :
  - Box size : $L_{box} = 200h^{-1}Mpc$
  - Number of particle : $N_p=1024^3$
  - Mass of a particle : $m_p=5.34\times10^8h^{-1}M_{sun}$
  - Initial redshift : $z_i=50$
  - Softening parameter : $\varepsilon=10h^{-1}kpc$

Halos in our simulation

- Halo identification : SO, $200\times\rho_{crit}(z)$
- At $z=0.36$,
  number of halos : 229,805 ($5\times10^{10} - 5\times10^{14}\ h^{-1}M_{sun}$)
- We use *N*-body outputs at $z=0.36$ to calculate the mean surface density profile around sample halos with comoving-$100h^{-1}Mpc$ projection thickness.
- Also use $z=0.36$ outputs to measure the amount of dark matter around halos (later in the talk).

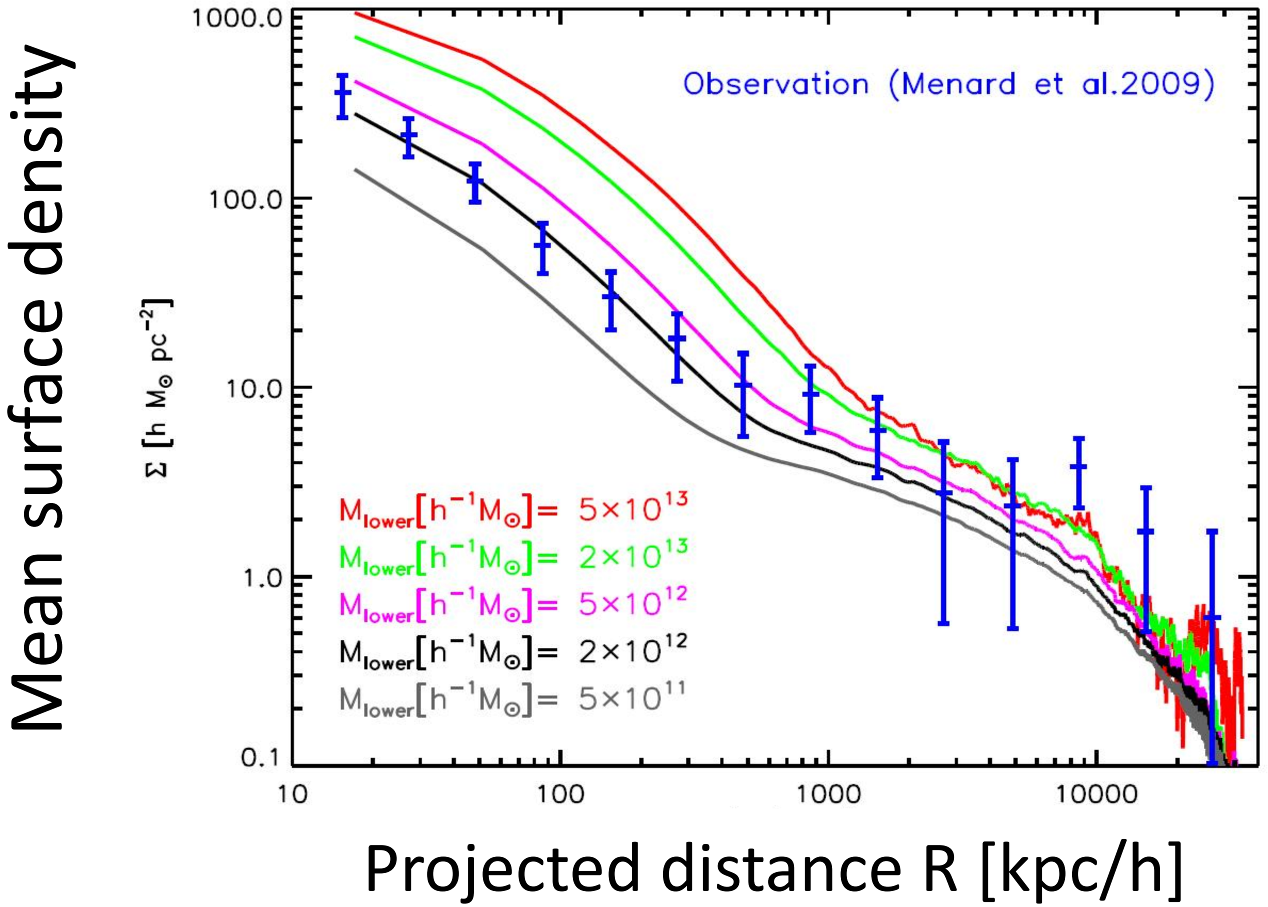
Surface mass density profile

N-body vs. Observation



- The mass range of the sample halos used in ensemble avaraging : 2×10^{12} - $1\times10^{14}\,h^{-1}M_{sun}$ (number : 9,970)
- At R<100h^{-1}kpc : dominated by the one-halo term
- ***The simulation result agrees with the observational result well, both in the amplitude and in the overall shape.***

Effects of halo mass range



- The lower limit of the sample halo mass range affects the amplitude in the one-halo regime strongly. It reflects the halo mass function on the ensemble averaging.
- ***The case of $M_{lower} = 2\times10^{12}\, h^{-1} M_{sun}$ agrees with the observational result well, and the mass may correspond to the typical halo mass of the sample galaxies.***

Halo model approach

- $\Sigma(R)=\Sigma^{1h}(R)+\Sigma^{2h}(R)$
- *One-halo term :*
  number weighted 2D NFW profile

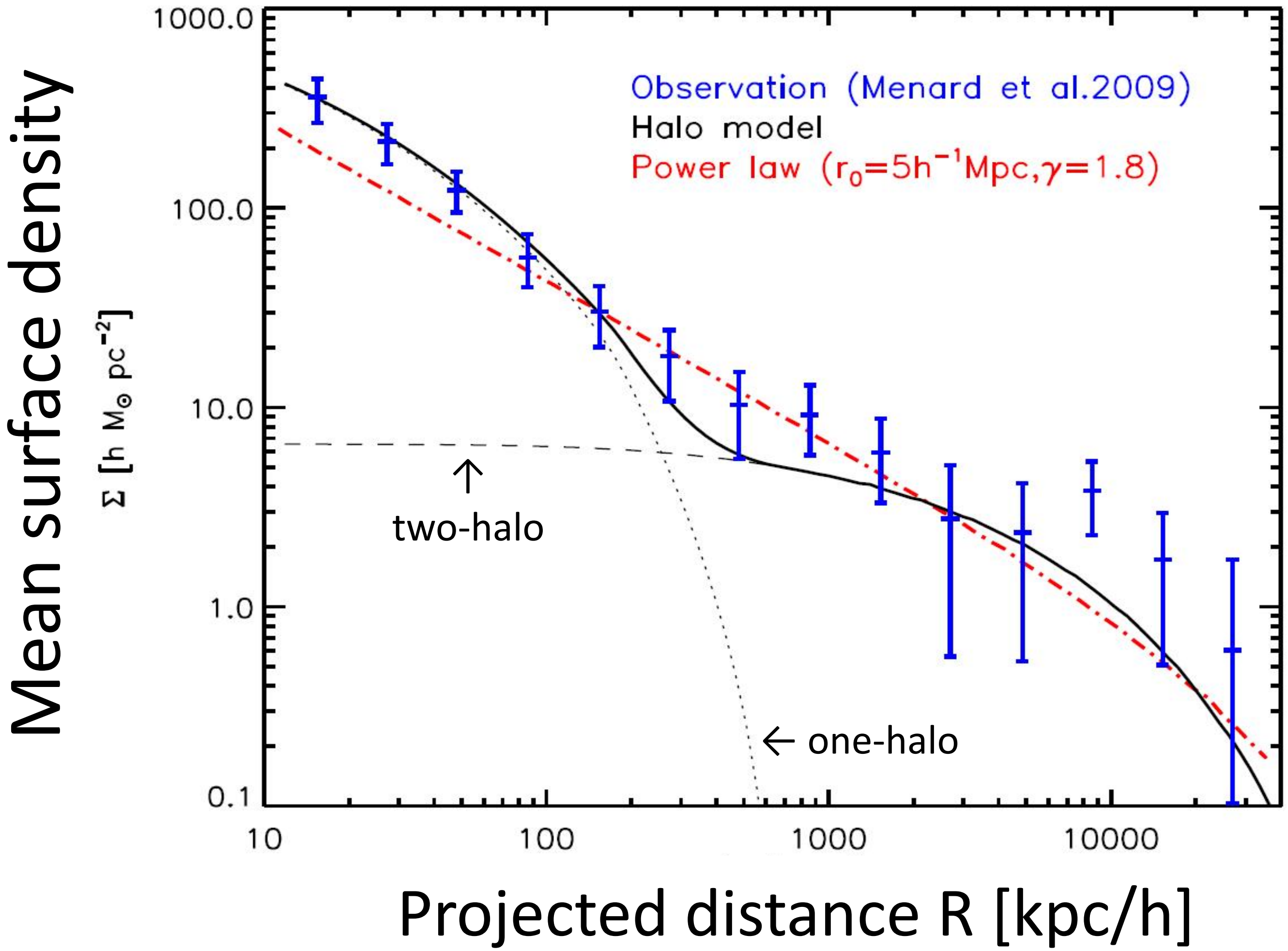
$$\Sigma^{\rm 1h}(R) = \frac{1}{n_{\rm halo}} \int dM \frac{dn}{dM} [\Sigma_{\rm NFW}(R|M) - 2R_{\rm vir}(M)\bar{\rho}_{\rm m}], \quad n_{\rm halo} = \int dM \frac{dn}{dM}$$

- *Two-halo term :*
  projection of halo-matter correlation (e.g. Seljak '00)

$$P_{\rm hm}^{\rm 2h}(k) = P_{\rm lin}(k) \left[\frac{1}{\bar{\rho}} \int dM \frac{dn}{dM} M b(M) u(k|M)\right] \left[\frac{1}{n_{\rm halo}} \int dM \frac{dn}{dM} b(M) u(k|M)\right]$$

$$\Sigma^{\rm 2h}(R) = 2\rho_{\rm m} \int_0^\infty d\chi \xi_{\rm hm}(r = \sqrt{R^2 + \chi^2}) = 2\rho_{\rm m} \int_R^\infty dr \frac{r\xi_{\rm hm}(r)}{\sqrt{r^2 - R^2}}$$

Halo model prediction

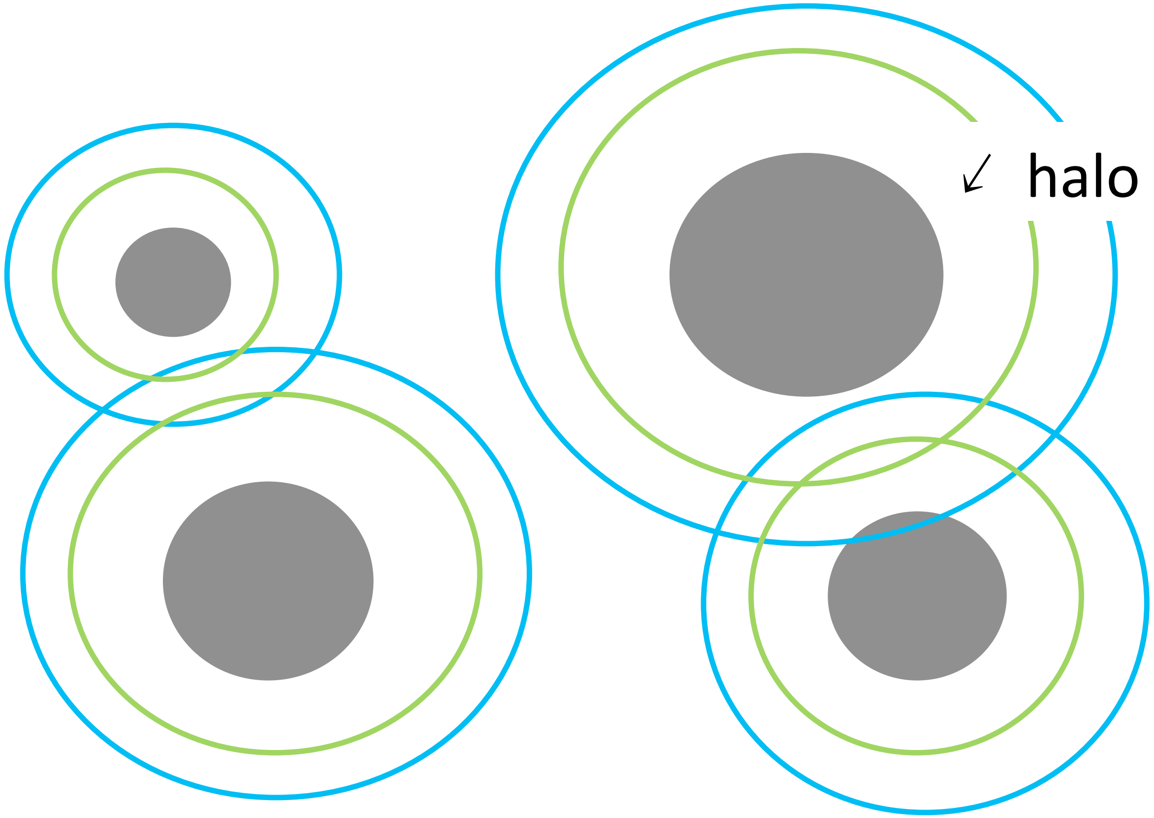


- The red dotted-dashed line : $\xi_{hm}(r) = (r/5h^{-1}Mpc)^{-1.8}$ for comparison
- ***Our halo model approach can predict the observed Σ well.***

Amount of dark matter around halos

Numerical experiment

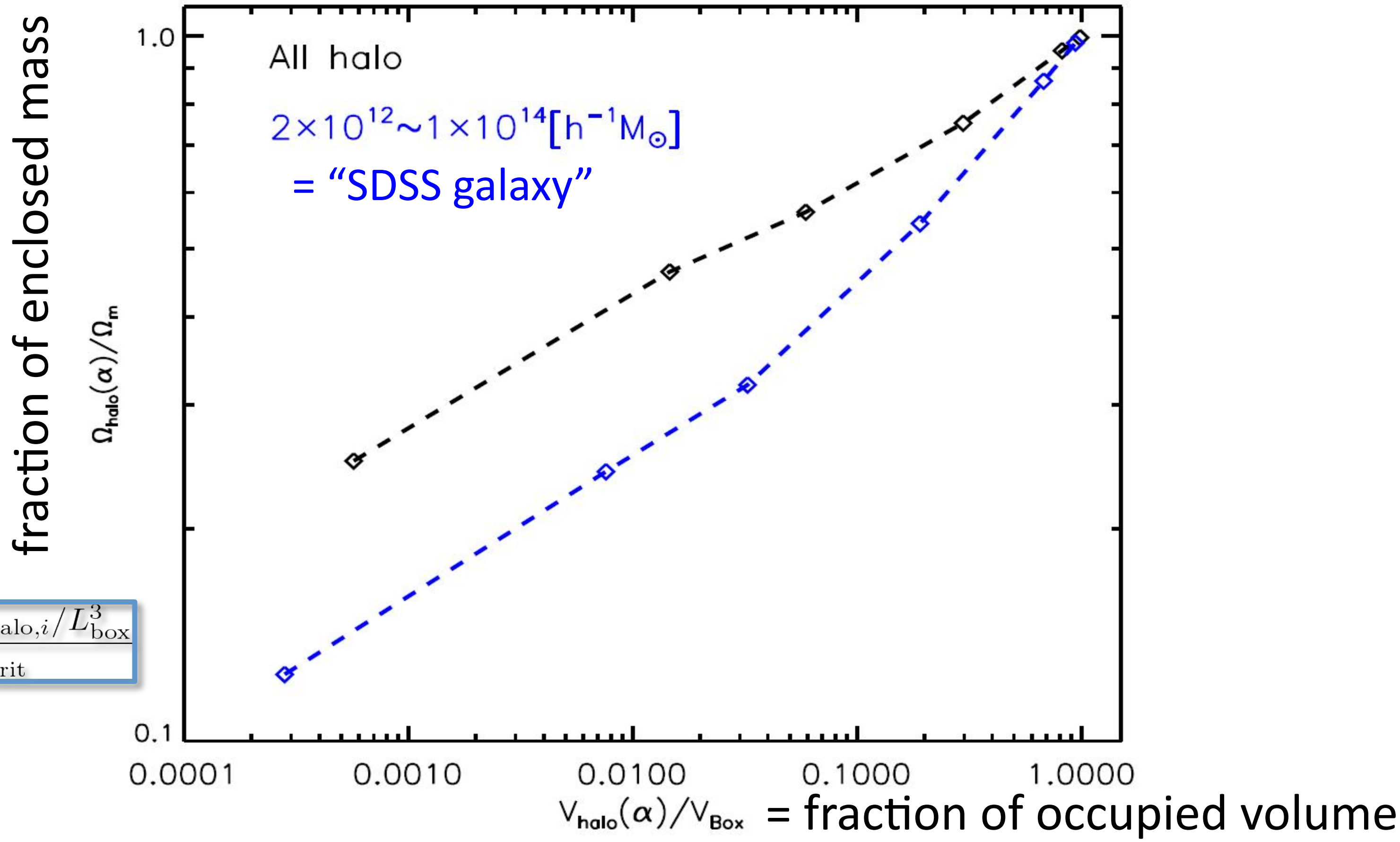
- Counting the enclosed mass and occupied volume of αR_{vir} spheres (α=1,3,5,10,20 and 30) which has same center of halos.



∗We do not double count about volume/mass.

∗Halo sample : halos identified $z=0.36$

Where is the mass distributed ?



$$\Omega_{\rm halo}(\alpha) \equiv \frac{\sum_i M_{\alpha-{\rm halo},i}/L_{\rm box}^3}{\rho_{\rm crit}}$$

- Each data point corresponds to α = 1, 3, 5, 10, 20 and 30.
- ***About 30% of the total mass is enclosed in around "SDSS galaxies" (2×10^{12} - $1\times10^{14}\ h^{-1}M_{sun}$) and the corresponding occupied volume is about 3% (α=5).***

N-body vs. Observational estimate (preliminary)

- Estimate from *M*/*L* and luminosity density observation
  (e.g.Fukugita & Peebles'04)

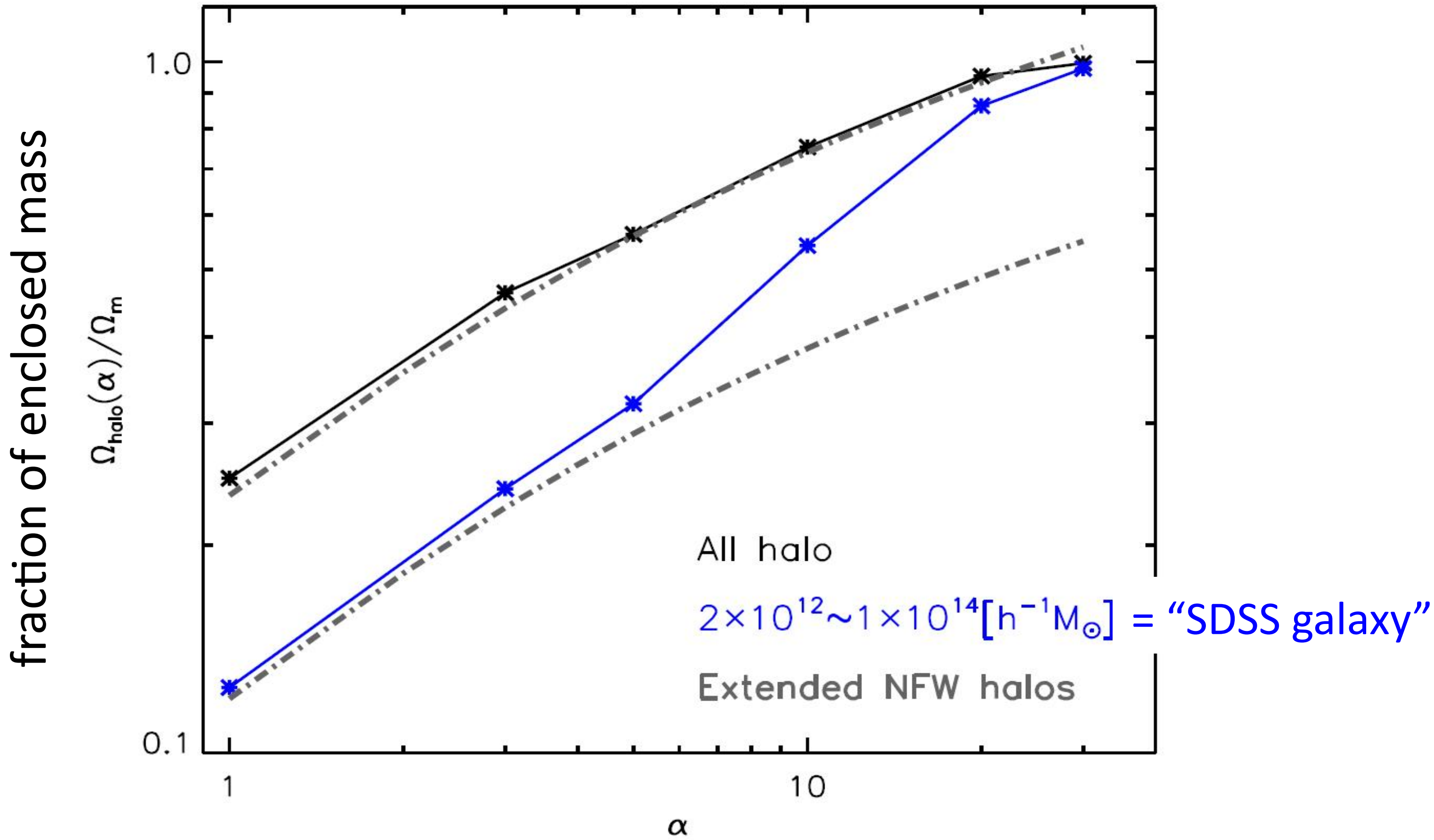
$$\Omega_{halo}=0.585\Omega_{matter}$$
probed region : <260kpc/h

- Suggestion from our *N*-body (case of all halo)

$$\Omega_{halo}(\alpha=3)=0.463\Omega_{matter}$$
average radius : 95kpc/h $\times 3 = 285$ kpc/h

→ *N-body & observation match well for the associate masses.*

How is the mass distributed ?



- The grey dotted-dashed line : the case for infinitely extended NFW profile model
- ***The figure implies that halos have no clear edge.***

Summary

- Λ CDM *N*-body simulation can reproduce the observed surface density profile around galaxies very well.
- The amplitude of the inner surface density profile can be an estimator of the typical halo mass of the sample galaxies.
- The observed surface density profile can be described well by a halo model.
- Our simulations suggest that the total mass around SDSS galaxies' host halos amounts to 30% of the total mass in the local universe.
- It is also implied that halos do not have a clear edge but a rather extended envelope.