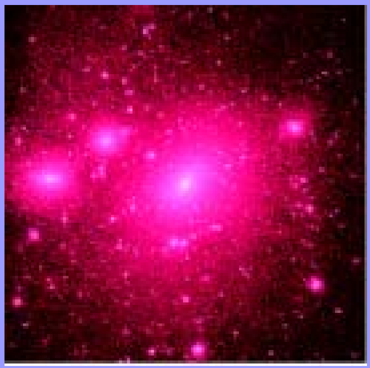

Clustering of dark matter halos on the light-cone

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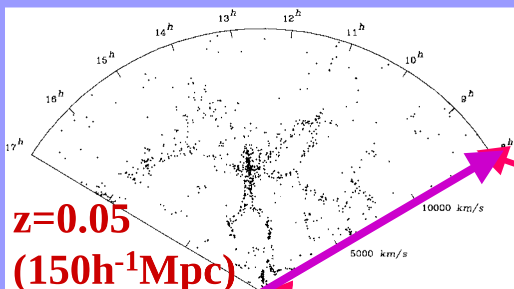
June 13, 2001@第八回台北天文物理検討会

Clustering on the light-cone

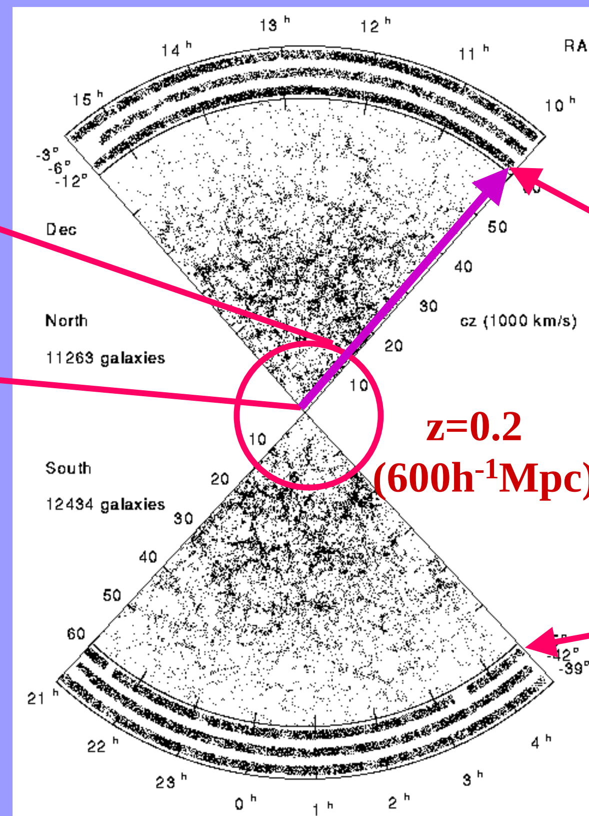
1986



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

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

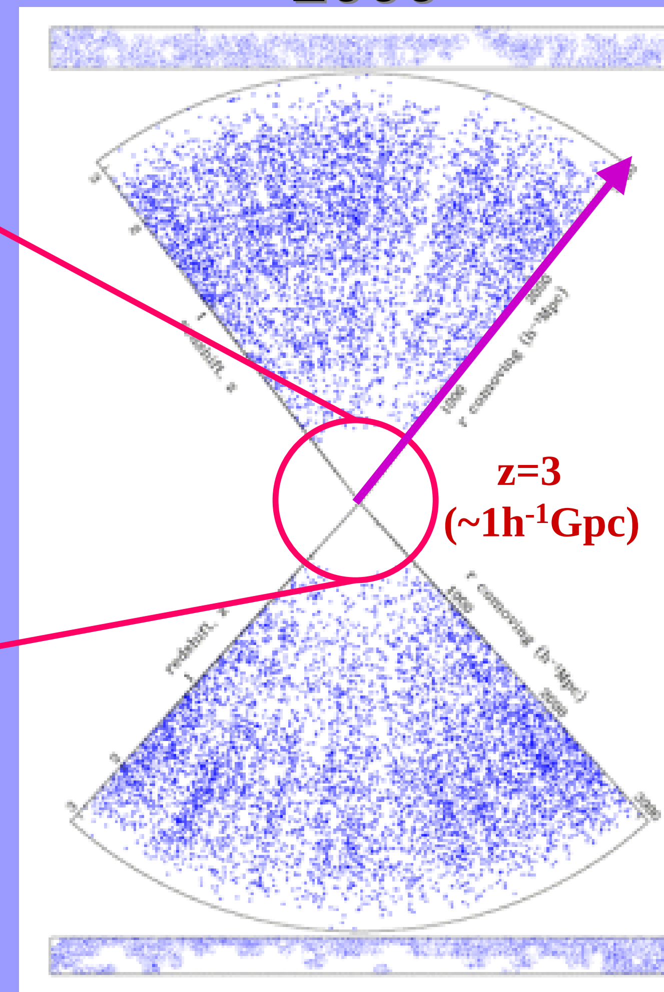
1996



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

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

2000

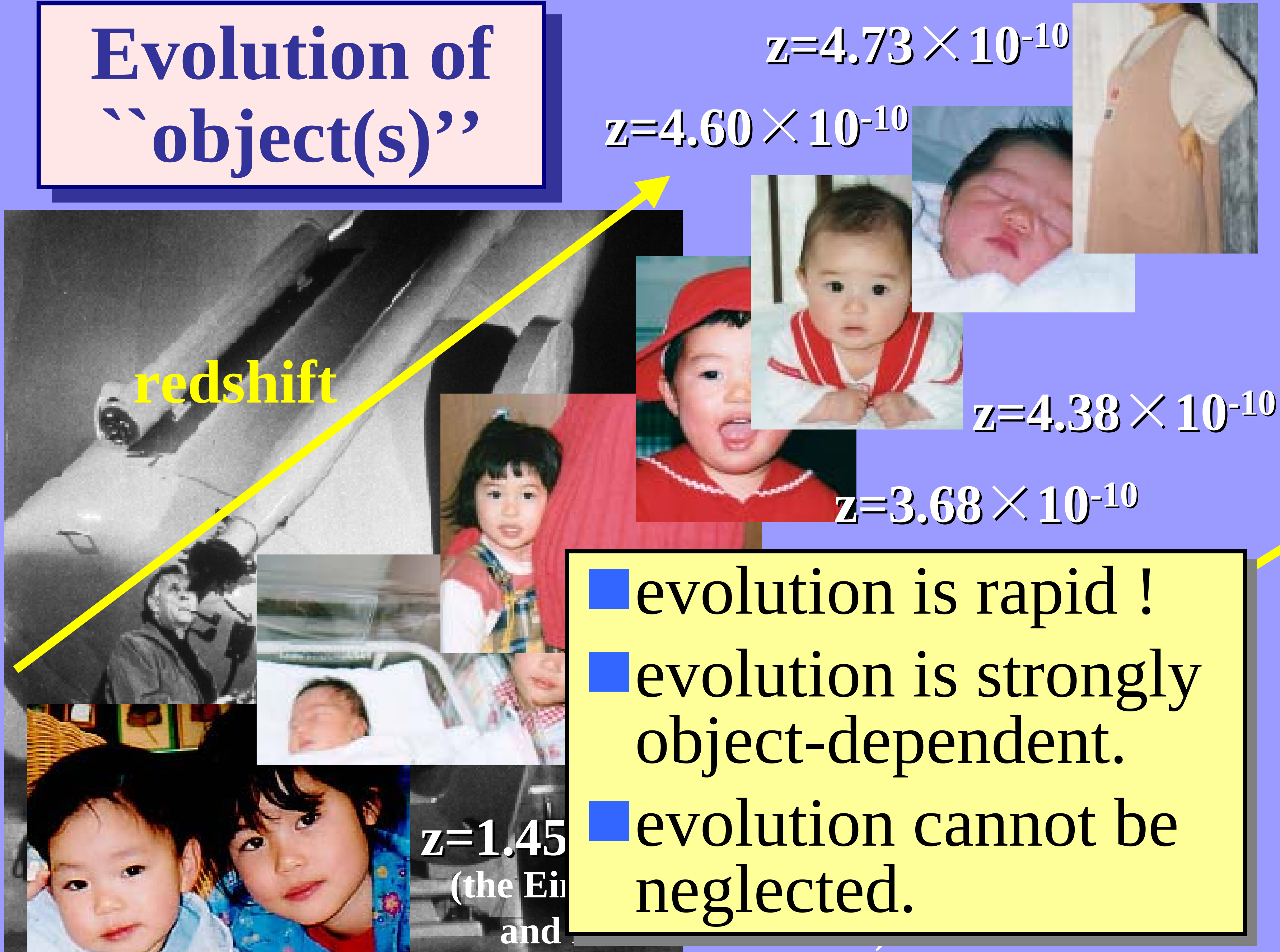


z=3
($\sim 1h^{-1}$Gpc)

2dF QSO survey: Shanks et al. (2000)

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

Evolution of ``object(s)''



- evolution is rapid !
- evolution is strongly object-dependent.
- evolution cannot be neglected.

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 (magnitude-limit, luminosity function, etc.)
  - object-dependent biasing relative to mass distribution
- ***observational selection function***
  - magnitude-limit and luminosity function
  - shape of the survey boundary

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

Predicting the clustering on the light-cone

- ***redshift-space distortion***

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

gravitational nonlinear evolution

linear and nonlinear redshift-space distortion

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

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

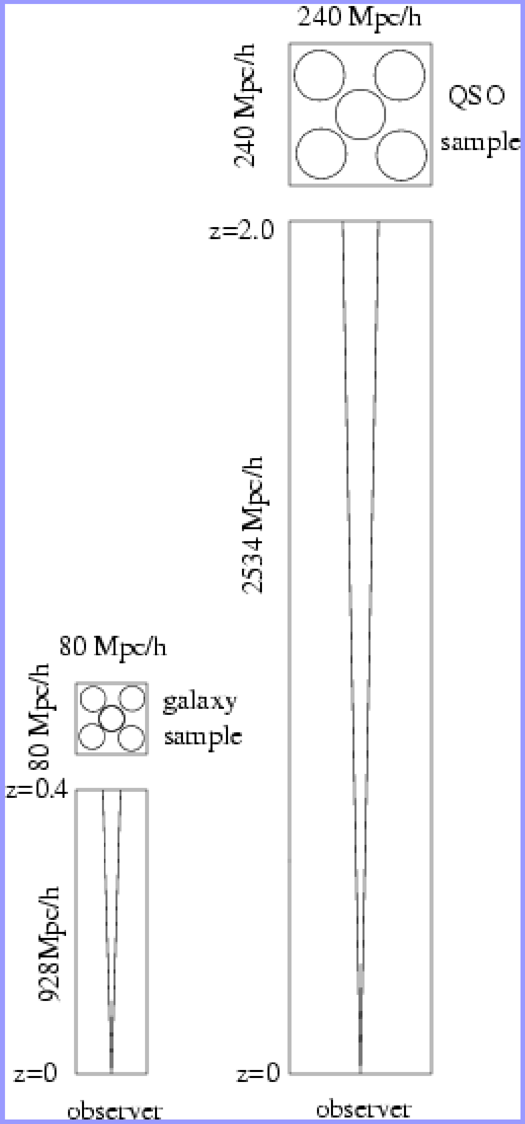
comoving volume element

selection function

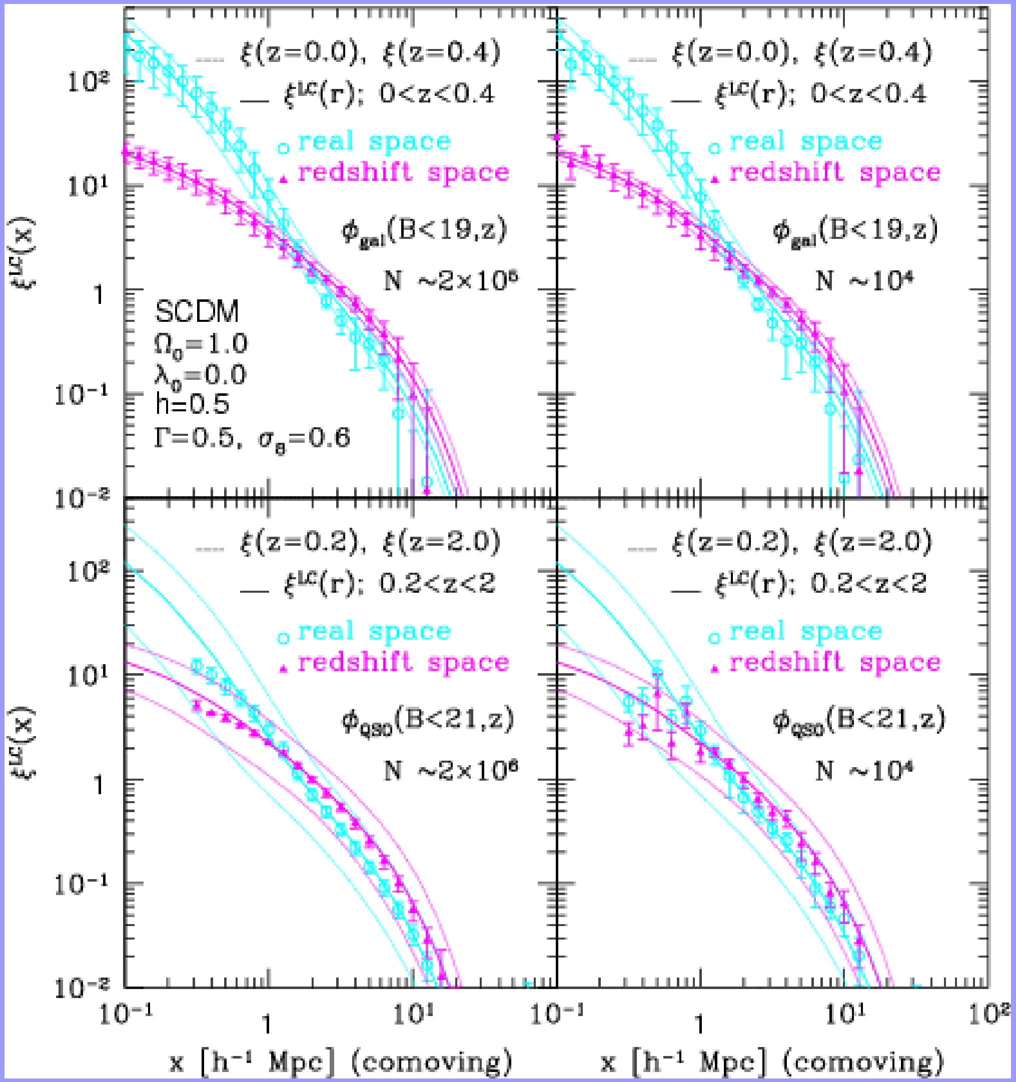
mean number density

Hamana, Colombi & Suto (2001)

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



Bias is ignored here.

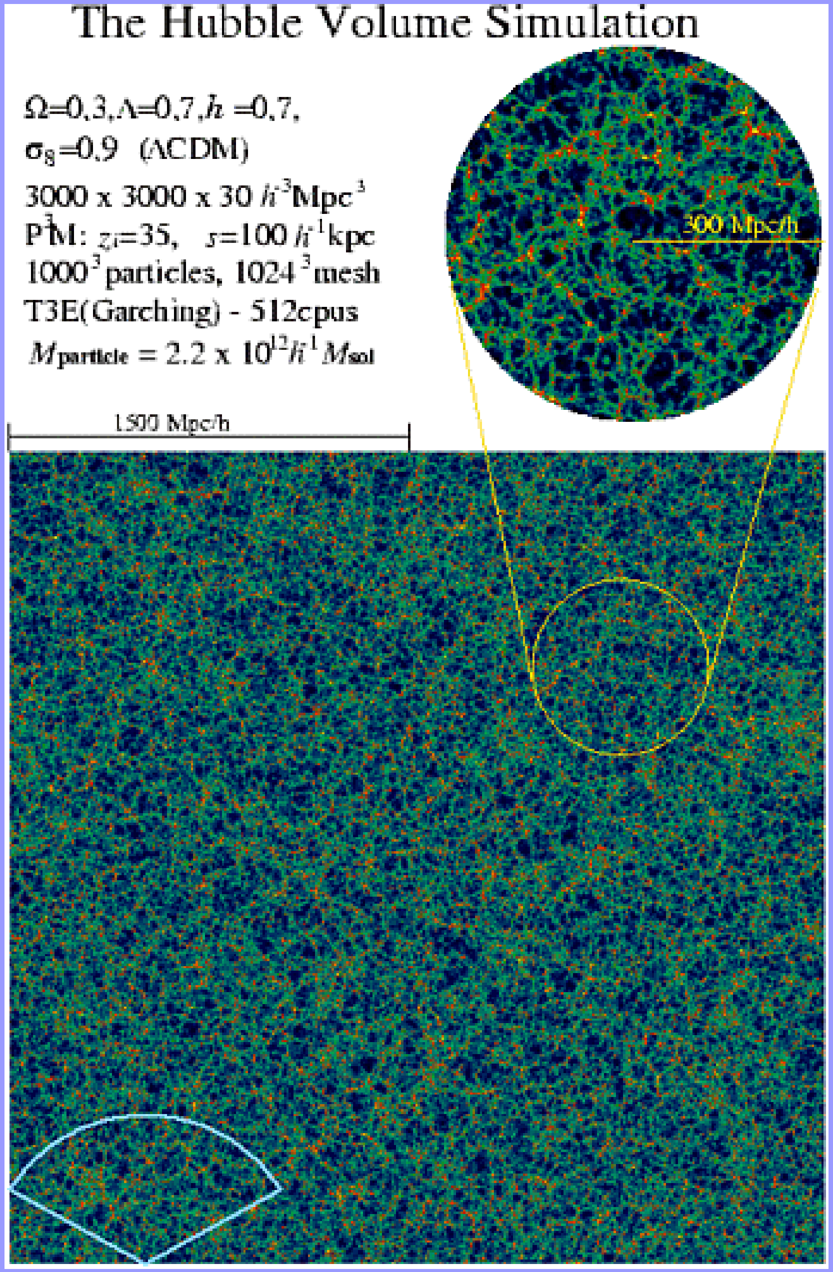


Hamana, Colombi & Suto (2001)

Hubble volume
ΛCDM simulation

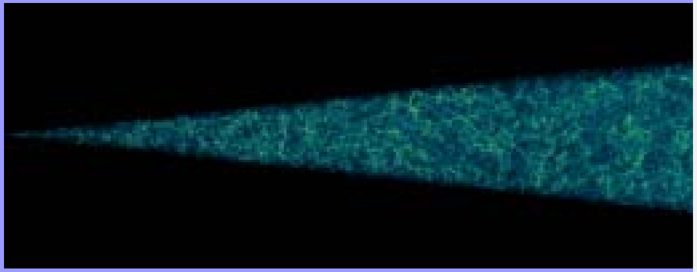
- P^3M N-body simulation
- $N=10^9$ particles in a $(3000h^{-1}Mpc)^3$ box
- ΛCDM: $\Omega_0=0.3$, $\lambda_0=0.7$, $h=0.7$, $\sigma_8=0.9$
- $m_{particle}=2.2\times10^{12}h^{-1}M_{sun}$
- $\varepsilon_{grav}=100h^{-1}kpc$

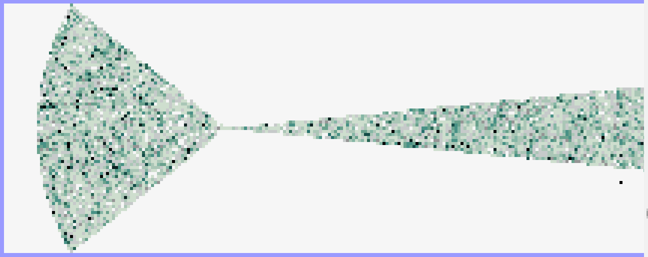
The Virgo Consortium
http://www.physics.isa.umich.edu/hubble-volume/

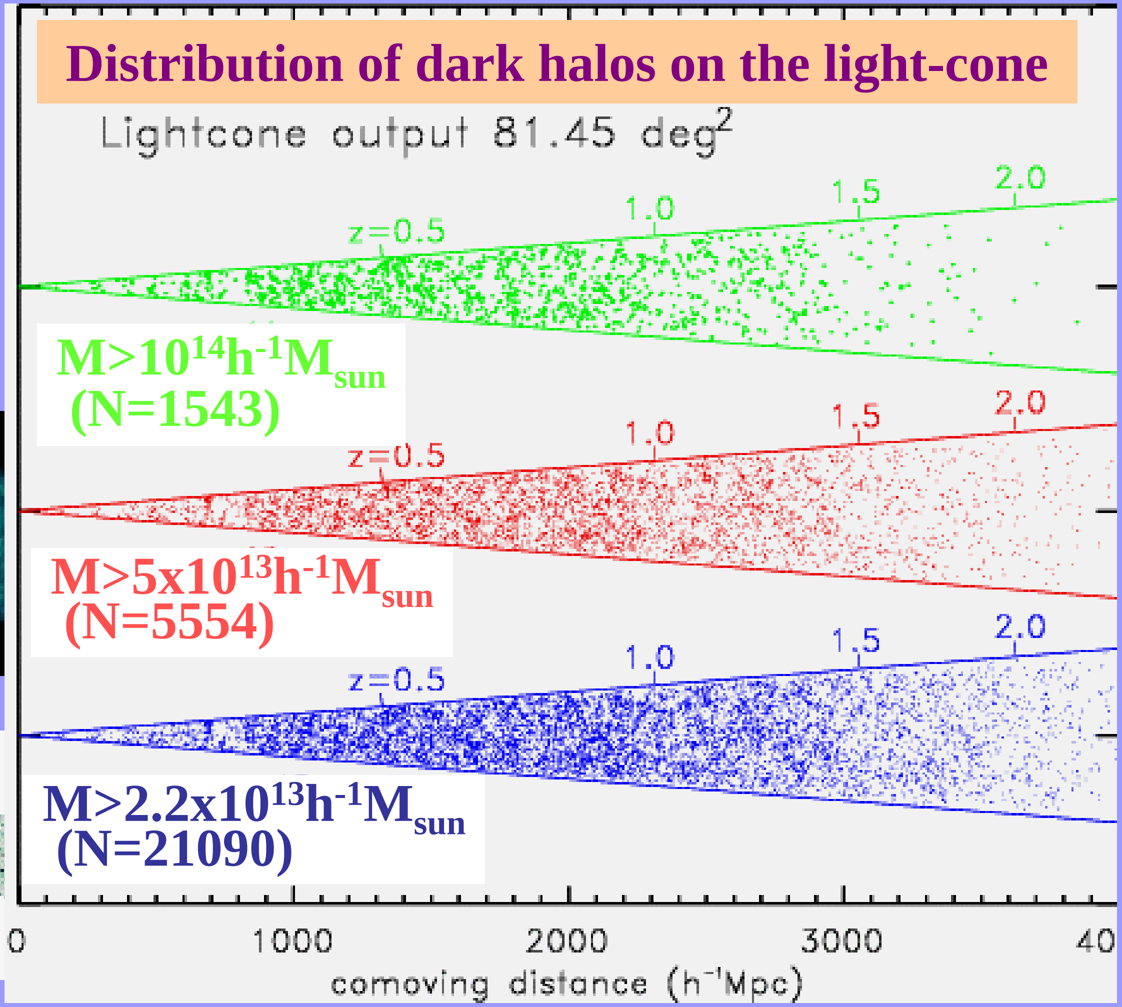


Light-cone output from the Hubble volume Λ simulation

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

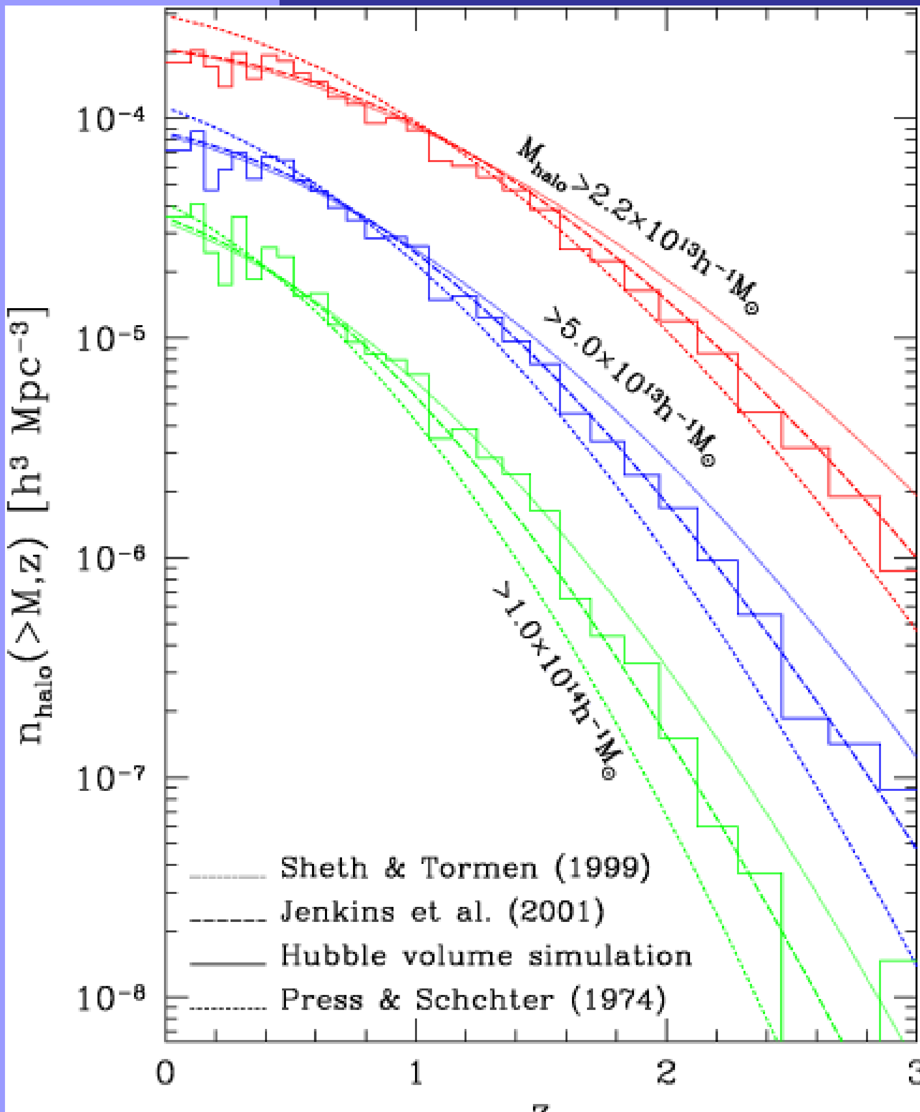






Hamana, Yoshida, Suto & Evrard (2001)

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)

Phenomenological model for scale- and mass-dependent halo biasing

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

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

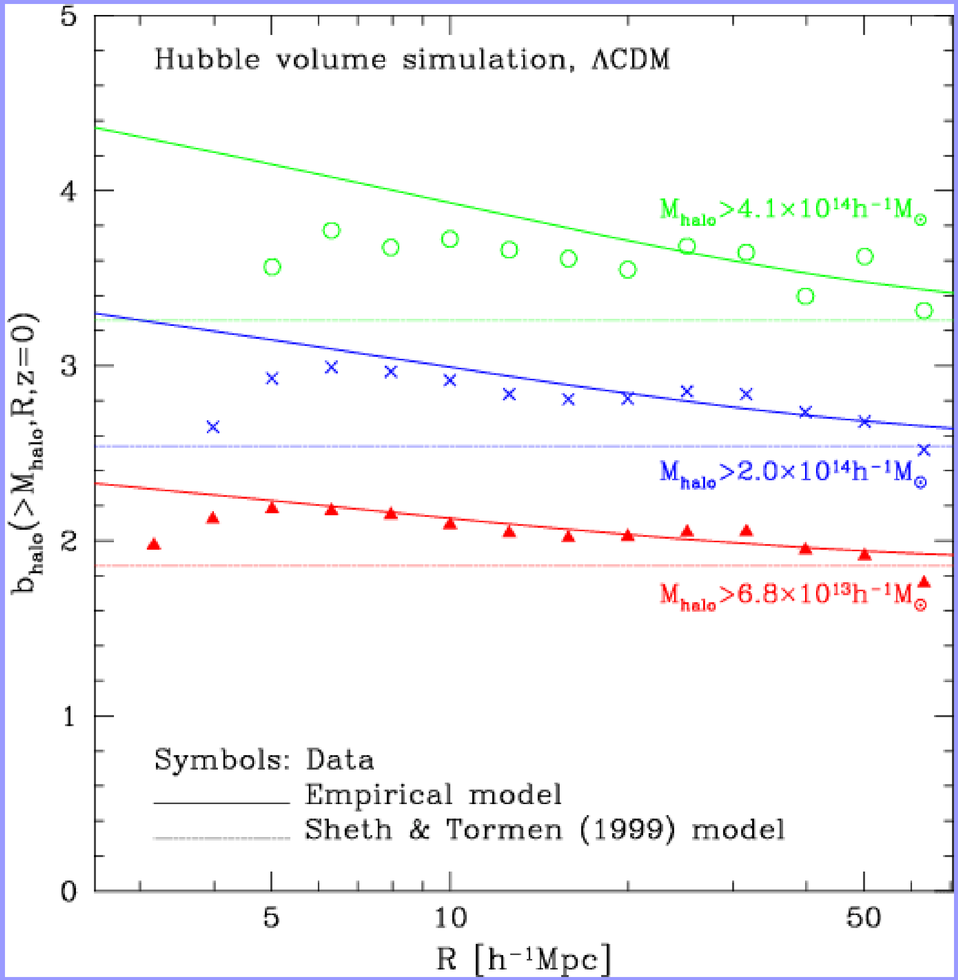
$$\xi_{halo}(M,R,z) = b_{halo}^2(M,R,z)\,\xi_{\mathrm{mass}}(R,z)$$

- ***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, Yoshida, Suto & Evrard (2001)

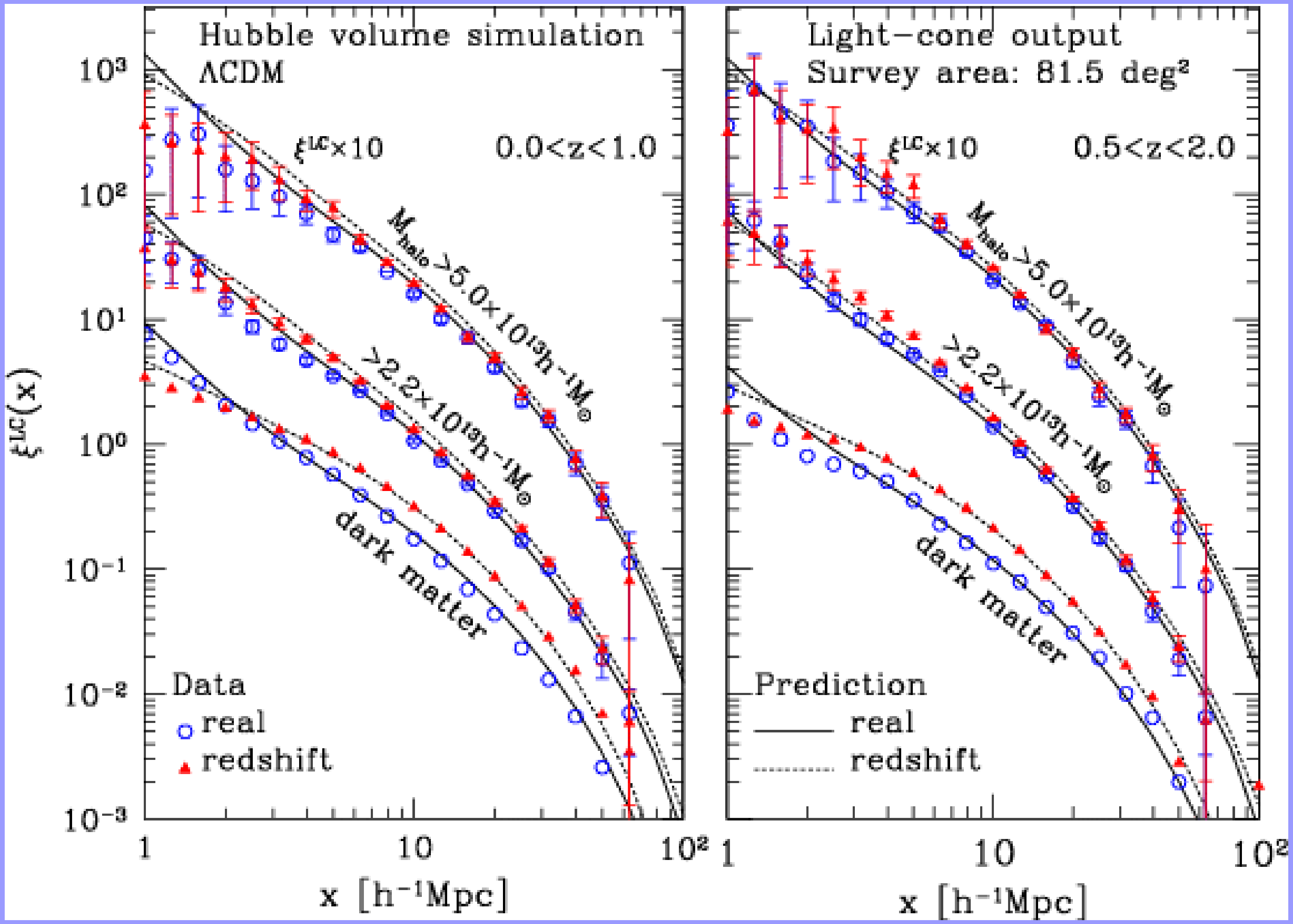
Calibrating our halo biasing model with the Hubble volume simulation at z=0



- Our empirical model works quite well at $R>20h^{-1}$Mpc.
- The suppression of biasing in simulation at $R<5h^{-1}$Mpc is ascribed to the exclusion effect of their finite size.
- For massive halos, our model underestimates the measured biaisng by <10% at $5h^{-1}\mathrm{Mpc}<R<20h^{-1}$Mpc, which would be less than other possible systematic errors.

Hamana, Yoshida, Suto & Evrard (2001)

Correlation functions of halos on the light-cone



Hamana, Yoshida, Suto & Evrard (2001)

In the last century, I would have concluded...

- We have developed an accurate empirical model which successfully describes the clustering of halos in the Hubble volume ΛCDM simulation on the light-cone up to $z=3$.
- Since those dark halos are trivially related to the observed galaxy clusters, our model can be easily applied to the clustering of X-ray/SZ-selected clusters. $\Rightarrow$ ***Precision Cosmology !***

But...

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

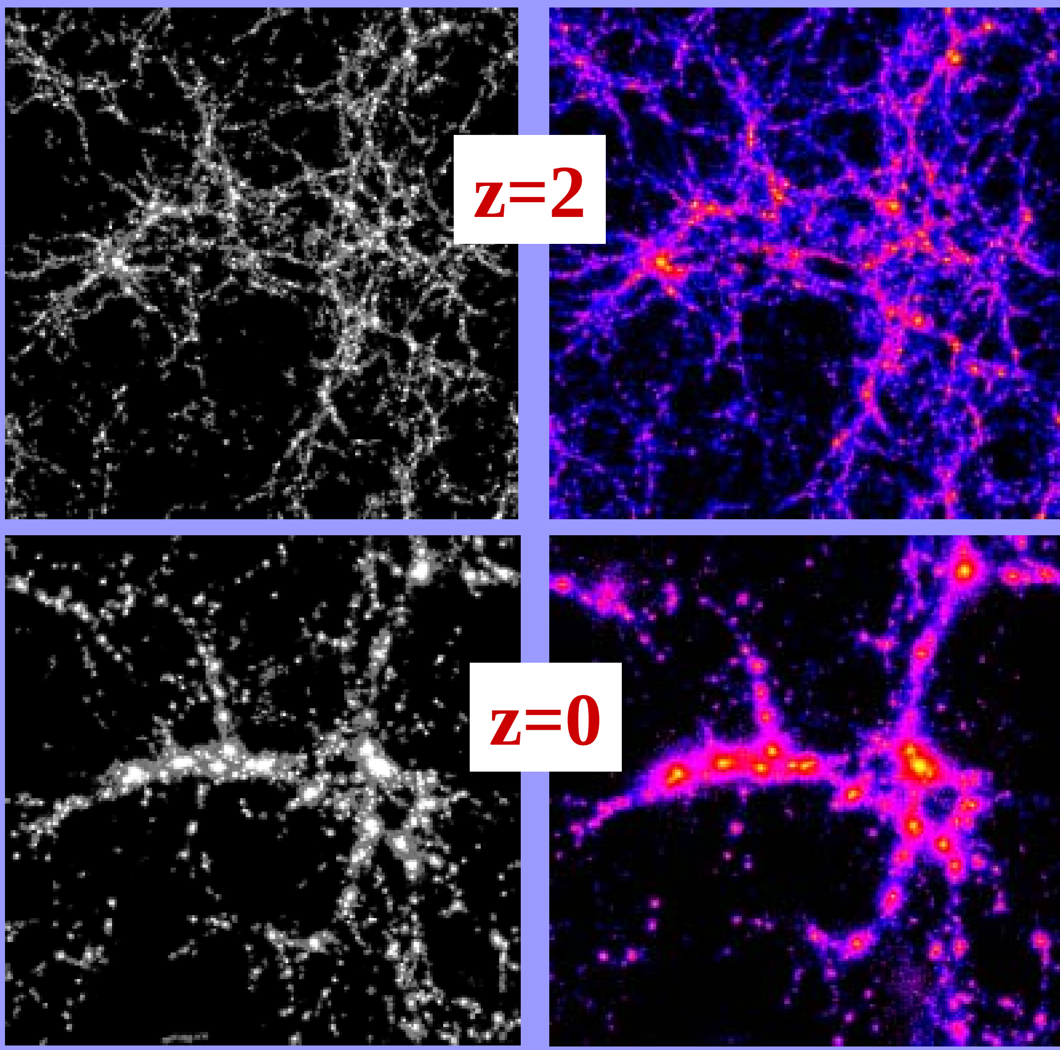
SZ clusters
$\Delta I_{SZ} \propto n_e T_e$

Halos in N-body simulations
friend-of-friend
linking length = 0.2

X-ray clusters
$S_x \propto n_e^2 T_e^{1/2}$

Relation between dark halos and clusters

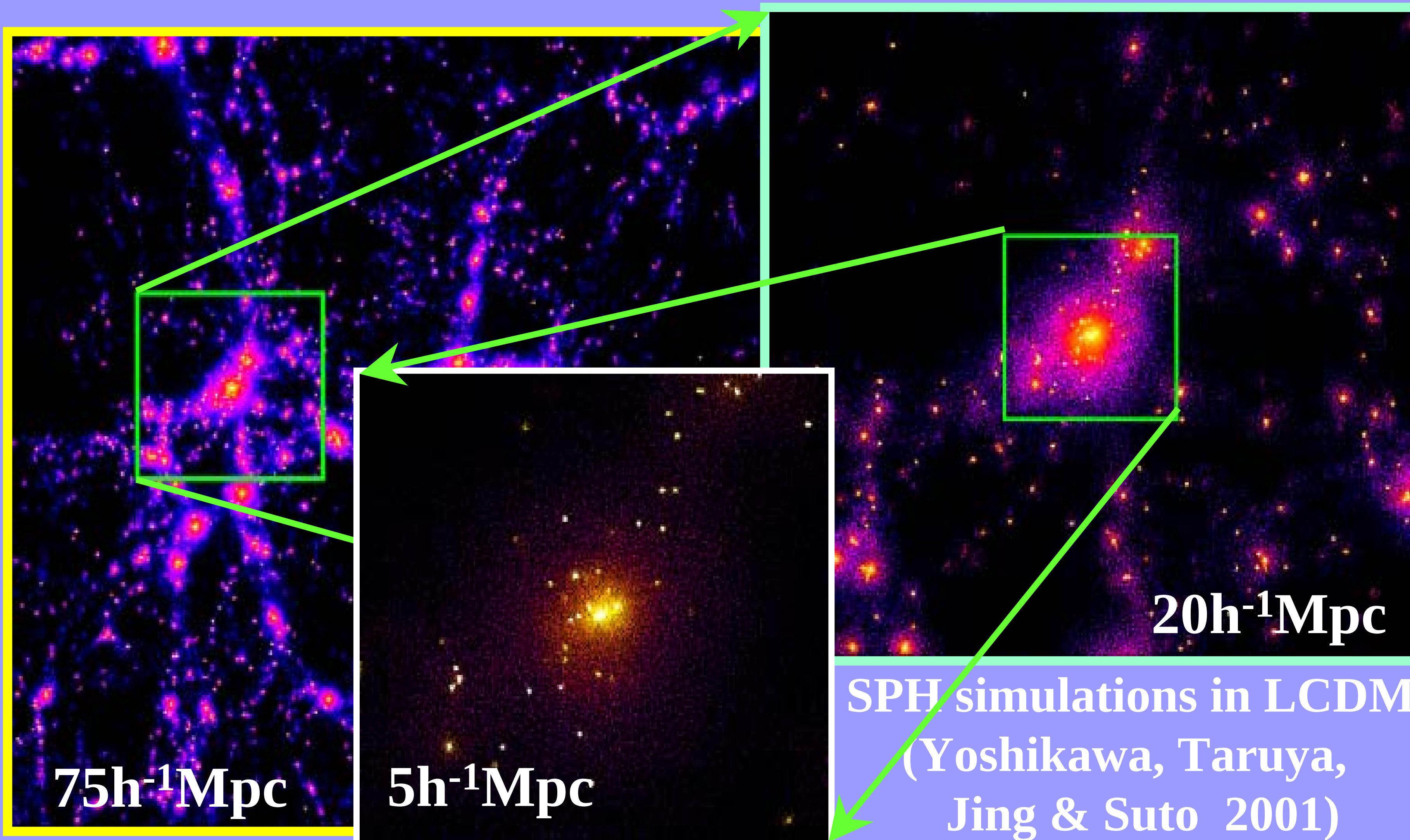
Dark matter **Hot gas**



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

SPH simulations in LCDM:
75x75x15 $h^{-3}Mpc^3$
(Yoshikawa, Taruya, Jing & Suto 2001)

Zooming in the simulated structure

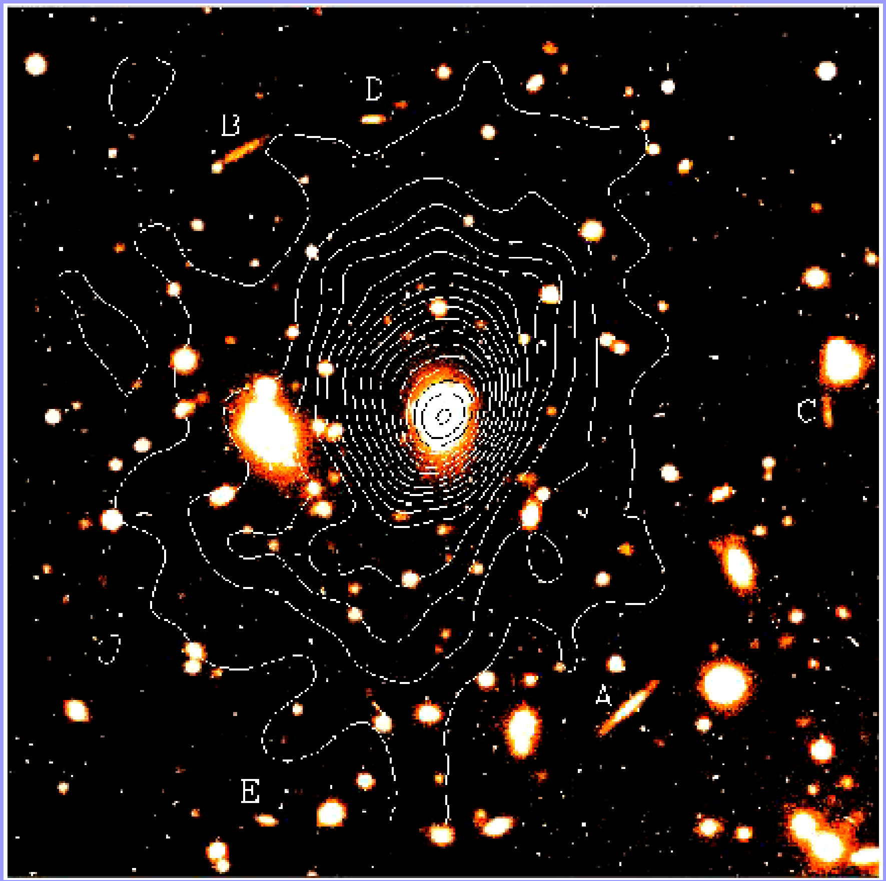


SPH simulations in LCDM
(Yoshikawa, Taruya,
Jing & Suto 2001)

An example: multi-band observation of the most luminous X-ray cluster RXJ1347-1145

- What do clusters look like in different wavelengths ?
- Systematic observational campaign for RXJ1347-1145: the most luminous X-ray cluster at z= 0.45
  - optical (ESO, NTT)
  - X-ray (ROSAT, ASCA)
  - submm SZ (SCUBA at J.C. Maxwell telescope, Hawaii)
  - mm SZ (NOBA at Nobeyama radio observatory, Japan)
- Collaborators: **E.Komatsu (小松英一郎)**, T.Kitayama, M.Hattori, H.Matsuo, R.Kawabe, H.Matsuo, K.Yoshikawa, K.Kohno, N.Kuno, S.Schindler

Optical and X-ray images of RXJ1347-1145



Optical: ESO NTT 3.5m I-band
X-ray: ROSAT/HRI

- the most luminous high-z X-ray cluster
- strong cooling flow

$z = 0.45$

$L_X h_{50}^2 = 2 \times 10^{46}$ erg s^{-1}

$M(< 2 h_{50}^{-1}\mathrm{Mpc}) = 10^{15} h_{50}^{-1} M_{sun}$

$T = 9.3\,\mathrm{keV}$

$\theta_c = 8''.4 \left(57\, h_{50}^{-1}\mathrm{kpc}\right)$

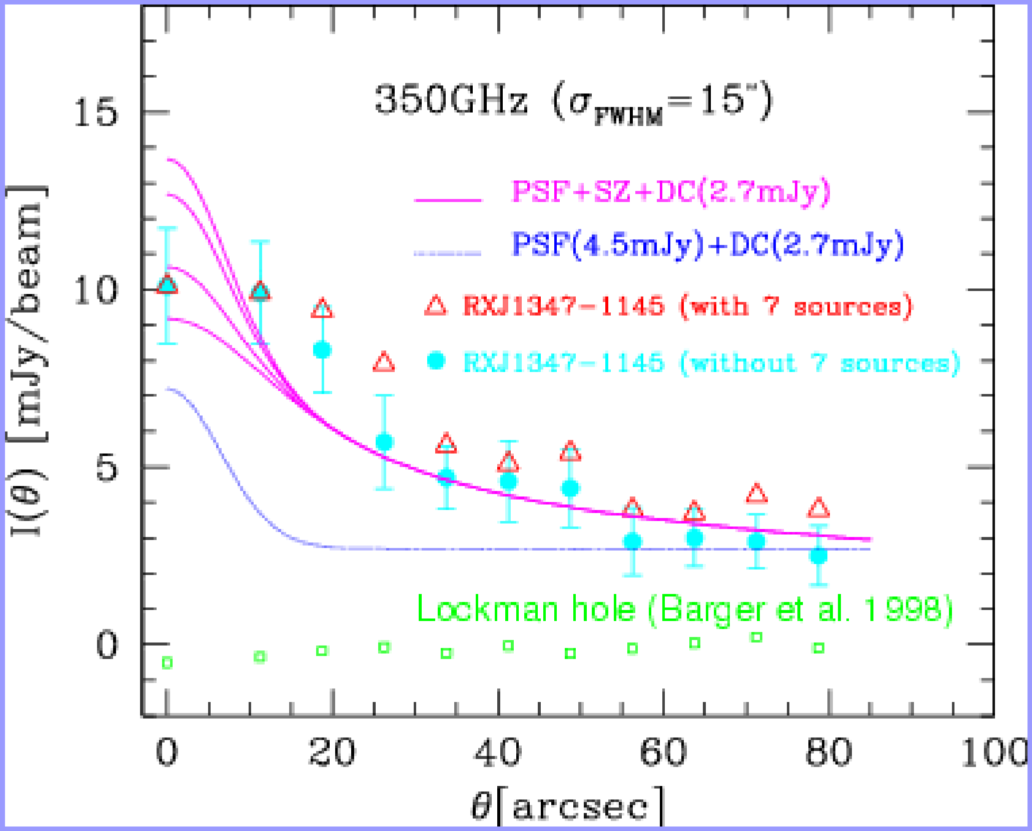
$n_{e0} h_{50}^{-1/2} = 0.094\ \mathrm{cm}^{-3}$

$\beta = 0.57$ Schindler et al.(1997)

$T = 15.9^{+6.5}_{-2.7}\,\mathrm{keV}$ Ettori et al. (2001)

Radial profile via submm SZ effect

- first detection of the radial profile of a cluster in the submm SZ effect at 350GHz (temperature increment)

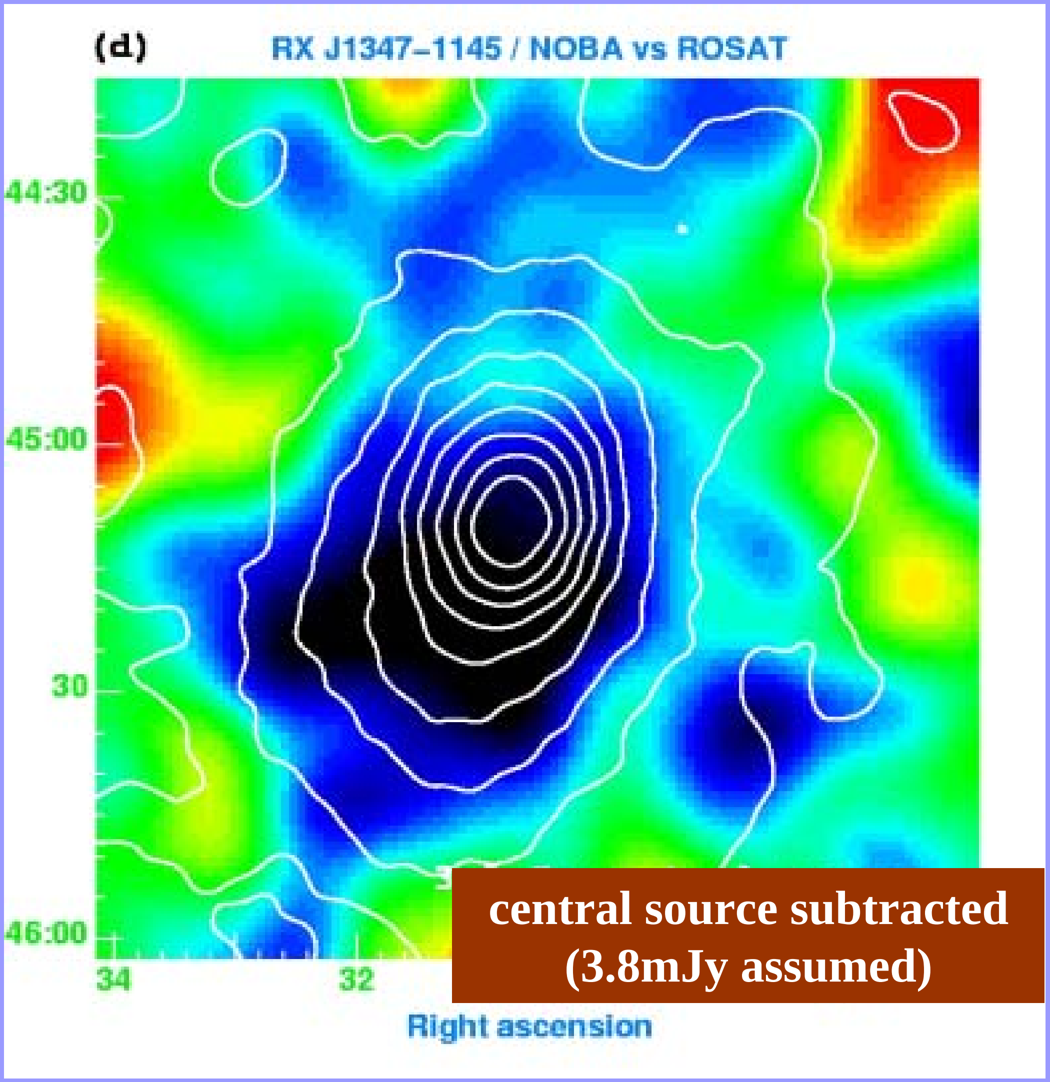


350GHz with SCUBA at J.C.Maxwell telescope on May 30, 31, 1998

central point source with ～ 3.5mJy + extended SZ profile

Komatsu et al. ApJ 516(1998)L1

SZ map of RXJ1347-1145 at 150 GHz



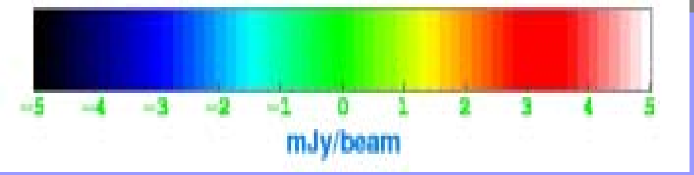
central source subtracted (3.8mJy assumed)

Komatsu et al. PASJ 53(2001)57

150GHz with NOBA (Nobeyama Bolometer Array) at Nobeyama 45m telescope in March, April, 1999 and February 2000

σ_{FWHM}=13"

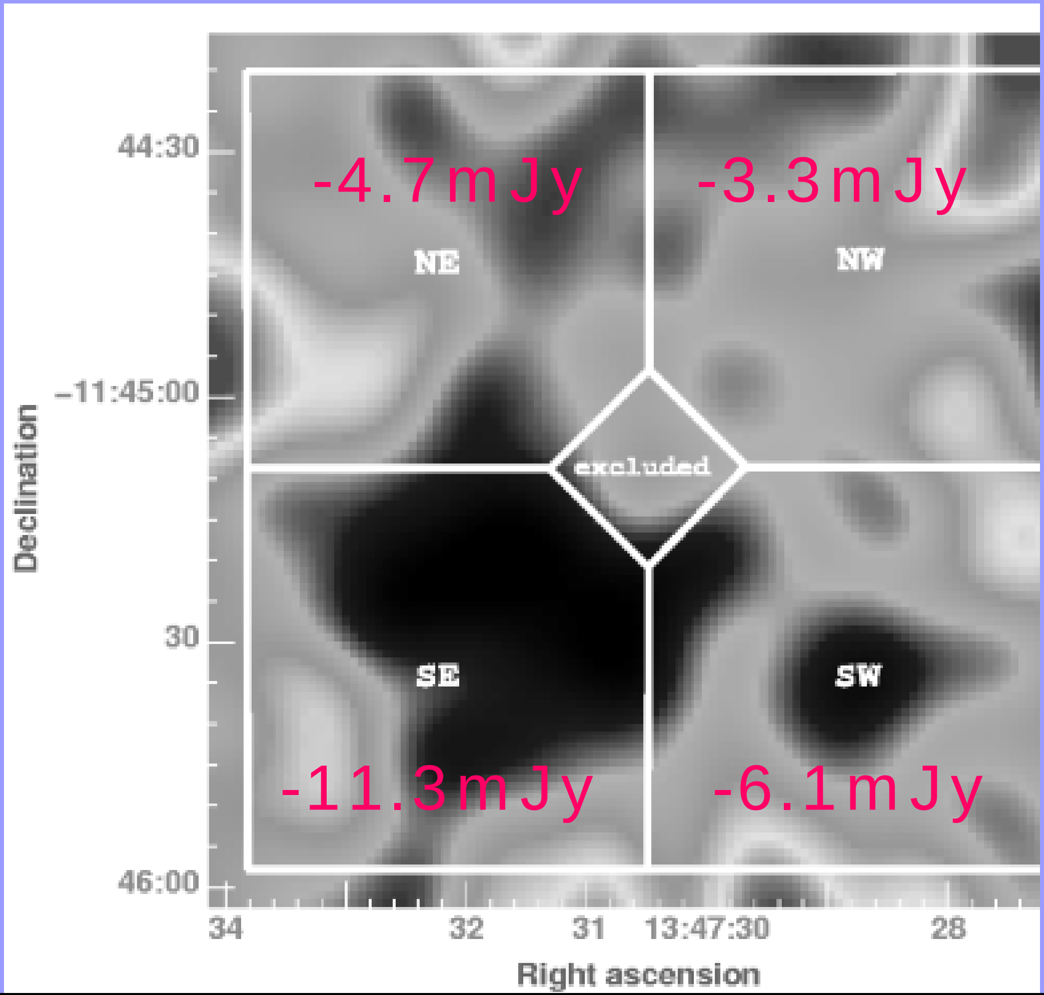
- Globally similar morphology to the X-ray image
- Substructure in the South-East direction



Substructure in the 150GHz SZ image

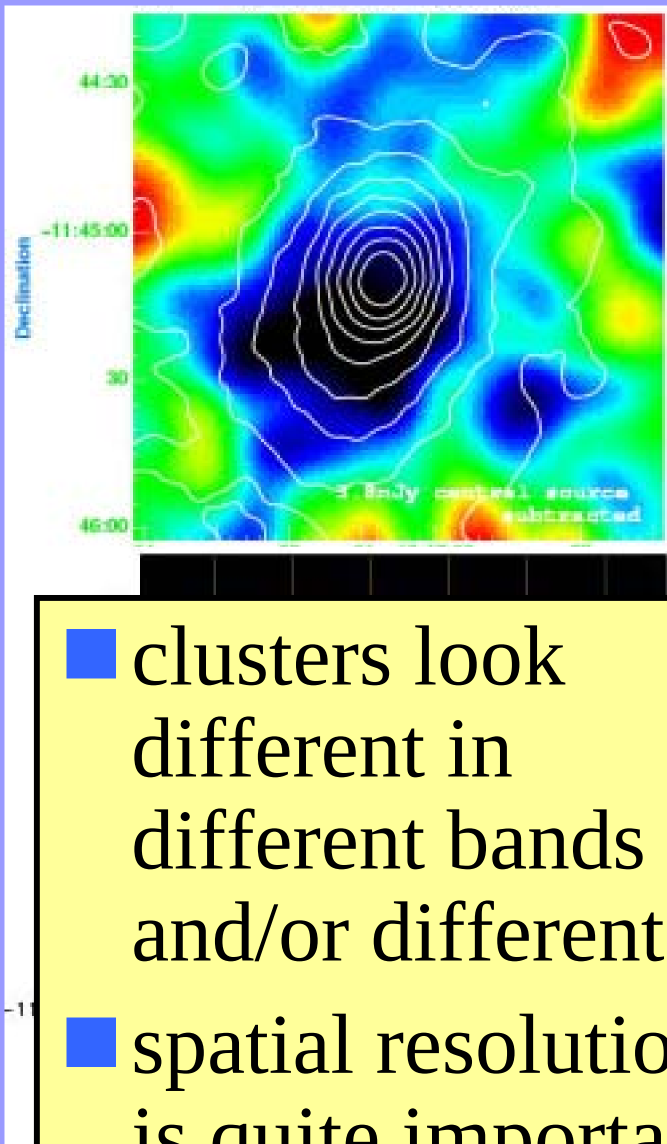
σ=2.0mJy

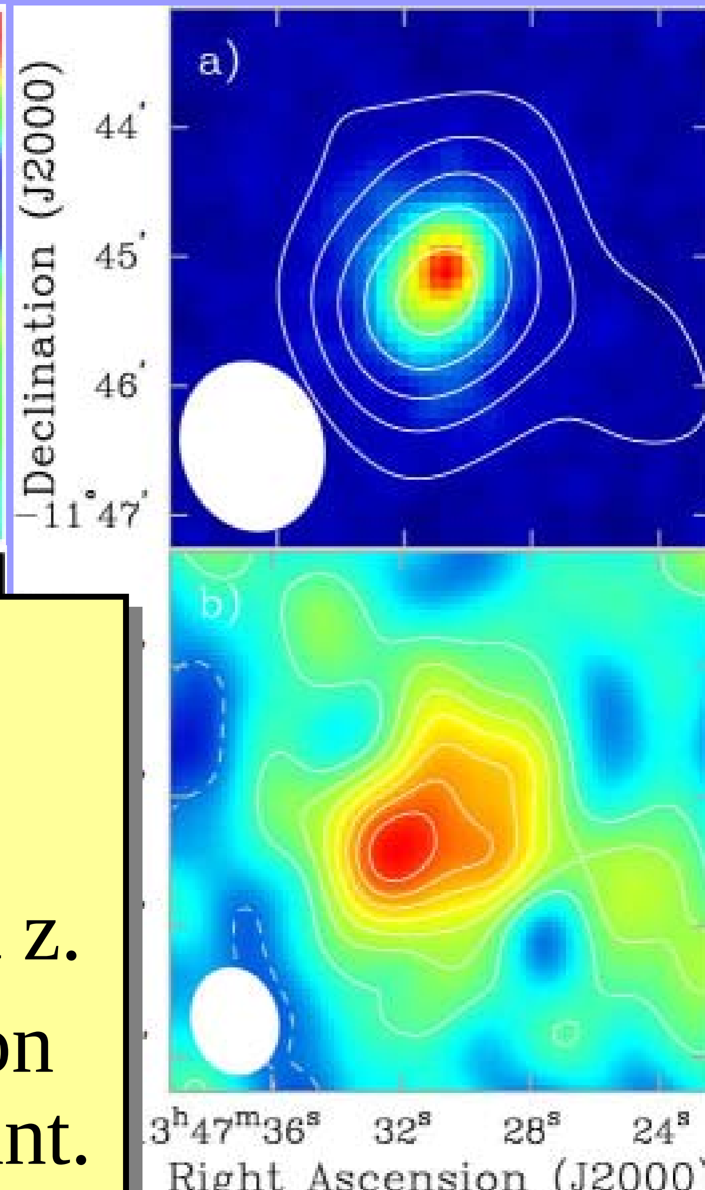
RXJ1347@ 150GHz
Komatsu et al. (2001)



- divided in 4 regions
  - mean observed flux: -6.4±1.0mJy
  - predicted flux: -5.1mJy(9.3keV), -8.8mJy(16.2keV)
- large asymmetry/substructure

Confirmed by Chandra and BIMA observations





- clusters look different in different bands and/or different z.
- spatial resolution is quite important.

RXJ1347-1145

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

Carlstrom et al. (2001)

BIMA@30GHz

40”x50” beam

(10.3mJy point source removed)

Conclusions

- We have developed an accurate model for clustering of ***dark matter halos*** on the light-cone.
  - gravitational nonlinear evolution
  - redshift-space distortion
  - mass-, time-, and scale-dependent bias of halos
  - selection function
- The model can be applied to predicting the clustering of X-ray/SZ-selected clusters, ***provided a good physical model for halo-cluster connection beyond the unrealistic one-to-one correspondence in the last century.***
- ***The goal of the next generation cluster surveys is not precision cosmology*** (***independent*** check/confirmation of the values of cosmological parameters is just boring), ***but is to understand ``what are the clusters of galaxies''***.