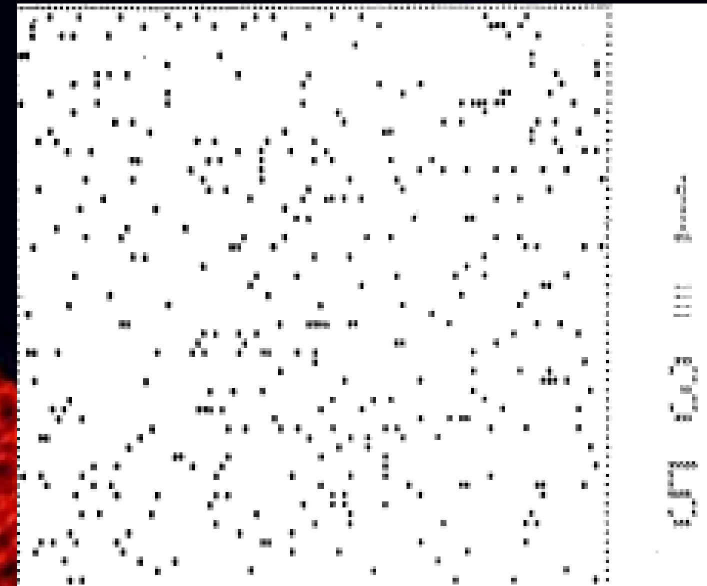
Miyoshi & Kihara (1975)

1/4 century

Evrard et al. (2002)



IAU symposium 216

"Maps of the Cosmos"

July 14, 2003, Sydney, Australia

Simulations of large-scale structure in the new millennium

Yasushi Suto

Department of Physics, University of Tokyo

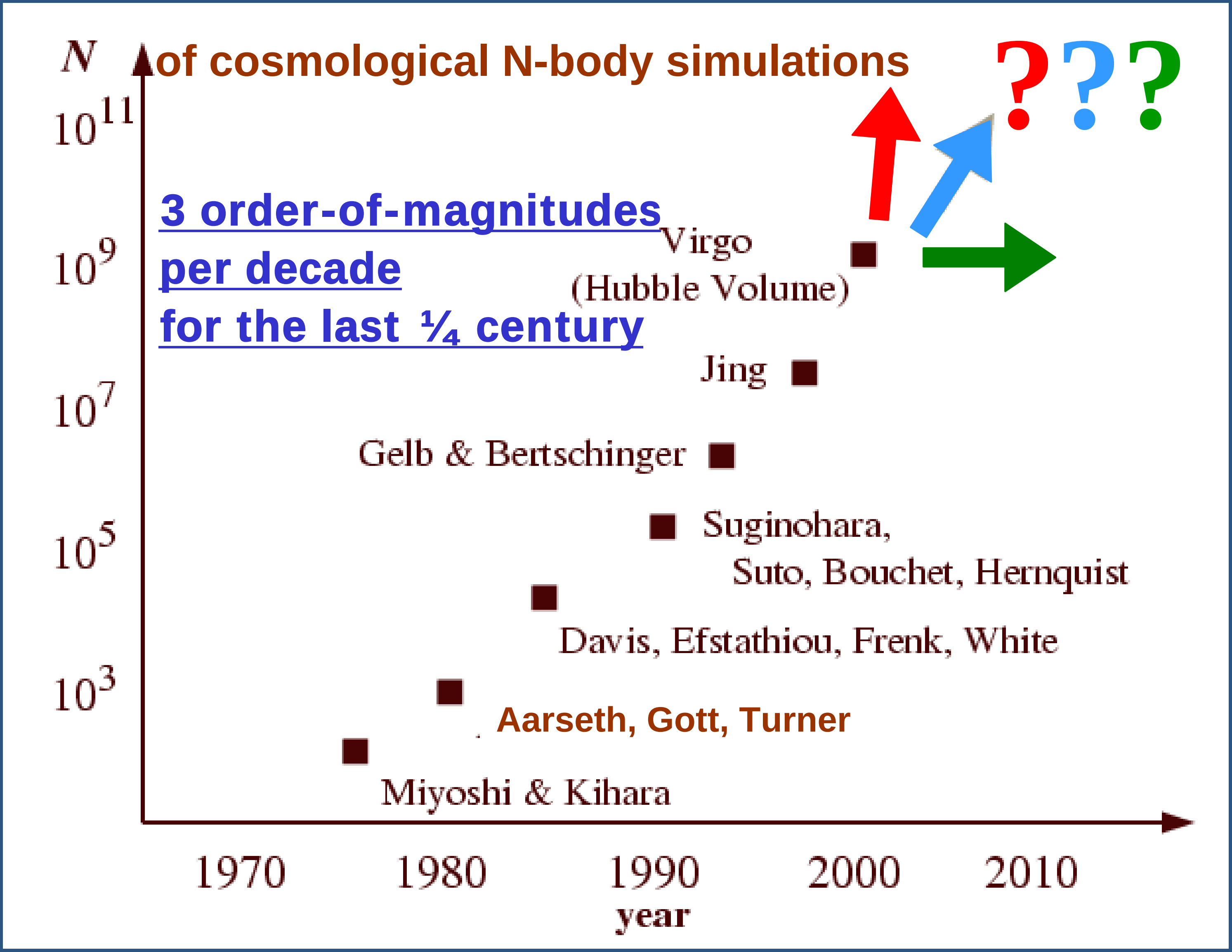
Outline of the talk

- a brief overview of the "evolution of simulations" of large-scale structure
  - **1970s:** describing the nonlinear gravitational evolution of "particles"
  - **1980s:** empirical modeling of galaxy - dark matter connection
  - **1990s:** realistic/accurate/precision description of luminous objects
- unsolved problems in this millennium

Cosmological N-body simulations in the last century

- **Miyoshi & Kihara:** PASJ 27 (1975) 333
  - First N-body simulations of large-scale structure in a comoving, periodic cube, N=400
- **Aarseth, Gott, & Turner :** ApJ 228 (1979) 664
  - in expanding spheres, N=980, 1000, 4000
- **Davis, Efstathiou, Frenk & White:** ApJ 292 (1985) 371
  - P^3M simulations, N=32768, biasing, 2pt & 3pt func
- **Navarro, Frenk & White**: ApJ 462 (1996) 563
  - Universal density profile of dark matter halos
- **Evrard et al. :** ApJ 573 (2002) 7
  - Hubble volume simulations, $N=10^9$, light-cone outputs

Well-known exponential evolution of "N"



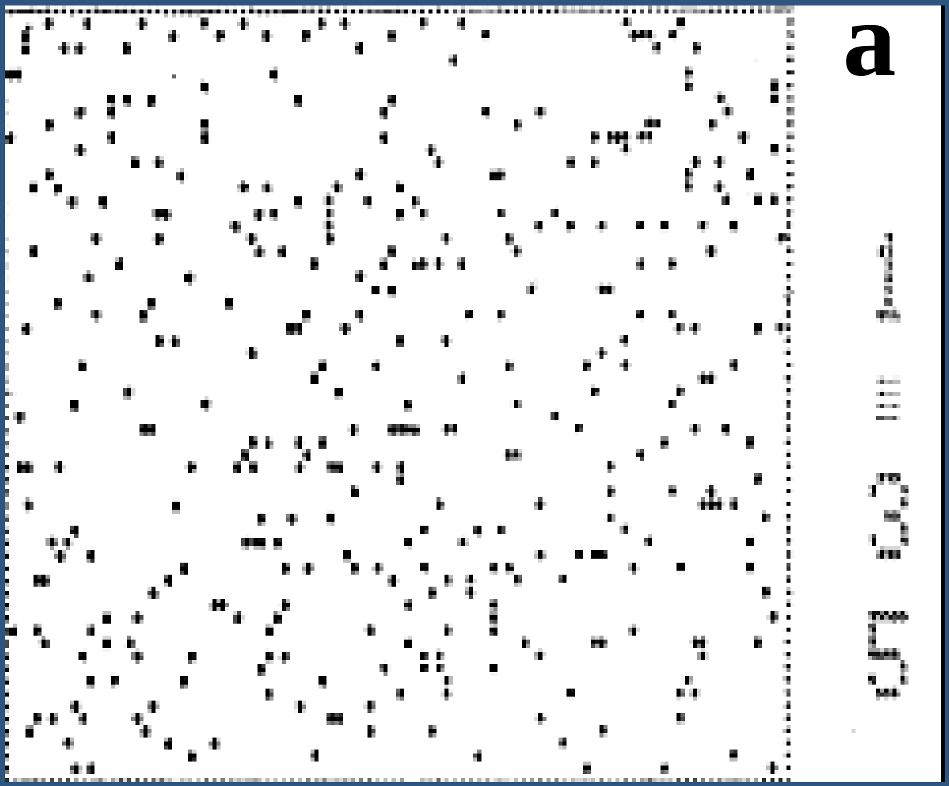
Yoshida (2003)

Evolution of LSS simulations

- **1970s: aiming at understanding nonlinear gravitational clustering in the expanding universe**
  - Simulation particles = galaxies (why not ?)
  - Statistical description of LSS using two-point correlation
  - More physics-oriented than astronomy
- 1980s: predicting galaxy distribution from dark matter simulations
- 1990s: accurate/precision modeling of distribution of luminous objects

The first views of large-scale structure of the universe ***traced by 8***

Gif animation from ADS scans



Miyoshi & Kihara
PASJ 27 (1975) 333

- N=400
- White-noise initial condition
- Comoving coordinates in the Einstein – de Sitter universe
- Periodic boundary condition
- Plotted on line printer papers (probably using “8” to represent particles to maximize the area)

Motivations of Miyoshi & Kihara (1975) : many years ahead in time

As regards the correlation function of the galaxy distribution, main points of interest are the following.

(i) Is the correlation function an inverse power function of the distance? If so, what value do the power index and the characteristic length take?

(ii) How does the correlation function depend on time?

The first problem was analyzed by TOTSUJI and KIHARA (1969). Their results obtained by processing the data of galaxy counts (SHANE and WIRTANEN 1967) are $g(r)=(r_0/r)^s$ with $s=1.75\pm0.05$ and $r_0=(4.4\pm0.6)$ Mpc. PEEBLES (1974) also obtained the index $s=1.77$, mainly working with the same data. The second problem cannot be solved with the observational data, and the purpose of the present paper is to obtain some information by computer simulations.

- Does the correlation function of "galaxies" naturally approach a power-law form as discovered by Totsuji & Kihara (1969) ?
- What are the power-law index and the characteristic length predicted by simulations ?
- Evolution of the correlation function ?

The first movie of cosmological N-body simulations

a (scale factor)

- N=1000 (400Kbyte memory)
- White-noise initial condition
- Expanding sphere in the Einstein – de Sitter universe
- a=1 to 30

Courtesy of Ed Turner (Princeton):
digitized from his old 16mm movie film (2min30sec)
on the basis of Aarseth, Gott, & Turner (1979)

A significantly improved movie

does not always guarantee the

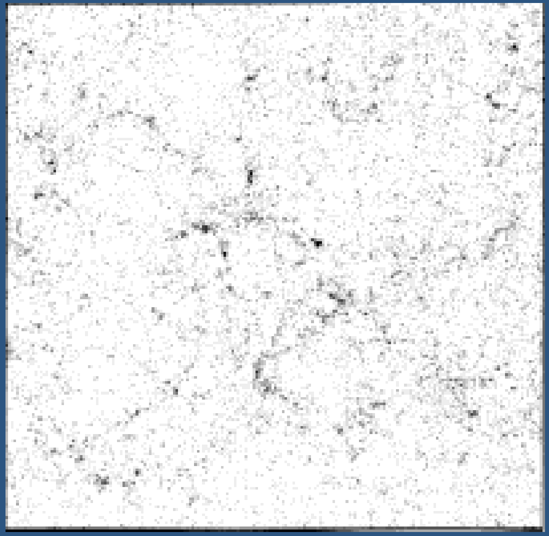
better scientific outcome !

Evolution of LSS simulations

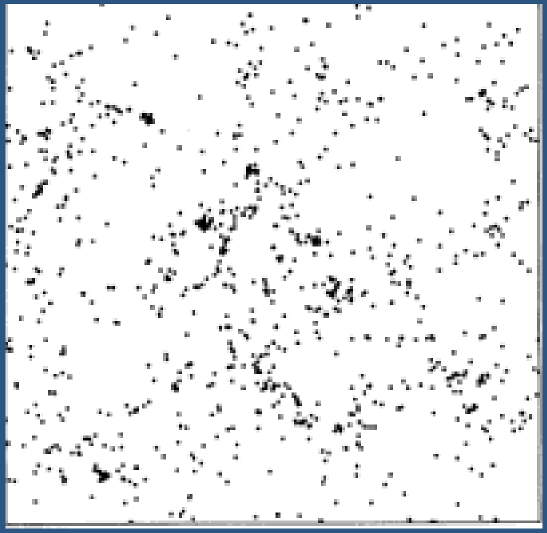
- 1970s: aiming at understanding nonlinear gravitational clustering in the expanding universe
- **1980s: predicting galaxy distribution from dark matter simulations**
  - Toward more realistic predictions
  - Simulation particles ≠ galaxies
  - i.e., galaxy biasing (why not ?)
  - Systematics like redshift-space distortion
  - Calibrating analytic formulae for nonlinear power spectrum and halo mass function
- 1990s: accurate/precision modeling of distribution of luminous objects

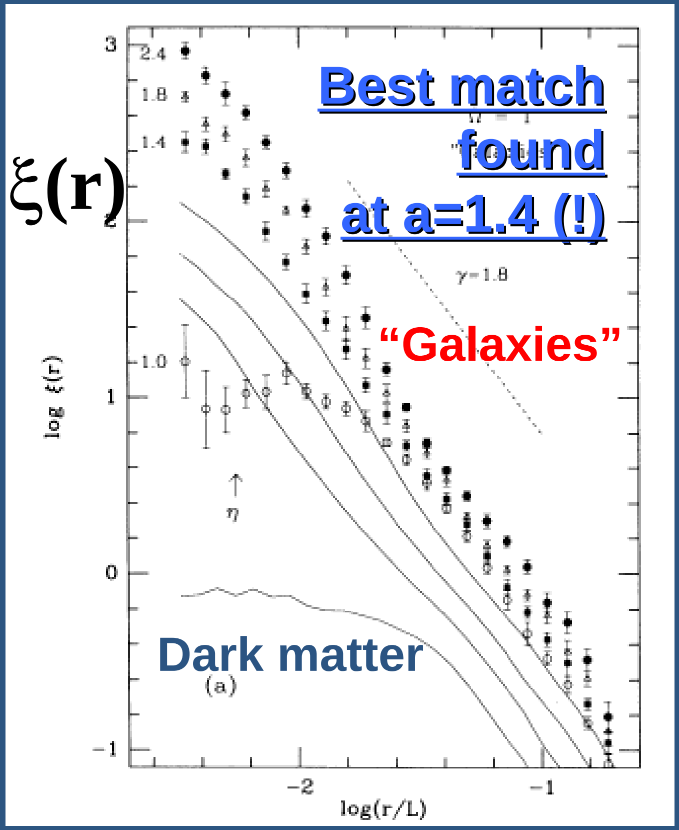
Biased galaxy formation

CDM (Ω=1)



"Galaxies" (2.5σ peaks)





Davis, Efstathiou, Frenk & White (1985)

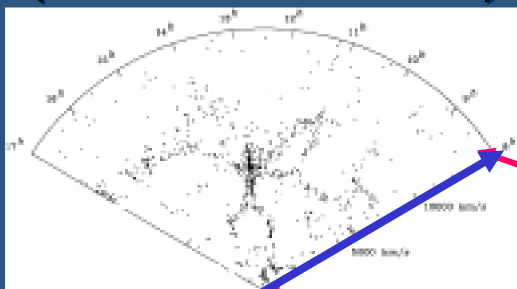
- Many seminal results were derived from their simulations evolved from a=1 up to **a=1.4** !
- ***Illustrates that*** the most important is not the quality of simulations but those who interpret.

Evolution of LSS simulations

- 1970s: aiming at understanding nonlinear gravitational clustering in the expanding universe
- 1980s: predicting galaxy distribution from dark matter simulations
- **1990s: accurate/precision modeling of distribution of luminous objects**
  - Very accurate fitting formulae for nonlinear power spectrum, redshift-space distortion, halo mass functions, halo biasing and density profile of dark matter halos
    - **accurate model predictions are now possible analytically even without simulations at all !**
  - Reasonably good hydrodynamical simulations
  - Combination of N-body merging trees with semi-analytic model of galaxy formation

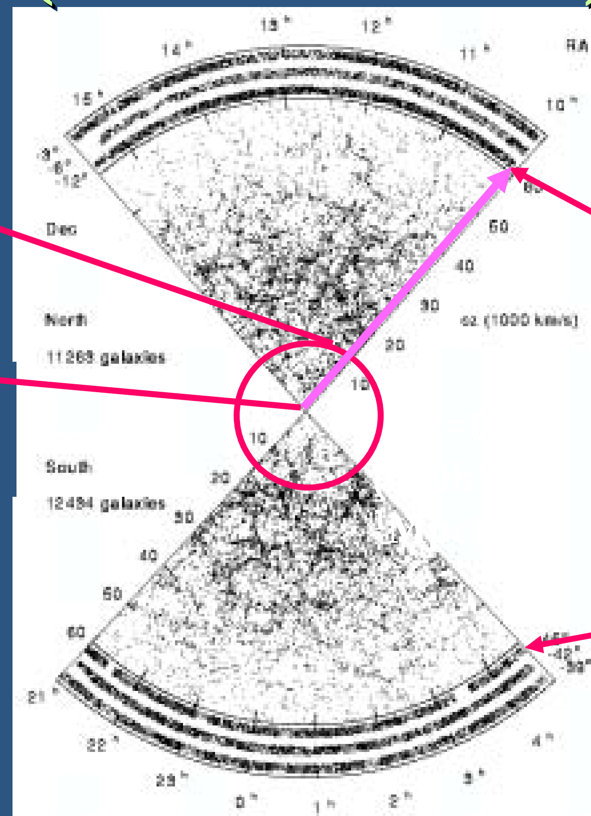
Clustering of luminous objects on the light-cone

1986 (local universe)



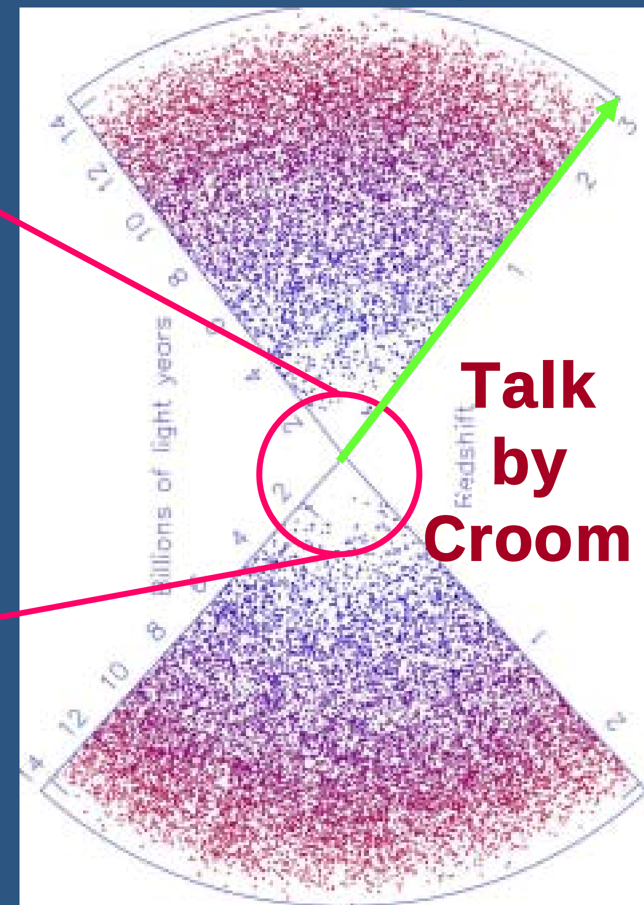
CfA redshift survey: de Lapparent et al.(1986)

1996 (shallow universe)



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

2001 (universe on the light-cone)



Talk by Croom

2dF QSO survey: http://www.2dfquasar.org

- Evolution along the light-cone is directly accessible now !

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

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

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

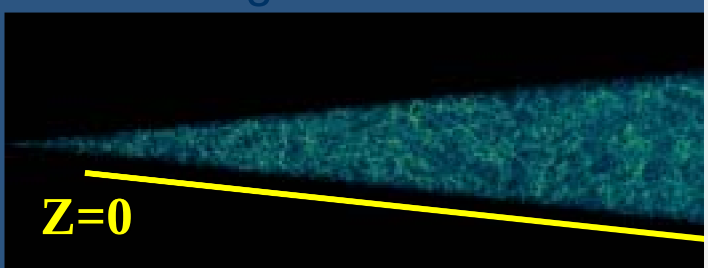
selection function

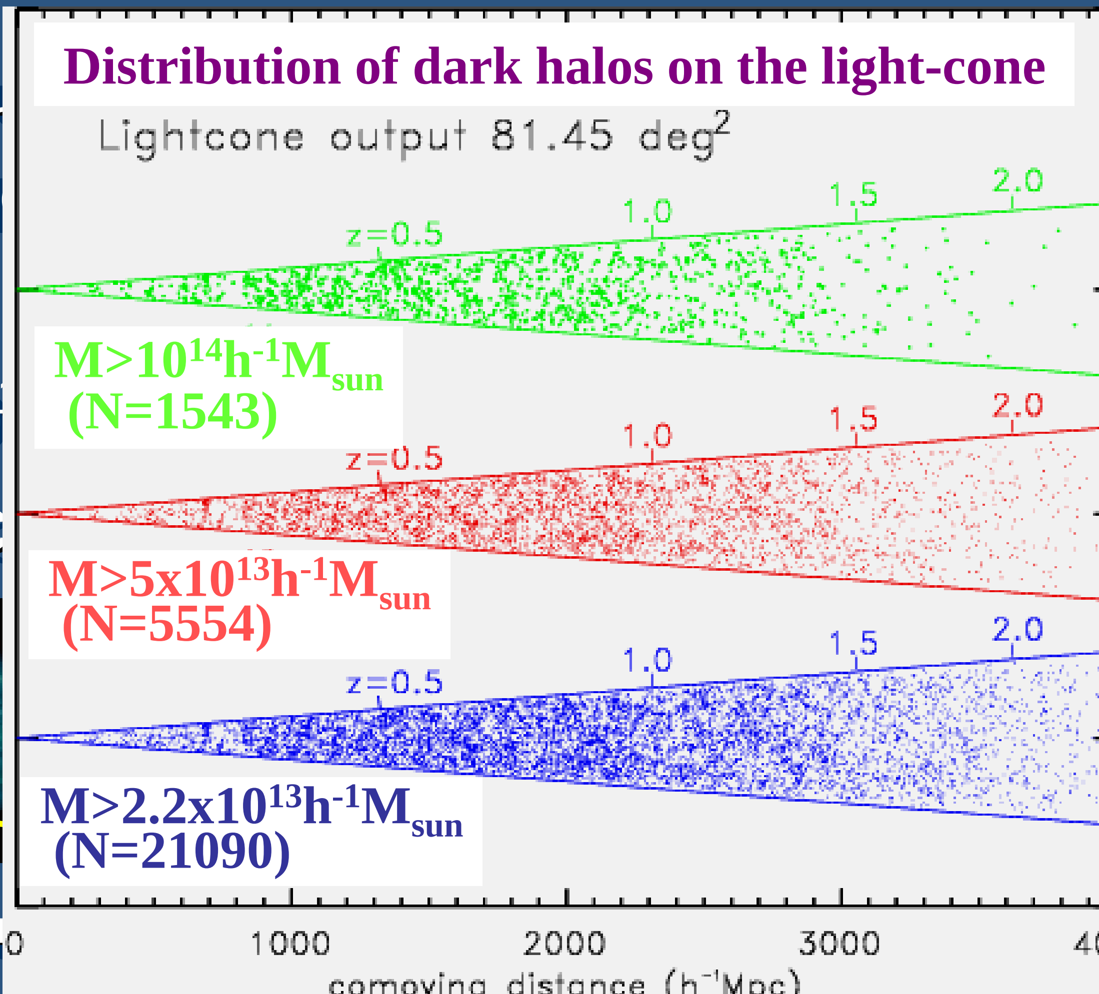
mean number density

Hamana, Colombi & Suto (2001)

Comparison of the semi-analytic light-cone predictions against the light-cone output of the Hubble volume ΛCDM simulation

- P^3M N-body simu
- $N=10^9$ (!) particl
- ΛCDM: $\Omega_m=0.3$,
- $m_{particle}=2.2\times10$
- $\varepsilon_{grav}=0.1h^{-1}$Mpc

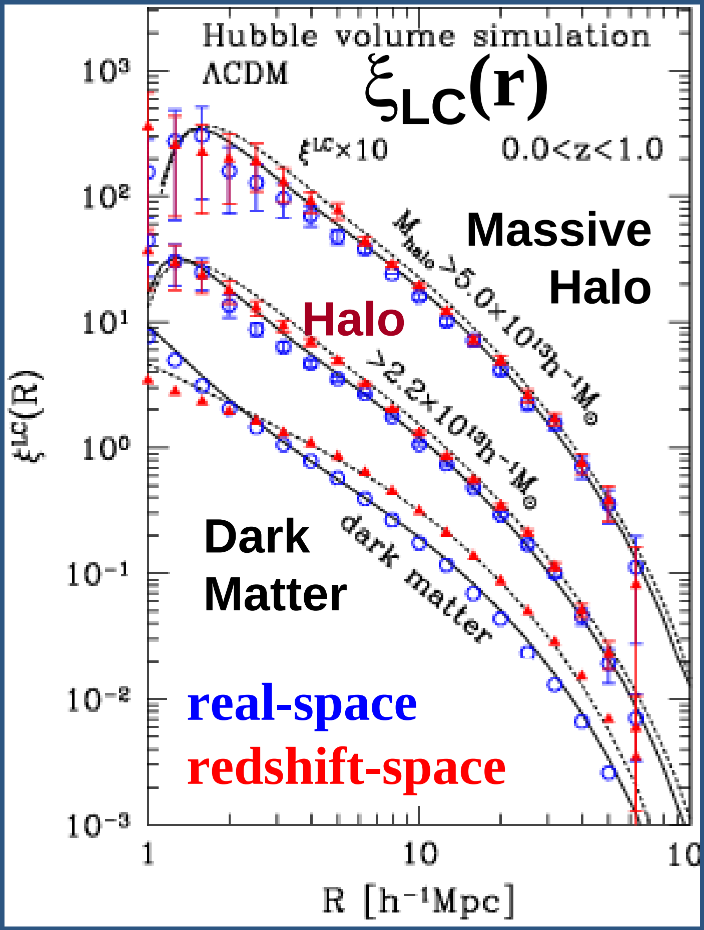




http://www.physics.isa.umich.edu/hubble-volume/ lightcones.htm

Hamana, Yoshida, Suto & Evrard (2001)

2pt correlation functions of dark matter and halos on the light-cone



Hamana, Colombi & Suto (2001)
Hamana et al. (2001)

- Accurate fitting formulae exist for
  - Nonlinear power spectrum
  - Redshift-space distortion
  - Dark halo biasing

(Peacock & Dodds 1996; Jing 1998)

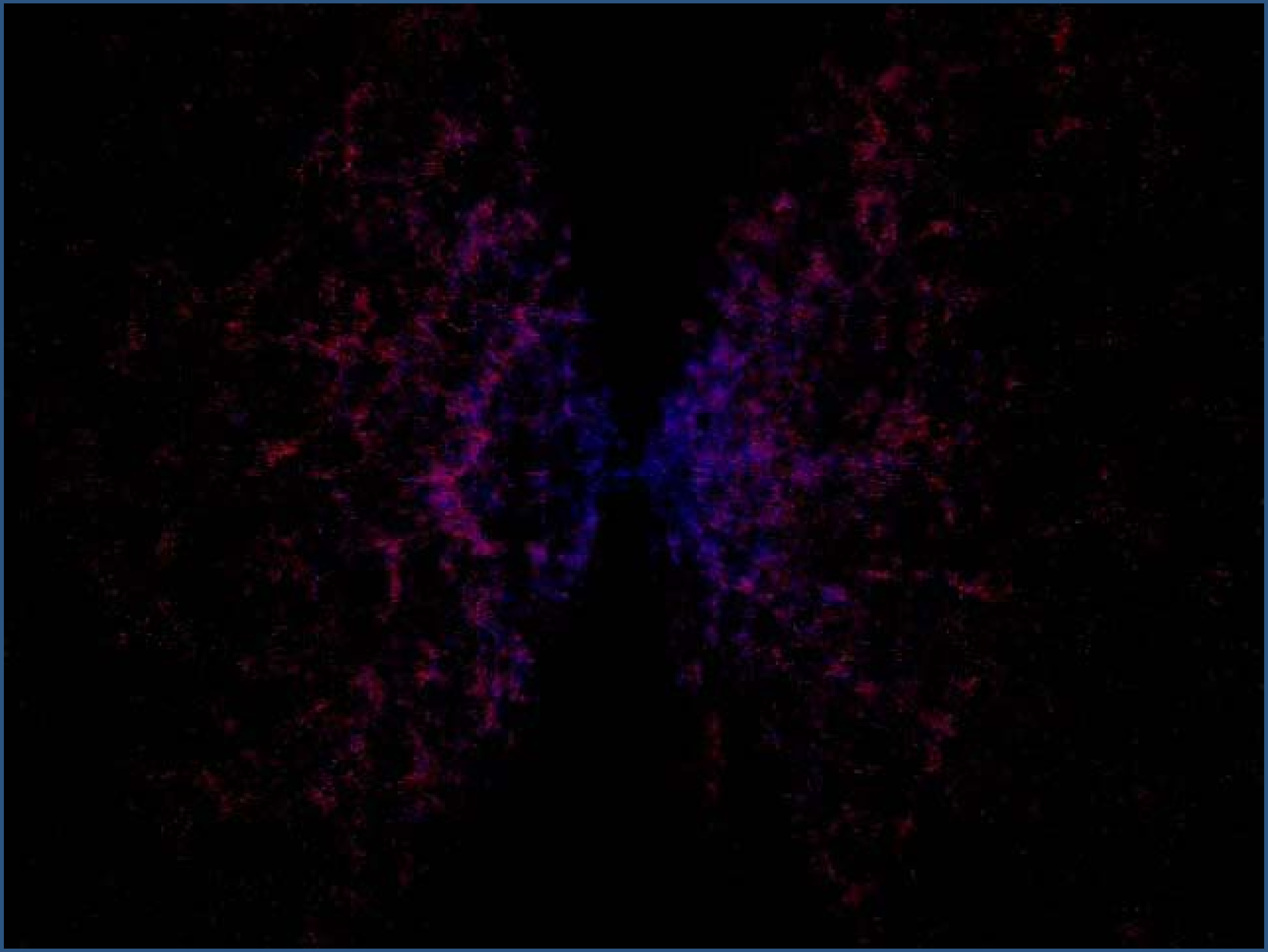
- Light-cone averaging procedure also works fine (Mataresse et al. 1997; Yamamoto & Suto 1998)
- Simulations are not any more needed for 2-pt functions

The latest slice of the universe: Tour of SDSS Data Release 1

c.f., Talk by Alex, later in this session http://www.sdss.org/dr1/

from Japanese TV program "Science ZERO" (NHK)

SDSS DR1 galaxies: morphology dependent clustering



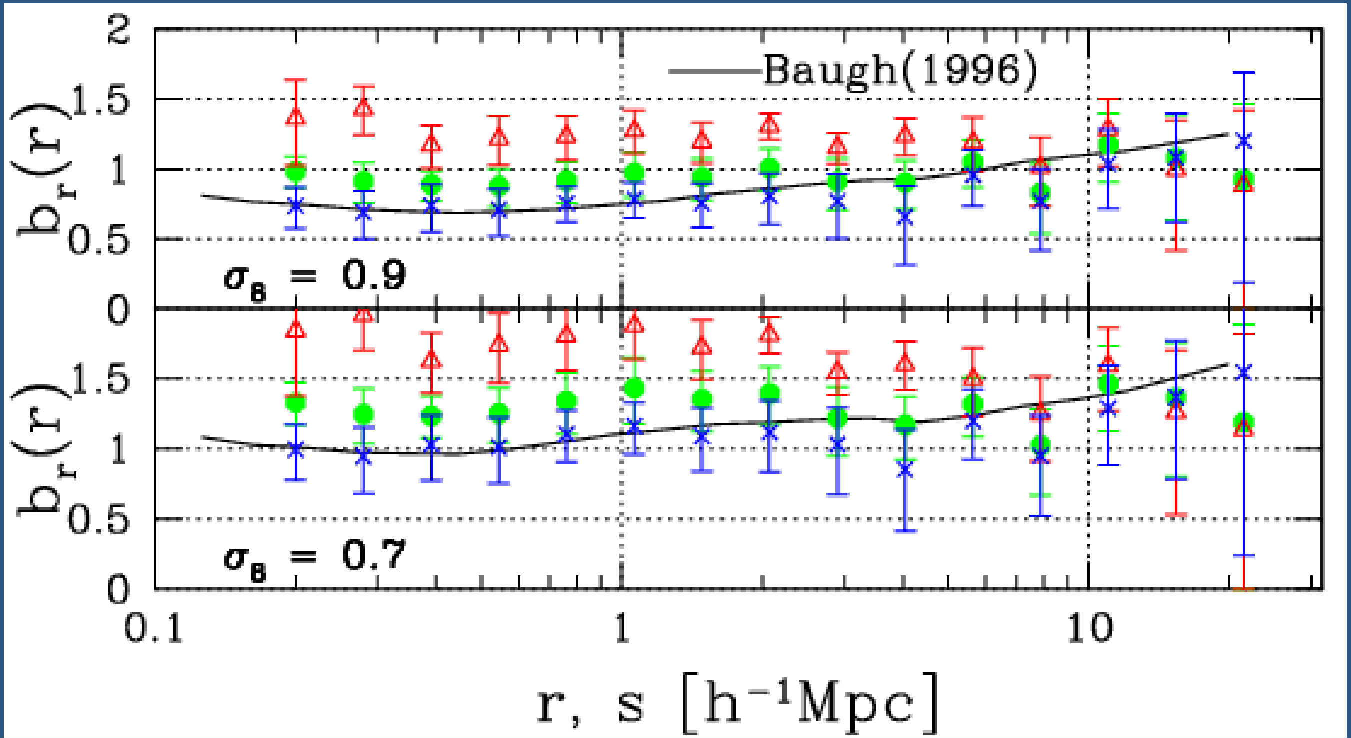
- **Late-types in blue**
- **Early-types in red**
- Density-morphology relation is barely visible

from Japanese TV program “Science ZERO” (NHK)

Morphology-dependent SDSS galaxy bias

early-type
average
late-type

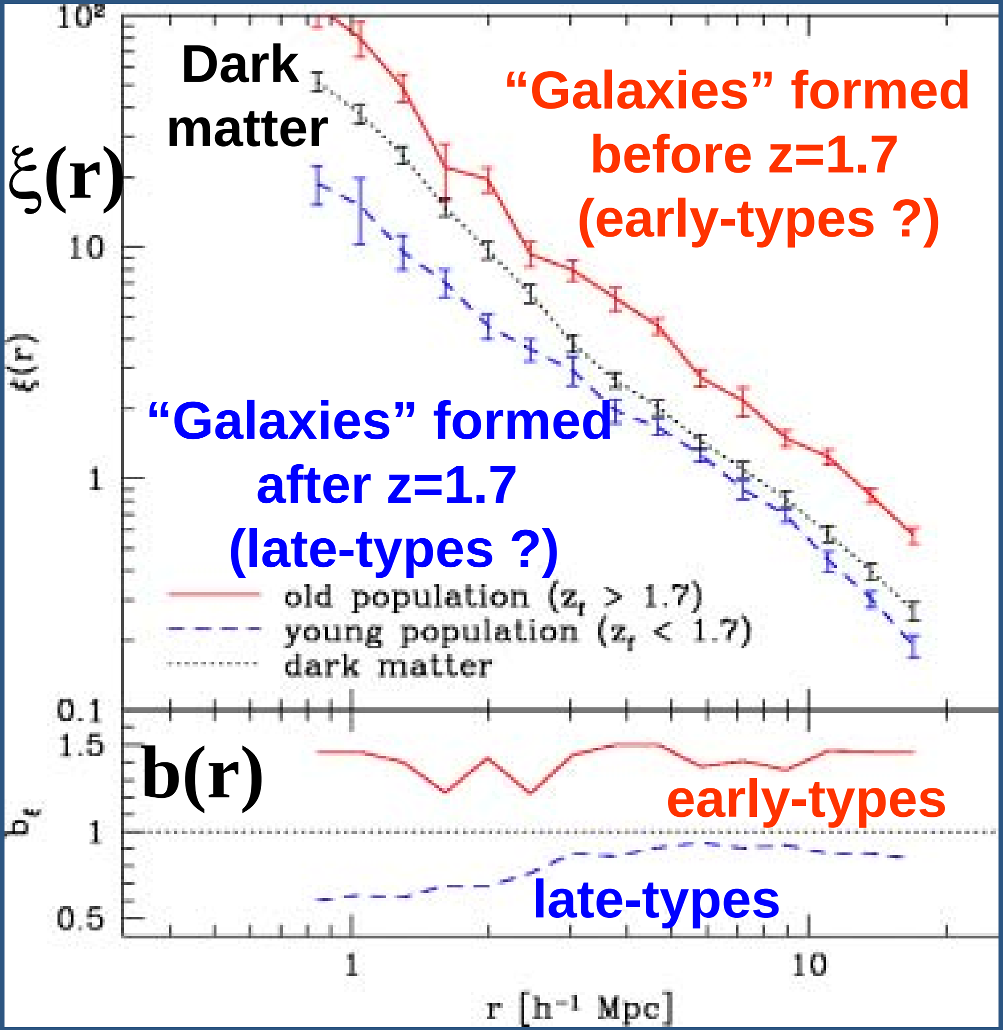
$$b \equiv \sqrt{\frac{\xi(galaxies)}{\xi(\Lambda CDM)}}$$



- Galaxy bias is fairly scale-independent
- **Clear morphology dependence:** b=1.2〜1.5 for "early"-types and b=0.7〜0.9 for "late"-types with respect to ΛCDM with σ_8=0.9 (computed semi-analytically using the light-cone average described before)

Kayo, Suto, Fukugita, Nakamura, et al. (2003)

Previous predictions from SPH simulations with “galaxy” formation



- Simulated “galaxies” formed earlier are more strongly biased
- Recently formed galaxies preferentially avoid high-density regions
- Quite consistent with the morphology-dependent galaxy bias derived from the recent SDSS DR1 !

Yoshikawa, Taruya, Jing & Suto (2001)

Large-scale structure traced by missing baryons

$(75h^{-1}\mathrm{Mpc})^3$ box

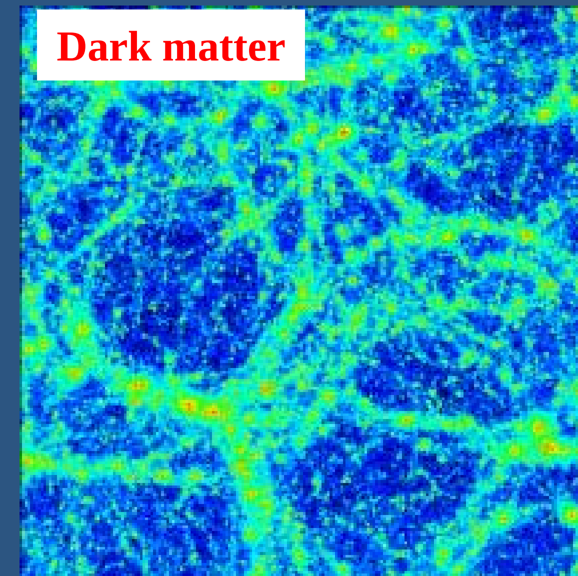
ΛCDM SPH @ z=0

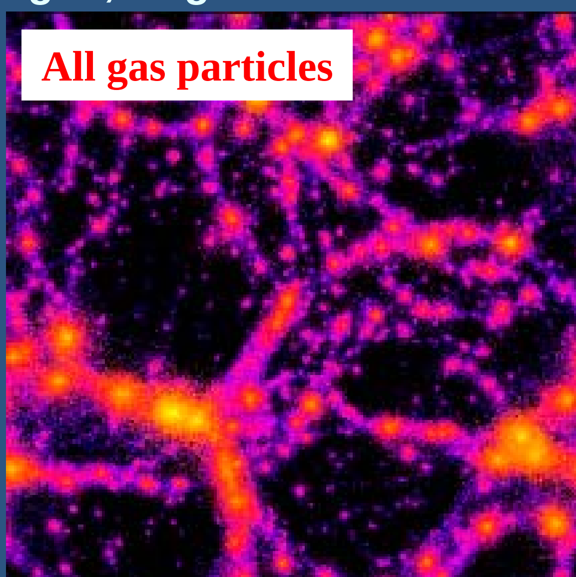
$N=128^3$:DM

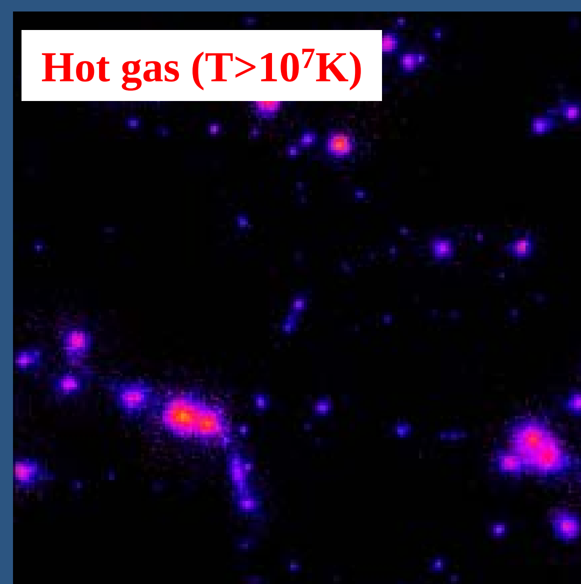
$N=128^3$:gas

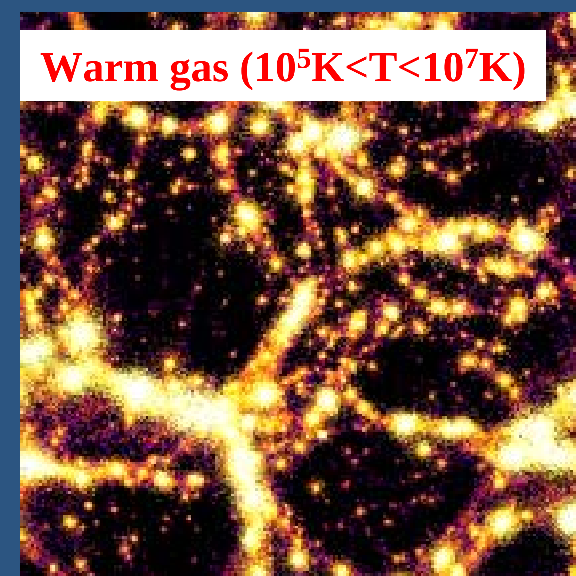
(Yoshikawa et al. 2001)

c.f., “Cosmic baryon budget”
(Fukugita, Hogan & Peebles 1998)





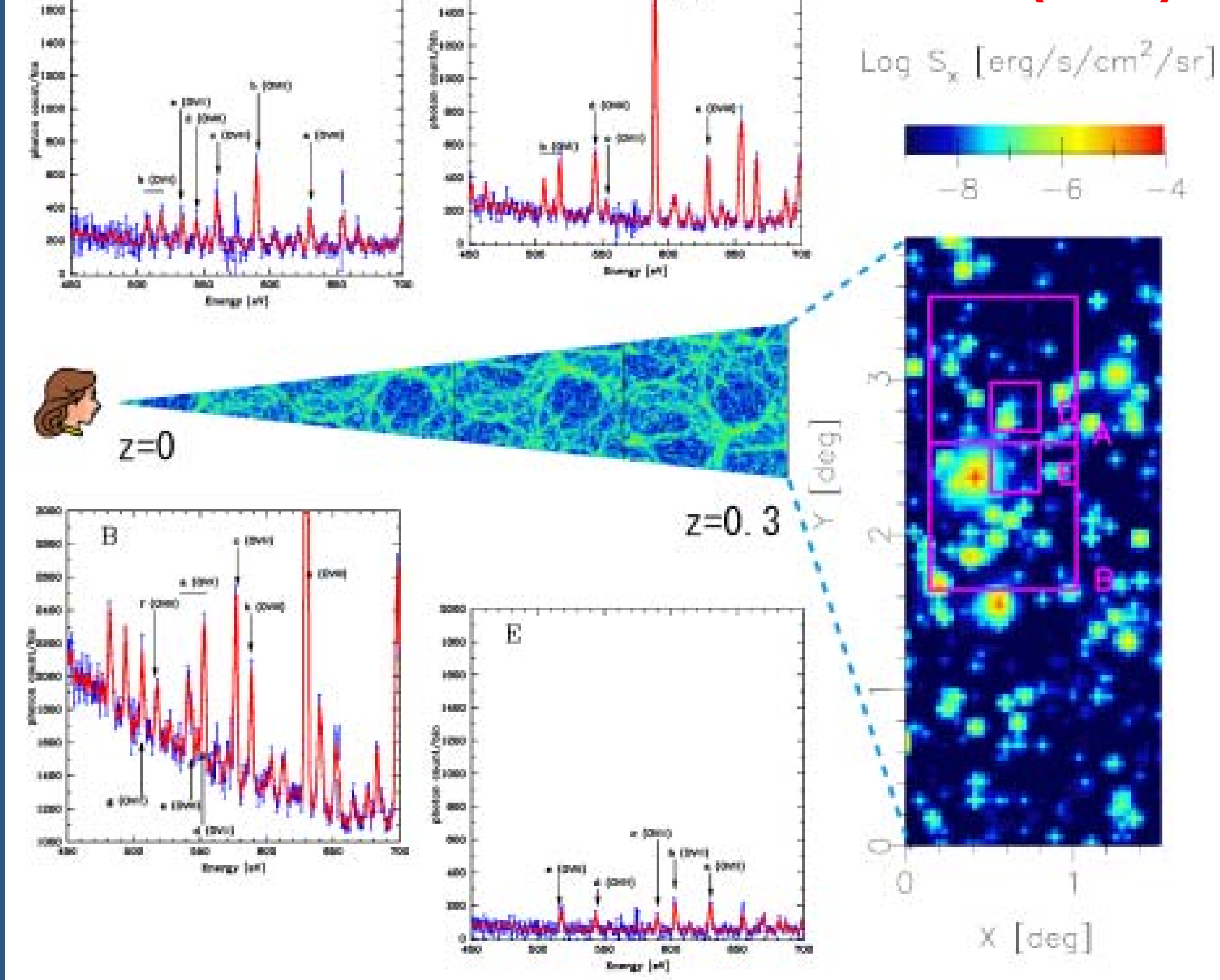




Warm/Hot Intergalactic Medium ? (Stay tuned to talk by Dave on Wednesday)

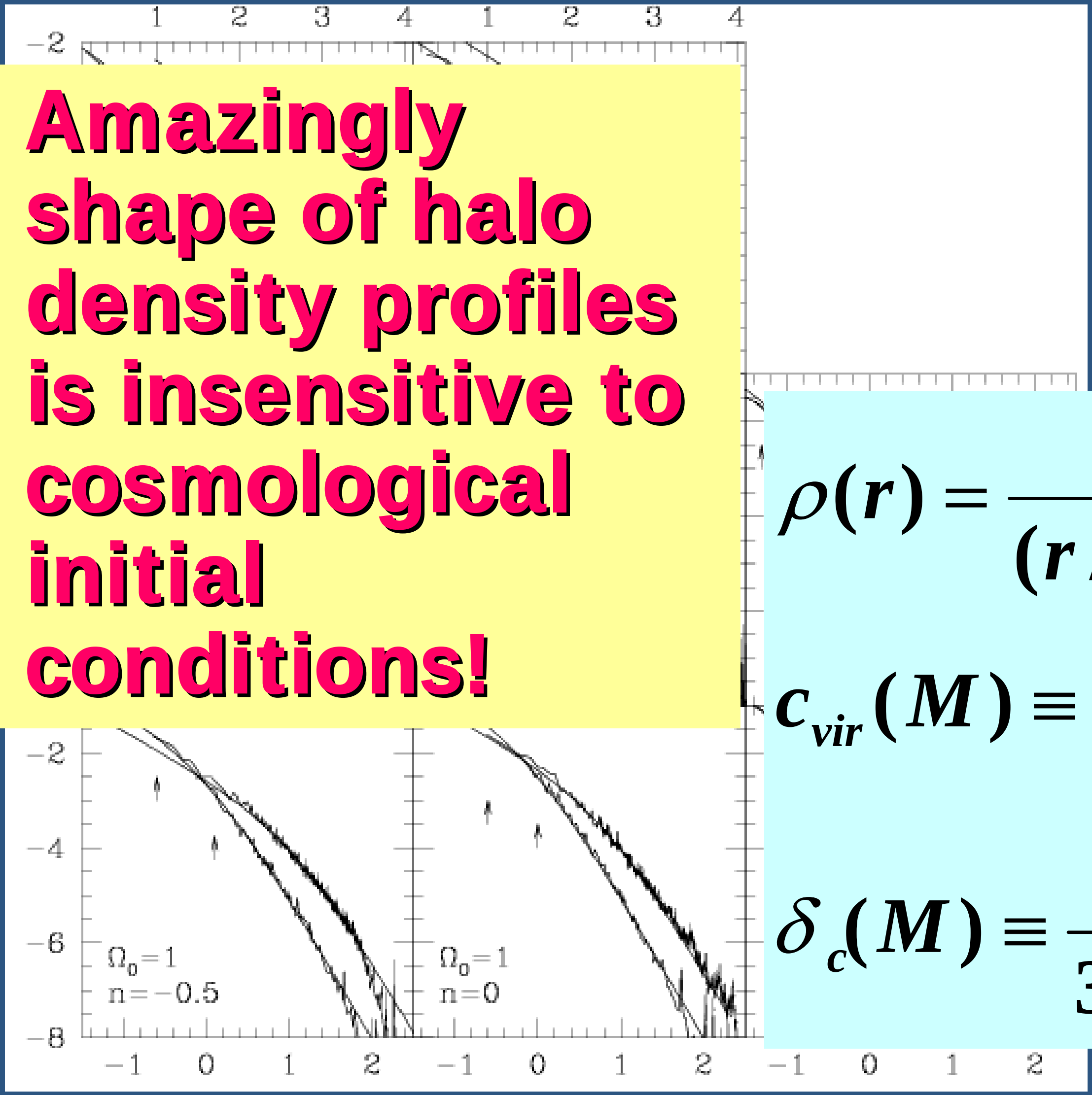
Feasibility of dedicated X-ray mission to search for missing baryons via Oxygen emission lines

astro-ph/0303281
PASJ(2003) October issue, in press



Univ of Tokyo:
K. Yoshikawa
Y.Suto
ISAS:
N. Yamasaki
K. Mitsuda
Tokyo Metropolitan Univ.:
T. Ohashi
Nagoya Univ.:
Y. Tawara
A. Furuzawa

NFW universal density profile



log(radius)

- **Amazingly 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

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

Density profile of collisionless CDM halos: still confusing

High-resolution simulations

universal central cusp $\propto r^{-1\sim-1.5}$

Navarro, Frenk & White (1996)
Fukushige & Makino (1997, 2001)
Moore et al. (1998)
Jing & Suto (2000)

Theory

Central cusp or softened core ?
Dependent on initial condition ?

Syer & White (1998), Weinberg & Katz (2002)

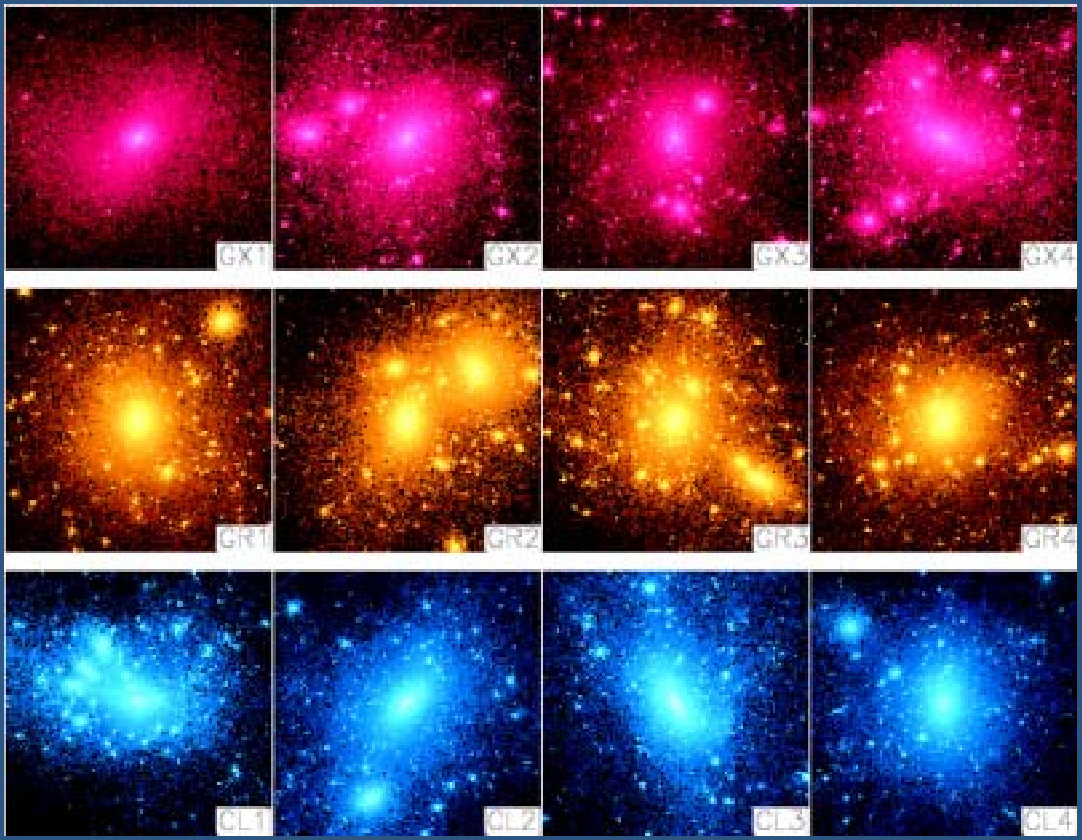
Observations

Core from dwarf galaxies
Cusp from lensing

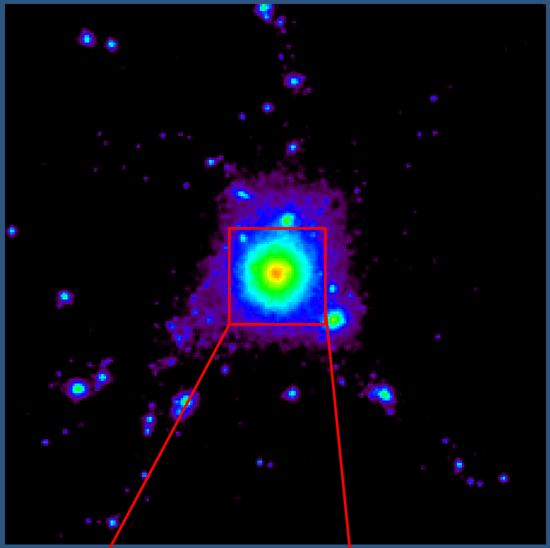
Moore et al. (1999), de Blok et al. (2000)
Salucci & Burkert (2000)
Oguri (2003), Oguri, Lee & Suto (2003)

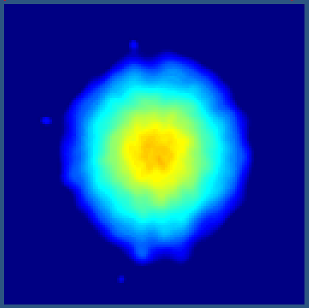
Are Dark Halos Spherical ?

Collisionless CDM: NO



Jing & Suto (2000)



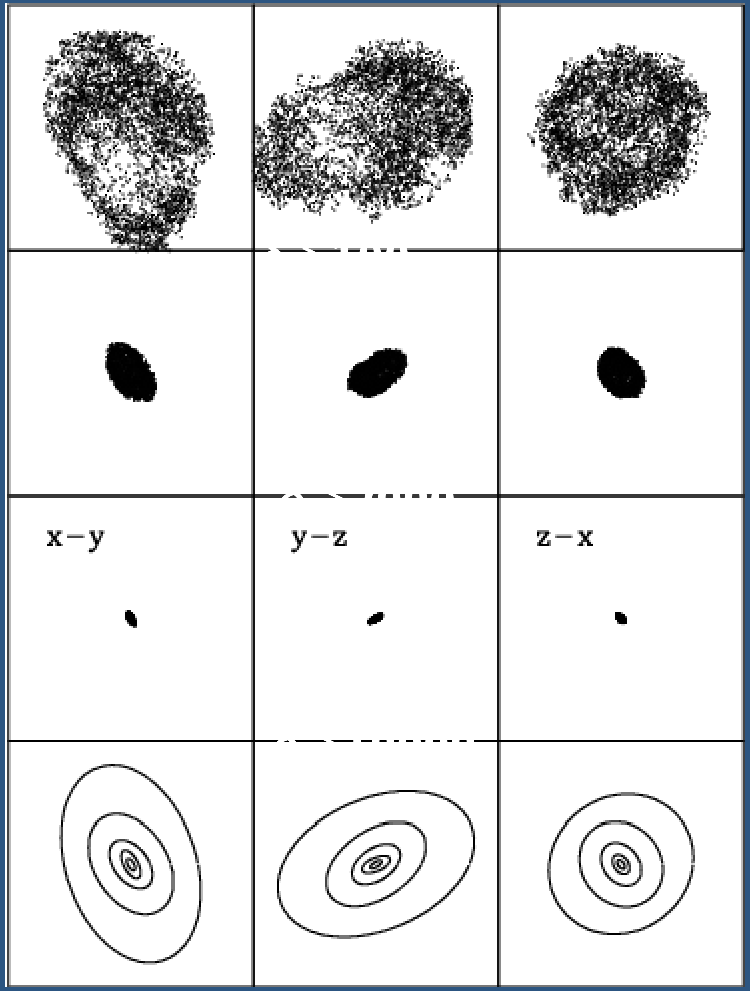


Yoshida et al. (2000)

Collisional DM: YES

An improved model for dark matter halo: triaxial universal density profile

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, ApJ, 574 (2002) 538

- Non-spherical effects have several important implications for X-ray, Sunyaev-Zel'dovich, and lensing observations

Unsolved issues for LSS simulations

- **Clustering:**
  - Higher-order clustering statistics beyond 2pt correlation
  - evolution of bias: “galaxies” at higher redshifts

    (c.f., talk by Nagamine)
- **Halo density profile:**
  - Consistent picture for the density profile from theory, observations and simulations ?
  - Non-spherical modeling and substructure
- **From dark halos to luminous objects:**
  - Criteria of formation of luminous objects
  - Non-gravitational effects inside dark halos: cooling and heating, star/galaxy formation, preheating, supernova feedback, etc. **(c.f., the next talk by Steinmetz)**

Conclusions

- **Aim of simulations**
  - Repeat/improve simulations extensively to such an extent that those numerical experiments are not needed any more to understand the underlying physics (Dai-ichiro Sugimoto, the father of GRAPE)
- **Historical lesson that I learned**
  - Good science favors the prepared mind, not the largest simulation at the time (even though the latter is sometimes helpful)