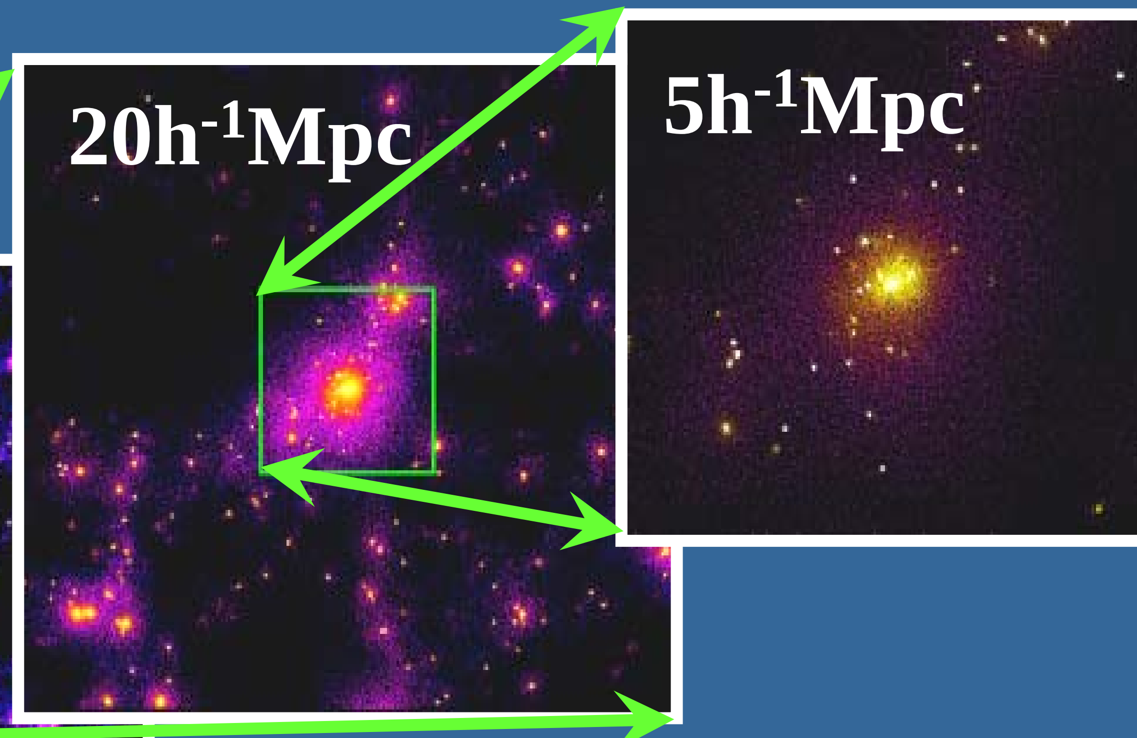
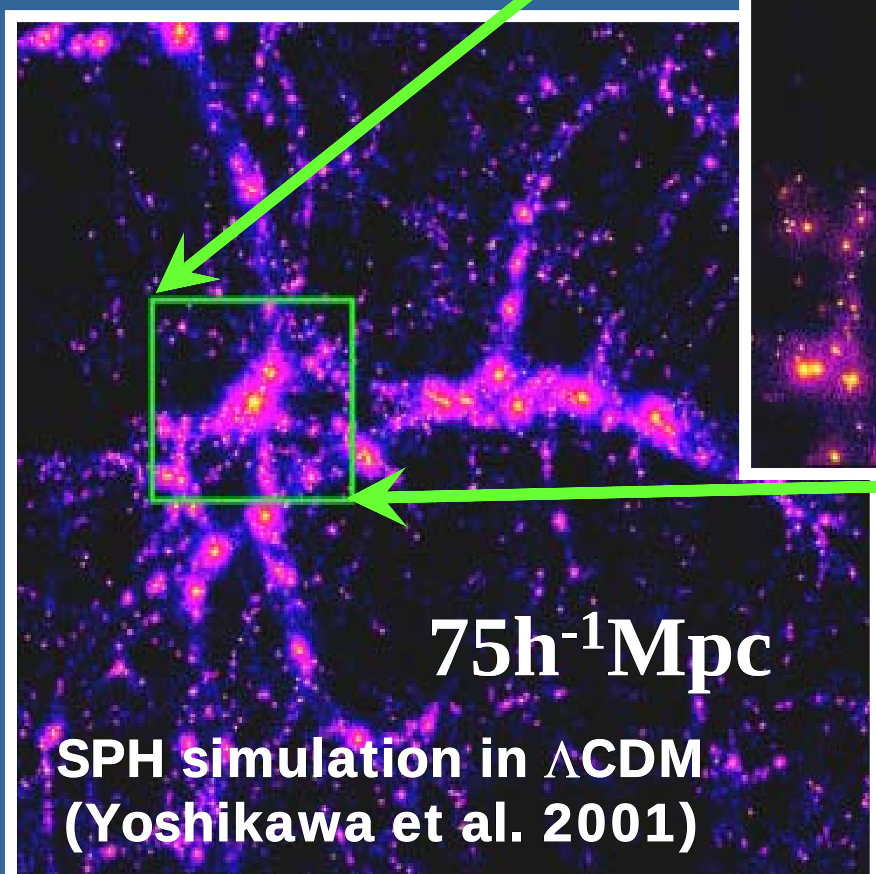
Looking into CDM predictions: from large- to small-scale structures





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October 2, 2003, Kashiwa, Japan

Outline of the talk

1. Convergence of cosmological N-body simulations
2. Clustering of the 2dF and the SDSS galaxies
3. Density profiles of dark matter halos
4. Estimate of the value of σ_8 from cluster abundances
5. Searching for cosmic missing baryon via oxygen emission lines (DIOS: Diffuse Intergalactic Oxygen Surveyor)

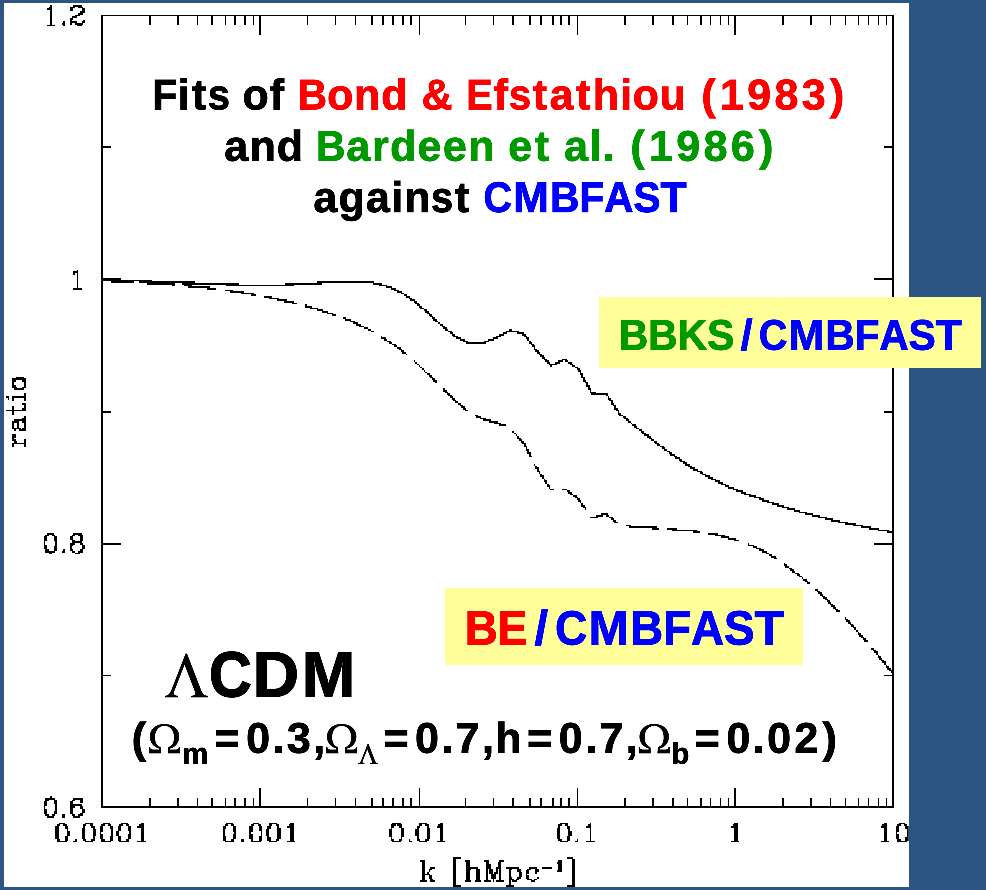
Part 1:

Convergence of cosmological

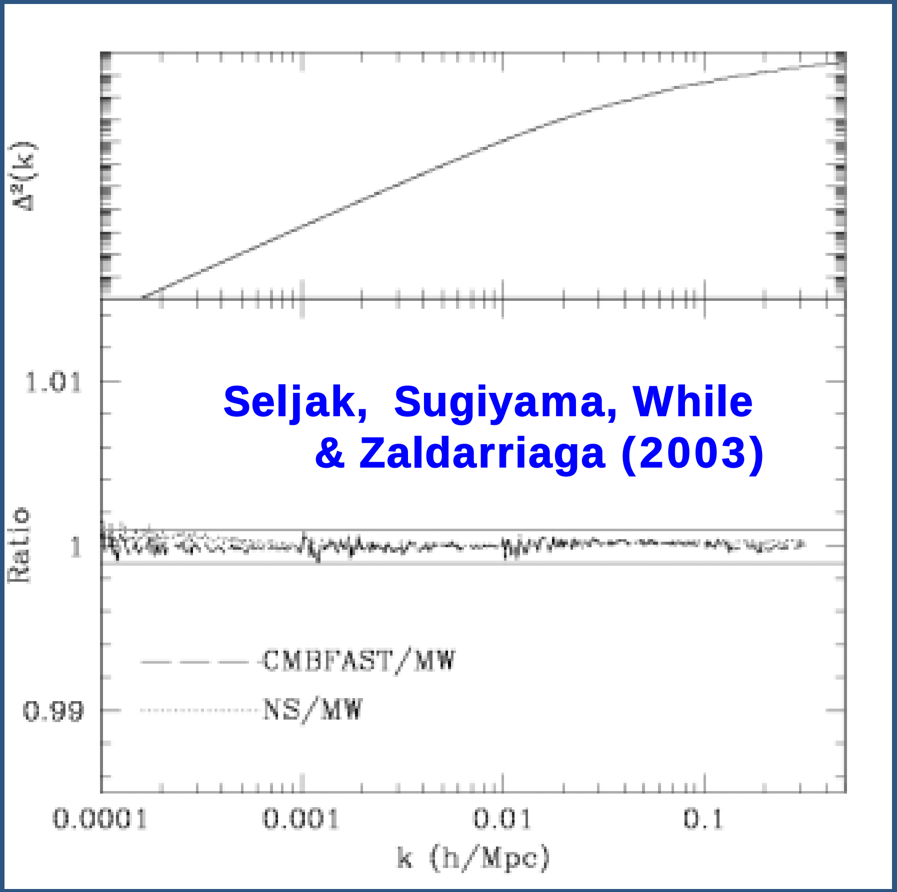
N-body simulations

CDM transfer function

Comparison of T(k)



Boltzmann codes

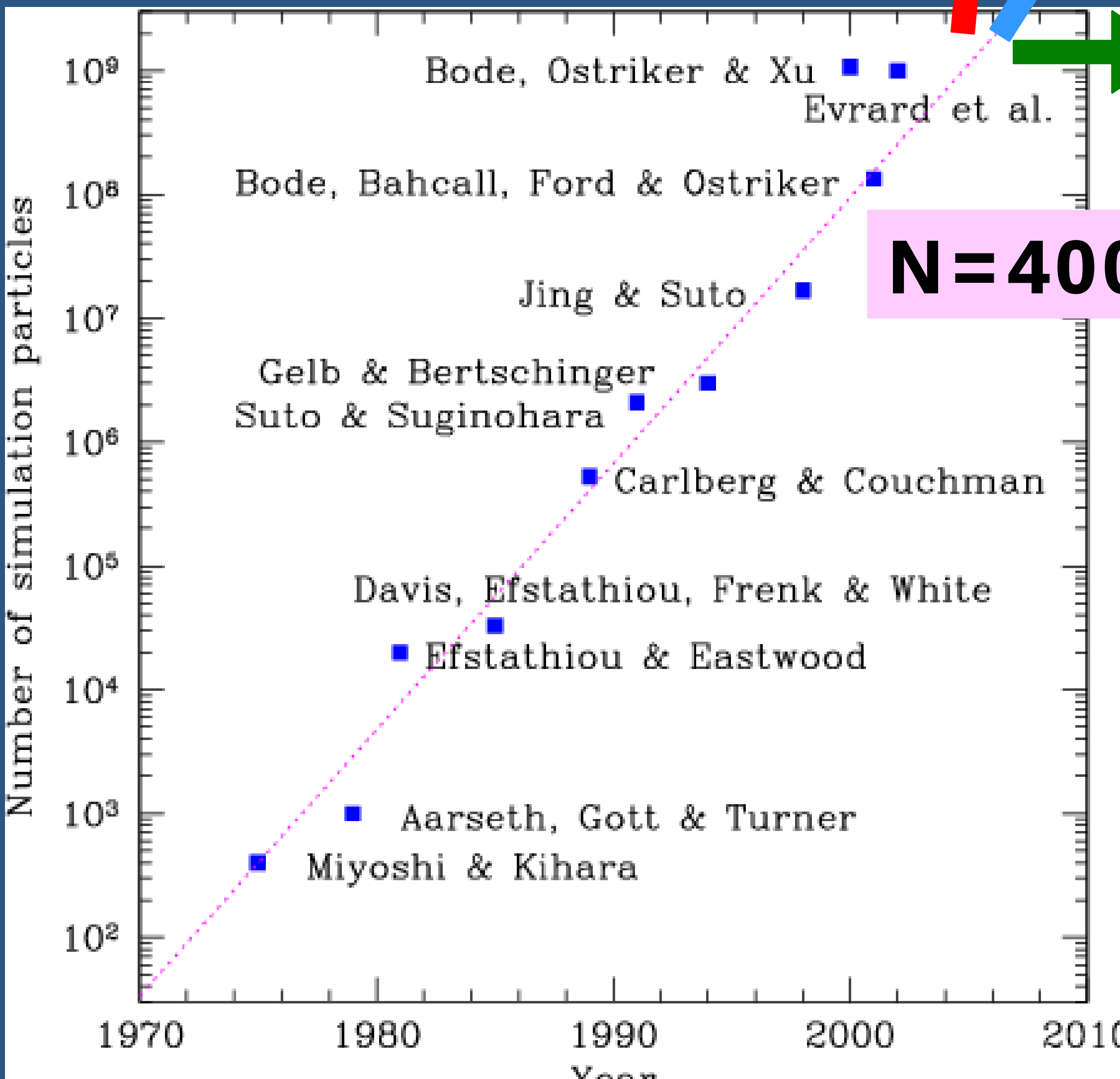


Existing N-body/SPH simulations (in ΛCDM)

$L_{box}[h^{-1}Mpc]$	N	$m[h^{-1}M_{sun}]$	reference
N-body			
100	256^3	5.0×10^9	Jing & Suto (1998)
100	512^3	6.1×10^8	Jing (2001)
240	256^3	6.9×10^{10}	Jenkins et al. (1998; Virgo)
300	256^3	1.3×10^{11}	Jing & Suto (1998)
1000	1024^3	7.6×10^{10}	Bode, Ostriker & Xu (2000)
1000	512^3	6.1×10^{11}	Bode, Bahcall, Ford & Ostriker (2001)
3000	1000^3	2.25×10^{12}	Evrard et al. (2002; Hubble vol.)
SPH			
1	324^3	730 (DM)	Yoshida et al. (2003)
75	128^3	2.4×10^{10} (DM)	Yoshikawa, Jing & Suto (2000)
100	216^3	7.0×10^9 (DM)	White, Hernquist & Springel (2002)

Well-known exponential evolution of "N" in cosmological N-body simulations

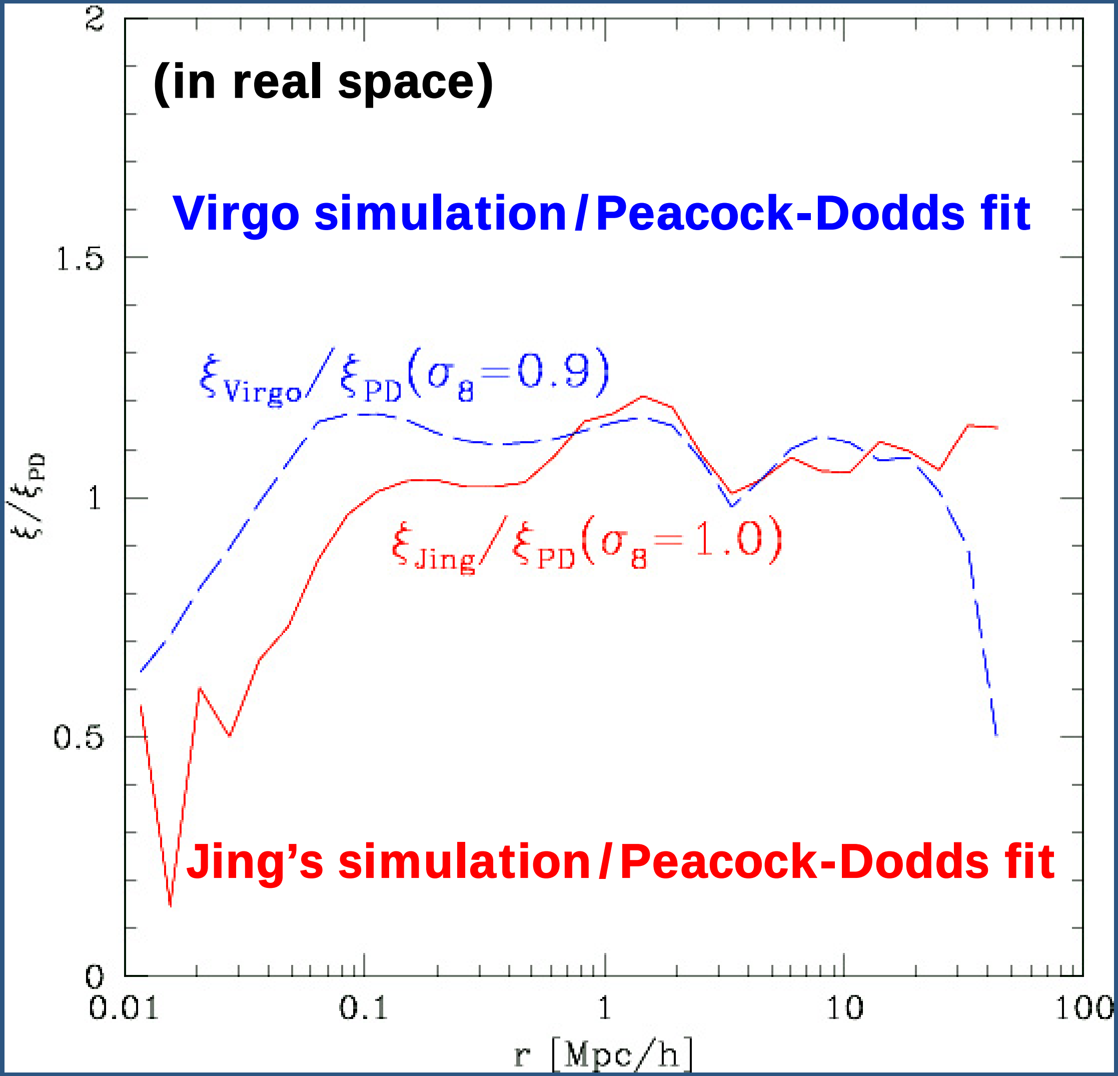
???



$$N=400\times10^{0.215(\mathrm{Year}-1975)}$$

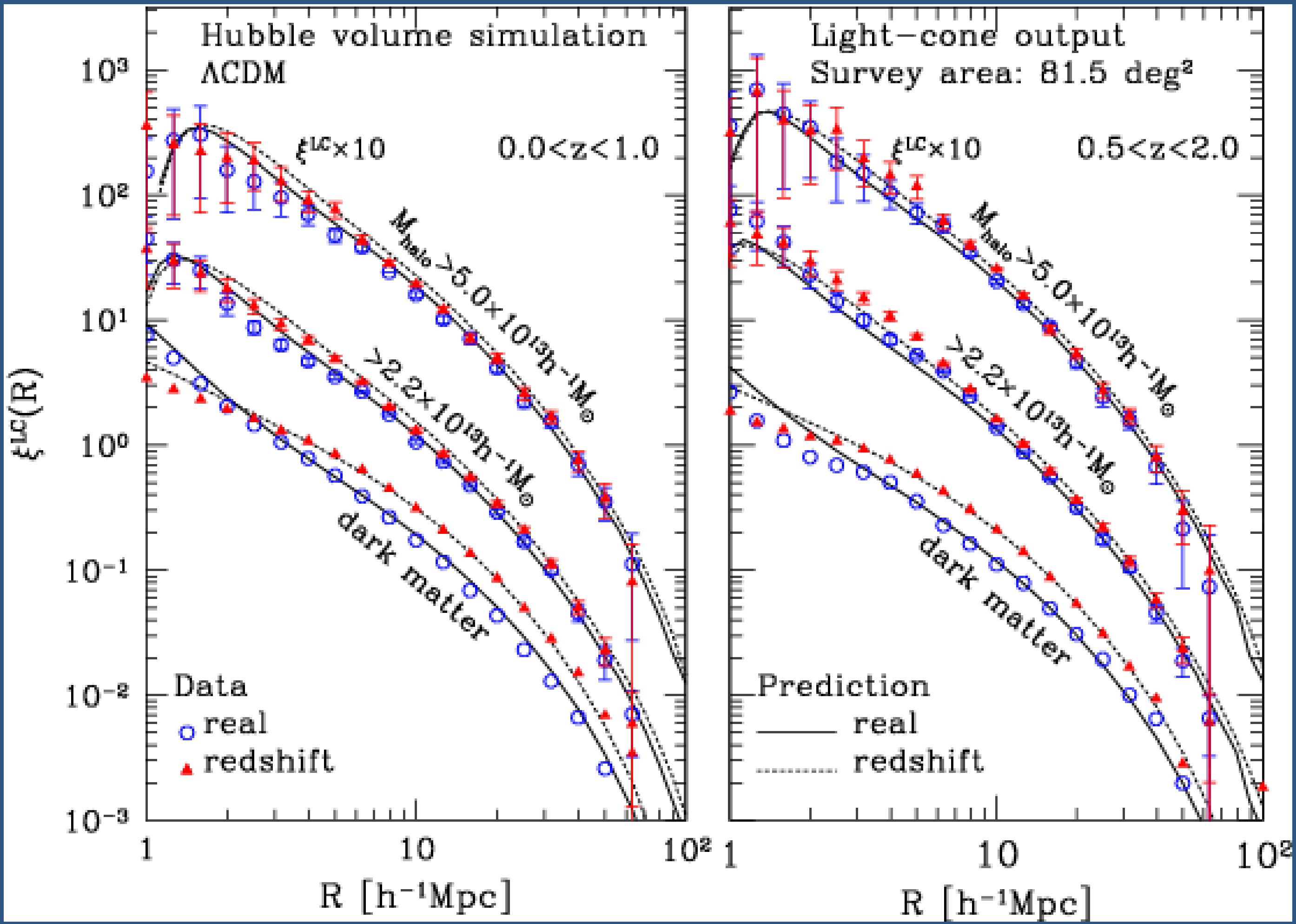
- The number of simulation particles in a $(1h^{-1}\mathrm{Gpc})^3$ comoving cube exceeds the real number of CDM particles in the box
    - December, 2348 (if $m_{CDM}=1\mathrm{keV}$)
    - February, 2386 (if $m_{CDM}=10^{-5}\mathrm{keV}$)

Two-point correlation functions from different simulations



The Peacock-Dodds fitting formula, Virgo simulation and Jing's simulation agree within ±10% for $0.05h^{-1}$Mpc < r < $20h^{-1}$Mpc

Correlation functions of halos on the light-cone



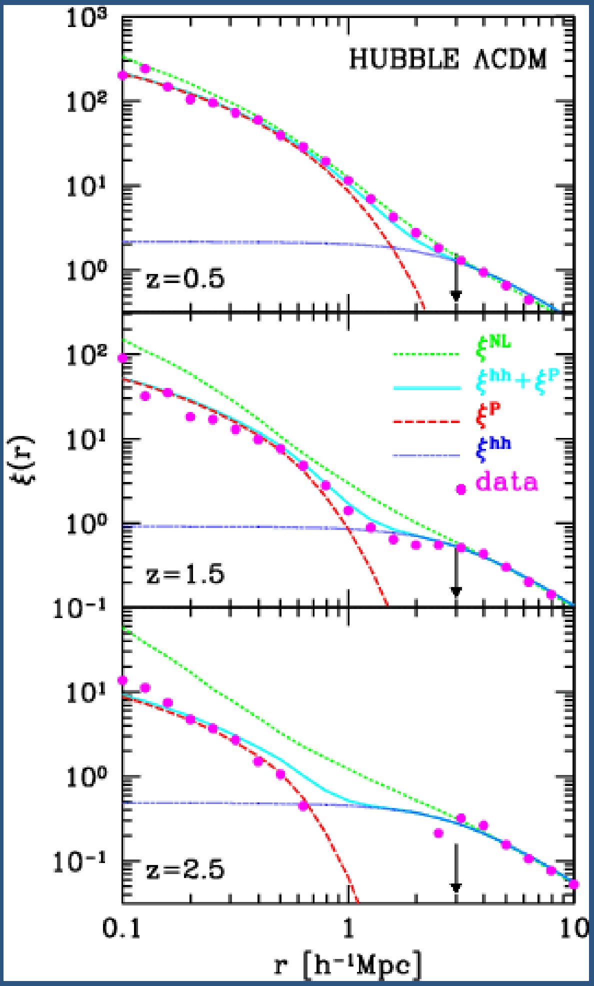
Light-cone out put from Hubble volume LCDM simulation

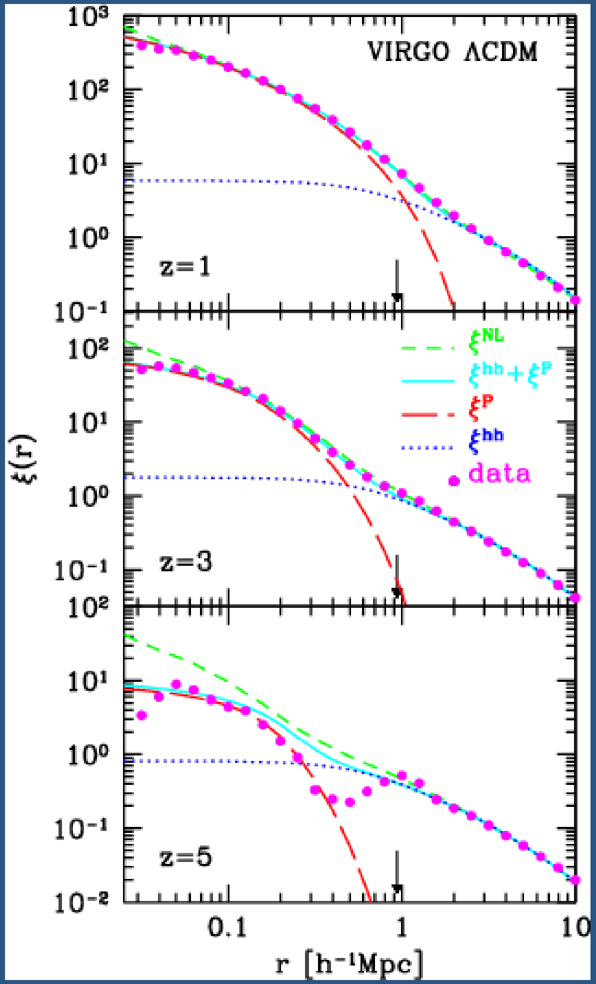
VS

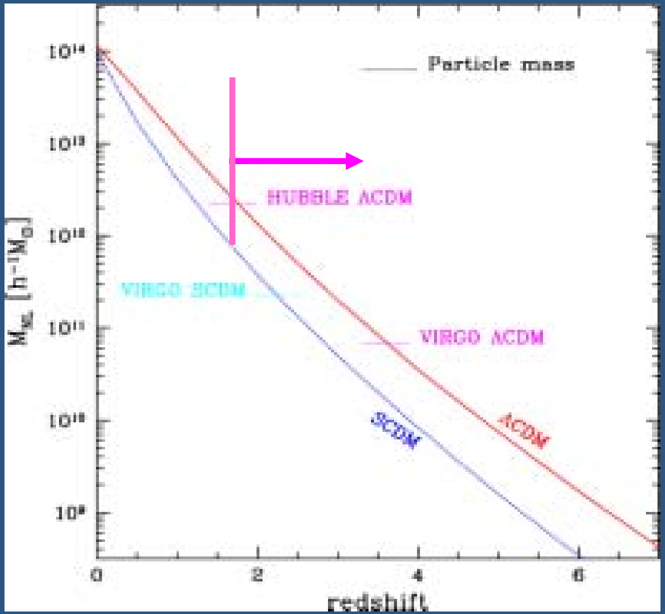
Peacock-Dodds fiiting formula
+
Halo bias
+
(redshift distortion)
+
average over lightcone

Hamana, Yoshida, Suto & Evrard (2001)

Finite mass resolution effect in cosmological N-body simulations







$$z_{crit} = 0.72\left[\log_{10}\left(\frac{2\times10^{15}h^{-1}M_{sun}}{n_{halo}\ m_{part}}\right)\right]^{1.25} - 1$$

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

Universal mass function of dark halos

$$n(\sigma^{-1}(M)) = A\exp[-|\ln\sigma^{-1}(M)+B|^{\varepsilon}]$$

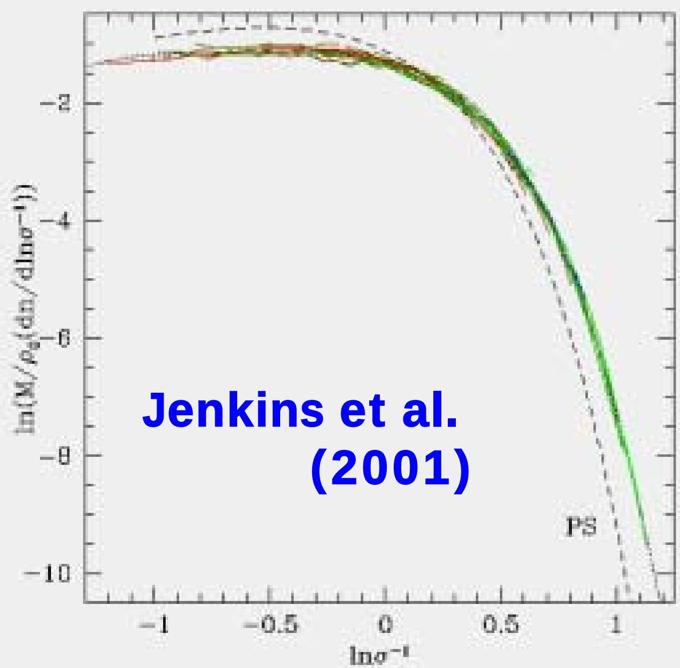


Figure 7. The FOF(0.2) mass functions of all the simulation outputs listed in Table 2. Remarkably, when a single linking length is used to identify halos at all times and in all cosmologies, the mass function appears to be invariant in the $f-\ln\sigma^{-1}$ plane. A single formula (eqn. 9), shown with a dotted line, fits all the mass functions with an accuracy of better than about 20% over the entire range. The dashed curve show the Press-Schechter mass function for comparison.

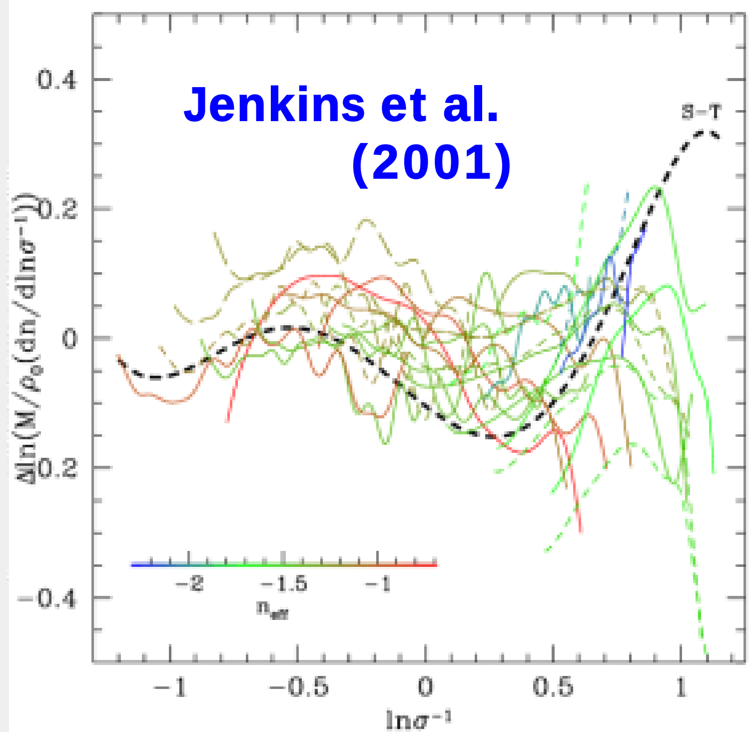
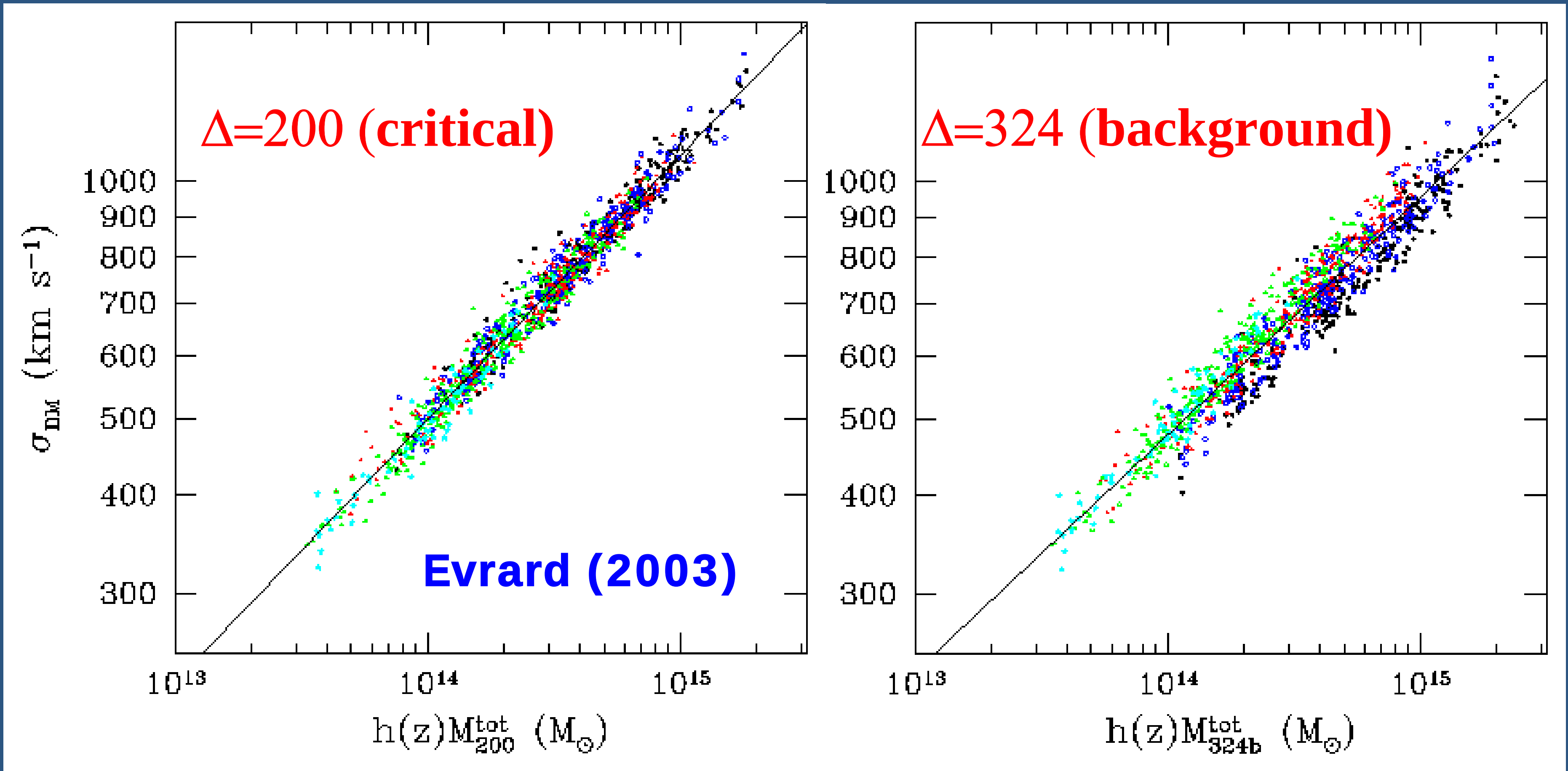


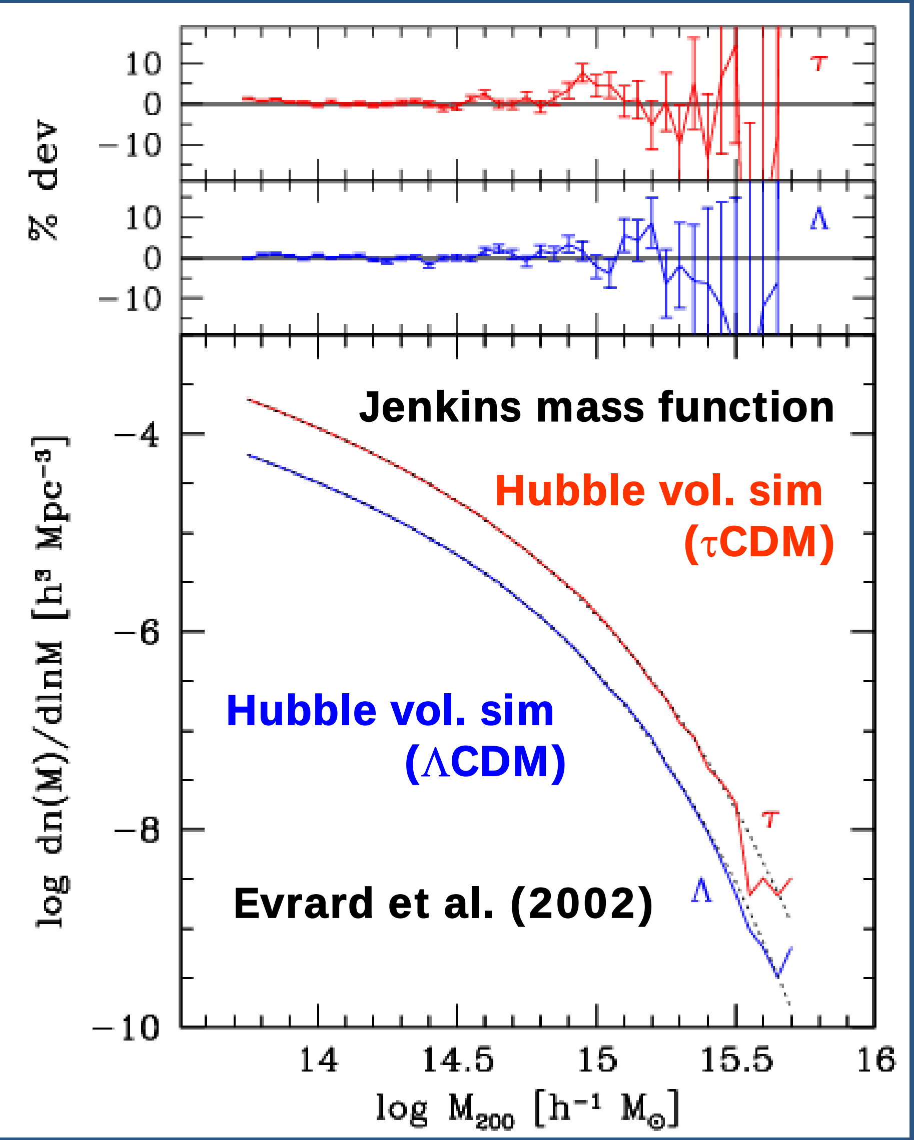
Figure 8. The residual between the fitting formula, eqn. 9, and the FOF(0.2) mass functions for all the simulation outputs listed in Table 2. Solid lines correspond to simulations with $\Omega = 1$, short dashed lines to flat, low Ω_0 models, and long dashed lines to open models.

Dark matter virial theorem: halo mass - velocity dispersion relation for different mass definitions



In contrast to a simple theory, numerical simulations prefer halos defined by overdensity of 200 with respect the critical mean density independently of the background cosmology (puzzling…)

Dark halo mass functions



- **Claim :**
  - **Dark halos should be defined by critical SO(200), i.e., spherically averaged density exceeds 200 times the critical density (independently of the background cosmology).**
  - **Then the resulting mass functions are "universal".**
- **What's wrong with the conventional spherical infall model prediction ?**
- **Why universal scaling is desired (even if the scaling itself is surprising) ?**

What is *the* definition of galaxy clusters ?

Abell (optical) clusters

the Abell radius

$m_3<m<m_3+2$

richness class

Press-Schechter halos

spherical collapse

$\Delta_{vir}=18\pi^2\Omega_m^{-0.6}$

SZ clusters

ΔI_{SZ}

$\propto n_e T_e$

Halos in N-body simulations

friend-of-friend

linking length = 0.2, Δ_{vir}=200?

X-ray clusters

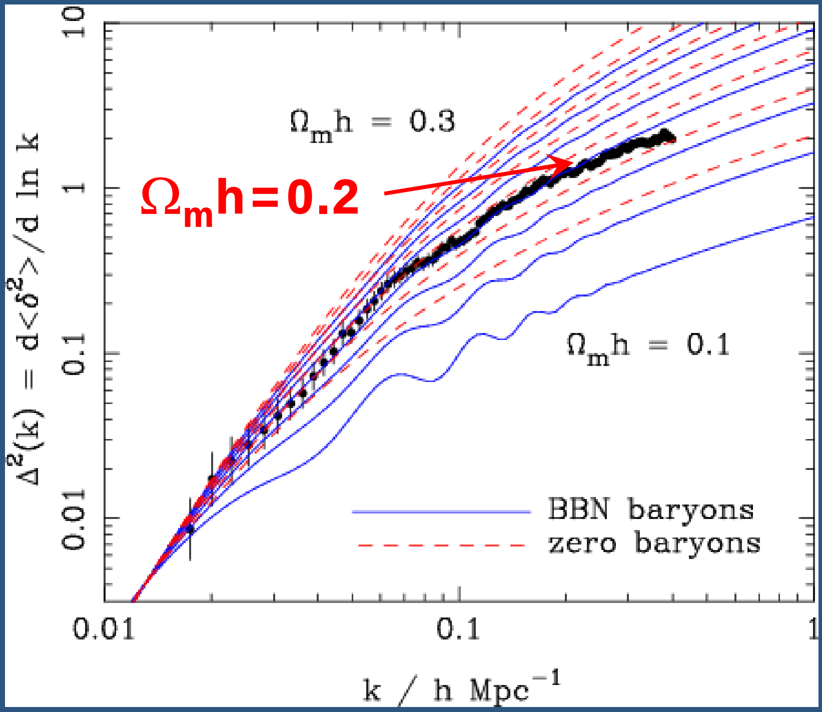
$S_x \propto n_e^2 T_e^{1/2}$

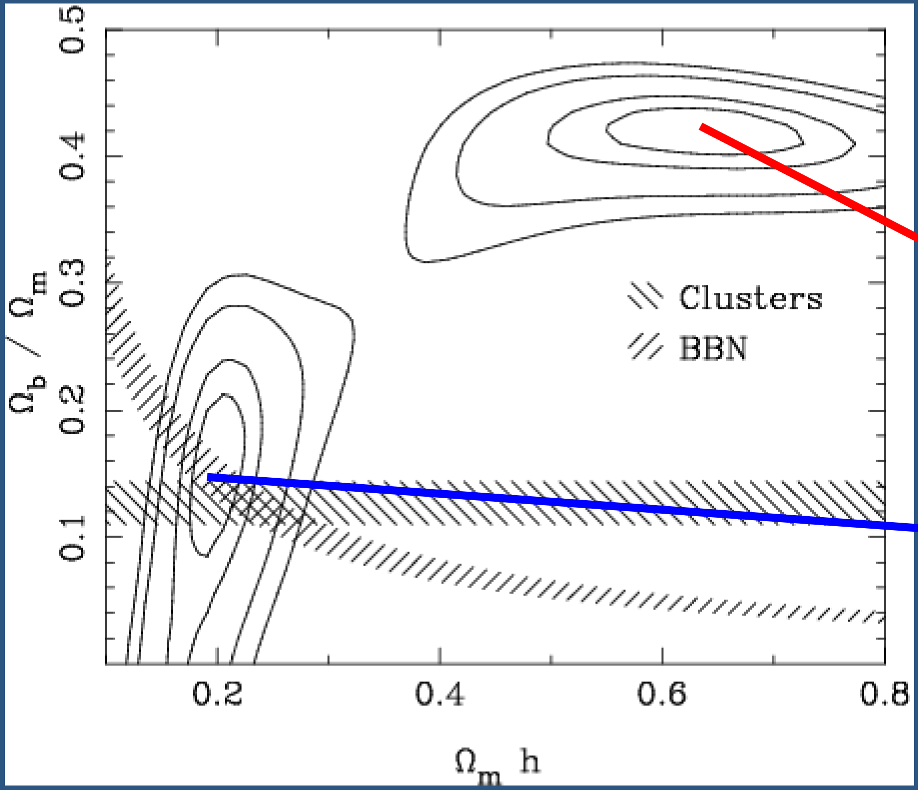
Apparently they are closely related, but we desperately need to understand better what we mean by clusters

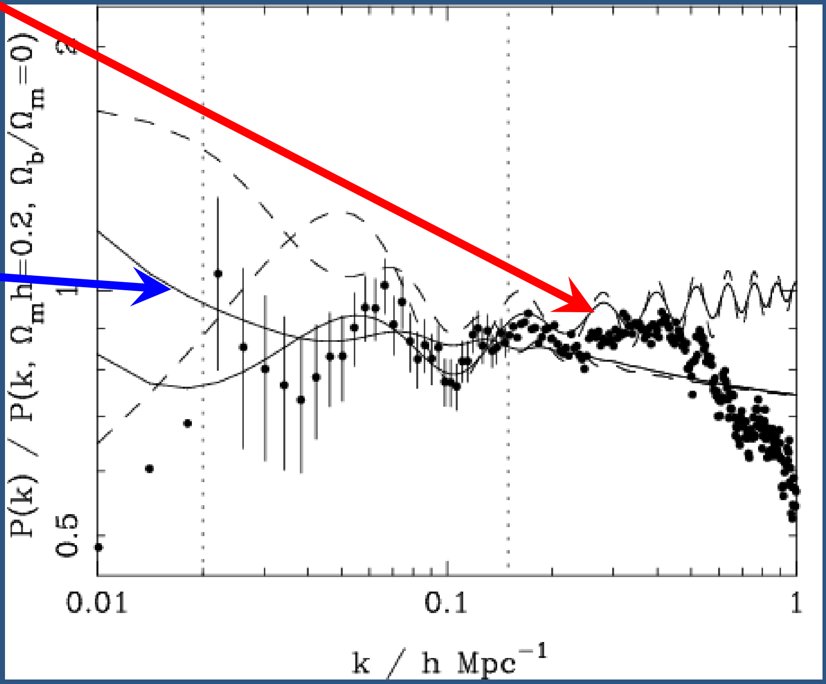
Part 2:

Clustering of the 2dF and the SDSS galaxies

Ω_m from power spectrum of 2dFGRS

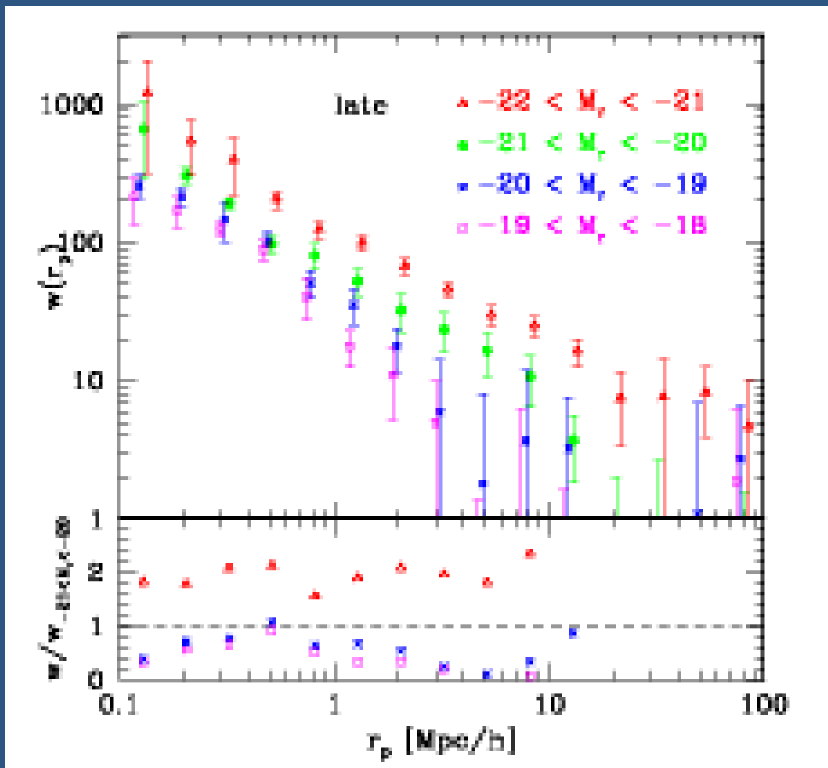


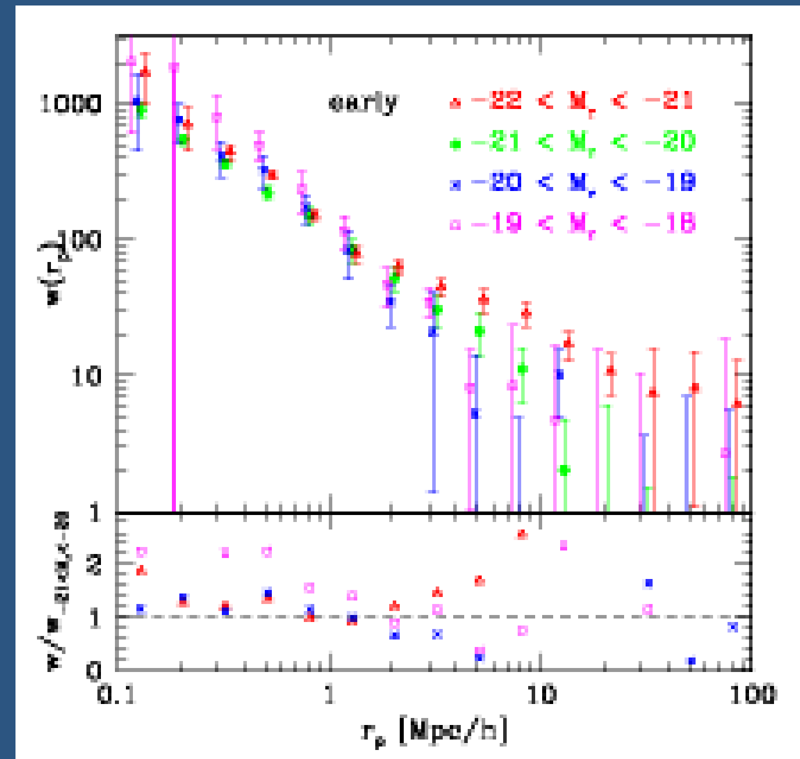




Peacock (2003) astro-ph/0309240

luminosity dependence of $w(r_p)$ from SDSS volume-limited galaxy sample

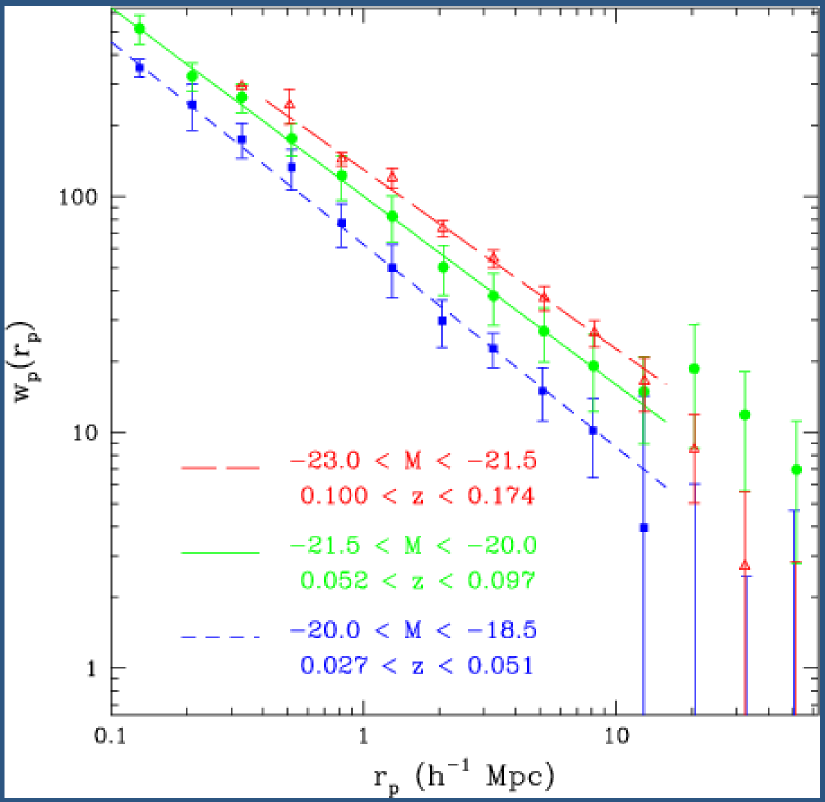


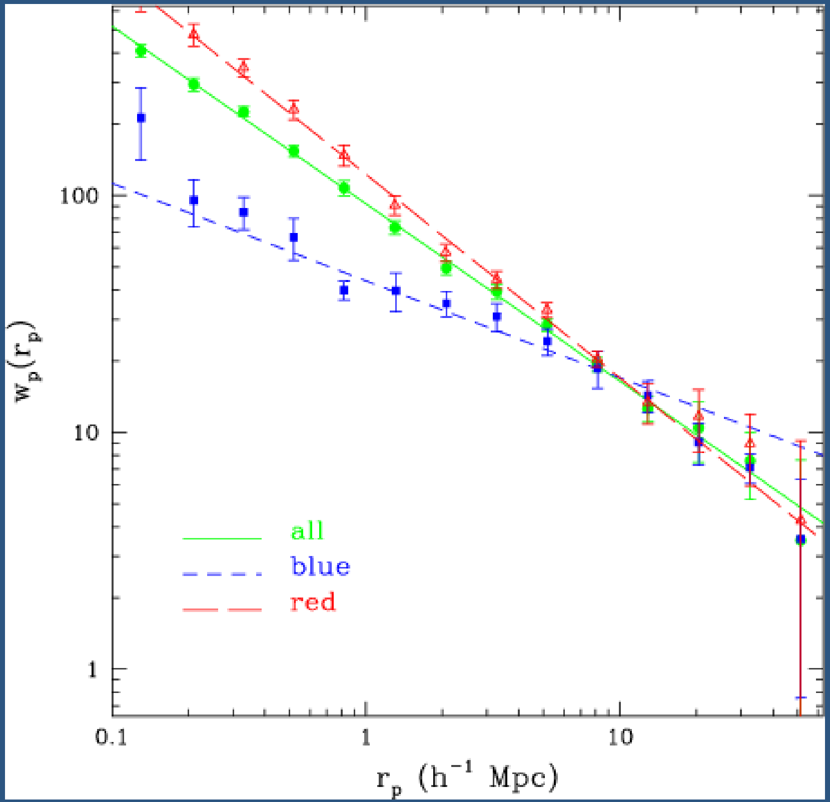


Kayo et al. (2003)

- early-types are more strongly biased than late-types
- for late-types, luminous galaxies show stronger clustering
- for early-types, the clustering amplitudes are fairly independent of the absolute luminosities of galaxies

Luminosity and color dependence of $w(r_p)$ from SDSS volume-limited galaxy sample





Zehavi et al. (2001)

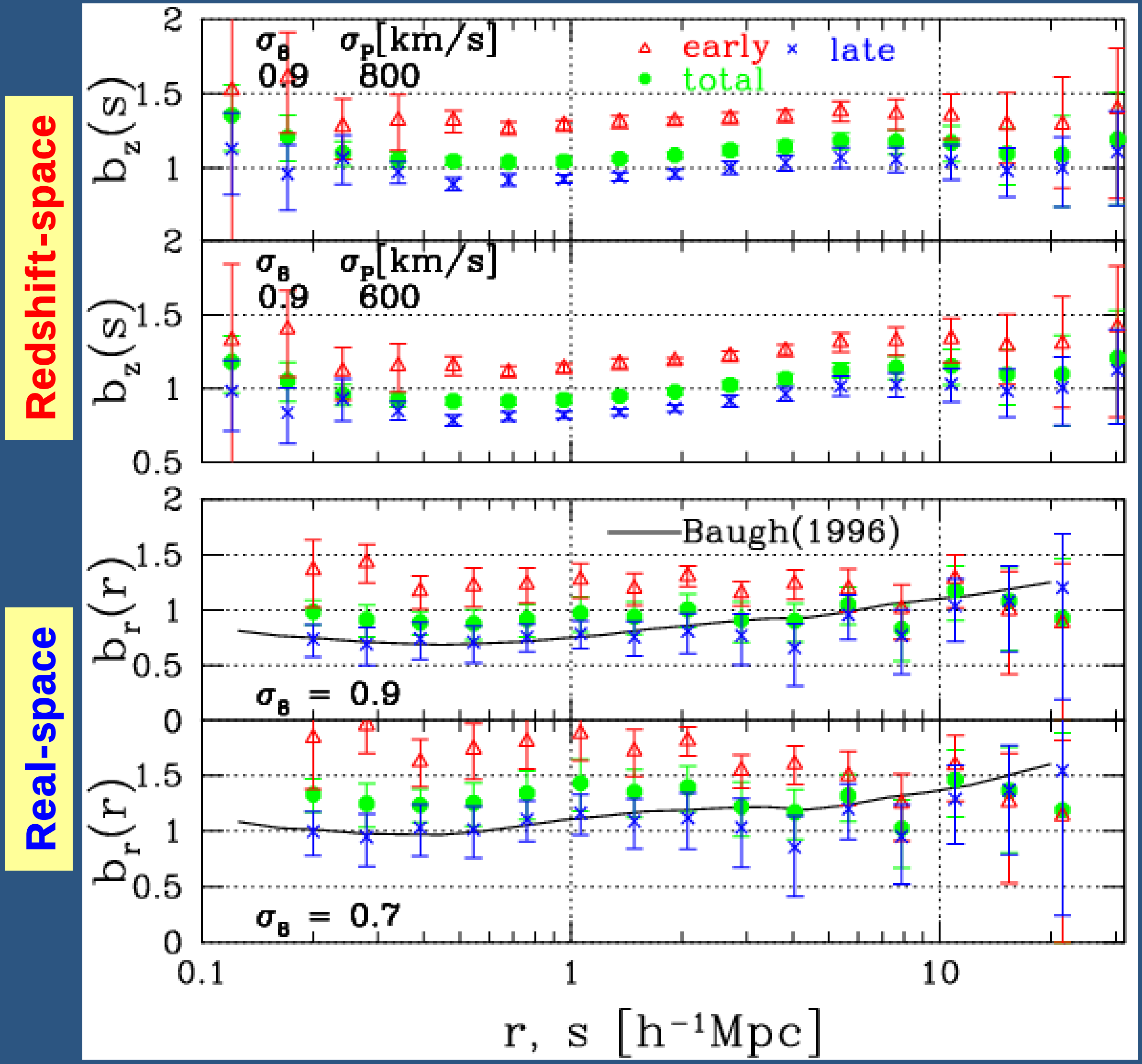
- red/luminous galaxies show stronger clustering
- the slope of the red-galaxy correlation is steeper

Morphology-dependence of galaxy bias from SDSS magnitude-limited sample

early-type
average
late-type

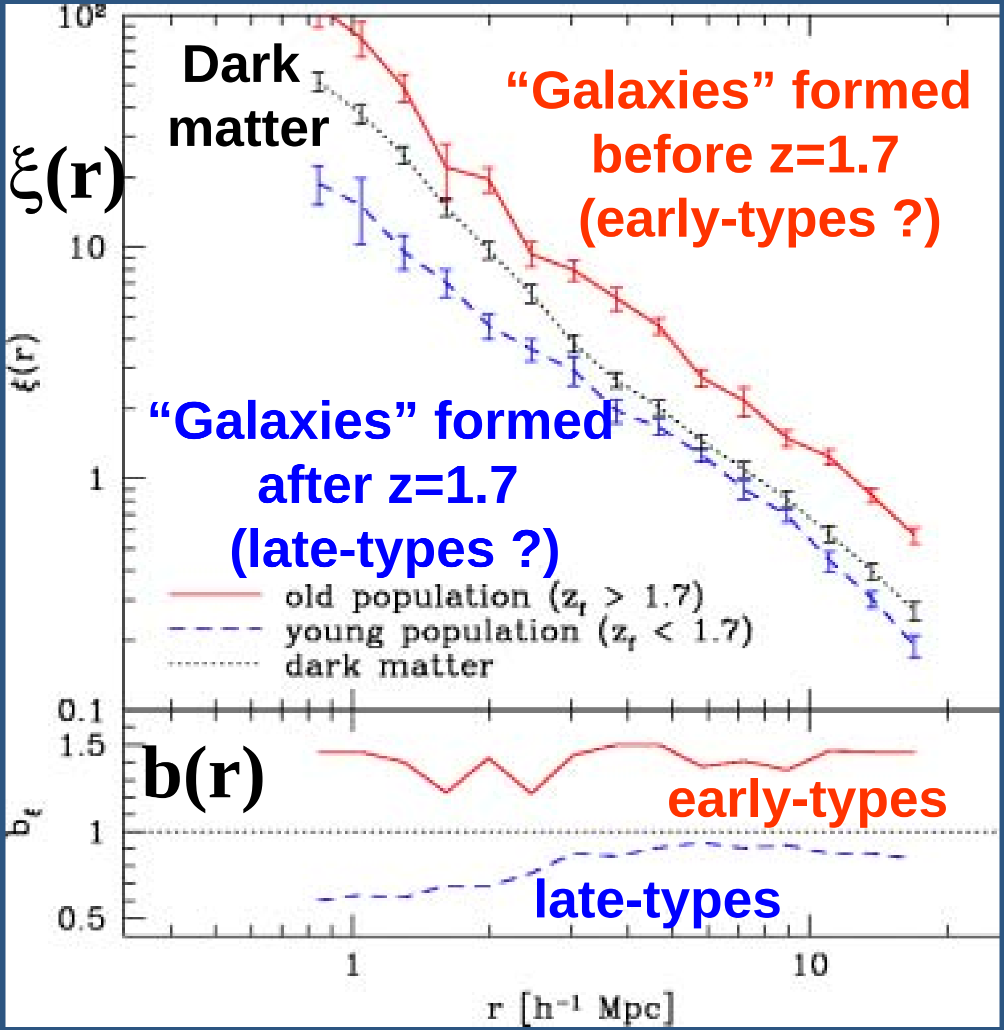
$$b \equiv \sqrt{\frac{\xi(galaxies)}{\xi(\Lambda CDM)}}$$

- Galaxy bias is fairly scale-independent
- Clear morphology dependence with respect to ΛCDM (computed semi-analytically over light-cone)



Kayo et al. (2003)

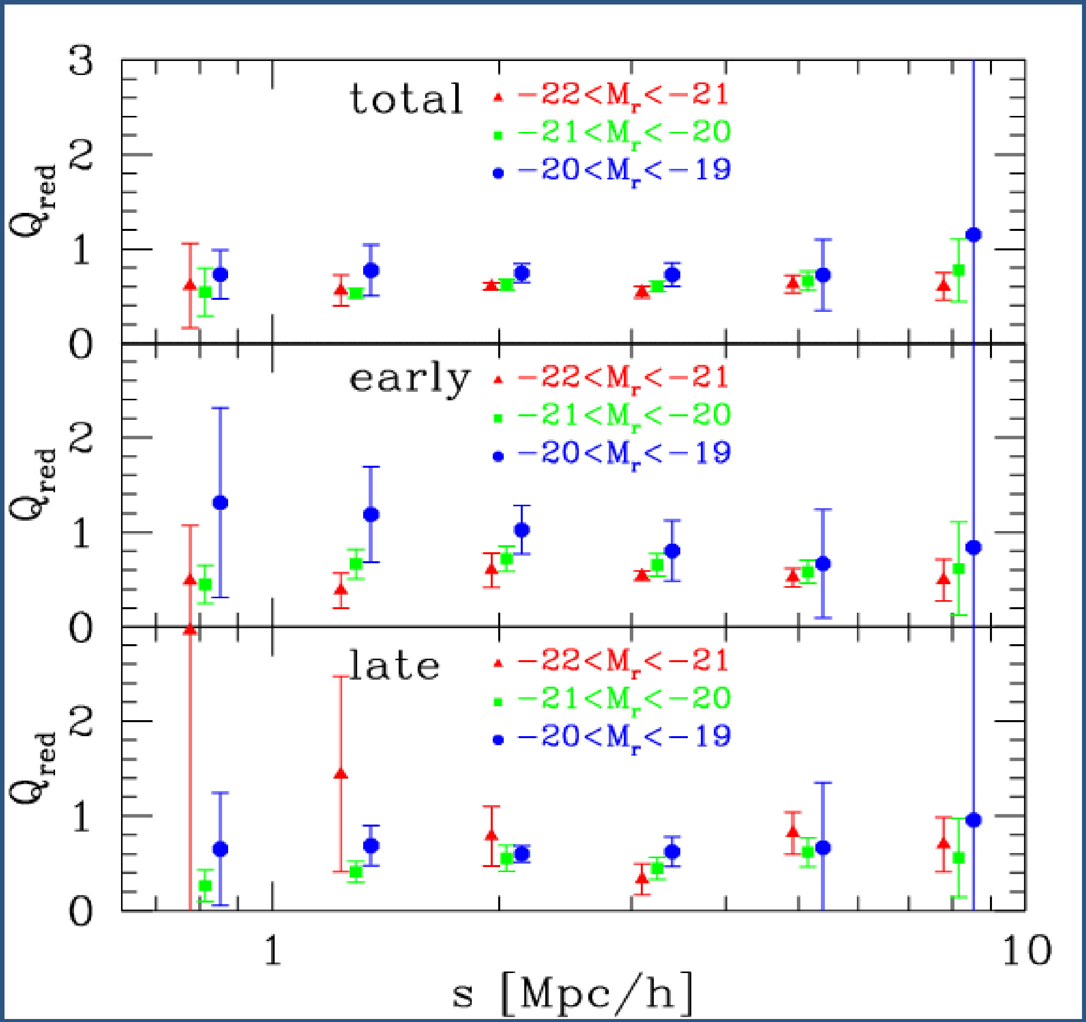
Previous predictions from SPH simulations with “galaxy” formation



- 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)

Three-point correlation functions in redshift space

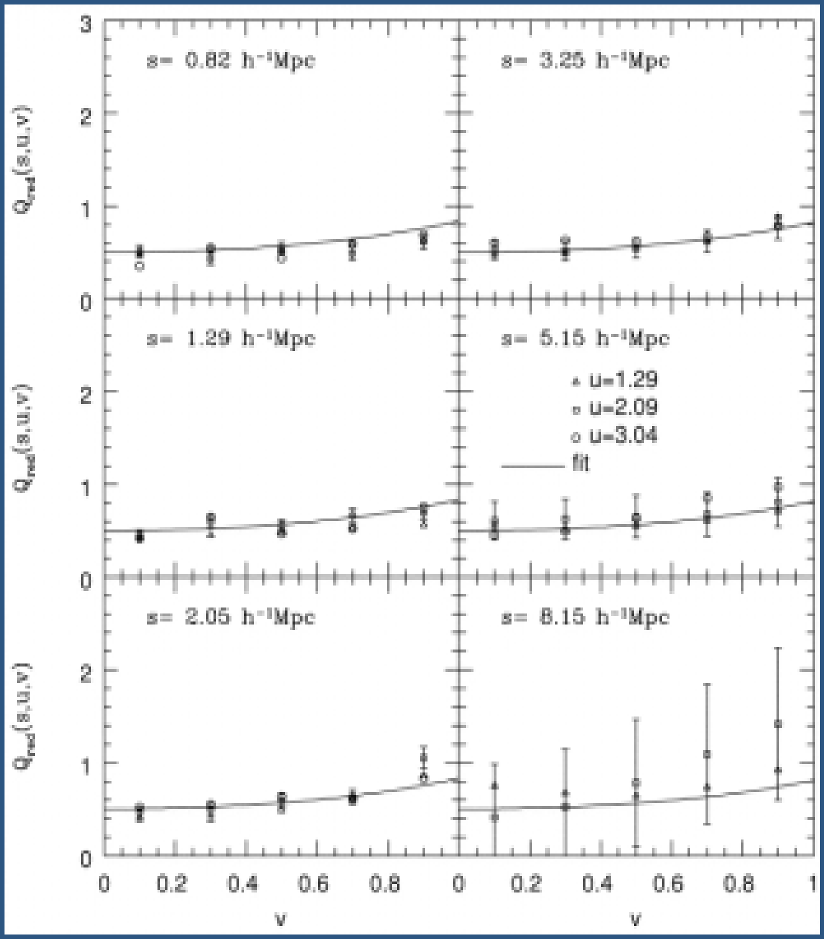


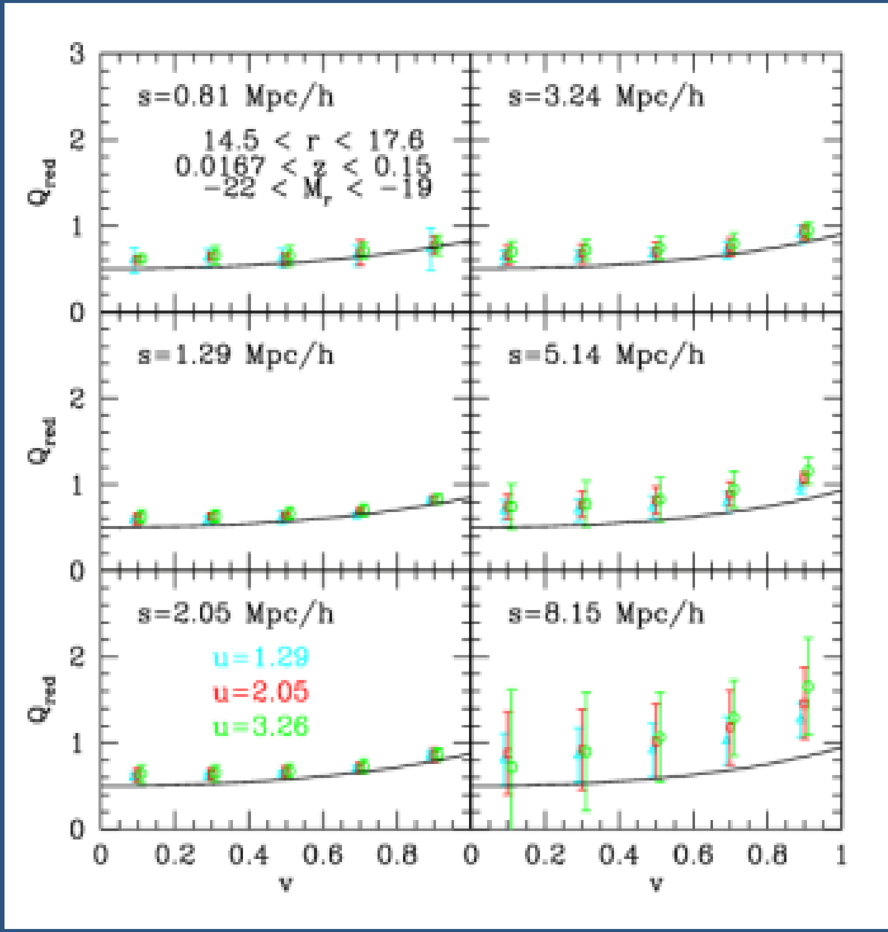
$$Q_{red} \equiv \frac{\zeta(s_1, s_2, s_3)}{\xi(s_1)\xi(s_2)+\xi(s_2)\xi(s_3)+\xi(s_3)\xi(s_1)}$$

equilateral triangles

- Q ~ 0.5 – 1.5
- Weak dependence on scale of triangles (hierarchical ansatz is valid)
- Weak dependence on Luminosity
- Weak dependence on Morphology

Comparison with previous work on three-point correlation functions

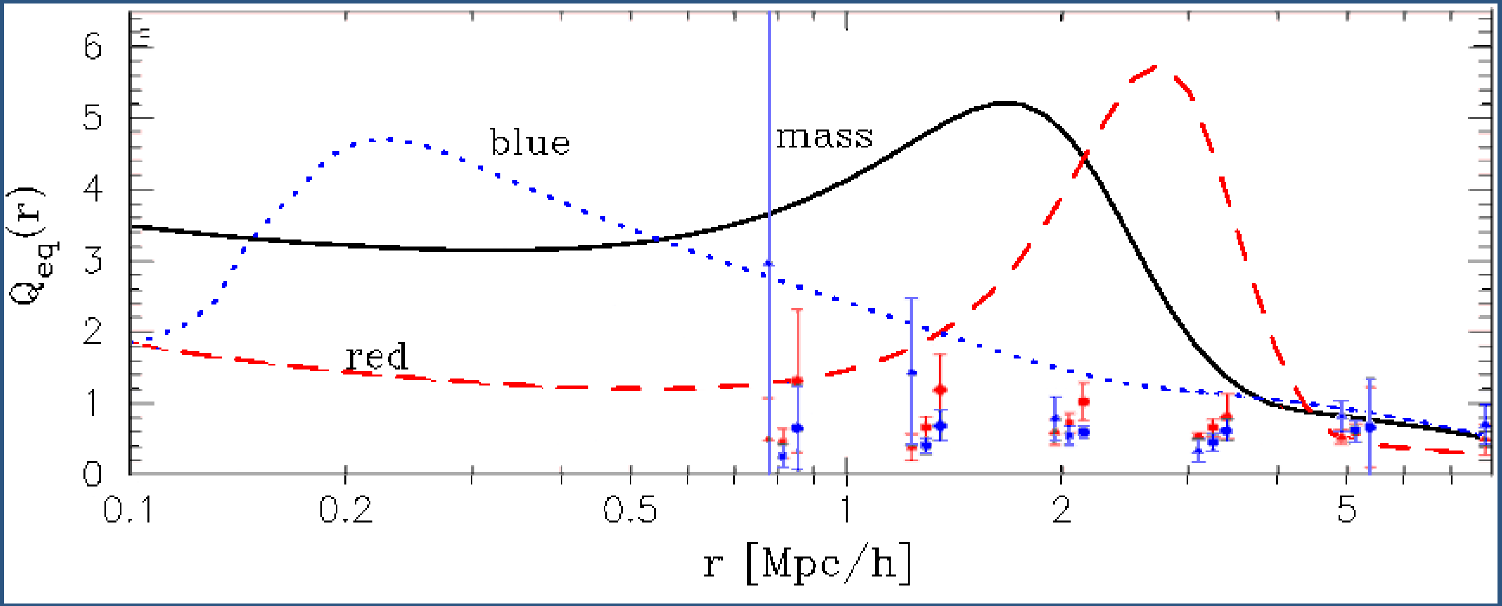




Jing & Börner (1998)
LCRS: 20,000 galaxies

Kayo et al. (2003)
SDSS: 90,000 galaxies

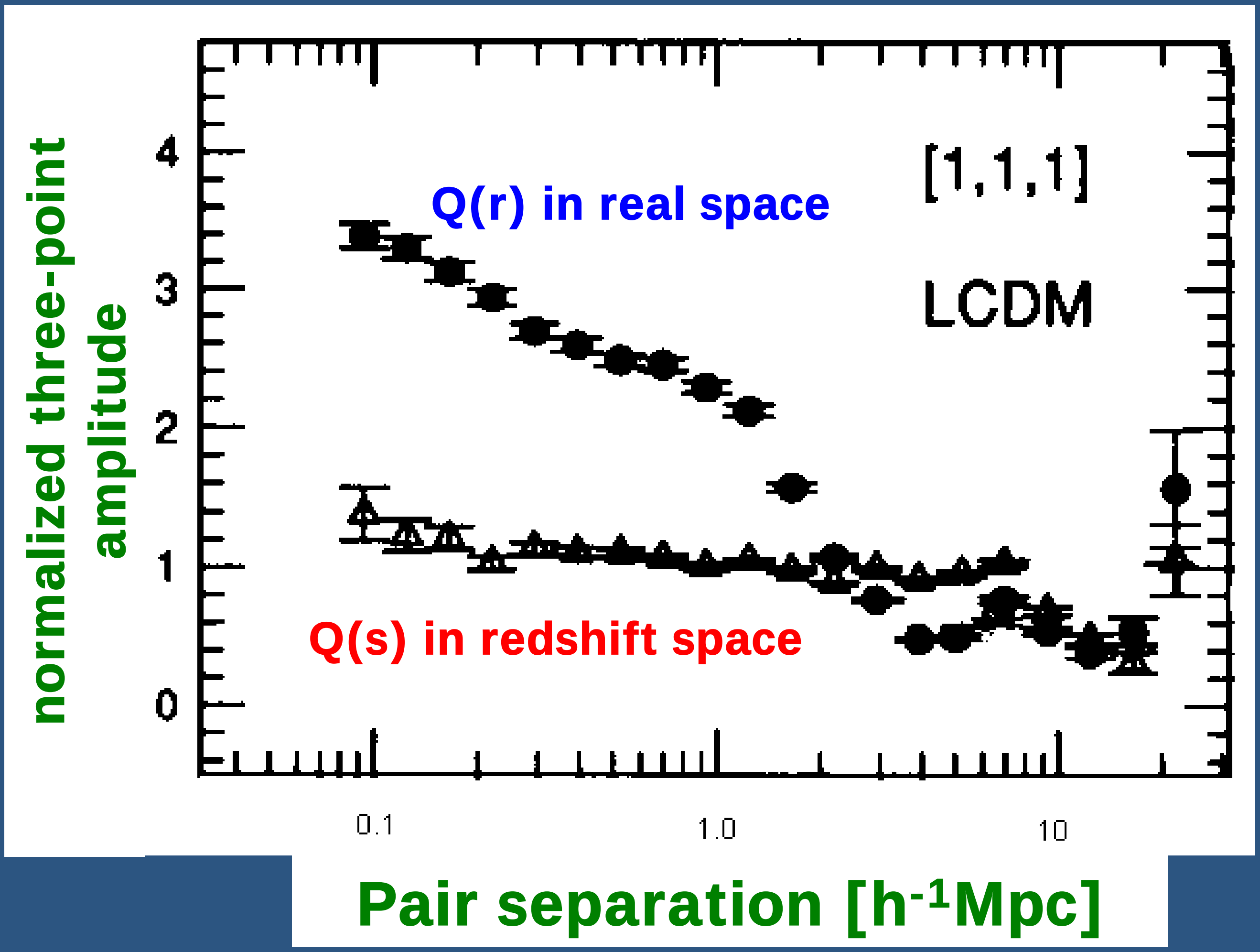
Comparison with theoretical predictions in real space



Lines: model (Takada & Jain 2003)
Symbols: SDSS results (Kayo et al. 2003)

- Very different behaviour, but maybe mostly due to the redshift-space distortion effects that theoretical models are not yet successful in incorporating properly

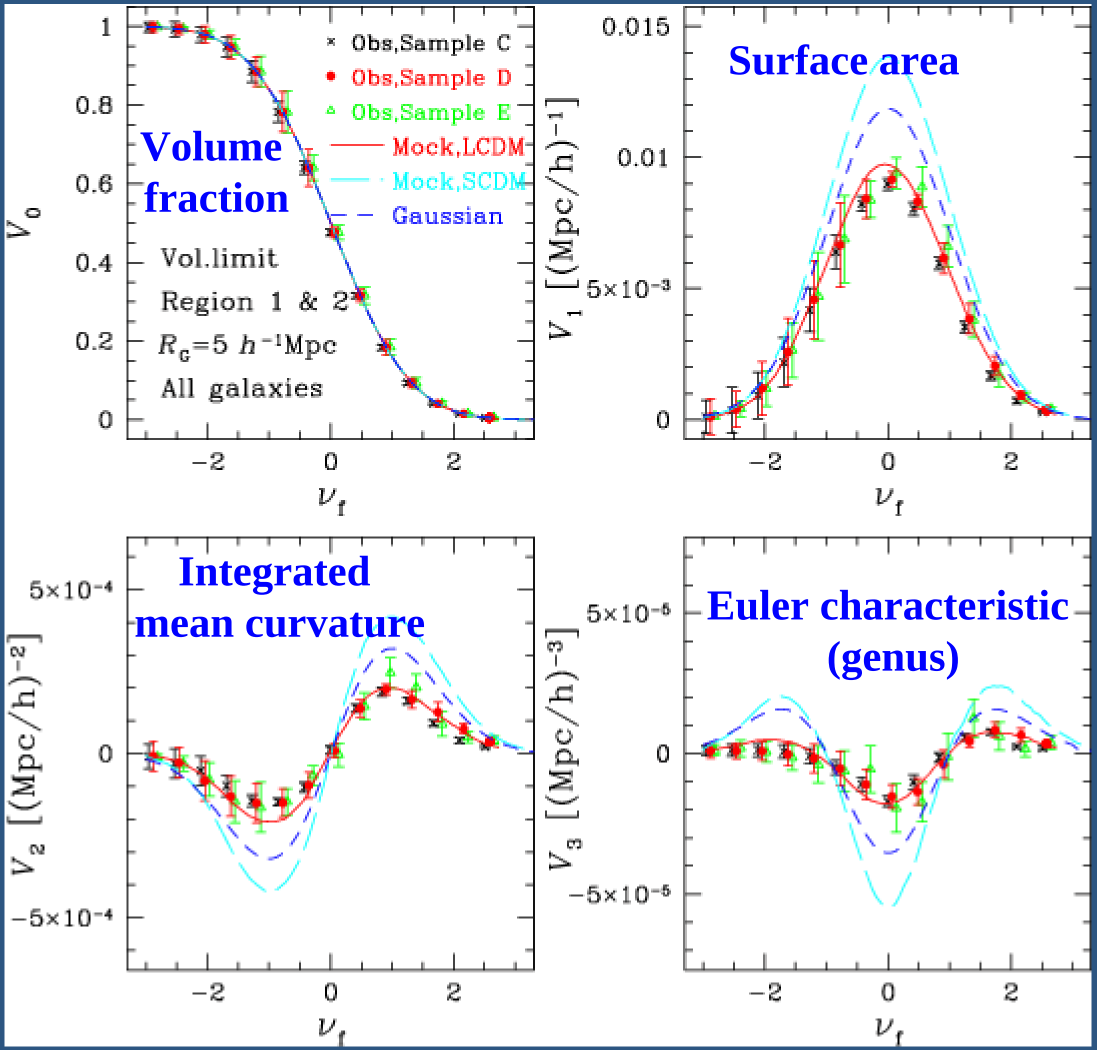
Redshift-space distortion from simulations



- N-body simulations imply a significant degree of redshift-space distortion

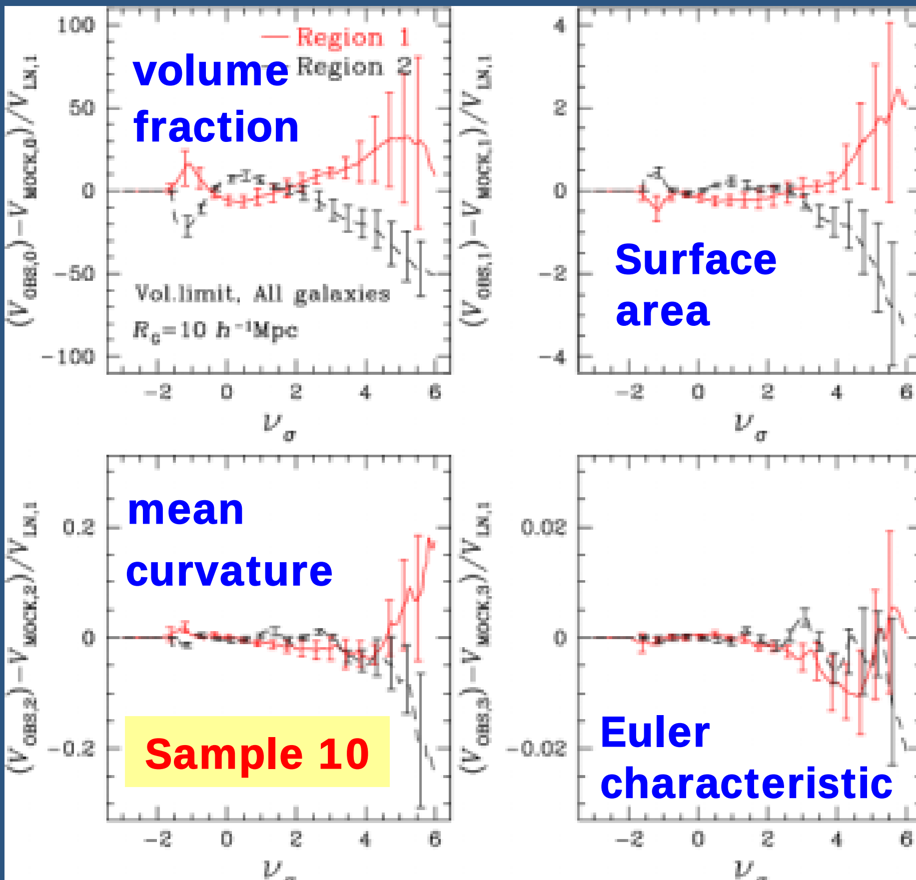
Matsubara & Suto (1994)

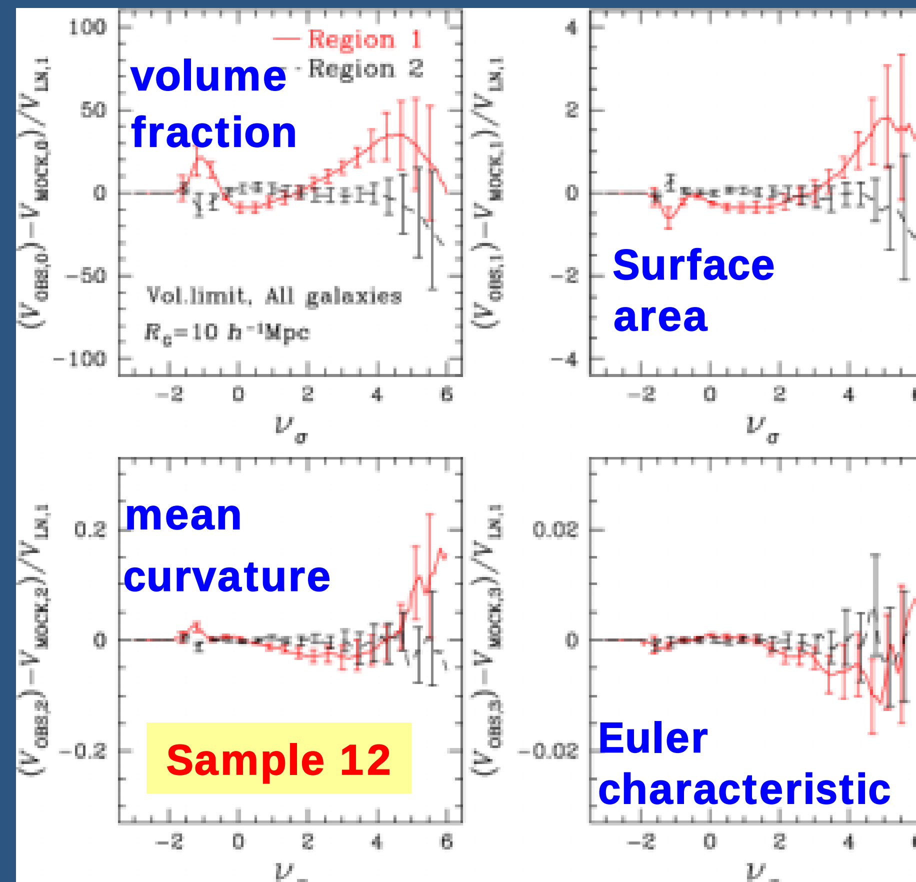
Topology of SDSS galaxy distribution



- Topology of SDSS galaxy distribution (measured with Minkowski Functionals) is consistent with those originated from the primordial random-Gaussian field in ΛCDM (Hikage, Schmalzing, Buchert, Suto et al. 2003 PASJ).

SDSS data represent a fair sample of the universe ?





Hikage et al. (2003)

- Difference of MFs for two independent regions of SDSS
- Two regions in Sample 12 barely converge within the error bars from Mock samples

Part 3:

Density profiles

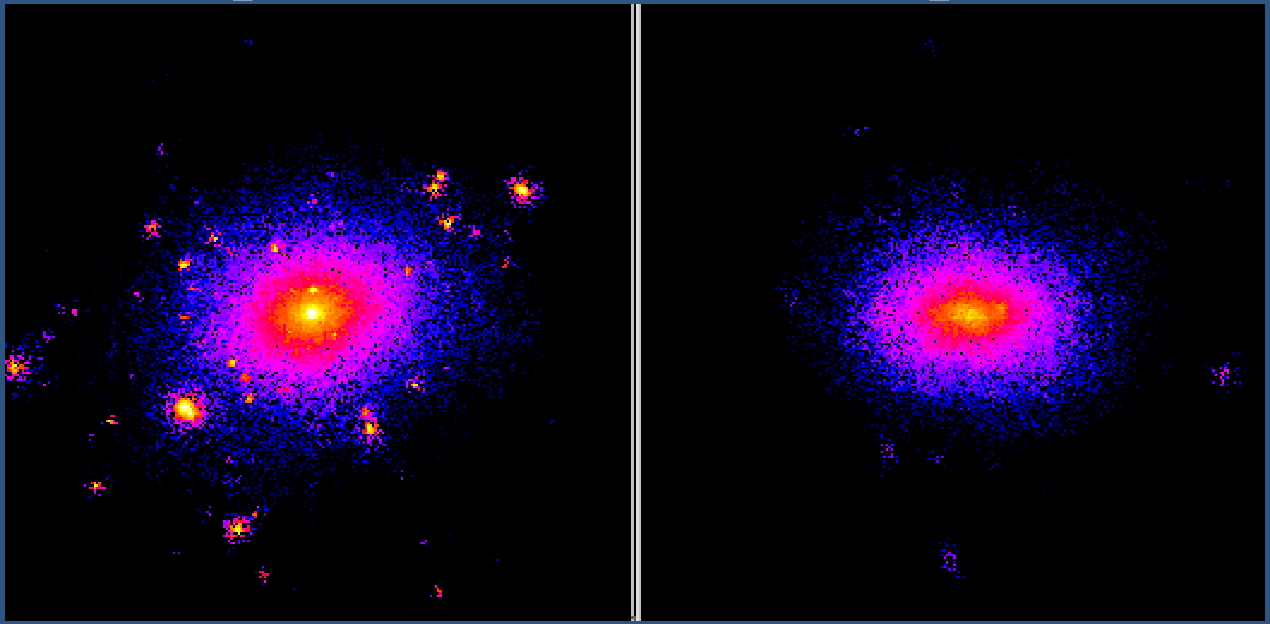
of

dark matter halos

Importance of high-resolution simulations

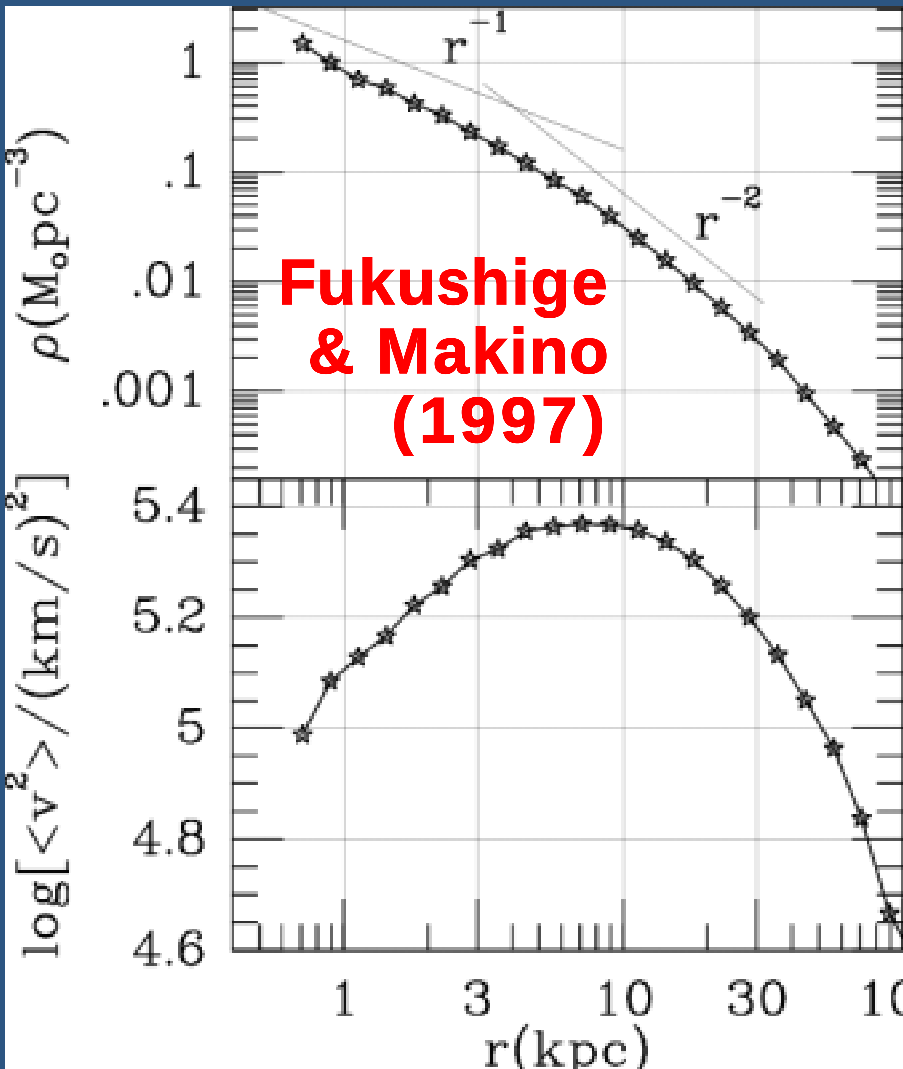
- low mass/force resolutions
  ⇒ shallower potential than real
  ⇒ artificial disruption/overmerging
  (especially serious for small systems)

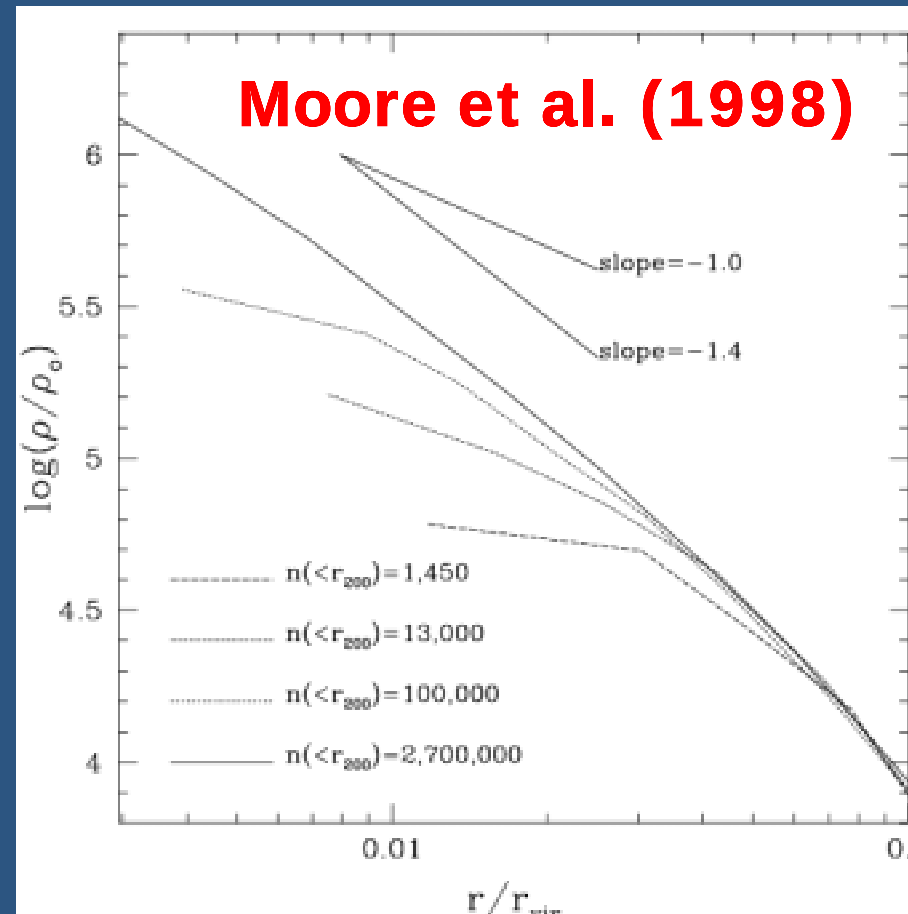
ε = 1kpc **ε = 7.5kpc** **Moore (2001)**



central 500kpc region of a simulated halo in SCDM

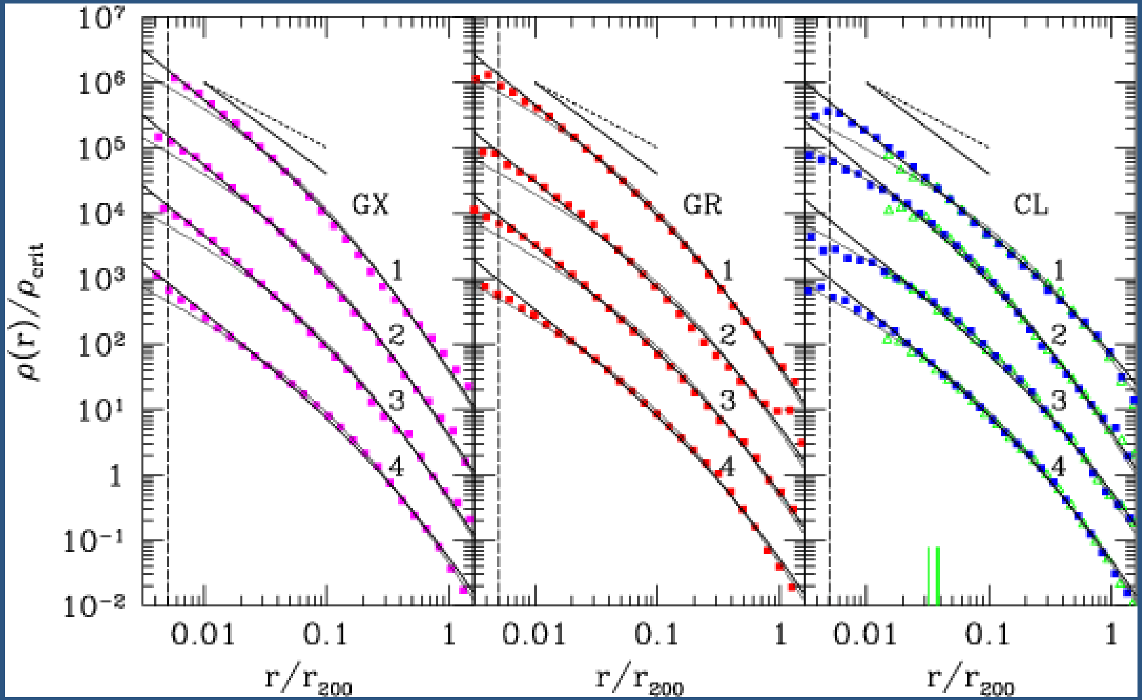
Profiles in higher-resolution simulations



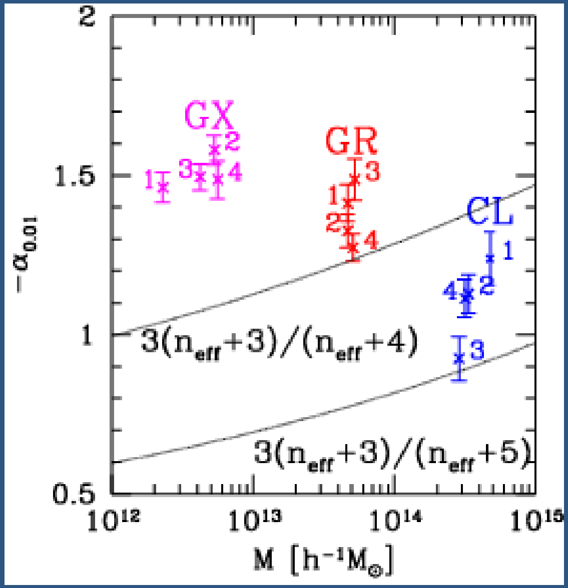


inner slope is steeper (~ 1.5) than the NFW value (1.0)

variation of the halo density profiles



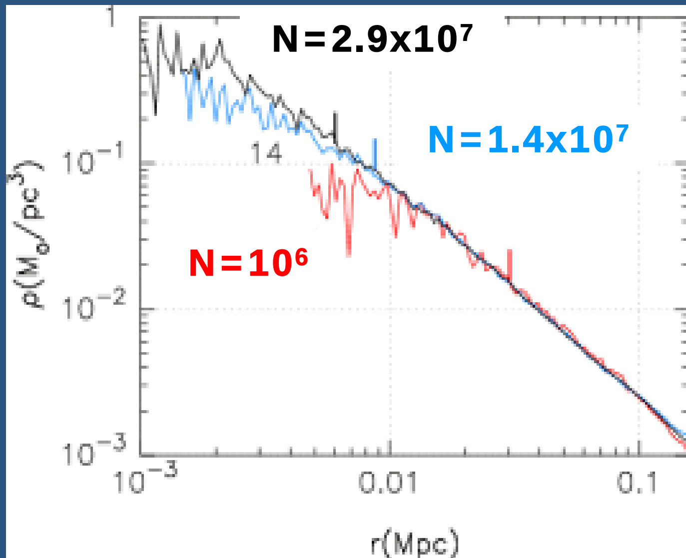
Jing & Suto (2000)

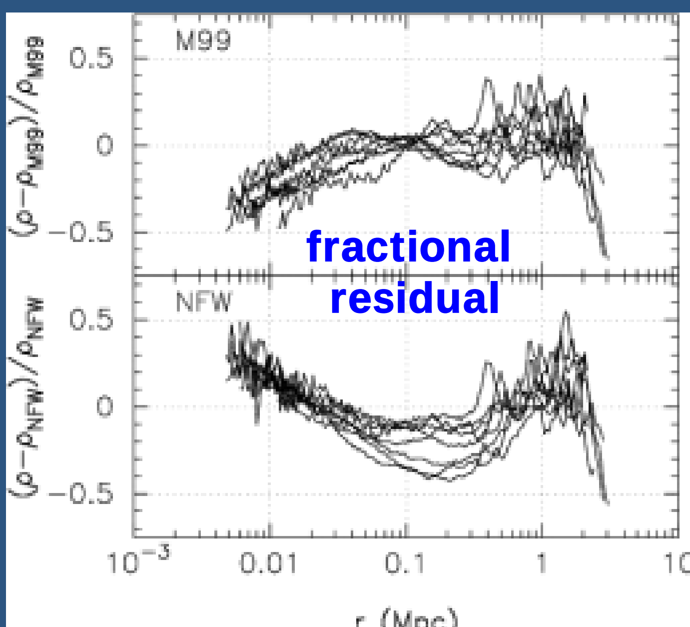


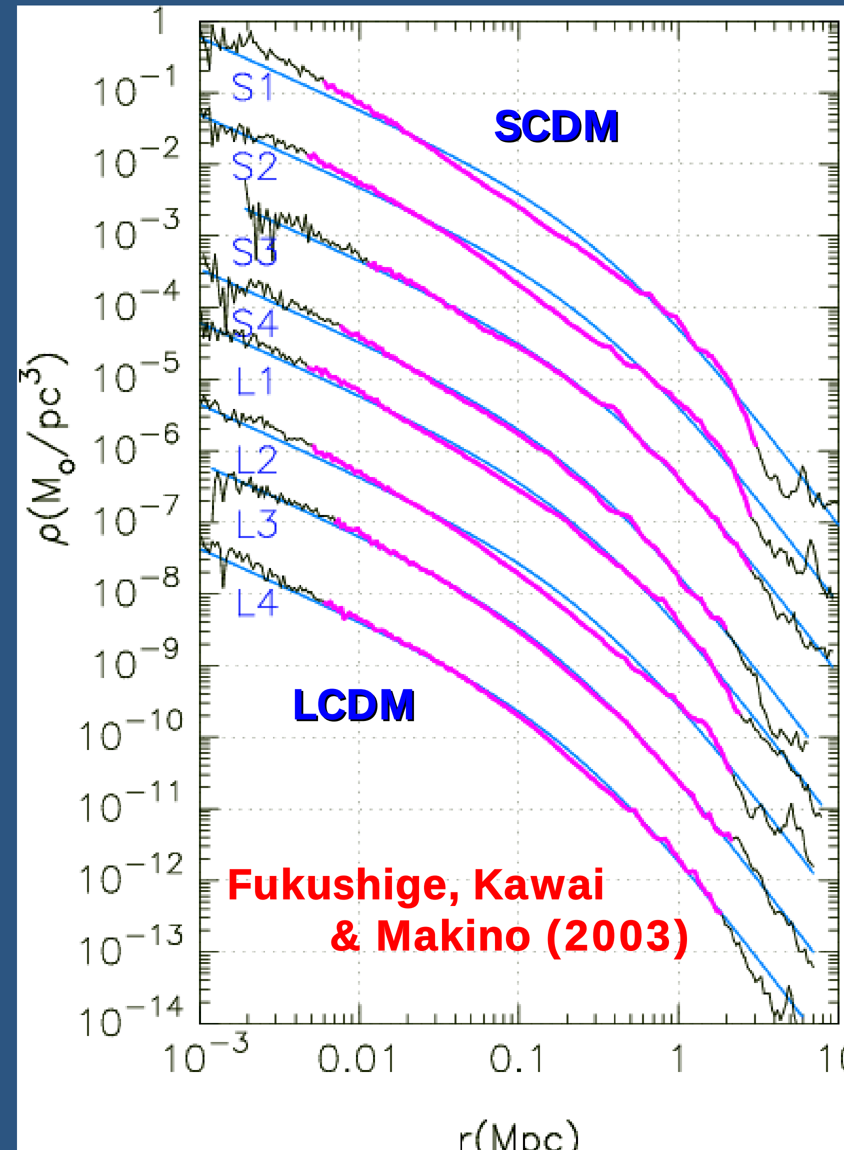
- Density profiles of collisionless CDM halos are well approximated by the following expression, but not necessarily universal

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

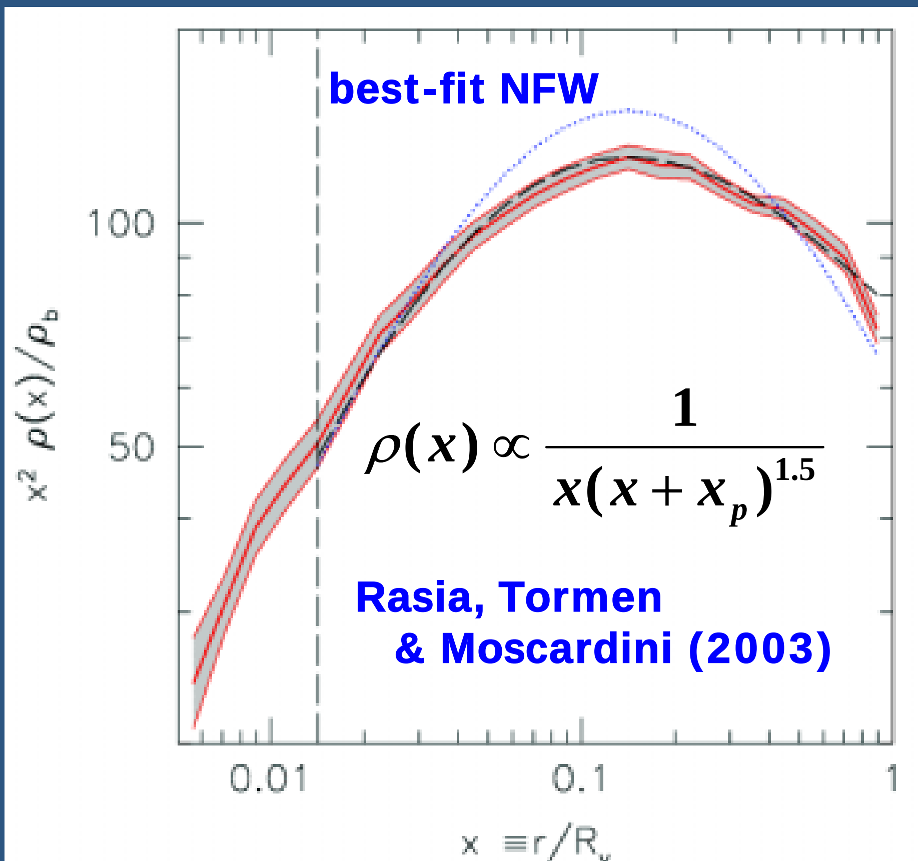
More recent simulations I:

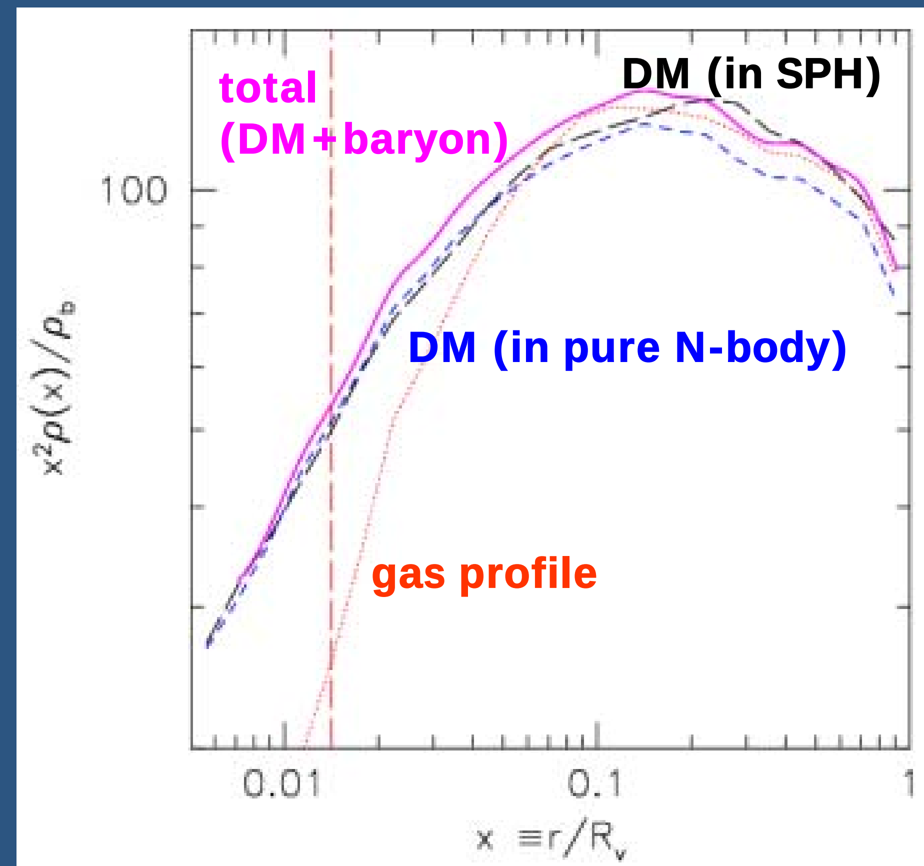






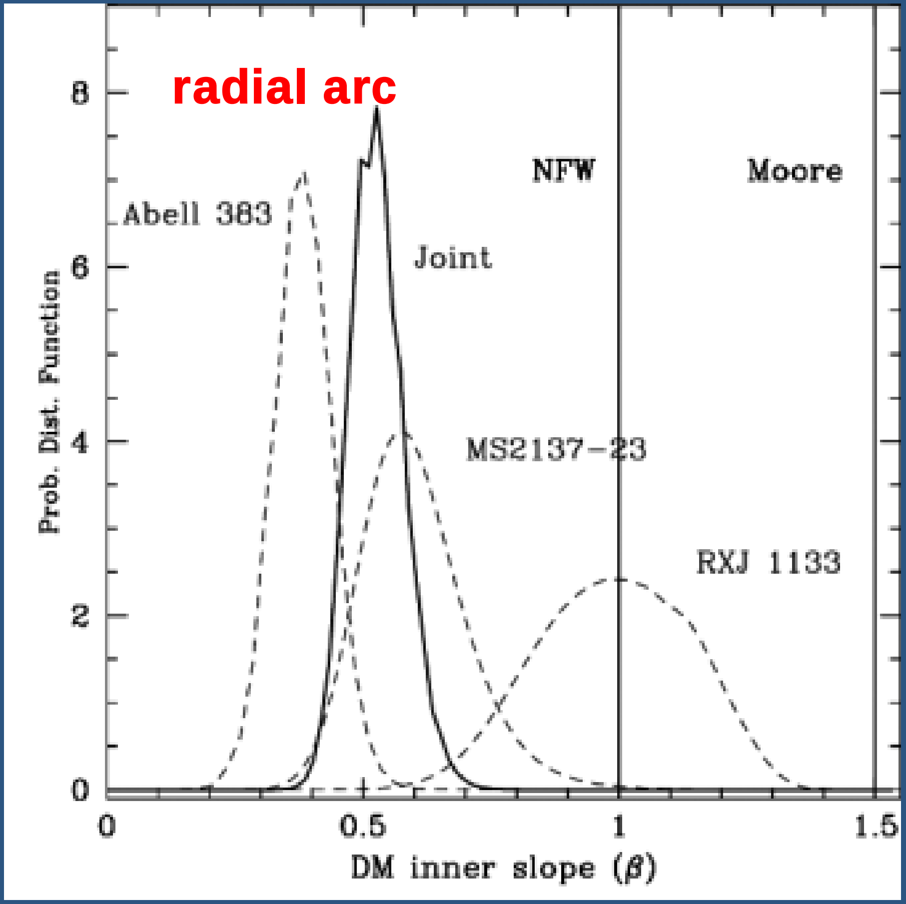
More recent simulations II:

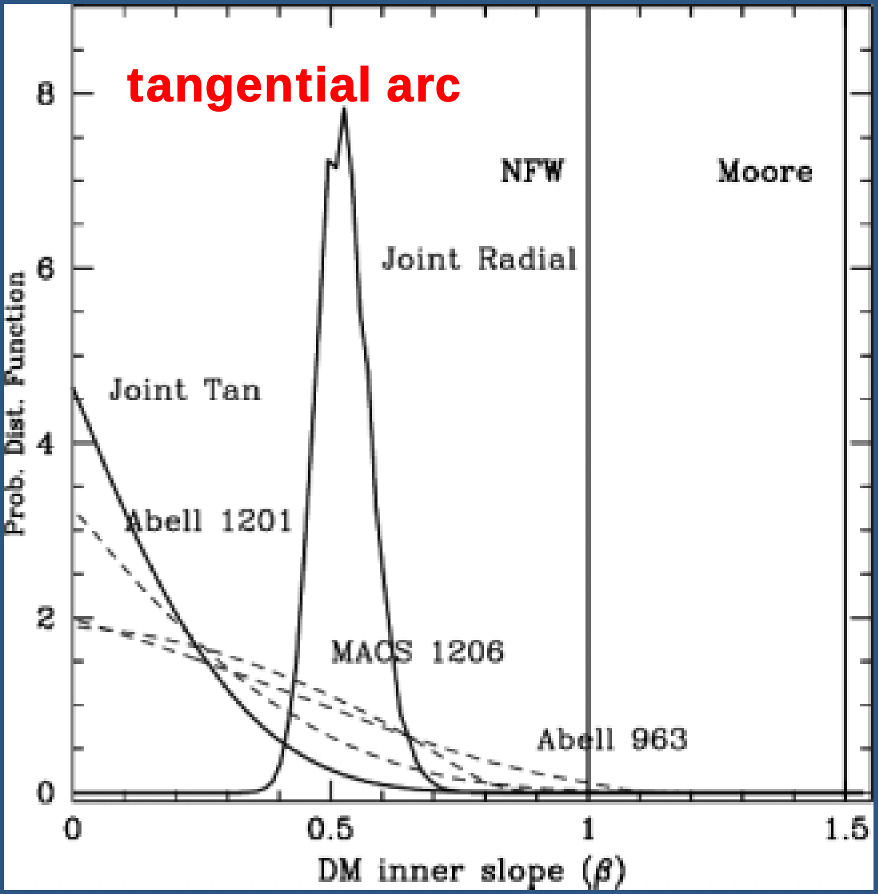




- Claim: hydrodynamic/gas effect results in the compression of the halo density profiles at large radius (?)

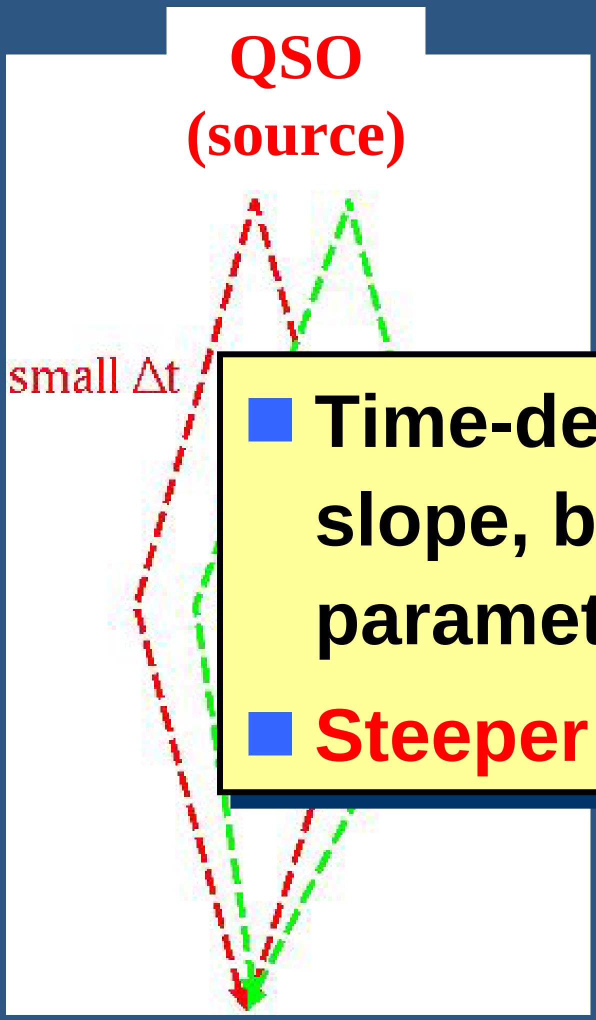
Inner profiles of clusters from lensing analysis

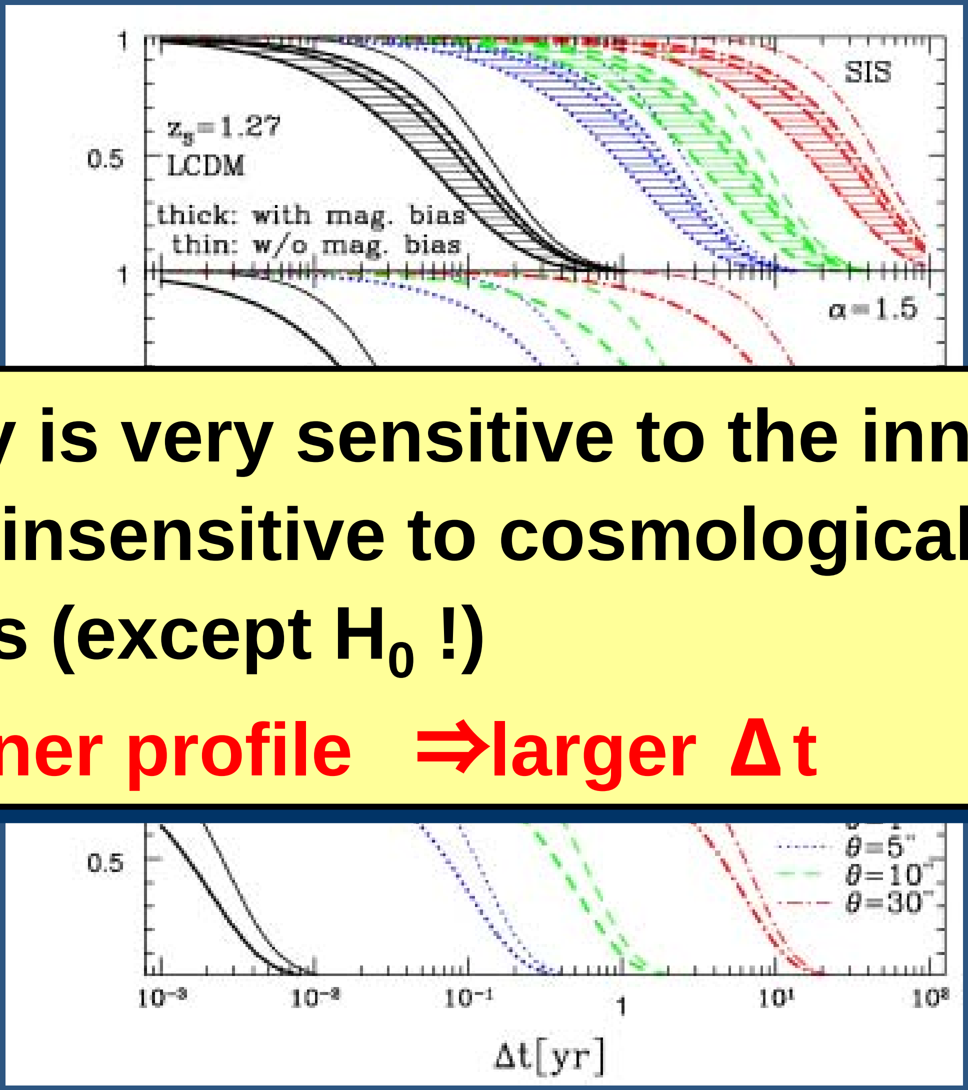




Sand, Treu, Smith & Ellis (2003)

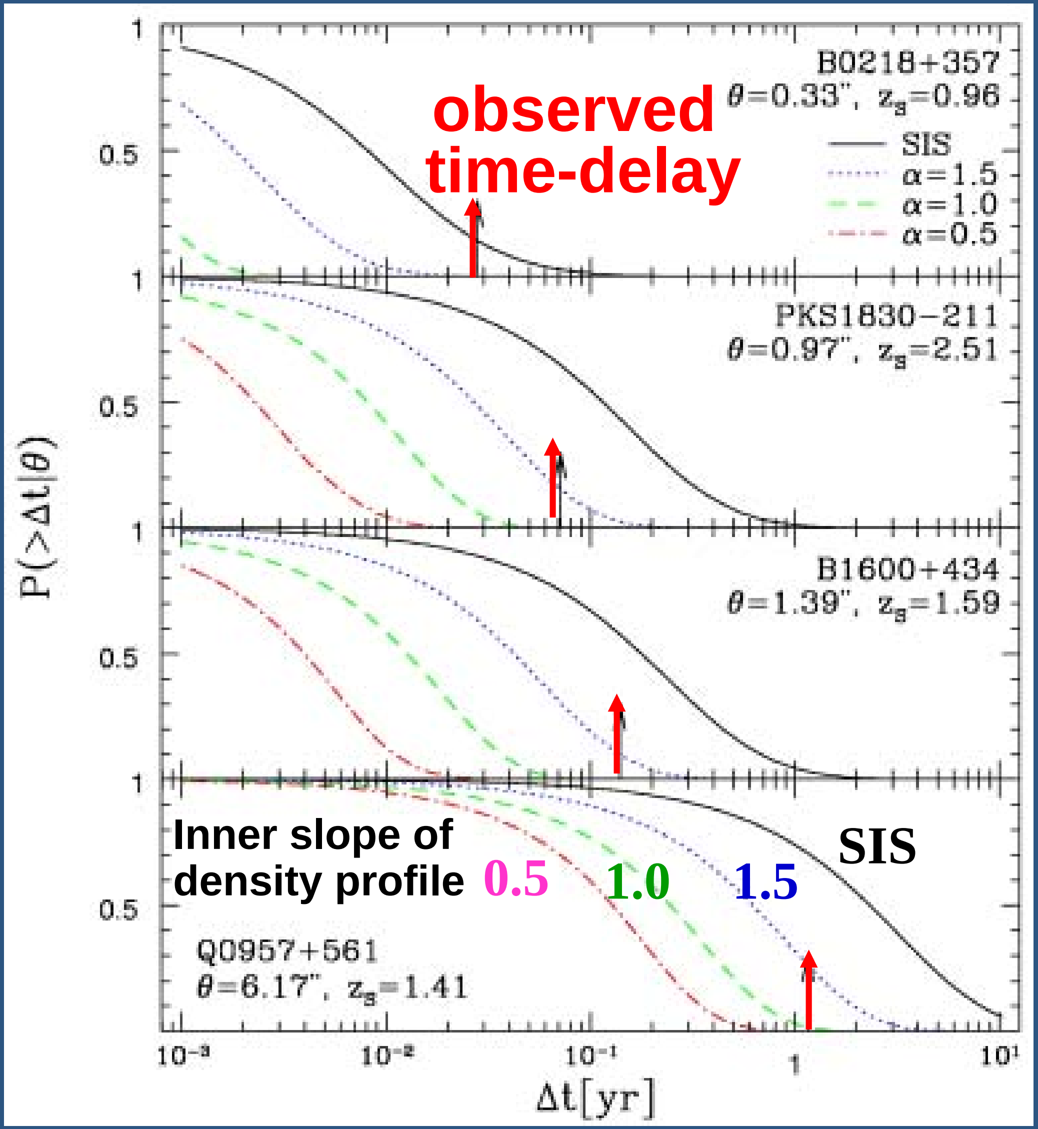
Time-delays in QSO multiple images to probe the halo density profile





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

Tentative applications to 4 lens systems

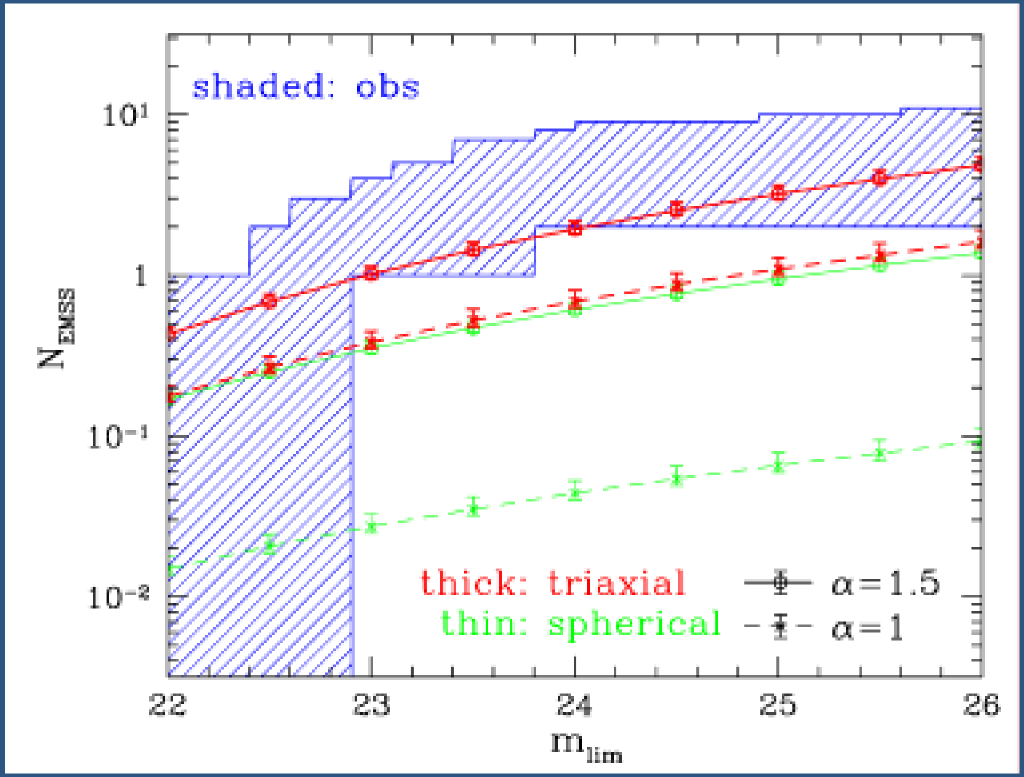


- Observed time-delays generally prefer a steeper central cusp
  $\propto r^{-1.5}$
- needs future statistical study

Oguri, Taruya, Suto & Turner (2002)

Comparison with observed arc statistics

Previous model predictions are known to be significantly smaller than the observed number of lensed arcs (Luppino et al. 1999)



More realistic modeling of dark halos from simulations (inner slope of α=1.5 and non-sphericity) reproduces the observed frequency of arcs.

Oguri, Lee + YS (2003)

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 ?

?

Observations

Core from dwarf galaxies
Cusp from lensing

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

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

Part 4:

Estimate of the value of σ_8 from cluster abundances

Mass fluctuation amplitude: σ_8

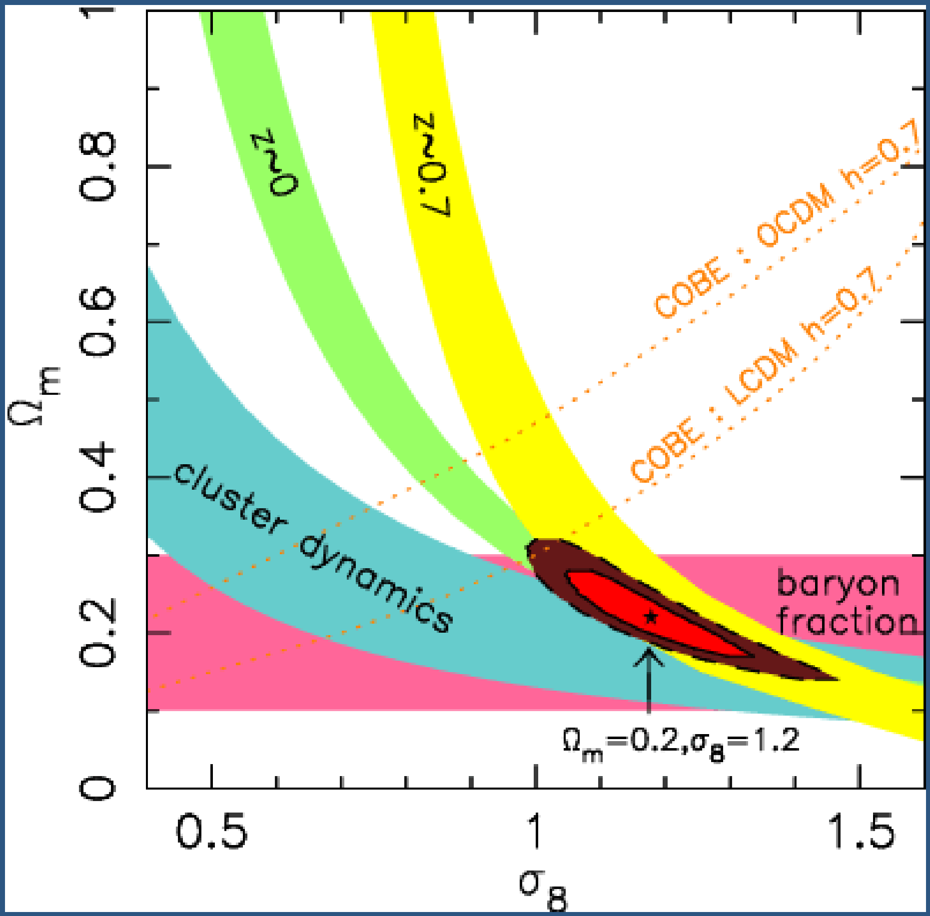
- **WMAP (ΛCDM)**
  - $\sigma_8 = 0.9 \pm 0.1$
- **WMAP+ACBAR +CBI+2dFGRS +Lyα (ΛCDM)**
  - $\sigma_8 = 0.84 \pm 0.04$
- **Lensing**
  - $\sigma_8 = 0.7 \sim 1.0$
- **Cluster abundance**
  - $\sigma_8 = 0.7$ or 1.0 ???

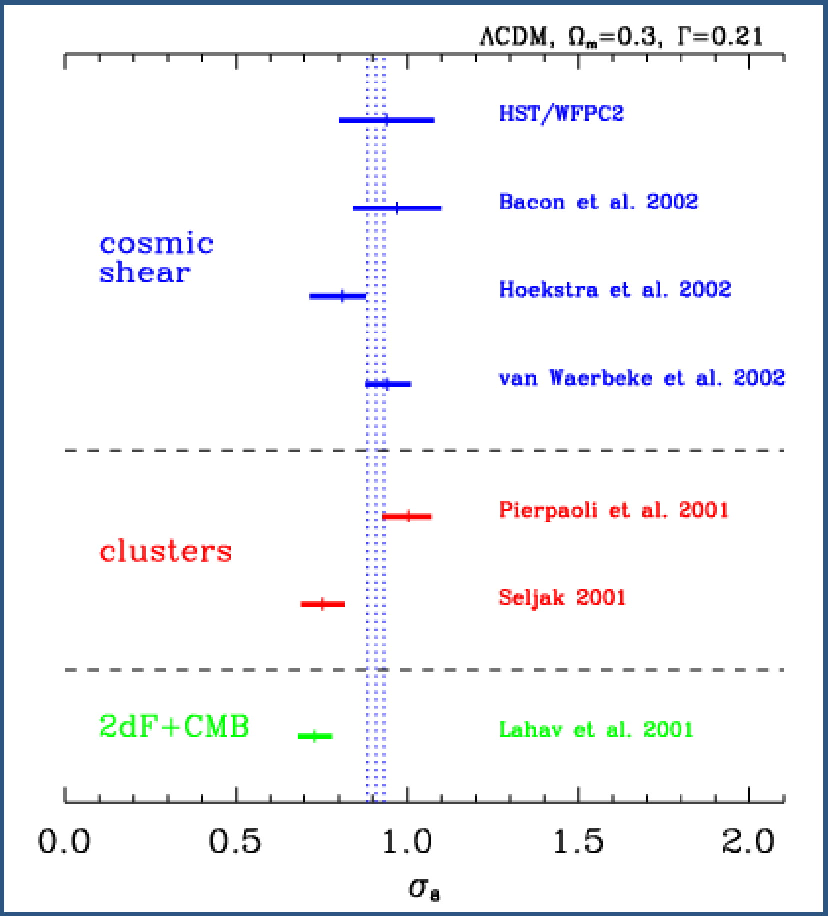
Method	σ_8	Reference
PL CDM+*WMAP*	0.9 ± 0.1	Spergel et al. 03
Weak lensing	0.72 ± 0.18	Brown et al. 02
Weak lensing	0.86	Hoekstra et al. 02
Weak lensing	0.69	Jarvis et al. 02
Weak lensing	0.96 ± 0.12	Bacon et al. 02
Weak lensing	0.92 ± 0.2	Refregier et al. 02
Weak lensing	0.98 ± 0.12	Van Waerbeke et al. 02
Galaxy vel. fields	0.73 ± 0.1	Willick & Strauss 98
CBI SZ detection	1.04 ± 0.12	Komatsu & Seljak 02
High-z clusters	0.95 ± 0.1	Bahcall & Bode 02

Scaled to ΛCDM case with $\Omega_m=0.28$

Spergel et al. (2003)

σ_8 from cluster abundances and lensing



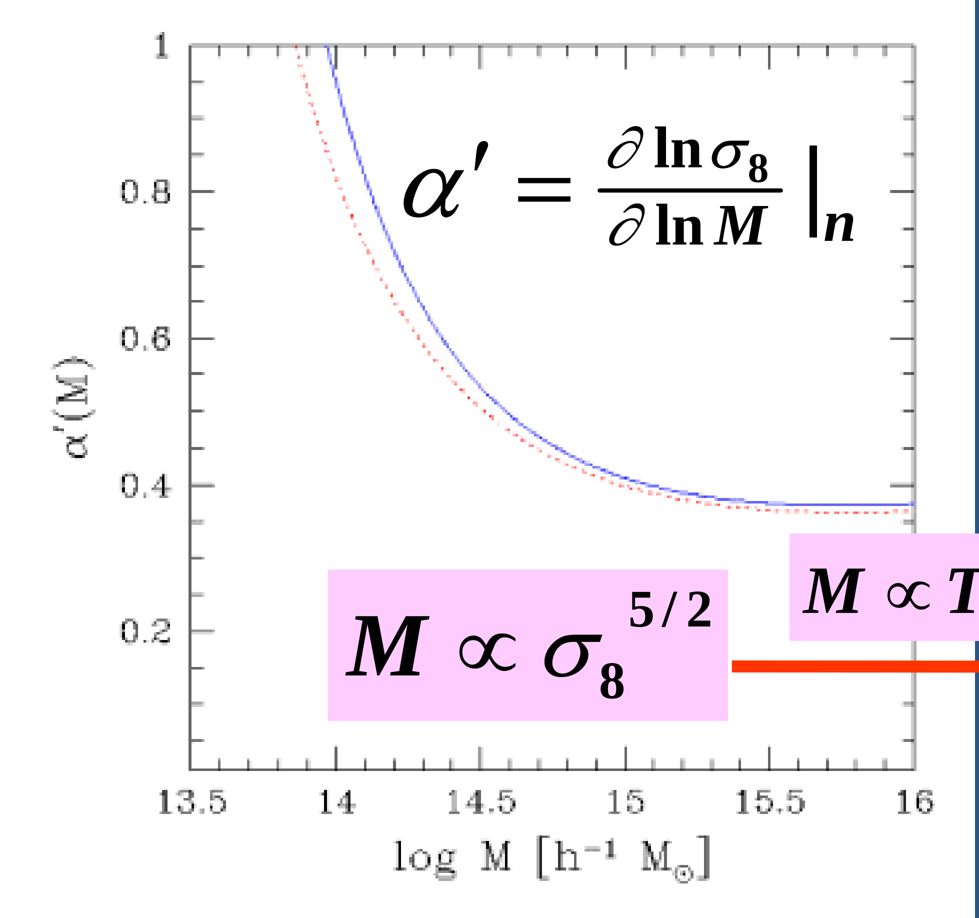


N.Bahcall:
Physica Scripta T85(2000)32

Refregier et al.
ApJ 572(2002)131

From mass to temperature of X-ray clusters

$$n(M) \xrightarrow{\text{Virial Theorem}} n(\sigma_{\text{DM}}) \xrightarrow{\beta} n(T_X)$$



$$\alpha' = \frac{\partial \ln \sigma_8}{\partial \ln M}\Big|_n$$

$$M \propto \sigma_8^{5/2}$$

$$M \propto T_X^{3/2}$$

ratio of specific energies

$$\beta = \frac{\mu m_p \sigma_{DM}^2}{kT_X}$$

to match observed n(T): degeneracy between ICM physics & power spectrum normalization

$$\beta \propto \sigma_8^{5/3}$$

Evrard et al. (2002)

Fitting to the local temperature function

Evrard (2003)

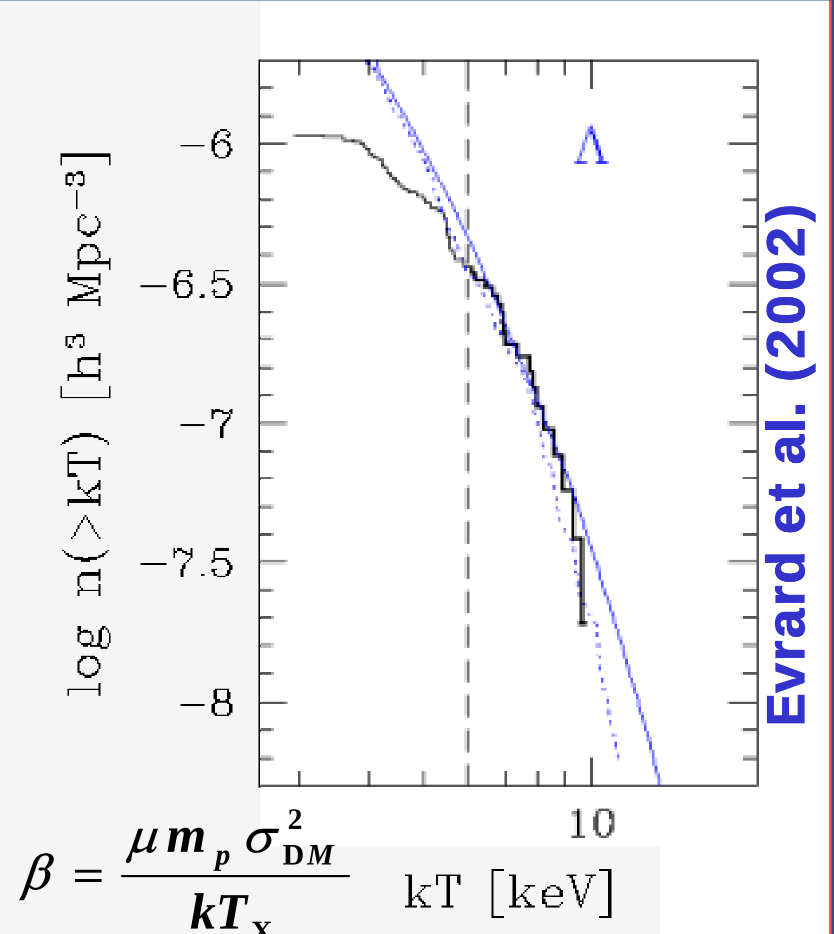
best fit:

$\beta = (1.10 \pm 0.07)\sigma_8^{5/3}$

from the observed n(>T) by Markevitch (1998) and the Hubble volume simulations (Evrard et al. 2002)

+ virial theorem (σ_{DM}-M)

⇒ mass scale calibration (c=5 NFW)



$$\beta = \frac{\mu m_p \sigma_{DM}^2}{kT_X}$$

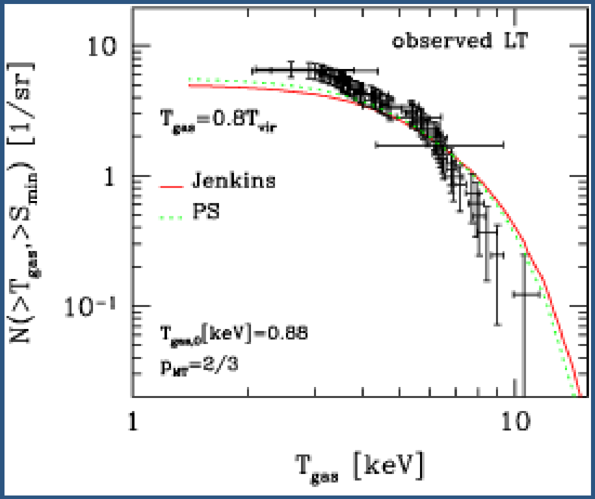
$$hM_{500}^{tot}(6\ \mathrm{keV}) = (0.64 \pm .06)\sigma_8^{5/2} \times 10^{15}\,\mathrm{M_{sun}}$$

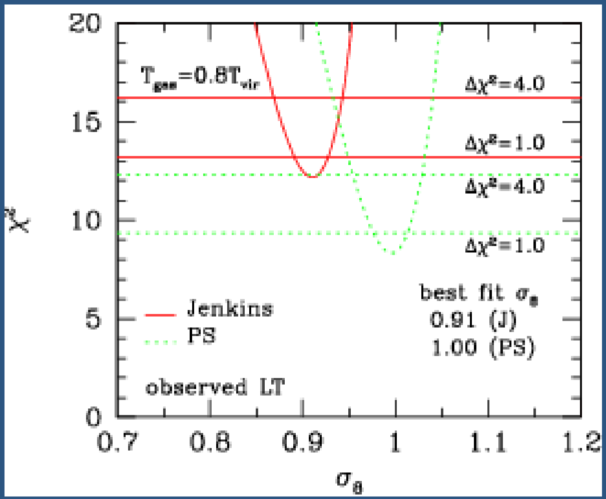
What is the absolute mass scale of cosmic structure ?

References	M_{500}(6 keV) ($10^{15}h^{-1}$ M_{sun})	Comments
Evrard, Metzler & Navarro 96	0.52	Lagrangian hydro
Bryan & Norman 98	0.78	Eulerian hydro
Mathiesen & Evrard 01	0.87 0.83	spectral T, 0.5-9.5 keV spectral T, 2-9.5 keV
Mohr, Mathiesen & Evrard 99	0.47	from beta-model fit to A1795
Nevalainen, Markevitch & Forman 00	0.17	ASCA radial T gradients
Finoguenov, Reiprich & Bohringer 01	0.30	ASCA radial T gradients (larger sample)
Allen, Schmidt & Fabian 02	0.39	Chandra radial T (Δ=2500)
Shimizu, Kitayama, Sasaki & Suto 03	0.40	Lx-T relation & XTF (Ikebe)
Henry 00	0.66	σ_8 = 0.9 (Ω_m =0.3)
Pierpaoli, Scott & White 01	0.58	σ_8 = 1.0 (Ω_m =0.3)
Ikebe et al 02	0.59	σ_8 = 0.9 (Ω_m =0.3)
Seljak 02	0.23	σ_8 = 0.7 (Ω_m =0.35)
average	$0.64\sigma_8^{5/2}$	JMF+VT+local T-ftn (ΛCDM)

Evrard (2003)

σ_8 from the observed TF of X-ray clusters



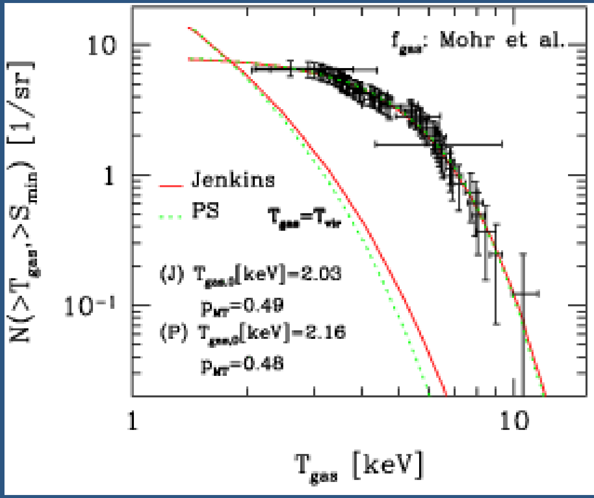


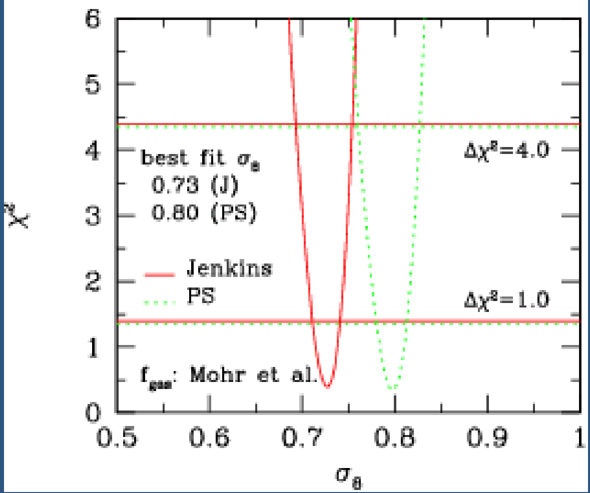
Self-similar MT relation

XTF at (5〜7) keV

σ_8=1.00 (PS)

σ_8=0.91 (Jenkins et al.)





best-fitted MT relation

XTF at (2.5 〜10) keV

σ_8=0.80 (PS)

σ_8=0.73 (Jenkins et al.)

Ω_0=0.3, λ_0=0.7, h=0.7 CDM assumed (Shimizu et al. 2003)

A puzzling (?) summary on σ_8 from cluster abundance

- Recent mass ftn + virial th^m calibrations allow precise calculation of the expected number of clusters as a function of their dark matter gravitational potential depth, $n(\sigma_{DM}^2)$
- Matching the observed temperature ftn, $n(T_X)$, requires that the ratio of specific energies in DM and ICM gas be $\beta=(1.10\pm0.07)\sigma_8^{5/3}$

two scenarios for `standard' ΛCDM (Ω_m=0.3, Ω_Λ=0.7)

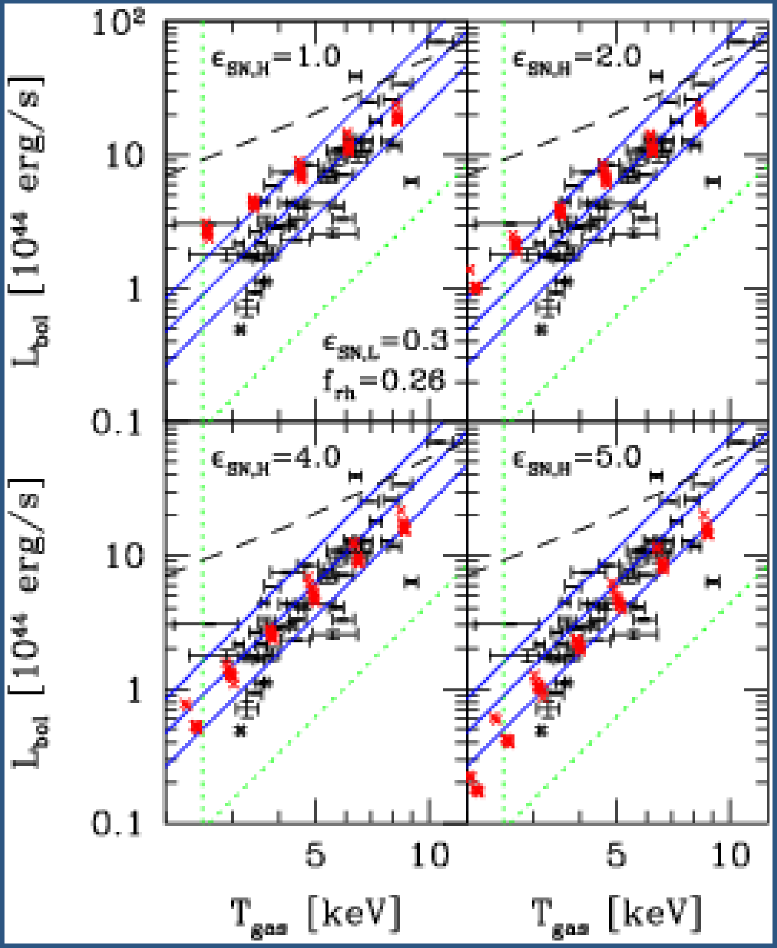
1) high normalization: $\sigma_8=1.0 \pm 0.1$ $\beta=(1.1\pm0.2)$
   + ICM thermal energy consistent with gravitational heating (+mild PH)
   + galaxies velocity dispersion matches that of dark matter

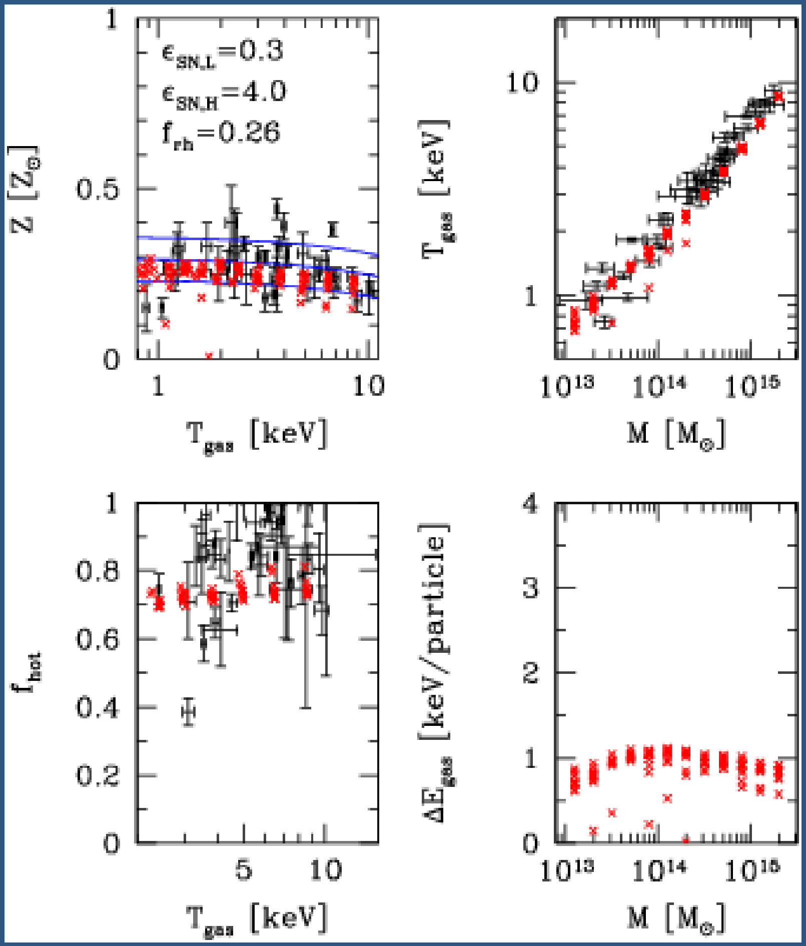
2) low normalization: $\sigma_8=0.7 \pm 0.1$ $\beta=(0.61\pm0.15)$
   - ICM must be heated to 1.8 times level of gravitational infall
   - galaxies must be hotter than dark matter by a similar factor (in σ^2)

Low σ_8 normalizations create problems for cluster energetics!

Evrard (2003)

Enhanced heating model at high-z



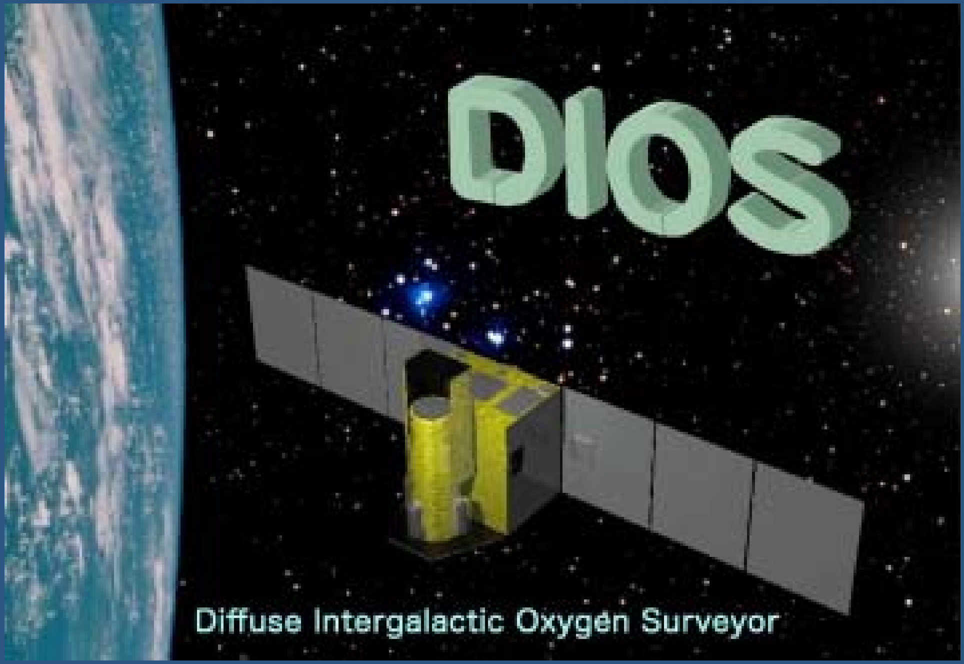


Shimizu et al. (2003)

- ε_{RG} =0 for simplicity
- ε_{SN} = 0.3 (z<7) and ε_{SN} = 1, 2, 4 or 5 (z>7)

Part 5:

Searching for cosmic missing baryon via oxygen emission lines



DIOS

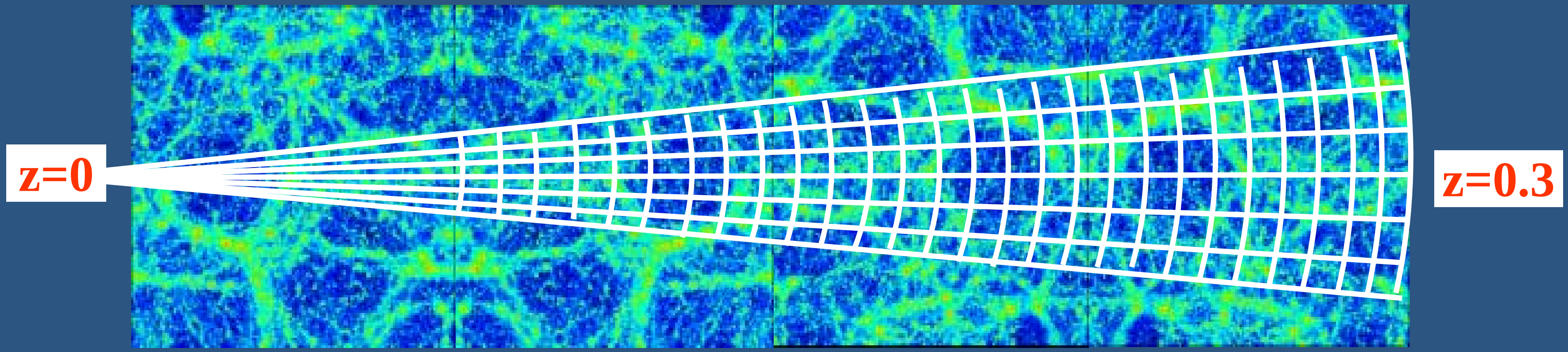
Diffuse Intergalactic Oxygen Surveyor

DIOS: **D**iffuse **I**ntergalactic **O**xygen **S**urveyor

A Japanese proposal of a dedicated X-ray mission to search for missing baryons

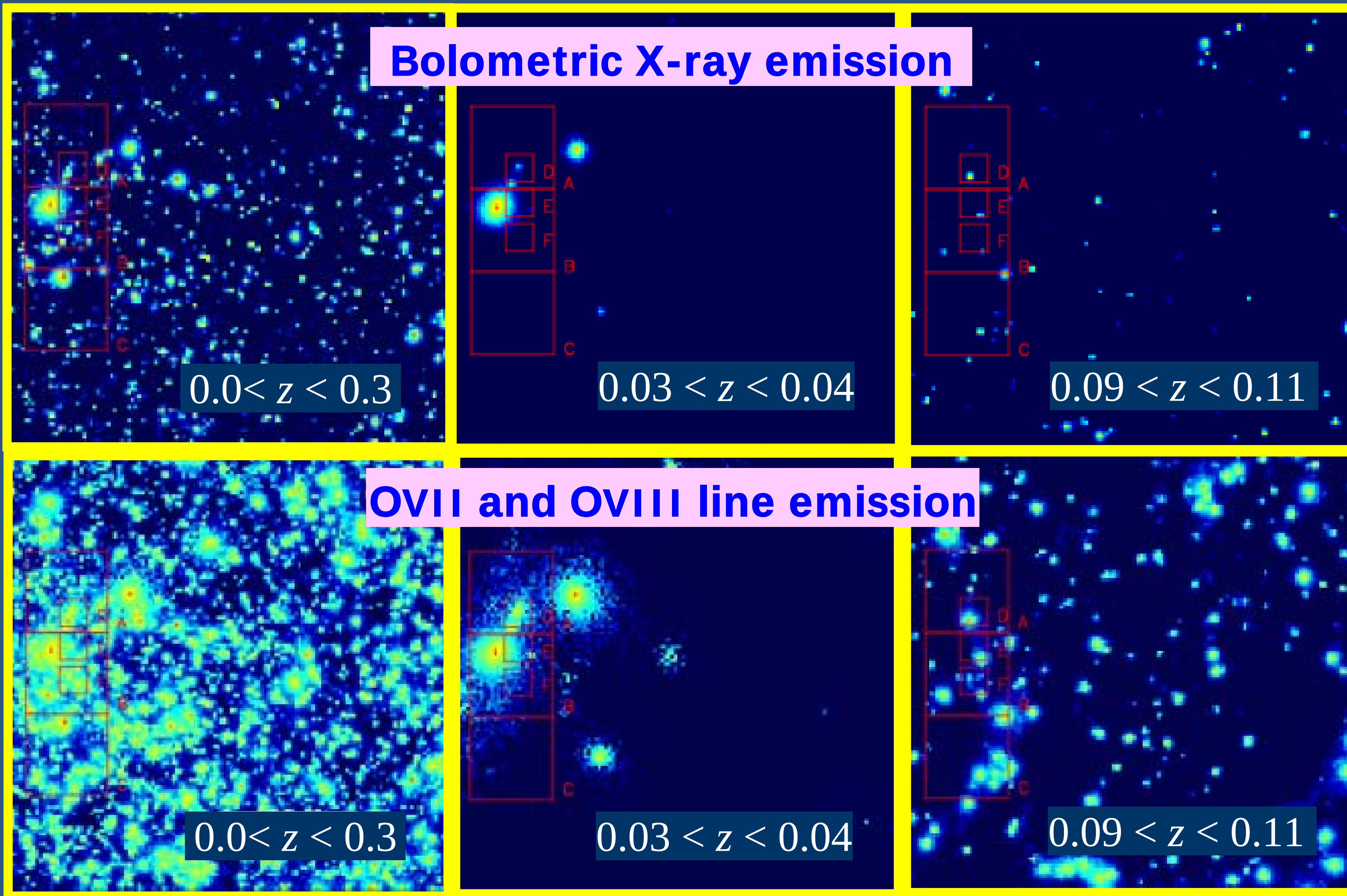
- A dedicated satellite with cost < 40M USD to fill the gap between Astro-E2 (2005) and NeXT (2010?). Launch at Japan in 2008 (?).
- Unprecedented energy spectral resolution ΔE=2eV in soft X-ray band (0.1-1keV)
- Aim at detection of (20-30) percent of the total cosmic baryons via Oxygen emission lines
  - ΔE=2eV, $S_{eff}\,\Omega$=100 [cm^2 deg^2]
  - flux limit = 6×10^{-11} [$erg/s/cm^2/str$]
- PI: Takaya Ohashi (Tokyo Metropolitan Univ.)

Light-cone output from simulation



- **Cosmological SPH simulation** in Ω_m=0.3, Ω_Λ=0.7, σ_8=1.0, and h=0.7 CDM with N=128^3 each for DM and gas (Yoshikawa, Taruya, Jing, & Suto 2001)
- **Light-cone output from z=0.3 to z=0** by stacking 11 simulation cubes of ($75h^{-1}$Mpc)^3 at different z
- **5°×5° FOV mock data** in 64x64 grids on the sky
- 128 bins along the redshift direction (Δz=0.3/128)

Surface brightness on the sky



Metallicity models

Oxygen enrichment scenario in IGM

Type-II SNe → galaxy wind merging → metal pollution in IGM

Metallicity of WHIM is quite uncertain

Adopted models for metallicity distribution

Model I : uniform and constant

$$Z = 0.2\, Z_{solar}$$

Model II : uniform and evolving

$$Z = 0.2\, Z_{solar}\, (t/t_0)$$

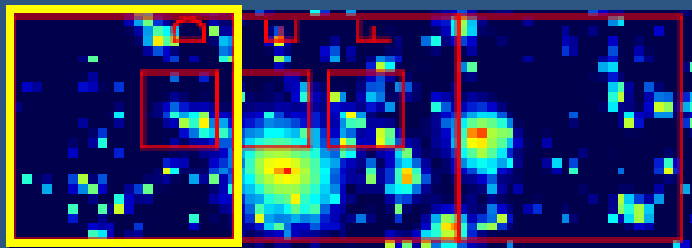
Model III : density-dependent (Aguirre et al. 2001)

$$Z = 0.005\, Z_{solar}\, (\rho/\rho_{\rm mean})^{0.33}$$ (galactic wind driven)

Model IV : density-dependent (Aguirre et al. 2001)

$$Z = 0.02\, Z_{solar}\, (\rho/\rho_{\rm mean})^{0.3}$$ (radiation pressure driven)

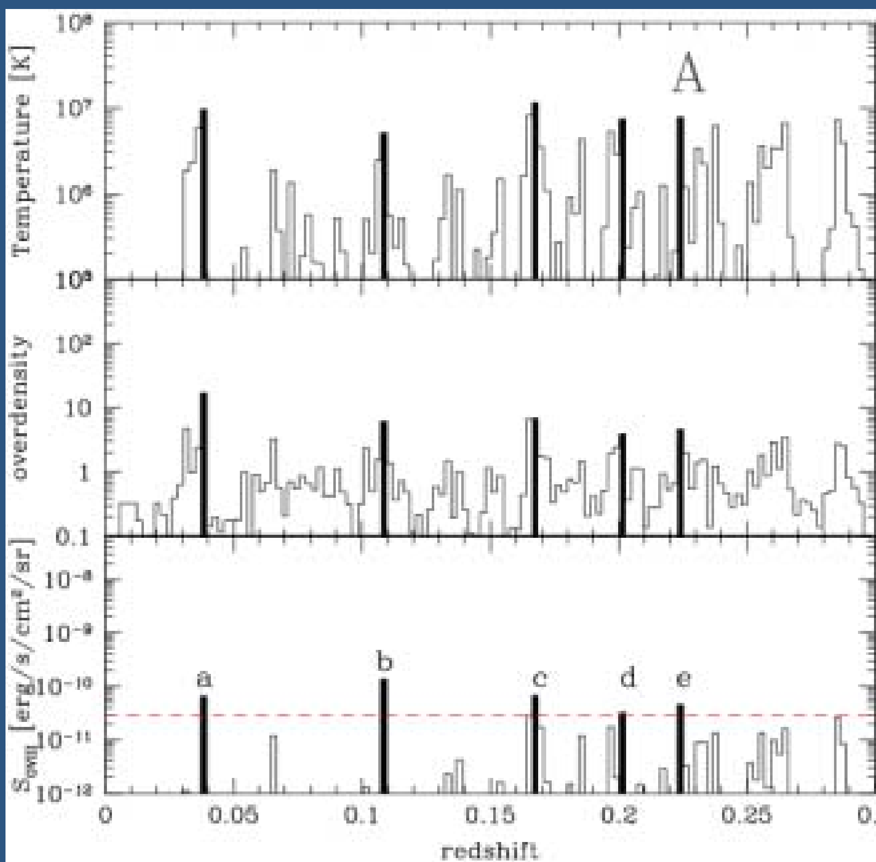
Simulated spectra: region A

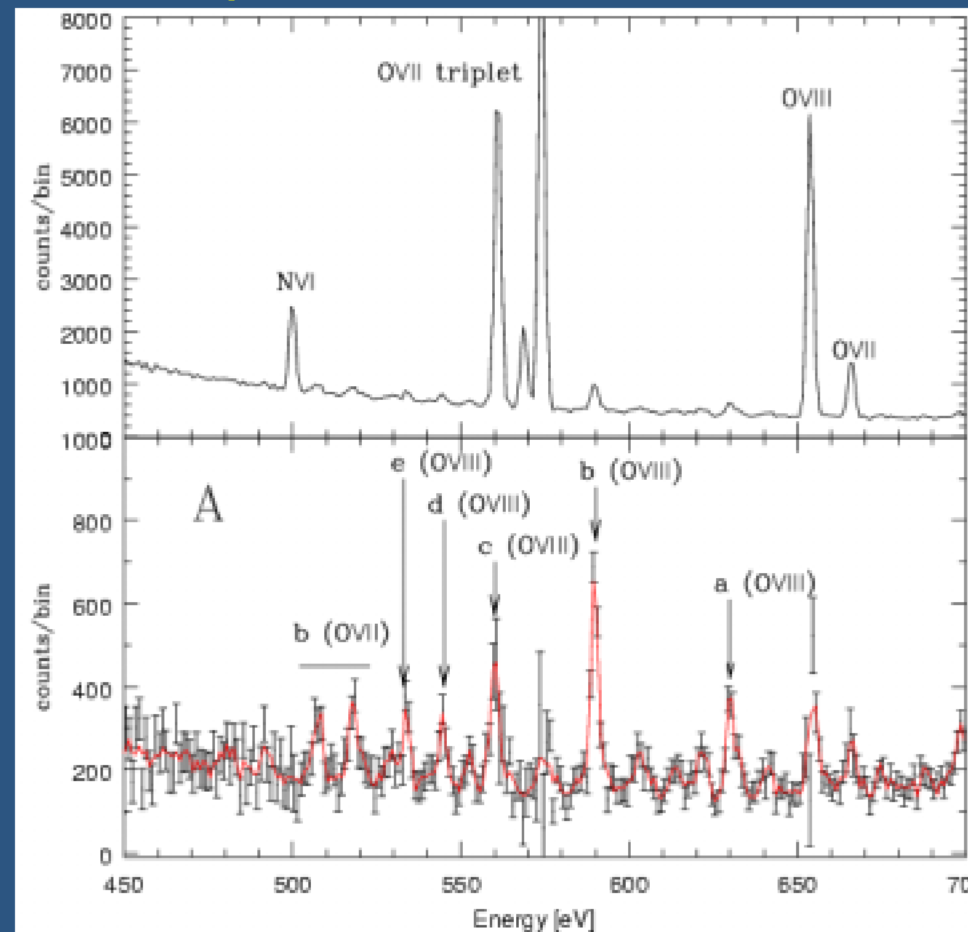


A

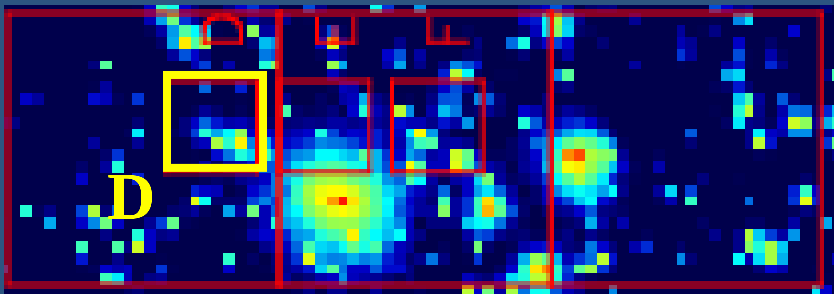
$0.94° \times 0.94° = 0.88\ deg^2$

$T_{exposure} = 3x10^5 sec$



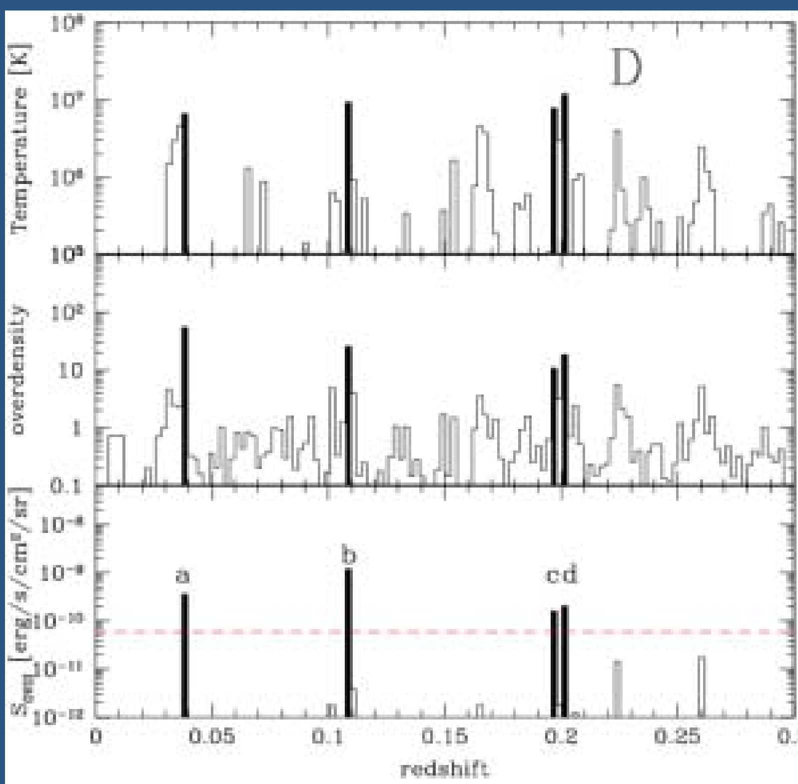


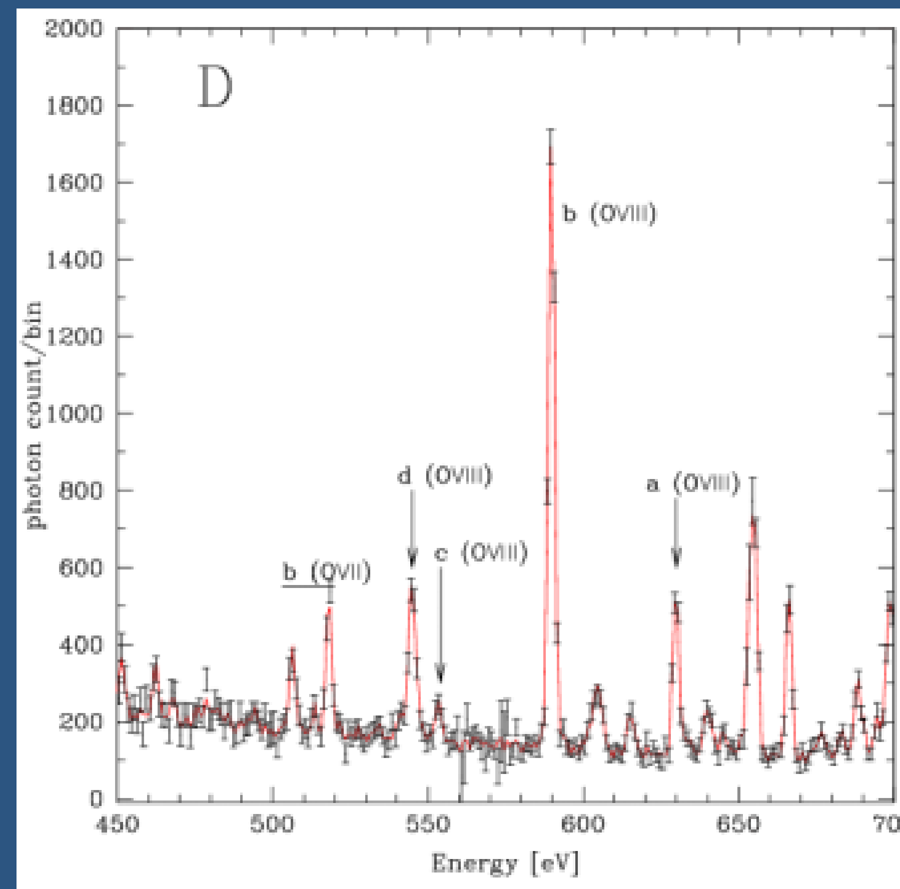
Simulated spectra: region D



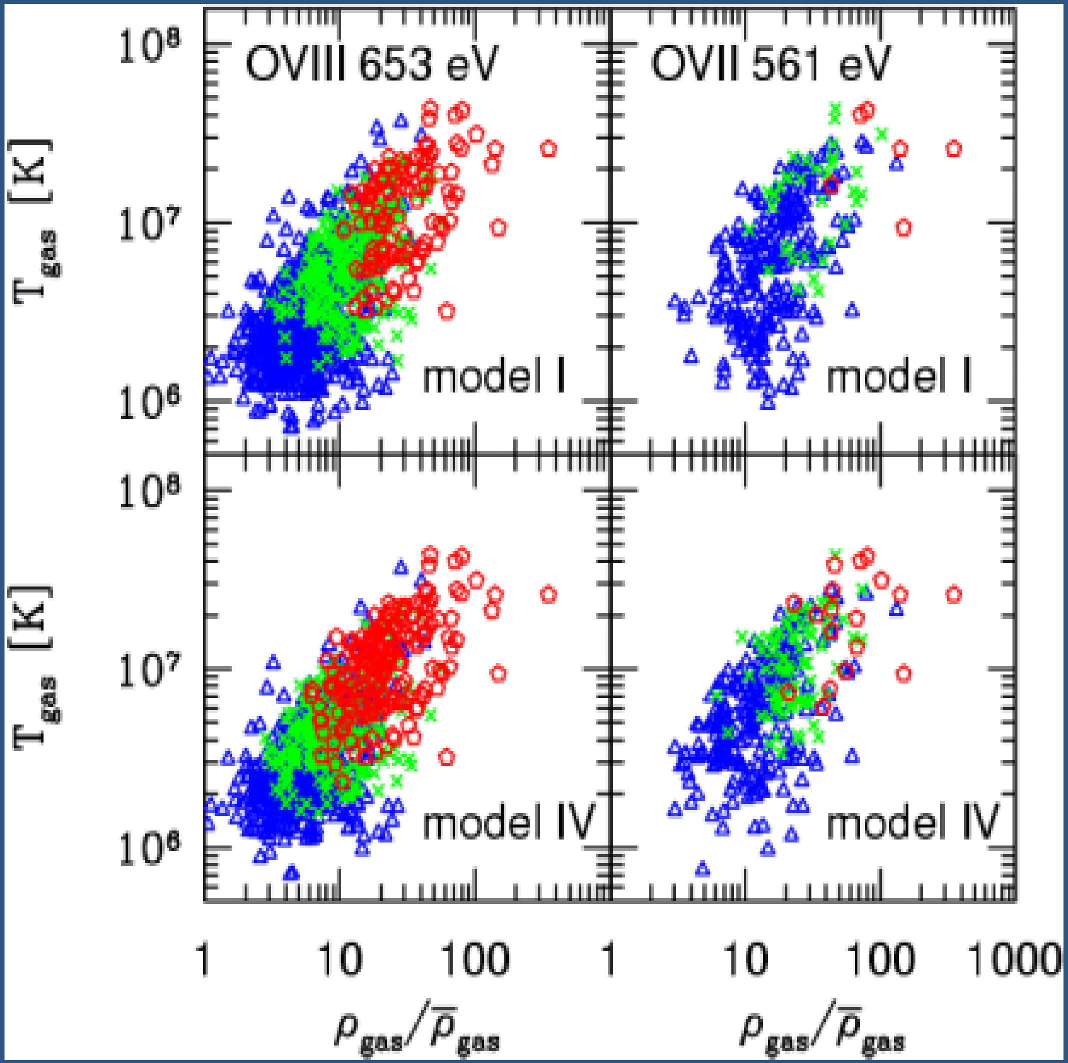
$19' \times 19' = 0.098\ deg^2$

$T_{exposure} = 10^6 sec$





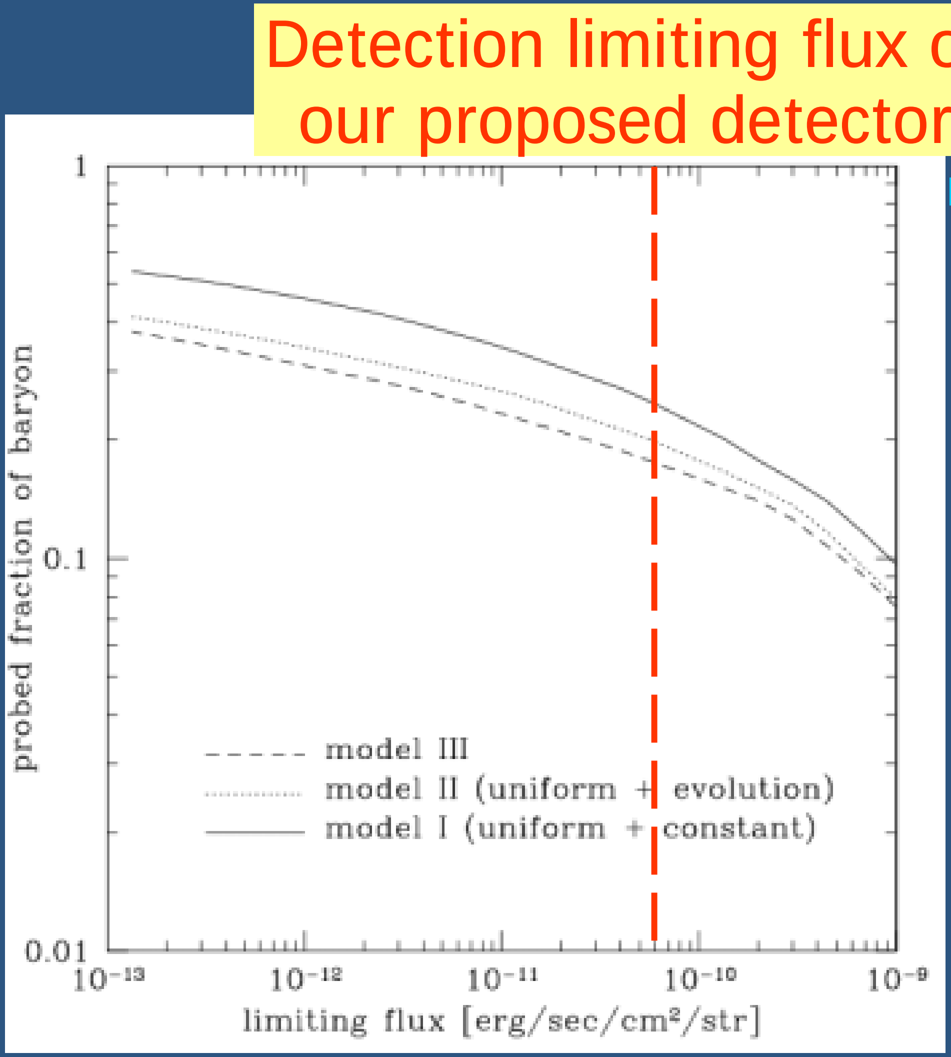
Physical properties of the probed baryons



Each symbol indicate the temperature and the over-density of gas at each simulation grid (4x4 smoothed pixels over the sky and $\Delta z=0.3/128$)

- (red pentagon) $S_x > 3\times10^{-10}$ [erg/s/cm^2/sr]
- (green cross) $S_x > 6\times10^{-11}$ [erg/s/cm^2/sr]
- (blue triangle) $S_x > 10^{-11}$ [erg/s/cm^2/sr]

Expected fraction of WHIM detectable via Oxygen emission lines (in principle)

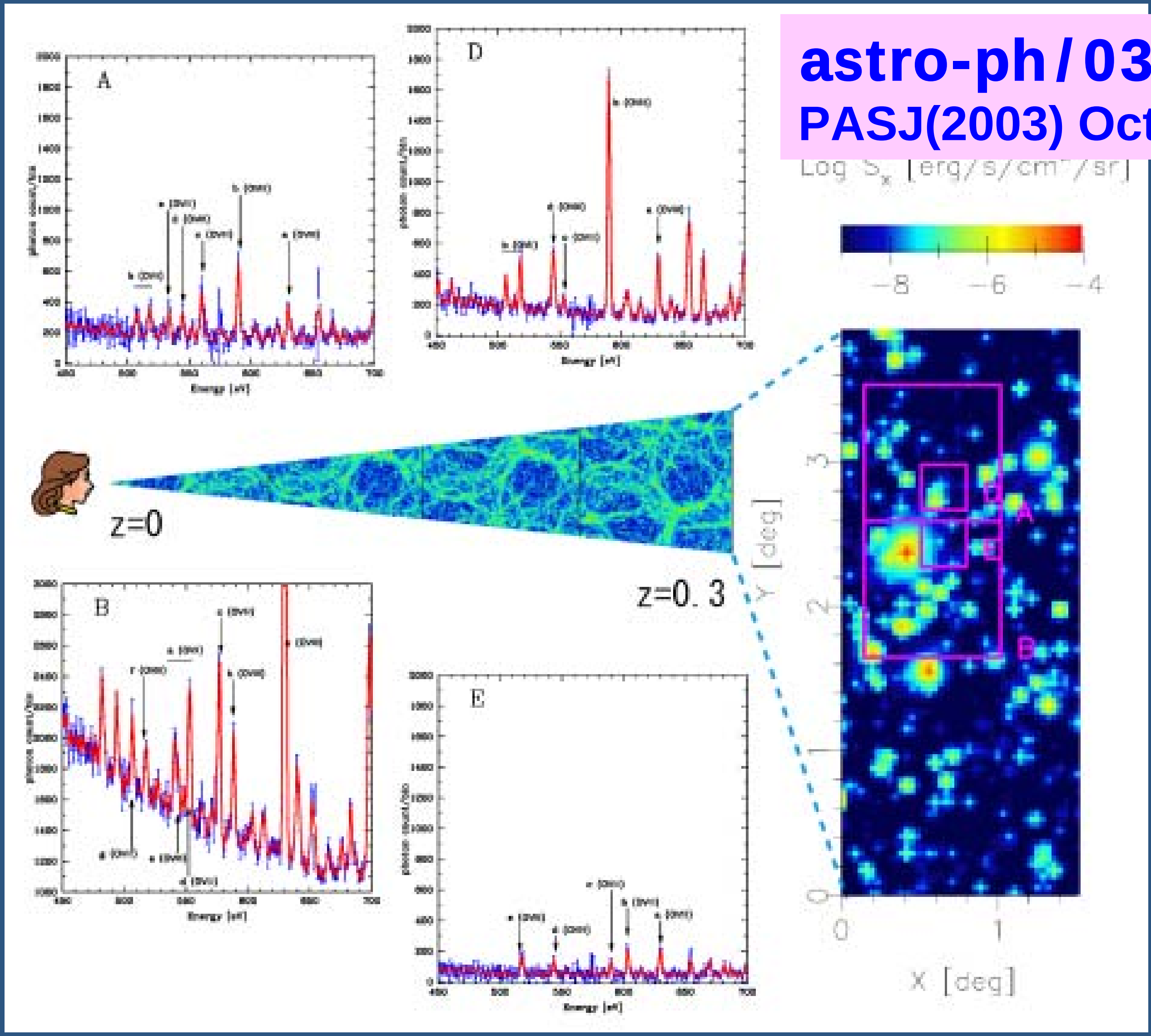


- Our proposed mission (flux limit = 6×10^{-11} [erg/s/cm^2/str]) will be able to detect (20-30) percent of the total cosmic baryons via Oxygen emission lines **in principle**.

Detectability of Warm-Hot Intergalactic Medium via Oxygen emission lines

- Mock spectra from cosmological SPH simulation
- **With our proposed mission (20-30) percent of the total cosmic baryons will be detected via Oxygen emission lines** in principle.
  - ΔE=2eV, $S_{eff}\ \Omega$=100 [cm^2 deg^2]
  - flux limit = 6×10^{-11} [erg/s/cm^2/str]
- Things remain to be checked
  - Validity of the collisional ionization equilibrium ?
  - How to properly identify the oxygen lines from the background/noises in reality ?

DIOS: Japanese proposal of a dedicated X-ray mission to search for missing baryons



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

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