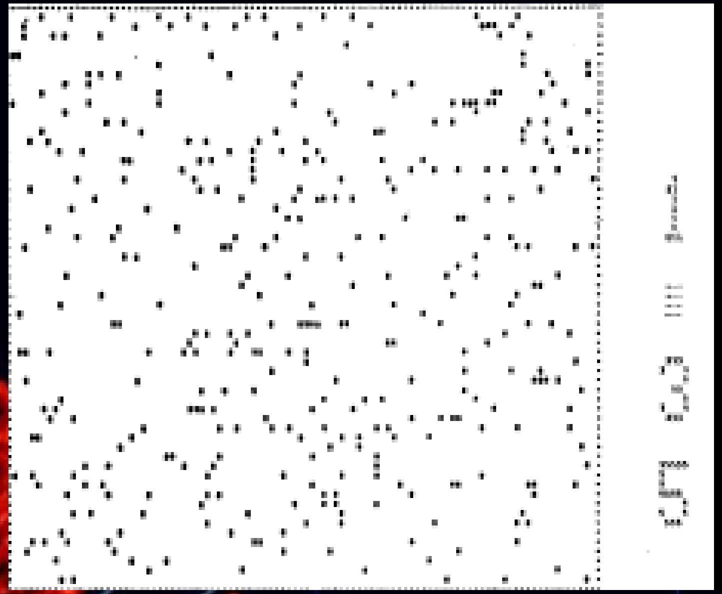
Miyoshi & Kihara (1975)



1/4 century

Evrard et al. (2002)

Ludwig-Maximilians-University

August 6, 2003

Munich, Germany

Confronting the CDM paradigm with numerical simulations

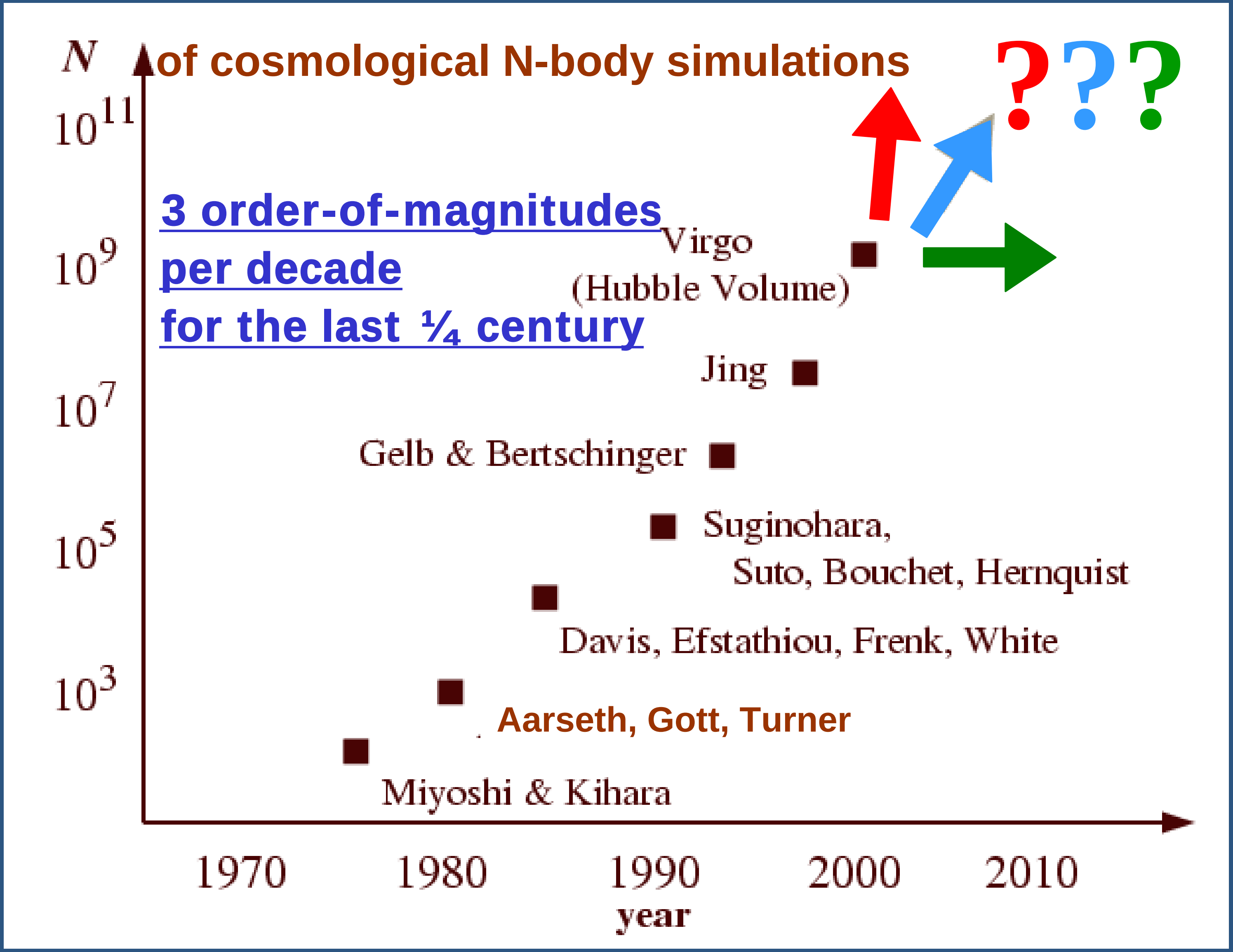
Yasushi Suto

Department of Physics, University of Tokyo

Outline of the talk

- **A brief overview of the "evolution of simulations" of large-scale structure**
- Results from recent analyses of the SDSS (Sloan Digital Sky Survey) galaxy distribution
- Searching for cosmic missing baryon via oxygen emission lines
- Density profiles of dark matter halos

Well-known exponential evolution of "N"



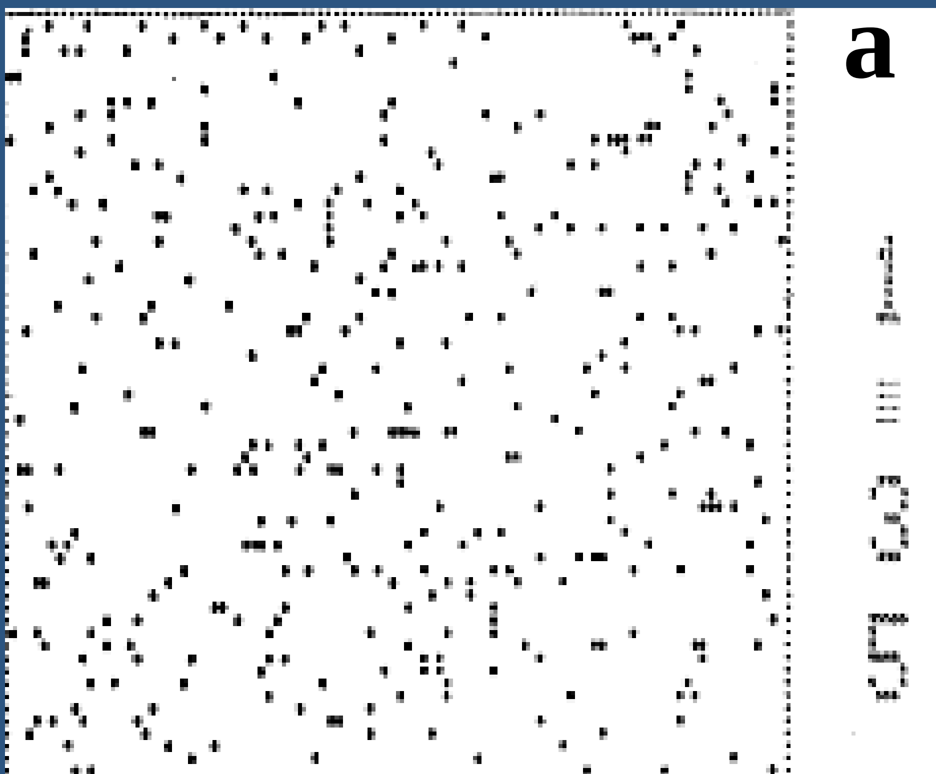
Yoshida (2003)

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)

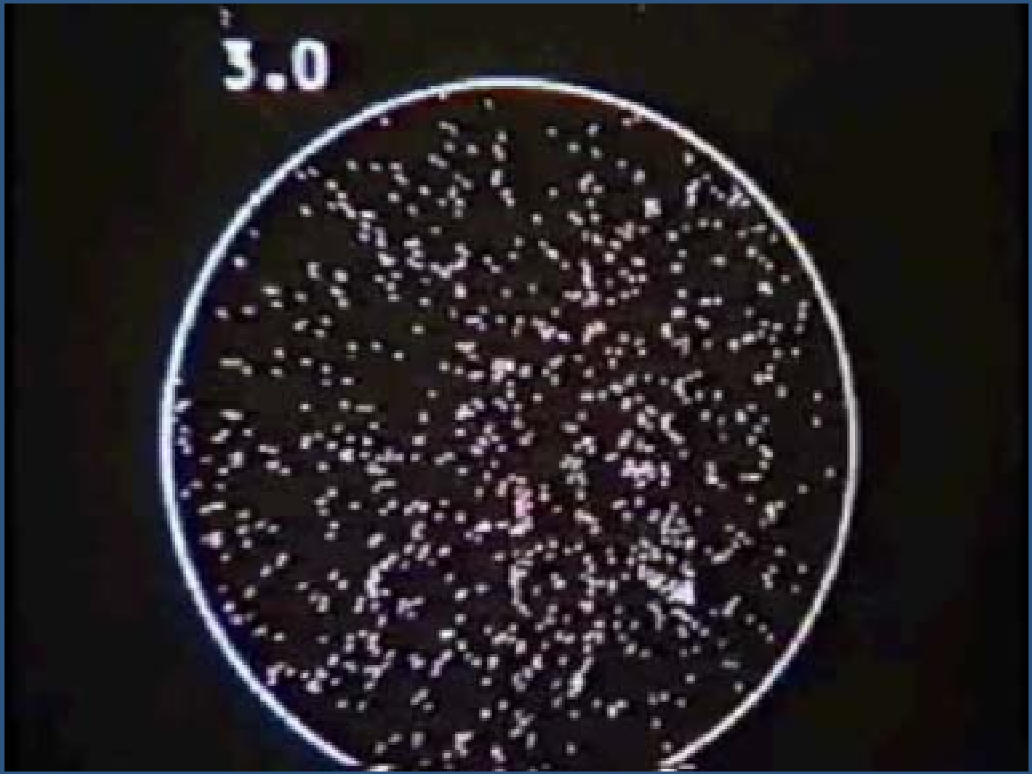
Motivations of Miyoshi & Kihara (1975) : many years ahead in time

> 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):

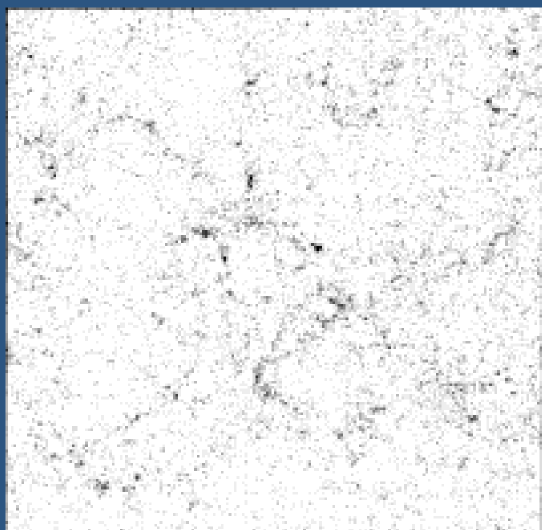
digitized from his old 16mm movie film (2min30sec) on the basis of Aarseth, Gott, & Turner (1979)

Evolution of LSS simulations

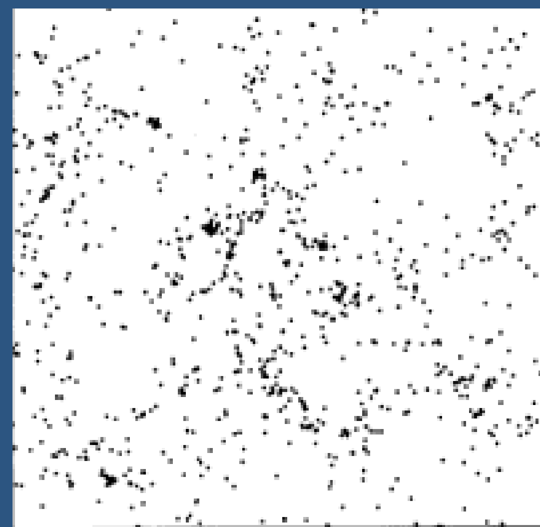
- 1970s: aiming at understanding nonlinear gravitational clustering in the expanding universe
- **1980s: predicting galaxy distribution from dark matter simulations**
  - Toward more realistic predictions
  - Simulation particles ≠ galaxies
  - i.e., galaxy biasing (why not ?)
  - Systematics like redshift-space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

Biased galaxy formation

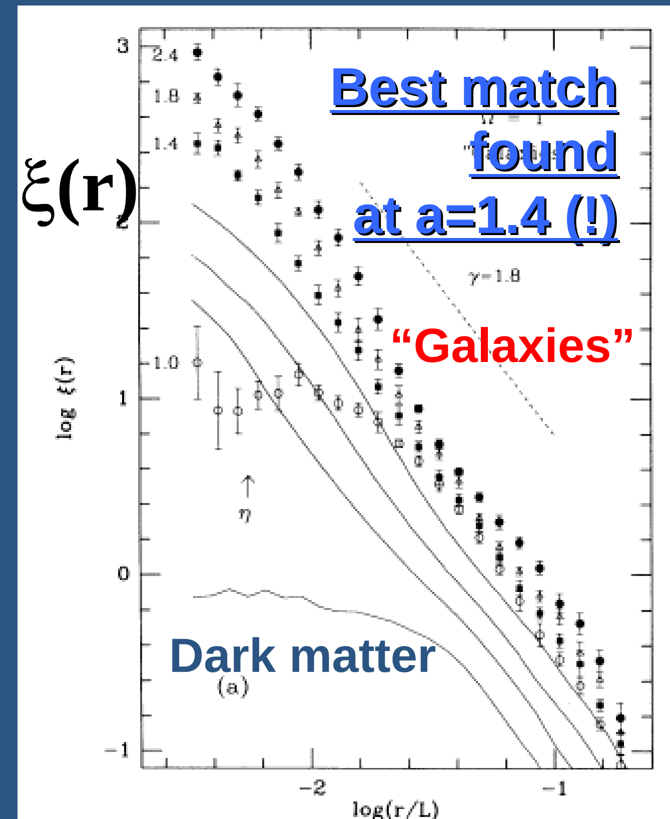
CDM (Ω=1)



“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.

A latest simulation movie

SPH simulation in ΛCDM :

dark matter ⇒ X-ray emitting hot gas ⇒ galaxy

(Yoshikawa, Taruya, Jing & Suto 2001)

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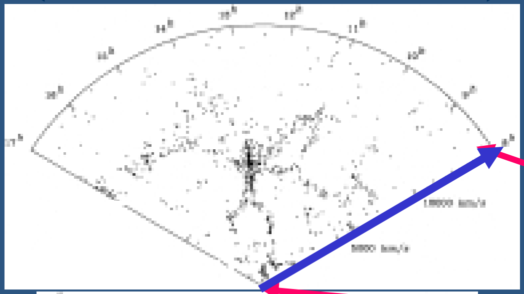
Clustering of luminous objects on the light-cone

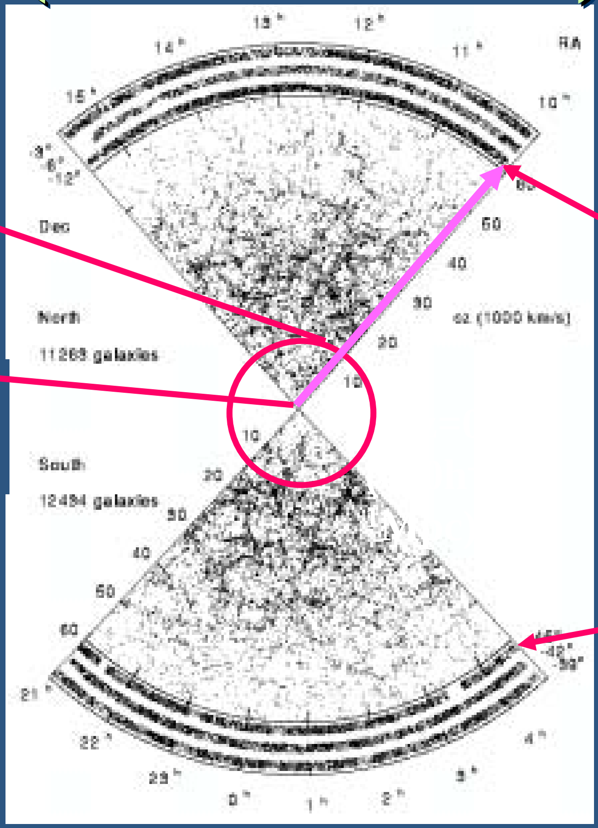
1986
(local universe)

1996
(shallow universe)

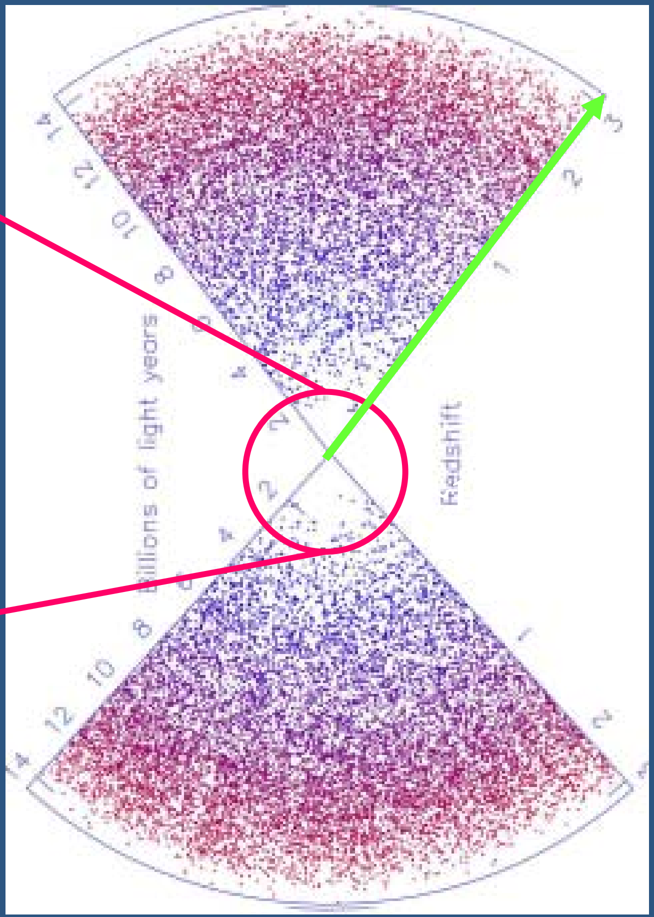
2001
(universe on the light-cone)



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



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

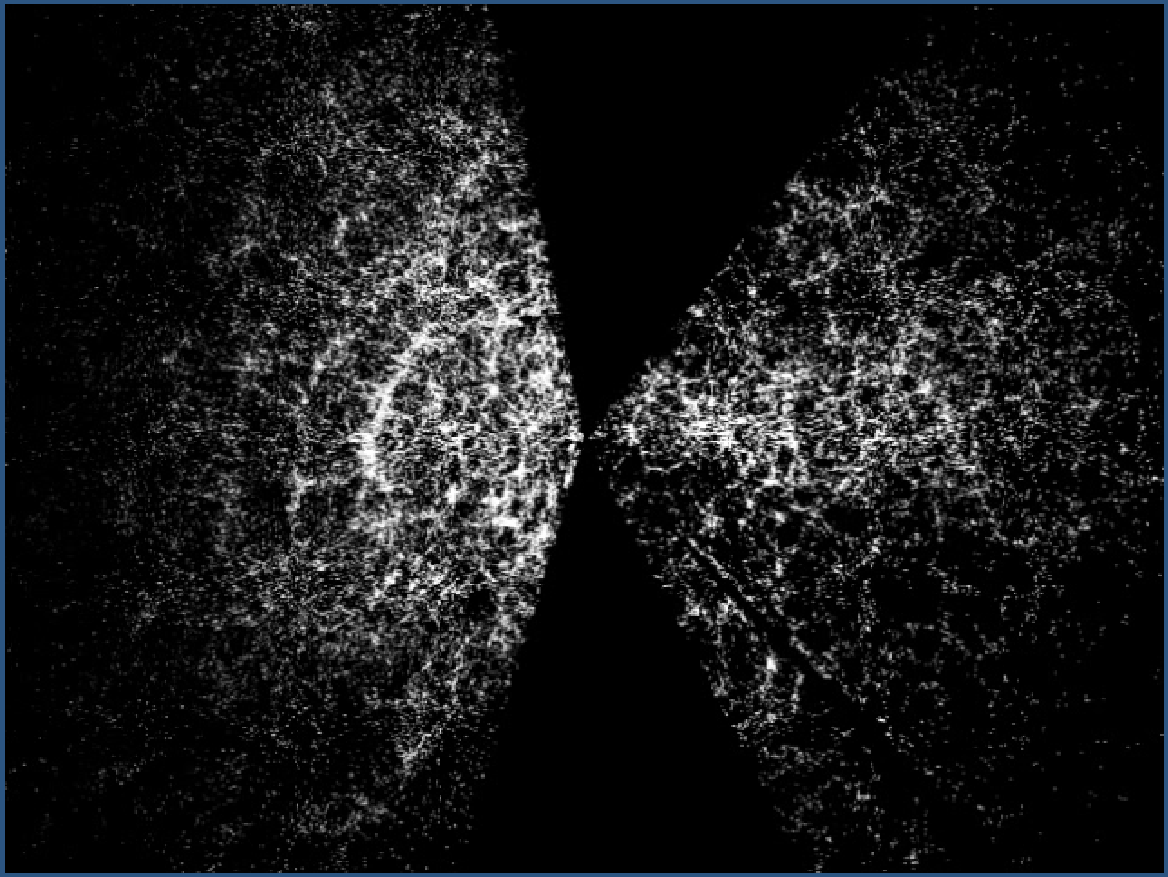


2dF QSO survey:
http://www.2dfquasar.org

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

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

http://www.sdss.org/dr1/

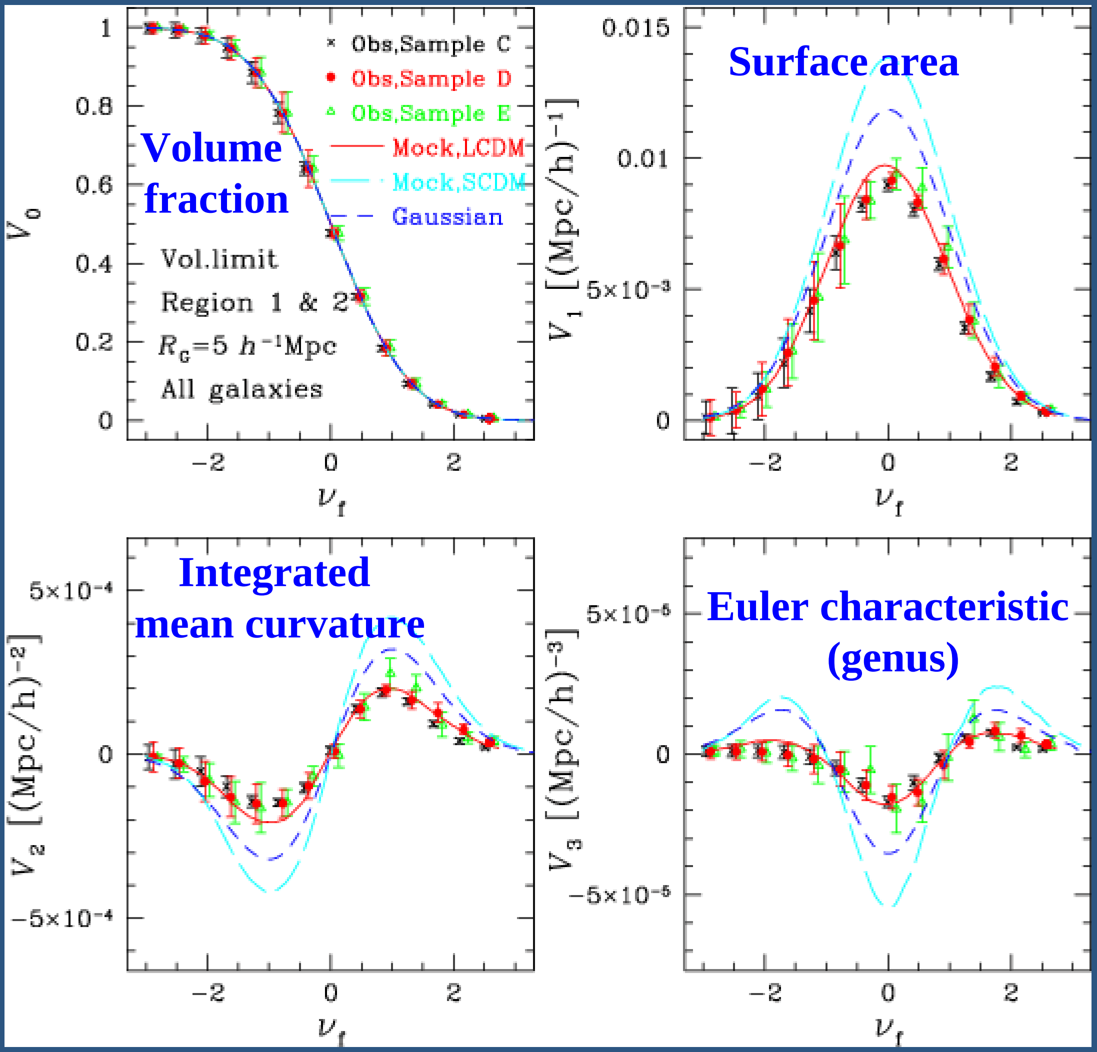


from Japanese TV program “Science ZERO” (NHK)

Tour in SDSS DR1 galaxies

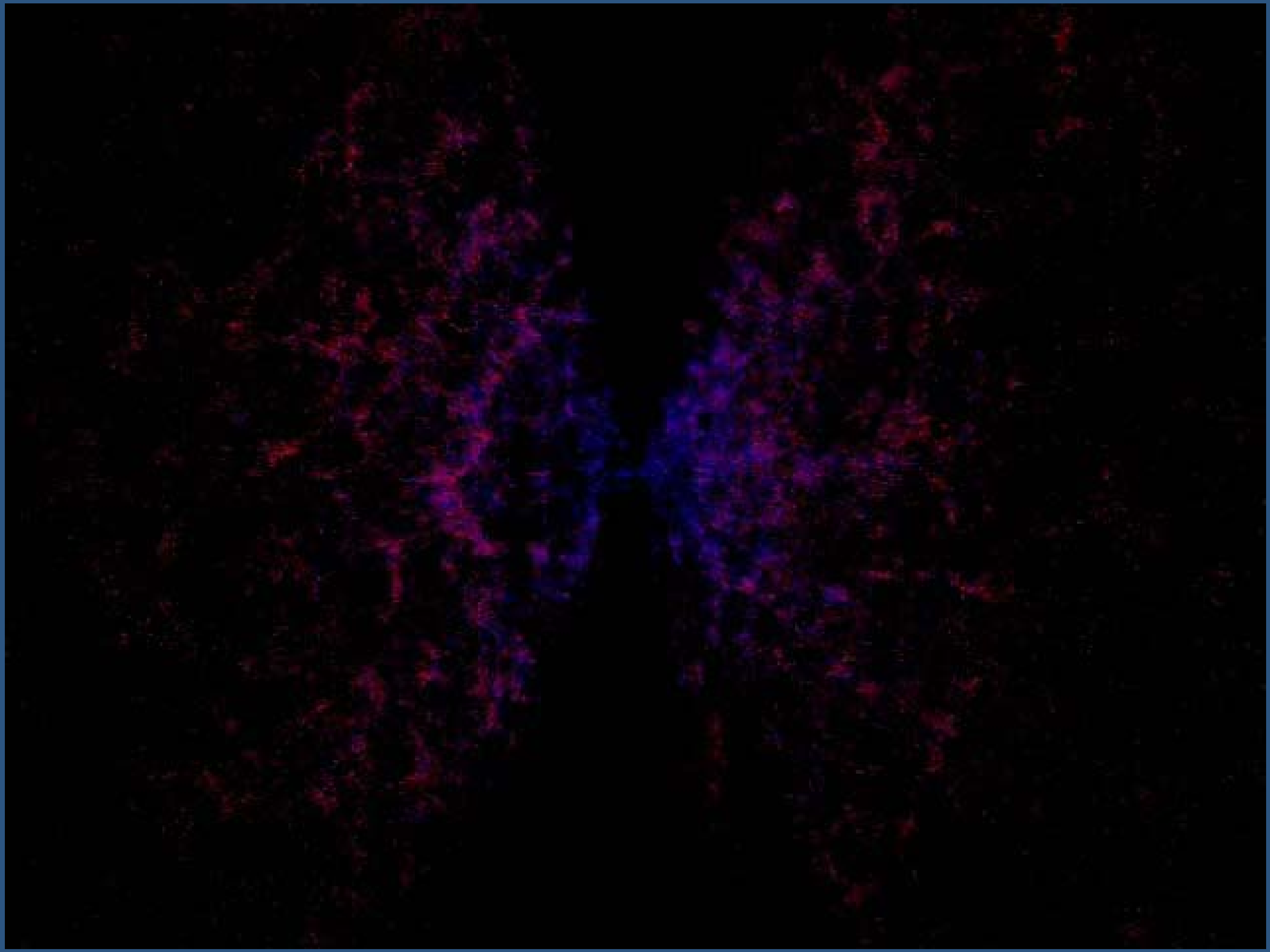
from Japanese TV program “Science ZERO” (NHK)

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 DR1 galaxies: morphology dependent clustering



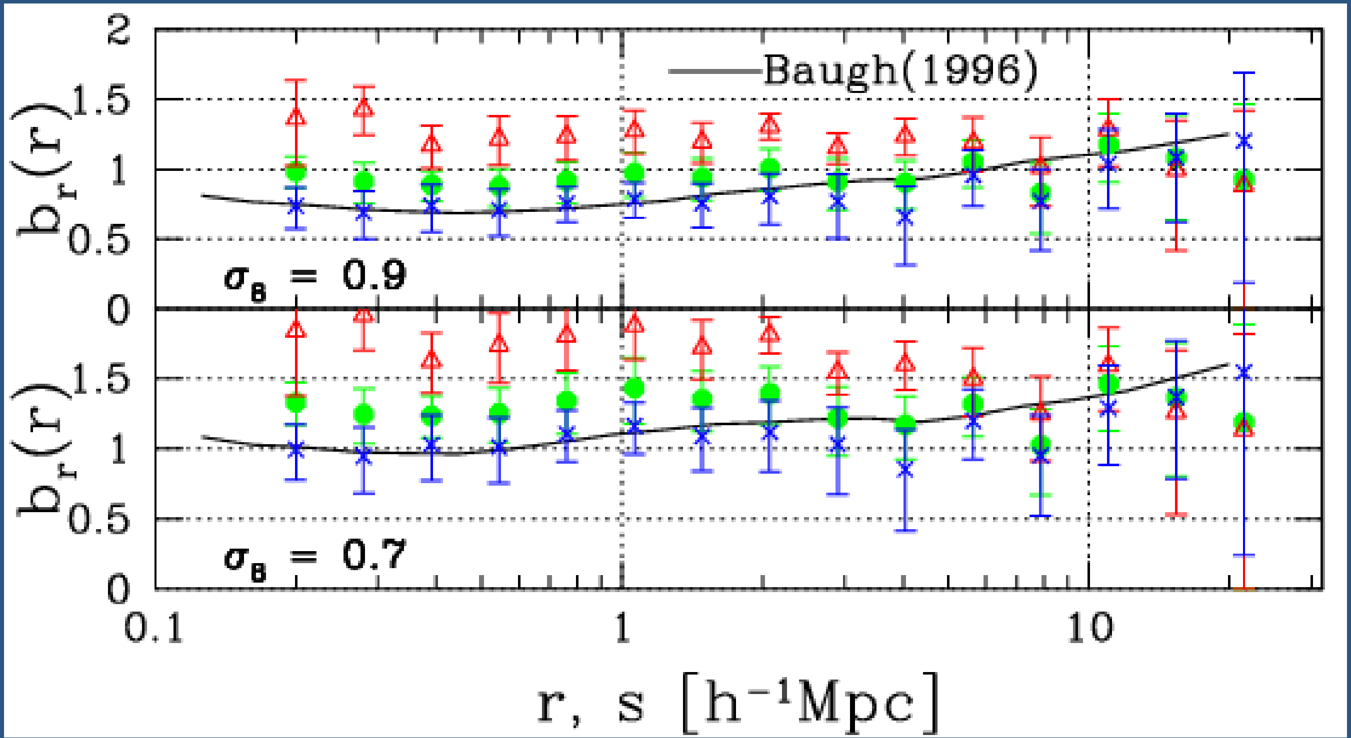
- **Late-types in blue**
- **Early-types in red**
- Density-morphology relation is barely visible

from Japanese TV program “Science ZERO” (NHK)

Morphology-dependent SDSS galaxy bias

early-type
average
late-type

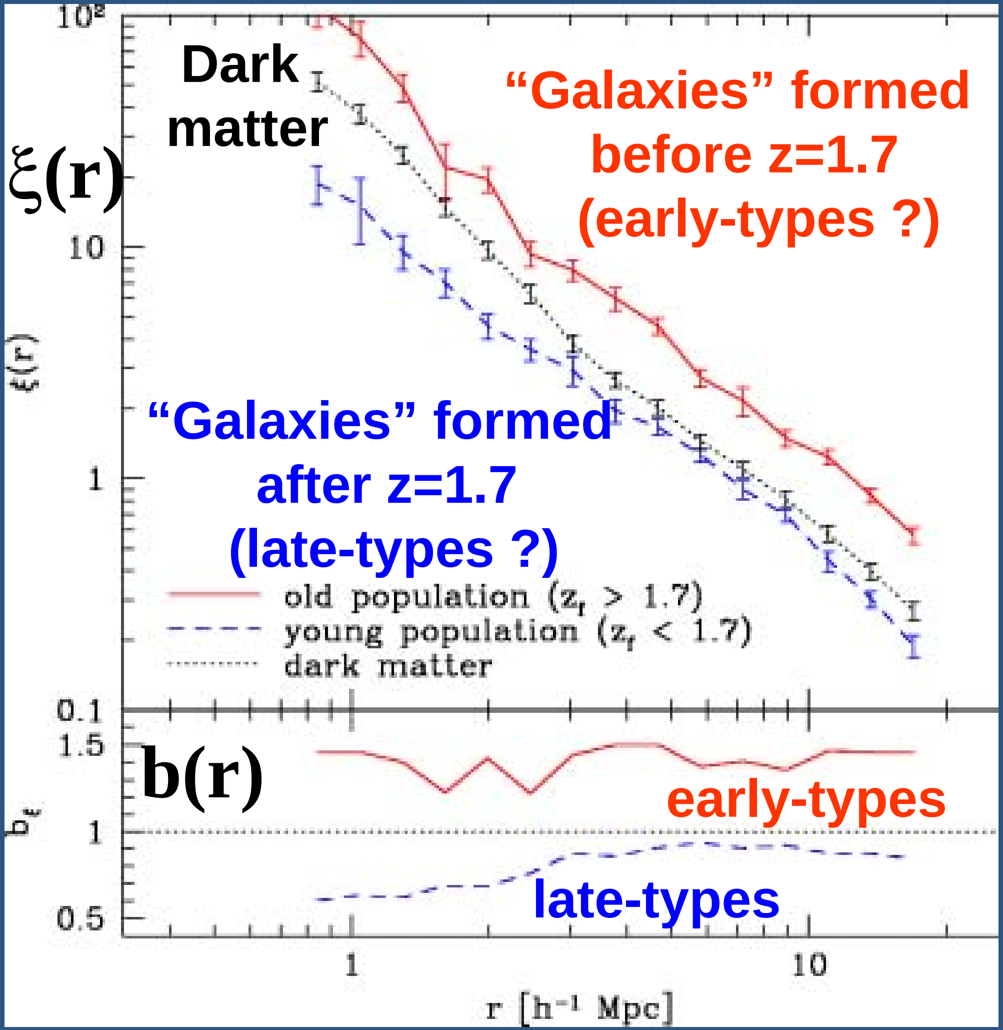
$$b \equiv \sqrt{\frac{\xi(galaxies)}{\xi(\Lambda CDM)}}$$



- 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 <u>with respect to ΛCDM with σ_8=0.9 (computed semi-analytically using the light-cone average described before)</u>

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)

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Where are the baryons ? cosmic baryon budget

$$\Omega_{star} + \Omega_{HI} + \Omega_{H_2} + \Omega_{hot\,X-ray} = 0.0068^{+0.0041}_{-0.0030} \quad vs \quad \Omega_{BBN} = 0.04 \quad (h = 0.7)$$

Component	Central	Maximum	Minimum	Grade[a]
Observed at $z \approx 0$				
1. Stars in spheroids	$0.0026\ h_{70}^{-1}$	$0.0043\ h_{70}^{-1}$	$0.0014\ h_{70}^{-1}$	A
2. Stars in disks	$0.00086\ h_{70}^{-1}$	$0.00129\ h_{70}^{-1}$	$0.00051\ h_{70}^{-1}$	A –
3. Stars in irregulars	$0.000069\ h_{70}^{-1}$	$0.000116\ h_{70}^{-1}$	$0.000033\ h_{70}^{-1}$	B
4. Neutral atomic gas	$0.00033\ h_{70}^{-1}$	$0.00041\ h_{70}^{-1}$	$0.00025\ h_{70}^{-1}$	A
5. Molecular gas	$0.00030\ h_{70}^{-1}$	$0.00037\ h_{70}^{-1}$	$0.00023\ h_{70}^{-1}$	A –
6. Plasma in clusters	$0.0026\ h_{70}^{-1.5}$	$0.0044\ h_{70}^{-1.5}$	$0.0014\ h_{70}^{-1.5}$	A
7a. Warm plasma in groups	$0.0056\ h_{70}^{-1.5}$	$0.0115\ h_{70}^{-1.5}$	$0.0029\ h_{70}^{-1.5}$	B
7b. Cool plasma	$0.002\ h_{70}^{-1}$	$0.003\ h_{70}^{-1}$	$0.0007\ h_{70}^{-1}$	C
7′. Plasma in groups	$0.014\ h_{70}^{-1}$	$0.030\ h_{70}^{-1}$	$0.0072\ h_{70}^{-1}$	B
8. Sum (at $h = 70$ and $z \simeq 0$)......	0.021	0.041	0.007	...

Fukugita, Hogan & Peebles: ApJ 503 (1998) 518

- The observed baryons in the present universe amount merely to (10〜50) **%** of the nucleosynthesis prediction

Four phases of cosmic baryons

Dave et al. ApJ 552(2001) 473

- ***Condensed:*** **δ >1000, T<10^5K**
  - Stars + cold intergalactic gas
- ***Diffuse:*** **δ <1000, T<10^5K**
  - Photo-ionized intergalactic medium
  - Ly α absorption line systems
- ***Hot:*** **T>10^7K**
  - X-ray emitting hot intra-cluster gas
- ***Warm-hot:*** **10^5K<T<10^7K**
  - Warm-hot intergalactic medium (***WHIM***)

Large-scale structure traced by missing baryons

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

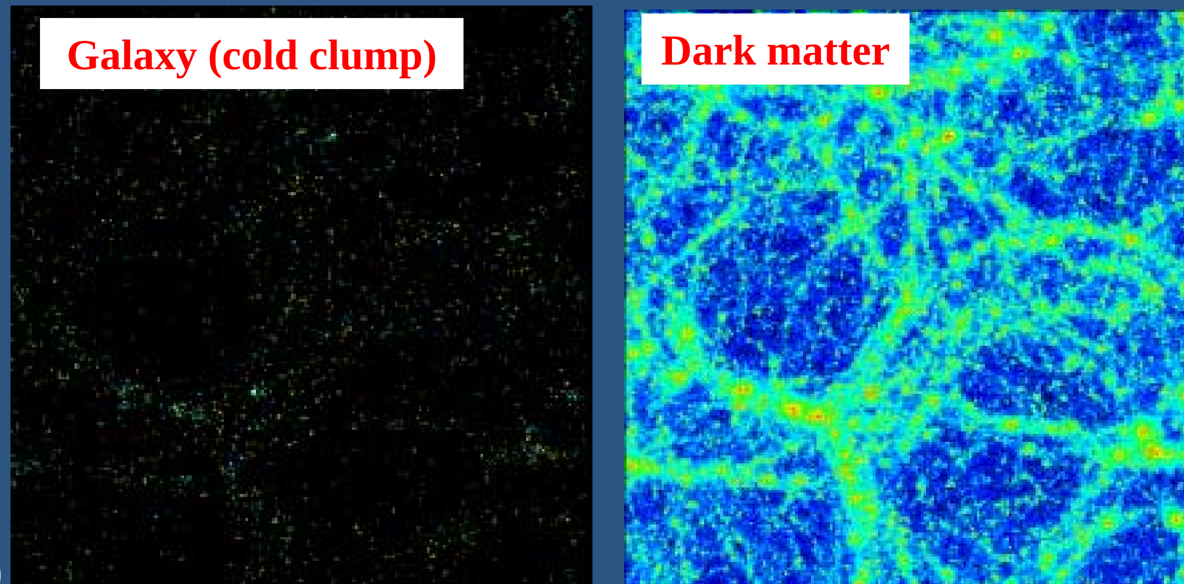
ΛCDM SPH @ z=0

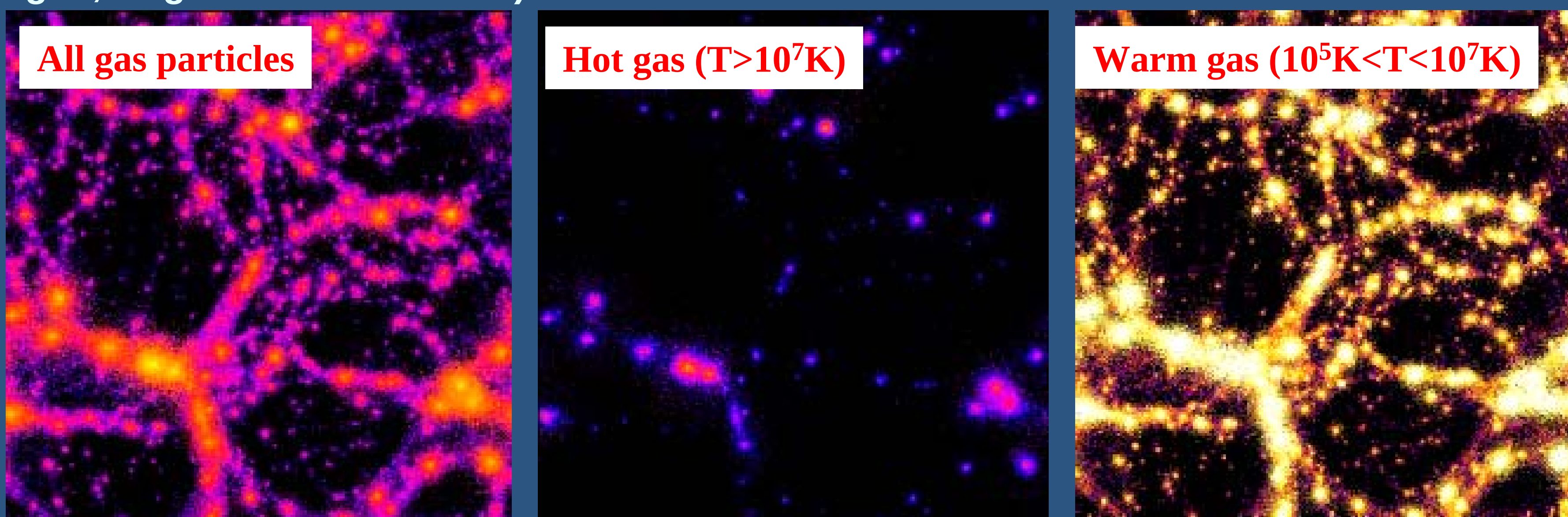
$N=128^3$:DM

$N=128^3$:gas

(Yoshikawa et al. 2001)

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





Warm/Hot Intergalactic Medium (WHIM)

WHIM as cosmic missing baryons

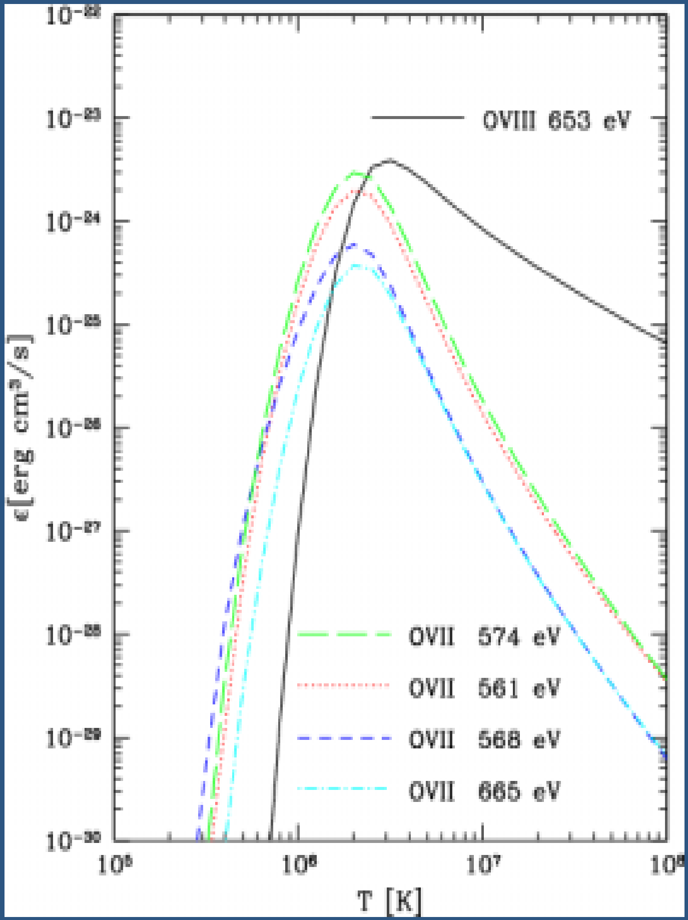
- ~40% of the total cosmic baryons may exist as Warm-Hot Intergalactic Medium (WHIM) with $10^5 K < T < 10^7 K$
- WHIM is supposed to distribute diffusely along filamentary structures connecting nearby clusters/ groups of galaxies
- Direct detection of WHIM is difficult
  - OVI absorption line systems in UV (1032Å, 1038Å doublets)
  - OVII (574.0 eV) and OVIII (653.6 eV) absorption line systems in X-ray spectra of background QSOs
  - Bumpy features in Soft X-ray background spectrum

Emission lines of Oxygen in WHIM

OVII (561eV, 568eV, 574eV, 665eV) , OVIII (653eV)

- Why oxygen emission lines ?
  - Most abundant other than H and He
  - Good tracers of gas around $T=10^6 \sim 10^7$ K
  - No other prominent lines in E=500-660eV
  - Not restricted to regions towards background QSOs

⇒ ***systematic WHIM survey***



Oxygen lines

O VII	$1s^2 - 1s2s\ (^3S_1)$	561eV	22.1 Å
O VII	$1s^2 - 1s2p\ (^3P_1)$	568eV	21.8 Å
O VII	$1s^2 - 1s2p\ (^1P_1)$	574eV	21.6 Å
O VIII	1s – 2p (Ly α)	653eV	19.0 Å
O VII	$1s^2 - 1s3p$	665eV	18.6 Å
O VIII	1s – 3p (Ly β)	775eV	16.0 Å
Ne IX	$1s^2 - 1s2s\ (^3S_1)$	905eV	13.7 Å
Ne IX	$1s^2 - 1s2p\ (^3P_1)$	914eV	13.6 Å
Ne IX	$1s^2 - 1s2p\ (^1P_1)$	921eV	13.5 Å

Requirements for detection

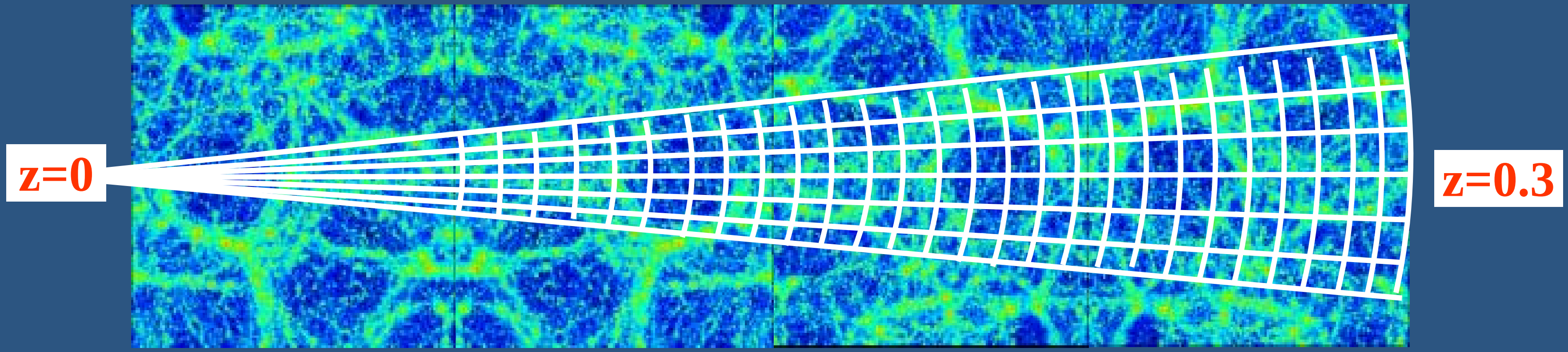
- Good energy resolution to identify the emission lines from WHIM at different redshifts
  - $\Delta E < 5\text{eV}$ ⇒ X-ray calorimeter using superconducting TES (Transition Edge Sensor)
- Large field-of-view and effective area for survey
  - $S_{eff} = 100\text{cm}^2$, $\Omega = 1\text{deg}^2$ ⇒ 4-stage reflection telescope
- Angular resolution is not so important (but useful in removing point source contaminations)

$$\theta \approx 1^\circ \left(\frac{600\, h^{-1}\mathrm{Mpc}}{D} \right) \left(\frac{L}{10\, h^{-1}\mathrm{Mpc}} \right)$$

Comparison with other missions

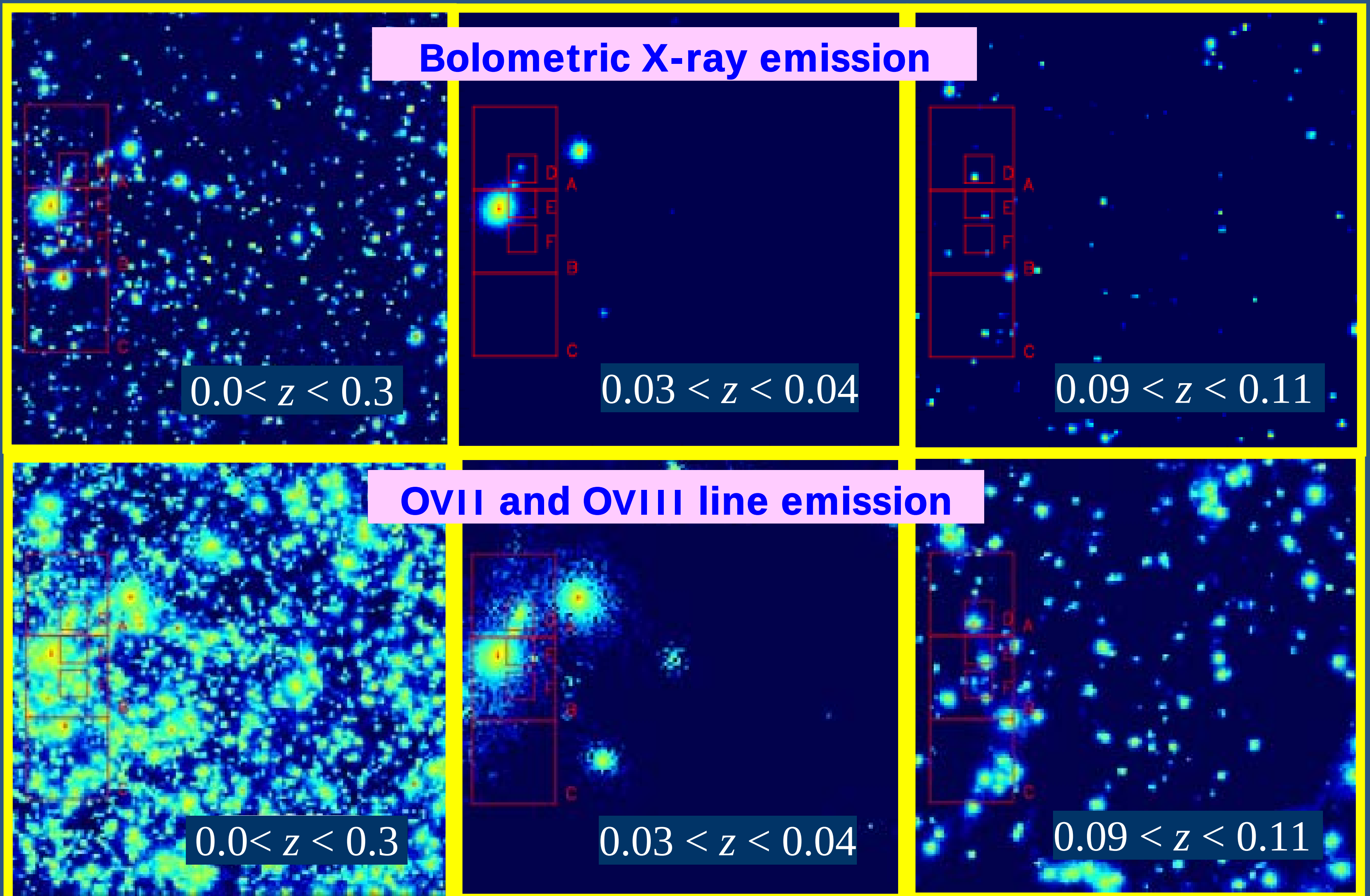
	$S_{eff}\Omega$ [cm^2 deg^2]	ΔE [eV]	f_{limit} [$erg/s/cm^2/sr$]
Chandra ACIS-S3	12	80	10^{-9}
XMM-Newton EPIC-pn	100	80	$3x10^{-10}$
Astro-E II XRS	0.23	6	$2x10^{-8}$
Astro-E II XIS	36	80	$6x10^{-10}$
XEUS-I	16.7	2	$2.5x10^{-10}$
our proposed detector	**100**	**2**	**$6x10^{-11}$**

Light-cone output from simulation

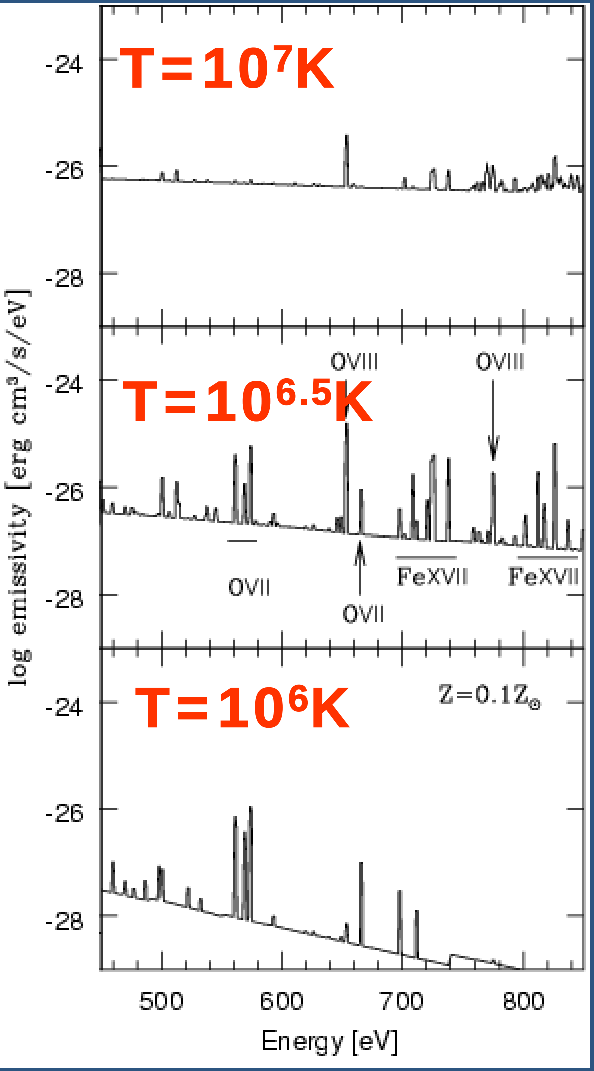


- Cosmological SPH simulation in Ω_m=0.3, Ω_Λ=0.7, σ_8=1.0, and h=0.7 CDM with N=128^3 each for DM and gas (Yoshikawa, Taruya, Jing, & Suto 2001)
- Light-cone output from z=0.3 to z=0 by stacking 11 simulation cubes of ($75h^{-1}$Mpc)^3 at different z
- 5°×5° FOV mock data in 64x64 grids on the sky
-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

Surface brightness

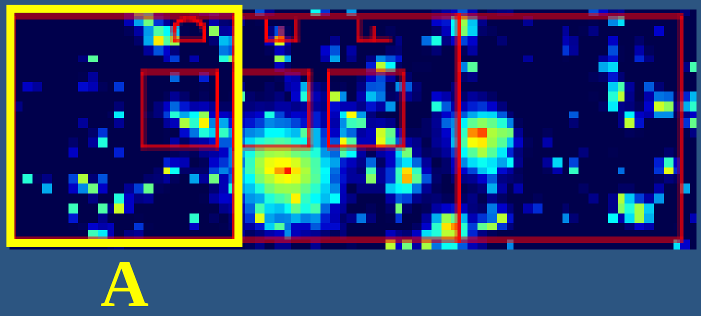


Creating Mock spectra from light-cone output

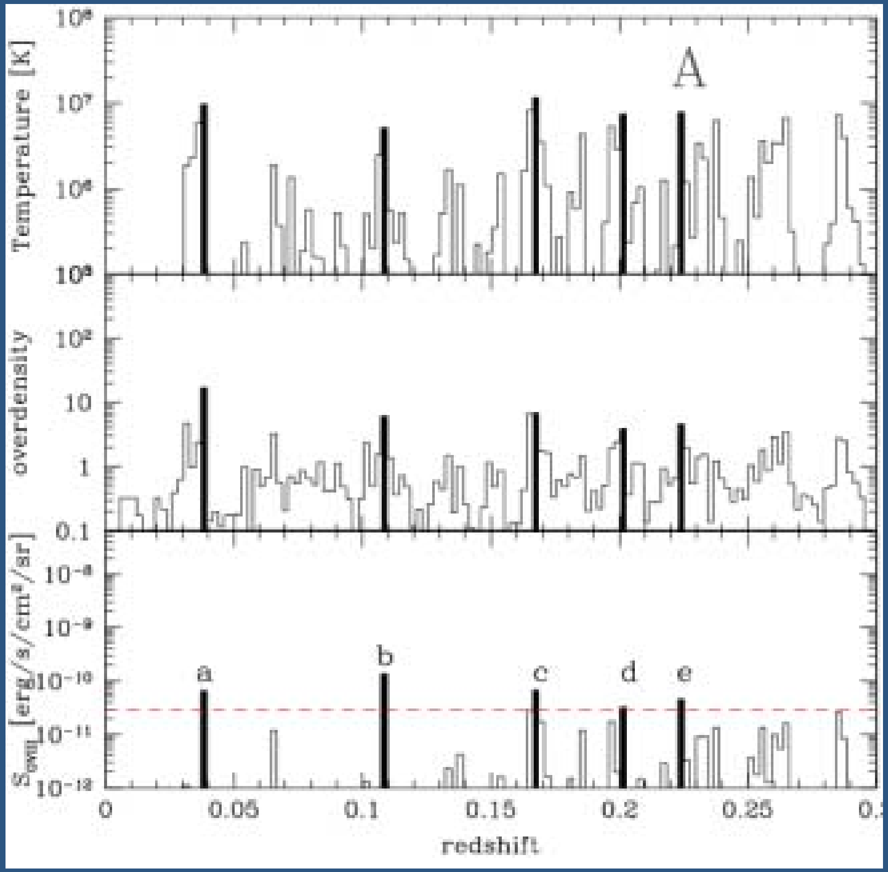


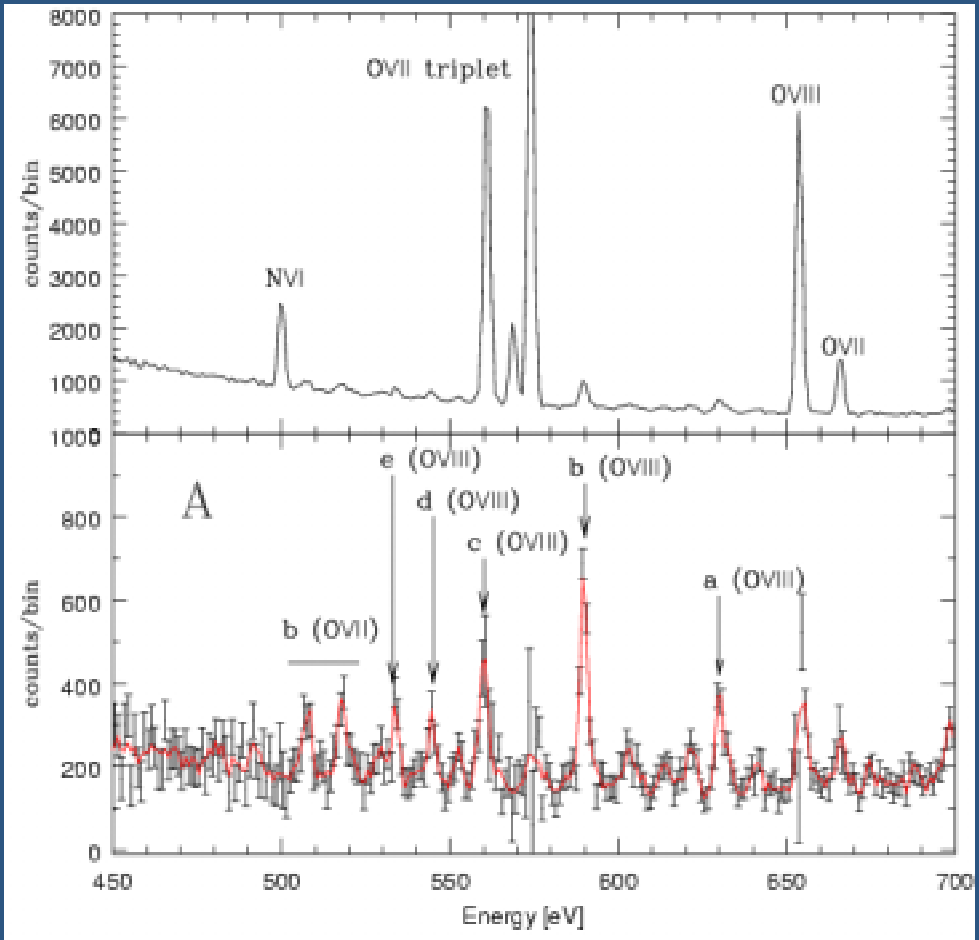
- For a given exposure time,
  - convolve the emissivity according to gas density and temperature in $(5°/64)^2$ pixels over the lightcone
  - Add the Galactic line emission (McCammon et al. 2002)
  - Add the cosmic X-ray background contribution (power-law+Poisson noise)
- Then statistically subtract the Galactic emission and the CXB and obtain the residual spectra for ΔE=2eV resolution.

Simulated spectra: region A

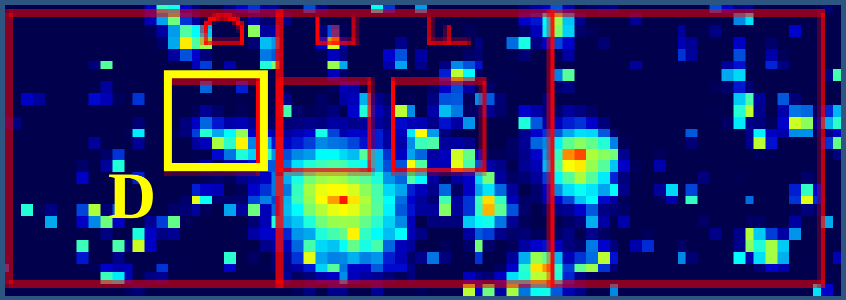


12x12 pixels (0.88 deg^2)
$T_{exposure}$=3x10^{5}sec



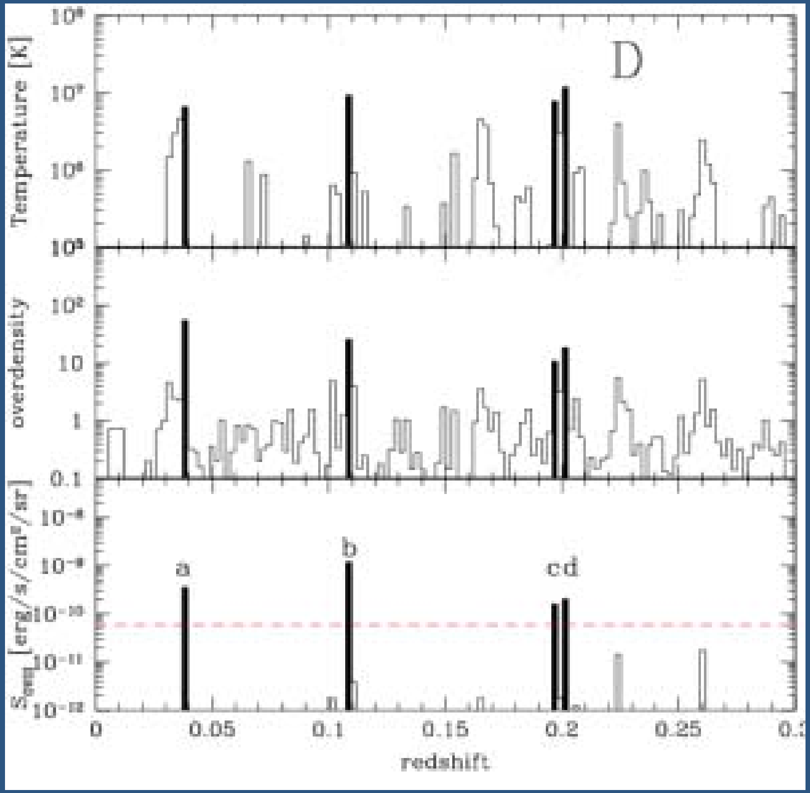


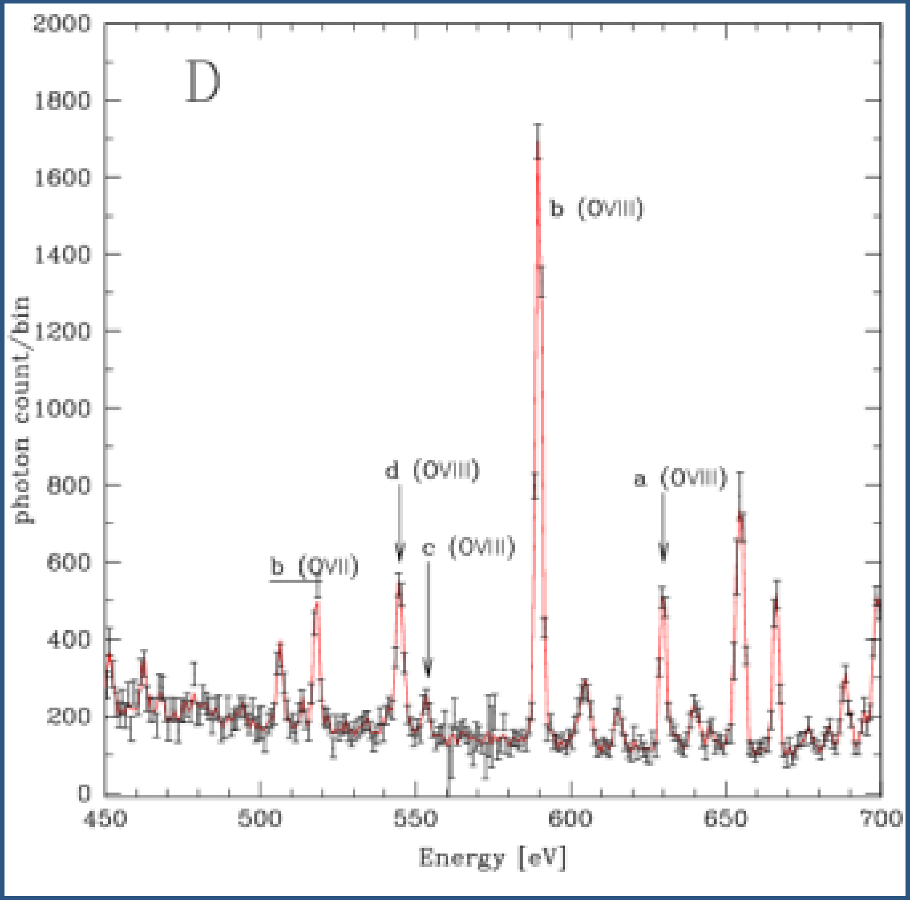
Simulated spectra: region D



4x4 pixels (0.098 deg^2)

$T_{exposure}$=10^6sec

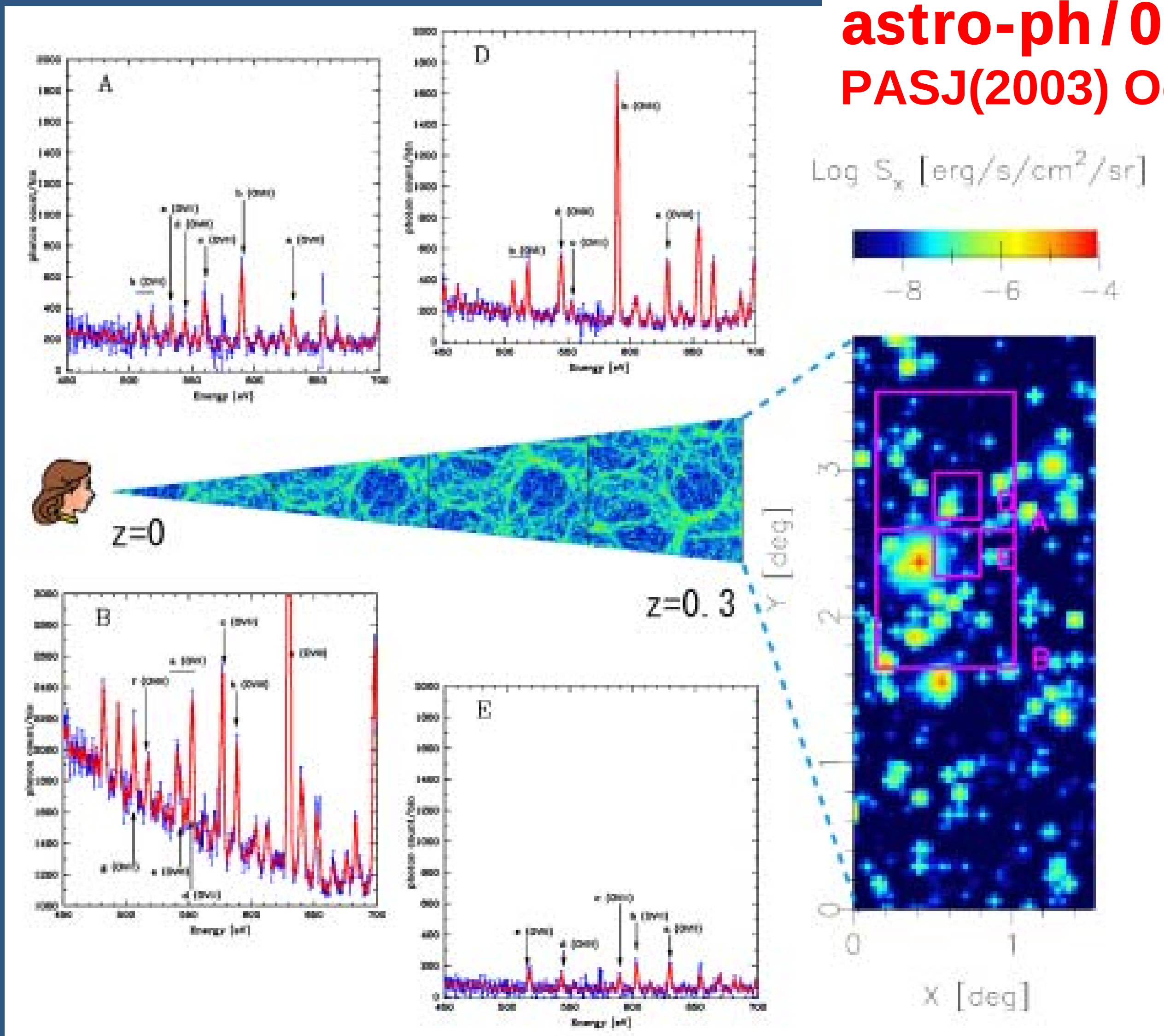




Feasibility of dedicated X-ray mission to search for missing baryons via Oxygen emission lines

astro-ph/0303281

PASJ(2003) October issue, in press



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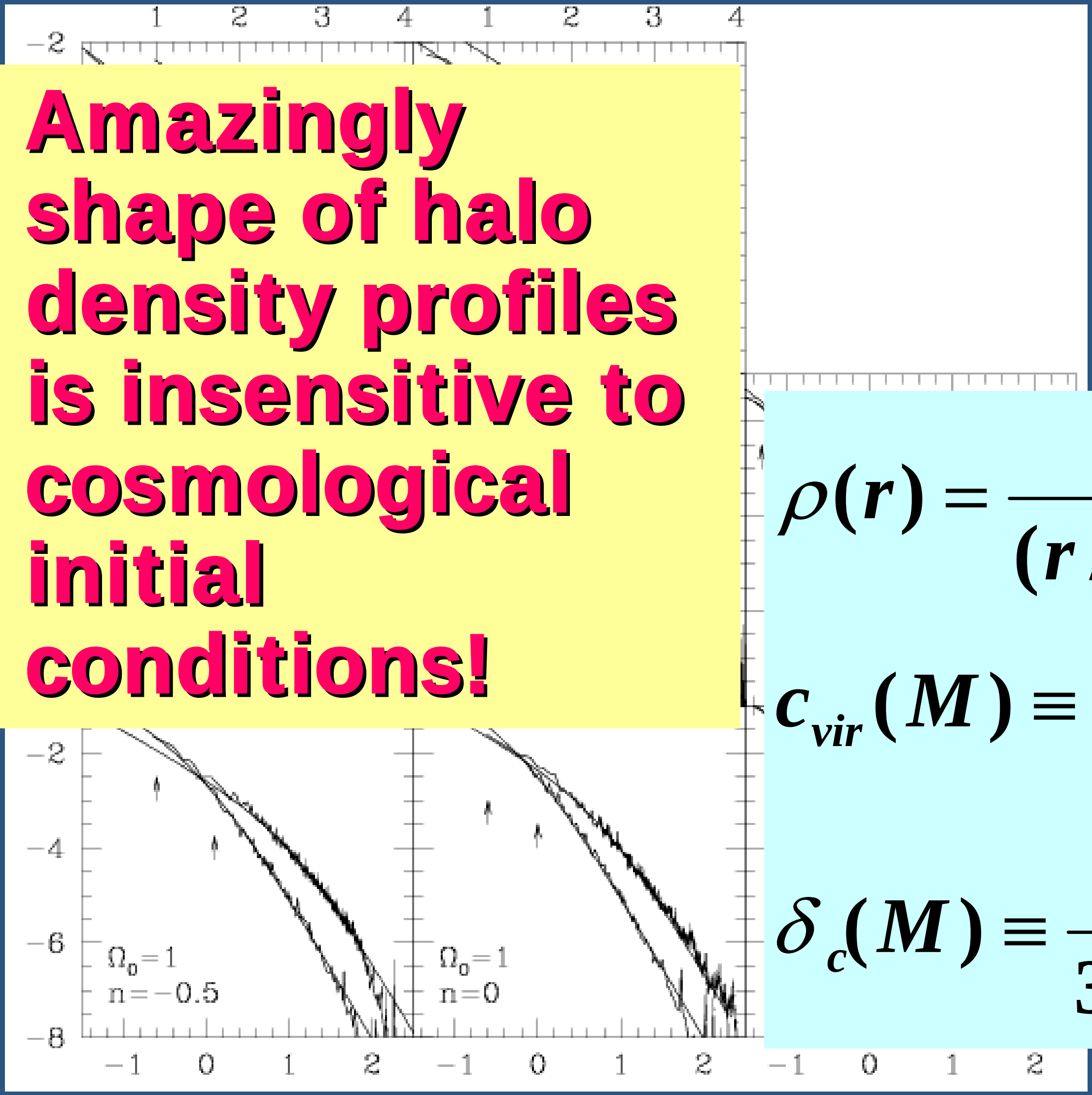
- Searching for cosmic missing baryon via oxygen emission lines
- **Density profiles of dark matter halos**

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:** ***testing cosmology and/or nature of dark matter***
  - galactic rotation curve, gravitational lensing
  - X-ray/SZ observations of clusters
  - modeling the dark matter clustering

NFW universal density profile

- **Amazingly shape of halo density profiles is insensitive to cosmological initial conditions!**



log(radius)

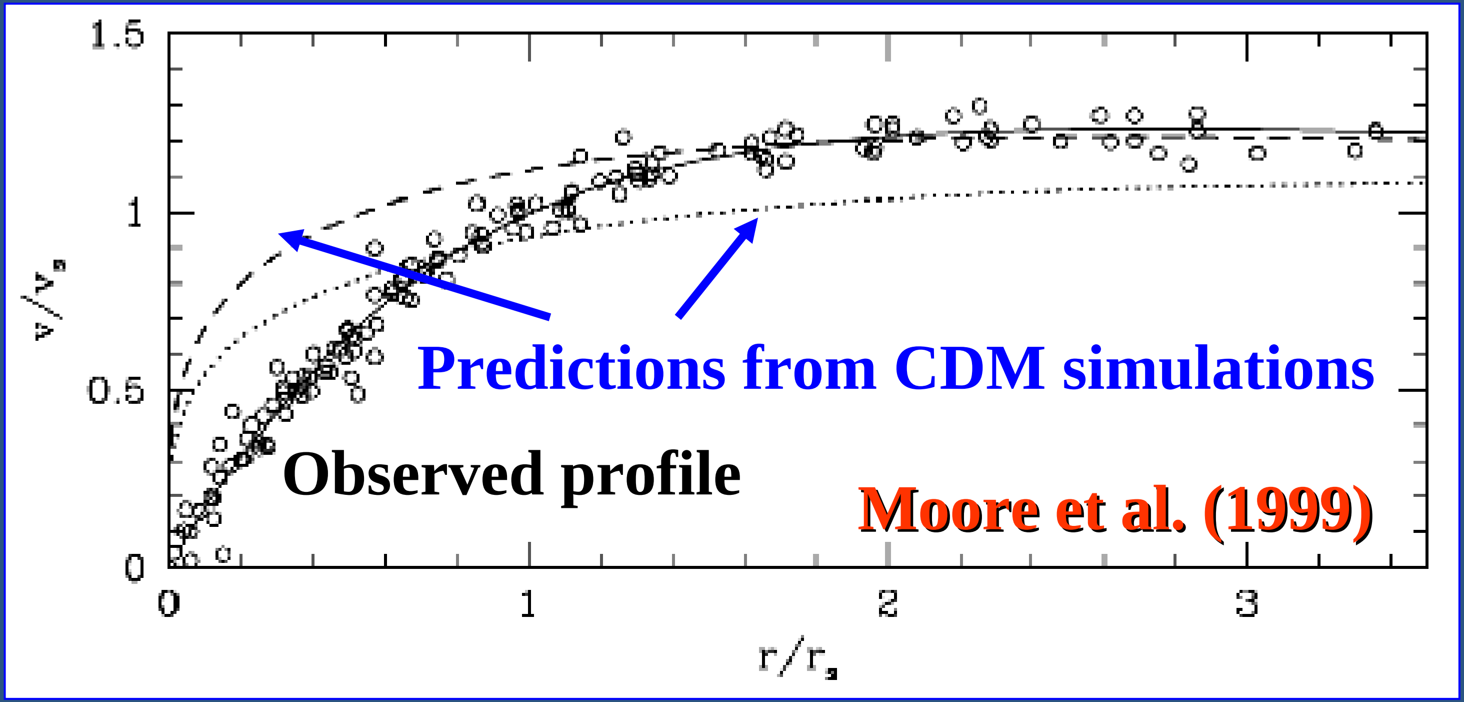
Navarro, Frenk & White (1997)

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

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

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

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)

Constraining halo central density profiles with gravitational lensing

- **Statistics of QSO multiple images**
  (Wyithe, Turner & Spergel 2001; Keeton & Madau 2001; Li & Ostriker 2001; Takahashi & Chiba 2001)
- **Arc statistics of clusters of galaxies**
  (Bartelmann et al. 1998; Molikawa & Hattori 2001; Oguri, Taruya + YS 2001, Oguri, Lee + YS 2003)
- **Time-delay statistics of QSO multiple images**
  (Oguri, Taruya, YS + Turner 2002)

$\Rightarrow$ *generally favor a steep cusp ($\alpha \sim -1.5$)*

Self-interacting dark matter ?

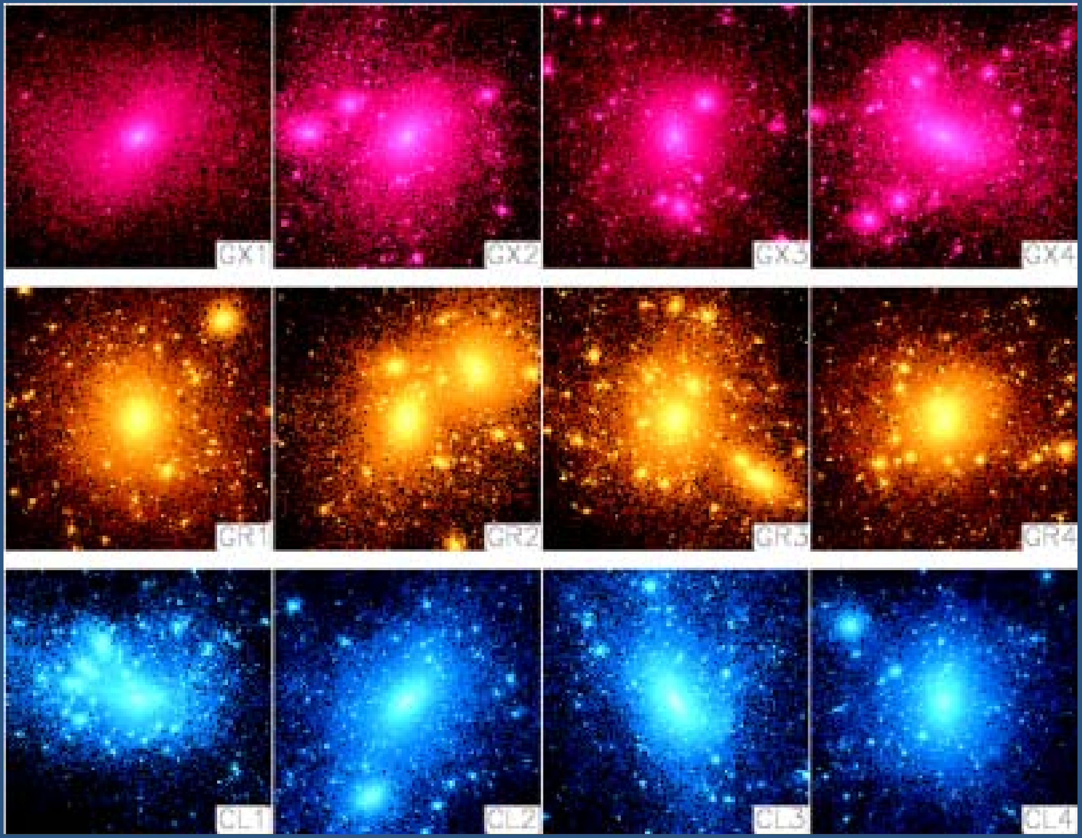
- ***Collisionless dark matter***
  - reproduces nicely the observed large-scale structure of the universe ($r \gg 1$Mpc)
  - **problems on smaller scales ($r < 1$Mpc)**

    LSB rotation curves, soft core in CL0024+1624, prediction of a factor of ten more subhalos than observed in the Local Group
- Required scattering cross section for self-interacting dark matter

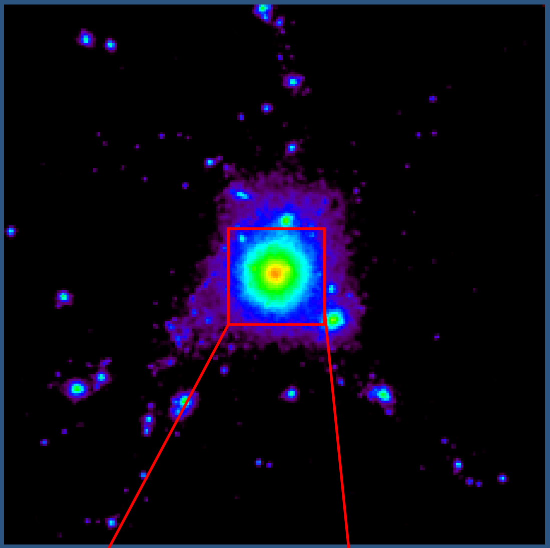
$$(mn)\frac{\sigma}{m}\ell = 1 \quad \Rightarrow \quad \frac{\sigma}{m} = 2\mathrm{cm}^2/\mathrm{g}\left(\frac{10^4 \rho_{\mathrm{crit}}}{\rho_{\mathrm{center,cl}}}\right)\left(\frac{1\mathrm{Mpc}}{\ell}\right)$$

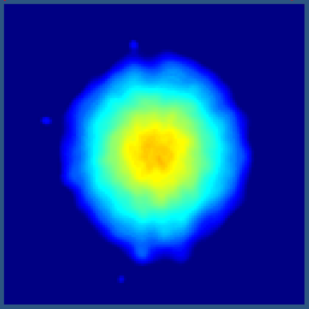
Are Dark Halos Spherical ?

Collisionless CDM: NO



Jing & Suto (2000)



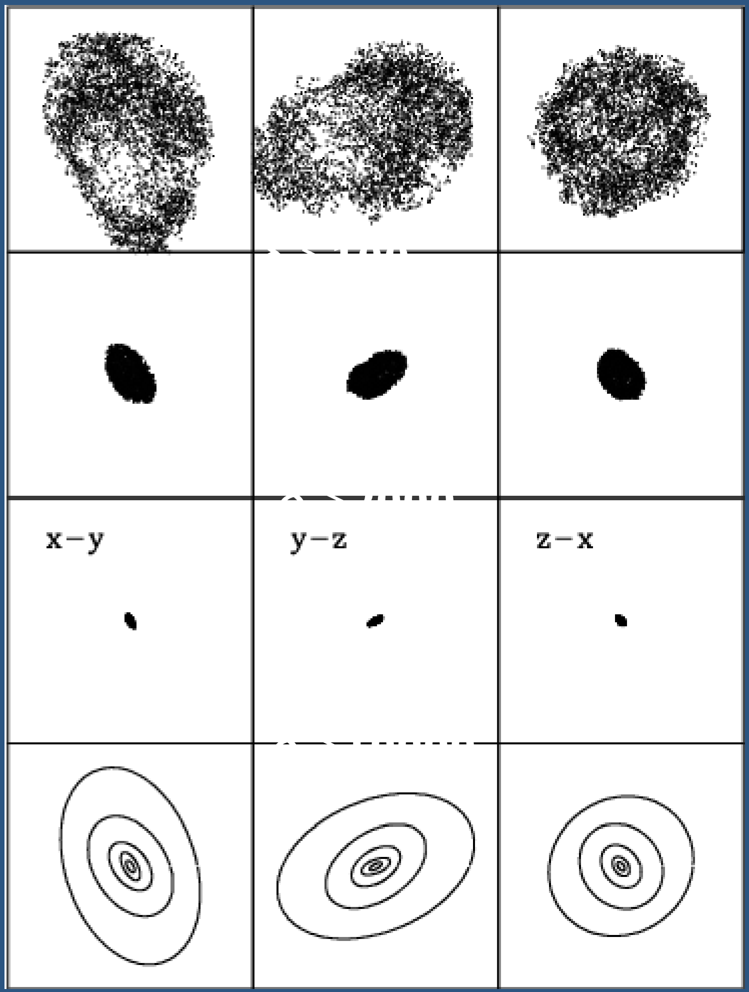


Yoshida et al. (2000)

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

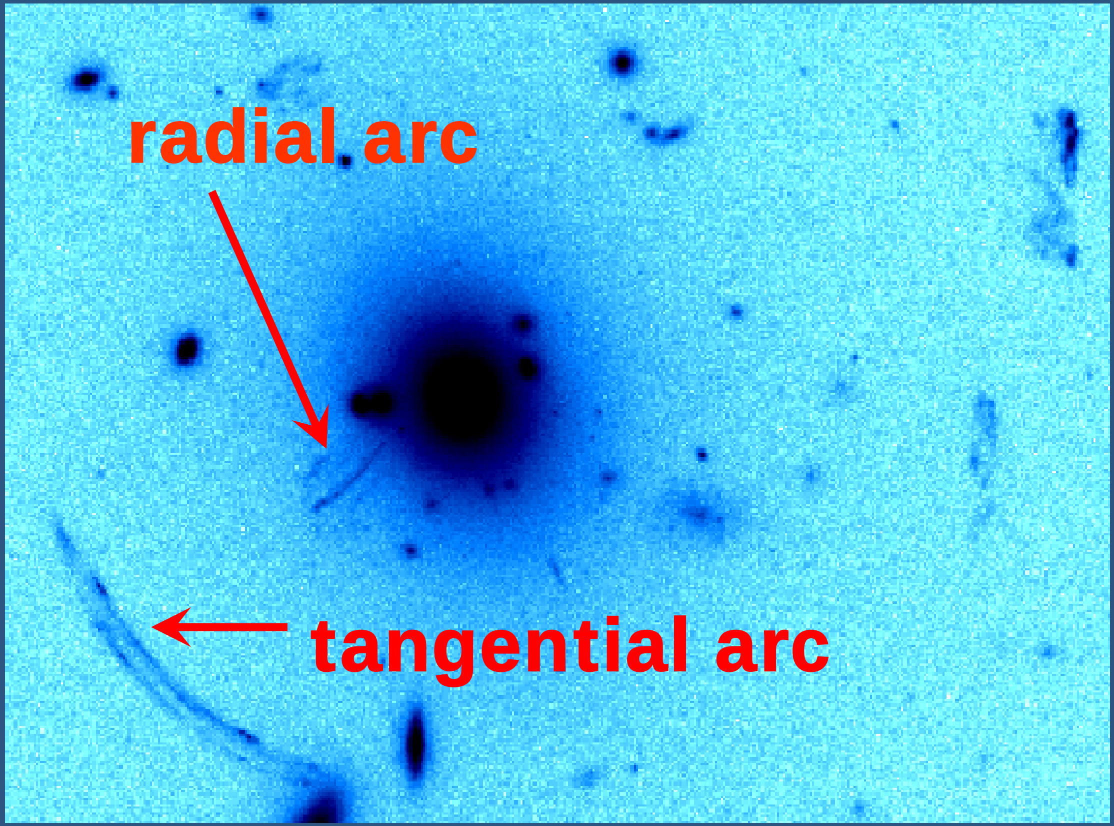
Lensed Arcs in Galaxy Clusters

Cluster of galaxies distort the images of background galaxies by gravitational lensing

↓

(lensed) arcs

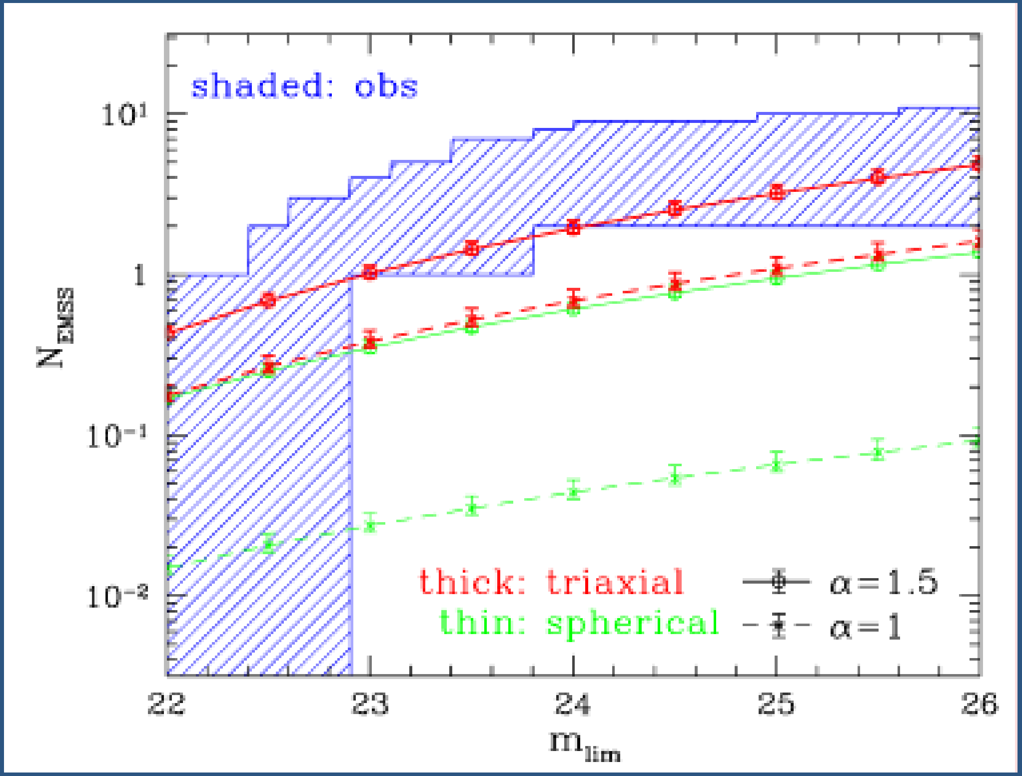
~30 giant arcs are observed so far



Hammer et al. (1997)

Comparison with observed 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 ?

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)

Unsolved issues for LSS simulations

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