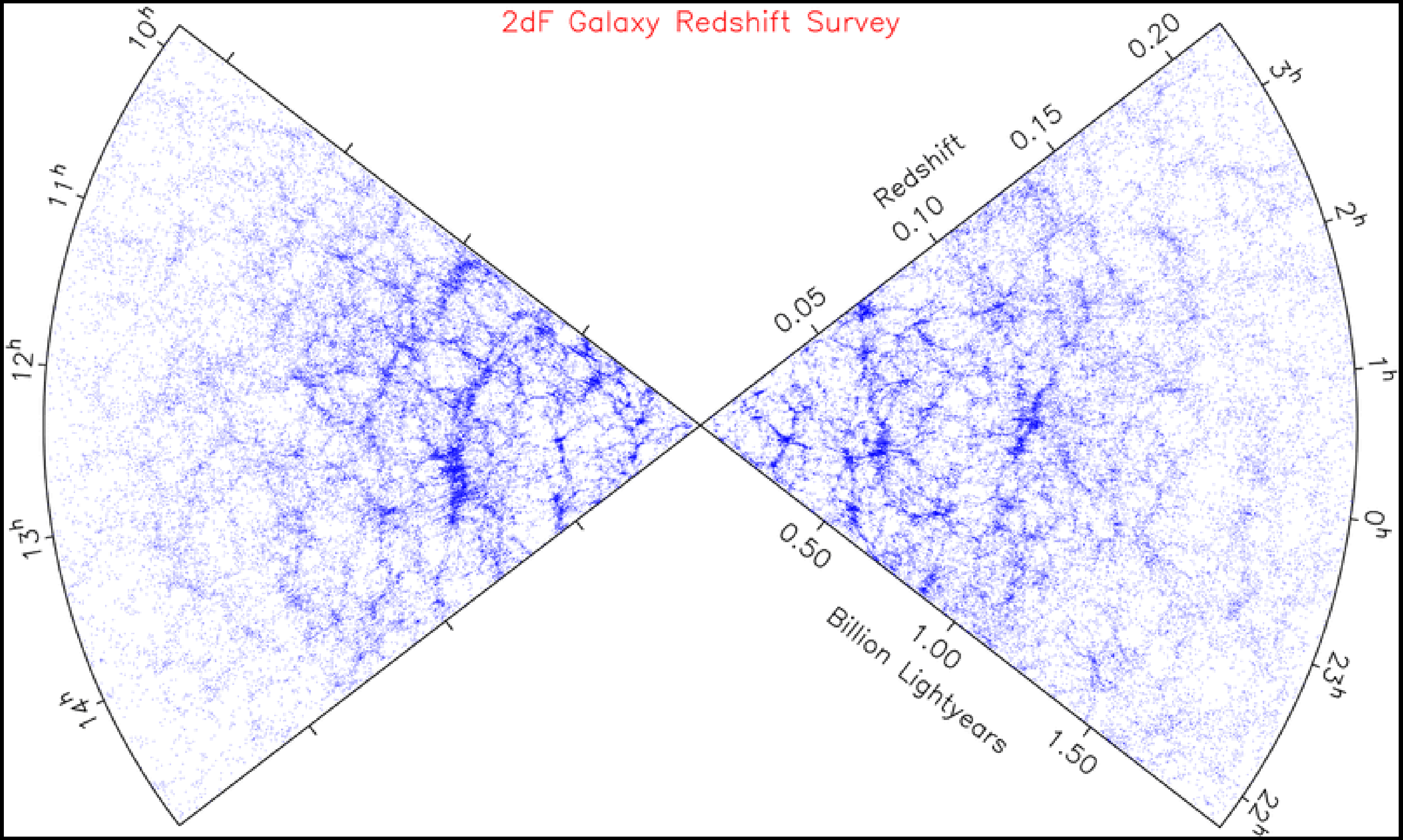
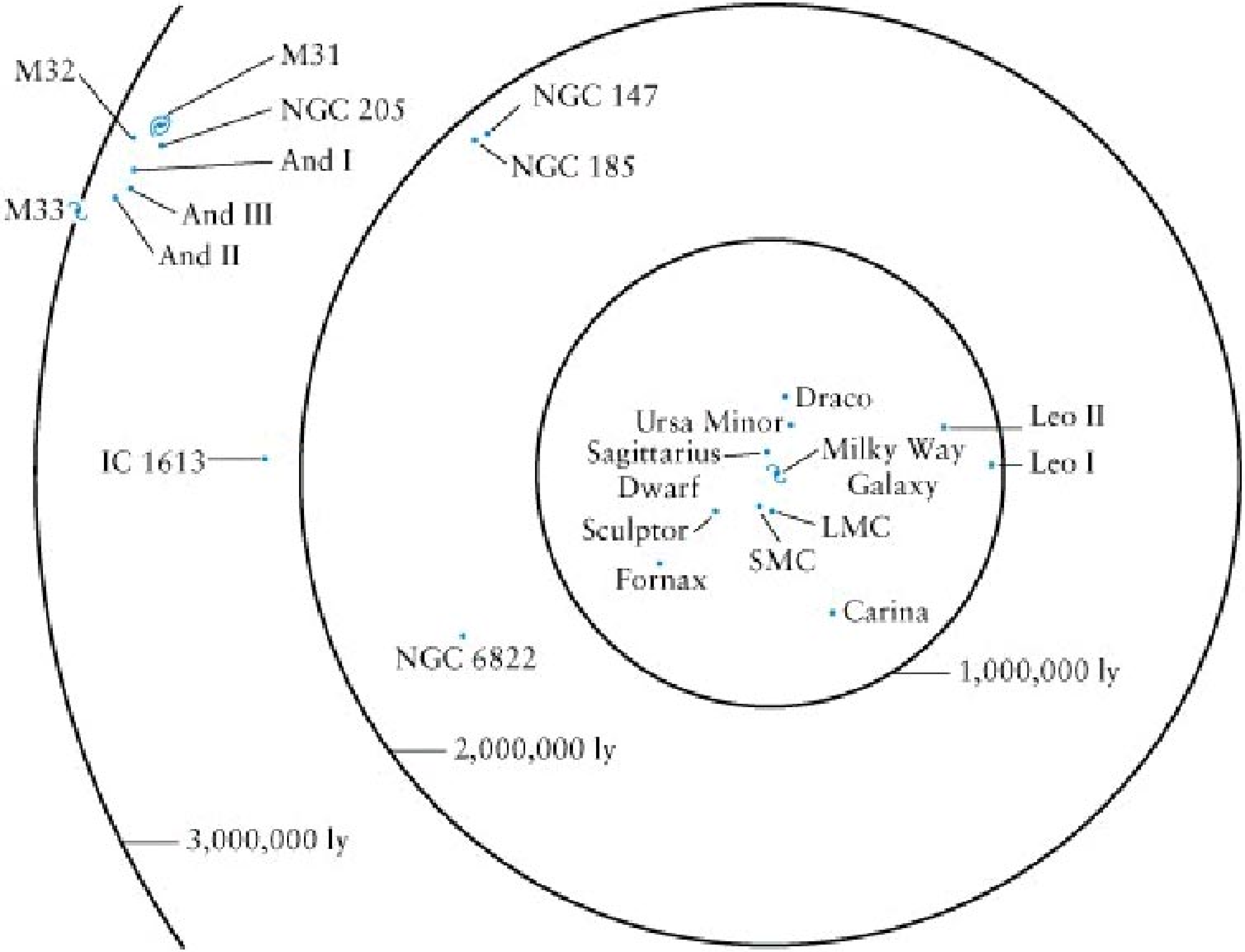
Lecture 8 Large scale structure



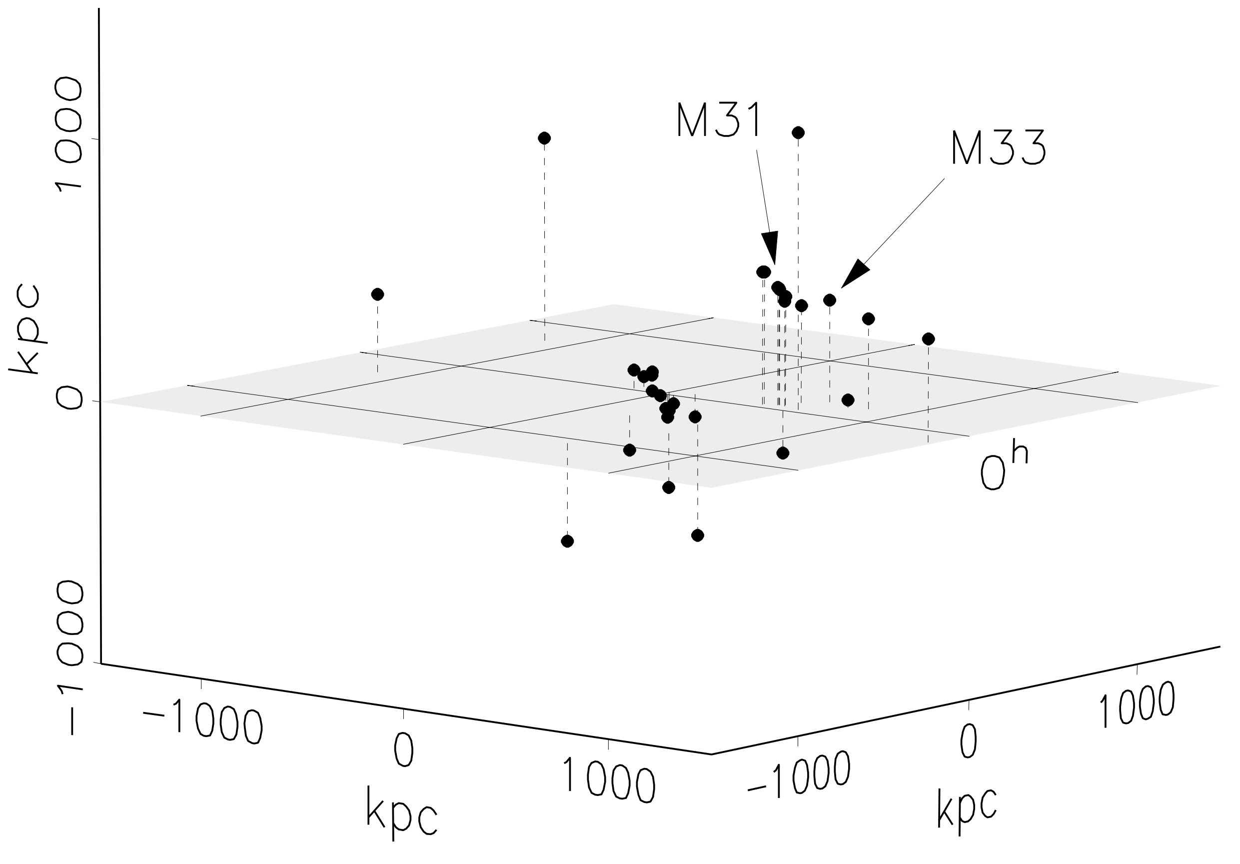
Galaxies are grouped into clusters and superclusters.

- Galaxies are not scattered randomly throughout the galaxy.
- Galaxies are found in ***clusters***
  - The Milky Way is part of the *Local Group* of about 35 galaxies.
- Clusters of galaxies are clustered as well in groups called ***superclusters.***
  - Our Local Group is part of the *Local Supercluster*.
- The majority of space is empty - called ***voids***.

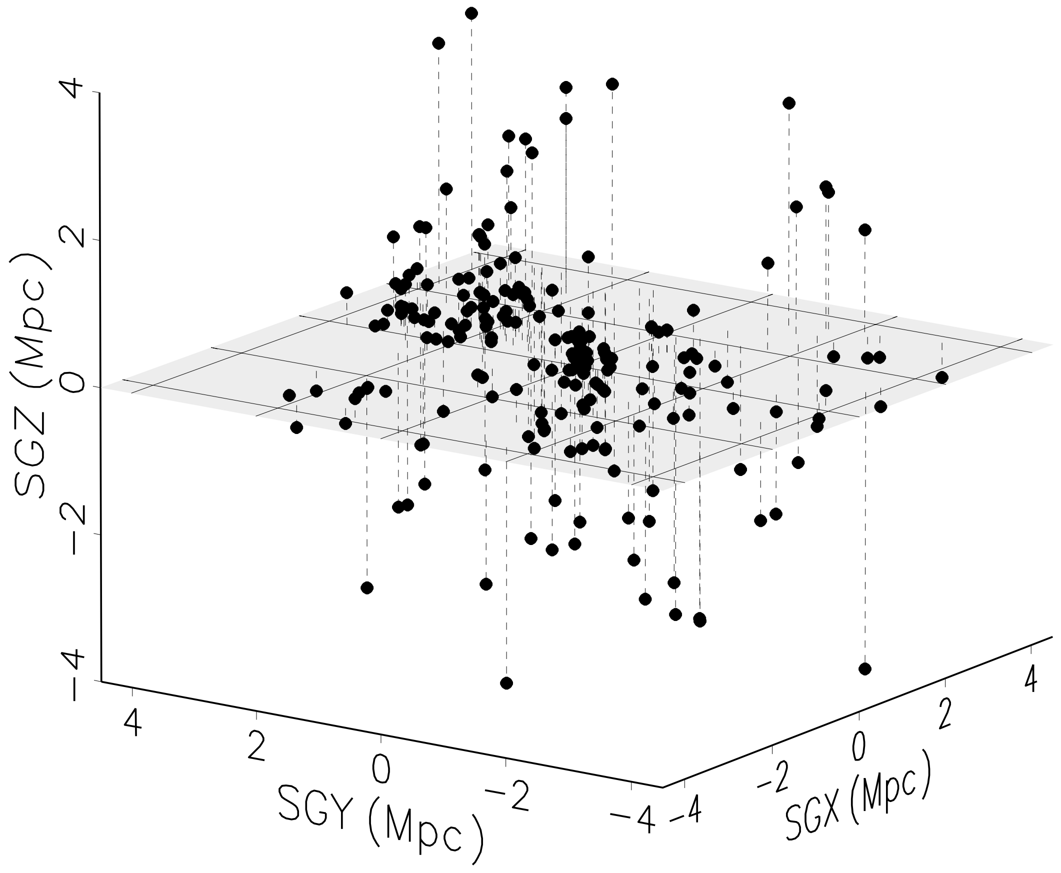
The Local Group



The Local Group

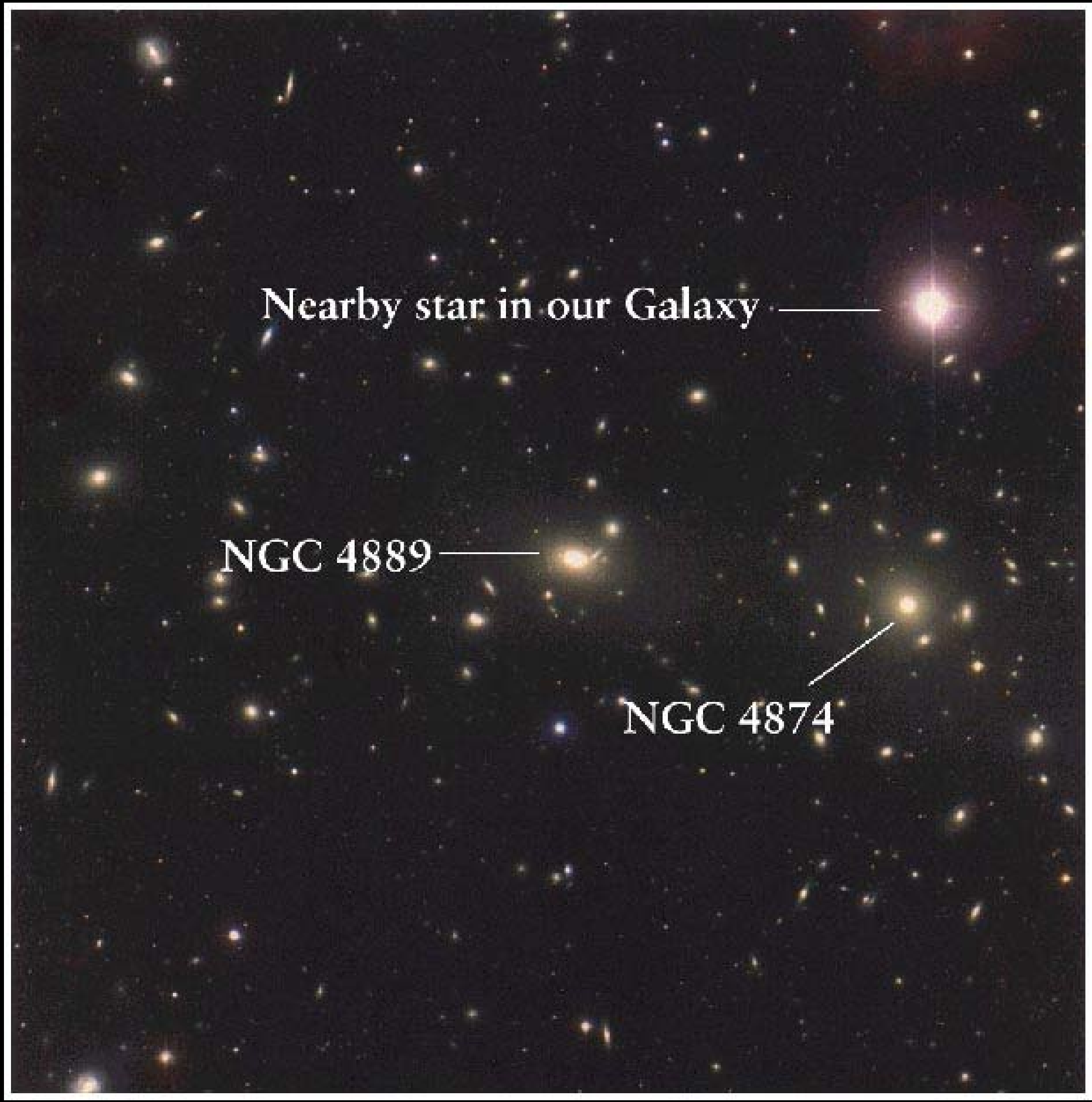


”Nearby” Galaxies

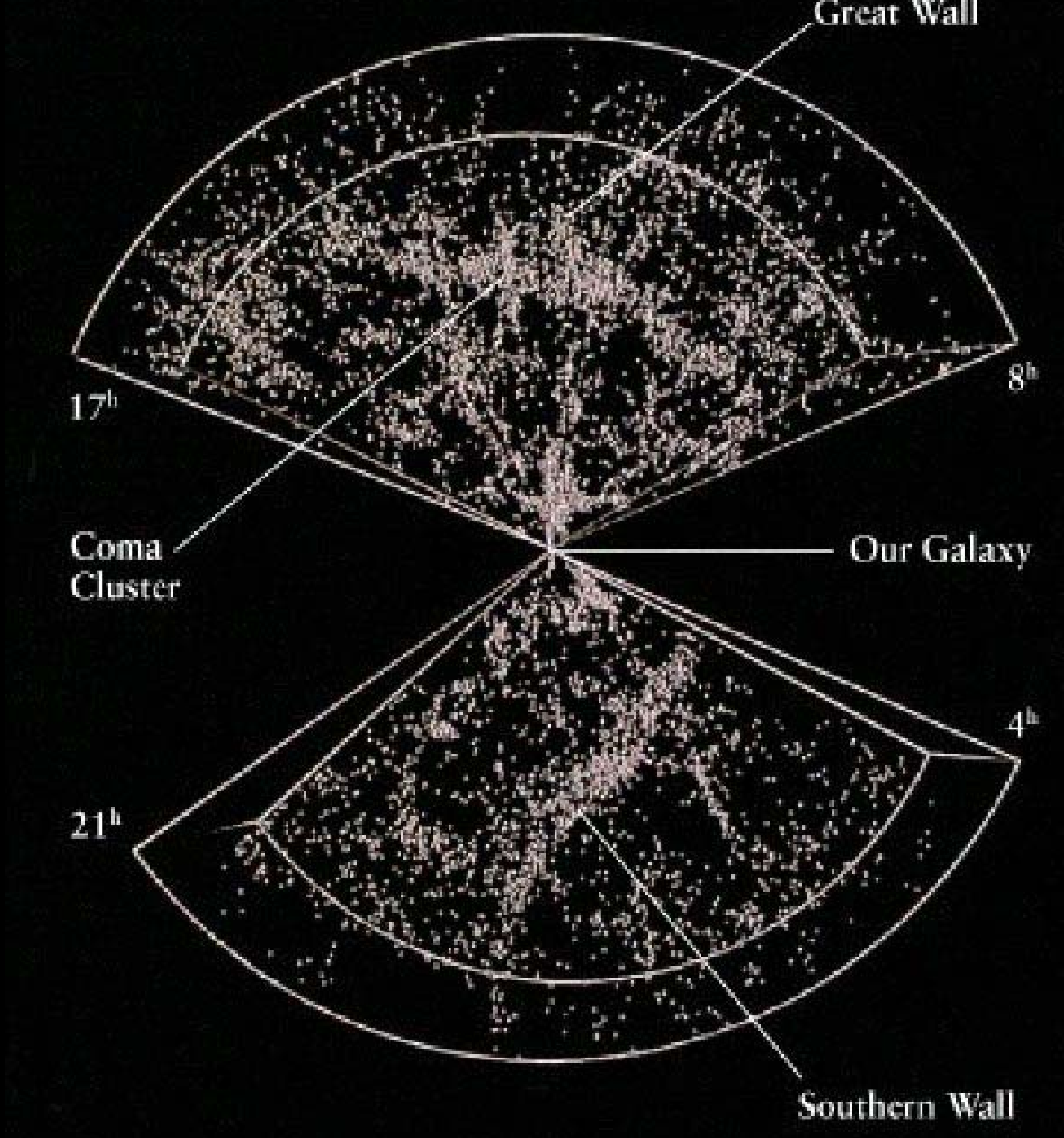


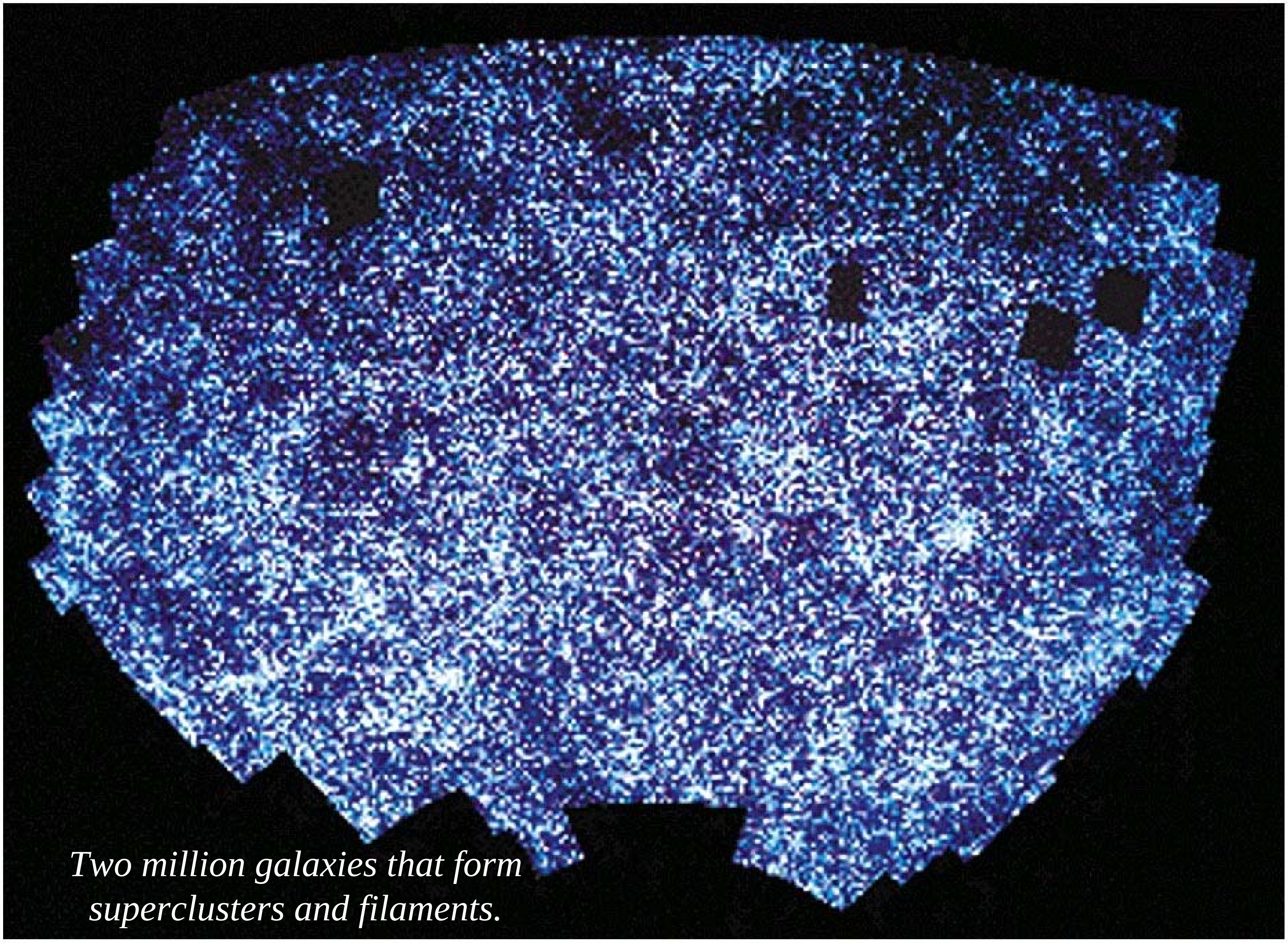

Hercules
Cluster

Coma Cluster



Each dot represents a single galaxy.

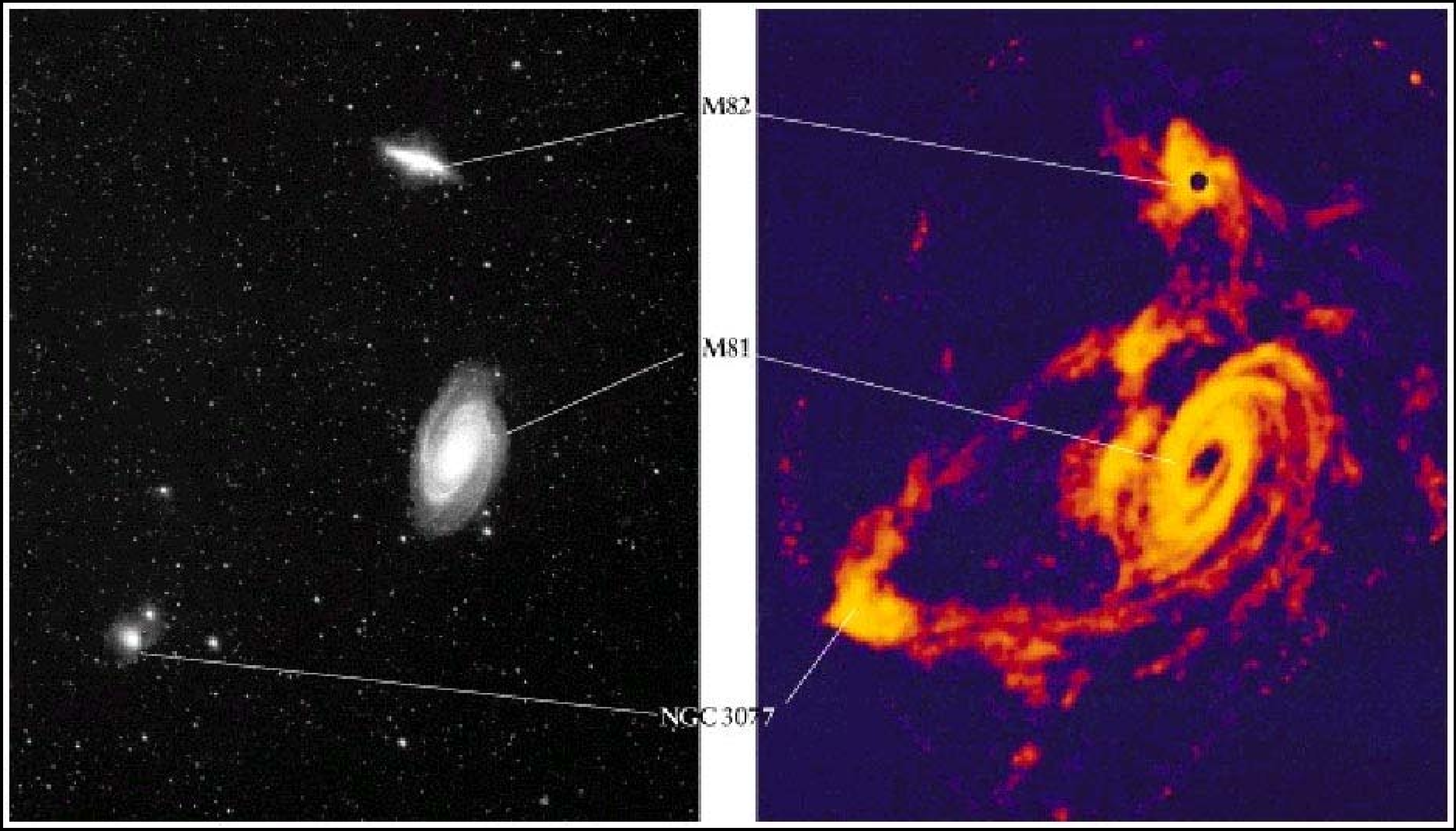




Two million galaxies that form superclusters and filaments.

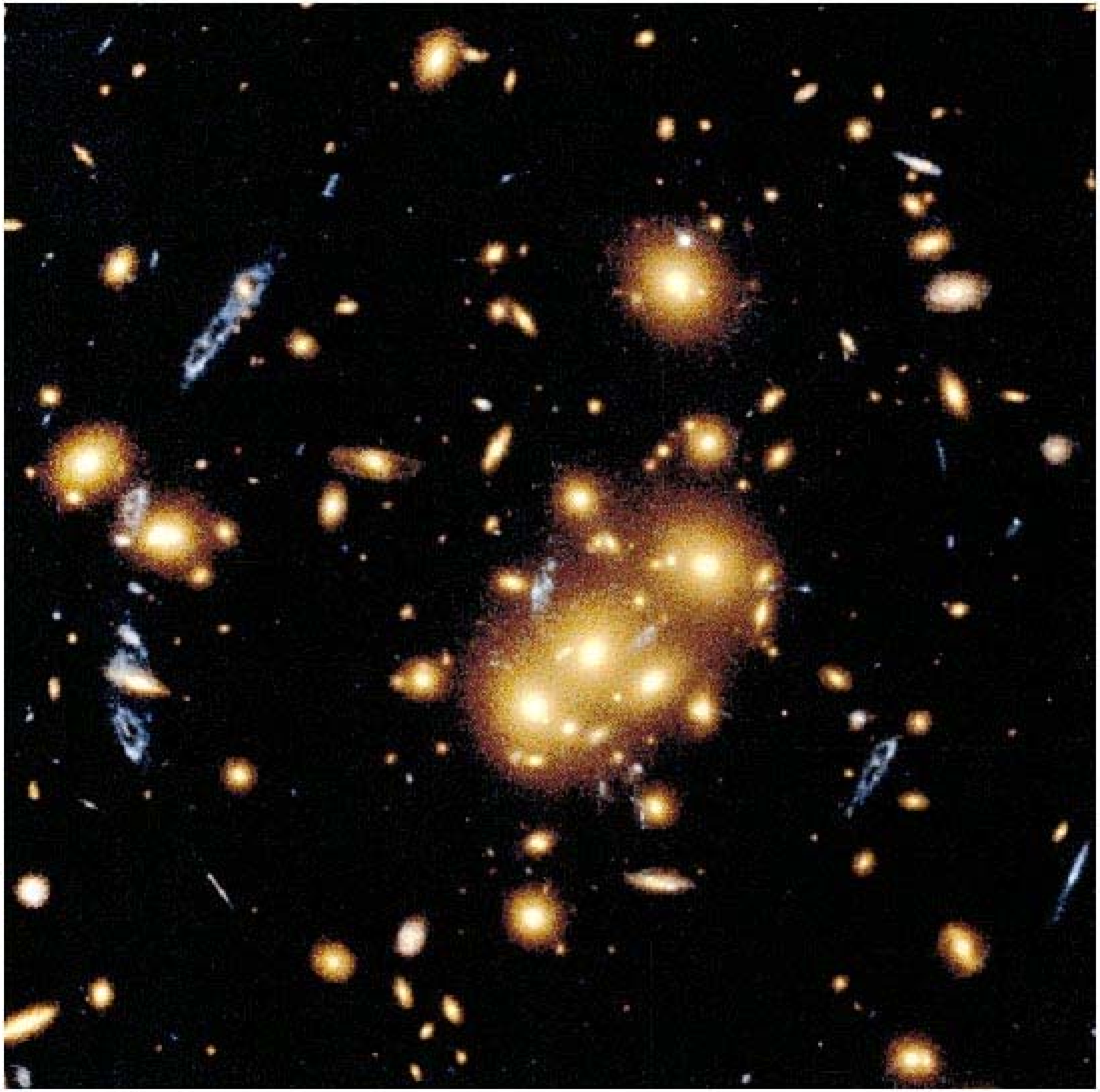
Three galaxies, M81 (big), M82 (medium), and NGC 3077 (small)

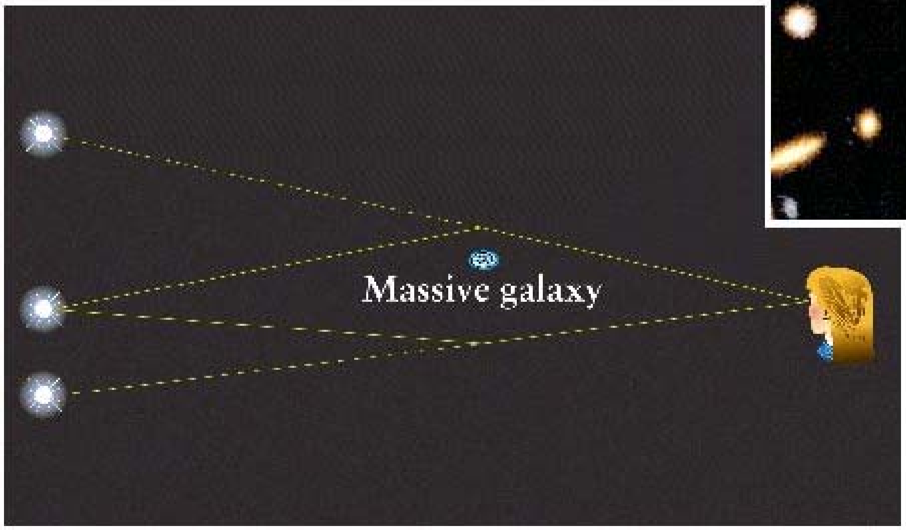
Are they related to one another?



M82
M81
NGC 3077

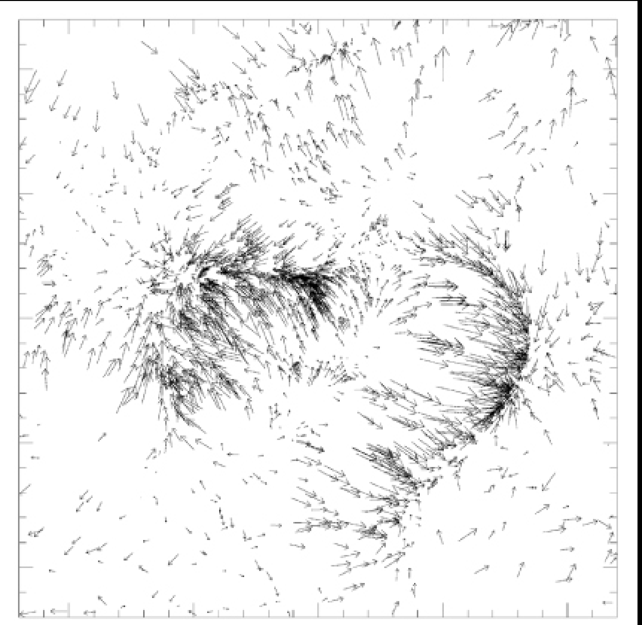
Gravitational lens





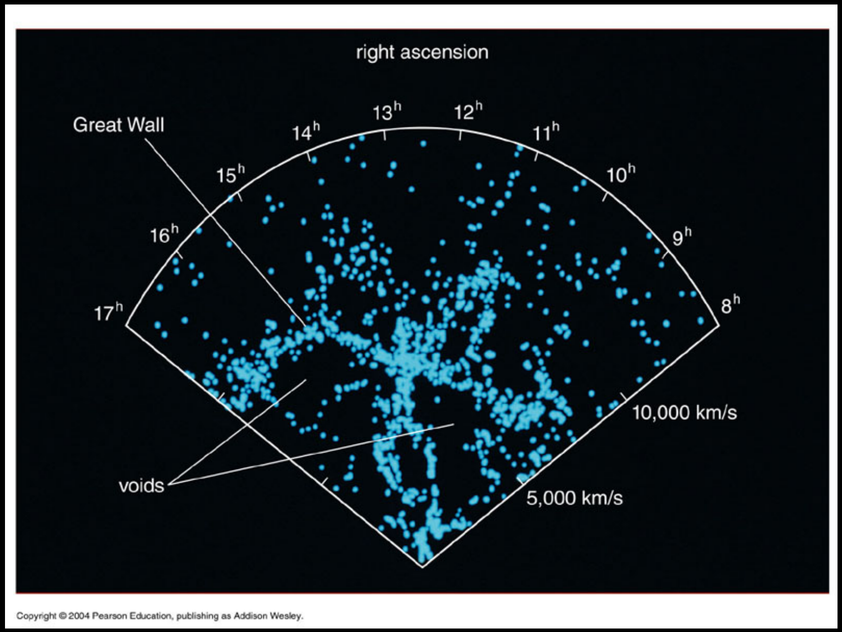
The Growth of Structure

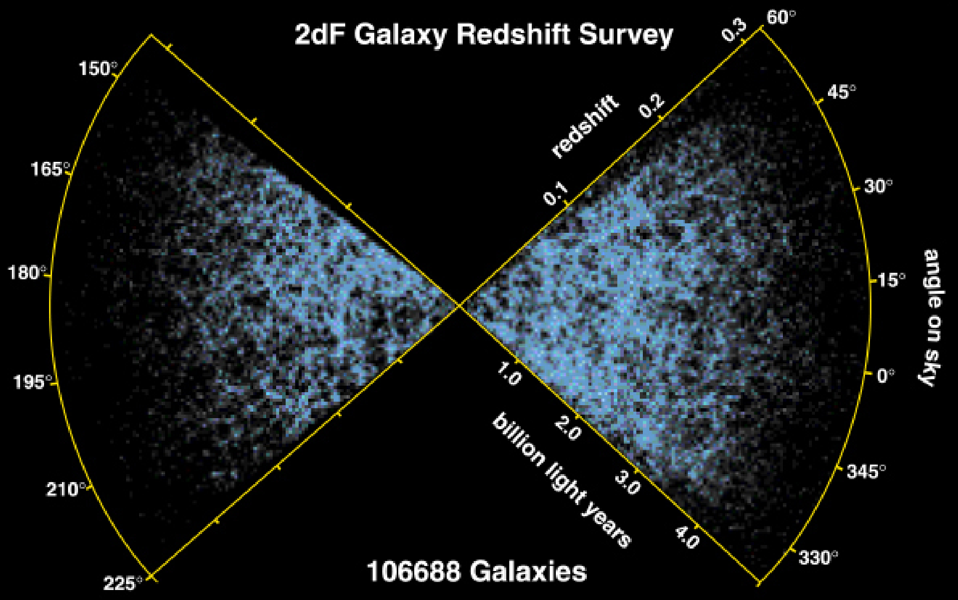
- At close range, gravitational attraction overcomes the Hubble expansion.
  - we see this in a galaxy's **peculiar velocity**
  - although the Universe as a whole expands, individual galaxies attract one another
  - peculiar velocity is a galaxy's deviation from the Hubble Law
  - can measure it for galaxies out to 3 x 10^8 ly



- We project that Universal structure began with slight enhancements in the density of matter in the early Universe.
  - these regions collapsed into protogalactic clouds to form *galaxies*
  - individual *galaxies* fell in towards one another to form *clusters*
  - individual *clusters* are now congregating to form *superclusters*
- These "collapses" against Universal expansion are facilitated by dark matter.

Large Scale Structure of the Universe





slice of the Universe out to 7 x 10^8 ly

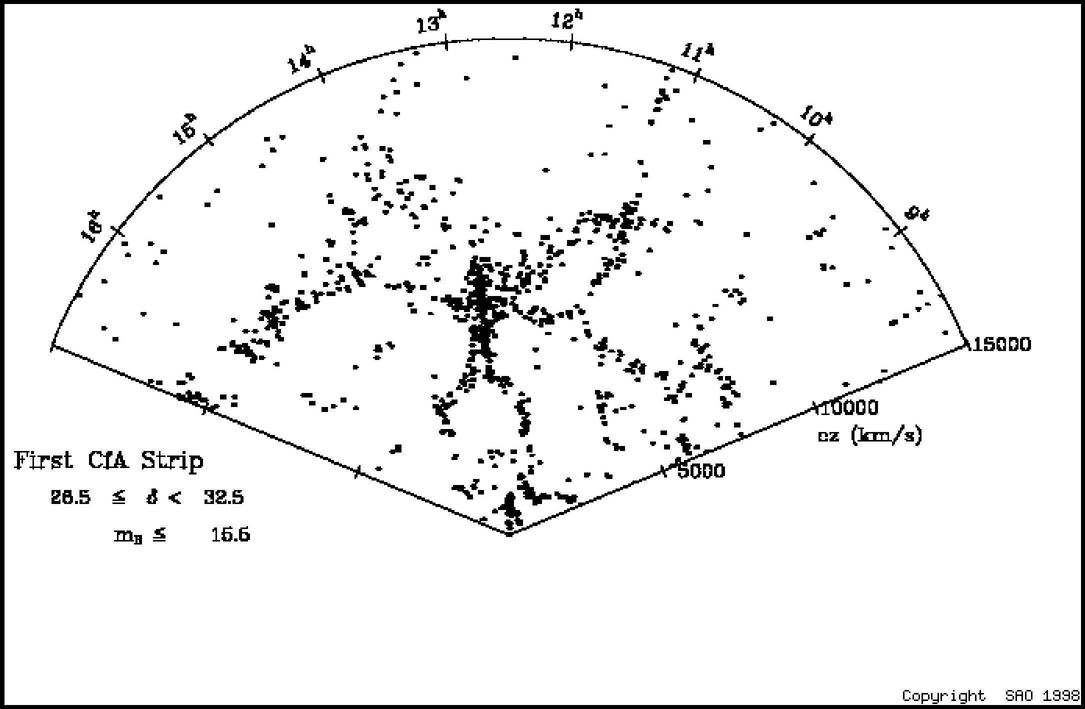
slice of the Universe out to 4 x 10^9 ly

- On scales of 10^8 ly, galaxies are distributed in gigantic chains and sheets surrounding great voids.
  - the chains come from the initial regions of density enhancement
  - the voids come from the initial regions of density depletion
- On scales of several x 10^9 ly, galaxies appear evenly distributed.

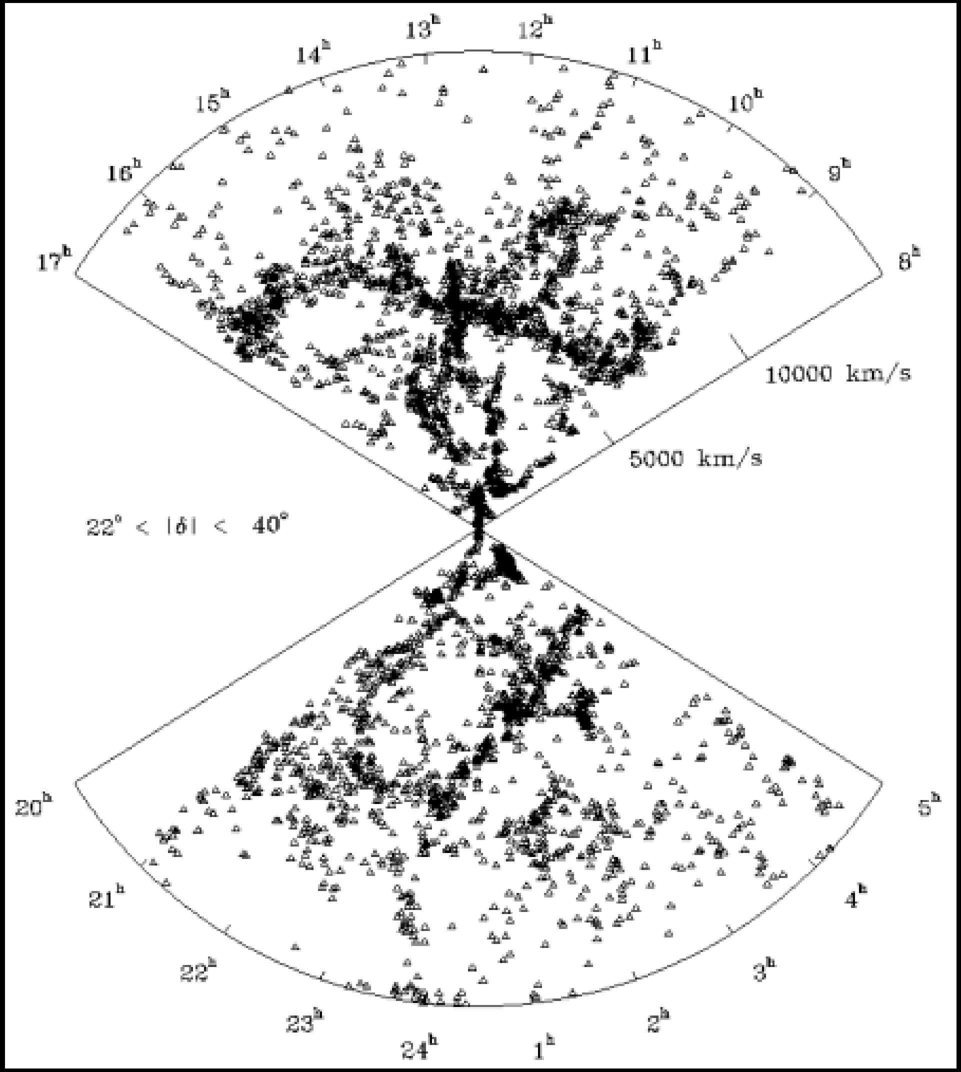
CfA survey (1982)

- Approx 1,100 galaxies cz = 15 000 km/s means a redshift of

  $z = 0.05$, or a distance of 230 Mpc.



CfA2 survey

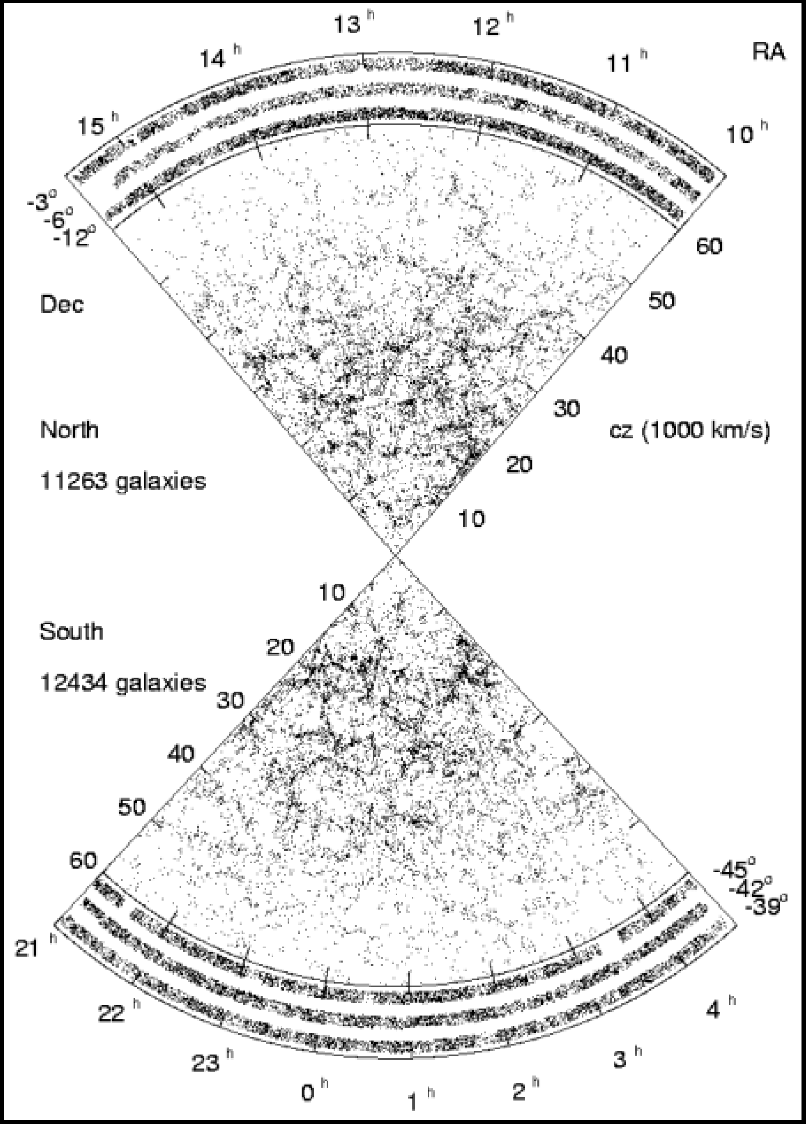


- 18,000 galaxies

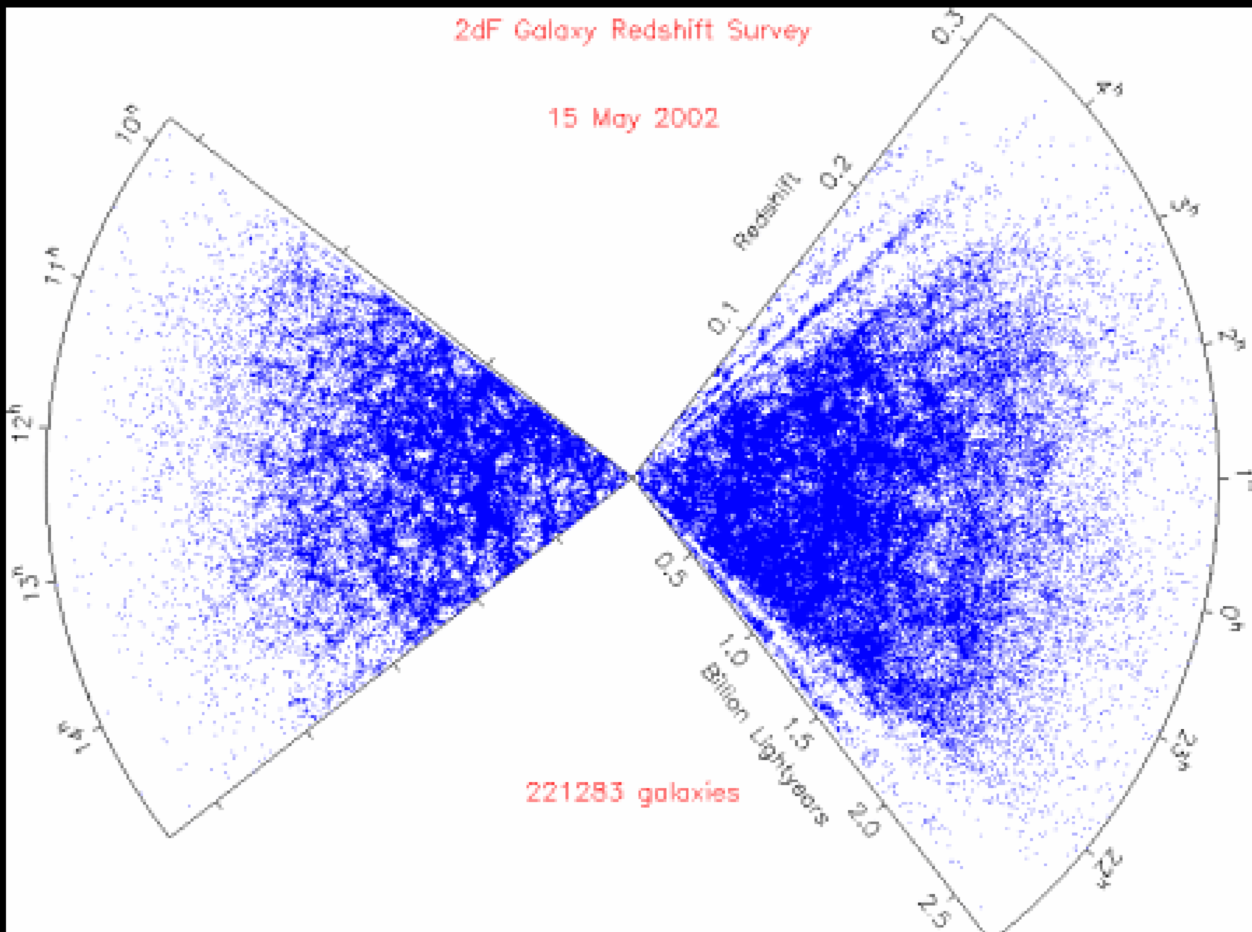
Las Campanas Redshift Survey

- cz = 60,000 km/s equals a redshift of z = 0.2,

  or a distance of roughly 880 Mpc



2dF sky survey

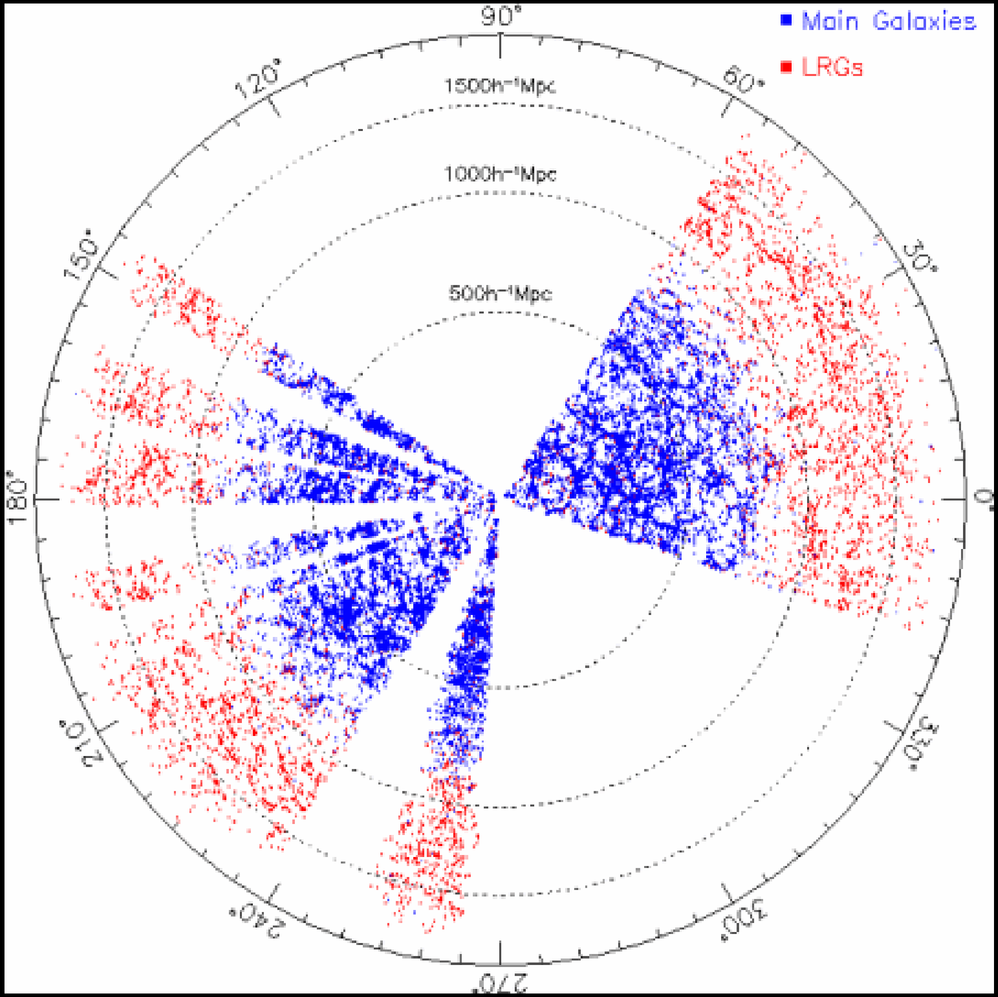


- 221,283 galaxies out to $z = 0.3$

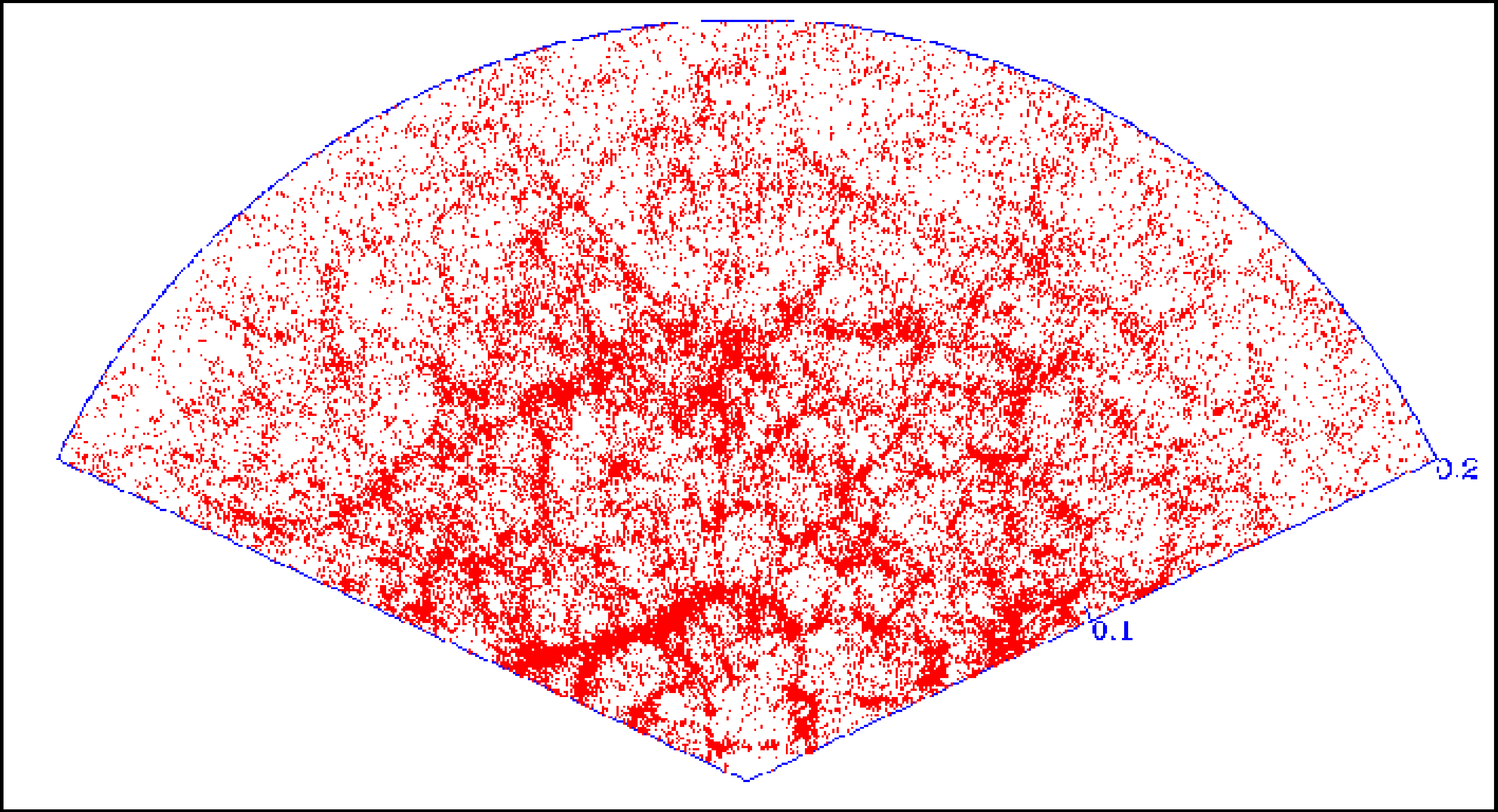
  (or a distance of 1.29 Gpc)

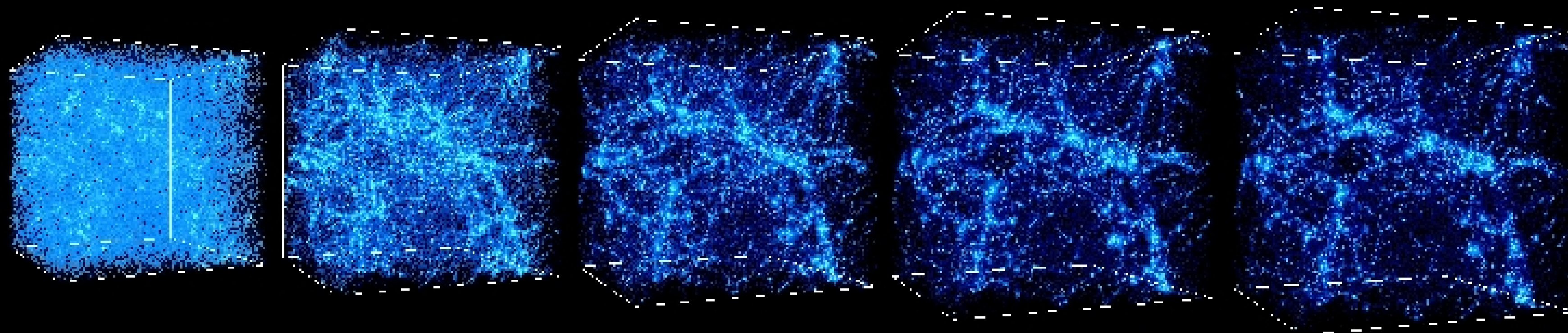
Sloan Digital Sky Survey (early release 2001)

- 50,000 "normal" galaxies (blue) and LRGs (Luminous Red Galaxies; in red).
- Normal galaxies out to $z = 0.2$ (880 Mpc), LRG's out to $z = 0.5$ (2.03 Gpc)

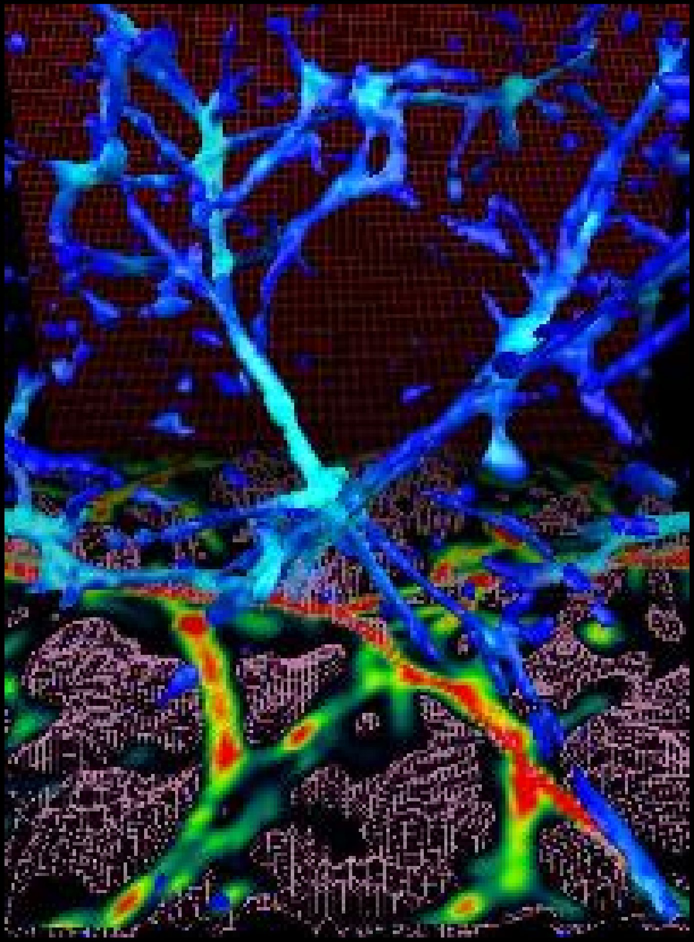


SDSS goal to map 100,000,000 galaxies

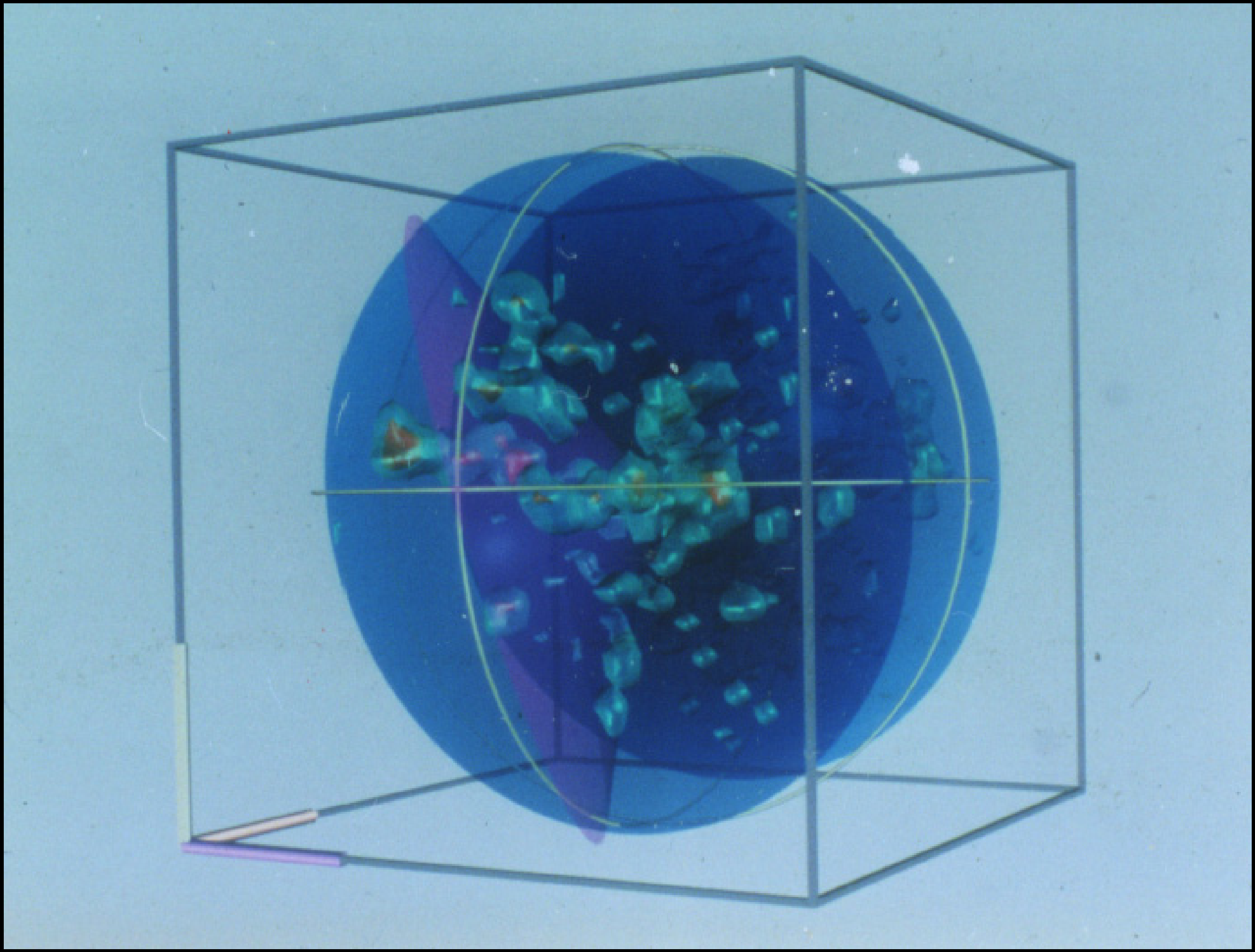


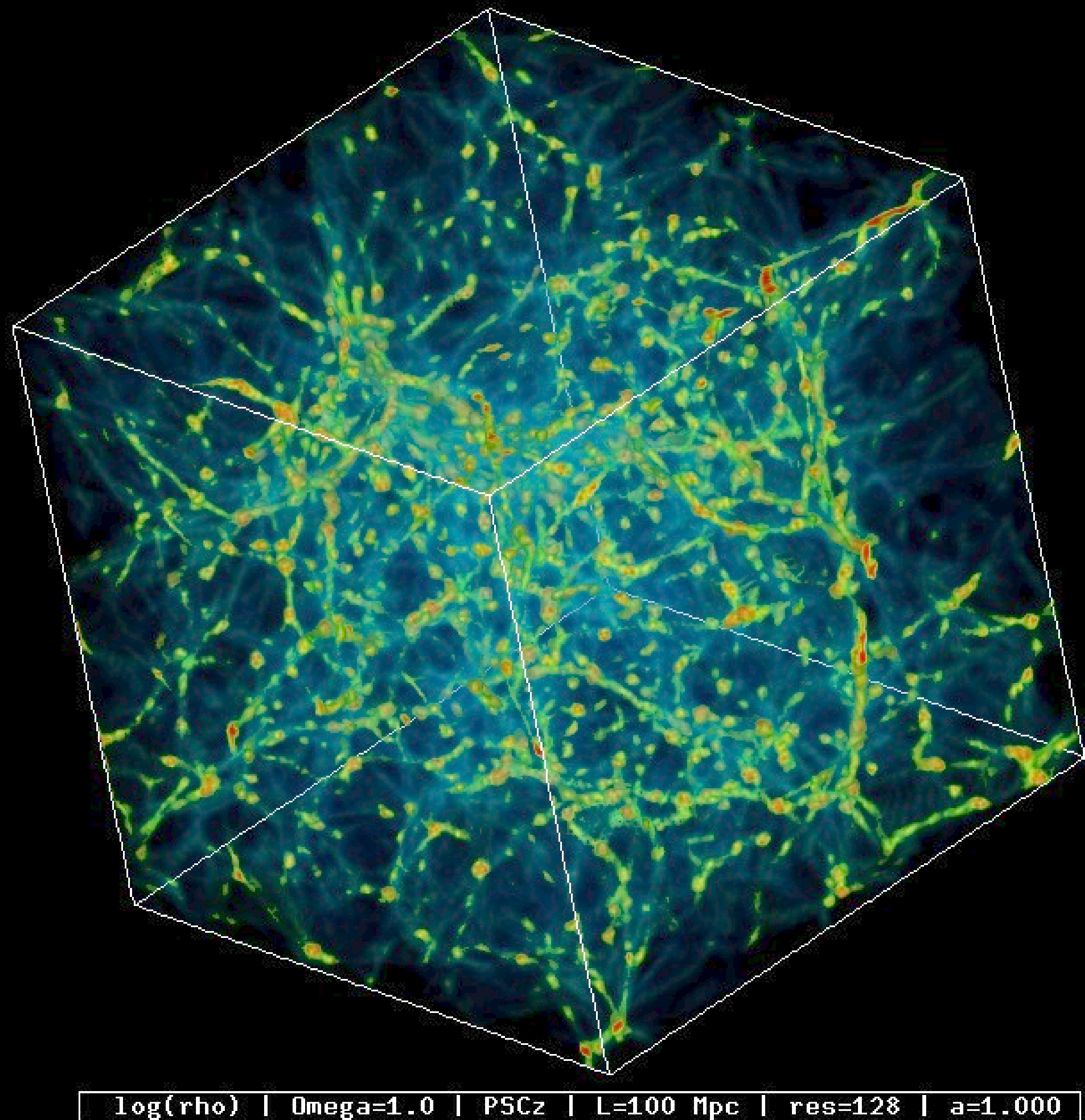


Voids and filaments

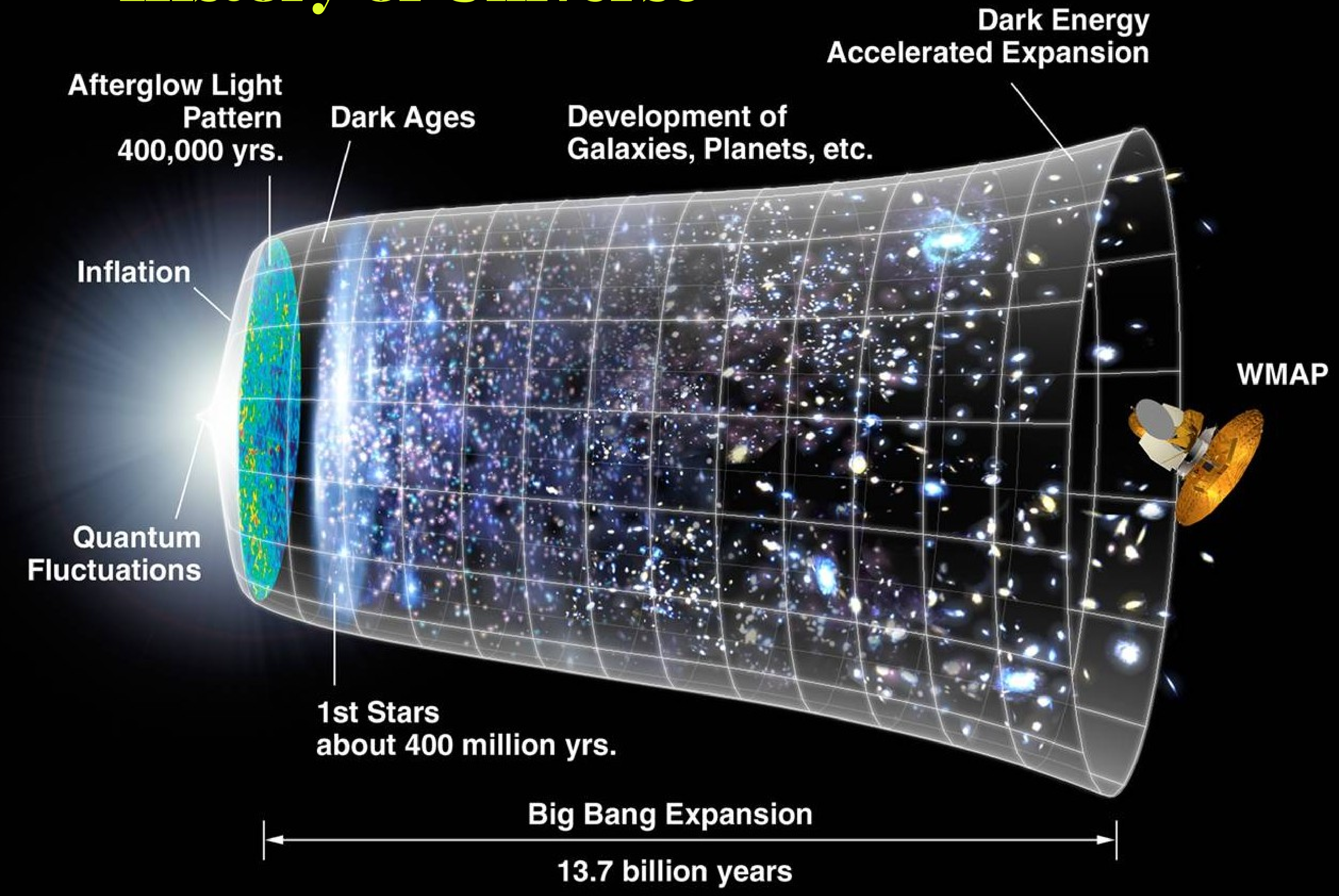


"Complexes of Galaxies" populate a sphere 600 Mpc , two billion light-years, across (R. B. Tully)



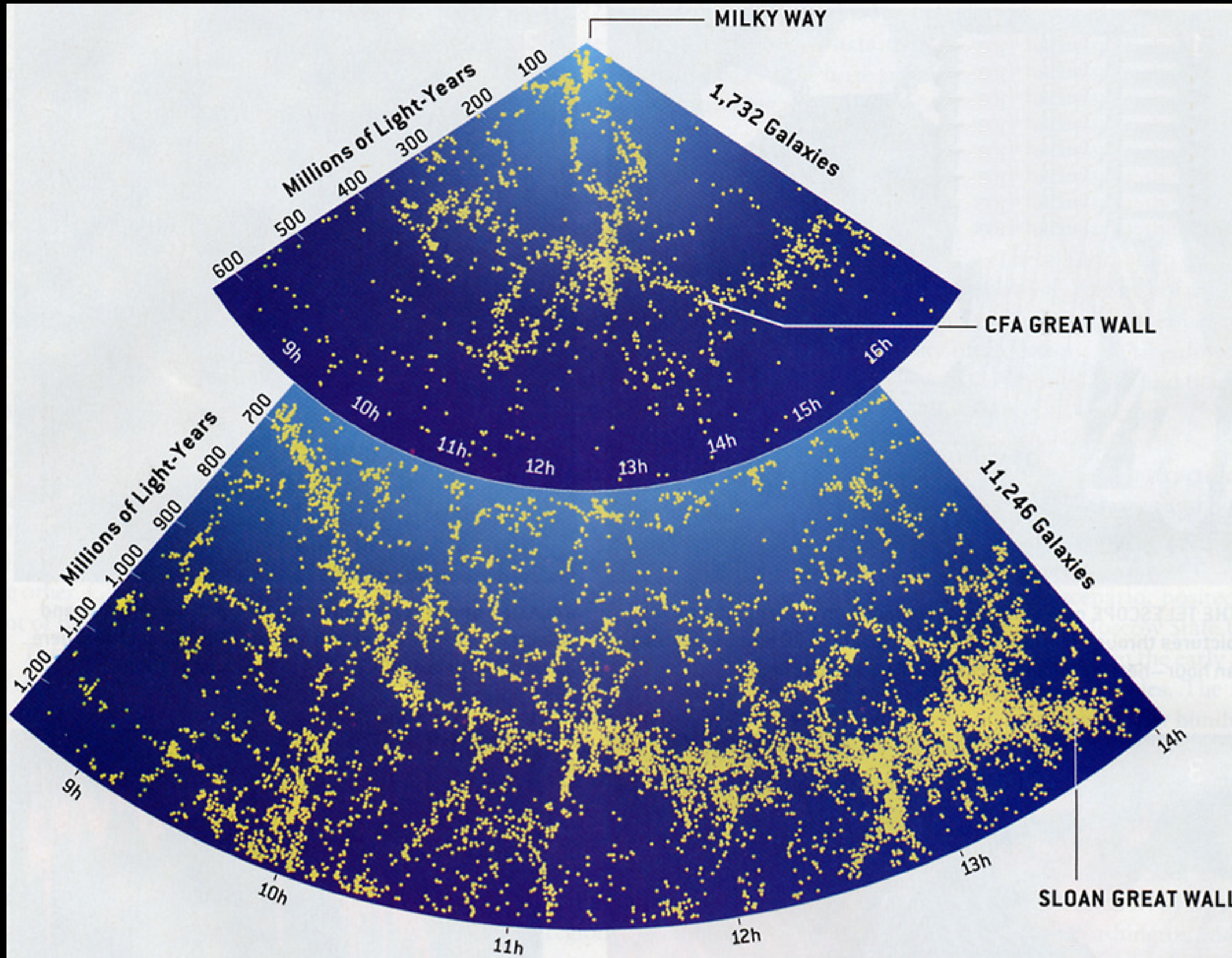

log(rho) | Omega=1.0 | PSCz | L=100 Mpc | res=128 | a=1.000

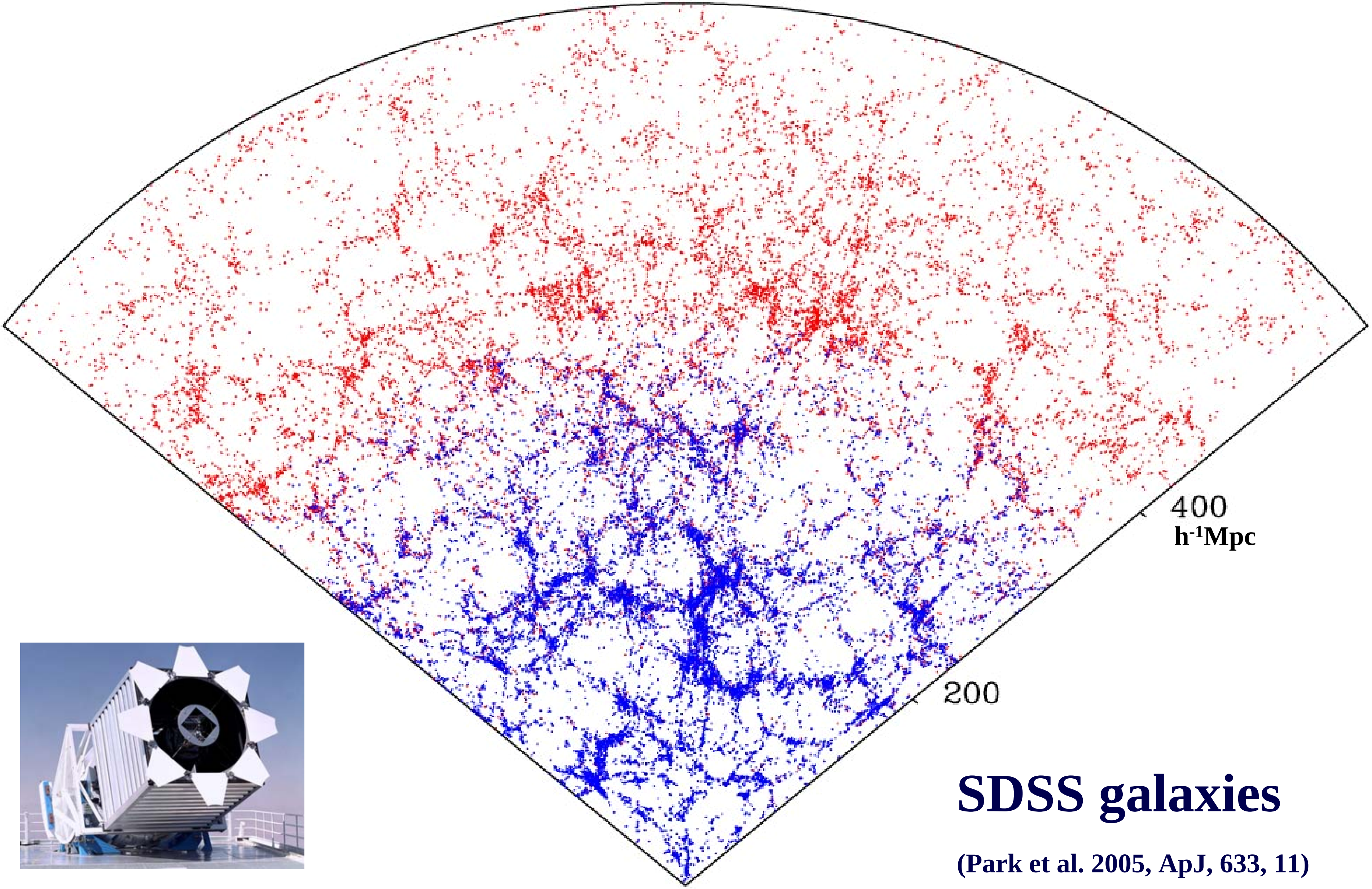
History of Universe



CfA1986

SDSS2006





SDSS galaxies

(Park et al. 2005, ApJ, 633, 11)

Cosmological N-Body Simulation

For PRECISION COMPARISON

between cosmological models with observations

→Effects of NL Gravitational Evolution, Biasing,
& Redshift Space Distortion
on galaxy clustering & properties

Cosmological N-Body Simulation

Requirement for galaxy formation study

1. Several times larger than largest survey >> 1000 Mpc

   : for LSS formation + galaxy formation, velocity field

   * SDSS[2006] ~ 500 Mpc * Hubble Depth S.[2015] ~ 2000 Mpc

2. Should resolve objects with $<<10^{11}$ M_{sun} (~ M_*+2)

   : mean separation < 0.2 Mpc

➔ currently 0.2~2000Mpc

Number of particles > 5000^3 ~ 10000^3 will do!

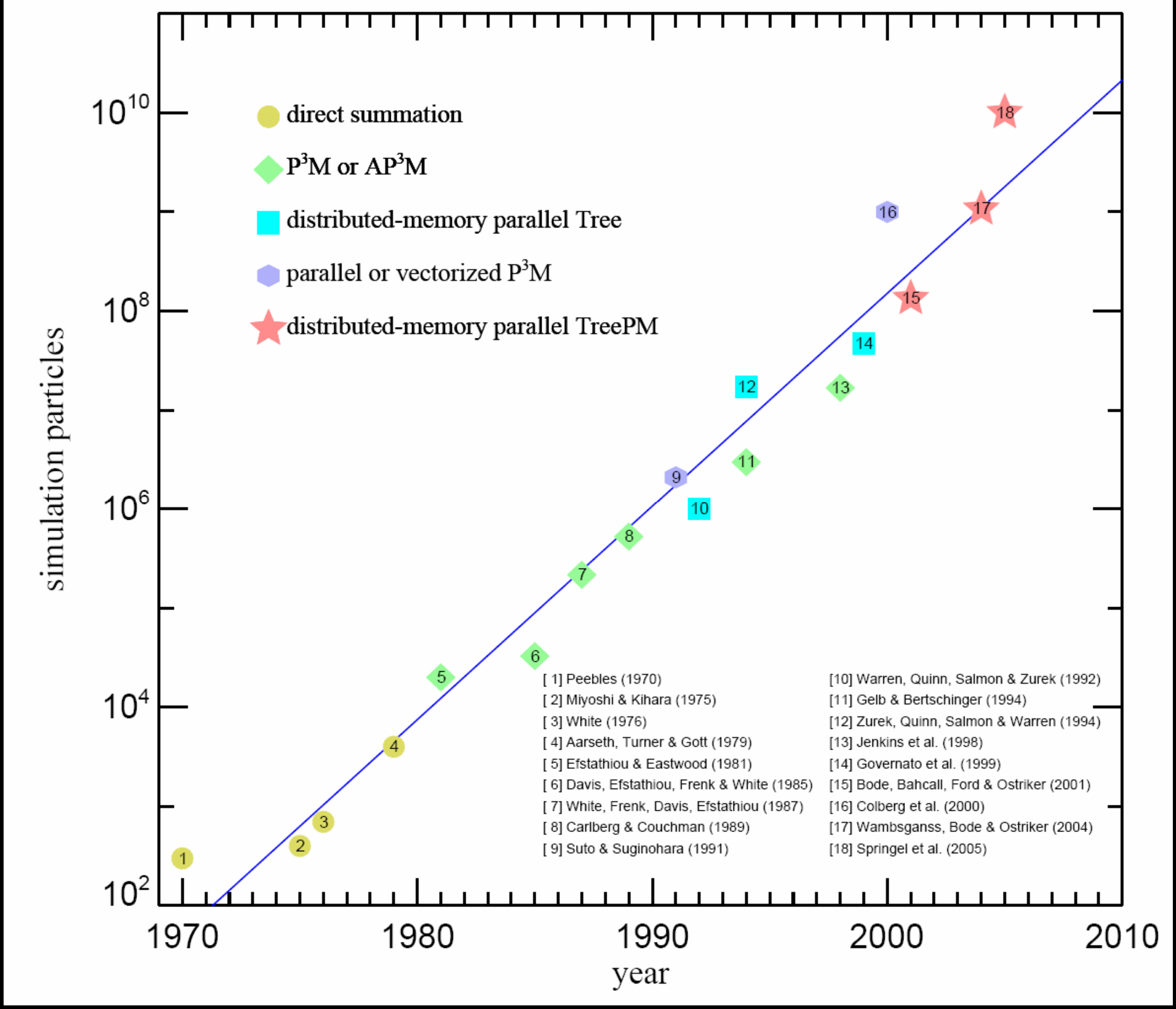
(100~1000 billion =10~100* current maximum)

Cosmological N-Body Simulation

Progresses

- ~ 10^4 CPUs
- > 10^{10} particles

Log N=0.2(Y-1970)+2



ΛCDM Simulations

(Kim & Park 2004. 7)

TreePM code GOTPM (Dubinski, Kim, Park 2003)

2048^3 mesh (initial condition)

2048^3 CDM particles

1024 & 5632 Mpc size boxes

50 & 275 kpc force resolutions

* Using IBM SP3 at KISTI, 128 CPUs, 900 Gbytes,

FOR PRECISION COMPARISON
between cosmological models & real universe

N-body Simulations

Table 1: Simulation Characteristics

	model	Ω_m	Ω_Λ	h	b	N_m [a]	N_p	$L(h^{-1}\mathrm{Mpc})$	z_i	N_{step}	code
a)	ΛCDM	0.27	0.73	0.71	1.11	2048^3	2048^3	1024	17	680	PMTree
	ΛCDM	0.27	0.73	0.71	1.11	2048^3	2048^3	5632	17	170	PMTree
b)	ΛCDM	0.3	0.7	0.7	1.11	512^3	512^3	128	23	980	PMTree
c)	ΛCDM	0.3	0.7	0.7	1.11	2048^3	1024^3	409.6	47	470	PM
	SCDM	1.00	0.00	0.5	1.5	2048^3	1024^3	1024	23	230	PM
	SCDM	1.00	0.00	0.5	1.5	2048^3	1024^3	409.6	47	470	PM

[a] Size of mesh on which initial conditions are defined.

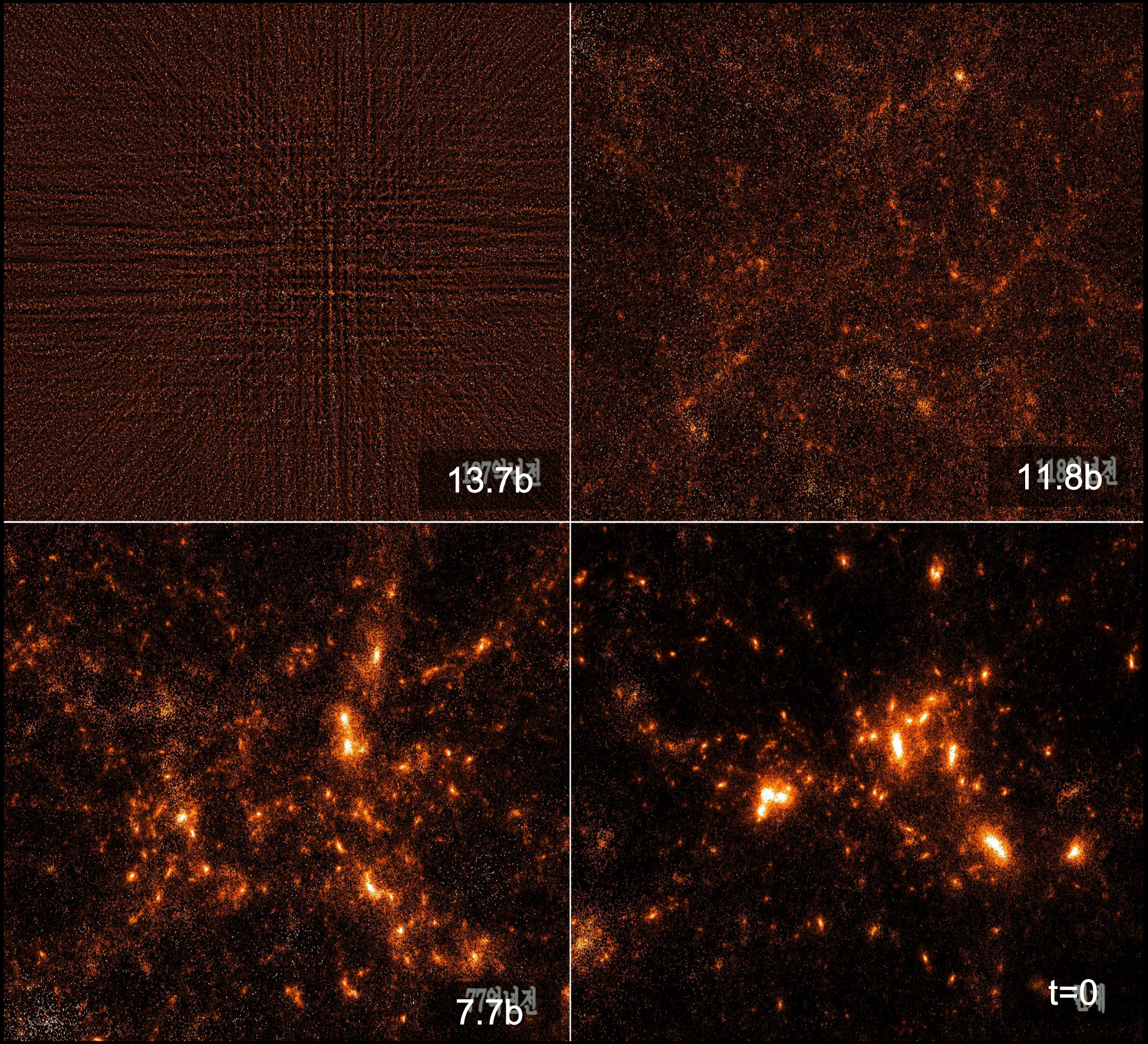
Ω_b=0.046

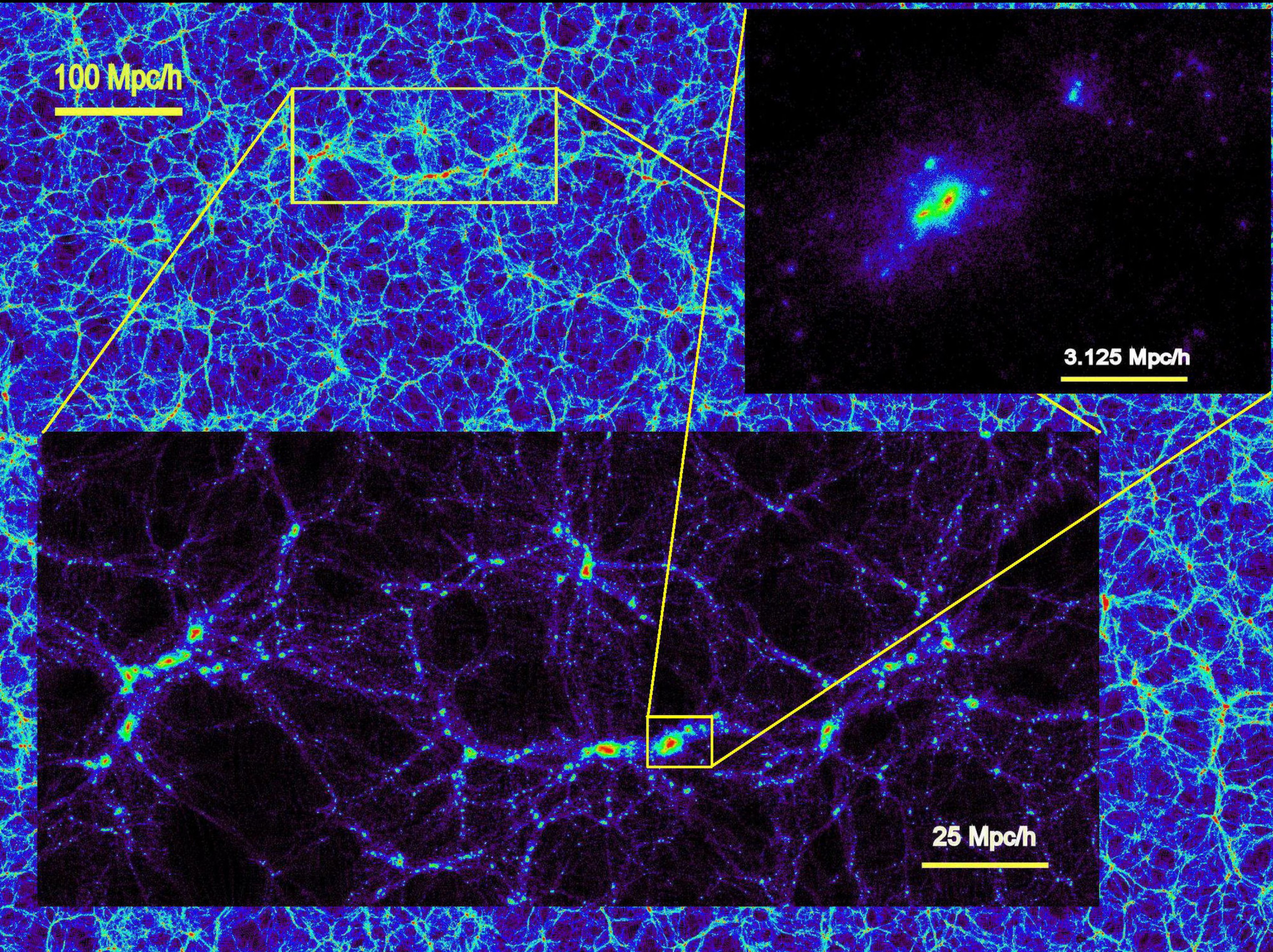
a) → IBM SP3 at KISTI, 128 CPUs, 900 Gbytes,

b) → IBM SP3 at SNU, 16 CPUs,

c) → QUEST at KIAS, 128 CPUs, 256 Gbytes,

Growth of Structures
from initial Density Fluctuations




100 Mpc/h
3.125 Mpc/h
25 Mpc/h

Dark Halo Identification

(Kim& Park 2006:

ΛCDM 1024 Mpc)

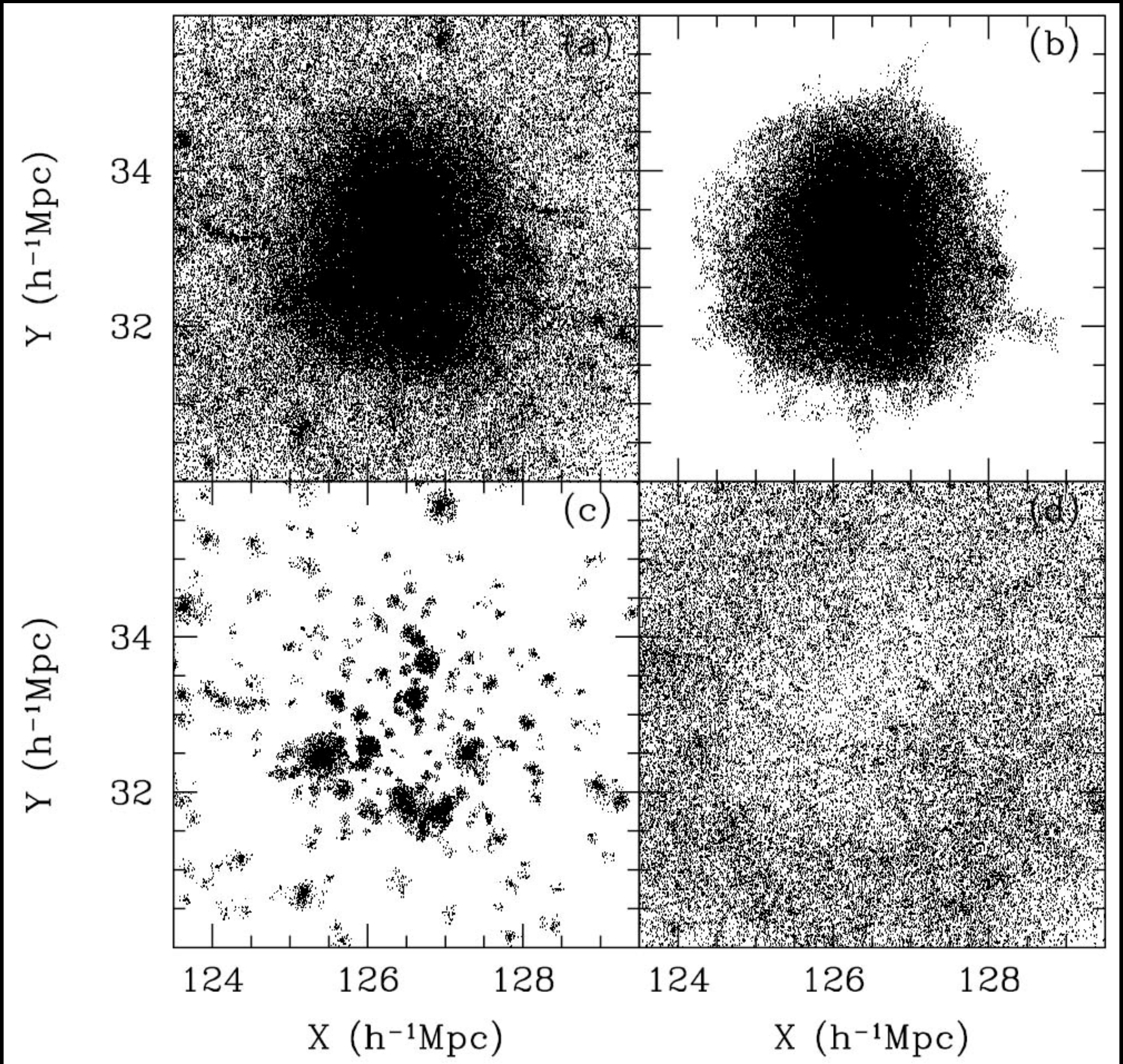
Physically Self-Bound Halos

Halo centers
- local density peaks

Binding E wrt local halo centers

Tidal radii of subhalos wrt bigger halos

Halos with >=53 particles ($5 \times 10^{11}\ M_\odot$)



Topology study

1. Gaussianity of the linear (primordial) density field predicted by simple inflationary scenarios

2. Topology of galaxy distribution at NL scales sensitive to cosmological parameters & to galaxy formation mechanism

3. Direct Intuitive meaning

Large Scales	Small Scales
Primordial Gaussianity	Galaxy Formation
	Cosmological Parameters

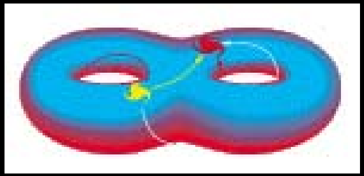
Genus – A Measure of Topology

- **Definition**

G = # of holes - # of isolated regions

in iso-density contour surfaces

= $1/4\pi \cdot \int_S \kappa \, dA$ (Gauss-Bonnet Theorem)

[ex. G(sphere)=-1, G(torus)=0,  **]**

: 2 holes – 1 body = +1

- **Gaussian Field**

Genus/unit volume $g(\nu) = A\,(1-\nu^2)\exp(-\nu^2/2)$

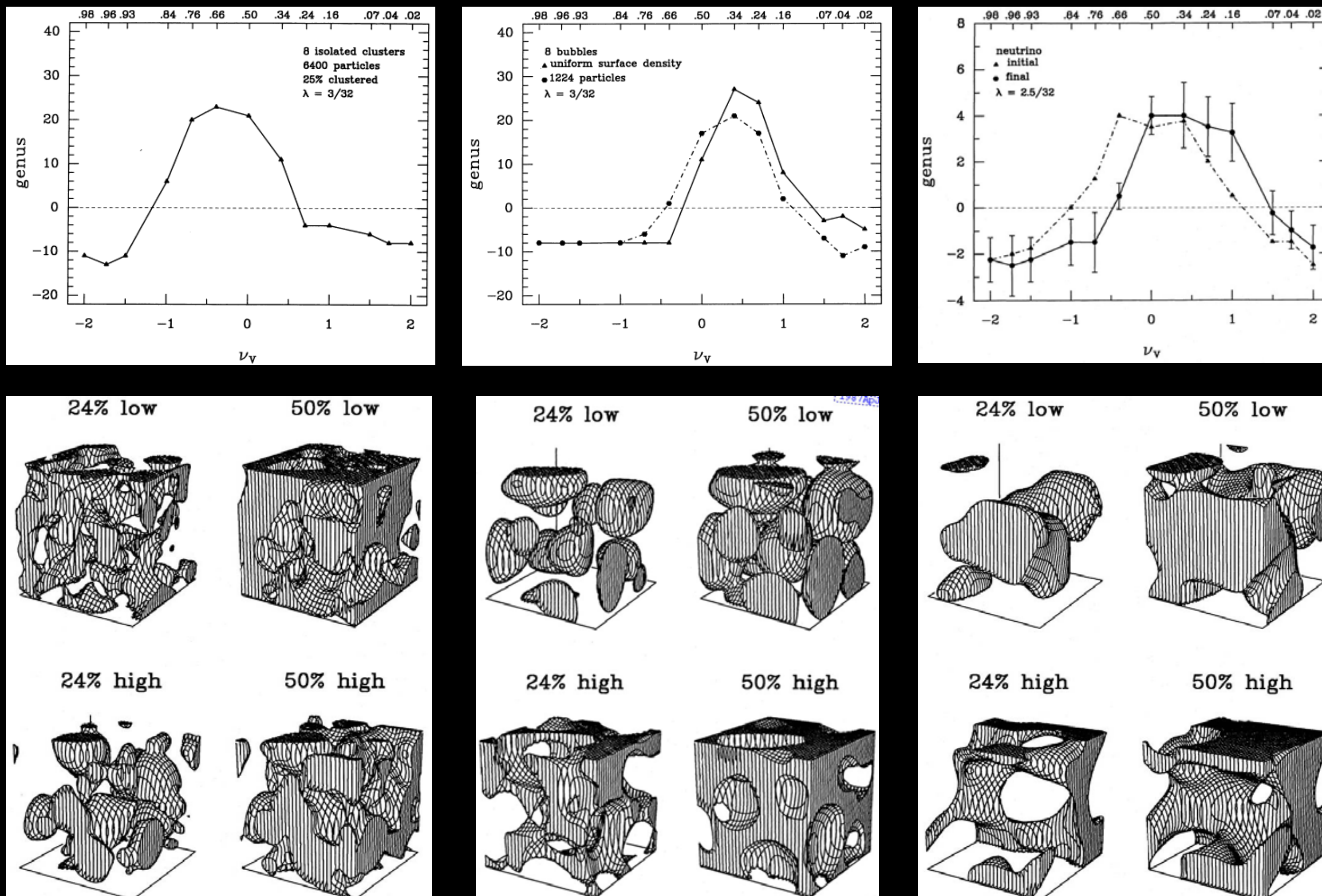
where $\nu=(\rho-\rho_b)/\rho_b\sigma$ &

$A=1/(2\pi)^2 \langle k^2/3\rangle^{3/2}$

if $P(k)\sim k^n$, $A\,R_G^{\,3} = [8\sqrt{2}\pi^2]^{-1} * [(n+3)/3]^{3/2}$

• Non-Gaussian Field (Toy models)

Clusters **Bubbles** **HDM**



(Weinberg, Gott & Melott 1987)

Future of
Cosmological N-Body Simulation

1. Useful for cosmology & galaxy formation study

   (until star formation can be properly simulated by radiative hydro-codes)

2. Need to reach # of particles >> $5000^3 \sim 10000^3$

   (10~100 current maximum)

Dynamic range for other studies

* Internal properties & environment: 1kpc ~ 100 Mpc
* Galactic structure & star formation : 0.1pc ~ 100kpc