Observational Basics of Modern Cosmology (part I)

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РЕКОМЕНДУЕМАЯ ЛИТЕРАТУРА

А.Д. Долгов, Я.Б. Зельдович, М.В. Сажин
«Космология ранней Вселенной»
Изд-во МГУ, 1988

М.В.Сажин
«Современная космология в популярном изложении»
Изд-во УРСС Москва, 2002.

Д.С. Горбунов, В.А.Рубаков
«Введение в теорию ранней Вселенной»

т.1 «Теория горячего Большого Взрыва»
Изд-во ЛКИ, 2008
т.2 «Космологические возмущения.
Инфляционная теория»
Изд-во КРАСАНД, 2009

С. Вайнберг
КОСМОЛОГИЯ.
Изд-во УРСС, 2012.

The Cosmology Today

Today cosmology is entered in “golden age”. Several scientific organization were established which are specially devoted to cosmological investigations. Discussion on the cosmology became popular among community. All that provides us with hope that cosmology will be necessary element of mankind culture for a long time.

Three sources of success:

1. The development of astronomical observation;

2. The development of physical theory;

3. The moral courage of the scientists.

Beginning of cosmology as "science"…

Cosmology at present time…

Three sources of success:

1. The development of astronomical observation;

2. The development of physical theory;

3. The moral courage of the scientists.

The observational basis of the Standard Cosmological Model

1. EXPANSION OF OUR UNIVERSE

2. EXISTENCE OF PRIMORDIAL RADIATION

3. THE DISCOVERY OF LARGE SCALE STRUCTURE OF OUR UNIVERSE

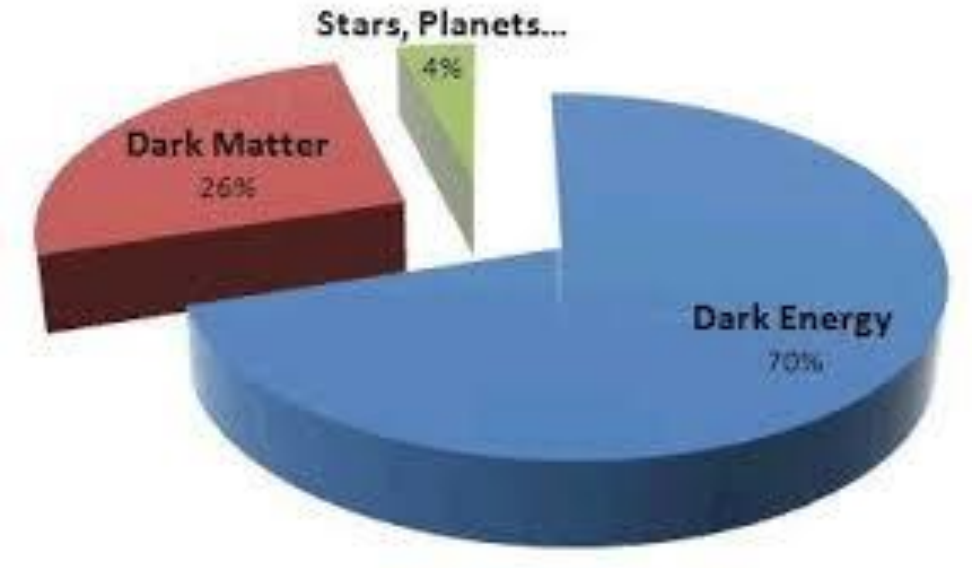
4. LIGHT ELEMENT ABUNDANCE IN OUR UNIVERSE

5. ANISOTROPY OF THE CMBR

New Discoveries of last century

1.DARK MATTER IN OUR UNIVERSE

2.DARK ENERGY IN OUR UNIVERSE



1. Expansion of our Universe

The experimental basis of modern cosmology is based on several experimental facts. Below the most important facts are presented.

The first fact is the expansion of our Universe. This fact was predicted by russian physicist **A.A. Friedman**, **1924** and discovered by american astronomer **E. Hubble**, **1929**.

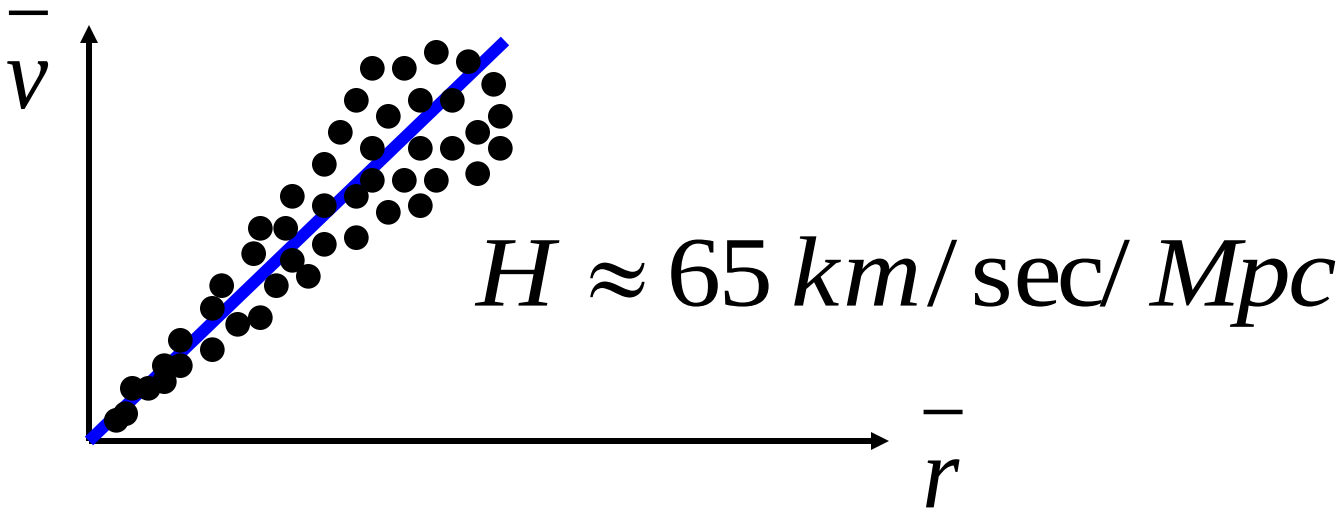
The expansion law is named now **"Hubble law".** The equation that describes the expansion law is very simple:

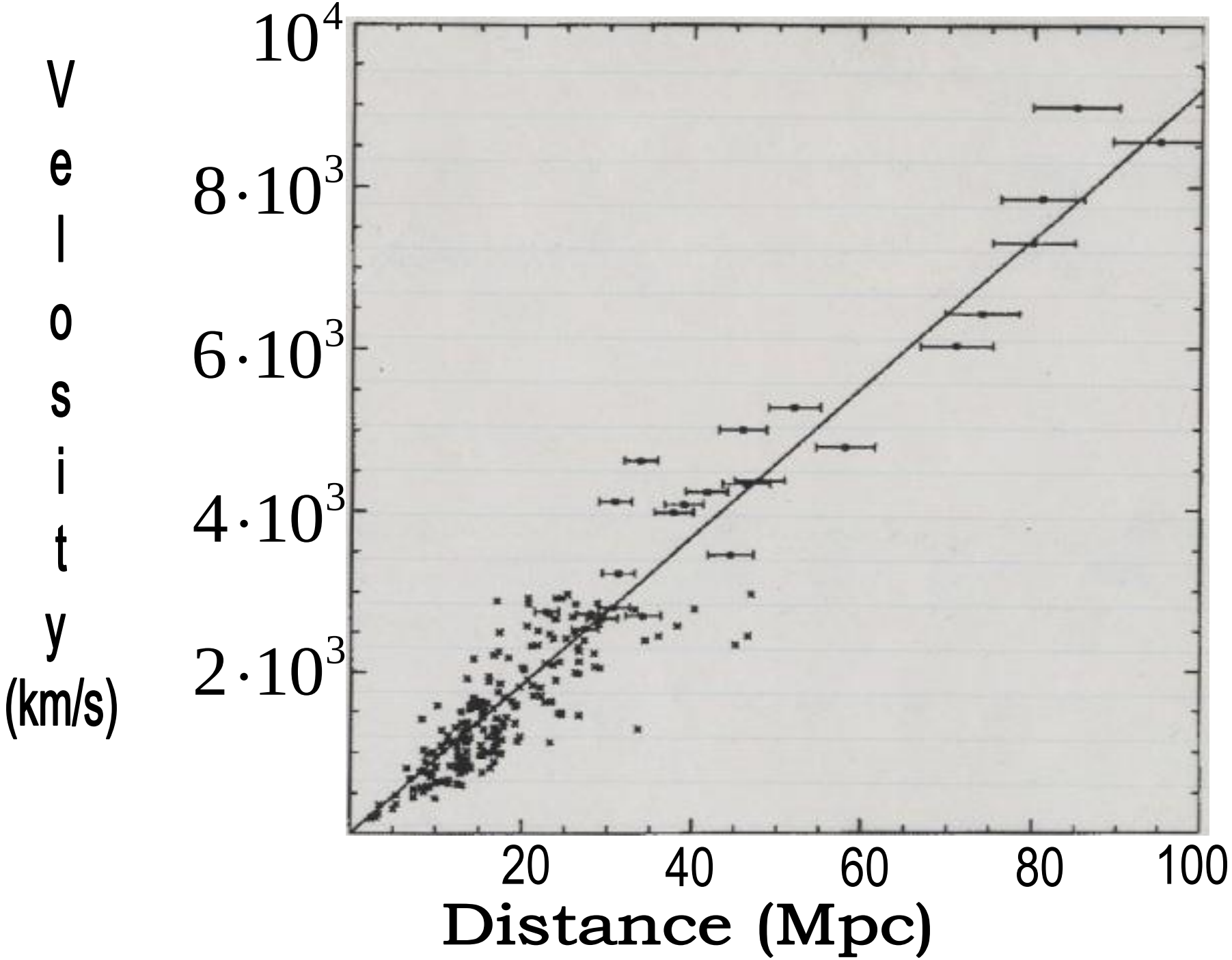
$$\vec{v} = H\vec{r}$$

$\bar{v}$ is velocity of a galaxy, $\bar{r}$ is distance from an observer to the galaxy,

H is Hubble constsnt, $[H] = \sec^{-1}$

the inclination is the Hubble constant



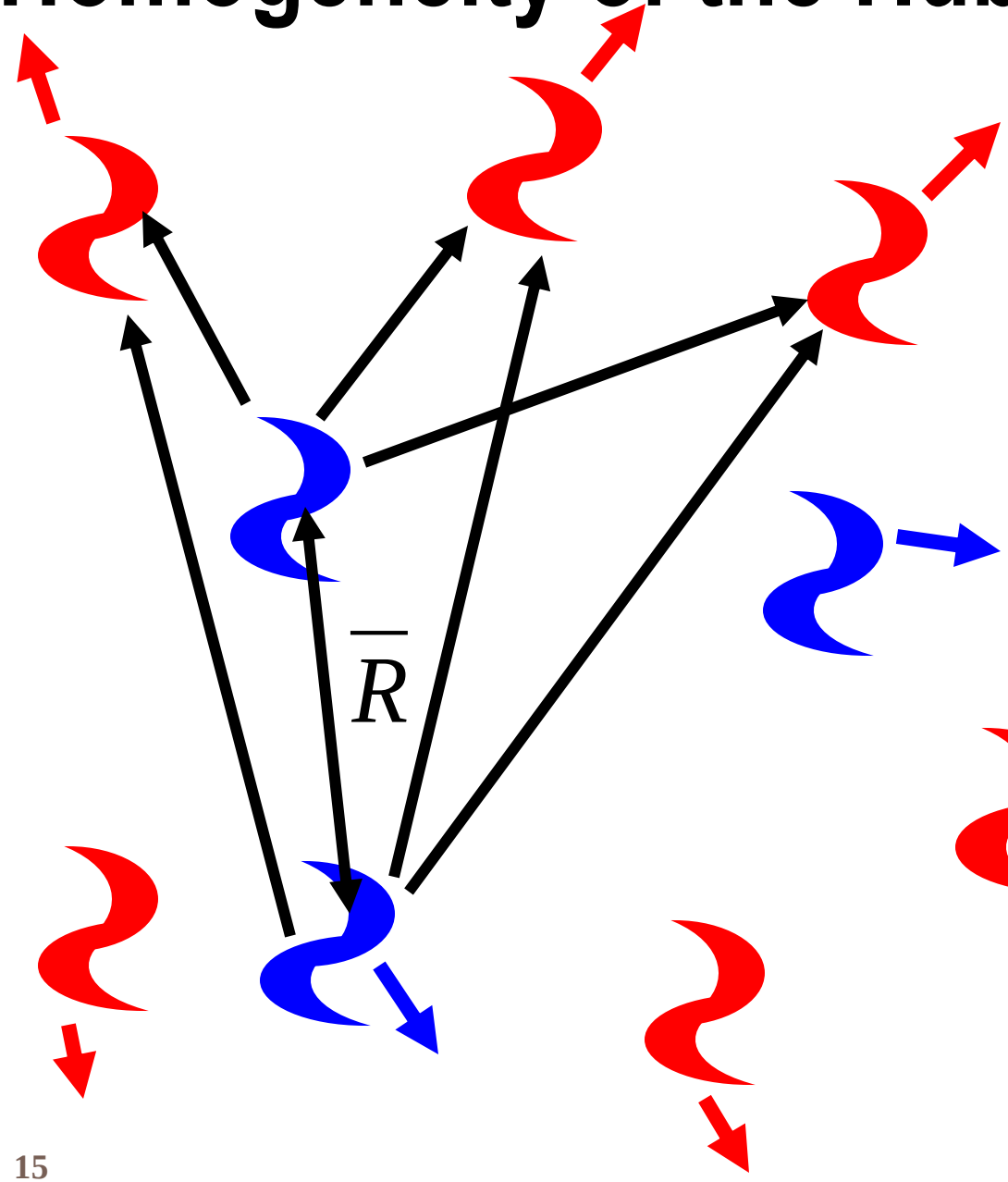

Velocity (km/s)
10^4
$8 \cdot 10^3$
$6 \cdot 10^3$
$4 \cdot 10^3$
$2 \cdot 10^3$
20
40
60
80
100
Distance (Mpc)

Size of our Universe

Our Universe is 14 Giga year old. Therefore the first light we see passes finite distance. We are inside the sphere. The distance to this sphere is called “particle horizon”. The radius of this sphere is

$$R = 3.4\frac{c}{H_0} \cong 14\ \mathrm{Gpc}$$

Homogeneity of the Hubble flow



$$\begin{cases} \overline{v} = \overline{H} \cdot \overline{r} \\ \overline{r} = \overline{\rho} + \overline{R} \\ \overline{v} = \overline{\upsilon} + \overline{H} \cdot \overline{R} \end{cases}$$

$$\Downarrow$$

$$\overline{\upsilon} = \overline{H} \cdot \overline{\rho}$$

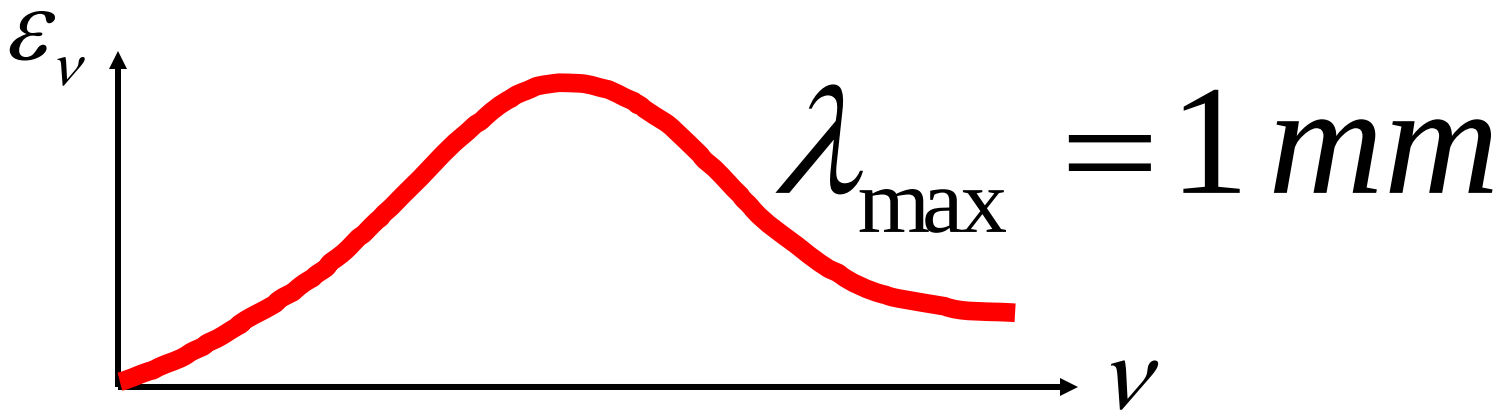
2. The existence of primordial radiation

In *russian literature* it is called **relic radiation**.
In *english literature* it is called **Cosmic Microwave Background Radiation** (**CMBR** or **CMB**).

It was predicted by **G. GAMOV** in 1946, who was a student of **A. FRIEDMAN**, and was discovered by american physicists Penzias and Wilson (1964). Penzias and Wilson were awarded by Nobel Prize for this discovery.

The CMBR is a blackbody radiation with temperature 2.75 K. It is the relic of the early stages of evolution of our Universe.

The spectrum of CMBR is Planckian



The discovery of the CMBR proved standard Big Bang model. Before the discovery of the CMBR there were two main models:

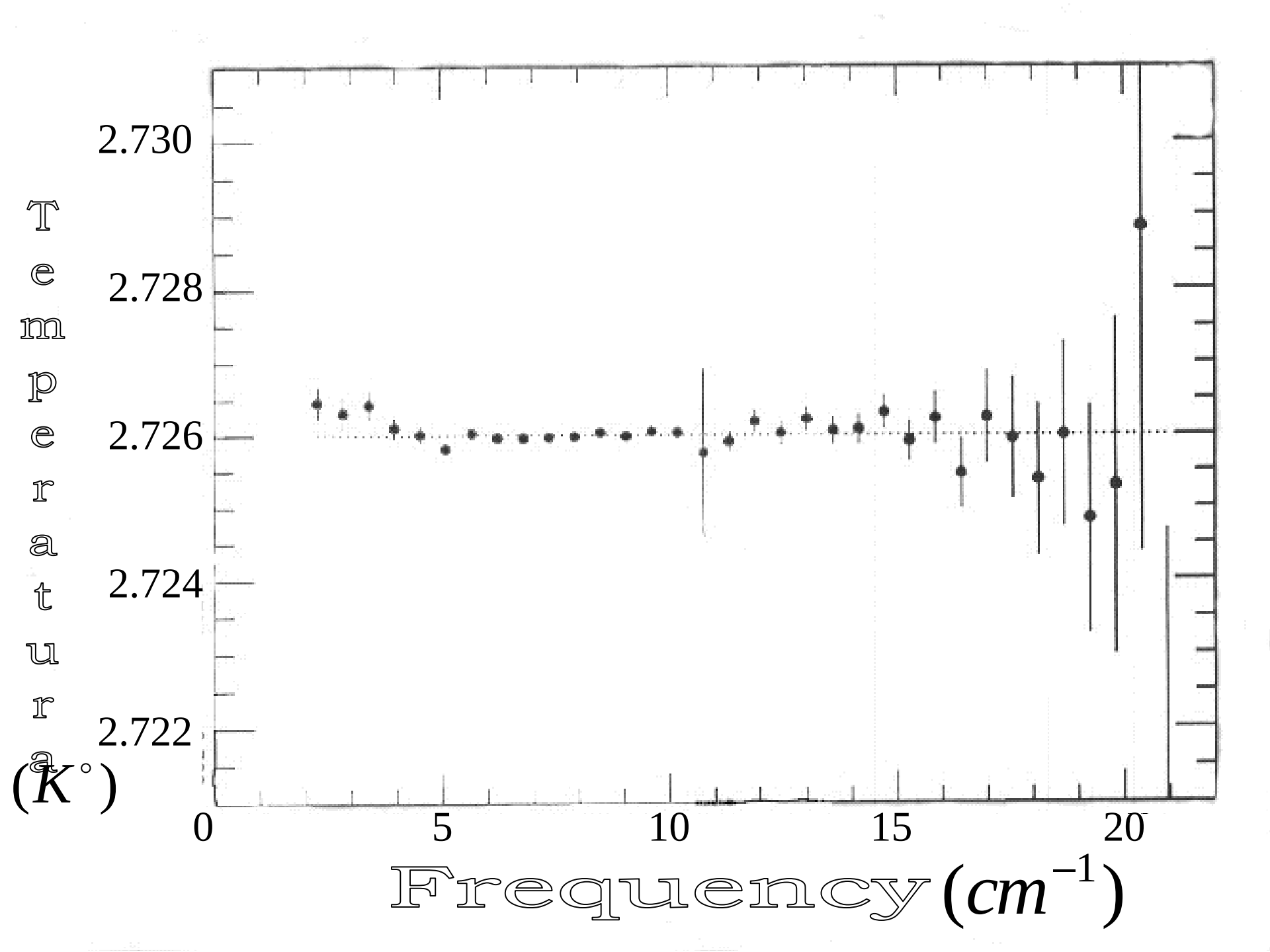
1. *HOT UNIVERSE* (standard Big Bang model);
2. *COLD UNIVERSE* (is forgotten now).

Encounters with CMBR

SHAKHBASOV (1957)

«ECHO» satellite (1961)

PENZIANS and **WILSON** discovered it and were awarded by Nobel prize in Physics


2.730
2.728
2.726
2.724
2.722
Temperature
(K°)
0
5
10
15
20
Frequency (cm⁻¹)

The “elementary particles” of our Universe

We are living on the Earth, one of the planet of our solar system orbiting the Sun. The Sun is a star of our Galaxy. It is a huge system which consists from stars of different types.

Here and below I’m using several slides which were prepared **by Prof.M.Capaccioli**.

Via Lattea: galassia a spirale

una massa di 200 miliardi di Soli

Casa, dolce casa ...

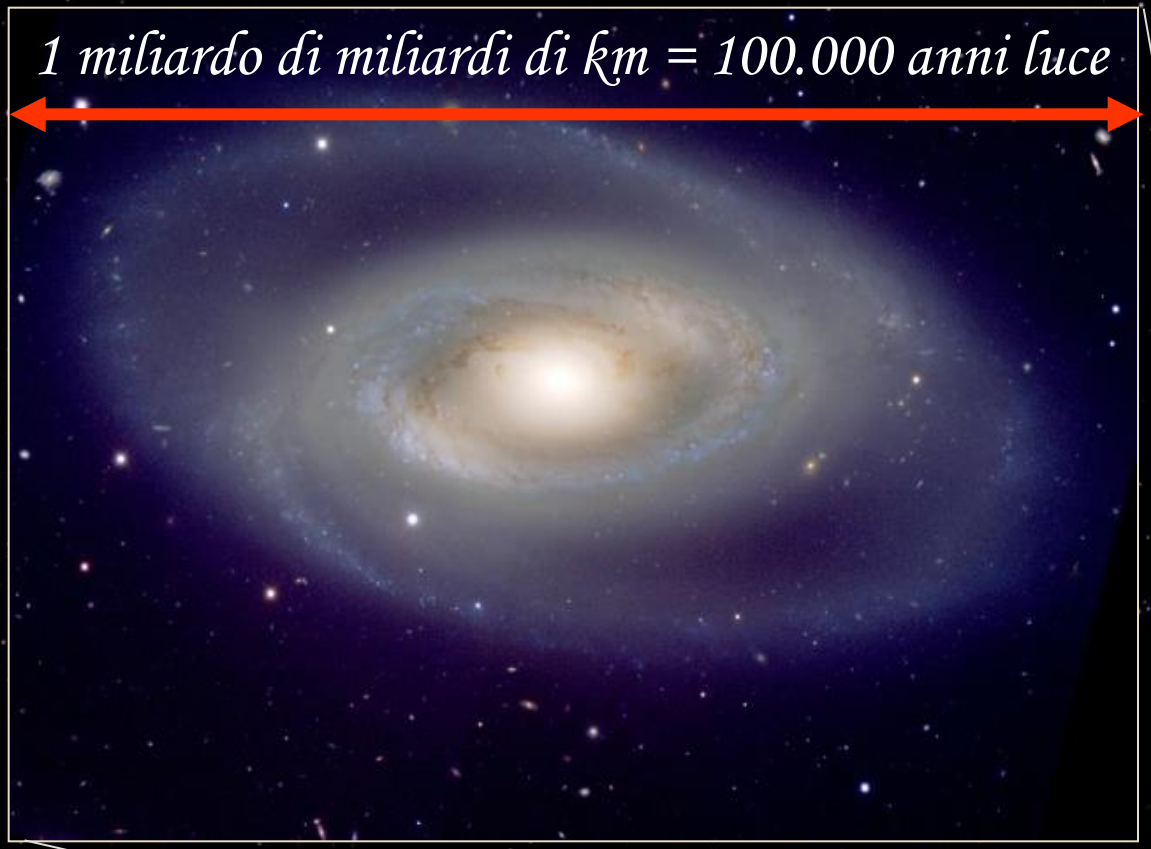
M87 in Virgo

M31 in Andromeda

Nana irregolare nel Sagittario

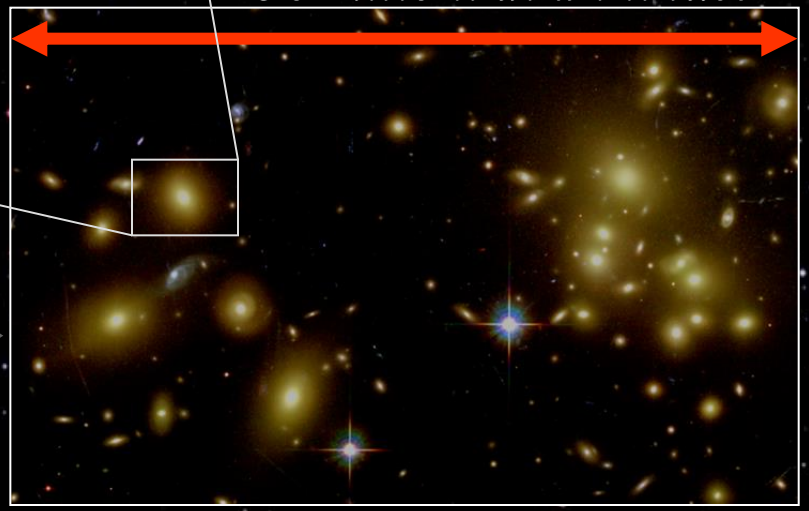
L'universo visibile contiene circa
100 miliardi di galassie

1 miliardo di miliardi di km = 100.000 anni luce



Una galassia è costituita da centinaia di miliardi di stelle

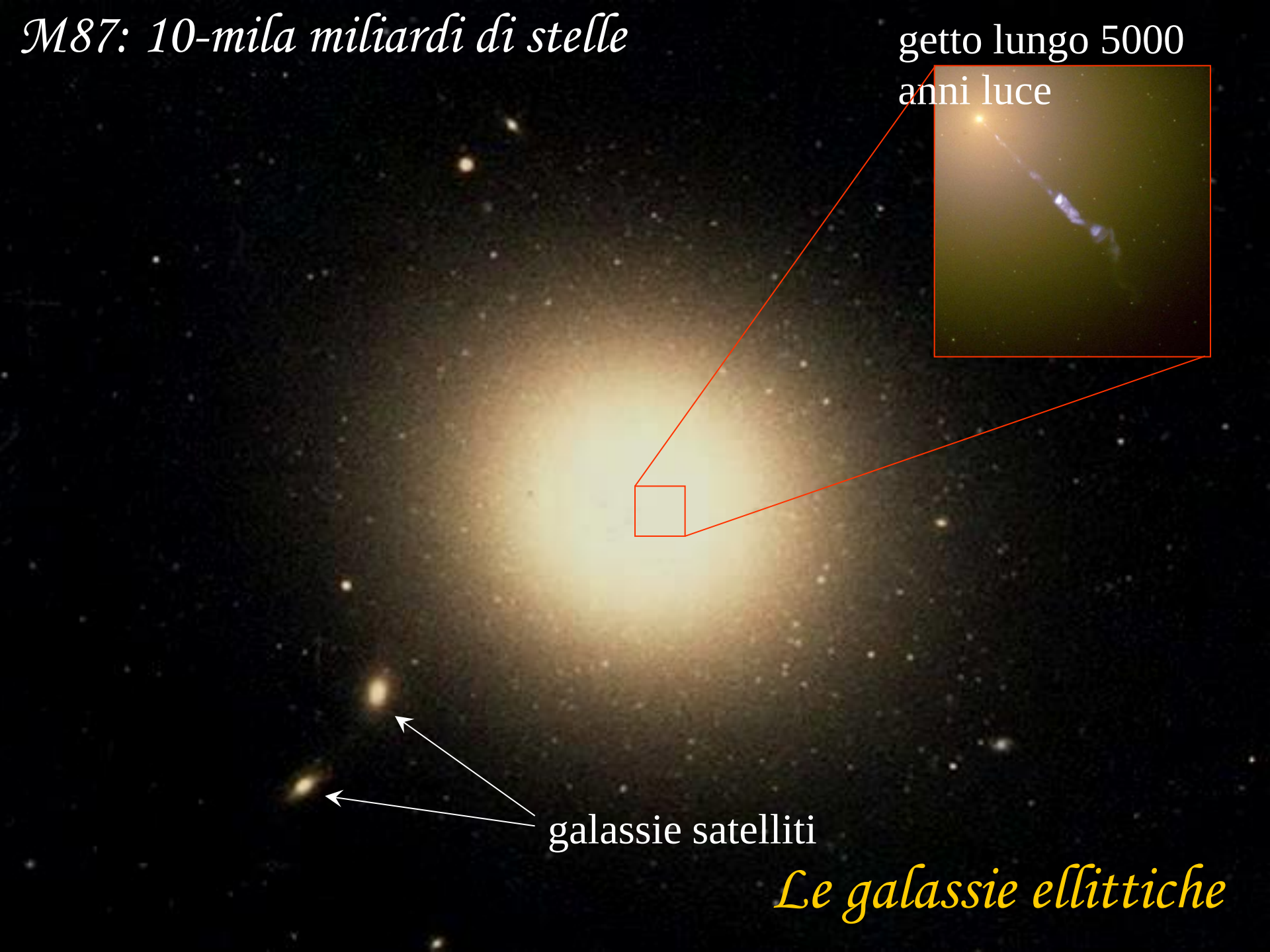
300 miliardi di miliardi di km = 30 milioni di anni luce



Un ammasso di galassie è costituito da centinaia o migliaia di galassie

Galactic of different types existe in our Universe:

Elliptic galaxies,
Spiral galaxies,
Active galaxies ….


M87: 10-mila miliardi di stelle
getto lungo 5000 anni luce
galassie satelliti
Le galassie ellittiche

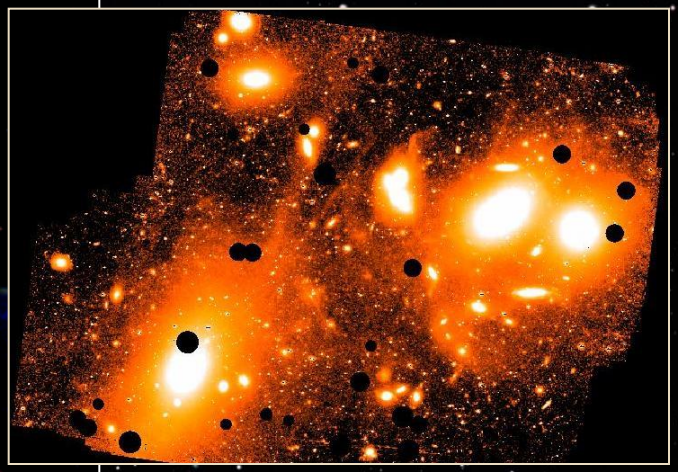
Le galassie a spirale

Galassie che esplodono

Galaxies form groups ….

Gruppi di galassie

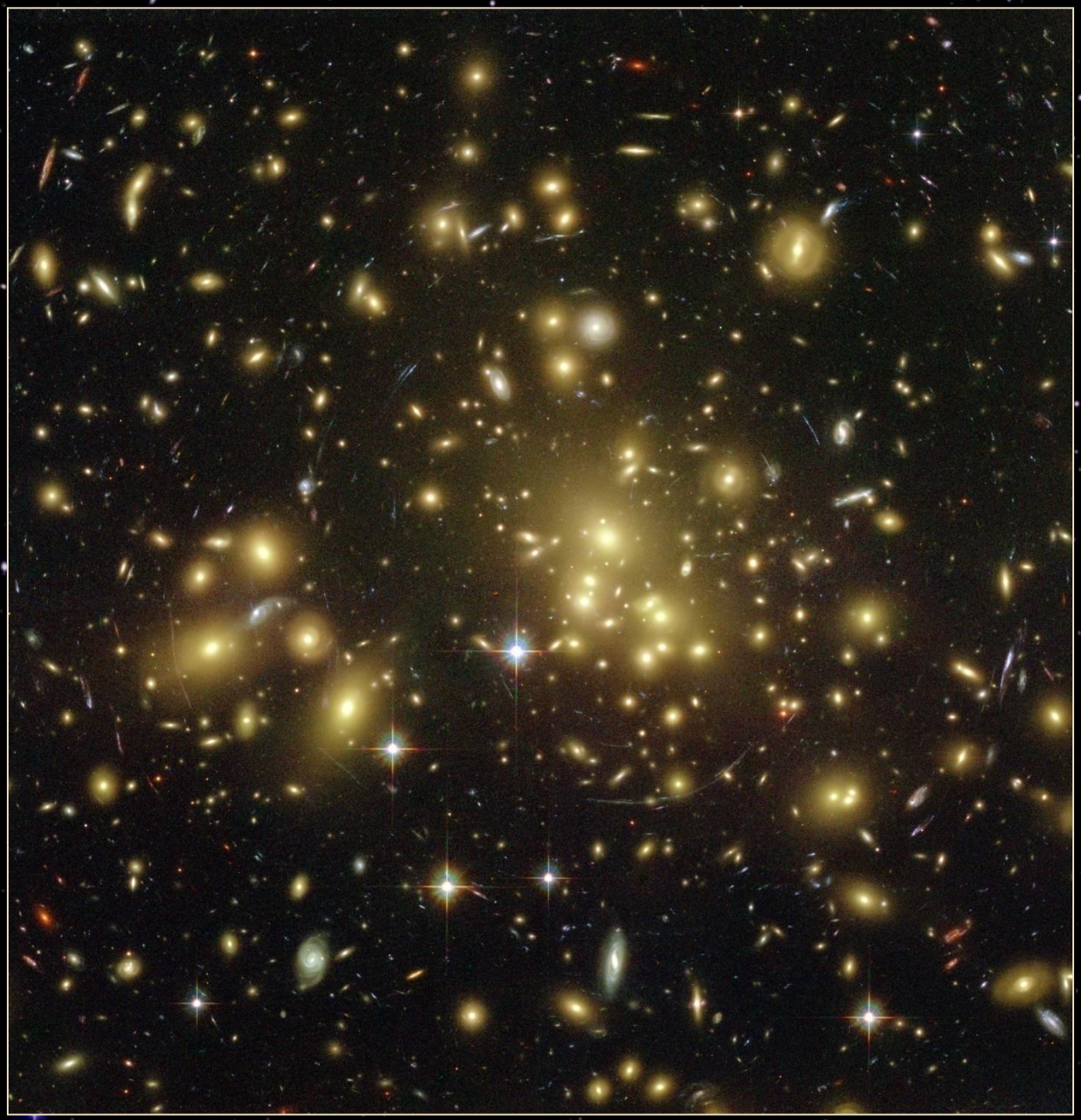
Galaxies form clusters ….



Superammasso della Vergine

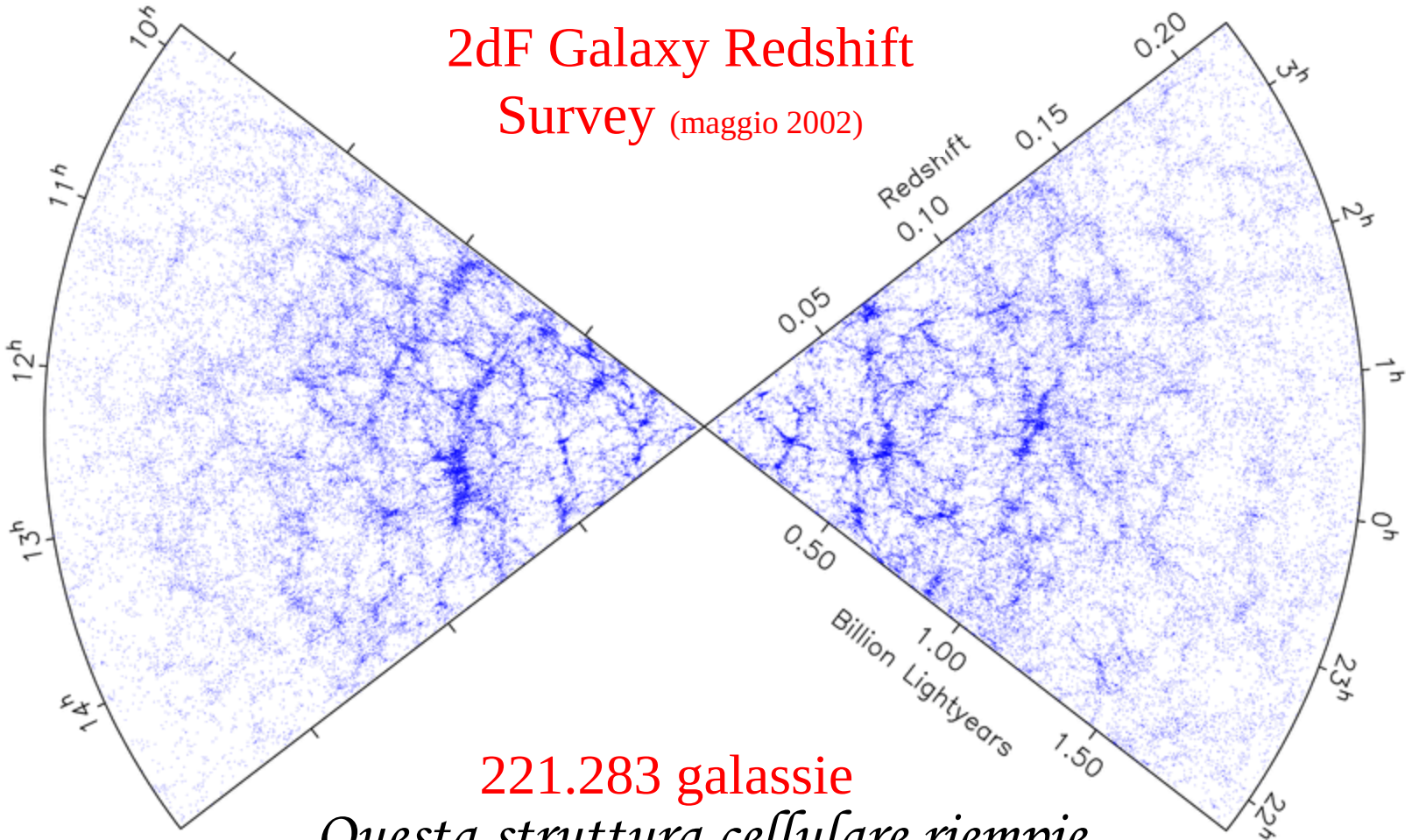
Distanza dal Sole: 50 milioni di anni luce

Superammasso con migliaia di galassie



. . . and galaxies form ***Large Scale Structure .***

Le galassie e gli ammassi di galassie sono distribuiti in una struttura cellulare, "spugnosa", con filamenti e muri di galassie, separati da enormi vuoti cosmici

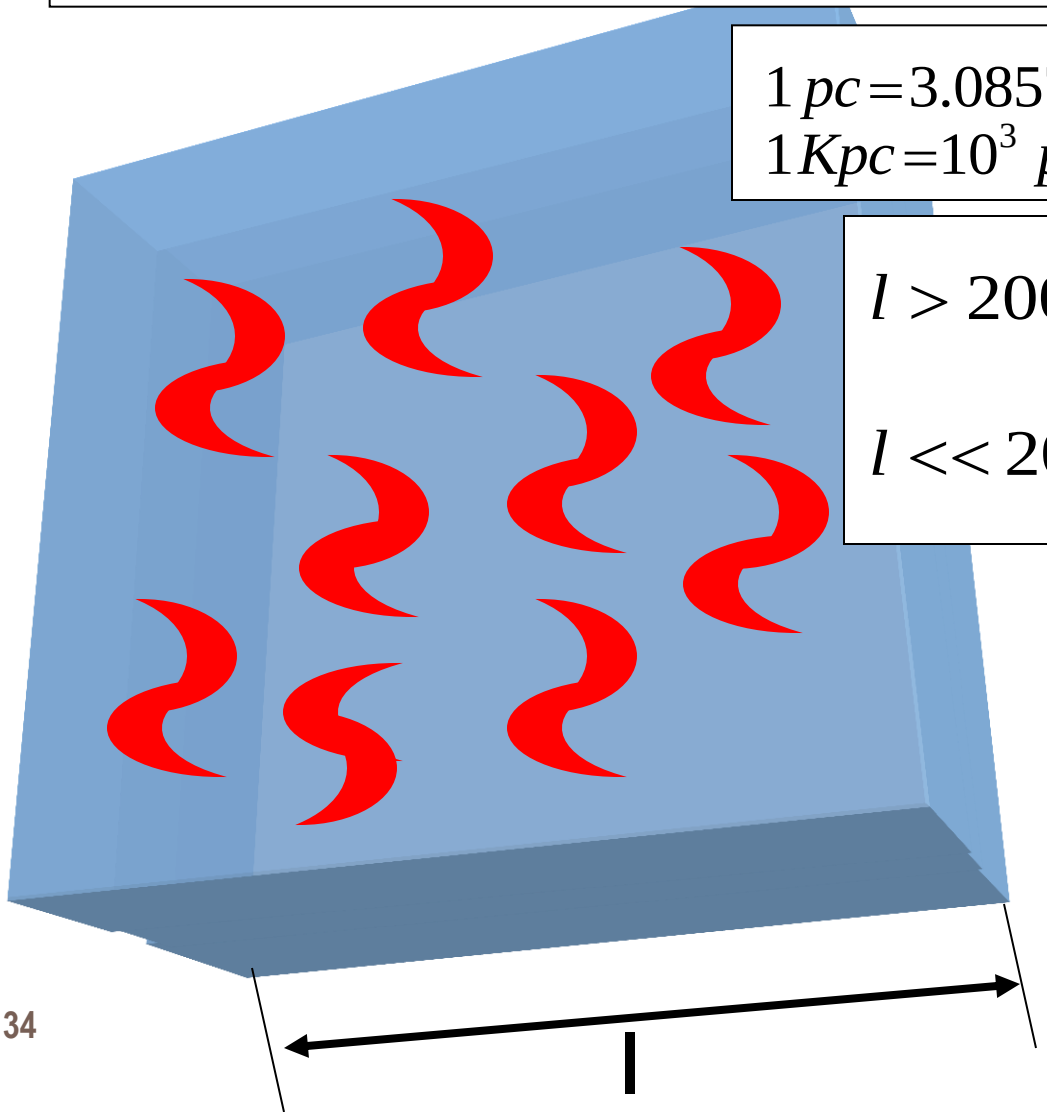


221.283 galassie

Questa struttura cellulare riempie uniformemente tutto l'universo "vicino"

3. The discovery of Large Scale Structure of our Universe

The Universe is uniform on big scales. The scale of transition from heterogeneity to homogeneity is around 200 Mpc.



$$1\,pc = 3.0857 \cdot 10^{16} m = 206265\,a.u. = 3.262\,l.y.$$
$$1\,Kpc = 10^3\ pc, 1\,Mpc = 10^6\ pc, 1\,Gpc = 10^9\ pc$$

$$l > 200\,Mpc, \frac{\delta\rho}{\rho} < 1$$

$$l << 200\,Mpc \quad (l \approx 1\,Mpc), \frac{\delta\rho}{\rho} >> 1$$

In the past (before the decoupling era) $\frac{\delta\rho}{\rho} \leq 10^{-4}$

in present day scale
10 Gpc - 10 Mpc.

Small inhomogeneity must exist in the past as far as we observe today the large density contrast on the small scales.

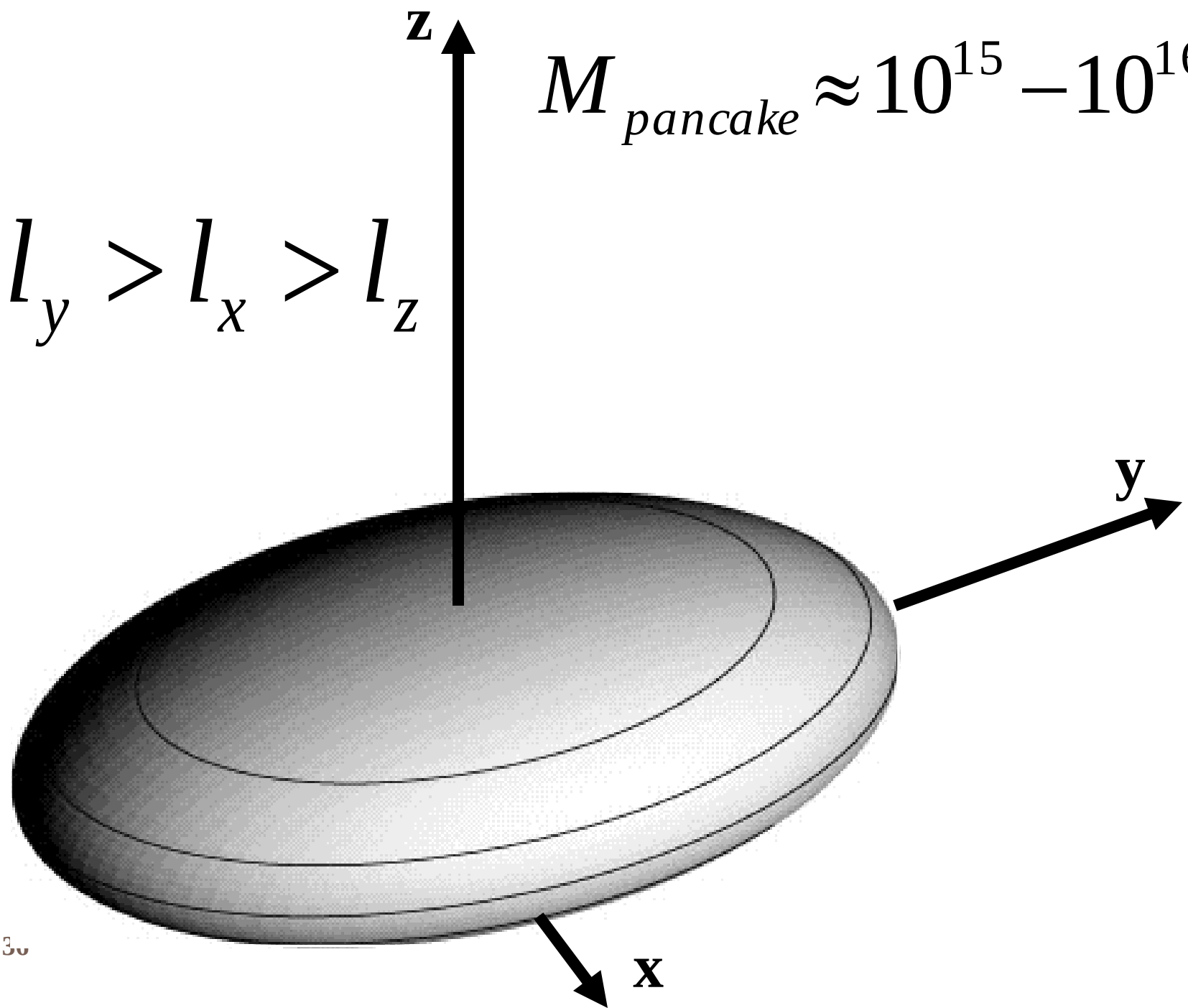
The perturbations in $\delta\rho/\rho$ increased after decoupling era due to gravitational instability (Jeans instability) and formed the present structure of our Universe.

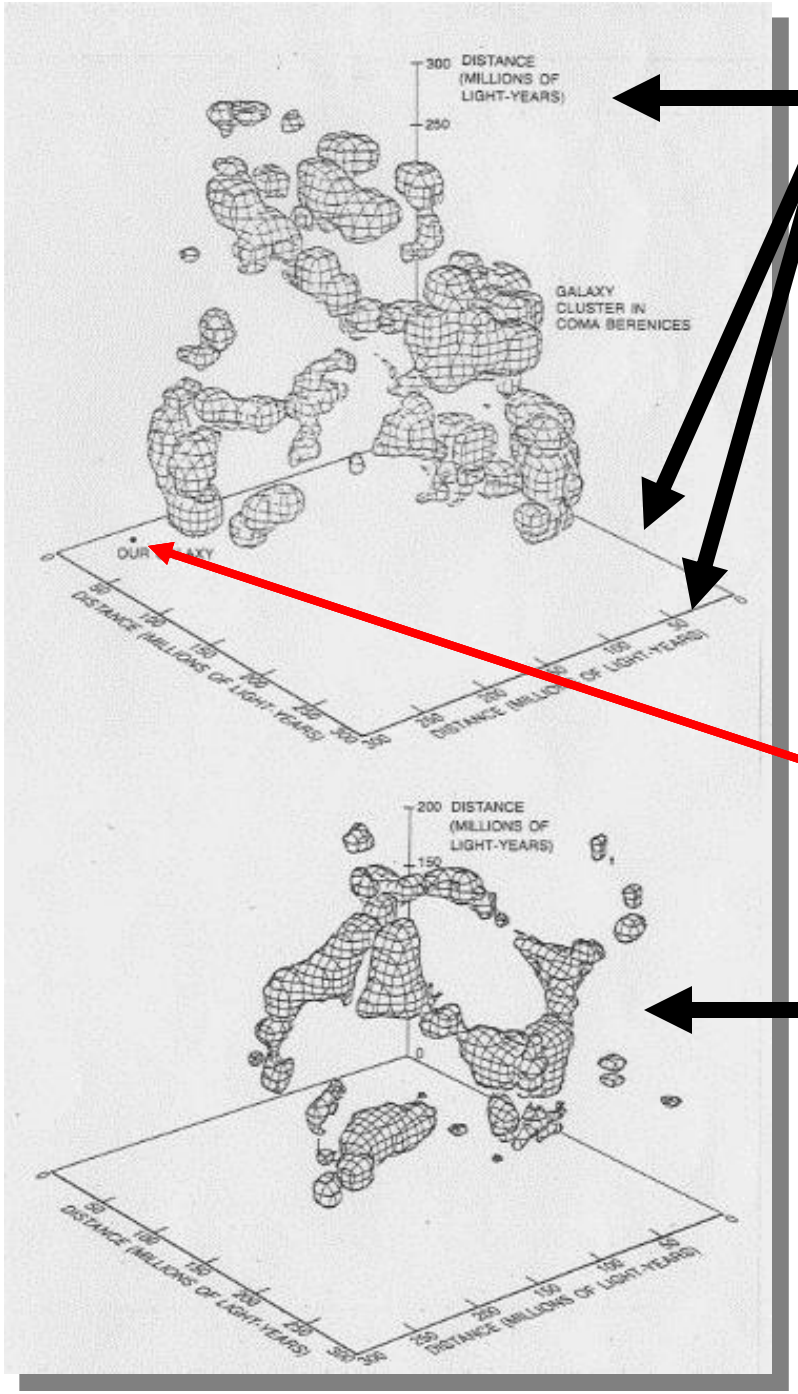
Such inhomogeneity had negligible influence in early cosmological evolution but later caused gravitational clustering.

JEANS, LIFSHITZ , ZELDOVICH , PEEBLES and many others.

$$M_{pancake} \approx 10^{15} - 10^{16} M_{\odot}$$

$$l_y > l_x > l_z$$



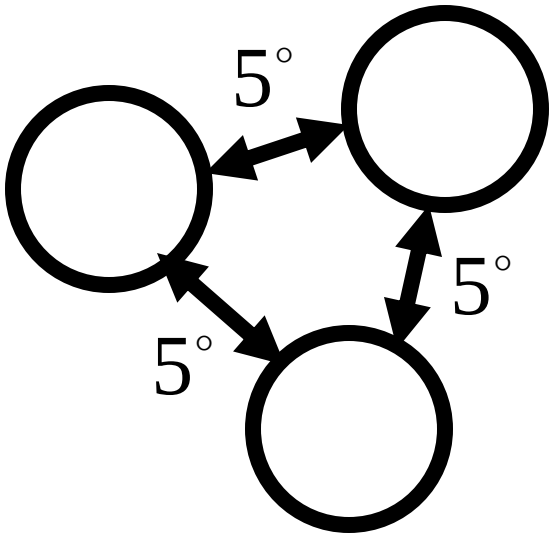


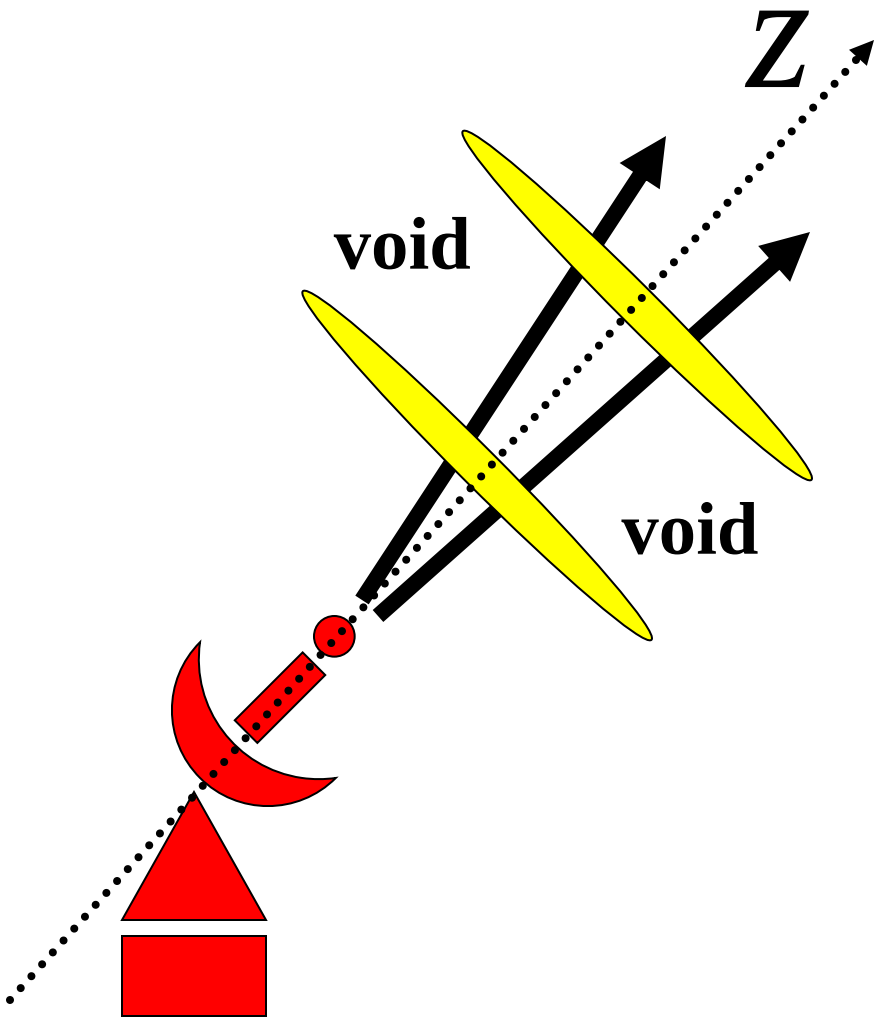
Diststance, $0 \div 300$ millions of light-years

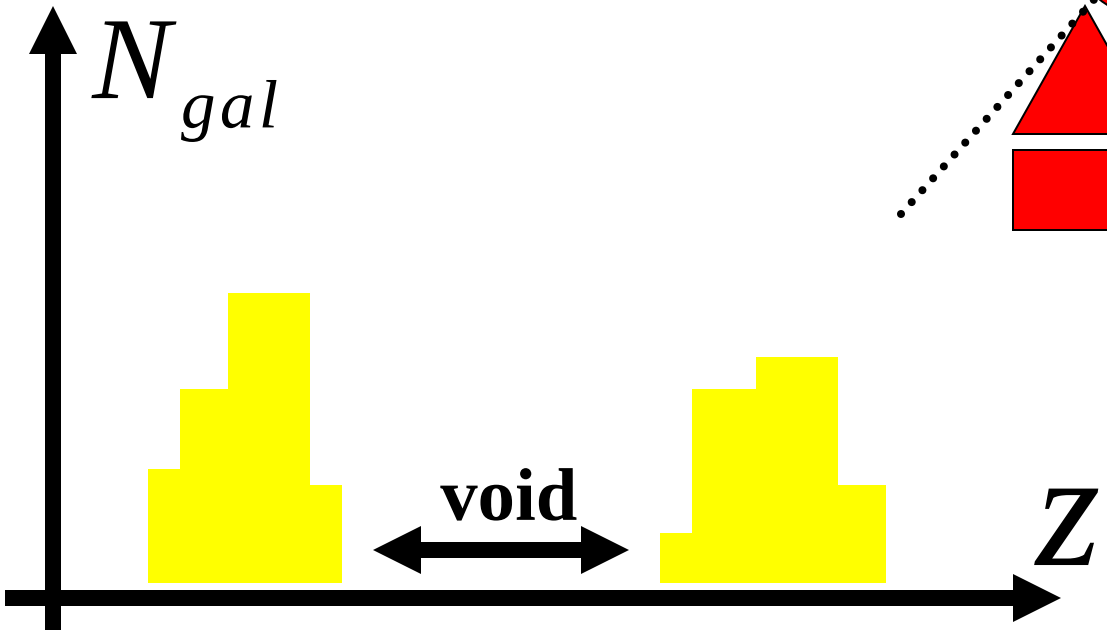
Galaxy clusters in COMA BERENICES

Our Galaxy

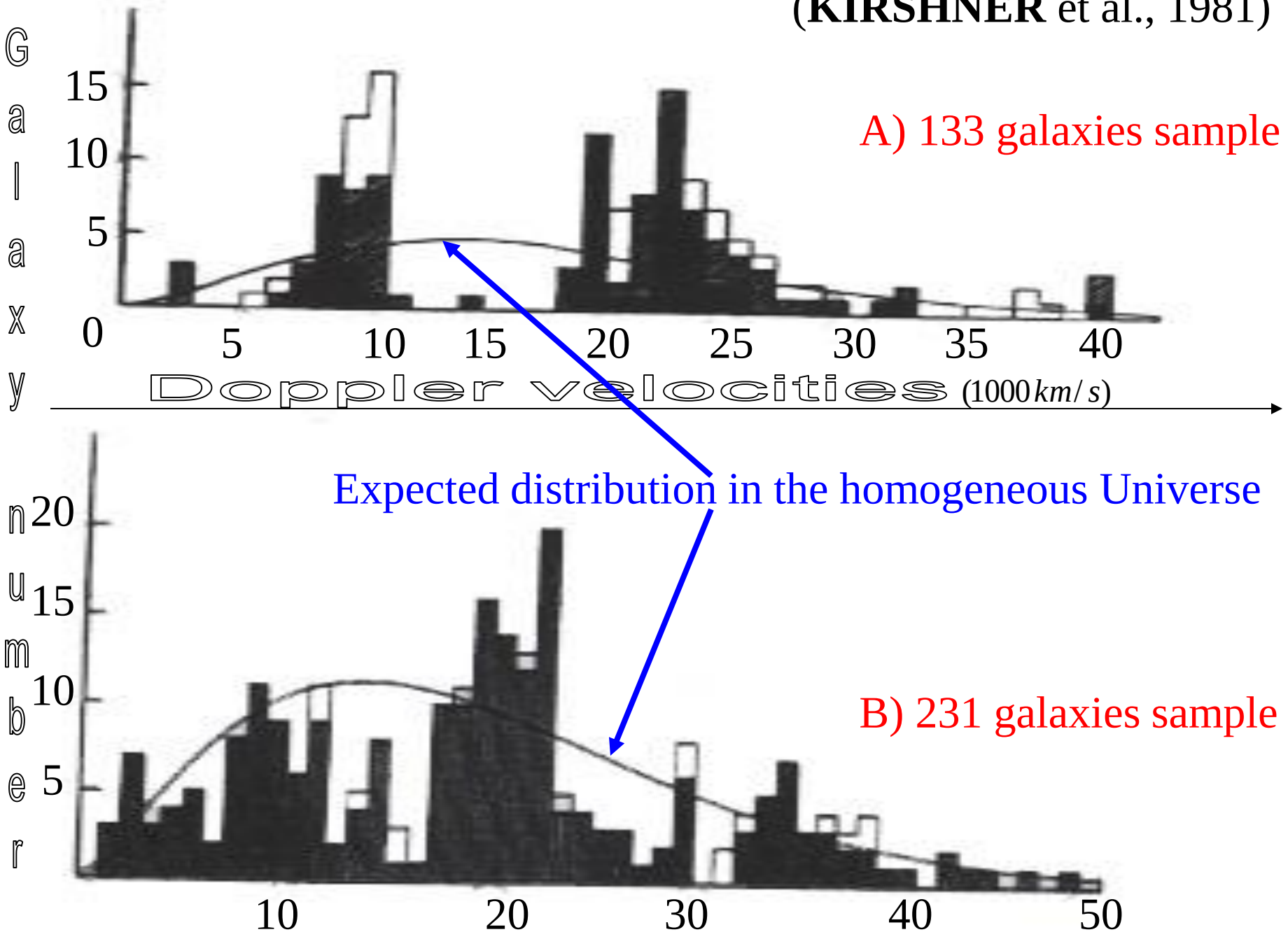
Simulation of the predictions of the pancake model on a computer (FRENK, WHITE, DAVIS)

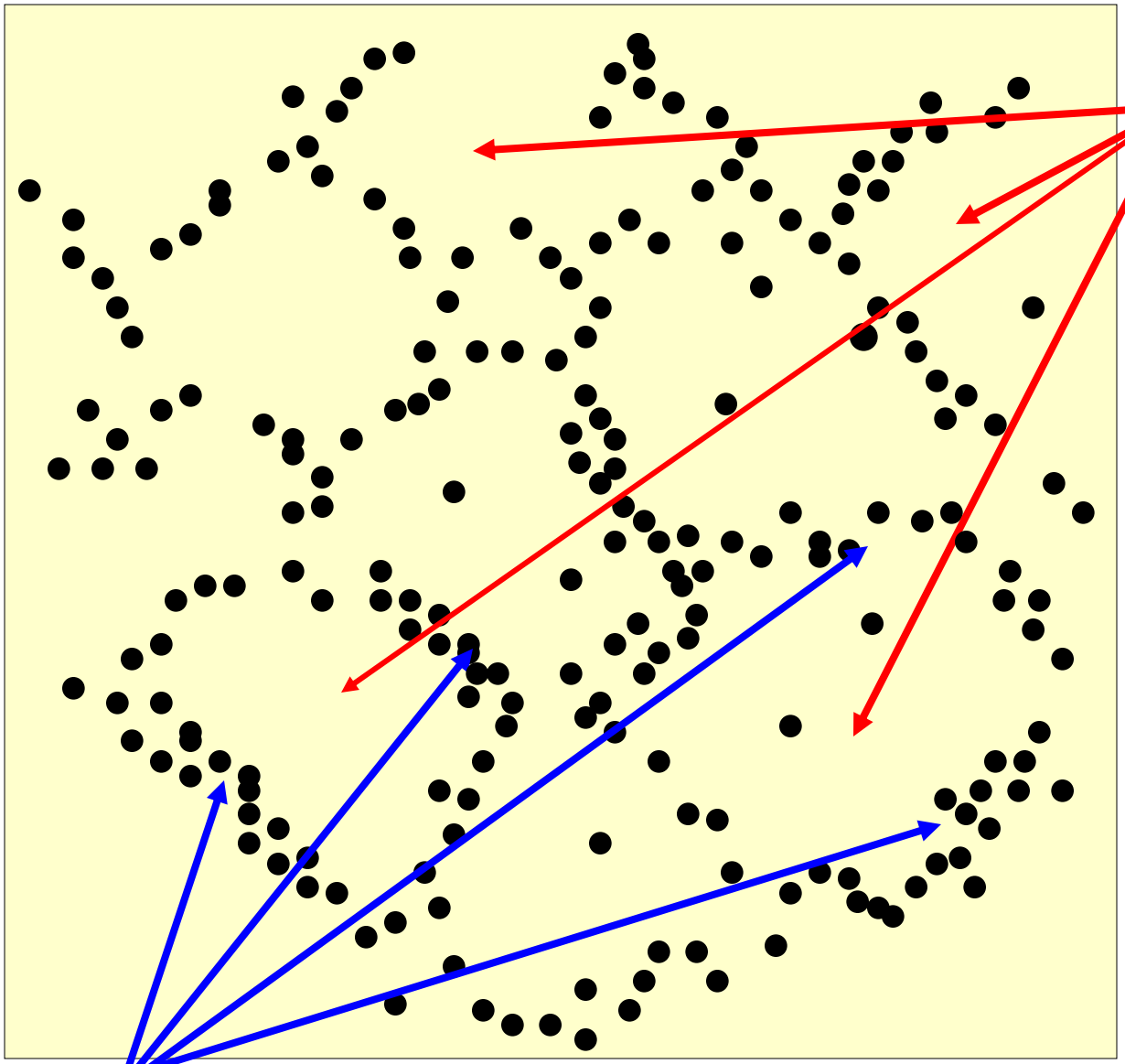

5°
5°
5°

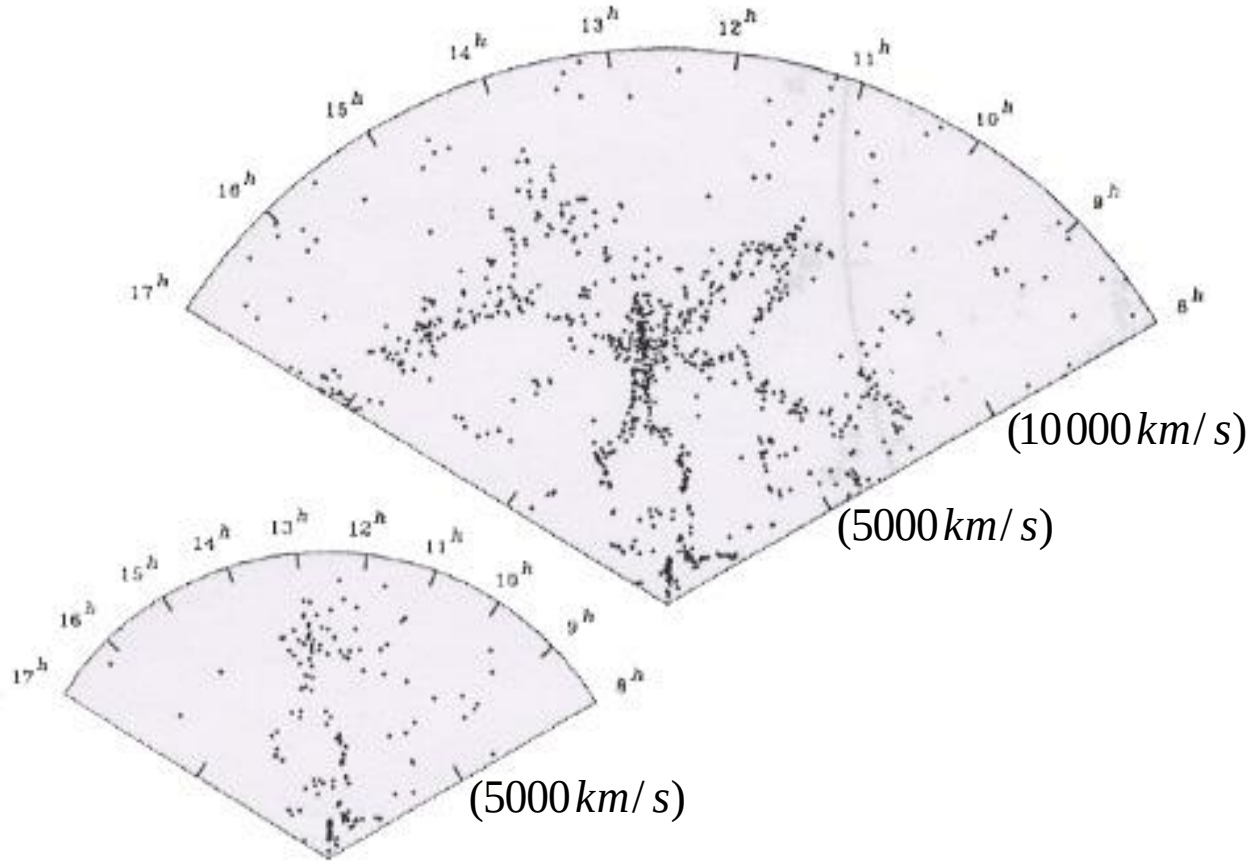

Z
void
void

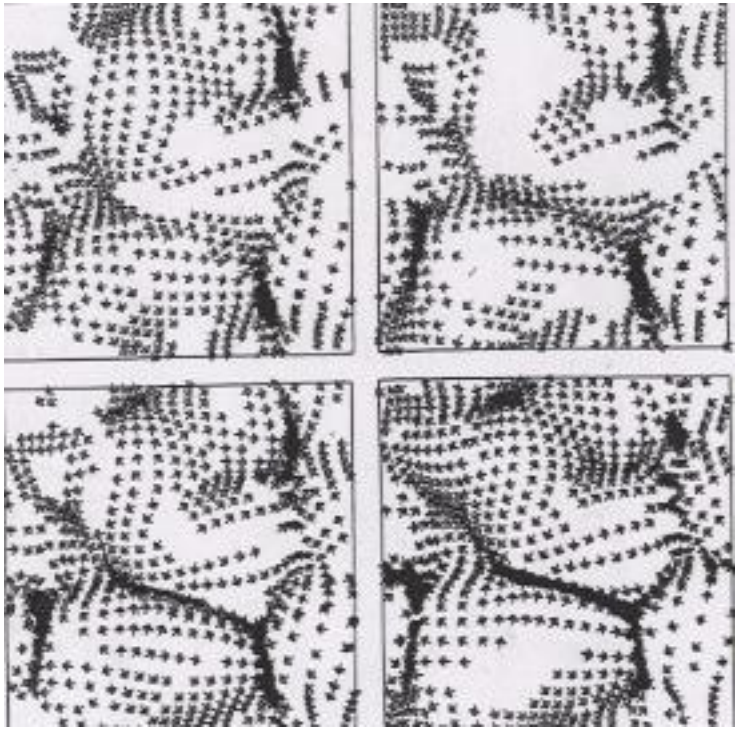

N_{gal}
void
Z

(**KIRSHNER** et al., 1981)

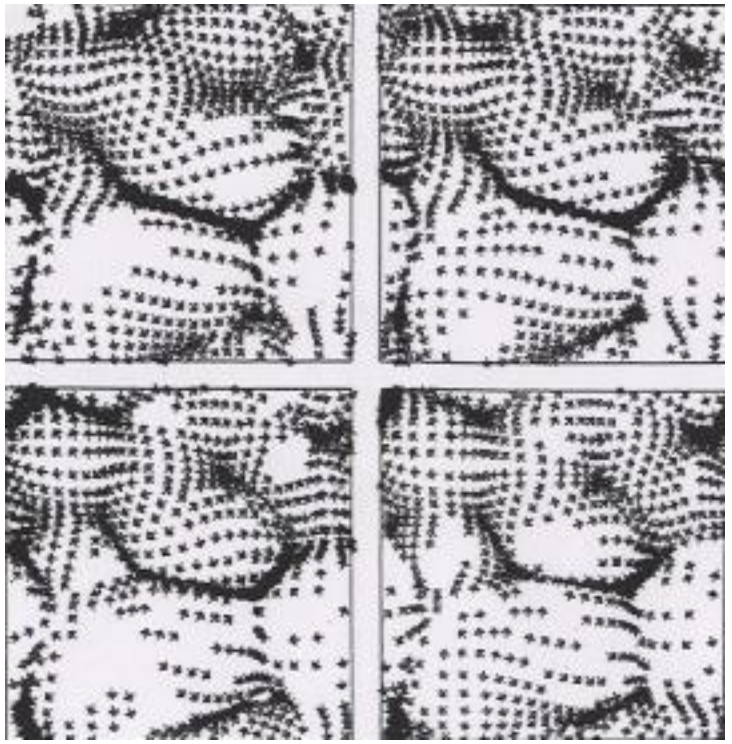



voids
pancakes


13h
12h
14h
11h
15h
10h
16h
9h
17h
8h
(10000 km/s)
(5000 km/s)
(5000 km/s)

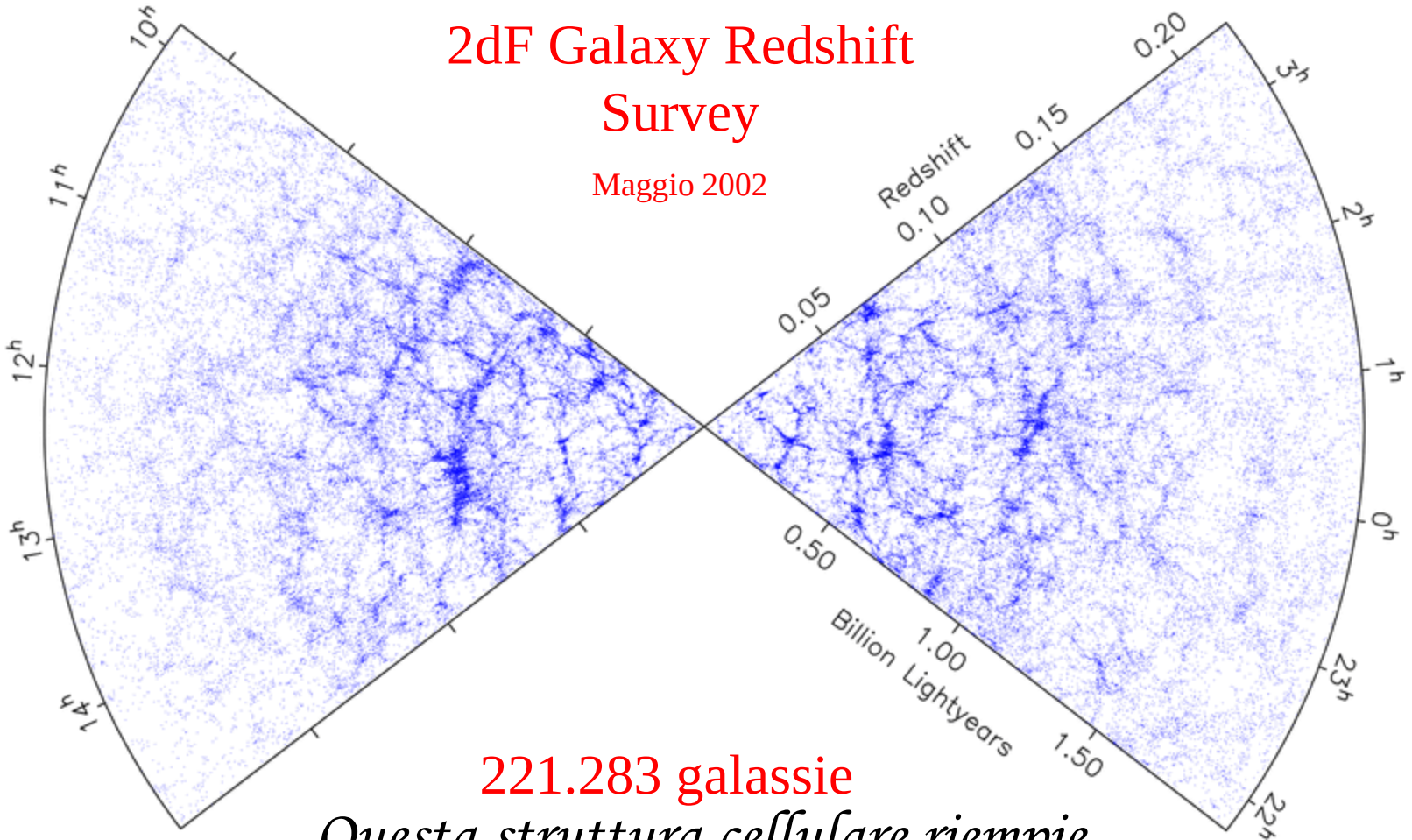


A



B

Le galassie e gli ammassi di galassie sono distribuiti in una struttura cellulare, "spugnosa", con filamenti e muri di galassie, separati da enormi vuoti cosmici



221.283 galassie

Questa struttura cellulare riempie uniformemente tutto l'universo "vicino"

4. Light element abundance in our Universe

Period from 1 sec to 200 seconds of expansion plays very important role in the history of our Universe. At that time our Universe was smaller and hotter. The temperature in the Universe was of the order of 1 billion degree. The Universe represents a great Nuclear reactor in which light chemical elements were created. Nuclei output are very sensitive to the ratio of neutrons over protons (n/p) at this time. This ratio is determined by equation:

$$\frac{n}{p} = \exp\left(-\frac{\Delta m}{T}\right)$$

Here **Δm** is mass difference of neutron and proton, and T is current temperature.

Thermal equilibrium was in the Universe during expansion. Particles of different types were in equilibrium. Here we interested in relative abudance of protons and neutrons. The equilibrium between them was maintained by week interaction:

$$n + \nu \leftrightarrow p + e^{-}$$

$$n + e^{+} \leftrightarrow p + \bar{\nu}$$

etc

When T drops below 0.7 MeV the neutron over proton ratio frozes and only frozen neutrons act in nuclear reaction.

Later neutrons became bound into deuterium (D) due to the process:

$$p + n \longrightarrow D + \gamma$$

or decay (the lifetime of free neutron is approximately 1000 sec).

In primordial nucleosynthesis deuterium, He^{3}, He^{4} and some amont of Li^{6}, Li^{7} were produced

No stable nuclei with A=5 that prevents to production of heavier elements.

The reaction of the types:

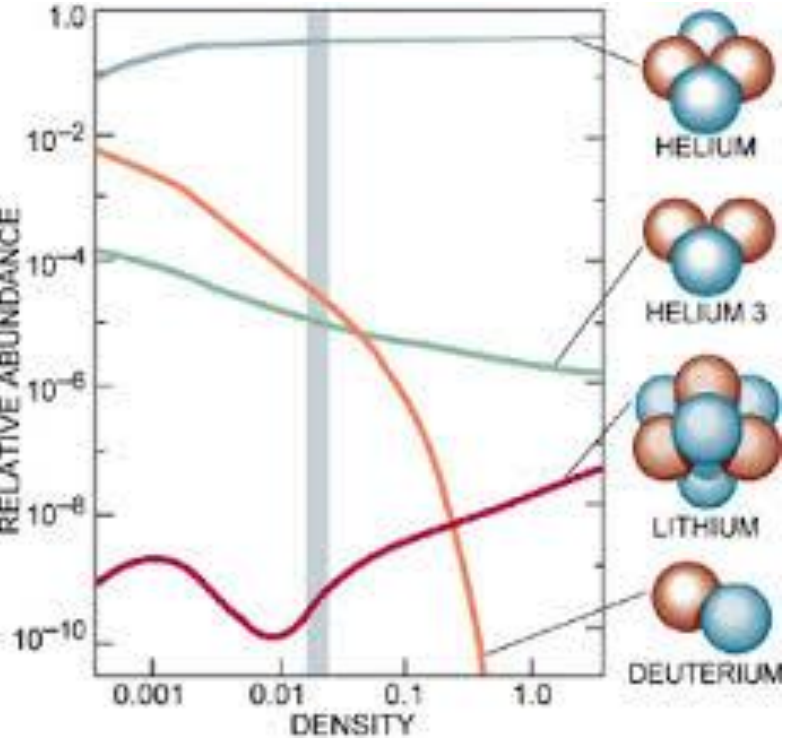
$$He^{3} + He^{4} \rightarrow Be^{7}$$

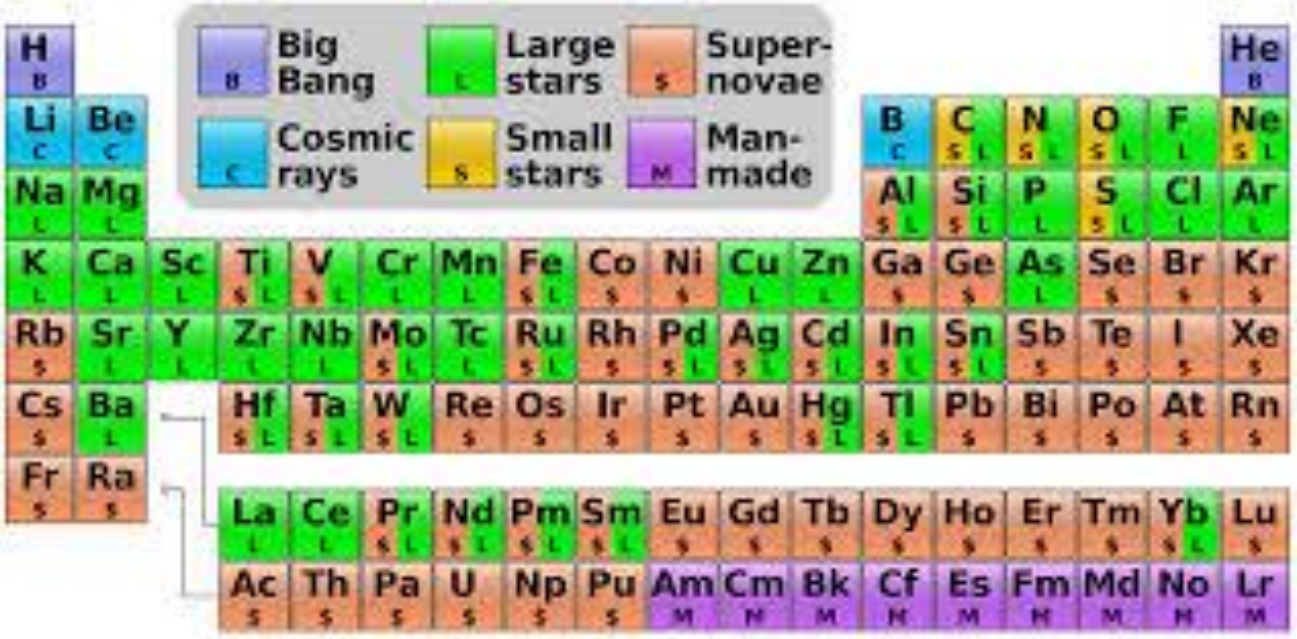
$$3He^{3} \rightarrow C^{12}$$

are rare and do not produced significant amount of elements.

That's why more heavy elements are produced in stars later.

The Big Bang theory predicts the correct amount of light elements.


1.0
10^{-2}
10^{-4}
10^{-6}
10^{-8}
10^{-10}
RELATIVE ABUNDANCE
0.001
0.01
0.1
1.0
DENSITY
HELIUM
HELIUM 3
LITHIUM
DEUTERIUM


Big Bang
Large stars
Super-novae
Cosmic rays
Small stars
Man-made
H B
He B
Li C
Be C
B C
C S L
N S L
O S L
F L
Ne S L
Na L
Mg L
Al S L
Si S L
P L
S S L
Cl L
Ar L
K L
Ca L
Sc L
Ti S L
V S L
Cr L
Mn L
Fe S L
Co S
Ni S
Cu L
Zn L
Ga S
Ge S
As L
Se S
Br S
Kr S
Rb S
Sr L
Y L
Zr L
Nb L
Mo S L
Tc L
Ru S L
Rh S
Pd S L
Ag S L
Cd S L
In S L
Sn S L
Sb S
Te S
I S
Xe S
Cs S
Ba L
Hf S L
Ta S L
W S L
Re S
Os S
Ir S
Pt S
Au S
Hg S L
Tl S L
Pb S
Bi S
Po S
At S
Rn S
Fr S
Ra S
La L
Ce L
Pr S L
Nd S L
Pm S L
Sm S L
Eu S
Gd S
Tb S
Dy S
Ho S
Er S
Tm S
Yb S L
Lu S
Ac S
Th S
Pa S
U S
Np S
Pu S
Am M
Cm M
Bk M
Cf M
Es M
Fm M
Md M
No M
Lr M

Thank you for attention