Particles and Universe: Evolution of the Universe

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June 7, 2016

Redshift

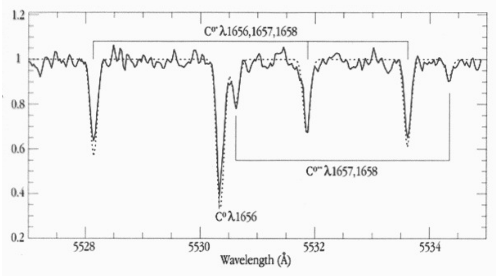
If the source of light recedes from the observer the measured wave length is elongated:

$$\lambda' = \lambda \sqrt{\frac{1+\beta}{1-\beta}} \equiv \lambda\,(1+z)$$

$z = \frac{\Delta\lambda}{\lambda}$: redshift

Absorption lines of known elements can be identified in spectra of distant stars and galaxies - significant redshifts are observed...

Carbon lines in measured spectra of PKS 1232+0815:



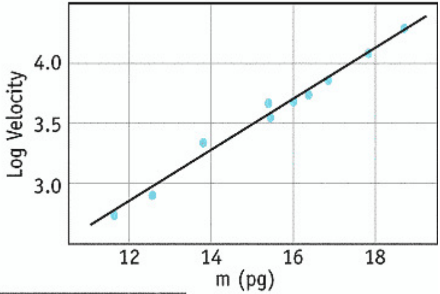
Wavelength shift corresponding to z=2.34

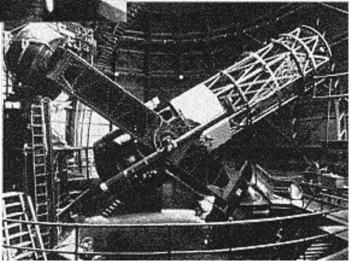
$(\lambda' = 3.34\ \lambda)$!

Hubble's Law

Discovery of Expanding Universe

Edwin Hubble





Mt. Wilson
100 Inch
Telescope

Redshift

First observed in spectra of distant galaxies by Hubble in 1929 r.
He noticed also that the escape velocity increases with distance: (Hubble's Law)

$$v = H\,r$$

r - distant from Earth,
H - Hubble's constant

Value given by Hubble:

$$H \approx 500\ km/s/Mpc$$

almost an order of magnitude too large :-)

Oryginal Hubble's results:

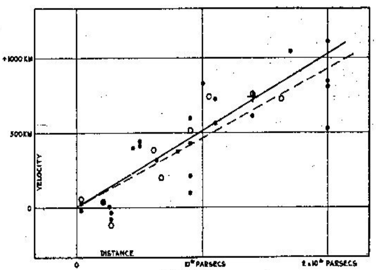


FIGURE 1

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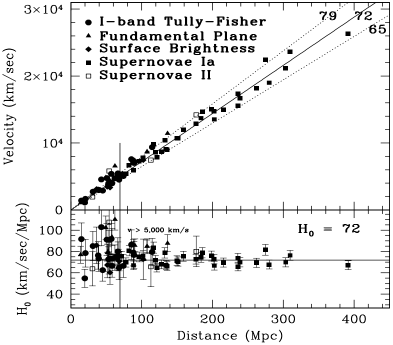
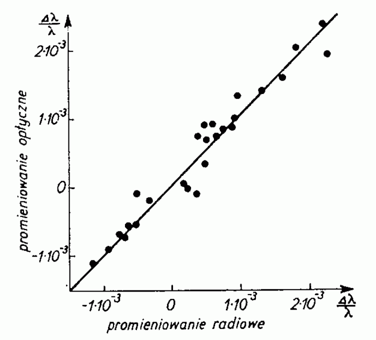
Obecne pomiary:
$H \sim 70\ km/s/Mpc$

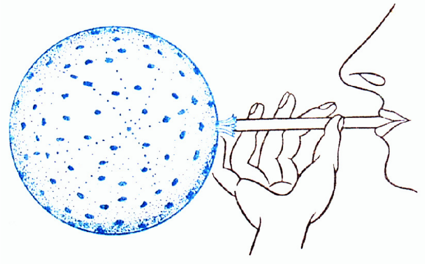


Redshift observed is the same in all bands of electromagnetic spectra

Comparison of opticla and radio shifts:



Hubble's observation means that distance between all objects increases, our reference frame is not singled out.



Any two objects will always move away from each other...

Cosmological principle

Cosmology tries to describe the Universe on the scales larger than all known structures ⇒ "cosmological scales"

Cosmological principle: distribution of matter in the universe is homogeneous and isotropic when viewed on cosmological scales

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All types of particles were produced and annihilated at the same rate.
Timescales for these processes are much shorter than expansion timescale

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All fundamental particles were equally abundant just after the Big Bang.

While the Universe expanded, average particle energies (temperatures) decreased. Heavier particles were no longer reproduced and disapeared...

Or they "decoupled" from "ordinary" matter, if interacting very weakly...

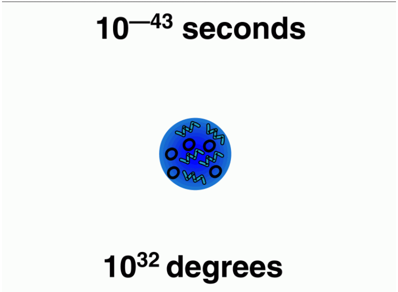
Singularity

We assume that the Universe started its evolution from the single point, singularity, with infinite energy density...

10^{-43} **seconds**

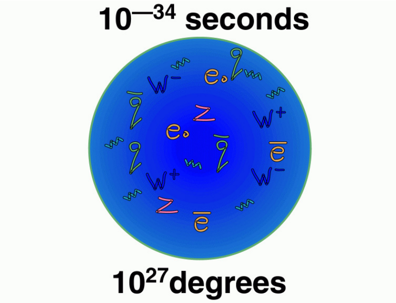
The Universe is expanding very fast (so called inflation), indistinguishable gauge bosons are in equilibrium with all fundamental matter (and anti-matter) particles

eg. $W^+W^- \leftrightarrow q\bar{q}$



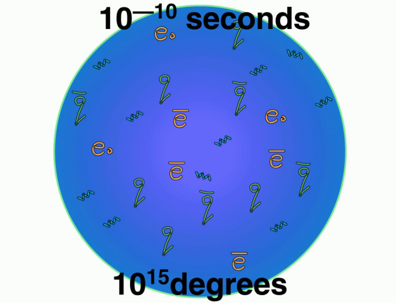
10^{-34} seconds

Expansion ⇒ decreasing energies of particles. Matter is in the state of Quark-Gluon Plasma (QGP). Strong interactions differentiate from electroweak ones.



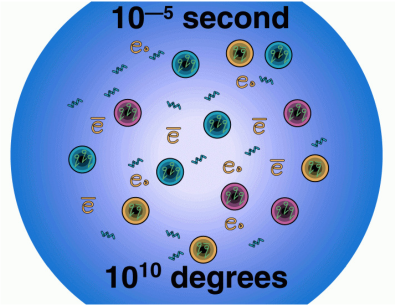
10^{-10} seconds

Separation of electromagnetic and weak interactions. Free $W^{\pm}$ and Z° bosons disappear (no longer in thermal equilibrium with photons)



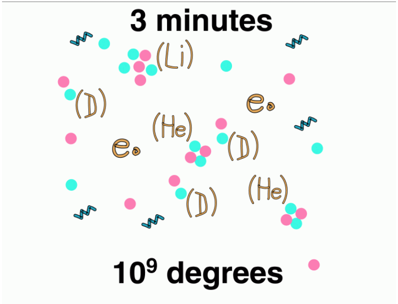
10^{-5} seconds

Quarks form neutrons i protons. Antymatter starts to disappear as radiation is too weak to produce it any more. Earlier, barion symmetry $B-\bar{B}$ had to be violated...



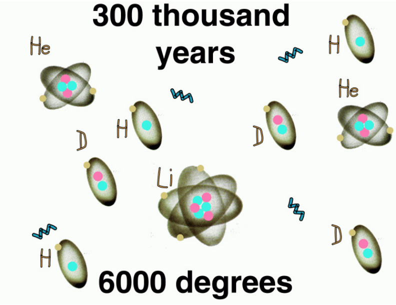
3 minutes

Protons and neutrons create nuclei of light elements. When the thermonuclear processes stop due to temperature decrease, their relative abundance in the Universe is fixed...



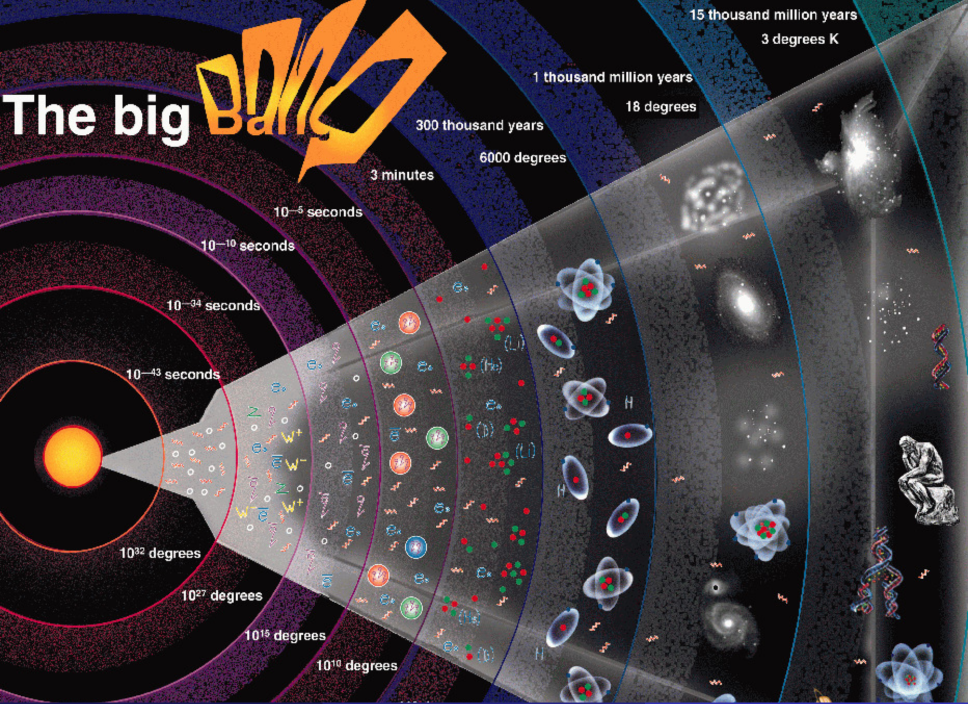
300 000 years

Electrons are captured by nuclei creating neutral atoms. The Universe starts to be transparent for photons



1 000 000 000 years

Galaxy formation, synthesis of heavier elements in stars.



The big Bang
15 thousand million years
3 degrees K
1 thousand million years
18 degrees
300 thousand years
6000 degrees
3 minutes
10^{-5} seconds
10^{-10} seconds
10^{-34} seconds
10^{-43} seconds
10^{32} degrees
10^{27} degrees
10^{15} degrees
10^{10} degrees

Explained by the model

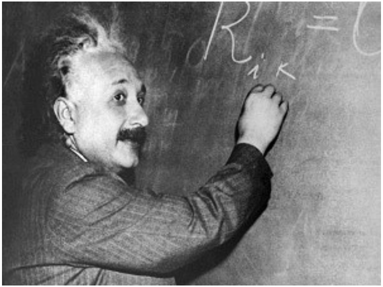
- Expansion of the Universe
- Cosmic Microwave Background (CMB)
- Fluctuations of CMB
- Composition of the Universe (Primordial Nucleosynthesis)

Questions with no answer so far...

- Why did antimatter disapear?
- How did different structures formed?
- What the Dark Matter is?
- Is there any Dark Energy?

General Relativity

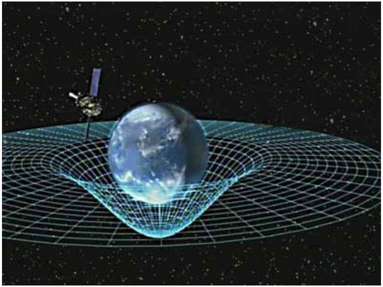
Evolution of the Universe needs to be described within the General Relativity, as introduced by Einstein in 1916.



General Relativity

Evolution of the Universe needs to be described within the General Relativity, as introduced by Einstein in 1916.

Gravitational field is described as the curvature of space.



Mater distorts space.
All masses move as free bodies,
but curvature of space decides about their trajectories...

Cosmological principle: distribution of matter in the universe is homogeneous and isotropic on cosmological scales

We do not need to analyze the motion of matter in space (position depending on time: $r = r(t)$) $\Rightarrow$ we can study evolution of the Universe in the **comoving coordinate frame**.

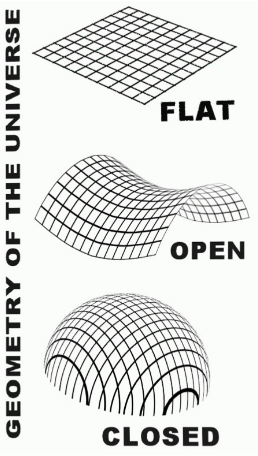
In the comoving frame matter (averaged over cosmological scales) is at rest ($r \equiv r_0$). Change of distance between objects is now described by a time dependent metric:

$$ds^2 \;=\; dt^2 - R^2(t)\left[\frac{dr^2}{1-k\,r^2} + r^2\left(d\theta^2 + d\phi^2 \sin^2\theta\right)\right]$$

Friedmann-Lemaitre-Robertson-Walker metric

$k = -1, 0, 1$: curvature of space

Curvature of space



$k = 0$

$k = -1$

$k = +1$

Friedmann equations

In the FLRW metric Einstein equations can be reduced to equations on the scale $R(t)$:

$$H^2 = \left(\frac{\dot{R}}{R}\right)^2 = \frac{8\pi G}{3}\rho - \frac{k}{R^2} + \frac{1}{3}\Lambda$$

$$\frac{\ddot{R}}{R} = \frac{\Lambda}{3} - \frac{4\pi G}{3}(\rho + 3p)$$

where: ρ - matter density, p - preasure

Einstein introduced cosmological constant Λ to "save" static and flat solution...

Critical density

Friedmann equations give dependence between matter density in the Universe and curvature of space.
Critical density:

$$\rho_c \quad = \quad \frac{3H^2}{8\pi G} \sim 10^{-26}\frac{kg}{m^3} \sim 10\frac{GeV}{c^2/m^3}$$

Density parameters
(density in units of ρ_c):

$$\Omega_m \quad = \quad \frac{\rho}{\rho_c}$$

$$\Omega_\Lambda \quad = \quad \frac{\Lambda}{3H^2}$$

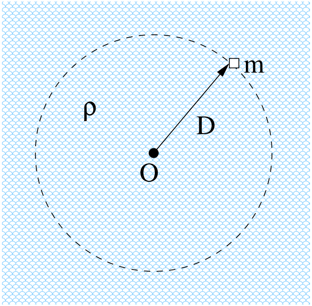
If $\Omega_{tot} = \Omega_m + \Omega_\Lambda = 1$
$\Rightarrow$ Universe is 'flat' (euclidean)
curvature $k = 0$

If $\Omega_{tot} < 1$
$\Rightarrow$ Universe is 'open'
curvature $k = -1$

If $\Omega_{tot} > 1$
$\Rightarrow$ Universe is 'closed'
curvature $k = +1$

Classical picture

Uniform mass distribution



Acceleration of mass m at the distance of $D = r \cdot R(t)$ from the origin of frame:

$$m\ddot{D} = -\frac{GmM}{D^2} = -\frac{Gm}{D^2} \cdot \frac{4\pi}{3} D^3 \rho$$

$\Rightarrow$ equation for $R(t)$ ($r = const$):

$$\ddot{R} = -\frac{4\pi G}{3} \rho R$$

Conservation of energy:

$$\frac{m\dot{D}^2}{2} - \frac{GmM}{D} = const$$

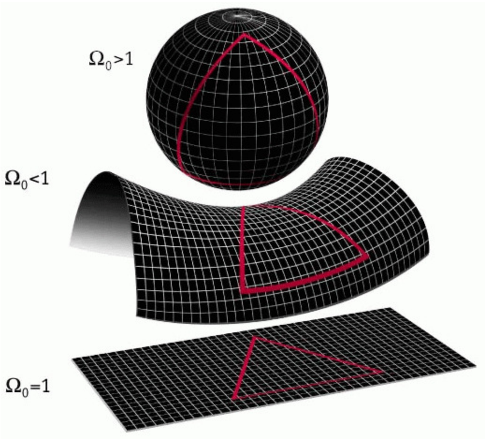
$$\Rightarrow \dot{R}^2 = \frac{8\pi G}{3} \rho R^2 - k$$

Sign of k is opposite to the sign of total energy...

Total matter/energy density in the Universe determines the space curvature on cosmological scales

Locally we know, that space is flat (sum of triangle angles is 180°).

But it is very hard to check on large distances...



Evolution of the Universe

Particular case: $\Lambda = 0$

$\Rightarrow$ density of matter (space curvature) uniquely determines fate of the Universe

$\Omega_m < 1$ $(k = -1)$

$\Rightarrow$ the Universe will expand forever

$\Omega_m = 1$ $(k = 0)$

$\Rightarrow$ the Universe will eventually stop (asymptotically)

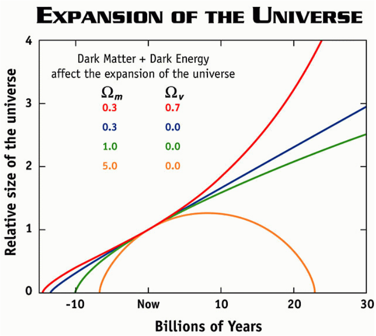
$\Omega_m > 1$ $(k = +1)$

$\Rightarrow$ the Universe will start to contract at some point

For description of the evolution (in the simplest model) three parameters are required:

$$H, \Omega_m, \Omega_\Lambda$$

Evolution scenarios



How to estimate the density of matter in the Universe? $\Omega \equiv \rho/\rho_c$

Many possible approaches:

- looking at radiation of stars and interstellar matter
  $\Rightarrow$ luminous matter $\Omega_{lumi} \sim 0.006$
- from the abundance of light elements + Primordial nucleosynthesis model (BBN)
  $\Rightarrow$ baryonic matter
- measurement of gravitational interactions and structure formation
  $\Rightarrow$ "gravitational" matter (total ?)
- from fitting ΛCDM model to CMB measurements

About 10^{-5} s after the Big Bang quarks formed nucleons.
For another second protons and neutrons are in thermal equilibrium maintained by two reactions:

$$p + e^- \longleftrightarrow n + \nu_e$$
$$n + e^+ \longleftrightarrow p + \bar{\nu}_e$$

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$$
\begin{aligned}
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\end{aligned}
$$

But about 1 s after Big Bang:

- thermal (kinetic) energy becomes comparable to the mass difference between neutron and proton
- reactions above (weak interactions) are no longer efficient due to decreasing density (expansion of the Universe)

Ratio of neutron to proton number is fixed at the level of about 1 : 6

Primordial nucleosynthesis

Free neutrons are not stable, they decay with $\tau \approx 880$ s:

$$n \longrightarrow p + e^- + \bar{\nu}_e$$

At the same time deuterium production can take place:

$$p + n \longleftrightarrow d + \gamma$$

But at the beginning, produced deuterium nuclei are disintegrated fast by high energy photons...

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Deuterium fraction starts to grow only at $t \sim 100$ s, where the Universe cools down to $kT \sim 0.1$ MeV $\Rightarrow$ photons too "weak" to break the nucleus

Deuterium production "freezes" the neutron fraction in the Universe at the level of $1:7$

Primordial nucleosynthesis

When deuterium is produced, a wide range of nuclear reactions open resulting in helium production, eg.:

$$d + p \longrightarrow He^3 + \gamma \qquad\qquad He^3 + n \longrightarrow He^4 + \gamma$$

Once produced, helium nucleus is not likely to be disintegrated, as its binding energy (28MeV) is much higher than in for deuterium (2.2 MeV).

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Small fraction of helium nuclei can be used to produce heavier elements:

$$He^3 + He^4 \longrightarrow Be^7 + \gamma \qquad\qquad Be^7 + n \longrightarrow Li^7 + p$$

But elements heavier than lithium are not produced. In expanding Universe, Nucleosynthesis stops due to Coulomb repulsion...

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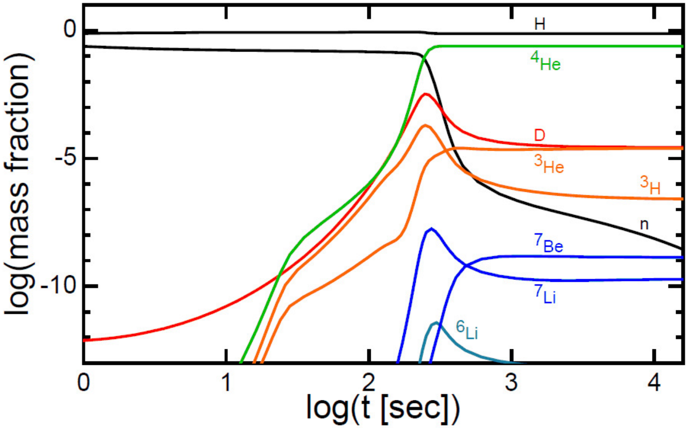
Rate of different reactions depends on the (baryonic) matter density.

"Freeze out" time depends on the expansion rate.

Summary

Dependence of element abundance on time



Nucleosynthesis strongly depends on the initial baryon density

We can use the measured helium fraction:

$$He^4/H \;=\; 0.249 \pm 0.009$$

and deuterium fraction:

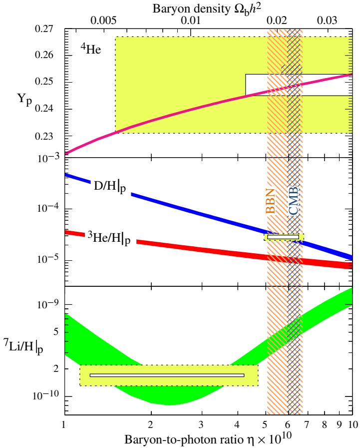
$$H^2/H \;=\; (2.82 \pm 0.21) \times 10^{-5}$$

to put constraints on the baryon matter density of the Universe.

Fit result:

$$0.019 \;\leq\; \Omega_b\, h^2 \;\leq\; 0.024 \qquad (95\% CL)$$

where: $h \;=\; \dfrac{H}{100 \frac{km}{s \cdot Mpc}} \;\sim 0.7$



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  $\Rightarrow$ baryonic matter $\Omega_b \sim 0.04 - 0.05$
- measurement of gravitational interactions and structure formation
  $\Rightarrow$ "gravitational" matter (total ?)
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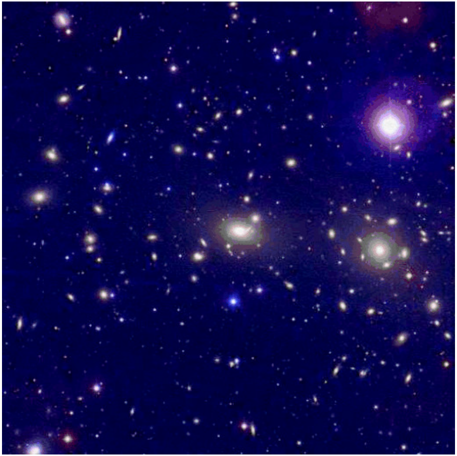
In 1933, while examining the Coma galaxy cluster, Fritz Zwicky realized that the velocity spread of objects in the cluster is too large.

Velocity spread should be related to the total potential energy of the cluster $\Rightarrow$ can be used to estimate the mass of the system



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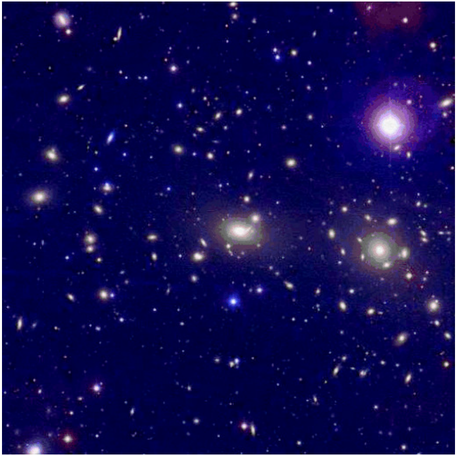
The result was surprising: "gravitational" mass was about 400 times larger than expected from observed luminosity.
$\Rightarrow$ some of matter must be "dark"...



We can measure distribution of star velocities in the arms of the spiral galaxy very precisely (from Doppler shift).

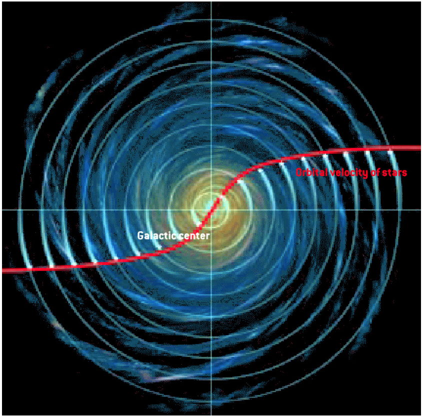
From the classical laws of motion we expect

$$v_{circ} = \sqrt{\frac{G_N M(r)}{r}}$$

gdzie $M(r)$ - mass inside the radius r

If the mass is concentrated in the center of galaxy (as the stars are):

$$v_{circ} \sim 1/\sqrt{r}$$



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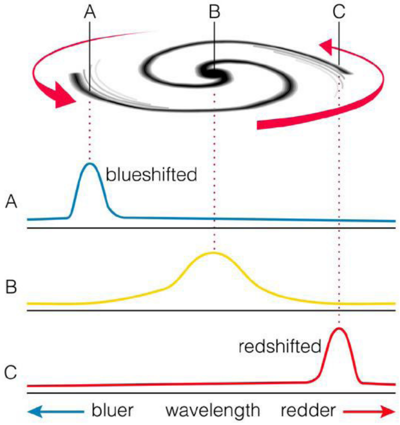
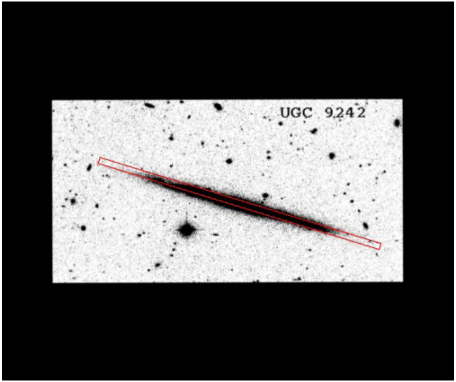
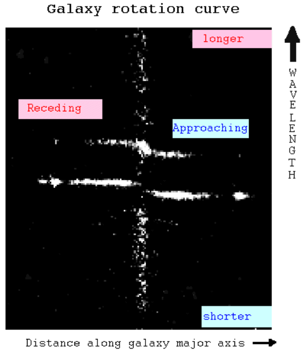


Measurements

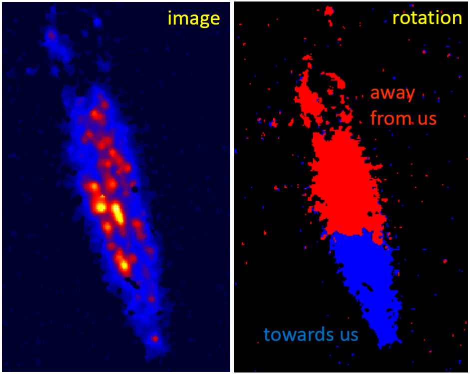
In the past, measurements were made separately for each galaxy

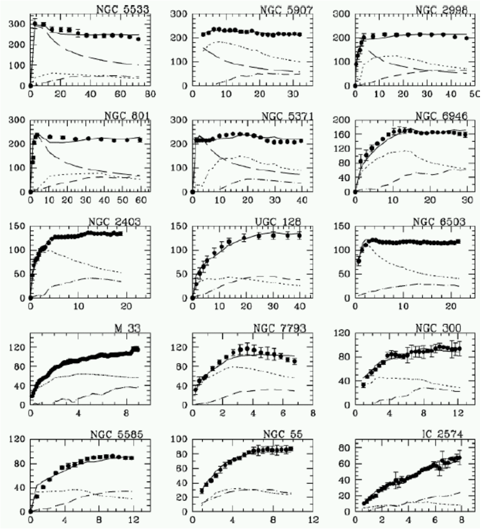




Measurements

New imaging methods and digital analysis allow us to obtain much more precise results and analyze big sets of objects at the same time

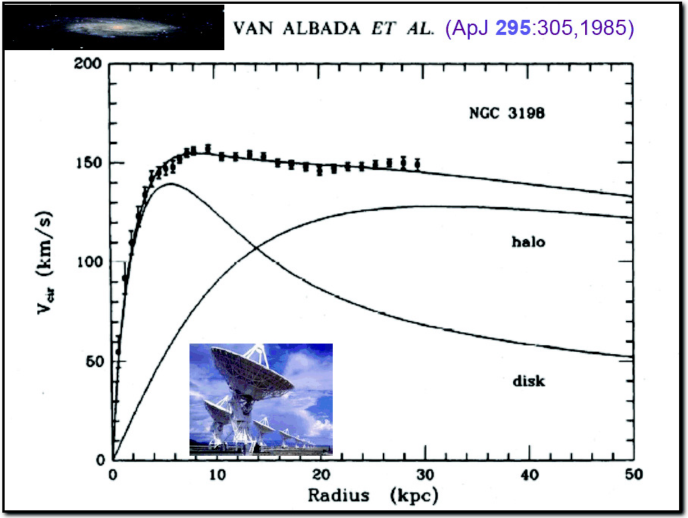




Results indicate, that rotation velocities do not decrease (and often increase) with the distance from galactic center

it is not consistent with the visible distribution of matter materii.

to explain the rotation curves, one need to assume that "visible" galaxy is placed inside a spherical "halo" with a much bigger mass...


VAN ALBADA ET AL. (ApJ 295:305,1985)
NGC 3198
halo
disk
V_{cir} (km/s)
Radius (kpc)
0
50
100
150
200
0
10
20
30
40
50

Structure formation

Still 20 years ago, the sky was “flat” for us.

We could only measure object positions on the celestial sphete - 2D

We were able to calculate the absolute distance from Earth only for a very limited set of objects (from Doppler redshift).

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In the recent years, enormous progress has been made thanks to new projects and instruments. We learned how to estimate the redshift from the limited number of measurements in different filters (wavelengths). Dedicated instruments allow for the simultaneous measurement of redshift for up to 1000 objects.

$\Rightarrow$ sky starts to be "3-D"...

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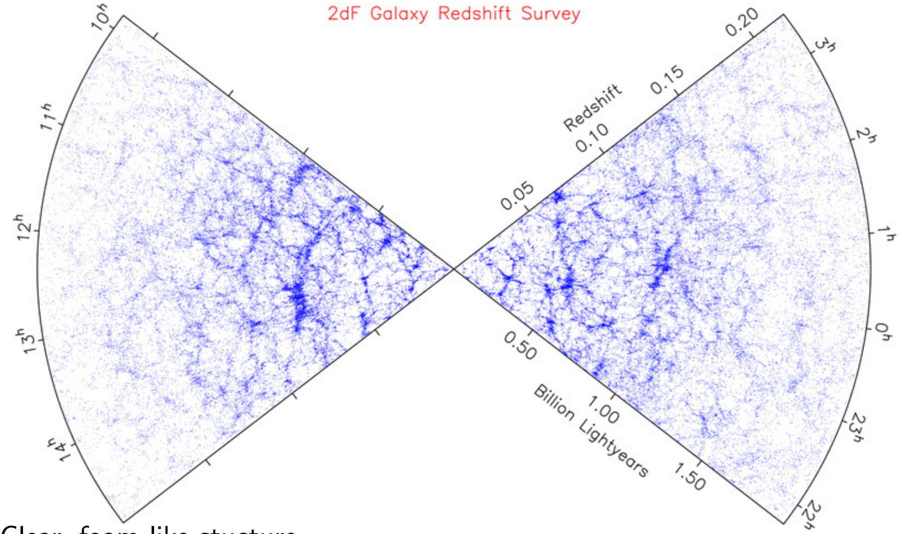
$\Rightarrow$ sky starts to be “3-D”...

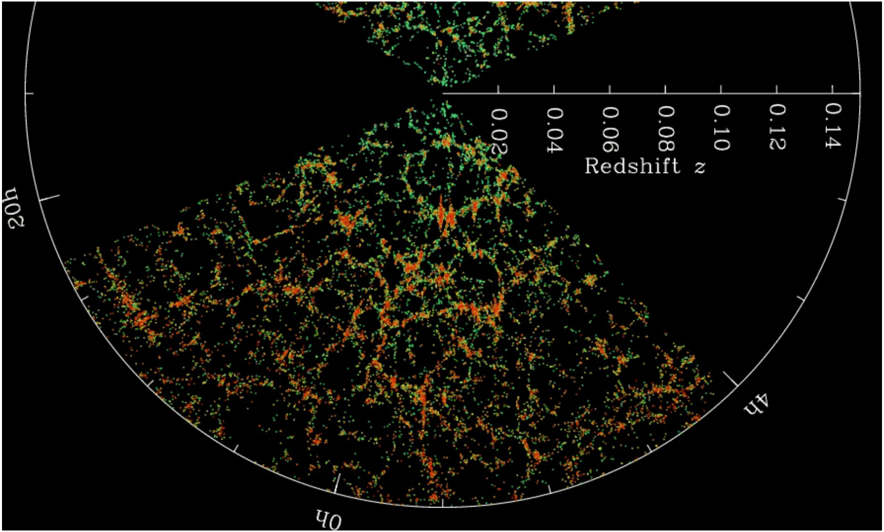
We already know distances to more than a million galaxies...
Most data come from the subsequent phases of the Sloan Digital Sky Survey project...

2dFGRS results: distribution of galaxies in distance from Earth and angle



Clear, foam-like stucture...

SDSS results



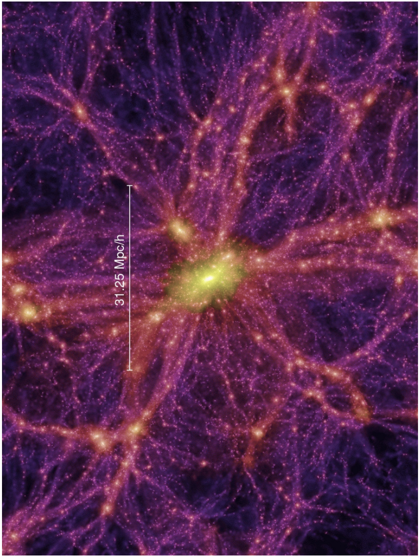
Structure formation

At the stage when atoms formed, density fluctuations in the Universe were at the level of 10^{-5}

Gravitational interactions amplify these irregularities, but not fast enough!

Density of baryonic matter is not sufficient to explain structure formation in the Universe

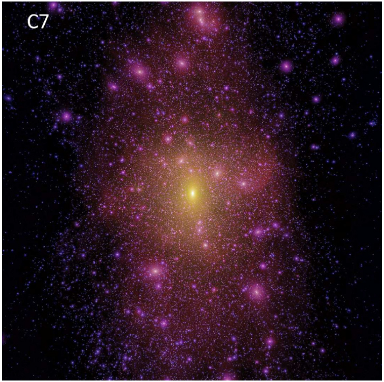
We can estimate how much Dark Matter is needed using dedicated computer simulations.



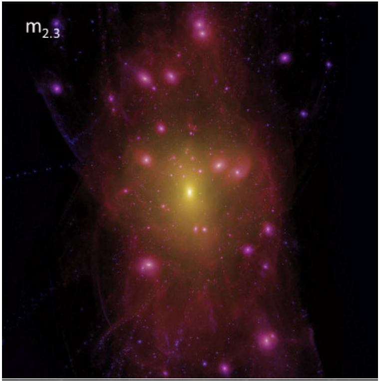
Density fluctuations

To describe formation of small structures, dark matter has to be “cold” (heavy, non-relativistic particles). Otherwise structures would be dispersed...

Cold dark matter

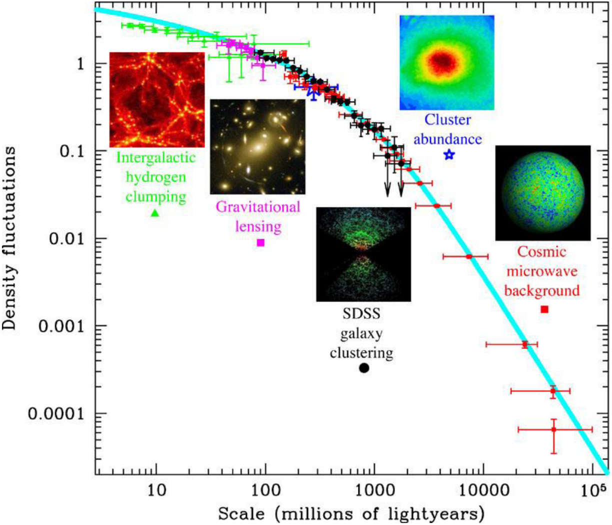


Warm dark matter



Density fluctuations

Cosmological model including the so called Cold Dark Matter (ΛCDM) describes very well density fluctuations observed in the Universe at different distance scales



How to estimate the density of matter in the Universe? $\Omega \equiv \rho/\rho_c$

Many possible approaches:

- looking at radiation of stars and interstellar matter
  $\Rightarrow$ luminous matter $\Omega_{lumi} \sim 0.006$
- from the abundance of light elements + Primordial nucleosynthesis model (BBN)
  $\Rightarrow$ baryonic matter $\Omega_b \sim 0.04 - 0.05$
- measurement of gravitational interactions and structure formation
  $\Rightarrow$ "gravitational" matter (total ?)
  $\Omega_m \sim 0.3$
- from fitting ΛCDM model to CMB measurements (next week)

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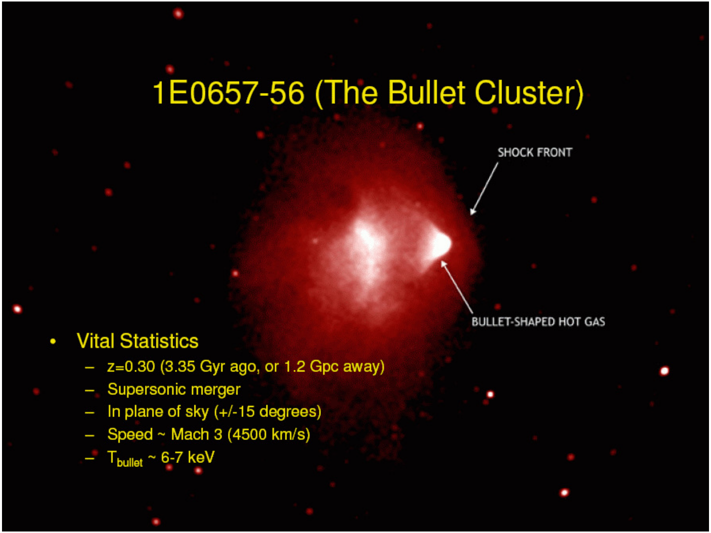
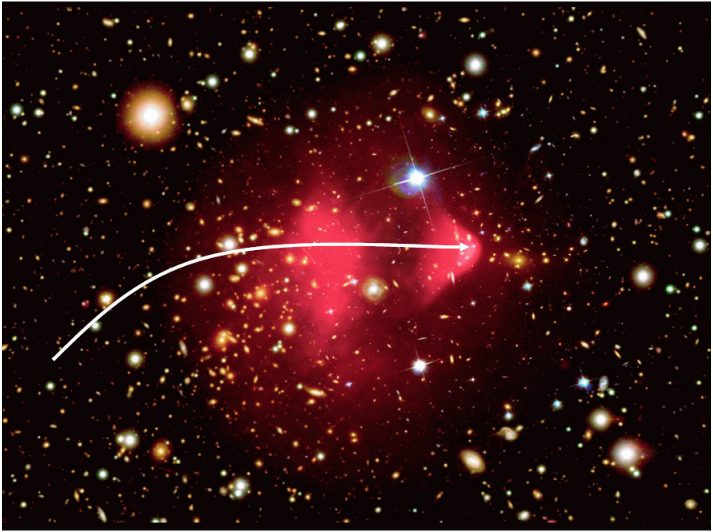
Comparison of different results indicate, that in addition to "ordinary" (baryonic) matter the Universe consists also of the so called Dark Matter...

In visible light

In X-ray


1E0657-56 (The Bullet Cluster)
SHOCK FRONT
BULLET-SHAPED HOT GAS
• Vital Statistics
– z=0.30 (3.35 Gyr ago, or 1.2 Gpc away)
– Supersonic merger
– In plane of sky (+/-15 degrees)
– Speed ~ Mach 3 (4500 km/s)
– T_{bullet} ~ 6-7 keV

Visible vs X-ray looks like collision between two galaxies

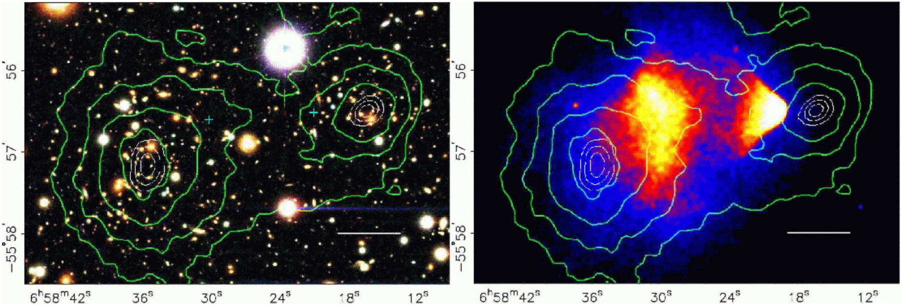


Bullet cluster

Based on the measurements of the weak gravitational lensing we could also evaluate the “gravitational” mass distribution in the cluster.

It is compatible with the star distribution.

Non compatible with the interstellar matter distribution!



Luminous mass far too small

⇒ evidence for weakly interacting Dark Matter

Bullet cluster

Summary

We know that dark matter:

- is "cold" (non-relativistic)
- is non-baryonic
- is stable (does not decay)
- interacts very weakly (gravitational only?)
- contributes to about $1/4$ of critical density ($5\times$ baryon matter)

We do not know:

- What it consists of (one or more paricles)?
- How to observe it directly?

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- How to observe it directly?

One of the candidates is the Lightest Supersymmetric Particle (LSP), which we hope to find at LHC...

But we also consider other models and different measurements...