

Evolution of the Universe

Particles and Universe

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June 6, 2017

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- 6 Structure formation
- 7 Bullet cluster

Hubble's Law

Redshift

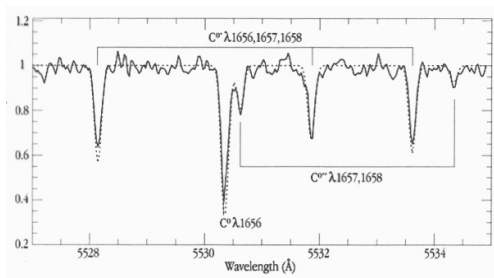
If the **source** of light **recedes** from the observer the measured wave length is **elongated**:

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

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



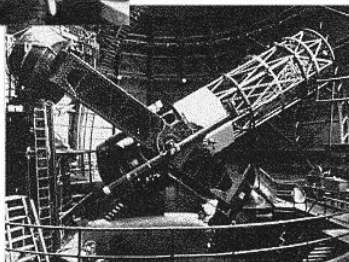
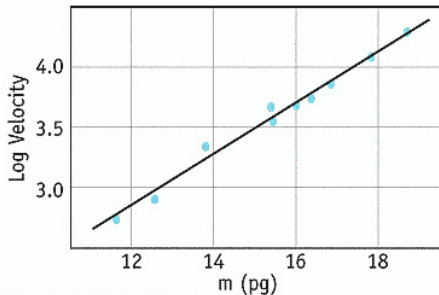
Wavelength shift corresponding to $z=2.34$

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

DISCOVERY OF EXPANDING UNIVERSE



Edwin Hubble



Mt. Wilson
100 Inch
Telescope

Hubble's Law

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)

$$v = H r$$

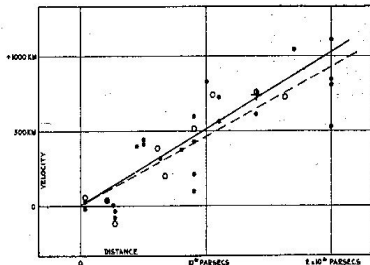
r - distant from Earth,
 H - Hubble's constant

Value given by Hubble:

$$H \approx 500 \text{ km/s/Mpc}$$

almost an order of magnitude too large :-)

Oryginal Hubble's results:



Hubble's Law

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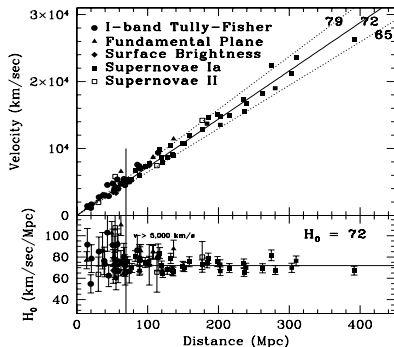
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Recent results:

$$H \sim 70 \text{ km/s/Mpc}$$

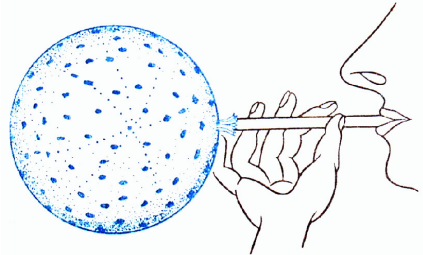
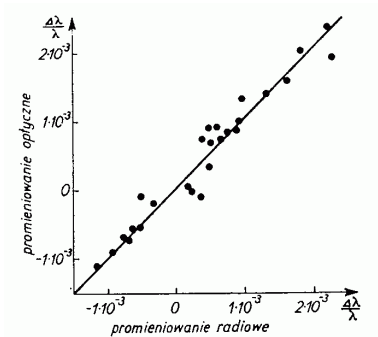


Hubble's Law

Redshift observed is **the same** in **all** bands of electromagnetic **spectra**

Comparison of optical 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 \Rightarrow “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.

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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 **disappeared...**

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

The big



10^{-43} seconds

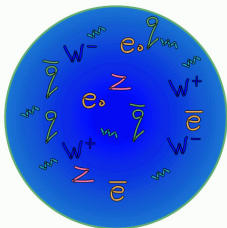


10^{32} degrees

10^{-34} seconds

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

10^{-34} seconds

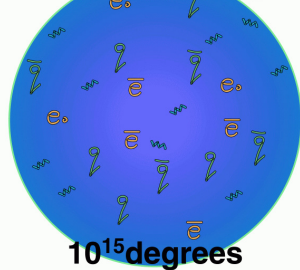


10^{27} degrees

10^{-10} seconds

Separation of electromagnetic and weak interactions. **Free W^\pm and Z^0 bosons** disappear (no longer in thermal equilibrium with photons)

10^{-10} seconds



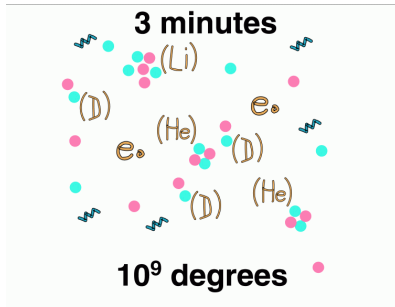
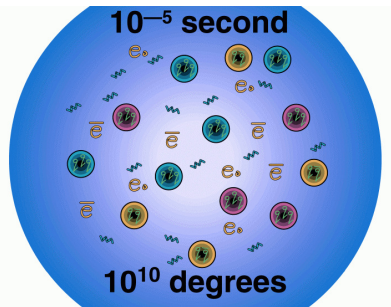
10^{15} degrees

10^{-5} seconds

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

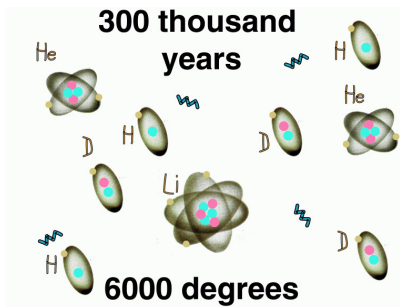
3 minutes

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

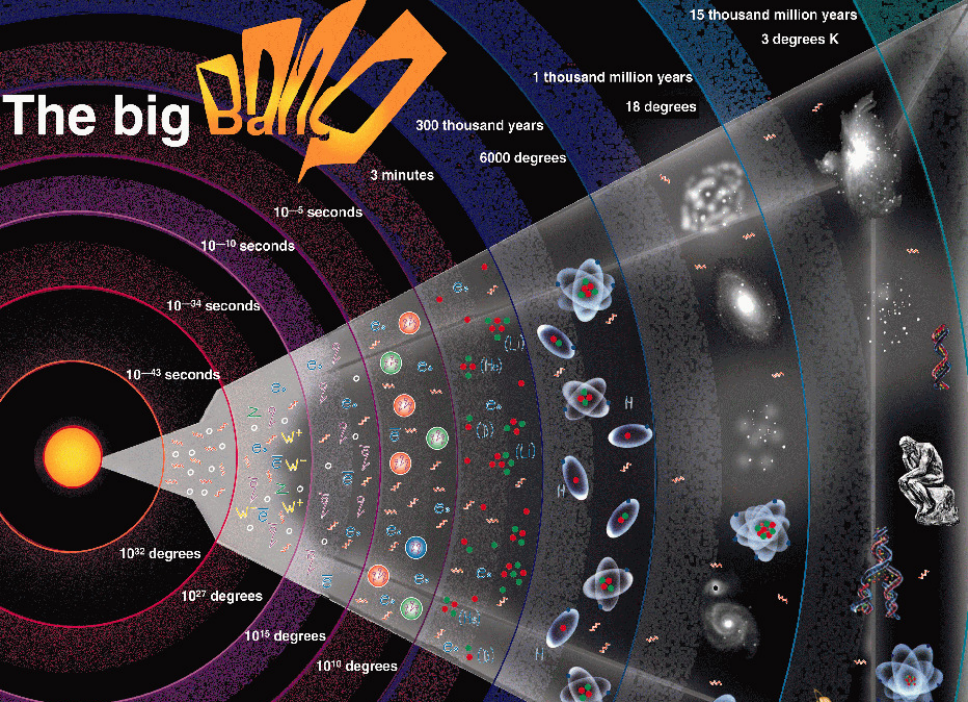


1 000 000 000 years

Galaxy formation, synthesis of heavier elements in stars.



The big Bang



Explained by the model

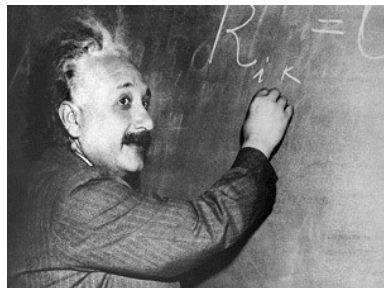
- Expansion of the Universe
- Cosmic Microwave Background (CMB)
- Fluctuations of CMB
- Composition of the Universe (Primordial Nucleosynthesis)

Questions with no answer so far...

- Why did antimatter disappear?
- 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.



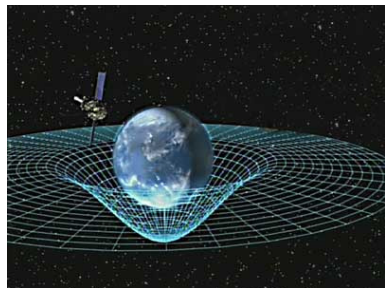
General Relativity

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.

Matter 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**.

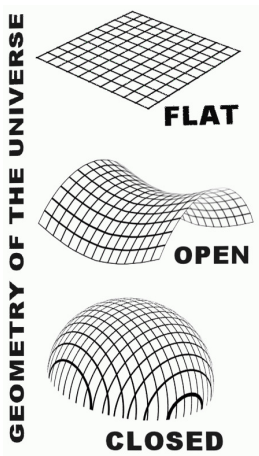
In the comoving frame matter (averaged over cosmological scales) is at rest ($r \equiv r_0$). Change of distance between objects is now described by a **time dependent metric**:

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

Friedmann-Lemaître-Robertson-Walker metric

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

Curvature of space



Friedmann equations

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

$$k = 0$$

$$k = -1$$

$$k = +1$$

$$H^2 = \left(\frac{\dot{R}}{R} \right)^2 = \frac{8\pi G}{3} \rho - \frac{k}{R^2} + \frac{1}{3} \Lambda$$
$$\frac{\ddot{R}}{R} = \frac{\Lambda}{3} - \frac{4\pi G}{3} (\rho + 3p)$$

where: ρ - matter density, p - pressure

Einstein introduced cosmological constant Λ to “save” **static** and **flat** solution...

Evolution of the Universe

Critical density

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

Critical density:

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

Density parameters

(density in units of ρ_c):

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

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

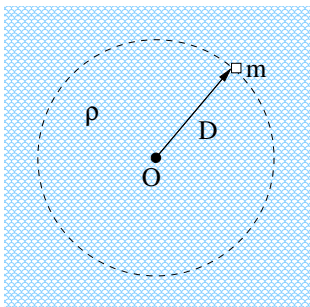
If $\Omega_{tot} = \Omega_m + \Omega_\Lambda = 1$
 \Rightarrow Universe is 'flat' (euclidean)
 curvature $k = 0$

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 $R(t)$ ($r = \text{const}$):

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

Conservation of energy:

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

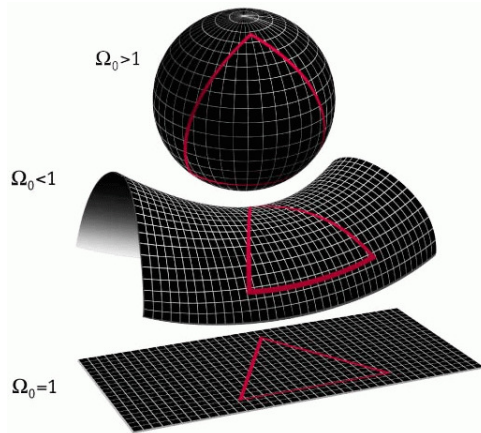
$$\Rightarrow \dot{R}^2 = \frac{8\pi G}{3} \rho R^2 - k$$

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)

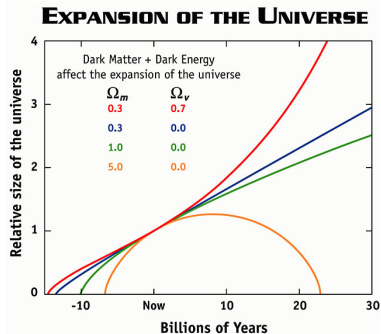
$\Omega_m > 1$ ($k = +1$)

\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?

$$\Omega \equiv \rho/\rho_c$$

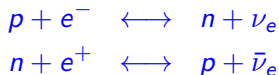
Many possible approaches:

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



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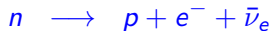


But about **1 s** after Big Bang:

- 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**

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

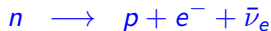


At the same time deuterium production can take place:



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

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

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

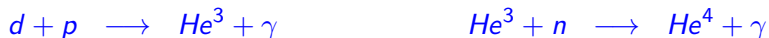
Deuterium production “freezes” the neutron fraction in the Universe at the level of **1 : 7**

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



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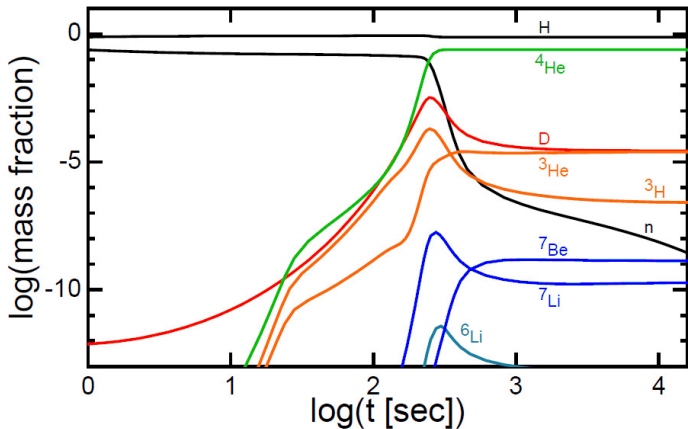
Rate of different reactions depends on the (baryonic) **matter density**.

“Freeze out” time depends on the **expansion rate**.

Primordial nucleosynthesis

Summary

Dependence of element abundance on time



Primordial nucleosynthesis

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:

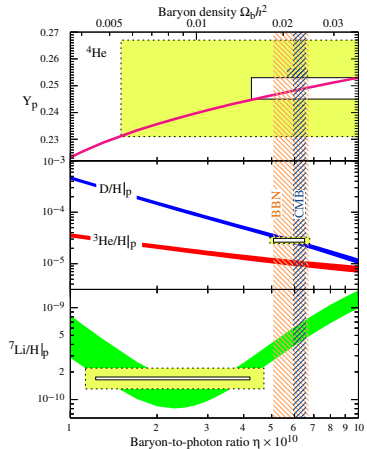
$$H^2/H = (2.82 \pm 0.21) \times 10^{-5}$$

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

Fit result:

$$0.019 \leq \Omega_b h^2 \leq 0.024 \quad (95\% CL)$$

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



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
⇒ **luminous** matter $\Omega_{lumi} \sim 0.006$
- from the abundance of **light elements** + **Primordial nucleosynthesis** model (**BBN**)
⇒ **baryonic** matter $\Omega_b \sim 0.04 - 0.05$
- measurement of **gravitational** interactions and structure formation
⇒ **“gravitational”** matter (**total ?**)
- from fitting **Λ CDM** model to **CMB** measurements

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).

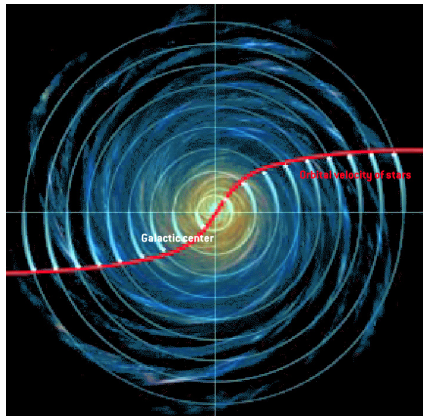
From the classical laws of motion we expect

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

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

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

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



Galaxy rotation curves

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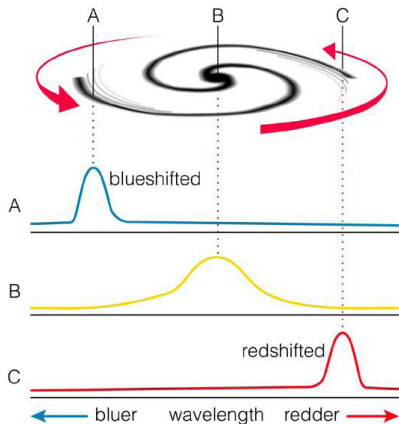
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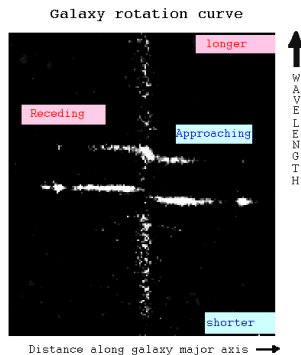
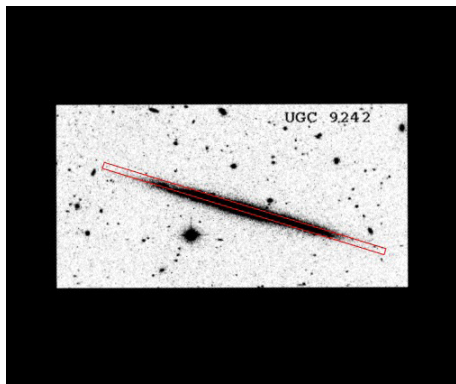
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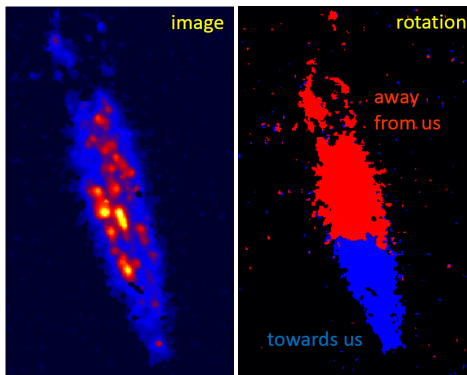
Measurements

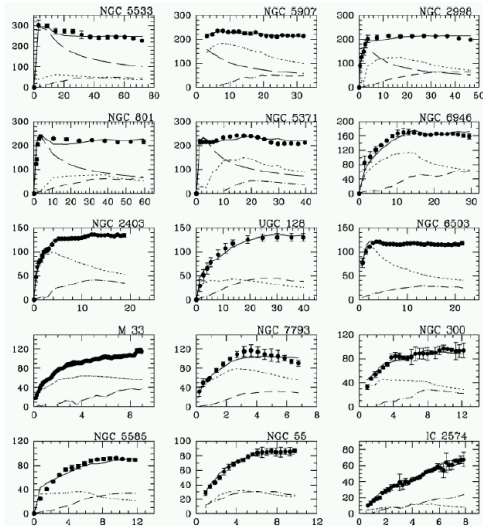
In the past, measurements were made separately for each galaxy



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

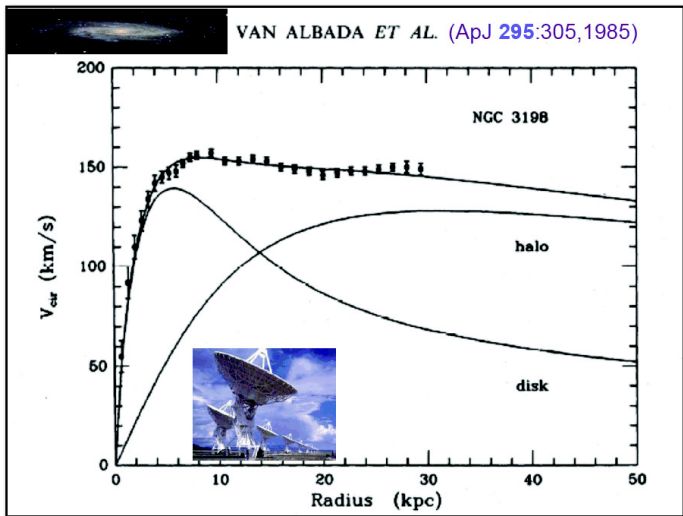




Results indicate, that rotation velocities do not decrease (and often increase) with the distance from galactic center
it is not consistent with the visible distribution of matter materii.

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

Galaxy rotation curves



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

We could only measure object positions on the celestial sphere - 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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Dedicated instruments allow for the simultaneous measurement of redshift for up to 1000 objects.

⇒ sky starts to be “3-D” ...

Structure formation

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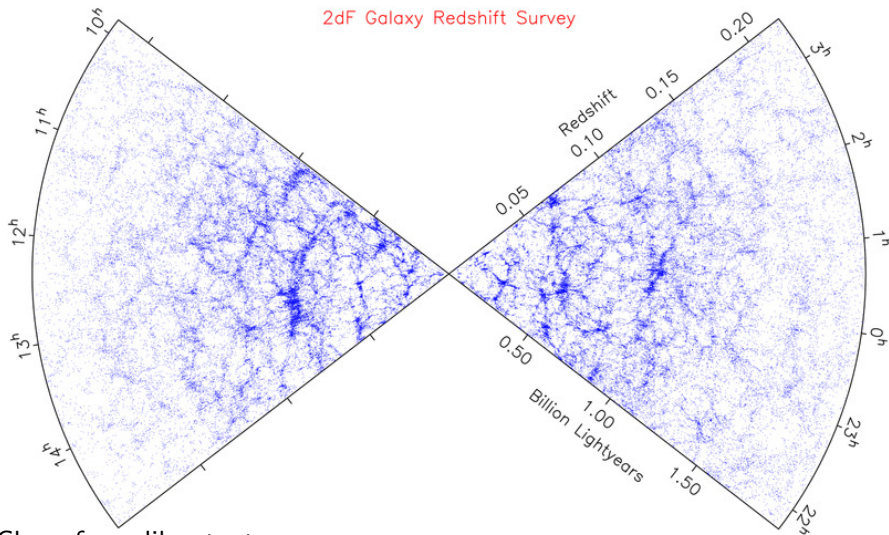
⇒ sky starts to be “3-D” ...

We already know distances to more than a million galaxies...

Most data come from the subsequent phases of the Sloan Digital Sky Survey project...

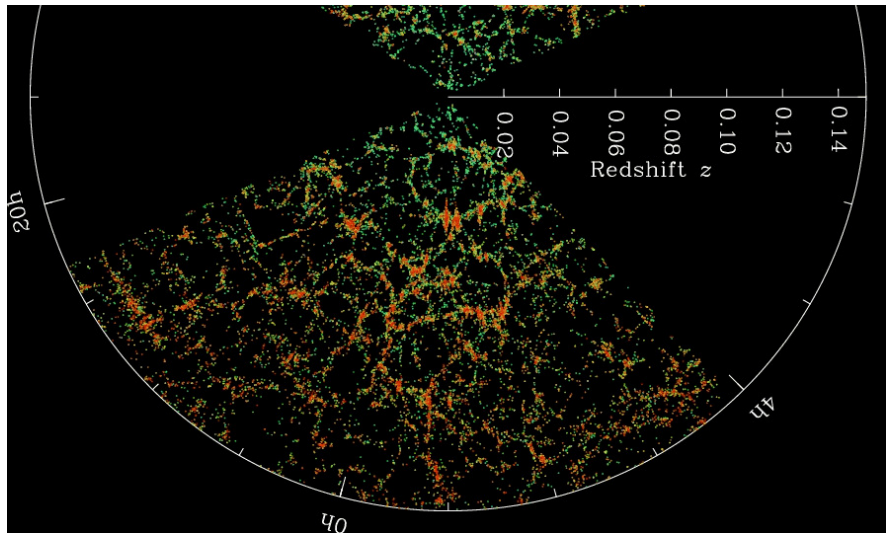
2dFGRS results: distribution of galaxies in distance from Earth and angle

2dF Galaxy Redshift Survey



Clear, foam-like structure...

SDSS results

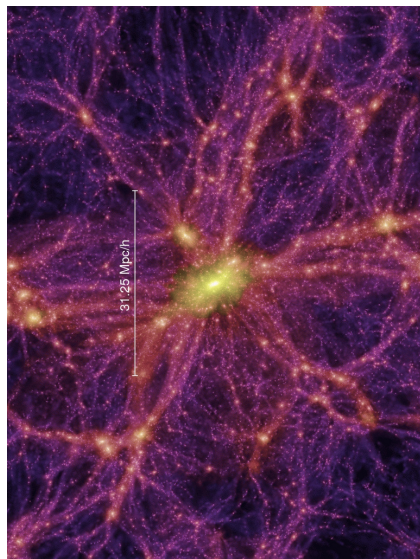


At the stage when atoms formed, density fluctuations in the Universe were at the level of 10^{-5}

Gravitational interactions amplify these irregularities, but **not fast enough!**

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

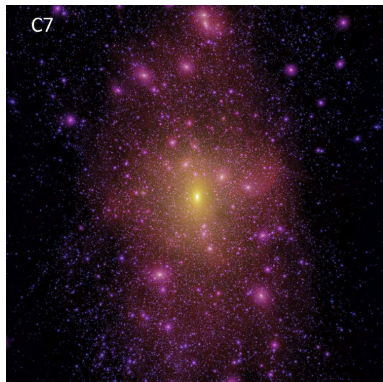
We can estimate how much Dark Matter is needed using dedicated computer simulations.



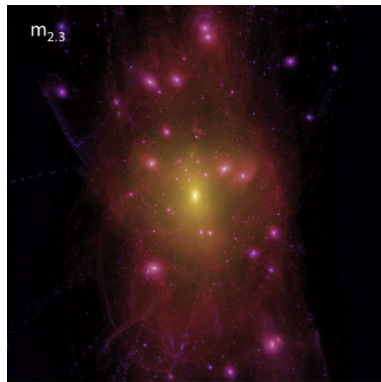
Density fluctuations

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

Cold dark matter

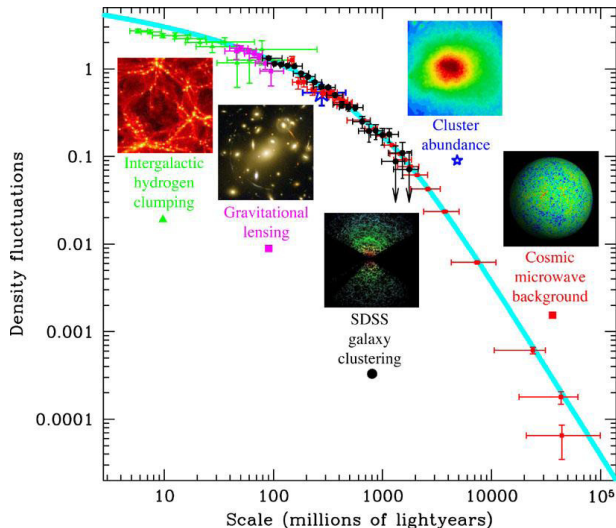


Warm dark matter



Density fluctuations

Cosmological model including the so called **Cold Dark Matter** (Λ CDM) 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

⇒ **luminous** matter

$$\Omega_{lumi} \sim 0.006$$

- from the abundance of **light elements** + **Primordial nucleosynthesis** model (BBN)

⇒ **baryonic** matter

$$\Omega_b \sim 0.04 - 0.05$$

- measurement of **gravitational** interactions and structure formation

⇒ **"gravitational"** matter (total ?)

$$\Omega_m \sim 0.3$$

- from fitting **Λ CDM** model to **CMB** measurements (next week)

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

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⇒ **baryonic** matter

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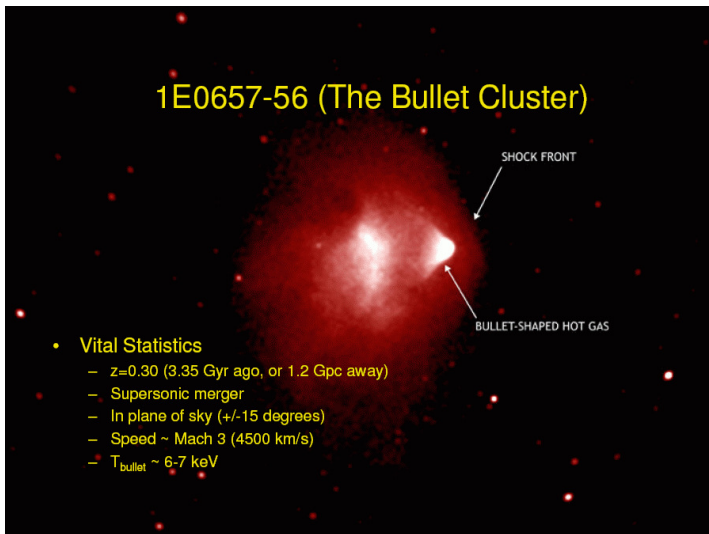
- from fitting **Λ CDM** model to **CMB** measurements (next week)

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

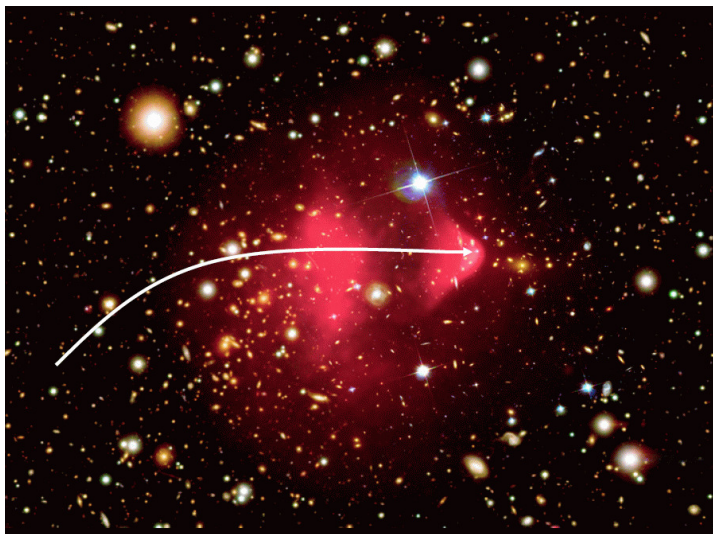
In visible light



In X-ray



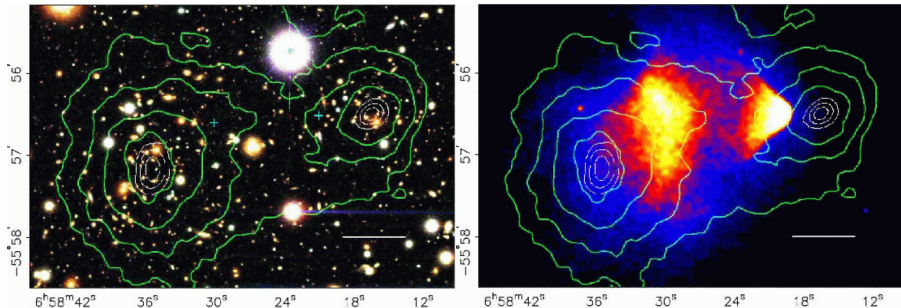
Visible vs X-ray looks like collision between two galaxies



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

Optical Dark Matter X-ray Gas



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 particles**)?
- How to observe it directly?

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We do not know:

- What it consists of (**one or more particles**)?
- 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...