Where Astronomy Meets Particle Physics

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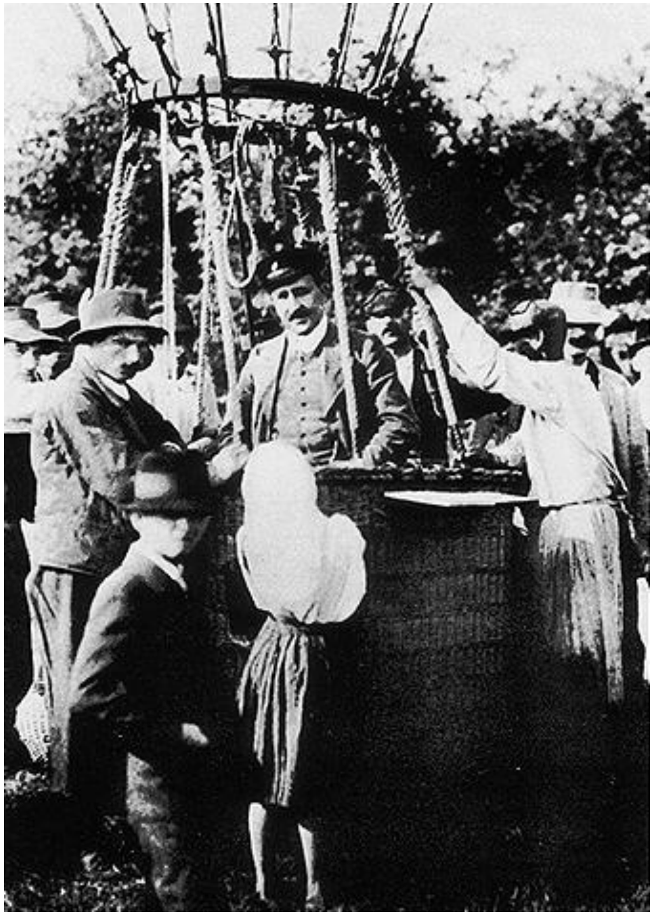
Lecture topics

- 1. **Cosmic ray’s** interaction with the atmosphere and their origin.
- 2. Main **thermonuclear reactions** in stars and **solar neutrino** problem.
- 3. **Supernova** event, **neutrino burst** and a **pair-instability supernova**.
- 4. Creation of **chemical elements** in the Universe.
- 5. The **beginning** and the **end** of the **Universe**.
- 6. **Dark matter** and **dark energy** problems.

1. **Cosmic ray's** origin and their interaction with the atmosphere

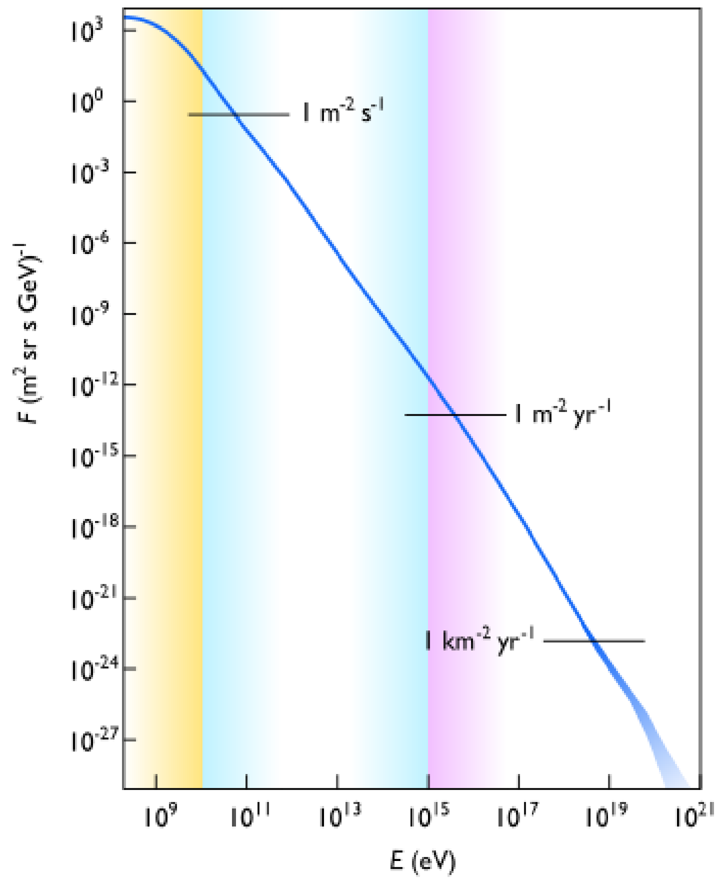
Cosmic rays are not rays

- High energy particle physics started with the discovery of cosmic rays a century ago.
- In 1912 while flying with a balloon, Austrian physicist Victor Francis Hess found that the radiation increased rapidly with the altitude, and suggested it had extraterrestrial origins.
- A cosmic ray is a high-speed particle – either an atomic nucleus or an electron.
- Up to that moment different types of "radiation" were discovered, X-rays by K. Röntgen, radioactivity by H. Becquerel.



Then what are they?

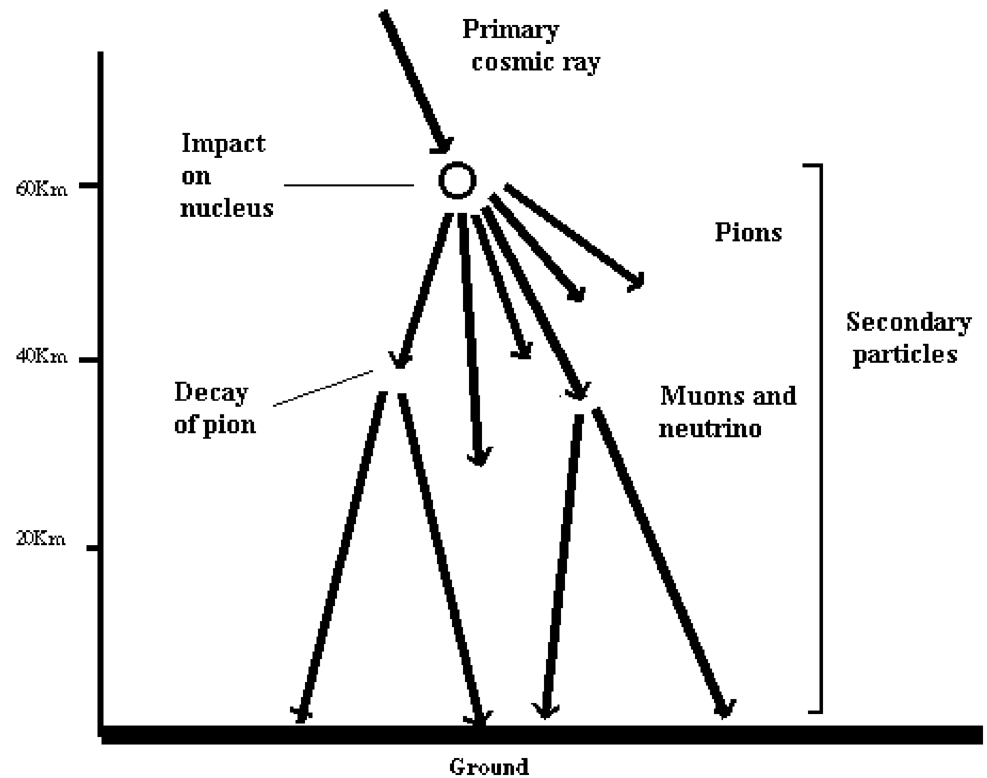
- Cosmic rays originate outside Solar system or come from the Sun.
- About 89% are protons (hydrogen nuclei); 9% are alpha particles (helium nuclei); 1% are the nuclei of heavier elements; 1% are electrons.
- Solar particle energy is typically 10 to 100 MeV, occasionally reaching 1 to 10 GeV.
- Most galactic cosmic rays have energies between 100 MeV and 10 GeV. They travel at nearly the speed of light.
- Record braking energy of one cosmic ray particle corresponds to the fast flying baseball. Oh-My-God particle.
- It is about 40 million times the energy of particles accelerated by the Large Hadron Collider.



The number of cosmic rays with energies beyond 1 GeV decreases by about a factor of 50 for every factor of 10 increases in energy.

Air showers

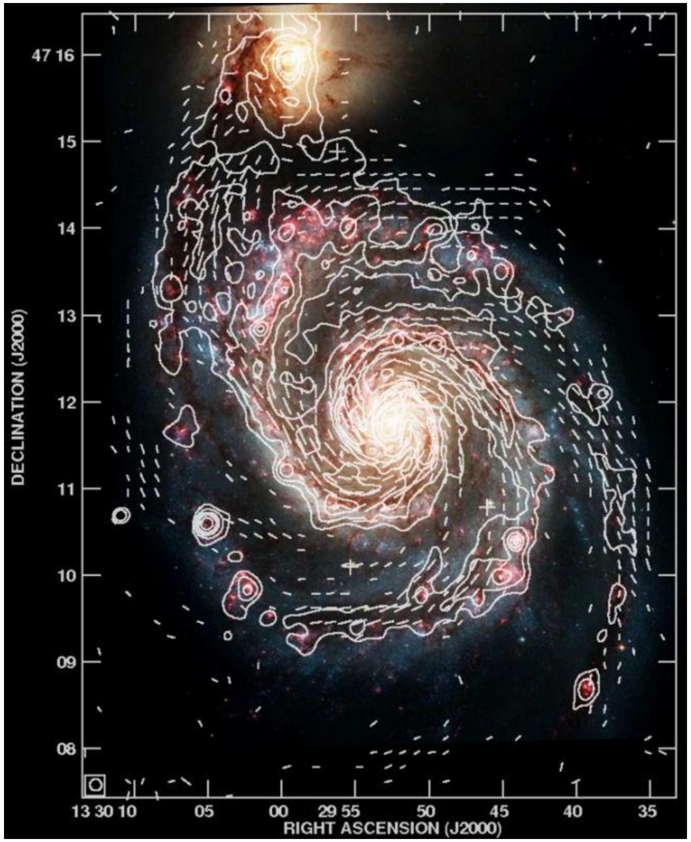
Hold out your hand for 10 seconds. A dozen electrons and muons just zipped unfelt through your palm.



- When a high-energy proton hits the Earth's atmosphere, it will collide with one of the nuclei of the atmospheric gas molecules.
- In these high-energy collisions many secondary particles are produced, including pions.
- The high-energy charged pions make the high-energy muons.
- Only a small fraction of the particles comes down to the ground.

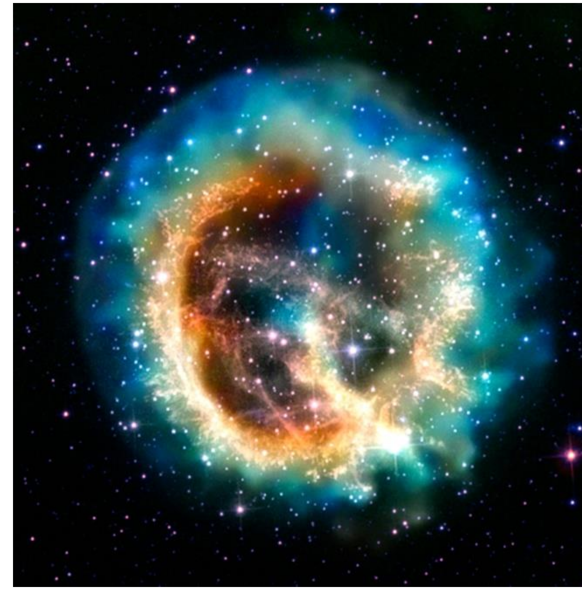
Where do they come from?

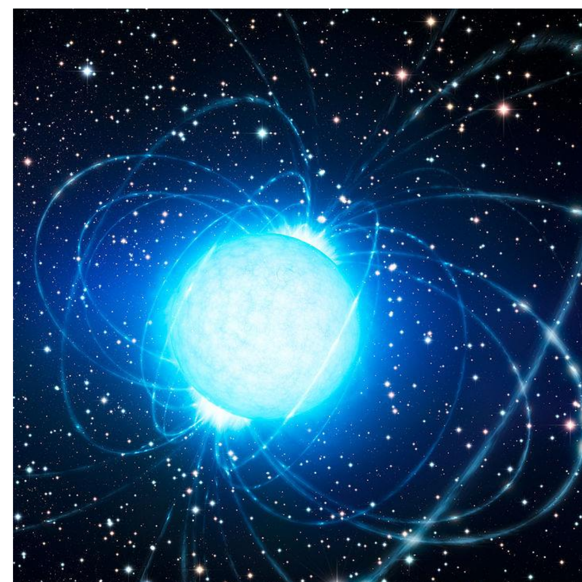
- The amount of energy of galactic cosmic rays is big because they occur in objects with the dimensions or/and magnetic fields far exceeding those in the Solar System.
- The cosmic source works like a particle accelerator on Earth. Finally local magnetic field can no longer hold the particle, and it“goes away”.
- Then the charged particles move along the magnetic field lines of the Galaxy and change their direction of movement.
- On Earth they come from all directions in the sky. That’s why it is so hard to tell the origin of the particles.



Origins of galactic cosmic rays (1)

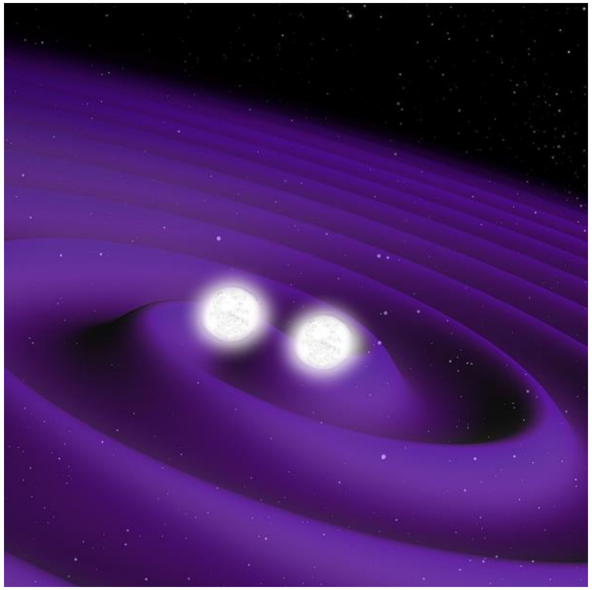
- A. **Supernovae**. The main source of galactic cosmic rays. Most of them are created in the shockwave when the ejected material collides with the interstellar medium, creating a millions of degrees hot, rarefied gas bubble. 10-20% of all the shockwave energy is converted into particles energy.
- B. **Magnetars**. A special class of pulsars with a rotation period of less than one second and a VERY strong magnetic field. The rate of the pulses decreases with time. It seems like the cosmic rays take away magnetar's rotational energy. Magnetars are also likely to create a specific "subspecies" of cosmic rays, a pair of high-energy electron and positron.





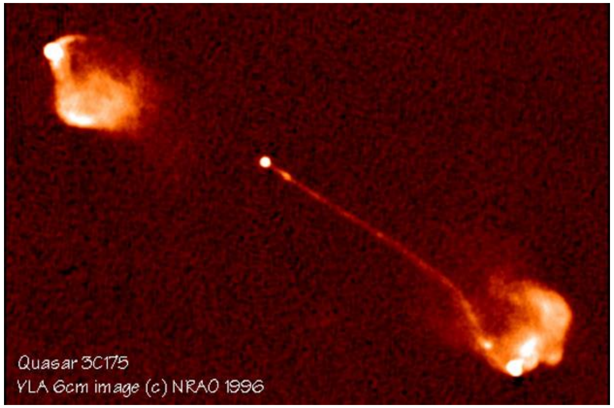
Origins of galactic cosmic rays (2)

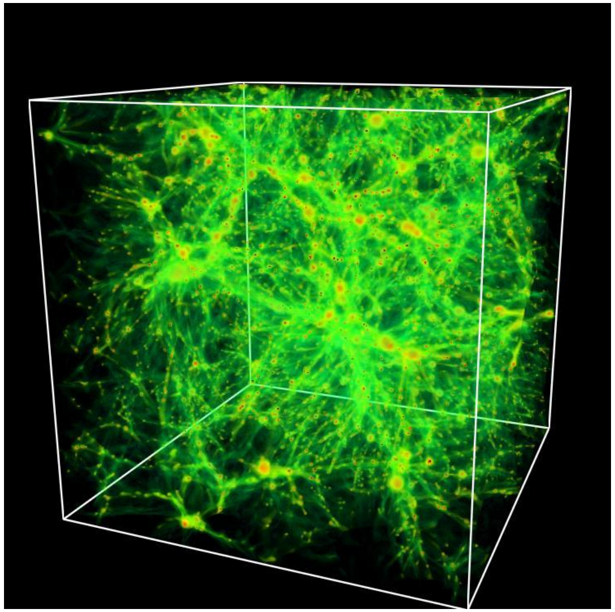
- C. **Collision of massive objects**. In recent years gravitational waves have become the subject of astronomical research. The spectacular convergence of two neutron stars or neutron star and the black hole creates not just the gravitational waves. These events may also include beams of ultra-high-energy cosmic rays.
- D. **Superbubbles**. Supernovae explosions create hot, ionized gas bubbles in the interstellar medium of the Galaxy. When such bubbles merge, the so-called “super-bubble” is created. In them, cosmic rays are accelerated to high energy and can carry away about 20% of bubble energy.



Origins of galactic cosmic rays (3)

- E. **Active galaxies**. Cosmic rays of the highest energy (~10^{20} eV) come from the active galaxies. Black hole sends a few percent of its mass in the form of powerful jets. The jets interact with the intergalactic gas, creating shockwave lobes. Magnetic fields of the lobes create ultra-high-energy cosmic rays. It's like a galactic particle cannon.
- F. **Gas between galaxies**. Hot intergalactic gas occupies a huge volume in space and can produce ultra-high-energy cosmic rays. They are created by shockwaves that occur in the interaction of galaxies.

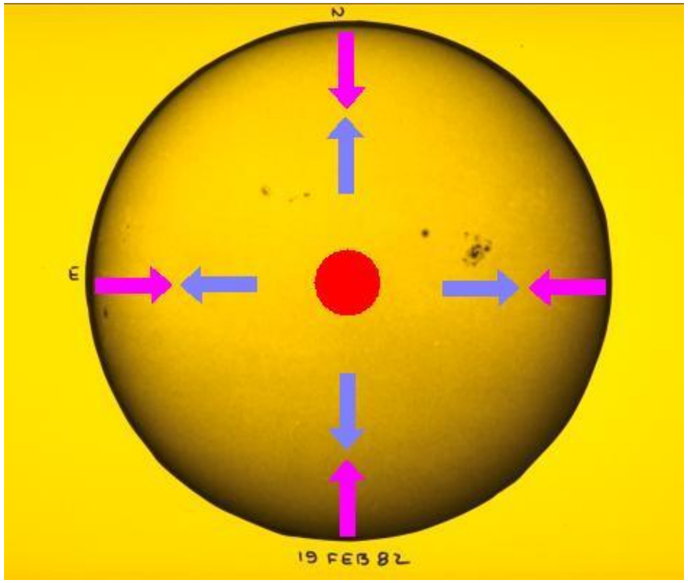




2. Main **thermonuclear reactions** in stars and **solar neutrino problem**

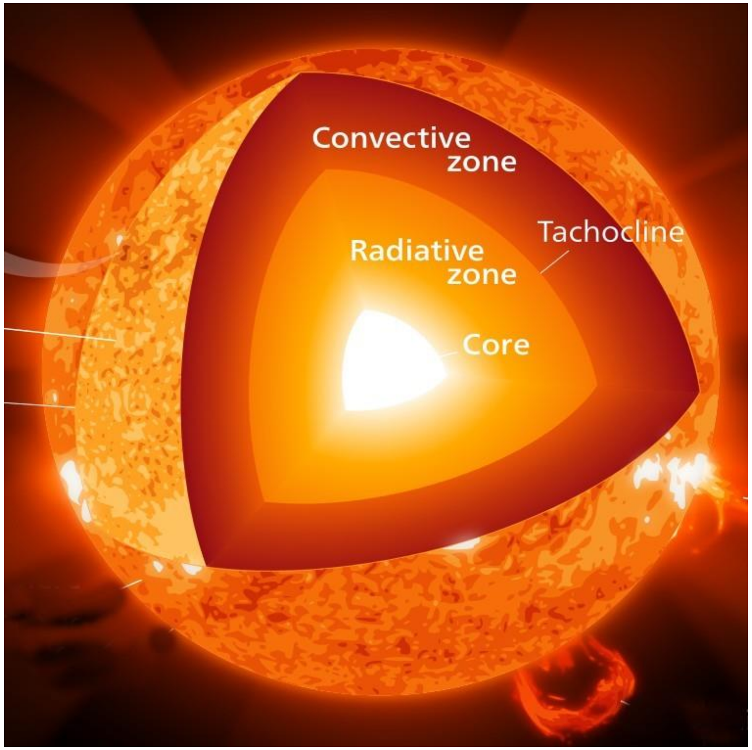
Stars are simple objects

- At the first look a star seems like very simple object. It is a round ball of hot plasma.
- Stars tend to contract under their own gravity. The gravity force is compensated by the gas pressure force. Most stars are in the equlibrium. The do not expand nor contract.
- High pressure inside the star is maintained by high temperature. High temperature is created by the energy release at the central part of the star.
- The energy source for "normal stars" are the thermonuclear reactions.



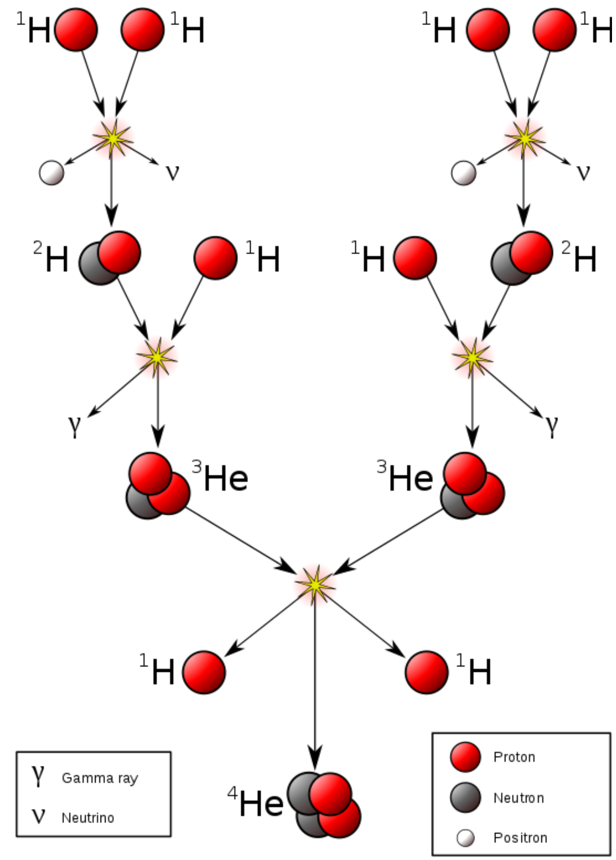
Where the energy comes from?

- There are two main thermonuclear reaction cycles, **proton–proton reaction** and **CNO cycle**. In both cases from 4 protons one alpha particle (helium-4 nucleus) is created. Hydrogen is converted into helium.
- In this process 0,7 percent of the mass of 4 protons is converted into energy. The total energy yield of one reaction is 26,73 MeV.
- This energy can be calculated using the famous Einstein equation $E = mc^2$, where $m = 4{,}752 \times 10^{-29}$ kg (mass defect), c – speed of light (3×10^8 m/s). $E = 4{,}277 \times 10^{-12}$ J or 26,73 MeV (1 eV = $1{,}6 \times 10^{-19}$ J).



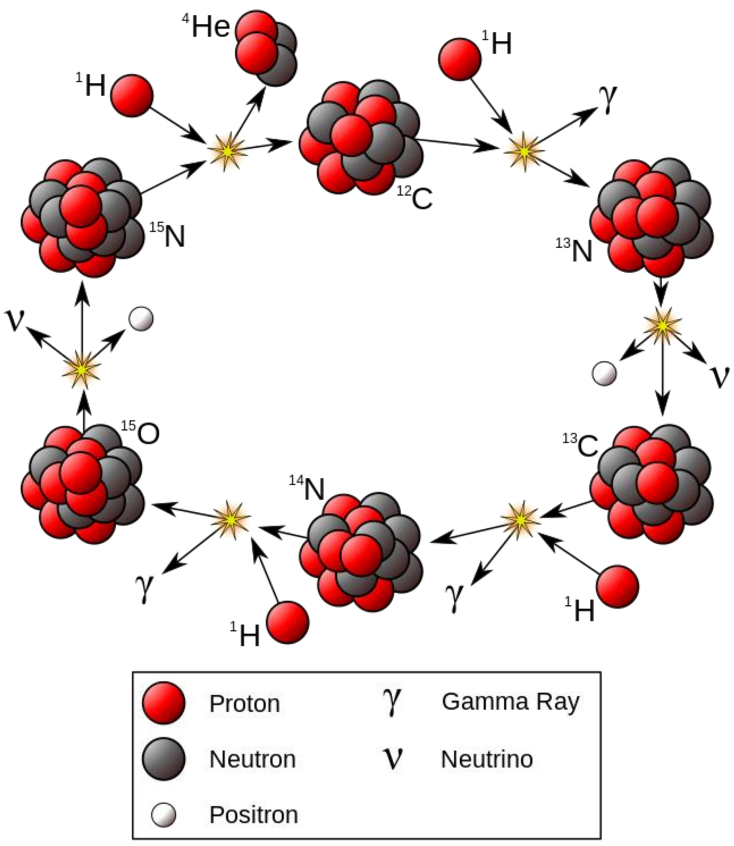
Proton–proton reaction

- Proton–proton reaction dominates in Sun-like stars (where temperature at the center is relatively low).
- **Step 1.** Fusion of two protons into deuterium, releasing a positron and a neutrino while one proton changes into a neutron. This step is slow, otherwise the star would explode.
- **Step 2.** Deuterium fuses with another proton to produce the helium-3 nucleus. Two gamma rays are produced.
- **Step 3.** Two helium-3 nuclei are converted into one nucleus of helium-4. Two protons are released. There ar several branches of this reaction. Picture shows the main one.
- Neutrino takes away about 2% of energy, the rest is converted into the heat.



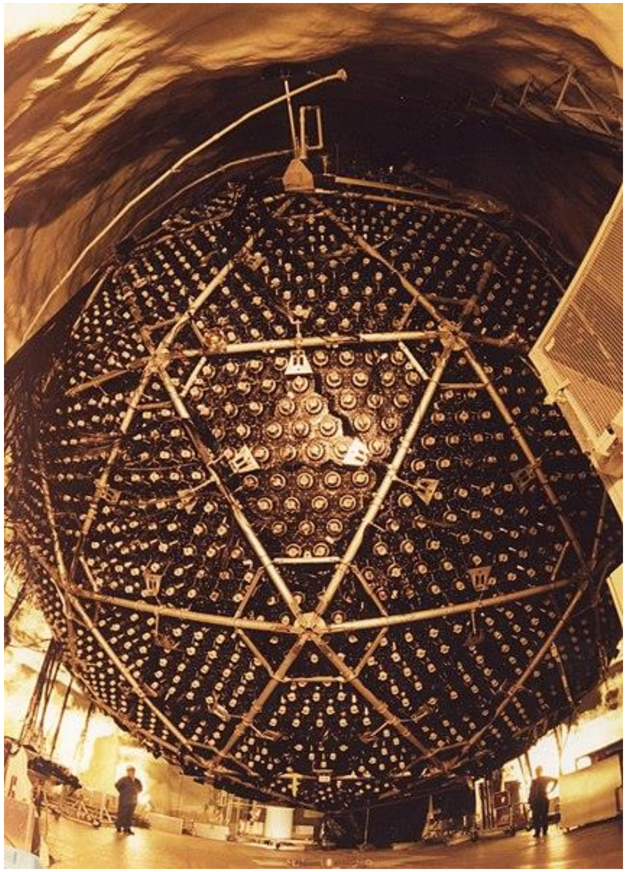
CNO cycle

- CNO (carbon–nitrogen–oxygen) cycle is dominant in stars more than 1,3 times more massive than the Sun.
- In the CNO cycle carbon, nitrogen, and oxygen isotopes are used as catalysts. Their amount is not changing.
- There are various paths but the same net result: 4 protons are converted into one helium-4 nucleus.
- 2 positrons annihilate with electrons, releasing gamma rays. 2 neutrinos escape from the star carrying away about 6% of energy.



Neutrinos, where are they?

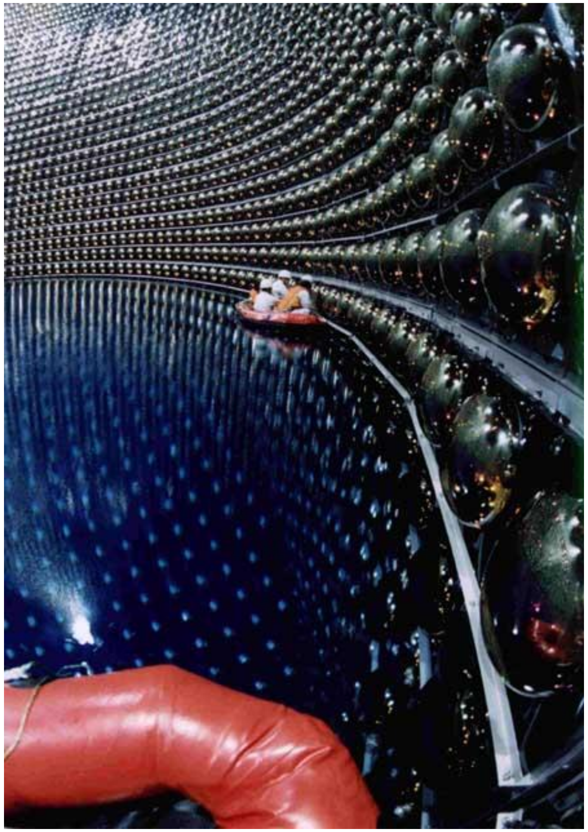
- The flux of neutrinos on Earth is several tens of billions per square centimetre per second, coming mostly from the Sun's core.
- The flux of solar neutrinos measured was 2 – 3 times less than predicted. The discrepancy was first observed in the mid-1960s.
- Is the model of solar thermonuclear reactions wrong? The problem was finally resolved around 2002.
- Neutrinos are not massless particles. Electron neutrino changes during propagation into a mixture of electron neutrinos, muon neutrinos and tau neutrinos.
- The Sun produces only electron neutrinos.



Sudbury Neutrino Observatory detector was one of those which detected the deficit of neutrinos.

How this was done?

- Strong evidence for neutrino oscillation came in 1998 from the Super-Kamiokande in Japan. Muon neutrinos produced by cosmic rays changed into tau neutrinos inside the Earth.
- Super-Kamiokande is located 1000 m underground. The tank is about 40 m in height and diameter and holding 50 000 tons of ultrapure water.
- In 1999 the Sudbury Neutrino Observatory started collecting solar neutrino data. Employing a large quantity of heavy water they observed all flavors of neutrinos.
- The fraction of electron-neutrinos was about 34%, in agreement with the prediction.

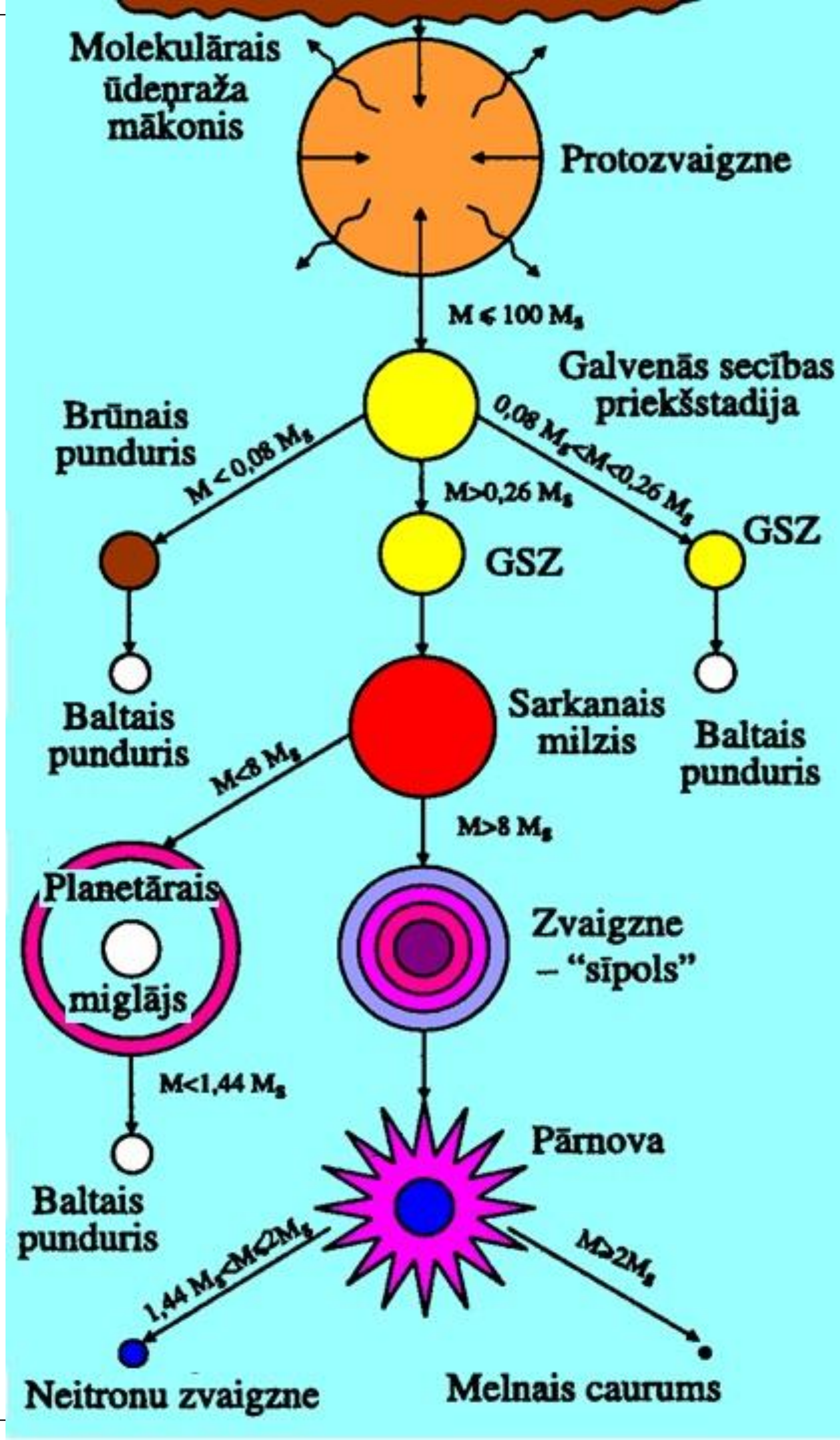


A neutrino interaction with water produces an electron or positron that moves faster than the speed of light in water. 13 000 photomultiplier tubes detect light of Cherenkov radiation.

3. **Supernova** event, **neutrino burst** and a **pair-instability supernova**.

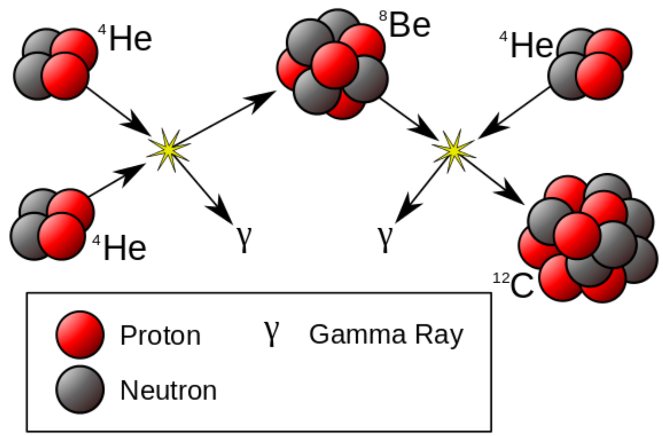
Evolution of stars

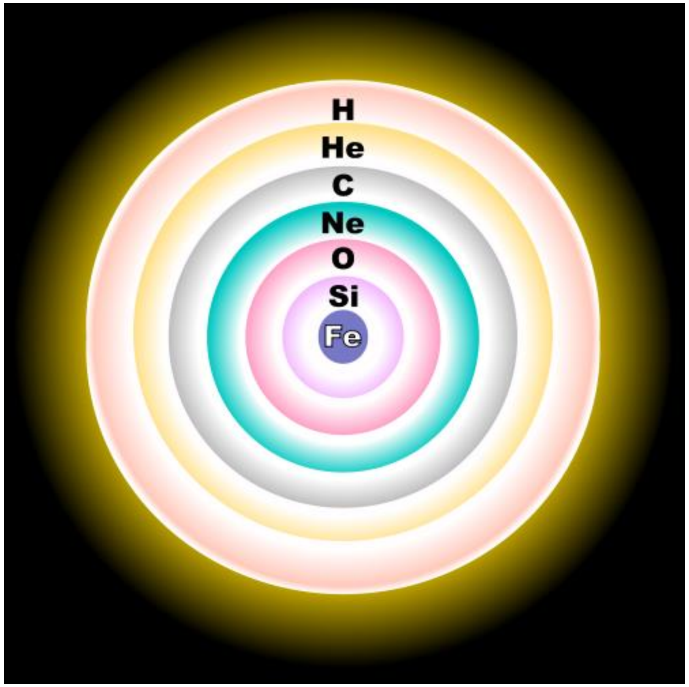
- Huge hydrogen and helium clouds contract under gravity. A star is born!
- Energy source of main sequence stars is hydrogen “burning”.
- Massive stars have big luminosity, they stay on the main sequence only few millions of years. *Live fast die young!*
- For small stars this stage of evolution lasts for hundreds of billions of years.
- Sooner or later hydrogen at the center of the star is spent and star “retires”.
- The “fate” of the star depends on its mass left:
  - Small mass – white dwarf;
  - Big mass – neutron star;
  - Very big mass – black hole.



Massive stars have layers

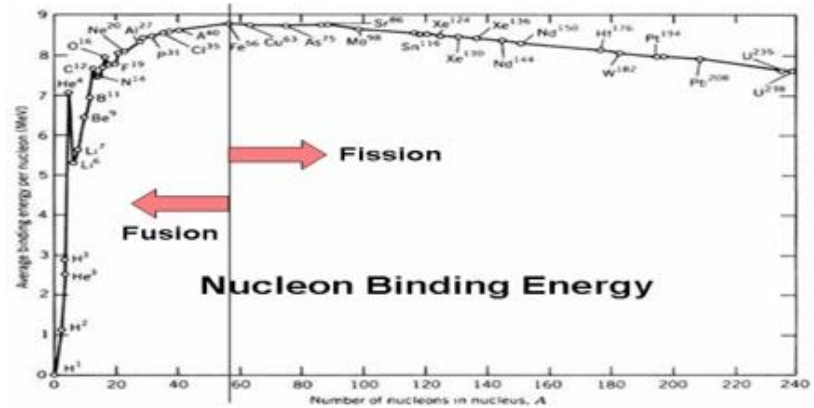
- During red giant phase carbon is produced in stars by triple alpha process. As a by-product of adding one more alpha particle oxygen is created.
- In massive stars the core temperature reaches or exceeds one billion kelvins and thermonuclear reactions continue further:
  - Carbon burning process: **neon, sodium, magnesium, aluminium**.
  - Neon burning process: **oxygen, magnesium**.
  - Oxygen burning process: **silicon, sulphur, argon, calcium**.
  - Silicon burning process: **nickel** (decays into **iron**).
- Chemical elements are produced in layers. Star becomes like an onion (simplified model).



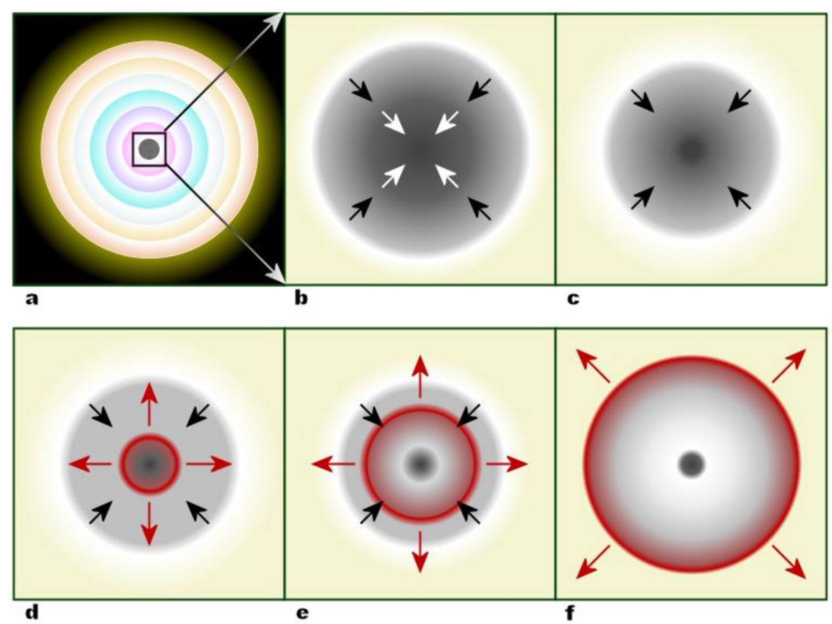


Collapse, then explosion

- To create elements heavier than the iron, energy is required. Reaction becomes energy consuming.
- Less energy means less pressure in the core of the star. Gravity wins at last!
- The core loses its equilibrium and starts to collapse. It happens in less than one second.
- Sudden compression increases the temperature of the inner core up to 100 billion kelvins.
- Outer layers fall to the core and bounce off. The energy of shock wave disrupts the stellar material in a supernova explosion.



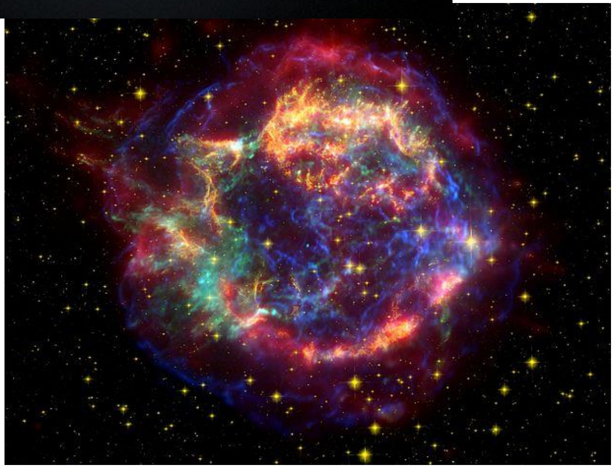
Nuclear binding energy is an energy needed to move nucleons away from each other.



A very bright flash

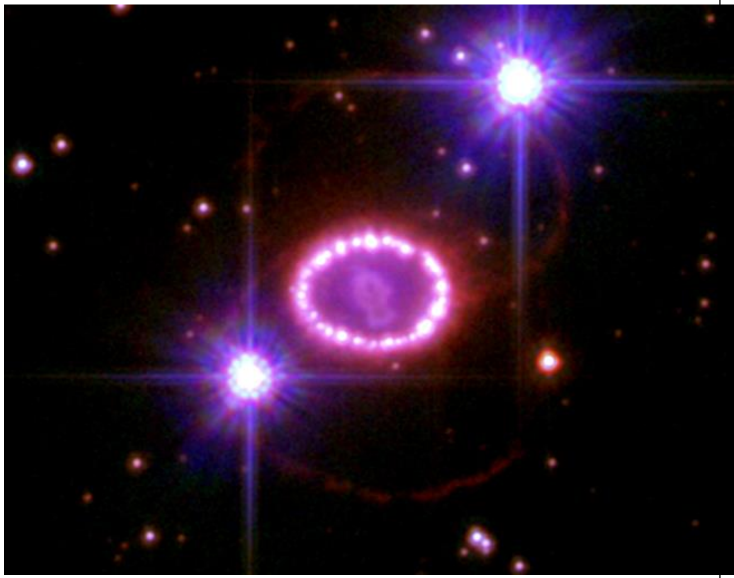
- The outer layers are expelled from the star even before the explosion.
- At the maximum of brightness supernova can outshine a whole galaxy.
- A flash can last for a weeks or months. Supernova radiates about the same amount of energy as the Sun in 10 billion years.
- Outer layers expand rapidly (up to 30 000 km/s), creating a **supernova remnant**.
- Supernovae are typically observed in other galaxies. In our Galaxy supernovae exploded in years 1006, 1054, 1572, 1604.
- Astronomers are waiting for the next one…





Neutronisation and neutrino burst

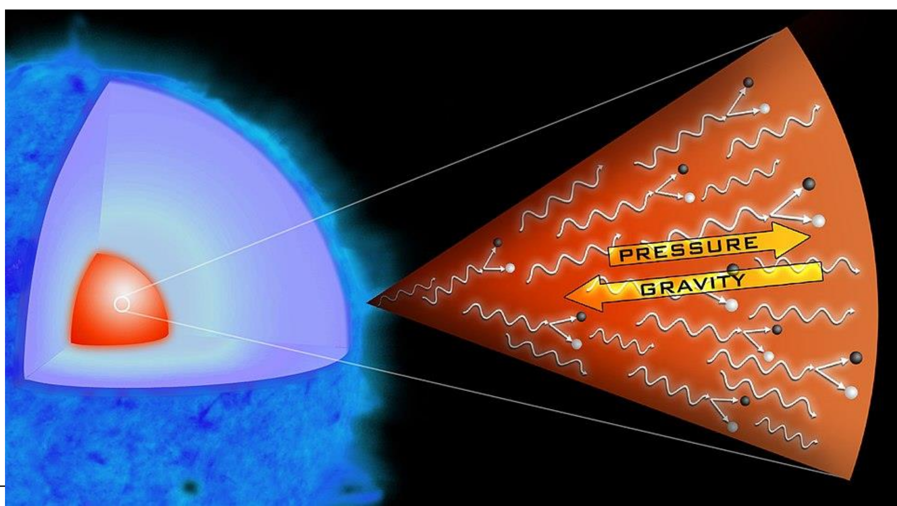
- When temperature exceeds 5×10^9 K, an energy absorbing **photodisintegration**, the breaking up of iron nuclei into alpha particles by high-energy gamma rays, occurs.
- The diversity of previously produced chemical elements in the core of the star is lost.
- As the temperature climbs higher, electrons and protons combine to form neutrons via electron capture, releasing a flood of neutrinos (**neutronisation**). $p + e^- \rightarrow n + \nu_e$.
- Neutrinos take away about 10^{46} joules in a ten-second burst.
- 2 – 3 h before the light from supernova 1987A reached Earth, a burst of neutrinos was observed at three neutrino observatories.



Supernova 1987A remnant 20 years after discovery.

A star is gone

- Huge 130 to 250 solar mass stars become **pair-instability supernovae**.
- Gamma rays produced in the core become so energetic that they produce particle and antiparticle pairs (**pair production**).
- The resulting drop in pressure causes the star to partially collapse.
- After the collapse, runaway thermonuclear reactions ensue and the star explodes, spewing the remains into space.
- No core is left at the place of explosion, just the supernova remnant.
- Recently observed objects SN 2006gy, SN 2007bi,[3] SN 2213-1745, and SN 1000+0216[4] could be pair-instability supernovae.

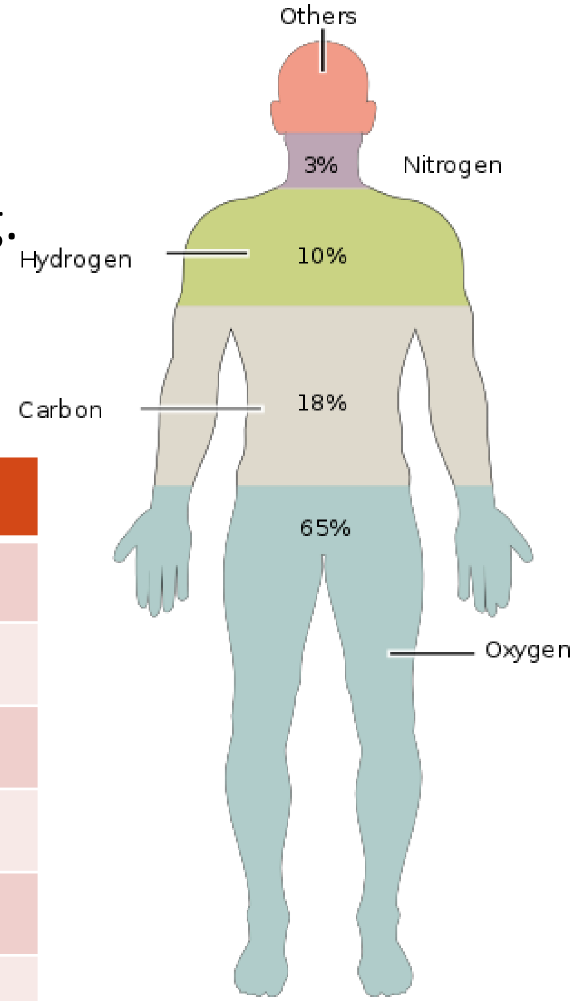


4. Creation of **chemical elements** in Universe

We are made of star-stuff. Carl Sagan

- Four main elements by mass that compose our bodies are oxygen, carbon, hydrogen, nitrogen.
- Other important elements: Ca, P, K, S, Na, Cl, Mg.
- We are more similar to the chemical composition of our Galaxy than to our planet.

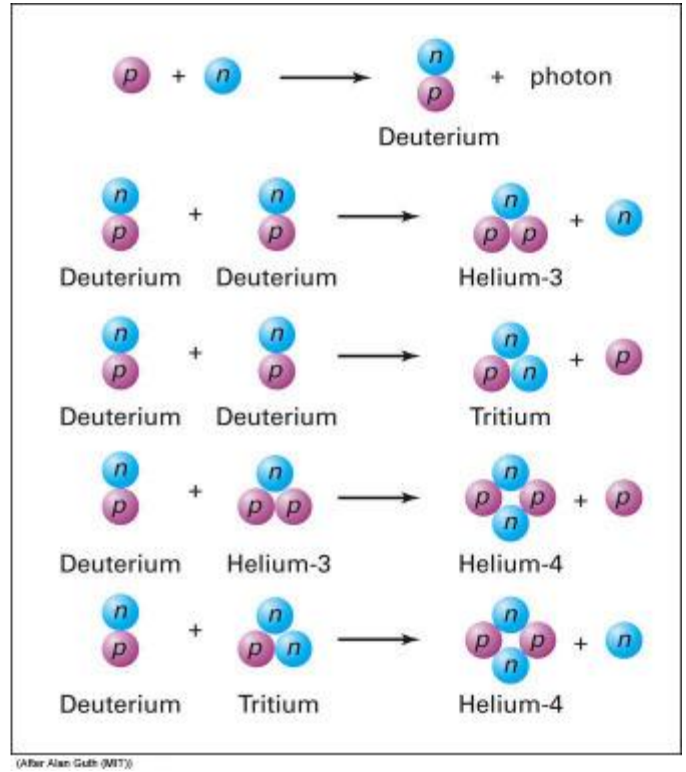
Element	Earth, % by mass	Galaxy, % by mass
Oxygen	29,7	10,4
Carbon	0,1	4,6
Neon	Traces	1,3
Iron	31,9	1,1
Nitrogen	Traces	1,0
Silicon	16,1	0,7
Magnesium	15,4	0,6



Hydrogen and helium are not included in the table.

Big Bang nucleosynthesis

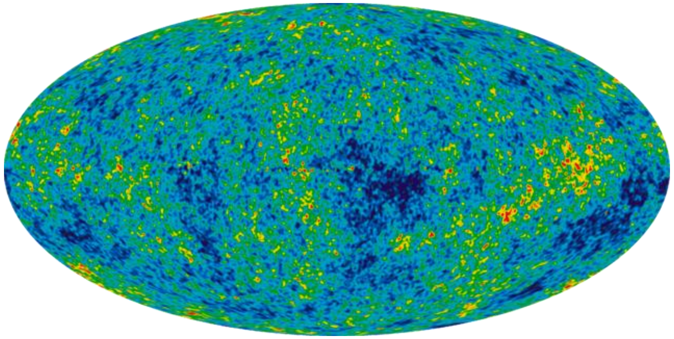
- 1. **Big Bang nucleosynthesis**. About 10 seconds after the Big Bang our Universe contained protons, neutrons, and other particles. The Universe continued to expand and cool down.
- The fusion of nuclei occurred between roughly 10 seconds to 20 minutes after the Big Bang. Later the universe cooled to a point at which the nuclear fusion ended.
- 20 minutes after the Big Bang ordinary matter of our Universe was made of about 75% hydrogen, 24% helium, and traces of other elements/isotopes such as lithium and deuterium. Observations are consistent with the Big Bang theory.



Some Big Bang nucleosynthesis reactions.

Stellar nucleosynthesis

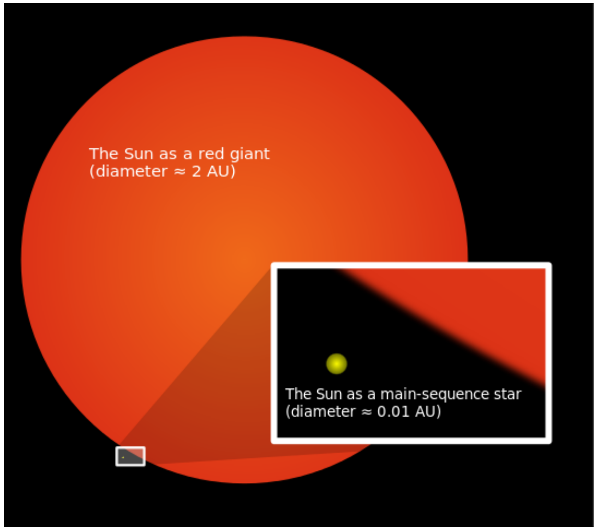
- When the Universe was around 377 000 years old, it has cooled to a point where free electrons can combine with the **hydrogen nuclei** (protons) and **helium nuclei** to form neutral atoms.
- Perhaps there was the dark matter as well.
- About 200 millions years later first stars formed from clouds of hydrogen and helium. **Stellar nucleosynthesis** started. No planets yet.
- During the loss of mass in stars (stellar wind, expelled shells, planetary nebula, supernova explosions) Galaxy environment was enriched by elements from carbon to iron.
- From this and the initial material new stars and planets were formed and life arose.

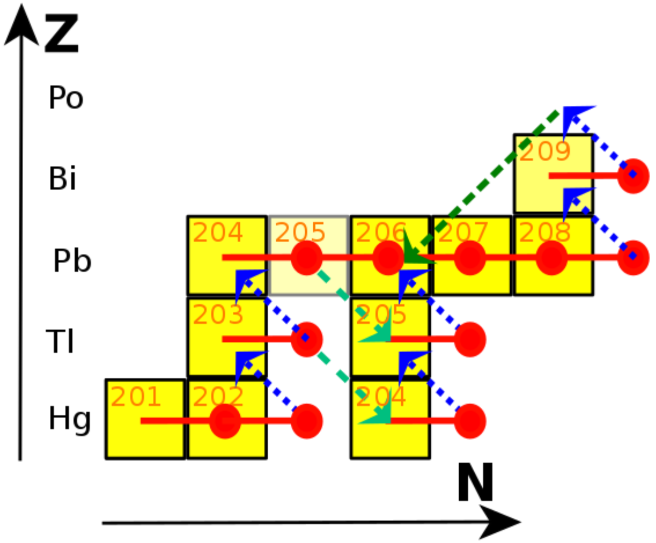


Stars are factories of chemical elements

Elements heavier than iron?

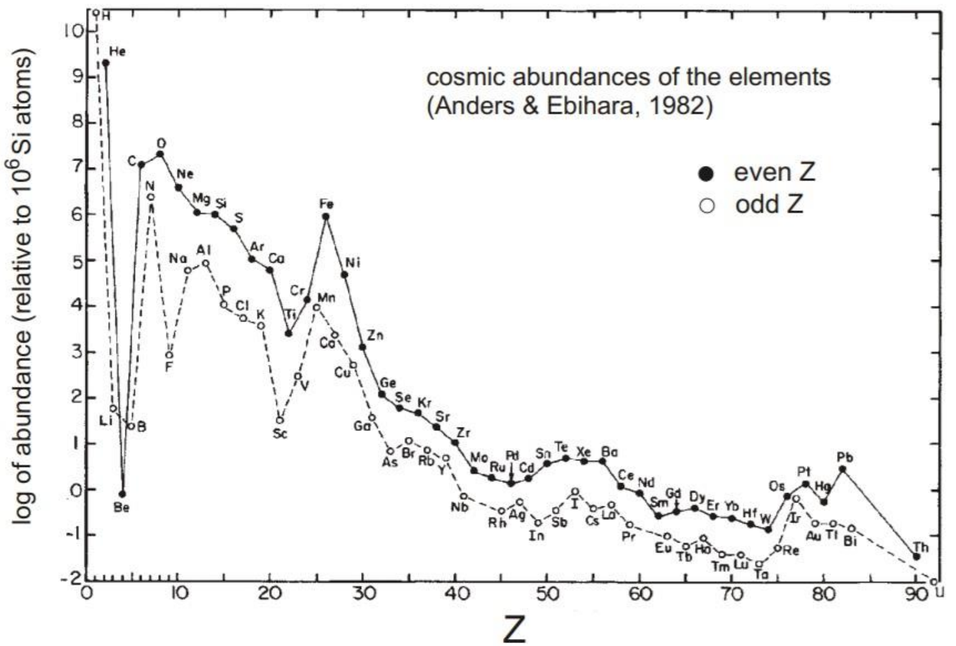
- Periodic table of elements does not end with the iron. First 94 elements occur naturally.
- Then enters the neutron capture. The slow neutron-capture or **s-process** occur in red giants. It is responsible for the creation of approximately half the atomic nuclei heavier than iron.
- Nucleus undergoes neutron capture to form an isotope with one higher atomic mass A:
- $(Z, A) + n \rightarrow (Z, A+1) + \gamma$. If the new isotope is stable, a series of increases in mass can occur.
- If the isotope is unstable, beta decay produces an element of the next highest atomic number Z: $(Z, A+1) \rightarrow (Z+1, A+1) + e^{-}$ + anti ν.





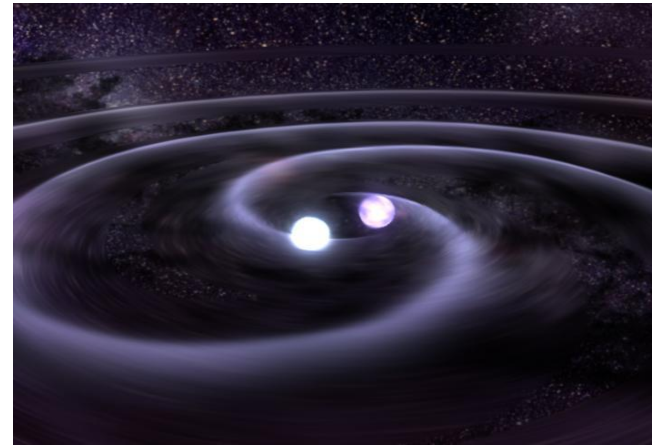
Explosive nucleosynthesis

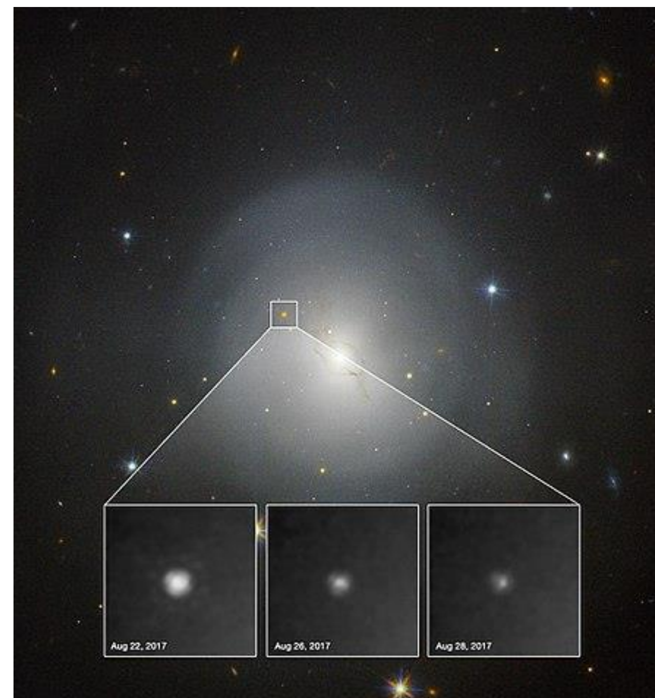
- In the **r-process**, successive neutron captures are rapid and happen more quickly than the beta decay occur.
- R-process that occurs in supernova explosions and neutron star collisions produces heavier elements and more neutron-rich isotopes than the s-process.
- Together the s-process and r-process account for most of the relative abundance of chemical elements heavier than iron.
- During the supernova explosions **nuclear fusion** produces elements heavier than iron as well.

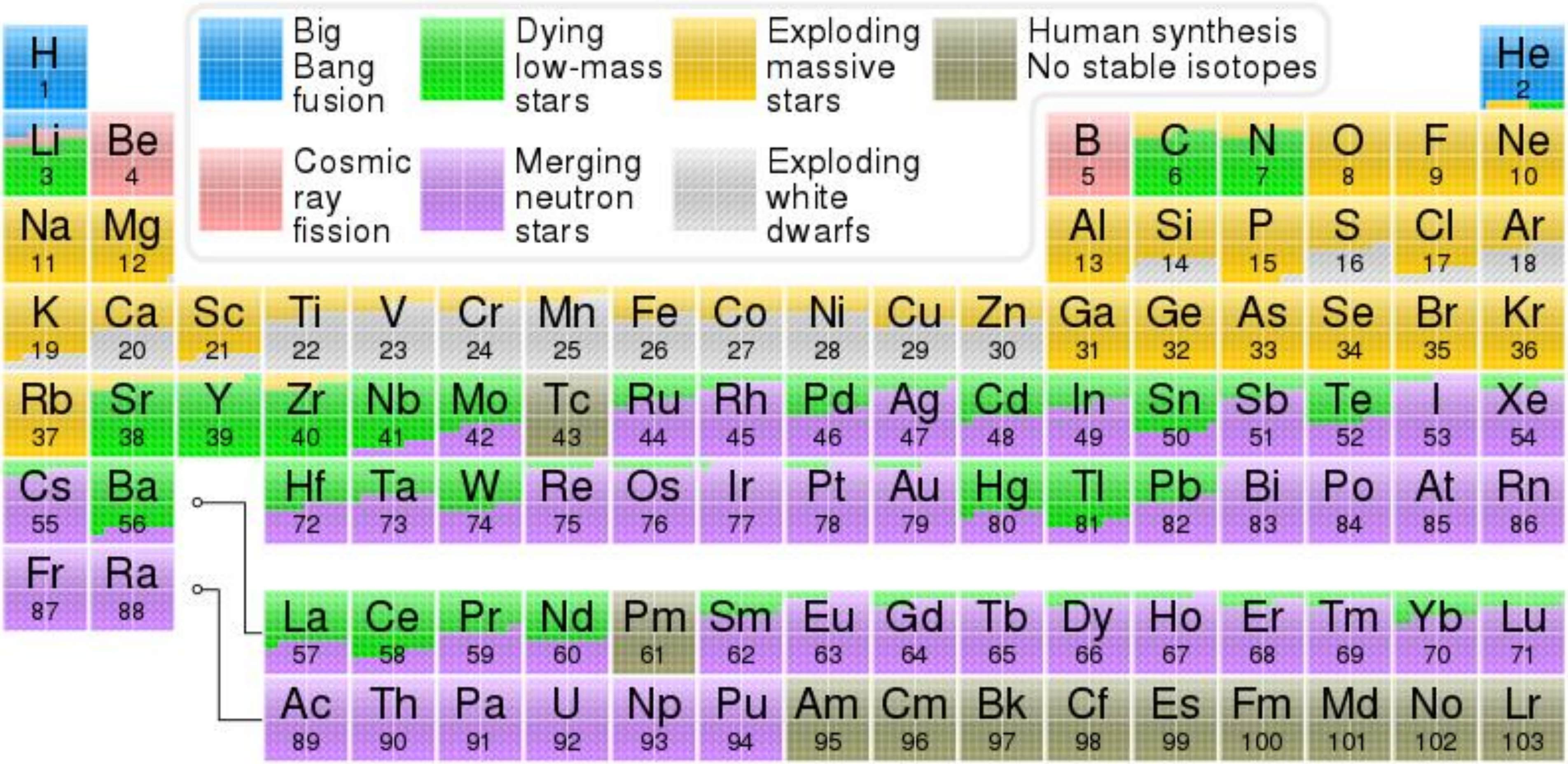


Neutron star collisions

- **Neutron stars** are the smallest and densest stars. They have a radius about 10 km and a mass lower than a 2,2 solar masses.
- When two neutron stars merge, they emit strong gravitational waves and form either a more massive neutron star, or a black hole.
- Sometimes they are observed as **kilonovae**. They emit electromagnetic radiation due to the radioactive decay of heavy r-process nuclei that are produced and ejected during the merger process.
- On 17 August 2017 a gravitational wave was observed. It coincided with the gamma-ray burst. Later this source was observed by 70 observatories across the EM spectrum.





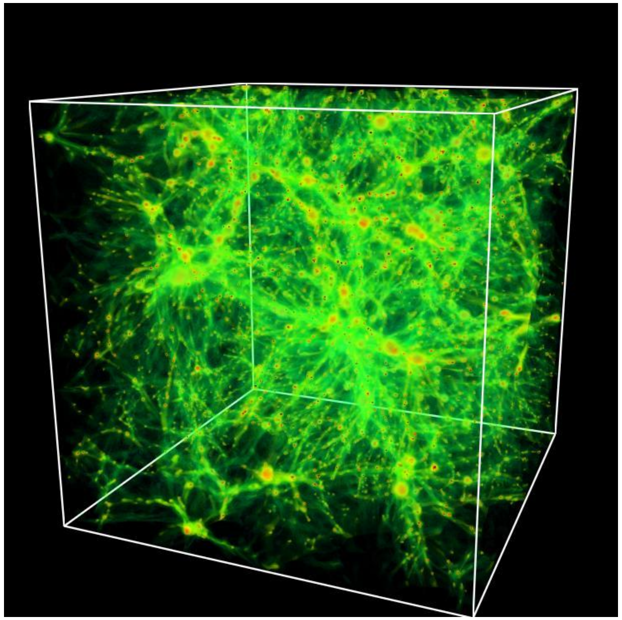


Dying low-mass stars release heavy elements produced by previous generations of stars

5. The **beginning** and the **end** of the **Universe**

Why do we trust in a Big Bang?

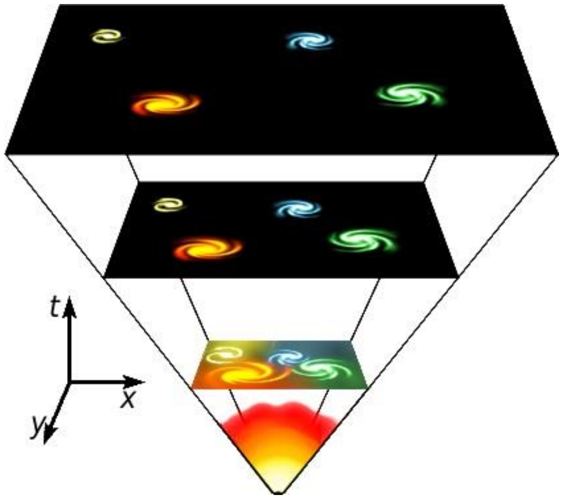
- Once upon a time 13,799 ± 0,021 billion years ago… No, this is not a fairy tale.
- Big Bang theory describes the past and the future of the Universe. It is widely recognized by scientists and fits very well to the observations of:
  - Cosmic microwave background.
  - Large scale structure of the Universe.
  - Amount of hydrogen and helium.
  - Expansion of the Universe.
- Accurate name: Lambda-CDM (cold dark matter) model or the standard model of cosmology.



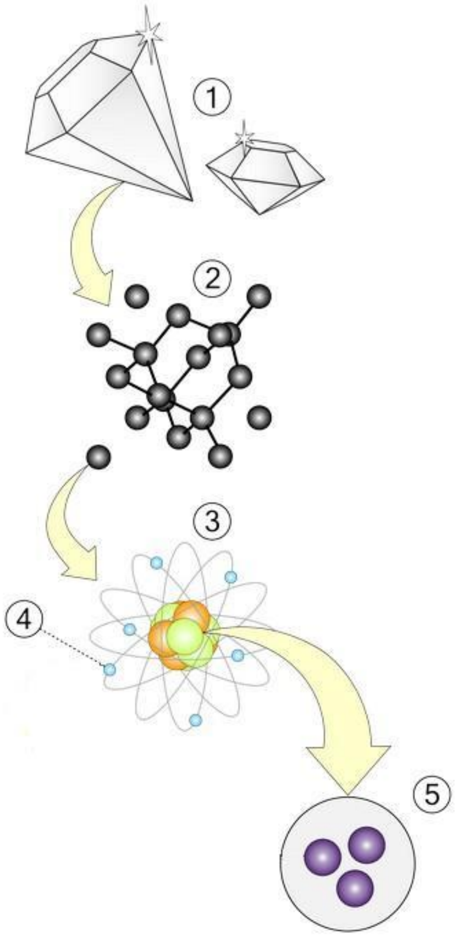
Filaments of galaxy clusters form the large scale stucture of the Universe.

What is not covered by the Big Bang theory?

- Universe expands and in the past galaxies were closer to each other.
- At the begining our Universe was very hot and dense. Many of the processes are well described by particle physics at this stage.
- Model of the expansion is based on the Einstein's Theory of General Relativity. It predicts that at the very beginning the Universe was infinitely small and dense (singularity).
- Quantum effects become a significant factor, and general relativity fails to make accurate predictions. Unfortunately there is still no complete and consistent quantum theory of gravity.
- The smallest time we can describe is approximately 10^{-43} s (Planck time). **Theory does not describe exactly how our Universe started**.



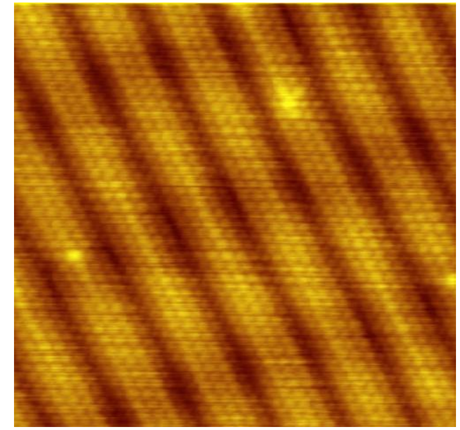
Matryoshka style



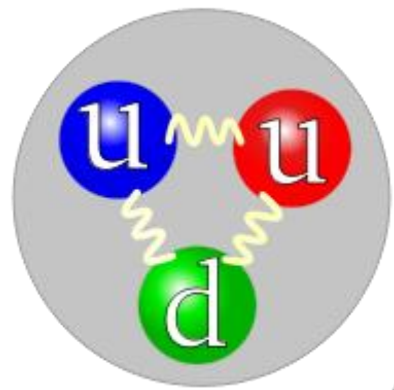
- Physical objects are made of matter.
- Matter is made of molecules.
- Molecules are made of atoms.
- Nucleus of an atom consists of protons and neutrons. It is surrounded by electrons.
- Electron is an elementary particle.
- Protons and neutrons have internal stucture.

Deep inside matter

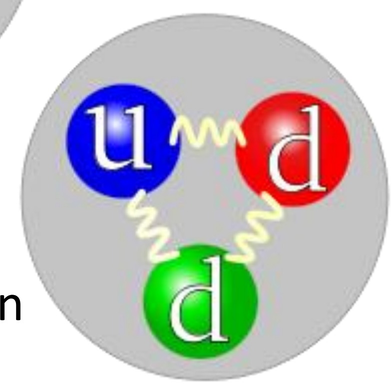
- The smallest structures we can "see" are individual atoms.
- Images of smaller objects are conventional. Protons are not spheres!
- A proton consists of two up quarks and one down quark.
- A neutron consists of two down quarks and one up quark.
- Quarks are elementary particles. Free quarks are not observable unless the amount of energy is very high.
- There is strong interaction between quarks that is mediated by gluons – "glue particles".



Atoms of gold in a scanning tunneling microscope

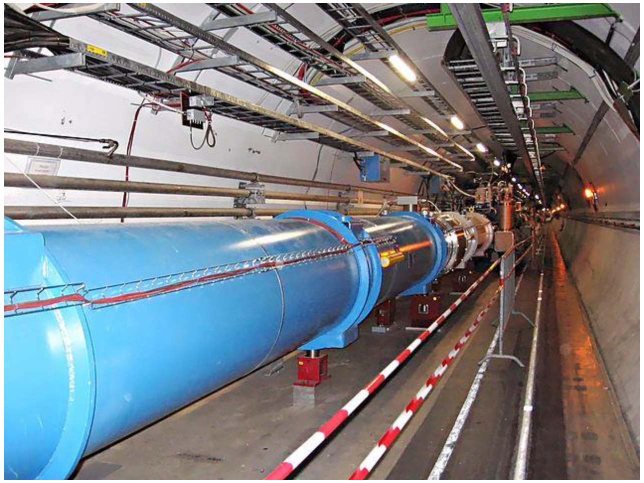


Proton

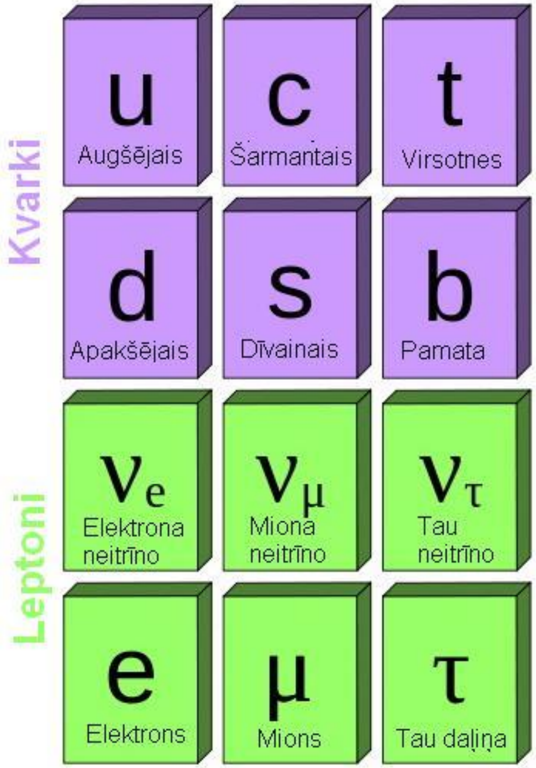


Neutron

The stuff around us

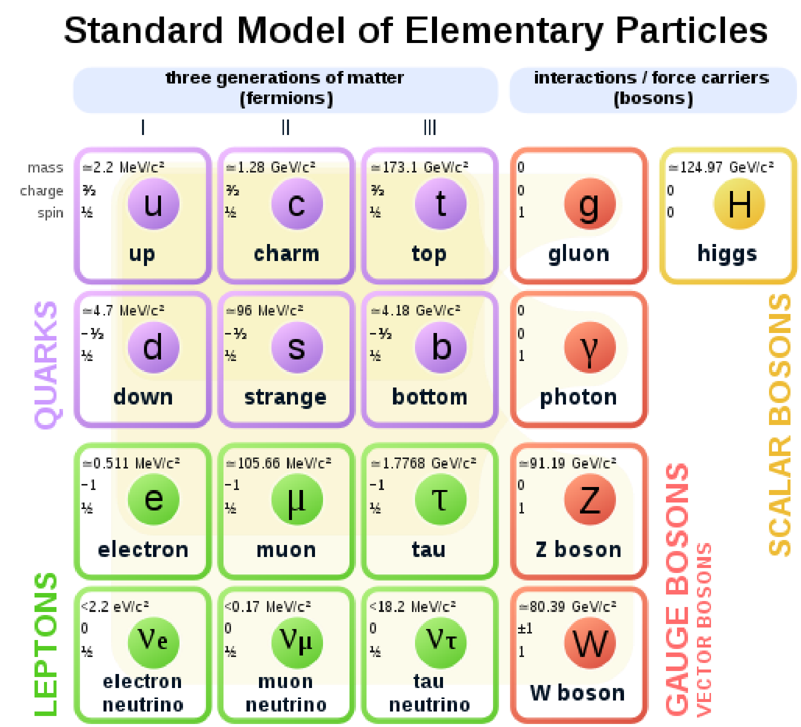


- There are 6 quarks and 6 leptons (very light particles). 6 + 6 = 12.
- Almost all matter on Earth and in space is made of up quarks, down quarks and electrons.
- Other particles can be found in places where a large amount of energy is concentrated.
- Large Hadron Collider, cosmic rays…



Lego for the "Creator of the worlds"

- What is needed to build our world?
- As far we know, we would need:
    - 6 quarks + 6 leptons (together they are "particles of matter");
    - 4 force carriers + Higgs boson.
    - 17 particles in total.
    - Do not forget about the gravity...
- Plus 13 corresponding antiparticles, because photon, gluon, Z boson and Higgs boson are their own antiparticles.
- "Magic number" is 30. Instead of 42!

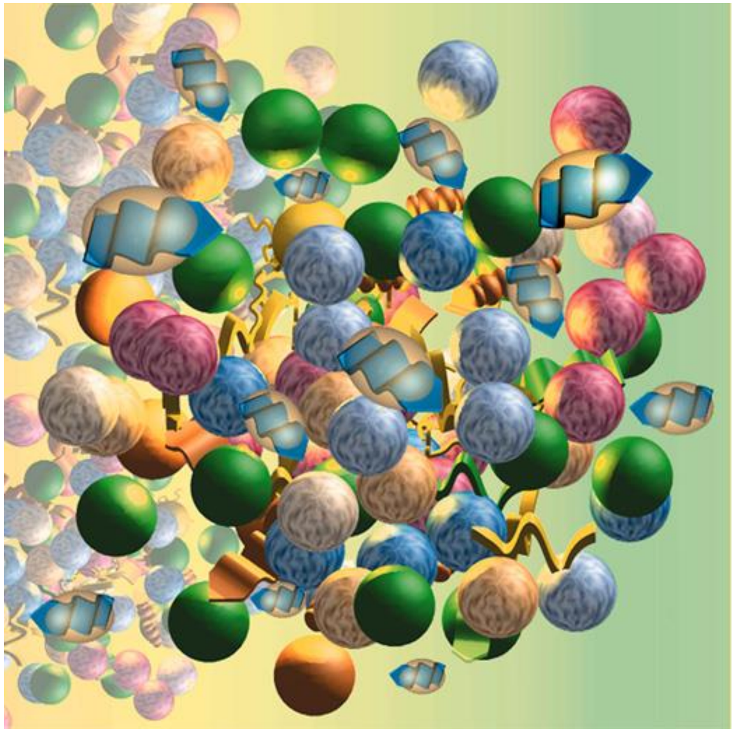


First 20 minutes in the life of the Universe

Epoch	Time	Temperature
1. Planck epoch	$0 – 10^{-43}$ s	$>10^{32}$ K
2. Grand unification epoch	$10^{-43} – 10^{-36}$ s	$>10^{29}$ K
3. Inflationary epoch/ Electroweak epoch	$10^{-36} – 10^{-32}$ s	$10^{27} \sim 10^{22}$ K
4. Quark epoch	$10^{-12} – 10^{-6}$ s	$>10^{12}$ K
5. Hadron epoch	$10^{-6} – 1$ s	$>10^{10}$ K
6. Lepton epoch	1 – 10 s	$10^{10} – 10^{9}$ K
7. Big Bang nucleosynthesis	10 s – 20 min	$10^{9} – 10^{7}$ K

Quark epoch, $10^{-12} - 10^{-6}$ s

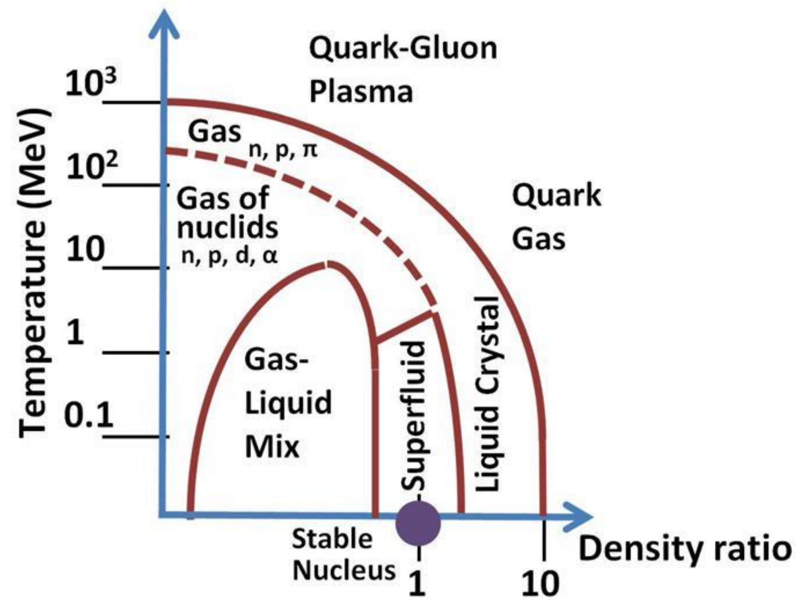
- Fundamental interactions of gravitation, electromagnetism, the strong interaction and the weak interaction are separated.
- Temperature is still too high (more than 10^{12} K), to allow quarks to bind together to form protons and neutrons.
- The universe is filled with a dense, hot quark–gluon plasma, containing quarks, leptons and their antiparticles.
- The quark epoch ended when the average energy of particle interactions fell below the specific threshold.



CERN picture

Quark-gluon plasma

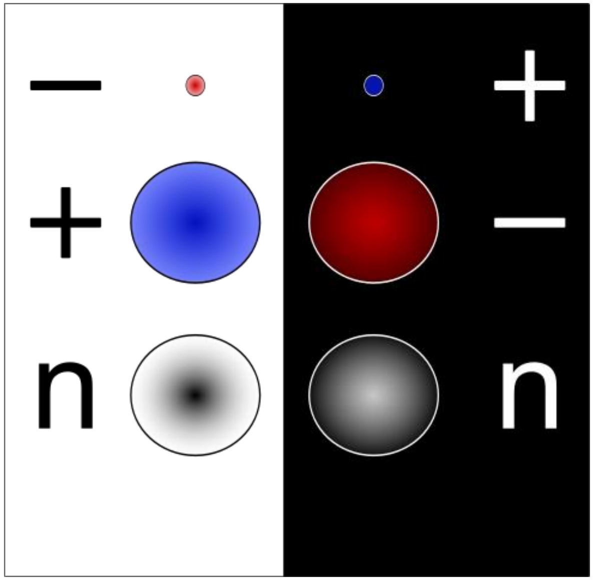
- A quark–gluon plasma (QGP) exists at an extremely high temperature and/or density, consists of asymptotically free quarks and gluons.
- Artificial quark matter has been produced at CERN's LHC. It is unstable and decays radioactively into stable particles (hadronization) that can be detected.
- QGP can be created by heating matter up to a temperature of 2×10^{12} K, which amounts to 175 MeV per particle.
- It is believed that few milliseconds after the Big Bang, known as the quark epoch, the Universe was in a quark–gluon plasma state.

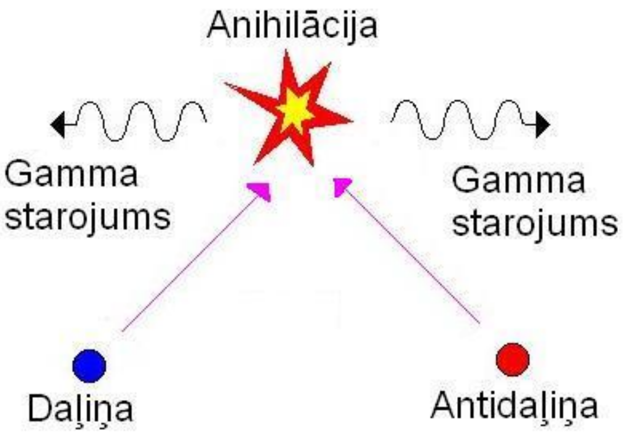


Colliding lead ions in August 2012, a record breaking temperature of $5{,}5 \times 10^{12}$ K was achieved at LHC.

Particles vs antiparticles

- Every particle has its own antiparticle with the same mass but with opposite physical charges.
- The antiparticle of the electron is an antielectron or positron, antiparticle of the proton is an antiproton.
- The antiparticle of the neutron is an antineutron. These particles are not identical because antineutron is made of antiquarks.
- Particle–antiparticle pairs can annihilate each other, producing photons. Since the charges of the particle and antiparticle are opposite, total charge is conserved.





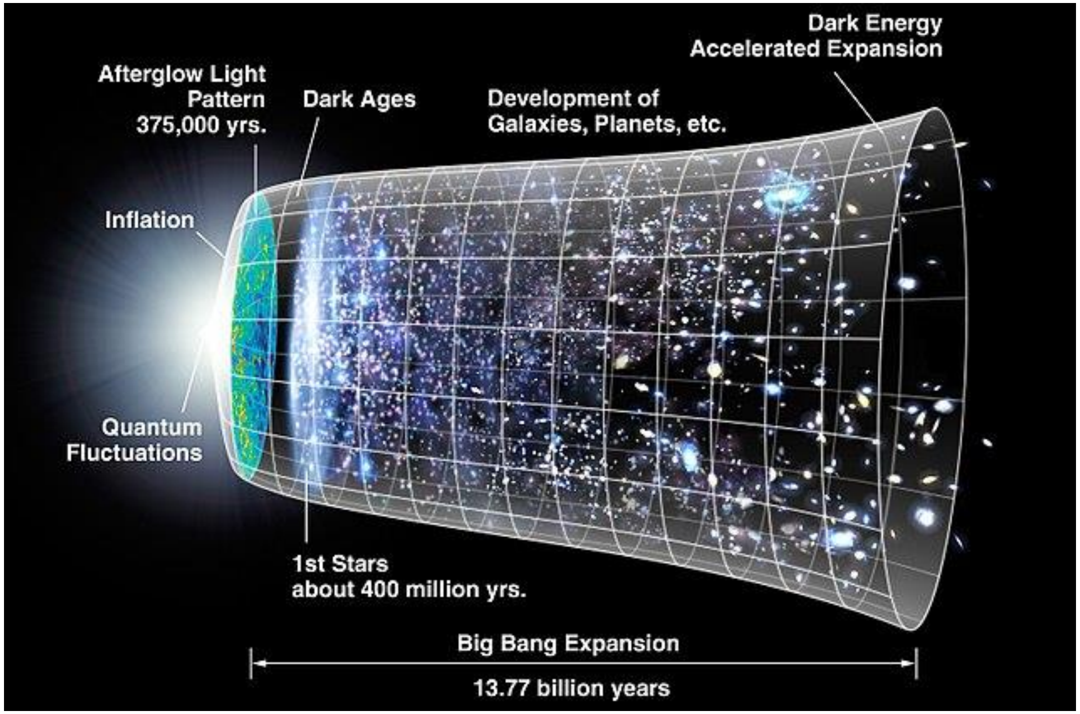
Where has all the antimatter gone?

- Bananas produce antimatter, releasing one positron about every 75 minutes because they contain some radioactive potassium-40.
- Almost all matter observable from the Earth is made of matter rather than antimatter. If antimatter-dominated regions of space existed, the gamma rays would be detectable.
- The Big Bang should have produced equal amounts of matter and antimatter that should have annihilated during hadron and lepton epoch.
- Only a small residue – about one particle per billion – managed to survive.
- Several competing hypotheses exist, however, there is no consensus theory. Charge-parity (CP) symmetry violation…

Antiparticles are rare. Why? Nobody knows for sure. Seems that particles and antiparticles are not completely "symmetric".

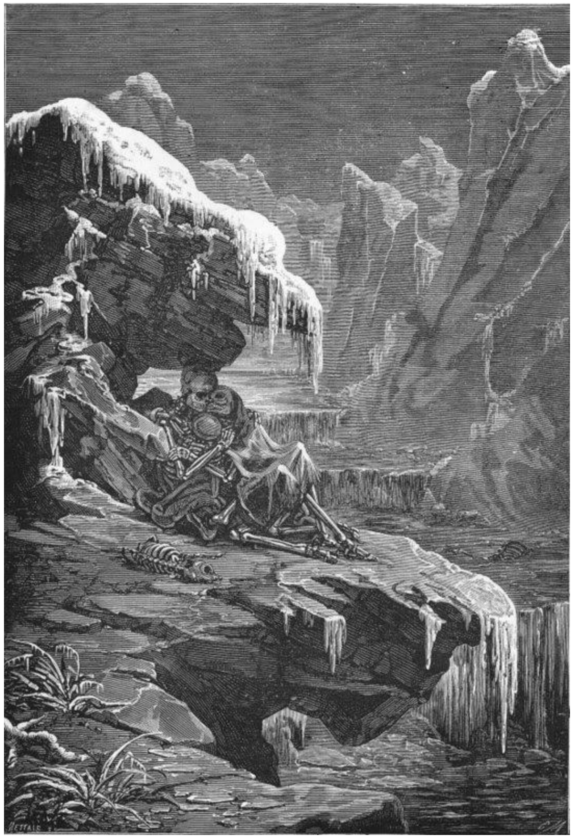
14 billion years in one slide

- Matter in the Universe was not completely homogeneous, small density fluctuations existed at the beginning.
- Under the force of gravity large clouds of **dark matter**, hydrogen and helium compressed.
- They formed galaxies, and first stars started to shine. Several generations of stars followed each other. Planets, including Solar System are created.
- Stars produce the chemical elements and throw them out into the space.
- Complex chemical compounds are created, life and intelligence emerges.
- Humans start to wonder how all this is created an what will happen next.
- Today: 13,799 billion years.



Scenarios of the future of the Universe

- Most cosmologists believe the universe is flat and will expand forever (the Big Freeze).
- But the nature of the **dark energy** is unknown, so let's look at two more scenarios: the Big Crunch and the Big Rip.
- After a few decades, as science develops, this part of the story may look different.



At the end of 19th century it was "clear" that Earth will freeze when the Sun will stop to shine.

Big Crunch

- Reasons of symmetry. If the universe started with the Big Bang, it could end with something similar.
- The theory assumes that the average density of the universe is big enough and gravity will turn the expansion into compression.
- All objects will come very close and will converge into one infinitely dense singularity – **Big Crunch**.
- It is also possible that the cycle is repeated when the Big Crunch is immediately followed by a new Big Bang.
- **Verdict**: not in line with observations.

- Enthropy vs cyclical Universe

In an isolated system, entropy never decreases.
Entropy as a measure of disorder (an example with a deck of cards).
In a cyclical (eternal) Universe, entropy rises to infinity.

Big Rip

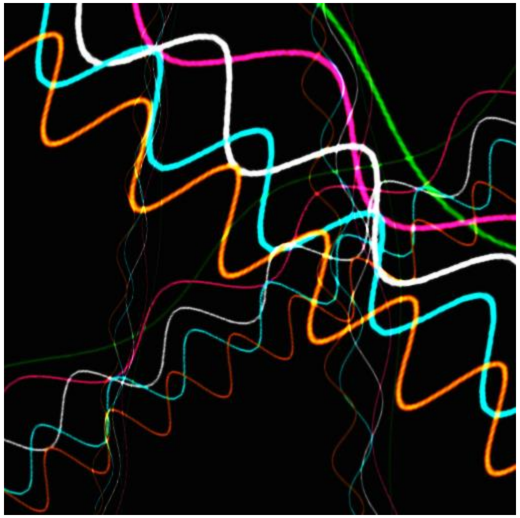
- In the specific case of dark energy, the universe not only expands fast, but also increases its acceleration.
- All objects, from galaxies to humans, are fractured in individual particles, and the particles move away from each other.
- The "density" of dark energy and the rate of expansion grow endlessly. Singularity occurs approximately after 20 billion years from now.
- **Verdict**: Not excluded, but observations do not approve this version.

Time before Big Rip:

- 60 million years – Milky Way disruption;
- 3 months – Solar System disrupted;
- 30 minutes – Earth is ripped apart;
- 10^{-19} seconds – atoms dismantled.

Big Freeze

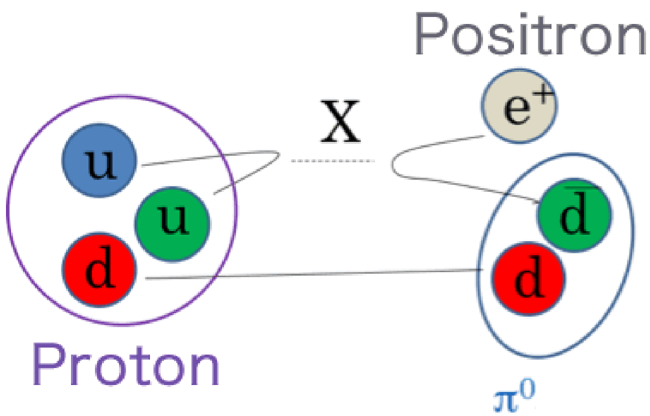
- The Universe continues to expand, temperature approaches absolute zero. **What happens**:
- $10^{11} – 10^{12}$ years. The nearest galaxies bound by gravity merge together.
- $2×10^{12}$ years. Due to the Universe expansion, other galaxies are no longer visible.
- 10^{14} years. The formation and evolution of stars ends. Brown dwarfs, white dwarfs, neutron stars and black holes remain. The universe is getting dark.
- $10^{15} – 10^{20}$ years. Planets are kicked out of their orbits, stars – out of the Galaxy.
- $10^{40} – 10^{100}$ years. Protons and neutrons decay (?) into leptons and photons, black holes evaporate.
- **Verdict**: credible.



10^{100} years. Photons rule the Universe.

Hypothetical proton decay

- According to the Standard Model protons are stable. Period.
- Some beyond-the-Standard Model theories ”allow” protons to decay, for example, into neutral pion and a positron with a half-life of 10^{31} to 10^{36} years.
- Neutral pion decays into 2 gamma ray photons. If a positron meets a free electron, they annihilate. Only the electromagnetic radiation is left.
- Despite significant experimental effort, proton decay has never been observed.
- Neutrons inside atomic nuclei are also expected to decay with a half-life comparable to that of protons.

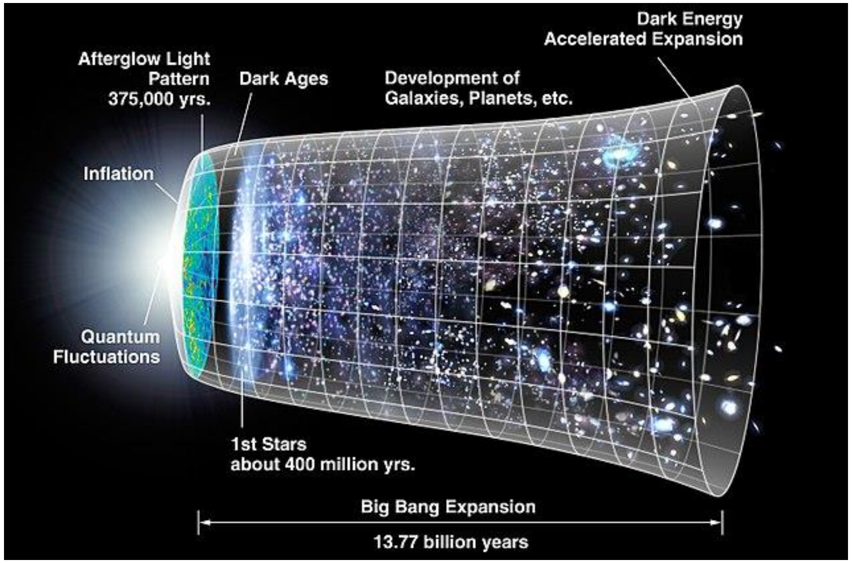


$p^+ \rightarrow e^+ + \pi^0$. $\pi^0 \rightarrow 2\ \gamma$

6. **Dark matter** and **dark energy** problems

Accelereted expansion comes as a surprise

- In 1998, two groups of scientists, observing supernova Type Ia explosions, concluded that the expansion of the Universe accelerates.
- It can't be happening for no reason. Gravity is slowing down the expansion. The unknown factor was called **dark energy**.
- After a period of embarrassment, theories bristled like mushrooms after the rain.
- The 2011 Nobel Prize awarded heightened public's attention.



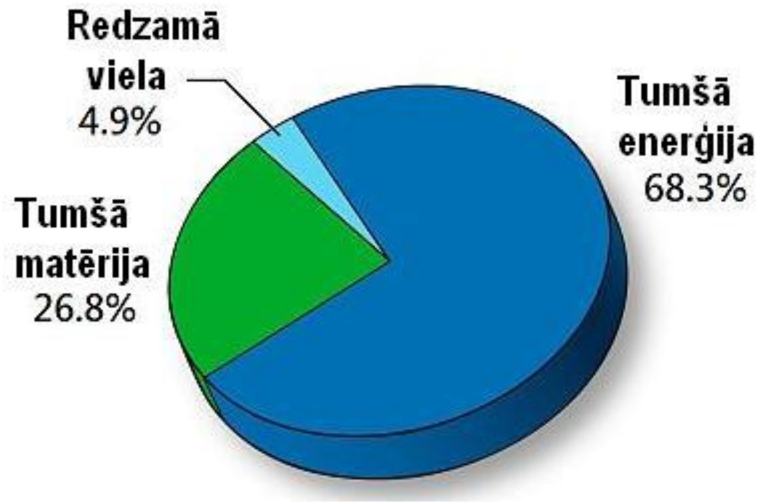
The universe is darker than it seems

- With the discovery of dark energy, the question of **dark matter** was also raised.
- Since 1933, there has been a suspicion (Fritz Zwicky) that galaxies contain more mass than can be seen.
- A small part of it may be the remnants of stellar evolution, but most should be unknown elementary particles.
- The only interaction that can be observed is a gravitational interaction.

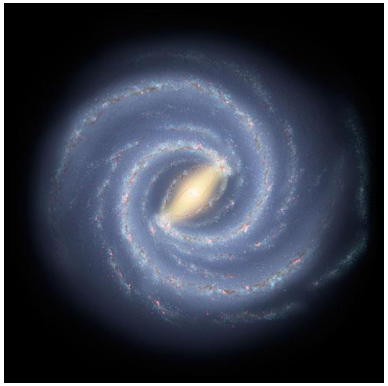
Dark matter is shown here in a blue colour.

Paradigm shift in the 21st century

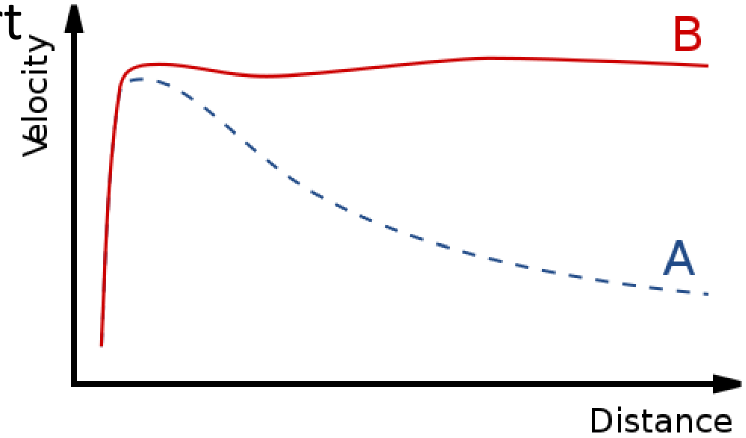
- Using the Einstein mass-energy equivalence $E = mc^2$ we can compare mass and energy.
- Dark matter (27% of mass-energy) and dark energy (68% of mass-energy) dominate.
- Astronomers have only studied 5% of the Universe so far! A wide field of work opens…
- So far, new discoveries affect only our understanding of Universe structure and evolution.
- The numerical supremacy of the unknown is formal. The visible part of the universe is very diverse and will continue to surprise us.



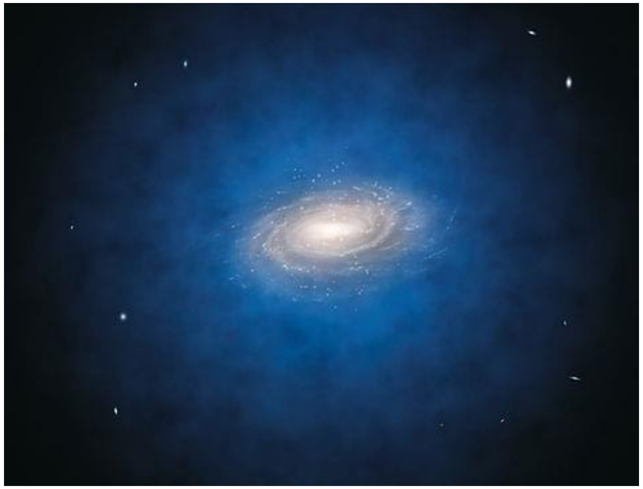
Proof No. 1: movement



- We can calculate the mass of the luminous substance in the galaxy, by knowing the speed of the galaxy rotation. The outer part of the galaxy revolves more quickly “than expected”.
- Blue curve – only the stars and gas are taken into account. Red curve represents observation data. The amount of dark matter is calculated from the difference.

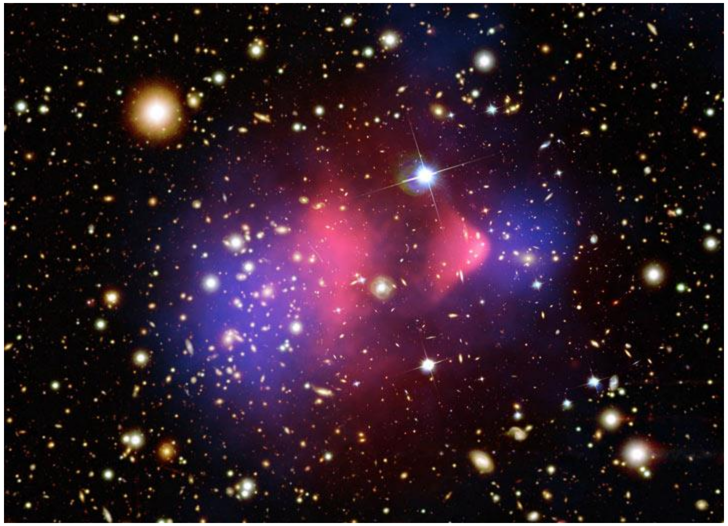


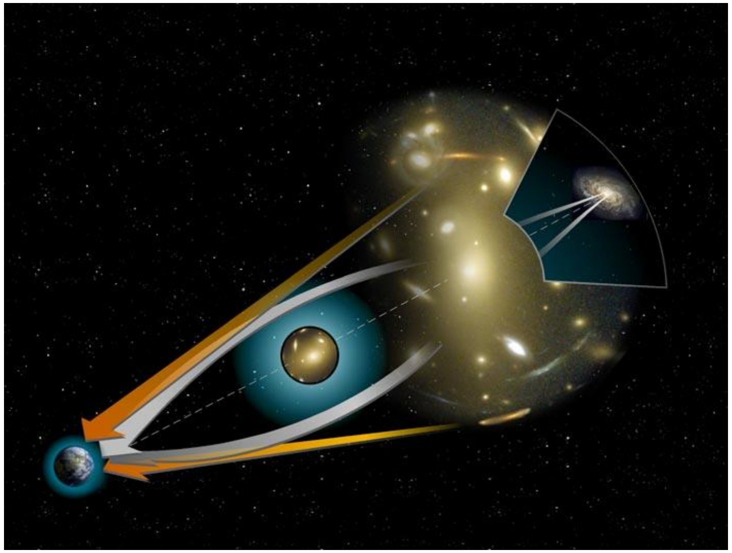
- There is about 10 times more dark matter than visible matter. It forms a huge cloud around the galaxy.
- Similarly, the movement of galaxies in galaxy clusters is analysed. Galaxies move fast because of dark matter.



Proof No. 2: gravity

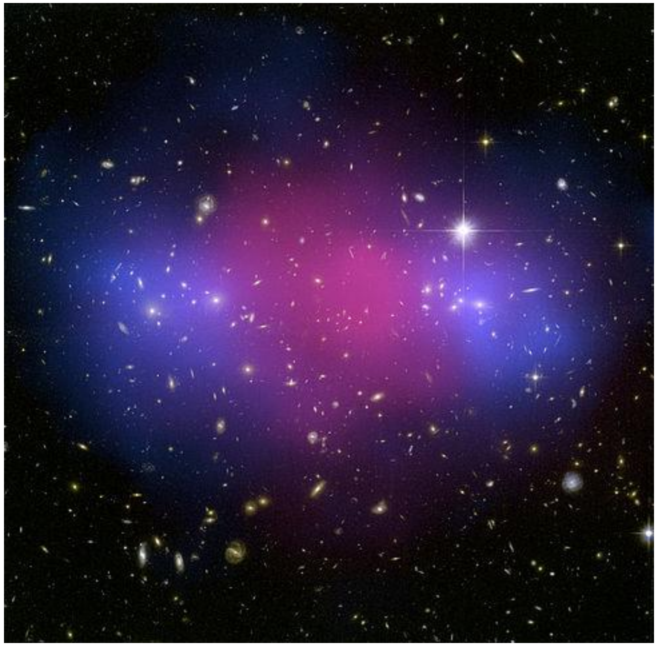
- This figure shows a collision between two galaxy clusters. Ordinary substance (hot gas, red) has slowed down. Dark matter (blue) continues to move and creates two separate clouds.
- Dark matter can be found using the bending of the background light in the gravitational field of the galaxies.
- Gravitational lenses are predicted by the general theory of relativity.
- Gravitational lenses (strong and weak) are widely used in astronomical observations.





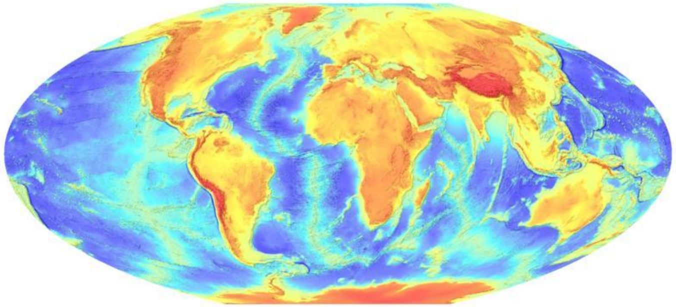
Proof No. 3: hot gas

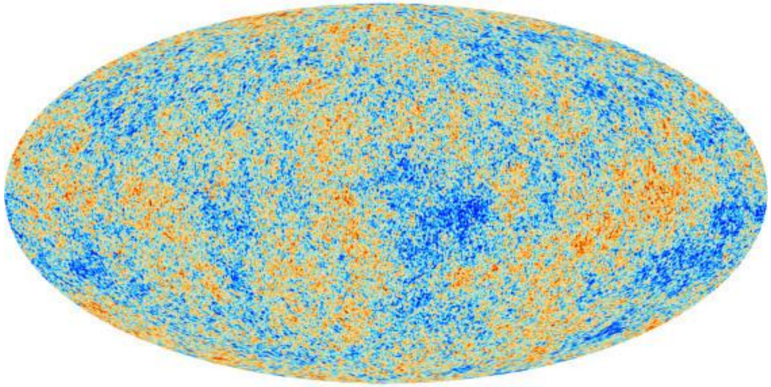
- In galaxy clusters, there is a rarefied but very hot gas between the galaxies (pictured in red).
- Using X-ray observations, it is possible to estimate the mass of the galaxy cluster.
- The mass of dark matter (blue) is much higher than the visible mass of galaxies, representing only 12-15%.



Dark matter is not ordinary matter

- It is assumed that the dark matter is not made of “ordinary matter” such as protons and neutrons (“remnants of stars”).
- A. Big Bang Nucleosynthesis theory says that “ordinary matter” is a small fraction needed to achieve the critical density. The large-scale structure of the Universe shows that total mass is much larger as well.
- B. Massive compact halo objects (MACHO) have not been detected by microlensing. If they exist, there are very few of them.
- C. An analysis of the cosmic microwave background shows that approximately 5/6 of matter is in a form that does not interact with the other matter or light.

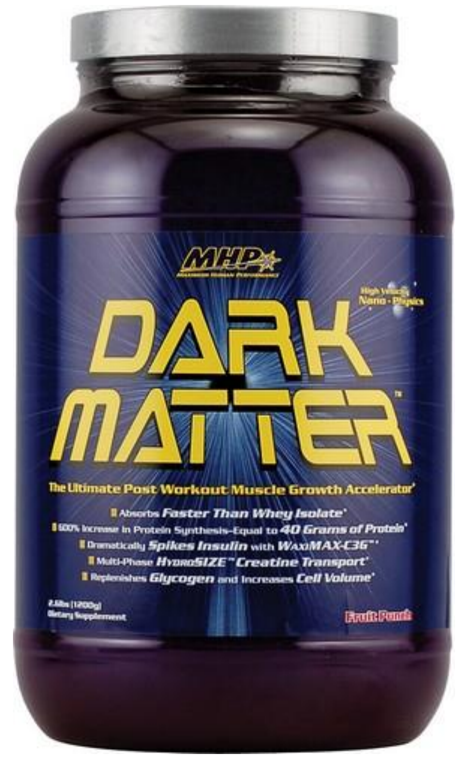




Cosmic microwave background is not completely homogenous.

What is it then?

- Dark matter has mass because it affects other objects with gravity.
- It does not emit or absorb light. It has no electric charge and does not form atoms (?). In other words, it doesn't have an electromagnetic interaction with the "normal" substance. It only has the gravity interaction and maybe the weak interaction.
- Most cosmologists believe that dark matter consists of not yet discovered particles. **The unknown is explained by the undiscovered**. Suspicious…



Muscle Growth Accelerator *Dark Matter* does not emit light and it has the mass. Unfortunately it is made of atoms.

Dark. But cold, warm or hot?

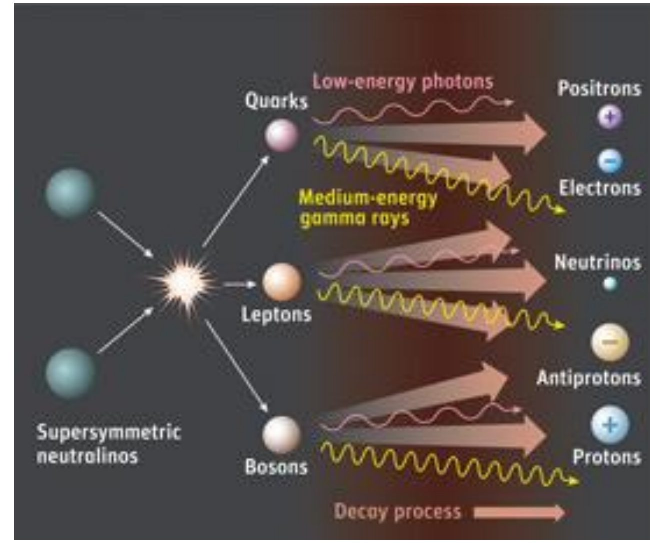
- “Heat” doesn't apply to temperature, but to the speed of particles in the early Universe.
- In case of hot dark matter the structure of the Universe would be formed “from top to bottom.” The mass of the candidate – neutrino is too small.
- Although warm dark matter could explain the visible structure of the Universe, there are no suitable candidate particles.
- At present, the most likely model is the **cold dark matter** (CDM) composed of hypothetical WIMPs or axions. In this case, the structure of the universe forms “from down to top”.

Large scale 3D distribution of the dark matter according the data of weak lensing.

A more exotic idea: gravitationally-interacting massive particles (GIMPs), “singular structures of spacetime in a geometry whose average forms the dark energy”.

Weakly Interacting Massive Particles (WIMPs)

- WIMP is a new elementary particle which interacts via gravity and any other force (or forces), which is as weak as or weaker than the weak nuclear force.
- **Supersymmetry** is a principle that proposes a relationship between two basic classes of elementary particles: bosons and fermions.
- Each particle from one group would have a superpartner, the spin of which differs by a half-integer. For example, there would be a **selectron**, a bosonic partner of the electron. Another example is **photino**, a fermionic superpartner of the photon.
- Recent null results from direct-detection experiments along with the failure to produce evidence of supersymmetry in the LHC has cast doubt on the simplest WIMP hypothesis.



Supersymmetric extensions of the Standard model readily predict a new particle with required properties, for example, **neutralino**.

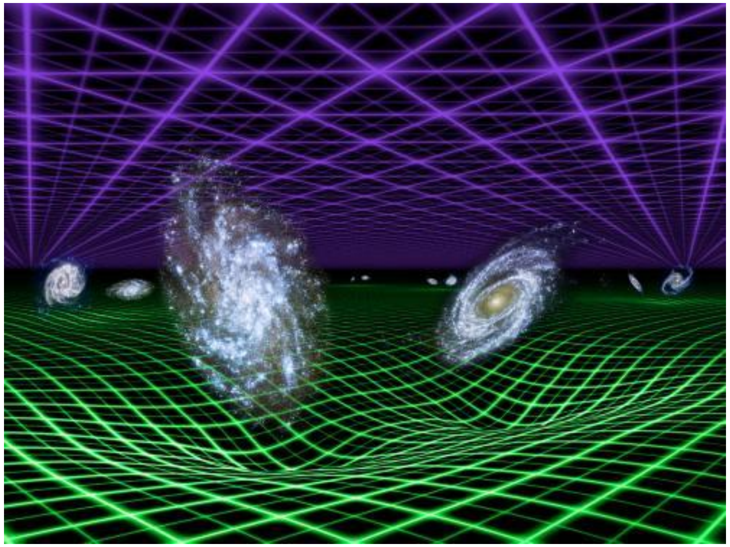
Search in laboratories

- If WIMPs exist, thousands of particles per second pass through the cm^2 of the Earth's surface. Many laboratory experiments are already under way or are planned.
- Two options: to record a particle interaction with an atomic nucleus, or to see a WIMP annihilation in which gamma radiation or an electron-positron pair might occur.
- It is still possible to create WIMPs with the LHC. If the energy “disappears” in the proton collision, it could have been carried away by particles of dark matter.
- The DAMA collaboration has detected an annual modulation in the rate of events in their detectors, which they claim is due to dark matter.
- In 2013, the AMS detector on ISS recorded “excess” cosmic rays.

Alpha Magnetic Spectrometer is mounted on the International Space Station.

Dark energy, what is it?

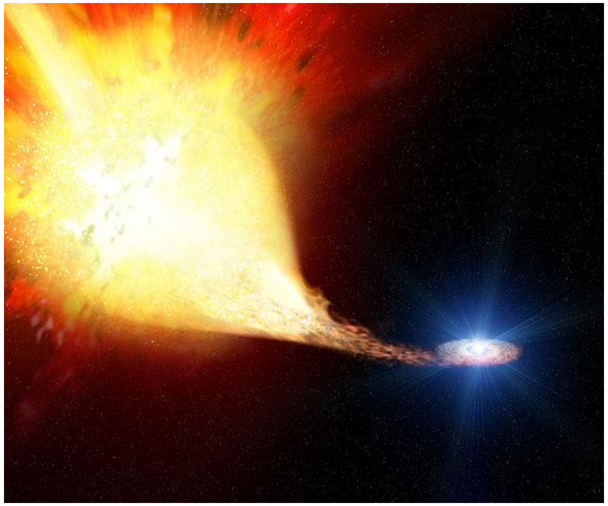
- A hypothetical form of energy that fills up the space and creates a repulsion force that causes the Universe to accelerate.
- It contains 68% of the mass-energy of the Universe (a fraction of the dark matter is only 27%).
- There are two most reliable models: **cosmological constant** and quintessence.
- The dark energy is uniform and so diluted that its observations in the laboratory are impossible.
- The mass equivalent of dark energy inside Pluto's orbit is just 6 metric tons!
- How do we know that dark energy exists?

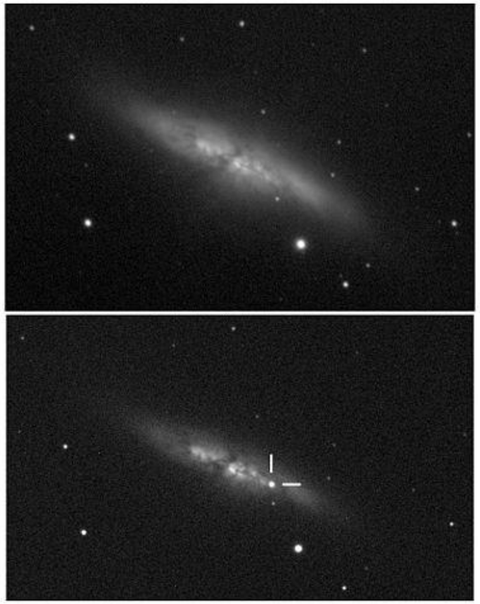


Dark energy (in violet) dominates over the gravity (in green).

Proof No.1: supernovae

- In 1998 two teams of researchers found that distant supernovae are farther away than they should be, according to the model of the Universe.
- This means that the Universe has expanded faster and is larger than expected.
- The study used Type Ia supernovae, which are "standard candles." In a double system, the substance flows from the normal star to the white dwarf.
- When the mass reaches 1,4 solar masses, a thermonuclear explosion occurs in which the same energy is always released.
- By knowing the star's visible brightness it is possible to calculate the distance.

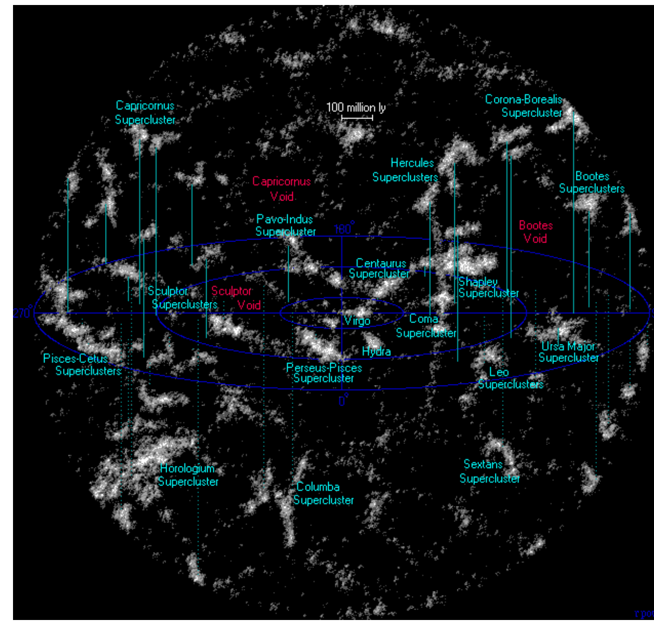




Type Ia supernova in M82 galaxy, 2014.

Proof No. 2: Large scale structure

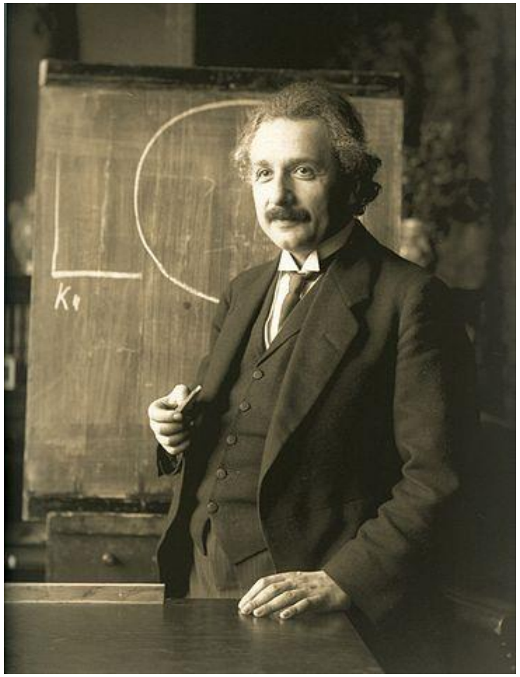
- Galaxy clusters are not uniformly distributed, they are situated in the walls of "bubbles" – voids. Galaxy clusters form the large-scale structure of the Universe.
- The latest observations and theoretical modelling of galaxy distance show that the density of normal substance and dark matter together amounts to approximately 30% of critical density. It is not enough.



Objects of the Universe up to a distance of one billion light years.

Explanation No. 1: cosmological constant

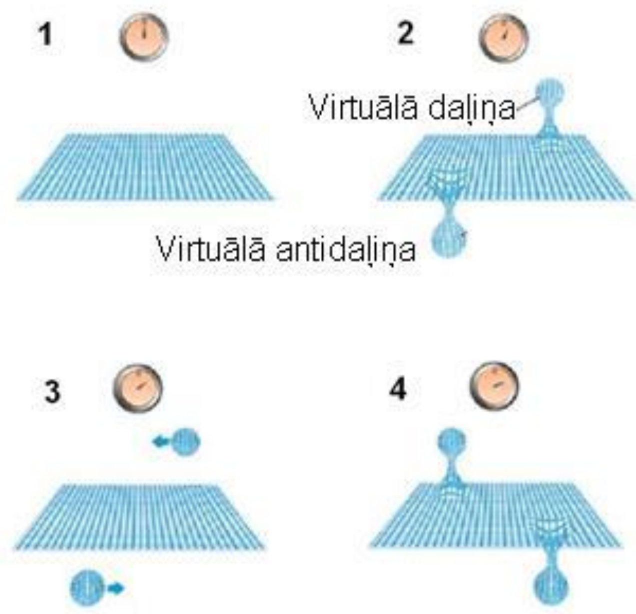
- Dark energy fills the space smoothly. The cosmological constant in the volume unit does not change. It also doesn't change with the time.
- But as the space expands, the amount of dark energy increases.
- The cosmological constant Λ was introduced by Albert Einstein to produce a static model of the Universe. He later called this "biggest blunder of his life". These days the mistake has turned into success.
- This is the simplest and "most economic" model that explains many observations.
- Along with the cold dark matter, it is included into the standard model of cosmology (Lambda-CDM model).



Dark energy is the price "we have to pay" for using the space.

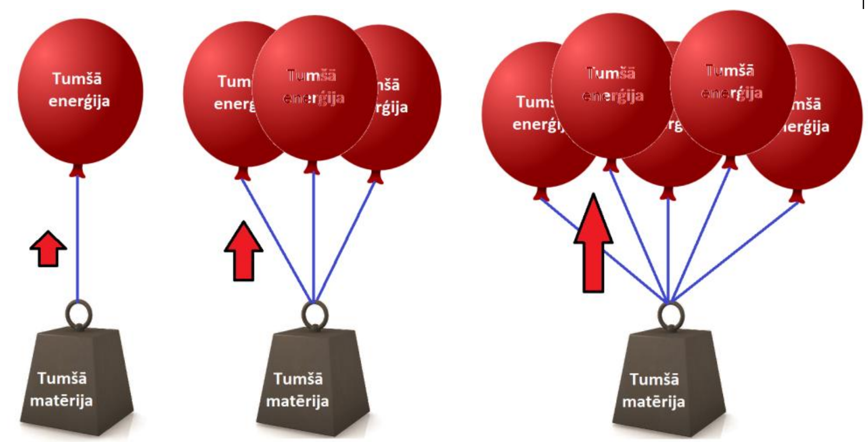
Lets talk about virtual particles

- Quantum theory has the energy corresponding to the cosmological constant, it is a vacuum energy.
- An empty space (vacuum) posesses internal, fundamental energy. It has “negative pressure” that causes a repulsion.
- The vacuum is not completely empty, and there are quantum fluctuations (random deviations) that result in an emergence of virtual particles. They appear and vanish in pairs.
- The main problem is that quantum theory predicts the energy of the vacuum 10^{100} times higher than derived from the cosmological constant. It is the the largest discrepancy of modern physics.



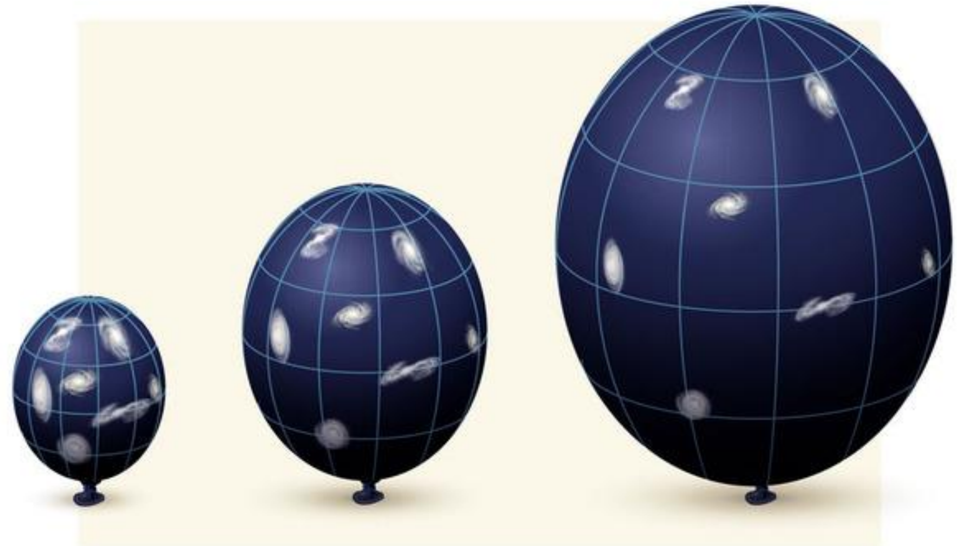
Dark energy takes the lead

- The universe began its accelerated expansion 5-7 billion years ago.
- Before that, dark matter dominated, its gravitational force slowed the expansion down . The effects of dark energy were insignificant.
- As the universe grew, the volume of space increased, but the amount of dark matter remained unchanged.
- Dark energy that is proportional to the volume of the space, overcame the gravity of dark matter.
- The universe began to expand faster and faster.



Where does the extra energy come from?

- Isn't the energy conservation law violated? No!
- The positive dark energy is balanced by the negative energy of the gravitational field.
- As the volume of space expands, more dark energy is created in the volume, but this is balanced by a growing negative term in the energy equation.



Thank you! Any questions?