MINISTRY OF SCIENCE AND HIGHER EDUCATION OF THE RUSSIAN FEDERATION

FEDERAL STATE AUTONOMOUS EDUCATIONAL INSTITUTION OF HIGHER EDUCATION

«NATIONAL RESEARCH NUCLEAR UNIVERSITY «MEPhI» (NRNU «MEPhI»)

INSTITUTE OF NUCLEAR PHYSICS AND TECHNOLOGY

DEPARTMENT №40 «ELEMENTARY PARTICLE PHYSICS»

Referat on the course «Introduction to the cosmoparticle physics» on the topic: «Dark atoms in the Universe»

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Moscow 2021

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INTRODUCTION

One of the most important, fundamental and urgent problems of modern physics is the study of dark matter, which makes up most of the energy density of the nonrelativistic matter of the Universe.

At the beginning of the last century, experimental evidence appeared that some stars and galaxies behave differently than predicted by theory, namely, the rotation of more distant parts of galaxies did not obey the laws of mechanics. These phenomena were explained by the fact that the mass of galaxies can be much greater than observed directly. This marked the beginning of the search for a new type of mass, which in the aftereffect was called dark matter. The presence of such invisible matter can be recognized by its gravitational effect on the known baryonic matter [1].

Baryonic matter is matter consisting of baryons (neutrons, protons) and electrons. That is, the familiar form of matter. According to modern concepts, 7% of its mass is contained in stars, 7% cold and hot gas inside galaxies, 4% gas in galactic clusters, 28% cold intergalactic gas, 15% warm intergalactic gas, 40% in rarefied gas with a filamentous structure [2, 3]. There is also baryonic antimatter, or antimatter.

If we take into account all forms of baryonic matter, such as interstellar gas, brown and white dwarfs, neutron stars and black holes, it turns out that a significant proportion of non-baryonic matter is needed to explain all the observed phenomena. Plank and WMAP measurements show that the contribution of dark matter to the total density of matter in the modern Universe is about 25%. We we assume that it consists of new massive particles that are absent in the Standard Model. Such particles must be nonrelativistic, stable, and poorly interact with each other.

Dark matter is what causes the dynamic effect that is necessary for the formation of Galaxies. Dark matter must detach from radiation and plasma before neutral gas is produced during recombination. That is, at the stage when nonrelativistic matter dominates, but the baryonic matter is still ionized and is a plasma. This plasma is coupled to radiation and the growth of inhomogeneity does not occur until recombination occurs. During this period, something is needed that will increase the heterogeneity, so that after the baryonic matter is neutralized, it would be picked up by these inhomogeneities. As a result, the general indignation would grow and lead to the formation of structures in the Universe. That is why dark matter must be detached and must not interact electromagnetically.

Dark matter is a type of matter unknown to us, different from dark energy and the known baryonic matter. The name reflects the fact that dark matter is invisible in the electromagnetic spectrum of radiation.

The density of matter in the Universe ρ is usually given in units of the critical density:

$$\rho_c = \frac{3H^2}{8\pi G} \approx 5,5 \;\; \text{KeV/cm}, \qquad (1)$$

where H is Planck's constant and G is the gravitational constant.

The interpretation of the CMB anisotropy data obtained during the work of the WMAP (Wilkinson Microwave Anisotropy Probe) suggests that the observed density $\Omega = \frac{\rho}{\rho_c}$ is close to critical. This means that the universe is flat and open.

The observed density of the Universe consists of various components:

$$\Omega = \Omega_{DM} + \Omega_B + \Omega_\nu + \Omega_\Lambda + \Omega_{rad}, \qquad (2)$$

where $\Omega_{DM}, \Omega_B, \Omega_\Lambda, \Omega_{rad}$ is the density of dark matter, baryonic matter, neutrinos, dark energy and radiation, respectively.

The distribution data for the components turned out to be as follows: $\Omega_{DM} = 26,3\%$, $\Omega_B = 4,2\%$, $\Omega_\nu = 0,5\%$, $\Omega_\Lambda = 69\%$, $\Omega_{rad} = 8,6 \cdot 10^{-3}\%$.

Experimental detection of the existence of dark matter is of fundamental importance for cosmology and particle physics. The theory predicts the existence of new particles that go beyond the Standard Model, which are candidates for the role of dark matter particles. One can formulate the set of conditions under which new particles can be considered as candidates to dark matter for review and reference): they should be stable, saturate the measured dark matter density and decouple from plasma and radiation at least before the beginning of matter dominated stage [4].

Some types of such particles should be available for direct experimental search. The annihilation and decay of dark matter particles can be observed indirectly by the effects in cosmic rays and gamma radiation [5]. On accelerators, it is possible to search for weakly interacting particles using the missing energy. The dark atoms that make up the hidden mass may consist of new charged stable particles, which can also be detected at particle accelerators.

I. EVIDENCE FOR THE EXISTENCE OF DARK MATTER

1. GALACTIC ROTATION CURVES

One of the pieces of evidence for the existence of dark matter came from looking at the rotational velocities of stars in the galaxy. To a first approximation, the central region of the galaxy can be considered spherical, i.e. in the inner part of the galaxy, a linear increase in the rotation rate is expected with increasing distance from the center $v \propto r$.

In the outer region of the galaxy, the mass M is practically constant and it is assumed that movement of stars should be described by the following law:

$$v(r) = \sqrt{\frac{GM}{r}}, \tag{3}$$

where M is the entire mass of matter inside a sphere of radius r.

The behavior of the experimentally measured rotation curves of spiral galaxies did not correspond to a decrease in the rotational velocity with increasing radius. Instead, it turns out that the rotation curve flattens out with increasing distance. The constancy of $v(r)$ at large values of the radius means that the mass concentrated under the radius r also increases with increasing radius: $M(r) \propto r$.

This can be explained by the presence of additional non-emitting components of matter outside the visible part of the galactic disk. Stars are moving faster than predicted by theory.

Rotation curves are usually obtained by combining observations of the 21cm line with optical surface photometry. Observed rotation curves usually exhibit a characteristic flat behavior at large distances, i.e. out towards, and even far beyond, the edge of the visible disks (see a typical example in Fig. 1).

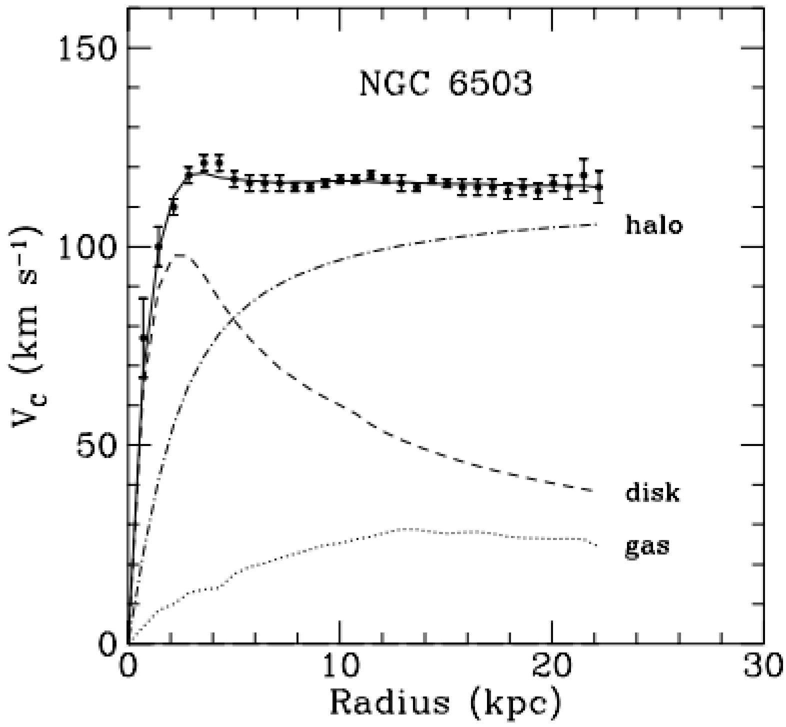

Figure 1: Rotation curve of NGC 6503. The dotted, dashed and dash-dotted lines are the contributions of gas, disk and dark matter, respectively. From Ref. [6]

The shapes of the rotation curves show that the density of dark matter in the galaxy is distributed as follows:

$$\rho(r) \propto \frac{M(r)}{r^3} \sim \frac{1}{r^2}. \tag{4}$$

Based on these observations, the existence of a spherical dark matter halo surrounding the galaxy and explaining the behavior of the obtained rotational curves was postulated.

2. THE EMERGENCE OF GALAXIES

Dark matter is critical to the Big Bang theory as a component that directly corresponds to the measurements of parameters in the solutions of the Friedmann equation in general relativity. Since the contribution of dark matter to the gravitational interaction should dominate the contribution of ordinary matter, it is inextricably linked with the formation of galaxies and galaxy clusters.

For galaxies to appear, density inhomogeneities are required in the Universe. Galaxies could arise in such spatial regions where the density is higher than in the surrounding space. As a result of the gravitational interaction, these areas had time to cluster faster than their rarefaction occurred due to general expansion.

The accumulation of matter should have begun after the formation of atoms from nuclei and electrons, since in the early stages of the evolution of the Universe, matter was in a state of dynamic equilibrium: radiation could not escape from this matter. At that time, noticeable fluctuations in the density of ordinary matter were ruled out down to very low levels by the isotropy of the background radiation. After the stage of formation of atoms, the radiation ceases to be in a state of thermodynamic equilibrium with matter, so the density fluctuations that arise after this are no longer reflected in the nature of the radiation.

Modeling shows that for the detected inhomogeneities of baryonic matter at the time of recombination $\sim 10^{-5}$ ($z \sim 1000$), the formation of large-scale structures (stars, galaxies, galaxy clusters, superclusters) is impossible (the inhomogeneities will be $\sim 10^{-2}$, $z \sim 1$) without cold dark matter, because structures are formed hierarchically, first small, then large.

The problem can be solved by requiring the existence of massive particles that have left the state of thermodynamic equilibrium at an earlier stage, so that these particles have the opportunity to manifest themselves as some basis for condensation of ordinary matter around them. In this case, it is necessary to take into account the requirement that the background cosmic radiation is isotropic.

3. DYNAMICS OF GALAXY CLUSTERS

The dynamics of galaxy clusters testifies to the existence of dark matter. When the motion of a system, the potential energy of which is a homogeneous function of coordinates, occurs in a limited spatial region, then the time-averaged values of the kinetic and potential energies are related to each other by the virial theorem. It can be used to estimate the density of matter in clusters of a large number of galaxies:

$$2 < T > + < U >= 0. \tag{5}$$

The average kinetic and potential energies of a cluster of N galaxies are given by the following expressions:

$$< T >= \frac{N < mv^2 >}{2}, \tag{6}$$

$$< U >= \frac{GN(N-1) < m^2 >}{2 < r >}. \tag{7}$$

Taking into account that $Nm = M$ and $N - 1 \approx N$, we obtain the following estimate for the dynamic mass:

$$M = \frac{2 < v^2 >< r >}{G}. \tag{8}$$

Measurements of the average distance $< r >$ and average velocity $< v >$ give the value of the dynamic mass, which is about two orders of magnitude greater than the mass obtained from the analysis of the luminosity of galaxies. This fact can be used as further evidence in favor of the existence of dark matter.

This argument also has its weak points. The virial theorem is valid only for averaging over a long time period, when closed systems are in equilibrium. However, measurements of galaxy clusters provide information about a specific point in time. Moreover, galaxy clusters are not closed systems, they are related to each other. Finally, it is not clear whether they have reached a state of equilibrium or not.

4. GRAVITATIONAL LENSING

The method of gravitational lensing consists in a phenomenon associated with the field equations of general relativity, namely, in the deflection of electromagnetic radiation in the vicinity of massive bodies. As a rule, for a noticeable distortion of the image, masses of the order of the size of galaxies or their clusters are needed. The cluster's gravitational field bends the rays of light emitted by the galaxy behind the cluster, so the gravitational field acts like a lens on the light.

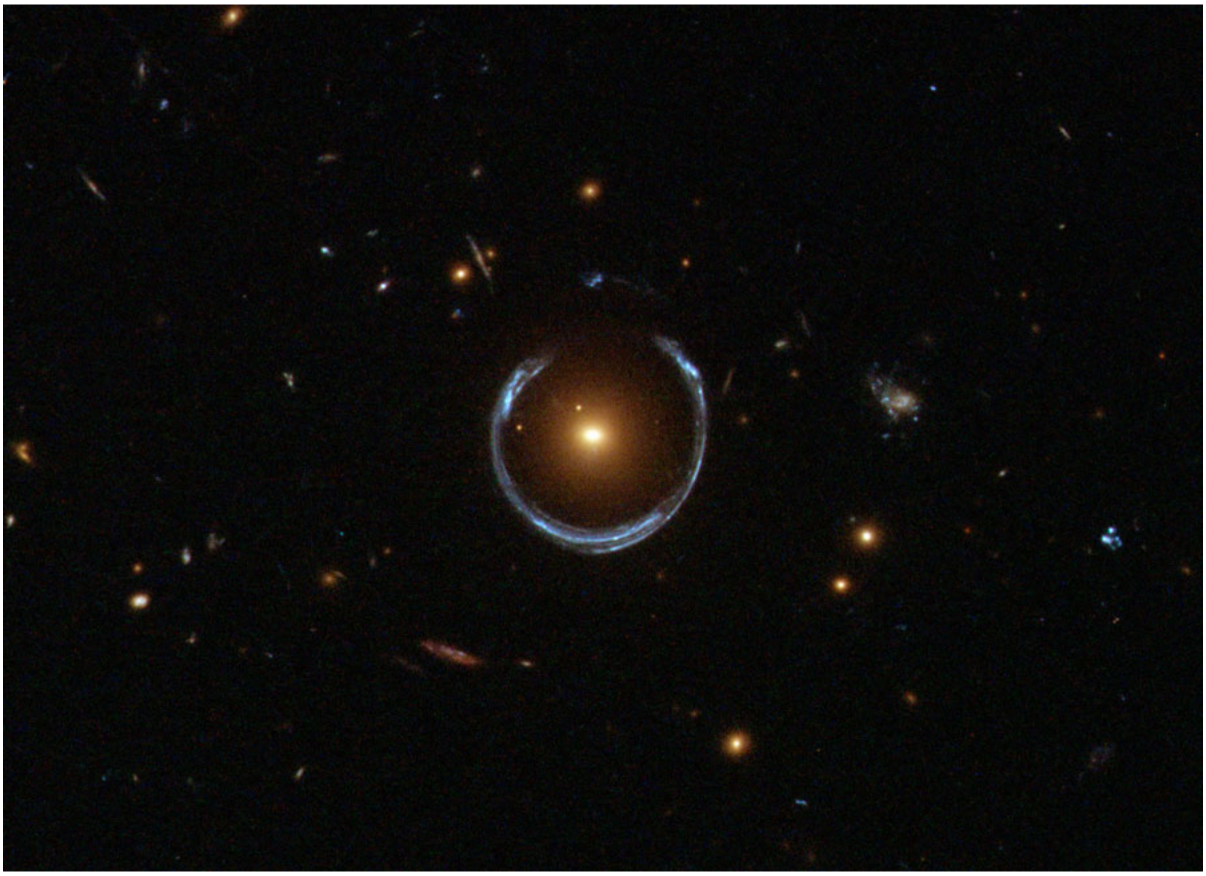

Figure 2: Taken by the Hubble telescope of the so-called. "Space horseshoe a giant elliptical galaxy at $z = 0,45$, lensing a dwarf galaxy at $z = 2,38$. Image from https://apod.nasa.gov/apod/ap111221.html.

A cluster of galaxies creates a gravitational lens in Figure 3 on the left. It distorts the shape of objects located behind the lens - stretching their images in one direction. According to the magnitude and direction of pulling, a group of scientists plotted the mass distribution, which is shown in the right image. As you can see, much more mass is concentrated in the cluster than can be seen through a telescope. In this case, dark matter presumably participates in the role of a gravitational lens.

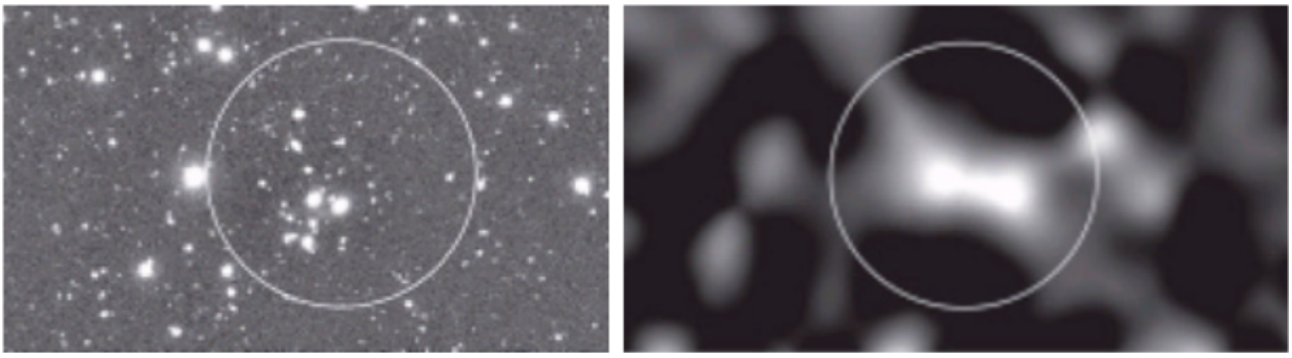

Figure 3: Left: A cluster of galaxies creates a gravitational lens. Right: Mass distribution for a given galaxy cluster

5. CMB ANISOTROPY

The data of the WMAP experiment [7] showed that the distribution of the CMB temperature over the celestial sphere corresponds to random fluctuations with a normal distribution. The parameters of the function describing the measured distribution are consistent with the model of the Universe, which consists of 4% of ordinary matter, 23% of dark matter and 73% of dark energy, causing the accelerated expansion of the Universe.

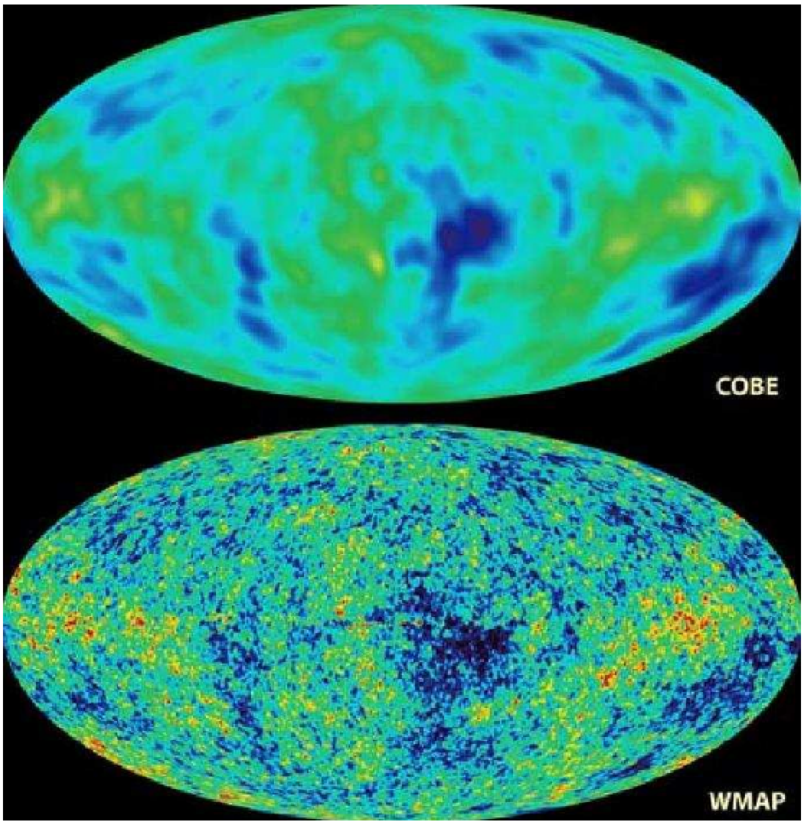

Figure 4: CMB Temperature fluctuations: A comparison between COBE and WMAP. Image from http://map.gsfc.nasa.gov/.

The data obtained also allow us to assert that dark matter is cold (that is, it consists of heavy particles, not light ones). Otherwise, particles of hot dark matter moving with relativistic velocities would smooth out the inhomogeneities of the density of matter on scales of the order of the Hubble, which would lead to small fluctuations of density in the early Universe.

6. BARYON ASYMMETRY OF THE UNIVERSE

The introduction of a new particle-antiparticle pair allows one to solve the problem of baryon asymmetry. It is assumed that the particle X decays into neutrons more often than $\bar{X}$ into antineutrons, as a result of which the equilibrium shifts towards baryons. In this way, CP-violating decays of X sequester antibaryon number in the hidden sector, thereby leaving a baryon excess in the visible sector. The antibaryonic hidden states are stable darkmatter [8].

The Walking Technicolor (WTC) hypothesis providing a composite Higgs model could also lead to a new approach to dark matter, revealing its composite nature. In the WTC, $-2n$ can be generated, where n is a natural number, of charged stable techno particles in excess compared to their $+2n$ charged partners, balanced by transitions of sphalerons with an excess of baryons. The relationship between the excess of $-2n$ and baryonic asymmetry can explain the observed ratio of the densities of baryonic matter and hidden mass [9–11].

II. DARK MATTER CLASSIFICATION AND COSMOLOGICAL CONSTRAINTS

1) Classification by baryon charge.

1.a) Baryonic dark matter.

Baryonic dark matter consists of baryonic matter, which for some reason weakly interacts in an electromagnetic way and therefore is undetectable when studying, for example, emission and absorption lines.

This type of dark matter can include already discovered space objects, for example, dark galactic halos, brown dwarfs and massive planets, compact objects at the final stages of evolution, such as white dwarfs, neutron stars, black holes. In addition, hypothetical objects such as quark stars may also be part of baryonic dark matter.

The problems of this approach are manifested in the cosmology of the Big Bang: if all dark matter is represented by baryons, then the ratio of the concentrations of light elements after primary nucleosynthesis, observed in the oldest astronomical objects, should be different, sharply different from the observed one. In addition, experiments on the search for gravitational lensing of light from stars in our Galaxy show that a sufficient concentration of large gravitating objects such as planets or black holes to explain the mass of the halo of our Galaxy is not observed, and small objects of sufficient concentration should absorb the light of stars too much.

1.b) Non-baryonic dark matter.

Non-baryonic dark matter can be represented by a variety of new particles that go beyond the Standard Model predicted in a variety of theories.

2) Stability classification.

2.a) Stable.

2.b) Unstable.

2.c) Decaying.

Particles of dark matter can be unstable with a lifetime exceeding the age of the Universe [12]. If these particles are capable of decay, the decay product is practically monochromatic photons. This property makes it possible to search for such decays using space observatories and cosmic ray detectors. A similar signal could also come from the two-photon annihilation of dark matter.

Plank data suggests that the universe is currently expanding at a much faster rate than expected from an analysis of the CMB. A possible explanation is offered by the DDM (Decaying Dark Matter) model [13].

This theory assumes [14] that dark matter consists of several components, and one component consists of unstable particles, whose lifetime is quite long: at the moment of hydrogen formation, they are still in the Universe, and in our time they have already disappeared, decaying into neutrinos or other relativistic particles. The amount of dark matter in this case in the past and today will be different.

To explain the observed inconsistencies, the decay of a relatively small amount of dark matter is required - from 2.5 to 5% of its total mass. Now all this matter has decayed, and the remaining stable part of the latent mass behaves as described by the CDM theory. On the other hand, it is possible that it continues to disintegrate.

3) Classification by the number of components.

3.a) One-component.

Contains only one kind of particles.

3.b) Multicomponent.

Contains two or more kinds or grades of particles.

4) Classification by the number of particles.

4.a) Single particle.

Particles of dark matter are in a free state.

4.b) Composite.

Particles of dark matter can form new states with ordinary particles (for example, a dark atom XHe).

5) Classification by the presence of symmetry.

5.a) Symmetrical.

The cross section of annihilation and the mass of particles are of great importance, since they determine the concentration of dark matter particles.

5.b) Asymmetrical.

The decay cross section does not matter much, since matter is initially asymmetric, but the concentration depends on the magnitude of the excess of particles or antiparticles.

6) Classification by "temperature".

Assuming that dark matter particles were in thermodynamic equilibrium with ordinary matter in the early stages of the evolution of the Universe. At a certain point in time, these particles were out of equilibrium, and since then have been spreading freely. Depending on the temperature T_f (freeze-out) at which this happened, dark matter is divided into “hot”, “warm” and “cold”.

6.b) Hot Dark Matter (HDM).

If at the moment of going out of equilibrium the energy of particles much exceeded their mass ($T_f > M_x$) $M_x \approx 10 - 100\ eV$, dark matter is called "hot". Such could be light particles moving with near-light speeds such as neutrinos, but cosmological data exclude the possibility that the latter make up a significant fraction of dark matter.

6.b) Warm dark matter (WDM).

If M_x is of the order of KeV, then one speaks of "warm"dark matter. The difference between hot and warm dark matter is that by the time of the transition from the radiation-dominated stage to the dusty one, HDM is relativistic, and warm is already nonrelativistic [15].

6.c) Cold dark matter (CDM).

If the particles of dark matter have detached from the cosmic plasma already being nonrelativistic, that is, if T_f is much less than the mass of particles M_x, then such dark matter is called "cold". It should consist of massive slowly moving (and in this sense "cold") particles or clumps of matter. It is most preferable from the point of view of cosmology, since HDM particles moving with relativistic velocities would smooth out the inhomogeneities of matter density on scales of the Hubble order at the early stages of the evolution of the Universe and, thus, would prevent the formation of large-scale structures, which contradicts observational data. In fact, the behavior of particles already with masses above 30 KeV reveals all the properties of cold dark matter.

Cosmological restrictions on the masses of new stable particles.

In the process of quenching, the concentration of weakly interacting particles is established, which will then form the large-scale structure of the Universe. The characteristic scale L, which determines the short-wavelength cutoff of the mass spectrum, which can form during the development of gravitational instability, is associated with the mass m of particles as:

$$L = m_{pl}\left(\frac{m_{pl}}{m}\right)^2. \qquad (9)$$

III. CANDIDATES FOR ROLE OF DARK MATTER

1. NEUTRINO

Experiments to detect neutrino oscillations have proven that these particles have a nonzero mass, therefore, they must contribute to dark matter. To achieve

$\Omega = \frac{\rho}{\rho_c} = 1$, neutrino masses of the order of $\frac{(15 \div 65)}{N_i}$ eV are required, where N_i denotes the number of types of light neutrinos.

Neutrinos left the state of thermodynamic equilibrium about 1 second after the Big Bang at a temperature of 1010 K (which corresponds to an energy of 1 MeV). Thus, they possessed relativistic energies and therefore are considered to be particles of hot dark matter.

The best laboratory constraint on neutrino masses comes from tritium β – decay experiments at Troitsk and Mainz [16], pointing to the following upper limit on the neutrino mass:

$$m_\nu < 2,05 \text{ eV}. \tag{10}$$

Moreover, studying variations in the cosmic microwave background using Plank gave the following restrictions on the sum of the masses of three types of neutrinos:

$$M_{\nu sum} \leq 0,320 \pm 0,081 \text{ eV}. \tag{11}$$

Thus, the neutrino is practically ruled out as a candidate for the dominant component of dark matter.

2. HEAVY NEUTRINOS

Heavy neutrinos are unstable, single-particle, symmetric, cold, non-baryonic, and one-component candidates for the role of dark matter.

Heavy neutrinos should have small mixing angles with ordinary neutrinos, and their decays should manifest themselves as additional peaks in the spectrum of charged leptons accompanying neutrinos in meson decays. The absence of additional peaks in the positron spectrum from the decay $\pi^+ \to e^+\nu_e$ excludes the existence of neutrinos with masses in the region of 50 $MeV \leq m_\nu \leq$ 130 MeV [17].

In models with supermassive neutrinos, the masses of the latter are assumed to be 45 $GeV \leq m_\nu \leq 1$ TeV The lower limit appears from the condition of non-detection of the production of such neutrinos in experiments at LEP (from the decay width Z, the existence of only three types of neutrinos with masses

$m_\nu \leq \dfrac{m_Z}{2}$ follows).

Heavy neutrinos exceeding half the mass of the Z boson cannot play the dominant role of dark matter, since their number is suppressed by additional annihilation channels. In general, the following processes can lead to the annihilation of heavy neutrinos in the Universe:

$$\nu\bar{\nu} \rightarrow f\bar{f}, W^+W^-, ZZ, ZH, HH. \tag{12}$$

As shown in [18], the dominant process is $\nu\bar{\nu} \rightarrow f\bar{f}$ below the birth threshold W^+W^- and $\nu\bar{\nu} \rightarrow W^+W^-$ above the birth threshold W^+W^-.

Fourth generation neutrinos can be both left- and right-handed. A theoretical calculation of the cross section for direct detection of fourth-generation left-handed polarized neutrinos showed [19] that the cross section turns out to be too large, which contradicts previous experimental data. With a coupling constant corresponding to the electroweak interaction, and under the assumption that a neutrino is scattered by a proton, it turns out to be 10^{-38} cm^2 per nucleon, while experiments on the search for dark matter give limitations of the order of 10^{-44} cm^2 per nucleon (according to the experimental data CDMS and XENON [20]). Consequently, the mass of such neutrinos is even too large to be considered good candidates, and besides, it is difficult to explain why they remain stable at such a large mass.

In this case, we can assume the existence of another massive gauge boson - Z', with the help of which right-handed polarized neutrinos interact. Its mass and coupling constant differ from the analogous characteristics of an ordinary Z –boson [21]. After the introduction of a new gauge $U(1)$ symmetry, which is quite possible to realize and which is consistent with the general idea of the fourth generation, a theory is obtained in which right-handed neutrinos exist, are massive and stable. The new neutrinos will be Majorana and will prove to be good candidates for the role of dark matter particles. Numerical estimates of the interaction cross section give almost zero result if the mixing between right- and left-handed neutrinos is considered negligible. The mass of the Z' –boson should be on the TeV scale, however, its search at the LHC is very difficult due to its almost zero cross section.

According to the law of increasing collisionless particles [22], the density of heavy neutrinos is determined by the formula:

$$\rho_\nu(t) = \Big(\rho_b(t)\Big)^{3/4}, \tag{13}$$

where $\rho_b(t)$ is the density of baryonic matter. Therefore, in the centers of galaxies, the contribution of the latent mass in the form of neutrinos or other collisionless particles is not more than 10%.

3. STERILE NEUTRINOS

Sterile neutrinos are stable, single-particle, symmetric, warm, non-baryonic, and one-component candidates for the role of dark matter.

Sterile neutrinos do not interact weakly, unlike ordinary ones. Based on the data of the $SDSS$ experiment on the Lyman-alpha Les spectra [23,24] and taking into account the fact that observations did not detect gamma emission from galactic clusters with characteristic energies of the order of $10\,keV$, a limit on the mass of sterile neutrinos was obtained [25,26] (the limitation was obtained by simulating the effect of different neutrino masses on the Lyman-alpha Les spectra):

$$m_{sterile} \geq 14 \text{ keV}. \tag{14}$$

Some of the possible extensions of the Standard Model involve the introduction of sterile neutrino-lefty fermions mixed with ordinary active neutrinos. Sterile neutrinos are supposedly involved only in gravitational interaction.

The existence of three generations of neutrinos has been verified and studied in experiments with neutrinos of atmospheric origin, with neutrinos produced in nuclear reactors, and with neutrinos obtained at an accelerator.

However, there are a number of experimental facts indicating that the measured flux ν turned out to be less than the calculated one. These are the $LSND$ accelerator experiments [27] at Los Alamos and the subsequent $MiniBooNE$ [28] at Fermilab. The $LSND$ result is the very first and still has the greatest statistical significance. Another experimental fact is the "gallium anomaly"that arose during the calibration of gallium neutrino detectors in the $Gallex$ experiment [29] using an artificial source $\bar{\nu_e}\ ^{51}Cr$.

Finally, the existence of a reactor antineutrino anomaly was announced

[30]. New, more accurate calculations showed that the measured flux $\bar{\nu}_e$ turned out to be much less than expected. The authors of the works stated about the deficit of registered events in neutrino experiments. The data obtained may support the existence of a sterile neutrino. If sterile neutrinos exist, they could contribute to the known density Ω_{DM}.

4. WEAKLY INTERACTING MASSIVE PARTICLES (WIMP)

As the name implies, WIMPs are involved only in weak and gravitational interaction. This is why they are extremely difficult to detect. The WIMP mass should be at least ten times greater than the proton mass. The search for WIMP has been carried out in many experiments over the past 20 – 30 years, but despite all efforts, they have not yet been found.

Usually, particles are considered with masses and annihilation cross sections that allow them to go out of equilibrium in the early Universe, with a density of the order of the density of dark matter. The requirement for effective annihilation of WIMPs means a sufficiently strong interaction with ordinary matter to be able to register them by a direct method.

Estimation of the modern WIMP density [31]:

$$\Omega_{WIMP}h^2 \approx \frac{3 \cdot 10^{-27} cm^3 s^{-1}}{< \sigma_{ann} \upsilon >}, \tag{15}$$

at that $< \sigma_{ann} \upsilon >_{max} \approx 1/m^2_{WIMP}$ [32, 33].

Restriction on the mass of WIMPs [32]:

$$m_{WIMP} \leq 340 \ \ \text{TeV}. \tag{16}$$

WMAP data [7] give more stringent restrictions [34]:

$$m_{WIMP} \leq 120 \ \ \text{TeV}. \tag{17}$$

One of the WIMP search methods is based on the assumption that during their existence various astronomical objects (Earth, Sun, center of our Galaxy) should capture WIMPs, which accumulate in the center of these objects, and annihilate with each other to produce a neutrino flux. Attempts to detect excess neutrino flux from the center of the Earth towards the Sun and the center of the Galaxy were undertaken using underground and underwater neutrino detectors MACRO, LVD (Gran Sasso laboratory), NT-200 (Lake Baikal, Russia), SuperKamiokande, AMANDA (Scott-Amundsen station, South Pole), but have not yet led to a positive result.

Direct detection of dark matter particles is carried out on underground scintillation detectors (EDELWEISS [35], LUX [36], DarkSide [37], XENON [38], etc.), on a bubble chamber (BubXe), and many other experiments. Scintillation detectors are aimed at recording the energy release in the detector volume caused by possible scattering of a heavy particle by the scintillator nucleus. The transmission energy is only tens of keV.

Energy release of this magnitude should occur with frequency:

$$\nu = \upsilon_x n_x N_A \sigma_{NX}, \tag{18}$$

where σ_{NX} is the cross section for elastic scattering of WIMP on a nucleus, υ_x is the WIMP velocity, local by the density of the number of these particles $n_x = \rho_{CDM}/M_x$, N_A is the number of nuclei in the detector. For example, at a cross section $\sigma_{NX} \sim 10^{-38} cm^2$ and WIMP mass $M_x = 10\,\text{GeV}$ in a detector with a mass of 10 kg filled with target nuclei with A = 100, it is expected that $\nu \sim 5 \cdot 10^{-8} s^{-1}$, that is, on the order of one event per year. The absence of a signal makes it possible to exclude the corresponding region in the parameter space (M_x, σ_{NX}) (see Figure 5).

Experiments to search for WIMPs are also actively carried out at particle accelerators. Having accelerated particles to high energies and colliding them with each other, one can expect the production of pairs of other particles and antiparticles (including WIMP), the total mass of which is equal to the total energy of the colliding particles. But accelerator experiments have also not yet led to a positive result.

5. SUPERSYMMETRIC PARTICLES

Supersymmetry is the symmetry between bosons and fermions. Most supersymmetric theories contain one stable particle, which is a new candidate for dark matter. The existence of a stable supersymmetric particle follows from

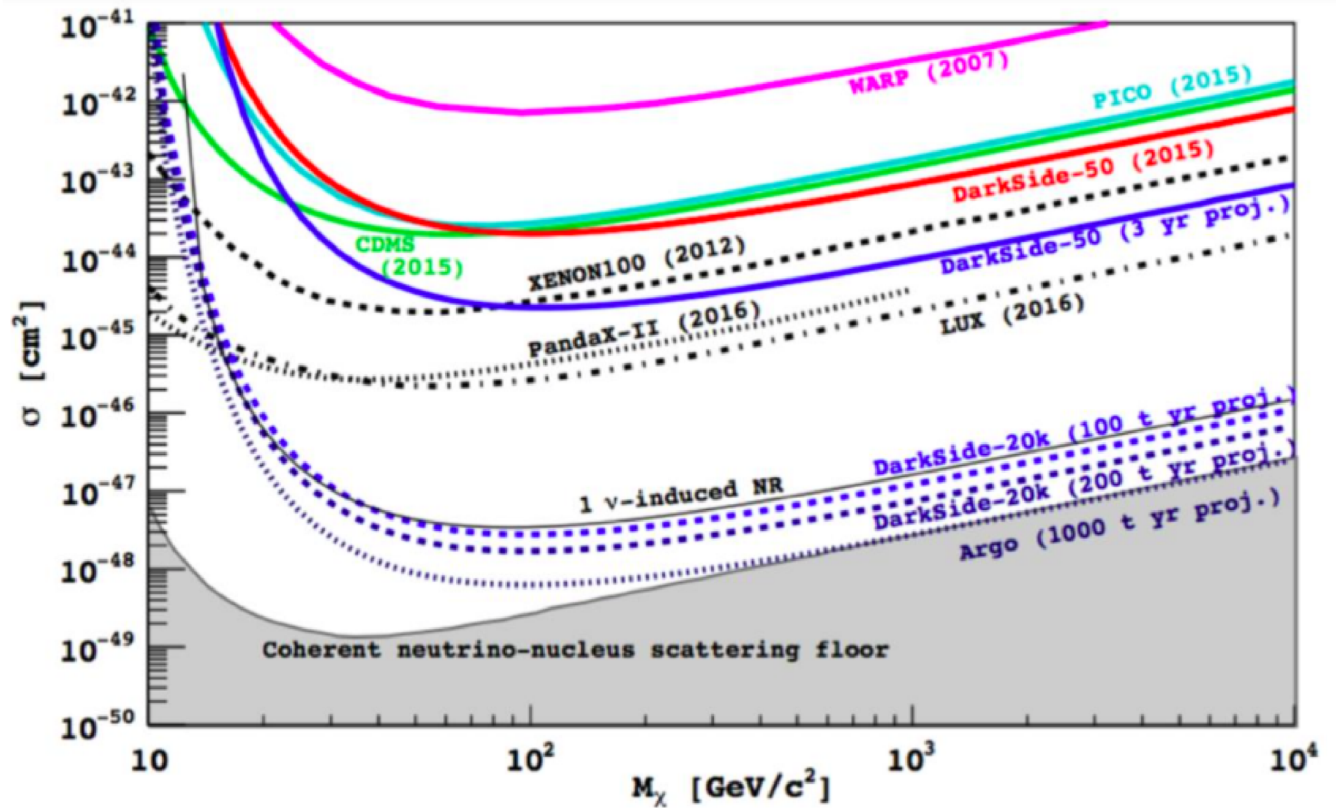

Figure 5: The spaces above the curves show the regions of parameters in which the corresponding experiments to search for WIMPs have worked or will begin their work.

the conservation of the multiplicative quantum number - R-parity, which takes on the value +1 for ordinary particles, and -1 for their superpartners. This is the R-parity conservation law. According to this conservation law, SUSY particles can only be formed in pairs and SUSY particles can only decay into an odd number of SUSY particles. Therefore, the lightest supersymmetric particle must be stable. Also, it should not have an electric and color charge, otherwise it would form heavy ions with an ordinary substance, which contradicts the experimental data.

Potential candidates for the neutral lightest supersymmetric particle include photino (S = 1/2) and zino (S = 1/2), as well as higgsino (S = 1/2), sneutrino (S = 0), and gravitino (S = 3/2). Taking into account all the conditions, the most suitable particle for the role of dark matter is neutralino - a superposition of zino, photino and two higgsinos. Its mass is likely to be greater than 10 GeV. Considering SUSY particles as dark matter is of particular interest, since they appeared in a completely different context and were not specially introduced to solve the problem of (non-baryonic) dark matter. The search for supersymmetric particles is one of the main tasks of experiments in the field of high-energy physics, in particular, the search for superpartners is being carried out at the LHC.

From the point of view of registration, the most important reactions are pair annihilation and elastic scattering by nucleons. In the modern era, neutralinos are essentially nonrelativistic with the main channels of annihilation into fermion-antifermion pairs (predominantly heavy), gauge boson pairs, and final states containing the Higgs boson.

In addition to neutralino, snutrino and gravitino are candidates for hidden mass. But sneutrinos have too large expected cross sections for snetrino-nucleon interactions [39], which contradicts the data obtained in the course of a direct search for dark matter. Gravitino is of little interest for direct searches, since it interacts only gravitationally.

6. KALUZA-KLEIN PARTICLES

The Kaluza-Klein particle is a cold, single-particle, symmetric, unstable, non-baryonic and multicomponent particle that is a candidate for the role of dark matter.

In theories with extra dimensions, massive Kaluza-Klein gravitons arise, which can be born in the form of real and virtual particles. In the four-dimensional world, KK-gravitons appear as a series of massive excited states. In a theory with unified extra dimensions (UED), all SM particles and fields can propagate in extra dimensions. In UED theories, KK excitations are observable states, and the lightest of them are candidates for dark matter. Estimates for the masses of the lightest KK-excitations [40]:

$$m_{KK} \approx 400 - 1200 \;\; \text{GeV}. \tag{19}$$

7. SUPER WIMP (SWIMP)

The main difference between SWIMPs and WIMPs is the superweak interaction with ordinary matter, which is why they cannot be detected in direct experiments. The annihilation cross section for these particles is so suppressed that indirect detection methods will also fail. The only observable consequence of the existence of SWIMPs could be related to the decay of WIMPs into SWIMPs with the emission of photons. The presence of a peak in the spectrum of diffuse gamma quanta could signal the presence of SWIMPs.

Gravitinos in supersymmetric models and KK excitations in theories with additional dimensions, as well as axions and axinos, are considered as candidates for the role of SWIMPs. In models with axions [41], the superweak interaction of axions with matter should indicate that they were not in thermal equilibrium in the early Universe. One of the most essential properties of axions is two-photon interaction, which allows axion-photon conversion in an electromagnetic field. Most searches for axions are based on this process [42].

8. WIMPZILLA, SIMPZILLA

The limitation on the WIMP mass $m_{WIMP} \leq 120\,\text{TeV}$ was obtained based on the assumption that dark matter particles are thermal relics of the Universe. However, it is possible that dark matter particles were not in thermodynamic equilibrium during the evolution of the Universe, so their mass can be much larger than the mass of thermal WIMPs and reach values of $10^{12} \div 10^{19}$ GeV. For the first time, the possibility of the formation of supermassive quasi-stable particles was considered in [43].

Such superheavy particles could be born from vacuum fluctuations during inflation or the transition between inflation and the regime of dominance of matter (radiation) due to the non-adiabatic expansion of space-time at the stage of the early Universe [44, 45]. Almost stable, they could survive to this day.

Superheavy particles can decay and annihilate relatively close to the Earth, since they are not associated with astrophysical objects. Decay products - nucleons, nuclei, neutrinos and gamma quanta - can store a significant part of their energy until the moment of registration in a detector. If the observed cosmic rays beyond the cutoff of the Greisen-Zatsepin-Kuzmin spectrum are caused by the decays of superheavy particles, then their mass should be $m \geq 10^{13}$ GeV. Such particles can be weakly interacting WIMPZILLA and strongly interacting SIMPZILLA, the difference between which is, in fact, in the value of the cross section for interaction with ordinary matter. The main observation opportunity is the registration of decay and annihilation products high-energy gamma quanta and neutrinos.

9. Q-BALLS

Supersymmetric generalizations of the Standard Model, in particular the MSSM, predict the existence of non-topological solitons called Q-balls [46]. Supersymmetric Q-balls are coherent states of squarks, sleptons, and Higgs fields with an arbitrary baryon number. In the particular case of a large baryon number, solitons are completely stable and could have been produced in large numbers in the early Universe [47].

A soliton with a baryon number Q_B has a mass $M_Q \sim m_0 Q_B^{3/4}$ and a radius $R_Q \sim m_0^{-1} Q_B^{1/4}$. Usually it is assumed $100\,\mathrm{GeV} \leq m_0 \leq 100\,\mathrm{TeV}$. The baryon number of a stable soliton should be greater than $10^{15}\left(\dfrac{m_0}{1\ \mathrm{TeV}}\right)^4$.

The passage through the detector of Q-ball with $Q_B \sim 10^{24}$ is accompanied by the release of $\sim 10\,GeV$ per $1\,mm$ of path. Modern experimental restrictions on the flux of electrically charged solitons [48]:

$$\Phi < 1,1 \cdot 10^{-14} \frac{1}{cm^2 \cdot s \cdot sr}. \tag{20}$$

What gives the lower limit on the baryon charge of dark matter, consisting of Q-balls: $Q_B \geq 10^{21}$.Restriction on the baryon charge of electrically neutral solitons: $Q_B \geq 10^{24}$ for $m_0 \approx 1$ TeV [49].

10. MAGNETIC MONOPOLES

Magnetic monopole is a hypothetical elementary particle with a nonzero magnetic charge; it is a point source of a radial magnetic field. The idea of the existence of monopoles was put forward by Dirac in 1931 to explain the quantization of the electric charge [50]. The lower estimate for the mass of the

Dirac monopole can be estimated based on the classical radius of the electron:

$$m_D = \frac{m_e}{4\alpha_E} \approx 2,4 \text{ GeV}. \qquad (21)$$

Magnetic monopoles arise in spontaneously broken non-Abelian gauge theories, which essentially underlie all grand unified theories (GUT), as one of the stable solutions corresponding to topological defects. If the mass of a typical gauge boson in the GUT theory is m_X, then the monopole mass can be written as $m_M \propto \alpha_X^{-1} m_X$ where α_X^{-1} is the dimensionless coupling constant at the scale m_X in the GUT model. According to theories with a scale of $m_X \approx 10^{15}$ GeV if $\alpha_X \approx 0,025$, a monopole is formed with a mass of $m_M \approx 10^{17}$ GeV. It was shown in [51] that massive monopoles formed in large quantities during phase transitions in the early Universe will annihilate very slowly and by now their density should be of the same order of magnitude as the density of baryons. Since the mass of the monopole is about 10^{16} times greater, the density of matter would be at least 10^{14} times higher than the critical one, and the Universe would have collapsed long ago. The problem of the abundance of relict GUT-monopoles is solved due to the inflation mechanism, so that today their content is comparable to the upper cosmological and experimental levels.

It is also possible that monopoles with lower masses $m_M \sim 10^7 \div 10^{13}$ GeV exist, which could have formed at a much later moment in the early Universe than that determined by the time scale of the GUT theory [52].

So far, none of the experiments has recorded an event associated with a monopole. The best limits on the monopole flux were obtained with the MACRO detector [53]:

$$\Phi < 1,4 \cdot 10^{-16} \frac{1}{cm^2 \cdot s \cdot sr}. \qquad (22)$$

11. TOPOLOGICAL DEFECTS

At the meeting points of regions with different phases of the scalar field, stable topological defects of various configurations could form: point-like particles, linear extended objects (cosmic strings), two-dimensional membranes (domain walls), three-dimensional defects (textures). All these objects have, as a rule, a large mass and could make a dominant contribution to dark matter. At the moment, no such objects have been found in the Universe.

The most important are point-like defects. They must carry an isolated magnetic charge, that is, be magnetic monopoles. Linear defects, that is, cosmic strings, can form in a similar way. These filamentous objects have a characteristic linear mass density of the order of $\sim 10^{22} g/cm$ and can be either closed or open. Due to gravitational attraction, they could serve as seeds for the condensation of matter, as a result of which galaxies were formed. Large values of masses make it possible to detect such strings through the effect of gravitational lenses.

The possibility of a superconducting state in cosmic strings is also discussed. Electrically charged particles, such as electrons, in a symmetric vacuum, strings would be massless because they acquire their masses only as a result of symmetry breaking through the Higgs mechanism. Thus, particle-antiparticle pairs moving at the speed of light can be created here at very low energy costs. The result is a superconducting current. Superconducting strings could pass into an excited state by interacting with charged particles, the removal of this excitation would be carried out by the emission of radio waves.

12. PRIMORDIAL BLACK HOLES

Light black holes ($M_{BH} \ll M_{\odot}$) could make up cold dark matter. To date, the region of allowed masses for such black holes [54]:

$$10^{-16} M_{\odot} \leq m_{PBH} \leq 10^{-7} M_{\odot}. \tag{23}$$

One of the experimental techniques aimed at registering PBHs is based on the effect of gravitational microlensing. With microlensing, a black hole passes between the Earth and a distant star, as a result of which the observed brightness of the latter increases for a short time.

13. COMPOSITE DARK MATTER

Dark matter does not emit radiation, while charged particles are sources of electromagnetic radiation. Therefore, neutral weakly interacting elementary particles are usually considered as candidates for the role of dark matter.

However, if charged stable particles form neutral objects, they can play the role of dark matter in the universe. The search and study of such neutral objects can make it possible to determine the properties of charged stable particles that make up their composition.

Glashow Model

Glashow's model is an extension of the Standard Model by introducing an additional symmetry group SU(2) [55]. An additional symmetry group is associated with the existence of heavy partners of ordinary particles (terapartners), the mass of which is determined by the free parameter S:

$$\frac{m_E}{m_e} = \frac{m_U}{m_u} = \frac{m_D}{m_d} = S_6 = \frac{S}{10^6}. \tag{24}$$

The lightest partners are theoretically stable.

$$\begin{pmatrix} \nu_e' \\ E^- \end{pmatrix}, \begin{pmatrix} U \\ D \end{pmatrix}. \tag{25}$$

$\nu_e' \to$ heavy unstable particle.
$E^- \to m \sim 500$ GeV, stable particle.
$U \to m \sim 3$ TeV, heavy metastable particle.
$D \to m \sim 5$ TeV, $D \Rightarrow U + E^- + \bar{\nu_e}'$.

This extension allows one to eliminate such SM problems as CP-parity violation in strong interactions and the neutrino mass problem. Glashow also suggested the existence of a composite neutral dark matter, consisting of new charged particles. He found that the heavy configuration (UUU) is stable (analogue in SM - (uud)). Another assumption is the formation of tera-helium (UUUEE) in the early stages of the evolution of the Universe, which plays the role of dark matter.

The implementation of this model faces a number of problems: the existence of a postulated excess of particles does not mean suppression of anti-tera particles; along with tera-helium, other states should be born – $(^4HeE^-)^+$, E^+, (UUUE), (UUuE), (UduE). To solve these problems, (Ep) – catalysis is introduced, the result of which is the destruction of the products of incomplete annihilation and binding:

$$[(UUU)E] + (Ep) \to [(UUU)EE] + p,$$
$$E^+ + (Ep) \to (E^+E) + p. \tag{26}$$

But even before the required temperature reaches 25 keV, all free E are captured by primary helium, resulting in the formation of $(^4HeE^-)^+$ ions, which do not allow the implementation of this model [10].

Modern models of composite dark matter

If we introduce a new particle (O^{--}) with a charge of -2 (in the general case $-2n$, where n is a natural number, we will denote them by X) in excess with respect to its antiparticle, then the problems of the Glashow model do not arise. O^{--} at a temperature of 100 keV forms a bound state OHe with primary helium [4, 9, 56–58]:

$$O^{--} + He^4 \to (OHe) + \gamma. \tag{27}$$

The Bohr radius for the bound state of OHe is $2 \cdot 10^{-13}\, cm$, which is comparable to the radius of the helium nucleus. In models with four or five generations of fermions [59, 60], the formation of an excess of antiparticles is possible. In this case, the existence of a stable state with a charge of -2 is possible, similar to tera-helium [61]:

$$\Delta^{--}_{\bar{U}\bar{U}\bar{U}} = (\bar{U}\bar{U}\bar{U}). \tag{28}$$

With the participation of $\Delta^{--}_{\bar{U}\bar{U}\bar{U}}$ neutral OHe can be formed:

$$(\bar{U}\bar{U}\bar{U}) + He^4 \to [(\bar{U}\bar{U}\bar{U})He] + \gamma. \tag{29}$$

OHe is one of the promising candidates for the role of dark matter. The existence of the O– helium hypothesis is important because it can explain the conflicting results of experiments on the direct search for dark matter due to the peculiarities of the interaction of "dark"atoms with the matter of underground detectors [62]. For example, positive results on the detection of dark matter particles in experiments such as $DAMA/NaI$ and $DAMA/LIBRA$, which seem to contradict all other experiments, for example, with $XENON100$, LUX, $CDMS$, giving a negative result.

Charged components of compound dark matter

1) The fourth generation of fermions.

$$\begin{pmatrix} N \\ E^- \end{pmatrix}, \begin{pmatrix} U \\ D \end{pmatrix}. \tag{30}$$

$N \to m \sim 50$ GeV quasi-stable particle.
$E^- \to 100$ GeV $< m <\sim 1$ TeV, $E \to Nl\nu$, unstable particle.
$U \to 220$ GeV $< m <\sim 1$ TeV, $U \to N + (light fermions)$, long-lived particle.
$D \to 220$ GeV $< m <\sim 1$ TeV, $D \to Ul\nu$, unstable particle.

2) AC leptons.

The AC model is an extension of the SM within the framework of the approach proposed by Alan Kohn and based on the principles of almost commutative geometry [63–66]. In this model, two additional doubly charged A^{--} and C^{++} leptons and their antiparticles interacting with photons and Z – boson are introduced. It is also assumed that there is an excess of these particles in comparison with their antiparticles, which allows the formation of AC atoms, which can play the role of cold dark matter.

3) New particles in the technicolor model.

The technicolor model assumes the existence of a new type of interaction, which connects a new type of quarks [5,67]. This model has its own mechanisms of mass formation in particles and spontaneous symmetry breaking of the electroweak interaction.

In the first versions of this model, fundamental concepts for techniquarks and broad symmetry groups of technicolor were used in order to provide a technicolor scale of confinement in the TeV region. The serious difficulties of these models have been overcome in the current model, in which the coupling constant changes very slowly with the transferred momentum (Walking TechniColor model). This made it possible to implement the idea of technicolor in the framework of the SU(2) symmetry, in which techniquarks are transformed according to the adjoint representation.

Technibaryons are considered within the framework of the theory of technicolors, which are particles formed from techniquarks and having their own type of interaction (which does not manifest itself explicitly at energies below the confinement scale in terms of technicolor) and charge. The existence of the fourth generation of technileptons is also introduced.

A family of techniparticles

Particles	Type	Charge
U,D	Techniquarks	
υ, ζ	Technileptons	$\frac{1-3y}{2}, \frac{-1-3y}{2}$
UU,UD,DD	Technibaryons	$y+1,\ y,\ y-1$

y is a real number, for $y = 1$ new candidates for the role of stable doubly negatively charged particles are obtained: $\bar{U}\bar{U}$ – antitechnibaryons, ζ – technileptons.

Depending on the existence of conservation laws, there are three variants of dark matter from techniparticles:

1) The technibaryon number is preserved. The main contribution is made by technibaryons.

2) The technical lepton number is saved. The main contribution is made by technileptons.

3) Both are preserved. Both technibaryons and technileptons are contributing.

IV. CONCLUSION

In this work, the evidence of the existence of dark matter and possible candidates for its role were considered, experimental confirmation or refutation in favor of one or another theory, explaining the essence of dark matter, was also considered. It should be noted that there are still a number of candidates for the role of dark matter that were not considered in this work, but the most promising candidates did not go unnoticed.

To explain the observed amount of dark matter, the parameters of some models may take on unrealistic values or require additional assumptions. The predictions for the density of dark matter in such theories turn out to be strongly model dependent. In this case, particles cannot be called natural candidates, since from a theoretical point of view there is no reason to expect that the parameters will actually take on the values they need.

To date, several experiments are discovering new unknown particles and there are hypotheses that suggest candidates for the role of dark matter that can explain the results of these experiments. But, unfortunately, the results of the corresponding experiments do not correspond to each other. Therefore, the problem of dark matter requires further study. The situation should be clarified by new detectors and experiments that will confirm or deny previously obtained data.

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