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Thesis on the course «Cosmoparticle physics» on the topic: «Dark atoms in the Universe»

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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.

A serious study of dark matter, including on an extragalactic scale, actually began with the work of Fritz Zwicky, who in 1933 discovered [1] an unusually large spread in the radial velocities of eight galaxies in the Coma cluster and, applying the virial theorem, concluded that for the stability of the cluster, its complete the mass should be 400 times greater than the mass of the stars included in it.

Soon, another problem emerged with the mass distribution and mass/ luminosity ratio for spiral galaxies, obtained from their rotation curves [2]. So, in 1939, the American Hores Babcock published in his dissertation a detailed rotation curve of the Andromeda nebula galaxy - the speed of rotation of stars around its center did not decrease, as predicted by celestial mechanics, inversely proportional to the distance to the center, but remained almost constant. 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 [3].

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 [4, 5]. 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.

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. Galaxies form and grow due to gravitational instability from initial density perturbations in the early Universe. 400 000 years after the Big Bang, these density fluctuations were still very small ($\sim 10^{-5}$ relative to the density itself). And if in the Universe at that moment there was only ordinary baryonic matter, then these inhomogeneities simply would not have time to amplify to such an extent as to create the observed variety of structures - for this, fluctuations in the epoch of primary recombination would have to be of the order of 10^{-3}. The solution to this paradox is the assumption that there is a significant amount of non-baryonic dark matter in the Universe. The CMB photons interact only with baryonic matter, and therefore the temperature anisotropy of the background radiation carries information only about the density fluctuations of ordinary matter. At the time of recombination, the non-baryonic matter could already be much more crowded, thus forming the basis for the growth of future galaxies and their clusters [6].

Dark matter is a type of matter unknown to us, different from dark energy and the known baryonic matter. The density of matter in the Universe ρ is usually given in units of the critical density:

$$\rho_c = \frac{3H^2}{8\pi G} \approx 5,5 \ \ \mathrm{KeV}/cm^3, \tag{1}$$

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 $\Omega = \dfrac{\rho}{\rho_c}$ is close to critical. This means that the universe is flat and open.

The observed density of the Universe consists of various components:

$$\Omega = \Omega_{DM} + \Omega_B + \Omega_\nu + \Omega_\Lambda + \Omega_{rad}, \tag{2}$$

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.These particles can be considered as candidates for the role of dark matter if they satisfy a certain set of conditions: 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 [7].

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 [8]. On accelerators, it is possible to search for weakly interacting particles using the missing energy. The dark atoms that make up dark matter can be composed 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.

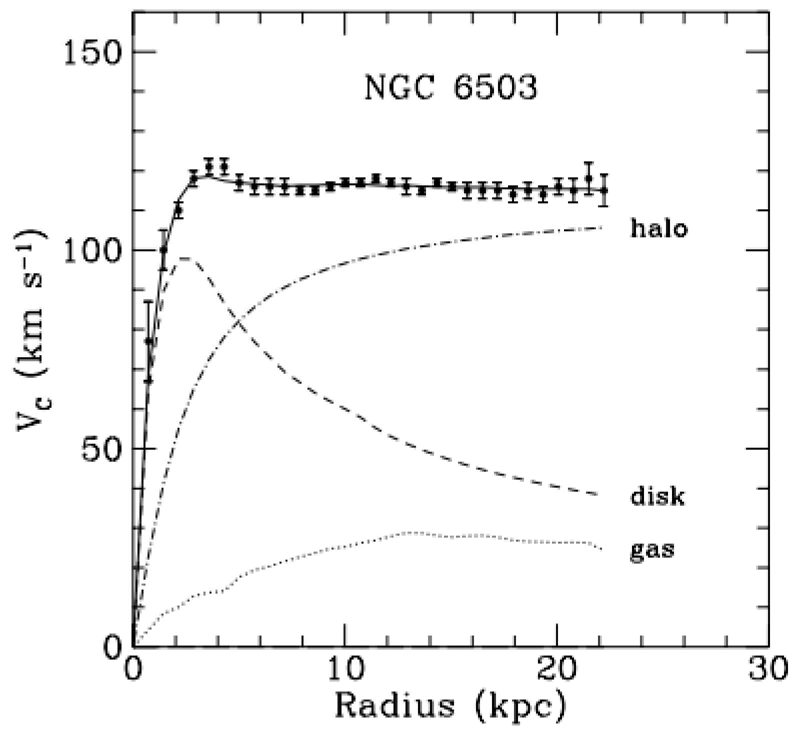

Figure 1: Rotation curve of NGC 6503. The dotted, dashed and dash-dotted lines are the contributions of gas, disk and dark matter, respectively. From Ref. [9]

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).

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 the emergence of galaxies, gravitational instability is necessary, that is, an increase with time of spatial fluctuations in the velocity and density of matter under the action of gravitational forces. Gravitational instability leads to the formation of inhomogeneities in an initially homogeneous medium and is accompanied by a decrease in the gravitational energy of the system, which transforms into kinetic energy of the contracting substance, which, in turn, can transform into thermal energy and radiation.

According to current models, the protogalactic collapse occurred with the participation of electrically neutral dark matter, which does not interact with radiation: its fluctuations formed dark halos shortly after the Big Bang, and baryonic matter began to concentrate under the influence of dark halo gravity. In the absence of dark matter, fluctuations in the density of baryonic matter would grow very slowly due to the expansion of the Universe and galaxies would not have had time to form by now [10, 11].

A highlighted moment in the evolution of the large-scale structure of the Universe can be considered the moment of hydrogen recombination. For some time before recombination, the evolution of ordinary and dark matter is synchronous, but due to the interaction with radiation, the temperature of ordinary matter decreases more slowly. There is a kinematic and thermal separation of dark matter and baryonic matter. It is assumed that this moment occurs at $z = 10^5$. In that epoch, the amplitude of perturbations in the density of the baryon component did not increase or decrease, but experienced acoustic oscillations. At the same time, dark matter did not experience such oscillations, since neither the pressure of light, nor the pressure of baryons and electrons exerted an effect on it. Moreover, the amplitude of her indignation grew. After recombination, ordinary matter rolls into potential holes formed by dark matter [12].

According to the hierarchical concept, the formation of galaxies began with the condensation of fluctuations of cold dark matter. Initially, the fluctuations of its density had a contrast of no more than 10^{-5}, but under the influence of gravity they condensed and merged over time, increasing in mass and size - that is why the concept got its name. In 0,5 billion years after the Big Bang, dark halos with a mass of $10^7 \div 10^8 M_\odot$ were formed, and after 2 billion – $10^{10} M_\odot$. At the moment, the mass of such halos should be $10^{14} \div 10^{15} M_\odot$, which corresponds to the mass of galaxy clusters. Gas, the mass of which is 6 times less than the mass of dark matter, in this scenario is only carried away behind dark halos, tending to their centers. The gas heated during the collapse collects in a halo and, when cooled, settles into the disk, where star formation begins. A completely disk galaxy without a spheroidal component is formed - that is, a late-type spiral galaxy or an irregular galaxy [10].

Modeling also shows that for the detected inhomogeneities of CMB $\sim 10^{-5}$ ($z \sim 1000$), 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.

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.

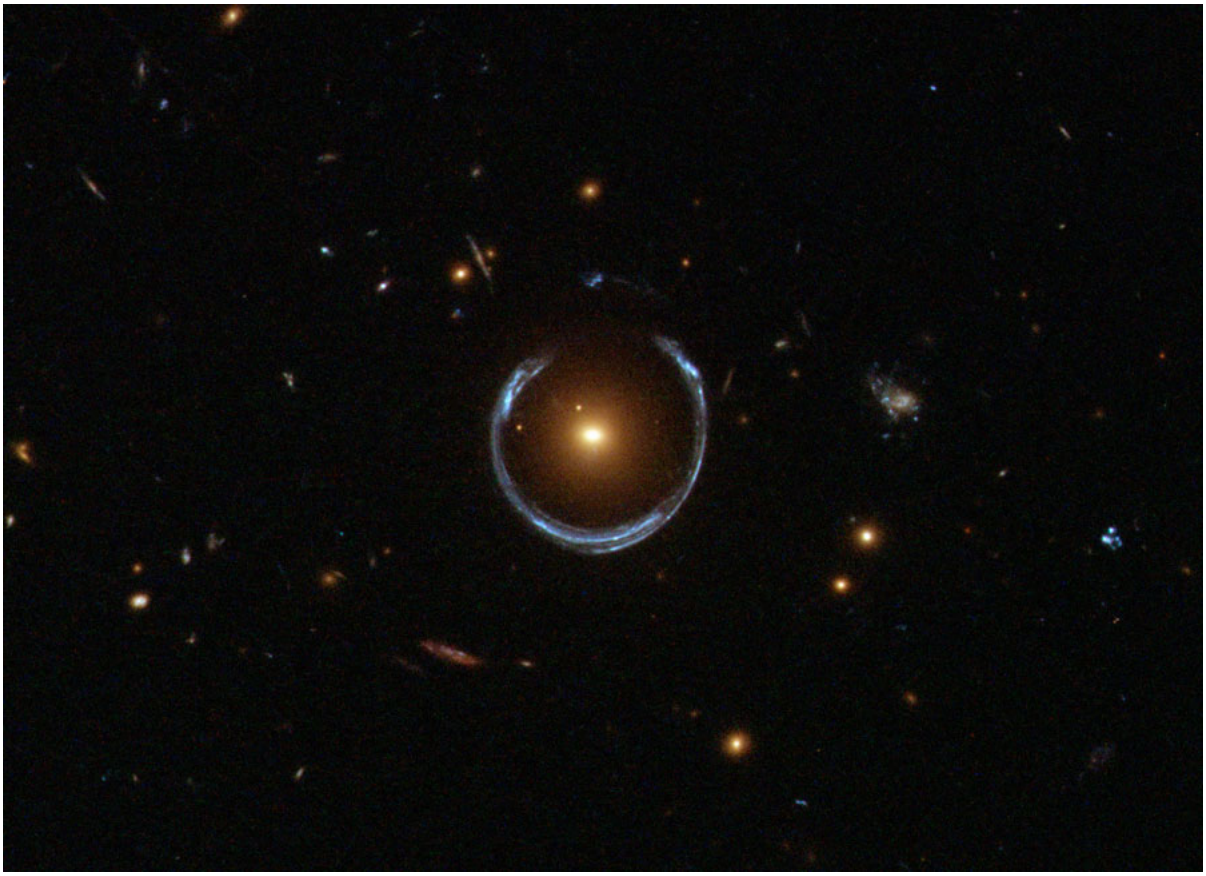

Figure 2: Taken by the Hubble telescope of the so-called. "Space horseshoe a giant elliptical galaxy at $z = 0,45$, lensing a dwarf galaxy at $z = 2,38$. Image from https://apod.nasa.gov/apod/ap111221.html.

There are three classes of gravitational lenses [13,14]:

1) Strong gravitational lensing, causing easily distinguishable distortions such as Einstein's ring, arcs, and duplicated images.

2) Weak gravitational lensing, which causes only minor distortions in the image of an object that is behind the lens (hereinafter referred to as the background object). These distortions can be recorded only after a statistical

analysis of a large number of background objects, which makes it possible to find a small consistent distortion of their images. Lens appears as a slight stretching of the image perpendicular to the center of the lens. By studying the shape and orientation of a large number of distant background galaxies, we are able to measure the lensing field in any area. This data, in turn, can be used to reconstruct the mass distribution in a given region of space; in particular, this method can be used to study the distribution of dark matter. Since galaxies themselves are elliptical and distortion from weak lensing is small, this method requires observing a large number of background galaxies. Such surveys should carefully take into account many sources of systematic error: the proper shape of galaxies, the spatial response function of the photosensitive matrix, atmospheric distortions, etc. The results of these studies are important for assessing cosmological parameters, for a better understanding and development of the Lambda-CDM model, as well as for in order to provide a consistency check with other cosmological observations.

3) Microlensing does not cause any observable shape distortion, but the amount of light received by the viewer from the background object is temporarily increased. The lensing object can be the stars of the Milky Way, their planets, and the light source - the stars of distant galaxies or quasars located at an even farther distance. In contrast to the first two cases, the observed pattern under microlensing changes in a characteristic time from seconds to hundreds of days. Microlensing makes it possible to estimate the number of weakly luminous objects with masses of the order of stellar (for example, white dwarfs) in the Galaxy, which can make some contribution to the baryonic component of dark matter. In addition, microlensing is one of the methods for searching for exoplanets.

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.

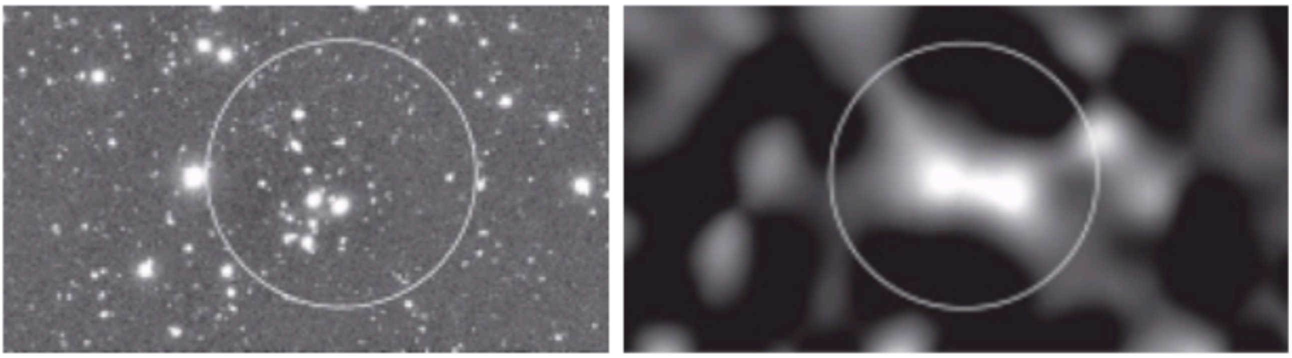

Figure 3: Left: A cluster of galaxies creates a gravitational lens. Right: Mass distribution for a given galaxy cluster

5. CMB ANISOTROPY

The relic radiation is a remnant of the earliest epochs of the development of our Universe, the most important observational evidence of the "Hot Universe" model, on the basis of which the modern Standard Cosmological Model is built. The CMB is very homogeneous and isotropic. Its temperature is uniform with an accuracy of 10^{-3}. But a slight anisotropy (inhomogeneity, temperature difference at different points in the sky) still exists. It carries the most important information about the early Universe and determines the cosmological parameters. The anisotropy of the relict radiation is usually represented in the form of an angular energy spectrum, which contains information about the formation of the Universe and its current state. The spectrum shows how much the temperature changes from point to point in the sky depending on the multipole ("angular frequency") (see Figure 4).

The influence of the values of the cosmological parameters on the angular power spectrum of the CMBR temperature anisotropy is shown in Fig. 5. The dependence of the angular power spectrum on the value of the curvature density parameter is shown in Fig. 5(a). There are two effects associated with the influence of spatial curvature on the angular power spectrum of the CMBR: the shift of the minima and maxima of the Doppler peaks and the strong dependence of the spectrum in the region with $l \leq 100$ on the value of the total energy density parameter, Ω_{tot}. The influence of dark energy (cosmological constant Λ) on the CMBR angular power spectrum in the case of a spatially flat universe is shown in Fig. 5(b). It can be seen that the location of the acoustic peaks is almost independent of the value of the dark energy density parameter, Ω_Λ.

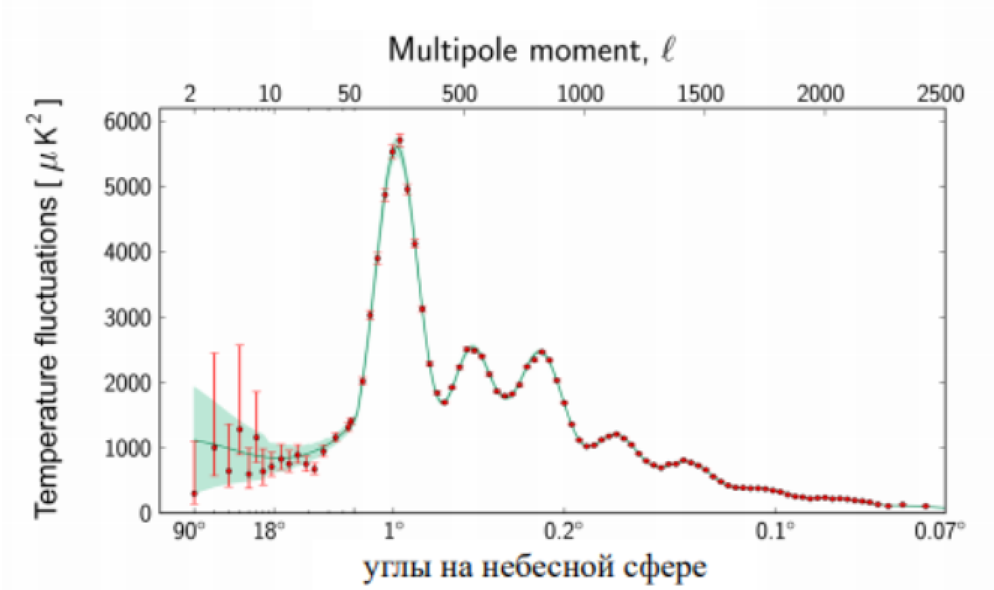

Figure 4: The angular energy spectrum of the CMB (data from the Planck space observatory)

The dependence on the value of the baryon energy density parameter is shown in Fig. 5(c). An increase in the baryon energy density parameter, $\Omega_b h^2$, leads to an increase in the amplitude of the first acoustic peak and to a decrease in the amplitude of the second acoustic peak. The influence of the value of the parameter of the energy density of matter, $\Omega_m h^2$, on the power spectrum of the CMBR is shown in Fig. 5(d). Changing the value of this parameter causes changes in the amplitudes of acoustic peaks and the location of these peaks [15].

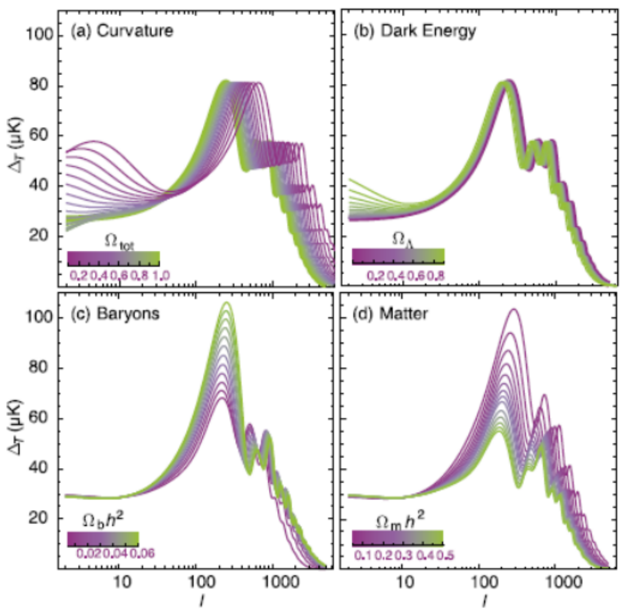

Figure 5: Influence of cosmological parameters on the angular power spectrum of the CMBR temperature anisotropy

The data of the WMAP experiment [16] 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.

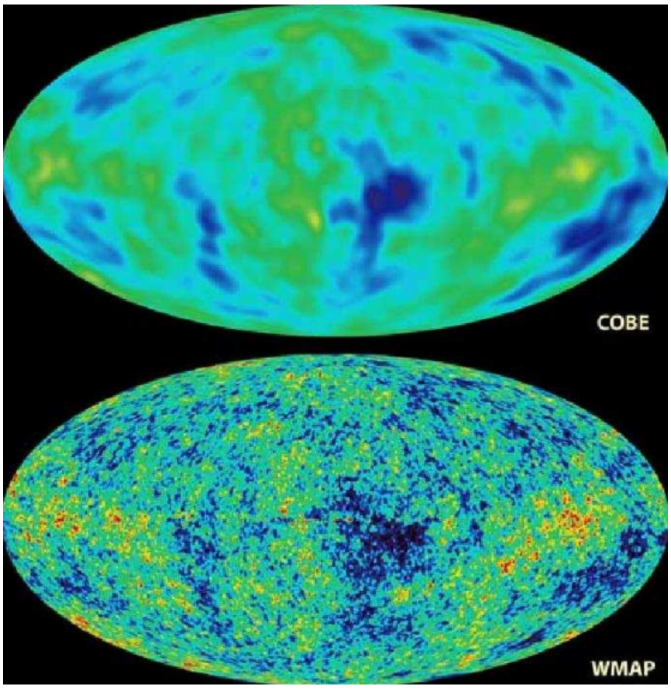

Figure 6: CMB Temperature fluctuations: A comparison between COBE and WMAP. Image from http://map.gsfc.nasa.gov/.

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.

II. DARK MATTER CLASSIFICATION AND COSMOLOGICAL CONSTRAINTS

The most important thing for dark matter particles, in order for them to be candidates for the role of dark matter, in addition to being stable, saturating the measured density of dark matter and separating from plasma and radiation, at least until the beginning of the stage of dominance of ordinary matter, is that all candidates for the role of dark matter particles in one way or another should reflect some additional, new symmetry of the microworld. Even if they are macroscopic candidates, because they are created in the very early Universe when physics is working outside the Standard Model. Thus, dark matter is an entity that reflects the existence of new conservation laws, new symmetries and is associated with the fundamental structure of the microworld.

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 [17]. 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 [38].

This theory assumes [19] 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".

In cosmology, decoupling refers to a period in the development of the universe when different types of particles fall out of thermal equilibrium with each other. This occurs as a result of the expansion of the universe, as their interaction rates decrease (and mean free paths increase) up to this critical point. The two verified instances of decoupling since the Big Bang which are most often discussed are photon decoupling and neutrino decoupling, as these led to the cosmic microwave background and cosmic neutrino background, respectively.

Decoupling may also have occurred for the dark matter candidates, like WIMPs. These are known as "cold relics meaning they decoupled after they became non-relativistic (by comparison, photons and neutrinos decoupled while still relativistic and are known as "hot relics"). By calculating the hypothetical time and temperature of decoupling for non-relativistic WIMPs of a particular mass, it is possible to find their density. Comparing this to the measured density parameter of cold dark matter today it is possible to rule out WIMPs of certain masses as reasonable dark matter candidates.

Many theories of Dark Matter (DM) genesis are based upon the mechanism of “thermal freeze out”. In this process DM particles have a large initial thermal density which, as the temperature of the hot plasma of the early universe drops below the mass, dilutes away until the annihilation to lighter species becomes slower than the expansion rate of the universe and the comoving number density of DM particles becomes fixed. The larger this annihilation cross section the more the DM particles are able to annihilate and hence a thermal distribution with an exponential Boltzmann factor is maintained to a lower temperature, giving a lower final yield. An attractive feature of the freeze-out mechanism is that for renormalisable couplings the yield is dominated by low temperatures with freeze-out typically occurring at a temperature a factor of $20 - 25$ below the DM mass, and so is independent of the uncertain early thermal history of the universe and possible new interactions at high scales.

There is an alternate mechanism, “freeze-in”. Suppose that at temperature

T there is a set of bath particles that are in thermal equilibrium and some other long-lived particle X, having interactions with the bath that are so feeble that X is thermally decoupled from the plasma. We make the crucial assumption that the earlier history of the universe makes the abundance of X negligibly small, whether by inflation or some other mechanism. Although feeble, the interactions with the bath do lead to some X production and, for renormalisable interactions, the dominant production of X occurs as T drops below the mass of X (providing X is heavier than the bath particles with which it interacts). The abundance of X "freezes-in" with a yield that increases with the interaction strength of X with the bath. Freeze-in can be viewed as the opposite process to freeze-out. As the temperature drops below the mass of the relevant particle, the DM is either heading away from (freeze-out) or towards (freeze-in) thermal equilibrium. Freeze-out begins with a full T^3 thermal number density of DM particles, and reducing the interaction strength helps to maintain this large abundance. Freezein has a negligible initial DM abundance, but increasing the interaction strength increases the production from the thermal bath. These trends are illustrated in Figure 7, which shows the evolution with temperature of the dark matter abundance according to, respectively, conventional freeze-out, and the freeze-in mechanism.

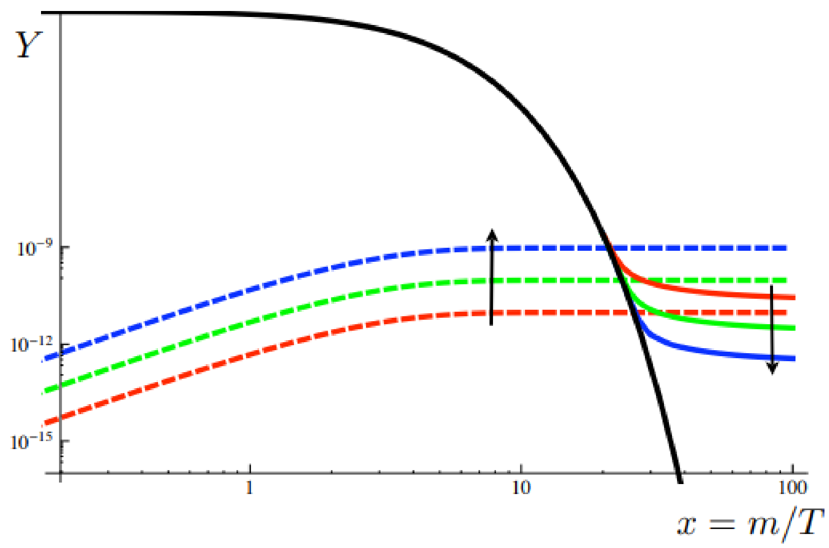

Figure 7: Log-Log plot of the evolution of the relic yields for conventional freezeout (solid coloured) and freeze-in via a Yukawa interaction (dashed coloured) as a function of $x = m/T$. The black solid line indicates the yield assuming equilibrium is maintained, while the arrows indicate the effect of increasing coupling strength for the two processes. Note that the freeze-in yield is dominated by the epoch $x \sim 2-5$, in contrast to freeze-out which only departs from equilibrium for $x \sim 20-30$ [20].

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 [21].

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:

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

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 10^{10} 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 $\beta-$decay experiments at Troitsk and Mainz [22], 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 stable, 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 $50\ MeV \leq m_\nu \leq 130\ MeV$ [23].

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:

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

As shown in [24], 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 [25] 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 [26]). 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 [27]. 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 [28], 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 [29,30] 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 [31,32] (the limitation was obtained by simulating the effect of different neutrino masses on the Lyman-alpha Les spectra):

$$m_{sterile} \geq 14 \text{ keV}. \quad (14)$$

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 [33] at Los Alamos and the subsequent $MiniBooNE$ [34] 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 [35] using an artificial source $\bar{\nu_e}$ ^{51}Cr.

Finally, the existence of a reactor antineutrino anomaly was announced [36]. 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. MIRROR MATTER

In physics, mirror matter, also called shadow matter or Alice matter, is a hypothetical counterpart to ordinary matter. It is currently being considered as a possible component of invisible dark matter.

The history of "mirror particles"began with the fact that in the mid-1950s Yang and Li put forward the theory of the parity degeneracy of particles in connection with the decay of a positive kaon. Then Landau proposed a temporary solution to the problem, calling mirror particles - antiparticles that differ from particles only in the sign of their charge. It was then that the idea of combined CP symmetry was born. However, the decays of the neutral kaon led to the violation of CP symmetry. After that, Okun, Pomeranchuk and Kobzarev suggested that each particle and antiparticle should have its own "mirror particle which differs only in Alice's number. A new type of symmetry was also introduced - CPA symmetry. The operation of mirroring is called the A-transformation [37].

Mirror particles interact amongst themselves in the same way as ordinary particles, except where ordinary particles have left-handed interactions, mirror particles have right-handed interactions. In this way, it turns out that mirror reflection symmetry can exist as an exact symmetry of nature, provided that a "mirror"particle exists for every ordinary particle. Parity can also be spontaneously broken depending on the Higgs potential [38,39]. While in the case of unbroken parity symmetry the masses of particles are the same as their mirror partners, in case of broken parity symmetry the mirror partners are lighter or heavier.

Mirror matter, if it exists, would need to use the weak force to interact with ordinary matter. This is because the forces between mirror particles are mediated by mirror bosons. With the exception of the graviton, none of the known bosons can be identical to their mirror partners. The only way mirror matter can interact with ordinary matter via forces other than gravity is via kinetic mixing of mirror bosons with ordinary bosons. These interactions can only be very weak. Mirror particles have therefore been suggested as candidates for the inferred dark matter in the universe [40–44].

Mirror matter could have been diluted to unobservably low densities during the inflation epoch. Sheldon Glashow has shown that if at some high energy scale particles exist which interact strongly with both ordinary and mirror particles, radiative corrections will lead to a mixing between photons and mirror photons [45]. This mixing has the effect of giving mirror electric charges a very small ordinary electric charge. Another effect of photon–mirror photon mixing is that it induces oscillations between positronium and mirror positronium. Positronium could then turn into mirror positronium and then decay into mirror photons. The mixing between photons and mirror photons could be present in tree level Feynman diagrams or arise as a consequence of quantum corrections due to the presence of particles that carry both ordinary and mirror charges. In the latter case, the quantum corrections have to vanish at the one and two loop level Feynman diagrams, otherwise the predicted value of the kinetic mixing parameter would be larger than experimentally allowed [45].

If mirror matter does exist in large abundances in the universe and if it interacts with ordinary matter via photon-mirror photon mixing, then this could be detected in dark matter direct detection experiments such as DAMA/NaI and its successor DAMA/LIBRA. In fact, it is one of the few dark matter candidates which can explain the positive DAMA/NaI dark matter signal whilst still being consistent with the null results of other dark matter experiments [46, 47].

5. 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.

Estimation of the modern WIMP density [48]:

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

at that $< \sigma_{ann} \upsilon >_{max} \approx 1/m^2_{WIMP}$ [49, 50].

Restriction on the mass of WIMPs [49]:

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

WMAP data [16] give more stringent restrictions [51]:

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

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 [52], LUX [53], DarkSide [54], XENON [55], DAMA [56], 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 8).

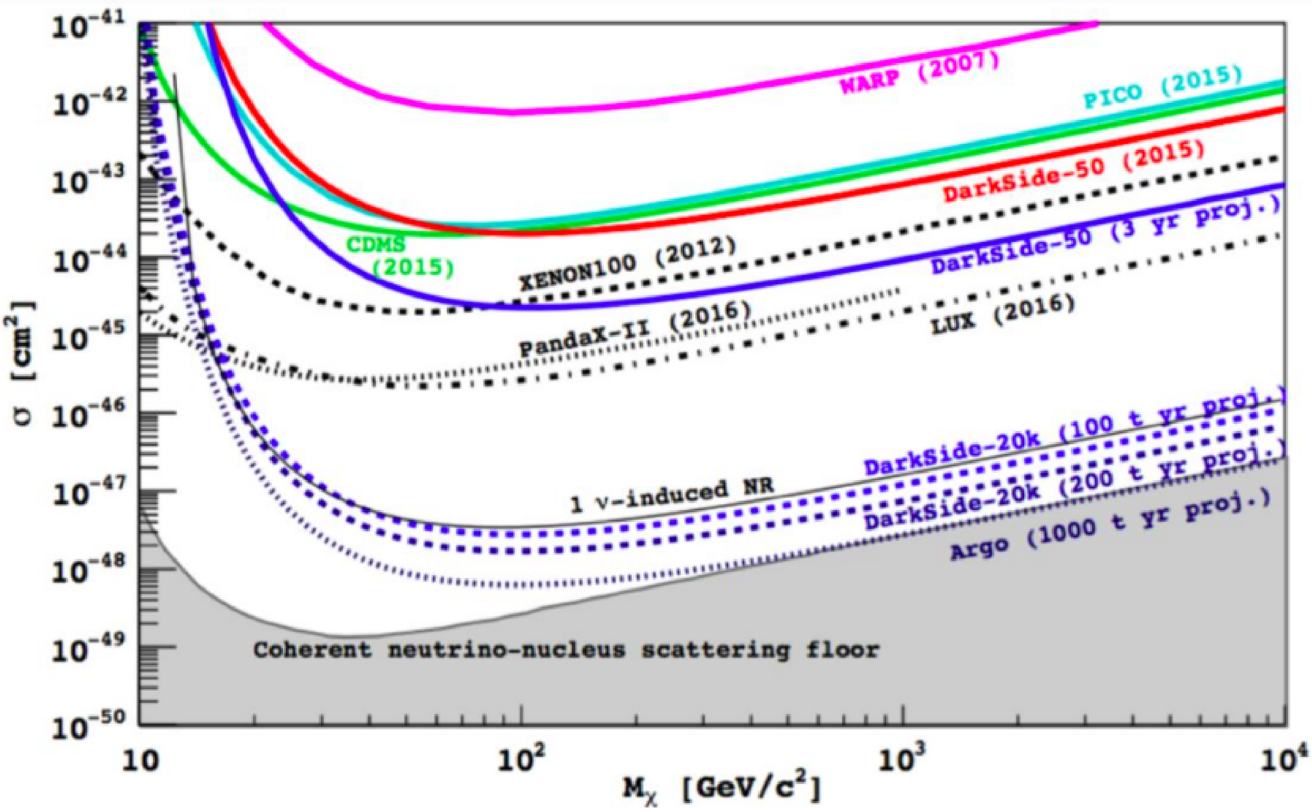

Figure 8: The spaces above the curves show the regions of parameters in which the corresponding experiments to search for WIMPs have worked or will begin their work.

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.

6. SUPERSYMMETRIC PARTICLES

According to cosmology, which provides observational evidence for the existence of dark matter, it is non-baryonic and cannot be explained by the Standard Model (SM) of particle physics. In addition, within the framework of this theory, it is not possible to explain why much more matter is observed in the Universe than antimatter. At the same time, there is still the problem of hierarchy and the problem of fine tuning. Therefore, in recent decades, theories have been actively developed that extend the SM and have an advantage in solving its internal problems. For example, supersymmetric (SUSY) generalizations of the SM have been widely considered. SUSY models are attractive as a solution to the problem of the divergence of the Higgs boson mass and can offer stable particles as candidates for dark matter [57, 58].

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 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 [59], 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.

7. KALUZA-KLEIN PARTICLES

The Kaluza-Klein particle is a cold, single-particle, symmetric, stable, 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. New DM candidate: the LKP (Lightest Kaluza–Klein Particle) which interacts with SM particles and is stable because of a Kaluza–Klein parity. The LKP arises in a generic class of models in which all fields propagate in extra dimensions. The model has many attractive features, including the fact that a relatively small number of parameters are sufficient to describe the LKP. Essentially one: its mass, which at tree level is the inverse of the compactification radius. The LKP is a Kaluza-Klein photon or it is a Kaluza–Klein neutrino.

For the LKP to be a well-motivated dark matter candidate, it should be electrically neutral and non-baryonic. Thus, the most promising candidates in the UED picture are first level KK modes of the neutral gauge bosons (analogues of the KK modes of the photon and Z), and the KK neutrino. One could also consider the first KK mode of the graviton, though this case seems less promising because its very weak gravitational interactions would imply that it will annihilate much less efficiently and could easily overclose the universe. Since similar incalculable loop corrections render the graviton mass a separate input of the theory, may simply consider that the graviton is heavier than the LKP, such that at the time scales of interest to us all of the KK gravitons have already decayed into the LKP and zero modes.

One advantage of this model is that the physics is dominated by a single parameter: the size of the extra dimension, R. Interestingly, for the UED model to explain the Dark Matter with the LKP, we find that R typically has to be of

the TeV scale, which is phenomenologically interesting and relevant at future colliders. Similarly to other WIMPs, the direct search for the LKP relies on the deposition of $\sim keV$ recoil energy when the WIMP scatters from a nucleus in a detector. In addition, indirect WIMP searches rely on the detection of γ rays, charged particles or neutrinos from WIMP annihilation. There are two places where annihilation can take place:
1)In the Sun where the LKP may be captured and annihilation greatly enhanced. This will generate a neutrino spectrum. The prediction essentially depends on the competition between the gravitational capture of the LKP by the Sun and the LKP annihilation so we would need to know the details of the capture rates and of the propagation of the neutrinos from the core to the surface of the Sun to make any statement.
2)In the core of the Milky Way. LKP annihilation is important in the galactic center where the matter density is higher. To compute the resulting spectrum, one needs to know the reprocessing of the direct products of LKP annihilation.

Estimates for the masses of the lightest KK-excitations [60]:

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

8. SUPER WIMP OR FEEBLY INTERACTING MASSIVE PARTICLES (FIMP)

The main difference between FIMPs 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 presence of a peak in the spectrum of diffuse gamma quanta could signal the presence of FIMPs.

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 FIMPs. In models with axions [61], 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 [62].

9. 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 [63].

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 [64, 65]. Almost stable, they could survive to this day.

Such superheavy particles can decay and annihilate relatively close to the Earth.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.

10. Q-BALLS

Supersymmetric generalizations of the Standard Model, in particular the MSSM, predict the existence of non-topological solitons called Q-balls [66]. 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 [67].

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 $100\,\text{GeV} \leq m_0 \leq 100\,\text{TeV}$. The baryon number of a stable soliton should be greater than $10^{15}\left(\frac{m_0}{1\ \text{TeV}}\right)^4$.

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 [68]:

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

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 [69].

11. TOPOLOGICAL DEFECTS

Topological defect (topological soliton) is a solution of a system of partial differential equations or equations of quantum field theory that is homotopically different from the vacuum solution. Examples are solitons, which exist in many exactly solvable models, screw dislocations in crystalline materials, skyrmions, and the Wess-Zumino-Witten model in quantum field theory. Homotopy theory is deeply related to the stability of topological defects. In the case of linear defects, if a closed path can be continuously deformed to one point, then the defect is unstable, and otherwise it is stable.

Some Grand Unification Theories (GUT) predict topological defects that must have formed in the early universe. Several GUTs have been proposed, but none are currently generally accepted. The most promising candidate is $SO(10)$ [70, 71]. $SO(10)$ (minimum GUT model) does not contain any exotic fermions (that is, additional fermions in addition to the fermions and right-handed neutrinos contained in the Standard Model), and it combines each of their generations into a single irreducible representation. A number of other GUT models are based on subgroups from $SO(10)$. Among them: the minimal left-right model, $SU(5)$, inverted $SU(5)$, and the Pati - Salam model. The GUT group E_6 contains $SO(10)$, but the models based on it are much more complicated. The main reason for studying the E_6 model follows from $E_8 \times E_8$ heterotic string theory. GUT models generally predict the existence of topological defects such as magnetic monopoles, cosmic strings, domain walls, and others. But none of these objects have yet been discovered. Their absence is known as the monopole problem in cosmology.

The existence of a topological defect can be demonstrated whenever the boundary conditions entail the existence of homotopically distinct solutions. Typically, this occurs because the boundary on which the conditions are specified has a non-trivial homotopy group which is preserved in differential equations; the solutions to the differential equations are then topologically distinct, and are classified by their homotopy class. Topological defects are not only stable against small perturbations, but cannot decay or be undone or be de-tangled, precisely because there is no continuous transformation that will map them (homotopically) to a uniform or "trivial"solution. The homotopy theory of defects uses the fundamental group of the order parameter space of a medium to discuss the existence, stability and classifications of topological defects in that medium [72]. Suppose R is the order parameter space for a medium, and let G be a Lie group of transformations on R. Let H be the symmetry subgroup of G for the medium. Then, the order parameter space can be written as the Lie group quotient [73] $R = G/H$. If G is a universal cover for G/H then, it can be shown [73] that $\pi_n(G/H) = \pi_{n-1}(H)$, where pi_i denotes the i-th homotopy group. Various types of defects in the medium can be characterized by elements of various homotopy groups of the order parameter space. For example, (in three dimensions), line defects correspond to elements of $\pi_1(R)$, point defects correspond to elements of $\pi_2(R)$, textures correspond to elements of $\pi_3(R)$.

Topological defects, of the cosmological type, are extremely high-energy. In the Big Bang theory, the universe cools from an initial hot, dense state triggering a series of phase transitions much like what happens in condensed-matter systems such as superconductors. Grand Unified Theories predict the formation of stable topological defects in the early universe during these phase transitions. Topological defects have not been observed by astronomers; however, certain types are not compatible with current observations. In particular, if domain walls and monopoles were present in the observable universe, they would result in significant deviations from what astronomers can see. Because of these observations, the formation of defects within the observable universe is highly constrained. On the other hand, cosmic strings have been suggested as providing the initial 'seed'-gravity around which the large-scale structure of the cosmos of matter has condensed.

If cosmic strings or other topological defects can form during a cosmological phase transition, then they will form. This was first pointed out in a cosmological context by Kibble, therefore the defect formation process is known as the Kibble mechanism. The simple fact is that causal influences in the early universe (as at any other time) can only propagate with the speed of light c. This means that at the moment of time t, the regions of the Universe separated by a distance more than $d = ct$ cannot know anything about each other. During the phase transition of symmetry breaking, different regions of the Universe will fall into different minima from a set of possible states (this set is known to mathematicians as a vacuum manifold). Topological defects are precisely the "boundaries"between such regions with differently chosen minima, and their formation is, in accordance with this, an inevitable consequence of the fact that different regions cannot agree on their choices.

Depending on the nature of symmetry breakdown, various solitons are believed to have formed in the early universe according to the Kibble-Zurek mechanism. The well-known topological defects are:

1) Cosmic strings are one-dimensional lines that form when an axial or cylindrical symmetry is broken.

2) Domain walls, two-dimensional membranes that form when a discrete symmetry is broken at a phase transition.

3) Monopoles, cube-like defects that form when a spherical symmetry is broken, are predicted to have magnetic charge, either north or south (and so are commonly called "magnetic monopoles").

4) Textures form when larger, more complicated symmetry groups are completely broken. They are not as localized as the other defects, and are unstable.

5) Skyrmions.

6) Extra dimensions and higher dimensions.

Other more complex hybrids of these defect types are also possible. As the universe expanded and cooled, symmetries in the laws of physics began breaking down in regions that spread at the speed of light; topological defects occur at the boundaries of adjacent regions. The matter composing these boundaries is in an ordered phase, which persists after the phase transition to the disordered phase is completed for the surrounding regions.

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. 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 [74]. The lower estimate for the mass of the Dirac monopole can be estimated based on the classical radius of the electron:

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

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 [75] 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 [76].

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 [77]:

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

13. 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 [78]:

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

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.

14. 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) [79]. 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.

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

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

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

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 [93].

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 [7, 80–82, 92]:

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

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 [83, 84], 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 [85]:

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

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 [86]. 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 [87–90]. 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 [8,91]. 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.

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 dark matter [92–94].

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	
v, 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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