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Referat on the “Introduction to cosmoparticle physics" course on the topic:

« DARK MATTER CANDIDATES IN STANDARD MODEL EXTENSIONS»

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TABLE OF CONTENTS

Introduction

Practically all modern elementary particles physics is currently described by the Standard Model (SM) [1]. It's a theoretical construction that includes all known interactions at the present moment, except for the gravitational one. Though it's a mathematical representation of the physical processes of the microworld, however, it leaves unsolved a large number of questions (such as mass hierarchies problem etc.). There are many indications that SM can be a low-energy limit of some more general theory, just as Galileo's principle of relativity is a special case of Einstein's relativity principle in Newtonian mechanics. That's why the issue of the Standard Model extending to a theory that is capable to describe microworld processes more fully and in detail as well as resolve the problems existing within the SM theory is extremely actual at the moment.

For the searching of "new physics" beyond the SM, there are basically two possible ways. One of them is studying of processes with the probable creation of hypothetical new particles, the other is searching for manifestations of the "new physics" in already known interactions [2]. It should, however, be borne in mind that the experimental confirmation of the theories using the first approach may not be possible at the present time due to the probable presence of the particles of the "new physics" only at higher energies that have not yet been achieved on accelerators.

This abstract is devoted to one of many hypothetical extensions of the Standard Model, the "Small Higgs" theory, in which the Higgs boson is not a fundamental, but a constituent particle, which leads to the elimination of some theoretical problems of the Standard Model.

This referat is devoted to some hypothetical extensions of the Standard Model, that leads to solutions of some theoretical problems of the Standard Model, and also provides opportunities for solving one of the most important problems of cosmology - the problem of dark matter searching.

1. Problems of the Standard Model

The Standard Model is a theory of strong and electroweak interactions based on the SU(3) xSU(2) xU(1) gauge group. The described interactions are gauge so they are carried out by exchange of gauge bosons: photons in the case of electromagnetic interactions, gluons in strong interactions and W and Z in the case of weak interactions.

In contrast to massless photons and gluons, W and Z are massive particles (with a mass of the order of 100 GeV). The presence of a mass of these particles is a consequence of the symmetry breaking with respect to the SU(2) xU(1) group. It can be a consequence of the existence of some scalar field. The expected vacuum value of this field leads to the presence of a certain direction in the space of generators of the group SU(2) xU(1). Then the fact of the presence of the mass of elementary particles (leptons, gauge ozone, etc.) is a consequence of the particles interactions with the given scalar field. The quantum of this field is Higgs boson.

However, the Higgs boson explains only the fact of electroweak symmetry breaking, but not it's mechanism. This theory does not explain why the potential of the Higgs field is unstable at zero. Therefore, the electroweak sector is apparently an interesting area for the search for "New Physics" that goes beyond the SM.

2."Little Higgs" model

2.1 Main idea

An analysis of the experimental data makes possible to make an unambiguous conclusion about the fact of electroweak symmetry breaking but the mechanism of this breaking is still not understood.

If one assumes that there are no new particles with masses smaller than the scale of the electroweak sector then the "new physics" in the electroweak sector is realised by multidimensional operators suppressed by the energy scales of the "new physics" (Λ~TeV). These operators can be classified according to the symmetries that they violate. For example, it can be violation of CP - symmetry and symmetry of flavours. Thus, these operators impose strict restrictions on the preservation of symmetries on the investigated scale ~ 1 TeV and SM extensions should not violate this boundary.

For understanding of the Higgs-boson mass stabilising possibility without violating these limitations, it is necessary to consider the reasons of the instability of the Higgs mass.

Let's now consider the main radiative corrections to the mass of the Higgs boson: one-loop diagrams with t-quarks (Fig. 1a), SU(2) gauge bosons (Fig. 1b) and Higgs boson (Fig. 1c) loops.

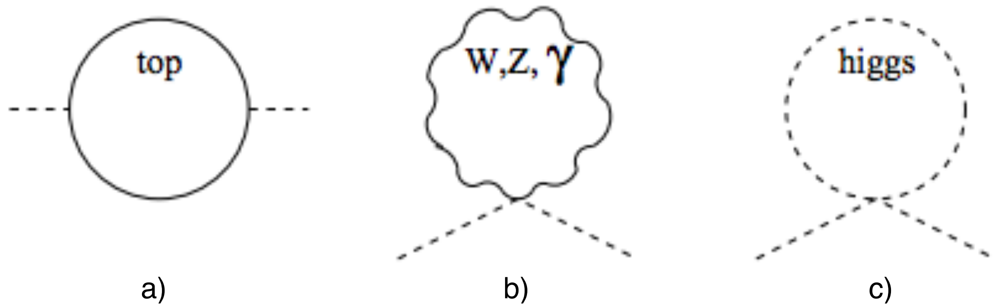

Fig. 1. Basic radiative corrections to the mass of the Higgs boson: a) single-loop diagrams with t-quarks b) single-loop diagrams with virtual Z and W bosons c) single-loop diagrams with Higgs bosons.

The contribution of the one-loop diagram is proportional to the square of the coupling constant [3], and this in turn is proportional to the mass of the virtual particle being formed. Since the mass of the t-quark significantly exceeds the masses of the other quarks (170 GeV is significantly higher than the next b-quark mass of the order of 4 GeV), all other contributions can be neglected. The remaining possible diagrams will give significantly lower contributions due to the smallness of their coupling constants in comparison with those considered.

If we assume that the SM remains true at energy scales of Λ ~ 10 TeV then the considered diagrams give a definite contribution to the mass of the Higgs boson (Table 1).

Diagram	Operator	contribution to $(m_H)^2$
t-quark loop	$-\frac{3}{8\pi^2}\lambda_t^2\Lambda^2$	~(2 ТэВ)^2
SU(2) - bosons loop	$\frac{9}{64\pi^2}g^2\Lambda^2$	~(700 ТэВ)^2
Higgs-bosons loop	$\frac{1}{16\pi^2}\lambda_t^2\Lambda^2$	~(500 ТэВ)^2

Table. 1. The contribution of the diagrams to the squared mass of the Higgs boson.

For the Higgs boson's mass remaining at the electroweak scale, the energy scale of cutting should be:

1) for a loop diagram with a top quark: $\Lambda \leq 2$ TeV;
2) for the loop diagram with gauge bosons: $\Lambda \leq 5$ TeV;
3) for the loop diagram with the Higgs-loop: $\Lambda \leq 10$ TeV.

Consequently, at the scale of energies of the order of 2 TeV one can expect the manifestation of a "new physics" associated with truncation of the divergent t-quark loop. It means that there have to exist new particles generating new loop diagrams that reduce the contribution from loops with the t-quark with the mass is equal to ~ 2 TeV and related by some symmetry to the t-quark.

Similarly at a scale of energies of the order of 5 TeV there must be new particles which are connecting with a similar type of symmetry with gauge bosons of the Standard Model, and at energies of the order of 10 TeV there must be new particles that cut the divergent loop with the Higgs boson.

One of the SM extensions solving this problem is the Little Higgs model,where the Higgs boson is a pseudo-Nambu-Goldstone boson. In this case global symmetries lead to a shift of the Higgs fields and as a result the Higgs mass does not contain single-loop divergences.

2.2 Nambu-Goldstone bosons

Nambu-Goldstone bosons are particles that arise due to spontaneous global symmetry breaking [4]. The simplest example is the case of an the U(1) group.

Suppose that we have a scalar field φ with a potential V (φ*φ). The U(1) group involves the invariance of the potential with respect to the transformations:

$$\varphi \to \varphi \cdot e^{i\alpha}. \tag{1}$$

Because of the minimum of the potential is not equal to zero but at some point f>0 (Figure 2) , U(1) symmetry spontaneously breaks.

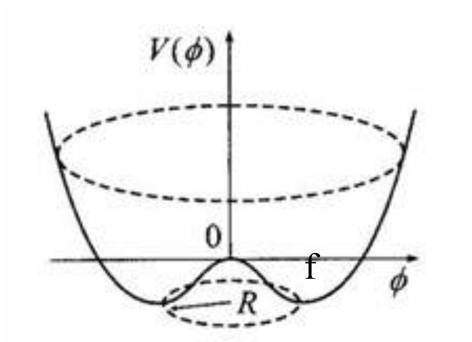

Fig. 2. Potential of spontaneous symmetry breaking of the U(1) group.

Let's assume that the deviations of the field from the minimum are small. In this case, the field near the vacuum value can be expanded in a series:

$$\phi(x) = \frac{1}{\sqrt{2}}(f + r(x)) \cdot \exp\left[\frac{i\theta(x)}{f}\right], \tag{2}$$

where r(x) is a massive radial mode, and θ (x) is a Nambu-Goldstone boson (NGB).

Because of the radial field r(x) must be invariant with respect to U(1) transformations, it can be shown that θ undergoes a shift to satisfy this condition: (3)

θ→θ+α, α<<θ.

It is important to note that the resulting effective Lagrangian must not contain the mass term of the field θ (x). The general form of the NGB Lagrangian is:

$$L = const + f^2 \left|\partial_\mu \phi\right|^2 + O\left(\partial^4\right). \tag{4}$$

2.3. Nambu-Goldstone bosons in non-abelian case

In the case of a spontaneous breaking of a non-abelian symmetry group each violated generator leads to the formation of one Nambu-Goldstone boson.

For example one can consider the case of violation of SU(N) -> SU (N-1) due to the expectation value of the vacuum field φ. The number of generators of the group decreases from $(N)^2$-1 to $(N-1)^2$-1 so the number of violated generators is:

$$(N)^2-1-((N-1)^2-1) = 2N-1.$$

It is convenient to use the following form: (5)

$$\phi = \exp\left[\frac{i}{f}\left(\begin{array}{ccc|c} \ddots & & \iddots & \pi_1 \\ & 0 & & \vdots \\ \iddots & & \ddots & \pi_{N-1} \\ \hline \pi_1^+ & \cdots & \pi_{N-1}^+ & \pi_0/\sqrt{2} \end{array}\right)\right]\begin{pmatrix} 0 \\ \vdots \\ f \end{pmatrix} = e^{\frac{i\pi}{f}}\phi_{0}, \tag{6}$$

The π_0 field is real and the remaining ones are complex.

2.4. Little Higgs formation

Let's consider the SU (3) -> SU (2) symmetry breaking. h is the doublet with respect to the undisturbed symmetry of the SU (2) group, as required by the Standard Model mechanism. However, since he undergoes a shift relative to the breaking of the SU (3) symmetry, h is a Nambu-Goldunian boson.

In this case:

$$\pi = \left(\begin{array}{cc|c} -\eta/2 & & h \\ & \eta/2 & \\ \hline h^+ & & \eta \end{array}\right) \tag{7}$$

moreover, the field η is a singlet with respect to SU (2).

Then:

$$\phi = \exp\left[\frac{i}{f}\begin{pmatrix} 0 & h \\ h^+ & 0 \end{pmatrix}\right]\begin{pmatrix} 0 \\ f \end{pmatrix} = \begin{pmatrix} 0 \\ f \end{pmatrix} + i\begin{pmatrix} 0 \\ h \end{pmatrix} - \frac{1}{2f}\begin{pmatrix} 0 \\ h^+h \end{pmatrix} \tag{8}$$

and:

$$f^2\left|\partial_\mu \phi\right|^2 = \left|\partial_\mu h\right|^2 + \frac{\left|\partial_\mu h\right|^2 h^+ h}{f^2}, \tag{9}$$

which describes the interaction suppressed by the symmetry breaking scale f. To determine the scale of the cutoff Λ, the contribution of the divergent one-loop diagram is taken into account in the second summand of the kinetic term. In case of cutting the divergence on the scale Λ, we find that the kinetic term is proportional to $\frac{1}{f^2}\frac{\Lambda^2}{16\pi^2}$. Based on the requirements on the coupling constant ≥1, we obtain the condition $\Lambda < 4\pi f$.

The next step is the construction of gauge interactions. It is important, however, to remember that the mechanism of gauge interactions should not contain quadratic divergences. For this, two Nambu-Goldoun bosons φ1 and φ2 are considered. Parametrize them:

$$\phi_1 = \exp\left(\frac{i\pi_1}{f}\right)\begin{pmatrix} \\ f \end{pmatrix}, \phi_2 = \exp\left(\frac{i\pi_2}{f}\right)\begin{pmatrix} \\ f \end{pmatrix}, \tag{10}$$

taking into account that the vacuum mean fields are the same: f1 = f2 = f.

Then the Lagrangian of such a system can be written as follows:

$$L = \left|D_\mu \phi_1\right|^2 + \left|D_\mu \phi_2\right|^2. \tag{11}$$

It includes the following diagrams:

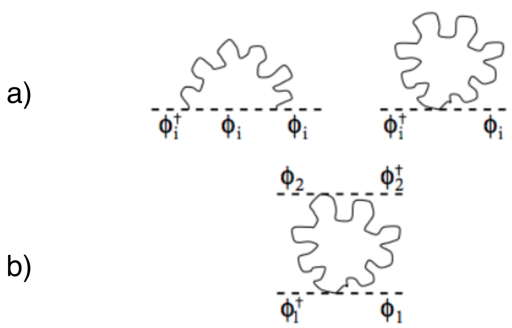

Fig. 3. Corrections to the interaction potential of one (a) and two (b) fields.

Contribution from diagrams containing only one field φ1 or φ2 (Figure 3a):

$$\frac{g^2}{16\pi^2}\Lambda^2\left(\phi_1^+\phi_1+\phi_2^+\phi_2\right)=\frac{g^2}{16\pi^2}\Lambda^2\left(f^2+f^2\right). \tag{12}$$

And from a diagram containing simultaneously the fields φ1 or φ2 (Fig. 3b):

$$\frac{g^2}{16\pi^2}\log\left(\frac{\Lambda^2}{\mu^2}\right)\left|\phi_1^+\phi_2\right|^2. \tag{13}$$

Forasmuch as:

$$\left|\phi_1^+\phi_2\right|=f^2-2h^+h+\ldots, \tag{14}$$

equation (13) can be rewritten in the form:

$$\frac{g^2}{16\pi^2}\log\left(\frac{\Lambda^2}{\mu^2}\right)f^2. \tag{15}$$

If the constant g is the coupling constant of SU(2) group, then f~1 TeV, and the contribution to the squared mass of the Higgs boson is ~v^2, which agrees with the Standard Model. In this case one-loop quadratic divergences in the mass of the Higgs boson are absent.

3. Experimental evidence of the "little Higgs"

All of the "little Higgs" models regardless of their implementation [5] include a vector-like quark that shortens the divergence of the single-loop t-quark diagrams, as well as a set of gauge bosons cuts bosonic loops.

The creation of these bosons occurs as a result of hadronic collisions, that is, one can expect the presence of these particles at the LHC experiment.

4. "Little Higgs" cosmological manifestation

Since the "little Higgs" model is a theory that considers the violation of electroweak symmetry, the natural step is to search for the cosmological manifestation of this model in the cosmology of the early Universe [6]. Specifically, of particular interest is the era of electroweak interactions, that is, the period between 1 10^{-32} and 10^{-12} seconds after the Big Bang, when the temperature of the Universe is high enough, and due to high energies such particles as W-boson, Z-boson and boson Higgs are formed [7].

It was shown above that the "little Higgs" model includes new particles on an energy scale of the order of 1 TeV. Since these particles are stable and weakly interacting, they can be candidates for the role of particles of dark matter, thus representing a solution to one of the main problems of modern cosmology [8].

According to the modern astrophysical representation, ordinary baryonic matter (intergalactic gas, stars, etc.) accounts for less than 5%, including ~ 68.5% of dark energy, ~ 0.5% of neutrinos, and the remaining 26.5% of dark matter [9]. Thus, almost 95% of the mass of the universe consists of a mass unknown to us at the moment, the study of which is of fundamental importance for cosmology [10].

4.1. ”Dark matter” problem

Let's consider the main evidence of the presence of dark matter [11]:

1) presence of rotation curves;
2) gravitational lensing;

4.1.1. Rotation curves

Galactic rotation curves are one of the most obvious proofs. According to Kepler's law, for the spiral galaxy the following relationship must be hold:

$$v^2(r) = \frac{G \cdot M(r)}{r},$$

where G is the gravitational constant and M(r) is the mass concentrated inside the cluster of radius r. It can be expressed as:

$$M(r) = \int \rho(r) r^2 \, dr,$$

where ρ (r) is the density distribution of matter inside the cluster.

In the outer region of the galaxy, the mass M(r) is practically constant and the velocity dependence on the distance corresponds to the case with a point mass in the center of the galaxy:

$$v(r) \sim \frac{1}{\sqrt{r}}.$$

The rotation speed v(r) is determined, for example, by measuring the Doppler shift in the emission spectrum of the He-II regions around the O-stars. However, the experimental data indicate that, with the distance from the center of the galaxy, the rotational velocity remains practically unchanged: $v(r) \approx const$.

The constancy of v(r) for large values of the radius means that the mass Mr also increases with increasing radius: Mr ~ r. This indicates the presence of invisible matter. The stars move faster than one would expect on the basis of the apparent amount of matter. As an example of such a measurement, we can give results for the spiral galaxy M33 (Fig. 4) [12].

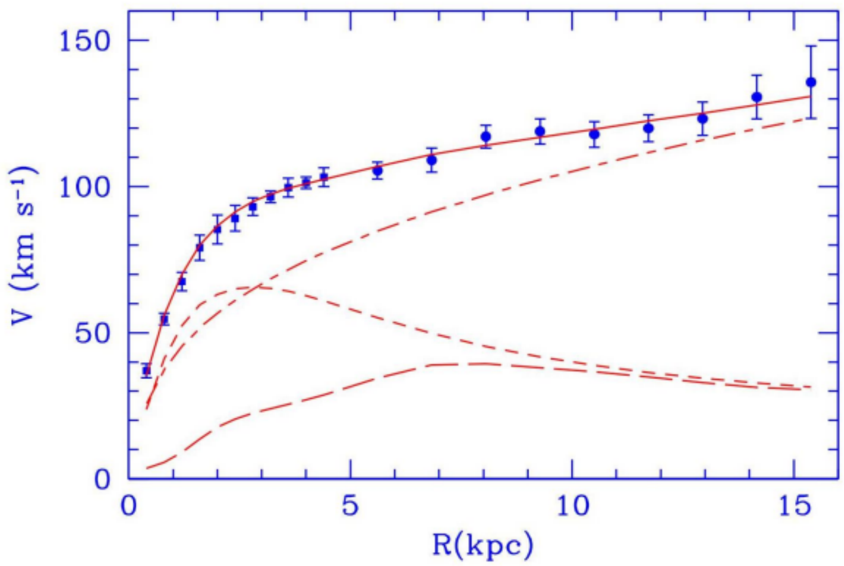

Fig. 4. Experimental rotational curve for the M33 spiral galaxy. The dot-dashed line takes into account the contribution of the halo to the theoretical model, and the short and long dotted line represents the stellar disk and the gas contribution, respectively.

4.1.2. Gravitational lensing

The phenomenon of gravitational lensing is the deflection of electromagnetic radiation near massive bodies. As a rule, for appreciable image distortion, we need masses of the order of the size of galaxies or their clusters. Such gravitational lenses can be clusters of hidden mass, which is confirmed by the data obtained using the Hubble experiment. Gravitational lensing allows, in particular, to calculate the expected quantitative contribution of dark matter.

4.1.3 Non-baryonic nature of dark matter

Of particular interest is the consideration of the nature of the matter of dark matter. The evolution of the universe is described by the Friedman equations [13]:

$$\begin{cases} \left(\dfrac{\dot{a}}{a}\right)^2 = \dfrac{8\pi G}{3}\varepsilon - \dfrac{K}{a^2} \\ \dfrac{\ddot{a}}{a} = -\dfrac{4\pi G}{3}(\varepsilon + 3p) \end{cases}$$

where G is the gravitational constant, ε is the energy density, p is the matter pressure. K is the curvature parameter. The case K = 0 corresponds to a flat world, K = 1 to a open world, and K = -1 to a closed world. The Hubble parameter in the case of a flat world:

$$H = \frac{\dot{a}}{a}$$

is expressed by the first Friedmann equation:

$$(H)^2 = \frac{8\pi G}{3}\varepsilon_{crit},$$

where the corresponding energy density is called critical:

$$\varepsilon_{crit} = \frac{3H^2}{8\pi G}.$$

The density of the component of matter is measured in units of critical density:

$$\Omega = \frac{\varepsilon}{\varepsilon_{crit}},$$

Where ε is the density of this component.

To measure the energy density, one can obtain from Friedmann's equations that:

$$\begin{cases} \dot{\varepsilon} = -3H(\varepsilon + p) \\ \Omega = 1 + \dfrac{K}{a^2} \end{cases}$$

The total energy density, estimated from the experimental data [14]:

$$\Omega \approx 1 \pm 0.1.$$

On the other hand, the total barionic density of matter, performed on the luminosity of galaxies:

$$\Omega_{bar} < 0.04.$$

For more precisely conclusion it can be used the analysis of the Cosmic Microwave Background (CMB).

The CMB is background radiation originating from the propagation of photons in the early Universe (once they decoupled from matter). It is known to be isotropic at the 10^{-5} level and to follow with extraordinary precision the spectrum of a black body corresponding to a temperature T = 2.726 K.

The observed temperature anisotropies in the sky are usually expanded as:

$$\frac{\delta T}{T}(\theta,\phi) = \sum_{l=2}^{+\infty} \sum_{m=-l}^{+l} a_{lm} Y_{lm}(\theta,\phi)$$

where $Y_{lm}(\theta, \varphi)$ are spherical harmonics. The variance C_l of a_{lm} is given by:

$$C_l \equiv < |a_{lm}|^2 > \equiv \frac{1}{2l+1} \sum_{m=-l}^{+l} |a_{lm}|^2 .$$

If the temperature fluctuations are assumed to be Gaussian, as appears to be the case, all of the information contained in CMB maps can be compressed into the power spectrum, essentially giving the behavior of C_l as a function of l. (Fig. 5).

From the analysis of the Wilkinson Microwave Anisotropy Probe (WMAP) data alone, the following values are found for the abundance of baryons and matter in the Universe

$$\Omega_b h^2 = 0.024 \pm 0.001; \ \Omega_M h^2 = 0.14 \pm 0.02.$$

Taking into account data from CMB experiments studying smaller scales (with respect to WMAP), such as ACBAR [348] and CBI [411], and astronomical measurements of the power spectrum from large scale structure (2dFGRS, see Ref. [414]) and the Lyman α forest (see e.g. Ref.[167]), the constraints become [457]:

$$\Omega_b h^2 = 0.0224 \pm 0.0009;\ \Omega_M h^2 = 0.135 \pm 0.009.$$

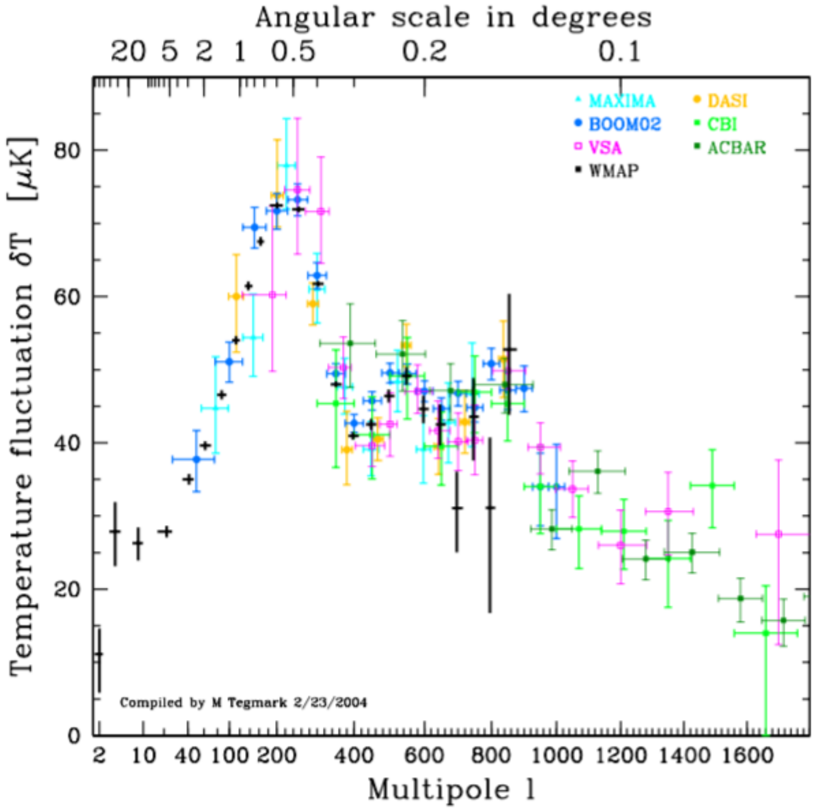

Figure 6: The observed power spectrum of CMB anisotropies. From Ref. [470].

The value of $\Omega_b h^2$ thus obtained is consistent with predictions from Big Bang nucleosynthesis (e.g. [403]) :

$$0.018 < \Omega_b h^2 < 0.023.$$

Besides those provided by CMB studies, the most reliable cosmological measurements are probably those obtained by Sloan Digital Sky Survey (SDSS) team, which has recently measured the three-dimensional power spectrum, P (k), using over 200,000 galaxies.

This discrepancy, firstly, is another confirmation of the fact of the presence of dark matter, and secondly - it makes possible to make a conclusion about the non-baryonic nature of the matter of dark matter.

4.2."Dark matter" problem's solution with "little Higgs" theory

4.2.1. Estimation of the density of dark matter

According to modern cosmological concepts, the density of matter of dark matter is in the range [15]

where h is Planck's constant and Ω_{DM} is the matter density of dark matter, measured in units of critical density.

On the other hand, it is possible to estimate the matter density of dark matter from the theoretical point of view [16]. In the early universe, dark matter particles were in thermal equilibrium with the rest of the cosmic plasma. In the process of cooling the universe, density decreases due to annihilation, which leads to the fact that for each particle annihilation becomes less likely due to a decrease in the concentration of the partner particles, therefore, over time the density will tend to a constant value, which corresponds to the stage of "freezing out" . Thus, the density of dark matter particles is completely determined at the time of freezing, which can be expressed by the condition of thermodynamic averaging of the cross section during the freezing time [17]:

$$\Omega_{\chi} h^2 \approx \frac{1.07 \cdot 10^{-9} GeV^{-1}}{M_{Pl}} \cdot \frac{x_F}{\sqrt{g_*}} \cdot \frac{1}{\langle \sigma v \rangle},$$

where M_{Pl} is the Planck mass, σv is the annihilation cross section of particles and antiparticles, and g_* is the number of relativistic degrees of freedom:

$$\langle \sigma v \rangle = 3 \cdot 10^{-26} sm^3 / \sec,$$

The x_F value parametrizes the freezing temperature and can be estimated from the solution of the equation:

$$x_F = \ln \left[c(c+2)\sqrt{\frac{45}{8}} \frac{g}{2\pi^3} \frac{m M_{Pl} \langle \sigma v \rangle}{\sqrt{g_*}\sqrt{x_F}} \right],$$

where c is a constant determined from the comparison of solutions for the early and late Universe.

As a result of solving this equation in the allowed range of matter density of dark matter:

$$0.094 < \Omega_{DM} h^2 < 0.126,$$

the following relation is obtained between the cut-off parameter f and the mass of dark matter:

$$f = 3.2M_{\chi} + 600,$$

where the mass and f are given in GeV.

4.2.1. Dark matter cross section of annihilation

On the other hand, we can consider the cross section for annihilation of particles and antiparticles [18]. The freezing out condition [19], in which the amount of particles of the hidden mass becomes constant:

where H is the Hubble parameter, σ_v is the annihilation cross section of particles and antiparticles, and n is the concentration of these particles. In order for the number of

$$H = n\langle \sigma v \rangle,$$

particles to correspond to the observed values, the annihilation cross section should be:

which in order of magnitude corresponds to weak interactions scale.

Since the little Higgs theory considers the electroweak sector of the Standard Model, the cross section for the annihilation of the produced particles is determined by the weak interaction, which ultimately leads to the conclusion that this theory does not contradict cosmological constraints and can be one of the possible candidates for dark matter particles

5. Sterile neutrinos

5.1. Theoretical model

Neutrinos are unique particles in the SM in that they interact solely through the weak interaction. As a consequence, in the SM, only the left-handed neutrino is active. A question then arises as to whether right-handed neutrinos exist and if they do, how do they fit into the SM? In the SM, right-handed neutrinos, if they exist, would be weak isospin singlets with no weak interactions except through mixing with the left-handed neutrinos. For this reason, the right-handed neutrinos are referred to as "sterile" neutrinos.

So, the sterile neutrino is a neutral lepton with no ordinary weak interactions except those induced by mixing. They are present in most extensions of the SM and can have any mass.

In details, a sterile (or singlet or right-handed) neutrino is an SU(2) singlet which does not take part in weak interactions except those induced by mixing with active (or left-handed) neutrinos. It may participate in, for example, Yukawa interactions involving the Higgs boson.

Chirality can be a conserved quantum number for massless fermions. However, fermion mass terms violate chirality and also break its equivalence to helicity, which is not a Lorentz invariant quantity. The chirality violation is due to the fact that a fermion mass term describes a transition between right and left chiral Weyl spinors:

$$-L = m\left(\overline{\psi_L}\psi_R + \overline{\psi_R}\psi_L\right),$$

where m has to be real and non-negative.

A Dirac neutrino mass term relates two distinct Weyl spinors:

$$-L_D = m_D\left(\overline{\nu_L}\nu_R + \overline{\nu_R}\nu_L\right) = m_D\overline{\nu_D}\nu_D$$

where ν_D is the Dirac field, ν_L and ν_R in a Dirac mass term are respectively active and sterile.

A Majorana mass term requires only one Weyl spinor. For an active neutrino ν_L:

$$-L_T = \frac{m_L}{2}\left(\overline{\nu_L}\nu_R^c + \overline{\nu_R^c}\nu_L\right) = \frac{m_L}{2}\overline{\nu_M}\nu_M$$

where ν_M is two-component Majorana field.

For a sterile neutrinos ν_R:

$$-L_S = \frac{M_R}{2}\left(\overline{\nu_L}\nu_R^c + \overline{\nu_R^c}\nu_L\right) = \frac{m_R}{2}\overline{\nu_{M_S}}\nu_{M_S}$$

where ν_{Ms} is a Majorana field.

When Dirac and Majorana mass terms are both present, one must diagonalize the resulting mass matrix:

$$-L = \frac{1}{2}\left(\overline{\nu_L^0}\nu_L^{0_c}\right)\begin{pmatrix} m_L & m_D \\ m_D & M_R \end{pmatrix}\begin{pmatrix} \nu_R^{0_c} \\ \nu_R^0 \end{pmatrix} + h.c.$$

The mass matrix can be diagonalized by a unitary matrix U:

$$U^+\begin{pmatrix} m_L & m_D \\ m_D & M_R \end{pmatrix}U^* = \begin{pmatrix} m_1 & 0 \\ 0 & m_2 \end{pmatrix}$$

because the matrix is symmetric.

5.2. Sterile neutrino as a Dark Matter candidate

The role of sterile neutrinos in cosmology strongly depends on the magnitude of their mass. For different choices of the mass scale, they can be responsible for various phenomena. The most interesting case is sterile neutino with keV masses.

A sterile neutrino is a neutral, massive particle and its lifetime can be very long. Therefore it is a possible DM candidate. However, to constitute 100% of the DM its mass should be above 0.4 keV. Indeed, as sterile neutrinos are fermions, they satisfy the so-called Tremaine-Gunn bound, i.e., their phase space distribution in a galaxy cannot exceed that of the degenerate Fermi gas. These quantities are very robust and close to the direct observables.

To be a DM candidate, keV sterile neutrinos need to be produced efficiently in the early Universe. Since they cannot thermalize easily, the simplest production mechanism is via mix- ing with the active neutrinos in the primordial plasma. Sterile neutrinos in equilibrium have the same number density as ordinary neutrinos, i.e., 112 cm^{-3}. With the lower bound on the sterile neutrino mass being 0.4 keV, this would lead to the energy density today $\rho_{sterile} \simeq 45$ keV/cm^3, which significantly exceeds the critical density of the Universe $\rho_{crit} = 10.5\ h^2$ keV/cm^3. Therefore, sterile neutrino DM cannot be a thermal relic. Assuming the validity of Big Bang theory already below T ~ 1 GeV, one can relate the sterile neutrino mass m_N and the mixing angle θ^2 needed to produce the correct DM abundance.

A keV sterile neutrino mixes with ordinary neutrinos. In the presence of sterile neutrinos, the leptonic weak neutral current is nondiagonal in mass eigenstates, so the N can decay at tree-level via Z-exchange. Its keV-scale mass makes the decay $N \rightarrow \nu_\alpha \nu_\beta \bar{\nu}_\beta$ possible (here α,β are neutrino flavors). The total decay width for $N \rightarrow 3\nu$ is given by:

$$\Gamma_{N\rightarrow 3\nu} = \frac{G_F^2 m_N^5}{96\pi^3} sin^2\theta = \frac{1}{4.7\times 10^{10}\,\sec}\left(\frac{m_N}{50keV}\right)^5 sin^2\theta,$$

and one requires that the corresponding lifetime should be much longer than the age of the Universe. This imposes a bound on the mixing angle θ^2 :

$$\theta^2 < 1.1\times 10^{-7}\left(\frac{50keV}{m_N}\right)^5 .$$

The production of the DM sterile neutrino via mixing becomes most efficient at temperatures T ~ 150 – 500 MeV resulting in the population of “warm” DM particles.

It has been demonstrated in many researches that resonantly produced sterile neutrino DM is fully compatible with all existing astrophysical and cosmological observations but, at the same time, it is “warm” enough to suppresses substructures in Milky-Way-size galaxies, consistent with observations. Therefore, the value of lepton asymmetry present in the plasma at these temperatures is an important parameter for such type of DM. It defines the fraction of CDM (when the spectra are approximated as CWDM mixture) and also the lifetime of the DM particles.

5. Conclusion

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