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«Elementary particle physics»

ABSTRACT:

The dark matter: simplified models

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Contents

Annotation

Our universe is made up of more than just visible matter. In fact, total contribution of baryonic matter accounts for as little as four percent of the total density of the universe. Twenty-three percent of our universe consists of the so-called dark matter, a type of matter that has so far only appeared through its gravitational effect and has not yet been detected. The dark matter is needed to describe various observable effects that could not be explained without their existence. The remaining 73% of our universe consists of a much less understood form of energy, the dark energy. The knowledge of the composition of our universe we owe to various experiments and measurements. Thus, from the fact of a flat universe, which fact can be confirmed by measurements of the background radiation [17], a connection can be deduced between the density of the dark energy and the total matter. Neglecting the radiation density ρ_s, and after introducing a density Ω normalized to the critical density ρ_c, the following relationship arises

$$\Omega_\lambda + \Omega_m = 1. \tag{1}$$

Here Ω_λ stands for the normalized density of the dark energy and Ω_m for the normalized density of the entire matter, including the total sum of the dark matter and the baryonic matter.

Another relationship between these two parameters can be established [18],

$$\Omega_\lambda = c + b \cdot \Omega_m \tag{2}$$

where the constants c and b can be determined from observations of the supernova explosions. By the two relations just mentioned one can conclude clearly on Ω_λ and Ω_m. This density can be determined from the power spectrum of the cosmic background radiation. Thus, the ratio of the height of the first peak to the height of the second peak gives a direct indication of the density of known baryonic matter

Ω_b [18]. If one summarizes all the results of the different measurements, the result is the familiar diagram describing the composition of our universe.

1. Evidence for dark matter

The existence of dark matter can be explained by three essential points. Thus, with the help of gravitational lenses, rotational velocities of stars in spiral galaxies and the structure of the universe one can infer the existence of matter, in addition to the baryonic matter. For example, the stars on the edge of spiral galaxies move at speeds far greater than they are likely to be due to visible matter and Kepler laws. If one assumes only a matter distribution, which corresponds to the visible one, would expect a drop of the rotation speed with $\frac{1}{\sqrt{R}}$ for large distances. Where R stands for the distance from the center of the galaxy. In fact, however, this drop could not be observed (see Fig. 1.). Thus, one can assume that more than just the visible mass must exist.

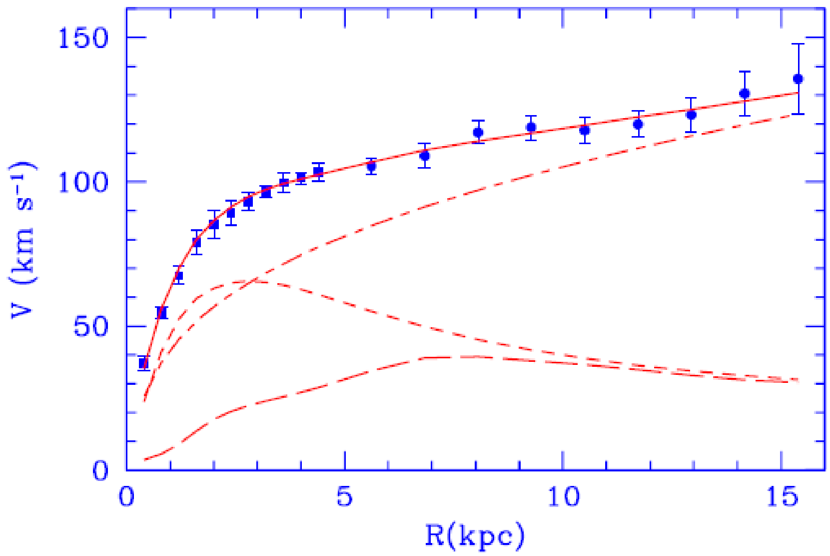

Figure 1. M33 rotation curve (points) compared with the best fit model (continuous line). Also shown the halo contribution (dasheddotted line), the stellar disk (short dashed line) and the gas contribution (long dashed line) [1].

Another evidence for DM existence and another method of measuring matter distribution in galaxies and clusters comes from gravitational lensing. For studying gravitational lensing in the beginning the most luminous clusters were selected. However, in modern times there are many clusters detected solely by lensing effects. Recent observations of Bullet cluster reveal separation of visible matter, inter cluster medium (ICM) and dark matter halo, which were individually located using X-ray observations and lensing technique. This is why Bullet cluster is often cited as one of the best astrophysical evidences for dark matter models.

Theoretically, effect of gravitational deflection of light, was firstly pointed out at the end of 18th century, independently by British, Henry Cavendish, and German, Johann G. von Soldner, physicists. They suggested that the light ray should deviate when passing close to massive celestial objects. With introduction of General relativity, Einstein recalculated the deflection angle in simple example of point-like objects. The correct value was shown to be two times larger than the one previously calculated in Newtonian mechanics:

$$\alpha = \frac{4GM}{bc^2}. \tag{3}$$

Here, α is the angle of deflection, *M* is the mass of gravitational lens, and *b* is the impact parameter of the bended light ray (fig. 2) [2].

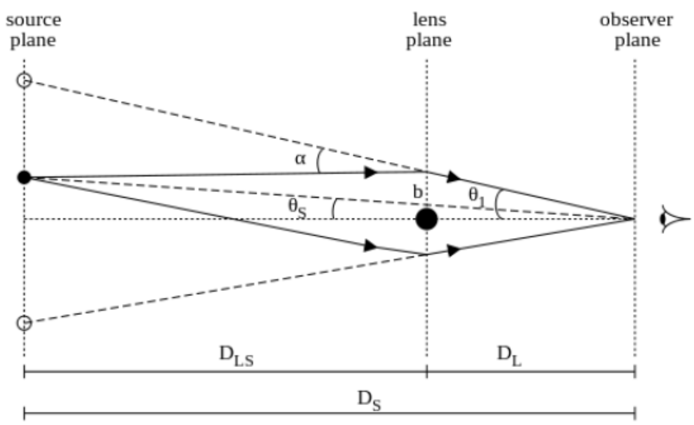

Figure. 2. Scheme of gravitational lensing [2]

1.1. Big Bang Nucleosynthesis

A critical prediction of the hot Big Bang cosmology is that protons and neutrons were fused to create the light elements, as it cooled to temperatures of the order of an MeV. Modulo the effect of neutrinos, the resulting elemental abundances depend only on the nuclear reaction rates and the baryon-to-photon ratio (η) at the time. The parameter η is completely equivalent to $\Omega_b h^2$ (up to a constant of proportionality), where Ω_b is the baryon density of the Universe and $h \equiv \frac{H_0}{100}$ km s^{-1} Mpc^{-1} is the dimensionless Hubble parameter. $H_0 \equiv \frac{v}{d}$ is the Hubble constant, describing the speed *v* at which galaxies at a distance *d* appear to be receding due to the expansion of the Universe. With observations of the true primordial abundances of the elements and an independent measurement of h, Big Bang Nucleosynthesis (BBN) therefore allows us to measure the primordial value of Ω_b.

The independent measurements of Ω_b from BBN and Ω_m from largescale structure together provide incontrovertible evidence for the existence of dark matter. Since matter essentially consists of baryons, $\Omega_m \approx 0.29.$ and $\Omega_m \approx 0.04$ together imply that the remaining $\Omega_{leftover} \approx 0.25$ must be dark matter. Furthermore, we have another invaluable piece of information about its nature: we see immediately that dark matter must be predominantly non-baryonic. Being non-baryonic allows the possibility that the dark matter is not interacting with photons electromagnetically (something baryons clearly are), which fits very well with the fact that it does indeed appear dark. This is also consistent with dark matter being dissipationless.[11]

It is worth mentioning that some amount of baryonic dark matter also remains unaccounted today $\Omega_b \approx 0.04$, in that it has not been directly observed in surveys of gas or galaxies. Nevertheless, we know this to be far less than what exists in non-baryonic dark matter. For the purposes of this thesis, ‘dark matter’ is taken as shorthand for the dominant, non-baryonic component.

1.2. Cosmic microwave background

Final confirmation comes from observations of the cosmic microwave background (CMB). The angular power spectrum of the CMB observed today is therefore sensitive to the full range of cosmological parameters which play a role in the evolution of the density fluctuations: the total energy density of the Universe, the baryon fraction and the spectral shape of the primordial perturbations. It is also sensitive to the large-scale geometry of the Universe since recombination, as the observed angular diameter of the characteristic scales frozen into the CMB at recombination depends upon the geometry of the space through which they have travelled to reach us. Thanks to the extremely high resolution of recent CMB missions, fits to the microwave background provide accurate measurements of the matter density of the Universe, as well as the baryon fraction. The 7-year Wilkinson Microwave Background Probe (WMAP) results [10] give posterior mean values of $\Omega_m = 0.267 \pm 0.026$, $\Omega_b = 0.0449 \pm 0.0028$, $\Omega_{DM} = 0.222 \pm 0.026$. These results are in excellent agreement with those obtained from BBN and large-scale structure, confirming the need for non-baryonic dark matter beyond any doubt. The fluctuations have been measured with an impressive accuracy, most recently by the Planck satellite also, leading to the values $\Omega_{DM}h^2 = 0.1198 \pm 0.0015$ and $\Omega_b h^2 = 0.02225 \pm 0.00016$ where $h = 0.6727 \pm 0.0066$ is the present-day Hubble constant H_0 expressed in units of 100 kms^{-1} Mpc^{-1}, as determined also by Planck [13].

1.3. Large scale structure

On very large scales, the Universe exhibits a pronounced structure in the form of laments of galaxy clusters with large voids in between, as observed e.g. by the Sloan Digital Sky Survey [35]. Within the ΛCDM model, these structures are interpreted as the result of the growth of the initial small density fluctuations in the primordial plasma, as they are imprinted in the CMB [36, 37]. The formation of structures can be modeled with the help of N-body simulations, which describe the dynamical evolution of the matter content in the expanding Universe. Interestingly, including a substantial amount of dark matter in such simulations is crucial for reproducing the observed large scale structure: dark matter allows for the efficient growth of the initial structures via gravitational instabilities, while baryons alone would not clump effectively enough due to the radiation pressure counteracting the formation of overdense regions. In particular, it is the presence of dark matter that leads to an hierarchical bottom-up picture of structure formation, where rst small structures such as dark matter (sub-)halos are formed, which then merge into larger objects such as galaxies and galaxy clusters, in good agreement with observations.

To be more precise, this mechanism requires dark matter to be cold, i.e. non-relativistic at the time most relevant for structure formation, as hot dark matter would have washed out the initial regions of enhanced matter density. As we will discuss in Sec. 1.3, this leads to important restrictions on the viability of several particle physics realizations for dark matter.

Finally, let us remark that while the large scale structure of the Universe is well compatible with the paradigm of cold dark matter, on scales relevant for individual galaxies, N-body simulations based on the ΛCDM model are in conflict with e.g. the number of observed satellite galaxies orbiting the Milky Way [38]. However, it is not yet established whether this is actually a problem of the model, which could point e.g. to warm dark matter or to strong self-interactions of dark matter, or whether it is an artefact of the simulations which do not fully take into account the baryonic effects in the formation of individual galaxies [39, 40].

2. Dark matter candidates

Dark Matter candidates are either baryonic or non-baryonic, or a mixture of both. The non-baryonic forms are usually subdivided into classes – Hot Dark Matter (HDM), Cold Dark Matter (CDM), Warm Dark Matter (WDM) etc. HDM requires a particle with near-zero mass (neutrinos are a prime example; axions, or supersymmetric particles and others). The Special Theory of Relativity requires that nearly massless particles move at speeds very close to c, the speed of light. However, HDM does not fully account for the large-scale structure of galaxies observed in the universe. They would be good at forming very large structures like superclusters but not smaller, galaxies, at neutrino masses corresponding to 10 eV to 100 eV.

CDM requires objects sufficiently massive that they move at sub-relativistic velocities. Comparisons between observed large-scale structure and N-body simulations favour CDM to be the major, if not total, component of Dark Matter. A major CDM candidate is WIMPs (Weakly Interacting Massive Particles). The search for these particles involves attempts at direct detection by sensitive detectors and production by particle accelerators.

Between these two limits, there exists an intermediate range of dark matter candidates generically called Warm Dark Matter (WDM). Their temperature is smaller and their free-streaming length shorter than that of ordinary neutrinos. For instance, thermal relics with a mass of order 1 keV and a density $\Omega_m \sim 0.25$ would have a free-streaming length comparable to galaxy scales ($\lambda_{FS} \sim 0.3$ Mpc).

There exist many WDM candidates whose origin is well known in particle physics. A prominent example is the gravitino, the supersymmetric partner of the graviton. The gravitino mass $m_{\frac{3}{2}}$ is generically of the order of $\frac{\Lambda_{susy}}{M_p}$, where Λ_{susy} is the scale of supersymmetry breaking and M_p is the Planckian scale. If, however, $\Lambda_{susy} \lesssim 10^6$ GeV, as predicted by theories where supersymmetry breaking is mediated by gauge interactions, the gravitino is likely to be the LSP. Such a light gravitino has a wide range of possible masses (from 10^6 eV up to the keV region).

At this time the number of degrees of freedom in the Universe is typically of order 100, much larger than at neutrino decoupling. The gravitino temperature is therefore always smaller than the neutrino temperature, and such light gravitinos can play the role of WDM [8]. Their velocity dispersion is non-negligible during the time of structure formation, but smaller than the velocity dispersion of active neutrinos with the same mass [9].

2.1. Gravitino freeze in mechanism

Gravitino freeze in mechanism is a mechanism for the production of gravitino dark matter whereby relic gravitinos originate from the decays of superpartners which are still in thermal equilibrium, i.e. via freeze-in. Contributions to the gravitino abundance from freeze-in can easily dominate over those from thermal scattering over a broad range of parameter space, e.g. when the scalar superpartners are heavy. Because the relic abundance from freeze-in is independent of the reheating temperature after inflation, collider measurements may be used to unambiguously reconstruct the freeze-in origin of gravitinos. In particular, if gravitino freeze-in indeed accounts for the present day dark matter abundance, then the lifetime of the next-to-lightest superpartner is uniquely fixed by the superpartner spectrum.

Unstable relic gravitinos are examples of weak sources of non-equilibrium particles. Since freeze-in mechanism happened in RD stage, the source of non-equilibrium particles (gravitino is non-equilibrium particle) is weak if the energy density of their products is small compared with the energy density of the thermal background [24]. The Boltzmann equation for the gravitino distribution function f(p, t) is

$$\frac{\partial f(p,t)}{\partial t} - H(t)\frac{\partial f(p,t)}{\partial p} = I$$

where $H(t)$ is the Hubble parameter. I – collision term, that comes from two-body decays and is given by

$$I = \frac{1}{2|\boldsymbol{p}|}\int \frac{d^3P}{2E(2\pi)^3}\frac{d^3p'}{2|\boldsymbol{p}'|(2\pi)^3}(2\pi)^4\delta^{(4)}(P-p-p')f_{th}(P,t)|\mathcal{M}|^2$$

Here **P, p, p′** are the 3-momenta of the decaying superparticle, gravitino and another decay product (SM particle), respectively; $E = \sqrt{M^2 + \mathbf{P}^2}$ is the energy of the decaying particle. The amplitude $\mathcal{M}$ is related to the decay rate in the rest frame of the decaying particle as $|\mathcal{M}|^2 = 16\pi M\Gamma$.

Upon integrating over the momentum of the SM particle and over the direction of **P**, the collision term takes the following form,

$$I = \frac{M\Gamma}{p^2}\int_{E_{min}}^{\infty} f_{th}(P,t)dE$$

where E_{min} is the minimum energy of the decaying superparticle capable of producing gravitino of momentum p. Slow gravitinos are born in peculiar decays of fast moving superparticles. The efficient production of slow gravitinos occurs at temperatures $T \gg M$, where M mass of decaying particle.

Take comoving momentum $q = a(t)p$ as the argument of the gravitino distribution function. Here $a(t)$ is the scale factor, whose present value is normalized to unity, $a(t_0) = 1$. The Boltzmann equation takes the form

$$\frac{df(p)}{dt} \equiv \frac{df(q,t)}{dt} = \frac{M\Gamma}{q^2}a^2(t)\int_{E_{min}}^{\infty} f_{th}(P,t)dE$$

Integrating we get

$$f(p) = \int_{t_R}^{t} dt' \frac{M\Gamma}{q^2}a^2(t')\int_{E_{min}}^{\infty} f_{th}(P,t')dE$$

where t_R refers to the beginning of the thermal phase of the cosmological evolution after reheating.

Thermal distribution function $f_{th}(P,t)$ of the decaying particles depends on the ratio $E/T(t)$ (Fermi-Dirac distribution?). Change the integration over production time for the integration over temperature. To this end we use the entropy conservation and the relation $T = \sqrt{\frac{M_{Pl}^*}{2t}}$ with $M_{Pl}^* \equiv M_{Pl}\sqrt{\frac{90}{8\pi^3 g_*}}$ valid at the radiation domination epoch. g_* is the effective number of relativistic degrees of freedom at the epoch of dark matter particle production stage.

$$f(p) = \int_0^{T_R} dT \frac{M\Gamma M_{Pl}^* T_{0,eff}^2}{q^2 T^5} \int_{E_{min}}^{\infty} f_{th}\left(\frac{E}{T}\right) dE$$

Here $T_{0,eff}^2 \equiv T_0 \left(\frac{g_{*0}}{g_*}\right)^{1/3}$, g_* and $g_{*0} \equiv \frac{43}{11}$ are the effective number of relativistic degrees of freedom at gravitino production and at present epoch, respectively [25].

2.2. Weakly interacting massive particles (WIMPs)

The class of dark matter candidates that has attracted the most attention over the past four decades is weakly interacting massive particles (WIMPs). WIMPs appeared for a long time as a perfect dark matter candidate, as new particles at the weak scale would naturally be produced with the right relic abundance in the early universe [3], while at the same time they might alleviate the infamous hierarchy problem [4], that has been a main driver of particle physics for roughly four decades [5]. Despite much effort, no particle other than a Standard Model-like Higgs boson has been convincingly detected at the weak scale so far, a circumstance that, as long anticipated [6], now raises the possibility that natural WIMPs is not exist [7].

The prototypical natural theory is the minimal supersymmetric (SUSY) standard model, which introduces an additional partner for each Standard Model particle. In addition, the partners of the W and Z bosons are predicted to be WIMPs and thus are natural dark matter candidates. However, most of the parameter space of natural simple supersymmetric models is essentially ruled out. Although it is still possible to identify ‘natural’ realizations of SUSY, e.g. in regions of parameter space of the phenomenological Minimal Supersymmetric Model, it is undeniable that null searches are constraining larger and larger portions of the parameter space of supersymmetric theories, which begs the question of how much fine-tuning one is willing to accept before giving up the hope to discover SUSY [7].

2.2.1. Supersymmetric WIMPs

In order for a SUSY particle to realistically constitute dark matter, it must somehow be stabilised against decay into lighter SM states. The most common way this is achieved is to postulate that aside from supersymmetry, a discrete $\mathbb{Z}_2$ symmetry exists between the SM particles and their SUSY partners. The corresponding conserved quantum number is known as R-parity, and has the form

$$R = (-1)^{3(B-L)+2s}, \quad (1)$$

where s is the particle's spin. All SM particles thus have R-parity +1 and all their SUSY partners R-parity -1.

If R-parity is conserved, then the lightest SUSY particle (LSP) is absolutely stable. If it is also weakly interacting and electrically neutral, then it is a viable WIMP. The most significant SUSY WIMP is the lightest neutralino, the lightest linear combination of the two neutral Higgsinos, the neutral wino and the bino,

$$\tilde{\chi}_1^0 = V_{1l}^* \tilde{H}_u^0 + V_{2l}^* \tilde{H}_d^0 + V_{3l}^* \tilde{W}_3^0 + V_{4l}^* \tilde{B}^0, \quad (2)$$

which mix following electroweak symmetry-breaking (EWSB) because they share quantum numbers. There are thus four neutralinos, corresponding to the different linear combinations; only the lightest is ever stable, and it is always this particle that is meant when people talk about `the neutralino' as a WIMP.

Sneutrinos, the spin-0 partners of neutrinos, are also weakly-interacting and neutral, so qualify as SUSY WIMPs when the lightest of their number is the LSP.

2.3. Alternatives to WIMPs

2.3.1. Axions

From the requirement that gluons should be pure gauge fields at spatial infinity, the QCD vacuum possesses a rather complex structure. A pure gauge is the set of field configurations obtained by a gauge transformation on the null-field configuration, i.e., a gauge-transform of zero. So it is a particular "gauge orbit" in the field configuration's space (i.e. 0). The vacuum structure arises because the pure gauge boundary condition introduces a freedom in the choice of boundary field, which translates into similar freedom in the choice of QCD vacuum. Because of this vacuum structure, the QCD Lagrangian picks up an additional effective term

$$\mathcal{L}_\theta = \theta \frac{g_s^2}{32\pi^2} G_a^{\mu\nu} \tilde{G}_{a\,\mu\nu}. \quad (3)$$

Here g_s is the strong coupling constant, $G_a^{\mu\nu}$ is the QCD field strength tensor for the ath gluon, and $\tilde{G}_{a\,\mu\nu} = \frac{1}{2}\epsilon_{\mu\nu\alpha\beta} G_a^{\alpha\beta}$ is its dual. Unlike the rest of the QCD Lagrangian $\mathcal{L}_\theta$ does not conserve CP. This additional term would induce effects, which have not been observed, like a non-zero electric dipole moment for the neutron. The limits on such a moment to date constrain the vacuum angle θ to be less than 10^{-9}.

Widely held assumption is that the solution to the strong CP problem lies in the existence of an additional spontaneously-broken, global chiral U(1) symmetry of the SM Lagrangian, known as the Peccei-Quinn symmetry [15]. The axion is the Goldstone boson of this broken [16]. It possesses a potential with a minimum that naturally sets the field to a value that cancels $\mathcal{L}_\theta$. This is true for essentially any value of the Peccei-Quinn symmetry breaking scale v_a, relieving the naturalness problem posed by the smallness of θ.

The two photon vertex not only allows axion decay to two photons, but allows axion conversion to photons (and vice versa) in the presence of electromagnetic fields. This feature is used as the prime phenomenological means for searching for axions.

Many constraints exist on axions and axion-like models. A class of searches characterised by the ADMX experiment [14] uses a magnetic field to convert the background of axions on the Earth into an electromagnetic signal, and has successfully excluded a window of axion parameter space with masses around 2 μeV, and future data taking is expected to probe masses up to about 40 μeV. In addition, there is vigorous theoretical activity exploring new ideas to probe a wider range of axion masses [7].

Certain classes of axions, dubbed `invisible axions', make very good dark matter candidates because they interact extremely weakly with normal matter. This class of axion involves a very high Peccei-Quinn breaking scale, and therefore very light axions. Such axions have virtually no kinematically-accessible decay channels, so are stable on cosmological timescales. These axions constitute cold dark matter despite being so light, because they are never in thermal equilibrium in the early Universe.

2.3.2. Sterile Neutrinos

One of the most suitable candidate particles for the dark matter in the Universe is the sterile neutrino – an electrically neutral fermion with a mass on the order of keV–MeV that couples to ordinary matter only through a tiny mass mixing with Standard Model (SM) neutrinos. In the simplest sterile neutrino scenarios, it is assumed that they are produced through their mixing with SM (active) neutrinos v_a.

While their residual weak interactions predict that they will ultimately decay, if their mass and mixing are both small enough, the decay may slowly occur that they remain in the Universe today as a form of dark matter. They can be produced in the early Universe through a variety of different physical mechanisms with an appropriate abundance.

While sterile neutrino playing the role of dark matter, its lifetime must be long enough that the vast majority of such particles have not yet decayed, quantum mechanics dictates that some will decay more rapidly, leading to a source of mono-energetic photons with energy close to half of its mass. In fact, an unidentified emission line at 3.5 keV in the X-ray spectrum of 73 galaxy clusters has prompted the suggestion that it might be a hint of the decay of a sterile neutrino, though debate about the origin of this line is still ongoing. Future X-ray telescopes such as eRosita, XARM, Athena, and/or Lynx should help to clarify the origin of this emission, and future accelerator searches such as SHIP will provide a complementary probe of the relevant parameter space [7].

2.3.3. Composite dark matter from fourth generation

Hypothesis of heavy stable quark of fourth family can provide a nontrivial solution for cosmological dark matter if baryon asymmetry in fourth family has negative sign and the excess of U antiquarks with charge (-2/3) is generated in early Universe. Excessive U antiquarks form $(\bar{U}\bar{U}\bar{U})$ antibaryons with electric charge -2, which are all captured by ^{4}He and trapped in $[\,4He^{++}(\bar{U}\bar{U}\bar{U})^{--}]$ O-helium OHe "atom", as soon as ^{4}He is formed in Big Bang Nucleosynthesis. Interaction of O-helium with nuclei opens new path to creation heavy nuclides in Big Bang nucleosynthesis. Due to large mass of U quark and small baryon number density, OHe "atomic" gas decouples from baryonic matter and plays the role of dark matter in large scale structure formation with structures in small scales being suppressed. Development of gravitational instabilities of O-helium gas triggers large scale structure formation, and composite nature of O-helium makes it more closer to cold, but a bit warmer dark matter [20]. Owing to nuclear interaction with matter cosmic O-helium from galactic dark matter halo are slowed down in Earth below the thresholds of underground dark matter detectors. The first evident consequence of the proposed scenario is the inevitable presence of O-helium in terrestrial matter, which is opaque for (OHe) and stores all its infalling flux.

In underground detectors (OHe) “atoms” are slowed down to thermal energies and give rise to energy transfer $\sim 2.5 \cdot 10^{-4} eV\ A/S_5$, where $S_5 = m_U/350\ GeV$ far below the threshold for direct dark matter detection. However, (OHe) destruction can result observable effects [20].

However, experimental test of this hypothesis is possible in search for OHe in balloon-borne experiments and for U hadrons in cosmic rays and accelerators. OHe "atoms" might form anomalous isotopes and can cause cold nuclear transformations in matter, offering possible way to exclude their existence. O-helium collisions in the galactic bulge can lead to excitation of O-helium. If the 2S level is excited, pair production dominates over two-photon channel in the deexcitation by $E0$ transition and positron production with the rate $3 \cdot 10^{42} S_3^{-2} s^{-1}$ is not accompanied by strong gamma signal. This rate of positron production for $S_3 \sim 1$ is sufficient to explain the excess in positron annihilation line from bulge, measured by INTEGRAL [21].

3. Other candidates

3.1. Primordial black hole

Primordial black holes (PBHs) are another dark matter candidate with significant problems. These would be formed from small-scale primordial density perturbations which are so strong that they cause the all mass of horizon at the time (or at least a very substantial fraction of it) to collapse directly into a black hole. The fluctuations would be produced before matter-radiation equality, either during inflation or by phase transitions in the early dust-like stages. Because PBHs form before BBN or the CMB, in early Universe temperature is higher, as a result of which the quark bonds are immediately destroyed, that's why PBHs are not formed of baryons in early Universe. Like MACHOs, they would escape detection via shadowing effects today simply by virtue of their compactness. The difficulty with this scenario is that the density contrast $\delta = \delta\rho/\rho$, where ρ is the mass density. [12]. In comparison, the initial density perturbations from in action were about $\delta{\sim}10^{-5}$. A very bottom-heavy spectrum of perturbations is then required in order to provide enough power on small scales to produce a substantial number of PBHs without violating the level of large-scale anisotropy seen in the CMB.

3.2. Strongly Interacting Massive Particle

SIMPs are Strongly Interacting Massive Particles which could form colourless bound states and hide their strong interactions, whilst milli-charged particles might manage to appear dark because they carry only a very small fractional electric charge. Both these options are very strongly constrained at the present time.

3.3. Mirror matter

Candidates for the exotic component of DM are: WIMPS, axions and mirror matter are examples. The observation of microlensing events from the Small and Large Magellanic Clouds is consistent with the existence of Massive Compact Halo Objects (MACHOs) in the halo of the Milky Way. The inferred average mass is about $0.5M_\odot$, where $M_\odot$ is the mass of our sun. The most reasonable conventional identification sees MACHOs as white dwarfs, although there are several strong arguments against this. For example, the heavy elements that would have been produced by their progenitors are not in evidence. This argues against the conventional white dwarf scenario, and in favour of exotic compact objects.

Mirror matter is an interesting candidate for some of the required exotic DM. It can be independently motivated by the desire to see the full Poincare Group, including improper transformations (parity and time reversal), as an exact symmetry group of nature. The basic postulate is that every ordinary particle (lepton, quark, photon, etc.) is related by an improper Lorentz transformation with an opposite parity partner (mirror lepton, mirror quark, mirror photon, etc.) of the same mass. Both material particles (leptons and quarks) and force carriers (photons, gluons, W and Z bosons) are doubled. Mirror matter interacts with itself via mirror weak, electromagnetic and strong interactions which have the same form and strength as their ordinary counterparts (except that mirror weak interactions couple to the opposite chirality). Because ordinary matter is known to clump into compact objects such as stars and planets, mirror matter will also form compact mirror stars and mirror planets. Since mirror matter does not feel ordinary electromagnetism, it will be dark. Gravitation, by contrast, is common to both sectors. Mirror matter therefore has the correct qualitative features: it is dark, it clumps, and it gravitates. It has been speculated that MACHOs might be mirror stars, and the observed extrasolar planets might be composed of mirror matter [23].

An important question that arises naturally is whether or not the existence of mirror particles can lead to other observable consequences. In particular, it is essential to find constraints on the possible concentration of mirror particles in the Earth. Two main approaches to our problem are possible. First, one can trace the fate of the mirror particles starting from the early Universe epoch through the structure formation periods (galaxies, solar system and finally the Earth). Second, we can use geophysical data to get a more direct limit on the concentration of mirror matter in the Earth regardless of possible cosmological bounds.

While exotic unstable particles abound in extensions of the standard model, completely new stable degrees of freedom pose a more profound model-building challenge. The problem of stability is fully met by mirror matter.

Conclusion

While its existence is nowadays a widely accepted fact, the lack of an unambiguous positive signal in an experiment searching for a non-gravitational interaction of dark matter leaves the determination of its particle physics properties to be a still open task. In this essay, different models of dark matter were considered.

All the dark matter candidates appear as consequences of physics beyond the Standard model.

Hypothesis of heavy stable quark of 4th family can provide a nontrivial solution for cosmological dark matter if baryon asymmetry in 4th family has negative sign and the excess of $\bar{U}$ antiquarks with charge (-2/3) is generated in early Universe.

Taking together all of these arguments, the existence of dark matter hence strongly points towards physics beyond the Standard Model. Interestingly, also completely independent arguments suggest an extension of the Standard Model of particle physics, most notably the non-zero neutrino masses, the observed baryon asymmetry in the Universe, as well as the unexplained origin of the apparently unnatural huge separation between the weak and the Planck scale, commonly known as the hierarchy problem. Indeed, there are several proposed theories which try to address one or several of these shortcomings of the Standard Model, and at the same time provide a viable dark matter candidate. Popular examples include supersymmetric theories featuring the neutralino or the gravitino as the possible dark matter particle, dark matter in form of axions, a scenario motivated by the strong QCD problem, or sterile neutrino dark matter with a mass in the keV range, which in combination with other sterile neutrinos could be related to the non-zero masses of the Standard Model neutrinos. However, up to date the true particle nature of dark matter is still obscure, and hence remains as one of the most pressing open questions in modern particle physics.

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