DARK MATTER IN FLAVOUR PHYSICS

MITJA ŠADL

Fakulteta za matematiko in fiziko
Univerza v Ljubljani

This article presents dark matter from the particle physics point of view. Initially, we present an overview of the Standard Model. Then we explain, why there is dark matter in our Universe and what could be its constituents. What follows, is the description of dark sectors, proposed by particle physics as a source of dark matter candidates. Next, we discuss two models, one dealing with axions and the other with dark gauge bosons or dark photons. We focus more on the latter one. In conclusion, we look at the opportunities for future experiments.

TEMNA SNOV V FIZIKI OKUSOV

Članek predstavlja problem temne snovi z zornega kota fizike delcev. Sprva je narejen pregled standardnega modela. Nato je pojasnjeno, zakaj obstaja temna snov in kaj so njeni kandidati. Opisani so temni sektorji, katerih delci bi lahko bili kandidati za temno snov. Sledi opis dveh modelov. En vključuje delce aksione, drugi pa temne umeritvene bozone, ki jih imenujemo temni fotoni. Večji poudarek je dan slednjemu. Na koncu so omenjeni eksperimenti, s katerimi bi v prihodnje lahko zaznali delce temne snovi.

Introduction

It was in 1933 when the astronomer Fritz Zwicky studied the motions of distant galaxies. He estimated the total mass of a group of galaxies by measuring their brightness. Using a different method, galaxy velocities, he computed the mass of the same galaxy cluster and came up with a number that was 400 times his original estimate. In the 70's scientists found out that only large amounts of hidden mass could explain many of their observations. Nowadays, taking into account the cosmic microwave background measurements, we are sure that there exists matter that interacts primarily through gravitational force [1, 2].

The Standard Model (SM), a mathematical description of the elementary particles and the fundamental forces, by which they interact, has achieved remarkable success. This is a result of several decades of constantly pushing the boundaries of our knowledge of theory, experiment and technology. The Standard Model consistently describes all known interactions except gravitation. It does also not address several pieces of evidence for new physics beyond the Standard Model (BSM).

One example of new physics comes from the existence of dark matter, which dominates the matter density in our Universe but not much is known about it. Its existence provides a strong hint that there may be a *dark sector*, consisting of particles that do not interact with the known strong, weak or electromagnetic forces. Actually, many dark sectors could exist, each with its own beautiful structure, distinct particles and forces. These dark (or hidden) sectors may contain *new light weakly-coupled particles* that interact only feebly with ordinary matter. In the past experimental searches, we could easily have missed these particles. However, a rich experimental program has now been arranged to look for several possibilities [3].

Section 1 contains a short introduction to the Standard Model and its open questions as a motivation. In section 2, we mention some key facts about cosmology. In section 3, we discuss the evidence for dark matter and describe the possible dark matter candidates in section 4. In section 5, dark sectors are introduced. What follows is the summary of two different sectors: The sector containing axions is described in section 6 and the sector containing dark photons in section 7. The last section contains a brief conclusion.

1. Standard Model

1.1 Brief introduction to the Standard Model

There are three types of Standard Model elementary particles: fermions or matter particles (quarks and leptons), which are constituents of matter, gauge bosons or force particles, which are force carriers, and a Higgs boson. Gauge bosons mediate interactions among fermions. All elementary particles are structureless at the smallest distances currently probed by the highest-energy accelerators.

Both quarks and leptons have spin 1/2[a]. Leptons are electron, muon, tau, which have electric charge -1[b], and the corresponding neutrinos without electric charge. Quarks are composed of 6 flavours: quarks u, c, t with electric charge 2/3 and d, s, b with electric charge $-1/3$. They have an additional quantum number – color. They are red, blue or green. Despite this fact, we cannot detect any colorful hadron.

The second type of the particles, gauge bosons have spin 1 (vector bosons). Interactions of particles are explained within the concept of *gauge theories*. Each symmetry is associated with a conserved quantity, but we will be interested in conserved charges. Each interaction conserves a charge and therefore corresponds to some symmetry group. The number of different force carriers of some interaction equals to the number of generators of the corresponding group. In the table 1, all interactions are presented.

Table 1. Summary table of the SM fundamental forces. SM is a gauge quantum field theory containing the local symmetries of the unitary product group $\mathrm{SU}(3)_C \times \mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$.

Interaction	Symmetry group	Intermediate particles	Conserved charge	Fermions act as:
electromagnetic	U(1)	1 massless photon	electric charge	singlets
weak interaction	SU(2)	3 massive weak bosons	weak isospin	doublets
strong interaction	SU(3)	8 massless gluons	color charge	triplets

If one takes into account very high energies, then the electromagnetic and the weak interaction are actually unified in an electroweak interaction. The Standard Model weak bosons ($\mathrm{W}^\pm$ and Z) and the photon are produced by the *spontaneous symmetry breaking* of the electroweak symmetry from $\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y$ to $\mathrm{U}(1)_Q$ caused by the *Higgs mechanism*. The generators of $\mathrm{U}(1)_Q$, $\mathrm{SU}(2)_L$ and $\mathrm{U}(1)_Y$ are electric charge (Q), weak isospin (T_3) and weak hypercharge ($Y = 2(Q - T_3)$) respectively.

The last type of the particles is the Higgs boson, which is spinless and so the first elementary scalar particle discovered in nature.

Here are some crucial assumptions SM is based on:

- Renormalizability condition: The theory must be renormalizable, thus the Lagrangian density before the spontaneous symmetry breaking must be invariant under the gauge transformations.
- Because of the renormalizability, all the SM fields are massless! Massive theories are non-renormalizable. Therefore, none of the Standard Model fermions or bosons can begin with mass, but must acquire it by some other mechanism (Higgs mechanism).
- Before-mentioned massive weak bosons get their masses through the coupling with the Higgs field. The spontaneous symmetry breaking of the initial gauge group

$$\mathrm{SU}(2)_L \times \mathrm{U}(1)_Y \to \mathrm{U}(1)_Q \tag{1}$$

[a] in units of $\hbar$

[b] measured in units of elementary charge e_0

leads to 3 massive weak fields (broken symmetry) and a massless electromagnetic field (conserved symmetry).

- To describe the current phenomenology, the Lagrangian density must contain a fermionic part (Dirac Lagrangian density), a vectorial part, consisting of tensors of free gauge fields, scalar part and a Yukawa fermion-scalar coupling part, which is responsible that fermions gain mass [4, 5].

1.2 Open questions in the Standard Model

Despite being the most successful theory of particle physics, the SM is imperfect. There are problems with the SM. This is the reason, why theoretical physicists propose various forms of new physics BSM that would modify the Standard Model in ways subtle enough to be consistent with existing data.

Unexplained fundamental physical phenomena

These are experimentally proven phenomena that SM cannot describe: gravitation, cosmological inflation, *dark matter*, dark energy, matter-antimatter asymmetry, neutrino masses and their oscillations [6].

Unexplained measurement results

There are always several experimental results that are slightly different from the Standard Model expectations, although many of these have been found to be statistical fluctuation or systematical errors as more data have been collected. Note that any BSM physics would necessarily first manifest experimentally as a statistically significant difference between an experiment and the theoretical prediction. Here are some experimental measurements that disagree with the theoretical calculations: proton charge radius [7], muon anomalous magnetic dipole moment [8] and B meson decay (violation of lepton flavour universality) [9].

Theoretical problems

We will list some problems that do not arise because of some discrepancy between experimental results and theoretical predictions. These open questions are more like why did we measure exactly this value and why can't we predict it: We do not understand yet why fermions are replicated in 3 and only 3 nearly identical copies. Why the pattern of masses and mixings is what it is? Are the masses the only difference among the three fermion families? What is the origin of the SM flavour structure? Why is CP symmetry in strong interaction not violated, although theoretically, it could be (the strong CP problem) [4]?

If one wants to propose new particles to solve one of the problems, one should take into account also, how new particles influence on other problems. E.g. if one predicts a dark matter candidate, one should study the size of a new parameter, which can solve e.g. the proton radius puzzle and the muon anomalous magnetic moment problem.

2. Cosmology and the Big Bang

At the present, there is only about 4 % of the matter we are made of (baryonic or normal matter) in the Universe. The rest of the Universe consists of strange dark matter (26 %) and even stranger dark energy (approximately 70 %).

Dark energy appears to be associated with the vacuum in space. It is distributed evenly through the universe. This means that it does not have any local gravitational effects, but a global effect on the Universe as a whole. This leads to a repulsive force that accelerates the expansion of the universe. We can measure the rate of the expansion and its acceleration. With these measurements and other scientific data, the existence of dark energy is confirmed [10].

Cosmological principle or Copernican principle tells us that our place in the Universe is not special and that the Universe looks everywhere the same. Most of the civilizations in the history believed the opposite. This principle is the most fundamental in modern cosmology and is the basis of the Big Bang theory, the most successful theory of our Universe. It describes the evolution from the earliest known periods through the period of large-scale structure formation. According to Big Bang cosmology, the Universe expanded out of the gravitational singularity and became smooth on large scales. Therefore at this scales, the Universe is homogeneous and isotropic [1].

3. Evidence for dark matter

Dark matter does not emit or interact with observable electromagnetic radiation, such as light, and is thus invisible. Based on several measurements we are sure that dark matter exists. In this section, we will try to answer the question: What is the observational evidence for the existence of the dark matter?

3.1 Galaxy rotation curves

One of the most impressive and direct evidence on galactic scales comes from the observations that various luminous objects like stars, gas clouds, globular clusters and entire galaxies move faster than one would expect if they only felt the gravitational attraction of other visible objects. The best example is the measurement of galactic rotation curves. Let us consider for example a galaxy. Its circular velocity is

$$v(r) = \sqrt{\frac{GM(r)}{r}}, \tag{2}$$

where G is the gravitational constant,

$$M(r) = 4\pi \int_0^r \rho(R) R^2 \, dR \tag{3}$$

is the mass inside the orbit and ρ is the density. For r larger than the radius of the optical disk one expects $v(r) \propto 1/\sqrt{r}$. If there is no mass beyond the visible part of the galaxy, then $M(r)$ is constant in r. But the velocity beyond the luminous matter is not falling (see Fig. 1). It remains constant with the rising radius. This implies the existence of a dark halo with $\rho(r) \propto 1/r^2$ so that $M(r) \propto r$. In other words, galaxies' mass continues to grow, even when there is no luminous component to account for this increase. At some $r = r_0$, $\rho(r)$ should fall faster to keep the total mass of the galaxy finite, but it is yet unknown how much r_0 is [5].

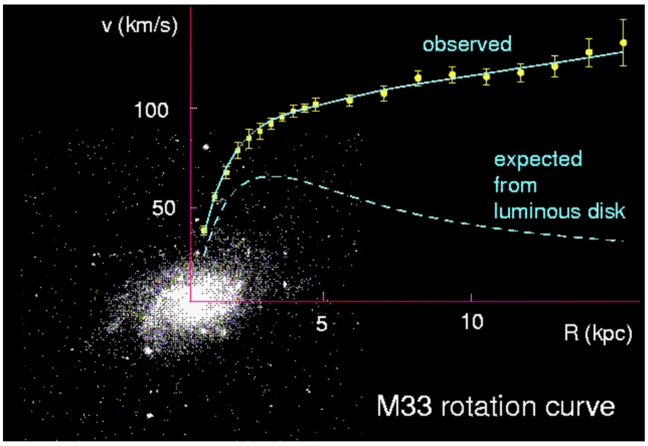

Figure 1. This picture shows the observed rotation curve of the dwarf spiral galaxy M33 and the expected one derived from the equation (2). Reproduced with permission of V. Sahni (2004) [11].

3.2 Gravitational lensing and X-ray observations

We can independently determine galaxy cluster's mass using the gravitational lensing and X-ray observations. Techniques using weak gravitational lensing are important in studying mass distribution in the universe. The projected mass distribution of foreground gravitational structures distorts the images of the background galaxies. This gravitational distortion provides a direct measurement of the projected mass density. X-ray observations used to derive estimates for the masses of galaxy clusters are based on the profile of X-ray emission that traces the distribution of hot emitting gas within the clusters. These two methods are in agreement that clusters contain much more matter than the visible galaxies and gas, which is another indication of dark matter.

A fascinating example involves the Bullet Cluster, which on cosmological time scales passed through another cluster. The X-ray observations reveal a bullet-like gas subcluster exiting the collision; the weak gravitational lensing mass map shows a dark matter clump lying ahead of the collisional gas bullet (see Fig. 2). This is a clear indication that dark matter self-interactions are weak [5].

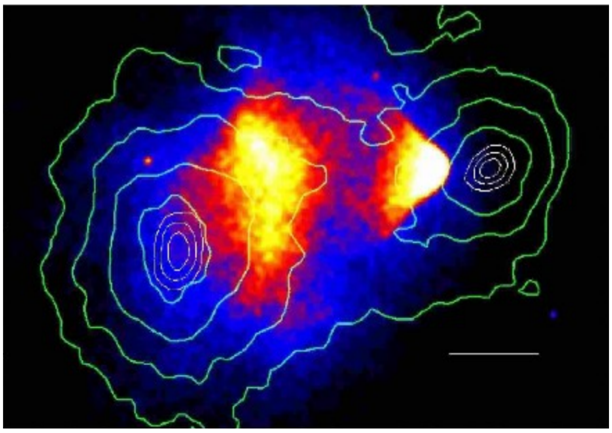

Figure 2. Combined Bullet cluster images: overlay of the weak lensing mass contours on the X-ray image. The gas bullet lags behind the dark matter subcluster. Reprinted figure with permission from [12] Copyright (2018) by the American Physical Society.

3.3 Evidence on cosmological scales

Observations of galaxies and galaxy clusters provide interesting evidence of dark matter. Nevertheless, these observations do not allow us to determine the total amount of dark matter in the Universe. To get this information one can analyze the cosmic microwave background (CMB) on cosmological scales.

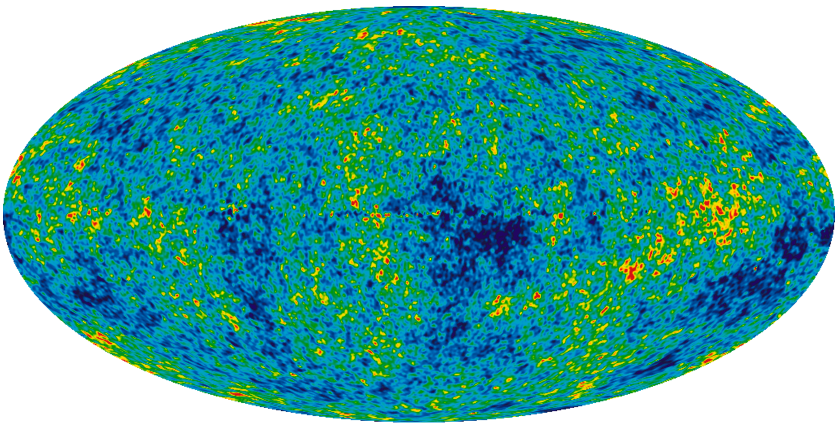

Figure 3. This is the detailed all-sky picture of the early Universe created from nine years of Wilkinson Microwave Anisotropy Probe (WMAP) data. The image shows $13.77 \cdot 10^9$ years old temperature fluctuations shown as color differences, which represent a range of $200\,\mu$K, that correspond to the seeds that grew to become the galaxies. Reproduced from [13].

At the beginning, the Universe was a hot gas of mostly photons and electrons. Because of the high density, photons were in a thermodynamic equilibrium and they could travel only a few meters before they scattered on an electron. As the Universe expanded, the temperature fell and first atoms were formed. The hot electron plasma disappeared, so that the photons could move freely and the CMB, the oldest source of information in the early Universe, was born. The CMB is known to be isotropic at the 10^{-5} level (see Fig. 3) and has a spectrum close to that of an ideal black body. Today CMB's temperature is $T_{\mathrm{cmb}} = 2.725\,\mathrm{K}$ [14]. The anisotropies in the CMB are explained as acoustic oscillations in the photon-baryon plasma. With the analysis of CMB anisotropies, cosmological models are precisely tested.

Combining measurements of high-redshift supernova luminosity distances, CMB fluctuations, from the satellite Wilkinson Microwave Anisotropy Probe (WMAP), and baryon acoustic oscillations (BAO) in the galaxy distribution gives tight constraints on the present mass density of matter in the Universe. We usually express this in the ratio

$$\Omega_m = \frac{\rho_m}{\rho_{\text{crit}}}, \tag{4}$$

where

$$\rho_{\text{crit}} = h^2 \cdot 1.9 \cdot 10^{-29}\,\text{g}\,\text{cm}^{-3} \tag{5}$$

and $h = 0.704 \pm 0.014$ is the derived present value of the Hubble constant in units of $100\,\text{km}\,\text{s}^{-1}\,\text{Mpc}^{-1}$. The obtained values for dark matter is

$$\Omega_{\text{dm}} h^2 = 0.1186 \pm 0.0020, \tag{6}$$

which is around five times higher than the value for baryonic matter

$$\Omega_b h^2 = 0.02226 \pm 0.00023. \tag{7}$$

Additionally, the WMAP data predicts with a precision of 1 %, that the Universe is flat [2, 5].

4. Dark matter candidates

4.1 Baryonic dark matter

Not all of the dark matter is non-baryonic. Additionally, the majority of baryonic matter is invisible and therefore “dark”. Where could these dark baryons be? One possibility is that they are smoothly distributed as dark gas and dust. They could also be bound up in clumps of matter such as substellar objects (planets and brown dwarfs[c]) or stellar remnants[d]. If our understanding of Big Bang theory and the formation of the light elements is correct, then the baryonic dark matter represents only a small part of the total dark matter [15].

4.2 Non-baryonic dark matter

There are two kinds of non-baryonic dark matter: cold and hot dark matter. This classification refers to velocity rather than to an actual temperature. At some constant energy, particle’s mass determines its velocity. Because hot dark matter travels faster than the cold dark matter particles, latter are theorized to be much heavier.

Hot dark matter consists of ultrarelativistic particles. We already detected some of the hot dark matter candidates. These are neutrinos. We know that neutrinos cannot provide all of the dark matter density because then neutrino’s rest mass should be around 10 eV, while the Planck Collaboration reported the following upper limit on the sum of the neutrino masses: $\sum_j m_j < 0.23\,\text{eV}$, 95 % CL [5].

Present observational evidence shows that majority of dark matter must be cold. Thus the amount of hot dark matter is small. Also, the overall cold dark matter density is believed by many cosmologists to exceed that of the baryons by at least an order of magnitude. Cold dark matter offers the simplest explanation for most cosmological observations and is the focus of dark matter research.

[c] Brown dwarfs form like stars, but do not have enough mass to begin nuclear fusion reactions that cause stars to shine brightly.

[d] neutron stars, black holes, white, red and black dwarfs

Its constituents are unknown [15]. Although the most of the activities have focused on the possibility of weakly-interacting massive particles (WIMPs) with a weak scale mass ($m_{\rm weak} \sim 100\,\mathrm{GeV}-1\,\mathrm{TeV}$), this is certainly not the only possibility. We will discuss some of new light weakly-coupled particles (axions, dark photons, milli-charged particles, etc.) as dark matter candidates [3].

5. Dark sectors

The term dark sector refers to a set of unobserved quantum fields and the corresponding hypothetical particles that do not directly interact via the SM particles. These dark matter particles could be dark photons, scalars, pseudo-scalars, pseudo-vectors and fermions. Dark sectors include a gauge group that is typically independent of the SM gauge group and can be generally non-Abelian. Nevertheless, all matter including particles from the dark sector still interacts through the gravitational force. Dark sectors arise in many theoretical extensions to the SM and have the possibility to solve the puzzle of dark matter. Although they can solve other unsolved problems too. It would be nothing wrong if the dark sector or sectors would contain not only dark matter candidates but also other particles. Powerful motivations for introducing new hidden sectors include the strong CP problem and experimental findings, e.g. the discrepancy between the calculated and the measured anomalous magnetic moment of the muon and puzzling results from astrophysics.

Besides gravity, there are relatively few well-motivated interactions allowed by SM symmetries that provide a portal from the SM sector into the dark sector. These portals are listed in the table 2. The Higgs portal is best explored at high-energy colliders. The best example of an energy frontier collider is the LHC in Geneva. Further, neutrino portal can be explored at neutrino facilities

Table 2. This table presents the allowed portals to dark sectors [3]. We will focus on the vector and axion portals.

Portal	Particles	Operator(s)
"Vector"	dark photons	$-\frac{\varepsilon}{2}F_{\mu\nu}F'^{\mu\nu}$
"Axion"	pseudoscalars	$\frac{a}{f_a}F_{\mu\nu}\tilde{F}^{\mu\nu}$, $\frac{a}{f_a}G_{i\mu\nu}\tilde{G}_i^{\mu\nu}$, $\frac{\partial_\mu a}{f_a}\bar{\psi}\gamma^\mu\gamma^5\psi$
"Higgs"	dark scalars	$(\mu S + \lambda S^2)H^\dagger H$
"Neutrino"	sterile neutrinos	$y_N LHN$

(neutrino accelerators, detectors and telescopes). On the other hand, although vector and axion portals can also be explored at the cosmic and energy frontiers, they present particularly well-motivated targets for several low-cost, high-impact experiments at the intensity frontier. These are experiments, which use intense particle beams and highly sensitive detectors.

6. Axions

One of the problems of the theory of strong interaction (quantum chromodynamics or QCD) is the so-called strong CP problem: The weak interaction is known to violate CP symmetry, the symmetry to the combined transformation of charge conjugation and space inversion, but the strong interaction also contains a CP-violating term in the Lagrangian

$$\theta_{\rm eff}\frac{g^2}{32\pi^2}G^a_{\mu\nu}\tilde{G}^{\mu\nu}_a, \tag{8}$$

where $G^a_{\mu\nu}$ is the gluon field strength tensor and $\tilde{G}^a_{\mu\nu} = \varepsilon_{\mu\nu\lambda\rho}G^{\lambda\rho}_a$ is its dual. So that for nonzero quark masses, the strong interaction should theoretically violate the CP symmetry, but experimentally it is clear that it does not.

The CP symmetry will be preserved by imposing an additional spontaneously broken global chiral symmetry on the full SM Lagrangian, which implies the existence of a new scalar particle called axion (a), present in the following term

$$\mathcal{L}_a = \xi \frac{a}{f_a} \frac{g^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{\mu\nu}_a, \tag{9}$$

where f_a is the axion decay constant and ξ is a model-dependent coefficient. Joining together (8) and (9), we get an effective potential for the axion field,

$$\mathcal{L}_{G\tilde{G}} = \left(\theta_{\text{eff}} + \xi \frac{a}{f_a}\right) \frac{g^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{\mu\nu}_a, \tag{10}$$

This potential has a minimum at the vacuum expectation value of the axion,

$$\langle a \rangle = -\frac{\theta_{\text{eff}} f_a}{\xi}, \tag{11}$$

for which the whole term $\mathcal{L}_{G\tilde{G}}$ vanishes. By expanding the physical axion as

$$a_{\text{phys}} = a - \langle a \rangle, \tag{12}$$

we rewrite the $G\tilde{G}$ term as

$$\mathcal{L}_{G\tilde{G}} = \xi \frac{a_{\text{phys}}}{f_a} \frac{g^2}{32\pi^2} G^a_{\mu\nu} \tilde{G}^{\mu\nu}_a. \tag{13}$$

Thus the parameter θ_{eff} is gone from the Lagrangian and CP symmetry in strong interaction is conserved. This solution somehow promotes the static parameter θ_{eff} to a dynamical field whose excitations around zero are associated with the axion. The axion mass is predicted to be $m_a \sim 6\,\text{meV}$. Its coupling to ordinary matter is proportional to $1/f_a$ and can be calculated in specific models. It interacts generically to quarks, or hadrons at low energies, photons and, in some theories, also to leptons. All of these different interactions play a role in searches for the axion and allow the axion to be produced or detected in the laboratory[e] and emitted by the sun or other stars. Axions naturally serve as the dark matter, meaning that the galactic halo may be formed partly or entirely from these particles [3, 16].

7. Dark photons

We will study a dark sector that contains an abelian gauge group $\text{U}(1)_\text{d}$[f]. This theory describes a new force mediated by a $\text{U}(1)_\text{d}$ gauge boson A' that couples very weakly to electrically charged particles through kinetic mixing with the photon. This boson is usually called U-boson, hidden-sector, dark, heavy or secluded photon. We will refer to it as a dark photon. If the dark sector gauge group was a simple group $\text{U}(1)_\text{d}$ instead of a direct product $\text{U}(1)_\text{d} \times \ldots$, this would be a minimal extension of the SM.

Our model assumes the existence of an elementary Higgs boson called dark Higgs boson that spontaneously breaks the $\text{U}(1)_\text{d}$ symmetry. Therefore, besides the SM electromagnetic field A_μ and the $\text{U}(1)_\text{d}$ gauge field A'_μ, we also have a single complex scalar dark Higgs field ϕ. The phenomenology of decays of A' and ϕ will depend on assumptions about the particle content in the dark sector, but we will assume that any extra dark sector particles, e.g. the WIMP candidate, are heavier than the minimal set containing A' and ϕ [3, 17].

[e] An example of axion production experiments are laser experiments.

[f] The subscript d stands for dark.

The Lagrangian takes the form

$$\mathcal{L} = \mathcal{L}_{\text{gauge}} + |D_\mu \phi|^2 - V(\phi), \tag{14}$$

where

$$\mathcal{L}_{\text{gauge}} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{\varepsilon}{2}F'_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu}. \tag{15}$$

Here the first term is the $\mathrm{U}(1)_Y$ and the last the $\mathrm{U}(1)_\mathrm{d}$ gauge kinetic term. Our new dark sector is not charged under the SM and the other way around. All interactions with the SM proceed through the kinetic mixing term of the dark photon with the SM photon [the second term in equation (15)]. We will neglect mixing with the Z boson.

$$V(\phi) = -\mu^2|\phi|^2 + \lambda|\phi|^4 \tag{16}$$

is the dark Higgs potential invariant under the local gauge transformation $\phi(x) \to e^{i\alpha(x)}\phi(x)$, $D_\mu = \partial_\mu + ie'A'_\mu$ is a covariant derivative with $\mathrm{U}(1)_\mathrm{d}$ charge e', $F_{\mu\nu} = \partial_\mu A_\nu - \partial_\nu A_\mu$ is the $\mathrm{U}(1)_Y$ and $F'_{\mu\nu} = \partial_\mu A'_\nu - \partial_\nu A'_\mu$ the $\mathrm{U}(1)_\mathrm{d}$ field strength tensor. The potential has the form, which for $\mu^2 > 0$ allows the spontaneous breakdown of the $\mathrm{U}(1)_\mathrm{d}$ symmetry. The dark Higgs acquires a vacuum expectation value $\langle\phi\rangle = v'/\sqrt{2}$ with $v' = \sqrt{\mu^2/\lambda}$. After expanding around this vacuum, $\phi = (v' + h')/\sqrt{2}$, the unitary-gauge Lagrangian containing the physical dark Higgs field h' takes the form

$$\mathcal{L} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} + \frac{1}{2}m_{A'}^2 A'^2_\mu + \frac{1}{2}(\partial_\mu h')^2 - \frac{1}{2}m_{h'}^2 h'^2 + \mathcal{L}_{\text{int}}, \tag{17}$$

where $m_{A'} = e'v' = e'\mu/\sqrt{\lambda}$, $m_{h'} = \sqrt{2\lambda}v' = \sqrt{2}\mu$ and

$$\mathcal{L}_{\text{int}} = -\frac{\varepsilon}{2}F'_{\mu\nu}F^{\mu\nu} - \frac{m_{A'}^2}{v'}h'A'^2_\mu + \frac{m_{A'}^2}{v'^2}h'^2A'^2_\mu - \frac{m_{h'}^2}{2v'}h'^3 - \frac{m_{h'}^2}{8v'^2}h'^4. \tag{18}$$

How to spontaneously break the $\mathrm{U}(1)_\mathrm{d}$ symmetry is in principle similar to the breakdown of the SM symmetry group (1). The notation v', h' specifies that we are dealing with a new hidden sector Higgs instead of the known SM Higgs. We should take into account that the dark photon gained a nonzero mass $m_{A'}$, which is unfixed by the theory. The interaction Lagrangian (18) contains different interactions: the second term is the three-point interaction between the dark photon and the dark Higgs, the third is their four-point interaction and the last two are the dark Higgs self-interactions. For simplicity, we could neglect all interactions except the kinetic mixing and the $h'A'A'$ coupling.

We may study this conveniently by making the field redefinition $A_\mu \to A_\mu - \varepsilon e A'_\mu$, which removes the kinetic mixing and also changes the A' kinetic terms by an irrelevant $O(\varepsilon^2)$ amount. What we get, is the effective parity-conserving coupling between the electromagnetic current and the dark photon

$$\mathcal{L}_{\text{int}} = \varepsilon e A'_\mu J^\mu_{\text{EM}} + \dots \tag{19}$$

suppressed relative to the electric charge e by the parameter ε. This redefinition is good as long as ε is small, but theoretically, this is not required. This new interaction is the reason, why a $\mathrm{U}(1)_\mathrm{d}$ gauge boson (dark photon) naturally opens a path into any dark sector [3, 17, 18].

This is a simple model, which may be extended or generalized. One generalization [19] will be obtained by allowing for the possibility of mass matrix mixing between the dark photon and the heavy Z boson of the SM. In this case, the dark photon couples to both the electromagnetic (J_μ^{EM}) and the weak neutral (J_μ^{NC}) current. So the dark photon may be renamed as "dark Z" and labelled Z_d because of its Z-like properties.

The mass of dark gauge boson can take on a large range of values. Models that involve supersymmetry often predict $m_{A'}$ to be in the MeV-GeV range, e.g. [20]. Different hidden sectors are also included in many string theory constructions. Some models are specifically constructed in a way that lowers the discrepancies between measured and present theoretical values of the anomalous magnetic moment of the muon and the proton charge radius [21].

Having constructed a model, one can now study its phenomenology. An example is to analyze the production and decay modes of the new particles. These modes depend on other particles. One has to examine separately different regimes. E.g. predicting that all dark sector particles are heavier than the dark photon[g], one can study independently two cases $m_{A'} < 2m_{\mathrm{SM}}$ and $m_{A'} > 2m_{\mathrm{SM}}$. m_{SM} is the SM particle's mass, e.g. m_μ or m_π. The first possibility forbids a decay to a pair of particle-antiparticle. On the other hand, the second one allows this decay. The interaction term responsible for this is the kinetic mixing term or (19) [3].

The dark photon A' can be efficiently produced in electron or proton fixed-target experiments, as well as at e^+e^- and hadron colliders. Analyses from this experiments will give new constraints on the $(m_{A'}, \varepsilon)$ parameter space [3].

8. Conclusion

Dark matter experiments suggest new low-energy gauge interactions BSM. If a dark sector exists, it will dramatically change our understanding of the structure of nature. Searches in existing collider data offer a simple but powerful investigation of this new dynamics. New dark sector particles with couplings around $\varepsilon \sim 10^{-3}$ can be efficiently produced in low-energy e^+e^- colliders and may decay spectacularly so that potential discoveries are within the reach of searches in existing data from experiments using these colliders, e.g. BaBar and BELLE [18].

It is clear that, even if current experiments have not been able to directly detect the axion, there are many orders of magnitude of mass, which need to be investigated. Axion is a highly compelling idea as an extension of the SM because detecting them means also detecting dark matter, which is at the forefront of modern physics. It is, therefore, reasonable to expect the axion to play an important role in the future.

While searching for new physics, there is no need to be constrained only on high energies, at the TeV-scale and above. It could well be found at the low-energy frontier experiments. Indeed, experiments that use intense beams of photons and sensitive detectors may be used to directly produce and study new, weakly-interacting particles. Existing facilities and technologies enable the exploration of dark sectors. A rich, diverse and low-cost experimental program is already active. It has the potential for a game-changing discovery. Current ideas for extending the searches to smaller coupling constants and higher masses increase this potential greatly. Especially experiments searching for axions have all before-mentioned characteristics. The high energy physics plan needs to include these experimental searches, especially when the investment is modest, the motives so clear and the possible new discoveries so spectacular. Since we do not know which guiding principle for finding new physics will to yield results, the support for a diverse experimental program is crucial [3, 16].

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[g] In this case, A' can kinematically not decay into dark sector particles.

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