Constrains on an uniform model for Dark Matter and Dark Energy

G N Izmaïlov

Moscow Aviation Institute (National Research University), 125993 Moscow Volokolamskoe sh., 4, Russia

E-mail: izmailov@mai.ru

Abstract. In this paper, outlined some of the most important concepts about Dark Matter and methods of their registration, in particular by using SQUIDs, a toy uniform model for Dark Matter and Dark Energy is analyzed. In the frame of the model Dark Matter particles is interpreted as excitations of Dark Energy field. Some constrains are considered. The devices based on SQUID, in particular the SQUID-paramagnetic absorber and the SQUID-magnetostrictor systems, both suitable for investigations of above problems, are considered. Estimates, are carried out within this model, indicate the possibility of experimental detection of the "ether wind" pressure, created by the non-corpuscular incoming flow, corresponding to the galactic orbital motion of the Earth.

1. Introduction

The accelerating expansion of the universe poses challenges for cosmologists. Among the contenders claiming to be the main contributor to uneven and different-temporal expansion at different cosmological distances, we note dark energy (DE), dark matter (DM), dark radiation (DR), and dark gravity (DG). Dark matter (latent mass) is unevenly distributed, thereby explaining the formation of galaxies and their clusters, but leaving the spaces between them free of masses, that opens up the possibility of the action of dark energy. DE is a continuous and homogeneous medium responsible for the accelerated increase in the distances between inhomogeneities. Possible DE-DM interaction leads to the appearance of radiation, part of which have characters that have not yet been detected. A fundamentally different approach to explaining the phenomenon of anomalous expansion is a modification of the laws of gravity, briefly referred to as DG.

The nature of dark matter (DM) is one of the most urgent unsolved problems in modern physics, so physicists persistently try to find signs of elusive dark matter that pulls everything but emits no light. History of observations and theoretical arguments for the DM existence are described in a recent review [1]. Besides large number of independent astrophysical and cosmological observations, such as galaxy rotation curves [2], large structure formation [3], and the observed spectrum of the cosmic microwave background [4-6], indicates that about 26% of the total mass-energy of the Universe is non-baryonic and non-relativistic cold component, which is not subject to electromagnetic interactions. Despite the long history of observations the particle content of DM remains unknown [7-9]. One possible solution would be the existence of new particles beyond the Standard Model (axions, dark photons, sterile neutrinos?).

Among many candidates for DM particles the most favored are the so-called WIMPs (weakly interacting massive particles) with a mass in the GeV to TeV range [10,11]. The WIMPs existences are well motivated, as provide solutions for outstanding issues in both cosmology and particle physics.

These particles appear in extensions to the Standard Model such as supersymmetry with R-parity conservation, and freeze out in the early Universe with an abundance that matches cosmological observations. Now DM particles can be detected in the laboratory experiments via elastic scattering off nuclei, causing recoils of a few keV in energy. However, no experimental indication for a standard WIMP was found in high sensitivity direct search experiments like EDELWEISS [12], XENON100 [13], LUX [14], SuperCDMS [15] for more than a few tens of GeV/c^2 mass.

Thermal relics with masses below 100 GeV/c^2 are also disfavored both from constraints set by Fermi-LAT searches for annihilation signals from Milky Way dwarf galaxies [16], and from the impact that WIMP annihilation would leave on the cosmic microwave background anisotropies [17]. Furthermore search for dark matter particles directly produced in proton-proton collisions in the CERN LHC experiments ATLAS and CMS did not show any indications of such particles so far [18-20].

On the other hand, in [21, 22] some researches insist on in the region of light WIMPs below 30 GeV/c^2, some experiments such as DAMA/LIBRA [21], CoGeNT [22], CRESST [23], CDMS II Si [24] claim or are interpreted as finding dark matter signals.

It is obvious that for observation of low-energy WIMP-induced nuclear recoils, detectors with both low detection threshold and a very low background are needed. The sensitivity of a dark matter direct detection experiment depends on the WIMP mass and on the nature and strength of its coupling to atomic nuclei.

Alternative to the quest of WIMP particles is a search of ultralight DM particles such as neutrino, dark photons or axions. Again, there is no indication that the high-energy neutrinos originating from dark matter annihilations in the Sun, which can escape and be observed by neutrino telescopes, such as Baksan [25], Super-Kamiokande [26], ANTARES [27] and IceCube [28].

When arguing the existence of DM, which exceeds the mass of the visible Universe by about five times, with the help of light particles, a compelling cold dark matter candidate is axion. It has feeble coupling to ordinary matter, moves with non-relativistic energies, and early universe cosmology consistent with dark matter phenomenology. Mass of a pseudoscalar boson – axion is $m_a \sim 10^{-11} \div 10$ eV. This range is probed by the tuple of experimental groups [29, 30].

Axions were introduced as a consequence of an extension of the Standard Model. The expansion, in particular, follows from the desire to preserve CP invariance, which is violated by the absence of an electric dipole moment in the proton, and axions, as particles of a new field that preserves CP invariance, play this role [31–33]. Moreover, new particles have no electric charge. Unexpectedly, it turned out that astrophysical and cosmological problems of the energy balance when calculating the emission budget of stars, the existence of halos around galaxies [34, 35], the cooling processes of white dwarfs [35], and the shortening of the duration of the SN 1987A supernova explosion [36, 37] can also be described more simply, using the existence of axions. (According to estimates [30, 38], the particle density is $\sim 10^{21}$ m^{-3}). Thus, the axions that make up the DM can be detected not only at accelerators, but also in laboratories studying cosmic radiation, since it serves as a source of axions [39, 40].

To describe the axion - photons conversion Primakoff mechanism was proposed [41]. It had been offered to explain the decay of muons. The form of this mechanism was used to count the axion - photons conversion in an external magnetic field and it was chosen as a mechanism which is convenient for an axions registration. In such case the probability of axion-photons conversion is proportional to $(g_{a\gamma\gamma}BL)^2$ where $g_{a\gamma\gamma} \lesssim 10^{-10}\text{GeV}^{-1}$ is a constant of axion-photons interaction, B is the magnetic field and L is its length [42]. Also the reverse process of transformation of photons into axions is possible. As it can be shown it is possible in the laboratory to use sources of powerful coherent radiation (lasers with intense laser beams $\sim 10^{21}$W/cm^2) and with their help simulate the conversion of photons into axions, as well as the reverse process [43]. An additional impetus to research on the conditions for observing axions was the applied problem of detecting the passage of an axion beam through the thickness of matter without a significant weakening of its intensity - the LSTW (light shining through walls) experiment [44, 45]. It was proposed to use a small interaction cross section to establish communication through massive opaque obstacles or very long distances, for example, the Earth-Earth or Earth – Moon.

As noted above, Primakoff mechanism uses low-frequency virtual photons of the magnetic field that resonate with the field of axions. The probability of the axion-photons conversion is $p \sim (g_{a\gamma\gamma}BL)^2$. Due to a very weak interaction the strong enough magnetic fields B ($B \gtrsim 10^2$T) along the entire path L ($\sim 10^2$m), where the conversion takes place for such reactions are required. Because during solar flares on Sun surface there are a lot of photons piercing spacious magnetic field in the protuberance form, then it is possible to observe axion generation by helioscope (IAXO project) [46].

The contemporary paradigm states that DE is a hypothetical all-pervading substance that may be responsible for additional acceleration in Hubble's law of galaxy recession. At the same time we consider DM as a kind of matter with only inertial properties. The DM will keep galaxies as a whole if parts of them break off as they move rapidly. (For example, if Mercury revolves around the Sun in orbit of Pluto at the same speed as in its original orbit, it will leave our system. Thus, in a spiral galaxy, it is DM needed to explain the flattening of the rotation curves). Can we assume that DM has only the inertial property?

A number of recent observations suggest that DM can interact with both baryonic matter, primordial black holes and/or dynamically interactive DE. This appears when 21cm radio signals are analyzed using DM interactions with baryons and/or primary BHs [47]. The possible excess of the 21-centimeter line at the cosmic dawn can be explained also by the active background of the dynamic interactive DE. The active interaction at an early dark energy dominated stage with dynamically interacting dark energy, which manifests itself in the excessive brightness of the 21 cm signal is investigated in [48]. Moreover, in recent astrophysical observations of DM made with the satellite gamma ray telescope Fermi-LAT and DE survey the detection of gamma rays from approximately 45 dwarf spheroidals (dSphs) of the Milky Way in the dense region of galactic centers was reported. Revealing γ-rays indicates processes inside DM and is attributed to the result of self-annihilation of DM, which is another mechanism of activity [49].

Thus, it becomes possible to reveal not only the inertial properties of DM. Both DE and DM play a key role in modern models of galaxy formation and evolution. The discovery of new properties of DM type would provide a clue to the DM-DE interaction.

In recent time some investigators expected the time intervals measurements suppose that they are hint for DM observation [50, 51].

2. A toy uniform model for Dark Matter and Dark Energy

The clues we get from the analysis of astrophysical observations [47-49, 52] can be used to create a unified model in the form DE + DM = DS. In [53] there was considered an approach for DM description, based on the possibility that DM and Dark Energy (DE) are two different aspects of the one cosmological essence, named "Dark Substance", which is characterized by variable ς. Subsequently, in DS, which has a primary viscosity, but not a form - the original topology - one can describe a property that allows one to construct local maps continuously conjugate to each other and use the smoothness condition (differentiability of smooth forms) to connect them. The reason is that the use of locally flat maps creates the basis for the construction of inertial frames of reference. When constructing, one should use the principle of general relativity - the independence of fundamental systems of physics from the background (DS), which means covariance under a diffeomorphism as a smooth deformation of a spacetime manifold.

The means of offered approach were anticipated from integrated Sachs – Wolfe effect. It points on a correlation between anisotropy of local equilibrium temperature for CMB (i.e. fluctuations of photons) and large scale Universe structure, or in accordance with Einstein GR, of gravitational potential due to the massive particles that do not otherwise interact, i.e. the DM. And both photons and DM are in a primordial soup – DE. So the temperature fluctuation is directly related to the gravitational potential fluctuation by some constant [54]. The influence of scales (hierarchy of scales) can be observed at all levels. Water in the usual macro representation - a continuous, viscous liquid - in the micro representation consists of particles - molecules, which manifests itself in phase transitions. In the Universe, galaxies and galaxy clusters with different astrophysical regularities of the distribution of the gravitational field and the distribution of stars serve as an example, which led to the recognition of the existence of DM and DE. The long-scale structure depends on a matter density, the CMB anisotropy – is defined by fluctuations of a cosmological gravitational potential, which changes the photon frequency, which is consistent with the notion of the absence of scale invariance in an empty Universe. The effect is in a good agreement with the prediction of the concordance ΛCDM cosmology [55-57]. On the other hand, the view of DE as the frame of reference in which DM is located ("river frame + fishes" model) may well be used to represent the DE ↔ DM relationship by using both coordinate transformations and gauge ones [58].

According to an offered model, with origin density of about 300 TeV/m^3, it represents the unperturbed state of "Dark Substance", while its swings or perturbations play the role of elementary DM heavy particles. These particles will be stable if all their decay channels into any combination of other particles are blocked, or also, in our case, if their potential will have local minima, i.e., local traps providing metastable excited states. The density of Hamiltonian with metastable traps can be represented in 2D spacetime, for example, as follows:

$$H = \frac{1}{2}\left(\frac{\partial\varsigma}{\partial x}\right)^2 + \frac{1}{2c^2}\left(\frac{\partial\varsigma}{\partial t}\right)^2 + \alpha\varsigma * \varsigma - \beta\cos\gamma\sqrt{\varsigma * \varsigma}. \quad (1)$$

Here α, β, γ are coefficients. The nonlinear wave equation, corresponding to this Hamiltonian, and describing the dynamics of perturbations to Dark Substance will be like the "quasi-sine-Gordon" equation

$$\frac{\partial^2\varsigma}{\partial x^2} - \frac{1}{c^2}\frac{\partial^2\varsigma}{\partial t^2} + \alpha\varsigma * + \frac{1}{2}\beta\gamma\sqrt{\varsigma */\varsigma}\sin\gamma\sqrt{\varsigma * \varsigma} = 0. \quad (2)$$

Moreover, the nonlinear potential $\Pi(\varsigma) = \alpha\varsigma * \varsigma - \beta\cos\gamma\sqrt{\varsigma * \varsigma}$ appearing in (1), has the analytic structure very similar to the "parabolic washboard potential" [59] used to describe metastable states in the superconducting ring of a SQUID with one Josephson junction, namely:

$$\Pi(\varsigma) = \alpha|\varsigma|^2 - \beta\cos\gamma|\varsigma| \Leftrightarrow E(\Phi) = \frac{1}{2L}\Phi^2 - I_C\Phi_o\cos\frac{2\pi}{\Phi_o}\Phi, \quad (3)$$

where Φ is the magnetic flux piercing the superconducting ring and L is the inductance of the curcuit itself. We represent the profile of the washboard potential in figure 1 of [53]. Some comments about this figure are needed. For small ς (when the disturbance has not yet reached the first trap) folds of the Dark Substance potential have a quasi-harmonic character, and their quanta will have a mass $m = \frac{\boldsymbol{h}}{c}\sqrt{2\alpha + \beta\gamma^2}$. However, such particles may be unstable, and the rate of decay from classical positions will correspond to the viscosity of the Dark Substance [60, 61]. At large amplitudes of ς, the disturbance at some moment will "catch" the lowest energy trap. The trajectory of the oscillation ς will now be a circle in the plane {ς, ς*}, corresponding to a local minimum of potential. The rotation around the circumference of a local minimum is similar to the mechanism of occurrence of massless Goldstone bosons in Weinberg-Salam's model. However, in this example, the mass of excitations ("zero energy") is determined by the height of the bottom of the trap with respect to the main vacuum state ς=0, ς*=0, and will be non-zero. The stability of such excitations, playing (in this example) the role of DM particles, is guaranteed by the height of the wall of the potential well, occurring in the vicinity of the local potential minimum. Due to the model local minimum positions are the metastable states of DM particles. The lower local minimum is associated with a light (or also hot) component of DM, and the top one with a heavy (or also cold) component of DM. The absolute minimum lies in the region of negative energies and is associated with antigravitational properties of DE. For comparison the exemplary shape of potential used in models of spontaneous symmetry breaking is adopted [53].

3. Non-corpuscular "ether wind" and possible registration of its pressure by the SQUID-magnetostrictor system

Therefore, the search of DM particles, as stable moving excitations of Dark Substance, may be intimately connected with the research of the action of the DE non-corpuscular flux on the ordinary matter. By knowing that the free mean path is connected to the cross section of interaction by the relation $\ell^* \approx 1/(\sigma n_A)$, we may say that DE transfers to a slab of material, consisting of ordinary atoms of concentration n_A, with area S and "maximum depth" ℓ, a momentum $q=\ell^* S\rho_{DE}/\upsilon$, where υ is the DM particles speed relative to the substance. In this way, Dark Substance exerts the pressure

$$p^*_{DE}=F/S=(\ell^* S\rho_{DE}/\upsilon)((\ell^*/\upsilon)S)^{-1}=\rho_{DE} \quad (4)$$

on the slab, where ρ_{DE} is an evaluation of DE energy density. Thus, the effective pressure drop across the length ℓ is estimated as $p_{DE}=p^*_{DE}\,\ell/\ell^*=\rho_{DE}\,\ell\sigma n_A$. In accordance with the generally accepted value of the average density of Dark Energy $\rho_{DE}\approx 300\,\mathrm{TeV/m^3}$, taking into account the above-obtained "optimistic" estimation of the interaction cross section $\sigma\approx 10^{-35}\mathrm{cm}^2$, the pressure drop across a one-meter barrier, having a concentration of atoms $n_A\approx 3\times 10^{22}\mathrm{cm}^{-3}$, will be of the order of $p_{DM}(\ell=1\,м)\approx 7\times 10^{-16}$ Pa.

In order to register such pressure, a dynamometer that performance capable to fix the strength of 10^{-16} N at the end of the cylinder, which dimensions $\ell\times S\approx 1\mathrm{m}\times 0.15\ \mathrm{m}^2$, is required. Apparently, the suitable candidate for the role of the super-high-sensitivity dynamometer is the SQUID-magnetostrictor system [62-64] which has been previously supposed to be used in projects for the detection of gravitational waves, etc. (Figure 1).

Ultra-high sensitivity is achieved by means of this system. In fact, high strain-gauge effectiveness of the sensor can be achieved, since it operates on the principle of the reverse magnetostrictive effect, generated, in its turn, by collective quantum solid-state effects [61]. On the other hand, the high ("quantum scale" level) sensitivity of SQUID systems, used as measuring instruments, allows accurate registration of events.

The physical quantity describing the reverse magnetostrictive effect (discovered by Emilio Villari in 1865) in a particular material is the ratio of the internal magnetic induction field to the growth of its outside pressure, i.e., $\Lambda^{-1}=\frac{\partial B}{\partial P}$. For example, an alloy made up of 54% Pt and 46% Fe, with $\mu\approx 14000$, will have $\Lambda^{(-1)}\approx 10^{-4}$T/Pa (which is basically not a record value). Thus the magnetic response, measured by the SQUID, is related to the force action δF by this expression $\delta\Phi=\Lambda^{(-1)}\delta F$. Accordingly, the capability to register the pressure of non-corpuscular Dark Matter flow, estimated above for $\sigma\approx 10^{-35}cm^2$ at $\delta F\approx 10^{-16}$ N, requires an "absolute" (not reduced to the time of the signal accumulation) SQUID sensitivity for the magnetic flux of the order of magnitude of 10^{-20} Wb $\approx 5\times 10^{-6}\,\Phi_0$. The actual value of a good DC-SQUID is of about $\delta\Phi\approx 10^{-6}\,\Phi_0/\sqrt{\mathrm{Hz}}$, which provides the desired sensitivity with a margin of approximately 2 orders of magnitude (at least) due to the possibility of a 3-hour signal accumulation.

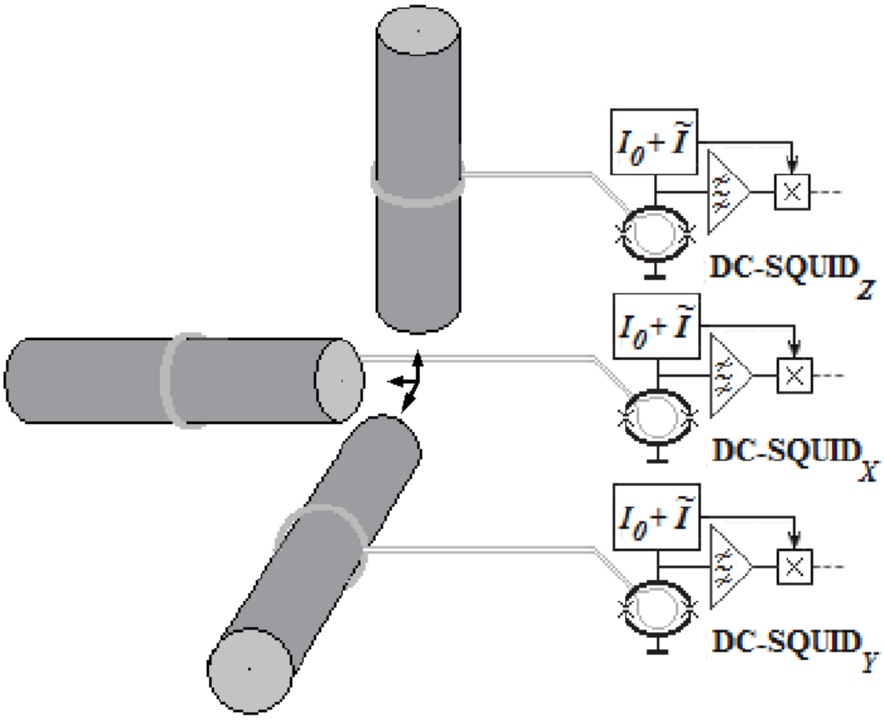

Figure 1. Schematic view of the SQUID-magnetostrictor 3D system for the detection of gravitational waves (the magnetostrictive cylinders are represented in grey) which can be used to determine the action of DE [65].

4. Discussions

In this paper, starting from an introduction about DM and its cosmological properties, in the context of "unifying" trend, clearly dominant in the modern elementary particle physics a simple unimodel is proposed, where it is considered the corpuscular Dark Matter (DM) and non-corpuscular Dark Energy (DE) from single approach. This is the proposed model, in which the DE is an absolutely continuous substance, playing the role of a room for metastable excitations, which can be identified as DM particles.

These excitations, clustering themselves, bind baryonic matter more and more, leaving the intermediate space empty, free for expansion under the action of DE.

From this point of view, we cannot assume DE as a medium suitable for the role of absolute spacetime, relative to which the states of other objects are considered. DE is rather an active medium, one of the manifestations of the activity of which is the effect of the production of DM particles.

The coefficients α, β, γ have some uncertainties need to be reduced in order to satisfy the limiting cosmological models of the classical picture of general relativity. In [66] an unexpected unification between general relativity and QFT was noted due to the superposition of fields, which manifests itself in the existence of entangled states that justify connectivity. From this point of view, the existence of linked DM particles explains the connectivity leading to "emergent geometry". At the same time, it paves the way to theoretical concepts of information.

In modern cosmology, there is an irreconcilable contradiction between the experimentally confirmed position of the accelerating Universe expanding (the Big Bang theory) and the recorded constancy of world constants, leading to an alternative assumption about the constancy of particle density – the Quasi-State-model [67]. Within the framework of the above proposed model, the statement about an increase in the number of particles with time, which leads to the constancy of the density of matter and radiation, is partially confirmed.

Estimates, carried out within that model, indicate the possibility of experimental detection of the "ether wind" pressure, created by the non-corpuscular incoming flow, corresponding to the galactic orbital motion of the Earth. It is argued that these classes of investigations could be performed by using the SQUID-magnetostrictor experimental system. At the same time, the concept of quantizing the continuity of the medium, which was used in the article, should undergo some modification in order to establish the boundaries of possible quantization both in the energy scale and in the spatial one.

It can be noted also that the proposed model admits the existence of negative values of mass (energy) - a long-awaited donate for the theory of gravity.

References

[1] Bertone G and Hooper D 2018 *Rev. Mod. Phys.* **90** 45002 (*Preprint* astro-ph.CO/1605.04909)
[2] Rubin V C, Thonnard N and Ford Jr. W K 1980 *Astrophys. J.* **238** 471
[3] Springel V *et al* 2005 *Nature* **435** 629 (*Preprint* astro-ph/0504097)
[4] (WMAP Collaboration) 2007 Wilkinson Microwave Anisotropy Probe (WMAP) three year results: implications for cosmology *Astrophys. J.* Suppl. **170** 377 (*Preprint* astro-ph/0603449)
[5] (Planck Collaboration) 2014 Planck 2013 results XVI Cosmological parameters *Astron Astrophys* **571** A16 (*Preprint* astro-ph.CO/1303.5076)
[6] Ade P A R *et al* (Planck Collaboration) 2015 Planck 2015 results. XIII Cosmological parameters (*Preprint* astro-ph CO/1502.01589)
[7] Bergstrom L 2000 *Rept.Prog.Phys.* **63** 793
[8] Bertone G, Hooper D and Silk 2005 *J. Phys. Rep.* **405** 279
[9] Olive K A *et al* (Particle Data Group) 2014 *Chinese Phys*. C **38** 090001
[10] Ryabov V A, Tsarev V A and Tskhovrebov A M 2008 *Physics- Uspekhi* **51** 1091
[11] Feng J L 2010 *Ann. Rev. Astron. Astrophys*. **48** 495
[12] Armengaud E *et al* (EDELWEISS Collaboration) 2017 *JINST* **12** P08010 (*Preprint* astro-ph GA/1706.01070)
[13] Aprile E *et al* (XENON100 collaboration) 2012 *Phys. Rev.Lett.* **109** 181301
[14] Akerib D S *et al* (LUX collaboration) 2019 *Phys. Rev. Lett.* **122** 13101 (*Preprint* physics.ins-det/ 1811.11241)
[15] Agnese R *et al* (SuperCDMS collaboration) 2014 Search for Low-Mass Weakly Interacting Massive Particles with Super CDMS *Phys. Rev. Lett.* **112** 241302
[16] Mazziotta M N *et al* (Fermi-LAT Collaboration) 2019 *PoS* ICRC **2020** 531
[17] Ade P A R *et al* (Planck Collaboration) Planck 2015 results. XIII. Cosmological parameters. (*Preprint* astro-ph CO/1502.01589)
[18] Aad G *et al* (ATLAS Collaboration) 2015 *Eur. Phys. J.* C, **75** 299
[19] (ATLAS Collaboration) 2018 *Phys. Rev.* D **98** 032016 (*Preprint* hep-ex/1805.09299)
[20] Khachatryan V *et al* (CMS Collaboration) 2020 *Preprint* hep-ex/2012.04120
[21] Belli P, Bernabei R, Danevich F A *et al*. (DAMA Collaboration) 2019 *Eur. Phys. J*. A **55** 140 (*Preprint* nucl-ex/1908.11458)
[22] Aalseth C E *et al* (CoGeNT collaboration) 2011 *Phys.Rev.Lett.* **106** 131301
[23] Angloher G *et al* (CRESST Collaboration) 2017 *Eur Phys J* C **77** 299 (*Preprint* hep-ex/1612.07662)
[24] Agnese R *et al* (superCDMS Collaboration) 2019 *Phys. Rev.* D **99** 062001
[25] Boliev M M *et al* 2013 *JCAP09* **1309** 019 (*Preprint* astro-ph.HE/1301.1138)
[26] Suzuki Y 2019 *Eur. Phys. J.* C **79** 298
[27] Albert A *et al* 2020 *Phys. Lett.* B **805** 135439
[28] Abbasi *et al* 2021 *Phys.Rev.*D **103** 10 102001 (*Preprint* astro-ph.HE/2101.00610)
[29] Sloan J V *et al* 2016 *Physics of the Dark Universe* **14** 95
[30] Di Luzio L, Giannotti M, Nardi E and Visinelli L 2020 *Phys. Rept.* **870** 1
[31] Peccei R D and Quinn H R 1977 *Phys. Rev. Lett.* **38** 1440
[32] Weinberg S 1978 *Phys. Rev. Lett.* **40** 223
[33] Wilczek F 1978 *Phys. Rev. Lett.* **40** 279
[34] Sikivie P 1983 *Phys. Rev. Lett.* **51** 1415

[35] Giannotti M, Irastorza I, Redondo J and Ringwald A 2016 *JCAP* **05** 057 (*Preprint* astro-ph.HE/1512.08108)
[36] Melendez B Bertolami M M and Althaus L 2012 (*Preprint* hep-ph/1210.0263)
[37] Okun L V, 1982 *Sov. Phys. JETP* **56** 502
[38] Ringwald A 2015 (*Preprint* hep-ph/1506.04259)
[39] Du N *et al* (ADMX Collaboration) 2018 *Phys. Rev. Lett.* **120** 151301
[40] Aprile E *et al* (XENON Collaboration) 2019 *Phys. Rev. Lett.* **123** 251801
[41] Primakoff H. 1951 *Phys. Rev.* **81** 899
[42] Sikivie P, Tanner D and van Bibber K 2007 *Phys. Rev. Lett.* **98** 172002 *(Preprint* hep-ph/0701198*)*
[43] Gorelik V S, Izmailov G N 2011 *Bulletin of LPI (KSF English)* **6** 177
[44] Jaeckel J, Redondo J and Ringwald A 2009 *EPL* **87** 10010
[45] Redondo J and Ringwald A 2011 *Contemporary Physics* **52** 211
[46] Irastorza I G, Pivovaroff M and Kate H T 2014 *CERN Courier*
[47] Halder A, Pandey M. (*Preprint* astro-ph.CO/2101.05228)
[48] Li C, Ren X, Khurshudyan M and Cai Y-F 2020 *Physics Letters* B **801** 135141
[49] Halder A, Banerjee S, Pandey M and Majumdar D 2020 *Mon.Not.Roy.Astron.Soc.* **500** 5589
[50] Kennedy C J *et al* 2020 *Phys. Rev. Lett.* **125** 201302
[51] Pedrozo-Peñafiel E S *et al* 2020 *Nature* **588** 414
[52] Bhattacharya A *et al* 2017 *JCAP* **07** 027 (*Preprint* hep-ph /1706)
[53] Giordano A, Izmailov G N, De Luca R, Ryabov V A, Zherikhina L N and Tskovrebov A M 2016 *(Preprint* astro-ph.HE/1611.04651v1)
[54] Sachs R K, Wolfe A M 1967 *Astrophys. J.* **147** 73
[55] Maeder A 2017 *The Astr. J.* **834** 194
[56] Nishizawa A J 2014 *Progress of Theoretical and Experimental Physics* **6** 06B110
[57] Kovács A 2018 *Monthly Notices of the Royal Astronomical Society* **475** 1777
[58] Roldan O 2018 *JCAP* **03** 014
[59] Barone A, Paternò G 1982 *Physics and applications of the Josephson effect* (New York: J Wiley & Sons) pp 529
[60] Velten H, Schwarz D J, Fabris J C and Zimdahl W 2013 *Phys. Rev.* D **88** 103522
[61] Velten H, Wang J and Meng X 2013 *Phys. Rev.* D **88** 123504
[62] Golovashkin A I *et al* 1994 *JETP letters* **60** 612
[63] Izmailov G N, Zherikhina L N, Ryabov V A and Tskhovrebov A M 2010 *In Dark Energy: Theories, Developments, and Implications* (Nova Sc. Pub.)
[64] Golovashkin A I *et al* 2012 *Quantum Electronics* **42** 1140
[65] Izmaïlov G N *et al* 2018 *J. Phys.: Conf. Ser.* **1051** 012016
[66] Seltmann M 2018 *In Experimental Search for Quantum Gravity* (Cham: Springer Int. Publ. AG) pp 91-104
[67] Narlikar J V, Vishwakarma RG and Burbidge G 2002 (*Preprint* astro-ph/0205064v2)