Thermal Leptophilic Light Vector Dark Matter with Spinor Mediator and Muon (g-2) Anomaly

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Abstract

Inspired by the recently new measurement of $(g-2)_\mu$ at FermiLab and reported upper bound for electron-dark matter (DM) recoil by the XENON1T collaboration, we revisited phenomenology of a light MeV scale vector dark matter in a leptophilic extension of standard model while a new spinor field plays the role of mediator. A viable parameter space is considered to discuss the possibility of light dark matter relic density as well as anomalous magnetic moment of the muon. We study DM-electron direct detection and cosmological bounds on the parameters space of the model. It is shown that although new bound of $(g-2)_\mu$ anomaly greatly confines the parametric space of the model, the thermal light dark matter can exist for $M_{DM} \sim 10^{-1} - 10^1$ GeV.

1 Introduction

As it is well-known, the existence of DM on many scales in the universe has been widely established, but its nature remains an unsolved problem. Traditional DM candidates, in many beyond standard model (BSM) scenarios are weakly interacting massive particle (WIMP) with mass close to the electroweak scale and weak couplings with Standard Model (SM) particles. However the lack of any signal in direct, indirect detection experiments and search at the LHC, has opened the door to wide spreading DM models possibility covering small value ranges in DM masses and interaction coupling strengths.

Furthermore, physics of BSM may leave affect in low-energy precise measurements via possible deviations between the SM and experimental evidences. Some of these deviations include the LHCb [1] and the muon anomalous magnetic moment (AMM) $a_\mu = (g_\mu - 2)/2$ which was recently reported by FermiLab experiment (3.3 σ) [2] challenging lepton universality. Combining this result for AMM with the earlier measurement at the Brookhaven National Laboratory, this now amounts to a 4.2 σ deviation from the SM prediction [3]. This result leaves an open window to new particles which can contribute to muon $g - 2$ through direct coupling to the muon. Many models related to DM candidates and $(g-2)_\mu$ anomaly have been proposed, including axion-like particle (ALP) explanation [4–7], SUSY-DM explanation [8–11], two Higgs doublet

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models (2HDM) plus singlet explanation [12], and others [13–27]. Also it should be noted that if we compare to the latest QCD lattice calculations this decrease to about 1.4 σ [28]. In order to clarify the origin of this difference, a new experiment aiming to measure the contribution of hadronic corrections is being prepared at CERN [29]. One should also note that the drastic change in Hadronic Vacuum Polarization (HVP) leads to tensions elsewhere [30–32].

The primary purpose of direct detection experiments is the search for thermal relic particles (WIMPs) with GeV-scale mass. However, recently, there has been significant interest in models of DM in which DM particle has a mass $m \leq \mathcal{O}(\text{GeV})$. This is appealing because such models evade nearly all constraints on DM imposed by nucleon-DM direct detection experiments, since direct detection experiments are insensitive to the small recoil energies characteristic of $m \leq \mathcal{O}(\text{GeV})$. An alternative scenario in direct search is the interaction of DM particles exclusively with the SM leptons and possibly having loop suppressed interactions with nucleons. However in this case, DM still obtain its relic abundance from Freez-out mechanism.

In this light, direct detection strategies are proposed for DM particles with KeV to MeV mass. In this range, DM scattering with electrons can cause single-electron ionization signals, which are detectable with current technology. Ultraviolet photons, individual ions, and heat are interesting alternative signals. For example, the light DM regime (1 MeV to 10 GeV) where DM interacts with atomic electrons via recoiling is now significantly constrained by recent data from the XENON1T [33], DarkSide50 [34] and SENSEI [35] experiments.

The goal of this paper is to broaden the scope of BSM physics. We propose light vector DM candidates with mass regime (1 MeV to 10 GeV). The interaction of DM with SM is leptophilic and DM particles only interact with SM leptons via spinor mediators. Scattering of vector DM from electron could be consistent with XENON1T [33] experiment bounds for DM-electron direct detection. The leptophilic models are particularly interesting when we look at the anomalous magnetic moment of the leptons. In this way, we attempt to find out parameter space of the model to explain the newest muon magnetic moment anomaly.

The outline of this paper is as follows: In Section 2, we introduce framework for a light vector DM. In Section 3, we study anomlous magnetic of muon in context of the model. We consider relic density and DM-electron recoil bounds on parameters of the model in section 4 and 5. The Section 6 contains the influence of various experimental constraints on the model parameters. Finally, we present combined result in last section.

2   The Model

Here, we present a vector DM model, which extends the SM with massive spinor mediators which couples to vector dark matter (VDM) particles and SM leptons. The only renormalizable interaction is taken as follows:

$$\mathcal{L} \supset \sum_{\ell=e,\mu,\tau} X_\mu \overline{\psi}_l \gamma^\mu [g_s + g_p \gamma^5] \ell + \text{H.C.}, \tag{2.1}$$

where X_μ is the VDM candidate, and ψ_ls are (Dirac) spinor mediators. Generally, the interaction terms $X_\mu \overline{\psi}_l \gamma^\mu [g_{s\psi} + g_{p\psi} \gamma^5] \psi_l$ and $X_\mu \overline{l} \gamma^\mu [g_{sl} + g_{pl} \gamma^5] l$ can also exist. However, these interactions

will lead to X_μ being unstable. To avoid such interactions we impose a Z_2 discrete symmetry under which both X_μ and ψ_l are odd but all SM fields are even. In our analysis, we have assumed universal couplings between the mediators and the SM leptons. For simplicity, we have eluded mixing between ψ_ls and lepton generations. If different lepton flavors couple with a same ψ and X_μ, then at one-loop level we should face the charged lepton flavor violation (CLFV) problem (for a review on the muon anomalous magnetic moment and the quest for lepton flavor violation see [36]). In such a scenario, at one-loop level, we should have muon to electron transition process $\mu \to e + \gamma$ which has been stringently constrained. In (2.1), to avoid CLFV, we have considered different ψ_ls for each lepton flavor. However, to keep the model minimal, we suppose all spinor mediators have the same mass. In order to avoid DM decay, we suppose $M_\psi > M_X$. By considering this constraint X_μ will be stable and can serve as DM. Since X_μ is neutral with no electric charge, for spin 1/2 mediators, the spinor ψ_ls have positive electric charges (and therefore couple to photon) that is equal but opposite to the charged leptons. Therefore, X_μ and neutrinos cannot couple together via charged spin 1/2 mediators. VDM stability commands that no tree level mixing between the Z-boson and X_μ is allowed. Therefore in our model, we have 4 independent parameters M_X, M_ψ, g_s and g_p. Finally, we emphasize that our approach in this paper, is quite phenomenological. We have not considered gauge invariance of Lagrangians under some gauge group, and the model is not UV-complete. For example, we supposed that ψ_ls are $SU(2)_{\text{Weak}}$ singlet while have $U(1)_{\text{EM}}$ charge; in constructing a gauge invariant model such assumption should be considered more carefully.

3   Anomalous Magnetic Moment (AMM) of the Muon

As it is well-known, there are some discrepancies between SM predictions and measurements in low energy experiments. One long-standing discrepancy is the anomalous magnetic dipole moment of muon:

$$a_\mu = (g_\mu - 2)/2. \tag{3.1}$$

Comparisons with experimental measurements a_{exp}^l results in studies of the magnetic moments of leptons being a powerful indirect search of new physics. The SM prediction of the anomalous magnetic moment is determined from the sum of all sectors of the SM which include the QED contributions, the electro-weak contributions, the hadronic vacuum polarization contributions and hadronic light-by-light scattering contributions. The uncertainty of a_{SM} is completely dominated by the hadronic contributions due to the non-perturbative nature of the low energy strong interaction. It is estimated from experimental measurements of the ratio of hadronic to muonic cross sections in electron-positron collisions [37–58]. The combined results of muon anomalous magnetic moment in two experiments at FermiLab (FNAL E989) [2], and Brookhaven National Laboratory (LabBNL E821) [3] yield overall deviation from the SM central value:

$$\Delta a_\mu = a_\mu^{exp} - a_\mu^{\text{SM}} = (25.1 \pm 5.9) \times 10^{-10}, \tag{3.2}$$

which corresponding to a significance of 4.2 σ.

In light of the results, we study constraints on the parameter space of the model. Since in our model, VDM particles interact with the SM leptons via a massive mediator, a significant effect on the anomalous magnetic moment of the leptons is expected.

In the present work, as we mentioned before, we consider universality for all interactions of leptons. Therefore, we only consider the magnetic moment of the muon and ignore weaker constraints on the AMMs of tau and electron. The model contribution to muon magnetic moment arises from the one-loop mediated by VDMs. The analytical expression for Δa_μ^ψ is [59]- [60]:

$$\Delta a_\mu^\psi = \frac{1}{8\pi^2}\frac{m_\mu^2}{M_X^2}\int\frac{g_s^2 P_s(x) + g_p^2 P_p(x)}{(1-x)(1-\lambda^2 x) + \epsilon^2\lambda^2 x}dx \tag{3.3}$$

where

$$P_s(x) = 2x(1-x)(x - 2(1-\epsilon)^2) + \lambda^2(1-\epsilon)^2 x^2(1+\epsilon-x)$$
$$P_p(x) = 2x^2(1+x+2\epsilon) + \lambda^2(1-\epsilon)^2 x(1-x)(x-\epsilon)$$

and $\epsilon = M_\psi/m_\mu$, $\lambda = m_\mu/M_X$ (m_μ is the muon mass, M_ψ and M_X are spinor mediator and DM mass). Therefore the contribution of a generic spinor mediator to the muon anomalous magnetic moment is given by:

$$\Delta a_\mu^\psi = \left(\frac{m_\mu}{2\pi M_X}\right)^2\left\{\left[\frac{M_\psi}{m_\mu} - \frac{2}{3}\right]g_s^2 + \left[-\frac{M_\psi}{m_\mu} - \frac{2}{3}\right]g_p^2\right\}, \tag{3.4}$$

where g_s and g_p are couplings of the SM leptons with new fields in accordance with interaction terms of Eq. (2.1). Figs. 1-a and b show allowed region in $M_X - M_\psi$ plane for random values of couplings which is consistent with BNL E821 and FNAL E989 experiments. As it is seen in figures, for masses of spinor and DM between a few hundred MeV to 100 GeV, the contribution of the model can explain a_μ anomaly. Note that in each plot, we turn on both couplings (g_s and g_p).

Before the next section, we comment on the electron g-2 result as a comparison. There is a 2.4 σ discrepancy between the theoretical prediction [61] and the existing experimental measurement [62,63] of the electron anomalous magnetic moment,

$$\Delta a_e = a_e^{exp} - a_e^{SM} = (-87 \pm 36) \times 10^{-14}. \tag{3.5}$$

Given the negative sign of the above relation, to explain both electron and muon g-2 in this model, according to (3.4), one should consider different couplings for electron and muon generations. Otherwise, $\Delta a_\mu^\psi > 0$ leads to $\Delta a_e^\psi > 0$. However, considering the significance of 4.2 σ of muon anomalous magnetic moment and ignoring 2.4 σ electron g-2 anomaly, we continue to assume universal couplings between the mediators and the SM leptons.

4 Relic Density of DM

Cosmological observations point toward the existence of DM, whose cosmological relic abundance is approximately a fourth of the energy budget of the Universe. According to the recent measurements from the PLANCK [67] collaboration DM relic density is:

$$\Omega_{DM}h^2 = 0.120 \pm 0.001, \tag{4.1}$$
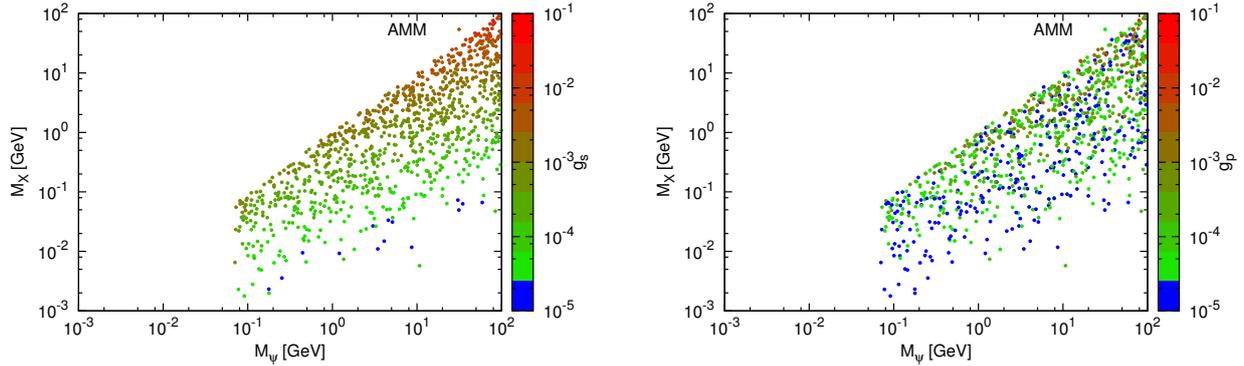
Figure 1: Scatter-points consistent with AMM of the Muon. We scanned over all free parameters of the model. Note that, the parameter space could be limited by other experiments, such as BaBar, Belle II and LEP II. However, maybe the case of a small mass difference of $M_\psi - M_X = \delta > 0$ with $\delta/M_\psi \ll 1$ is still allowed by experiments (with large missing energy plus soft electrons/muons), like the case of supersymmetry. In addition, if $2M_\psi$ is lighter than the tau lepton m_τ, the decay spectrum and width of tau lepton will be changed. Thus, the parameter space left are smaller than that in this figure. To see how these experiments limit the parameter space see, e.g., [64–66]
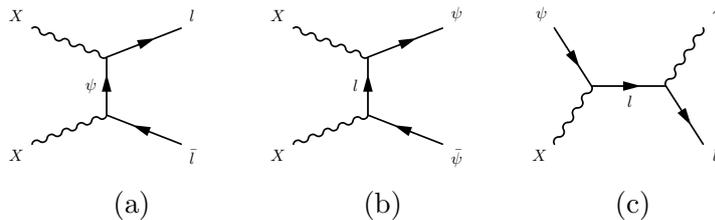
Figure 2: Feynman diagrams for DM annihilation into (a) leptons and (b) spinor mediators. For every t channel there is associated u channel not depicted here. DM coannihilaion is depicted in (c).

where $h \sim 0.7$ is the Hubble expansion rate at present times in units of $100 \ (km/s)/Mpc$.

We suppose the mechanism that generates DM cosmological relic density is thermal freeze-out described by a Boltzmann equation of the form

$$\frac{dn_\chi}{dt} + 3Hn_\chi = -\langle \sigma_{eff} | v_{rel} | \rangle (n_\chi^2 - n_{\chi,eq}^2), \tag{4.2}$$

where n_χ is the number density of vector DM, H is the Hubble parameter, and $\langle \sigma_{eff} | v_{rel} | \rangle$ is the thermally averaged of effective cross section including both DM annihilation and coannihilaion channels [68] (see figure 2).

The constraint from DM relic density on the vector DM have been determined by implementing the model in the numerical package `MicrOMEGAs` [69]. The allowed parameter space corresponding to this constraint is depicted in figure 3.

Note that the annihilation channel in Fig. 2 (b) is phase-space suppressed and the main

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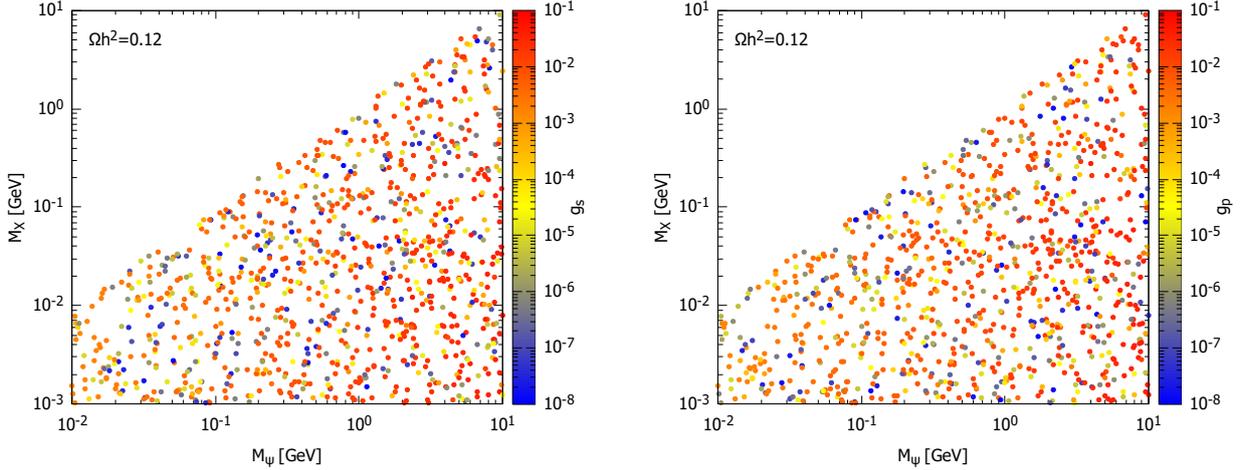
Figure 3: Dark matter relic density consistent with Planck data. We scanned over all free parameters of the model

channel is Fig. 2 (a). The s-wave annihilation $X X \to e^+ e^-$ is restricted by the CMB observation (see, e.g. [70]) for the mass of dark matter about < 10 GeV, and the AMS-02 observation (see, e.g. [71,72]) for the mass of dark matter from a few GeV to 100 GeV. There is nearly no parameter space left with joint constraints. Thus, the relic density of X equal to 0.12 seems to be in tension with CMB and AMS-02 observations. To resolve this issue, we consider coannihilation effect with $M_\psi - M_X = \delta > 0$ and $\frac{\delta}{M_\psi} \ll 1$. The particles X and ψ_l can be in thermal equilibrium for a while in the early universe via processes like Fig. 2 (b), and the abundance of X will be reduced by processes such as Fig. 2 (c). However, in our combined analysis, Sec. 7, we see that the relic density of X should be smaller than 0.12. Therefore, we consider $\Omega_X h^2 < 0.12$ as DM relic density constraint. This means X cannot be the only DM component.

5   Direct Detection and Electron recoil

Let us now turn our attention to the direct detection possibilities of DM in the framework. As it is mentioned, we consider the hypothesis that the VDM particle X_μ only couples directly to leptons in particular the electrons but not to quarks. For this reason, DM-nucleon interaction is absent at tree level. However, DM-electron elastic scattering of spin-independent type is feasible at tree level. In the following, we ignore the loop suppressed DM-nucleon interaction. In comparison to underground experiments focused on neutrino detection, that are typically sensitive to energy depositions above a few hundred keV, Xenon-based dark matter detectors provide the leading sensitivity for electronic energy depositions of 100 keV and below. In our model the relevant interaction is described by the Lagrangian 2.1. Electron recoil can occur corresponding to Feynman diagrams in Fig. 4. Therefore, in non-relativistic limit the elastic

scattering cross section of the DM-electron has following form [73]:

$$\sigma_{DM-e} \approx \frac{g_s^4 \mu_{eX}^2}{2\pi M_X^2 M_\psi^2},\tag{5.1}$$

where μ_{eX} is the DM-electron reduced mass. The cross section that includes g_p is zero due to the odd number of γ^5 in the trace. So far, in direct detection experiments there is found no evidence of DM-electron elastic scattering. Nevertheless several experiments have set upper bounds on this cross section: XENON1T [33], DarkSide50 [34] and SENSEI [35]. We consider upper bound from the XENON1T experiment to search for DM interacting with electrons [33].
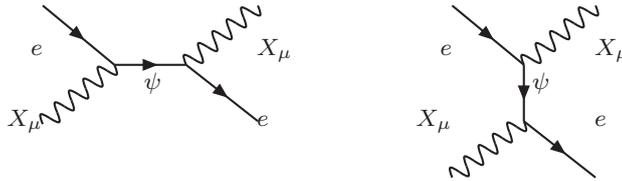
Figure 4: DM-electron Feynman diagram

6 Additional constraints on the leptophilic VDM interaction

Thus far in this paper, we have included discussion of the relic density, direct detection and $(g-2)_\mu$ constraints. In this section, we look at the various experimental constraints on the muon-VDM interaction in the model. Two kinds of these experimental constraints are as follows:

- Big Bang Nucleosynthesis (BBN) constrains the DM physics by three generic ways, the number of the excited relativistic degrees of freedom, energy injection due to annihilation or decay of heavy particles, and particle catalysis of nuclear reactions. For the first case, traditionally, this procedure is interpreted in terms of a bound on the effective number of neutrino. Note that in our model, X_μ is neutral and cannot couple neutrino via charged spin 1/2 mediators. In a more general way, this bound can be translated into a limit on dark radiation. In [74], it have been shown that BBN constraint as a limit on dark radiation which is massless or nearly-massless degrees of freedom that have the expected scaling as the Universe expands $\rho_{dr} \approx a^{-4}$. They assume that the additional relativistic component does not exchange energy with any SM species. This viewpoint can then be easily applied to the thermally decoupled extra degrees of freedom. For this reason, in our model in which new particles are not massless, the parameter space is not sensitive to the number of the excited relativistic degrees of freedom. Nevertheless, constraints on $\langle \sigma v \rangle$ from electromagnetic energy injection are proportional to temperature and dark matter mass. In [75], it was shown that BBN procedure rules out DM annihilation to e^+e^- for the DM mass region 30 MeV $\lesssim m_\chi \lesssim$ 77 MeV.

(a)   (b)
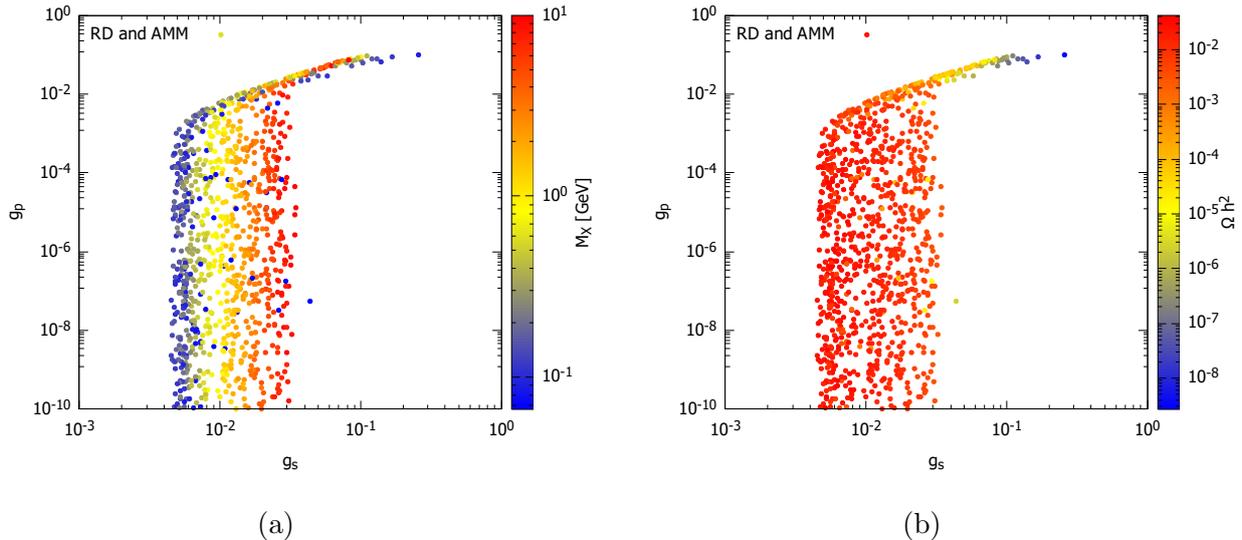
Figure 5: Scatter-points consistent with Anomalous Magnetic Moment (AMM) of the Muon and DM relic density (RD).

- The observation of cosmic charge leptons have reported in wide range of the data (10 GeV-10 TeV); Fermi-LAT has reported a measurement of the CR electron-positron spectrum from 7 GeV to 2 TeV [76]. The PAMELA satellite experiment [77] released an abundance of the positron in the CR energy range of $15 - 100$ GeV. Also the results of a CR electron-positron spectrum, between 10 GeV and 3TeV, have been reported based upon observations with CALET [78]. The DAMPE collaboration [79, 80] has been presented a measurements of the electron-positron spectrum in the energy range 25 GeV to 4.6 TeV. These observations are both considered as signs of standard astrophysical sources or DM annihilation. In our model, DM has mass smaller than 10 GeV then the parameter space is not sensitive to these observations.

7   Combined Results

In this section, we present a combined analysis of all observational constraints described in the previous sections. The constraints discussed are summarized by Fig. 5. As it is seen, for narrow region in parameter space, all constraints are satisfied. Remarkable point is for light DM ($\mathcal{O}$ (MeV)), implying we can have thermal DM which explain anomalous magnetic moment of the muon.

To obtain the parameter space consistent with all constraints, i.e., muon anomalous magnetic moment, DM relic density, and DM-electron direct detection constraints, first we solve Eq. (3.4) with respect to g_s:

$$g_s = \sqrt{\frac{12\pi^2 M_X^2}{m_\mu(3M_\psi - 2m_\mu)}\Delta a_\mu^\psi + \frac{3M_\psi + 2m_\mu}{3M_\psi - 2m_\mu}g_p^2} \tag{7.1}$$

Since Δa_μ^ψ is positive, $M_\psi > \frac{2}{3}m_\mu$, and therefore $g_s > g_p$. Now, to obtain the parameter space
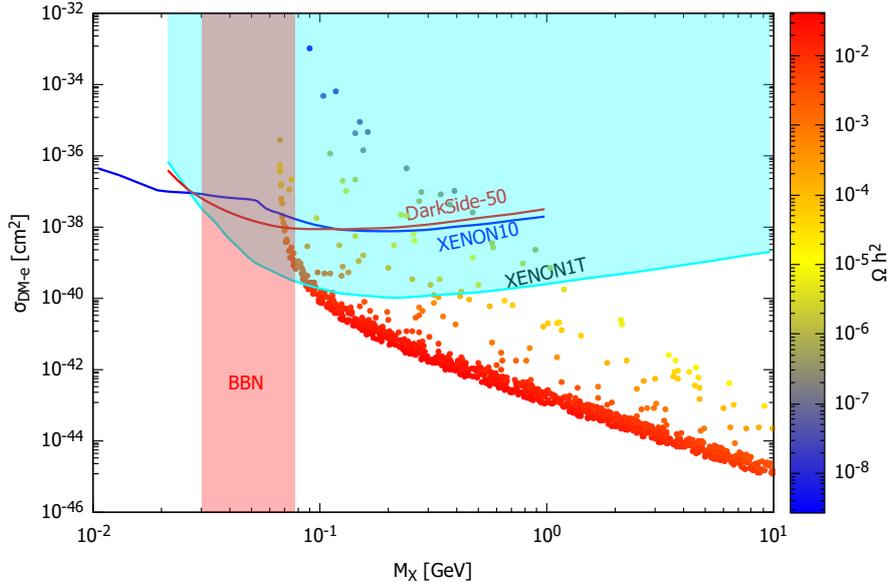
Figure 6: Scatter-points consistent with AMM of the Muon and DM relic density (RD). Some points will be excluded by XENON1T upper bound on DM-electron cross section. Points that are located in a narrow red area are excluded by BBN.

consistent with DM relic density ($\Omega_X h^2 < 0.12$), we scan over random points for M_ψ, g_p with the extra condition $M_\psi - m_e - \Delta < M_X < M_\psi - m_e$ (where M_X is chosen randomly and we put $\Delta = 10^{-6}$) and for g_s we use Eq. (7.1) where Δa_μ^ψ is chosen randomly in a domain given by Eq. (3.2). In this way, we obtain the parameter space which gives the correct value of both DM relic density and muon anomalous magnetic moment. Finally we keep the points that are also consistent with direct detection constraint. The result of our combined analysis is depicted in Fig. 6.

8   Conclusions

SM has achieved great success for its high accuracy to describe electroweak and strong interaction. However, there remains problems such as DM which SM can not explain. In addition, recent results about muon anomalous magnetic moment brings new challenges to the SM. The 4.2 σ discrepancy between experiment and SM prediction seems to indicate new physics behind ($g_\mu - 2$) anomaly and gives possible hints to the BSM physics. In light of these results, we consider a vector DM model with a leptophilic spinor mediator coupled to the SM charged leptons. From phenomenological point of view, we probed the parameter space of the model for light DM $\mathcal{O}$ (MeV) and sub-GeV spinor mediator. To conclude, the anomalies associated to the muon physics can be successfully addressed in light VDM regime. If the anomalies are confirmed by forthcoming experimental analyses, our results show that the model can be surveyed by DM-electron direct detection.

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