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Minimal Dark Matter in the sky

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Summary. — We discuss some theoretical and phenomenological aspects of the Minimal Dark Matter (MDM) model proposed in 2006, which is a theoretical framework highly appreciated for its minimality and yet its predictivity. We first critically review the theoretical requirements of MDM pointing out generalizations of this framework. Then we review the phenomenology of the originally proposed fermionic hyperchargeless electroweak quintuplet showing its main γ-ray tests.

1. – Introduction

The nature of Dark Matter (DM) is one of the most exciting open questions at the interface between cosmology and particle physics. Since several decades, we have compelling macroscopic evidences of unseen mass at different scales. Despite lacking a unique description of DM in terms of elementary particles, a number of requirements to fit the observations have been identified. One of the most important characteristic that all the DM candidates must have is stability on cosmological scales.

Stability may be explained in terms of symmetries via two main mechanisms. One may impose a symmetry on a DM model *by hand* to stabilize the DM candidate, hoping this symmetry may be naturally justified in a UV completions of the model. On the other hand, a more elegant and robust way to ensure stability, is instead via accidental symmetries. Indeed, the only exact fundamental symmetries known so far are gauge symmetries and the Poincaré group. However, other exact or approximate global symmetry are possible as accidental gifts of the specific matter content of the model. For example in the Standard Model (SM), once we impose gauge symmetry, the accidental gift we get is the baryonic number conservation that makes the proton stable.

Ensure stability through accidental symmetries is the main idea of the MDM model proposed in ref. [1]. The scope of this work is to review some theoretical and phenomenological aspects of the MDM paradigm. In particular sect. **2** is based on ref. [2] where we critically review the theoretical requirements of MDM pointing out generalizations of this framework. Section **3**, based on ref. [3], is instead devoted to review the γ-ray tests of the originally proposed MDM quintuplet.

2. – A critical take on Minimal Dark Matter

In the MDM setup, the SM is augmented with a new generic multiplet χ with quantum number $(\mathbf{c}, \mathbf{n}, Y)$ under the SM gauge group $SU(3)_{\rm c} \times SU(2)_{\rm L} \times U(1)_Y$, without introducing new symmetries to stabilize the DM field. In the original paper, the quantum numbers of the χ particle are chosen accordingly to the following requirements:

- The condition of stability enforces the selection of the quantum numbers of χ. In particular, in order to avoid that the lightest component of a given multiplet quickly decays, only those for which an accidental symmetry exists are allowed.

- The Landau pole of the electroweak gauge coupling must be above the assumed cut-off at the Planck-scale. This condition allows to put an upper bound on the electroweak quantum number $\mathbf{n}$ of the multiplet χ.

- The stringent constraints on colored particles [4, 5] exclude most of the parameter space for thermal DM production. Hence, we can only consider color-neutral multiplets with $\mathbf{c} = \mathbf{1}$.

- The bounds coming from direct DM experiments imply that the tree-level couplings with the Z boson and the photon must be suppressed. This only leaves the possibility that $\mathbf{n}$ must be odd and the multiplets must have a very small hypercharge (either $Y = 0$ as in the original MDM setup, or $Y = \epsilon$ with ϵ small and positive).

As a results, the authors of [1] single out a fermionic $\mathrm{SU}(2)_{\rm L}$ quintuplet $(\mathbf{1}, \mathbf{5}, 0)$ and a scalar eptaplet $(\mathbf{1}, \mathbf{7}, 0)$ both color- and hypercharged-neutral. References [2, 6] have demonstrated that the scalar eptaplet is no longer a viable MDM candidate because it decays very quickly due to a previously overlooked dimension-5 operator with trilinear coupling in the DM multiplet $\chi^3 H^\dagger H$ that let the scalar eptaplet to decay in few seconds even assuming a Planck-scale cutoff.

Before moving on with the phenomenology of the quintuplet, it is worth stressing here that the requirement of $Y = 0$, used in the original paper, is not strictly mandatory to avoid the bounds from direct DM searches. Indeed, as briefly mentioned above, what we really need to avoid the tree-level couplings with the Z boson and photon, is that χ is odd under the weak interaction group. Therefore, we can introduce a new class of MDM candidates which are still odd under $SU(2)_{\rm L}$ but with a small millicharge ϵ which is compatible with direct detection experiments (the bounds on ϵ from LUX are shown in the left panel of fig. 1 of ref. [2]).

Assigning a small millicharge to a given multiplet will have to immediate consequences: i) χ must be in a complex representation under the SM gauge group. Hence, the new MDM candidates have the double of degrees of freedom with respect to either a Majorana or a scalar field; ii) these new candidates are absolutely stable because their stability is protected at all order in Effective Field Theory (EFT) expansion by electric charge conservation. Hence, unlike the original MDM setup where multiplets with $\mathbf{n} > 7$ were discarded, we can also consider multiplets with larger multiplicity because the presence of the Landau pole of the electroweak gauge coupling below the cutoff does not spoil the stability of the candidate.

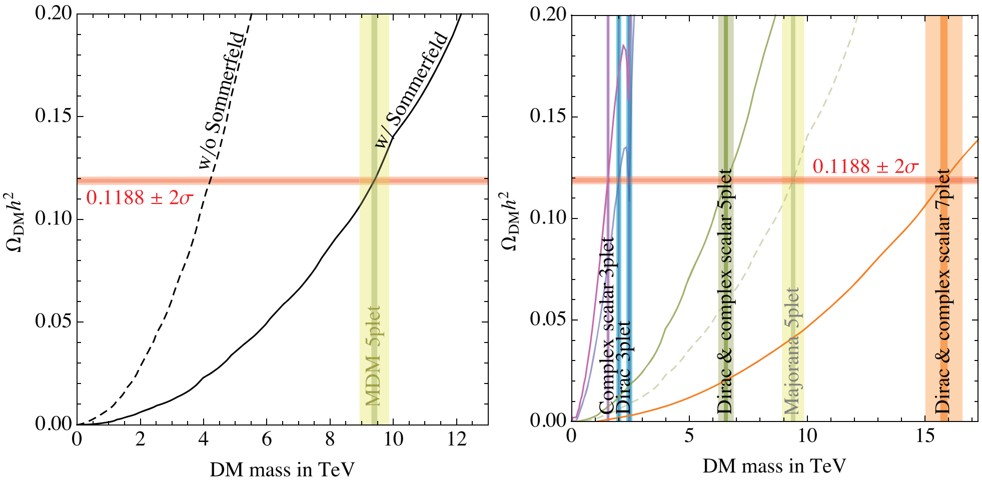

Fig. 1. – Relic abundance computations for the MDM candidates. Left Panel: DM density as a function of the DM mass, with (solid line) and without (dashed line) the Sommerfeld enhancement for the MDM quintuplet with $Y = 0$. Right Panel: DM densities as a function of the DM mass for the new MDM candidates with small hypercharge $Y = \epsilon$. In all panels the uncertainties on $M_{\rm DM}$ are indicated by a double vertical band: the inner, darker band reflects the 2σ uncertainty on Planck's measurement, while the outer, lighter band shows the theoretical uncertainty estimated as ±5% of the DM mass.

In summary, driven by the same spirit of minimality, we can re-classify the MDM candidates into two main sub-categories: the originally proposed fermionic quintuplet both color- and hypercharge-neutral $(\mathbf{1}, \mathbf{5}, 0)$. A new class of MDM candidates with small millicharge $(\mathbf{1}, \mathbf{n}, \epsilon)$ which are absolutely stable.

2˙1. *Mass of the MDM multiplets.* – In this subsection we briefly review the results for the relic density computations of our MDM candidates. In particular, since the gauge couplings and mediators are those of the SM, the annihilation cross sections into SM particles can be fully computed in Electroweak Theory including the non-perturbative Sommerfeld effect as well. As a result, the mass of a given multiplet $M_{\rm DM}$, which is the only free parameter of the model, can be univocally determined by demanding that its neutral charge component makes all the observed DM energy density measured by Planck ($\Omega_{\rm DM}h^2 = 0.1188 \pm 0.0010$).

The left panel of fig. 1 shows how the DM energy density $\Omega_{\rm DM}h^2$ varies as a function of the mass of the lightest component of the originally proposed fermionic quintuplet. More specifically, the solid and dashed lines refer to the computations with and without accounting for the non-perturbative Sommerfeld corrections of the annihilation cross sections into SM particles respectively. As one can see, the solid line crosses the measured DM density in the Universe by Planck when the mass of the neutral component of the quintuplet is $M_{\rm DM} = 9.40 \pm 0.47\,\text{TeV}$. Further details on the computations of the thermal mass of the quintuplet can be found in ref. [3].

In the right panel of the same figure we show the results for the millicharged MDM candidates. As one can see, since now the DM fields are absolutely stable due to electric charge conservation, we can go from a complex-scalar triplet with a mass of $M_{\rm DM} = 1.55 \pm 0.08\,\text{TeV}$, to a very heavy complex-scalar or dirac eptaplet with a mass of $M_{\rm DM} = 15.8 \pm 0.79\,{\rm TeV}$. Larger representations, can in principle be considered, but for $\mathbf{n} \geq 9$ the Landau pole of the electromagnetic coupling ends up at the cutoff, which is in this case at the DM mass. Further details on the computations of the thermal mass of the millicharge MDM candidates can be found in ref. [2].

3. – Phenomenology of the MDM fermionic quintuplet

Once we know the mass, all the parameters of the model are fixed, the theory is remarkably predictable, and therefore all the phenomenological signatures, in direct detection, indirect detection and production at colliders can be univocally determined. In the remaining party of this work, the phenomenology of the originally proposed fermionic quintuplet both colour- and hypercharge-neutral is briefly discussed.

We start from the production at colliders because is the simplest. In particular, since the mass of the candidate is very heavy, the production cross section is very suppressed. Therefore there is no hope to reach the thermal mass of 9.4 TeV at LHC, but even the prospects for futuristic collider are bleak. Further details on the production of electroweak multiplets at colliders can be found in refs. [7,8]. More specifically, in figs. 2, 3, we depict the current limit from LHC on the mass of the quintuplet ($M_{\rm DM} \lesssim 300\,{\rm GeV}$) as a vertical grey shaded region.

Concerning direct searches, this strategy is also very challenging, because the lightest component of the quintuplet does not couple at tree level with the Z boson and the photon. The scattering cross section up to the NLO corrections has been computed in a series of recent works. In particular ref. [9] found that the spin independent DM-nucleon cross section is around $2 \times 10^{-46}\,{\rm cm}^2$ well below the bounds coming from currently operating experiments. The most stringent bound from the LUX detector rules out scattering cross section bigger than $\simeq 10^{-43}\,{\rm cm}^2$ for $M_{\rm DM} \simeq 10\,{\rm TeV}$ [10].

3˙1. *Gamma ray tests of the MDM quintuplet.* – Indirect DM detection remains the most promising strategy for studing the parameter space of electroweak multiplets. In this subsection we focuss on the γ-ray test of the MDM quintuplet with $Y = 0$ considering both continuum and γ-ray line searches analysis towards different virialized astrophysical objects.

The first basic ingredients we need to compute are the annihilation cross sections into electroweak gauge bosons. Since the mass of the quintuplet is larger than the mass of the SM gauge bosons the non-perturbative Sommerfeld corrections of the annihilation cross section are pretty large due to the fact that an attractive potential between the initial state DM particles arise. These corrections are particularly relevant in astrophysical objects where the DM relative velocity is deeply non relativistic (*e.g.* Milky Way's Halo around 220 km/s and dwarf Spheroidal galaxies (dSphs) around 10 km/s). In the right panel of fig. 1 of ref. [3] the Sommerfeld enhanced cross sections into several final states for the MDM quintuplet at $v/c = 10^{-3}$ are shown. As one can see, thanks to the Sommerfeld effect, the total annihilation cross section into electroweak gauge bosons for $M_{\rm DM} \simeq 10\,{\rm TeV}$ is around $10^{-24}\,{\rm cm}^3/{\rm s}$ well above the reference thermal cross section value of $3 \times 10^{-26}\,{\rm cm}^3/{\rm s}$. Furthermore, it is also important to stress here that the annihilation cross section into γ-ray lines ($\gamma\gamma$ and γZ), which is zero at tree-level, is largely boosted due to the fact that the Sommerfeld effect mixes the neutral bound state $\chi_0\chi_0$ with the charged ones that couple with the photon in a relevant way. Further details on the computation of the Sommerfeld factors and cross sections for the MDM quintuplet can be found in ref. [3].

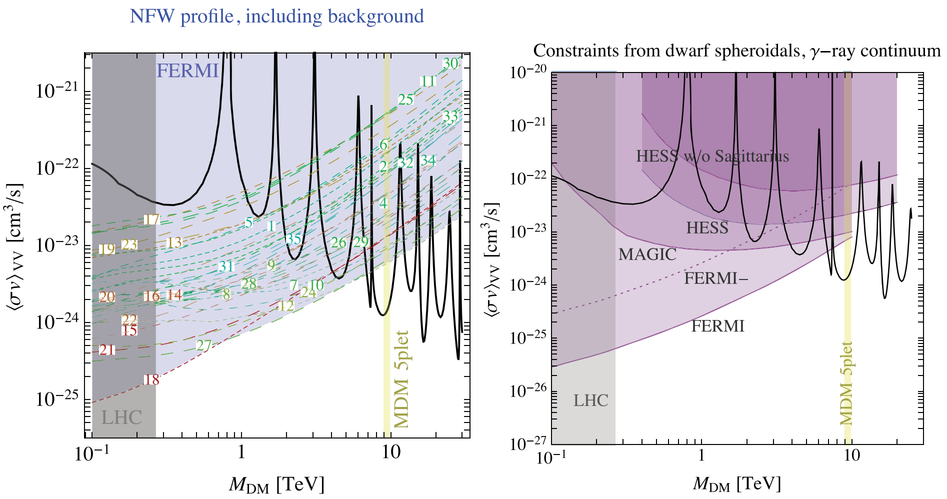

Fig. 2. – Constraints on the annihilation cross section into massive gauge bosons as a function of the DM mass from γ-ray continuum measurements. The theoretical prediction for the MDM quintuplet is depicted in black solid, while its thermal value is shown as a vertical yellow band. Left Panel: bounds from the measurement of the galactic diffuse emission by Fermi in 35 non-overlapping regions considering a NFW profile. Right Panel: constraints imposed by several experiments coming from the null observations of γ-ray continuum towards dSph galaxies of the Milky Way.

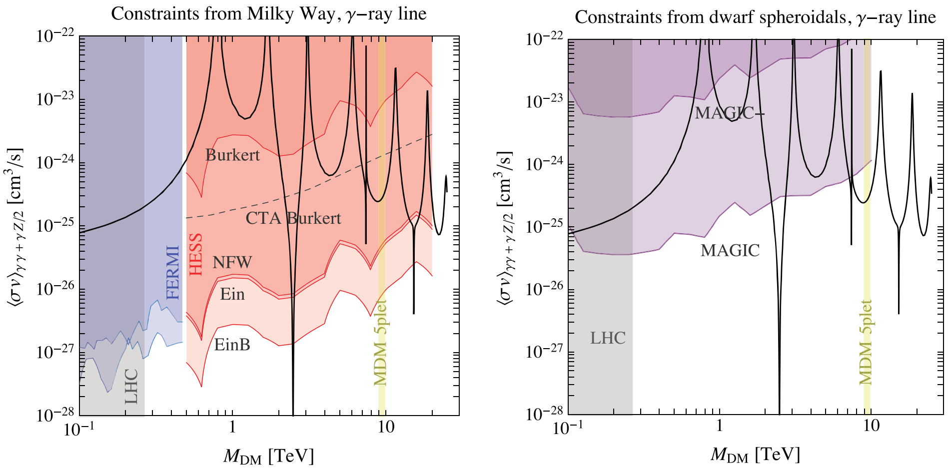

Fig. 3. – Constraints on the annihilation cross section in γ-ray lines as a function of the DM mass. The theoretical prediction of the annihilation cross section into $\gamma\gamma$ and $\gamma Z/2$ for the MDM quintuplet is depicted in black solid, while its thermal value is shown as a vertical yellow band. Left Panel: bounds coming from 112 h observations of the GC by H.E.S.S. considering several DM profiles. Right Panel: bound from an observation of Segue 1 by the MAGIC experiment.

Having at our disposal the theoretical predictions of the annihilation cross sections into electroweak bosons, we can compute the γ-rays fluxes expected from different astrophysical objects. In particular, since the DM annihilation into massive gauge bosons produces a continuum of γ-rays, we have to compare the total cross sections into WW, ZZ and $Z\gamma/2$ with the bounds coming from γ-ray continuum measurements. On the other hand, the cross section into $\gamma\gamma$ and $Z\gamma/2$ must be confronted with the constraints from γ-ray lines searches.

3˙1.1. Gamma ray continuum of the MDM quintuplet. The first class of constraints we consider are those coming from the measurement of the galactic diffuse emission by the Fermi satellite. The procedure for deriving the bounds proceeds as follows: i) we first divide the sky in 35 non-overlapping regions (see fig. 3 of ref. [3]); ii) then we model in each region the diffuse background considering several components; iii) finally by adding the DM signals we draw our constraints. The left panel of fig. 2 shows the constraints on the annihilation cross section into massive gauge bosons as a function of $M_{\rm DM}$ coming from our regions considering a NFW profile. In solid black, we compare these bounds with the predicted value of the Sommerfeld-enhanced annihilation cross in the Milky Way halo ($v/c \simeq 10^{-3}$). We see that the measurements rule out essentially all the region below $M_{\rm DM} \simeq 7\,\text{TeV}$. For larger masses, small islands are excluded up to about 25 TeV. The MDM quintuplet is however not excluded. Further details on the derivations of the constraints from Fermi, where we also consider a smoother DM profile and can be found in ref. [3].

Always related to the constraints coming from γ-ray continuum, another class of interesting bounds we consider are those coming from the observations in γ-rays of dSph galaxies of the Milky Way. In the right panel of fig. 2 we compare the theoretical prediction of the MDM quintuplet with the bounds on the annihilation cross section as a function of the DM mass(¹). We use the constraints coming from a staking analysis of 15 dSphs by Fermi [11], a staking analysis of 4 dSphs + Sagittarius by H.E.S.S. [12] and from an observation of Segue 1 by MAGIC [13]. We see that the most stringent bound comes from a staking analysis by Fermi and is almost touching the predicted value of the annihilation cross section of the quintuplet. On the other hand, it is worth mentioning here, that the bound in ref. [11] are obtained by using optimistic estimations of the J-factor which set the normalization of the DM signals at Earth towards dSph galaxies. A more realistic estimation of the J-factors in different dSphs have been done in ref. [14]. In particular in the bottom panel of their fig. 6 they show the logarithmic value of the J-factor together with its statistical error in different dSph galaxies. We see that the predictions in ref. [14] (blue squares with large statistical uncertainties) are quite different with respect to those used by the experimental collaborations. This is particularly evident, in case of Segue 1, where the MAGIC collaboration has used a value of the J-factor which is largely overestimated of at least 2 order of magnitudes.

3˙1.2. Gamma ray lines of the MDM quintuplet. In this subsection we move to γ-rays lines searches that can be very promising. Indeed, as briefly mentioned in sect. **3**˙1, the total annihilation cross section into $\gamma\gamma$ and $\gamma Z/2$ is largely enhanced by the non-

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(¹) Notice that the theoretical prediction of the annihilation cross section towards dSphs are identical with respect to that from the galactic halo despite the DM velocity is smaller ($v/c \simeq 10^{-4}$). This is due to the fact that Sommerfeld factors saturate for v/c smaller than 10^{-2} in case of the MDM quintuplet.

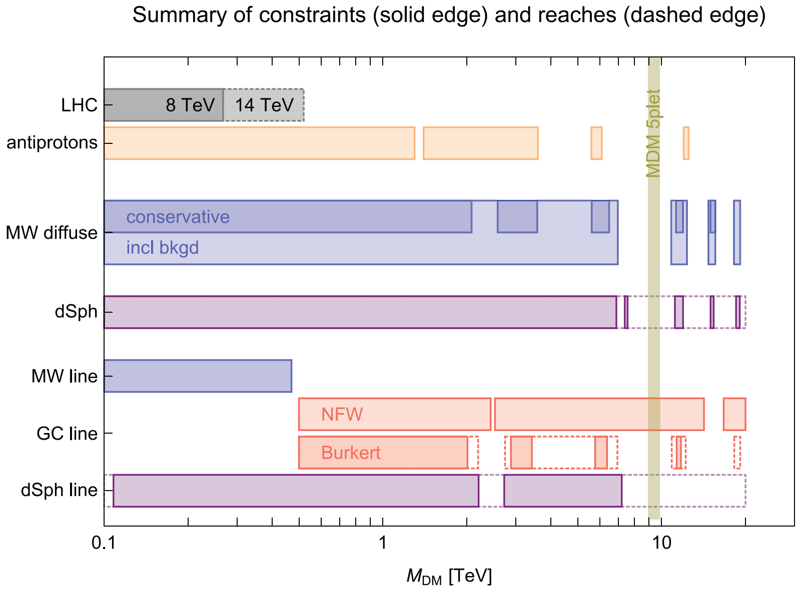

Fig. 4. – *Summary chart* of the constraints (solid edge) and the reaches (dashed edge) of the originally proposed MDM fermionic quintuplet with $Y = 0$.

perturbative Sommerfeld effect. The left panel of fig. 3 shows in solid black the theoretical prediction of the quintuplet and we compare it with the bound coming from 112 h observations of the Galactic Center (GC) by the H.E.S.S. cherenkov telescope array [15]. For a sake of completeness the bound coming from Fermi [16] are shown as well, but since the energy threshold is well below the thermal value of the mass of the quintuplet this bound plays clearly no role. As one can see, if we consider a cupsy profile, like NFW, the constraint completely rules out the entire parameter space of the MDM quintuplet. On the other hand, if we consider a cored profile, like Burkert, this bound moves up of 2 order of magnitude, making the MDM quintuplet still alive. In view of this large uncertainties on the determination of the constraints coming from GC observations, would perhaps be better to point the cherenkov telescope array experiments towards dSph galaxies. Indeed, in these astrophysical objects, the bound are in principle affected by smaller uncertainties. The right panel of the same figure shows the only available bound from the MAGIC experiment [13]. Nevertheless, since the collaboration decided to point the array towards Segue 1, such bound must be rescaled of two order of magnitude because, as we mentioned above, the J-factor used by the MAGIC collaboration was largely overestimated.

4. – Conclusions

In conclusion, in this work we critically review the framework of MDM and we show that of the two candidates proposed in the original paper, only the fermionic quintuplet is still a good DM candidate. Then, we show that it is possible to introduced a new class of MDM candidates with a small hypercharge which are absolutely stable and their stability is protected at all order in EFT expansion by electric charge conservation. Finally, we discuss the phenomenology of the originally proposed fermionic quintuplet with $Y = 0$

and we find that γ-rays are a powerful probe for this class of models. In particular the MDM quintuplet is ruled out or still allowed depending on the DM profile at the GC. Significant future progress is possible and may notably come from the observation of dSph galaxies of the Milky Way. Figure 4 is a summary chart of the constraints (solid edge) and the reaches (dashed edge) of the MDM fermionic quintuplet.

REFERENCES

[1] Cirelli M., Fornengo N. and Strumia A., *Nucl. Phys. B*, **753** (2006) 178, doi:10.1016/j.nuclphysb.2006.07.012 [arXiv:hep-ph/0512090].

[2] Del Nobile E., Nardecchia M. and Panci P., *JCAP*, **1604** (2016) 048, doi:10.1088/1475-7516/2016/04/048 [arXiv:1512.05353 [hep-ph]].

[3] Cirelli M., Hambye T., Panci P., Sala F. and Taoso M., *JCAP*, **1510** (2015) 026, doi:10.1088/1475-7516/2015/10/026 [arXiv:1507.05519 [hep-ph]].

[4] Starkman G. D., Gould A., Esmailzadeh R. and Dimopoulos S., *Phys. Rev. D*, **41** (1990) 3594, doi:10.1103/PhysRevD.41.3594.

[5] Taoso M., Bertone G. and Masiero A., *JCAP*, **0803** (2008) 022, doi:10.1088/1475-7516/2008/03/022 [arXiv:0711.4996 [astro-ph]].

[6] Di Luzio L., Gröber R., Kamenik J. F. and Nardecchia M., *JHEP*, **1507** (2015) 074, doi:10.1007/JHEP07(2015)074 [arXiv:1504.00359 [hep-ph]].

[7] Low M. and Wang L. T., *JHEP*, **1408** (2014) 161, doi:10.1007/JHEP08(2014)161 [arXiv:1404.0682 [hep-ph]].

[8] Cirelli M., Sala F. and Taoso M., *JHEP*, **1410** (2014) 033, Erratum: *JHEP*, **1501** (2015) 041, doi:10.1007/JHEP01(2015)041, 10.1007/JHEP10(2014)033 [arXiv:1407.7058 [hep-ph]].

[9] Hisano J., Ishiwata K. and Nagata N., *JHEP*, **1506** (2015) 097, doi:10.1007/JHEP06(2015)097 [arXiv:1504.00915 [hep-ph]].

[10] LUX Collaboration (Akerib D. S. *et al.*), *Phys. Rev. Lett.*, **116** (2016) 161301, doi:10.1103/PhysRevLett.116.161301 [arXiv:1512.03506 [astro-ph.CO]].

[11] Fermi-LAT Collaboration (Ackermann M. *et al.*), *Phys. Rev. Lett.*, **115** (2015) 231301, doi:10.1103/PhysRevLett.115.231301 [arXiv:1503.02641 [astro-ph.HE]].

[12] HESS Collaboration (Abramowski A. *et al.*), *Phys. Rev. D*, **90** (2014) 112012, doi:10.1103/PhysRevD.90.112012 [arXiv:1410.2589 [astro-ph.HE]].

[13] Aleksi J. *et al.*, *JCAP*, **1402** (2014) 008, doi:10.1088/1475-7516/2014/02/008 [arXiv:1312.1535 [hep-ph]].

[14] Bonnivard V. *et al.*, *Mon. Not. R. Astron. Soc.*, **453** (2015) 849, doi:10.1093/mnras/stv1601 [arXiv:1504.02048 [astro-ph.HE]].

[15] HESS Collaboration (Abramowski A. *et al.*), *Phys. Rev. Lett.*, **110** (2013) 041301, doi:10.1103/PhysRevLett.110.041301 [arXiv:1301.1173 [astro-ph.HE]].

[16] Fermi-LAT Collaboration (Ackermann M. *et al.*), *Phys. Rev. D*, **91** (2015) 122002, doi:10.1103/PhysRevD.91.122002 [arXiv:1506.00013 [astro-ph.HE]].