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$\mathcal{O}$(100 MeV) All-Sky Maps and Search for Point-Like Dark Matter Sources

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Abstract. Modern gamma-ray telescopes are known to have poor energy and angular resolutions for E_γ ∼100 MeV. In the following decade, however, several new γ-telescopes are expected to be built. They will have unprecedented sensitivity in this particular energy range, which will open new opportunities for studying new exotic particles and interactions. Among the key questions that will be addressed are the mechanisms leading to the creation of Dark Matter and the nature of its constituents. In this contribution, we discuss a possible application of such new technologies for both detection of regions with enhanced Dark Matter concentration, and study of fundamental particles and their interactions.

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1 Introduction

The nature of Dark matter (DM) and the mechanisms leading to its creation is one of the biggest open questions in modern physics. Currently, it is estimated that about 27% of our Universe consists of Dark matter. Thus, in the last decade(s) the search for DM has attracted considerable interest. Previously, it was suggested that the dark matter (DM) consists of weakly interacting massive particle (WIMP) that naturally emerge from the super-symmetric extension of the Standard model. Such a WIMP was predicted to have a mass of the order of 100 GeV. However, no such particle was found experimentally and the search for Dark matter candidates is now being carried out in other directions.

With the present letter, we emphasize the importance of the development of new instruments capable of detecting gamma radiation in the range of 100 MeV.

2 Interaction between the Dark and Visible Sectors

Recently, the idea of involving a complete hidden sector of new particles, was revitalized. This hidden sector naturally incorporates the DM and interacts only through a limited number of processes with the visible sector, usually through the so-called mediator, as shown in Figure 1.

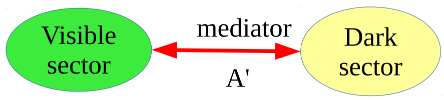

Figure 1. A connection between the visible and the hidden sector through a vector mediator.

Even though neither the nature of the DM particle(s) (χ) nor the mechanism that generates it is known, there is indirect experimental evidence suggesting that χ is indeed a weakly interacting particle. Given that, it is natural to assume that the annihilation, and/or its decay, will involve leptons, as shown in Figure 2. These can be electrons and positrons, but also muons, which can be generated via annihilation $\chi + \chi \to \mu^+ + \mu^-$ and/or decay $\chi \to \mu^+ + \mu^-$. It should be noted, however, that similar scenario is not forbidden for the τ particles either, but the cross-section for formation of two-tauon bound state is negligible, and hence, the observation of a signature of true taonium is considered to be less likely [1]. The advantage of using muonium annihilation lines for searching of Dark Matter particles is that muon mass is much larger than the $e^{\pm}$ and, hence, the expected signal will be cleaner.

The simplest effective interaction that can be used to describe the process is:

$$L \sim g'q'\bar{\psi}(\gamma_\mu + \alpha'\gamma_\mu\gamma^5)\psi A'^\mu \ , \qquad (1)$$

where A' is the mediator between the Dark and Visible sectors. Here ψ is the leptonic field and g' is the new interaction coupling constant. Usually $\alpha'_a = 0$.

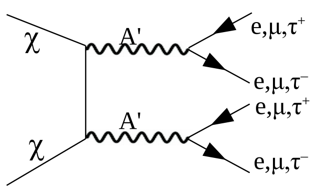

Figure 2. Feynman diagram for Dark matter annihilation into lepton final states.

The charges, q_i, are in general free parameters and for the some of the flavours it might vanish - $q_i \to 0$. The branching ratios for $A' \to e^+ + e^-$, $A' \to \mu^+ + \mu^-$, and other competitive at higher energies processes are given in ref. [2]. There is a threshold of 1022 keV for $e^\pm$ creation and a 210 MeV for the $\mu^\pm$ creation. At higher energies other channels are enabled. In most of the studied scenarios, it is assumed also that the mediator decays with the same strength to different lepton-anti-lepton pairs. But this may prove not to be true due to the lepton non-universality, which may lead to an enhancement of creation (μ^+, μ^-) pairs via the annihilation reaction $\chi + \chi \to \mu^+ + \mu^-$. New experimental results on the muon magnetic moment [3] and the proton radius [4–6], indeed, seem to support the different behavior of the electrons and muons with respect to the weak interaction. The $g_\mu - 2$ anomaly may be, indeed, related to a new weakly interacting particle, which lies outside the Standard model, and which would be the best candidate for the DM χ particle.

An all-sky mapping of the 511-keV line was already performed and it is considered to be among the major achievements in the γ-ray astronomy. But the origin of the positrons in the Galaxy is still dubious. They can be generated in different process – from nuclear reactions and decays, through black hole evaporation, to decay and/or annihilation of Dark Matter particles. Hence, it is difficult to disentangle the processes leading to DM creation. The key to the problem may lie in the possible complementary channels. The other two types of electrically charged leptons in the Standard model, which can annihilate into photons, are the muons μ and tauons τ with masses $M_\mu = 105.6$ MeV and M_τ=1777 MeV, respectively [7]. It is worth noting that in contrast to the electrons and positrons, the muons and the tauons can not be produced in radioactive decays of atomic nuclei, owing to their superior masses. As such, the maps based on the $\mu^+ + \mu^-$ and/or $\tau^+ + \tau^-$ annihilation peaks can provide a cleaner signal and a new information about the sites of enhanced DM concentration which would be complementary to the data obtained from the 511-keV surveys.

Further, the leptons can be created not only via processes involving DM particles such as $\chi + \chi \to l^+ + l^-$, but in high energy astrophysical environments a significant numbers of them can be also produced via the $\gamma + \gamma \to l^- + l^+$ and $e^- + e^+ \to l^- + l^+$ reactions. However, the muons created in these high-energy environments have energies much higher than the ionization energy (E_{ion} ≈1.4 keV) of the true muonium [1] and, hence, only a small fraction of pairs with energies less then E_{ion} will form a bound system. The muonium has two states, depending on the particles spin orientation. These are para- and orto-muonium. The para-muonioum predominantly decays via two-photon annihilation, while the orto-muonium – via electron-positron annihilation. The energy released in the two-photon annihilation is $E = 105.66$ MeV [1]. Thus, the detection of the muonium annihilation gamma rays will provide an opportunity to study their production mechanism or at least to put constraints to the model predictions.

Also, the advantage of using unstable leptons, rather than using electrons, for allocation of DM particles is in their finite lifetime. The tauons have a lifetime of 2.9×10^{-13} s., while the muons have lifetimes of 2.2μs. Their finite lifetimes provide an unique opportunity for mapping of DM regions with an enhanced precision. Thus, for example, DM particles with masses higher than $M_\chi = 100$ MeV will either annihilate or decay into muons. Estimated mean free path of the muons, before they decay, is of the order of 1000 km, which provides an excellent tool for mapping of regions of DM particles. Given that, the $\mu^+\mu^-$ annihilation could happen only close to their production site, such processes could provide a higher precision all-sky maps of the DM distribution in our Galaxy and the Universe. Thus development of telescopes capable of detecting gamma-ray with energies of the order of 100 MeV is of paramount importance for the understanding not only the mechanisms of DM particles generation, but also will provide a vital information on the fundamental particles and their interactions.

3 $\mathcal{O}$(100 MeV) All-Sky Map

A map of the $\mathcal{O}$(100 MeV) gamma emission was generated from FERMI Large Area Telescope [8] pass 8, release 2 data [9], and is shown in Figure 3. The Galactic plane, Vela, Crab, and Geminga pulsars are clearly visible. However, FERMI (NASA) angular and energy resolutions in this low energy range are poor ($\Delta E/E \sim 20\%$ and worse), which makes it difficult to observe weak point-like sources. Therefore, a development of a new telescope with enhanced sensitivity in the 100 MeV range is of paramount importance. Indeed, plans exist for R&D of gamma-telescopes, capable of detecting gamma-rays in the $\mathcal{O}$(105 MeV) range. The ESA project – e-ASTROGAM (our team is a member of the e-ASTROGAM collaboration) [10], has just been submitted to ESA and is under review process. The NASA counterpart mission AMEGO [11] is already approved and scheduled for 2028.

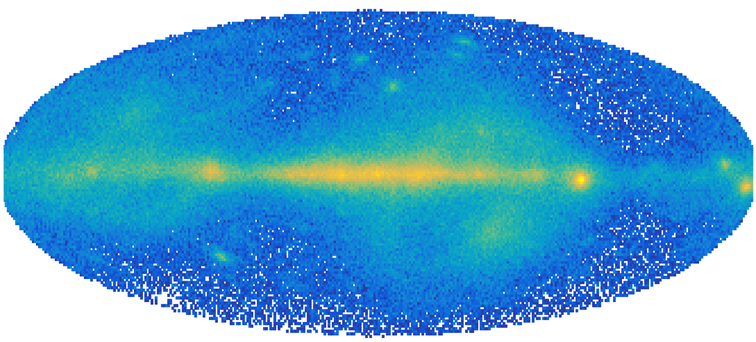

Figure 3. A map of the emission in the range between 100 MeV and 110 MeV obtained from the early FERMI data.

4 Conclusions

Due to low cross-section, the process of muon annihilation into two photons has not been observed experimentally so far. On the other side, some astrophysical environments where regions with large abundance of Dark Matter can provide unique opportunity for the observation of such exotic channels. Novell telescopes such as e-ASTROGAM, being superior than predecessors in the $\mathcal{O}$(100 MeV) region [10], will be capable of addressing these long standing questions by directly detecting some of the most exotic particle reactions, or at least to put constrains on some of the production rates.

Acknowledgements

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