Low Mass Dark Matter: Some Perspectives

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Abstract. The low mass (10 GeV scale) dark matter is indicted and favored by several recent dark matter direct detection experimental results, such as DAMA and CoGeNT. In this talk, we discuss some aspects of the low mass dark matter. We study the indirect detection of dark matter through neutrino flux from their annihilation in the center of the Sun, in a class of models where the dark matter-nucleon spin-independent interactions break the isospin symmetry. The indirect detection using neutrino telescopes can impose a relatively stronger constraint and brings tension to such explanation, if the dark matter self-annihilation is dominated by heavy quarks or τ-lepton final states. The asymmetric dark matter doesn't suffer the constraints from the indirect detection results. We propose a model of asymmetric dark matter where the matter and dark matter share the common origin, the asymmetries in both the matter and dark matter sectors are simultaneously generated through leptogenesis, and we explore how this model can be tested in direct search experiments.

1. Introduction

It is now well established that Dark Matter (DM) dominates the matter in the universe and plays an essential role in the formation of large scale structure in it. From the current observational constraints, we know that dark matter is essentially non-baryonic, cold or warm, neutral and stable or long-lived, but the identity of DM remains unclear.

The most popular class of candidates for dark matter are the stable weakly interacting massive particles (WIMPs), which arise in many well-motivated TeV scale extensions of the standard model. Their stability is guaranteed by some symmetry, e.g., R-parity in supersymmetry or KK-parity in the case of extra dimension models. While the WIMP dark matter does not decay due to the symmetry, pairs of them can annihilate and their relic density is determined by the freeze-out of the annihilation from equilibrium to the SM particles. The fact that their observed relic density can be naturally explained by the weak scale annihilation cross section makes these models quite appealing. This coincidence is usually called as the "WIMP miracle".

The direct detection experiments aim to decode the DM non-gravitational interactions by observing the scattering of DM off detector materials [1]. Many efforts have been made to search for such events for decades. Two collaborations, DAMA [2] and CoGeNT [3], have claimed the evidences for annual modulation in the differential event rate, which is a characteristic property due to the motion of the Earth around the Sun [4]. The simplest explanation points to a low mass $\mathcal{O}(10)$GeV DM spin-independently (SI) elastic scattering off nucleon with cross sections around $(2-5) \times 10^{-4}$ pb. In this talk, we will discuss some aspects of the low mass dark matter based on the works [7–9].

2. The IVDM and Neutrinos From the Sun

It turns out that DAMA tends to favor a relatively larger cross section than CoGeNT does. Moreover, they contradict with the null experiments CDMS [5] and XENON [6] results, which put most stringent constraints on the SI DM-nucleon scattering cross sections.

In order to alleviate the tension between the CoGeNT, DAMA results and the constraints of CDMS and XENON, various theoretical attempts and solutions have been put forward [10,11]. Among them, isospin-violating dark matter (IVDM) [11–15] draws a lot of interests. It was proposed that the DM particles might couple differently to the protons and neutrons. Under this generic assumption, one therefore gains an additional degree of freedom, f_n/f_p, the ratio between the two couplings. If it satisfies $f_n/f_p = -Z/(A - Z)$ for a given nuclear isotope (A, Z), the scattering amplitudes will interfere destructively and cancel each other. Therefore, the constraints from the corresponding isotope could be completely evaded .

For ground-based direct detection experimental target containing a certain element i with nucleon and proton numbers (A_i, Z_i), the ratio of the isospin-violating (IV) cross section to isospin-conservative (IC) cross section is

$$\frac{\sigma_i^{\mathrm{IV}}}{\sigma_i^{\mathrm{IC}}} \sim \frac{[Z_i + (A_i - Z_i)f_n/f_p]^2}{A_i^2} . \tag{1}$$

The phenomenologically favored ratio is found to be $f_n/f_p \approx -0.7$. Due to destructive interference in the amplitude, the direct detection rate gets reduced significantly. The suppression factor turns out to be about 10^{-4} for Xenon and 10^{-3} for Germanium, while it is about 10^{-2} for Sodium. This feature acts as the key factor to reconcile the results of DAMA, CoGeNT and XENON experiments.

On the other hand, the capture of DM in the Sun is dominated by light elements for low mass DM favored by CoGeNT and DAMA results, namely Helium for isospin-conserving case and Hydrogen for isospin-violating case. The contributions of heavier elements are suppressed by their small chemical abundance.

Taking into account of the presence of different isotopes, we list the reduction factors in direct detection and solar capture rates in Table. 1. The key observation from Table. 1 is the hierarchy in the suppression factors, amongst which solar capture rate receives the weakest suppression from isospin violation. For DM mass around $10\,\mathrm{GeV}$, the capture rate is reduced only by a factor of 0.04.

Element	Xe	Ge	Na	Solar capture
Suppression	1.3×10^{-4}	2.6×10^{-3}	1.3×10^{-2}	4.0×10^{-2}

Table 1. The suppression factors in the direct detection experiments and solar capture process, with $f_n/f_p = -0.7$ and $m_\chi = 10\,\mathrm{GeV}$.

Therefore, the indirect detection using the neutrino flux can give relatively stronger bounds on the DM-nucleon SI interactions, if the interactions are isospin violating. Weakly interacting DM can be captured in astrophysical bodies like the Sun. The capture process usually happens due to the scattering between DM and the nuclei. As DM particles are accumulated near the core region of the Sun, there can be significant annihilation process whose rate is proportional to its squared number density. There is in principle a competition between the capture and annihilation processes happening around the center of the Sun. It has been shown that for the DAMA and CoGeNT favored region, the capture-annihilation equilibrium has been reached [17]. In fact, for fixed spin-independent interaction $\sigma_{\chi N}^{\mathrm{SI}}$ and annihilate rate $\langle \sigma v \rangle$, in isospin-violating scenario the processes reach equilibrium more quickly due to a smaller capture rate. After the

capture and the annihilation processes become balanced, the flux of the annihilation process will be completely controlled by the capture rate.
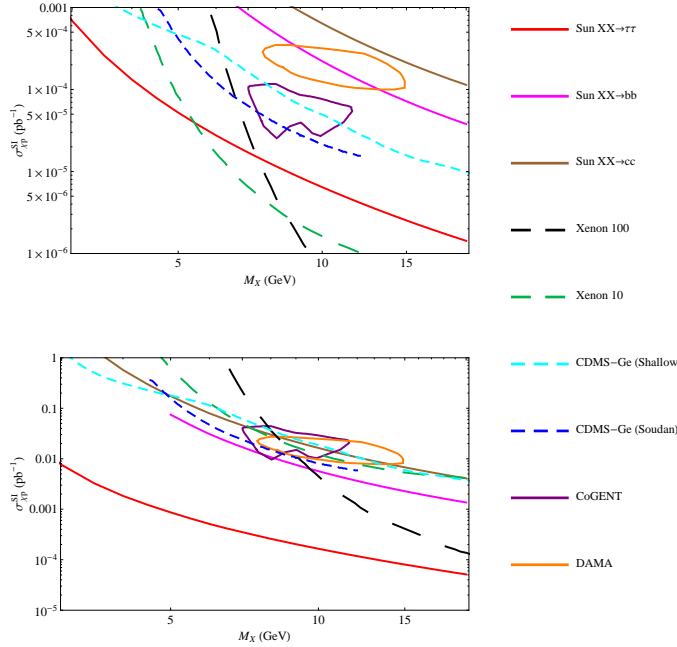

Figure 1. Positive signals from DAMA (orange circle) and CoGeNT (purple circle) in view of other direct detection experiments (dashed line) and indirect detection of neutrino flux (solid curves) from DM solar capture and annihilation, in isospin conserving (upper panel) and violating (lower panel) cases. In each panel, from up to down the solid curves represent annihilation to final states $c\bar{c}$, $b\bar{b}$ and $\tau\bar{\tau}$, assuming 100% branching ratio.

We mainly are interested in the final state neutrinos from the annihilation which can be detected by the neutrino telescopes such as the Super-K experiment. We use the results of Ref. [18] to obtain the neutrino spectrum $(dN_{\nu_i}/dE_{\nu_i})_F$ per process, taking into account of hadronization, hadron stopping, neutrino absorption and assuming the effect of neutrino oscillation to the earth averages the three neutrino flavors [19]. Here F denotes the annihilation product of the DM. For light DM, the important final states are $\tau\bar{\tau}$, $b\bar{b}$ and $c\bar{c}$, which can further decay to neutrinos.

The Super-K experiment [20] measures the Cherenkov radiation of energetic muons generated in the charge-current interactions. The effective area of detection is around $A_{\text{eff}} = 900\,\text{m}^2$, and the $\tau = 1679.6$ live days measurement allows at most 11 events other than originating from the atmosphere neutrino background [16] at 95% confidence level. We use this as the upper bound on the number events from DM annihilations in the Sun.

We have plotted the constraints on DM-nucleon cross section in Fig. 1, including both direct detections and indirect detection via neutrinos from the Sun. We focus on the low mass DM region in light of the recent direct detection excitement. As was noticed in [13], the positive signals from DAMA and CoGeNT can be reconciled by including isospin-violating DM-nucleon interactions. Isospin violation effect can also relieve the tension with the null results of XENON experiments, but cannot remove the constraints from CDMS which uses the same material as CoGeNT.

An interesting finding is that the indirect detection with neutrinos from DM annihilation in

the Sun imposes a stronger constraint if the annihilation final states are neutrino-rich, i.e., $\tau\bar{\tau}$ or $b\bar{b}$ (or marginally $c\bar{c}$), as shown by the solid curves in the Fig. 1. The annihilation to light quarks or muon is still allowed, since they would lose most energy before decay, due to relatively longer lifetimes. Therefore, the qualified IVDM candidates should annihilate preferably into light flavors, which brings challenge for the IVDM model building.

3. Leptobigenesis: a common origin for matter and dark matter

The asymmetric dark matter (ADM) in contrast does not suffer the constraints from indirect detection results, since the ADM doesn't self-annihilate. The ADM models build a bridge connecting the abundance of the dark matter with the baryon asymmetry in the Universe and therefore may answer the question why the densities of matter and dark matter are in the same order [21].

The observed dark matter density would represent an asymmetry between dark matter and anti-dark matter densities exactly as the case for the observed asymmetry between familiar matter and anti-matter. If these two asymmetries could arise from a common mechanism, it would be a major step towards understanding why their contributions to Ω are of the same order. An elegant way to generate the Baryon-antibaryon asymmetry in the universie (BAU) is through leptogenesis in the framework of seesaw mechanism which naturally explains the smallness of the observed neutrino masses. In these models, lepton asymmetry is generated through the out-of-equilibrium decay of the very heavy right-handed (RH) neutrinos which then get converted to baryon asymmetry through the non-perturbative $B + L$ violating electroweak sphaleron process. The appealing mechanism of baryogenesis via leptogenesis combined with the fact that the relic abundances of baryons and dark matter are of the same order of magnitude inspire us to think whether genesis of dark matter could also have its origin in a manner similar to leptogenesis.

3.1. The model [8]

We propose a model of asymmetric dark matter where the dark sector is an identical copy of both forces and matter of the standard model (SM) as in the mirror universe models. The two sectors communicate with each other by gravity and possibly some SM singlet interactions which are very weak at the current age of the Universe. There is a dark baryon and lepton number in the mirror sector which is the exact analog of the familiar baryon and lepton number. The main hypothesis is that the same leptogenesis mechanism that could be producing matter-anti-matter asymmetry, is also producing asymmetry of dark matter-anti-dark-matter. This then links the dark matter energy density of the Universe to that contributed by matter making them of the same order.

A key ingredient in our attempt to connect the matter asymmetry to dark matter asymmetry is the assumption that the visible and the mirror sectors talk to each other not only through gravity but also through a common set of three right-handed neutrinos coupled to leptons and Higgs fields in each sector through Yukawa couplings [22], as shown in Fig. 2. Since the RH neutrinos are standard model singlets, this is consistent with gauge invariance. Also mirror symmetry makes the $N\ell H$ couplings on both sides equal. The out-of-equilibrium decays of right-handed neutrinos in the early universe can then produce lepton number asymmetries in both sectors, which are then transferred to baryon and dark baryon numbers through the sphaleron processes in each sector. If one imposes exact mirror symmetry on the theory, the primordial lepton asymmetries generated in each sector are equal and after sphaleron interaction produce the same number density for baryons and dark baryons in the early universe. Since we expect the symmetry breaking pattern in both sectors to be different for the model to be consistent with cosmology (see below), the resulting energy density contributions can be different and in the ratio $\Omega_B : \Omega_{DM} \approx 1 : 5$ if we require that mass of the dark baryons is five times the mass of
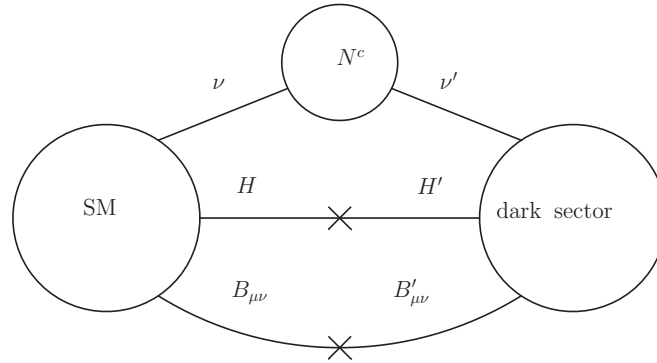
Figure 2. The connection between the standard model and the dark sector.

the familiar SM baryons. This mass difference can arise from the difference in the scales of two $SU(3)_c$ strong interactions ($\Lambda_{QCD}, \Lambda'_{QCD}$). It turns out that this difference depends on the ratio of two electroweak scales v_{wk} and v'_{wk}, with $v_{\mathrm{wk}} : v'_{\mathrm{wk}} \sim 1 : 10^3$ giving the required difference between Ω_B and Ω_{DM}.

In the SM, the neutron is slightly heavier than the proton due to $m_u < m_d$ and a free neutron will decay to a proton through beta decay. With the exact mirror Yukawa couplings, the dark neutron is expected to be heavier than the dark proton as in the SM. The situation could be different for two Higgs doublets $H^{(\prime)}_{u,d}$, with $\tan\beta = v_u/v_d, \tan\beta' = v'_u/v'_d$ different. $H^{(\prime)}_u$ only couples to up-type (mirror) quarks and (mirror) neutrinos while $H^{(\prime)}_d$ to down-type (mirror) quarks and charged (mirror) leptons, respectively, by imposed Z_2 symmetries in both the two sectors. When $\tan\beta'/\tan\beta > m_d/m_u$, the dark neutron is lighter than the dark proton and then taken as the dark matter candidate.

The spectra of the SM neutrinos ν_α and the dark neutrinos ν'_α are determined by the inverse seesaw and type-I seesaw mechanisms, respectively, with the mixing between the ν_α and ν'_α given by the ratio $v_{\mathrm{wk}}/v'_{\mathrm{wk}}$. The dark neutrinos can decay into the SM particles due to this mixing.

In addition to the common set right-handed neutrinos, the SM sector and the mirror sector can also be connected through Higgs interaction and the kinetic mixing between the $U(1)$ gauge bosons consistent with gauge invariance (as shown in Fig. 2). The photon sector mixing is necessary for the model to be consistent with Big Bang Nucleosynthesis (BBN). In this work we assume the photon in the mirror sector acquires a mass around 50 MeV through the spontaneous symmetry breaking so that the mirror-electrically charged particles which are heavier, pair annihilates into it before the BBN, and the mirror photon itself decays to the electron-positron pair through the kinetic mixing. To generate this small mass two Higgs doublets are needed in the mirror sector. The kinetic mixing between the photon and mirror photon also plays an important role in the direct detection.

3.2. Energy dependence of the direct detection cross section [9]
The dark baryon (ADM) can be detected directly by observing the nucleus recoil at low background experiments. In this section, we explore how the dark nucleon can be tested in direct search experiments. In particular, we point out that if the dark matter happens to be the mirror neutron, the direct detection cross section has the unique feature that it increases at low recoil energy unlike the case of conventional WIMPs.

The interaction of nucleons with the mirror photon can then be written as

$$\mathcal{L} = \varepsilon_\gamma e \bar{p} \gamma^\mu p A'_\mu + \varepsilon_\gamma \frac{\mu_N}{2} \bar{N} \sigma^{\mu\nu} N F'_{\mu\nu} \, , \tag{2}$$

where $N = p, n$ stands for proton and neutron, respectively, and μ_N is the anomalous magnetic dipole of the nucleons.

Consider a particle from the mirror sector as the dark matter candidate, and it carries vanishing mirror electric charge. Therefore, it interacts with the mirror photon through its anomalous magnetic dipole moment or other higher dimensional operators. In analogy to the effective field theories of nucleons in QCD, we write down all possible operators up to dimension six.

$$\mathcal{L}' = c_1 \frac{e}{2m_\chi} \bar{\chi} \sigma^{\mu\nu} \chi F'_{\mu\nu} + c_2 \frac{e}{2m_\chi^2} \bar{\chi} \gamma^\mu \chi \partial^\nu F'_{\mu\nu} + c_3 \frac{e}{m_\chi^2} \bar{\chi} \gamma^\mu \partial^\nu \chi F'_{\mu\nu} + \text{h.c.} \, , \tag{3}$$

where $\mu_\chi = c_1 e / m_\chi$ is defined as the anomalous mirror magnetic dipole moment of the mirror neutron. It is easy to check that other operators such as $(e/m_\chi^2) \varepsilon^{\mu\nu\rho\sigma} \bar{\chi} \gamma_\mu \gamma_5 \partial_\nu \chi F'_{\rho\sigma}$ can be decomposed into linear combinations of the above three.

The matrix element of the low-energy scattering between the nucleon and dark matter can be obtained by integrating out the mirror photon.

$$\begin{aligned}
\mathcal{M}_{\text{eff}} &= \varepsilon_\gamma \frac{c_1}{m_\chi} \frac{e^2}{m_{\gamma'}^2} (\bar{p} \gamma^\mu p) q^\nu (\bar{\chi} \sigma_{\mu\nu} \chi) + i \varepsilon_\gamma \frac{c_1 \mu_N}{m_\chi} \frac{e}{m_{\gamma'}^2} (\bar{N} \sigma^{\mu\nu} N) q_\mu q^\alpha (\bar{\chi} \sigma_{\alpha\nu} \chi) \\
&+ i \varepsilon_\gamma \frac{c_2}{2m_\chi^2} \frac{e^2}{m_{\gamma'}^2} (\bar{p} \gamma^\mu p) q^2 (\bar{\chi} \gamma_\mu \chi) + i \varepsilon_\gamma \frac{c_3}{m_\chi^2} \frac{e^2}{m_{\gamma'}^2} (\bar{p} \gamma^\mu p) q^\nu \left[\bar{\chi} (\gamma_\mu P_\nu - \gamma_\nu P_\mu) \chi \right] , \tag{4}
\end{aligned}$$

where q is the momentum transfer and P is the sum of momenta of the initial and final nucleons.
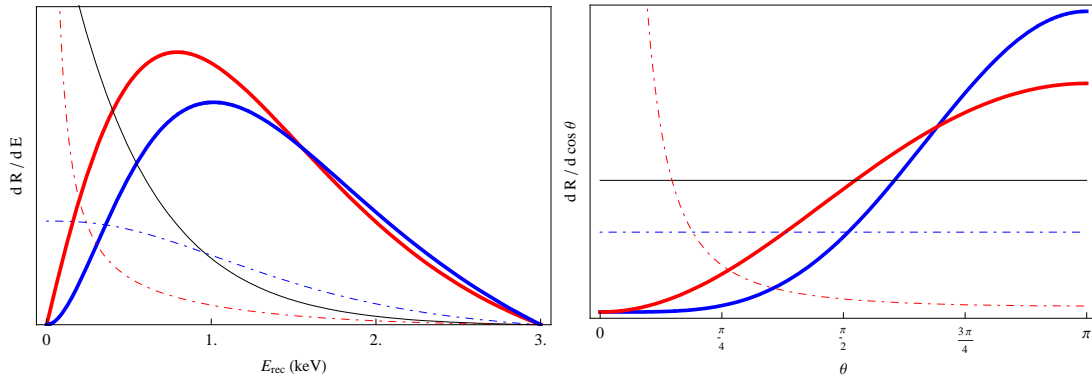

Figure 3. These two graphs display the spectral and angular distribution of SI (blue solid line) and SD (red dashed line) differential cross sections. The dot-dashed blue (SI) and red (SD) lines represent the special cases when $m_{\gamma'} = 0$, while the black thin solid line stands for the conventional SI (SD) interactions. We have chosen dark matter mass to be 5 GeV, $c_2 = 0$ and used an arbitrary scale in making the above plots.

We found that the spectral distribution of the cross sections are quite different from the conventional SI and SD interactions, as shown in Fig. 3. We also plot the SI and SD differential cross sections as a function of the scattering angle θ in the CM frame. This is a distinct feature of the new type of interactions which could be tested in low threshold direction sensitive DM detectors [23].

4. Summary

In summary, we discuss some aspects of the low mass DM. We studied the capture of low mass isospin-violating DM in the Sun and the corresponding neutrinos flux from their subsequent annihilation. We find that the indirect detection of neutrino signals through the neutrino telescope Super-K sets stronger constraints on the DM-nucleon interactions and brings further tension to such explanation, if the IVDM particles annihilate into neutrino-rich final states, e.g., tau leptons or bottom quarks. The asymmetric dark matter (ADM) doesn't suffer such constraints from the indirect detection results. We propose a model of asymmetric dark matter where the matter and dark matter share the common origin. The dark matter of the Universe be identified with the lightest baryon of a possible mirror duplicate of the standard model with the only difference between the two sectors being in the symmetry breaking patterns. The mirror photon in our model is massive but mixes with the normal photon to avoid the BBN constraints. We also explored how this model can be tested in direct search experiments. There is an energy dependence in the direct detection cross section as well as an angular dependence different from the usual symmetric WIMP case.

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