The 4 Basic Ways of Dark Matter Creation Through a Portal

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Abstract

We consider the possibility that the dark matter particle lies in a hidden sector that has its own interactions and communicates with the Standard Model visible sector through a portal. Depending solely on the DM particle mass, on the portal and on the DM hidden sector interaction, we show how the observed DM relic density can be obtained. We find four basic regimes, freeze-in/reannihilation/hidden sector freeze-out/portal freeze-out, resulting in a characteristic relic density phase diagram, with the shape of a "mesa". To illustrate this picture we consider an explicit model where DM consists in the lightest, and hence stable, particle charged under an unbroken U(1) structure. This hidden QED structure can communicate with the SM through a kinetic mixing portal. For such a structure all four regimes could be tested experimentally by forthcoming DM direct detection experiments, even the freeze-in one which is based on a tiny kinetic mixing interaction.

1 Introduction

There is a long list of properties that a particle must fulfil to be a viable dark matter (DM) candidate. It must: be dark (neutral); stable over cosmological time scale; relatively cold; account for about 23% of the energy in the Universe; have a cross section on nuclei smaller than present direct detection bounds; have a flux of cosmic rays from annihilation or decay that is smaller than the current observations; etc. This leaves nevertheless a lot of freedom regarding the mass of the DM particle and its interactions. For example, nothing guarantees that DM was ever in thermal equilibrium with the Standard Model particles in the Universe. And, in particular, nothing forbids that DM could be part of a hidden sector that interacted only feebly, or not at all, with the SM visible sector species.

In this talk we will consider such a possibility, *i.e.* a visible sector/DM hidden with a sector/mediator structure. We will be interested in the determination of all the various ways such a structure could account for the observed DM relic density. More specifically we will be interested in how this relic density could be created from the visible sector through the mediator interaction(s). This possibility appears to be quite natural for 2 reasons. First, if the visible and hidden sectors are only feebly connected, it is likely that reheating after inflation occurs dominantly in one sector (where the inflaton lies) rather than in both sectors. In this case the other sector particles can be only generated afterwards, through the mediator. Second, given the severe constraints on new relativistic degrees of freedom in the early Universe, there is very little room for a hidden sector which would have the same (or similar temperature) T' as the SM ones (today); for the time being, we can at most accommodate at most one massless hidden photon at the same temperature. Thus, if $T' < T$, it is much easier to create the hidden sector from the visible one, rather than the contrary (although the opposite situation is not inconceivable).

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2 The four basic DM regimes

In presence of a visible/hidden sector/mediator structure, the general structure of the Boltzmann equations that dictate the evolution of the DM number densities takes the form

$$z\frac{H}{s}\frac{dY}{dz} = \sum_i \langle\sigma_{connect} v\rangle_i (Y_{eq}^2(T) - Y^2) + \langle\sigma_{HS} v\rangle (Y_{eq}^2(T') - Y^2)\,. \tag{1}$$

where $Y \equiv n/s$ stands for the various number densities of the states entering in the DM processes, normalized to the total entropy density s (visible plus hidden sectors). Here $\langle\sigma_{connect} v\rangle_i$ stands for the $SM_iSM_i \leftrightarrow DMDM$ mediating processes with i the various SM species, whereas $\langle\sigma_{HS} v\rangle$ stands for any DM annihilation process which could thermalize the DM particle within the hidden sector, $DMDM \leftrightarrow PP$ with P some hidden sector particle. These abundances involve the DM equilibrium number densities expressed as a function of T and T' respectively. Note that in the Boltzmann equation we need to distinguish $Y_{eq}(T) = n_{eq}(T)/s$ from $Y_{eq}(T') = n_{eq}(T')/s$. The first one, $Y_{eq}(T)$, parametrizes the number of SM particles participating in the $SM_iSM_i \rightarrow DMDM$ processes. The second one, $Y_{eq}(T')$, parametrizes the number of hidden sector particle P participating in the $PP \rightarrow DMDM$ process, which may thermalize the DM particle within the hidden sector.[1] This distinction is important, as in the following we will consider situations for which $T' \ll T$, corresponding to $Y_{eq}(T') \ll Y_{eq}(T)$. In order to be able to integrate this Boltzmann equation in the case where the hidden sector would thermalize (i.e. in the case where the $Y_{eq}(T')$ term would be important in this equation), one needs to know T' at a given time. To this end, one needs to calculate the value of the energy density in the hidden sector, ρ'. Starting from the assumption that there is basically no hidden sector particles at the end of reheating, the energy can come only from the visible sector through the mediator process. Therefore it can be calculated from an energy transfer Boltzmann equation which, for $T' \ll T$, takes the form

$$\frac{d(\rho'/\rho)}{dT} = -\frac{1}{H(T)T\rho}\frac{g_1 g_2}{32\pi^4}\int ds\cdot\sigma(s)(s-4m^2)sTK_2(\frac{\sqrt{s}}{T})\,, \tag{2}$$

where ρ is the energy density of the visible sector and K_2 is the usual modified Bessel function. From this equation for energy transfer, T' can be determined in the same way as T in the visible sector, *i.e.* by counting the number of species that are relativistic in the hidden sector (taking also into account the transfer of entropy from the species, like DM, that may become non-relativistic at some point).

The evolution of the class of scenarios we consider is therefore determined by a system of Boltzmann equations for both the number densities and the energy transfer. We argue that, from such a system of equations, one can get the observed relic density along 4 characteristic regimes. To exemplify this, we discuss a particularly simple model, which, as we will see, has interesting phenomenological properties. We consider a hidden sector that consists of new particles charged under an unbroken $U(1)'$ gauge symmetry, with a gauge boson that we call γ'. We also assume that all the SM particles are neutral and we consider the lightest hidden particle charged under $U(1)'$, for instance a fermion that we call e'[2] This particle is stable in the same way as the electron in the SM. In other words we assume, on top of the SM, the simplest gauge structure one could consider, *i.e.* a hidden version of QED,

$$\mathcal{L} = \mathcal{L}_{SM} + \bar{\psi}'(i\not{D}' - m_{\psi'})\psi' - \frac{1}{4}F'_{\mu\nu}F'^{\mu\nu} \tag{3}$$

[1] Here we consider annihilation processes. In Ref. [1] we also consider the possibility of decay processes. For decays see also Ref. [4, 5].

[2] The results would be essentially the same for a scalar particle, except for the existence, in this case, of a possible additional interaction through the Higgs portal; this also give rise to the same 4 characteristic regimes, see Ref. [1].

with $D'_\mu = \partial_\mu + ie'A'_\mu$. Now the visible and hidden sector can be coupled in an unique way through the kinetic mixing portal [10, 11]

$$\mathcal{L} \ni -\frac{\epsilon}{2} F_Y^{\mu\nu} F'_{\mu\nu} \,. \tag{4}$$

where $F_Y^{\mu\nu}$ is the hypercharge field strength. We find it quite remarkable that the addition to the SM of the simplest gauge structure one can think of leads to a viable DM candidate [7, 8, 9, 1]. Furthermore this model involves only three new parameters: $\alpha' = e'^2/4\pi$, ϵ and $m_{e'} = m_{DM}$.

The non-canonical kinetic term implies a mixing between the visible and hidden sector photons, γ and γ', as well as between the Z boson and γ'. From a non-unitary transformation between both massless gauge bosons, it is possible to go to a basis in which the γ' couples only to the e' whereas the photon couples to both SM particles and to the DM particle, see Ref. [1], giving the following couplings to the SM and DM currents:

$$\mathcal{L} \ni -e_{EM} J^\mu_{EM}\,\gamma_\mu + e' \frac{\varepsilon \cos\theta_\varepsilon}{\sqrt{1-\varepsilon^2}} J^\mu_{DM}\,\gamma_\mu - e' J^\mu_{DM} \gamma'_\mu - e' \frac{\varepsilon \sin\theta_\varepsilon}{\sqrt{1-\varepsilon^2}} J^\mu_{DM} Z_\mu - g \frac{\cos\theta_W}{\cos\theta_\varepsilon} J^\mu_Z Z_\mu \,, \tag{5}$$

where we have defined

$$e_{EM} = \frac{e \cos\theta_\varepsilon}{\cos\theta_W \sqrt{1-\varepsilon^2}} = \frac{e}{\sqrt{1-\varepsilon^2\cos^2\theta_W}}$$

and with J^μ_{SM} and J^μ_{DM} the corresponding $U(1)_{em}$ and $U(1)'$ currents. In this basis the relevant processes are those mediated by a γ , $SM_i SM_i \leftrightarrow e'\bar{e}'$, and the dominant hidden sector thermalizing process, $e'\bar{e'} \leftrightarrow \gamma'\gamma'$; the former (mediator) process is proportional to $\kappa^2\alpha$ with $\kappa \equiv \hat{\epsilon}\sqrt{\alpha'/\alpha}$.

We show in Fig. 1 the DM relic abundance we get from the resolution of the system of Boltzmann equations, as a function of α' and κ and for various values of m_{DM}. As announced, these plots reveal the existence of essentially 4 distinct regimes or phases. The first regime (phase I) is that of freeze-in, which corresponds to no thermalization, neither through the connector, nor through the hidden gauge interaction. Alternatively, if thermalization takes place between the visible and the hidden sectors, freeze-out of the hidden gauge (phase III) or connector (phase IV) interactions can occur, depending on which interaction is dominant. A fourth possibility is related to the existence of an intermediate reannihilation regime (phase II). In this regime, there is a subtle interplay between the connector and the hidden gauge interactions. The plot has the simple characteristic shape of a "mesa", where in each regime the relic density is essentially determined by only one coupling for a given mass, the connector effective coupling κ or the hidden sector coupling α'. The second parameter however determines the boundary of each regime.

Freeze-in: If both κ and α' are sufficiently small, none of the interactions may thermalize the DM particle, neither with the SM sector, nor with the γ'. The relic density is therefore given by the (by now standard) freeze-in mechanism [2, 3]: the number of DM particles is simply given by twice the number of e' pair creations. This leads to the left-hand-side cliff of the "mesa" shown in Fig. 1: the relic density is independent of α' since these interactions are negligible, and in this regime the relic density depends only on κ. In practice, it means that the last three terms of Eq. (1) can be neglected and the relic density is simply given by integrating $\gamma_{connect}$ over time, which gives the number of e' particles produced per unit time per unit volume. Equivalently it is given by the integral over temperature of $dY/dT = -\gamma_{connect}/(T\,H(T)\,s)$. The freeze-in production is infrared dominated because, for large T, one has $dY/dT \sim 1/T^2$ (for a cross section which behaves like $1/s$ for large values of s, as is the case here). As a result we can approximate the total number of e' particles produced by the number of e' produced per unit time, $\gamma_{connect}$, times the Hubble time at $T = max[m_i, m_{DM}]$, with m_i the mass of the initial SM particle in the pair production process. The origin of this cutoff on T is that, at later times,

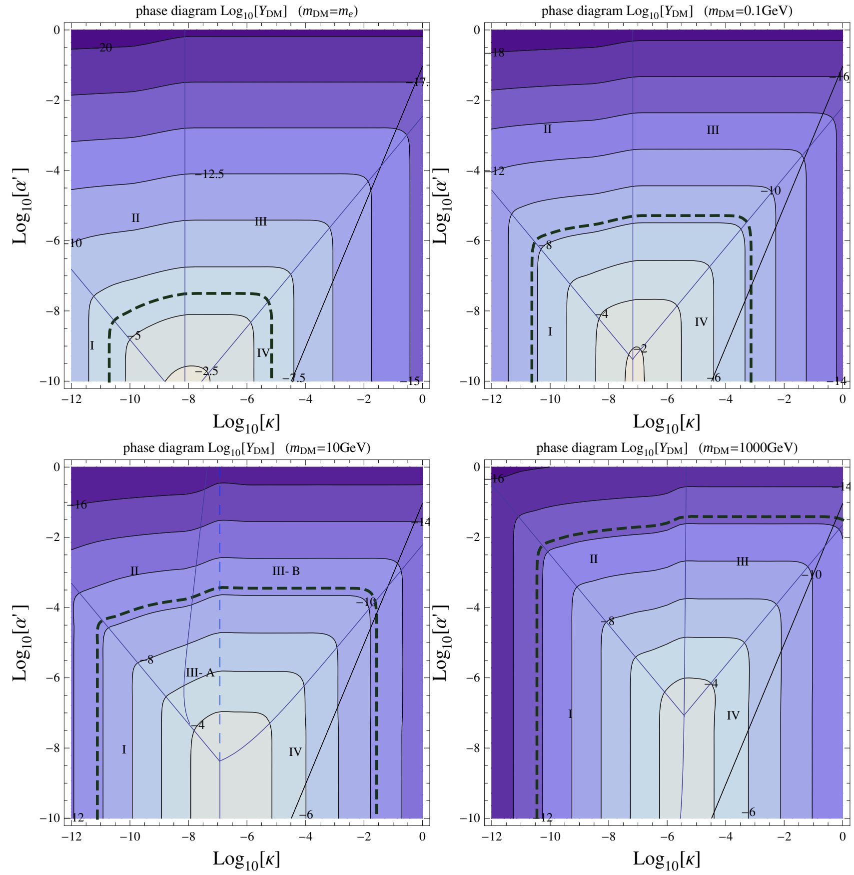

Figure 1: Phase diagrams for the kinetic mixing portal: contours of Y_{DM} as a function of κ and α' for $m_{DM} = m_e$, $0.1\,\text{GeV}$, $10\,\text{GeV}$, $1\,\text{TeV}$. The dashed thick line gives $\Omega_{DM} h^2 = 0.11$, or in other words $Y_{DM} m_{DM} = 4.09 \cdot 10^{-10}$ GeV. We have drawn the "transition lines" delimiting the 4 phases. Phases I, II, III, IV correspond to the freeze-in, reannihilation, hidden sector freeze-out and connector freeze-out phases respectively.

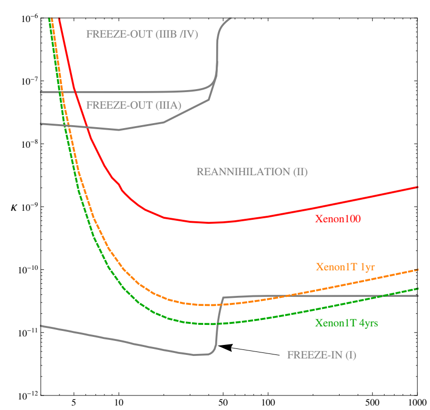

Figure 2: Exclusion limits at 90 % C.L. from the current Xenon100 data and forecast for Xenon1T for one year (dashed, orange) and 4 years (dashed, green) exposures. The light grey line at the bottom corresponds to the pure freeze-in regime. The dip is due to the effect of the Z resonance on freeze-in, see Ref. [1]. The upper, light grey lines delimit the region where reannihilation (below it) and hidden sector freeze-out (above it) regimes are possible (imposing the DM relic density constraint).

the production becomes Boltzmann suppressed because less and less SM particles may produce DM pairs. In other words, Y grows monotonously as $1/T$ until it reaches a plateau where it freezes-in, with the value

$$Y_{DM} = c\,\frac{\gamma_{connect}}{sH}\bigg|_{T=max[m_i,m_{DM}]}\,, \tag{6}$$

with c is a coefficient of order 1.

Reannihilation: Starting from a freeze-in situation, if one increases κ and/or α', at some point, to be defined below, there are enough DM particles and the interactions in the hidden sector are fast enough for the hidden photon γ' and the dark matter particle e' to thermalize, even if the connector interaction remains out-of-equilibrium. Therefore one may in principle define a hidden sector temperature T', with $T' \leq T$. In this case, we may determine the dark matter relic density in two steps. First we estimate the hidden sector energy density, ρ', as a function of the visible sector temperature T, and define a hidden temperature T', which depends only on κ and m_{DM}, through $\rho' \propto T'^4$. This step gives us in turn a way to define the DM equilibrium number density *in the hidden sector*, $Y_{eq}(T') \neq Y_{eq}(T)$. From these, in a second step, we may integrate the Boltzmann equation for the DM number density, Eq. (1), taking into account both the source connector and annihilation in the hidden sector. Starting from an initially insignificant abundance of hidden sector particles, the DM number density follows the freeze-in regime until the γ' and e' thermalize. The condition for chemical equilibrium between the γ' and e' is

$$\Gamma_{annih} \equiv \langle\sigma_{HS} v\rangle n_{eq}(T') > H\,. \tag{7}$$

In terms of the cross sections, Eq. (7) can be written as

$$\langle\sigma_{eff} v\rangle n_{eq}(T)\sqrt{c} > H \quad \text{with} \quad \langle\sigma_{eff} v\rangle \equiv \sqrt{\langle\sigma_{HS} v\rangle\langle\sigma_{connect}\rangle}\,, \tag{8}$$

where c is a constant of order unity. This reflects the fact that $n_{eq}\langle\sigma v_{HS}\rangle$ is proportional to the number density of DM particle, which itself is proportional to $\langle\sigma_{connect} v\rangle n_{eq}^2(T)/H$. Taking this condition at $T \simeq m_{DM}$ gives the "phase transition" line between the freeze-in and reannihilation regimes. Once the hidden sector has thermalized, the DM number density is just that of equilibrium, which for $T' \gtrsim m_{DM}$ is

$$Y_{eq}(T') = \frac{45\zeta(3)}{2\pi^4}\frac{g_{e'}}{g_{*s}}\,\xi^3\,, \tag{9}$$

in which $\xi = T'/T < 1$, $g_{e'} = 2$ is the number of degrees of freedom of e' and T' is defined by the equilibrium relation

$$\rho' = \frac{\pi^2}{30} g_*^{HS}\, T'^4. \tag{10}$$

Later on, the number density Y follows the equilibrium one $Y_{eq}(T')$ and does so until the e' is so heavy compared to T' that the $\gamma'\gamma' \to DMDM$ process is unable to maintain the chemical equilibrium in the hidden sector. However the Boltzmann equation at this stage is different from the one in the standard freeze-out as it contains an extra source term from the connector, Eq. (1). This makes the reannihilation regime a bit complex. Actually, while the $Y_{eq}(T')$ term becomes negligible in the Boltzmann equation at $T' \lesssim m_{DM}$, the abundance still does not freeze. A period of reannihilation begins during which the abundance of DM is not directly related to the energy density in the hidden sector. This will stop only when the source term itself becomes Boltzmann suppressed; since $T' < T$, this occurs only at a later stage when T gets below m_{DM}. During this period the DM abundance follows a quasi-static equilibrium evolution, where both the $SM_iSM_i \to DMDM$ source and $DMDM \to \gamma'\gamma'$ hidden sector terms compete. Ultimately, when the source term gets Boltzmann suppressed at $T \lesssim m_{DM}$, both these terms cease simultaneously to have any effect and the abundance freezes out. Altogether this leads to a final abundance which scales as $\log[\kappa]/\alpha'^2$, as can be seen in Fig. 1. For more details and analytic estimates, see Ref. [1].

Hidden sector freeze-out: If one increases further the value of the connector effective coupling κ, eventually the connector interaction thermalizes, which gives $T = T'$. At this point, one enters a regime in which the connector does not play any further role than to thermalize both sectors. The DM thermal freeze-out is determined by the size of the connector cross section, as it is larger than the connector cross section. As is usual for freeze-out, the relic density is inversely proportional to the cross section, $\Omega_{DM} \propto 1/\langle\sigma_{HS}v\rangle$, which requires that $\langle\sigma_{HS}v\rangle \simeq 10^{-26}\text{cm}^3/s$.

Connector freezeout: Finally, for even bigger values of κ, $\langle\sigma_{connect}v\rangle$ becomes larger than $\langle\sigma_{HS}v\rangle$ and the freeze-out is dominated by the connector, with $\Omega_{DM} \propto 1/\langle\sigma_{connect}v\rangle$ which, in the same way, requires that $\langle\sigma_{connect}v\rangle \simeq 10^{-26}\text{cm}^3/s$. This leads to the right-hand-side cliff of the "mesa" in Fig. 1 where the relic density depends only on κ.

3 Phenomenology

Given that a large part of the parameter space in Fig. 1 corresponding to the observed relic density involves very small values of the connector and/or hidden sector couplings, one could question whether such a scenario could ever be tested? This criticism could certainly be done for massive mediator portals, such as the Higgs portal.[3] However for the kinetic mixing portal it turns out –and this is a quite remarkable property of this model– that all the phase diagram could be tested by direct detection experiments (for a range of values of m_{DM}). This stems from the fact that the cross section has a collinear infrared divergence, leading to a direct detection elastic cross section proportional to $1/E_r^2$, *i.e.* which is enhanced by many orders of magnitudes for the low nuclear recoil energies E_r that direct detection experiments are probing. Fig. 2 shows that for $m_{DM} >$ few GeV, both freeze-out regimes are currently excluded, whereas the reannihilation regime is strongly constrained by Xenon100 (100 days exposure). The freeze-in regime is currently allowed for any DM mass. As for the future, interestingly the Xenon-1T experiment may be able to probe a large fraction of the reannihilation regime and could even test the freeze-in regime within a mass range between ~ 45 GeV and, for 4 years of exposure, about 500 GeV. Moreover, a positive signal with a recoil energy spectrum that is in accordance with a $1/E_r^2$ scattering cross section on nuclei would allow to distinguish this model from a more standard DM candidate, which usually predicts a constant cross-section. In principle, it should be possible to distinguish this model from mirror models, which *a priori* display the same $1/E_r^2$ dependence (see for instance [16]), but which have a distinct velocity distribution and, in general, a multi-component halo of dark matter with particles masses in the few GeV range.

Finally, let us mention that quite a lot of astrophysical and cosmological constraints exist on such a model, all associated to the long range nature of the hidden sector U(1) interaction [7, 8, 9, 12, 13, 14, 15, 1]. A review of these constraints for the model we consider can be found in Ref. [1]. There it is shown in particular how the stringent galactic ellipticity constraint (which are compatible with the relic density constraints for DM masses above ~ 100 GeV gets considerably relaxed when one considers a slightly massive, rather than a massless, γ'.

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