Regular Article

Feebly interacting dark matter

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Abstract We briefly review scenarios with feebly interacting massive particles (FIMPs) as dark matter candidates. The discussion covers issues with dark matter production in the early universe as well as signatures of FIMPs at the high energy and high intensity frontier as well as in astroparticle and cosmology.

1 Introduction

Despite the strong evidence for dark matter (DM) on galactic, clusters, and cosmological scales, the nature of DM remains a mystery. Although the relic density of DM has been measured with great precision $\Omega h^2 = 0.1188 \pm 0.001$ [1], this still leaves several possibilities for DM that span dozens of orders of magnitude in mass and/or in interaction strength. The lack of evidence for the well-motivated weakly interacting massive particles (WIMP) in direct/indirect and collider searches aroused the interest in opening possibilities for DM candidates of different mass scales and interaction strengths. In this presentation, we will address the possibility of feebly interacting massive particles as dark matter (FIMPs) and of DM production through the freeze-in (FI) mechanism. We will discuss the signatures of FIMPs at colliders, in direct detection and in cosmology.

2 Dark matter formation

When DM particles (hereafter denoted as χ) are feebly interacting, they cannot reach thermal equilibrium in the early universe. DM production is achieved through the freeze-in mechanism and results from the collision or decay of standard model (SM) or beyond the standard model (BSM) particles in the thermal bath [2, 3].This is called thermal freeze-in.

The interactions between the dark and the visible sector can be either through non-renormalizable operators or renormalizable interactions. In the former case, known as UltraViolet (UV) freeze-in [4], the DM abundance is obtained via effective operators. Here, the large scale factor suppresses the interaction strength between the SM and the dark sector and therefore keeps DM out of thermal equilibrium. DM production occurs at high temperature, and the DM abundance features a strong dependence on the reheating temperature. The latter case is known as InfraRed (IR) freeze-in [2], where the freeze-in is generated in a class of models where different sectors are connected via renormalizable operators. In the following, we will concentrate on IR freeze-in, a review of FIMP models can be found in Ref. [5].

The number density of DM, n_χ, follows a Boltzmann equation

$$\frac{\mathrm{d}n_\chi}{\mathrm{d}t} + 3Hn_\chi = \sum_X \langle\sigma v\rangle_{X\bar{X}\to\chi\bar{\chi}}\,\bar{n}_X^2(T) + \sum_{X'} \Gamma_{X'\to\chi\bar{\chi}}(T)\,\bar{n}_{X'}(T), \tag{1}$$

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where $\bar{n}_X$ is the equilibrium density, $\langle\sigma v\rangle$ is the cross section for the production of DM through pair annihilation, $X\bar{X} \to \chi\bar{\chi}$, and $\Gamma_{X'\to\chi\bar{\chi}}$ is the decay width of $X' \to \chi\bar{\chi}$. Here X, X' are particles that belong to the thermal bath. DM is produced from annihilation or decays until the number density of SM particles becomes Boltzmann suppressed, at this point n_χ/s becomes constant and "freezes-in". This occurs at $T \approx M$ where M is the mass of X particles or of DM. Note that the term that corresponds to depletion of DM through pair annihilation into SM particles which in general appears in the evolution equation for the number density in the freeze-out (FO) scenario is neglected considering the small initial abundance of χ.

The above equation is usually written in terms of the abundance, $Y_\chi = n_\chi/s$ where s is the entropy density. The abundance today (Y_χ^0) is obtained by solving the evolution equation from the temperature at which DM production starts, referred to as the reheating temperature T_R, to the present day temperature. In contrast with the case of WIMP freeze-out, the DM abundance increases with the interaction strength. The typical value of the coupling for weak scale FIMPs is in the range 10^{-10}–10^{-12}. Note that when decay is possible it usually dominates over annihilation. The DM relic density is simply related to Y_χ^0 as,

$$\Omega_\chi^{\mathrm{FI}}h^2 = \frac{2m_\chi Y_\chi^0 s_0\, h^2}{\rho_c}, \tag{2}$$

where $s_0 = 2.8912 \times 10^9\,\mathrm{m}^{-3}$ is the entropy density today, $\rho_c = 10.537\,h^2\,\mathrm{GeV\,m}^{-3}$ denotes the critical density, h the scaling factor for the Hubble expansion rate and m_χ the DM mass.

For dark sectors containing several new particles, FIMPs can also be produced from the decay of a WIMP(χ') after it freezes out. This is called the superWIMP or non-thermal freeze-in (NTFI) mechanism and was considered long ago in SUSY models with gravitinos [6]. In this mechanism, the abundance of the FIMP is inherited from that of the WIMP and the total relic density of the FIMP can receive both contributions from thermal and non-thermal freeze-in,

$$\Omega_\chi^{\mathrm{NTFI}}h^2 = \frac{M_\chi}{M_{\chi'}}\Omega_{\chi'}^{\mathrm{FO}}h^2 \;\;;\;\; \Omega_\chi h^2 = \Omega_\chi^{\mathrm{NTFI}}h^2 + \Omega_\chi^{\mathrm{FI}}h^2, \tag{3}$$

where $\Omega_{\chi'}^{FO}h^2$ is the relic density of the WIMP obtained through the freeze-out mechanism. In this general picture, one must solve two coupled Boltzmann equations for χ and χ'. Figure 1 shows an example where decay processes before and after FO both contribute to the total relic density. Here the model is the SM extended with triplet fermions (ρ) with hypercharge $Y = 0$, a singlet fermion (N) as well as a triplet scalar. One of the triplet fermion and the singlet fermion are odd under a discrete Z_2 symmetry and can be the dark matter, the triplet being a WIMP while the singlet can act as a FIMP. There is a small mixing between the two neutral scalars, H_1 corresponds to the SM Higgs while H_2 corresponds dominantly to the neutral component of the scalar triplet. The decay $H_2 \to N\rho$ gives the main contribution to the production of N at early times, while the decay $\rho \to NH_1$ which is suppressed by the small mixing angle between the scalars, takes place mostly after the FO of ρ.

Alternatively, it may be that the WIMP rather than the FIMP is the lightest particle of the dark sector, hence the WIMP is the DM. Nevertheless the FIMP can contribute to DM production through its late decay into the WIMP after it freezes out, thus increasing the relic density of the WIMP [2, 7]. In these scenarios the DM signatures would then correspond to the usual search for WIMPs although the WIMP annihilation can be larger than in the standard freeze-out scenario, thus leading to a boost factor for indirect detection.

Fig. 1 Left: production of DM in the singlet/triplet fermionic model with the contributions from thermal and non-thermal freeze-in, see details in [7]. Right: relic density in the singlet scalar DM model for $\lambda_{\mathrm{HS}} = 10^{-11}$ assuming Maxwell–Boltzmann (red) or Bose–Einstein statistics (black) [8]
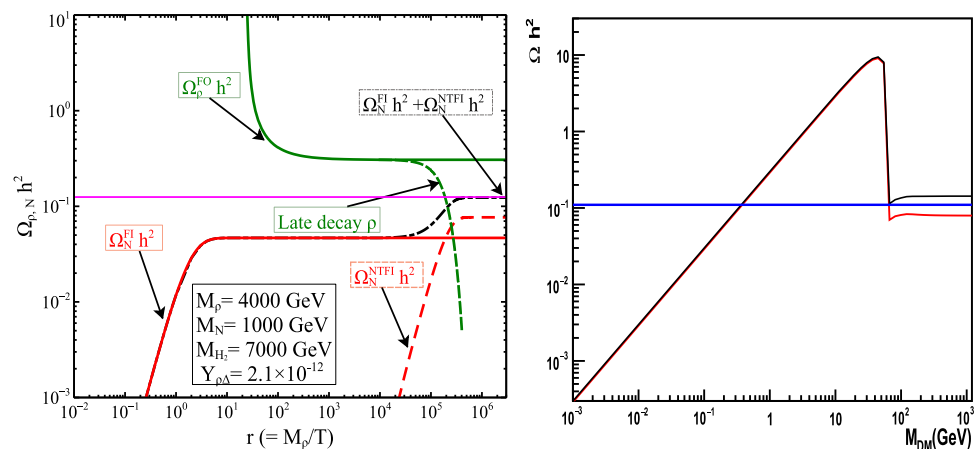
The freeze-in production of self-interacting DM in connection to the small-scale problem was discussed in [9–11]. Typically the models involve a light mediator (keV–MeV) and non-perturbative effects enhance the DM self-interactions.

2.1 Statistics, thermal masses, symmetry breaking

In the freeze-in framework, DM production starts at high temperatures, this entails a dependence on initial conditions and potentially on the details of reheating as well as on several other effects that can become important, namely, quantum statistics, finite temperature corrections as well as phase transition and symmetry breaking effects.

It is customary to assume that the phase space distribution of bath particles follows a Maxwell–Boltzmann(MB) distribution, a proper treatment of freeze-in however may require to take into account the Fermi–Dirac or Bose–Einstein phase space distribution of bath particles. In Ref. [8], it was shown that the inclusion of quantum statistics effects could lead to a factor two variation in the predicted value of the relic density especially when driven by annihilation processes initiated by bosons. The effect is smaller in the case of fermions and especially when decays are the dominant processes. Figure 1 (right) illustrates the difference in the relic density using Maxwell–Boltzmann and Bose–Einstein (BE) distributions in the case of the scalar singlet dark matter (S) model. Here the coupling is taken to be $\lambda_{hS} v/\sqrt{2}\, hS^2$ with $\lambda_{hS} = 10^{-11}$. At low masses the decay process $h \to SS$ dominates DM formation and MB approximates well the exact result, the measured value for the relic density is obtained for $M_{\mathrm{DM}} \approx 0.3\,\mathrm{GeV}$. When this process is no longer kinematically accessible, it is rather the annihilation processes through gauge bosons pair annihilation that become dominant, here we see a large increase in the relic density with the BE distribution. Note that the impact of quantum statistics effects is somewhat tamed when including finite temperature effects [12].

At the high temperatures in the Early Universe where freeze-in starts, interactions with the plasma modify interactions among particles. In the hard thermal loop approximation, it was argued in Ref. [13–15] that these effects can be taken into account by replacing the pole mass by the Debye mass, which is $\mathcal{O}(\sqrt{\alpha_{\mathrm{s}}}T)$ or $\mathcal{O}(\sqrt{\alpha_{\mathrm{W}}}T)$ for strongly or weakly interacting particles, respectively, and by renormalizing all couplings at the scale $\mu = 2\pi T$ using renormalization group equation in vacuum. Introducing a thermal mass can regulate the enhancement in the forward direction for t-channel processes and/or can open up new annihilation or decay channels, for example new decay processes involving the massive photon or gluon [16, 17]. These effects can strongly impact the relic density. The calculation of DM production including finite temperature effects is discussed in Ref. [18].

Another effect of DM production at high temperature is that it starts in a regime where electroweak symmetry is not broken. This is typical in models where DM connects to SM via Higgs portal. Apart from the fact that DM production channels differ substantially before and after electroweak symmetry breaking (EWSB) and therefore gives rise to different phenomenology [19], if the DM is a scalar (S), there is an additional production during the electroweak phase transition, when the temperature is very close to the critical temperature ≈ 160 GeV. This additional production arises from the temperature dependent mixing angle, which becomes substantially enhanced for a short period of time right after EWSB and causes rapid conversion of Higgs boson into S through oscillations [20]. In this scenario, S acquires a vev and can decay, however its lifetime is larger than the age of the Universe, thus S remains a good DM candidate.

2.2 Beyond standard FIMP production

In models with an extended dark sector, several phases of out-of-equilibrium DM production can occur, depending on the interaction strength within the dark sector. One such phase is the sequential freeze-in as proposed in Ref. [21], which consists of the out-of-equilibrium production of mediators from SM particles followed by DM production from non-thermalized mediator annihilation/decay. It occurs when the very small coupling of the mediator to the SM prevents it from reaching equilibrium with the bath. To be concrete, let us consider a simplified model where the SM is extended with a light scalar mediator, ϕ, and a Dirac fermion, χ, the latter being the DM candidate [17],

$$\mathcal{L}_{\mathrm{int}} = y_\chi\, \phi\bar{\chi}\chi + y_q\, \phi\bar{q}q \ . \tag{4}$$

Depending on the size of the couplings there are three DM production modes, (1) $q\bar{q} \to \chi\chi$, (2) $\phi\phi \to \chi\chi$ where ϕ is in equilibrium with the thermal bath and (3) $\phi\phi \to \chi\chi$, where ϕ is out-of-equilibrium. The first two cases are straightforward and lead to a relic density proportional to $y_q^2 y_\chi^2$ and y_χ^4 respectively. However in the third case where ϕ is not in equilibrium, its phase space distribution $f_\phi(p)$ does not follow a thermal distribution and one needs to first solve an unintegrated Boltzmann equation for the production of ϕ before solving for DM production induced by $\phi\phi$ annihilation. Here, the thermal masses of quarks, gluons, and photons play an important role in mediator production [17]. For further discussion on FI from out of equilibrium particles, see also Ref. [22].

Fig. 2 LHC constraints for the lepton-like simplified FIMP scenarios in the lifetime $(c\tau)$–mass of LLP (m_F) plane. The lines correspond to contours $\Omega_s h^2 = 0.12$ for the values of the DM mass, m_s and reheating temperature T_R given in the legend [27]
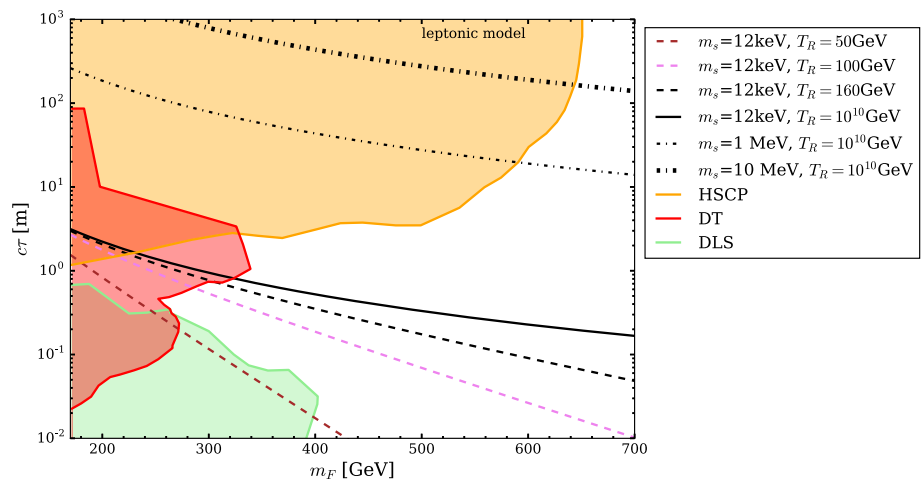
3 Signatures of FIMPs

3.1 Colliders

Typically, the couplings of FIMPs are too small for these particles to be directly pair produced at a collider. However they can be produced from the decay of a heavier particle, F, which is in thermal equilibrium with the thermal bath. At the LHC, F could be copiously produced and because of the feeble coupling would be long-lived. Thus, the most relevant searches are those for long-lived particles (LLPs), either stable at the collider scale or leading to displaced vertices. For the standard freeze-in scenario, the lifetime of the particle F with a mass at the weak scale is greater than $c\tau \approx 10^4$ m, thus the most relevant searches are those for heavy stable charged particles (HSCP) when F is charged. When F is neutral and long-lived, its invisible decays can lead to the usual missing transverse energy (MET) signatures at the LHC, while the visible decay modes will be best probed in planned detectors located some distance from the interaction point such as MATHUSLA [23].

Several scenarios have discussed the possibility of larger couplings and thus shorter lifetime within the freeze-in context leading to interesting displaced vertices signatures. These include DM production during the matter dominated era [24, 25], lowering the mass of the DM [26] and/or lowering the reheating temperature [27]. A concrete example of a FI model which can be probed via LLP signatures at the LHC was considered in [27]. This simplified model includes a singlet scalar DM, S, and a vector like fermion, F, that couples to an ordinary fermion and DM with a Yukawa coupling. In the case that the vector fermion couples only to leptons, the impact of varying the reheating temperature and the DM mass on the LHC limits for HSCP, disappearing tracks (DT) and displaced leptons (DLS) is displayed in Fig. 2.

For light DM (GeV scale or below) an extensive search program for feebly coupled particles is being put in place at the high energy and high intensity frontier, see [28] for a comprehensive presentation. While it is generally challenging to probe the small couplings relevant for FIMPs, in specific scenarios—for example with a right-handed neutrino—it was shown that the FI parameter space can be probed in beam-dump or fixed target experiments [29]. In addition, a light mediator (with a mass $\lesssim 10$ GeV) can potentially be probed in the beam-dump experiments dedicated to the decays of rare mesons provided its coupling to quarks is not too suppressed [17].

3.2 Direct detection

Considering the small couplings involved, one might think that looking for FIMPs via direct detection of its interaction with nuclei in a large detector would be fruitless. However the small coupling can be somewhat compensated by having a light mediator of mass m_ϕ. The rate for direct detection on nuclei [30, 31] is given by,

$$\frac{\mathrm{d}N}{\mathrm{d}E} = \frac{\rho_0 \bar{\sigma}_{SI}}{2m_\chi \mu_{\chi N}^2} M_{\mathrm{det}} T F^2(q) I(E) \frac{m_\phi^4}{(q^2 + m_\phi^2)^2}, \tag{5}$$

where $\bar{\sigma}_{SI} \propto 1/m_\phi^4$ is the spin-independent cross section at zero momentum transfer, $\mu_{\chi N}$ is the DM-nucleus reduced mass, ρ_0 is the DM density today, M_{det} is the detector mass, and T is the exposure time. $F(q)$ is a form factor with q the momentum transfer, and $I(E) = \int_{v_{\min}(E)} f(v)/v \, \mathrm{d}v$ takes into account the DM velocity distribution. Note that the large enhancement of the cross section saturates when the mass of the mediator becomes

of the order of $q^2 = 2EM_N$, which is typically 100 MeV for a weak scale DM. Ref. [32, 33] showed that freeze-in could be probed for light mediators.

Direct detection can also probe freeze-in scenarios with larger couplings, for example those where the DM mass is above the reheating temperature [34].

For DM at the GeV scale or below, it was suggested to exploit DM scattering on electrons. Studies have shown that future detectors can cover the favored freeze-in region in the case of a light vector mediator for example [35–37].

3.3 Indirect detection

The feeble couplings between DM and the SM particles typically suppresses all indirect detection signals. Allowing for larger couplings, for example when DM is produced during the early matter dominated era, enhances the prospects [38]. One class of scenario that lead to interesting signatures is the one where DM interaction with a mediator is not so suppressed, thus the dominant channels are DM annihilation (or semi-annihilation) into mediators with the mediators decaying into a pair of SM particles. These can be probed in the photon [39, 40] or neutrino channel [41].

3.4 Cosmological aspects

The presence of FIMPs, which often leads to LLPs, can impact the successful predictions of Big Bang Nucleosynthesis on the abundance of light elements. Indeed, the decay of LLPs can inject energetic particles that can trigger non-thermal nuclear processes. For particles with lifetime ranging from 0.1 to 10^4 s the relevant bounds are due to the hadronic part of the decay which can alter the n/p ratio thus shifting the predictions for He^4 and D/H. The key elements are the hadronic branching ratio of the LLP, B_{had}, the net energy carried away by hadrons, E_{vis}, the yield of the LLP, Y_{LLP} and the lifetime of the LLP, τ_{LLP}. Generic constraints in the plane $B_{\text{had}}E_{\text{vis}}Y_{\text{LLP}}$ vs τ_{LLP} using both the D/H ratio—relevant for $\tau > 100$ s – and the abundance of He^4 for shorter lifetimes were derived in Ref. [42, 43]. These have been shown to put strong constraints on models with FIMP DM and a LLP, for example in the triplet/singlet fermionic model [7] and in an inert doublet and singlet model [44].

LLPs with longer lifetimes can also impact the CMB leading to spectral distorsions as well as to anisotropies in the power spectra. The former provides constraints on the amount of electromagnetic energy injected before 10^{12} s while the latter constrains particles with lifetimes $\tau > 10^{12}$ s [45, 46].

Light DM also contributes to the cooling of stars. The observations of globular clusters severely constrain DM lighter than 100 keV, in particular for the parameter space preferred by freeze-in [47].

4 Conclusion

In summary, different mechanisms can contribute to feeble particle production in the early Universe, and contrary to freeze-out this mechanism may depend on the initial conditions and on the reheating temperature T_R. Moreover thermal effects can be important. Despite the very small couplings of the FIMP, various signatures of FIMPs can be detectable at the high energy and/or high intensity frontier, including direct searches of LLPs or indirect searches for the mediator. Moreover FIMPs can be probed via direct detection if the mediator is light and with cosmology, in particular through effect on BBN and/or distorsions of the CMB.

Data availability No data associated in the manuscript.

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