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Antisymmetric tensor portals to dark matter

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ABSTRACT

Both freeze-in of very weakly coupled dark matter and freeze-out of initially thermalized dark matter from the primordial heat bath provide interesting possibilities for dark matter creation in the early universe. Both scenarios allow for a calculation of baryon-dark matter coupling constants as a function of dark matter mass m_χ, $g = g(m_\chi)$, due to the constraint that freeze-in or freeze-out produce the observed dark matter abundance. Here we compare the resulting coupling constants in the two scenarios if dark matter couples to baryons through an antisymmetric tensor portal. The freeze-in scenario predicts much smaller coupling in agreement with the nonthermalization postulate. We find that the couplings as a function of mass behave very differently in the two scenarios.

The development of consistent models for dark matter creation in the early universe is a triumph of astroparticle physics that draws on expertise in every area of modern theoretical physics, including statistical mechanics, cosmology, particle physics, and quantum field theory.

A widely discussed mechanism, informed by early calculations of relic neutrino abundances, is based on dark matter freeze-out [1]. This framework assumes that dark matter was reciprocally created and annihilated in thermal equilibrium with the primordial heat bath after the reheating stage of the universe. This process continued until the expansion rate of the universe suppressed the reactions which maintained thermal equilibrium between the baryonic and the dark sectors. The decoupled nonrelativistic dark matter density then grew with respect to the still relativistic heat bath with the scale factor $a(t)$ according to $\varrho_{CDM}(t)/\varrho_b(t) \propto a(t)$ because the relativistic baryons were still performing expansion work due to their higher pressure.

Freeze-out theory is an integral part of the "WIMP miracle", *viz.* that weakly coupled massive particles (WIMPs) in the GeV to TeV mass range could easily explain the observed dark matter abundance. Though the present lack of detection of nucleon recoils from dark matter places constraints on the preferred parameter range for WIMPs from thermal freeze-out, it does not completely rule out thermal freeze-out scenarios. Another promising framework for the creation of dark matter in the early universe concerns the "freeze-in" mechanism, which occurs through annihilation of baryons in the thermal heat bath[1]. Contrary to dark matter that is frozen-out from the primordial heat bath, freeze-in assumes that the dark matter particles are so weakly coupled to the baryonic sector that thermal equilibrium was never achieved between the baryonic and dark sectors [2,3]. Instead, baryon annihilation since reheating gradually built up the dark matter density to its present value. Particles with such extraordinarily weak couplings are often referred to as "feebly interacting massive particles" or FIMPs.

Both of the aforementioned dark matter creation mechanisms require the use of rate equations involving baryon-to-dark matter annihilation cross sections. However, they contrast in that freeze-out employs a thermal decoupling criterion and subsequent evolution of the decoupled dark component during the expansion of the universe to calculate the relic dark matter density, whereas freeze-in integrates baryon annihilation to dark matter from the time of reheating. Accordingly, while using the same kind of fundamental physics in terms of baryon-dark matter annihilation cross sections, the actual calculations of the relic dark matter abundance are very different. Nonetheless, the different central premises on dark matter thermalization imply that, within every given particle physics model for dark matter, its coupling to baryons as a function of dark matter mass should be greater in magnitude in the freeze-out scenario than in freeze-in. The primary focus of this study is to compare the dark matter coupling, $g(m_\chi)$, predicted from thermal freeze-out to those from freeze-in for models where a dark Dirac fermion χ, couples to baryons through the exchange of an antisymmetric tensor field, $C_{\mu\nu}$.

We are particularly interested in an antisymmetric tensor portal because the discovery of fundamental fields of this type in particle physics would indicate an extension of the Standard Model through supergravity or string theory. The proposals of supergravity and string theory were motivated as approaches to a theory of quantum gravity,

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[1] Note that prior to around 2010, the terms "freeze-in" and "freeze-out" were used interchangeably to describe what is presented as freeze-out in this paper.

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and it is an intriguing question whether dark matter can shed light on this open problem. In this regard, it is also of interest that Manton and Alexander recently pointed out that parity violating gravitational interactions of antisymmetric tensor fields can provide an alternative approach to antisymmetric tensor detection through gravitational wave signals [4].

An antisymmetric tensor field, $C_{\mu\nu}$, can couple to Standard Model fermions, f, through dipole terms,

$$\mathcal{L}_{fC} = -\sum_f g_f \overline{\psi}_f S^{\mu\nu}(a_{f,m} + \mathrm{i}a_{f,e}\gamma_5)\psi_f C_{\mu\nu}, \quad (1)$$

where we use the spinor representation of the Lorentz generators,

$$S^{\mu\nu} = \frac{1}{2}\sigma^{\mu\nu} = \frac{\mathrm{i}}{4}[\gamma^\mu, \gamma^\nu], \quad (2)$$

in the dipole operators. The parametrization of the couplings in (1) is redundant in that we can absorb g_f into the magnetic dipole coupling $a_{f,m}$ and the electric dipole coupling $a_{f,e}$. We keep g_f separate for now to point out that the couplings (1) can arise from the low-energy limit of $SU(2)\times U_Y(1)$ invariant couplings in the form $g_f = v_h/M_f$, where v_h is the Higgs expectation value and M_f is a coupling scale for the fermion f [5]. String origins of these couplings from antisymmetric tensor oscillations of closed strings, or from the Kalb-Ramond 2-form gauge fields that couple to string world sheets, are discussed in Refs. [6,7].

The couplings (1) imply decay of the antisymmetric tensors with a decay constant

$$\Gamma_C = \sum_f [a_{f,m}^2(m_C^2 - 4m_f^2) + a_{f,e}^2(m_C^2 + 8m_f^2)] \times \frac{g_f^2}{192\pi m_C^2}\sqrt{m_C^2 - 4m_f^2} \quad (3)$$

where the sum runs over fermions with masses $m_f < m_C/2$. This implies that primordial antisymmetric tensor fields that couple to electromagnetic dipole moments are constrained by the requirement of longevity, $\tau > 10^{18}$ s. This limits the masses of relic primordial tensors to very small values unless we assume extremely weak coupling to electrons and neutrinos. On the other hand, extremely weak couplings cannot be excluded, and the constraint on the couplings is less severe in freeze-in dark matter production with low reheating temperature. Freeze-in production of antisymmetric tensor dark matter was recently discussed by Capanelli et al. [8]. In the present paper, we evade the longevity constraint by pursuing an alternative dark matter connection of antisymmetric tensor fields, *viz.* through an antisymmetric tensor portal to fermionic dark matter.

We also note that the absence of corresponding resonances in collider experiments limits the antisymmetric tensor mass to $m_C > 200$ GeV for hadrophobic antisymmetric tensors, and to $m_C > 1$ TeV for antisymmetric tensors that couple to dipole moments of quarks. The couplings (1) give rise to an antisymmetric tensor portal if the antisymmetric tensor also couples to a dark fermion χ,

$$\mathcal{L}_{\chi C} = -g_\chi \overline{\chi} S^{\mu\nu}(a_{\chi,m} + \mathrm{i}a_{\chi,e}\gamma_5)\chi C_{\mu\nu}. \quad (4)$$

Constraints from Bhabha scattering limit the coupling to electrons and the antisymmetric tensor mass m_C to $m_C m_e/\sqrt{a_{em}^2 + a_{ee}^2} > 7.1\times 10^4\,\mathrm{GeV}^2$ or $g_e\sqrt{a_{em}^2 + a_{ee}^2} < m_C/(290\,\mathrm{GeV})$ [5]. However, our primary focus here is on the internal consistency of freeze-out versus freeze-in dark matter production, as expressed by the requirement of smaller coupling in the freeze-in scenario. We will compare antisymmetric tensor portal couplings and masses for freeze-in and freeze-out in Section 1.

1. Antisymmetric tensor couplings for freeze-in and freeze-out dark matter production

Here we absorb the coupling constants g_f and g_χ in Eqs. (1) and (4) into the corresponding dipole coupling constants $a_{f,m}$ and $a_{f,e}$, or $a_{\chi,m}$ and $a_{\chi,e}$, respectively.

The procedures for the calculation of relic dark matter abundances from thermal freeze-out or freeze-in are well established and documented in the literature. The required ingredient from the specific dark matter model concerns the annihilation rates that connect the baryons to the dark matter particles. In our case this yields annihilations of Standard Model fermions f into dark fermions χ with the annihilation cross section (with $s > 4m_f^2$)

$$\begin{aligned} v\sigma_{f\overline{f}\to\chi\overline{\chi}}(s) = {} & \frac{1}{64\pi s^2}\frac{\mathrm{Re}\sqrt{s(s-4m_\chi^2)}}{(s-m_C^2)^2 + m_C^2\Gamma_C^2} \\ & \times\Big[a_{f,m}^2 a_{\chi,m}^2(s-4m_f^2)(s-4m_\chi^2) \\ & + a_{f,m}^2 a_{\chi,e}^2(s-4m_f^2)(s+4m_\chi^2) \\ & + a_{f,e}^2 a_{\chi,m}^2(s+4m_f^2)(s-4m_\chi^2) \\ & + a_{f,e}^2 a_{\chi,e}^2(s+4m_f^2)(s+4m_\chi^2) \\ & + 32a_{f,e}^2 a_{\chi,e}^2 m_f^2 m_\chi^2 \\ & - \frac{1}{3}(a_{f,m}^2 + a_{f,e}^2)(a_{\chi,m}^2 + a_{\chi,e}^2) \\ & \times(s-4m_f^2)(s-4m_\chi^2)\Big]. \end{aligned} \quad (5)$$

The cross section for the reverse process $\chi\overline{\chi}\to f\overline{f}$ (with $s > 4m_\chi^2$) is nearly identical, except for the replacement $m_\chi \to m_f$ under the radical,

$$\begin{aligned} v\sigma_{\chi\overline{\chi}\to f\overline{f}}(s) = {} & \frac{1}{64\pi s^2}\frac{\mathrm{Re}\sqrt{s(s-4m_f^2)}}{(s-m_C^2)^2 + m_C^2\Gamma_C^2} \\ & \times\Big[a_{f,m}^2 a_{\chi,m}^2(s-4m_f^2)(s-4m_\chi^2) \\ & + a_{f,m}^2 a_{\chi,e}^2(s-4m_f^2)(s+4m_\chi^2) \\ & + a_{f,e}^2 a_{\chi,m}^2(s+4m_f^2)(s-4m_\chi^2) \\ & + a_{f,e}^2 a_{\chi,e}^2(s+4m_f^2)(s+4m_\chi^2) \\ & + 32a_{f,e}^2 a_{\chi,e}^2 m_f^2 m_\chi^2 \\ & - \frac{1}{3}(a_{f,m}^2 + a_{f,e}^2)(a_{\chi,m}^2 + a_{\chi,e}^2) \\ & \times(s-4m_f^2)(s-4m_\chi^2)\Big]. \end{aligned} \quad (6)$$

The velocity-weighted dark matter annihilation cross sections are thermally averaged following the procedure of Gondolo and Gelmini [9],

$$\langle v\sigma\rangle(T) = \frac{1}{8m_\chi^4 T K_2^2(m_\chi/T)} \times\int_{4m_\chi^2}^\infty ds\,\sqrt{s}\left(s-4m_\chi^2\right)\sigma(s)K_1(\sqrt{s}/T), \quad (7)$$

where the annihilation cross sections $\sigma(s)$ need to be calculated and substituted into the integral using the specific dark matter model under consideration. Here these are the cross sections (6), summed over all Standard Model fermions.

In freeze-out, the thermally averaged annihilation cross section determines the evolution of the relic dark matter density after freeze-out, whereas in freeze-in we have to use the thermally averaged production cross section to evaluate dark matter production from the baryonic heat bath since reheating. We noticed already that low reheating temperature alleviates the longevity constraint on antisymmetric tensor dark matter [8]. However, since we employ antisymmetric tensor fields only as messengers between the dark and the baryonic sectors, we use a reheating temperature $T_R = 10^{15}$ GeV, as it would generically appear in Susy-GUT models and in string theory if threshold effects are taken into account [10].

The requirement that the relic dark matter density evolves to the observed dark matter abundance is a primary constraint on dark matter model parameters. For the antisymmetric tensor portals ((1), (4)), this

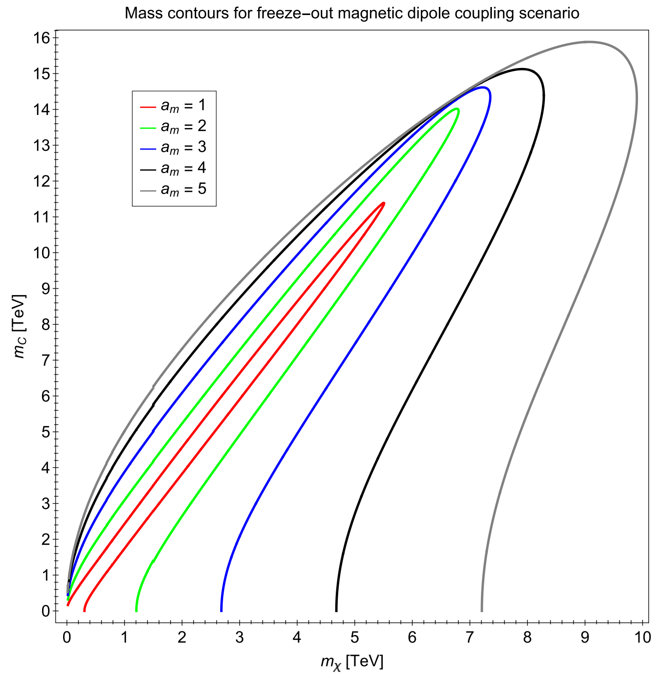

Fig. 1. Relation between antisymmetric tensor mass m_C and freeze-out dark matter mass m_χ for increasing a_m.

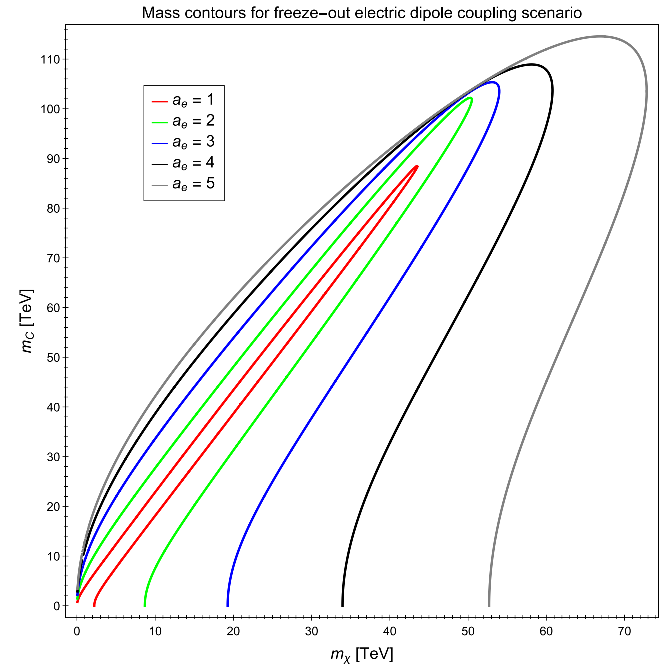

Fig. 2. Relation between antisymmetric tensor mass m_C and freeze-out dark matter mass m_χ for increasing a_e.

corresponds to a 52-dimensional parameter space through up to 48 couplings $a_{f,m}$ and $a_{f,e}$, 2 couplings $a_{\chi,m}$ and $a_{\chi,e}$, and two masses m_C and m_χ. However, we are primarily interested in the impact of the different dark matter creation scenarios on the parameters. As such, we restrict the parameter space through the assumption of universality of the magnetic dipole couplings, $a_{f,m} = a_{\chi,m} \equiv a_m$, with $a_{f,e} = a_{\chi,e} = 0$, or of the electric dipole couplings, $a_{f,e} = a_{\chi,e} \equiv a_e$, with $a_{f,m} = a_{\chi,m} = 0$. We also require perturbativity, $a^2_{m,e} < 8\pi \approx 5.01$.

We find that the resulting three-dimensional parameter spaces can still yield the observed dark matter density $\varrho_c = \Omega_c \varrho_{\text{crit}}$ both through freeze-in or through freeze-out. We use the values from the Particle Data Group, $\Omega_c = 0.12h^{-2}$ and $\varrho_{\text{crit}} = 1.053672\times10^{-5}h^2\,\text{GeV/cm}^3$, where the reduced Hubble constant h cancels in the evaluation of ϱ_c [11]. We also use the Standard Model masses from the Particle Data Group for the calculation of the cross sections.

Mass relations $m_C = m_C(m_\chi)$ for different magnetic dipole couplings a_m are displayed for freeze-out in Fig. 1, and for freeze-in in Figs. 3–5. Mass relations $m_C = m_C(m_\chi)$ for different electric dipole couplings a_e are displayed for freeze-out in Fig. 2, and for freeze-in in Fig. 6.

We first note that freeze-in (Figs. 3–6) produces the required dark matter density for much weaker couplings than freeze-out (Figs. 1, 2), consistent with the basic freeze-in tenet that the coupling was too weak for dark matter thermalization after reheating.

There are also several other interesting observations that follow from comparison of the dark matter parameters in the two scenarios:

Freeze-in (Figs. 3–6) yields antisymmetric tensor masses in the PeV range and can generate dark matter over a very wide mass range. We found that every decrease of a_m by an order of magnitude yields an increase of the dark matter mass m_χ by four orders of magnitude. Larger coupling produces more dark matter particles from freeze-in, and this naturally restricts the maximal possible dark matter mass from the abundance requirement $(n_\chi+n_{\overline{\chi}})m_\chi = 2n_\chi m_\chi = \rho_{CDM}$. Since production rates scale with a_m^4 (because the impact of the decay constant Γ_C is small for very weak couplings), the increase in $m_\chi \propto a_m^{-4}$ for decreasing a_m and constant m_C is expected. Furthermore, since scaling $a_m \to a_m/10$ approximately scales $m_\chi(m_C) \to 10^4 m_\chi(m_C)$, the ordinate $m_C \simeq 13$ PeV for $m_\chi \to 0$ is preserved.

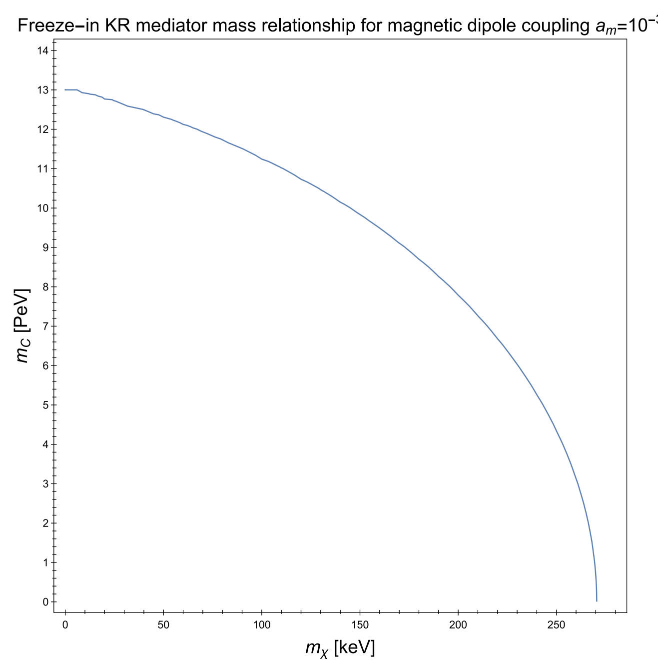

Fig. 3. Relation between antisymmetric tensor mass m_C and freeze-in dark matter mass m_χ for $a_m = 10^{-3}$.

Contrary to the very small dipole couplings required for freeze-in, we found viable mass ranges for freeze-out only for relatively large dipole coupling near the perturbativity limit, $a^2_{m,e} \lesssim 8\pi$. This yields TeV-scale masses both for the antisymmetric tensor and the dark matter in the case of magnetic dipole coupling, see Fig. 1, and in the tens of TeV scale for electric dipole coupling, see Fig. 2.

We did not cut off the graph for freeze-out through a magnetic dipole coupling (Fig. 1) below m_C = 1 TeV, but note that these low antisymmetric tensor masses are ruled out in the present model through absence of resonances at the LHC.

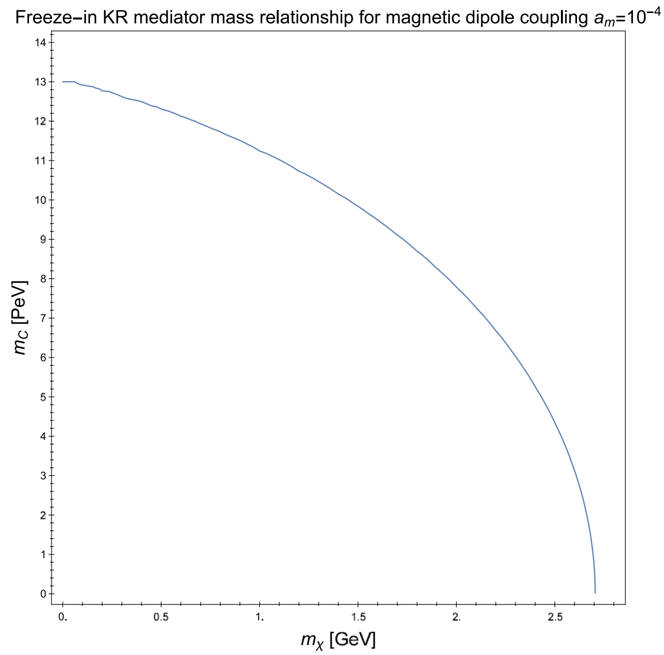

Fig. 4. Relation between antisymmetric tensor mass m_C and freeze-in dark matter mass m_χ for $a_m = 10^{-4}$.

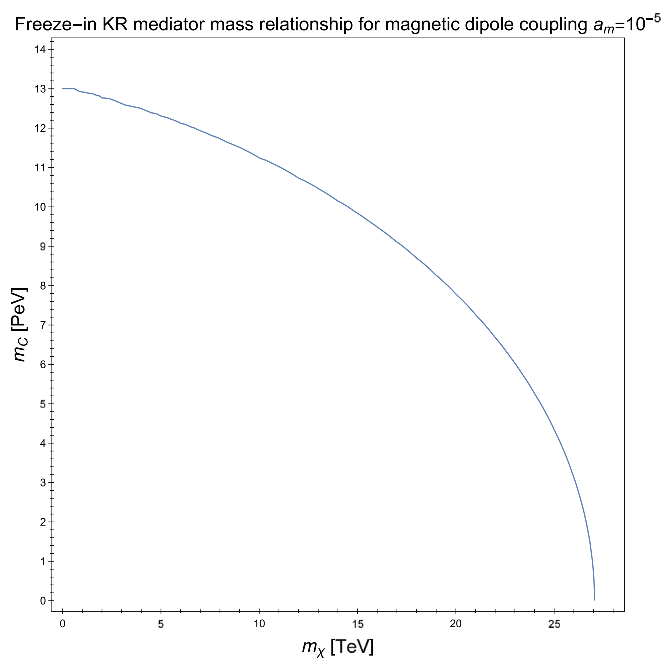

Fig. 5. Relation between antisymmetric tensor mass m_C and freeze-in dark matter mass m_χ for $a_m = 10^{-5}$.

As a novel feature of dark matter freeze-out through dipole couplings, we find two possible dark matter mass values m_χ for every allowed m_C both for the magnetic dipole coupling (Fig. 1) and the electric dipole coupling (Fig. 2), except at the maxima of the (m_χ, m_C) curves. This is in contrast to freeze-out in simpler models, e.g. minimal Higgs portal models (see e.g. [12–21]), where the dark matter coupling to baryons depends on a single coupling constant. An increase in dark matter mass m_χ implies a decrease in the required relic dark particle density n_χ. This implies later freeze-out from the primordial heat bath, which requires larger cross sections [1], which in turn can be achieved through larger coupling g to baryons. Generically, this yields a monotonically increasing coupling function $g(m_\chi)$ in freeze-out models. However, thermal averaging throws a wrench into this reasoning. Thermal averaging introduces a factor

$$\frac{1}{K_2^2(x_f)} \simeq \frac{2x_f}{\pi}\exp(2x_f) \tag{8}$$

in $\langle v\sigma\rangle(T_f)$, where $x_f = m_\chi/T_f \gg 1$ is the ratio between dark matter mass and freeze-out temperature, see Eq. (7). This ratio increases logarithmically with dark matter mass. The factor $1/K_2^2(x_f)$ can therefore increase $\langle v\sigma\rangle(T_f)$ with increasing dark matter mass, and this can generate the required increase in $\langle v\sigma\rangle(T_f)$ without changing the coupling parameters m_C and a_m or a_e, respectively.

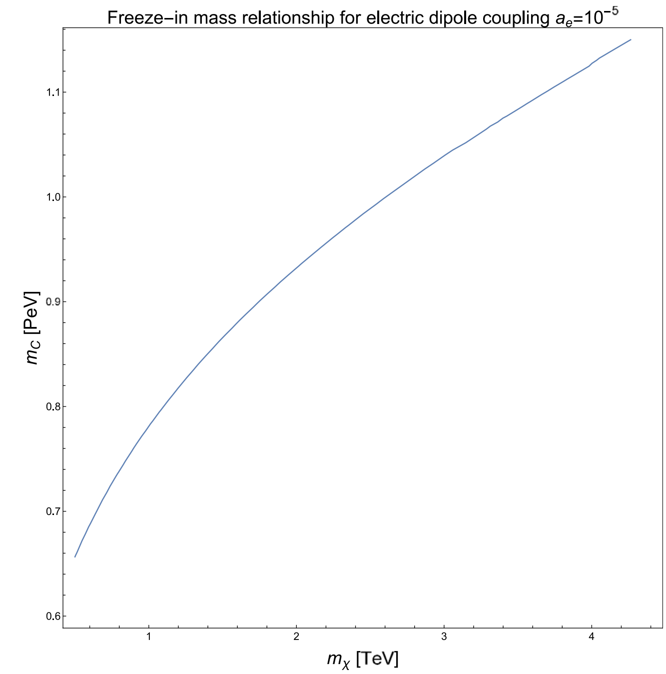

Fig. 6. Relation between antisymmetric tensor mass m_C and freeze-in dark matter mass m_χ for $a_e = 10^{-5}$.

For the comparison between freeze-out and freeze-in, we also note that both the much larger dipole couplings and the much smaller m_C values in freeze-out versus freeze-in enhance the coupling of dark matter to baryons. This complies with the assumption of thermalization of dark matter in the early universe before freeze-out, as opposed to the absence of thermalization in the freeze-in scenario.

2. Conclusions

We find that freeze-in through an antisymmetric tensor portal requires much smaller dipole couplings $a_{m,e}$ and larger antisymmetric tensor mass m_C than freeze-out through the antisymmetric tensor portal, in agreement with the assumption that interactions with the primordial baryonic heat bath were too small to ever thermalize the dark matter. Freeze-in requires an antisymmetric tensor mass in the PeV range, whereas the dark matter mass m_χ can vary over a large range depending on the dipole coupling. In particular, we find that that m_χ can range from keV to TeV values for $10^{-3} \geq a_m \geq 10^{-5}$. For freeze-out, we find solutions with both m_C and m_χ in the TeV mass range for magnetic dipole coupling, and in the tens-of-TeV mass range for electric dipole coupling, if the corresponding dipole coupling is near the upper limit of the perturbative range. In the mass range for freeze-out, we generically find two possible values for the dark matter mass m_χ for given $a_{m,e}$ and m_C, although higher dark matter mass requires later freeze-out corresponding to stronger coupling. However, we point out that the calculation of the thermal average $\langle\sigma v\rangle(T_f)$ generates a positive feedback between dark matter mass and coupling strength to baryons (as expressed through $\langle\sigma v\rangle(T_f)$), and this explains why the same set $(a_{m,e}, m_C)$ of coupling parameters to baryons can comply with more than one possible dark matter mass for freeze-out.

Unfortunately, the large mediator masses, and in the case of freeze-in also the small dipole coupling constants, push our estimates for recoil cross sections well below the neutrino floor. However, the TeV mass scales of both the antisymmetric tensor and the dark fermion make the freeze-out scenario interesting for next generation hadron colliders.

CRediT authorship contribution statement

Alexander J. Magnus: Writing – review & editing, Writing – original draft, Visualization, Software, Investigation. **Joshua G. Fenwick:** Writing – review & editing, Visualization, Software, Investigation. **Rainer Dick:** Writing – review & editing, Writing – original draft, Supervision, Software, Project administration, Methodology, Investigation, Funding acquisition, Formal analysis, Conceptualization.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

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Data availability

No data was used for the research described in the article.

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