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Erratum: Complementarity of DM searches in a consistent simplified model: the case of Z'

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Abstract: We correct the mistakes in the original version of the paper and recalculate the relevant bounds on the Z'-mediated DM. The mistakes of the published version have to do with the calculation of the annihilation cross sections. In particular in this erratum we properly take into account:

- the effects of the Z exchange due to the mixing that are parametrically not smaller than the effects of the Z' exchange;
- the complex mass scheme that changes the behavior on the resonances.

This changes the dominant annihilation channels, in particular suppressing the Zh channel. The bounds that we derive change appropriately.

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Contents

1 Annihilation cross section and non-relativistic scattering

As we have emphasized in the original paper, if the DM interactions with the SM are mediated by an anomaly free Z', the Z' necessarily mixes with the SM Z, inducing therefore tree level annihilations of DM into EW gauge bosons (including the Higgs) as well as SM fermions. There we calculated these interactions both at tree and one loop level, assuming that the dominant effect was coming from the Z' exchange. However, due to the above-mentioned mixing between the Z and the Z', one should also take into account both the contributions of Z and Z'. Although the former has a suppressed coupling to the DM, since it is much lighter than the Z' and its coupling to the gauge bosons are unsuppressed, it is expected to be of the same order of magnitude as the contributions of the Z' [1].

Explicitly the relevant vertices that involve the neutral gauge bosons Z and Z' are:

$$Z'\chi\chi \to 2ig_{Z'}g_\chi\gamma^\mu\gamma^5 \tag{1.1}$$

$$Z\chi\chi \to 2i(-\sin\psi)g_{Z'}g_\chi\gamma^\mu\gamma^5 \tag{1.2}$$

$$Z'f\bar{f} \to ig_{Z'}\gamma^\mu(c^{Z'}_{V,f} + c^{Z'}_{A,f}\gamma^5) \tag{1.3}$$

$$Zf\bar{f} \to ig_Z\gamma^\mu(c^{Z}_{V,f} + c^{Z}_{A,f}\gamma^5) \tag{1.4}$$

$$Z'Zh \to ig_{Z'}\cos\theta m_Z\eta^{\mu\nu} \tag{1.5}$$

$$ZZh \to ig_Z m_Z\eta^{\mu\nu}\,. \tag{1.6}$$

Hereafter we use the fact that $m_Z \ll m_{Z'}$ and keep only the terms up to order $\mathcal{O}(m_Z/m_{Z'})^2$. In this approximation $\cos\psi \approx 1$ and $\sin\psi \approx -\cos\theta\frac{g_{Z'}}{g_Z}\frac{m_Z^2}{m_{Z'}^2}$, so that the mixing angle ψ is proportional to the ratio of the neutral gauge bosons squared masses.

When we take into account all the diagrams of the same order in $\mathcal{O}(m_Z/m_{Z'})^2$ we find important cancellations between the SM Z and Z' contributions. In particular, we find that for a DM axially coupled to the Z' *there are no s-wave annihilation channels.*[1] The would-be s-wave contribution of the Z' precisely cancels out against the analogous contribution of the SM Z. More importantly, we need to sum the contribution of the Z and the Z' in order to see that the process $\chi\chi \to Z^{(L)}h$ vanishes at $\mathcal{O}(E^2)$, such that unitarity is not violated.

[1]This statement is true at any order of $m_Z/m_{Z'}$ for the fermion channels up to the helicity suppression, and holds at least at one loop level and at first order in $m_Z^2/m_{Z'}^2$ for the boson channels.

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Due to these effects we find that, contrary to the claim that we make in the original paper, $t\bar{t}$ and Zh are generically not the dominant annihilation channels both in the Galactic Center and in the Sun. Instead the annihilation Branching Ratios are dominated by light SM fermions, posing in this sense an additional challenge to the neutrino telescopes and indirect detection experiments. Moreover, the total annihilation rate is suppressed. Among the channels that contribute to the hard neutrino signal observable at IceCube, we find that the bound is driven by comparable contributions of $\nu_i\bar{\nu}_i$, $\tau^+\tau^-$, $\mu^+\mu^-$, and a smaller contribution of $t\bar{t}$. We show the relevant branching ratios in figure 5, which supersedes the plots on figure 6 in the original text.

We also include the Z-exchange diagrams in our calculations of the NR scattering. The effect on the DD is mild, but it is appreciable on the DM Solar Capture. In particular we find that the NR scattering operator $\mathcal{O}_4$ *vanishes at the leading order*, and therefore the DM scattering with nucleons is controlled by $\mathcal{O}_8$ and $\mathcal{O}_9$, which are velocity and momentum suppressed, respectively. This changes the prospects for neutrino telescopes. In particular, we find that due to these suppressions the amount of the DM captured by the Sun *is not yet in equilibrium*, except for the resonance DM masses. We plot the ratio between the equilibrium time and the Sun lifetime on figure 6. Later, whenever the DM is out of equilibrium we rescale the Ice Cube bound by the factor $\tanh^2(t_\odot/\tau_{\rm eq})$.

Another important point that we properly take into account in our revised calculation is the complex mass scheme, that removes unphysical effects near the resonances. The correct application of the mass scheme requires the replacement of all the m^2 factors by $m^2 - im\Gamma$, both in the propagator and the mixing angles [2]. In particular, near the Z and the Z' resonances the propagators and the mixing angle have the following structure:

$$\frac{-i}{p^2 - m_Z^2}\left(\eta^{\mu\nu} - \frac{p^\mu p^\nu}{m_Z^2}\right) \quad\longrightarrow\quad \frac{-i}{p^2 - (m_Z^2 - im_Z\Gamma_Z)}\left(\eta^{\mu\nu} - \frac{p^\mu p^\nu}{(m_Z^2 - im_Z\Gamma_Z)}\right), \tag{1.7}$$

$$\frac{-i}{p^2 - m_{Z'}^2}\left(\eta^{\mu\nu} - \frac{p^\mu p^\nu}{m_{Z'}^2}\right) \quad\longrightarrow\quad \frac{-i}{p^2 - (m_{Z'}^2 - im_{Z'}\Gamma_{Z'})}\left(\eta^{\mu\nu} - \frac{p^\mu p^\nu}{(m_Z^2 - im_{Z'}\Gamma_{Z'})}\right), \tag{1.8}$$

$$s_\psi = -\cos\theta\frac{g_{Z'}}{g_Z}\frac{m_Z^2}{m_{Z'}^2} \quad\longrightarrow\quad s_\psi = -\cos\theta\frac{g_{Z'}}{g_Z}\frac{m_Z^2 - im_Z\Gamma_Z}{m_{Z'}^2 - im_{Z'}\Gamma_{Z'}}. \tag{1.9}$$

Note that after applying this scheme the BRs near the $m_{Z'}$ resonance are smooth (cf. figure 5), in agreement with similar results obtained in [3].

We also notice, that we have found a bug in our calculation of the maximal allowed couplings $g_{Z'}$ as a function of the angle θ. We show the correct results on figure 1 that supersedes the plot on figure 1 in the original text.

2 Results

After fixing these errors we have replotted all the figures, since all of them are affected by the above mentioned changes in the calculations, albeit some of these corrections are truly minor. Hereafter in figures 1, 2, 3, 4, 5 and 7 we bring all the redone plots and indicate

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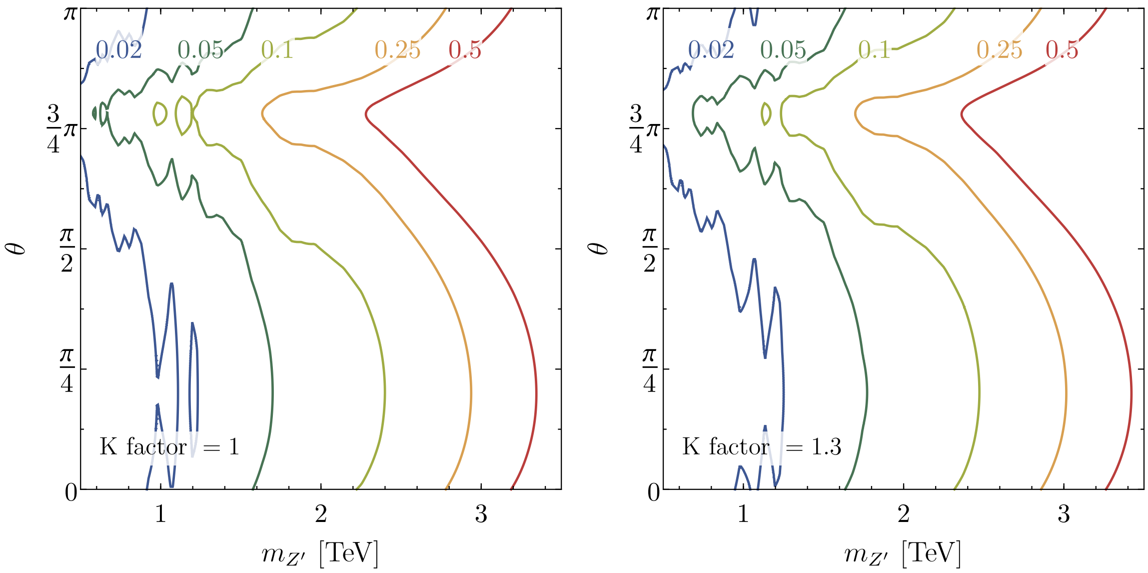

Figure 1. (*Replaces figure 1 of the original paper.*) Contours on the maximal allowed $g_{Z'}$ as functions of $m_{Z'}$ and θ for K-factors of 1 and 1.3 (to account for non-perturbative QCD effects).

which of the figures they supersede in the original paper. At the end we also provide a full list of diagrams that we calculate, because it slightly differs from one that we present in the appendix of the original paper. We also collect the formulæ obtained for the annihilation cross sections of DM at tree level (up to corrections $\mathcal{O}(m_Z^4/m_{Z'}^4)$).

We collect here the results for the annihilation cross sections of two DM particles into SM pairs of fermions or bosons, computed from the diagrams of figure 8.

The most important annihilation channels are fermions, for which

$$\sigma(\chi\chi\to f\bar{f}) = \frac{g_\chi^2 g_{Z'}^4\, N_c^f}{3\pi s\left((s-m_{Z'}^2)^2+m_{Z'}^2\Gamma_{Z'}^2\right)}\sqrt{\frac{s-4m_f^2}{s-4m_\chi^2}} \tag{2.1}$$

$$\times\left[\left((c_{V,f}^{Z'})^2(s-4m_\chi^2)(s+2m_f^2)+(c_{A,f}^{Z'})^2\left(s(s-4m_\chi^2)-4m_f^2\left(s-7m_\chi^2-\frac{3s\,m_\chi^2(s-2m_{Z'}^2)}{m_{Z'}^2(m_{Z'}^2+\Gamma_{Z'}^2)}\right)\right)\right)\right. \tag{2.2}$$

$$+\cos^2\theta\,\frac{m_Z^2(m_Z^2+\Gamma_Z^2)}{m_{Z'}^2(m_{Z'}^2+\Gamma_{Z'}^2)} \tag{2.3}$$

$$\cdot\left((c_{V,f}^{Z})^2(s-4m_\chi^2)(s+2m_f^2)+(c_{A,f}^{Z})^2\left(s(s-4m_\chi^2)-4m_f^2\left(s-7m_\chi^2-\frac{3s\,m_\chi^2(s-2m_{Z'}^2)}{m_{Z'}^2(m_{Z'}^2+\Gamma_{Z'}^2)}\right)\right)\right) \tag{2.4}$$

$$+\cos\theta\,\frac{1}{m_{Z'}^2(m_{Z'}^2+\Gamma_{Z'}^2)\left((s-m_Z^2)^2+m_Z^2\Gamma_Z^2\right)}\left(c_{V,f}^{Z}c_{V,f}^{Z'}(s-4m_\chi^2)(s+2m_f^2)\,\mathscr{C}\right. \tag{2.5}$$

$$\left.\left.+\,c_{A,f}^{Z}c_{A,f}^{Z'}\left(s(s-4m_\chi^2)\,\mathscr{C}-4m_f^2\left(s\,\mathscr{C}-7m_\chi^2\,\mathscr{C}-3s\,m_\chi^2\,\mathscr{D}\right)\right)\right)\right], \tag{2.6}$$

where

$$\mathscr{C} = (s-m_Z^2-\Gamma_Z^2)(s-m_{Z'}^2-\Gamma_{Z'}^2)m_Z^2m_{Z'}^2+s^2m_Zm_{Z'}\Gamma_Z\Gamma_{Z'}\,, \tag{2.7}$$

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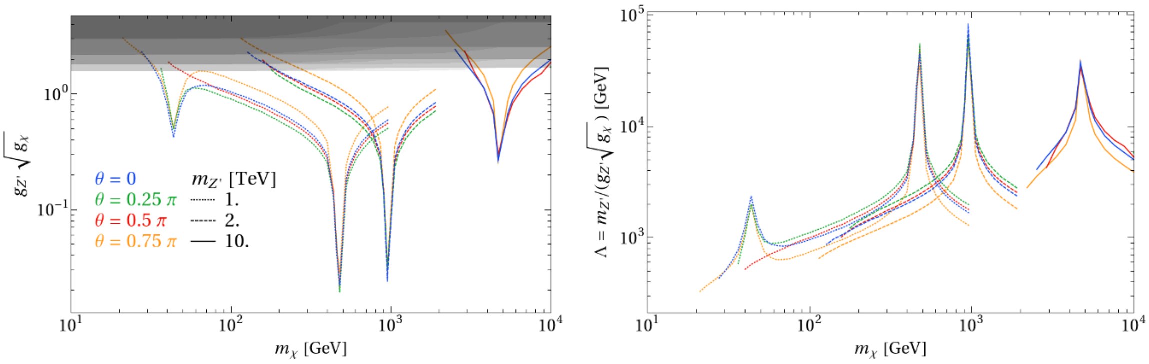

Figure 2. (*Replaces figure 2 of the original paper.*) Lower limits on the couplings $g_{Z'}, g_\chi$ and corresponding upper limits on the effective scale $\Lambda = m_{Z'}/(g_{Z'}\sqrt{g_\chi})$ from the requirement of not overclosing the universe. The gray shaded region in the upper panel correspond to a value of the couplings such that $\Gamma_{Z'} > m_{Z'}$, signaling the breakdown of the perturbative description.

$$\mathscr{D} = m_Z^2 m_{Z'}^2 (m_{Z'}^2 + m_Z^2 + \Gamma_{Z'}^2 + \Gamma_Z^2) + s^3 - s\left(\left((s-m_Z^2)^2 + m_Z^2\Gamma_Z^2\right) + \left((s-m_{Z'}^2)^2 + m_{Z'}^2\Gamma_{Z'}^2\right)\right. \tag{2.8}$$

$$\left. + m_Z m_{Z'}(3m_Z m_{Z'} - \Gamma_Z \Gamma_{Z'})\right) \,. \tag{2.9}$$

For a gauge group $\mathrm{U}(1)' = \cos\theta\ \mathrm{U}(1)_Y + \sin\theta\ \mathrm{U}(1)_{B-L}$ the gauge boson Z' has axial couplings $c_{A,f}^{Z'}$ related to the axial couplings of the Z boson $c_{A,f}^{Z}$ by $c_{A,f}^{Z'} = -\cos\theta\, c_{A,f}^{Z}$. This relation implies that the term proportional to the axial coupling in $\sigma(\chi\chi \to f\bar{f})$ is velocity suppressed for any value of m_f. This arises as a consequence of the sum of the Z and Z' exchanges in the propagator (whereas the Z' exchange would give just eq. (2.2), with an s-wave contribution). Therefore the parametric behaviour in the limit $m_{Z'}, m_\chi \gg m_f, m_Z$ is

$$\sigma(\chi\chi \to f\bar{f}) \sim \frac{\sqrt{s}\sqrt{s-4m_\chi^2}}{\max(s^2, m_{Z'}^4)} \,. \tag{2.10}$$

The annihilation cross section into WW bosons reads

$$\sigma(\chi\chi \to W^+W^-) = \alpha_W \cos^2\theta_W \frac{g_\chi^2 g_{Z'}^4 \cos^2\theta}{g_Z^2}\left(s-4m_W^2\right)^{3/2}\sqrt{s-4m_\chi^2}$$
$$\times \frac{(m_{Z'}^2 - m_Z^2)^2 + (m_{Z'}\Gamma_{Z'} - m_Z\Gamma_Z)^2}{((s-m_{Z'}^2)^2 + m_{Z'}^2\Gamma_{Z'}^2)((s-m_Z^2)^2 + m_Z^2\Gamma_Z^2)} \times \begin{cases} \frac{2}{3s} & \text{for } W^{+(T)}W^{-(T)} \\ \frac{4}{3m_W^2} & \text{for } W^{\pm(T)}W^{\mp(L)} \\ \frac{(2m_W^2+s)^2}{12m_W^4 s} & \text{for } W^{+(L)}W^{-(L)} \end{cases} \tag{2.11}$$

and the asymptotic cross section for $m_{Z'}, m_\chi \gg m_W, m_Z$ reads

$$\sigma(\chi\chi \to WW) \sim \cos^2\theta\, \frac{\sqrt{s}\sqrt{s-4m_\chi^2}}{\max(s^2, m_{Z'}^4)} \times \begin{cases} \frac{m_W^4}{s^2} & \text{for } W^{+(T)}W^{-(T)} \\ \frac{m_W^2}{s} & \text{for } W^{\pm(T)}W^{\mp(L)} \\ 1 & \text{for } W^{+(L)}W^{-(L)} \,. \end{cases} \tag{2.12}$$

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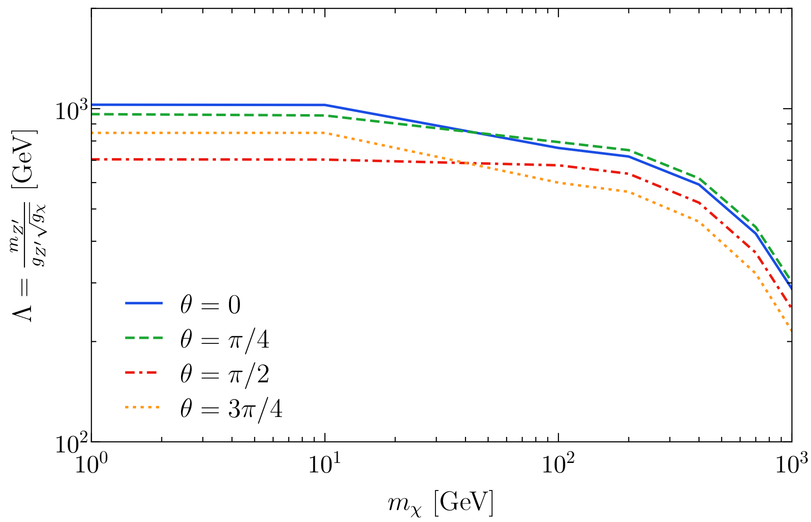

Figure 3. (*Replaces figure 3 of the original paper.*) Bounds on Λ for each value of θ from the monojet search.

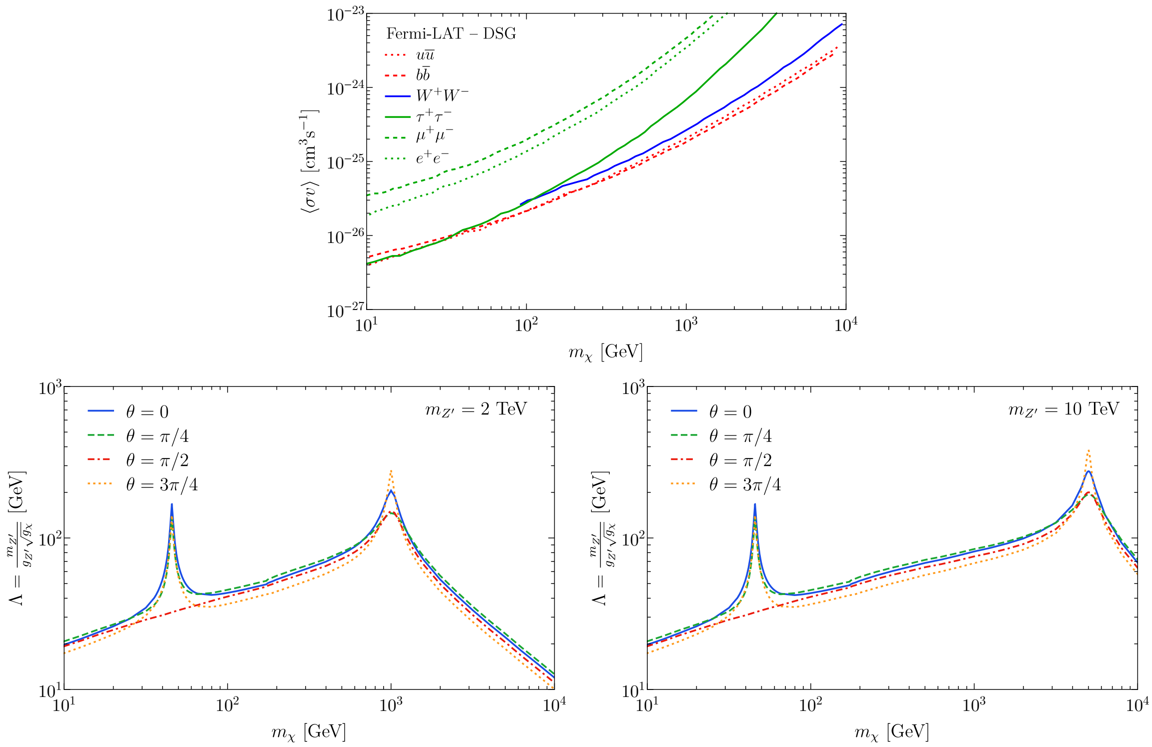

Figure 4. (*Replaces figure 5 of the original paper.*) *Top*: bounds on $\langle\sigma v\rangle$ from Fermi-LAT observations of dSph, assuming 100% BR in the channels shown in the legend. *Bottom*: bounds on $\langle\sigma v\rangle$ from Fermi-LAT observations of dSph in our model, for the four values of θ we have chosen, and for $m_{Z'} = 2\,\text{TeV}$ (*left*) and $10\,\text{TeV}$ (*right*).

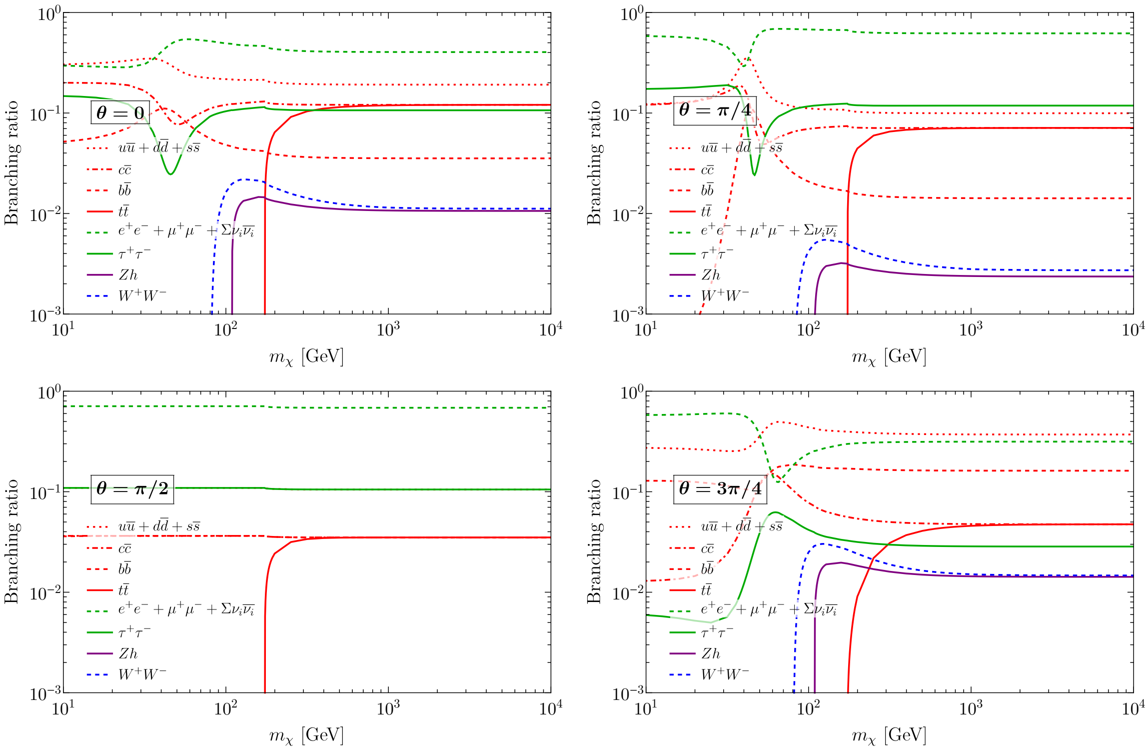

Figure 5. (*Replaces figure 6 of the original paper.*) Branching ratios for DM annihilations, for four different values of θ. Annihilation at different energies have the same behavior, given that all the channels are in p-wave, and the branching ratios are independent of $m_{Z'}$.

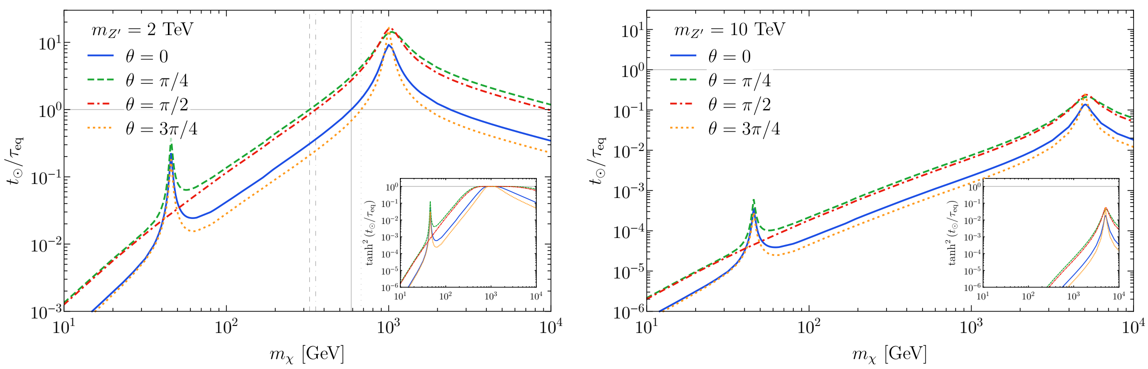

Figure 6. Ratio of the age of the Sun over the timescale for the reach of equilibrium between capture and annihilation of DM, for $m_{Z'} = 2\,\text{TeV}$ (*left*) and $10\,\text{TeV}$ (*right*). The ratio $t_\odot/\tau_{\rm eq}$ scales as Λ^{-4}.

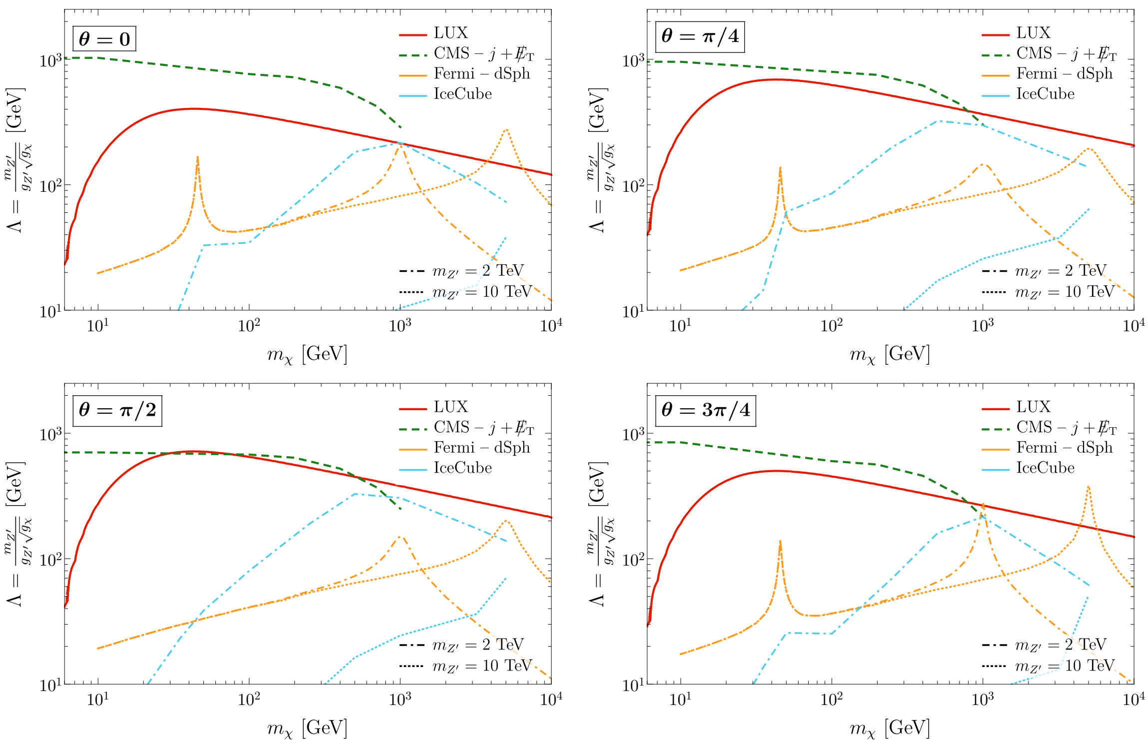

Figure 7. (*Replaces figure 7, 8 of the original paper.*) Exclusion limits for the four values of θ we consider. The bound on spin dependent cross section for $\theta = 0$ (as on figure 7 of the original paper) is not shown, since there is no such scattering. For the Fermi and IceCube bounds, we show two lines corresponding to $m_{Z'} = 2$ or 10 TeV.

Finally, the cross section for the tree level annihilation into Zh turns out to be

$$\sigma(\chi\chi \to Zh) = g_\chi^2 g_{Z'}^4 \cos^2\theta \, \frac{\sqrt{s-4m_\chi^2}\sqrt{s}}{6\pi} \, \frac{\sqrt{(s-(m_h^2+m_Z^2))^2-4m_h^2m_Z^2}\sqrt{m_Z^2(m_Z^2+\Gamma_Z^2)}}{m_{Z'}^2}$$
$$\times \frac{(m_{Z'}^2-m_Z^2)^2+(m_{Z'}\Gamma_{Z'}-m_Z\Gamma_Z)^2}{((s-m_{Z'}^2)^2+m_{Z'}^2\Gamma_{Z'}^2)((s-m_Z^2)^2+m_Z^2\Gamma_Z^2)} \times \begin{cases} 1 & \text{for } Z^{(T)}h \\ \frac{(s+m_Z^2-m_h^2)^2}{8sm_Z^2} & \text{for } Z^{(L)}h \end{cases} \tag{2.13}$$

and its asymptotic behaviour in the limit $m_{Z'}, m_\chi \gg m_Z, m_h$ is

$$\sigma(\chi\chi \to Zh) \sim \cos^2\theta \, \frac{\sqrt{s}\sqrt{s-4m_\chi^2}}{\max(s^2, m_{Z'}^4)} \times \begin{cases} \frac{m_Z^2}{s} & \text{for } Z^{(T)}h \\ 1 & \text{for } Z^{(L)}h\,. \end{cases} \tag{2.14}$$

The asymptotic expansions (2.10), (2.12), (2.14) of the cross sections show that all these annihilation channels are velocity suppressed, and explains why the branching ratios shown in figure 5 are basically independent of $m_{Z'}$.

Acknowledgments

We are grateful to Yanou Cui and Francesco D'Eramo for useful communication and for pointing us out the importance of the Z exchange.

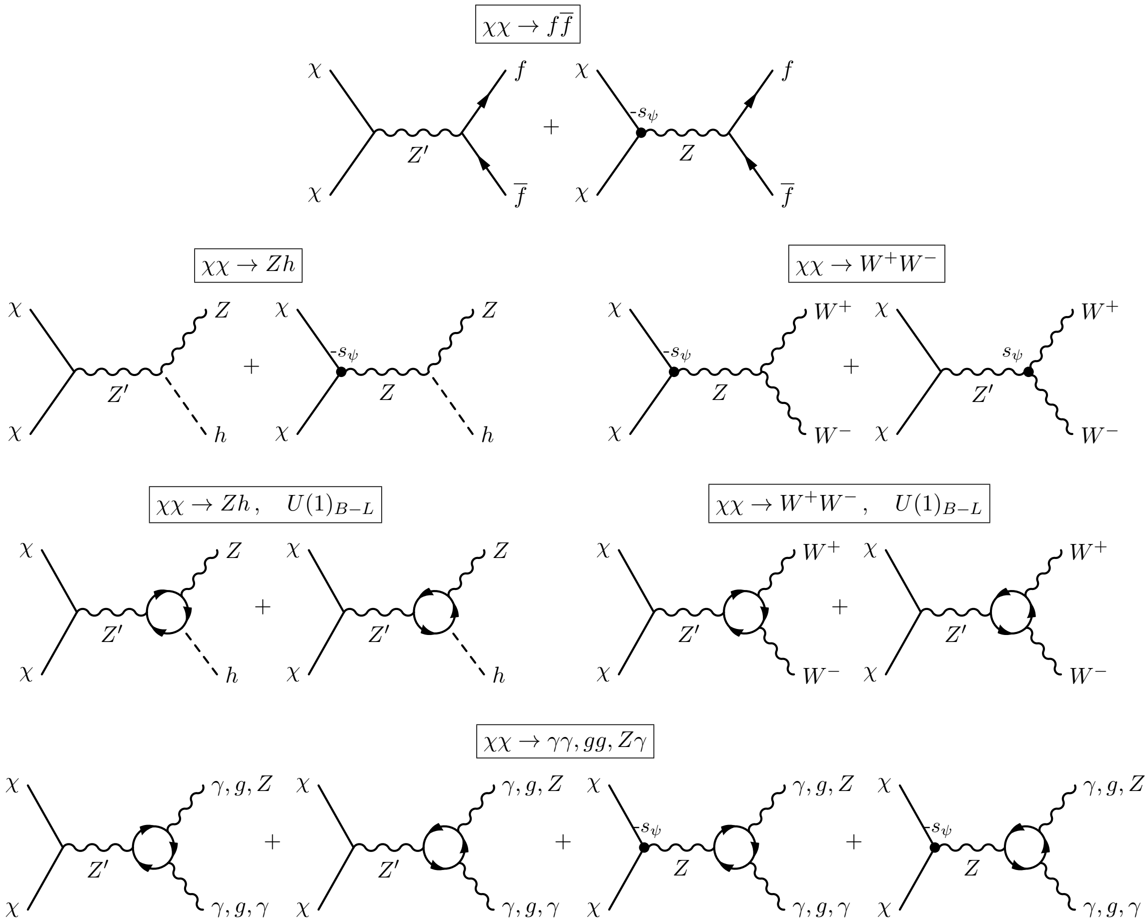

Figure 8. (*Replaces figure 9 of the original paper.*) Feynman diagrams for the annihilation channels $f\bar{f}$, Zh, W^+W^-, $\gamma\gamma$, gg, $Z\gamma$.

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