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Erratum: Gamma-ray boxes from axion-mediated dark matter

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Abstract. Here we report a mistake in the dark matter annihilation amplitudes presented in the published version of this work. In particular, we provide the corrected version of eqs. (3.4)–(3.6) and derive the corresponding repercussions on our results. None of our conclusions changes due to this correction.

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1 Corrected annihilation amplitudes

A mistake was detected in the squared amplitudes of the annihilation channels $\chi\bar{\chi} \to as, aa, ss$, i.e. in eqs. (3.4)–(3.6) of the published manuscript. Before giving the recalculated amplitudes, let us first generalise the annihilation cross section times velocity originally given in eqs. (3.1)–(3.3):

$$(\sigma v)_{ij} = \frac{1}{32\pi^2 \kappa s}\left(1 - \frac{(m_i - m_j)^2}{s}\right)^{1/2}\left(1 - \frac{(m_i + m_j)^2}{s}\right)^{1/2}\int d\Omega \overline{|\mathcal{M}|^2_{ij}} \qquad (3.1')\text{–}(3.3')$$

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with $\kappa = 1$ or 2 for the annihilation channels $ij = as$ or $ij = aa, ss$, respectively. For later convenience, instead of using the centre-of-mass energy $E_{\rm CM}$ and the transfer momentum q as in the published manuscript, we shall use throughout the Mandelstem variables s, t, u:

$$
\begin{aligned}
s &= 4m_\chi^2 \left(1 - \frac{v_{\rm rel}^2}{4}\right)^{-1} \simeq 4m_\chi^2 \left(1 + \frac{v_{\rm rel}^2}{4}\right) , \\
t &= \frac{1}{2} \left(m_i^2 + m_j^2 + 2m_\chi^2 - s\right) + \frac{v_{\rm rel}}{4} \cos\theta \Big[\left(m_i^2 - m_j^2 + s\right)^2 - 4 s m_i^2 \Big]^{1/2} \\
&\simeq \frac{1}{2} \left(m_i^2 + m_j^2 - 2m_\chi^2 - m_\chi^2 v_{\rm rel}^2\right) + \frac{v_{\rm rel}}{4} \cos\theta \Big[\left(m_i^2 - m_j^2 + 4m_\chi^2\right)^2 - 16 m_\chi^2 m_i^2 \Big]^{1/2} , \\
u &= \frac{1}{2} \left(m_i^2 + m_j^2 + 2m_\chi^2 - s\right) - \frac{v_{\rm rel}}{4} \cos\theta \Big[\left(m_i^2 - m_j^2 + s\right)^2 - 4 s m_i^2 \Big]^{1/2} \\
&\simeq \frac{1}{2} \left(m_i^2 + m_j^2 - 2m_\chi^2 - m_\chi^2 v_{\rm rel}^2\right) - \frac{v_{\rm rel}}{4} \cos\theta \Big[\left(m_i^2 - m_j^2 + 4m_\chi^2\right)^2 - 16 m_\chi^2 m_i^2 \Big]^{1/2} ,
\end{aligned}
$$

where $v_{\rm rel}$ is the Möller velocity and the approximate expressions are valid in the non-relativistic limit up to order $\mathcal{O}(v_{\rm rel}^2)$.

We now provide the recalculated squared amplitudes of the annihilation channels as, aa, ss originally given in eqs. (3.4)–(3.6):

$$
\overline{|\mathcal{M}|^2_{as}} = \frac{|\lambda_\chi|^4}{8} \frac{(t + u - 2m_\chi^2)^2}{(t - m_\chi^2)^2 (u - m_\chi^2)^2} \Big[\left(m_s^2 + m_\chi^2 - t\right) \left(m_s^2 + m_\chi^2 - u\right) - m_s^2\, s + 4 m_a^2 m_\chi^2 \Big] , \qquad (3.4')
$$

$$
\overline{|\mathcal{M}|^2_{aa}} = \frac{|\lambda_\chi|^4}{8} \left(\frac{1}{t - m_\chi^2} - \frac{1}{u - m_\chi^2} \right)^2 \Big[\left(m_a^2 + m_\chi^2 - t\right) \left(m_a^2 + m_\chi^2 - u\right) - m_a^2\, s \Big] , \qquad (3.5')
$$

$$
\begin{aligned}
\overline{|\mathcal{M}|^2_{ss}} = \frac{|\lambda_\chi|^4}{8} \frac{1}{(t - m_\chi^2)^2 (u - m_\chi^2)^2} \Big[&(u - t)^2 \Big(\left(m_s^2 + m_\chi^2 - t\right) \left(m_s^2 + m_\chi^2 - u\right) - m_s^2\, s \\
&+ 4 m_\chi^2 (t + u - 2m_\chi^2) \Big) + 4 m_\chi^2 (s - 4m_\chi^2)(t + u - 2m_\chi^2)^2 \Big] . \qquad (3.6')
\end{aligned}
$$

2 Repercussions on the published results

Let us examine how the above corrections impact our published results and figures. To begin with, using eqs. (3.1′)–(3.6′), the annihilation cross sections times velocity[1] for the three annihilation channels in the non-relativistic regime read

$$
\begin{aligned}
(\sigma v_{\rm rel})_{as} &\simeq \frac{|\lambda_\chi|^4}{64 \pi m_\chi^2} \frac{\left(m_a^2 - m_s^2 + 4m_\chi^2\right)^2}{\left(m_a^2 + m_s^2 - 4m_\chi^2\right)^2} \left(1 - \frac{(m_a - m_s)^2}{4m_\chi^2}\right)^{1/2} \left(1 - \frac{(m_a + m_s)^2}{4m_\chi^2}\right)^{1/2} , \\
(\sigma v_{\rm rel})_{aa} &\simeq \frac{|\lambda_\chi|^4}{96\pi} \frac{m_\chi^6}{\left(m_a^2 - 2m_\chi^2\right)^4} \left(1 - \frac{m_a^2}{m_\chi^2}\right)^{5/2} v_{\rm rel}^2 , \\
(\sigma v_{\rm rel})_{ss} &\simeq \frac{|\lambda_\chi|^4}{96\pi} \frac{m_\chi^2}{\left(m_s^2 - 2m_\chi^2\right)^4} \left(2 \left(m_s^2 - 2m_\chi^2\right)^2 + m_\chi^4\right) \left(1 - \frac{m_s^2}{m_\chi^2}\right)^{1/2} v_{\rm rel}^2 .
\end{aligned}
$$

Clearly, the process $\chi\bar{\chi} \to as$ is s-wave, whereas the processes $\chi\bar{\chi} \to aa$, ss are both p-wave. Therefore, the annihilation today ($v_{\rm rel} \sim 10^{-3}$) is largely dominated by the as channel if this

[1] Note that, unlike in the original eqs. (3.8)–(3.10), here we give the annihilation cross section times velocity without thermal average.

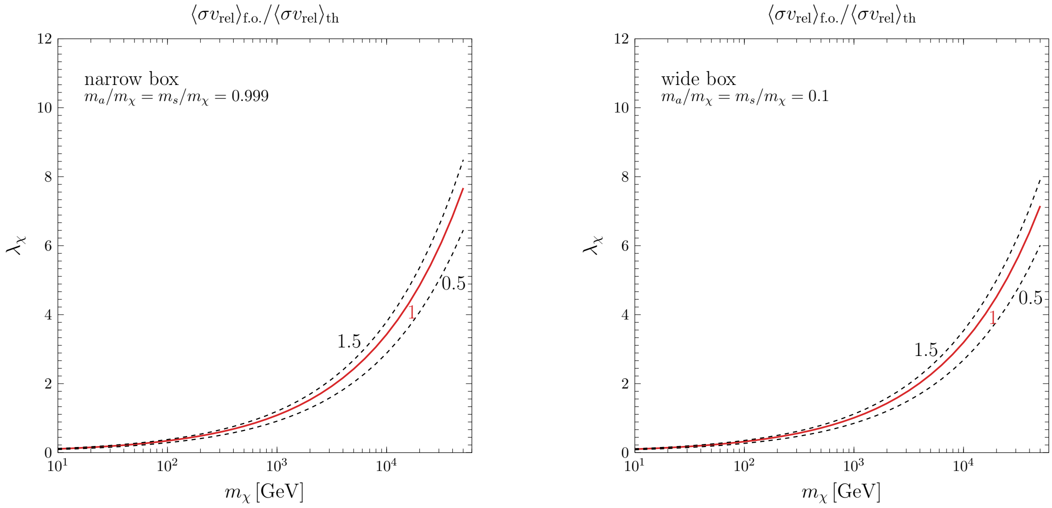

Figure 3′. Contours of the total annihilation cross section at freeze-out $\langle\sigma v\rangle_{\rm fo}$ in units of the thermal cross section for Dirac dark matter particles, $\langle\sigma v\rangle_{\rm th} = 6\times 10^{-26}\,{\rm cm^3\,s^{-1}}$, as a function of m_χ and λ_χ. The left (right) panel shows the narrow (wide) box scenario with $m_a/m_\chi = m_s/m_\chi = 0.999$ (0.1).

is kinematically accessible and, if not, by either the aa or the ss channels. Notice that, if the as channel is kinematically forbidden, either only the aa channel or only the ss channel are accessible. This renders figure 2 in the published version of our work obsolete — it should be replaced by a trivial figure where ${\rm BR}(\chi\bar\chi \to as, aa, ss) \simeq 1, 0, 0$ for $m_a + m_s < 2m_\chi$; ${\rm BR}(\chi\bar\chi \to as, aa, ss) \simeq 0, 1, 0$ for $m_a < m_\chi$ and $m_a + m_s > 2m_\chi$; and ${\rm BR}(\chi\bar\chi \to as, aa, ss) \simeq 0, 0, 1$ for $m_s < m_\chi$ and $m_a + m_s > 2m_\chi$.

The thermally averaged cross sections are obtained from the full cross section expressions eqs. (3.1′)–(3.6′) by applying the full averaging procedure (see, for instance, eq. (3.8) in ref. [1]) with a freeze-out temperature $T_{\rm fo} = m_\chi/25$. The repercussions of the corrections to the annihilation amplitudes on the thermal cross sections, i.e. on the published version of figures 3 and 4, are less dramatic than for the present branching ratios discussed above, but for completeness we provide here an updated version of both figures, see figures 3′ and 4′. All the comments to these figures in the published version of the work hold true.

Finally, we also update the gamma-ray spectrum expected for our narrow box and wide box scenarios, i.e. figure 6 in the published version. The corrected annihilation branching ratios and cross section ratios read ${\rm BR}(\chi\bar\chi \to as, aa, ss) \simeq 1, 0, 0$ and $\langle\sigma v\rangle_0/\langle\sigma v\rangle_{\rm fo} \simeq 0.238$ for the narrow box ($m_\chi = 250\,{\rm GeV}, m_s = m_a = 249.75\,{\rm GeV}$), and ${\rm BR}(\chi\bar\chi \to as, aa, ss) \simeq 1, 0, 0$ and $\langle\sigma v\rangle_0/\langle\sigma v\rangle_{\rm fo} \simeq 1.013$ for the wide box ($m_\chi = 150\,{\rm GeV}$, $m_a = m_s = 15\,{\rm GeV}$). The updated plots are shown in figure 6′. Note that the original figure 5, which shows the limits for the annihilation channel $\chi\bar\chi \to aa$, still holds true since it is model-independent. However, for the benchmark models discussed above the only relevant channel is now $\chi\bar\chi \to as$; the model-independent limits for this channel are a factor 2 weaker than the ones plotted in the original figure 5 (assuming $m_s = m_a$).

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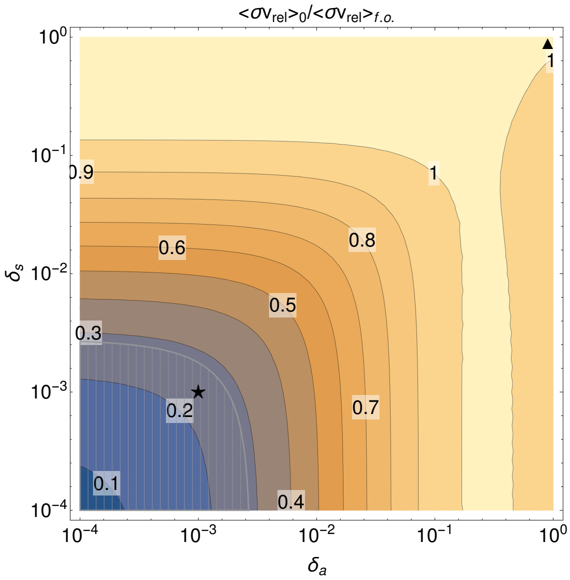

Figure 4′. Contours of the ratio of the present to thermal total annihilation cross sections $\langle\sigma v\rangle_0/\langle\sigma v\rangle_{\rm fo}$ as a function of $\delta_a \equiv (m_\chi - m_a)/m_\chi$ and $\delta_s \equiv (m_\chi - m_s)/m_\chi$. The hatched region marks the parameter space where the width of the box is 10% or less than the maximum energy of the photons. We also show the location of our exemplary points with $m_a/m_\chi = m_s/m_\chi = 0.999$ for the narrow box scenario (★) and 0.1 for the wide box scenario (▲).

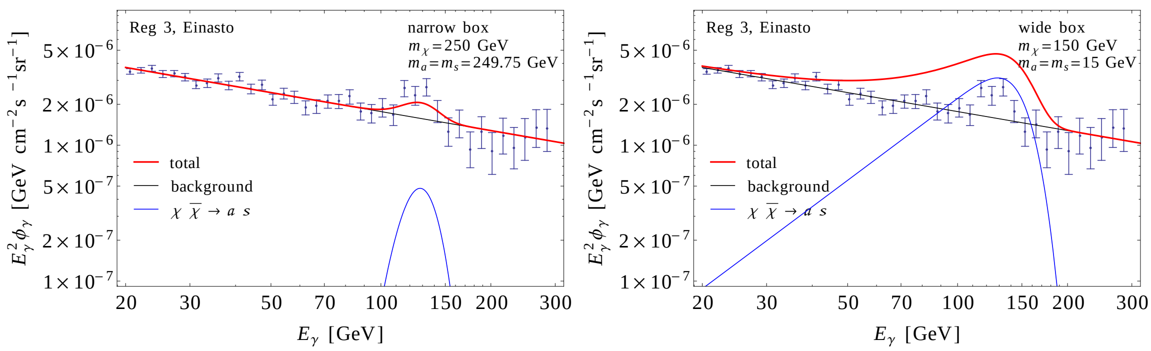

Figure 6′. Predicted gamma-ray spectrum for a narrow box scenario with $m_\chi = 250\,\text{GeV}$, $m_s = m_a = 249.75\,\text{GeV}$ assuming $c_1/c_2 = 3$ (left) and for a wide box scenario with $m_\chi = 150\,\text{GeV}$, $m_a = m_s = 15\,\text{GeV}$ (right). In both panels, the dark matter coupling λ_χ is determined as a function of dark matter mass by the thermal annihilation cross section $\langle\sigma v\rangle_{\rm th} = 6\times10^{-26}\,\text{cm}^3\,\text{s}^{-1}$ (see figure 3′) and the present annihilation cross section follows from figure 4′. The branching ratio for the different annihilation channels and the branching ratios for the axion decay are predicted by the model, see text. The background flux is assumed to be a power law in the energy range shown and has been chosen to fit the data below 70 GeV (black line).

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