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Erratum: Lightest sterile neutrino abundance within the νMSM

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The following corrections should be implemented in the formulae. In eq. (3.6), the two factors $\frac{3}{4}$ should be replaced with $\frac{1}{2}$. In table 1, the factor $\frac{9}{4}$ should be replaced with $\frac{3}{2}$, and the factor $-\frac{3}{4}$ with $-\frac{1}{2}$. In addition, in eqs. (3.7) and (3.8), one should switch $a_{\rm L} \leftrightarrow a_{\rm R}$, which implies $b \to -b$, $d \to -d$. The numerical effect of these corrections on $\text{Im}\,\Sigma$ can be up to $\sim 25\%$ at $T < 20\,\text{MeV}$ for $\alpha = 1$, but is only on the few percent level at $T > 100\,\text{MeV}$. The effect on the right-handed neutrino production rate is thus much smaller than hadronic uncertainties at $T > 100\,\text{MeV}$.

The reason for the last correction is subtle. Given that weak interactions of Standard Model neutrinos take place through vertices with the Dirac structure $\sim \gamma^\mu a_{\rm L}$, where $a_{\rm L} \equiv (1-\gamma_5)/2$ is a chiral projector, their inverse propagator is of the form [52]

$$S^{-1}(Q) = a_{\rm R} \left(\not{Q} + \not{\Sigma} \right) a_{\rm L} \,. \tag{1}$$

Because of the chiral projectors, the (retarded) self-energy can be expressed as

$$\not{\Sigma} = a \not{Q} + b \not{u} \,, \tag{2}$$

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where a, b are complex functions. With this form, the left-handed neutrino propagator reads [52]

$$S(Q) = a_{\rm L} \frac{(1+a)\,\not{Q} + b\,\not{u}}{[(1+a)\,Q + b\,u]^2}\, a_{\rm R}\,. \tag{3}$$

It is this propagator which plays a role in our expressions. However, the imaginary parts of a, b originate at 2-loop level and then $\not{\Sigma}$ has a chiral structure which is *not* trivially of the form in eq. (2). For instance, hadronic effects contain a phase space integral (cf. eq. (3.4))

$$\begin{aligned} {\rm Im}\,\not{\Sigma} &\propto \int {\rm d}\Omega_{2\to 2}\ \gamma^\mu \not{P}_1 \gamma^\nu\ {\rm Tr}\left[\not{P}_2\,\gamma_\mu\,\not{P}_3\,\gamma_\nu\,a_{\rm L}\right] \\ &= 8 \int {\rm d}\Omega_{2\to 2} \left(P_1\cdot P_2\,\not{P}_3\,a_{\rm R} + P_1\cdot P_3\,\not{P}_2\,a_{\rm L}\right), \end{aligned} \tag{4}$$

where ${\rm d}\Omega_{2\to 2}$ denotes a phase space measure including appropriate initial or final state Fermi distributions, and P_1, P_2 and P_3 are four-momenta of the associated particles. Now, when considered in the context of eq. (1), the part containing $a_{\rm R}$ gets projected out. In contrast, if the full $\not{\Sigma}$ were inserted into the numerator of eq. (3) (which is inconsistent), the part containing $a_{\rm L}$ would get projected out. In order to get correct results, it is important to *first* take the projection that sets the self-energy in the form of eqs. (1), (2).

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