Dark Matter

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Exercise sheet 2

Problem 5: Relic density calculations with DarkSUSY

For concreteness, let us consider a simple toy model of DM composed of Dirac fermions ψ that couples to the standard model only via the 5D operator

$$\mathcal{L} \supset \Lambda^{-1} \bar{\psi} \psi \, |H|^2 \,, \tag{1}$$

where H is the SM Higgs doublet and Λ is a parameter with mass dimension one.

1. Compare this to the Scalar singlet model (see, e.g., Appendix D in the DarkSUSY paper) and convince yourself that the same type of diagrams are relevant in this case in order to describe DM annihilation. Concretely, how does Eq. (D.3) change? For the purpose of this exercise, you can assume that (D.5) receives the same overall modification (this is just an approximation, and with more time available you could of course compute the correction exactly).

2. Modify the ScalarSinglet model that ships with the code such that you can use it to compute annihilations for the model given in Eq. (1) instead; try to do this *without modifying the downloaded code*, i.e. by using the concept of replaceable functions (see the tutorial for details). Compare the value of Λ, as a function of m_ψ, that is necessary to obtain the correct relic density with the corresponding value of the coupling λ in the ScalarSinglet model.
   [Hints: (i) Take a look at src_models/silveira_zee/an/dssigmavpartial.f. *(ii) Is the DM particle still self-conjugate in this model? How about the internal degrees of freedom? Try to identify where these changes need to be implemented.]*

3. Compute the value of $\langle \sigma v \rangle$ at freeze-out in the model above and compare it to *(i)* the corresponding value in the ScalarSinglet model and *(ii)* the corresponding value of the generic_wimp model. What do you notice?
   [Hint: Take a look at examples/aux/ScalarSinglet_thermal_averages.f.*]*

Problem 6: More advanced numerical relic density calculations

You are now in a very good position to numerically explore further avenues of DM production that were discussed in the lecture. For example:

- Compute the value of Λ, again as a function of m_ψ, that is necessary to obtain the correct relic density for *freeze-in* production!

- Back to freeze-out calculations, it was mentioned in the lecture that the standard Boltzmann equation potentially breaks down close to resonances, due to *early kinetic decoupling*. In the model considered here, explore by how much the value of $\Omega_\psi h^2$ calculated in the standard approach can be off for $m_\psi \lesssim m_h/2$!

- Now replace $|H|^2 \to \phi^2$ in Eq. (1), where ϕ is a scalar particle in an otherwise completely decoupled *dark sector*. Assume that $m_\phi \ll m_\psi$ and that the dark sector and the SM were in equilibrium for $T > T_c$ (e.g. through a $|H|^2 \phi^2$ term in $\mathcal{L}$), with $T_c \gg m_\psi$, but that $T_\chi \neq T$ for $T < T_c$. Compute the value of Λ necessary to provide the correct relic density in this case!

For all these problems, you can find simple demonstration programs in examples/aux *that will guide you in the correct direction. Note that most likely the time of the exercises will not suffice to attempt even one of the above suggestions – so they are really only meant as an indication of what you could try for further exploring the code. If at any point, even after the school, you have questions about this – please don't hesitate to get in touch!*