Introduction to Strongly Interacting Massive Particles (SIMP) as dark matter candidates

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The SIMP miracle

Idea: let us consider a new scenario in which the observed abundance of relic dark matter (DM) is determined not by $2 \to 2$ annihilation into Standard Model (SM) particles like in the well-known WIMP scenario, but by the 5-point $3 \to 2$ process within the secluded dark sector, i.e. by the DM self-interactions! [1]

The number density of the DM particles n_χ follows Boltzmann equation :

$$\frac{\partial n_\chi}{\partial t} + 3Hn_\chi = -\left\langle \sigma v^2 \right\rangle_{3\to 2}\left(n_\chi^3 - n_\chi^2 n_\chi^{\rm eq}\right),$$

where the thermally averaged cross section can be parametrised as $\left\langle \sigma v^2 \right\rangle_{3\to 2} \equiv \alpha_{\rm eff}^3 / m_\chi^5$. The $3 \to 2$ process plays an important role as long as the DM particles are close enough. While the Universe expands the particles become so diluted so that interaction no more happens.

The number density *freezes out* and then follows the $n_\chi \sim a(t)^{-3}$ law. The freeze-out time can be estimated as follows:

$$\Gamma_{3\to 2} \sim n_\chi^2(T_F)\left\langle \sigma v^2 \right\rangle_{3\to 2} \sim H(T_F).$$

Tracing back n_χ from the matter-radiation equality ($T_{\rm eq} \sim 0.8$ eV), assuming that at the time of freeze-out the Universe in the radiation domination phase, i.e. $H(T_F) \sim m_\chi^2/(x_F^2 M_{\rm Pl})$, and $x_F \sim 20$ we get the estimate for the mass of DM particle:

$$m_\chi \sim \alpha_{\rm eff}\left(T_{\rm eq}^2 M_{\rm Pl}\right)^{1/3} \sim \alpha_{\rm eff} \cdot (100 \text{ MeV}).$$

We conclude that if $\alpha_{\rm eff} \sim O(1)$, i.e. of the order of the strong coupling, then we arrive to the strong-scale mass. DM models with such masses are less constrained by direct detection experiments.

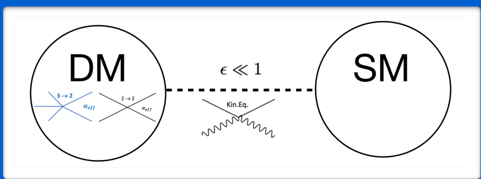

Figure 1: Reproduced from [1]. SIMP paradigm.

Coupling to SM

The dark sector can not be completely secluded, otherwise $3 \to 2$ process heats it up altering structure formations. To keep the dark sector in thermal equilibrium with SM particles $2 \to 2$, elastic scattering should exist. This process should be active during $3 \to 2$ freeze out, however, the connected (via the crossing symmetry) $2 \to 2$ annihilation must be subdominant:

$$\frac{\Gamma_{\rm cool}}{\Gamma_{3\to 2}}(T_F) \gtrsim 1, \quad \frac{\Gamma_{\rm ann}}{\Gamma_{3\to 2}}(T_F) \lesssim 1.$$

The SM particles can be coupled to the dark sector via the dark photon portal: the gauge field of an additional dark $U(1)_V$ symmetry couples kinetically to the $U(1)_Y$ gauge boson, i.e. $\mathscr{L} \supset -B_{\mu\nu}\mathscr{A}^{\mu\nu}$ [3].

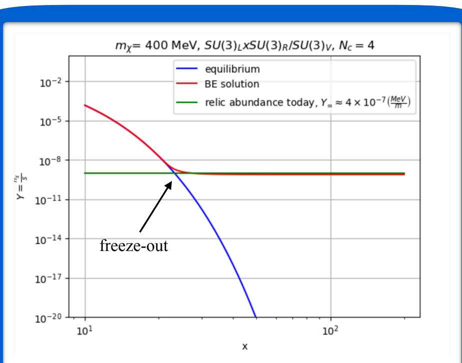

Figure 3: Solution of the Boltzmann equation in terms of DM yield Y. Freeze-out of the $3 \to 2$ process happens at $x_F \approx 15$. After the freeze-out the yield is constant.

Pionic QCD-like DM

Let us consider a dark sector charged under $SU(N_c)$ gauge theory with N_f flavours of dark quarks with degenerate mass [2]. The theory performs a $SU(N_f)_L \times SU(N_f)_R \to SU(N_f)_V$ symmetry breaking leading to appearance of $N_f^2 - 1$ pseudo-Goldstone-bosons: dark pions. Like in low-energy QCD, where a 5-point interaction $K^+K^- \to \pi^+\pi^-\pi^0$ exists, the dark pions can undergo $3 \to 2$ annihilation via the topological Wess-Zumino-Witten term:

$$\mathscr{L}_{\rm WZW} = \frac{N_c}{15\pi^2 f_\pi^5}\epsilon^{\mu\nu\rho\sigma}{\rm Tr}\left(\pi\partial_\mu\pi\partial_\nu\pi\partial_\rho\pi\partial_\sigma\pi\right), \quad \pi = \pi^a T^a.$$

The self-scattering $2 \to 2$ cross-section is determined by the ratio m_χ/f_π which, in turn, is defined by the relic abundance.

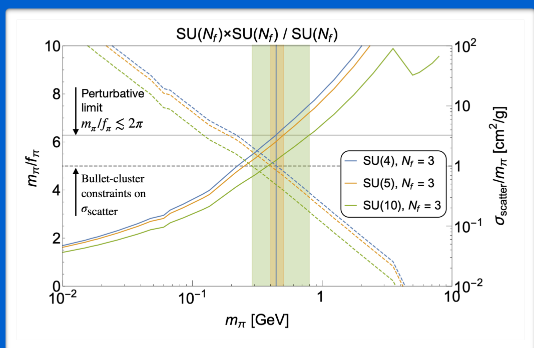

Figure 2: Reproduced from [2]. Solid curves: m_π/f_π is given for every m_π so that the correct relic abundance is obtained as a result of solving the Boltzmann equation. Dashed curves: the self-scattering cross section $\sigma_{\rm scatter}/m_\pi$ as function of m_π.

References

1) Y. Hochberg, E. Kuflik, T. Volansky and J. G. Wacker, Phys. Rev. Lett. **113**, 171301 (2014)
2) Y. Hochberg, E. Kuflik, H. Murayama, T. Volansky and J. G. Wacker, Phys. Rev. Lett. **115**, 021301 (2015)
3) Y.Hochberg, SciPost Phys. Lect. Notes 59 (2022)
4) Y. Hochberg, E. Kuflik and H. Murayama, J. High Energy Phys. **05**, 090 (2016)