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Ultra-relativistic freeze-out: a bridge from WIMPs to FIMPs

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We re-examine the case for cold dark matter (DM) produced by ultra-relativistic freeze-out (UFO). UFO is the mechanism by which Standard Model (SM) neutrinos decouple from the radiation bath in the early universe at a temperature $T_d \approx 1$ MeV. This corresponds to chemical freeze-out without Boltzmann suppression, such that the freeze-out (decoupling) temperature T_d is much greater than m_ν and the neutrinos are therefore ultra-relativistic at freeze-out. While UFO has historically been rejected as a viable mechanism for DM production due to its association with hot DM and the accompanying incompatibility with ΛCDM, we show that when the approximation of instantaneous reheating after inflation is lifted, UFO can produce cold DM and account for the entire observed relic density in large regions of parameter space, without invoking exotic cosmological histories. In fact, DM with masses ranging from sub-eV to PeV scales can undergo UFO and be cold before structure formation, given only a simple perturbative, post-inflationary reheating period prior to radiation domination. We demonstrate that for some interactions, such as a contact interaction between the Higgs and DM scalars, there is a seamless transition between the WIMP and FIMP regimes which excludes UFO. However, for many other interactions, such as SM fermions producing fermionic DM via a heavy scalar or vector mediator, the WIMP to FIMP transition occurs \textit{necessarily} via a large intermediate region corresponding to UFO. This mechanism is highly robust and does not require fine tuning. In particular, we find that UFO during reheating can produce the correct relic density ($\Omega_\chi h^2 = 0.12$) for DM masses spanning about 13 orders of magnitude, reheating temperatures spanning 17 orders of magnitude, and beyond the Standard Model (BSM) effective interaction scales spanning 11 orders of magnitude. Finally, we identify an important distinction between UV and IR UFO, where the relic abundance for the former is determined by the freeze-out temperature, while the latter is sensitive to $T_{\rm RH}$ and m_χ but not the freeze-out temperature.

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