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Nonthermal heavy dark matter from a first-order phase transition

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We study nonthermal production of heavy dark matter from the dynamics of the background scalar field during a first-order phase transition, predominantly from bubble collisions. In scenarios where bubble walls achieve runaway behavior and get boosted to very high energies, we find that it is possible to produce dark matter with mass several orders of magnitude above the symmetry breaking scale or the highest temperature ever reached by the thermal plasma. We also demonstrate that the existing formalism for calculating particle production from bubble dynamics in a first-order phase transition is not gauge invariant, and can lead to spurious results. Thus, we provide a practical prescription for the computation that avoids unphysical contributions and should provide reliable order-of-magnitude estimates of this effect. Furthermore, we point out the importance of three-body decays of the background field excitations into scalars and gauge bosons, which provide the dominant contributions at energy scales above the scale of symmetry breaking. Using our improved results, we find that scalar, fermion, and vector dark matter are all viable across a large range of mass scales, from O(10) TeV to a few orders of magnitude below the Planck scale, and the corresponding phase transitions can be probed with current and future gravitational wave experiments.

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