Contribution ID: **17** Type: **not specified**

Signatures of Non-thermal Dark Matter with Kination and Early Matter Domination: Gravitational Waves versus Laboratory Searches

Thursday, September 22, 2022 4:50 PM (20 minutes)

The non-thermal production of dark matter (DM) usually requires very tiny couplings of the dark sector with the visible sector and therefore is notoriously challenging to hunt in laboratory experiments. Here we propose a novel pathway to test such a production in the context of a non-standard cosmological history, using both gravitational wave (GW) and laboratory searches. We investigate the formation of DM from the decay of a scalar field that we dub as the reheaton, as it also reheats the Universe when it decays. We consider the possibility that the Universe undergoes a phase of kination (w_kin >1/3) before the reheaton dominates the energy density of the Universe and eventually decays into Standard Model and DM particles. We then study how first-order tensor perturbations generated during inflation, the amplitude of which may get amplified during the kination era and lead to detectable signals at the GW detectors such as LISA, ET, u-DECIGO, BBO, etc. Demanding that the reheaton produces the observed DM relic density, we show that the reheaton's lifetime and branching fractions are dictated by the cosmological scenario we show that it is long-lived and can be searched in DUNE, FASER, FASER-II, MATHUSLA, SHiP, etc. experiments and identify the parameter space where one may complement with the detectable GW signals. In particular we find that a kination-like period with an equation-of-state parameter w_kin ~ 0.5 and a reheaton mass O(0.5–5) GeV and a DM mass of O(10-100) keV may lead to sizeable imprints in both kinds of searches satisfying Big Bang Nucleosynthesis (BBN) constraints.

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Session Classification: Session 3 (late pm)