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Radiative Symmetry Breaking, Freeze-In Dark Matter and Gravitational Waves in a Scale-Invariant $U(1)_{L_\mu - L_\tau}$ Model

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We present ongoing work on a classically scale-invariant extension of the Standard Model based on the anomaly-free gauge symmetry $U(1)_{L_\mu - L_\tau}$. The model contains a complex scalar, responsible for the radiative breaking of the new gauge symmetry through the Gildener-Weinberg mechanism, a real singlet scalar, and a vector-like Dirac fermion playing the role of dark matter. The vacuum expectation value of the complex scalar induces the singlet vacuum through a scalar portal, leading dynamically to the dark-matter mass.

We discuss the resulting symmetry-breaking pattern, scalar and gauge spectra, and the main mechanisms for freeze-in production, including vector and scalar decays, scattering processes, and possible cascade production. Particular attention is given to the thermalization of the mediator states and to the impact of the phase transition and reheating on the final relic abundance. We also outline the connection with first-order phase-transition gravitational-wave signatures. The present contribution summarizes the theoretical setup and preliminary progress toward a complete phenomenological analysis.

Primary author(s) : ARTEAGA TUPIA, Martín Dionisio (PUCP / ULIMA)

Co-author(s) : RIVERA GAMBINI, Guillermo Gerardo (Universidad Nacional de Ingenieria); NETO, Jacinto Paulo (IIP, Natal - Brasil); SILVA MALPARTIDA, Javier (PUCP)

Presenter(s) : ARTEAGA TUPIA, Martín Dionisio (PUCP / ULIMA)

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