DOCTORAL DEFENSE

Particle Dynamics in Cosmological Spacetime

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Abstract: This thesis studies the evolution of quantum fields in the curved spacetime of the expanding early universe, focusing on applications to the pressing, open questions of cosmology, with special concentration on particle theories of dark matter. In particular the processes of particle production and decay are analyzed in detail.

The usual, static spacetime calculation of particle decay rates proceeds by a perturbative approach which supposes global energy conservation, a property not manifest in an expanding universe. We therefore demonstrate how the decay law of scalar particles decaying during the radiation dominated epoch of a standard cosmological model can be obtained by introducing an adiabatic approximation valid for degrees of freedom with typical wavelengths much smaller than the particle horizon at a given time. Furthermore, this decay law is calculated, treating the cosmological expansion consistently, through non-perturbative methods borrowed from quantum optics and adapted for cosmology. Both scalar to scalar and scalar to fermion (with Yukawa couplings) decays are studied within this framework. The effects of cosmic expansion, such as cosmic redshift and the confluence of time-dependent particle frequencies with a renormalizable theory, both of which lead to salient differences from the usual static spacetime results, are highlighted. In particular, we suggest implications for very long-lived particles (such as DM) and baryogenesis.

We also present the results of our study of non-adiabatic cosmological production of dark matter. By stipulating that the dark matter be described by a spectator field in its Bunch-Davies vacuum state during inflation and concentrating on modes outside the particle horizon at the onset of radiation domination, the particle production for scalar dark matter, considering both minimal and conformal coupling to gravity, and fermionic dark matter is analytically computed. In all cases, the distribution of produced particles is peaked at low comoving momentum, self-consistent with the consideration of superhorzion modes. We obtain the full energy momentum tensor, show explicitly its equivalence with the fluid-kinetic one in the adiabatic regime, and extract the abundance, equation of state and free streaming length (cutoff in the matter power spectrum) for the dark matter. For both fermions and minimally coupled scalars, this production mechanism yields a cold dark matter particle consistent with astronomical observations, without any coupling to Standard Model species, and with solely gravitational interactions. Thus these models represent theories of the *darkest* of dark matter. We argue that the abundance from non-adiabatic production yields a lower bound on generic scalar (ULDM) and axion-like particles (ALP) that must be included in any assessment of (ULDM)/(ALP) as a dark matter candidate. For fermions, we highlight how this production surprisingly leads to a nearly thermal distribution with an emergent temperature; a result which warrants further analysis.