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Reevaluating the cosmological redshift: insights into inhomogeneities and irreversible processes

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Understanding the expansion of the Universe remains a profound challenge in fundamental physics. The complexity of solving General Relativity equations in the presence of intricate, inhomogeneous flows has compelled cosmological models to rely on perturbation theory in a homogeneous FLRW background. This approach accounts for a redshift of light encompassing contributions from both the cosmological background expansion along the photon's trajectory and Doppler effects at emission due to peculiar motions. However, this computation of the redshift is not covariant, as it hinges on specific coordinate choices that may distort physical interpretations of the relativity of motion.
In this study, we show that peculiar motions, when tracing the dynamics along time-like geodesics, must contribute to the redshift of light through a local volume expansion factor, in addition to the background expansion. By employing a covariant approach to redshift calculation, we address the central question of whether the cosmological principle alone guarantees that the averaged local volume expansion factor matches the background expansion.
We establish that this holds true only in scenarii characterized by a reversible evolution of the Universe, where inhomogeneous expansion and compression modes mutually compensate. In the presence of irreversible processes, such as the dissipation of large-scale compression modes through matter virialization and associated entropy production, the averaged expansion factor becomes dominated by expansion in voids that cannot be compensated anymore by compression in virialized structures. Furthermore, a Universe where a substantial portion of its mass has undergone virialization, adhering to the background evolution on average leads to significant violations of the second law of thermodynamics. Our approach shows that entropy production due to irreversible processes during the formation of structures plays the same role as an effective, time-dependent cosmological constant, i.e. dynamical dark energy, without the need to invoke new unknown physics. Our findings underscore the imperative need to reevaluate the influence of inhomogeneities and irreversible processes on cosmological models, shedding new light on the intricate dynamics of our Universe.

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