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Tracking the validity of the quasi-static and sub-horizon approximations in modified gravity

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Within the framework of modified gravity, the quasi-static and sub-horizon approximations are widely used in analyses aiming to identify departures from the concordance model at late-times. In general, it is assumed that time derivatives are subdominant with respect to spatial derivatives given that the relevant physical modes are those well inside the Hubble radius. In practice, the perturbation equations under these approximations are reduced to a tractable algebraic system in terms of the gravitational potentials and the perturbations of involved matter fields. Here, in the framework of $f(R)$ theories, we revisit standard results when these approximations are invoked using a new parameterization scheme that allows us to track the relevance of each time-derivative term in the perturbation equations. This new approach unveils correction terms which are neglected in the standard procedure. We assess the relevance of these differences by comparing results from both approaches against full numerical solutions for two well-known toy-models: the designer $f(R)$ model and the Hu-Sawicki model. We find that: i) the sub-horizon approximation can be safely applied to linear perturbation equations for scales $0.06\,h/\mathrm{Mpc}$
$lesssimk$
$lesssim0.2\,h/\mathrm{Mpc}$, ii) in this "safety region", the quasi-static approximation provides a very accurate description of the late-time cosmological dynamics even when dark energy significantly contribute to the cosmic budget, and iii) our new methodology performs better than the standard procedure, even for several orders of magnitude in some cases. Although, the impact of this major improvement on the linear observables is minimal for the studied cases, this does not represent an invalidation for our approach. Instead, our findings indicate that the perturbation expressions derived under these approximations in more general modified gravity theories, such as Horndeski, should be also revisited.

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