Title:	Dark Energy Perturbations beyond Linear Perturbation Theory
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Abstract:	Two of the most prominent challenges for modern cosmology are dark matter and dark energy. Observations show that rate of expansion of the Universe is increas- ing. Our current theory of gravitation: Einstein's General Relativity (GR) cannot account for this accelerated expansion if the Universe contains only normal mat- ter and radiation. For GR to explain this late time acceleration, one needs to assume the presence of a new constituent in the energy budget. This constituent is dubbed "Dark Energy (DE)" and needs to have unusual properties like negative pressure. A number of DE models have been proposed. The "standard" model of cosmology (ΛCDM) has the Cosmological Constant (Λ), that acts as dark energy with a constant density and pressure. In contrast, there are theories of dark energy e.g. quintessence, chaplygin gas, tachyonic field, k-essence, etc. where density and pressure can vary in space-time. Although, ΛCDM is consistent with data, theo- retical basis of such a constant is problematic. There are issues like the fine-tuning problem, coincidence problem, etc. This provides motivation for models beyond Λ. Methods need to be developed that can help distinguish between these models. Study of perturbations can help achieve this as perturbations might evolve differ- ently in different models. Perturbations are studied at varying levels of approxi- mation, e.g., linear theory approximation, spherical/ellipsoidal symmetry, N-body simulations, etc. This sets the context for this thesis. In this thesis, we study perturbations in scalar field based dark energy models: quintessence and tachy- onic fields. We do relativistic, spherically symmetric simulations for both fields, with minimal assumptions. We derive equations in spherically symmetry, start- ing directly from action, without imposing any additional limitation on clustering properties of dark energy. We numerically calculate the evolution of this system for several lengthscales for initially overdense and underdense halos. We find that, even though we start with a homogeneous scalar field, perturbations are induced in quintessence because of minimal coupling. Induced perturbations grow with time but the amplitude remains small even when matter perturbations become nonlinear. DE density and equation of state (w) become functions of space-time. We also show that at late times, perturbation growth rate is slightly faster than that predicted by linear theory. Dark energy perturbations are stronger in large voids. Length scales play an important role as perturbations at large scales show faster growth for the same dark matter perturbation amplitude. We also study the prospects of distinguishing these two models using results from spherical collapse and linear perturbation theory. For the purpose of comparison between models we need methods of reconstructing potentials to reproduce a given expansion his- viitory. For quintessence and tachyonic fields we reconstruct potentials for a given w(z). We show that closed form expressions for V (φ) can be obtained only for a limited classes of w(z). We derive the necessary equations and then outline a numerical schema for reconstructing potentials for any general w(z). This scheme is based on numerical interpolation technique of cubic splines. We also reconstruct potential for a coupled quintessence model, where background expansion mimics the ΛCDM model. A unique investigation that we carry out is this: if the back- ground cosmology for two different models is tuned exactly, so that observations like supernovae cannot distinguish these, can the two models be distinguished by perturbations (linear and spherically symmetric nonlinear)? We do a system- atic comparison of quintessence and tachyonic scalar fields. This is done using methodologies for reconstruction of potentials for two field models, given a partic- ular background expansion. This allows us to delineate differences coming from different background and those coming from differences in dynamics of pertur- bations, owing to different nature of Lagrangians for quintessence and tachyonic models. We find that differences in dark matter and metric perturbations are weak and dependent on deviation of background from $w = -1$. Expansion his- tories that deviate significantly from Λ or $w = -1$, show large differences while models close to $w = -1$ show very little difference. Dark energy perturbations do show differences between the two classes of models, but these remain too weak to affect the metric/matter fluctuations. For the background expansions constrained by current data, the prospects of distinguishing models just on the basis of per- turbations are not promising. We also consider the question of distinguishing tachyonic and quintessence mod- els with the same expansion history using Cosmological (Linear) Perturbation Theory. We show that while dark energy perturbations show differences, these are insignificant for effects on observables. Consistent with results from previous chapter, we find that for expansion histories allowed by data, distinguishing two models is extremely difficult on the basis of dark energy perturbations. To vali- date this result, we use parametric form for effective speed of sound for tachyonic and quintessence models, modify CMB code CLASS, and try to constrain these parameters. We find that the parameters remain unconstrained by present data. We also use CMB data to constrain common tachyonic models.
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