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Cosmic growth and expansion conjoined

Eric V. Linder*

[a] Berkeley Center for Cosmological Physics & Berkeley Lab, University of California, Berkeley, CA 94720, USA
[b] Energetic Cosmos Laboratory, Nazarbayev University, Astana 010000, Kazakhstan

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ABSTRACT

Cosmological measurements of both the expansion history and growth history have matured, and the two together provide an important test of general relativity. We consider their joint evolutionary track, showing that this has advantages in distinguishing cosmologies relative to considering them individually or at isolated redshifts. In particular, the joint comparison relaxes the shape degeneracy that makes $f\sigma_8(z)$ curves difficult to separate from the overall growth amplitude. The conjoined method further helps visualization of which combinations of redshift ranges provide the clearest discrimination. We examine standard dark energy cosmologies, modified gravity, and "stuttering" growth, each showing distinct signatures.

1. Introduction

The histories of the expansion of the universe and the growth of large scale structures within it are key observables that provide insights into the cosmological model. In particular, within general relativity the two are tightly tied together, even more so within models close to the concordance cosmological constant plus cold dark matter, ΛCDM. In standard models, these histories are quite smooth and gently varying, generally on a Hubble expansion timescale, and thus discriminating between cosmologies is not easy, even with reasonably precise measurements. That is, one does not have sharp or oscillating features the way one does when analyzing, for example, cosmic microwave background (CMB) power spectra.

Although the amplitudes of the growth or growth rate history, for example, may differ between cosmologies, this is often nearly degenerate with the initial conditions of the mass fluctuations, or the present mass fluctuation amplitude σ_8. Without a clear distinction in the shape of the history curve over the epochs where precise data exists, this makes cosmological characterization problematic.

We therefore seek a way to interpret the data such that the difference in the shapes of the evolutionary tracks becomes more pronounced. The simple solution we find is to contrast the expansion history in terms of the Hubble expansion rate $H(z)$ directly with the growth history in terms of the growth rate $f\sigma_8(z)$, rather than each as a function of redshift. Just as the tracks in a Hertzsprung–Russell (HR) diagram of luminosity vs temperature, or a supernova plot of magnitude vs color, can illuminate the physics more clearly than plotting either vs its dependent variable (age or time), so too do the cosmic histories when plotted against each other rather than as a function of time or redshift. Of course no extra physics is added by this change in visualization, just readier recognition, identification, and interpretation of the existing physics, i.e. deviations from general relativity or standard cosmology and particular redshift ranges of interest.

In Section 2 we exhibit the difficulties in distinguishing cosmologies in the standard approach of the evolutionary tracks vs time, as well as a new combination of both histories. We introduce the HR-type approach of considering histories conjointly in Section 3 and investigate it for several types of cosmologies, including quintessence, modified gravity, and stuttering growth. Section 4 discusses the impact of future measurements on exploring the cosmic expansion and growth histories, and we conclude in Section 5.

2. Histories vs time

The expansion history can be most directly considered in terms of the Hubble expansion rate $H(z)=\dot{a}/a$, where $a=1/(1+z)$ is the cosmic scale factor and z is the redshift. The Hubble parameter sets the scale for cosmic distances and age. Distances are integrals over the expansion history so $H(z)$ is more incisive concerning the conditions at a given redshift. The growth history similarly is best examined by means of an instantaneous quantity, the growth rate $f=d\ln D/d\ln a$, where $D(z)$ is the overall growth factor from some initial condition to a redshift z.

* Correspondence address: Berkeley Center for Cosmological Physics & Berkeley Lab, University of California, Berkeley, CA 94720, USA.
E-mail address: evlinder@lbl.gov

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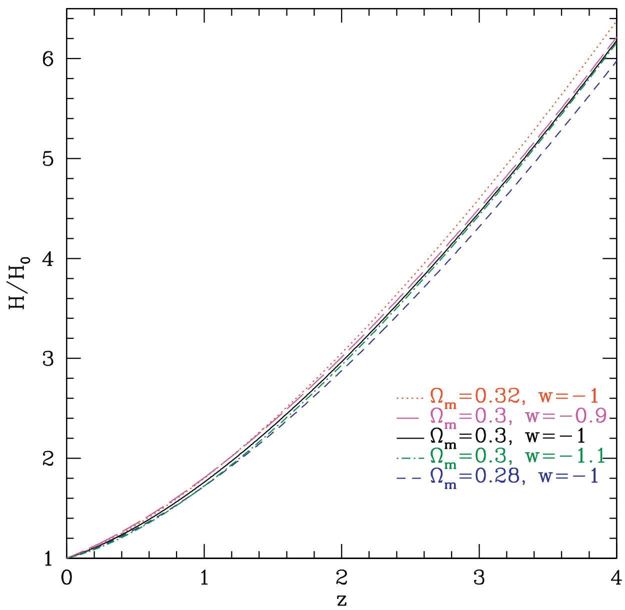

Fig. 1. The Hubble expansion parameter $H(z)/H_0$ is plotted as a function of redshift for cosmological models with matter density $\Omega_m = 0.28,\ 0.3,\ 0.32$ (blue dashed, black solid, red dotted curves respectively) for LCDM ($w = -1$), plus $w = -0.9,\ -1.1$ (magenta long dashed and green dot-dashed curves, respectively) for $\Omega_m = 0.3$. The curves from top to bottom are the models $\Omega_m = 0.32$ LCDM, $\Omega_m = 0.3$ with $w = -0.9,\ -1,$ and -1.1, and $\Omega_m = 0.28$ LCDM. The curves are smooth without localized features and degeneracies are apparent. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

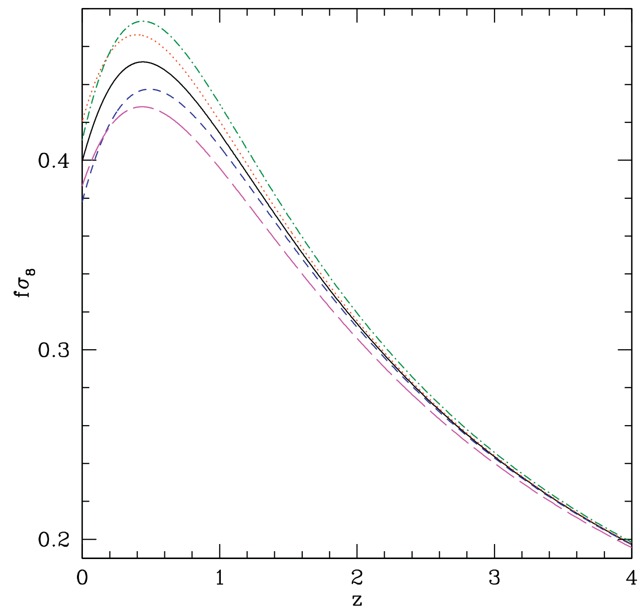

Fig. 2. As Fig. 1 but plotting the growth rate $f\sigma_8$ as a function of redshift. The curves from top to bottom at $z = 0.5$ are $\Omega_m = 0.3$ with $w = -1.1$, LCDM with $\Omega_m = 0.32,\ 0.3,\ 0.28$, and $\Omega_m = 0.3$ with $w = -0.9$. The models show more discrimination but at $z \approx 0.5$–1.5 are mostly similar shapes with scaled amplitudes.

In fact, observations are sensitive to a product $f\sigma_8 \propto fD$, where $\sigma_8(z)$ measures the rms mass fluctuation amplitude at redshift z. Remarkably, measurements of the clustering of large scale structure provide both H and $f\sigma_8$, so a cosmic redshift survey delivers both the expansion history and growth history. The expansion rate comes from using the baryon acoustic oscillations in the clustering pattern as a standard ruler, and in particular the radial distances measure $H(z)r_d$, where r_d is the sound horizon at the baryon drag epoch in the early universe. The growth rate comes from redshift space distortions of the clustering pattern, caused by the (gravitationally induced) velocities of the galaxies or other tracers.

Both $H(z)$ and $f\sigma_8(z)$ tend to be smooth, slowly varying functions. In particular, $H(z)$ is generally monotonic and changes on a Hubble, or e-folding, time scale, while $f\sigma_8(z)$ has a broad peak which means that its value changes little during recent cosmic history where the data is best measured. Fig. 1 shows $H(z)$ for several models while Fig. 2 illustrates the properties of $f\sigma_8(z)$ for the same models.

Note that not only is $f\sigma_8(z)$ reasonably constant, but the shapes of the curves for different cosmologies are fairly similar, mostly being simply offsets in amplitude. That is, they have different rms mass fluctuation amplitudes at present, σ_8, but otherwise look similar for different cosmological physics. Standard models will have this broad peak due to simple physical constraints: at high redshift, in the matter dominated era, $f \to 1$ and $D \to a$ so $f\sigma_8 \propto a$ independent of model specifics. The linear increase with a in $f\sigma_8$ is counteracted at recent times by the suppression of growth caused by accelerating expansion – this reduces f below 1 and causes D to grow more slowly so the net effect is a gradual turnover during the accelerating epoch.

This lack of strong, cosmology dependent features in H and $f\sigma_8$ is disappointing since recent redshift surveys such as BOSS [1–11] and WiggleZ [12–14] have demonstrated precision measurements of these quantities and next generation spectroscopic surveys such as PFS, DESI, Euclid, and WFIRST will greatly improve on this. While a full statistical analysis will constrain the cosmological parameters, the visual "smoking gun" of a deviation from the standard model may not be apparent, and the results may depend more on the parametrization and the build up of signal to noise over redshift range. Thus, the motivation exists to find a more incisive, ideally visually clear method of using this expansion and growth data to discriminate between cosmologies.

In general relativity, expansion and growth are tied together, with expansion (and any microphysics such as sound speed) determining growth. That is, the linear growth equation depends solely on $H(z)$ and the present matter density. However, cosmologies where accelerated expansion is caused by extensions to Einstein gravity generally break this close relation, allowing for greater changes to the H and $f\sigma_8$ histories. This suggests that simultaneous consideration of these two functions may give greater insight. This has been explored, with some interesting results, at individual redshifts, i.e. the expansion at redshift z_1 vs the growth at redshift z_1 [1,15–19].

Here we extend this to conjoint investigation of expansion and growth as full functions, i.e. their histories or evolutionary tracks. The first thing one might try, motivated by the above discussion about the generic behavior of $f\sigma_8$ (and H) in the matter dominated era, is to combine the functions together. We have good reasons to believe that a matter dominated era must exist, whatever the late time cosmology: breaking matter domination would give a huge Sachs–Wolfe effect on the CMB in contradiction to observations, plus severely impact the formation of large scale structure. Fig. 1 of [20] shows the dramatic effect of even 0.1 e-fold of early acceleration on the CMB.

Given early matter domination, recall that $f\sigma_8 \propto a$ and $H^2 \propto a^{-3}$. This suggests that all reasonable cosmologies should go to $f\sigma_8 H^{2/3} =$ constant during that epoch. To investigate whether convolving the expansion and growth histories in such a way improves distinction between models, we plot this combination vs redshift in Fig. 3.

The evolutionary tracks are quite similar, lying in a fairly narrow band. In particular, the curve shapes do not have any dis-