The Rise of Dark Energy

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While dark energy has dominated cosmic dynamics only since $z \approx 0.7$, its energy density was still $\gtrsim 5\%$ of the total out to $z \approx 2.5$. We calculate model independent constraints on its fraction from future galaxy surveys, finding that the rise of dark energy could be detected at $3\sigma$ nearly out to $z \approx 2.5$.

I. INTRODUCTION

A frontier for the next generation of cosmic surveys after the ones now getting underway will be pushing to higher redshift, earlier in the evolution of the universe. Cosmically, this is not simply a dull era of complete matter domination: the dark energy density at redshift $z = 2$ is expected to be about double the current baryon density and one quarter the current matter density. How dark energy rises to dominate the current expansion may also offer clues to its nature. For example, at $z = 2.5$ the dark energy density fraction in different viable models could be $50\%$ greater (or less) than in the cosmological constant ($\Lambda$CDM) case.

We explore whether such distinctions are within the reach of next generation surveys of distance and structure growth. Such experiments being conceived include DESI1 [1], FOBOS [2], LSSTspec [3], Mauna Kea Spectroscopic Explorer [4], MegaMapper [5], SpecTel [6], not to mention those using not galaxies as tracers but intensity mapping, Lyman alpha forest, etc. (see, e.g., [7]). A wide variety of cosmic science cases at $z \gtrsim 2$ is discussed in [8].

Section II illustrates the relevance of the $z \approx 1.5$–2.5 redshift range for mapping the rise of dark energy. Section III describes the method we use to constrain the dark energy density at various redshifts, and Sec. IV presents the results. We discuss and conclude in Sec. V.

II. DARK ENERGY RISING

Today the fractional contributions to the total energy density of the universe are approximately 70% dark energy, 25% cold dark matter, and 5% baryons. Their dynamical influence however also depends on their equation of state $w$, as $1 + 3w$, so dark energy with $w \approx -1$ has twice the impact as nonrelativistic matter with $w = 0$. Thus, though dark energy-matter equality occurs at $z \approx 0.3$, the cosmic expansion began accelerating at $z \approx 0.7$.

Especially given the profound mystery of dark energy, we should not fail to explore it even during the time that it amounts to only a few percent of the total energy density (i.e. about as much as baryons are today). Moreover, the manner in which dark energy rises could provide important insights into its nature. Consider going all the way back to the epoch of cosmic microwave background (CMB) last scattering: at $z \approx 1090$, the energy density fraction due to a cosmological constant was only about $10^{-9}$ of the total, however in other dark energy models the contribution could be $10^{-3}$ – six orders of magnitude difference! (Current constraints on the early dark energy fraction are somewhat model dependent, but generally below $10^{-2}$ [9].) We do not have clear ideas for how to detect contributions in this range, but next generation galaxy surveys will probe $z \gtrsim 2$. Though the differences between models are less there, the absolute level of dark energy density is higher.

Consider models that may define the envelope of viable, smoothly evolving dark energy models. Our fiducial cosmology is $\Lambda$CDM, where the dark energy is a cosmological constant, $w = -1$. One may come up with a wide variety of behaviors for other models, but they must be viable under current constraints. In particular, they must nearly preserve the distance to CMB last scattering, accurately measured by CMB surveys. This involves a redshift integral over the dark energy density, so one could imagine models where a dramatic departure at one redshift is compensated by an opposite departure at another redshift, outside the range where other probes can see. These are somewhat constrained by the integrated Sachs-Wolfe effect and the growth of matter structure (too long or too little time in full matter domination affects gravitational potentials and structure growth). We therefore assume monotonic dark energy evolution, i.e. a steady rise of dark energy influence.

Dark energy models specifically designed to preserve the distance to CMB last scattering are known as mirage dark energy [10]. These will form an envelope around $\Lambda$CDM, i.e. the viable models with predictions furthest from $\Lambda$CDM and most difficult to detect. Mirage dark energy has an equation of state $w(a) = w_0 + w_a(1-a)$ with $w_a = -3.6(1+w_0)$, where $a = 1/(1+z)$. Thus it is a one parameter family (with $\Lambda$CDM a subcase with $w_0 = -1$). We take our envelope of models to be those with $w_0 = [-1.2, -0.8]$, hence between $(w_0, w_a) = (-1.2, +0.72)$ and $(-0.8, -0.72)$, with $\Lambda$CDM in the middle. More extreme models are disfavored by lower redshift observations such as supernova and baryon acoustic oscillation (BAO) distances.

Figure 1 shows the dark energy density fraction of the
total energy density as a function of redshift, $\Omega_{de}(z)$, for \Lambda CDM and the two envelope mirage dark energy models. At redshift $z = 1.5$ we have $\Omega_{de}(z) = 0.146, 0.130, 0.116$ for the mirage $w_0 = -1.2$, \Lambda CDM, mirage $w_0 = -0.8$ cases respectively; at $z = 2$, $\Omega_{de}(z) = 0.102, 0.080, 0.062$; at $z = 2.5$, $\Omega_{de}(z) = 0.076, 0.052, 0.035$. (Throughout this article we take a flat cosmology with fiducial present matter density $\Omega_m = 0.3$.) Thus at $z = 1.5$ they all contribute over 10%, and at $z = 2.5$ the dark energy density is still several percent.

![FIG. 1](image-url) The fractional energy densities in dark energy $\Omega_{de}(z)$, all matter $\Omega_m(z)$, and baryons $\Omega_b(z)$ are shown vs redshift. The heavier middle curves are for \Lambda CDM; the lighter curves are for mirage dark energy, with the $w_0 = -1.2$ case lying above the $w_0 = -0.8$ case at high redshift for $\Omega_{de}(z)$ and below for $\Omega_m(z)$, $\Omega_b(z)$. The green dotted horizontal lines indicate 10% and 1% of the total energy density.

### III. Constraining Dark Energy Density

Next generation cosmic surveys will use various methods to constrain cosmology; the leading probes for mapping evolution of a cosmic quantity such as $\Omega_{de}(z)$ involve distances $d(z)$ such as derived from supernovae and BAO, radial distance intervals that can be viewed as a measure of the inverse Hubble parameter $H^{-1}(z)$ from radial BAO, and the growth rate of cosmic structure, $f\sigma_8(z)$. The impact of the different rises of dark energy on these observables is presented in Figure 2 as the deviation

$$\Delta X(z) = \frac{X_{\text{mir}12}(z) - X_\Lambda(z)}{X_\Lambda(z)}, \quad (1)$$

between mirage dark energy with $w_0 = -1.2$ and \Lambda CDM, for $X = d$, $H^{-1}$, and $f\sigma_8$. (Mirage dark energy with $w_0 = -0.8$ looks similar, with the signs of the deviations flipped.)

![FIG. 2](image-url) The deviations $\Delta X(z)$ between mirage dark energy with $w_0 = -1.2$ and \Lambda CDM are shown for $X = d$, $H^{-1}$, and $f\sigma_8$.

We see that observations need to be at the percent level to distinguish clearly differences in the rise of dark energy. As well known, the sensitivity to dark energy density is greatest at moderate redshifts $z < 1$, and this is the target of the current generation of experiments. However, there is secondary sensitivity around $z \approx 2$, and this is what we focus on in this article. At high redshift $z > 3$ there is diminishing sensitivity to dark energy density. Our emphasis here is on the range $z = [1.5, 2.5]$, so as to supplement current experiments and yet still have sensitivity to measure dark energy density. From Figure 1 we saw that at $z = 2.5$, the \Lambda CDM dark energy density fraction is 0.052 so a 2–3$\sigma$ detection of any dark energy density requires observational precision such that $\sigma(\Omega_{de}(z = 2.5)) \approx 0.017–0.026$. That would also give a $\sim 1\sigma$ distinction between \Lambda CDM and either mirage model. Weaker constraints would not be informative about the rise of dark energy.

We emphasize that we adopted the mirage models simply as a reasonable envelope that allows some quantitative estimation of the magnitude of the impact from changing dark energy density. Going forward we instead employ a model independent approach. We allow the dark energy density to float freely in five independent redshift slices of width $dz = 0.2$, from $z = [1.5, 1.7]$ to $z = [2.3, 2.5]$.

The dark energy density in each slice, $\Omega_{de}(z_i)$, where
\[ i = 1 - 5 \text{ is the slice number, is a new cosmological parameter that we constrain through the information matrix formalism. Transitions between slices are tanh smoothed, with a width of 0.01 in ln(1 + z). In addition the present matter density } \Omega_m \equiv \Omega_m(z = 0) \text{ is a free parameter, as is } \sigma_8 = \sigma_8(z = 0) \text{ when we use } f \sigma_8(z) \text{ as a probe. Outside the redshift slices the cosmology is fixed to the fiducial LCDM. Thus our free parameters are } p = \{ \Omega_m, \Omega_{\text{de}(z_1)}, \Omega_{\text{de}(z_2)}, \Omega_{\text{de}(z_3)}, \Omega_{\text{de}(z_4)}, \Omega_{\text{de}(z_5)}, \sigma_8 \} \text{ and we apply the information matrix formalism to constrain them.} \]

That is,

\[ F_{jk}^X = \sum_{z_i} \frac{\partial X(z_i)}{\partial p_j} \frac{\partial X(z_i)}{\partial p_k} \frac{1}{\sigma^2(X_i)}, \tag{2} \]

where \( X = d, H^{-1}, f \sigma_8 \) are the measurements, and \( X_i = X(z_i) \). These are of course not directly measurable, but derived from observations of supernova magnitudes and the galaxy power spectrum BAO and redshift space distortions. However we seek a high level answer to the question of whether there is a dark energy density science case for observations at \( z \geq 2 \), before considerations of any survey specifics. Therefore we assume as a first step here that we can obtain measurements of precision \( \sigma(X_i) \) in each redshift slice. We chose the slice widths \( dz = 0.2 \) so that the correlations between measurements in different slices should be ignorable (of course real world surveys need to ensure that common mode systematics are small after correction). In addition, the measurements via different probes are taken to be independent, so the measurement noise matrix is diagonal, simply \( \sigma^2(X_i) \). Again, to go beyond this first estimation of constraints would require detailed survey design.

We now have all the elements necessary for parameter constraints, with \( \sigma(p_j) = \sqrt{(F^{-1})_{jj}} \), marginalized over the other parameters. We consider probes singly and in combination. Since next generation experiments will also have external constraints from current generation experiments, we also study the effect of Gaussian priors \( \pi(\Omega_m) = 0.01 \) and \( \pi(\sigma_8) = 0.02 \), and variations. For the probe precisions, we take these to be fractionally constant for all five redshift slices, i.e. \( \sigma(X_i) = \sigma_{X,0} X_i \). For next generation surveys we take the precisions \( \sigma_{X,0} \) on \( d, H^{-1}, f \sigma_8 \) to be 1%, 1.4%, 1% respectively. For radial BAO, taking its precision to be \( \sqrt{2} \) times the transverse BAO precision is reasonable, given its two times fewer modes. We also study variations of all these precisions.

### IV. RESULTS

Beginning with one probe at a time, we find that data in only the range \( z = [1.5, 2.5] \) has a difficult time constraining \( \Omega_{\text{de}(z)} \): the probe evolution is too slight over this limited redshift range and becomes degenerate with either a neighboring slice or the present matter density \( \Omega_m \). However, once we apply either a prior on \( \Omega_m \) (e.g. standing in for current generation experiments) or combine two probes, then the densities become well estimated.

For \( d(z) \) plus the \( \Omega_m \) prior, the constraints on the dark energy densities are unexciting: \( \sigma(\Omega_{\text{de}(z_1)}) \sim 0.3 - 0.6 \). Even fixing \( \Omega_m \) does not appreciably approve on these. The reason is that \( d(z) \) is an integral measure and a change in \( \Omega_{\text{de}(z)} \) is diluted by the long path length out to \( z \approx 2 \). We saw this as well in Fig. 2 where the deviation between the mirage model and LCDM was only \( \sim 0.6 \% \) at \( z = 2 \), falling to 0.4\% at \( z = 2.5 \).

For \( H^{-1}(z) \) plus the \( \Omega_m \) prior, the situation is much better. Now the constraints are \( \sigma(\Omega_{\text{de}(z_1)}) \approx 0.027 \) for each redshift slice. Furthermore, the slices are substantially uncorrelated, with correlation coefficients \( r \approx 0.5 \). This leverage is since \( H^{-1}(z) \) is a point measurement, depending on conditions at that particular redshift and not diluted by others.

For \( f \sigma_8(z) \) we must add a prior on the new parameter \( \sigma_8 \equiv \sigma_8(z = 0) \) otherwise it is highly covariant with the dark energy density variations. We take external data, as from current generation experiments, to impose the prior \( \pi(\sigma_8) = 0.02 \). Even so, this delivers only a weak \( \sigma(\Omega_{\text{de}(z_1)}) \sim 0.3 - 0.4 \), again because \( f \sigma_8(z) \) is an integral measure (this time the growth from high redshift down to \( z \)). In fact, even fixing \( \Omega_m \) does not alleviate this, nor does tightening the prior to \( \pi(\sigma_8) = 0.01 \).

Combining probes helps considerably however. Using both \( d(z) \) and \( H^{-1}(z) \) delivers \( \sigma(\Omega_{\text{de}(z_1)}) \approx 0.023 \), and further imposing the \( \Omega_m \) prior reduces the uncertainty to 0.021. Without the prior, \( \Omega_m \) is determined to 0.0065, and the correlation coefficients between dark energy density slices is a modest \( r \approx 0.4 \). The combination of \( d(z) \) and \( f \sigma_8(z) \) does not do well, with \( \sigma(\Omega_{\text{de}(z_1)}) \approx 0.25 \), or 0.23 with \( \Omega_m \) prior. The integral natures of \( d(z) \) and \( f \sigma_8(z) \) do not allow incisive constraints. Using \( H^{-1}(z) \) and \( f \sigma_8(z) \) enables \( \sigma(\Omega_{\text{de}(z_1)}) \approx 0.021 \), or 0.020 with \( \Omega_m \) prior, with the former having \( r \approx 0.4 \) and \( \sigma(\Omega_m) = 0.0088 \). Finally, all three probes together yield \( \sigma(\Omega_{\text{de}(z_1)}) \approx 0.0019 \), with \( r \approx 0.2 \) and \( \sigma(\Omega_m) = 0.0051 \), so there is no need for a \( \Omega_m \) prior.

Figure 3 shows the key results. We can see that \( H^{-1}(z) \) (plus a \( \Omega_m \) prior) provides the key leverage. Either \( d(z) \) or \( f \sigma_8(z) \) can substitute for the \( \Omega_m \) prior, and further tightens the constraint by a factor 1.2–1.3. All three together give a factor 1.4 improvement.

A constraint on \( \Omega_{\text{de}(z)} \) of 0.02 would deliver a 6.5, 4.0, and 2.6\sigma evidence of nonzero dark energy density at \( z = 1.5, 2, 2.5 \) respectively, within a LCDM cosmology. The envelope spanning the mirage models would lie at \( \pm 1\sigma \). Thus, while it would not in itself distinguish between reasonable, viable monotonically evolving dark energy models, if the results lay outside the envelope (and

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\footnote{Fortunately we also have the current generation of experiments probing \( z < 1.5 \) in detail. These could, for example, narrow the deviation of \( \omega_0 \) from -1 and hence constrain mirage models.}
hence greater than 1σ from ΛCDM) then we would have not simply a hint of dark energy different from ΛCDM, but dark energy behaving in a particularly exotic manner.

We can examine the scaling of the results with the measurement precisions, and the prior, to see how the constraints improve or degrade with stronger or weaker experiments. With all three probes combined, having no prior on Ω_m vs fixing it changes σ(Ω_{de}(z_i)) from 0.020 to 0.018. Each of the two probe combinations shows a similar 10% change in constraints. Only for H^{-1}(z) alone is the level of the Ω_m prior influential, with fixing Ω_m tightening the density constraints to 0.019 from 0.027. Conversely, loosening the prior to π(Ω_m) = 0.02 weakens this constraint to 0.042 (but has no effect on the two and three probe combinations).

If the precision on H^{-1} measurements weakens by a factor 2, to 2.8%, then the density constraints from H^{-1} plus the Ω_m prior weaken by a factor 1.5, to σ(Ω_{de}(z_i)) ≈ 0.041. With both d and H^{-1} precisions worse by a factor 2, then σ(Ω_{de}(z_i)) ≈ 0.040. For all three precisions, including fσ_8, worse by a factor 2, then σ(Ω_{de}(z_i)) ≈ 0.037. Conversely, if H^{-1} is better by a factor 2 than our baseline (hence 0.7%), then with the Ω_m prior we find σ(Ω_{de}(z_i)) ≈ 0.021. For d + H^{-1} better by a factor 2, then σ(Ω_{de}(z_i)) ≈ 0.011. Adding also fσ_8 still at 1% yields σ(Ω_{de}(z_i)) ≈ 0.011 too. For such precision on H^{-1}, when combined with d the 0.01 prior on Ω_m is irrelevant. Density estimation uncertainties at the 0.011 level would deliver > 5σ evidence for dark energy in each redshift slice, and distinguish ΛCDM from the mirage dark energy envelope at ~ 2σ.

V. CONCLUSION

The epoch before dark energy domination was not one of pure matter domination. Rather, the dark energy density is still expected to constitute > 5% of the total energy density (for comparison, greater than the baryon energy density today) out to z = 2.5. The precisions required to make an informative measurement of the dark energy density at such redshifts – first, detection of a nonzero contribution, and second, measurement of the value for comparison between ΛCDM and other dark energy models – are just outside the reach of the currently starting generation of dark energy experiments.

We demonstrate that next generation experiments with precision measurements of transverse and radial BAO, and the growth rate from redshift space distortions, over the range z = 1.5 − 2.5, can achieve significant constraints on dark energy in this epoch. We set the scale of constraints to aim for by considering the envelope of smoothly evolving dark energy models that preserve the distance to CMB last scattering (“mirage dark energy”), but then carry out the detailed analysis in a model independent manner through information matrix constraints on independently varying dark energy densities in redshift slices.

Measurements of H^{-1}(z) through radial BAO are the most incisive, due to their local, nonintegral, nature. Combining this with distances d(z) from transverse BAO, or fσ_8(z) from redshift space distortions, delivers constraints at the level of σ(Ω_{de}(z_i)) ~ 0.02. This corresponds to detection of dark energy at the level of ~ 6.5σ at z = 1.5 to ~ 2.6σ at z = 2.5. Distinction between ΛCDM and mirage dark energy will require combination with the current, lower redshift experiments.

Surveys extending deeper than z = 2.5 run into the double issue of increasing difficulty to achieve the necessary measurement precision while also facing declining probe sensitivity to dark energy density at the higher redshifts. Examining the impact of measurement precision over z = 1.5 − 2.5, we confirm that H^{-1} has the greatest leverage, and a survey strengthening its accuracy to the 0.7% level could deliver σ(Ω_{de}(z_i)) ≈ 0.011. This could give significant insight on the rise of dark energy in our universe.

\footnote{In the final stages of this work, we learned that surveys with a wide range of redshifts z > 2 are explored in [11].}
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