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# The Accelerated Acceleration of the Universe

Csaba Csáki[a,*], Nemanja Kaloper[b,†] and John Terning[b,‡]

[a] *Newman Laboratory of Elementary Particle Physics, Cornell University, Ithaca, NY 14853*

[b] *Department of Physics, University of California, Davis, CA 95616*

We present a simple mechanism which can mimic dark energy with an equation of state $w < -1$ as deduced from the supernova data. We imagine that the universe is accelerating under the control of a quintessence field, which is moving *up* a very gently sloping potential. As a result, the potential energy and hence the acceleration increases at lower redshifts. Fitting this behavior with a dark energy model with constant $w$ would require $w < -1$. In fact we find that the choice of parameters which improves the fit to the SNe mimics $w = -1.4$ at low redshifts. Running up the potential in fact provides the best fit to the SN data for a generic quintessence model. However, unlike models with phantoms, our model does not have negative energies or negative norm states. Future searches for supernovae at low redshifts $0.1 < z < 0.5$ and at high redshifts $z > 1$ may be a useful probe of our proposal.

* csaki@lepp.cornell.edu
† kaloper@physics.ucdavis.edu
‡ terning@physics.ucdavis.edu

A wide range of observational evidence indicates that our universe may be accelerating [1–4]. If we assume that long-range gravity obeys Einstein's General Relativity (GR), this suggests that most of our universe is in some form of smooth dark energy, which can comprise $\sim 70\%$ of the critical energy density. In order to drive cosmic acceleration this dark energy must have negative pressure, which should satisfy $w = p/\rho \lesssim -2/3$ to fit the observations [5, 6]. Benchmark models of dark energy are a cosmological constant or a time-dependent quintessence field [7–10], which must be finely tuned to fit the data [11, 12]. There are but a few examples of quintessence which are natural from the point of view of the 4D effective field theory, where quintessence is a pseudo-scalar Goldstone boson [13], with a radiatively stable mass and naturally weak couplings to the visible matter. There are also models where dark energy is in the form of a network of domain walls, whose coarse-grained dynamics is described by an equation of state $w = -2/3$ [14].

One of the greatest challenges in modern cosmology is to discern the nature of dark energy. To this end, currently the most sensitive probe of dark energy are the Type Ia supernovae [1]. However, the results of supernova observations cannot completely constrain the dark energy equation of state yet. First of all, the supernova data give us the Hubble diagram for luminosity distance versus redshift, which is related to the dark energy equation of state parameter $w$ through a double integral [15–17]. Therefore there is a great deal of degeneracy between dark energy models with different, and variable, equations of state parameters $w$. Further, there may be additional sources of supernova dimming, which do not imply cosmic acceleration, as for example the gray dust of [18]. Another example is the photon-axion conversion which we have proposed in [19, 20]. In this case, the extragalactic magnetic fields may catalyze the conversion of photons into very light axions which renders the supernovae dimmer. While the CMB and large-scale structure alone support the existence of dark energy [6], they do not yet imply stringent bounds on the equation of state, and the ones obtained from supernovae observations can be significantly relaxed with photon-axion conversion [19, 20]. Various aspects of the photon-axion mechanism have been considered in [19–26].

Exploiting the limitations of the current data sets, researchers have even argued that more exotic models of dark energy, yielding $w < -1$ are allowed [27–29]. The simplest models of this kind stretch the philosophy of quintessence scalars by postulating that the scalar is a *phantom*: i.e. a ghost, having negative kinetic terms [27–30]. Phantoms are in fact scaled down models of super-exponential inflation, invented by Pollock in 1985 [31]. In the realm of GR, they inevitably violate the dominant energy condition, $|p| \leq \rho$, yielding energy density which *increases* with the expansion of the universe and produces a future singularity. They are also plagued with instabilities even without GR: they do not have a stable ground state [30, 32, 33], have classical runaway modes [30], and violate the lore of effective field theory [32]. The debate of whether $w$ may have dipped below $-1$ at low redshifts still continues [34–36], and while it is not at all clear from the data that the inferences on $w$ being below $-1$ are reliable [16, 37], there has been a lot of exploration of phantoms [38].

In our opinion, probing for $w < -1$ (see e.g. [39]) would be *considerably* more motivated if less occult methods for predicting $w < -1$ were easier to come by. Chasing phantoms is interesting, but one might prefer to have better prospects for discovering a new twist to dark energy based on $w < -1$. Motivated by this line of thought, we have already exorcised the phantom from $w < -1$ once [20], having shown that photon-axion conversion combined with cosmic acceleration driven by a cosmological constant can easily fool an observer into thinking that $w < -1$, in fact faking $w$ as low as $-1.5$. Another, less efficient and more fine tuned, method to fake $w < -1$ without ghosts could be to weaken gravity in the far infrared [40, 41]. Thus at least in principle it is possible to have the dark energy equation of state parameter $w$ *appear* to be more negative than $-1$ without any phantasms.

In this note, we present yet another method to mimic $w < -1$. It is very simple. It involves a quintessence field going *up* the potential slope. Imagine that the quintessence potential is asymmetric around some minimum, with a curvature which may change by $\mathcal{O}(\phi)$ contributions as the field passes through the minimum. The field may end up initially frozen by Hubble friction on a steeper side of the potential well. Then as the universe cools, the field is eventually released as $H$ decreases below the effective mass, and starts to roll down the steeper slope picking up speed (see Fig. 1). We imagine that this occurs some time around $z = 2 - 3$. As the field picks up speed the kinetic energy is converted into potential energy and the universe will eventually be dominated by dark energy. Because the quintessence field is rolling up the potential, the cosmic acceleration increases at lower redshifts, lifting the Hubble diagram curve up at low redshifts. The quicker the increase, the higher the lift. Reproducing such behavior in a model of dark energy with a constant $w$ requires $w < -1$. Because the effect is embedded in the metric relations in the universe, it could in principle be seen in the CMB and large-scale structure observations as an increase of the acceleration rate, to be properly identified as dark energy with variable* $w > -1$. However those observations do not yet have the ability to discern such fine structure in $w$ [6]. Hence, the upward mobility of the quintessence can trick an observer into deducing $w < -1$ from the geometry of the universe. Nevertheless, this is accomplished without negative energies or negative norm states. The effective field theory is perfectly normal.

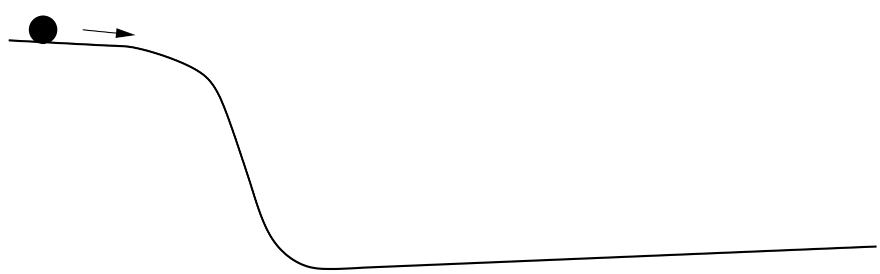

Figure 1: Sketch of the form of the potential including an example of the possible non-linear behavior before the onset of the linear regime.

For such dynamics one needs a potential for the quintessence field with a very gentle slope, which the quintessence field has been climbing for the significant part of the last 14 billion

*Some aspects of possible misidentification of varying $w$ as a dark energy with $w < -1$ have been considered in [16].

years, which was preceded by a more curvaceous part. Clearly, one needs to arrange for the right properties of the potential: the value of the quintessence potential $V \sim 10^{-12}\mathrm{eV}^4$, its curvature $\partial_\phi^2 V \gtrsim H_0^2$ which changes with $\phi$, quickly vanishing as $\phi$ exceeds some value $\mathcal{O}(M_{Pl})$, and sufficiently weak couplings to the visible sector matter. Of course, this means that the quintessence sector needs to be finely tuned. The fine tunings are more severe than for the natural quintessence candidates based on pseudo-scalar Goldstones [13], but not worse than many other oft-quoted quintessence models in the literature [7,8,12]. On the other hand, the advent of the Landscape paradigm [42] may offer new means to accomplish the dramatic separation of scales needed here[†]. Indeed, a quintessence field might be some modulus-like degree of freedom, whose potential arises from SUSY breaking in some hidden sector, which is transmitted to the quintessence sector very weakly. Typical such potentials are of the form [44]

$$V(\phi) = \lambda\, M_{Pl}^4\, f\left(\frac{\phi}{M_{Pl}}\right)\,, \tag{1}$$

where $\lambda$ needs to be tuned to $10^{-123}$, but the coefficients in the Taylor expansion of $f(x)$ may be numbers of $\mathcal{O}(10)$. From this point of view the fine tunings do not look too severe. Such potentials with some mild tuning, so that the ratio of the slopes on the two sides is of $\mathcal{O}(10)$, could perform our task. We will illustrate the conceptual aspects of the mechanism with a detailed analysis of the simplest imaginable quintessence field, which in the region where the field is moving uphill is approximated by a linear potential [7],

$$V(\phi) = \mu^3 \phi\,, \tag{2}$$

where $\mu \sim$ few $\times\, 10^{-13}$ eV, and $\phi(\mathrm{now}) \sim 10^{19}$ GeV. With a shift of $\phi(\mathrm{now})$, this is just the leading Taylor series expansion of any quintessence potential, valid for small enough $\Delta\phi$. Our results can readily be extended to more complicated potentials. As a result of running up the potential, the cosmic acceleration is itself accelerated: it is greater at late times and lower redshifts. This raises the Hubble diagram at lower redshifts, and in fact is a slightly better fit to the existing supernova sample [2]. An observer who tries to fit it with quintessence with a constant $w$ would conclude that a value of $w < -1$ is needed [16]. Further, this behavior happens at low redshifts, which is curious since if there is any support for $w < -1$ in the data, it seems to arise precisely from such a regime [34–36]. This is the regime with relatively few data points, and thus the future searches for the supernovae in the low redshift range, $0.1 < z < 0.5$ may be helpful.

Let us now consider the details of the mechanism. In line with the observations [6], we will ignore the curvature of the spatial sections and imagine that the universe is described by a spatially flat FRW line element,

$$ds^2 = -dt^2 + a^2(t)\, d\vec{x}^2\,, \tag{3}$$

where the scale factor is a solution of the Friedmann equation

$$3H^2 = \frac{\rho}{M_{Pl}^2}\,. \tag{4}$$

[†]Other interesting cosmological consequences have been recently discussed in [43].

The Hubble parameter is $H = \dot{a}/a$, where the dot represents the derivative with respect to the comoving time $t$. We use the notation where the Newton's constant and the Planck mass are related by $8\pi G_N = 1/M_{Pl}^2$. At the scales where the observations relevant for exploring dark energy are concerned, the total energy density receives contributions from dark matter and dark energy. Normalizing the scale factor today to unity, we can write $\rho$ as

$$\rho = \rho_{cr} \frac{\Omega_M}{a^3} + \rho_{DE} \, , \tag{5}$$

where $\rho_{cr} = 3H_0^2 M_{Pl}^2$ is the critical energy density of the universe now. As we have said above, the dark energy sector is a quintessence field, with energy density

$$\rho_{DE} = \frac{1}{2}\dot{\phi}^2 + V \, , \tag{6}$$

and whose evolution is controlled by the usual zero mode field equation

$$\ddot{\phi} + 3H\dot{\phi} = -\,\partial_\phi V \, . \tag{7}$$

As we have explained above, to ensure that the quintessence field is arrested by friction in the early universe, the potential must have a mass $m(\phi) = (\partial_\phi^2 V)^{1/2}$ that initially obeys $m(\phi) < H$. Here $H$ is on the order of the current expansion rate of the universe $H_0$. Once $H$ is small enough, but still during the matter domination era, the friction term looses to the restoring force pulling the quintessence field toward the minimum. The field begins to roll down the steeper section (see Fig. 1) of the potential $\sim m^2(\phi)\phi^2$, picking up speed. Once it enters the gentler regime of the potential $V(\phi)$, it begins to dominate the cosmic expansion, but continues to slowly climb the slope since it still has $\dot{\phi}_0 \neq 0$.

To explore the climbing phase for concreteness we will consider a potential of the form (2) for $\phi > \phi_*$. Here $\phi_*$ is the initial value of the field at the onset of the linear potential regime. We will take $z_* = 1$ or 2 for the purposes of our calculations. Let us first estimate the values of the parameters in the above potential that could plausibly describe our Universe. Since we do not want the kinetic and potential energies in the scalar field to overclose the Universe, but still be non-negligible components of the total energy density, we have

$$\frac{1}{2}\dot{\phi}_*^2 \lesssim M_{Pl}^2 H_0^2 \tag{8}$$

$$\mu^3 \phi_* \lesssim M_{Pl}^2 H_0^2 \tag{9}$$

Finally, we want the variation of the scalar field to be sizable over a Hubble time, so we require

$$\dot{\phi}_*/H_0 \sim \phi_* . \tag{10}$$

From these we see that we get the right orders of magnitudes for

$$\begin{aligned} \mu^3 &\lesssim M_{Pl} H_0^2 \, , \\ \phi_* &\gtrsim M_{Pl} \, , \end{aligned} \tag{11}$$

which is precisely consistent with our choice of the potential (2). These choices of parameters are also consistent with (1), where the quintessence field has a $4D$ effective theory *vev* $\sim \mathcal{O}(M_{Pl})$. Once the main fine tuning $\lambda \sim 10^{-123}$ is done, the rest of the required shape of the potential can be accomplished with mild tunings of the expansion of $f(x)$.

To gain some more insight into how this system could fake $w < -1$, let us review the simplest limit when the friction term in (7) is negligible. While this does not apply to the relevant solutions which we have obtained numerically, it is very useful for illustrational purposes. In this case the field equation (7) corresponds to a conservative mechanical system, and we would find (assuming that the scalar field stops rolling just about now)

$$\frac{1}{2}\dot{\phi}_*^2 + V(\phi_*) = V_0. \tag{12}$$

Thus we can see that $V_0 > V(\phi_*)$, due to the kinetic energy being converted into potential energy (in general friction only reduces the amount of kinetic energy which is converted into the potential energy). An observer who is not aware of the presence of the kinetic term would interpret this as a growth of the dark energy density, and infer from it that $w < -1$. Indeed we will show later using the numerical solutions of the full equations that the solution for the luminosity distance vs. redshift curves for the upward rolling scalar field cannot be distinguished from that of a phantom matter at low redshifts $z < 1$. This behavior is completely general for an arbitrary modulus-like potential (1) which curves upward, and not only the linear potential which we have focused on.

We stress yet again that the true $w$ remains safely above $-1$ throughout the regime we describe, since there are no negative energy or negative norm states here. Clearly, in a generic case the slowdown of the field is faster in steeper potentials, and so the epoch imitating $w < -1$ will be confined to a narrower range of redshifts. We will extract quantitative statement about just how negative the fake $w$ may seem from the numerical fits to the supernova data of [2].

To get a precise description of the effect we now turn to numerical integration of the field equations and the explicit determination of the luminosity-distance relationship. We use the technique of recasting the field equations in terms of the redshift instead of the time variable. With our normalizations, $z = 1/a(t) - 1$, and so the field equations are [34]

$$\frac{\mu^3\phi(z)}{\rho_c} = \frac{H^2(z)}{H_0} - \frac{1+z}{6H_0^2}\frac{dH^2(z)}{dz} - \frac{1}{2}\Omega_M(1+z)^3 \tag{13}$$

$$\frac{1}{\rho_c}\left(\frac{d\phi(z)}{dz}\right)^2 = \frac{2}{3H_0^2(1+z)}\frac{d\ln H(z)}{dz} - \frac{\Omega_M(1+z)}{H^2(z)}. \tag{14}$$

while the luminosity-distance and the magnitude as a function of the redshift is given by

$$D_L(z) = (1+z)H_0\int_0^z \frac{1}{H(z')}dz' \ , \tag{15}$$

$$m(z) = 5\log_{10} D_L(z). \tag{16}$$

To compare with the gold data set of type Ia SNe [1], we first subtract the magnitude in a universe with the best fit cosmological constant ($\Omega_\Lambda = 0.71$) to get the magnitude differences

$$\Delta m(z) = m(z) - m_{\mathrm{best}\,\Lambda}(z) \ . \tag{17}$$

We do the same subtraction for the SNIa gold data set, and to calibrate the overall magnitude of the supernovae we subtract the average of these relative magnitudes for the near-by supernovae ($z < 0.1$). The difference obtained this way can be directly compared to the theoretical expressions of $\Delta m(z)$ above.

For a fixed value of $\Omega_M$ (assuming a flat Universe, $\Omega_{tot} = 1$) we need to specify the fraction of the kinetic energy $\Omega_{kin}$ of the scalar field today, and the steepness of the potential $\mu$. This completely fixes the initial conditions to be

$$\phi(0) = \frac{(1 - \Omega_{kin} - \Omega_M)\rho_c}{\mu^3} \tag{18}$$

$$H(0) = H_0. \tag{19}$$

We then scan over the parameters $\Omega_{kin}$ and $\mu$ for fixed values of $\Omega_M$ to find the best fit (lowest $\chi^2$ values).

In Fig. 2 we have plotted the residual magnitudes of the type Ia SN gold data sample from [2] (relative to the best fit model with a cosmological constant, which is given by the flat line). We can see that the experimental data prefers a slightly more accelerated Universe at low redshifts (and perhaps a slightly less accelerated one at high redshifts, though the data is very sporadic there and with large error bars). We have shown two curves in Fig. 2 that would achieve such modifications in the Hubble plot. The first is the linear potential model with the field rolling up the hill that we presented in this paper, which has slightly lower $\chi^2$ than the best cosmological constant fit. The best fit corresponds to $\mu^3 = H_0^2 \times 2.3 \times 10^{18}$ GeV, and $\Omega_{kin,0} = 8 \times 10^{-4}$. To show that the accelerated acceleration is robust we also show a second parameterization of the Hubble plot where the equation of state parameter of the dark energy suddenly changes at some intermediate value $z_c$. This parameterization actually gives – to our knowledge – the lowest $\chi^2$ of all the parameterizations tried so far, if the value of $w$ changes from -0.73 for $z > 0.47$ to $w = -1$ for $z < 0.47$ with $\Omega_{DE,0} = 0.80$. This jump in $w$ also gives an accelerated acceleration. However we do not know of a simple physical model that could give this kind of Hubble diagram. Note, that a step potential would not be equivalent to this parameterization, but would rather give a curve very similar to the linear potential case.

In Table 1 we present a summary of the fits to different dark energy models. We include four models: a cosmological constant, the linear potential model elaborated on in this paper, a model with phantom matter, and a hypothetical model with a jump in the equation of state as explained above. We can see that the minimal $\chi^2$ of the linear potential model is lower than that for the cosmological constant (and comparable to that of the phantom), however since there is one more parameter in this model the $\chi^2/(\mathrm{d.o.f.})$ is comparable to the case of the cosmological constant. The best fit is for the model with a jump in $w$. However, of the

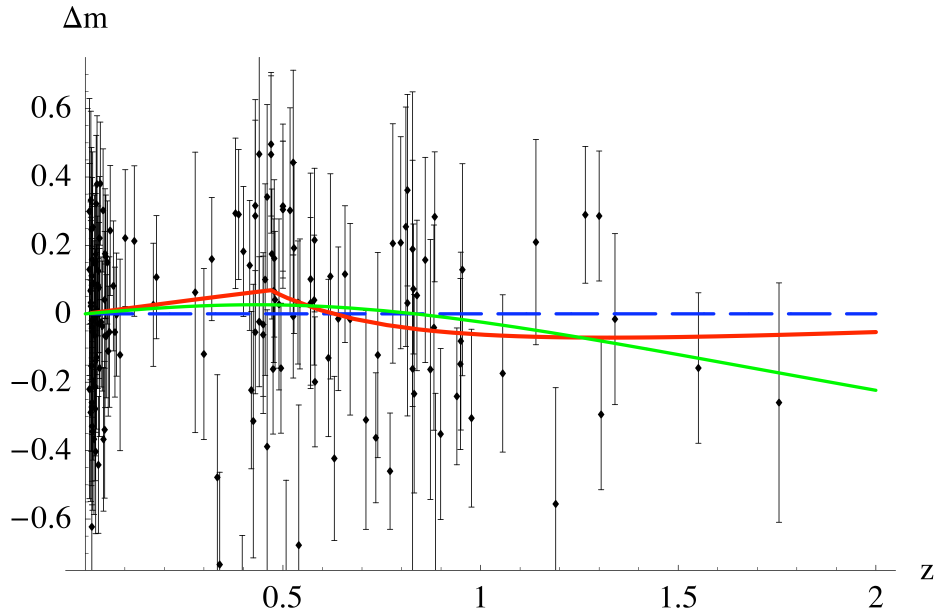


Figure 2: Residual magnitudes for high redshift supernovae data relative to a universe with a best fit cosmological constant. The dashed line thus gives the prediction for $\Omega_\Lambda = 0.71$. The green (light) line gives the best fit for a linear potential with $\Omega_{DE,0} = 0.77$ and $z_* = 2$, which requires the field to run up the potential. The red (dark) line gives the best fit for a change in $w$ from -0.73 for $z > 0.47$ to $w = -1$ for $z < 0.47$ with $\Omega_{DE} = 0.80$.

scenarios with a scalar in a potential the best fit is always for a field rolling up a potential. It is interesting to note that the accelerated acceleration model prefers a low value of $\Omega_M$ while the phantom prefers a large value of $\Omega_M$, however the accelerated acceleration model is less sensitive to the value of $\Omega_M$. Thus an improved determination of $\Omega_M$ would help to distinguish between the two.

In Fig. 3 we show the energy density components and the effective equation of state parameter for the best fit linear potential case. The definition of $w$ for a scalar field is found by comparing the 00 and $ii$ terms in the energy-momentum tensor

$$w_{eff} = \frac{\frac{1}{2}\dot{\phi}^2 - V(\phi)}{\frac{1}{2}\dot{\phi}^2 + V(\phi)}. \tag{21}$$

To keep $\Omega_{kin}$ from dominating the universe we have put in a simple toy model for the behavior of the asymmetric part of the potential. We matched onto a quadratic plus linear potential that makes the potential and its first derivative continuous at $\phi(z_* = 1)$. Here we have chosen the parameters of the potential (for $z > 1$) so as to avoid kinetic energy domination at all times. The behavior for $z < 1$ is well constrained by the supernova data, but is quite model dependent for $z > 1$. Note that the modification of $w_{eff}$ at redshifts $1 < z < 3$ could

| model | $\Omega_{DE,*}$ | $\Omega_{DE,0}$ | $\Omega_{M,*}$ | $\Omega_{M,0}$ | $\chi^2$ | $\chi^2/(\text{d.o.f.})$ |
|---|---|---|---|---|---|---|
| cosm. const. | 0.08 | 0.71 | 0.92 | 0.29 | 177.4 | 1.14 |
| $w = -1.2$ | 0.03 | 0.65 | 0.97 | 0.35 | 176.0 | 1.14 |
| linear pot. | 0.02 | 0.74 | 0.36 | 0.26 | 175.8 | 1.14 |
| linear pot. | 0.01 | 0.77 | 0.26 | 0.23 | 175.6 | 1.14 |
| $w = -1.4$ | 0.01 | 0.6 | 0.99 | 0.4 | 175.0 | 1.13 |
| $w$ jump | 0.21 | 0.80 | 0.79 | 0.20 | 172.0 | 1.12 |

(20)

Table 1: The best $\chi^2$ fits for different dark energy models for different values of $\Omega_{M,0}$. The subscript $*$ refers to $z_* = 2$. The second and fifth rows show the best fits for phantoms, while the last row shows a hypothetical model where the equation of state of the dark energy suddenly jumps (as explained in the text).

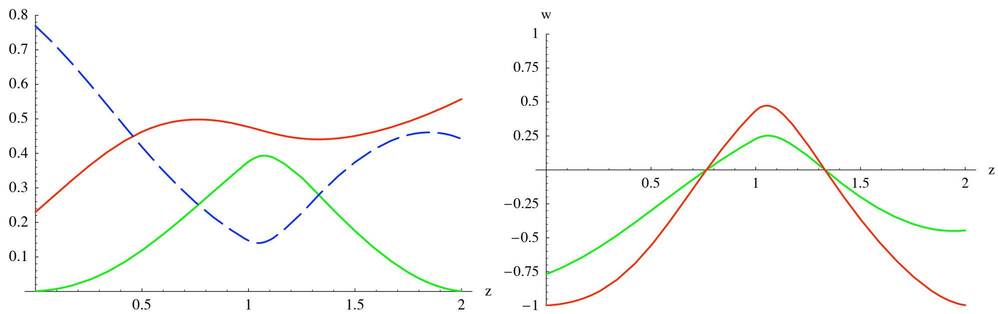


Figure 3: On the left we show $\Omega_M$ as a function of $z$ with the red (dark) line which dominated for $z > 0.5$, $\Omega_{kin}$ with the green (light) line, and $\Omega_{DE}$ with the dashed line for a scalar field with the best fit linear potential for $z < 1$ and with a simple toy model for the asymmetric part of the potential for $z > 1$ as described in the text. On the right we show in red (dark) the time dependent effective equation of state parameter $w_{eff}$ for the scalar field in the same scenario, while in green (light) we show the full $w_{eff}$ including dark matter.

affect structure but only at the largest scales, and in a model dependent way. More detailed work would be needed to evaluate these effects.

In Fig. 4 we show the Hubble plots for the model with the best fit linear potential with $z_* = 2$, the linear potential matched to a quadratic at $\phi(z_* = 1)$, the best fit phantom, and the binned supernova data. It is clear from the binned data why an accelerated acceleration is preferred for the fit. All but one of the the data points that lie above the cosmological constant fit occur with $z < 0.9$ while all but one of the data points that lie below the cosmological constant fit occur for $z > 0.9$. This seems to show a systematic trend. We can see that for $z < 1$ the curves for the phantom and the linear potential are practically indistinguishable from each other, and hence the linear potential model could easily be mistaken as a Universe with phantom matter. For larger values of $z$ the two curves start deviating from each other. A precision measurement of SN Ia from future dark energy probes

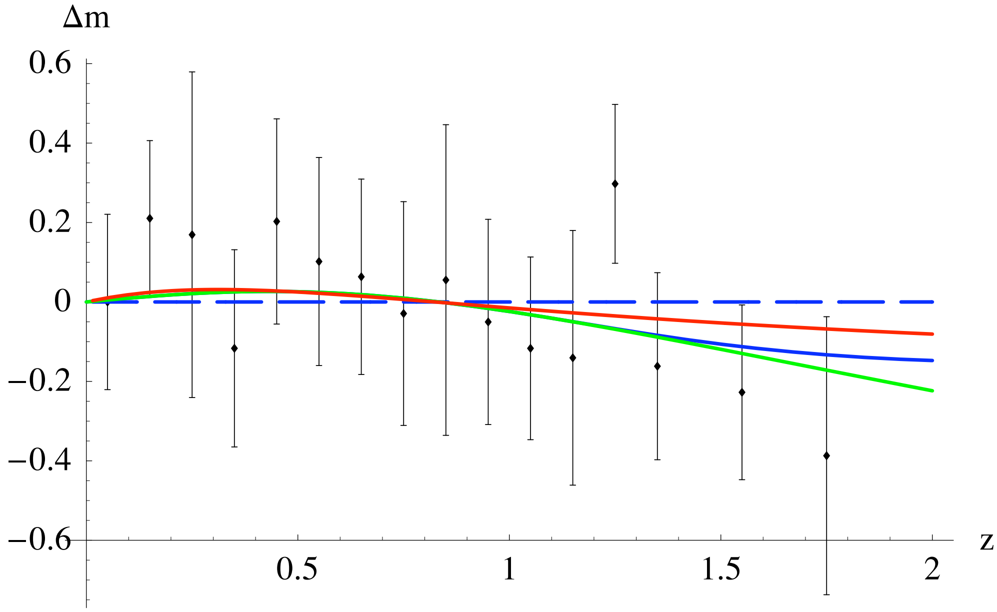


Figure 4: Residual magnitudes relative to a flat universe with a best fit cosmological constant. Data points are SN Ia gold data in redshift bins of 0.1. The bottom, green (light) line gives the best fit for a linear potential, with $\Omega_{DE,0} = 0.77$. The top, red (dark) line gives the best fit for a phantom with $w = -1.4$ with $\Omega_{DE} = 0.6$. The blue (darkest) line gives the behavior when the linear potential is matched onto a quadratic potential at $\phi(z_* = 1)$, as described in the text.

may be able to distinguish between these two models, however the region $1 < z < 2$ is a more model dependent part of this scenario because it depends on the details of the non-linear part of the potential.

To conclude, we have presented a very simple model of a conventional quintessence field which can mimic the equation of state $w < -1$ without any ghosts, negative energies or negative norm states. The key ingredient is to imagine that during the epoch of current cosmic acceleration the quintessence field has been persistently moving up the potential slope. This requires fine tunings, but of a kind familiar from a generic quintessence setup. The advantage of the mechanism is that it provides a simple, yet potent method of impersonating $w < -1$ in a way which is completely grounded in conventional $4D$ physics. At the moment, this behavior provides a lower $\chi^2$ fit to the SN data than a genuine cosmological constant. Searches for more supernovae in the regime of low redshifts $0.1 < z < 0.5$, where the turnover of the luminosity distance-redshift curve is located, and at high redshifts $z > 1$, where the luminosity distance-redshift curve dips below the one for cosmological constant will improve the precision for the fits and may be instrumental for discerning accelerated acceleration from a cosmological constant.

## Note added

While this manuscript was in preparation Ref. [45] appeared which also considers models with fields rolling up a linear potential. They note that these models would in fact give the best fits to the data, however discard this scenario due to the assumption that the potential is linear for all values of $\phi$. We have argued here that an asymmetric potential could easily remove the unwanted kinetic energy dominated phase for large $z$ without changing the analysis for $z < 2$.

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