8-29-2014

Dark Energy Scaling from Dark Matter to Acceleration

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(Dated: March 14, 2018)

The dark sector of the Universe need not be completely separable into distinct dark matter and dark energy components. We consider a model of early dark energy in which the dark energy mimics a dark matter component in both evolution and perturbations at early times. Barotropic aether dark energy scales as a fixed fraction, possibly greater than one, of the dark matter density and has vanishing sound speed at early times before undergoing a transition. This gives signatures not only in cosmic expansion but in sound speed and inhomogeneities, and in number of effective neutrino species. Model parameters describe the timing, sharpness of the transition, and the relative abundance at early times. Upon comparison with current data, we find viable regimes in which the dark energy behaves like dark matter at early times: for transitions well before recombination the dark energy to dark matter fraction can equal or exceed unity, while for transitions near recombination the ratio can only be a few percent. After the transition, dark energy goes its separate way, ultimately driving cosmic acceleration and approaching a cosmological constant in this scenario.

I. INTRODUCTION

The present energy budget of the Universe contains two significant components beyond the Standard Model of particle physics – dark matter and dark energy – with little definitely known about their nature. Today, they act very differently, with dark matter clustering into galaxies and enhancing gravitational attraction while dark energy appears spread nearly homogeneously throughout space with a tension that causes the acceleration of the cosmic expansion. Here we consider whether they might have been more closely related in the past.

Such a concept might be realized if dark matter and dark energy arose from the same, or related high energy physics processes. Indeed, such connections might arise from decaying moduli in string theory, e.g. see [1] for such a case connecting dark matter and dark radiation. Modified gravity can also cause evolution of the couplings to and between different sectors, e.g. the early transition model of [2]. In particular, the dark sector could have a different character at high redshift, and dark energy could have contributed dynamically at early times, perhaps with density at certain epochs comparable to that of dark matter. Several high energy physics origins for dark energy, such as Dirac-Born-Infeld scalar fields [3–5] or dilatons [6, 7], predict such early dark energy, and in many cases it acts in a decelerating manner, possibly scaling as the dominant component of energy density, or simply like dark matter. Moreover, such models often involve a non-relativistic sound speed of perturbations. Thus, such cold, early dark energy can act substantially like cold dark matter.

For probing the early universe, measurements of the cosmic microwave background (CMB) offer the best evidence, and have already been used to place percent-level limits on dark energy at recombination [8, 9]. Here we investigate whether viable models exist in which the early dark energy density at some prerecombination epoch can be of order (or even greater) than the dark matter density, while possessing many of the same properties.

Since the dark energy should today be accelerating and fairly smooth, this requires an evolution in its behavior in both equation of state and sound speed. Moreover, so as not to disagree with formation of galaxies and clusters, the dark energy must quickly fade away from the early universe into the matter dominated era where structure grows. Recently, [10] investigated a model where such a transition occurred after recombination. However, they kept the fluctuation sound speed in the dark energy to be the speed of light, reducing the effect of perturbations, and adopted a purely phenomenological model for the density evolution.

Because the model here behaves like dark matter in both the expansion and perturbations at times before the transition, then if the transition occurred after recombination such additional energy density would just look like added dark matter and be faced with the usual CMB constraints on the dark matter density. Therefore we concentrate on the more interesting case for our model of a prerecombination transition and adopt for the dark energy the barotropic aether [11, 12], a model with useful and interesting properties.

In Sec. II we explore the physical effects of the barotropic aether as it evolves from dark matter-like behavior at early times to cosmic acceleration at late times. We confront the model with recent CMB data in Sec. III, and discuss what this may teach us about the dark sector in Sec. IV.

II. FROM DARK MATTER TO ACCELERATION

The general models we are interested in exploring here are ones where the dark energy resembles dark matter and can be a significant fraction of the dark matter density at early times, but accelerates the expansion and has $w \approx -1$ to accord with observations at late times. In order for this to work, there must be a period where the dark energy density rapidly declines relative to the matter – what [10] called freeze out behavior – in order to satisfy both CMB constraints on the dark matter density and satisfy the growth of structure constraints during the matter dominated era. Essentially this means that the dark energy must gain a positive equation of state, such as during kination, a period of kinetic dominated dynamics where $w = +1$. This will constrain the physical classes viable to produce this scenario.

A. Models

We approach this problem through the barotropic aether model [11, 12], which is well suited to these behaviors, rather than through attempts to actually unify dark energy and dark matter. Such unified models often have issues with incompleteness, e.g. how perturbations behave, fine tuning or difficulties matching observations.

For example, one approach is to tailor a scalar field potential to give exactly the density evolution behavior desired. Inverse power law potentials, for example, have attractor solutions where the dark energy density scales as some power of the expansion factor [13]. The dark energy equation of state is $w = (nw_b - 2)/(n + 2)$ for power law index $-n$ and background equation of state w_b, so by taking $n = 6$ one can arrange dark energy to track the matter density during radiation domination. However to institute the kination phase, the potential has to steepen drastically, à la slinky model [14], and then become shallow to allow for late time acceleration. This seems quite fine tuned.

A second approach is to allow explicit interactions between dark matter and dark energy. Such a scenario can lead to a constant ratio between their densities, or at least a long period where they are comparable, but generally within the matter dominated rather than radiation dominated era. An interaction term

$$\Gamma = 3wH \left[\frac{1}{\rho_{de}} + \frac{1}{\rho_{dm}} \right]^{-1} ,\tag{1}$$

entering with opposite signs in the $\dot{\rho}_{de}$ and $\dot{\rho}_{dm}$ evolution equations, where w is the bare equation of state of the dark energy and $H = \dot{a}/a$ is the Hubble parameter, will give $w_{de} = w_{dm}$. But endowing dark matter with even a small amount of pressure tends to cause disagreements with observations, certainly during the matter dominated era where it causes a large integrated Sachs-Wolfe signal

in the CMB. Furthermore, there is no clear mechanism to later obtain kination, and then acceleration, which would require Γ to change sign. This also introduces two arbitrary functions: the scalar field potential and the interaction.

Another class of models that are related to the barotropic aether is based on phenomenological properties of the dark fluid. Interesting examples are the generalized Chaplygin gas [15] and the condensate cosmology [16]. These are all motivated by unifying dark energy and dark matter to one dark fluid in the early universe. Physically, this seems problematic as these two dark species must simultaneously exist today, and have been invoked to explain very different and apparently incompatible phenomena. One provides extra gravitational attraction on small length scales, and the other seems to cause gravitational repulsion on large length scales. One appears to aggregate and clump, and the other appears to be very smooth. On the other hand, it seems reasonable to explore connections between the two species, such as interactions or a possible related origin in a dark sector.

One could also attempt to carry out the desired dynamical evolution by changing the kinetic structure of the theory, i.e. using a k-essence model [17, 18]. This also avoids the necessity for a potential (e.g. [11, 19]) and adds richness to the perturbation evolution by determining a time varying sound speed. However the structure of the kinetic function would need to be essentially as complicated as the scalar field potential in the quintessence approach. The barotropic aether we next consider is closely related to k-essence but with a simpler structure and with desirable properties that ameliorate many of the issues.

B. Barotropic Aether

The barotropic aether model has the advantages that it has some physical foundation – the pressure is an explicit function of the energy density – it can be viewed as a purely kinetic k-essence model or a quintessence model, and its phase space evolution is nontrivial, allowing a rapid freezeout of the aether component and approach to current acceleration.

Barotropic models have the same number of degrees of freedom as quintessence models, but also allow the sound speed to differ from the speed of light. In contrast, a quintessence scalar field that scales like matter with vanishing pressure, $w = 0$, does not cluster like dark matter since it still possesses a relativistic sound speed, equal to the speed of light. For barotropic models, the sound speed is determined by the equation of state, or vice versa, and barotropic aether models can have both $w = 0$ and $c_s = 0$. The dynamics of barotropic models is given by

$$\frac{d\,w}{d\ln a} = -3(1 + w)(c_s^2 - w) ,\tag{2}$$

so we can write $w(c_s)$ or $c_s(w)$, i.e. we only have to specify one function. Note that for these dynamics we have $c_s^2 = \delta p/\delta \rho$. There is also an attractor solution to $w = -1$, exactly what we need for late time acceleration. As pointed out by [12], the transition to $w = -1$ is quite rapid, usually within an e-fold, validating the observation of a present value close to -1.

If we model the early time behavior such that $c_s \to 0$ or $w \to 0$ (one enforces the other), then we also have a partial solution to the coincidence problem, in that there can be a period with a constant ratio of dark energy to dark matter densities. These characteristics – early time scaling, rapid transition, late time $w = -1$ – motivate consideration of the barotropic aether early dark energy as an effective transition model.

Since the late time behavior of the aether models converges on the de Sitter state with $w = -1$, we can consider the barotropic energy density as the sum of a constant and the deviations from the asymptotic density, $\rho_{de} = \rho_\infty + \rho_{ae}$. Indeed [12] showed that one can always split a barotropic model into a constant density piece and an "aether" piece that is itself barotropic and has positive equation of state $0 \leq w_{ae} \leq 1$. We therefore choose w_{ae} to go from 0 in the past to 1 at later times, using the e-fold form

$$w_{ae}(a) = \frac{1}{1 + (a_t/a)^{1/\tau}} \ , \qquad (3)$$

where a_t is the transition scale factor and τ is the rapidity of the transition in e-folds of expansion factor. This then determines all the dynamics, with the total dark energy equation of state given by

$$w(a) = w_{ae}\frac{\rho_{ae}}{\rho_{de}} - \frac{\rho_\infty}{\rho_{de}} \qquad (4)$$

$$= -1 + (1 + w_{ae})\frac{\rho_{ae}}{\rho_{de}} \ , \qquad (5)$$

going from 0 in the distant past, to 1 just after the transition, to -1 at late times, and the sound speed given by

$$c_s^2 = \frac{1}{1 + (a_t/a)^{1/\tau}} \left[1 - \frac{1}{3\tau}\frac{1}{1 + 2(a/a_t)^{1/\tau}} \right] \ , \qquad (6)$$

going from 0 at early times to 1 at late times.

The form for w_{ae} in Eq. (3) allows analytic calculation of the energy density

$$\rho_{ae}(a) = \rho_{ae,0}\, a^{-3} \left(1 + a_t^{-1/\tau} \right)^{3\tau} \left[1 + \left(\frac{a}{a_t} \right)^{1/\tau} \right]^{-3\tau} \qquad (7)$$

where the scale factor $a = 1$ at the present day. At early times this evolves as a^{-3}, leading to a constant density ratio $R = [\rho_{de}/\rho_m](a \ll a_t)$ relative to matter (independent of whether the expansion is dominated by radiation or matter), and then at times later than the transition it dies off quickly as a^{-6}, as for a free field. In this sense, we regard a_t as the transition to freeze out.

Figure 1 illustrates these behaviors. We have three parameters: the time of transition a_t, width of transition τ, and asymptotic early time ratio R of dark energy to dark matter density. The last quantity also determines the present ratio of the aether piece to the constant density in the dark energy.
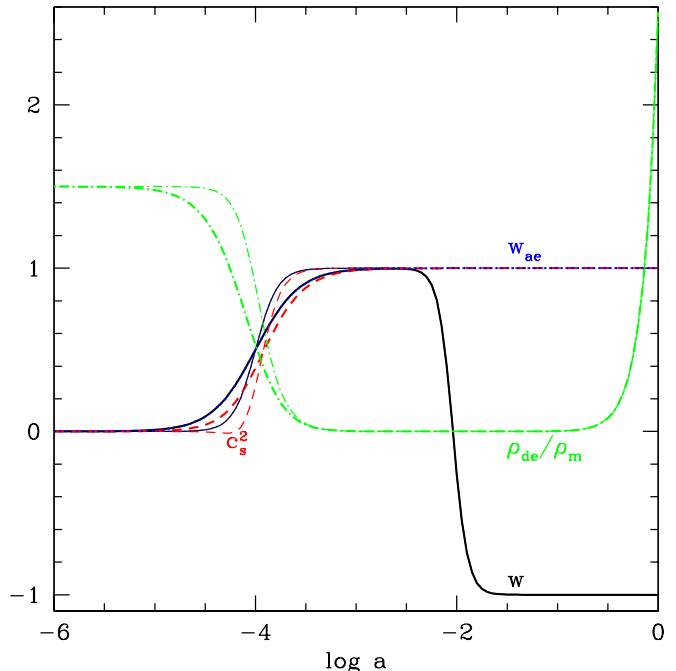

FIG. 1. For the barotropic aether we plot the ratio of the total dark energy density to the matter density ρ_{de}/ρ_m, the total dark energy equation of state parameter w, the dark energy sound speed squared c_s^2, and the aether equation of state parameter w_{ae}. Thick curves take $\tau = 0.5$, thin curves $\tau = 0.25$, with both having $a_t = 10^{-4}$ and $R = \rho_{de}/\rho_m(a \ll a_t) = 1.5$.

We see several interesting properties. Due to the rapidity of the transition, if the transition takes place sufficiently before recombination then the dark energy does not affect the dark matter component at recombination, and the CMB power spectra should show little effect. (Note that [10] considered transitions after recombination to avoid disturbing the CMB power spectra.) Nevertheless for the earlier history of the universe there can be a tie between the components of the dark sector, possibly alleviating the coincidence problem. While at late times, w is extremely close to -1 and the ΛCDM model is an excellent approximation.

However, signatures exist around the transition. The sound speed begins to deviate from 0, as w_{ae} deviates from 0, and so the dark energy acts differently from dark matter, changing the evolution of matter perturbations and the matter density power spectrum. Indeed, the dark energy itself can start to cluster, but this is usually a smaller effect than its influence (through the gravitational potential) on the matter (see, e.g., [20]). For a rapid transition, with $\tau < 1/3$, there is an epoch with

$c_s^2 < 0$, which leads to instabilities in the dark energy clustering; therefore we only consider $\tau > 1/3$. For slower transitions the distinction between the dark energy and dark matter starts sooner and the dark energy density declines to lower values more quickly, leading to smaller signatures. For $\tau \gg 1$, the model approaches ΛCDM.

It is instructive to analyze the dependence of the equation of state (EOS) of the aether, Eq. (5), on the model parameters. The transition scale factor a_t determines the time when the EOS deviates from dark matter behavior $w = 0$ and rises up to aether domination $w \to 1$. The subsequent rapid redshifting and drop to the dark energy attractor behavior $w \to -1$ gets delayed for large values of R. Nevertheless, as we later see, R will generally be constrained to be at most a few percent for late time transitions, so the dark energy reaches its attractor behavior $w \to -1$ at redshifts well before the present. Figure 2 illustrates these dependences.
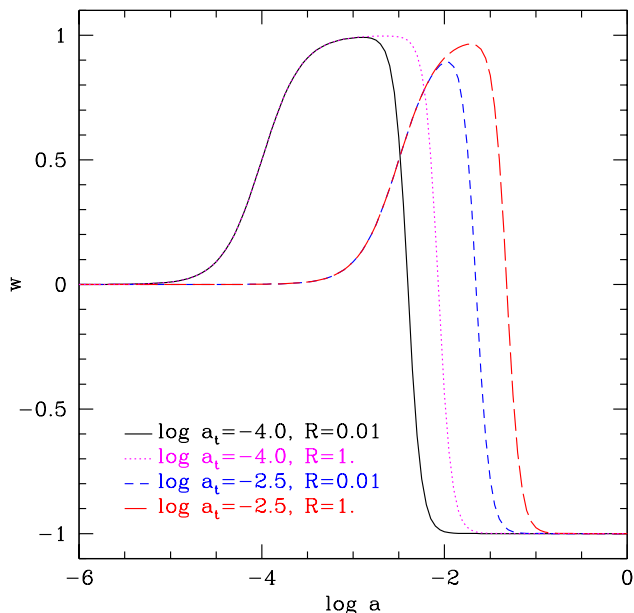

FIG. 2. The total dark energy equation of state $w(a)$ is plotted for several values of the transition scale factor a_t and early dark energy-dark matter density ratio R (for fixed $\tau = 0.5$). The location of the transition away from dark matter behavior $w = 0$ is determined by a_t and the length of aether dominated behavior ($w = 1$) by R, but at late times all curves go to the dark energy attractor with $w = -1$.

Moreover, the additional energy density of the early dark energy changes the expansion rate of the universe (assuming we do not reduce the dark matter density to compensate). Around the time of the transition, the total dark energy equation of state w rises through the radiation value of $1/3$ while the dark energy density is still appreciable. This can be written in terms of a time

varying, additional number of effective neutrino species:

$$\Delta N_{\rm eff} = \left[\frac{7}{8} \left(\frac{4}{11} \right)^{4/3} \right]^{-1} \frac{\rho_{de}(a)}{\rho_\gamma(a)} , \qquad (8)$$

where ρ_γ is the photon energy density and the numerical factors arise from converting to effective neutrino species.

Figure 3 shows the induced $\Delta N_{\rm eff}$ for various cases of transition time and width. The more rapid the transition (smaller τ), the longer the dark energy density has been preserved and so the larger $\Delta N_{\rm eff}$. Holding the ratio R fixed but moving the transition earlier has the effect of lowering $\Delta N_{\rm eff}$ since the radiation density was higher at those early times; conversely a later transition would enhance the bump in $\Delta N_{\rm eff}$. Finally, the amplitude of the bump scales linearly with R. CMB data should be sensitive to the value of $\Delta N_{\rm eff}$ near recombination. In particular, note that

$$\Delta N_{\rm eff} \approx \left(\frac{a}{10^{-3}} \right) \left(\frac{\rho_{de}(a)/\rho_m(a)}{0.04} \right) . \qquad (9)$$
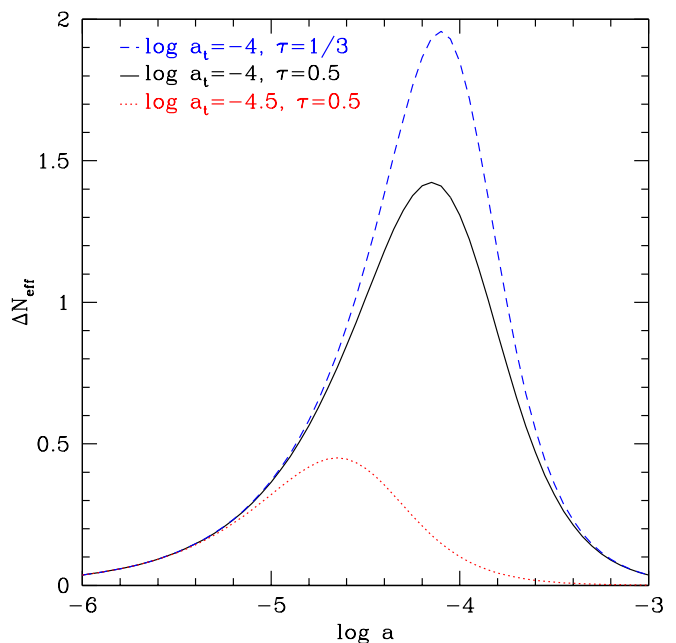

FIG. 3. The effective number of extra neutrino species equivalent to the early dark energy density is plotted vs scale factor for different cases of the transition scale factor a_t and width τ, with fixed $R = 1.5$.

The perturbation equations for the barotropic aether are all standard and follow from the Einstein equations by including the property of barotropy that $\delta P/\delta\rho = c_s^2$. With this, in the synchronous gauge using the definitions from [21] we get

$$\delta' = -(1+w) \left(\theta + \frac{h'}{2} \right) - 3 \frac{a'}{a} \left(c_s^2 - w \right) \delta$$

together with

$$\theta' = -\frac{a'}{a}(1-3w)\theta - \frac{w'}{1+w}\theta + \frac{c_s^2}{1+w}k^2\delta$$

where derivatives are taken with respect to conformal time. The matter density perturbation is defined by $\delta = \delta\rho/\rho$ and θ is the divergence of the fluid velocity $\theta = \nabla^j v_j$, while h is the trace of the metric perturbation.

The effect of the barotropic aether on the CMB power spectrum is displayed in Fig. 4, for various choices of parameters that we will later see give deviations from ΛCDM at between 68–95% confidence level for current data. Deviations in the power spectrum at the 1% level, too small to be seen by eye, can still be distinguished by data. Note that a post-recombination transition affects all acoustic peaks due to the geometric shift and can easily be detected, while pre-recombination transitions have more influence on the higher multipole damping tail.
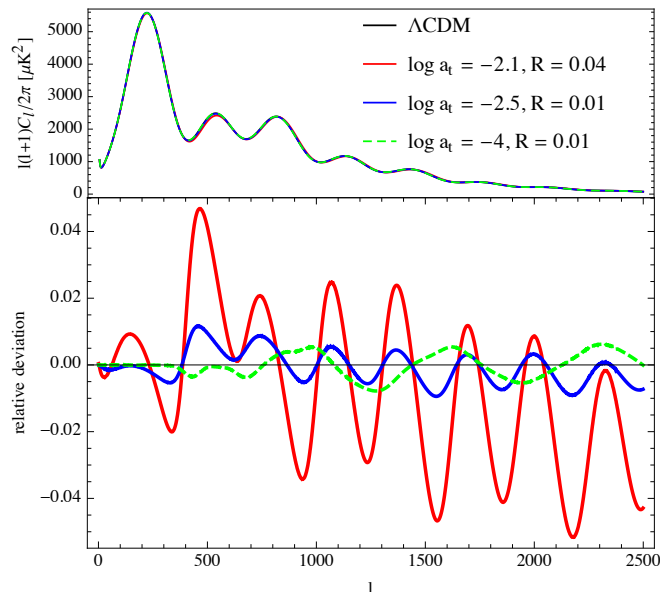

FIG. 4. The CMB temperature power spectrum for ΛCDM and several barotropic aether models are shown (top panel) along with the relative deviations from ΛCDM (bottom panel). Post-recombination transitions can be readily distinguished while subpercent level pre-recombination models are consistent with data. For this plot we fix the other cosmological parameters and set $\tau = 1$.

III. CONSTRAINTS FROM DATA

The dark energy component affects the CMB fluctuations through changing the expansion rate (including the time of "matter"-radiation equality and effective relativistic degrees of freedom) and perturbation evolution. The dominant effect tends to be from the expansion rate and so depends mostly on the dark energy density contribution. From Eq. (7) the energy density has a nonlinear

dependence on the transition location a_t and width τ, while scaling linearly with R. We can relate the dark energy to matter density ratio at CMB last scattering to its early time asymptote by

$$\frac{\rho_{de}(a_{\mathrm{lss}})}{\rho_m(a_{\mathrm{lss}})} = R \left[1 + \left(\frac{a_{\mathrm{lss}}}{a_t}\right)^{1/\tau}\right]^{-3\tau}. \qquad (10)$$

As a guide, if we want to keep the dark energy contribution at last scattering to below some number, say 0.4% as a rough limit from Planck ([8], for a different, specific early dark energy model), then this defines an allowed region in the R-a_t-τ space. Figure 5 illustrates this region in the R-τ plane for various slices of a_t.
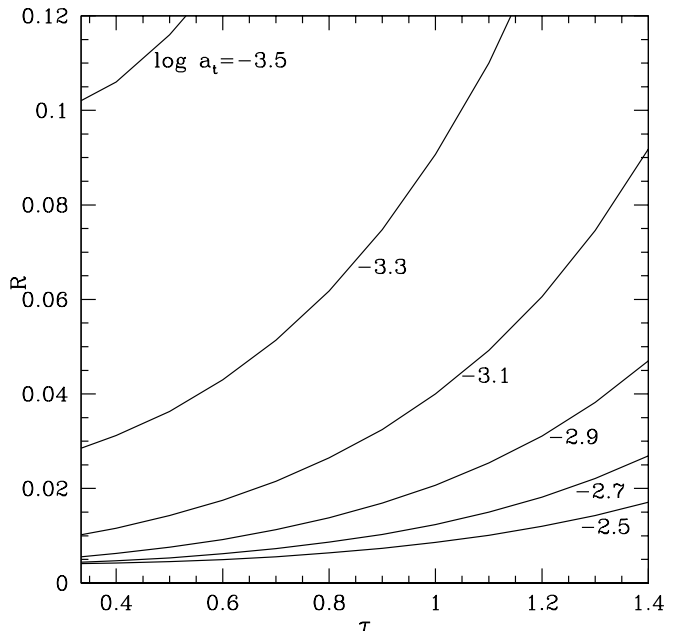

FIG. 5. Assuming a bound on the dark energy to dark matter density at recombination imposes constraints on the dark energy parameters. Here for an upper bound of 0.4%, only the parameter space below the respective $\log a_t$ curves is allowed.

The area below each curve is allowed, and we see that as the transition moves to much earlier times before recombination ($\log a_{\mathrm{lss}} = -3.04$) then much larger values of the asymptotic dark energy to dark matter density ratio R are permitted. Indeed for $a_t \ll a_{\mathrm{lss}}$ the ratio R grows as a_t^{-3} so for $\log a_t = -3.9$ (-4.3) we can have early dark energy dominating dark matter by R up to 1.5 (24), for any valid value of $\tau > 1/3$, and still expect to have good agreement with CMB measurements.

For robust constraints we modify CAMB inside CosmoMC [22] to include the barotropic dark energy component. To constrain cosmology, including the new parameters of this theory $\{R, \tau, a_t\}$, we use CMB data from the Planck satellite [23] including the lensing potential. We complement the high-multipole tail with ACT and SPT data [24–26] extending up to multipole $l \sim 3000$. To help

break other degeneracies we use the Hubble constant constraints from HST data [27]. Large scale structure data is included from the WiggleZ [28] survey with GiggleZ corrections [29], along with BAO data from the Sloan Digital Sky Survey (SDSS) DR9, DR7 [30, 31] and the Anglo-Australian Observatory (AAO) 6DF survey [32]. Supernova data is taken from the Union 2.1 sample [33].

Our Markov Chain Monte Carlo (MCMC) analysis has 40 parameters, including the 6 standard cosmology parameters (a flat universe is assumed), 3 dark energy parameters, and the rest deal with instrumental and foreground effects. We let five chains run independently from each other to check convergence using the Gelman and Rubin (variance of chain means)/(mean of chain variances) R_{GR} statistic [34]. At the end of the MCMC run the worst-performing parameter with respect to this statistic, a_t, reached $R_{GR} = 0.00115$. This demonstrates excellent chain convergence.

Since for early a_t the constraints loosen drastically, as implied by Fig. 5, in our MCMC fitting of the model to data we will only consider the range $\log a_t \in [-3.3, -2.0]$. We do not extend the range to later times since the growth of cosmic structure rather than the CMB will impose the main constraints there, and the trend is already clear as discussed later in this section; furthermore similar late-time constraints were shown by [10] for another transition model. Given that large τ moves the model closer and closer to ΛCDM, we only consider the range $\tau \in [0.33, 1.2]$. Finally, because we have no a priori expected value for R, we use a logarithmic range of $\log R \in [-3.0, -1.3]$. We only expect larger R to be allowed in the presence of large τ or early a_t, where constraints are weak. We have also tested wider prior bounds on $\log a_t$ and confirmed that the interesting behavior happens in the range used above; for early a_t there is no constraining power since even large R (initial dark energy to dark matter ratio) fades by the time of recombination.

Figure 6 shows the dark energy and dark matter joint constraints. The physics behind the dark energy influence can be clearly traced. Low values of R, early values of a_t, and large values of τ are all mildly preferred. These each push the model in a direction consistent with ΛCDM. The best fit parameters for this dark energy model give a likelihood with $\Delta\chi^2 = 6$ below ΛCDM, with 3 more parameters.

First consider transitions earlier than the recombination epoch. The data has little constraining power because even for high values of R a wide range of τ is allowed that gives sufficient time for the dark energy to fade away by recombination. At these early times, the dark energy is mimicking dark matter but less perfectly as the transition time approaches. As its sound speed and equation of state climbs above zero, this starts to cause decay of early dark matter gravitational potentials; to compensate for this (in the brief period before the dark energy fades to insignificance) the dark matter density needs to be slightly higher.

For later transitions, the fit of this dark energy model

to the data holds only for progressively smaller values of R. For modest values of R there is a complicated interplay between the dark energy density at last scattering and its behavior (w and c_s). If the transition away from dark matter behavior ($w = 0$, $c_s = 0$) starts to happen before recombination, and there is sufficient dark energy density for this deviation to have physical effect, then the data disfavor this behavior. At a given $\log a_t$ after recombination, large τ causes the dark energy behavior to deviate before recombination, but the dark energy density fades more quickly (see Fig. 1), and the model may be viable. Conversely, small τ preserves the matter-like dark energy behavior at recombination, and again the model can survive. However, for moderate τ the rate of fall of the dark energy density and the rise of the deviation in w and c_s can balance sufficiently to have an appreciable effect on the CMB (decaying gravitational potentials), which is disfavored by the data. Since the deviation occurs roughly at $\log a \approx \log a_t + \tau$, this region (for sufficiently large R) is disfavored, leading to the "blank stripe" seen in the joint confidence contour of $\log a_t$–τ.

This interaction between the parameters is made clearer by showing the confidence contours when selecting from the MCMC chains only those entries with various levels of R. Figures 7 and 8 illustrate the physical effects we have discussed. For example, for $R > 0.02$, only very early a_t is allowed, so the early dark energy can fade away appreciably by recombination (this is further helped by large τ, which causes the fade to start earlier). For $R > 0.01$, we add a region allowing late time transitions, but with relatively low R, and these can have smaller τ as well. Note the "blank stripe" in the $\log a_t$–τ plane starts to narrow relative to the $R > 0.02$ plot as the lower R means the deviation of the dark energy behavior from dark matter has less impact. For $R < 0.01$ even more of the parameter space is allowed.

In summary, as a rule of thumb the data favors those regions of parameter space that are not too different from a ΛCDM-like cosmology. Note from Eqs. (9) and (10) that a 95% CL bound of $R \lesssim 0.05$ for $a_t = 10^{-3}$, say, implies $\Delta N_{\rm eff} \lesssim 0.5$.

IV. CONCLUSIONS

The dark sector of the Universe presents us with multiple, fundamental mysteries. Observations concentrate at the present epoch, where two quite distinct components appear: clustering, pressureless dark matter and highly smooth, strongly negative pressure dark energy. Within the visible sector of the Universe, the Standard Model of particle physics teaches us that apparently distinct entities can be unified at high energies, corresponding to early times in cosmic history. We have explored a phenomenological model for such a merging of dark matter and dark energy at early times, where barotropic aether dark energy has the properties of dark matter,
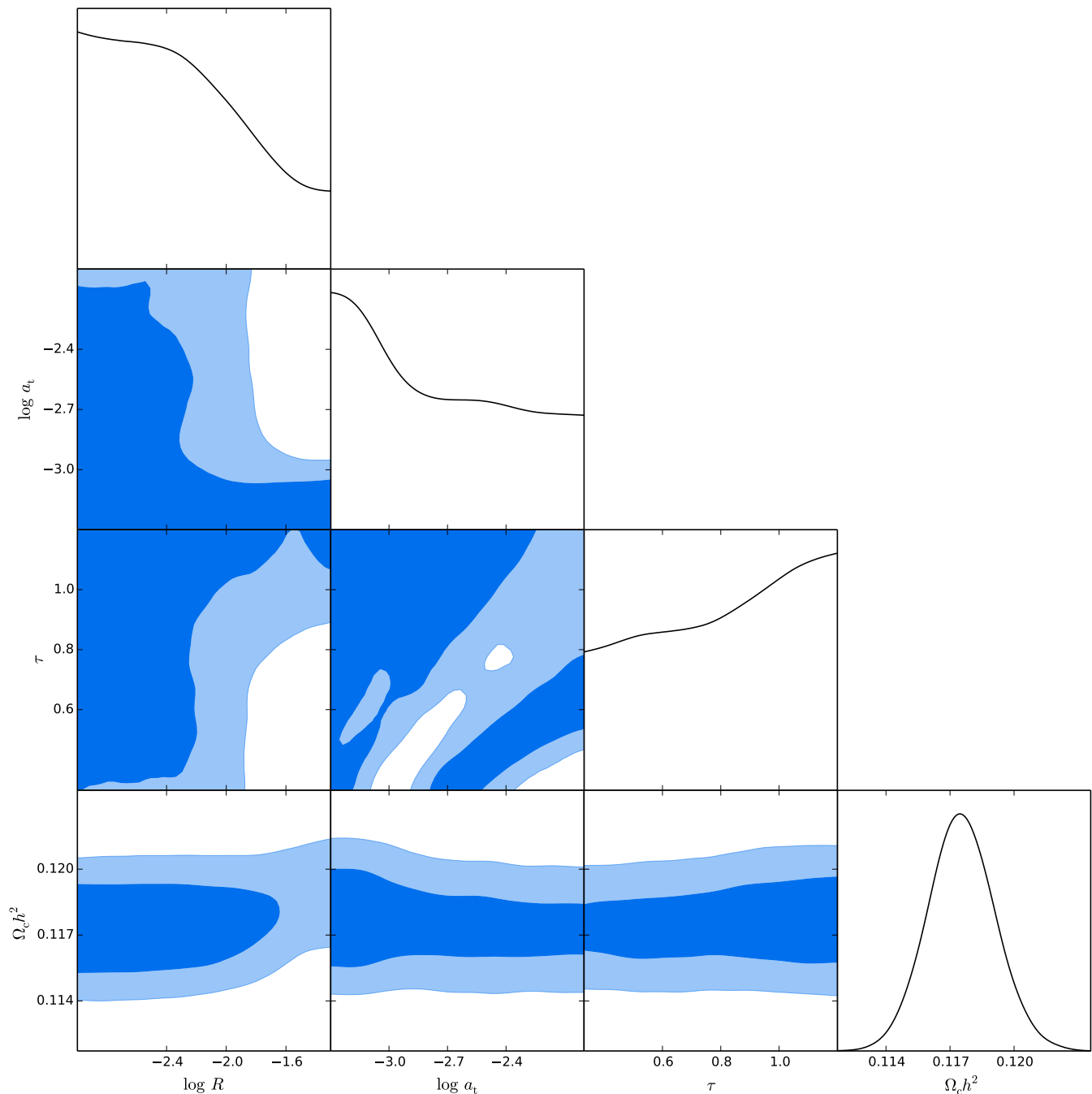
FIG. 6. 2D joint confidence contours at 68% CL (dark) and 95% CL (light) are shown for the dark energy and dark matter parameters, marginalized over all other parameters. The fully marginalized 1D PDFs are shown on the diagonal.

perhaps through some unspecified direct interaction. At late times this behavior is gone, releasing the two components to evolve very differently.

A barotropic aether model has the desired properties of naturally appearing like dark matter ($w = 0 = c_s^2$) at early times, and then a very rapid evolution away, toward a late time attractor with $w = -1$ and $c_s^2 = 1$, acting like a cosmological constant. This would give added, rich structure to the dark sector and, if confirmed,

a substantial clue to high energy physics. We show that the transition in this model cannot take place arbitrarily rapidly, but must take longer than a number of e-folds $\tau \geq 1/3$.

Confronting this model with current data, we find that such a model is wholly acceptable if the transition occurs sufficiently before recombination. For example, the asymptotic early ratio of dark energy to dark matter density can be larger than unity if the transition is at
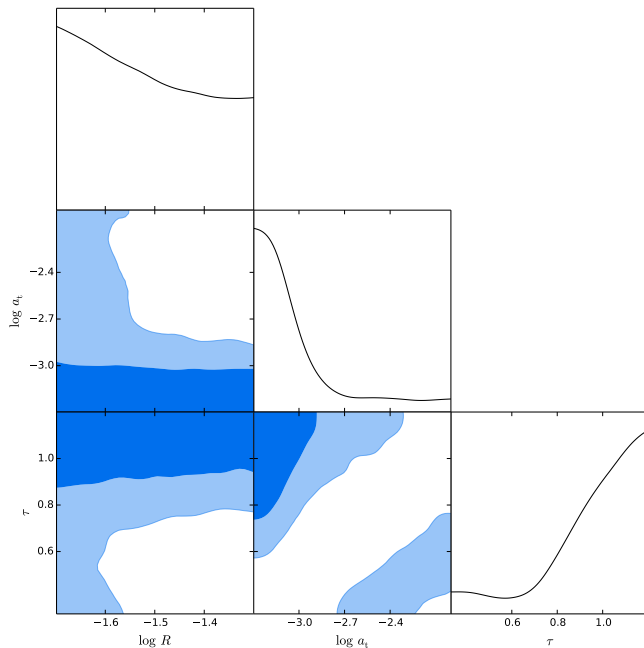
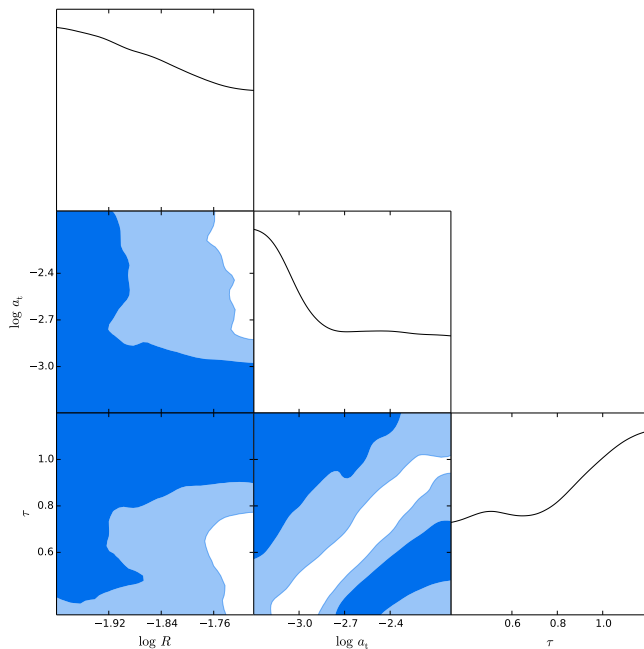FIG. 7. As Figure 6, but restricted to $R > 0.02$.

FIG. 8. As Figure 6, but restricted to $0.01 < R < 0.02$.

$a_t < 10^{-3.84}$, or larger than 100 for $a_t < 10^{-4.5}$.

Later transitions however are severely constrained by data, especially the CMB temperature power spectrum. We find that the early dark energy to dark matter density ratio cannot exceed 5%, similar to other early dark energy models, for transitions much after recombination. Even later transitions have been constrained by other work, e.g. [10]. Even so, a ratio $R = 0.025$ at, say,

$a_t = 10^{-3}$ can contribute energy density interpreted in terms of an effective number of extra neutrino species of $\Delta N_{\text{eff}} = 0.25$. Thus early dark energy remains of interest.

An interesting generalization is to consider a whole spectrum of barotropic fields, with all allowed values of sound speed $c_s^2 = [0, 1]$ (see Appendix A). This scenario has intriguing properties, with each component dominating in sequence and then fading away, similar to isotopes with different half lives. Because of the physical constraint $c_s^2 \geq 0$ the late time universe is left with only the $c_s^2 = 0$ component of dark energy, corresponding to the barotropic aether considered here. However, while somewhat attractive as a way to avoid naturally a coincidence that dark energy only dominates today, it does suffer from increased fine tuning (unless a way can be found to cancel the positive and negative contributions).

If the dark sector does come together at high energies, we might expect the transition epoch not to be at eV scales ($\log a_t \approx -3$), but at GeV or higher scales. As this is above the primordial nucleosynthesis scale, observational constraints are lacking. Future work will explore whether inflation – a very early dark energy period – can constrain or benefit from such "mimic" dark energy.

Appendix A: A Spectrum of Barotropy

Barotropic fluids can present a partial solution to the question of why $w \approx -1$ today, due to their rapid attraction to a de Sitter state. We have also used them to influence the early expansion, through an unspecified interaction that makes them behave as matter in the early universe.

Some attempts to solve the coincidence problem ask whether dark energy could have occasional influence, at several epochs early on. This does not necessarily require acceleration – which in any case was ruled out for the last factor 10^5 of expansion before the present epoch [35] – but simply to be dynamically relevant. This can be done with a single scalar field with a sufficiently sculpted potential, e.g. [14, 36], or with a spectrum of fields [37–39]. To avoid fine tuning, [38] took exponential scalar field potentials that trace the background energy density (keep a constant ratio, see [40, 41]), but the parameters of tracer dark energy necessary to give acceptable later

conditions such as $w \approx -1$ then exceed early time observational bounds, making it difficult for dark energy to impact expansion at a variety of epochs.

Here we briefly speculate about applying the idea of a spectrum of fields to the barotropic case. We emphasize that this is independent from the rest of the article, but perhaps it may motivate further ideas.

Suppose we have a suite of barotropic fluids with a spectrum of sound speeds between 0 and 1 (recall that the sound speed determines the full barotropic dynamics). Those fluids with $c_s^2 > 1/3$ may dominate in the early universe, but their energy density quickly redshifts away, as

$$\rho_{de,j} \sim e^{-3(1+c_{s,j}^2)N} \sim a^{-3(1+c_{s,j}^2)} , \qquad (A1)$$

where $N = \ln a$ is the e-folding parameter, leaving radiation to dominate. We just must ensure that they fade before primordial nucleosynthesis.

Those fluids with $0 < c_s^2 < 1/3$ may affect the transition from radiation to matter domination, but this need not be fatal. In fact, their energy density will give an effective number of neutrino species $N_{\rm eff} > 3.046$, which may accord with the data. They will also fade away as matter comes to dominate. Again, we must make sure they fade before matter dominated growth is affected.

However, since the lower limit for stable barotropic flu-

ids is $c_s^2 = 0$, then once matter dominates the only effect from the barotropic dark energy arises from the constant density piece. This effectively explains why there is no acceleration or dark energy influence from recombination until the present epoch of acceleration: barotropic dark energy *can* be an occasional phenomenon but once matter dominates then dark energy automatically appears as an approach to a de Sitter state. This is an attractive property of this speculative model.

Note that we have in no way solved the fine tuning issue, since barotropic fluids are not tracing fields (their evolution is determined by their sound speed, not dynamically attracted to scale in proportion to the background fluid). Indeed, we have exacerbated it since each fluid in the spectrum has conditions on its amplitude. One intriguing possibility is that the constant density pieces of each barotropic fluid do not all have to be positive. If some are positive and some negative, perhaps there is some way to enforce cancellation to more naturally end up with a small constant density.

Thus the idea of using a spectrum of fields has some promising aspects, with the advantage of barotropic fluids that they quickly fade to $w \approx -1$, but fine tuning remains. This is the converse of solving fine tuning through tracing fields (which though, since they never fade, are not viable).

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