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Dark energy from the motions of neutrinos

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ABSTRACT

Ordinarily, a scalar field may only play the role of dark energy if it possesses a potential that is either extraordinarily flat or extremely fine-tuned. Here we demonstrate that these restrictions are lifted when the scalar field undergoes persistent energy exchange with another fluid. In this scenario, the field is prevented from reversing its direction of motion, and instead may come to rest while displaced from the local minimum of its potential. Therefore almost any scalar potential is capable of initiating a prolonged phase of cosmic acceleration. If the rate of energy transfer is modulated via a derivative coupling, the field undergoes a rapid process of freezing, after which the field's equation of state mimicks that of a cosmological constant. We present a physically motivated realisation in the form of a neutrino–majoron coupling, which avoids the dynamical instabilities associated with mass-varying neutrino models. Finally we discuss possible means by which this model could be experimentally verified.

1. Introduction

In the standard Lambda Cold Dark Matter (ΛCDM) paradigm, the hierarchy of the four key contributors to the cosmic energy budget (photons, neutrinos, dark matter, dark energy) has inverted over the past ten e-folds. This necessarily involved six points of equality, in addition to other notable events such as recombination and the onset of nonlinear structure formation.

The traditional coincidence problem in cosmology, casually stated as "why now?", relates to the close proximity in scale factor between our existence and the onset of dark energy domination. This is arguably the most straightforward coincidence to resolve - in the simplest models (see e.g. Carter and McCrea [1]), the emergence of complex life represents a Poissonian sample in time (as opposed to a sample of the logarithmic scale factor). Therefore if the Universe were to recollapse or rip within the next trillion years, our existence is not especially close to the onset of dark energy. Some of the other coincidences appear more stubborn, however. Why did the four major contributors to the cosmic energy budget all cross paths with each other in rapid succession?

The seemingly congested cosmic timeline, as outlined in Table 1, can be remedied by the presence of correlations between different events. For example, nonlinear structure formation was catalysed by the onset of matter domination, so they ought not to be interpreted as wholly independent events. Can we reduce this list of four independent events still further? In particular, could the onset of dark energy be a direct consequence of another recent event? Upper bounds on the coupling strength between dark energy, dark matter, and neutrinos (see e.g. [2,3]) are extremely weak compared to interactions between particles in the Standard Model [4]. It is therefore feasible that non-gravitational interactions are present, and were responsible for instigating the current period of cosmic acceleration.

A number of models have been proposed which invoke energy exchange between a scalar field and a second fluid [5]. The possibility that neutrinos act as the second fluid is in part motivated by the approximate equivalence of the neutrino mass and the energy scale of dark energy (i.e. $\rho_\Lambda^{1/4}$). Scenarios in which the neutrino mass is modulated by a scalar field have already been investigated in some detail [6–10]. However these models tend to suffer from instabilities in their perturbations [11]. More recently, a class of models involving a derivative coupling at the fluid level was presented in Ref. [12], and explored further by Refs. [13–15].

In this work we shall first explore the generic means by which energy exchange can facilitate the formation of dark energy. Then we present the particular case of a derivative coupling at the particle level, between neutrinos and a scalar field.

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Table 1
A selection of recent cosmic events. A minimum of three distinct events are required in order for the four fluids to reverse their positions in the density hierarchy (since reordering N objects requires $N-1$ moves). These are represented here by three moments of equality. Known correlations limit the number of independent events in this table to four. As-yet undiscovered correlations may further reduce this number.

Event	Scale factor	Correlations
1) Matter-Radiation Equality	$10^{-3.5}$	
2) Recombination	10^{-3}	
3) Neutrinos become non-relativistic	10^{-2}	
4) Dark Energy - Matter Equality	1	
5) Neutrino-Radiation Equality	10^{-2}	Caused by (3)
6) Nonlinear Density Perturbations	10^{-1}	Requires (1)
7) Our Existence	1	Requires (6)

2. Freezing a scalar field

In the presence of energy exchange, the Klein–Gordon equation for the evolution of a scalar field ϕ is given by [16,17]

$$\ddot{\phi} + 3H\dot{\phi} + V_\phi = -\frac{Q}{\dot{\phi}}\,, \tag{1}$$

where $V_\phi \equiv \mathrm{d}V/\mathrm{d}\phi$, overdots denote derivative with respect to time t, and the coupling term Q dictates the rate at which the field loses energy to a secondary fluid X, whose coupled equation of motion may be expressed as

$$\dot{\rho}_X + 3H(p_X + \rho_X) = Q\,. \tag{2}$$

A derivation of these expressions is provided in the Appendix. To proceed, we shall work in terms of the normalised energy transfer rate, defined such that $q(t) \equiv Q\ddot{\phi}^{-1}$.

If a scalar field is to reverse its direction of motion, it must pass through a point in phase space which satisfies $\dot{\phi} = 0$. Before reaching this turning point, it will necessarily enter a regime which satisfies $|\dot{\phi}| \ll |q|$ and $|\dot{\phi}| \ll |V_\phi H^{-1}|$, provided the gradient V_ϕ is non-zero. In which case, the dynamics of Eq. (1) simplify to the following form

$$\ddot{\phi} = -\left[\frac{V_\phi}{q}\right]\dot{\phi}\,. \tag{3}$$

Instead of acting with its full 'force', the influence of the potential V_ϕ is progressively weakened as the scalar slows. The general solution for $\phi(t)$ is given by

$$\phi(t) = \phi(t_0) + \dot{\phi}(t_0)\int_{t_0}^{t} \exp\left[-\int_{t_0}^{t'} \frac{V_\phi(t'')}{q(t'')}\mathrm{d}t''\right]\mathrm{d}t'\,. \tag{4}$$

The integrand remains positive for all t, ensuring $\phi(t)$ is monotonic. The kinetic term is damped on a timescale given by $T_d \sim \frac{q}{V_\phi}$. Provided $\dot{T}_d \ll 1$, the decay of the kinetic term is well approximated by

$$\dot{\phi} \propto \exp\left(-\frac{V_\phi}{q}t\right)\,. \tag{5}$$

Despite the presence of a gradient in the potential V_ϕ, the scalar is prevented from rolling backwards ($\dot{\phi} < 0$) due to the presence of the coupling term. This holds for any energy transfer Q that does not vanish as the field comes to rest. In other words, while any positive energy transfer persists, the field is never allowed to arrive at a complete stop. This is also evident from the right hand side of Eq. (1), which would be pathological if we ever reached $\dot{\phi} = 0$. It should be stressed that this process is not a peculiar feature of scalar fields. Entirely analogous behaviour can be found in the classical motion of a particle in any potential well.

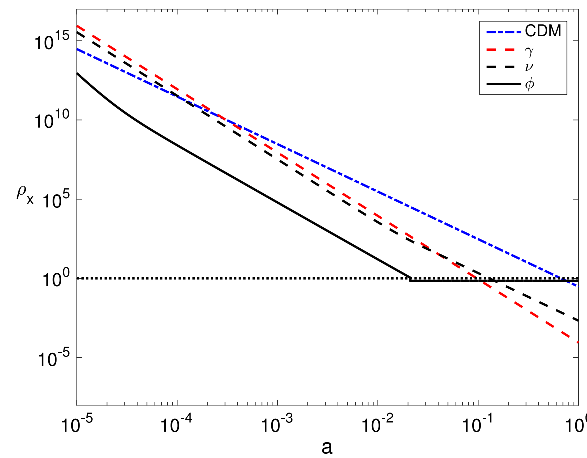

Fig. 1. The energy densities associated with the four major cosmological fluids (photons, neutrinos, dark matter, and dark energy) in units of the present day critical density. The solid line represents the decaying energy density of a derivatively coupled field ϕ which demonstrates how the dark energy could acquire its present day value, while having a negligible impact on the other fluids.

The trajectory of Eq. (5) implies that the field's equation of state $w \equiv p/\rho$, with $p = \frac{1}{2}\dot{\phi}^2 - V$ and $\rho = \frac{1}{2}\dot{\phi}^2 + V$, rapidly converges towards that of a cosmological constant,

$$w(t) \simeq -1 + [1 + w(t_0)]\exp\left[-\frac{2V_\phi}{q}(t - t_0)\right]\,. \tag{6}$$

Once frozen in place, the field's energy budget will quickly become dominated by any non-zero contribution from $V(\phi)$.

3. Direction of transfer

There are two qualitatively distinct phenomenologies which can emerge, depending on the sign of the energy transfer q. If q is positive, the field can become frozen as it climbs uphill, and this state can be maintained with a vanishingly small injection of energy. Conversely if q is negative, this leads to the extraction of kinetic energy from the scalar. This acts as a braking mechanism, allowing the field to freeze as it rolls downhill.

A broad class of scalar potentials $V(\phi)$, including the inverse power laws (ϕ^{-n}), have the attractive feature of tracking the background density [18–20]. This alleviates the fine-tuning requirements of the initial conditions. However in their simplest form, these tracking solutions produce an equation of state $w > -0.8$ [21], in conflict with cosmological observations. Yet if some energy is *extracted* from the field, then its downhill roll will grind to a halt. Much like the uphill case, a secondary fluid is capable of permanently impeding the scalar's descent, merely by intaking a vanishingly small energy flux. A simplistic example is shown in Fig. 1, where a scaling potential $V(\phi) \sim \exp(-\kappa\lambda\phi)$ ($\kappa^2 \equiv 8\pi G$) approximately follows the ambient density, $\Omega_\phi = 3\gamma/\lambda^2$, until the freezing process is initiated. In the following we shall explore a physically motivated example of how this scenario could arise.

4. Gradient coupling

In the Standard Model of particle physics, the only anomaly-free global symmetry is the difference in baryon number B and lepton number L. This fact has led in the past to proposed extensions of the Standard Model which invoke a continuous symmetry B-L [22]. The spontaneous breaking of lepton number would give rise to a massless Nambu–Goldstone (NG) boson called the majoron [23],