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Cosmology and broken scale invariance

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The cosmological consequences of a simple scalar field model for the generation of Newton's constant through the spontaneous breaking of scale invariance in a curved space are presented and discussed.

Considerable interest has been dedicated recently to the derivation of Einstein gravity as a symmetry-breaking effect.¹ In particular, so as to maintain renormalizability, the introduction of masses and dimensional parameters in the Lagrangian density is avoided and they are expected to arise through the spontaneous breaking of scale invariance introduced by scalar^{1,2} or gauge fields.^{1,3}

The purpose of this note is to examine the cosmological consequences of the following globally scale-invariant Lagrangian density for a scalar field σ in a curved space-time⁴:

$$L = -\frac{1}{2}g^{\mu\nu}\partial_\mu\sigma\partial_\nu\sigma - \frac{\lambda}{4}\sigma^4 + \frac{\gamma}{2}\sigma^2R + L_m \quad (1)$$

where γ and λ are dimensionless positive constants, R is the curvature scalar, and L_m is the matter Lagrangian density which we assume does not contain σ . In flat space the above Lagrangian density has been shown to allow for spontaneous symmetry breaking,⁵ therefore let us consider the vacuum as a condensate of scalar particles and treat the presence of matter as a perturbation about a suitable ground-state (vacuum) solution to Eq. (1). Such an approach has been shown to lead,⁶ in the weak-field limit, to essentially the same equations (up to a redefinition of the fields) as are obtained from the Brans-Dicke theory.⁷ In contrast to that case, however, here one has a background solution (prior geometry) associated with a small, but nonzero, positive cosmological constant. This work further differs from other approaches for the generation of Einstein gravity through the use of scalar fields and spontaneous symmetry breaking,² in that in the latter approach the scalar field rather than being massless, as

in our case, has a mass of the order of the Planck mass ($\sim 10^{19}$ GeV).

We therefore expect that the approach suggested by the Lagrangian density Eq. (1) will lead to cosmological predictions differing from Einstein gravity less than the Brans-Dicke theory (because of the stabilizing potential term) but more than other approaches involving massive scalar fields (or very deep potential wells) and the purpose of this note is to exhibit the results obtained.

Let us consider a Robertson-Walker universe with line element given by

$$ds^2 = -dt^2 + S^2(t) \left[\frac{dr^2}{1-kr^2} + r^2 d\theta^2 + r^2 \sin^2\theta d\phi^2 \right] \quad (2)$$

and matter behaving like an isotropic perfect fluid having energy-momentum tensor

$$T_{\mu\nu} = \rho g_{\mu\nu} + (\rho + p)u^\mu u^\nu \quad (3)$$

where $\rho(t)$, $p(t)$, and u^μ are the energy density, pressure, and velocity four-vector, respectively. The Einstein equations obtained from Eq. (1) will become

$$\ddot{\rho} - 3\frac{\dot{S}}{S}(\dot{\rho} + \dot{p}) = 0 \quad (4)$$

$$\frac{\dot{S}^2}{S^2} + \frac{\dot{S}}{S^2} = \frac{\rho}{3\gamma\sigma^2} + \frac{1}{6\gamma}\frac{\dot{\sigma}^2}{\sigma^2} - 2\frac{\dot{S}}{S}\frac{\dot{\sigma}}{\sigma} + \frac{1}{12\gamma}\lambda\sigma^2 \quad (5)$$

$$\frac{d}{dt}(\sigma\dot{\sigma}S^2) = \frac{(\rho - 3p)}{6\gamma + 1}S^2 \quad (6)$$

where the dot denotes differentiation with respect to the time t .

In the absence of matter ($\rho = p = 0$) we have the

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