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# ORDER-UNITY ARGUMENT FOR STRUCTURE-GENERATED "EXTRA" EXPANSION*

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Self-consistent treatment of cosmological structure formation and expansion within the context of classical general relativity may lead to "extra" expansion above that expected in a structureless universe. We argue that in comparison to an early-epoch, extrapolated Einstein–de Sitter model, about 10–15% "extra" expansion is sufficient at the present to render superfluous the "dark energy" 68% contribution to the energy density budget, and that this is observationally realistic.

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## 1. Introduction

In contrast to Friedmann–Lemaître–Robertson–Walker (FLRW) cosmological models, inhomogeneous curvature and inhomogeneous expansion in an initially FLRW model can be taken into account relativistically by using the spatially averaged Raychaudhuri equation and Hamiltonian constraint [1–5]. We write the latter [3, Eq. (41)] at the current epoch

$$\Omega^{\mathrm{eff}}_{\mathcal{R}0} = 1 - \Omega^{\mathrm{eff}}_{\mathrm{m}0} - \Omega^{\mathrm{eff}}_{\mathcal{Q}0}\,, \tag{1}$$

where $\Omega^{\mathrm{eff}}_{\mathcal{R}0}$, $\Omega^{\mathrm{eff}}_{\mathrm{m}0}$, and $\Omega^{\mathrm{eff}}_{\mathcal{Q}0}$ are the effective (averaged) present-day scalar (3-Ricci) curvature, matter density, and kinematical backreaction, respectively, appropriately normalised by the expansion rate squared, and we assume zero dark energy. The recent emergence of average negative scalar

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curvature ($\Omega^{\text{eff}}_{\mathcal{R}0} > 0$) in tight coupling with kinematical backreaction may lead to an effective scale factor $a_{\text{eff}}(t, P_k^{\text{init}})$, where $P_k^{\text{init}}$ is the initial power spectrum of density fluctuations, that avoids the need to introduce non-zero dark energy when matching FLRW models to observations ([1,3,6,7]; *cf.* [8]).

## 2. Early-epoch, extrapolated Einstein–de Sitter "background"

We adopt an early-epoch Einstein–de Sitter (EdS) "background" model that we extrapolate to the present, with scale factor $a_{\text{bg}}$ and expansion rate $H_{\text{bg}}$ given by

$$a_{\text{bg}} := \left(3H_1^{\text{bg}} t/2\right)^{2/3}, \qquad H_{\text{bg}} := \dot{a}_{\text{bg}}/a_{\text{bg}} = 2/(3t)\,, \tag{2}$$

where the early-epoch-normalised EdS Hubble constant $H_1^{\text{bg}} = 37.7 \pm 0.4$ km/s/Mpc is estimated by using the Planck 2015 calibration [9, Table 4, sixth data column] as a phenomenological proxy for many observational datasets [10, Eq. (11)]. For the effective scale factor to be observationally realistic, it would need to satisfy $a_{\text{eff}} \approx a_{\text{bg}}$ at early times $t \ll t_0$ and reach unity at the present $t_0 \equiv t_{a_{\text{eff}}=1}$. We assume bi-domain scalar averaging [4,8] and virialisation of collapsed (overdense) regions (stable clustering). We define a present-day background Hubble constant

$$H_0^{\text{bg}} := H_{\text{bg}}(a_{\text{eff}} = 1) \tag{3}$$

and our stable clustering assumption leads to [11, Eq. (2.27)]

$$H_0^{\text{eff}} \approx H_0^{\text{bg}} + H_{\text{pec},0}^{\text{void}}\,, \tag{4}$$

where $H_0^{\text{eff}}$ is the locally observed Hubble constant and $H_{\text{pec},0}^{\text{void}}$ is the present-day peculiar expansion rate of underdense regions, *i.e.*, typically that of voids, above that of the extrapolated background model (not a locally fit mean model).

The three Hubble constants can be related to one another thanks to matter conservation and the above equations [10, Eqs. (7), (10)]

$$H_0^{\text{bg}} = H_0^{\text{eff}} \sqrt{\Omega^{\text{eff}}_{\text{m0}}/a^3_{\text{bg0}}}\,, \qquad H_1^{\text{bg}} = H_0^{\text{eff}} \sqrt{\Omega^{\text{eff}}_{\text{m0}}} \tag{5}$$

and to the present age of the Universe via the EdS relation following from Eq. (2), *i.e.* $H_0^{\text{bg}} = 2/(3t_0)$.

## 3. Observational challenge

The above definitions and equations show that there is very little observational parameter freedom in this class of cosmological backreaction models. The Planck 2015 observational proxy $t_0 = 13.80 \pm 0.02$ Gyr gives $H_0^{\rm bg} = 47.24 \pm 0.07\,{\rm km/s/Mpc}$, yielding a present-day background scale factor of

$$a_{\rm bg0} = \left(H_1^{\rm bg}/H_0^{\rm bg}\right)^{2/3} = 0.860 \pm 0.007\,, \tag{6}$$

while microlensed Galactic bulge stars give a less FLRW-model-dependent estimate of $a_{\rm bg0} = 0.90 \pm 0.01$ [10, 12].

## 4. Conclusion

As shown in Fig. 1, only 10–15% "extra" expansion, *cf.* [13], is needed above that of the EdS background in order for a dark-energy-free cosmological backreaction model to fully replace the "dark energy" 68% contribution to the energy density budget, *i.e.* to provide an order-unity level, non-exotic alternative. The rough observational estimate of the void peculiar expansion rate [11], and the detected Sloan Digital Sky Survey environmental dependence of the baryon acoustic oscillation peak scale [14, 15] provide tentative observational support for the required $H_0^{\rm eff} - H_0^{\rm bg}$ and $a_{\rm bg0}$, respectively.

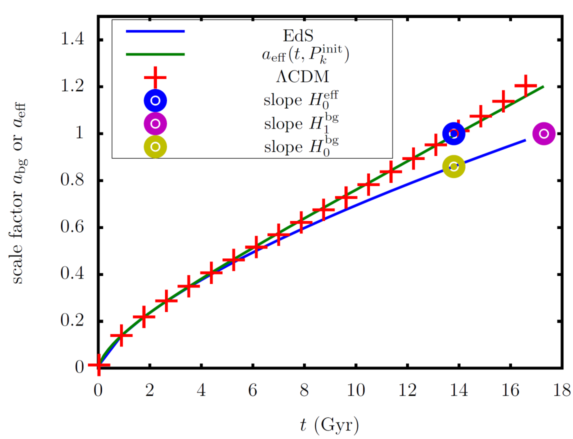


Fig. 1. (Colour on-line) Observationally required Hubble constants and required relation of the effective scale factor $a_{\rm eff}(t, P_k^{\rm init})$ (upper curve) to the background EdS scale factor $a_{\rm bg}(t)$ (lower curve). The observational proxy ($\Lambda$CDM model) is shown as + symbols. The left and right thick circular symbols at unity scale factor correspond to normalised slopes which are the locally estimated $H_0^{\rm eff}$ at $(t = 13.8\,{\rm Gyr}, a_{\rm eff} = 1)$ and the background $H_1^{\rm bg}$ at $(t = 17.3\,{\rm Gyr}, a_{\rm bg} = 1)$, while $H_0^{\rm bg}$ is the slope at $(t = 13.8\,{\rm Gyr}, a_{\rm bg0} = 0.86)$ (black/blue, grey/purple, light grey/yellow, respectively).

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