A Cosmological Concordance Model with Particle Creation

J. S. Alcaniz, H. A. Borges, S. Carneiro, J. C. Fabris, C. Pigozzo and W. Zimdahl

Abstract A constant-rate creation of dark particles in the late-time FLRW spacetime provides a cosmological model in accordance with precise observational tests. The matter creation backreaction implies in this context a vacuum energy density scaling linearly with the Hubble parameter, which is consistent with the vacuum expectation value of the QCD condensate in a low-energy expanding spacetime. Both the cosmological constant and coincidence problems are alleviated in this scenario. We discuss the cosmological model that arises in this context and present a joint analysis of observations of the first acoustic peak in the cosmic microwave background (CMB) anisotropy spectrum, the Hubble diagram for supernovas of type Ia (SNIa), the distance scale of baryonic acoustic oscillations (BAO) and the distribution of large scale structures (LSS). We show that a good concordance is obtained, albeit with a higher value of the present matter abundance than in the standard model.

The understanding of the gravitational role of vacuum fluctuations is in general a difficult problem, since their energy density usually depends on the renormalization method used and on an adequate definition of the vacuum state in the curved background. In the case of free massless fields in de Sitter spacetime, the renormalized vacuum density is $\Lambda \approx H^4$ [1–4], which in a low-energy universe leads to a too tiny cosmological term.

In the case we consider the vacuum energy of interacting fields, it has been suggested that in a low energy, approximately de Sitter background the vacuum conden-

J. S. Alcaniz
Observatório Nacional, Rio de Janeiro-RJ, Brazil

H. A. Borges · C. Pigozzo · S. Carneiro (✉)
Instituto de Física, Universidade Federal da Bahia,
Salvador, BA, Brazil
e-mail: saulo.carneiro.ufba@gmail.com

J. C. Fabris · W. Zimdahl
Departamento de Física, Universidade Federal do Espírito Santo,
Vitória-ES, Brazil

sate originated from the QCD phase transition leads to $\Lambda \approx m^3 H$, where $m \approx 150$ MeV is the energy scale of the transition [5–11]. These results are in fact intuitive. In a de Sitter background the energy per observable degree of freedom is given by the temperature of the horizon, $E \approx H$. For a massless free field this energy is distributed in a volume $1/H^3$, leading to a density $\Lambda \approx H^4$, as above. For a strongly interacting field in a low energy space-time, on the other hand, the occupied volume is $1/m^3$, owing to confinement, and the expected density is $\Lambda \approx m^3 H$.

Such a late-time variation law for the vacuum term can also be derived as a back-reaction of the creation of non-relativistic dark particles in the expanding spacetime [12]. The Boltzmann equation for this process is

$$\frac{1}{a^3} \frac{d}{dt} \left(a^3 n \right) = \Gamma n, \tag{1}$$

where n is the particle number density and Γ is a constant creation rate. By taking $\rho_m = nM$, it can also be written as

$$\dot{\rho}_m + 3H\rho_m = \Gamma \rho_m, \tag{2}$$

where M is the mass of the created particle. Let us take, in addition to (2), the Friedmann equation

$$\rho_m + \Lambda = 3H^2, \tag{3}$$

with the vacuum term satisfying the equation of state $p_\Lambda = -\Lambda$. Using (2) and (3) we obtain the conservation equation for the total energy,

$$\dot{\rho} + 3H(\rho + p) = 0, \tag{4}$$

provided we take[1]

$$\Lambda = 2\Gamma H. \tag{5}$$

This is the time-variation law predicted for the vacuum density of the QCD condensate, with $\Gamma \approx m^3$. Dividing it by $3H^2$, we obtain

$$\Gamma = \frac{3}{2} (1 - \Omega_m) H, \tag{6}$$

where $\Omega_m = 1 - \Omega_\Lambda \equiv \rho_m/(3H^2)$ is the relative matter density (for simplicity, we are considering only the spatially flat case). In the de Sitter limit ($\Omega_m = 0$), we have $\Gamma = 3H/2$, that is, the creation rate is equal (apart from a numerical factor) to the thermal bath temperature predicted by Gibbons and Hawking in the de Sitter spacetime [13]. It also means that the scale of the future de Sitter horizon

---

[1] Strictly speaking, this result is only exact if we neglect the conserved baryons in the balance equations. Since baryons represent only about 5 % of the total energy content, this can be considered a good approximation.

is determined, through Γ, by the energy scale of the QCD phase transition, the last cosmological transition we have. For the present time we have, from (6) (with $\Omega_m \approx 1/3$), $H_0 \approx \Gamma \approx m^3$, and hence $\Lambda \approx m^6$, where H_0 is the current Hubble parameter. The former result is an expression of the Eddington-Dirac large number coincidence [14]. The later—also known as Zeldovich's relation [15]—gives the correct order of magnitude for Λ.

The corresponding cosmological model has a simple analytical solution, which reduces to the CDM model for early times and to a de Sitter universe for $t \to \infty$ [16]. It has the same free parameters of the standard model and presents good concordance when tested against type Ia supernovas, baryonic acoustic oscillations, the position of the first peak of CMB and the matter power spectrum [12, 17–21]. Furthermore, the coincidence problem is alleviated, because the matter density contrast is suppressed in the asymptotic future, owing to the matter production [12, 20].

With $\Lambda = 2\Gamma H$ we obtain, from the Friedmann equations, the solution [16–19]

$$\frac{H}{H_0} \approx 1 - \Omega_{m0} + \Omega_{m0}(1 + z)^{3/2} \ , \tag{7}$$

where here, for simplicity, we have not added radiation. For high redshifts the matter density scales as $\rho_m(z) = 3H_0^2\Omega_{m0}^2 z^3$. The extra factor Ω_{m0}—as compared to the ΛCDM model—is owing to the late-time process of matter production. In order to have nowadays the same amount of matter, we need less matter in the past. Or, in other words, if we have the same amount of matter in the past (say, at the time of matter-radiation equality), this will lead to more matter today. We can also see from (7) that, in the asymptotic limit $z \to -1$, the solution tends to the de Sitter solution. Note that, like the ΛCDM model, the above model has only two free parameters, namely Ω_{m0} and H_0. On the other hand, it can not be reduced to the ΛCDM case except for $z \to -1$. In this sense, it is falsifiable, that is, it may be ruled out by observations.

The Hubble function (7) can be used to test the model against background observations like SNIa, BAO and the position of the first peak in the CMB spectrum [17–19]. The analysis of the matter power spectrum was performed in [20], where, for simplicity, baryons were not included and the cosmological term was not perturbed. In a subsequent publication a gauge-invariant analysis, explicitly considering the presence of late-time non-adiabatic perturbations, has shown that the vacuum perturbations are indeed negligible, except for scales near the horizon [21].

We show in Table 1 the best-fit results for Ω_{m0} (with H_0 marginalized) with three samples of supernovas: the SDSS and Constitution compilations calibrated with the MLCS2k2 fitter, and the Union2 sample. For the sake of comparison, we also show the best-fit results for the spatially flat ΛCDM model. We should have in mind that the Union2 dataset is calibrated with the Salt2 fitter, which makes use of a fiducial ΛCDM model for including high-z supernovas in the calibration. Therefore, that sample is not model-independent and, in the case of the standard model, the test should be viewed as rather a test of consistence. From the table we can see that for the model with particle creation the concordance is quite good. For the samples

Table 1 2σ limits to Ω_{m0} (SNe + CMB + BAO + LSS)

Test	$\Lambda(t)$CDM		ΛCDM	
	Ω_{m0}	χ^2_{min}/ν	Ω_{m0}	χ^2_{min}/ν
Union2 (SALT2)	$0.420^{+0.009}_{-0.010}$	1.063	0.235 ± 0.011	1.027
SDSS (MLCS2k2)	$0.450^{+0.014}_{-0.010}$	0.842	$0.260^{+0.013}_{-0.016}$	1.231
Constitution (MLCS2k2-17)	$0.450^{+0.008}_{-0.014}$	1.057	0.270 ± 0.013	1.384

calibrated with the MLCS2k2 fitter it is actually better than in the ΛCDM case. As anticipated above, the present matter density is higher than in the standard case, with $\Omega_{m0} \approx 0.45$.

With the concordance values of Ω_{m0} in hand, we can obtain the age parameter of the Universe, as well as the redshift of transition between the decelerated and accelerated phases. They are given, respectively, by [16–19]

$$H_0 t_0 = \frac{2 \ln \Omega_{m0}}{3(\Omega_{m0} - 1)}, \tag{8}$$

$$z_T = \left[2 \left(\frac{1}{\Omega_{m0}} - 1 \right) \right]^{2/3} - 1. \tag{9}$$

In the case of the SDSS and Constitution samples, this leads to $H_0 t_0 = 0.97$ and $z_T = 0.81$, in good agreement with standard predictions and astronomical limits [22]. For $H_0 \approx 70$ km/(s.Mpc), we have $t_0 \approx 13.5$ Gyr.

Particle creation is something expected in expanding spacetimes [23]. In spite of the difficulty in deriving the production rate and backreaction in general, this phenomenon may in principle be related with inflation [24] and with the present cosmic acceleration, a possibility already considered in different ways by some authors [25, 26] . We have shown that a constant-rate creation of non-relativistic dark particles at late times leads indeed to a viable concordance model.

References

1. Ford, L.: Quantum vacuum energy in general relativity. Phys. Rev. D **11**, 3370 (1975). doi:10. 1103/PhysRevD.11.3370
2. Dowker, J., Critchley, R.: Effective Lagrangian and energy momentum tensor in de Sitter space. Phys. Rev. D **13**, 3224 (1976). doi:10.1103/PhysRevD.13.3224
3. Davies, P.: Singularity avoidance and quantum conformal anomalies. Phys. Lett. B **68**, 402 (1977). doi:10.1016/0370-2693(77)90504-4
4. Starobinsky, A.: A new type of isotropic cosmological models without singularity. Phys. Lett. B **91**, 99 (1980). doi:10.1016/0370-2693(80)90670-X

5. Schützhold, R.: Small cosmological constant from the QCD trace anomaly? Phys. Rev. Lett. **89**, 081302 (2002). doi:10.1103/PhysRevLett.89.081302

6. Klinkhamer, F., Volovik, G.: Gluonic vacuum, q-theory, and the cosmological constant. Phys. Rev. D **79**, 063527 (2009). doi:10.1103/PhysRevD.79.063527

7. Urban, F., Zhitnitsky, A.: The cosmological constant from the ghost: A toy model. Phys. Rev. D **80**, 063001 (2009). doi:10.1103/PhysRevD.80.063001

8. Urban, F., Zhitnitsky, A.: The cosmological constant from the QCD Veneziano ghost. Phys. Lett. B **688**, 9 (2010). doi:10.1016/j.physletb.2010.03.080

9. Urban, F., Zhitnitsky, A.: The QCD nature of dark energy. Nucl. Phys. B **835**, 135 (2010). doi:10.1016/j.nuclphysb.2010.04.001

10. Ohta, N.: Dark energy and QCD ghost. Phys. Lett. B **695**, 41 (2011). doi:10.1016/j.physletb.2010.11.044

11. Holdom, B.: From confinement to dark energy. Phys. Lett. B **697**, 351 (2011). doi:10.1016/j.physletb.2011.02.024

12. Alcaniz, J., Borges, H., Carneiro, S., et al.: A cosmological concordance model with dynamical vacuum term. Phys. Lett. B **716**, 165 (2012). doi:10.1016/j.physletb.2012.08.014

13. Gibbons, G., Hawking, S.: Cosmological event horizons, thermodynamics, and particle creation. Phys. Rev. D **15**, 2738 (1977). doi:10.1103/PhysRevD.15.2738

14. Mena Marugán, G., Carneiro, S.: Holography and the large number hypothesis. Phys. Rev. D **65**, 087303 (2002). doi:10.1103/PhysRevD.65.087303

15. Bjorken, J.: Emergent photons and gravitons: the problem of vacuum structure. In: Kostelecký, V. (ed.) CPT and Lorentz Symmetry, pp. 1–5. World Scientific Publishing, Singapore, Hackensack, NJ (2011). doi:10.1142/9789814327688_0001

16. Borges, H., Carneiro, S.: Friedmann cosmology with decaying vacuum density. Gen. Relativ. Gravit. **37**, 1385 (2005). doi:10.1007/s10714-005-0122-z

17. Pigozzo, C., Dantas, M., Carneiro, S., Alcaniz, J.: Observational tests for Λ (t)CDM cosmology. J. Cosmol. Astropart. Phys. **2011**(08), 022 (2011). doi:10.1088/1475-7516/2011/08/022

18. Carneiro, S., Dantas, M., Pigozzo, C., Alcaniz, J.: Observational constraints on late-time $\Lambda(t)$ cosmology. Phys. Rev. D **77**, 083504 (2008). doi:10.1103/PhysRevD.77.083504

19. Carneiro, S., Pigozzo, C., Borges, H., Alcaniz, J.: Supernova constraints on decaying vacuum cosmology. Phys. Rev. D **74**, 023532 (2006). doi:10.1103/PhysRevD.74.023532

20. Borges, H., Carneiro, S., Fabris, J., Pigozzo, C.: Evolution of density perturbations in decaying vacuum cosmology. Phys. Rev. D **77**, 043513 (2008). doi:10.1103/PhysRevD.77.043513

21. Zimdahl, W., Borges, H., Carneiro, S., Fabris, J., Hipolito-Ricaldi, W.: Non-adiabatic perturbations in decaying vacuum cosmology. J. Cosmol. Astropart. Phys. **2011**(04), 028 (2011). doi:10.1088/1475-7516/2011/04/028

22. Hansen, B., Brewer, J., Fahlman, G., et al.: The white dwarf cooling sequence of the globular cluster messier 4. Astrophys. J. **574**, L155 (2002). doi:10.1086/342528

23. Parker, L., Toms, D.: Quantum Field Theory in Curved Spacetime: Quantized Fields and Gravity. Cambridge Monographs on Mathematical Physics. Cambridge University Press, Cambridge, New York (2009)

24. Carneiro, S., Tavakol, R.: On vacuum density, the initial singularity and dark energy. Gen. Relativ. Gravit. **41**, 2287 (2009). doi:10.1007/s10714-009-0846-2

25. Lima, J., Germano, A., Abramo, L.: FRW type cosmologies with adiabatic matter creation. Phys. Rev. D **53**, 4287 (1996). doi:10.1103/PhysRevD.53.4287

26. Zimdahl, W., Schwarz, D., Balakin, A., Pavon, D.: Cosmic anti-friction and accelerated expansion. Phys. Rev. D **64**, 063501 (2001). doi:10.1103/PhysRevD.64.063501