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A dark energy multiverse

Salvador Robles-Pérez,[1,*] Prado Martín-Moruno,[1,†] Alberto Rozas-Fernández,[1,‡] and Pedro F. González-Díaz[1,§]
[1]*Colina de los Chopos, Instituto de Matemáticas y Física Fundamental, Consejo Superior de Investigaciones Científicas, Serrano 121, 28006 Madrid, Spain*

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We present cosmic solutions corresponding to universes filled with dark and phantom energy, all having a negative cosmological constant. All such solutions contain infinite singularities, successively and equally distributed along time, which can be either big bang/crunchs or big rips singularities. Classicaly these solutions can be regarded as associated with multiverse scenarios, being those corresponding to phantom energy that may describe the current accelerating universe.

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Just like the word atom designated what in principle was thought to be indivisible and finally turned out not to be the case; the word universe, which was originally intended to describe the whole, has recently been reinterpreted to be just a single causally disconnected part from the whole spacetime. Different spacetimes could exist and our universe would be just one more among that ensemble of completely causally disconnected spacetimes. Actually, it was Giordano Bruno who first realized that there could exist many other worlds other than ours [1]. This idea has triggered several centuries later the development of different theories of the multiverse, this time with quite less risks. Quite possibly, the best known is the many-universes theory derived from the relative-state-formulation due to Everett when applied to cosmology [2, 3], which states that all branches of a wave function for the universe correspond to equally real different universes existing in parallel within an overall multiverse.

But there are multiverse models, too that appear outside the quantum realm, in the framework of general relativity. One example of a multiverse that does not make explicit recourse to a quantum formalism could be the chaotic inflationary multiverse [4]. In every flat space which has an event horizon, such as it happens in the inflationary universe, a closed causal region of spacetime is settled which can be influenced by observers. Since the universe is flat, it is infinite so for observers who are space-like separated by distances greater than the sum of their respective distances to the event horizons, their respective causal domains are disjoint and therefore every inflationary domain can be interpreted as a single universe in the framework of this classical multiverse. Another possible multiverse may appear when we consider the current accelerated expansion of the Universe. If we choose as dark energy phantom energy [5], then a singularity is predicted to occur in the finite future [6]. This singularity divides the universe into two classically non-connected regions, before and after the singularity [7]. Here an idea of the multiverse would also appear because that model necessarily requires a precise discretization of the parameter in the equation of state, if one wants to consider the region after the big rip as a part of the whole spacetime. Each value of the discretized parameter of the equation of state would then describe a single universe in the context of an in infinite multiverse.

Recently, string theory has also resorted to the multiverse idea to interpret the multiplicity of positive- energy vacua which rises up to order 10^{100} to 10^{500} [8]. The different subuniverses described by this string landscape [9] could be different regions of space, different eras of time in a single big bang, different regions of spacetime or different parts of quantum mechanical Hilbert space (being these alternatives not mutually exclusive) [10].

Furthermore, another multiverse model has been discussed by Smolin [11], who conjectured that new universes are spawned within black holes, and that this kind of baby universes will inherit the physics of the parent universe but with small random variations. The process could continue ad infinitum. Universes that produce many black holes would induce more progeny too, representing the largest volume of space.

On the other hand, in the ekpyrotic model of Steinhard and Turok [12], a brane collides with a confining three-dimensional boundary to a four-dimensional space to create the big bang. The four-dimensional space can be foliated with any number of branes each of which, in the absence of collisions, constitutes a universe.

Within the framework of the current accelerated expansion of the universe mentioned above, we have considered in this paper a new model in which we have taken into account the existence of a negative cosmological constant. A spacetime with a negative cosmological constant is worth investigating, since it allows a consistent physical interpretation and naturally appears in elementary particle theories. Indeed, in string theory, as in supergravity theories, the vacuum has a negative energy density, which means that it is described by anti-de Sitter (AdS) spacetime. In an important advance to understand quantum issues in strong gravitational fields it was conjectured in 1997 that string theory in an AdS background is equiv-

*Electronic address: salvarp@imaff.cfmac.csic.es
†Electronic address: pra@imaff.cfmac.csic.es
‡Electronic address: a.rozas@imaff.cfmac.csic.es
§Electronic address: p.gonzalezdiaz@imaff.cfmac.csic.es

alent to a conformal field theory (CFT) [13]. This is a beautiful and concrete example of the holographic principle in quantum gravity [14]. It is with this motivation that we in this paper consider a cosmic model of dark energy with a negative constant vacuum energy.

If we consider a quintessence field to describe dark energy, one can describe it as a perfect fluid with an equation of state $p = w\rho = w\rho_0(a(t)/a_0)^{-3(1+w)}$, where p and ρ are the pressure and energy density of the fluid, respectively, and w a constant parameter. The Friedmann equation for this flat model, which contains a negative cosmological constant Λ, can be written as

$$H^2 = -\lambda + Ca^{-3\beta}, \tag{1}$$

with $\lambda = |\Lambda|/3$, where $\lambda < 8\pi\rho_0/3$ in order for H_0 to be real; $C = 8\pi\rho_0/(3a_0^{-3\beta})$ and $\beta = 1 + w$. By integrating Eq. (1), we can obtain the cosmic scale factor, yielding

$$a(t) = a_0\left[\cos\left(\frac{3\beta}{2}\lambda^{1/2}(t-t_0)\right) + \left(\frac{C}{\lambda}a_0^{-3\beta} - 1\right)^{1/2}\sin\left(\frac{3\beta}{2}\lambda^{1/2}(t-t_0)\right)\right]^{\frac{2}{3\beta}} \tag{2}$$

For the case in which the dark energy is phantom energy, that is, when $\beta < 0$, this factor is converted into

$$a(t) = a_0\left[\cos\left(\alpha(t-t_0)\right) - b\sin\left(\alpha(t-t_0)\right)\right]^{-\frac{2}{3|\beta|}}, \tag{3}$$

where $\alpha = \frac{3|\beta|}{2}\lambda^{1/2}$ and $b = \left(\frac{8\pi}{3\lambda}\rho_0 - 1\right)^{1/2}$. It is easy to see that the scale factor diverges an infinite number of times along the full time interval. Each of such divergences actually describes a big rip singularity that takes place at

$$t_{br_n} = t_0 + \frac{2}{3|\beta|\lambda^{1/2}}\text{arctg}\left[\left(\frac{8\pi\rho_0}{3\lambda} - 1\right)^{-1/2}\right] + \frac{2n\pi}{3|\beta|\lambda^{1/2}}, \tag{4}$$

with n any natural number. We recover the expression for the big rip time obtained in a quintessence model of phantom energy without cosmological constant [6], when we set $n = 0$ in expression (4) and expand it for $\lambda << 1$,

$$t_{br} = t_0 + \frac{1}{|\beta|\left(6\pi\rho_0\right)^{1/2}}. \tag{5}$$

In the light of Eq. (4) we can in fact see that this model will have infinite big rip singularities. This can be interpreted as follows: classically, a singularity cuts off the space time, so the different regions between big rips would be isolated. Thus, each of them would correspond to a different universe, independent of the rest, i.e., another spacetime. But, as Eq.(3) tell us, these independent universes are identical among them and have the same physical characteristics. All of them begin at a big rip singularity, and then progressively contract until a given, constant, minimum value of the scale factor,

$$a_{\min} = a_0\left(\frac{8\pi\rho_0}{3\lambda}\right)^{1/3\beta} > 0, \tag{6}$$

after which the given universe starts expanding, all the way in an accelerated fashion, to again reach the next big rip singularity, (see Fig. 1). The minimum value in Eq. (6) has been obtained from the extremum value that corresponds to equating to zero Eq. (1). The lifetime of every of these universes is given by

$$t_u = \frac{2\pi}{3|\beta|\lambda^{1/2}}. \tag{7}$$

It follows from Eq. (7) that the smaller λ the longer the universe life t_u. It can be seen that if $\lambda = 0$, where we recover the quintessence model of phantom energy, these time differences are infinite, as in this model of usual phantom there is a unique big rip.

Given that, as we have said before, the infinite singularities have cut off the spacetime generating infinite causally disconnected spacetimes, we can re-scale and redefine the time in each of these spacetimes in some appropriate form, independently in each of them. This way, the scale factor reaches its minimum value in the zero of the so obtained new symmetrical time of symmetry. The aforementioned scale factor can be written in a more compact form as

$$a(\tau) = a_{\min}\left(\cos\tau\right)^{-\frac{2}{3|\beta|}}, \tag{8}$$

with the new time τ covering the interval $(-\pi/2, \pi/2)$ in every universe, reaching the initial and final big rips at the extrema. Each of the universes in the multiverse is something as though it were a faster-expanding de Sitter space defined along a finite time interval.

If we assumed that all these universes are classically identical and that our universe is in fact described by this model, we could dare to claim that such universes are governed by the same physical laws as ours, given that all of them would then be exactly physically equivalent. Classically, the existence of life in our universe might be justified as a byproduct of the anthropic principle in its various formulations. If we think that life exists because the initial conditions of our universe allow it to occur, the physical equivalence of the various universes would imply that, classical life existed such as we know it in all of them. But if we considered the emergence of life as a process somehow dependent on quantum effects, as it seems to be the case, it would no longer be consistent to extrapolate ideas about such existence based on a classical extension of the physical laws.

We could envisage a model where the expansion is not caused by a phantom fluid, but by dark energy itself, i. e., $\beta > 0$ in the equation of state. In this case, we would also obtain a multiverse scenario with the same characteristics among the universes, but these would now be closed universes that would decelerate from a big bang until its scale factor reached a finite maximum value (given by Eq.(6) with $\beta > 0$), from that value onwards the universe would contract in size until finally it died in a big crunch singularity (see Fig. 1); being therefore unable to explain the current accelerated expansion of our universe.

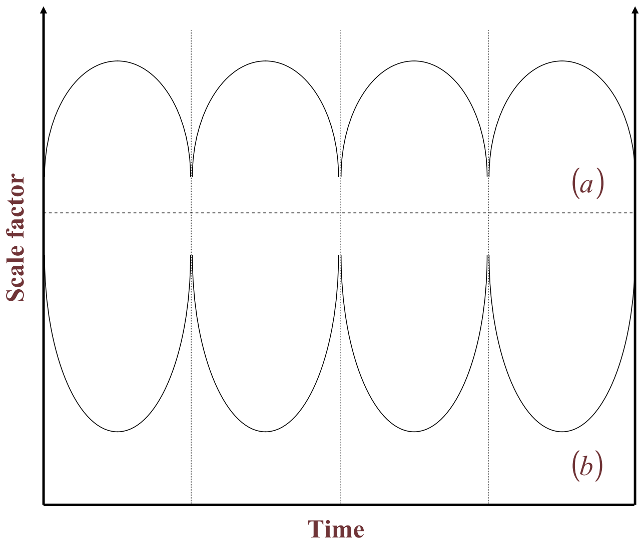

Figure 1: Time evolution corresponding to a universe equipped with a negative cosmological constant and: (a) quintessential dark energy with $\beta > 0$ and (b) phantom energy with $\beta < 0$.

In view of the results obtained in this work, it is worth mentioning that whereas the insertion of a negative cosmological constant in a phantom energy model has the effect of repeating the big rip singularity an infinite number of times, the analogous consideration of this in a model with dark energy slows down the accelerated expansion caused by this fluid, in such a way that it would cause not just one but infinite big crunches. Hence in both cases we obtain a classical multiverse scenario, in which the universes are identical among them. This scenario could be altered if we included the evolution of astronomical objects in this model [15].

As we said before, the models suggested in the present paper are purely classical, therefore considering quantum effects would probably smooth out the singularities [16], in such a way that we would no longer have an infinite set of isolated spacetimes, so implying the loss of the multiverse scenario.

The appeal of the multiverse models lies on that it points toward a less predominant position of what we call our universe in nature. It could well be that, once again, we would have missed the denomination of a physical system and, in a similar way to terms such as atom or elementary particles were once wrongly used to denote what it turned out to be essentially divisible systems, we could well be now applying the term "universe" to what is nothing but just a single part or product of it [17].

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[1] D. W. Singer, *Giordano Bruno, His Life and Thought, With Annotated translation of His Work - "On the Infinite Universe and Worlds (1584)"* (Schuman, New York, USA, 1950)
[2] H. Everett, Rev. Mod. Phys. **454**, 29 (1957).
[3] See papers by H. Everett III, J. A. Wheeler and B. S. DeWitt in: *The Many-Worlds Interpretation of Quantum Mechanics*, edited by B. S. DeWitt and N. Graham. (Princeton Univ. Press, Princeton, USA, 1973)
[4] A. Linde, Mod. Phys. Lett A **1**, 81 (1986).
[5] R. R. Caldwell, Phys. Lett. B **545**, 23 (2002) [arXiv:astro-ph/9908168]. S. M. Carroll, M. Hoffman and M. Trodden, Phys. Rev. D **68**, 023509 (2003) [arXiv:astro-ph/0301273].
[6] R. R. Caldwell, M. Kamionkowski and N. N. Weinberg, Phys. Rev. Lett. **91**, 071301 (2003) [arXiv:astro-ph/0302506].
P. F. González-Díaz, Phys. Lett. B **586**, 1 (2004) [arXiv:astro-ph/0312579].
P. F. González-Díaz Phys. Rev. D **69**, 063522 (2004) [arXiv:hep-th/0401082].
[7] S. Robles-Pérez and P. F. González-Díaz, (In preparation)
[8] K. Ashok and M. Douglas, JHEP **060**, 0401 (2004).
[9] L. Susskind, [arXiv:hep-th/0302219].
[10] S. Weinberg, [arXiv:hep-th/0511037].
[11] L. Smolin, *The life of the Cosmos*, Oxford University Press, (1997).
[12] P. Steinhard and N. Turok, Phys. Rev. D **65**, 126003 (2002), [arXiv:hep-th/0111098].
[13] J. Maldacena, Adv. Theor. Math. Phys. **2**, 231-252 (1998), [arXiv:hep-th/9711200].
[14] G. 't Hooft, [arXiv:gr-qc/9310026].
[15] P. F. González-Díaz, Prado Martín-Moruno and A. Yurov (In preparation)
[16] S. Nojiri and S. D. Odintsov, Phys. Lett. B **595** 1 (2004) [arXiv:hep-th/0405078]. S. Nojiri and S. D. Odintsov, Phys. Rev. D **70**, 103522 (2004) [arXiv:hep-th/0408170].
[17] P. F. Gonzlez-Daz, Hadronic J. Suppl. **2**, 437 (1986).