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Abstract

Observationally, the universe appears virtually critical. Yet, there is no simple explanation for this state. In this article we advance and explore the premise that the dynamics of the universe always seeks equilibrium conditions. Vacuum-induced cosmic accelerations lead to creation of matter-energy modes at the expense of vacuum energy. Because they gravitate, such modes constitute inertia against cosmic acceleration. On the other extreme, the would-be ultimate phase of local gravitational collapse is checked by a phase transition in the collapsing matter fields leading to a de Sitter-like fluid deep inside the black hole horizon, and at the expense of the collapsing matter fields. As a result, the universe succumbs to neither vacuum-induced run-away accelerations nor to gravitationally induced spacetime curvature singularities. Cosmic dynamics is self-regulating. We discuss the physical basis for these constraints and the implications, pointing out how the framework relates and helps resolve standing puzzles such as "why did cosmic inflation end?", "why is Λ small now?" and "why does the universe appear persistently critical?". The approach does, on the one hand, suggest a future course for cosmic dynamics, while on the other hand it provides some insight into the physics inside black hole horizons. The interplay between the background vacuum and matter fields suggests an underlying symmetry that links spacetime acceleration with spacetime collapse and global (cosmic) dynamics with local (black hole) dynamics.

1 Introduction

Cosmology is moving into a new chapter following the observational evidence [1] that the universe is currently accelerating. Cosmic dynamics can no longer be considered to result simply from a post-inflationary free expansion of spacetime, modulated by gravity. Notwithstanding, one still expects that the events leading to the current dynamical state of the universe are rooted in its early past and more and more understanding of the past will certainly help sort out the present puzzles.

One such standing puzzle can be framed in the question "why did the early cosmic inflation end?". Over the years following the introduction of the inflationary model of the early universe [2], various potentials have been constructed that seek to "gracefully" take the universe out of this initial de Sitter phase. To a varying extent, the constructions do achieve their aim of reconciling the events of the early universe with currently observed phenomena such as large scale structure and CMB anisotropy. Such constructions are, however, essentially phenomenological in nature, tailored to conform with a unique and known result. Of course this does not diminish the vital role the techniques have played and the consequent successes. In theory, though, the universe could have continued to inflate eternally. The physics of "why did the early cosmic inflation end?" is still not clear. Cosmology will have to address this question, in part, to provide a foundational framework for dealing with the current and any future cosmic acceleration scenarios. Interestingly, this question may be non-trivially related (see below) to the old Cosmological Constant Problem and also to some newly emerging puzzles. To date, for example, it is still not understood whether or not dark energy, the driver of the current cosmic acceleration, is in any way related to the field(s) responsible for cosmic inflation of the early universe. If the two are related (which is the

position taken in this work) then a resolution of the 'old' Cosmological Constant Problem may also help resolve the current Coincidence Problem (and vise versa). Beyond this, understanding the characteristics of dark energy is a necessary prerequisite to plotting the future dynamics of the universe. The relevant equation of state, (and indeed the general evolutionary character of the universe) is dependent, among other things, on whether or not dark energy does interact with matter fields and, if so, what the nature and extent of the interaction(s) is/are. In the end one wants to answer the following question: will the current universe lock itself into (the first ever) run-away[1] acceleration, in future, or will it find an exit as it did before (during the inflationary era)? The present lack of an answer to these questions constitutes what has been referred to as [3] *a dynamical problem.*

In a recent article [3] it was pointed out how the current cosmic acceleration does find an exit in future and how this behavior is related to a previous exit out of the inflationary era of the early universe. In both cases, the central feature is that cosmic (spacetime) acceleration always triggers the creation, from the background vacuum energy, of matter-energy (modes) fields which increase the universes' gravitational content. The behavior leads to an increase in spacetime inertia against vacuum-induced cosmic acceleration. This, in our approach, forms the physical basis for cosmic exit out of inflation (and indeed, out of any consequent accelerations). The justification is based on the following Cosmic Equilibrium Conjecture (CEC) we recently put forward which states that:

Conjecture 1 *The universe is always in search of dynamical equilibrium*[2]*, and will back-react to vacuum-induced tendencies to accelerate it, by increasing its inertia (at the expense of the vacuum energy).*

The conjecture implies a universe with certain characteristics which make cosmic dynamics relatively predictable. The aim of this article is, first to discuss the physical basis for (i.e. the character of the universe implied by) CEC, consistent with the observed universe. Then we point out how CEC resolves some current puzzles and ask what predictions it makes. Thereafter we generalize the conjecture into one that applies to any (and all) tendencies to shift the universe from equilibrium. The motivation for this generalization is straightforward. Besides spacetime stretching under the influence of vacuum energy, there are other ways cosmic equilibrium could be compromised. For example, spacetime could undergo total collapse under gravitational influences. We study the consequences of the generalized conjecture to find that it (i) is consistent with the observed universe; (ii) explains some of the current puzzles and (iii) is predictive.

The rest of the paper is organized as follows. In Section 2 we put forward a case for cosmic stability against vacuum-induced run-away accelerations and study the consequences. In Section 3 we discuss cosmic stability against gravitationally-induced run-away spacetime collapse. We then make a general case for a universe that self-regulates its dynamics. In Section 4 the paper is concluded

2 Case against run-away cosmic accelerations

2.1 Background

We begin by justifying the physical basis for CEC through the character of the universe it implies. With regard to spacetime acceleration, one feature that lends support to the influence of CEC has to do with the characteristics of the early de Sitter-like phase of the universe, and the fate of the cosmological 'constant' parameter Λ. Traditional field-theoretic considerations, based on the characteristics ascribed to de Sitter vacua, have generally required that the large potential energy $\sim 10^{94} gm\ cm^{-3}$ of the vacuum responsible for the early cosmic inflation should still be around, in the same form. The virtual absence of this energy leads to the traditional Cosmological Constant Problem. Here, we give a brief comment on this issue. Notwithstanding its rich symmetry, which

[1]A runaway situation exists if, for example, Λ is constant (as some models suggest) since the density of the matter fields always redshifts with cosmic expansion

[2]Dynamical equilibrium here (and henceforth) refers to the dynamical state of a critical universe

gives it a mathematical beauty, physically a de Sitter spacetime can not be time-invariant. To appreciate this one need only recall that such a geometry is known to possess a spacetime horizon at $\Lambda^{-\frac{1}{2}}$. Associated with such a horizon is a temperature $T_\Lambda = \frac{1}{2\pi}\left(\frac{\Lambda}{3}\right)^{\frac{1}{2}}$ which should give rise to a matter-energy radiation flux [4] (of power $\frac{dE}{dt}$ from the area A_Λ) i.e. $A_\Lambda \frac{dE}{dt} \propto T_\Lambda^4 \propto \Lambda^2$. The issue of whether such a radiation is physical, and the potential implications, has for sometime now been quite unclear. Lately researchers are revisiting this problem. For example, Parikh [5] has demonstrated that Hawking radiation from a de Sitter horizon can be put on the same footing as that from a black hole, in the sense that both result from a semi-classical tunneling process from the respective horizons. This view has recently been generalized by Medved [6] to apply to arbitrary dimensions. The potential implication that the idealized 'eternal' de Sitter state may not be entirely physical has also been raised lately. For example, in a recent article "Trouble with de Sitter space", N. Goheer, M. Kleban and L. Susskind [7] have argued on general grounds that the de Sitter space can not persist for times of order of the Poincare recurrence time. Citing previous works of other authors [8] to support their claim, they conclude that it is possible an eternal de Sitter space does not exist, because there are always instabilities which cause the space to decay in a time shorter than the recurrence time.

Such arguments lend credence to our assertion above that a physical de Sitter spacetime can not be time-invariant. Rather, soon as it comes into existence, the de Sitter state evolves a horizon-induced time-asymmetric behavior. Such behavior has been previously suggested by Padmanabhan [9]. In this respect therefore, it follows that the cosmological 'constant' Λ of the early universe (responsible for the inflationary cosmic acceleration) must decay with time into a radiation flux of matter fields[3]. In our model, the created matter fields increase the inertia of the universe by increasing the latter's gravitational content, and at the expense of the energy in the cosmological constant. Such particle flux $\sim \Lambda^2$ can be quite large in the early universe when Λ is known to be large.

A parallel, and possibly more illustrative, approach is to treat the universe as a cosmic engine. In this picture, a dominating vacuum energy $\frac{\Lambda}{8\pi G}$ fuels the universe, doing mechanical work on the spacetime by accelerating it. However, like any other engine, the universe can not convert all its fuel to pure work. Some of the fuel must be dissipated to create/increase *cosmic* inertia or internal energy. One identifies this cosmic internal energy as modes of radiation (matter) fields. Such dissipation of the (implied interacting) vacuum energy is clearly similar to the above mentioned time-asymmetric evolution of the (physical) de Sitter phase.

There are several consequences to this scenario, all of which justify the (initial) physical basis for CEC. First as already mentioned, the created matter fields become a source of cosmic inertia through their gravitating nature. Such matter creation, coupled with the consequent decay of Λ, compromises the existing vacuum-induced cosmic acceleration, driving the universe out of the inflationary and subsequent accelerations. In our model this provides the physically justified answer to "why did the early inflation end?". Through its time-asymmetric character, the de Sitter state dictates its own end. The universe is thereafter propelled into a radiation dominated state. Finally, the decay of Λ offers a venue for discussing "why is Λ small now?"[4] and, by extension, why the vacuum energy density ρ_v is coincidentally of the same order as that of the matter fields.

The framework implies that the post-inflationary radiation/matter dominated state can not be permanent, either. After inflation, when the universe becomes radiation/matter dominated it continues to expand, mostly under its own momentum. The density of the matter fields $\rho_m(a(t))$ redshifts with the scale factor $a(t)$ (modulated only by gravity) and follows the standard dilution power law of $-3\gamma = \{-4, -3\}$, depending on whether the fields are relativistic or cold and pressureless. Eventually ρ_m falls below ρ_v and the vacuum energy density dominates the universe again, albeit at a much lower value, leading to a weaker cosmic acceleration as observed currently. Applying the preceding reasoning once again, one can infer (as we find below) that, in future, the universe must exit out of the current low acceleration because of the creation of long wavelength

[3]The argument implies that there may, in fact, be no cosmological constant problem.

[4]In a different approach, Brandenberger has argued [10] that gravitational back-reaction may lead to a dynamical cancellation mechanism for a bare cosmological constant by giving rise to an evolving anti-de Sitter-like field.

modes. Although such modes $\sim \frac{1}{\sqrt{\Lambda}}$ may be too weak to detect currently they, nevertheless, gravitate. It also follows that the current cosmic acceleration must be variable.

In this model, such an interplay between the background vacuum energy and matter fields does underlie cosmic dynamics. The approach presents a history of cosmic dynamics consistent with both standard theoretical predictions e.g. inflation, and with observations e.g. the current cosmic acceleration, and the critical state of the universe. At the same time it suggests solutions to long standing puzzles, as mentioned above. Moreover, the approach offers a resolution to the *dynamical problem* by making the future dynamics of the universe predictable. A quantitative discussion of these issues can be found in [3]. Presently, we only wish to point out the implications of CEC and in this regard, we will highlight some of the ideas in [3] leading to the solution for the evolution of ρ_v and briefly point out those features of ρ_v relevant to the current discussion. Later, we generalize the conjecture to deal with all tendencies to shift cosmic dynamics from equilibrium and discuss the implications.

2.2 Framework

Generating the cosmic background vacuum (or dark) energy $\frac{\Lambda}{8\pi G}$ is a cosmological parameter Λ which in this model takes on the functional form

$$\Lambda\left(t\right) = m_{pl}^{4}\left(\frac{a_{pl}}{a(t)}\right)^{\sigma(t)} e^{-\tau H} = \Lambda_{pl}\left(\frac{a_{pl}}{a(t)}\right)^{\sigma(t)} e^{-\tau H}, \tag{2.1}$$

where m_{pl} is the Planck mass, a_{pl} (the fluctuation scale) is the size scale of a causally connected region of space at the Planck time $t_{pl,}$ and τ is of order of the Planck time. Further, H is the Hubble parameter and $a\left(t\right)$ is the cosmic scale factor. The power index σ is a (yet to be determined) function of time, which contains information about vacuum-matter interaction. A discussion of cosmic dynamics for $t < \tau$ requires a yet to be formulated quantum theory of gravity and is therefore beyond the scope of this article. Note however, that Λ is regular at $t = 0$, $(H \longrightarrow \infty)$, appearing to 'tunnel from nothing'. Thereafter, it quickly evolves towards its stationary point, $\frac{d\Lambda(t)}{dt} = 0$. During this ($\Lambda$-growth) period the effective equation of state $w\left(t\right)$ will approach -1 from below, to temporarily mimic a cosmological constant. In the immediate neighborhood of $\frac{d\Lambda(t)}{dt} = \left[\ln\left(\frac{l_{pl}}{a(t)}\right)\frac{d\sigma}{dt} - \sigma\left(t\right)H - \tau\frac{dH}{dt}\right] = 0$, Λ is virtually constant with maximum potential energy (possibly in the range $\langle\rho_{vac}\rangle = \frac{\Lambda}{8\pi G} \sim 10^{94}\, g\, cm^{-3}$). Such conditions will give rise to cosmic inflation, in the early universe. As the Hubble time H^{-1} grows, the quantity $e^{-\tau H}$ quickly approaches saturation $e^{-\tau H} \rightarrow 1$, subsequent upon which the dynamics of the universe becomes increasingly classical, being driven by the $a(t)^{-\sigma(t)}$ part of Λ. In the absence of a quantum theory of gravity, it is this latter (post-inflationary) phase that the present article addresses. In this classical regime the evolutionary behavior of ρ_v can be expressed as

$$\rho_v\left(t\right) = \frac{\Lambda\left(t\right)}{8\pi G} = \left(\frac{a\left(t_0\right)}{a\left(t\right)}\right)^{\sigma(t)} \rho_v^{(0)}, \tag{2.2}$$

where $\rho_{vac}^{(0)}$ and $a\left(t_0\right)$ are the current values of dark energy density and scale factor, respectively. We are interested in determining the functional form of the power index $\sigma\left(t\right)$ for the evolution of ρ_v which is consistent with the observations of a currently accelerating universe.

2.3 Energy equations

In setting up the relevant energy equations we consider the dynamical evolution of a self-gravitating cosmic medium, consisting of a two-component perfect fluid. The total energy momentum tensor $T_{\mu\nu}$ for all the fields is given by

$$T_{\mu\nu} = {}^{(m)}T_{\mu\nu} + {}^{(vac)}T_{\mu\nu} = \left[\rho + p\right] v_\mu v_\nu + p g_{\mu\nu}, \tag{2.3}$$

where ${}^{(m)}T_{\mu\nu}$ and ${}^{(vac)}T_{\mu\nu}$ are, respectively, the matter and the cosmic background vacuum (dark) energy contributions to $T_{\mu\nu}$, while $\rho = \rho_m + \rho_v$, $p = p_m + p_v$ and v_μ is the 4-velocity. The total cosmic energy is conserved, $v_\mu T^{\mu\nu}_{;\nu} = 0$, which leads to the standard continuity equation

$$\left[\dot{\rho}_m + (\rho_m + p_m)\,\theta\right] + \left[\dot{\rho}_v + (\rho_v + p_v)\,\theta\right] = 0, \tag{2.4}$$

where $\theta = v^{\alpha}_{;\alpha}$ is the fluid expansion parameter and $\dot{\rho}$ is the derivative taken along the fluid worldline, $\dot{\rho} = v^\alpha \nabla_\alpha \rho$. However, because of the assumed interacting nature of dark energy in this treatment, the individual components ${}^{(m)}T_{\mu\nu}$ and ${}^{(vac)}T_{\mu\nu}$ are, in general, not conserved[5]. This is a consequence of the *Cosmic Equilibrium Conjecture.* When dominant, the background vacuum energy will act as a source of dissipative processes, while the matter component acts as a sink of such processes. By implication, one can write

$$v_\mu \; {}^{(vac)}T^{\mu\nu}{}_{;\nu} = -v_\mu \; {}^{(m)}T^{\mu\nu}{}_{;\nu} = \Psi \tag{2.5}$$

where $\Psi > 0$ is the particle source strength. Note, however, that Eq. 2.5 is still consistent with Eq. 2.4. More explicitly Eq. 2.5 can be split into a source equation,

$$\dot{\rho}_v + (\rho_v + p_v)\,\theta = \pi_c \theta, \tag{2.6a}$$

and a sink equation

$$\dot{\rho}_m + (\rho_m + p_m)\,\theta = -\pi_c \theta, \tag{2.6b}$$

where π_c is the creation pressure [3]. As Eq. 2.2 shows, solving Eq. 2.6a for the evolution of the dark energy density ρ_v is equivalent to solving for the parameter $\sigma = \sigma(a)$. One finds (see [3] for details) that

$$\sigma(\psi) = 2 + \sin 2\psi \tag{2.7}$$

where ψ is given by $\frac{d\psi}{da} = \left[a \ln\left(\frac{a_0}{a}\right)\right]^{-1}$. This leads to the solution

$$\rho_v(a) = \rho_v^0 \left[\frac{a_0}{a}\right]^{(2+\sin 2\psi(a))} = \rho_v^0 \left[z+1\right]^{(2+\sin 2\psi(z))}, \tag{2.8}$$

where the second equality is written in terms of the redshift parameter $z = \frac{a_0}{a} - 1$ and now $\frac{d\psi}{dz} = \left[(z+1)\ln(z+1)\right]^{-1}$. Further, one finds from these results that the working equation of state for this interacting dark energy is

$$p_v = -\frac{1}{3}\left(1 - \sin 2\psi\right)\rho_{vac}. \tag{2.9}$$

The results in Eqs. 7 to 9 constitute, in our treatment, the formal solution for the post-inflationary evolution of the interacting background dark energy with the scale factor $a(t)$. The sinusoidal power index $\sigma(\psi)$ depicted in Eq. 2.7 accounts for the interactions between dark energy and matter fields. These interactions constrain the evolution of the two fields relative to each other (see Eq. 2.10). In turn, it is this feature that protects the universe from run-away vacuum-induced accelerations. The limiting forms of the above solution (both during the vacuum dominated and matter dominated regimes) can be used to put bounds on the post-inflationary $\left(e^{-\tau H} \longrightarrow 1\right)$ evolution of the dark energy ρ_v with respect to the matter fields ρ_m. One finds [3] that ρ_v evolves so that

$$\left(\frac{3K}{6K+2}\right)(3\gamma - 2)\,\rho_m \le \rho_v \le \left(\frac{3K}{6K-2}\right)(3\gamma - 2)\,\rho_m, \tag{2.10}$$

where $\gamma = \left[\frac{4}{3}, 1\right]$ and currently the dissipation parameter K is constrained to $\frac{1}{3} < K \lesssim \frac{4}{9}$. Through this constrained relative evolution of the fields, (Eq. 2.10, also see [3]), the approach explains the Coincidence Problem and leads to a predictable future dynamics of the universe, hence offering a resolution to the *dynamical problem.* Moreover, as the vacuum energy and matter fields oscillate

[5] The idea of an interaction between matter fields and the background was first suggested in the early 70s by Rustal [11].

into each other (see Eq. 2.10 and 8 and also [3]), they drive the universe into decaying oscillations about its time-evolving dynamical equilibrium state. Thus, as the universe ages, it also moves closer to being permanently critical. In this respect, it is therefore not surprising that the observed universe looks virtually critical.

In the initial limit $K \longrightarrow 0$, there is no dissipation. Then, and only temporarily, $\rho_{v_{(K=0)}}$ is the energy in the form of a pure cosmological constant, and the universe must inflate. Immediately after this however, K will assume non-trivial, positive, values and this signals the decay of Λ. Such a scenario is a consequence of the time-asymmetry of the de Sitter state. In this respect, the approach independently suggests inflation as a natural initial condition for the current cosmic dynamics and, as a by-product, suggests a potential role matter plays in the universe. The above results suggest that the current cosmic dynamics is based on the need for the universe to seek equilibrium conditions against run-away vacuum-induced accelerations. This, indeed, is the content of the *Cosmic Equilibrium Conjecture (CEC).*

3 Cosmic self-regulation

As was pointed out earlier in this article however, CEC as applied to cosmic dynamics so far, constitutes a one-sided part of what should be a more general and symmetrical statement. This is because spacetime may not only be (vacuum) accelerated but could also be (gravitationally) collapsed. To this end, one expects that there should exist a general principle which protects the universe from run-away behavior in both directions. In the remaining part of this article we set up a framework for such a principle. The framework is based on the following more encompassing statement, which (here and henceforth) is referred to as the *General Cosmic Equilibrium Conjecture (G-CEC):*

Conjecture 2 *The universe will resist all agents tending to move it away from dynamical equilibrium (be they vacuum energy based or gravitationally based).*

3.1 Case against run-away spacetime collapse

In the rest of this article we shift our discussion to the other side of cosmic equilibrium and search for the universe's stability to *total* or run-away gravitational collapse. Since in the physics literature there is no known observational evidence for a previous and/or future global cosmic collapse, we will (with no loss of generality) illustrate the validity of G-CEC based only on local spacetime (gravitational) collapse, namely the formation of black holes. As a useful by-product such an approach also will have the advantage of directly linking global cosmic dynamics to local spacetime (black hole) dynamics. In hind sight, such a link is natural in the sense that spacetime here is no longer simply 'a playing field' on which particle dynamics is described but is, instead, what is being either stretched by the vacuum energy or collapsed by gravity. In other words spacetime becomes a dynamical variable.

As we move to apply these concepts to gravitational collapse, we should briefly mention one issue that would seem to make such an extension difficult and later it will be pointed out how nature overcomes the difficulty. In [3] the original CEC was based on the argument that during periods of cosmic acceleration resulting from vacuum domination, increase in cosmic internal energy (i.e. matter creation) must be a one-way process. There, vacuum energy could create matter but not vise versa. This is because (under the conditions) a reverse process would globally violate the entropy law $s^{\mu}_{;\mu}. \geq 0$ and hence tend to rotate the thermodynamic arrow of time. The one-way creation feature is reflected in the solution (Eqs. 7 to 8) obtained previously for the evolution of the interacting vacuum energy density ρ_v. In this solution, the oscillations appear only in the power index $\sigma(a)$; and since manifestly $\sigma(\psi) = 2 + \sin 2\psi(a) > 0,\ \forall a(t)$, then the evolutionary slope of ρ_v always takes one, *and only one*, sign i.e. negative. As a result the decaying vacuum energy is always time-wise single valued. The alternative, in which vacuum energy ρ_v would be

multi-valued (i.e. 'creatable' from matter fields) would violate the entropy law. As we generalize CEC to G-CEC to include effects of gravitational collapse, we will revisit this question to find that with regard to gravitational collapse, nature renders moot the issues pertaining to possible violations of both the entropy law and the thermodynamic arrow of time.

The concept of gravitational collapse has effectively been with us since 1916 when Schwarzschild first presented a solution, to the Einstein field equations, for the gravitational field of a spherically symmetric mass. To date, the physics of these end-products has evolved both in breadth and depth, both theoretically and observationally, so much so that black holes are currently considered virtually discovered. The boundary of a black hole, a 2-sphere (geometrical singularity in Schwarzschild coordinates), provides (at least currently) the observational limit with regard to the dynamical evolution of the hole. It is, however, widely believed that during gravitational collapse of a spacetime region to form a black hole, the matter itself continues to collapse beyond the horizon towards a physical singularity. This perception has been motivated, from a theoretical view point, by the apparent absence of any known force that would otherwise counteract the action of gravity under such circumstances. Inquiries in the nature of spacetime singularities led to the famous Singularity Theorems [12]. It was conjectured then, as a Cosmic Censorship [13], that nature shielded the would-be naked singularities from exposure to external observers. To date, it is still widely believed that in spite of limitations relating to their observability, spacetime singularities should exist (naked or not)[6].

The classical singularity theorems [12] are built on the assumption that the physical fields involved obey the dominant energy condition, DEC, i.e. $\varrho \geq 0$ and $\rho + 3p \geq 0$ (for a review of these conditions, see e.g. [14]). On the other hand, gravitationally collapsing matter does exhibit two characteristics which become important in the proceeding discussion, in so far as they create conditions that eventually violate the dominant energy condition. These characteristics relate to (i) loss of particle kinetic energy from the collapsing system; (ii) losses in internal degrees of freedom in the collapsing system. To illustrate the importance of these points we begin with a familiar example, namely the formation of a neutron star, because here the initial signs of the above two effects can be observationally inferred. During the formation of a neutron star, it is believed that most of the orbital electrons do smash into the protons of the host nuclei through the inverse β-decay process ($e^- + p \longrightarrow n + \nu_e$). This process will increase the neutron content of the collapsing star while at the same time carrying away most of the particle kinetic energy and internal degrees of freedom (e.g. spin) through the escaping neutrinos ν_e. For larger stars collapsing into black holes, the losses of such degrees of freedom is expected to become much more extreme, leading to a growth of degeneracy in the particle states of the collapsing system. Moreover, the loss of particle kinetic energy will compound the situation by evolving such a 'degenerating' system towards a Bose-Einstein-like condensate. In case of a black hole such losses could be associated with Hawking radiation. In retrospect, this behavior is consistent with the "no hair theorem" [15]. The classic black hole manifests its presence only through its bulk (degenerate) mass and bulk angular momentum (individual particles degrees of freedom in the system having been compromised). Eventually, as a significant number of individual particles inside the black hole lose self-identity, the two effects will render the bulk matter (at the collapse core) to undergo a phase transition, taking on the form of a scalar field. The fraction of the original collapsing matter that will be in this scalar form will depend, among other things, on the stage of collapse. In any case, a rigorous field-theoretic description of a such scenario will certainly require a quantum theory of gravity, which is not in place yet. In this connection, however, one can already sense that the vacuum-matter interactions implied here and in the earlier discussion will likely require a theory involving higher order terms of the curvature scalar R and for which the Einstein theory, $R_{\mu\nu} - \frac{1}{2}Rg_{\mu\nu} = T_{\mu\nu}$, is a low energy limit[7].

Our present interest is not to derive such a theory; rather we only seek to validate G-CEC by demonstrating that it leads to results consistent with observations, helps explain existing paradoxes

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[6] *The debate (and bet) that was later to develop between Stephen Hawking and Kip Thorne, on the necessity (or not) of cosmic censorship is known even well beyond the relativistic astrophysics community.*

[7] The Einstein theory of gravity does not discuss vacuum-matter interactions and/or oscillations since there Λ is cosnstant.

and predicts, among other things, a self-regulating cosmic dynamics. It will therefore suffice to keep our discussion simple but illustrative. To this end, one finds that for illustrative purposes, one can still bring out those effects of gravitational collapse, consistent with the preceding argument, by simply treating the inner core of the collapsed system as a minimally coupled scalar field ϕ, with the familiar action [16],

$$S = \int d^4x\sqrt{-g}\left[\frac{1}{2}g^{\mu\nu}\partial_\mu\phi\partial_\nu\phi - V\left(\phi\right)\right], \tag{3.1}$$

where $g_{\mu\nu}$, in this case, is the local metric tensor of the spacetime inside the black hole, in the relevant region occupied by ϕ. The associated energy-momentum tensor is

$$T_{\mu\nu} = \frac{1}{2}\partial_\mu\phi\partial_\nu\phi + \frac{1}{2}g^{\alpha\beta}\partial_\alpha\phi\partial_\beta\phi - V\left(\phi\right)g_{\mu\nu}. \tag{3.2}$$

As pointed out earlier, loss of virtually all the particle kinetic energy through escaping relativistic particle fluxes leaves behind a one-state frozen condensate. This implies for the system that $\partial_\mu\phi = 0$, which effectively leaves the energy-momentum tensor of the scalar field part (Eq. 3.2) to be only proportional to the local spacetime metric $g_{\mu\nu}$, and one can write

$$T_{\mu\nu} = -\bar{\rho}_v g_{\mu\nu}. \tag{3.3}$$

Clearly, Eq. 3.3 represents the energy momentum tensor corresponding to a de Sitter geometry with a positive energy density $\bar{\rho}_v$, and negative pressure components $\bar{p}_v = -\bar{\rho}_v$. The latter provide the spacetime in consideration with an anti-gravitating character. During gravitational collapse, the amount of regular matter turning into this de Sitter-like fluid will grow, and do so at the expense of the regular matter available. The resulting increase in the negative pressure will slow down the overall gravitational collapse, eventually compromising it all together when $T^\mu_\mu\left(vac\right) \sim T^\mu_\mu\left(matter\right)$ in the region. This suggests, contrary to the traditional view, that gravitational collapse will not continue all the way to form a physical singularity. Consequently, according to the *General Cosmic Equilibrium Conjecture*, black holes do not form spacetime singularitities. And since black holes are the only known candidates that could induce such extreme spacetime curvature, it appears that nature does not just abhor 'naked' singularities but rather (nature) abhors all physical singularities altogether, naked or not.

One notes a symmetry that has so far developed in this discussion. Clearly, the process of matter turning into a cosmological constant-like vacuum energy, to offset the formation of spacetime singularities, is exactly opposite to the process discussed earlier in the article, in which a dominating vacuum energy will decay into (matter) fields that increase cosmic inertia and compromise the cosmic acceleration. Such a symmetry should, therefore, rotate vacuum energy into matter fields and vise versa, and should admit a duality between positive and negative spacetime curvature. The symmetry implied in the vacuum-to-matter and matter-to-vacuum processes suggests some deeper principle underlying the dynamics of the universe. A rigorous discussion of such a principle and the group-theoretic characteristics of the implied symmetry behind it is not treated in the current article and will be carried on elsewhere. Nevertheless, the inference here is that the universe is stable to, and hence self-regulating against, irreversible conditions arising from either extreme vacuum or positive curvature domination. This is the content of the *General Cosmic Equilibrium Conjecture*.

One may at this point wonder how it is that in turning matter fields into a de Sitter vacuum in black holes, nature would not violate the entropy law. The answer is two fold. First, one recalls that the late time process when such a transition begins to occur is already hidden from the external observer by the black hole horizon so that any such violations are not physically observable! In this regard, black hole horizons become inevitable natural participants in the "regulation conspiracy" process of spacetime dynamics. Moreover, any such horizon is endowed with a temperature T_H and an associated radiation flux directed towards the external observer. Such radiation flux carries entropy with it. The result is that from the vintage point of the external observer, the process does instead result in the increase of entropy. Consequently, the entropy law

is still protected here and, manifestly, the natural existence of the black hole horizon renders the issue moot. The universe may indeed be 'wiser' than it is often given credit for!

The notion that a black hole may not contain a spacetime singularity is not new. What is new here is putting forward a physically motivated justification as to why black holes should not contain such singularities and further tying this up (through G-CEC) to a bigger cosmic picture of a universe that self-regulates its dynamics. Since they were first suggested by Gliner [17], non-singular black holes, along with other related end-products, have been discussed for a while now, by several authors including [18], [19], [20], [21], [22]. In [18], Brandenberger first constructed an effective action based on higher derivative modification of Einstein's theory, in which all homogeneous solutions are nonsingular and asymptotically approached the de Sitter space for $r \longrightarrow 0$. This work was later extended [20] to study scenarios in which a universe can be born from a black hole resting in a parent universe. More recently, Hawking radiation of such a nonsingular black hole has been studied [22] by Easson. Moreover, in her works, Dymnikova has consistently (see [19] and citations), argued that the final end-product of gravitational collapse should be a nonsingular black hole with an r-dependent $\Lambda(r)$ de Sitter-like core and with an energy-momntum tensor falling in the Petrov classification [(II)(II)]. On the other hand, in [21] Mazur and Mottola discuss gravitational collapse in which the end-product with a de Sitter core does not form a horizon. All these works clearly indicate that nonsingular gravitational collapse is becoming of interest to relativistic astrophysics and cosmology. One hopes that the physical justification for nonsingular collapse suggested in the present article will further stimulate the debate on the issue.

4 Conclusion

In conclusion we have, in this article, proposed that the universe is self-regulating in its dynamics. The framework implies that the universe dictates its exit to inflation, on the one extreme, while on the other extreme it negates gravitational curvature domination and the formation of local spacetime singularities. The central feature of the proposal, which is expressed in the *General Cosmic Equilibrium Conjecture (G-CEC),* is that the universe always acts to off-set any tendencies to shift it away from dynamical equilibrium. It achieves this through a mechanism of interaction between the background vacuum energy and matter fields. We have shown, on the one hand, that whenever the universe is vacuum dominated, the consequent spacetime acceleration leads to creation of physical fields that increase its internal energy and hence its gravitational content. On the other hand, whenever spacetime is extremely matter dominated and faced with the prospect of total collapse the matter at the core of the resulting black hole undergoes a phase transition to a de Sitter-like vacuum, hence avoiding formation of a physical singularity. The model relates global cosmic dynamics with local spacetime (black hole) dynamics suggesting a deeper symmetry underlying cosmic dynamics. In essence this relation is natural when one considers that spacetime (in both cases) is no longer just a "playing field" for particle dynamics but is, indeed, itself dynamical. The approach, therefore, suggests some (yet to be explored) principle and its symmetry that governs cosmic dynamics, directing the universe away from extreme irreversible conditions, by facilitating the interaction of the fields involved. The scenario reflects a universe which is always in search of equilibrium. This is the content of G-CEC. To our knowledge, this is the first time in the literature that the existence of a common principle behind both global cosmic dynamics and local spacetime dynamics, and behind both spacetime acceleration and spacetime collapse, has been suggested.

As we summarize below, the model (A) re-traces the evolution of the universe in a way that is consistent with existing observations; (B) provides a natural explanation to existing problems/puzzles; (C) makes predictions.

A) **Consistency:** *the model*

(1) reiterates the early universe was dominated by a vacuum energy that set it in an inflationary acceleration;

(2) suggests that spacetime backreacts to this acceleration by creating radiation/matter fields that increase its gravitational content;

(3) holds that (i) A2$\Longrightarrow$ justification for cosmic exit out of inflation; (ii) A2$\Longrightarrow$ increased cosmic radiation after inflation.

B) **Explained Puzzles:** *the model implies that*

(1) since a de Sitter spacetime is time-asymmetric and radiative, or (as a corollary) since vacuum energy acting as cosmic fuel must degrade into matter fields, then the question of why Λ is small now is explained by its inevitable decay[8].

(2) since in a decaying-vacuum dominated universe matter creation is a one-way process, it is seen why the amplitudes of the densities ρ_m and ρ_v do approach each other as the universe expands and ages, which explains the Coincidence Problem;

(3) the premise that the universe is equilibrium seeking coupled with the observation that the amplitudes of the field densities approach each other (see (4) explains why the universe on the average appears critical and will appear more so in future.

C) **Predictions:** *the model predicts that*

(1) the assumption of an early inflationary phase, coupled with decay of Λ in an expanding universe is necessarily followed by a matter domination phase (see A1,2,3) which, in turn, necessarily leads to the current low density vacuum domination and cosmic acceleration. Conversely, the observed current low level acceleration predicts a previous matter dominated phase, preceded by an early vacuum dominated inflationary phase;

(2) the current and any other (prior/consequent) cosmic accelerations must be variable (time-dependent) due to the vacuum-matter oscillations;

(3) consistent with C1 and C2, there is a future exit to the current acceleration through creation of long wavelength modes as a backreaction;

(4) there will be future periods of alternating vacuum and matter domination with decaying and time-wise more comparable maxima in the field densities, which offers an explanation to the *dynamical problem*;

(5) the universe does not admit creation of (physical) spacetime singularities and, in particular, black holes do not contain such singularities.

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