

Why “nothing” balances “something”

Georgios Kofinas*, **Vasilios Zarikas†**

**Department of Physics, University of Crete, 71003 Heraklion, Greece*

†Department of Electrical Engineering, ATEI Lamias, 35100 Lamia, Greece

ABSTRACT: We propose a mechanism capable to provide a natural solution to two major cosmological problems, first cosmic acceleration and second the coincidence problem. Analyzing a specific brane-bulk energy exchange mechanism through astrophysical black holes it is possible first to understand and realize the natural interrelation between dark energy and matter density and second explain why dark energy can be of the same order of the matter density for a wide range of the involved parameters. Furthermore, the model can lead to a crossing of the phantom divide recently.

KEYWORDS: cosmic acceleration, brane cosmology, brane bulk energy exchange, D-branes, fuzzball conjecture.

Contents

1. Introduction	1
2. The framework: brane cosmology with 5-dim bulk energy exchange	3
3. A novel phenomenon: brane-bulk energy exchange inside galactic black holes and/or galactic core giant black holes	8
3.1 Energy loss from brane black holes	10
3.2 The proposed mechanism and the gravitational collapse on the brane	13
3.3 The proposed mechanism and the Hawking-like radiation	14
3.4 The proposed mechanism and the Fuzzball approach	15
4. Amount of produced cosmic acceleration	17
5. Conclusions	19
6. Acknowledgements	20

1. Introduction

During last decades it has been realized that the investigation of the problems associated with the cosmological constant would provide an insight into the structure and the properties of elusive quantum gravity. One may categorize the “cosmological constant” issue dividing it into two problems.

The first problem refers to the vast discrepancy between the value a theorist would expect and the very low value of the effective cosmological constant. As Zel’dovich [1] first noticed, the effective cosmological constant we measure is the sum of the pure geometric origin cosmological constant plus the energy density of the vacuum. It seems impossible to understand why the measured effective cosmological constant is so much smaller than the value of the vacuum energy calculated by a quantum field theorist (cosmic phase transition, quantum field zero-point energies). This puzzle challenges the inflationary scenario and the various models of quantum gravity.

The present work attempts to solve a recently emerged second problem regarding the cosmological constant issue which is related to the measured cosmic acceleration. One may expect that both two problems have a common explanation. It is however possible that different mechanisms are responsible for the explanation of each of them.

During the last decade it has been established through different independent pieces of astronomical data that empty space, devoid of the usual matter, is anti-gravitating. It creates gravitational

repulsion and gives rise to an accelerated cosmological expansion. According to our present-day understanding, this accelerated expansion could be induced by an effective cosmological “constant”-like term (vacuum or dark energy). According to the data, the magnitude of the required vacuum/dark energy is quite close to the critical (closure) cosmological energy density. Vacuum ($p = -\rho$) or dark energy ($p < -\frac{\rho}{3}$) makes approximately 70% of the latter. Why vacuum energy, which stays constant in the course of cosmological evolution, or why dark energy, which evolves with time quite differently from the normal matter, have similar magnitude with matter density just today, all being close to the value of the critical energy density?

There are several ideas in literature, though yet incomplete, that have the potential to provide solutions to the above mentioned problems. The present paper proposes that a *brane-bulk energy outflow occurring inside black holes* provides the mechanism that drives the measured cosmic acceleration.

The proposed mechanism assumes an RS-like cosmological brane [2], [3], [4]. It will be shown below that the brane can experience accelerated expansion only recently, overpassing well known problems of nucleosynthesis constraints [5]. The driving phenomenon is “off” in the period of nucleosynthesis and before, and “on” at late times. Furthermore, the magnitude of the mechanism is related to the current amount of matter density ρ_m . Thus it has the potential to provide a natural explanation of the observed $\rho_{vac} \approx 2.3 \rho_m$.

Both astrophysical black holes in haloes and supermassive black holes at the galactic centres appear after the large scale structure of the universe, weight a portion of ρ_m and are regions where high energy interactions occur. This remark will be at the center of the proposed mechanism. Assuming that a brane cosmological model describes our universe, it is natural to expect a moderate exchange of energy between the brane and the bulk. This exchange results to non-zero energy-momentum tensor components T_{05} and T_{55} and is able to provide the necessary conditions for a cosmic acceleration. The present paper comes to suggest a realistic outflow mechanism for developing such non zero T_{05} , T_{55} values: *Astrophysical black holes contain matter in an unknown form (i.e. effective quantum fluid arising from superposition of non empty black hole quantum spacetimes) and accrete continuously mass. Collapsing matter falling into a black hole accelerates and gets easily “thermalized” to temperatures close and above M (Planck fundamental mass). Furthermore, it is expected portion of black hole mass to be in the form of highly energetic states close to M , not only due to accreting matter interactions but also due to Hawking like particle production in the interior [6]. But for energy scales close to M , matter interactions result to graviton escape to the bulk. Therefore, energy outflow can occur in the interior of galactic halo black holes and galactic core supermassive black holes.*

For simplicity we assume that brane black holes are homogeneously distributed on the brane. Thus, instead of determining the modification of the expansion rate of a swiss cheese brane cosmological model with brane-bulk energy exchange, we will study a brane cosmological model consisting of a pressureless distribution of galaxies and black holes. It has been proven that brane swiss cheese cosmological models have only slightly different expansion rate and evolution compared to the corresponding dust models [7], thus we do not expect a large modification in our case too.

The paper is organized as follows. In the next section the mathematical framework is presented. It is followed by a detailed description of the physics of the energy exchange mechanism. In section

4 numerical computations are performed in order to show the success of the model. Finally, section 5 is dedicated to the conclusions.

2. The framework: brane cosmology with 5-dim bulk energy exchange

We begin with a model described by the Einstein-Hilbert action with matter and a 5D cosmological constant plus the contribution describing the brane

$$S = \int d^5x \sqrt{-g} (M^3 R - \Lambda + \mathcal{L}_B^{mat}) + \int d^4x \sqrt{-h} (-V + \mathcal{L}_b^{mat}), \quad (2.1)$$

where R is the Ricci scalar of the five-dimensional metric g_{AB} ($A, B = 0, 1, 2, 3, 5$), Λ is the bulk cosmological constant and h is the induced metric on the 3-brane. We identify (x, z) with $(x, -z)$, where $z \equiv x_5$ in order to impose the usual \mathbb{Z}_2 reflection symmetry of the AdS slice. Following the conventions of [2], we extend the bulk integration over the entire interval $(-\infty, \infty)$. \mathcal{L}_B^{mat} and \mathcal{L}_b^{mat} are the bulk and brane matter contents respectively. M is the five-dimensional Planck mass. The quantity V can include the brane tension as well as quantum contributions to the four-dimensional cosmological constant.

In order to search for solutions we consider a not too restrictive ansatz for the metric of the form

$$ds^2 = -n^2(t, z) dt^2 + a^2(t, z) \gamma_{ij} dx^i dx^j + b^2(t, z) dz^2, \quad (2.2)$$

where γ_{ij} is a maximally symmetric 3-dimensional metric with $i, j = 0, 1, 2, 3$ (we use $k = -1, 0, 1$ to parameterize the spatial curvature). The solution of the five-dimensional Einstein equations $G_{MN} = \frac{1}{2M^3} T_{MN}$ can be found in [8] and in the following few lines some key steps and assumptions are briefly described. A perfect cosmic fluid is assumed on the brane and an additional energy-momentum tensor in the bulk $T_N^M|_{m,B}$ (T_{MN} denotes the total energy-momentum tensor), i.e.

$$T_N^M = T_N^M|_{v,b} + T_N^M|_{m,b} + T_N^M|_{v,B} + T_N^M|_{m,B} \quad (2.3)$$

$$T_N^M|_{vac,b} = \frac{\delta(z)}{b} \text{diag}(-V, -V, -V, -V, 0), \quad T_N^M|_{vac,B} = \text{diag}(-\Lambda, -\Lambda, -\Lambda, -\Lambda, -\Lambda) \quad (2.4)$$

$$T_N^M|_{matter,b} = \frac{\delta(z)}{b} \text{diag}(-\rho, p, p, p, 0), \quad T_N^M|_{matter,B} = \text{diag}(-\rho_B, p_B, p_B, p_B, p_B + T_5^5), \quad (2.5)$$

where ρ and p are the energy density and pressure on the brane, respectively. The behaviour of $T_{MN}|_{m,B}$ is in general complicated in the presence of flows. The T_5^5 component expresses the pressure along the fifth dimension due to the existence of the energy exchange between brane and bulk. This pressure reduces to zero far away from the brane. The set of the Einstein equations at the location of the brane is

$$\dot{\rho} + 3\frac{\dot{a}_o}{a_o}(\rho + p) = -\frac{2n_o^2}{b_o} T_5^0 \quad (2.6)$$

$$\begin{aligned} \frac{1}{n_o^2} \left(\frac{\ddot{a}_o}{a_o} + \left(\frac{\dot{a}_o}{a_o} \right)^2 - \frac{\dot{a}_o \dot{n}_o}{a_o n_o} \right) + \frac{k}{a_o^2} &= \frac{1}{6M^3} \left(\Lambda + \frac{1}{12M^3} V^2 \right) \\ &- \frac{1}{144M^6} (V(3p - \rho) + \rho(3p + \rho)) - \frac{1}{6M^3} T_5^5 . \end{aligned} \quad (2.7)$$

Dots indicate derivatives with respect to t . We indicate by the subscript “ o ” the value of various quantities on the brane and T_{05}, T_{55} are the 05 and 55 components of $T_{MN}|_{m,B}$ evaluated on the brane. We have taken that $\rho_B, p_B \ll \Lambda$ in order to derive a solution that is largely independent of the bulk dynamics. This is also possible if we assume that the diagonal elements of the various contributions to the energy-momentum tensor satisfy the schematic inequality

$$|(\rho_B \text{ or } p_B) / \Lambda| \ll |(\rho_b \text{ or } p_b) / V| . \quad (2.8)$$

Therefore, the assumption is that the bulk matter relative to the bulk vacuum energy is much less important than the brane matter relative to the brane vacuum energy. In this case, the bulk is largely unperturbed by the exchange of energy with the brane. This is an important hypothesis since we do not want to lose predictability.

Since we are interested in a model that reduces to the Randall-Sundrum vacuum [2] in the absence of matter we set the bulk cosmological constant and the brane tension to satisfy $\Lambda + \frac{1}{12M^3} V^2 = 0$.

It is convenient to employ a coordinate frame in which $b_o = n_o = 1$ in the above equations. This can be achieved by using Gauss normal coordinates with $b(t, z) = 1$ and by going to the temporal gauge on the brane with $n_o = 1$. The assumptions for the form of the energy-momentum tensor are then specific to this frame. Using $\beta \equiv M^{-6}/144$ and $\gamma \equiv V\beta$, omitting the subscript o for convenience in the following, and defining an auxiliary quantity ψ by

$$\frac{\ddot{a}}{a} = -(2 + 3w)\beta\rho^2 - (1 + 3w)\gamma\rho - \sqrt{\beta}\Pi - \psi + \lambda , \quad (2.9)$$

we can rewrite equations (2.6), (2.7) in the equivalent form

$$\dot{\rho} + 3(1 + w)\frac{\dot{a}}{a}\rho = -T \quad (2.10)$$

$$\frac{\dot{a}^2}{a^2} = \beta\rho^2 + 2\gamma\rho - \frac{k}{a^2} + \psi + \lambda \quad (2.11)$$

$$\dot{\psi} + 4\frac{\dot{a}}{a}\psi = 2\beta\left(\rho + \frac{\gamma}{\beta}\right)T - 2\sqrt{\beta}\frac{\dot{a}}{a}\Pi . \quad (2.12)$$

Here, $p = w\rho$ and $T = 2T_5^0$, $\Pi = 2T_5^5$ are the discontinuities of the zero-five and five-five components of the bulk energy-momentum tensor. The effective cosmological constant on the brane $\lambda = (\Lambda + V^2/12M^3)/12M^3$ as we have mentioned before it will be set to zero, but for the time being we leave it intact. In the special case of no-exchange ($\Pi = 0$, $T = 0$), ψ represents the mirage radiation reflecting the non-zero Weyl tensor of the bulk.

In order to study further cosmic acceleration, we present a novel convenient set of differential equations (2.13), (2.14) for q, ρ (q is the usual deceleration parameter $q = -\frac{\ddot{a}}{a}H^{-2}$), equivalent to the last system of equations (2.10), (2.11), (2.12)

$$\frac{dq}{da} = 2\frac{1}{a}q(q+1) + H^{-2} \left[2(2+3w)\beta\rho\frac{d\rho}{da} + (1+3w)\gamma\frac{d\rho}{da} + \frac{d\psi}{da} + \sqrt{\beta}\frac{d\Pi}{da} \right] \quad (2.13)$$

$$\frac{d\rho}{da} = -\frac{1}{a} [3(1+w)\rho + T H^{-1}] , \quad (2.14)$$

where we should replace everywhere ψ and $d\psi/da$ by

$$\psi = -(2+3w)\beta\rho^2 - (1+3w)\gamma\rho + H^2q - \sqrt{\beta}\Pi + \lambda \quad (2.15)$$

$$\frac{d\psi}{da} = \frac{1}{a} \left[-4\psi + 2\beta\left(\rho + \frac{\gamma}{\beta}\right) T H^{-1} - 2\sqrt{\beta}\Pi \right] \quad (2.16)$$

and we substitute H^2 with the help of

$$H^2 = \frac{(3w+1)\beta\rho^2 + (3w-1)\gamma\rho + \frac{k}{a^2} - 2\lambda + \sqrt{\beta}\Pi}{q-1} . \quad (2.17)$$

The above system of differential equations (2.13), (2.14) does not depend on ψ or its derivatives and is the most appropriate for studying cosmic acceleration since it incorporates the cosmological energy density and the deceleration parameter as functions of the scale factor. It is worth mentioning that both Π and T , according to the proposed mechanism, depend on the astrophysical properties of black holes and do not depend on ψ .

In order to be able to proceed further and solve the system of the differential equations, T and Π have to be replaced. This requires to know the specific physical phenomena that generate them. According to the proposed mechanism these quantities are the total dark radiation and pressure that appear due to the energy loss to extra dimensions through the galactic black holes. A detailed description of this mechanism is given in the next session. We are going to distinguish two cases in our numerical study of the system (2.13), (2.14). Both are consistent with the details of the involved phenomena.

In the first case, which is valid for a study of the recent cosmological time period, i.e. z close to 0, the dark pressure Π can be modeled to be analogous to a known constant ϖ times the inverse Hubble volume. The same holds and for the dark radiation that can be approximated also to be analogous

to a known constant τ times the inverse Hubble volume. Therefore, we use $d\varpi/da = d\tau/da = 0$, which both are valid for the very recent time period of interest since the cosmic matter density rate is orders of magnitude larger than the black hole density rate $d\rho_{BH}/da \ll d\rho/da$ [9] (see also next session for justification). Therefore, we set $\Pi = \varpi H^3$ and $T = \tau H^3$, and consequently the derivative $\frac{d\Pi}{da}$ that appears in (2.13) should be replaced as follows

$$\frac{d\Pi}{da} = -\frac{3\varpi H^3(q+1)}{a} \quad . \quad (2.18)$$

Finally, H can be found solving exactly the cubic equation

$$-\sqrt{\beta}\varpi H^3 + (q-1)H^2 = (3w+1)\beta\rho^2 + (3w-1)\gamma\rho + \frac{k}{a^2} - 2\lambda \quad . \quad (2.19)$$

The above cubic equation, for all realistic parameters of late time cosmology, has always two real positive roots associated with expanding universe and one negative leading to contracting cosmological solutions. Thus, we can easily evaluate H from the two positive roots

$$H = s_1 + s_2 - A/3 \quad \text{or} \quad (2.20)$$

$$H = -\frac{1}{2}(s_1 + s_2) - \frac{A}{3} - i\frac{\sqrt{3}}{2}(s_1 - s_2), \quad (2.21)$$

where

$$s_1 = [\eta + (\vartheta^3 + \eta^2)^{1/2}]^{1/3}, \quad s_2 = [\eta - (\vartheta^3 + \eta^2)^{1/2}]^{1/3}, \quad A = \frac{1-q}{\sqrt{\beta}\varpi} \quad (2.22)$$

$$\vartheta = -\frac{1}{9}A^2, \quad \eta = -\frac{1}{2} \frac{(3w+1)\beta\rho^2 + (3w-1)\gamma\rho + \frac{k}{a^2} - 2\lambda}{\sqrt{\beta}\varpi} - \frac{1}{27}A^3 \quad . \quad (2.23)$$

Now, the system of differential equations (2.13), (2.14) can easily be solved numerically. Thus, it is possible to test if the measured cosmic acceleration can be produced from some sensible values of T_5^0, T_5^5 according to our scenario.

In the second case, which is more general, we do not assume a constant number of black holes since we are interested to include the dependence of the total mass of black holes on the scale factor evolution. In this way it will be possible to describe the cosmological behaviour for redshifts far away from $z = 0$. Our mechanism suggests in this second case that $\Pi = \widehat{\varpi} \rho_{BH}$ and $T = \widehat{\tau} \rho_{BH}$, where $\widehat{\varpi}$ and $\widehat{\tau}$ are known constants and ρ_{BH} is the density of the relevant black holes which is a function of the scale factor. The latter can be found in literature, see [10]. Now, the derivative $\frac{d\Pi}{da}$ that appears in (2.13), equals

$$\frac{d\Pi}{da} = \widehat{\varpi} \frac{d\rho_{BH}}{da} \quad . \quad (2.24)$$

Since it is possible to know estimations concerning the evolution of ρ_{BH} and consequently of $\frac{d\rho_{BH}}{da}$ as functions of a , it is possible to solve numerically the system (2.13), (2.14). In this second case, there is no need to solve any cubic equation since we can estimate H from (2.17).

Let's now see if we can learn from these dynamic equations something about the type of dark radiation or pressure we need to have in order to explain cosmic acceleration. Equation (2.17) provides

an important constraint that the cosmic acceleration should satisfy. From it, we can determine the current value of Π as a function of the present values

$$\Pi_0 = \left(-1 + q_0 + \frac{\Omega_{m,0}}{2}\right) \beta^{-1/2} H_0^2 \Leftrightarrow q_0 = 1 - \frac{\Omega_{m,0}}{2} + \Pi_0 H_0^{-2} \beta^{1/2}, \quad (2.25)$$

where we have replaced $\rho = \Omega_m \rho_{cr}$ and $k = 0$, $\lambda = 0$, $w = 0$. Note that the value of Π_0 is related to the value of T_0 due to the specific outflow process that is presented in next section. Now for $q_0 = -1$ and $\rho_0 \sim \frac{1}{3} \rho_{cr,0}$ (assuming the present value of the cosmic energy density close to the FRW critical density) we get

$$\Pi_0 = -\frac{11}{6} H_0^2 \beta^{-1/2}. \quad (2.26)$$

Such negative values can be easily realized in our scenario, coming from the proposed outflow mechanism. Nevertheless, it is interesting that the current value of the deceleration parameter q_0 can be estimated by such a simple expression as this in Eq. (2.25), depending only on Π_0, H_0^2 .

Since q is not directly measured, we have to express it as a function of the ratios of cosmological matter density to critical density and dark energy density to critical density. We define

$$\Omega_m = \frac{2\gamma\rho}{H^2} = \frac{\rho}{\rho_{cr}}, \quad \Omega_\lambda = \frac{\lambda}{H^2}, \quad \Omega_k = -\frac{k}{a^2 H^2} \quad (2.27)$$

and for the dark energy part

$$\Omega_{DE} = \frac{\beta\rho^2 + \psi}{H^2} = \frac{\rho_{DE}}{\rho_{cr}}. \quad (2.28)$$

Therefore, Eq. (2.11) gives

$$\Omega_m + \Omega_{DE} + \Omega_\lambda + \Omega_k = 1. \quad (2.29)$$

Finally, the deceleration parameter can be found from

$$q = \Omega_{DE} + \sqrt{\beta} \Pi H^{-2} + (1 + 3w) \frac{\Omega_m}{2} \left(1 + \frac{\beta H^2}{2\gamma^2} \Omega_m\right) - \Omega_\lambda. \quad (2.30)$$

This last equation is going to provide us the initial condition for $q_0 = q(z = 0)$.

As mentioned above, the system of differential equations (2.13), (2.14) is very convenient because it is not necessary to specify initial conditions for ψ which is unknown, but instead it suffices to set known/expected initial conditions. In the first case, these two initial conditions are $\rho(z = 0)$ and $\Omega_m(z = 0) = 0.3$, which suggest an initial $q(z = 0)$. This pair of initial conditions suffices to find a solution following a cosmological top down approach [11]. In the second case, the initial conditions are again $\rho(z = 0)$ and $\Omega_m(z = 0) = 0.3$, suggesting a known initial $q(z = 0)$, or alternatively we can set initial conditions at $z = 2$, i.e. $\rho_{BH}(z = 2)$ and $\rho(z = 2)$, known from astrophysical studies [10].

Another useful quantity used in physical cosmology is the coefficient w_{DE} of the equation of state of the dark energy. In our case the dark energy density encodes the density required to represent the energy exchange

$$\dot{\rho}_{DE} + 3(1 + w_{DE}) \frac{\dot{a}}{a} \rho_{DE} = T. \quad (2.31)$$

It is straightforward to prove that

$$w_{DE} = \frac{1}{3} + \frac{1 + 3w}{6} \frac{\beta \Omega_m^2 H^2}{\gamma^2 \Omega_{DE}} + \frac{2\sqrt{\beta} \Pi H^{-2}}{3\Omega_{DE}}. \quad (2.32)$$

This coefficient w_{DE} will be a prediction of our model.

Finally, an alternative useful expression that can be derived from equations (2.10), (2.11), (2.12) is the following single differential equation for $k = 0$ that depends on the energy density and which can be easily solved numerically

$$\begin{aligned} \frac{dq}{d\rho} = & 2q(q+1)Z^{-1} - 3H\sqrt{\beta}(q+1)\varpi Z^{-1} + \\ & + H^{-2} \left[2(2+3w)\beta\rho + (1+3w)\gamma - 4\psi Z^{-1} + 2\beta\left(\rho + \frac{\gamma}{\beta}\right)TZ^{-1}X - 2\sqrt{\beta}\Pi Z^{-1} \right], \end{aligned} \quad (2.33)$$

where

$$Z = -3(w+1)\rho - TX \quad (2.34)$$

$$X = (\beta\rho^2 + 2\gamma\rho - \frac{k}{a^2} + \psi + \lambda)^{-1/2} \quad (2.35)$$

and we replace everywhere H and ψ from equations (2.15), (2.20) or (2.17).

As mentioned, in the Randall-Sundrum model the effective cosmological constant λ vanishes, and this is the value we assume in the rest of the paper. We also set $k = 0$ since we are interested on flat universes. Finally, since we are analyzing the cosmic acceleration after the large scale structure of the universe we set $w = 0$.

3. A novel phenomenon: brane-bulk energy exchange inside galactic black holes and/or galactic core giant black holes

The scope of this work is to propose an explanation of the measured values of matter and dark energy densities, $\rho_{m,0} \approx 0.3 \rho_{cr,0}$ and $\rho_{DE,0} \approx 0.7 \rho_{cr,0}$, i.e. $\rho_{DE,0} \approx 2.3 \rho_{m,0}$. It is quite natural in the framework of brane cosmologies to expect a small energy exchange of our brane universe with the bulk space. This energy exchange phenomenon is a high energy phenomenon. The channels for energy exchange “open” when the relevant energies reach the relatively low Planck fundamental energy scale M . In the cosmological context, regions where such high energy phenomena could occur are not as many.

In general, we would expect a brane-bulk energy exchange through:

1. High energy interactions in some accretion disks and more importantly inside galactic centres/galactic black holes leading to energy loss to the bulk due to the production of gravitons from high energetic accelerated particles.

2. Gravitational attraction of a portion of the gravitons that were escaped into the bulk or gravitational accretion of bulk matter to brane black hole.
3. Attraction of bulk matter from the whole brane.
4. Decay of very massive scalars and/or fermions.

The third type of exchange can be seriously studied only if the bulk matter content is known in detail, see for example [12], and consequently only if we are sure about the geometry of the bulk space, its anisotropies and the motion of our brane in it. Various different approaches to describe bulk dynamics/matter can be found in [13], [14], [15], [16], [17].

The fourth exchange mechanism [18] works only for very massive particles like light supersymmetric particles with masses above 1TeV. The possibility to produce the measured acceleration is not very generic (see [19]). More importantly, this scenario cannot explain why the value of the dark energy is comparable to the present value of the matter density.

The second exchange mechanism regarding attraction due to the brane gravitational field contributes to dark pressure (on pressure not on energy flow, assuming non significant interaction of bouncing gravitons with brane matter), but only to a small amount [20] at late times, for which we are interested in. However, the attraction of bulk matter due to the gravitational field of leaking black holes may be not negligible for significant values of bulk matter density. Nevertheless, since we are interested to investigate energy leaking without losing predictability we assume that the matter energy density of bulk fluid is small or zero.

Note also that in the present paper we will not consider the possibility of an existing considerable amount of primordial black holes today, and therefore we will not study further scenarios with such black holes.

The present work tries to reach general and bulk independent conclusions based only on parameters like AdS radius $l = 1/L$, where L is the curvature scale $L = \sqrt{-\Lambda/6}$, the mean mass energy density of brane black holes and some astrophysical data. Therefore, we assume that the bulk cosmological constant is much larger than its matter content and therefore the bulk is largely unperturbed by the exchange of energy with the brane.

In next sections our proposed mechanism is analyzed working with a homogeneous distribution of galactic black holes on a brane. The study of a Swiss cheese brane world model with bulk energy exchange certainly would be a more precise modeling, however as it is pointed in [7] the correction to the late brane expansion is expected to be small. Therefore, the total brane-bulk energy exchange under consideration will be

$$T = T_e , \tag{3.1}$$

where T_e represents the outflow of energy due to the production of escaping gravitons from high energetic particles inside BHs.

3.1 Energy loss from brane black holes

Last years it became evident that every nearby massive galaxy possesses a central black hole with mass proportional to that of the galaxy spheroid. This implies that they also possess an Active Galactic Nuclei (AGN) [21]. In addition, there are evidences for the existence of a large amount of extra-galactic exposure at TeV energies [22], [23] and some of it can be associated to the presence of galactic black holes and galactic core supermassive black holes.

It is certainly a safe assumption that in the accretion discs and more importantly in the interiors of galactic black holes and galactic core supermassive black holes various particles as electrons and protons can be thermalised/accelerated to energies around M or above. Particle acceleration starts in the accretion discs outside the horizon and increases as the particle crosses it. Consequently, particle collisions become capable to produce gravitons escaping to the bulk space.

More accurately, assuming a black hole interior with characteristics close to the fuzzball conjecture, it is acceptable to use the picture of an effective fluid that fills the black hole and do not concentrate at the singular center. This effective fluid will be on a high temperature below or close to M . At these energies it is possible [20], [24] to recover rapid energy favored production of bulk gravitons from collisions of energetic brane matter. In a hot plasma the production rate per 3-volume is the thermal average of the cross section times the lost energy of the particles. Therefore, the total energy loss rate due to bulk graviton radiation is

$$\Delta\dot{\rho}_{pls} = 0.112 \frac{\Theta^4}{M^3} \rho_{pls} = 0.112 g_* \frac{\pi^2}{30} \frac{\Theta^8}{M^3}, \quad (3.2)$$

where M is the five dimensional Planck mass, Θ is the temperature and ρ_{pls} is the total energy density of the hot regions. The second equation in (3.2) is derived assuming a relativistic plasma with g_* the effective number of the relativistic degrees of freedom.

Now, adding all the leakage of energy from all galactic halo black holes and all black holes at the galactic central regions we get

$$T_e = 2 \sum \Delta\dot{\rho}_{pls}. \quad (3.3)$$

In our approach we assume :

1. The collapsing matter rapidly reaches energies of the order of M and above, while the effective fluid inside the black hole probably has a mean temperature well below M but certainly non negligible.
2. A portion of the mass of a black hole is near its center and another portion is distributed in the interior. A portion of the mass of a black hole will be on energies equal and below M . A part of the interior as well as of the center ($r \approx 0$) of the brane black string/cigar [25] will be on the brane and the rest on the bulk. There will be a leakage of the brane black string/cigar energy towards first to the bulk space exterior to the black string/cigar and second to the bulk portion of the center ($r \approx 0$) of the brane black string/cigar.

The above assumptions in the framework of pure general relativity cannot naturally be realized (one has to build models assuming non applicability of singularity theorems due to energy conditions violation and appropriate energy momentum tensors) since all the falling matter reaches in short time the singularity where the energy density becomes infinite. Consequently, the space between the singularity and the horizon will be empty. However, this is not a valid picture since in this case the vacuum near the horizon would be empty of information, a fact that makes the emitted Hawking radiation to be exactly thermal resulting to information loss. Assuming the fuzzball approach and conjecture [26], [27], [28], [29], [30] the interior of a black hole is filled with microstates with no horizon. Therefore, it is sensible first to expect energy leakage towards the bulk space and second to expect an effective description of the matter content of the black hole interior with a fluid. The effective equation of state of the fluid will be an emerging description arising from the quantum statistical description of the ensemble of fuzzball microstates. Note also that the property of fractionalization [31], [32] too, supports the previously mentioned arguments. Worth stressing that the energy leakage from the brane to the bulk can be attributed first to the fact that a portion of the black hole interior does not lie on the brane and second to the fact that hot matter inside the black hole can tunnel to the bulk. In the following we assume as main leakage mechanism the tunneling of the matter in the interior to the bulk.

In order to proceed to a rough estimation of the mean outflow energy rate, an effective mean black hole plasma energy mass density ρ_{pls}^{BH} is assumed inside brane black strings/cigars expressed with the help of an effective mean temperature Θ_{mean} . The following ansatz will be used

$$\rho_{pls}^{BH} \simeq g_* \frac{\pi^2}{30} \Theta_{mean}^4, \quad (3.4)$$

where $g_* = 106.75$. In order to evaluate the outflow we have to multiply the flow density given by (3.2) with the relevant volume that contains the mean black hole plasma energy mass density ρ_{pls}^{BH} and sum up all the contributions. Finally, we divide with the Hubble volume H^{-3} in order to evaluate the outflow density

$$T_e \simeq 0.224 g_* \frac{\pi^2}{30} \frac{\Theta_{mean}^8}{M^3} [N_{haloBH} V_{haloBH} + N_{coreBH} V_{coreBH}] H^3 \quad or$$

$$T_e \simeq \frac{0.224}{M^3} \Theta_{mean}^4 [N_{haloBH} M_{haloBH} + N_{coreBH} M_{coreBH}] H^3 = \tau H^3 \quad or \quad (3.5)$$

$$T_e \simeq \frac{0.224}{M^3} \Theta_{mean}^4 (\rho_{haloBH} + \rho_{coreBH}) = \hat{\tau} (\rho_{haloBH} + \rho_{coreBH}) = \hat{\tau} \rho_{BH}. \quad (3.6)$$

We assume the existence of galactic halo black holes with mean mass M_{haloBH} and galactic central regions carrying a supermassive black hole with a mean value equal to M_{coreBH} . Since the mean value of mass density ρ_{pls}^{BH} are very different among a typical halo black hole and a typical supermassive core black hole we substitute $V_{haloBH} = M_{haloBH} (\rho_{pls}^{hBH})^{-1}$ and $V_{coreBH} = M_{BHcore} (\rho_{pls}^{cBH})^{-1}$. N_{haloBH} is the number of galactic black holes in halos, while N_{coreBH} the number of central supermassive black holes. Although for simplicity in the above formulae the temperature appears as a common mean value, in reality Θ_{mean} can also be different between halo and core black holes and this point was taken under consideration in the numerical study of the solutions.

The under discussion phenomenon inside black holes most importantly results to the appearance of a negative pressure orthogonal to the fifth dimension. This pressure is due to the momentum of the escaping gravitons. The magnitude of this pressure close to the brane is approximately equal to the magnitude of the pressure of the collapsing/effective fluid when reaches high temperatures and starts leaking. Since our collapsing fluid is not an ideal fermi gas, we adapt a polytropic index $n = 1/(\hat{\gamma} - 1)$ for determining the pressure in the interior of both halo and core black holes, i.e.

$$p_{pls}^{BH} = \xi(\rho_{pls}^{BH})^{\hat{\gamma}}. \quad (3.7)$$

The constant ξ is determined by the thermal characteristics of the fluid and it can also be understood as a measure of the ratio of pressure to energy density at the centre of black hole. Therefore,

$$\begin{aligned} \Pi &= -2\xi[(\rho_{pls}^{hBH})^{\hat{\gamma}} N_{haloBH} V_{haloBH} + (\rho_{pls}^{cBH})^{\hat{\gamma}} N_{coreBH} V_{coreBH}] H^3 \\ &= -2\xi[(\rho_{pls}^{hBH})^{\hat{\gamma}-1} N_{haloBH} M_{haloBH} + (\rho_{pls}^{cBH})^{\hat{\gamma}-1} N_{coreBH} M_{BHcore}] H^3 = \varpi H^3 \end{aligned} \quad (3.8)$$

$$= -2\xi[(\rho_{pls}^{hBH})^{\hat{\gamma}-1} \rho_{haloBH} + (\rho_{pls}^{cBH})^{\hat{\gamma}-1} \rho_{coreBH}] = \widehat{\varpi} \rho_{BH}. \quad (3.9)$$

Regarding the two additive terms that appear in the above expressions it is worth mentioning that the mass density of a halo black hole and the mass density of a supermassive core black hole differ by orders of magnitude.

Finally, it should be noticed that this outflow mechanism has no similarity with scenarios that set the density of the plasma equal to the density of the overall cosmological fluid which cools as the universe expands (see [24], [20]).

Based on the above discussion we will illustrate the point that the proposed mechanism connects the cosmic acceleration with the present mass density of the universe. The energy loss due to the current outflow is evaluated multiplying the flow density given by (3.2) with the total relevant volume $N_{BH} V_{BH}$ that contains the mean black hole plasma energy mass density ρ_{pls}^{BH} , and sum up all the contributions. Finally, we divide with the present comoving volume V_0 in order to evaluate the current value

$$T_{e,0} = 2 \sum \Delta \dot{\rho}_{pls} = 0.224 \frac{\Theta_{mean}^4 N_{BH} M_{BH}}{M^3 V_0} = 0.224 \frac{\Theta_{mean}^4}{M^3} \rho_{BH,0} = 0.224 \frac{\Theta_{mean}^4}{M^3} \varepsilon \rho_0, \quad (3.10)$$

where ε is the portion of the present black hole mass density $\rho_{BH,0}$ relative to the present cosmic mass density ρ_0 . The final expression manifests the relation between the outflow energy and the current value of the cosmic mass density.

Similarly,

$$\begin{aligned} \Pi_0 &= -2\xi(\rho_{pls}^{BH})^{\hat{\gamma}-1} \frac{N_{BH} M_{BH}}{V_0} = -2\xi(\rho_{pls}^{BH})^{\hat{\gamma}-1} \rho_{BH,0} \\ &= -2\xi(g_* \frac{\pi^2}{30} \Theta_{mean}^4)^{\hat{\gamma}-1} \varepsilon \rho_0 \end{aligned} \quad (3.11)$$

and consequently

$$\begin{aligned} q_0 &= -\frac{\Omega_{m,0}}{2} + \Pi_0 H_0^{-2} \beta^{1/2} \\ &= -\frac{\Omega_{m,0}}{2} - 2\xi(g_* \frac{\pi^2}{30} \Theta_{mean}^4)^{\hat{\gamma}-1} H_0^{-2} \beta^{1/2} \varepsilon \rho_0. \end{aligned} \quad (3.12)$$

In section 4 it will be demonstrated that even for the most conservative values of all the involved parameters such negative values of q_0 can be achieved.

3.2 The proposed mechanism and the gravitational collapse on the brane

In this subsection estimations are presented concerning the evolution of a spherical collapse on the brane cosmology presented above. Our goal is to describe quantitatively the expected behavior that as the collapse of a fluid proceeds, its “temperature” rises. *In our case, strong quantum gravity corrections are not necessary* since our intention is to describe the collapse up to the point where the outflow becomes significant. This happens for temperatures close to the fundamental Planck scale which can be relatively low.

The spherical gravitational collapse on a brane with a realistic brane-bulk energy exchange will now be analyzed. The interior of the collapsing spherical region undergoing an Oppenheimer-Snyder collapse will be described by the brane cosmological metric (2.2) presented above, with nonzero T_{05}, T_{55} . Therefore the evolution has to be a contracting solution of the system of the brane cosmological equations (2.10), (2.11) and (2.12). Now, the energy density, the dark radiation and the dark pressure concern the plasma in the interior of black hole/collapsing region. Thus, the system of differential equations that the evolution of the collapsing region should respect is

$$\dot{\rho}_{pls} + 3(\rho_{pls} + p_{pls}) \frac{\dot{a}}{a} = -T_{pls} \quad (3.13)$$

$$\frac{\dot{a}^2}{a^2} = \beta \rho_{pls}^2 + 2\gamma \rho_{pls} - \frac{k}{a^2} + \psi + \lambda \quad (3.14)$$

$$\dot{\psi} + 4\frac{\dot{a}}{a}\psi = 2\beta\left(\rho_{pls} + \frac{\gamma}{\beta}\right)T_{pls} - 2\sqrt{\beta}\frac{\dot{a}}{a}\Pi_{pls} \quad , \quad (3.15)$$

where the dark radiation and dark pressure are given by

$$T_{pls} \simeq \frac{6.72}{\pi^2 g_*} \frac{1}{M^3} \rho_{pls}^2 \simeq 0.224 \frac{\Theta_{mean}^4}{M^3} \rho_{pls} \simeq 0.224 g_* \frac{\pi^2}{30} \frac{\Theta_{mean}^8}{M^3} \quad (3.16)$$

$$\Pi_{pls} = -2p_{pls} = -2\xi(\rho_{pls})^{\hat{\gamma}} \simeq -2\xi(g_* \frac{\pi^2}{30} \Theta_{mean}^4)^{\hat{\gamma}} \quad . \quad (3.17)$$

Collapsing plasma has been assumed to have an equation of state close to this of a polytropic fluid. The relation between the energy density and the temperature (local thermodynamic equilibrium) is given by the ansatz $\rho_{pls} \simeq g_* \frac{\pi^2}{30} \Theta_{mean}^4 \simeq \sigma \Theta_{mean}^4$. Pressure is expressed as $p_{pls} = \xi(\rho_{pls})^{\hat{\gamma}}$ (polytropic fluid with deviations from ideal gas behavior). Realistic quantum fluids can effectively be described by polytropic like fluids with deviations from ideal gas behaviour [33].

Therefore, in order to study the temperature evolution as the collapse continues, we have to find solution of the following system of differential equations

$$\dot{\Theta}_{mean} + \frac{3}{4}\Theta_{mean} \left(1 + \xi \sigma^{\hat{\gamma}-1} \Theta_{mean}^{4(\hat{\gamma}-1)}\right) \frac{\dot{a}}{a} + 0.056 \frac{\Theta_{mean}^5}{M^3} = 0 \quad (3.18)$$

$$\frac{\dot{a}^2}{a^2} = \beta \sigma^2 \Theta_{mean}^8 + 2\gamma \sigma \Theta_{mean}^4 - \frac{k}{a^2} + \psi + \lambda \quad (3.19)$$

$$\dot{\psi} + 4\frac{\dot{a}}{a}\psi = 0.448 \beta \left(\sigma \Theta_{mean}^4 + \frac{\gamma}{\beta} \right) \sigma \frac{\Theta_{mean}^8}{M^3} + 4\sqrt{\beta\xi}\sigma^{\hat{\gamma}} \frac{\dot{a}}{a} \Theta_{mean}^{4\hat{\gamma}} . \quad (3.20)$$

A simple study of the first equation shows that for expected parameters $\frac{\Theta_{mean}}{M} < 1$ and for $\dot{a} < 0$, which is the case of spherical collapse, we can get $\dot{\Theta}_{mean} > 0$, which is what we want to prove. The above system of the first and third equation can be solved numerically without difficulties, if we remove the $\frac{\dot{a}}{a}$ term using the second equation. A typical solution of this system is shown in Fig. 1, where time t is measured in GeV^{-1} and temperature Θ in GeV .

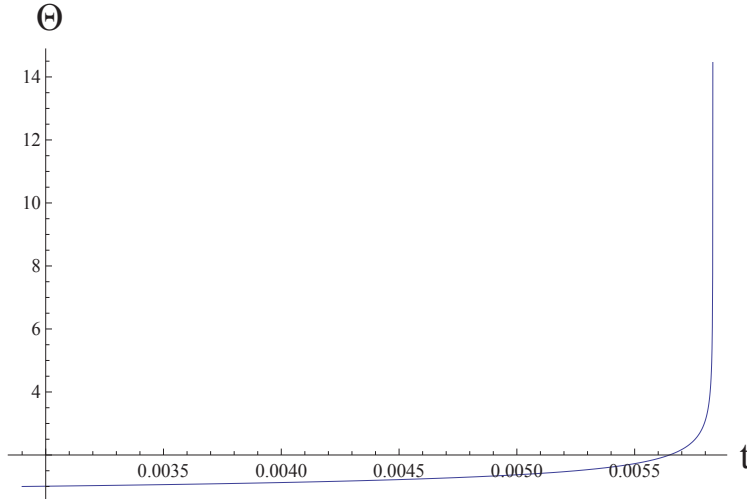


Figure 1: Temperature rise during a collapse for $M = 10^4 \text{ GeV}$

Note that we are not interested to find a static exterior for the above described collapsing spherical region [34].

3.3 The proposed mechanism and the Hawking-like radiation

An interesting work about the physics inside the forming horizon of collapsing shells or the interior of black holes accreting matter is this of Greenwood, Stojkovic [6]. In this work, Hawking radiation was studied as seen by an infalling observer. Based on functional Schrodinger formalism it is possible to calculate radiation in Eddington-Filkenstein coordinates which are not singular at the horizon. In these coordinates Hawking radiation does not diverge on the horizon. The estimated occupation numbers at any frequency, as measured by an observer crossing the horizon, were found to increase as the distance from the black hole center decreases. The spectrum is not thermal and therefore there is no well-defined temperature measured by the observer. Although this work does not refer to brane black holes, we expect similar qualitative behavior for this case too. Therefore, the above

discussion suggests that an observer entering the horizon encounters/interacts with more and more highly energetic particles which can escape easily to the bulk or cause through their interactions energy loss to the bulk. Estimations presented in [6] are not valid for distances close to the black hole centre where strong backreaction effects have to be considered. However, there is no need for that since energy loss can start inside and near the horizon for temperatures close to M .

3.4 The proposed mechanism and the Fuzzball approach

A fluid description is certainly a phenomenological picture which is traditionally followed in relativistic cosmology/astrophysics. Here we will attempt to discuss microscopically the reason why such a description can be based on fundamental physics. It is expected that in reality in the interior and most certainly near the centres of black holes the notion of classical spacetime is replaced by another not well understood “quantum” spacetime. The full treatment is still unknown; nonetheless it is expected that an *effective* description of the black hole interior with the help of a polytropic fluid without infinite density could be a fair approximation. Adopting this effective approach we assume that at the centre of the black hole’s classical spacetime, the density is large but finite and equals to $\rho_{pls}(r = 0)$. Therefore, if the physics in the interior of astrophysical black holes was known, one could in principle be able to reproduce an effective description estimating a mean value of the plasma density $\rho_{pls}^{BH} = \frac{4\pi}{V_{BH}} \int_0^R \rho_{pls}(r)r^2 dr$. The value of the effective radial dependent plasma density $\rho_{pls}(r)$ as well as the effective central finite value $\rho_{pls}(0)$ would then be determined by quantum gravity.

Although in pure general relativity such an expression has no meaning since the energy density becomes infinite and the spacetime description breaks at the centre, new ideas arising from string theory possibly allow an effective quantum statistical description of the black hole interior. A promising approach for addressing questions regarding physics inside black holes is the fuzzball proposal [26], [27], [28], [29], [30], [35], [36]. According to this view, the infinite “throat” that a classical geometrical description exhibits near the singularity is replaced by a long finite throat which ends in a quantum fuzzy cap. The fuzzball conjecture claims that the astrophysical black holes are described by microstates which all behave like the ones that have been constructed for extremal black holes in string theory. The bound states in string theory are not in general Planck sized or string sized, but have a size that grows with the degeneracy of the bound state. To make a big black hole a large number of elementary quanta need to be placed together. Regarding the size of the bound state one may think that this is equal to string or Planck scale l_{pl} . However, if this was true we would get the traditional picture of brane black holes with all matter placed at the singularity. The correct picture is that the size of the bound state increases with the number of quanta in the bound state. In the fuzzball approach the size of the bound state $\mathfrak{R} \sim N^a l_{pl}$ has been proven to be equal to the black hole horizon radius that we would find for the classical geometry which has the mass and charge carried by these N quanta. N is some count of the quanta and a depends on what quanta are being bound together.

The fuzzball theory allows present work to assume two important elements regarding the physics of the brane black holes interior. First, the matter content is distributed all over the interior, a fact

that allows an effective description with a quantum statistical fluid described by an exotic equation of state. Second, some of the quanta are free to tunnel into the bulk not due to Hawking black hole evaporation but due to the absence of microstate horizons and the brane-bulk geometry associated with a “small” value of M . Hawking radiation is due to fractional brane-antibrane annihilations, while outflow is the result of tunneling of string quanta of fractional and non fractional branes-antibranes towards the bulk space.

Let us think in more detail what may happens inside a black hole. If we increase the energy density of a collection of branes to very large values, it becomes entropically favorable to produce a large number of sets of mutually BPS branes and anti-branes. These branes “fractionate” each other, resulting to entropy that grows more rapidly as a function of energy compared to that of radiation or a Hagedorn type string or brane gas. Therefore, in the case of astrophysical black holes it is expected that after the beginning of the collapse energy density grows and matter reaches a Hagedorn phase of strings. Although this pressureless phase keeps its energy nearly constant (there are already significant open outflow channels) thanks to the continuing collapse the energy density increases further. Finally, we end up to an even higher energy scale phase with a soup of many fractional and less non fractional branes.

In the two charge system NS1-P bound state there is a string that loops n_1 times around S^1 (radius R) with a momentum charge P which is bound to the string in the form of traveling waves on the NS1 brane. The number of states that contribute more to the entropy is approximately equal to $\exp(\sqrt{n_1 n_p})$. These states are fractional with a length L_T equal to the classic geometry horizon (if we add one more charge). These fractional states have a low temperature/average energy (equal to Hawking temperature if we add one more charge) given by

$$T_H = \frac{\sqrt{n_1 n_p}}{L_T} , \quad (3.21)$$

where the total length of the string is large and equal to

$$L_T = 2\pi R n_1 \quad (3.22)$$

since in realistic astrophysical black holes n_1 can be very large.

However, in the black hole interior there are also fewer states with large temperature/energy because 1) L_T can be very small since R is very small, while n_1 is also small for non fractional states, 2) branes need a large time (evaporation timescale) to fractionate to very large lengths. These non fractional states tunnel immediately to the bulk space as long as

$$M \leq \frac{\sqrt{n_p}}{2\pi R \sqrt{n_1}} . \quad (3.23)$$

Now the disappearing states to the bulk due to tunneling are continuously replaced in the high energy density regions of the interior at the cost of the collapsing matter’s energy density. Thus, we have a non vanishing flow of energy towards the bulk.

In the three charge system there are n_5 NS5 branes and n_1 NS1 branes that define a system with a momentum charge P . Therefore, the bound system of these branes generate an “effective string”

with a total winding number $n_1 n_5$. All the above discussion for the two charge system and all relevant expressions remain the same replacing everywhere n_1 with $n_1 n_5$.

Apart from the outflow originated by these states in the black hole interior, there are two more outflow open channels. As we have previously mentioned, a portion of collapsing matter is still in the string/brane gas phase which is a very hot phase that certainly can leak to the bulk space. In addition, there must be a non negligible outflow from the portion of the collapsing matter that is between the string/gas phase and the electroweak energy scale ($\sim \text{TeV}$) as long as its local temperature is close or larger than M .

In summary, the reasoning that ensures outflow is the observation that astrophysical black holes are not non-perturbative configurations composed of wrapped strings or branes living at the Planck regime or M-theory landscape. They are objects created dynamically from collapsing matter initially respecting our U(1) vacuum. This matter unavoidably gets compressed to smaller and smaller volumes until it reaches very high energy scales where outflow is not negligible and unavoidable.

4. Amount of produced cosmic acceleration

The goal of the present work is to estimate for the proposed brane-bulk energy exchange mechanism the amount of the produced present cosmic acceleration for various values of the relevant parameters. This section presents the numerical results of our study. First we take under consideration astrophysical estimates reported in [10]. With the help of them we can describe the core black hole density evolution with the following relation

$$\log_{10}(\rho_{coreBH}) = -\mu z + \log_{10}(\rho_{coreBH}|_{z=0}) \quad . \quad (4.1)$$

Since $\rho_{coreBH}|_{z=0} = 4.3 \cdot 10^5 M_\odot Mpc^{-3}$ is the current galactic core black hole matter density and $\rho_{coreBH}|_{z=2} = 1.5 \cdot 10^5 M_\odot Mpc^{-3}$ is the density at redshift $z = 2$ we obtain

$$\mu = \frac{\log_{10}(\rho_{coreBH}|_{z=0}) - \log_{10}(\rho_{coreBH}|_{z=2})}{2} \quad . \quad (4.2)$$

Based on this expression it is possible to estimate the dependence on the scale factor of dark radiation and dark pressure from Eqs. (3.6), (3.9). The numerical investigation of (2.13), (2.14) reveals that for a wide range of the parameters n , M it is always possible to find a mean temperature Θ_{mean} that results to cosmological solutions with current cosmic acceleration $q < 1$, with w_{DE} around -1, and equally importantly with a deceleration era that only currently becomes acceleration. Table 1 presents some representative results, while Fig. 2 shows the evolution of the deceleration parameter q and w_{DE} for $n = 5$, $M = 10^4$.

input	assumption	assumption	output	output	output
n	M	Θ_{mean}	$T_{e,0}$	Π_0	$w_{DE,0}$
1.5	10^4TeV	$8 \cdot 10^{-5} \text{GeV}$	10^{-90}GeV^5	-10^{-62}GeV^5	-1
2	10^4TeV	$5 \cdot 10^{-6} \text{GeV}$	10^{-95}GeV^5	-10^{-62}GeV^5	-1
5	10^4TeV	$2.7 \cdot 10^{-13} \text{GeV}$	10^{-125}GeV^5	-10^{-62}GeV^5	-1
2	10^3TeV	$1.6 \cdot 10^{-7} \text{GeV}$	10^{-98}GeV^5	-10^{-65}GeV^5	-1

Table 1: Summary of results for various values of the parameters consistent with today acceleration

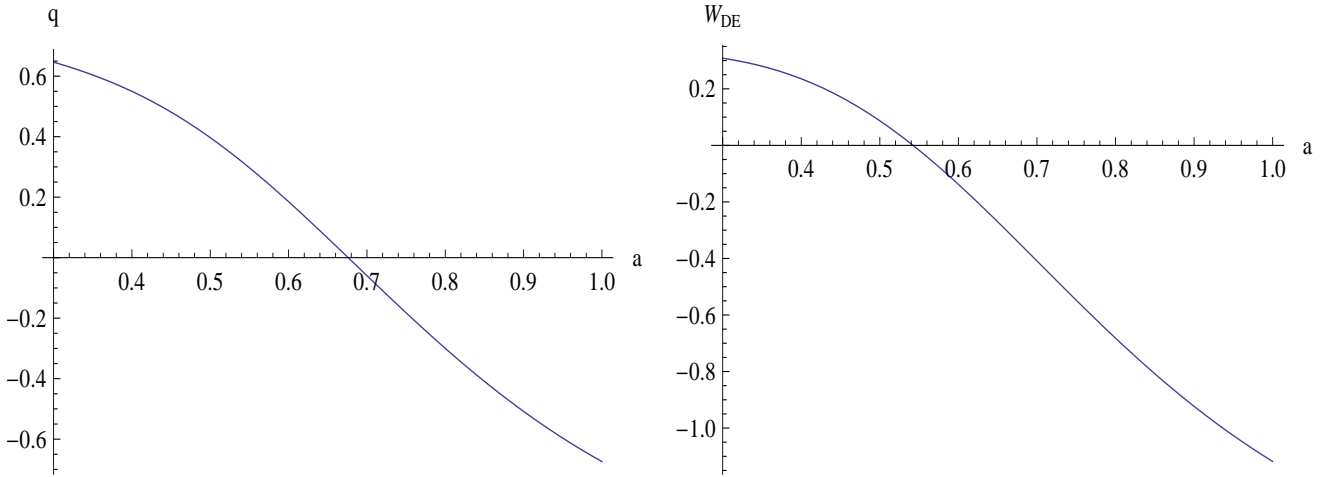


Figure 2: A typical evolution of q and w_{DE} as a function of the scale factor a

It is also worth mentioning that both T_{05} , T_{55} are zero before large scale structure. According to our cosmological scenario there is no outflow during nucleosynthesis since black holes have not appeared yet. Only after the large scale structure and the growth of a significant population of astrophysical black holes the mechanism is able to result to cosmic acceleration. The latter observation provides a natural solution to the coincidence problem.

A different valid approach although less general, is to study the behaviour of our mechanism for the recent epoch $z \sim 0$. If we are not interested to investigate the early time evolution of the cosmic acceleration but just to test if the estimated amount provide values with $\Omega_{DE,0} = 0.7$, $w_{DE,0} \simeq -1$, we can safely set in the relevant differential equations (2.13), (2.14) constant values for T_{05} , T_{55} . These values are estimated taking into account the present values of astrophysical data (number of galaxies, number of black holes etc.). More precisely the values of T_{05} , T_{55} depend on cosmic time (both decrease for decreasing scale factor as it has been numerically shown from the study presented in the beginning of this section) mainly through the time evolution of the mass density of the astrophysical black holes. The mass density decreases due to the cosmic expansion and increases due to matter accretion. However, for the current time period of interest ($z < 1$) the cosmic matter density rate is three orders of magnitude larger than the black hole density rate $d\rho_{BH}/dt \ll d\rho/dt$ [9], and therefore it is safe to set $d\varpi/da = d\tau/da = 0$ in the differential equations (2.13), (2.14).

Based on the derived expressions (3.5), (3.8) for the cosmic energy outflow $T_{e,0}$ and the associated pressure Π_0 , we will consider various cases for the cosmic matter content in order to evaluate the cosmic acceleration.

First we will consider as an extreme case a matter content with a large amount of black holes in halos suggested in [37]. In this case, we assume a universe with 10^{11} halos and 10^{10} large black holes per halo. Further we set as a crude mean mass for a halo black hole a value equal to $M_{haloBH} = 10^2 M_\odot$. Consequently, we estimate a total mass in the form of halo black holes equal to $N_{haloBH} M_{haloBH} = 10^{23} M_\odot$ (these numbers were taken from [37], however, note that the assumption appeared in [37] that all dark matter consists of black holes is not necessary or related to the present paper). Galactic core black holes contribute much less, i.e. there are 10^{11} supermassive black holes each with a mean mass $10^7 M_\odot$, i.e. $N_{coreBH} M_{BHcore} = 10^{18} M_\odot$. Therefore, in this extreme case all the cosmic acceleration comes from halo black holes. We can get $\Omega_{DE,0} = 0.7$, $w_{DE,0} \simeq -1$ for various combinations of the parameters. One such set is presented in the first row of Table 2.

It is more safe to assume that the mass density of galactic core black holes is larger than the density of halo black holes. Taking $N_{coreBH} M_{coreBH} = 10^{18} M_\odot$, again there are plenty of numerical solutions of (2.13), (2.14) for various parameters giving acceleration $\Omega_{DE,0} = 0.7$, $w_{DE,0} \simeq -1$. Similarly, assuming a more conservative case where $N_{coreBH} M_{coreBH} = 10^{11} M_\odot$ it is easy to find many numerical solutions of (2.13), (2.14) resulting to the required cosmic acceleration. Such representative results are presented in the other rows of Table 2.

As a final important remark it is worth emphasizing that all these estimated values of energy loss $T_{e,0}$ are small values that do not cause any astrophysical problem/inconsistency on galaxy dynamics/evolution or black hole life/dynamics.

astrophysical observation	assumption	assumption	output	output	output
$N_{BH} M_{BH}$	M	Θ_{mean}	$T_{e,0}$	Π_0	$w_{DE,0}$
$N_{coreBH} M_{BHcore} = 10^{18} M_\odot$	10^4TeV	$1.4 \cdot 10^{-9} \text{GeV}$	10^{-108}GeV^5	-10^{-62}GeV^5	-1
$N_{coreBH} M_{BHcore} = 10^{18} M_\odot$	10^3TeV	$7.7 \cdot 10^{-12} \text{GeV}$	10^{-114}GeV^5	-10^{-65}GeV^5	-1
$N_{coreBH} M_{BHcore} = 10^{11} M_\odot$	10^4TeV	$2 \cdot 10^{-4} \text{GeV}$	10^{-94}GeV^5	-10^{-62}GeV^5	-1
$N_{haloBH} M_{haloBH} = 10^{23} M_\odot$	10^4TeV	$2.5 \cdot 10^{-13} \text{GeV}$	10^{-118}GeV^5	-10^{-62}GeV^5	-1

Table 2: Summary of results for $n = 3$ and for various values of the parameters consistent with today acceleration

5. Conclusions

This work tries to explain why nothing (dark energy) balances something (matter density) and more accurately why slightly overbalances it. Based on the derived expressions we have shown that it is very easy to get the expected negative values of cosmic acceleration $\Omega_{DE,0} = 0.7$ and $w_{DE,0} \simeq -1$ even for *very conservative values of all the relevant parameters*, i.e. for small values of the mean temperature Θ_{mean} in the interior of the black holes, for small number of black holes in the galactic

cores and in the galactic halos and for large values of the five-dimensional Planck mass M . In order to proceed to specific estimations we have considered various cases about the cosmic matter content.

The proposed mechanism has several advantages: i) it is independent of the bulk matter and consequently retains predictability, ii) the associated values of ψ in the Hubble evolution (2.11) originate from the brane black hole astrophysical phenomenon of energy outflow T and its associated pressure Π along the fifth dimension, and not from the motion or the position of the brane in the bulk, thus again retaining predictability, iii) the mechanism is “on” at present times and “off” at the early stages of the cosmic evolution explaining naturally coincidence problem, iv) it relates the amount of the produced acceleration with the present matter content, v) unexpectedly, it produces very easily cosmic acceleration even for very conservative values of the relevant parameters (many acceptable values of ξ , n , M and Θ_{mean} are capable to give negative Π_0 around the required value of (2.26)).

In summary, the novelties of the present article are: 1) the presentation of a new mechanism of brane-bulk energy exchange, 2) new solutions describing the evolution of brane modified Einstein equations with non zero T_{05} , T_{55} , 3) new gravitational collapse solutions on a brane with non zero T_{05} , T_{55} , 4) numerical results estimating the produced cosmic acceleration.

As a future work it is certainly interesting to explore the connection of the proposed mechanism with issues related to accretion properties of brane black holes, gravitational lensing, the description of galactic metric and galactic rotational curves, galactic radius etc. on the same lines with the works [38], [39].

It is also worth exploring the possibility of obtaining brane black hole solutions with acceptable astrophysical characteristics, respecting the properties discussed in the present paper. Finally, the present work suggests that it would be interesting to explore in future properties of extremal black holes consisted of wrapped branes resulting to microstates with asymptotically AdS₅ geometries.

6. Acknowledgements

We would like to thank V. Charmandaris, T. Harko, E. Kiritsis and I. Papadakis for useful discussions and comments.

References

- [1] Y.B. Zeldovich, JETP Lett. 6 (1967) 316 [Pisma Zh. Eksp. Teor. Fiz. 6 (1967) 883].
- [2] L. Randall, R. Sundrum, Phys. Rev. Lett. 83 (1999) 4690; L. Randall, R. Sundrum, Phys. Rev. Lett. 83 (1999) 3370.
- [3] R. Maartens, Living Rev. Rel. 7 (2004) 7 [gr-qc/0312059].
- [4] R. Gregory, Lect. Notes Phys. 769 (2009) 259 [hep-th/0804.2595].
- [5] K. Ichiki, M. Yahiro, T. Kajino, M. Orito, G.J. Mathews, Phys. Rev. D66 (2002) 043521 [astro-ph/0203272].

- [6] E. Greenwood, D. Stojkovic, JHEP 0909 (2009) 058 [gr-qc/0806.0628].
- [7] L.A. Gergely, I. Kepiro, JCAP 0707 (2007) 007 [hep-th/0608195].
- [8] E. Kiritsis, G. Kofinas, N. Tetradis, T.N. Tomaras, V. Zarikas, JHEP 0302 (2003) 035 [hep-th/0207060].
- [9] T. Di Matteo, J. Colberg, V. Springel, L. Hernquist, D. Sijacki, astro-ph/0705.2269.
- [10] A. Merloni, S. Heinz, Mon. Not. R. Astron. Soc. 338 (2008) 1011.
- [11] S.W. Hawking, Cosmology from the Top Down, astro-ph/0304225.
- [12] M. Brandle, A. Lukas, B.A. Ovrut, Phys. Rev. D63 (2001) 026003 [hep-th/0003256]; A. Lukas, B.A. Ovrut, K.S. Stelle, D. Waldram, Nucl. Phys. B552 (1999) 246 [hep-th/9806051].
- [13] A. Kehagias and E. Kiritsis, JHEP 9911 (1999) 022 [hep-th/9910174].
- [14] P. Kraus, JHEP 9912 (1999) 011 [hep-th/9910149]; D. Ida, JHEP 0009 (2000) 014 [gr-qc/9912002].
- [15] P.S. Apostolopoulos, N. Tetradis, Class. Quant. Grav. 21 (2004) 4781 [hep-th/0404105].
- [16] N. Tetradis, Class. Quant. Grav. 21 (2004) 5221 [hep-th/0406183].
- [17] Y. Donagi, J. Khoury, B.A. Ovrut, P.J. Steinhardt, N. Turok, JHEP 0111 (2001) 041 [hep-th/0105199].
- [18] S.L. Dubovsky, V.A. Rubakov, P.G. Tinyakov, Phys. Rev. D62 (2000) 105011 [hep-th/0006046].
- [19] K. Ichiki, P.M. Garnavich, T. Kajino, G.J. Mathews, M. Yahiro, Phys. Rev. D68 (2003) 083518 [astro-ph/0210052].
- [20] D. Langlois, L. Sorbo, Phys. Rev. D68 (2003) 084006 [hep-th/0306281].
- [21] D.M. Alexander, W.N. Brandt, I. Smail, A.M. Swinbank, F.E. Bauer, A.W. Blain, S.C. Chapman, K.E.K. Coppin, R.J. Ivison, K. Menendez-Delmestre, Astron. J. 135 (2008) 1968 [astro-ph/0803.0634].
- [22] T. Herr, W. Hofmann, for the H.E.S.S. Collaboration, AIP Conf. Proc. 1085 (2009) 648 [astr-ph/0811.2897].
- [23] A.A. Zdziarski, J. Malzac, W. Bednarek astro-ph/0809.3255, MNRAS (Letters), in press.
- [24] A. Hebecker, J. March-Russell, Nucl. Phys. B608 (2001) 375 [hep-ph/0103214].
- [25] A. Chamblin, S.W. Hawking, H.S. Reall, Phys. Rev. D61 (2000) 065007 [hep-th/9909205].
- [26] O. Lunin and S. D. Mathur, Nucl. Phys. B623 (2002) 342 [hep-th/0109154].
- [27] O. Lunin and S.D. Mathur, Phys. Rev. Lett. 88 (2002) 211303 [hep-th/0202072].
- [28] S.D. Mathur, Int. J. Mod. Phys. D11 (2002) 1537 [hep-th/0205192].
- [29] S.D. Mathur, Fortsch. Phys. 53 (2005) 793 [hep-th/0502050].

- [30] S.D. Mathur, *Class. Quant. Grav.* 23 (2006) R115 [hep-th/0510180].
- [31] S.R. Das and S.D. Mathur, *Phys. Lett.* B375 (1996) 103 [hep-th/9601152].
- [32] J.M. Maldacena and L. Susskind, *Nucl. Phys.* B475 (1996) 679 [hep-th/9604042].
- [33] K.M. Udayanandan, P. Sethumadhavan, V.M. Bannur, *Phys. Rev.* C76 (2007) 044908; V.M. Bannur, *Phys. Lett.* B362 (1995) 7.
- [34] S. Pal, *Phys. Rev.* D74 (2006) 124019 [gr-qc/0609065].
- [35] K. Skenderis and M. Taylor, *Phys. Rept.* 467 (2008) 117 [hep-th/0804.0552].
- [36] I. Bena and N.P. Warner, *Lect. Notes Phys.* 755 (2008) 1 [hep-th/0701216]; N.P. Warner, *Prog. Theor. Phys. Suppl.* 177 (2009) 228 [hep-th/0810.2596].
- [37] P.H. Frampton, *JCAP* 0910 (2009) 016 [hep-th/0905.3632]; *Astropart. Phys.* 34 (2011) 617 [astr-ph/0910.1152].
- [38] C.G. Boehmer, T. Harko, *Class. Quant. Grav.* 24 (2007) 3191 [gr-qc/0705.2496].
- [39] T. Harko, K.S. Cheng, *Astrophys. J.* 636 (2005) 8 [astro-ph/0509576].