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Can Black Holes or Other Relativistic Space Objects Be a Source of Dark Energy?

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Abstract: We considered the hypothesis that the sources of dark energy (DE) could be black holes (BHs) or more exotic objects, such as naked singularities or gravastars. We proposed a definition of the presence of DE in the Universe and a criterion for what can be considered the source of this dark energy. It is based on the idea of the accelerated expansion of the Universe, which requires antigravity caused by large negative pressure. A recently proposed hypothesis was examined that mass of BHs increases with time according to the same law as the volume of the part of the Universe containing it and the population of BHs can mimic DE. We demonstrate the reasons why it cannot be accepted, even if all the assumptions on which this hypothesis is based are considered true.

Keywords: general relativity; cosmology; black hole; dark energy; naked singularity; gravastar

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1. Introduction

The modern paradigm assumes that objects of fundamentally different nature exist in the Universe. We are well familiar with baryonic matter, since we ourselves consist of it. If we add photons and neutrinos, we get the conventional category of ordinary matter. The properties of such objects have been studied by physics since its birth.

At present, we are confident in the existence of two still mysterious entities, which account for the lion's share of the mass of the contents of the Universe. Dark energy (DE) can either be a simple cosmological constant or a more complex variety, in the latter case its density and pressure vary over time [1,2]. It provides antigravity, i.e. general mutual repulsion, leading to accelerated expansion of the Universe. The leaders of the two teams of astronomers who discovered this accelerated expansion from observations of type Ia supernova explosions received the 2011 Nobel Prize in Physics. Formally, the cause of antigravity is the large negative pressure of the DE. According to existing estimates, the share of DE in the mass and energy density of the Universe is about 68%.

Dark matter (DM) is the next largest contributor to the total density. It is equal to 27%. The pressure of dark matter is positive, it is much less than its energy density. Therefore, dark matter gravitationally attracts. Ordinary matter provides about 5% of the density of the universe. Unlike dark matter, it participates in strong and electromagnetic interactions.

What else can be added to these three main components? These are black holes (BHs) or more exotic naked singularities (NSs). These are objects that are fundamentally impossible in the classical Newtonian theory of gravity or in the weak field approximation in General Relativity. Their integral part is the presence of a singularity in which both the invariants of space-time (ST) curvature and tidal forces become infinite. If a remote observer does not see the singularity located inside the semi-permeable event horizon, then it is a black hole. If there is no horizon and matter, radiation and information from a time-like singularity can move away, then this strange compact object is called a

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NS. It can have very unusual properties, especially near a singularity. Some of them are described in the review [3].

It is possible that yet undiscovered physical fields, such as scalar ones, may play an important role. There are hypotheses in which such fields play the role of DM or DE. They are also capable of transforming black holes into naked singularities, turning the horizon into a space-time singularity.

Naturally, having a limited set of actors, including dark matter and dark energy with their mysterious nature, scientists actively put forward hypotheses about their interaction or the transition of objects of one type to another. The transformation of ordinary matter into dark matter and vice versa, or the non-trivial interaction of DE and DM were considered. However, black holes have rarely participated in such hypotheses before. The only exception is the hypothesis that dark matter consists of a huge number of small primary black holes. Really, BHs have mass and do not consist of baryons.

At the beginning of 2023, an article [4] appeared, in which a source of DE was associated with an unusual version of BHs having effectively constant energy density. It was one of the first in an attempt to link BH and DE. It immediately raised many questions. We consider some of them in the Section 5. However, the main purpose is not to criticize the article [4] or the works on which it is based, but to look at the possible connection from a broader perspective. Naturally, we are not talking about simple gravitational interaction of objects of different types, for example, the influence of dark matter particles on the motion of a black hole and vice versa (see [5]), but about a more fundamental relation.

In this paper we try to discuss the possible sources of DE and, in particular, to find out whether black holes could be one of them. In doing so, we use all astronomical and cosmological data on the properties of both BH and DE. We consider this question exclusively within the framework of general relativity (GR).

2. Antigravity as a criterion for the DE presence

Before we begin to analyze possible sources of DE, this concept should be specified. In other words, agree on what exactly we mean by a dark energy, which ensures the accelerated expansion of the Universe. Let us immediately note that accelerated expansion is a sufficient, but not necessary condition for the presence of DE. Indeed, the accelerated expansion of the homogeneous and isotropic Universe corresponds to negative values of the deceleration parameter, defined as

$$q = -\frac{a\ddot{a}}{\dot{a}^2}. \tag{1}$$

Here a is the scale factor, and the dot above denotes the derivative with respect to cosmological time. For a flat ΛCDM model it is equal to

$$q = \frac{\Omega_m}{2} - \Omega_\Lambda, \tag{2}$$

where Ω_m and Ω_Λ are density parameters for pressure-less matter and cosmological constant. The value of Ω_m falls over time, the value of Ω_Λ increases, and their sum is equal to 1. This means that in the past, when Ω_m exceeded $2/3$, the Universe expanded with a deceleration. Nevertheless, DE in the form of a cosmological constant is present in the model.

I propose a criterion for the presence of DE related to the presence or absence of antigravity. Let me remind you of some details in this regard.

2.1. Weak gravitational field

In Newtonian theory, gravity is purely an attractive force. In GR this is not always the case. As an illustration, consider a weak gravitational field, i.e. Newtonian limit of Einstein's equations. In this case, the space-time metric is close to the Minkowski one and we can set $g_{00} \approx 1 + 2\phi c^{-2}$, where ϕ is the Newtonian gravitational potential, and c is the speed of light.

Let space be filled with matter and DE with total energy density $\varepsilon = c^2\rho$, where ρ is the density of matter and DE filling a given area of space at a given moment in time. We use the letter P to denote the

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total pressure of matter and DE in this place and time. The energy-momentum tensor of this matter in the accompanying frame of reference is equal to $T_\alpha^\beta = diag(\varepsilon, P, P, P)$ (see §35 in [6]). Therefore (00) component of the Einstein equations $R_0^0 = 8\pi G c^{-4}(T_0^0 - T/2)$ takes the form (see §96 in [6])

$$R_0^0 \approx c^{-2}\Delta\phi = 8\pi G c^{-4}(T_0^0 - T/2) = 4\pi G c^{-4}(\varepsilon + 3P). \quad (3)$$

Here G denotes the gravitational constant. In the Newtonian limit we obtain a solution to the equation $\Delta\phi = 4\pi G(\rho + 3c^{-2}P)$ in the form of the integral

$$\phi = -G\int \frac{(\rho + 3c^{-2}P)dV}{R}, \quad (4)$$

where R is the distance from the area with matter to the point at which the gravitational potential is sought. We see that parts of space-time with $\rho + 3Pc^{-2} > 0$ are sources of gravity, and ones with $\rho + 3Pc^{-2} < 0$ are sources of antigravity. The test body is gravitationally attracted to the first and repelled from the second.

2.2. Proposed criterion for the DE presence

Let us consider the possibility of ensuring the accelerated expansion of the Universe, usually associated with the presence of DE. This requires antigravity. Let's take a very simple approach. Let us divide all space-time (ST) into infinitesimal small four-dimensional pieces and assign each of them to regions that provide attraction or repulsion depending on the sign of the sum $\varepsilon + 3P$. If there are no areas or singularities in the entire ST that provide antigravity, then there is no accelerated expansion. This case is described, for example, by the classical FLRW metric without a cosmological constant or different type of DE. We consider the presence of at least one area with antigravity as a sign that some form of DE is present in the considered model.

This criterion is based on a weak field approximation, which is not applicable, for example, when considering black holes. However, dividing the ST into sections that are sources of either gravity or antigravity helps to understand the more general situation. Indeed, if the presence of BHs or other objects leads to an accelerated expansion of the universe and manifests itself in the motion of very distant galaxies, quasars and other cosmic objects, then the gravitational field of black holes obviously must be weak near them.

Let us demonstrate how this criterion works in the case of homogeneous isotropic FLRW models. They are described by solutions of the Friedmann equations which are obtained directly from Einstein's equations. However, they can also be obtained within the framework of non-relativistic cosmology. This is described in detail in the book [7]. Let's start with the case when the universe is spatially flat and filled with matter (DE is included) with the equation of state

$$P = w\varepsilon, w = const. \quad (5)$$

In this case, the scale factor is $a \propto t^\lambda$ with $\lambda = \frac{2}{3(1+w)}$. The deceleration parameter (1) is equal to $q = (1+3w)/2$. When $w < -1/3$ it is negative, and corresponds to the accelerated expansion of the Universe. But according to the proposed criterion, DE is present precisely at $w < -1/3$.

Naturally, the conclusion is not related to the form of the equation of state. It follows directly from the second Friedmann equation

$$\frac{\ddot{a}}{a} = -\frac{4\pi G}{3}\left(\rho + \frac{3P}{c^2}\right). \quad (6)$$

The sign of the deceleration parameter (1) is determined by the sign of $\ddot{a}$ and, therefore, the sign of the combination $\rho + 3Pc^{-2}$.

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Consider now a two-component model in which the universe is filled with two different kinds of content. For example, in the standard flat ΛCDM model these are the CDM and the cosmological constant. The sign of the deceleration parameter may change. This can be seen from formula (2). However, in this case, the density of DE ρ_Λ and its negative pressure $P_\Lambda = -c^2\rho_\Lambda$ are constant, while the density of pressureless matter (cold dark matter belongs to this category) falls over time. Therefore, in the future, the sum $\rho + 3c^{-2}P$ will obviously become negative for any ratio of the initial matter densities and the positive cosmological constant. This corresponds to the tendency of density parameters $\Omega_m \to 0$, $\Omega_\Lambda \to 1$, $q \to -1$ at $t \to \infty$. The proposed criterion detects the presence of DE despite the fact that the universe is expanding with deceleration during a certain time interval after the Big Bang.

An important feature of this criterion is that it is based on the local properties of individual parts of the space-time being analyzed. This means, in particular, that the presence or absence of antigravity does not depend on the distance from the source to the observer. This can easily be seen from the formula (4).Therefore, within the framework of general relativity, an object that demonstrates gravity near and antigravity at a distance is impossible, if it is not placed inside some medium with DE in its composition. But in this case, the source of DE is the environment, and not the object inside it.

However, our Universe is not so homogeneous. It has a large-scale structure and individual objects like the BHs and, possibly, the NSs. However, it is sufficient to consider the distribution of matter averaged over large scales to examine the question of its global accelerated expansion. In this case, individual relativistic objects like BHs and NSs are considered as something like pressureless gases, providing additional mass density on the right side of the equation (6). In the case of a negative mass NSs, this value is negative. This case is discussed in more detail below.

Naturally, near relativistic objects they gravitationally attract or repel surrounding objects. We can establish this by considering the ST metric near them, at distances significantly less than the scalar factor.

Can the proposed criterion be wrong? You can come up with a speculative model in which the Universe after the Big Bang is uniformly filled with two types of matter providing gravity and DE as the third component. Let's assume that one of the types of matter decays into DE, which, in turn, after a short time decays into a stable form of matter. It is possible to select the parameters of this gedanken (thought) model so that at any moment in time gravity prevails over antigravity. However, the question of whether something similar is possible from the point of view of the laws of physics and how exactly could we detect the presence of DE in this case is clearly beyond the scope of this article. Indeed, in the case of the real Universe we observe the accelerated expansion and the presence of DE is not questioned.

3. Sources of dark energy

Let us use the proposed criterion to study the issue of possible sources of DE. In the considered examples, DE was a certain substance with $\rho < -3c^{-2}P$, for example, with the equation of state (5) at $w < -1/3$. It is pointless to talk about some source of DE in this case, because it is initially included in the model. We can do this in the following case. There is a space-time without antigravity, and therefore without DE according to the proposed criterion. We put some configuration of objects inside it, e.g. some BHs or NSs. If as a result of this manipulation we get an accelerated expansion of the universe, then we call these objects sources of DE.

3.1. Black holes

Now, having agreed on the definition of the terms used, we can begin to analyze the hypothesis that black holes can be sources of DE presented in [4]. The Schwarzschild and Kerr metrics for non-rotating and rotating black holes are well known. They provide gravitational attraction both near and far from them. In accordance with the proposed criterion, there is no DE in this solution.

Moreover, we can assert that DE is absent in the more general case, when a black hole is surrounded by an ordinary matter.

We do not know the exact solutions for this case, but a conclusion can be drawn based on the proposed criterion. Near a black hole, the influence of surrounding matter is negligible compared to the influence of the black hole itself. Therefore, the ST should be approximately described by one of the following metrics: Schwarzschild, Kerr, Reisner-Nordström or Kerr-Newman. The last two describe the situation when a BH has a non-zero electric charge.

A black hole provides attraction near its event horizon. In the case under consideration, all sections of the ST outside the black hole are filled with ordinary matter and/or, possibly, an electromagnetic field. They also provide attraction. There are no areas with antigravity in the entire space-time outside the black hole and, in accordance with the criterion, there are no DE.

3.2. Naked singularities

However, the conclusion may change if we use objects of a different type instead of BH. I illustrate this possibility using the example of a ST described by the Schwarzschild metric with a negative mass (and a Schwarzschild radius, too). This exact vacuum solution of Einstein's equations describes a naked singularity (NS). Indeed, the singularity at $r = 0$, at which the curvature invariants diverge, in this case is not surrounded by an event horizon. A more general form of point-like NSs with a negative mass is considered in the article [8]. They provide gravitational repulsion nearby. Therefore, such singularities cannot be formed by collapse.

However, we can consider the speculative possibility that the Big Bang created a large number of point-like negative mass NSs that still fill the Universe, providing gravitational repulsion. They could be considered a source of DE according to the our criterion. However, it contradicts what we know about the evolution of the Universe. Indeed, new NSs with negative mass cannot be formed by gravitational collapse. Therefore, the concentration of such exotic objects would decrease with cosmological expansion. It would decrease so significantly during an inflationary era, that NSs could not provide the repulsion necessary for accelerated expansion.

But even in the absence of inflation, a lot of NSs with a negative mass could not replace DE. We do not know of any process as a result of which singularities would disappear, or the modulus of their negative mass would decrease with time. So it is natural to assume that the mass density of these objects, averaged over space, enters the energy-momentum tensor like the density of dust matter, but with a negative sign.

It is possible to include this component in the Friedmann equations. This would lead to evolution according to the same formulas that describe classical FLRW models without a cosmological constant. Only instead of the density of pressureless matter, a certain modified density would enter into the equation, equal to the difference between the density of matter and hypothetical NSs with negative mass. The deceleration parameter (1) would be positive in this case, which is ruled out by data on type Ia supernova outbursts. Thus, the hypothesis that the accelerated expansion of the universe is ensured by a large number of point-like naked singularities with negative mass formed by the Big Bang contradicts the conclusions following from the cosmological equations. NSs with positive mass are discussed below.

3.3. Gravastars

Let's mention hypothetical objects called gravitational vacuum condensate stars or gravastars. According to [9] gravastars are cold, low entropy, maximally compact objects characterized by a surface boundary layer and physical surface tension, instead of an event horizon. Within this thin boundary layer the effective vacuum energy changes rapidly, such that the interior of a non-rotating gravastar is a non-singular static patch of de Sitter space.

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The interest in these objects is due to the fact that the paper [4] alternately talks about black holes, then about vacuum energy interior BHs, more precisely singularity-free BH models, such as those with vacuum energy interiors. Apparently, they mean gravastars.

It should be noted that a black hole and a gravastar are completely different objects, even if the gravitational field outside is described by the same metric. Gravastar does not have an event horizon. Instead, there is a shell that holds inside a region filled with DE in the form of a cosmological constant. A black hole naturally arises as an exact vacuum solution of Einstein's equations. Gravastar is a hypothetical object. There is no argument that gravastars actually exist in nature.

Let's note that a gravastar can repel surrounding matter if the antigravity from DE exceeds the attraction to the shell, if the latter exists. In this case, it cannot be surrounded by an accretion disk; stars do not orbit around it. Therefore, it can remain undetected during astronomical observations.

I note that it would be strange to talk about gravastars as sources of DE. They a-priory have DE, the negative pressure, and anti-gravity inside. Gravastars seem to concentrate DE, which does not uniformly fill the entire space, as in the ΛCDM model, but is located only inside the shells of these hypothetical objects. In this case, the primary concept is DE, and gravastar is the form of its spatial distribution.

This consideration is enough in itself. Nevertheless, we not limit ourselves to a formal definition and consider the question of whether the set of gravastars can provide the accelerated expansion of the Universe if the entire DE is contained exclusively inside them.

To do this, the antigravity provided by DE inside gravastars must exceed the gravity provided by ordinary matter outside them. Let's make a rough estimate. From formula (4) we can conclude that everything depends on the sign of the combination $\rho + 3P$, which is the sum of the respective contributions of matter and gravastars, averaged over the volume. For CDM it is ρ_m, for gravastars $\rho_{gr} + 3P_{gr}$. Since $\rho_{gr} > 0$ and $P_{gr} < 0$, we get $\rho_{gr} + 3P_{gr} > 3P_{gr}$. For an ordinary cosmological constant with $P = -\rho$ this combination is equal to $2P_{gr} = -2\rho_{gr}$, but we are ready to consider the case of a non-standard vacuum inside gravastars. Anti-gravity for the whole Universe is possible if $3P_{gr} + \rho_m < 0$, that is, at $P_{gr} < -\rho_m/3$. However, even the most daring hypotheses do not suggest that gravastars provide a quarter of the total mass in the Universe, and in this case we cannot get accelerated expansion.

The same problems arise as in the case of a negative mass NSs considered above when trying to integrate the contribution of gravastars into the energy density and pressure included in the Friedmann equations. The problem is that their impact decreases over time because of the expansion of space. Indeed, in the standard ΛCDM model, the DE density in the form of a cosmological constant does not change with time. But if such energy is located inside the shells of gravastars moving away from each other, then even in the Newtonian limit the equation (4) reduces to the formula for the contribution of gravastars to the Newtonian potential

$$\phi_{GS} \approx G(1+3w)\sum \frac{m_i}{R_i}, \quad m_i = \int \rho_{DE} dV_i. \tag{7}$$

Here R_i is the distance to the i-th gravastar with the DE mass m_i inside the shell. The equation of state for the DE is chosen in the form (5). For the cosmological constant $w = -1$. Positive shell masses can only reduce the antigravity caused by gravastars.

If the masses m_i do not change (there is no fall of matter onto gravastars with repulsion), and the distances R_i increase with the expansion of the Universe in proportion to the scale factor a, then the influence of these objects on the evolution of the Universe decreases. In order to eliminate the influence of this factor and obtain a dependence $a(t)$ close to one provided by the ΛCDM model, the authors of [4] made a speculative assumption that the masses of gravastars, which they call BHs, increase with increasing scale factor according to the law

$$m_i(t) = m_i(0)(a(t)/a_0)^k \tag{8}$$

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with a constant parameter $k \approx 3$. They justify this dependence by the results of processing astronomical observation data, from which estimates of the BH masses are obtained (see, for example, [10]), i.e. objects other than gravastars. Values with subscript 0 in (8) refer to the moment of formation of the object, which in different places of [4] is called either a BH or a vacuum black hole.

Where does additional mass come from? The authors of [4] do not explain this detail, but it is obvious that one has to choose between two possibilities. Either the matter, baryonic or dark, is somehow transformed into DE, increasing its mass inside the gravastars, or we are dealing with a violation of the law of conservation of mass-energy, following from the equations of general relativity. Both options are so speculative that they are hardly worth considering as any valid hypotheses.

4. Black holes and other exotic astronomical objects

Black holes were once considered as controversial candidates for astronomical objects. However, most astronomers have long admitted their existence. Some stellar mass objects that are observed in the Galaxy may be black holes. Astronomers observe active galactic nuclei, quasars and other supermassive compact objects outside the Milky Way that are most likely black holes. However, the possibility cannot be ruled out that some of them are NS.

The supermassive black hole Sagittarius A* (Sgr A*) lies at the center of Milky Way. A group of astronomers received the 2020 Nobel Prize in Physics for the discovery of this supermassive compact object. There is a star cluster in its vicinity. Astronomers monitor the motion of each of the stars near the Sgr A*. Particular attention was paid to the star, which received the name S2 [12]. It is orbiting Sgr A* with a period of 16.0518 years, a semi-major axis of about 970 au, and a pericenter distance of 17 light hours (18 Tm or 120 au). Analysis of its motion confirmed the conclusions of general relativity [13]. The orbits of S2 and other stars in the vicinity of Sgr A* are close to ellipses. Deviations are associated with the attraction of other bodies and the difference between the geodesics in the field of the Schwarzschild black hole and the trajectory described by Kepler's laws.

Therefore, there is no doubt that Sgr A* attracts surrounding bodies. Astronomers cannot observe the movement of individual stars around distant active galactic nuclei, quasars and other supermassive black holes. However, there is no doubt that they are surrounded by accretion disks and, therefore, parts of these disks are gravitationally attracted. So, objects observed by astronomers attract surrounding bodies. All of them belong to BHs or at least have properties that make it possible to confuse them with black holes. Naturally, these cannot be NSs with a negative mass. If these objects are naked singularities, then only with a positive mass, which cannot be attributed to DE sources.

According to the above analysis, based on the proposed criterion for the presence of the antigravity, any object surrounded by ordinary matter without DE cannot exhibit attraction near and antigravity at a distance. So, it could be a DE source only if it repelled surrounding bodies in the past or is going to do this in the future, but among the candidates actually being considered there are no objects with such exotic properties.

5. Analysis of a recently proposed hypothesis about the source of DE

After general considerations, we can move on to the analysis of article Farrah et al [4] and the papers on which it is based. In it a source of DE was associated with BHs having effectively constant energy density. Or not quite black holes, for example gravastars. Judge for yourself. Formula (8) is the basis of the of the attempt to explain DE by the influence of BHs. It is proposed in [14] in the form

$$M_{BH}(a) = M_0(a/a_i)^k. \tag{9}$$

Explanations say that M_{BH} is the mass of an individual black hole, M_0 is the mass of the input stellar remnant, i.e. the mass of the black hole at the time of its formation, a is the current scale factor, a_i is the scale factor at which the remnant was formed, and k is a dimensionless constant. There seems to be no doubt that this is about the ordinary black holes formed during the collapse of massive bodies. On

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the other hand, article [4] mentions vacuum energy interior BHs, more precisely singularity-free BHs. This is similar to the description of gravastars. We examined both types of objects and came to the conclusion that they cannot be sources of DE.

Let us consider both cases: when we are talking about a BHs and when we are talking about gravastars. In doing so, we initially agree with all the assumptions proposed by [4]. Our goal is to show that we cannot explain the observed cosmological evolution even after accepting all these suppositions and hypotheses.

Formula (9) raises a natural question about what is meant by the BH mass M(a). As an assumption, we assume that this quantity is the same mass that astronomers have in mind and which they estimate from astronomical observations. Its estimation is based on model calculations carried out under the assumption that the object observed by astronomers is precisely a black hole, and not gravastar or NS.

Astronomers have estimated the masses of many black holes located at various distances. Analysis of this data makes it possible to determine the value of k. For this, mass estimates for supermassive black holes (SMBHs) were used. Additionally, the masses $M_{stellar}$ of the stellar population of high-redshift and low-redshift quiescent elliptical galaxies containing these SMBHs were estimated. The values mentioned were estimated from UV / optical spectra, in particular, from luminosities and full-widths half-maximum in Hα, Hβ, and Mg II emission lines. The details are described in [4,10,15].

In [4], it is stated that the offsets in stellar mass are small, and consistent with measurement bias, but the offsets in SMBH mass are much larger, reaching a factor of 7 between $z \sim 1$ and $z \sim 0$. This served as the basis for the estimates at 90% CL

$$k = 2.96^{+1.65}_{-1.46} \tag{10}$$

and

$$k = 3.11^{+1.19}_{-1.33}. \tag{11}$$

These estimates are close to $k = 3$ and practically exclude the case of $k = 0$.

However, there are also alternative opinions. The article [10] claims that the average BH-to-host stellar mass ratio appears to be consistent with the local value within the uncertainties, suggesting a lack of evolution of the $M_{BH} - M_{stellar}$ relation up to $z \sim 2.5$. We will not discuss the details of observations, sampling, data processing, etc. We simply note that the same data were used by [4] and [10]. Therefore, the difference in the conclusions cannot be explained by the difference in the observations or corrections used, e.g., for extinction, aperture, etc.

Nevertheless, let us assume that [4] are right and the BH masses increase with cosmological expansion, i.e. as the scale factor a increases. Let's discuss what could be causing this. The mechanisms of BH mass increase such as accretion of surrounding matter and collapse with the formation of BHs are well known. The authors specifically consider coupling of BH. It is quite possible that there may be several SMBHs inside the galaxy that merge together.

The process of galaxies merging is well known. In this case, the mass of the stellar population of the formed galaxy can be approximately considered equal to the sum of $M_{stellar}$ of the merged galaxies. Their SMBHs coexist for a while, but may later merge. However, in all these cases, the law of conservation of energy/mass works. During the merger, the mass of the formed BH does not exceed the sum of the masses of the original BHs. The total mass of all BHs in the galaxy may decrease because of an emission of gravitational waves in the process of BH merging. The general relativity's limitation is associated only with an increase in the total area of black hole horizons.

An increase in the BH mass at accretion or collapse is compensated by a decrease in the mass of matter outside the BH. In this case, the total mass of matter and BHs does not increase with expansion. The total mass of BHs considered separately from other types of matter (gas, dust, stars, dark matter) can increase, but it is difficult to imagine that the rate of accretion of matter on a BH is somehow related to the scale factor a. However, even here one can come up with a saving explanation: due to the expansion of space-time, the a value increases with increasing cosmological time t. We can consider a monotonically increasing function $a(t)$ and an inverse one $t(a)$ and formally reduce the function $M_{BH}(t)$ to $M_{BH}(a)$.

Be that as it may, the equation (9) includes a scale factor a. Maybe the reason for the increase in mass is somehow connected with cosmology? When considering vacuum stationary solutions describing BH (Schwarzschild and Kerr metrics), space-time far from BH becomes flat and the mass of the central object can be determined from the asymptotical form of the metric. However, there are other quantities or functions associated with alternative definitions of mass. If the space-time is not asymptotically flat far from the BH, then the problem of mass determination becomes much more complicated. Authors of [4] rightly point out that we do not know a solution that describes even a Schwarzschild BH, not to mention the Kerr one, against the background of a homogeneous isotropic FLRW space-time. Let us assume that in this incomprehensible situation we can accept formula (9) with the value $k \simeq 3$ according to (10) or (11) as a hypothesis or an empirical relationship.

But this raises a somewhat odd problem. The paper [15] compares estimates of SMBHs masses for samples with different z. It contains τ_{BH}: the translational offset between the high- and low-redshift samples along the SMBH mass axis. According to equation (5) from this article τ_{BH} between the COSMOS sample (high-z sample) and the low-redshift quiescent sample is equal to $1.15^{+0.25}_{-0.28}$ dex. So the SMBHs masses increase with z. This also follows from formula (18) from the same article [15], according to which at 90% confidence

$$\frac{M_{BH}}{M_{stellar}} = (1+z)^{3.5\pm1.4}. \tag{12}$$

In this case, the mass of the stellar population $M_{stellar}$ changes much weaker than the mass of the BHs. However, this statement is directly opposite to formula (9). The masses of black holes were estimated from the spectrum of radiation emitted by galaxies. For the high-z sample, this radiation was emitted long ago, when the scale factor of the Universe was $1+z$ times smaller. Therefore, according to (9), the BH masses should also be smaller.

Shortly after the article [4], an article [11] appeared stating that the mass functions of the two radial velocity black hole candidates in NGC 3201 place strong constraints on the cosmologically-coupled growth of black holes.

Let's just discard all doubts and agree with all the assumptions of the article [4]. Let's accept formula (9) with $k = 3$ as a hypothesis. Can we get some analogue of DE as a result? Of course not. The black hole system does not have negative pressure. Therefore, it does not provide anti-gravity and accelerated expansion. It cannot be considered as something that works as an analogue of DE. Moreover, at present, the influence of DE prevails in the cosmological expansion, while the mass of black holes is a very small fraction of the mass of everything that fills our Universe.

But [4] came to the opposite conclusion. Here are some quotes from the article [4]: "The redshift dependence of the mass growth implies that, at $z \lesssim 7$, black holes contribute an effectively constant cosmological energy density to Friedmann's equations. The continuity equation then requires that black holes contribute cosmologically as vacuum energy. We further show that black hole production from the cosmic star formation history gives the value of Ω_Λ measured by Planck while being consistent with constraints from massive compact halo objects. We thus propose that stellar remnant black holes are the astrophysical origin of dark energy, explaining the onset of accelerating expansion at $z \sim 0.7$. $< ... >$ From conservation of stress-energy, this is only possible if the BHs also contribute cosmological pressure equal to the negative of their energy density, making $k \sim 3$ BHs a cosmological dark energy species. $< ... >$ Taken together, we propose that stellar remnant $k = 3$ BHs are the astrophysical origin for the late-time accelerating expansion of the universe."

There is no mention in the article [4] of the reasons why the authors came to the conclusion that the BH population has a negative pressure, and it is huge in absolute value. Indeed, without the fulfillment of condition $\rho c^2 + 3P < 0$ there is no antigravity and, accordingly, no accelerated expansion. Standard concept of the properties of black holes rule out this possibility. The option in which astronomers

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actually observe gravastars, and not a black holes, also does not explain the observed accelerated expansion of the Universe for the reasons given above.

6. Conclusions

We considered the hypothesis that the sources of DE could be black holes or more exotic objects, such as naked singularities or gravastars. To do this, we proposed a definition of the presence of DE in the Universe and a criterion for what can be considered the source of this dark energy. The main condition is the accelerated expansion of the Universe, which requires antigravity caused by large negative pressure.

The analysis shows that the source of DE cannot be ordinary black holes, NS with positive mass, and their combinations. Any object that attracts surrounding matter cannot be a DE source. This applies to any object surrounded by an accretion disk or one around which other bodies orbit. NS with negative mass provide antigravity, but it cannot mimic DE. Hypothetical gravastars have DE inside and it is strange to consider them as a source of DE.

Section 5 discusses the hypothesis proposed in the article [4]. Even if we accept as a hypothesis all the assumptions of this paper, including the formula (9) and the violation of conservation laws, we cannot ensure the accelerated expansion of the Universe with the help of a BHs population. The latter requires an absent strong negative pressure.

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Abbreviations

The following abbreviations are used in this manuscript:

BH	Black hole
CDM	Cold dark matter
DE	Dark energy
DM	Dark matter
FLRW	Friedmann-Lemaître-Robertson-Walker
GR	General Relativity
NS	Naked singularity
SMBH	Supermassive black hole
ST	Space-time

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