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Astrophysical Constraints on Multidimensional Primordial Black Holes based on Neutron Stars Absorption

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A possibility of Multidimensional Primordial Black Hole (PBH) detection connected with neutron stars absorption is considered and respective constraints on the PBH mass fraction in the six-dimensional Arkani–Hamed–Dimopoulos–Dvali braneworld are obtained. It is shown that the absorption of a neutron star by an extra dimensional PBH imposes an upper limit of the six-dimensional Planck mass.

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Proposed first by Ya. B. Zeldovich and I. D. Novikov [1], Primordial Black Holes have become a very effective tool for the early Universe study [2]. These fundamental objects appear as a consequence of basic cosmological principles and carry information about the cosmological stages inaccessible by other means.

A discovery that our Universe can be a submanifold–"brane" embedded in a multidimensional bulk with even noncompact and infinite extra dimensions opens up a new perspective both for mini black holes production in particle collisions and for stability of celestial bodies with respect to absorption them by multidimensional black hole. Different aspects of the last question were considered in [3] using non relativistic approximation. In [4] consequences of a White Dwarf (WD) absorption by brane PBH is considered. Now we are interested in absorption of a Neutron Star (NS), thus one needs to consider a relativistic generalization of the equations for accretion on D-dimensional PBH.

Since matter is localized on the brane, the regular conservation equations for the energy–momentum tensor $\nabla_\nu T^{\mu\nu} = 0$ and baryons number $\nabla_\nu(nu^\nu) = 0$ can be used for a neutral and non rotating D-dimensional black hole with the Schwarzschild–Tangherlini metrics projected on the brane:

$$ds^2 = -\left(1-\left(\frac{r_g}{r}\right)^{D-3}\right)dt^2 + \frac{dr^2}{1-\left(\frac{r_g}{r}\right)^{D-3}} + r^2 d\Omega_2^2 \qquad (1)$$

where r_g is the gravitational radius, $d\Omega_2^2$ is the line element on unit 2-sphere. Taking energy-momentum tensor in the form of ideal fluid and using polytropic equation of state $p = Kn^\Gamma$, in the metric (1) conservation equations reads

$$v'v = -\frac{D-3}{2r}\left(\frac{r_g}{r}\right)^{D-3} - a_s^2\frac{n'}{n}\left(1-\left(\frac{r_g}{r}\right)^{D-3}+v^2\right), \qquad (2)$$
$$\frac{2}{r}+\frac{v'}{v}+\frac{n'}{n} = 0$$

where n is the baryons number density, v is the radial component of 4-velocity u^μ, $a_s = \sqrt{dp/d\rho}$ is the sound speed, $x' \equiv \partial x/\partial r$. The system (2) has the special ("sonic") point, which characterizes an existence of the only possible hydrodynamic solution near the black hole - transonic accretion. The distance to the sonic point r_s and the speed of matter v_s in it can be

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expressed through the speed of sound:

$$\left.\begin{aligned} r_s^{D-3} &= \frac{D-3-a_s^2(D-7)}{4a_s^2} r_g^{D-3}, \\ v_s^2 &= \frac{a_s^2\,(D-3)}{(D-3)+a_s^2(7-D)}. \end{aligned}\right\} \quad (3)$$

Integration of the second equation from (2) is quite obvious and leads to an accretion rate on PBH with mass M:

$$\frac{dM}{dt} = 4\pi v(r) r^2 m n(r) = \text{const} \quad (4)$$

where m is the mass of ambient matter particle. In turn integration of the first equation from (2), taking into account (3) give us D-dimensional generalization of relativistic Bernoulli equation for the adiabatic accretion problem:

$$\left(1 - \frac{a_s(r_s)^2}{\Gamma - 1}\right)^2 \left(1 - \frac{D-7}{D-3}\, a_s(r_s)^2\right) = \left(1 - \frac{a_\infty^2}{\Gamma - 1}\right)^2, \quad (5)$$

which allows to calculate thermodynamic parameters in sonic point (depending on the sound speed at sonic radius $a_s(r_s)$) through the sound speed at infinity a_∞. It is evident, that at $a_s \ll 1$ the equations (3) and (5) are reduced to the D-dimensional non relativistic form [3], but at $D = 4$ to the well known 4-dimensional relativistic equations [5].

Let us apply these equations for the accretion of nuclear matter onto multidimensional PBH. Consider the 6-dimensional gravity as the first experimentally allowed case of the braneworld with compact extra dimensions [6]. Recall, that the Bethe–Johnson polytrope with stiff index $\Gamma = 2.54$ can be regarded as an effective equation of state, describing well the properties of NS matter at neutron density in the range $0.1 fm^{-1} \leq n \leq 3 fm^{-1}$ [5]. According to Eq. (5) a compression of the matter at the sonic radius is not more than 20%, and thus insufficient for the formation of quark–gluon plasma in the accretion flow regardless of the dimensionality of PBH. Integrating Eq. (4) a characteristic time of PBH mass growth can be obtained. It can be shown that the duration of the 6-dimensional accretion stage when $r_s \leq L$ where L the scale of macroscopic extra dimensions, is of order of minutes, and for 4-dimensional one, until complete absorption of NS, is of order of hours.

Thus, the fact that NSs are stable and widely distributed allows one to impose the restrictions on the scale of the extra dimensions. For this purpose we consider a capture and deceleration of PBH in NS matter. We have found that slowing-down of the 6-dimensional PBH in NS allows to study a much wider interval of the 6-dimensional Planck mass 1 TeV $\leq M_6 \leq 10^6$ TeV compared to WD case [4]. In the range $M_6 \leq 10^2$ TeV the PBH can be completely stopped by a single passage through the NS. Taking the relativistic corrections in the conservation laws into account in the capture of the PBH by the NS and the prevalence of the latter in the Galaxy, one obtains limits on the density of the 6-dimensional PBH shown in Fig. 1, if one event of NS absorption for 10 years throughout the Galaxy occurs.

One can conclude that at $M_6 > 10^4$ TeV PBHs are overproduced comparing with dark matter (dashed line) and thus such values of M_6 are excluded.

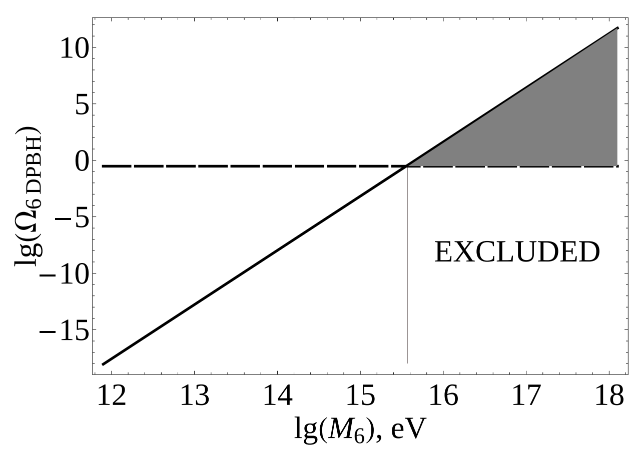

FIG. 1. Constraint on 6-D Planck mass M_6 due to NS absorption. Dashed line – dark matter density.

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