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Rotating black holes as sources of high energy particles

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Abstract. Ultrahigh energy particles in cosmic rays observed on the Earth can have their origin in the ergosphere of rotating black holes. This paper discusses production of these particles through decay of superheavy dark matter particles, such as multiparticle scattering near horizon, as well as a collision of particles with a large angular momentum and particles on white hole geodesics.

Keywords: rotating black hole, Kerr metric, ergosphere, particle collisions.

Introduction

Dark matter is one of the major questions of modern physics. Astronomical observations show that only five percent of matter is composed of visible matter, mainly protons, electrons and photons of the background radiation, while 69 percent is dark energy and 26 percent is composed of dark matter. The main hypothesis is that dark matter particles are weakly interacting massive particles (WIMP).

Grib and Pavlov (2002a; 2002b) formulated a hypothesis that dark matter particles are neutral scalar particles with the mass of the grand unification scale. Their mass is derived from the calculations of particle creation from vacuum by the strong gravitation field of the early universe. These calculations showed that the number of created particles with this mass equals the Eddington number—the number of visible particles (Grib, Mamayev, Mostepanenko 1994).

Thus, if the created particles later decayed into visible particles when the temperature of the universe was high, while some part of them survived at lower temperatures as dark matter particles, it explains both the number of visible particles and also the closeness of the visible particle density and the dark matter density (Grib, Pavlov 2008b).

This GP hypothesis (Grib, Pavlov 2008b) can be proved by indirect observation of a similar process, the decay of superheavy dark matter particles into usual particles at high energies. At low energies dark matter particles are stable. In cosmic rays, particles with high energies up to 1020 eV are observed (Aab, Abreu, Aglietta et al. 2017). They are called ultra high energy cosmic rays (UHECR). The main hypothesis of their origin is that they are produced in Active Galactic Nuclei (AGN). AGN are considered to be rotating black holes. General relativity gives the description of AGN in terms of the Kerr metric. Piran, Katz and Shaham (Piran, Shaham, Katz 1975) and Bañados, Silk and West (Bañados, Silk, West 2009) discovered that very high energies can be obtained in the process of particle collisions in the vicinity of the rotating black hole's horizon, or the so-called ergosphere. Thus, a black hole plays the role of a natural collider with energies much higher than those in the Large Hadron Collider (LHC) on the Earth. They can be of the grand unification scale and even of the Planck energy scale. However, it is possible to conclude that ergosphere processes taking place in the early universe, i.e. the decays of dark matter into usual particles, are still present (Grib, Pavlov 2008a; 2009). The products of these decays reach the Earth and are observed as UHECR. This paper presents an overview of the results obtained in the previous papers (Grib, Pavlov 2010; 2011; Grib, Pavlov, Piattella 2012; Grib, Pavlov 2013a; 2013b; 2015a; 2015b).

The structure of this paper is as follows. The first part presents basic notions for the description of rotating black holes in terms of general relativity. The second part discusses the Banados-Silk-West effect (the BSW effect) for extremal black holes and the GP effect—getting very high energies in the centre of mass frame—for nonextremal black holes. The possibility of getting high energy due to the large angular momentum of a particle is discussed in the third part. The fourth part considers the role of the "white hole" geodesics in the ergosphere. The conclusion provides a summary of research results.

The paper uses the system of units $G=c=1$ for the gravitational constant and the speed of light.

Kerr metric and geodesics

The Kerr metric of the rotating black hole (Kerr 1963) in the Boyer-Lindquist coordinates (Boyer, Lindquist 1967) is

$$ds^2 = \frac{\rho^2\Delta}{\Sigma^2}dt^2 - \frac{\sin^2\theta}{\rho^2}\Sigma^2(d\varphi-\omega dt)^2 - \frac{\rho^2}{\Delta}dr^2 - \rho^2 d\theta^2, \tag{1}$$

where

$$\rho^2 = r^2 + a^2\cos^2\theta, \qquad \Delta = r^2 - 2Mr + a^2, \tag{2}$$

$$\Sigma^2 = (r^2+a^2)^2 - a^2\sin^2\theta\Delta, \quad \omega = \frac{2Mra}{\Sigma^2}, \tag{3}$$

M is the mass of the black hole, aM is the angular momentum. Supposing that $0 \le a \le M$, the event horizon for the Kerr black hole is given by

$$r = r_H \equiv M + \sqrt{M^2 - a^2}. \tag{4}$$

The surface

$$r = r_C \equiv M - \sqrt{M^2 - a^2} \tag{5}$$

is the Cauchy horizon. The surface of the static limit is defined by

$$r = r_1 \equiv M + \sqrt{M^2 - a^2\cos^2\theta}. \tag{6}$$

The region of the space-time between the static limit and the event horizon is called ergosphere (Misner, Thorne, Wheeler 1973; Frolov, Novikov 2012). On the frontier of the ergosphere the function

$$S(r,\theta) = r^2 - 2Mr + a^2\cos^2\theta \tag{7}$$

is zero, while inside the ergosphere it is $S(r,\theta) < 0$.

The geodesics equations for the Kerr metric (1) (Chandrasekhar 1983; Frolov, Novikov 2012) are

$$\rho^2\frac{dt}{d\lambda} = \frac{1}{\Delta}\left(\Sigma^2 E - 2MraJ\right), \quad \rho^2\frac{d\varphi}{d\lambda} = \frac{1}{\Delta}\left(2MraE + \frac{SJ}{\sin^2\theta}\right), \tag{8}$$

$$\rho^2 \frac{dr}{d\lambda} = \sigma_r \sqrt{R}, \qquad \rho^2 \frac{d\theta}{d\lambda} = \sigma_\theta \sqrt{\Theta}, \tag{9}$$

$$R = \Sigma^2 E^2 - \frac{SJ^2}{\sin^2\theta} - 4MraEJ - \Delta\left[m^2\rho^2 + \Theta\right], \tag{10}$$

$$\Theta = Q - \cos^2\theta\left[a^2(m^2 - E^2) + \frac{J^2}{\sin^2\theta}\right]. \tag{11}$$

Here $E = const$ is the energy (relative to infinity) of the moving particle, J is the conserved angular momentum projection on the rotation axis, m is the rest mass of the particle, λ is the affine parameter along the geodesic. For the particle with $m \neq 0$, the parameter $\lambda = \tau / m$, where τ is the proper time. Q is the Carter constant. $Q = 0$ for the movement in the equatorial plane $(\theta = \pi/2)$. The constants $\sigma_r, \sigma_\theta = \pm 1$ define the direction of movement in coordinates r, θ.

It follows from (9) that the parameters characterising any geodesic must satisfy the conditions

$$R \geq 0, \qquad \Theta \geq 0. \tag{12}$$

The geodesic being the trajectory of the test particle moving outside the event horizon requires the "forward in time" movement

$$dt / d\lambda > 0. \tag{13}$$

The conditions (12) and (13) lead to inequalities in possible values of the energy E and the angular momentum projection J of the test particle at the point with coordinates (r, θ) with fixed value $\Theta \geq 0$ (Grib, Pavlov 2013b).

Outside the ergosphere $S(r,\theta) > 0$,

$$E \geq \frac{1}{\rho^2}\sqrt{(m^2\rho^2 + \Theta)S}, \quad J \in \left[J_-(r,\theta), J_+(r,\theta)\right], \tag{14}$$

$$J_\pm(r,\theta) = \frac{\sin\theta}{S}\left[-2rMaE\sin\theta \pm \sqrt{\Delta\left(\rho^4 E^2 - (m^2\rho^2 + \Theta)S\right)}\right]. \tag{15}$$

On the frontier of the ergosphere (for $\theta \neq 0, \pi$)

$$r = r_1(\theta) \;\Rightarrow\; \quad E \geq 0, \quad J \leq E\left[\frac{Mr_1(\theta)}{a} + a\sin^2\theta\left(1 - \frac{m^2}{2E^2} - \frac{\Theta}{4Mr_1(\theta)E^2}\right)\right]. \tag{16}$$

The value $E = 0$ is possible on the frontier of the ergosphere when $m = 0$, $\Theta = 0$. In this case, any value of $J < 0$ is possible.

Inside the ergosphere $r_H < r < r_1(\theta)$, $S < 0$

$$J \leq \frac{\sin\theta}{-S}\left[2rMaE\sin\theta - \sqrt{\Delta\left(\rho^4 E^2 - (m^2\rho^2 + \Theta)S\right)}\right] \tag{17}$$

and the energy of the particle, as it is known, can be either positive or negative.

According to (16) and (17), the angular momentum projection of the particles moving along geodesics for the fixed value of the energy can be negative on the frontier and inside the ergosphere and its absolute value number can be infinitely large. This property was first found by Grib, Pavlov (2013a; 2013b) for the Kerr metric and, as Zaslavskii (2013) showed later, it is valid in the ergosphere of any black hole with an axially symmetric metric.

Note that in the vicinity of the horizon (17) has the form

$$J(r) \leq J_H = \frac{2r_H ME}{a}, \quad r \to r_H. \tag{18}$$

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BSW-effect and multiparticle scattering

Energy in the centre of the mass frame $E_{c.m.}$ of two colliding particles with rest masses m_1 and m_2 is found by squaring the formula

$$\left(E_{c.m.}, 0, 0, 0\right) = p^i_{(1)} + p^i_{(2)}, \tag{19}$$

where $p^i_{(n)}$ means four-momenta of particles $(n = 1, 2)$. Due to $p^i_{(n)} p_{(n)i} = m_n^2$, one has

$$E^2_{c.m.} = m_1^2 + m_2^2 + 2 p^i_{(1)} p_{(2)i}. \tag{20}$$

Consider the collision of two massive particles. For massive particles $p^i_{(n)} = m_{(n)} u^i_{(n)}$, where $u^i = dx^i / d\tau$. In this case, as seen from (20), the energy $E_{c.m.}$ has the maximal value for given $u_{(1)}, u_{(2)}$ and $m_1 + m_2$, if the particle masses are equal: $m_1 = m_2$.

Let us find the expression of the energy in the centre of mass frame through the relative particle velocity v_{rel} at the moment of collision (Bañados, Hassanain, Silk 2011). The components of the particles' four-velocities in the reference frame of the first particle at this moment are obtained by

$$u^i_{(1)} = (1, 0, 0, 0), \ \ u^i_{(2)} = \frac{(1, \mathbf{v}_{rel})}{\sqrt{1 - v_{rel}^2}}. \tag{21}$$

Thus, $u^i_{(1)} u_{(2)i} = 1 / \sqrt{1 - v^2_{rel}}$,

$$v_{rel} = \sqrt{1 - \left(u^i_{(1)} u_{(2)i}\right)^{-2}}. \tag{22}$$

It is evident that these expressions do not depend on the coordinate system.

It follows from (20) and (22) that

$$E^2_{c.m.} = m_1^2 + m_2^2 + \frac{2 m_1 m_2}{\sqrt{1 - v_{rel}^2}}, \tag{23}$$

and the unlimited growth of the collision energy in the centre of mass frame occurs due to the growth of the relative velocity to the speed of light.

For free falling particles with energies E_1 and E_2 (relative to infinity) and angular momenta J_1, J_2, the geodesic equations give

$$\begin{aligned} E^2_{c.m.} = {} & m_1^2 + m_2^2 - \frac{2}{\rho^2} \sigma_{1\theta} \sigma_{2\theta} \sqrt{\Theta_1 \Theta_2} + \\ & + \frac{2}{\Delta \rho^2} \left[E_1 E_2 \Sigma^2 - 2Mra(E_1 J_2 + E_2 J_1) - J_1 J_2 \frac{S}{\sin^2\theta} - \sigma_{1r} \sigma_{2r} \sqrt{R_1 R_2} \right]. \end{aligned} \tag{24}$$

If particles move in radial coordinates in one direction ($\sigma_{1r} \sigma_{2r} = 1$), for collisions on the horizon solving the last term in (24) the indeterminacy of the form $0/0$ in the limit $r \to r_H$ gives

$$\begin{aligned} E^2_{c.m.} = {} & m_1^2 + m_2^2 - \frac{2}{\rho_H^2} \sigma_{1\theta} \sigma_{2\theta} \sqrt{\Theta_{1H} \Theta_{2H}} + \left(m_1^2 + \frac{\Theta_{1H}}{\rho_H^2} \right) \frac{J_{2H} - J_2}{J_{1H} - J_1} + \\ & + \left(m_2^2 + \frac{\Theta_{2H}}{\rho_H^2} \right) \frac{J_{1H} - J_1}{J_{2H} - J_2} + \frac{\rho_H^2}{4 M^2 r_H^2 \sin^2\theta} \frac{(J_{1H} J_2 - J_{2H} J_1)^2}{(J_{1H} - J_1)(J_{2H} - J_2)} \end{aligned} \tag{25}$$

(see also (24)). Here the subscript H in ρ_H and Θ_H indicates the value of the corresponding variable on the event horizon r_H. If one of the particles has the angular momentum projection $J = J_H$ -(the critical particle) and the other particle has $J \neq J_H$, then the energy of collisions is divergent on the horizon. For extremal rotating black holes this was found by Bañados, Silk and West (2009) (the BSW effect). For nonextremal black holes in the vicinity of the horizon, $J = J_H$ is not possible; however, it is possible in case of multiple collisions (Grib, Pavlov 2010; 2011) to have J that is very close to J_H for $r \to r_H$.

For the Schwarzschild black hole $(a = 0)$, the collision energy in the centre of mass frame (Grib, Pavlov 2012) is

$$E^2_{c.m.}(r \to r_H) = \frac{(E_1 J_2 - E_2 J_1)^2}{4M^2 E_1 E_2} + m_1^2\left(1 + \frac{E_2}{E_1}\right) + m_2^2\left(1 + \frac{E_1}{E_2}\right). \tag{26}$$

Here it is assumed that $\theta = \pi/2$.

To achieve the horizon of the black hole, a massive particle falling freely into the black hole in equatorial plane with dimensionless angular momentum $A = a/M$ being nonrelativistic at infinity $(E = m)$ must have angular momentum from the interval (l_L, l_R),

$$l_L = -2\left(1 + \sqrt{1 + A}\right), \quad l_R = 2\left(1 + \sqrt{1 - A}\right) \tag{27}$$

(here the notation $l = J/mM$ is used). For the Schwarzschild black hole, the maximal collision energy of two free falling particles with masses $m_1 = m_2 = m$ equals $2\sqrt{5}m$ if $l_1 = \pm 4$, $l_2 = \mp 4$ (Baushev 2009).

Putting the limiting values of angular momenta l_L, l_R into the formula (25) gives the maximal collision energy values of the particles falling freely from infinity

$$\frac{E^{max}_{c.m.}(r \to r_H)}{m_1 + m_2} = \sqrt{1 + \frac{2 m_1 m_2}{(m_1 + m_2)^2} \frac{(2 + \sqrt{1 + A} + \sqrt{1 - A})^2}{(1 + \sqrt{1 - A^2})\sqrt{1 - A^2}}}. \tag{28}$$

The dependence of $E^{max}_{c.m.}$ on the angular momentum of the black hole in the case $m_1 = m_2 = m$ is shown in Fig. 1.

For $A = 1 - \varepsilon$ with $\varepsilon \to 0$ the formula (28) gives

$$E^{max}_{c.m.} = 2\left(2^{1/4} + 2^{-1/4}\right)\frac{\sqrt{m_1 m_2}}{\varepsilon^{1/4}} + O(\varepsilon^{1/4}). \tag{29}$$

Therefore, even for values close to the extremal $A = 1$ of the rotating black hole, $E^{max}_{c.m.}/\sqrt{m_1 m_2}$ cannot be very large as mentioned by Berti, Cardoso, Gualtieri et al. (2009) and Jacobson and Sotiriou (2010) for the case $m_1 = m_2$. Thus, (28) for $A_{max} = 0.998$ considered as the maximal possible dimensionless angular momentum of the astrophysical black holes (Thorne 1974) gives $E^{max}_{c.m.}/\sqrt{m_1 m_2} \approx 18.97$.

However, this evaluation is enough for collisions of superheavy dark matter particles with the mass close to the grand unification scale to occur in the region of grand unification interaction physics, so that these particles can decay into quarks and be observed as the UHECR (Grib, Pavlov 2008a).

Moreover, taking into account the possibility of multiple scattering, so that the particle falling from infinity into the black hole with some fixed angular momentum changes its momentum in the result of interaction with particles in the accretion disc and then scatters again close to the horizon, then the scattering energy for usual particles can be unlimited.

The permitted interval in r for particles with $\varepsilon = 1$ and angular momentum $l = l_H - \delta$ falling in equatorial plane is obtained from (9). To do this, it is necessary to set the left side of (9) (for $dr/d\lambda$) to zero and find the root. In the second order in δ close to the horizon one has

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$$l = l_H - \delta \quad \Rightarrow \qquad x < x_\delta \approx x_H + \frac{\delta^2 x_C^2}{4 x_H \sqrt{1-A^2}}. \tag{30}$$

Here $x = r/M$, $x_H = r_H/M$, $x_C = r_C/M$. The effective potential for the case $\varepsilon = 1$ defined by the right side of (9)

$$V_{eff}(x,l) = -\frac{1}{2}\left(\frac{dr}{d\tau}\right)^2 = -\frac{1}{x} + \frac{l^2}{2x^2} - \frac{(A-l)^2}{x^3} \tag{31}$$

(see, for example, Fig. 2) leads to the following behaviour of the particle. If a particle goes from infinity to the black hole, it can achieve the horizon if the inequality (27) is valid. However, the scattering energy in the centre of mass frame given by (28) is not large. On the other hand, if a particle comes not from the infinity, but from some distance

defined by (30), then, due to the form of the potential, it can have values of $l = l_H - \delta$ larger than l_R and fall into the horizon. If a particle falling from infinity with $l \le l_R$ arrives to the region defined by (30) and interacts there with other particles of the accretion disc, or decays into a lighter particle which gets an increased angular momentum $l_1 = l_H - \delta$, then the scattering energy in the centre of mass system is

$$E_{c.m.} \approx \frac{1}{\sqrt{\delta}} \sqrt{\frac{2 m_1 m_2 (l_H - l_2)}{1 - \sqrt{1-A^2}}}, \tag{32}$$

and it increases without limit for $\delta \to 0$. For $A_{max} = 0.998$ and $l_2 = l_L$, $E_{c.m.} \approx 3.85 m / \sqrt{\delta}$. Note that for rapidly rotating black holes $A = 1 - \varepsilon$ the difference between l_H and l_R is not large

$$l_H - l_R = 2\frac{\sqrt{1-A}}{A}\left(\sqrt{1-A} + \sqrt{1+A} - A\right) \approx 2(\sqrt{2}-1)\sqrt{\varepsilon}, \quad \varepsilon \to 0. \tag{33}$$

For $A_{max} = 0.998$, $l_H - l_R \approx 0.04$, so the possibility of getting small additional angular momentum in interaction close to the horizon seems highly probable. The probability of multiple scattering in the accretion disc depends on its particle density and is large for large densities.

Role of particles with large angular momentum

Very large energy of collisions can be obtained if, due to multiple collisions or the external field, the particle has a negative angular momentum projection with a large absolute value (Grib, Pavlov 2013a; 2013b) for the fixed value of the particle energies due to (17). As it is shown by Grib and Pavlov (2013b), for the collision in ergosphere one has

$$E_{c.m.}^2 \approx J_2 \frac{r^2 - 2rM + a^2 \cos^2\theta}{\rho^2 \Delta \sin^2\theta} \left(\sigma_{1r}\sqrt{J_{1+} - J_1} - \sigma_{2r}\sqrt{J_{1-} - J_1}\right)^2, \ J_2 \to -\infty. \tag{34}$$

Thus, when particles fall on the rotating black hole, collisions with arbitrarily high energy in the centre of mass frame are possible at any point of the ergosphere if $J_2 \to -\infty$ and the energies E_1, E_2 are fixed. The energy of collision in the centre of mass frame is growing proportionally to $\sqrt{|J_2|}$. Note that for large $-J_2$ the collision energy close to horizon in the centre of mass frame can be either higher or lower then for collisions at the other points of ergosphere depending on values E_1, J_1.

Unbounded growth of the collision energy with growing $-J$ due to (23) is conditioned for the BSW effect by the growth of the relative velocity of particles to the speed of light. Contrary to the BSW effect, this effect can take place at any point of the ergosphere.

Outside the ergosphere, the collision energy is limited for given r, but for $r \to r_1$ it can be large if one of the particles gets an angular momentum in intermediate collisions close to J_- (see (15)). In Fig. 3 the dependence of the collision energy in the centre of mass frame in the coordinate r is shown for particles with $E_1 = E_2 = m_1 = m_2$, $J_1 = 0$ and $J_2 = J_-$ moving in the equatorial plane of a black hole with $a = 0.8M$.

Note that large negative values of the angular momentum projection are forbidden for fixed energy values of a particle out of the ergosphere. That is why collisions with $J_2 \to -\infty$ do not occur for particles falling from infinity. However, if a particle comes to the ergosphere and gets large negative values of the angular momentum projection (getting high energies is not necessary) there in the result of interactions with other particles, then its subsequent collision with the particle falling into the black hole leads to a high energy in the centre of mass frame.

Superhigh energies may be obtained in such a way from collisions of usual particles (i.e. protons); however, it is physically unrealistic. Instead, as follows from (34), the value of angular momentum necessary for getting the collision energy $E_{c.m.}$ is

$$J_2 \approx -\frac{aE_{c.m.}^2}{2E_1}. \tag{35}$$

Thus, the absolute value of the angular momentum J_2 must acquire the order $E_{c.m.}^2 / (m_1 m_2)$ relative to the maximal angular momentum value of the particle coming to ergosphere from infinity. For example, if $E_1 = E_2 = m_p$ (the proton mass), then $|J_2|$ must increase with a factor 10^{18} for $E_{c.m.} = 10^9 m_p$. It requires a very large number of collisions with getting additional negative angular momentum in each collision.

However, the situation is different for supermassive particles with mass of the grand unification scale created by gravitation in the end of the inflation era. In the ergosphere of the rotating black holes such particles can increase their energy from $2m$ to $3m$ and larger due to getting large relative velocities, so that the mechanism considered in this paper can lead to their decay, same as in the early universe. The number of intermediate collisions for them is not very large (approximately 10).

White hole geodesics

The energy of direct collisions ($\sigma_{1r}\sigma_{2r} = -1$) is divergent on the horizon

$$E_{c.m.}^2 \sim \frac{4a^2}{\Delta\rho^2}(J_{1H} - J_1)(J_{2H} - J_2) \to \infty, \quad r \to r_H, \tag{36}$$

if $J_i \neq J_{iH}$. Getting ultrahigh energy in this way is possible if one of the particles moves along white hole geodesic (Grib, Pavlov 2015a; 2015b).

Formulas (19)–(25), (34) and (36) are valid for any colliding particles with both positive and negative (relative to infinity) energy. For any value of the particle energies, the energy in the centre of mass frame satisfies the inequality

$$E_{c.m.} \geq m_1 + m_2, \tag{37}$$

because colliding particles in the centre of mass frame are moving one to another with certain velocities. All three ways of getting infinitely high energy from collisions are also possible for particles with negative (zero) energy.

The physical importance of these resonances is due to possible conversion of dark matter particles into visible ones in the ergosphere of astrophysical black holes (Grib, Pavlov 2008a; 2009).

Some calculations of the collision energy for two particles with equal masses m, one of which falls from the infinity into a black hole and another one has positive, zero or negative energy, and their results are presented in the paper by Grib and Pavlov (2017).

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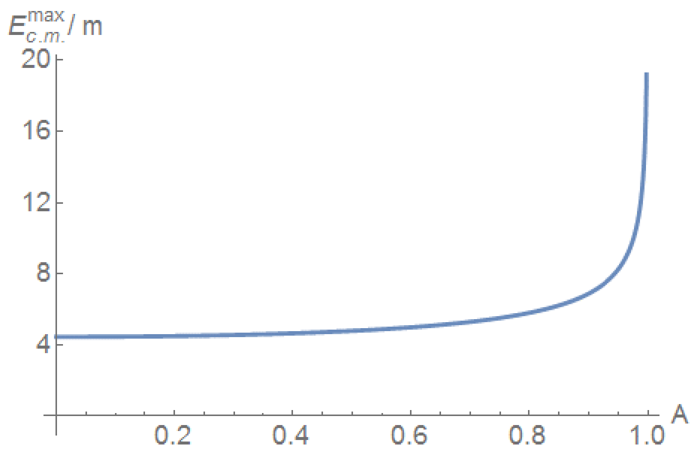

Fig. 1. The dependence of the maximal energy of collision for particles falling from infinity on the black hole angular momentum

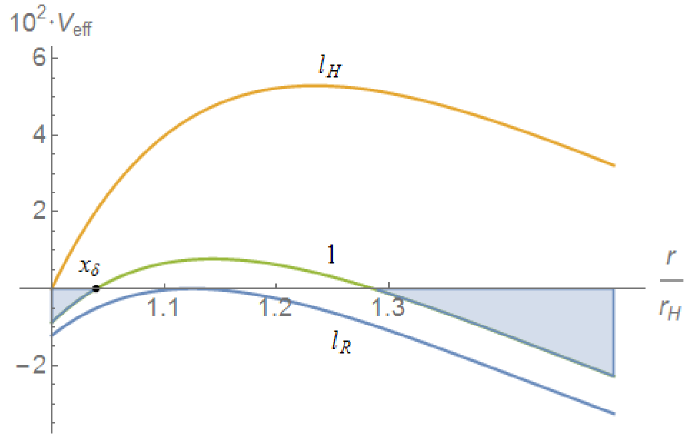

Fig. 2. The effective potential for $A = 0.96$ and $l_R = 2.4$, $l = 2.44$, $l_H \approx 2.67$. Allowed zones for $l = 2.44$ are shown by the gray color

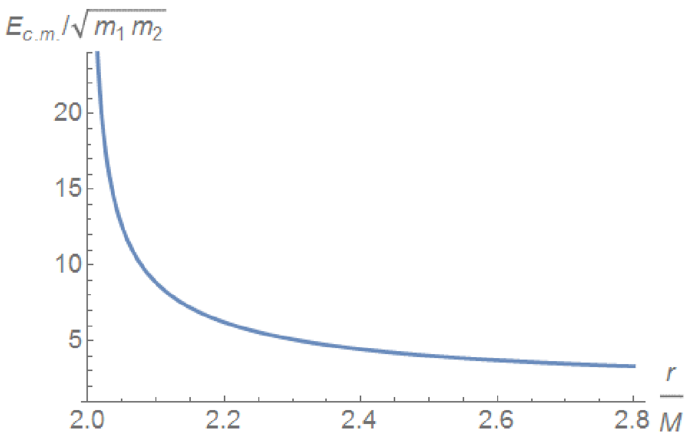

Fig. 3. The collision energy in the centre of mass frame for particles with $J_1 = 0$ and $J_2 = J_-$ out of the ergosphere

Conclusion

1. Energies of the grand unification and Planck scale in the centre of mass frame for two colliding particles can be obtained in the horizon vicinity of the Kerr nonextremal black hole, if one particle gets the critical angular momentum in previous multiple collisions.

2. Such energies can be obtained at any point of the ergosphere, if one of the particles has a negative angular momentum with a large absolute value.

3. "White hole" geodesics exist in the vicinity of black holes. They can be positive energy geodesics and Penrose geodesics with negative energies in the ergosphere. Particles on these geodesics can collide with ordinary particles and high energy can be obtained either in direct collisions or in case of large negative angular momentum of one of the particles.

4. The hypothesis of superheavy dark matter particles with grand unification mass which decayed partially into ordinary particles in the early universe, giving the observable Eddington number at the time close to the era of particle creation from vacuum, can be examined in the vicinity of Kerr black hole.

References

Aab, A., Abreu, P., Aglietta M. et al. (2017) Observation of a large-scale anisotropy in the arrival directions of cosmic rays above 8×10^{18} eV. *Science*, 357 (6357), 1266–1270. DOI: 10.1126/science.aan4338 (In English)

Bañados, M., Hassanain, B., Silk, J., West, S. M. (2011) Emergent flux from particle collisions near a Kerr black hole. *Physical Review D*, 83 (2), 023004. DOI: 10.1103/PhysRevD.83.023004 (In English)

Bañados, M., Silk, J., West, S. M. (2009) Kerr black holes as particle accelerators to arbitrarily high energy. *Physical Review Letters*, 103 (11), 111102. DOI: 10.1103/PhysRevLett.103.111102 (In English)

Baushev, A. (2009) Dark matter annihilation in the gravitational field of a black hole. *International Journal of Modern Physics D*, 18 (08), 1195–1203. DOI: 10.1142/S0218271809014509 (In English)

Berti, E., Cardoso, V., Gualtieri, L. et al. (2009) Comment on "Kerr black holes as particle accelerators to arbitrarily high energy". *Physical Review Letters*, 103 (23), 239001. DOI: 10.1103/PhysRevLett.103.239001 (In English)

Boyer, R. H., Lindquist, R. W. (1967) Maximal analytic extension of the Kerr metric. *Journal of Mathematical Physics*, 8 (2), 265–281. DOI: 10.1063/1.1705193 (In English)

Chandrasekhar, S. (1983) *The mathematical theory of black holes*. Oxford: Clarendon Press, 646 p. (In English)

Frolov, V. P., Novikov, I. D. (2012) *Black hole physics: Basic concepts and new developments*. S. l.: Springer Science & Business Media, 770 p. DOI: 10.1007/978-94-011-5139-9 (In English)

Grib, A. A., Mamayev, S. G., Mostepanenko, V. M. (1994) *Vacuum quantum effects in strong fields.* Saint Petersburg: Friedmann Laboratory Publ., 361 p. (In English)

Grib, A. A., Pavlov, Y. V. (2002a) Cold dark matter and primordial superheavy particles. *International Journal of Modern Physics A*, 17 (29), 4435–4439. DOI: 10.1142/S0217751X02013514 (In English)

Grib, A. A., Pavlov, Yu. V. (2002b) Superheavy particles in Friedmann cosmology and the dark matter problem. *International Journal of Modern Physics D*, 11 (03), 433–436. DOI: 10.1142/S0218271802001706 (In English)

Grib, A. A., Pavlov, Yu. V. (2008a) Do active galactic nuclei convert dark matter into visible particles? *Modern Physics Letters A*, 23 (16), 1151–1159. DOI: 10.1142/S0217732308027072 (In English)

Grib, A. A., Pavlov, Yu. V. (2008b) Is dark matter the relic of the primordial matter that created the visible matter of the universe? *Gravitation and Cosmology*, 14 (1), 1–7. DOI: 10.1134/S0202289308010015 (In English)

Grib, A. A., Pavlov, Yu. V. (2009) Active galactic nuclei and transformation of dark matter into visible matter. *Gravitation and Cosmology*, 15 (1), 44–48. DOI: 10.1134/S0202289309010125 (In English)

Grib, A. A., Pavlov, Yu. V. (2010) On the collisions between particles in the vicinity of rotating black holes. *JETP Letters*, 92 (3), 125–129. DOI: 10.1134/S0021364010150014 (In English)

Grib, A. A., Pavlov, Yu. V. (2011) On particle collisions in the gravitational field of the Kerr black hole. *Astroparticle Physics*, 34 (7), 581–586. DOI: 10.1016/j.astropartphys.2010.12.005 (In English)

Grib, A. A., Pavlov, Yu. V. (2013a) On the energy of particle collisions in the ergosphere of the rotating black holes. *EPL (Europhysics Letters)*, 101 (2), 20004. DOI: 10.1209/0295-5075/101/20004 (In English)

Grib, A. A., Pavlov, Yu. V. (2013b) Collision energy of particles in the ergosphere of rotating black holes. *Theoretical and Mathematical Physics*, 176 (1), 881–887. DOI: 10.1007/s11232-013-0075-4 (In English)

Grib, A. A., Pavlov, Yu. V. (2015a) Are black holes totally black? *Gravitation and Cosmology*, 21 (1), 13–18. DOI: 10.1134/S0202289315010065 (In English)

Grib, A. A., Pavlov, Yu. V. (2015b) High energy physics in the vicinity of rotating black holes. *Theoretical and Mathematical Physics*, 185 (1), 1425–1432. DOI: 10.1007/s11232-015-0351-6 (In English)

Grib, A. A., Pavlov, Yu. V. (2017) Black holes and particles with zero or negative energy. *Theoretical and Mathematical Physics*, 190 (2), 268–278. DOI: 10.1134/S0040577917020088 (In English)

Grib, A. A., Pavlov, Yu. V., Piattella, O. F. (2012) On collisions with unlimited energies in the vicinity of Kerr and Schwarzschild black hole horizons. *Gravitation and Cosmology*, 18 (1), 70–75. DOI: 10.1134/S0202289312010094 (In English)

Harada, T., Kimura, M. (2011) Collision of two general geodesic particles around a Kerr black hole. *Physical Review D*, 83 (8), 084041. DOI: 10.1103/PhysRevD.83.084041 (In English)

Jacobson, T., Sotiriou, T. P. (2010) Spinning black holes as particle accelerators. *Physical Review Letters*, 104 (2), 021101. DOI: 10.1103/PhysRevLett.104.021101 (In English)

Kerr, R. P. (1963) Gravitational field of a spinning mass as an example of algebraically special metrics. *Physical Review Letters*, 11 (5), 237. DOI: 10.1103/PhysRevLett.11.237 (In English)

Misner, C. W., Thorne, K. S., Wheeler J. A. (1973) *Gravitation*. San Francisco: W. H. Freeman & Company, XXVI, [2], 1279 p. (In English)

Piran, T., Shaham, J., Katz, J. (1975) High efficiency of the Penrose mechanism for particle collisions. *Astrophysical Journal Letters*, 196, L107. DOI: 10.1086/181755 (In English)

Thorne, K. S. (1974) Disk-accretion onto a black hole. II. Evolution of the hole. *Astrophysical Journal*, 191, 507–520. DOI: 10.1086/152991 (In English)

Zaslavskii, O. B. (2013) Acceleration of particles as a universal property of ergosphere. *Modern Physics Letters A*, 28 (11), 1350037. DOI: 10.1142/S0217732313500375 (In English)