"On the Hypothesis of Superheavy Particles as Particles of Dark Matter"

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[1] A.A.Grib and Yu.V.Pavlov, *Mod. Phys. Lett.* A **23**, 1151 (2008), arXiv:0712.2667v1 [gr-qc]; Gravit. & Cosmology, **15** (2009), 44, arXiv:0810.1724.

[2] The Pierre Auger Collaboration, *Science* **318**, 938 (2007).

[3] A.A. Grib and V.Yu. Dorofeev, *Int. J. Mod. Phys.* **D3**, 731 (1994).

[4] A.A. Grib, S.G. Mamayev and V.M. Mostepanenko, *Vacuum Quantum Effects in Strong Fields.* Friedmann Laboratory Publ., St.Petersburg, 1994.

[5] A.A. Grib and Yu.V. Pavlov, *Int. J. Mod. Phys.* **D11**, 433 (2002);
Int. J. Mod. Phys. **A17**, 4435 (2002);
Gravit. & Cosmology **8**, Suppl., 148; Suppl. II, 50 (2002);
11, 119 (2005); **14**, 1 (2008).

[6] R.Aloisio, V.Berezinsky, M.Kachelriess. *Phys. Rev.* **D74**, 023516 (2006)

[7] R. Penrose, *Rivista Nuovo Cimento* **I**, Num. Spec., 252 (1969).

[8] J. F. Navarro, C. S. Frenk and S. D. M. White, *Astrophys. J.* **462**, 563 (1996).

Superheavy particles in the early Universe

Inflaton field was the source of relativistic dark matter leading to Friedmann metric $a(t) = a_0\sqrt{t}$ and its gravity creates

$$N = n^{(s)}(t)\, a^3(t) = b^{(s)}\, M^{3/2}\, a_0^3 \tag{1}$$

pairs of particles of visible matter inside the Lagrange volume, where
$b^{(0)} \approx 5.3 \cdot 10^{-4}$ for scalar and $b^{(1/2)} \approx 3.9 \cdot 10^{-3}$ for spinor particles.

$N \sim \mathbf{10^{80}}$ — the Eddington number — for $M \sim \mathbf{10^{14}}$ **Gev** coinciding with the number of protons today.

For the time t_X there is an era of going from the radiation dominated model to the dust model of superheavy particles

$$t_X \approx \left(\frac{3}{64\pi\, b^{(s)}}\right)^2 \left(\frac{M_{Pl}}{M}\right)^4 \frac{1}{M}\,. \tag{2}$$

If $M \sim \mathbf{10^{14}}$ **Gev**, $t_X \sim \mathbf{10^{-15}}$ **sec** for scalar
and $t_X \sim \mathbf{10^{-17}}$ **sec** for spinor particles.

In analogy with K-meson decay one can introduce X_S and X_L-particles. The decay of X_S on quarks and leptons gives visible baryon charge.

A. D. Sakharov, *JETP Lett.* **5**, 24 (1967)

For example, the following processes can go in some simple models.

X decays with probability r on particles with baryonic charge B_1 and with probability $1-r$ on particles with baryonic charge $B_2 \neq B_1$ due to nonconservation of baryonic charge.

Then the full baryonic charge after decay of X is

$$B = rB_1 + (1-r)B_2 \,.$$

If $\overline{X}$ decays with probability $\overline{r}$ on particles with the baryonic charge $-B_1$ and with probability $1-\overline{r}$ on $(-B_2)$, then the baryonic charge after decay of $\overline{X}$ is

$$\overline{B} = -(\overline{r}B_1 + (1-\overline{r})B_2) \,.$$

So the CP-noninvariance $r \neq \overline{r}$ leads to origination of a nonzero baryonic charge after decay of $X, \overline{X}$ pairs

$$B + \overline{B} = (r - \overline{r})(B_1 - B_2) \,.$$

The simple example of X decays can be $X \longrightarrow qq$, where quarks q have baryonic charge $1/3$; $X \longrightarrow \overline{q}l$, where l is a lepton with zero baryonic charge. Then $B + \overline{B} = r - \overline{r}$.

The baryonic charge of the Universe will be

$$N(B+\overline{B}) = b^{(s)}\, M^{3/2}\, a_0^3 (r-\overline{r})\,.$$

Due to CPT non-invariance there is no necessity for non-equilibrium state

A.A. Grib, Yu.V. Kryukov, *Sov. J. Nucl. Phys.* **48**, 1109 (1988).

Discussion with A.D. Sakharov in 1988 in Leningrad.

It is possible that some of this X_L survive up to modern time and exist as part of cold dark matter. Then it is possible to identify the decay of X_L-particles in modern epoch as the UHE cosmic ray events. Let us define d — the permitted part of long living X-particles:

$$d \cdot \varepsilon_X(t_{rec}) = \varepsilon_{crit}(t_{rec}).$$

$$d = \frac{3}{64\pi\, b^{(s)}} \left(\frac{M_{Pl}}{M_X}\right)^2 \frac{1}{\sqrt{M_X\, t_{rec}}}\,. \qquad (3)$$

For $M_X = 10^{13} - 10^{14}$ Gev one has $d \approx 10^{-12} - 10^{-14}$ (for scalar),

$d \approx 10^{-13} - 10^{-15}$ (for spinor particles).

Our Scenario

I) $t_{Pl} - t_{GU}$ Inflation $p = -\varepsilon\,;$ $\varepsilon \neq 0, \quad p = 0\,;$ $p = \varepsilon/3\,;$	Inflation field or parallel Universe, quintessence. For example quintessence can be the scalar field non interacting with ordinary particles
II) $t_{GU} \approx 10^{-35}\,\mathrm{sec}$, $t_X \approx 10^{-15}\,\mathrm{sec}$	1) Creation of $X, \bar{X}$ by gravitation of the inflaton field. $M_X \approx M_{GU}, \;\; N_X \sim N_E$ 2) Decay of $X, \bar{X}$ on quarks and leptons and origination of the nonzero baryon charge. X_L, X_S. All X_S — decay, X_L — survive. 3) $t_X = 10^{-15}\,\mathrm{sec}$, X_L interact with baryon charge similar to K_L.
III) Modern epoch $p \approx -\varepsilon$ (Cosmological constant $\neq 0$).	$d\,N_E$ of X_L survive and form cold dark matter. X_L decay in AGN and the products are observable as UHECR.

Particle creation in Friedmann Universe

$$a(t) = a_0 t^{\alpha}, \qquad N(t) = \left(\frac{a(t_C)}{t_C}\right)^3 b_{\alpha}.$$

Figure 1: b_{α} for conformal scalar particles (numerical results).

Now let us construct the toy model which can give:

a) short living X–particles decay in time $\tau_q < t_X$ (more wishful is $\tau_q \sim t_C \approx 10^{-38} - 10^{-35}$ sec),

b) long living particles decay with $\tau_l \approx t_X$.

c) one has small $d \sim 10^{-14} - 10^{-12}$ part of long living X – mesons, forming the dark matter.

The matrix of the effective Hamiltonian

$$H = \begin{pmatrix} H_{11} & H_{12} \\ H_{21} & H_{22} \end{pmatrix} . \tag{4}$$

Let $H_{11} = H_{22}$.

Denote $\varepsilon = (\sqrt{H_{12}} - \sqrt{H_{21}}\,) \,/\, (\sqrt{H_{12}} + \sqrt{H_{21}}\,)$.

The eigenvalues $\lambda_{1,2}$ and eigenvectors $|\,\Psi_{1,2}>$ of matrix H are

$$\lambda_{1,2} = H_{11} \pm \frac{H_{12} + H_{21}}{2} \, \frac{1 - \varepsilon^2}{1 + \varepsilon^2} \,, \tag{5}$$

$$|\,\Psi_{1,2}> = \frac{1}{\sqrt{2\,(1 + |\varepsilon|^2)}} \Big[(1 + \varepsilon)\,|\,1> \pm (1 - \varepsilon)\,|\,2>\Big] . \tag{6}$$

Let us choose the effective Hamiltonian as

$$H = \begin{pmatrix} E - \frac{i}{4}\left(\tau_q^{-1} + \tau_l^{-1}\right) & \frac{1+\varepsilon}{1-\varepsilon}\left[A - \frac{i}{4}\left(\tau_q^{-1} - \tau_l^{-1}\right)\right] \\ \frac{1-\varepsilon}{1+\varepsilon}\left[A - \frac{i}{4}\left(\tau_q^{-1} - \tau_l^{-1}\right)\right] & E - \frac{i}{4}\left(\tau_q^{-1} + \tau_l^{-1}\right) \end{pmatrix}. \tag{7}$$

In our scenario the small $d \sim 10^{-15}$–10^{-12} part of long living X-particles with $\tau_l > t_U \approx 10^{18}$ sec (t_U is the age of the Universe) is forming the dark matter.

$$M_{X_L} < M_{X_S} \quad \text{if} \quad A > 0 \ \text{ in (7)}.$$

For $M_X = 10^{14}\,\text{Gev}$ and $n_X \approx 2 \cdot 10^{-20}\,\text{cm}^{-3}$ — ρ_{crit} at the modern epoch. In analogy with the regeneration mechanism for K^0-mesons.

$$H^d = \begin{pmatrix} 0 & 0 \\ 0 & -i\gamma \end{pmatrix}. \tag{8}$$

In case when $\gamma \ll \tau_q^{-1}$ for the long living component one obtains

$$\|\Psi_2(t)\|^2 = \|\Psi_2(t_0)\|^2 \exp\left[\frac{t_0 - t}{\tau_l} - \int_{t_0}^{t} \gamma(t)\, dt\right]. \tag{9}$$

$$\gamma = \alpha\, n^{(0)}(t)\,. \tag{10}$$

For $\tau_l \gg t_U$, $t \leq t_U$, $a(t) = a_0\sqrt{t}$ one obtains

$$\|\Psi_2(t)\|^2 = \|\Psi_2(t_0)\|^2 \exp\left[\alpha 2 b^{(s)} M^{3/2}\left(\frac{1}{\sqrt{t}} - \frac{1}{\sqrt{t_0}}\right)\right]. \tag{11}$$

So the decay of the long living component due to this mechanism takes place close to the time t_0. Let us suppose $t_0 \approx t_X$. Then from (3) and (11) one obtains the evaluation for the parameter α

$$\alpha = \frac{-3\ln d}{128\pi (b^{(s)})^2}\,\frac{M_{Pl}^2}{M^4}\,. \tag{12}$$

For $M = 10^{14}\,\mathrm{Gev}$ and $d = 10^{-15}$ one obtains $\alpha \approx 10^{-40}\,\mathrm{cm}^2$ corresponding to weak interaction. Products of decay of X_S have the temperature at t_X

$$T(t_X) = \frac{64\sqrt{\pi}}{3}\left(\frac{30}{N_l}\right)^{1/4}\left(b^{(s)}\right)^{5/4}(M\tau_s)^{1/8}\,\frac{M^3}{k_B M_{Pl}^2}\,, \tag{13}$$

where N_l is defined by the number of boson and fermion degrees of freedom of all kinds of light particles, $\tau_S \approx 1/M$. Particles can be created due to this temperature, but our calculations show that their number has the same order!

Decay of Super Heavy Particles in interaction with baryon matter

$$\tau = \frac{1}{\gamma} = \frac{1}{\sigma n v}\,, \qquad \sigma \approx 10^{-40}\,\mathrm{cm}^2 \tag{1}$$

Decay of SHP in interaction with **Galaxy Halo**:
$n \sim 1\,\mathrm{cm}^{-3}$, $v \sim 10^8\,\mathrm{cm/s}$,

$$\tau \approx 10^{32}\,\mathrm{s}\,. \tag{2}$$

Decay of SHP in **Sun**: $n \sim 10^{24}\,\mathrm{cm}^{-3}$, $v \sim 10^8\,\mathrm{cm/s}$,

$$\tau \approx 10^{8}\,\mathrm{s} \sim \mathrm{year}\,. \tag{3}$$

Decay of SHP in **Neutron Star**: $n \sim 10^{38}\,\mathrm{cm}^{-3}$, $v \sim 10^{10}\,\mathrm{cm/s}$,

$$\tau \approx 10^{-8}\,\mathrm{s}\,. \tag{4}$$

SHP are “burned” by neutron stars ($\rho \sim 10^{14}\,\mathrm{g/cm}^3$)

Quantity of SHP burned out by neutron stars:

$$\frac{\Delta N}{\Delta t} \approx \sigma_g \, n_X \, v_\infty \sim 10^{11} \, \mathrm{s}^{-1} \, , \tag{5}$$

$$\sigma_g \approx \pi R_{ns} \frac{2Gm}{v_\infty^2}, \qquad m \sim 2,6 \cdot 10^{33} \, \mathrm{g} \; , \quad R_{ns} \sim 10 \, \mathrm{km}, \quad v_\infty \sim 500 \, \mathrm{km/s} \, .$$

For $M_X \sim 10^{14}$ Gev, **luminosity**:

$$\frac{\Delta N}{\Delta t} M_X c^2 \sim 10^{22} \, \frac{\mathrm{erg}}{\mathrm{s}} \ll 10^{35} \, \frac{\mathrm{erg}}{\mathrm{s}} \; \text{(Crab)}. \tag{6}$$

Decay products are absorbed by neutron star because

$$\sigma_\nu \sim 10^{-31} \, \mathrm{cm}^2 \gg \sigma_X \sim 10^{-40} \, \mathrm{cm}^2 \, . \tag{7}$$

Internal heat of Planets and SH dark matter

Planet	Internal heat (TW)	Mass (g)	Radius (equator, km)
Earth	44	$5.98 \cdot 10^{27}$	6378
Jupiter	400×10^3	$1.90 \cdot 10^{30}$	71400
Saturn	200×10^3	$5.68 \cdot 10^{29}$	60400
Uranus	$\leq 10^3$	$8.70 \cdot 10^{28}$	24300
Neptune	3×10^3	$1.03 \cdot 10^{29}$	25050

For Earth — the decay of radioactive elements (uranium and thorium) produces $\approx 40\%$ of the total heat (antineutrino detectors, KamLAND). Hypothesis: G.D.Mack, J.F.Beacom, G.Bertone. Phys. Rev. D 76, 043523 (2007)— $\mathbf{2 \cdot 10^{13}\,W}$ from decay of dark matter. Then

$$\frac{\Delta E}{M_{Earth}\, c^2} \approx 10^{-21} \;\; \text{in 1 year;} \quad \approx 5 \cdot 10^{-12} \;\; \text{in } 4.5 \cdot 10^9 \text{ years} \tag{8}$$

$\mathbf{2 \cdot 10^{13}\,W} \quad \Leftrightarrow \quad \approx \mathbf{10^9}$ decays/sec for $\quad \mathbf{M_{SH} = 10^{14}}\,\mathrm{GeV}.$

Estimates for density of dark matter

in Solar system $\rho_{dm} < 1,5 \cdot 10^{-19}\,\mathrm{g/cm}^3$ (Khriplovich and Pitjeva)

Earth-bound dark matter $\rho_{dm} < 10^{-14}\,\mathrm{g/cm}^3$ (S.L.Adler, Phys. Lett. B**671**, 203 (2009))

$$\frac{dN}{N\,dt} = \sigma_{DM}\, n\, v_E \approx 3 \cdot 10^{-10}\,\mathrm{s}^{-1} \tag{9}$$

for $\sigma_{DM} \approx 10^{-40}\,\mathrm{cm}^2$, $v_E \approx 10\,\mathrm{km/s}$.

Then for $\approx \mathbf{10^9}$ decays/sec $\rho_{DM} \approx 6 \cdot 10^{-19}\ \mathrm{g/cm}^3$

Neutrino flux

$$\sigma_{\nu N} = 6,04 \pm 0,40 \left(\frac{E_\nu}{GeV}\right)^{0,358\pm 0,005} 10^{-36}\,\mathrm{cm}^2, \tag{10}$$

Let $\sigma_\nu \approx 5 \cdot 10^{-31}\,\mathrm{cm}^2$. Then $l_\nu = 6\,\mathrm{km}$ in Earth. Flux from Earth $J \approx 5 \cdot 10^{-13}\ \mathrm{s}^{-1}\ \mathrm{cm}^{-2}$

But Auger experiment etc. $J < 10^{-15}\ \mathrm{s}^{-1}\ \mathrm{cm}^{-2}$

New experiments are needed. Ice Cube etc. give new restrictions on density of SH dark matter.

Pierre Auger Observatory

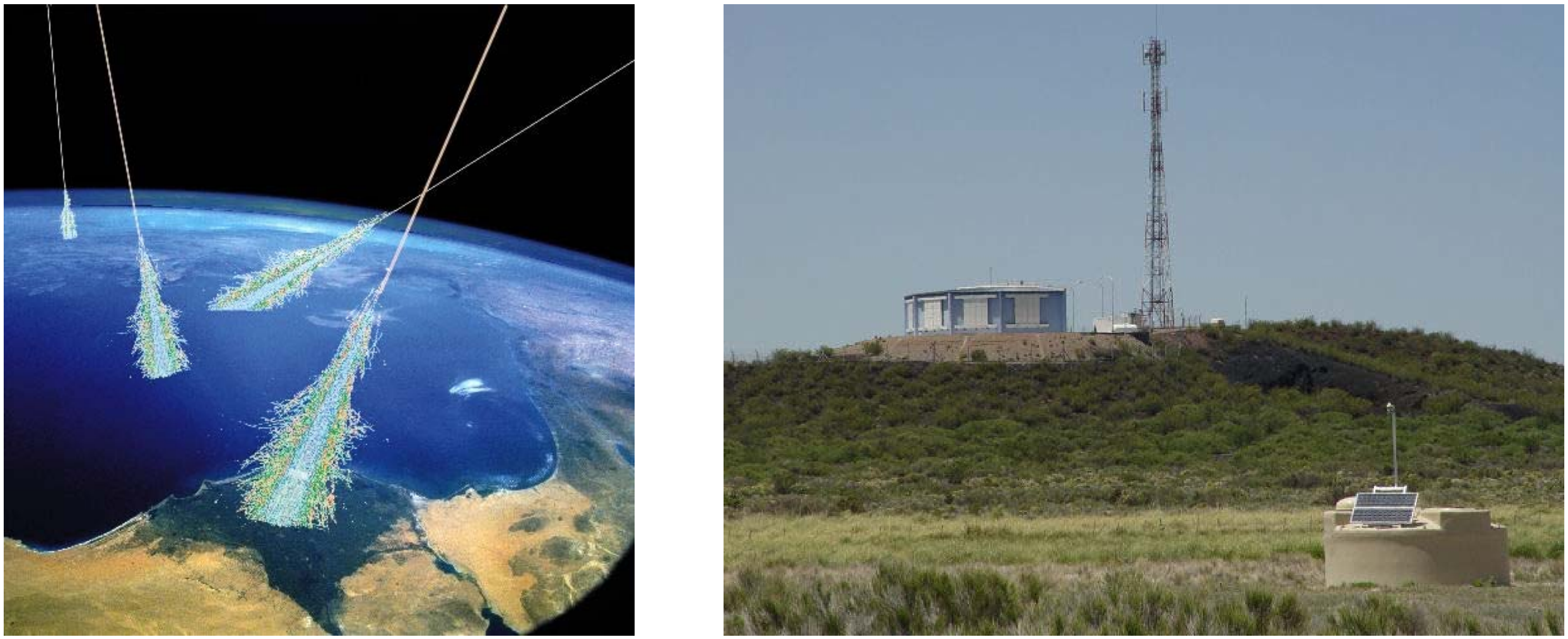


Figure 2: The Pierre Auger Observatory is a hybrid detector. On the hill is one of the 4 Fluorescence Detector buildings and communications tower. In the bottom foreground is one of the 1,600 Surface Detectors – water tanks (12,000 liter), each tank is separated from each of its neighbors by 1.5 kilometers.

Pierre Auger Collaboration, Science 2007, Vol.**318**, 938–943. "Correlation of the Highest-Energy Cosmic Rays with Nearby Extragalactic Objects"

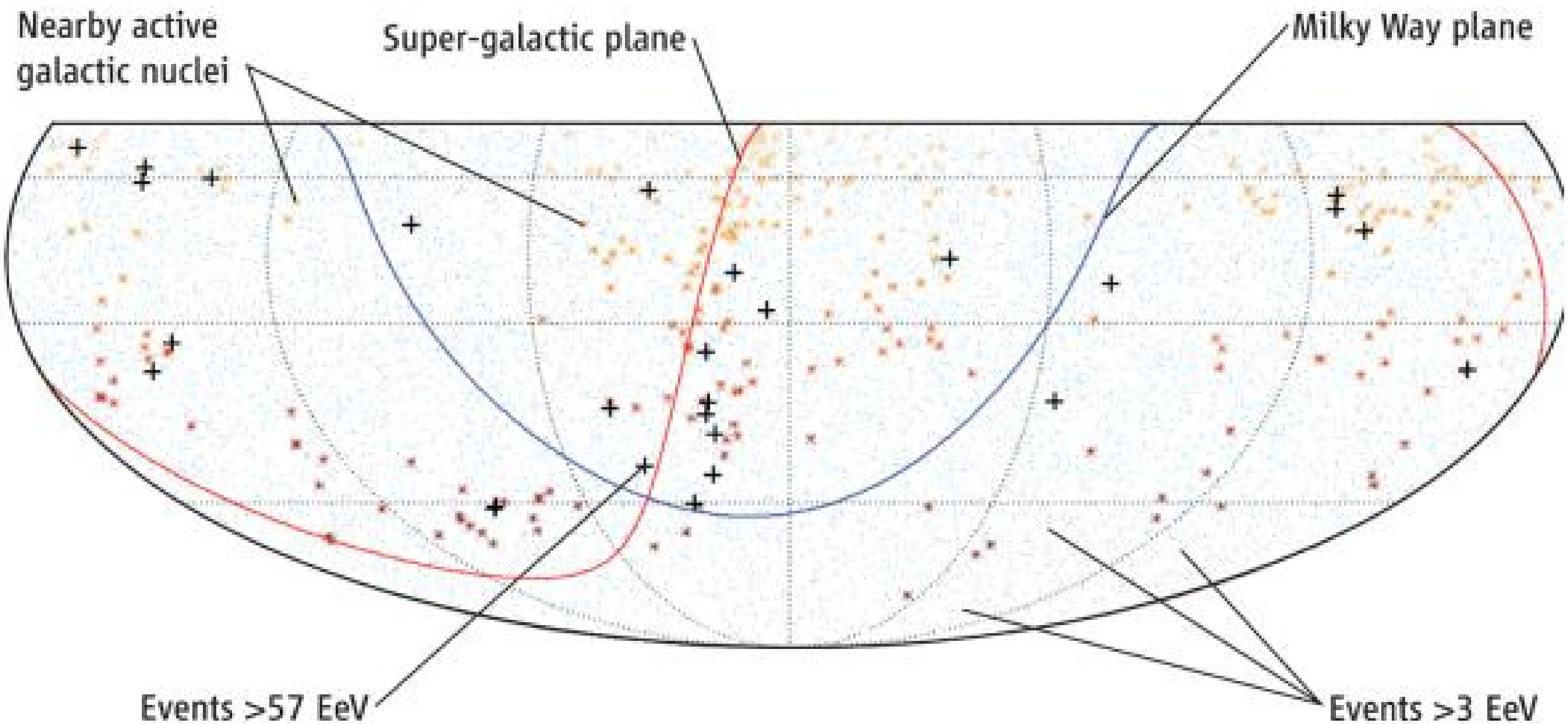


Figure 3: Sky mapshowing cosmic rays detected by the Pierre Auger Observatory. Low-energy cosmic rays appear to originate from evenly distributed sources (blue dots), but the origins of the highest-energy events (crosses) correlate with the distribution of local matter as represented by nearby active galactic nuclei (red stars). Thus, active galactic nuclei are a likely source of these rare high-energy cosmic rays.

Superheavy particles as source UHECR from AGN.

Some numerical estimates.

The Auger group registered 27 UHECR with energies higher than $57 \cdot 10^{18}\,\mathrm{eV}$. The integrated exposure of Auger observatory for these data is $9.0 \times 10^{3}\,\mathrm{km}^{2}\,\mathrm{sr\,year}$. The Auger group found the correlation of UHECR with nearby active extragalactic objects.

There are 318 AGN on the distance smaller than 75 Mpc.

$$j \approx 10^{39} \quad \text{UHECR in a year.}$$

2 UHECR from the AGN Centaurus A ($r \approx 11 \cdot 10^{6}$ l·y):

$$j \approx 3 \cdot 10^{37} \quad \text{UHECR in a year.}$$

If SHP $M = 10^{14}\,\mathrm{GeV}$ fall on the black hole $\Longrightarrow \Delta m \approx 10^{-9}\mathrm{g} \cdot j \approx 10^{28}\,\mathrm{g/y}$.

The capture cross-section of the non-relativistic particles by a Schwarzschild black hole is

$$\sigma_c = 4\pi \left(\frac{c}{v_\infty}\right)^2 r_g^2 \,. \tag{1}$$

For $\rho = 10^{-20}\,\mathrm{g/sm^3}$ and $M_{BH} = 10^8 M_S$

$$v_a = \frac{\Delta m}{\Delta t} = \sigma_c v_\infty \rho \approx 3 \cdot 10^{28} \quad \mathrm{g/year}$$

If one takes for the distribution density of dark matter the profiles

$$\rho(r) = \frac{\rho_0}{(r/r_0)^\beta (1 + r/r_0)^{3-\beta}} \tag{2}$$

($\beta = 1$ for Navarro-Frenk-White, $\beta = 1.5$ for Moore profiles),

$$v_a \sim 2 \cdot 10^{28} - 10^{30}\ \mathrm{g/year}.$$

One can also say that if one tries to go back from the observable current of UHECR to dark matter distribution that in case of superheavy dark matter one obtains the observable density of dark matter!

The Penrose process

R. Penrose, *Rivista Nuovo Cimento* **I**, Num. Spec., 252 (1969).

The Kerr metric

$$ds^2 = dt^2 - dr^2 - d\theta^2 + 2a\sin^2\theta\, dr\, d\varphi - \left(r^2 + a^2\right)\sin^2\theta\, d\varphi^2 - \frac{2mr}{\Sigma}\left(dr - a\sin^2\theta\, d\varphi + dt\right)^2, \quad (1)$$

where $m = GM, \quad a = J/M, \quad \Sigma = r^2 + a^2\cos^2\theta$

Stationary limit and the event horizon (ergosphere)

$$r = m + \sqrt{m^2 - a^2\cos^2\theta}\,, \qquad r_+ = m + \sqrt{m^2 - a^2} \quad (2)$$

The particle with momentum p_0^μ enters the ergosphere and there decays into a pair of particles with momenta p_1^μ and p_2^μ.

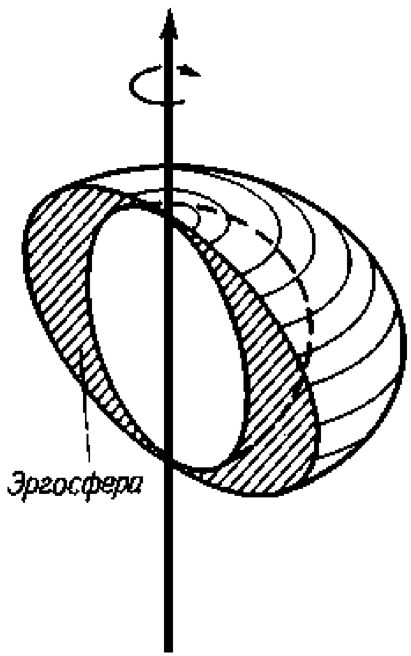
$$p_0^\mu = p_1^\mu + p_2^\mu \quad (3)$$

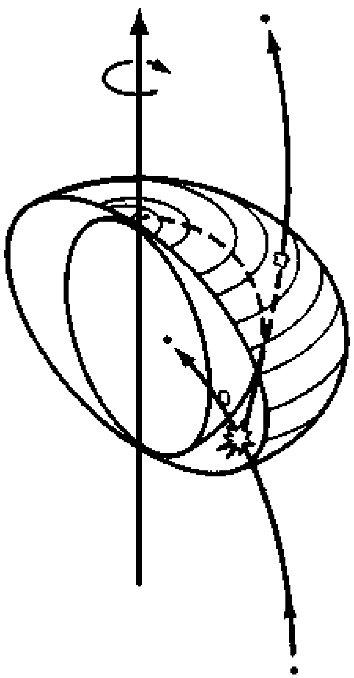
For a particle moving in a stationary spacetime with a Killing vector field ξ^μ, conserved quantity (energy ε) is

$$\varepsilon = p^\mu \xi_\mu \quad (4)$$

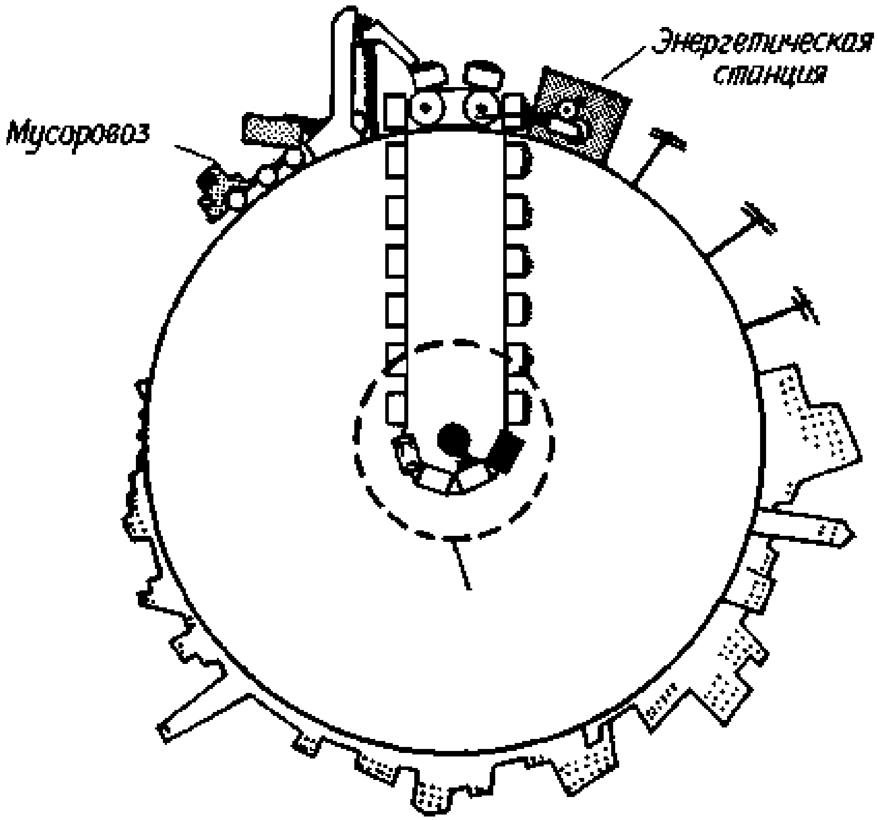
Some particles in the ergosphere may have $\varepsilon < 0$, then $\varepsilon_2 > \varepsilon_0$.

Ergosphere of a rotating black hole and Penrose process





Our hypothesis — *A. A. Grib, Yu. V. Pavlov,* Mod. Phys. Lett. **A 23** (2008), 1151; Gravit. & Cosmology, **15** (2009), 44 — **the decay of superheavy particles of a dark matter, which are stable in usual conditions, can occur due to Penrose process in ergosphere of a supermassive, quickly rotating black holes in active galactic nuclei.**



Restrictions on extraction of the energy from a rotating black hole **at Penrose process**.

From **Wald** inequality **for extraction of the energy at decay of a particle in ergosphere on two splinters it is necessary that speed of splinters was above half of light speed**

$$v > \frac{c}{2}$$

Figure. The city which is not polluting an environment. When the garbage from containers is thrown out from a conveyor tape in ergosphere, the tape of the conveyor gets acceleration. Attaching electrogenerator to the tape it is possible to use the energy taken from a black hole (see Misner, Torne, and Wheeler.)

Evaluation of the maximal value of ΔE in Penrose process

If E_u is the specific energy (energy/rest-mass) of the falling particle, ε, v are the specific energy and relative velocity of the fragment

$$\gamma \left(E_u - |v| \sqrt{E_u^2 - (1 - 2mr/(r^2 + a^2 \cos^2\theta))} \right) \leq \varepsilon, \tag{5}$$

where $\gamma = 1/\sqrt{1 - |v|^2}$ and $r_H < r < r_0$.

Let us consider the initial particle falling on the black hole to be non-relativistic on large distances from the black hole, i.e. $E \approx 1$. If the initial particle of mass M decays on two particles one of which is a light particle with mass μ, then $|v| \approx 1$ and $\gamma \approx M/2\mu$ can be taken. So one gets the limitation for the additional energy (mass) of the other fragment

$$\Delta E \leq \frac{M}{2} \left(\sqrt{\frac{2mr}{r^2 + a^2 \cos^2\theta}} - 1 \right). \tag{6}$$

Then

$$\Delta E \leq \frac{M}{2}\left[\left(1-\frac{1}{2}\left(1-\sqrt{1-\frac{a^2}{m^2}}\right)\right)^{-1/2}-1\right]. \tag{7}$$

The maximal value

$$\Delta E_M \approx M(\sqrt{2}-1)/2 \tag{8}$$

achieves for the black hole with the angular momentum close to the critical value $a = m$.

CPT is broken due to T breaking in vicinity of AGN.

$$X_L \to X_S + b\,, \qquad M_{X_S} > M_{X_L}\,, \qquad \varepsilon_b < 0\,. \tag{9}$$

X_S decays on quarks leading to the nonzero baryon charge as in the early Universe! It is the same process. In empty space and in static or slowly rotating black holes the process (9) is forbidden!

UHECR are protons. Photons due to collisions leading to particle – antiparticle pairs with $E > 10\,\text{TeV}$ are non-observed. However neutrino with superhigh energy can be observable.

Conclusions

1. Creation of superheavy particles by gravitation with their subsequent decay on light particles leads to the observable baryon charge of the Universe.

2. Visible matter could originate through decays of primordial superheavy particles so that some part of them survive and form modern dark matter. This can explain some coincidence of the amount of dark matter and visible one (23 % and 4 %).

3. Conservation of dark matter into visible one at AGN can lead to observable UHECR-s at the AUGER experiment.

4. UHECR neutrinos of very high energy close to GU scale can be observed from AGN and possibly from the interior of planets if some part of the interior heat of planets is due to interaction of visible and dark matter. This can be checked in the experiments by Ice Cube and other neutrino telescopes.