PROCEEDINGS OF SCIENCE

The highest energy cosmic rays from superheavy dark matter particles

Elena Arbuzova[a,b,*]

[a] *Department of Higher Mathematics, Dubna State University*
Universitetskay str. 19, Dubna, Russia

[b] *Physics Department, Novosibirsk State University,*
Pirogova str. 2, Novosibirsk, Russia

E-mail: arbuzova@uni-dubna.ru

It is commonly accepted that high energy cosmic rays up to 10^{19} eV can be produced in catastrophic astrophysical processes. However the source of a few observed events with higher energies remains mysterious. We propose that they may originate from decay or annihilation of ultra heavy particles of dark matter. Such particles naturally appear in some models of modified gravity related to Starobinsky inflation.

Frontier Research in Astrophysics – IV (FRAPWS2024)
9-14 September 2024
Mondello, Palermo, Italy

*Speaker

PoS(FRAPWS2024)026

1. Introduction

There is no single opinion on the origin of Ultra High Energy Cosmic Rays (UHECR). The traditional approach is that the high energy cosmic rays are created by astrophysical sources such as active galactic nuclei, Seyfert galaxies, or potentially hypernovae. For a recent review, see Ref. [1]. Other intriguing possibilities include cosmic ray emission from topological defects [2, 3], the decay of superheavy particles in supersymmetric theories influenced by instanton and wormhole effects [4–6], binary neutron star mergers, and similar phenomena.

There are two separate energy ranges for ultra high energy cosmic rays. Cosmic rays with energies $E \lesssim 10^{20}$ eV can potentially originate from stellar processes, where stellar material is accelerated during catastrophic events. These cosmic rays typically contain a significant fraction of nuclei. On the other hand, cosmic nuclei with energies $E \gtrsim 10^{20}$ eV are difficult to produce by stellar mechanisms. Such extremely energetic cosmic rays could, in principle, be generated through the decay of heavy particles.

Fig. 1 shows the UHECR spectrum, measured by the Pier Auger and Telescope Array observatories [7]. We are particularly interested in the very end of the spectrum, specifically the part corresponding to the highest energies, in the region of 10^{20} eV. It is clearly visible that there are several events with energies exceeding 10^{20} eV. Cosmic rays of such high energies are sometimes called as Extremely High Energy Cosmic Rays (EHECR). The origin of cosmic rays with such extremely high energies remains a mystery and the efforts of many scientists are focused on finding a solution to this problem.

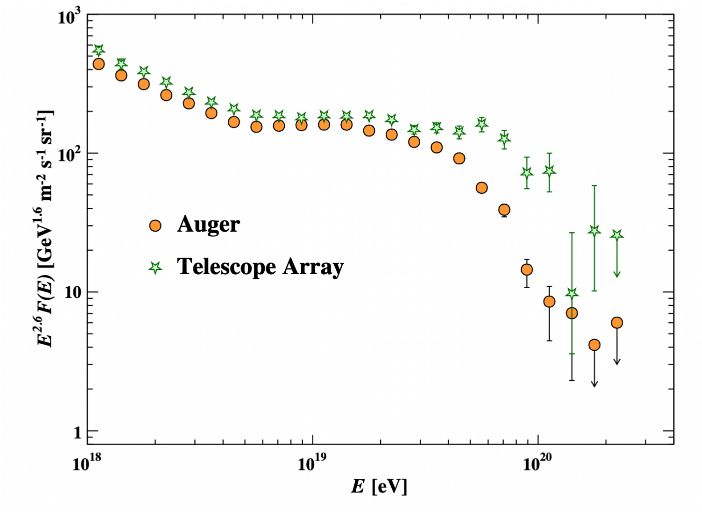

Figure 1: UHECR flux observations, from Fig. 30.10 of Ref. [7].

We suggest other possible sources of EHECR at energies $E \gtrsim 10^{20}$ eV: 1) the annihilation of superheavy Dark Matter (DM) particles created by the scalaron decay in R^2-modified gravity; 2) the decay of such superheavy particles via virtual black holes in multidimensional gravity.

We assume that superheavy dark matter particles are produced by the oscillating curvature scalar in the model of the Starobinsky inflation [8] with the action:

$$S(R^2) = -\frac{M_{Pl}^2}{16\pi} \int d^4x \sqrt{-g} \left[R - \frac{R^2}{6M_R^2} \right], \tag{1}$$

where $M_{Pl} = 1.22 \cdot 10^{19}$ GeV is the Planck mass[1]. The non-linear term in the action leads to the appearance of a new dynamical scalar degree of freedom, $R(t)$, known as *scalaron*. The parameter M_R represents the scalaron mass. As it is shown in Ref. [9], the temperature fluctuations of the cosmic microwave background radiation (CMBR) are expressed through the Planck and the scalaron masses in the following way:

$$\delta^2 \sim \left(\frac{M_R}{M_{Pl}} \right)^2, \tag{2}$$

where δ is the amplitude of the scalar fluctuations fixed by the observations. From this condition the scalaron mass is uniquelly determined to be $M_R \approx 3 \cdot 10^{13}$ GeV.

The calculations of the scalaron decay probabilities were performed in our paper [10], as well as in several others. In all these works, it was assumed that the masses of the decay products were much smaller than the scalaron mass, M_R. In our papers [11–13], the production of superheavy carriers of dark matter via scalaron decays into particles with masses up to $M \lesssim 10^{12}$ GeV was studied. In all cases the condition $(2M/M_R)^2 \ll 1$ was satified.

We now investigate an alternative source of high-energy cosmic rays, namely, the annihilation and decay of superheavy dark matter particles. We assume that these heavy dark matter particles are fermions directly produced by scalaron decays. Previous calculations of scalaron decay probabilities were performed in the limit of low masses for the decay products. For example, the width of scalaron decay into a fermion-antifermion pair was found to be:

$$\Gamma_{m_f} = \frac{m_f^2 M_R}{6M_{Pl}^2}, \tag{3}$$

where m_f is the fermion mass. For the decay width given by Eq. (3), the energy density of heavy fermions would be much larger than the averaged cosmological density of dark matter:

$$\rho_{DM} \approx 1 \text{ keV/cm}^3. \tag{4}$$

The probability of the decay would be strongly suppressed if the fermion mass M_f is extremely close to $M_R/2$:

$$\Gamma_f = \frac{M_f^2 M_R}{6M_{Pl}^2} \sqrt{1 - \frac{4M_f^2}{M_R^2}}, \quad M_f \sim \frac{M_R}{2}. \tag{5}$$

The phase space factor $(1 - 4M_f^2/M_R^2)^{1/2}$ allows for the energy density of the presumed dark matter particles f to be arranged such that it matches the observed dark matter density: $\rho_f \approx \rho_{DM}$.

The paper is organized as follows. In Sec. 2, we consider the flux of cosmic rays resulting from the annihilation of superheavy dark matter particles. Several regions of the universe where such annihilation could take place are studied. These include:

[1] Throughout the paper, we use the natural system of units, where the speed of light $c = 1$, the Boltzmann constant $k = 1$, and the reduced Planck constant $\hbar = 1$. The gravitational coupling constant is given by $G_N = 1/M_{Pl}^2$, where the Planck mass is $M_{Pl} = 1.22 \cdot 10^{19}$ GeV $= 2.17 \cdot 10^{-5}$ g. For reference, the following conversions apply: $1 \text{ GeV}^{-1} = 0.2 \cdot 10^{-13}$ cm, $1\text{sec} = 3 \cdot 10^{10}$ cm, and $1\text{yr} = 3.16 \cdot 10^7$ sec.

PoS(FRAPWS2024)026

- The entire universe under the assumption of homogeneous dark matter energy density.
- The high density dark matter clump in the Galactic Center.
- The cloud of dark matter in the Galaxy with realistic energy density distribution of dark matter.

In Sec. 3, we show that stable by assumption dark matter particles could decay via interactions with virtual black holes. In multidimensional gravity, where the scale of gravitational interaction is smaller, the decay of these ultra-massive particles can provide a noticeable contribution to the flux of UHECR. In the last section we conclude.

2. Annihilation of superheavy dark matter particles

Let us consider the flux of cosmic rays resulting from the annihilation of heavy dark matter particles, which were created during the scalaron decay process (for details, see Ref. [14]).

The flux of high energy particles is determined by the cross-section for the annihilation of heavy fermions:

$$\sigma_{ann} v \sim \alpha^2 \, g_* / M_f^2, \tag{6}$$

where v is the center-of-mass velocity, α is the coupling constant, $\alpha \sim 10^{-2}$, and g_* is the number of the open annihilation channels, $g_* \sim 100$. With fermion mass $M_f = 1.5 \cdot 10^{13}$ GeV we estimate $\sigma_{ann} v \sim 2 \cdot 10^{-56} \mathrm{cm}^2$. Below, following our work in Ref. [14], we propose a way to enhance the efficiency of the annihilation.

The rate of the decrease of the f-particle density per unit of time and volume is equal to:

$$\dot{n}_f = \sigma_{ann} v n_f^2 = \alpha^2 g_* n_f^2 / M_f^2, \tag{7}$$

We assume that the annihilation is sufficiently slow, such that the number density n_f significantly change over the age of the universe.

The annihilation of heavy f-particles results in a continuous contribution to the rate of cosmic ray production per unit time and unit volume, given by:

$$\dot{\rho}_f = 2 M_f \dot{n}_f . \tag{8}$$

The results in Eqs. (7) and (8) are valid for the total flux integrated over particle energy.

To compare our results with observational data, we need to determine the energy distribution of cosmic ray particles produced in the process of $f\bar{f}$ - annihilation. We postulate that the differential energy spectrum of the number density flux, $\dot{n}_{PP}(E)$, of the produced particles is stationary and adopts a form that we consider reasonable:

$$\frac{d\dot{n}_{PP}(E)}{dE} = \mu^3 \, \exp\left[-\frac{(E - 2M_f/\bar{n})^2}{\delta^2} \right] \theta(2M_f - E). \tag{9}$$

Here, μ is a normalisation factor, with dimension of mass (or equivalently inverse length), which will be determined later, and $\bar{n}$ is the average number of particles created in the process of $f\bar{f}$ - annihilation. This distribution ensures that the maximum energy of the annihilation products is

$E_{max} = 2M_f$ and the average energy per particle is approximately $\bar{E} \approx 2M_f/\bar{n}$, if the width of the distribution, δ, is sufficiently small.

The contribution from the annihilation of heavy particles to the cosmic ray flux is given by:

$$\frac{d\dot{\rho}_{PP}(E)}{dE} = E\,\frac{d\dot{n}_{PP}(E)}{dE}. \tag{10}$$

Correspondingly, the total energy density flux of the produced particles, with the number density spectrum given by Eq. (9), is:

$$\dot{\rho}_{PP} = \int_0^{2M_f} E\left(\frac{d\dot{n}_{PP}(E)}{dE}\right) dE \;\approx \sqrt{\pi}\,\mu^3\,\bar{M}\delta\,, \quad \bar{M} = 2M_f/\bar{n}. \tag{11}$$

We assume, that $\dot{\rho}_{PP} = const$, since the observed flux of the cosmic rays is stationary.

Taking $n_f = \rho_{DM}/2M_f$ and $M_f = 1.5 \cdot 10^{13}$ GeV we calculate the total energy rate of cosmic rays produced by $f\bar{f}$ -annihilation as follows:

$$\dot{\rho}_f^{(ann)} = 2M_f\dot{n}_f = 2\alpha^2 g_* n_f^2/M_f = 1.48 \cdot 10^{-54}\,\text{GeV}^{-1}\text{cm}^{-6}. \tag{12}$$

We determined the normalization factor μ^3 based on the condition of equality between $\dot{\rho}_{PP}$ from Eq. (11) and $\dot{\rho}_f^{(ann)}$ from Eq. (12):

$$\mu^3 = \frac{1.48 \cdot 10^{-54}\bar{n}}{2\sqrt{\pi}\text{GeV} \cdot \text{cm}^6 M_f\delta} = \frac{2.2 \cdot 10^{-109}\,\bar{n}}{\text{cm}^3}\left(\frac{\text{GeV}}{\delta}\right). \tag{13}$$

Let us estimate the energy flux of the products of the annihilation of dark matter particles "in the entire Universe" and reaching Earth's detectors, assuming that dark matter in the Universe is distributed uniformly and isotropically.

We calculate the flux of cosmic rays for the spherical volume of radius R assuming a homogeneous distribution of f-particles. We take $R_{max} \approx 10^{28}$cm, as beyond this distance the redshift cutoff becomes significant. Finally, we estimate the energy flux from the entire Universe, assuming (unrealistically) a homogeneous distribution of dark matter, as follows. The flux created by a source S from the spherical layer with radius R and thickness ΔR is given by:

$$\Delta L = \frac{S}{4\pi R^2} \times 4\pi R^2 \Delta R = S\Delta R. \tag{14}$$

Integrating over the homogeneity scale, we obtain the total flux:

$$L_{hom} = SR_{max}. \tag{15}$$

In the case under consideration, the source term, S_{hom}, is expressed as:

$$S_{hom} = \frac{d\dot{n}_{PP}}{dE}, \tag{16}$$

where $(d\dot{n}_{PP}/dE)$ is given by Eq. (9) with μ^3 determined by expression (13). Note that the dimension of S is $[eV^3]$ or $[cm^{-3}]$, and hence the dimension of L is $[cm^{-2}]$.

Now, we can calculate the contribution to the flux of high energy cosmic rays, arising from $f\bar{f}$ annihilation, as:

$$L_{hom} = \frac{2.23 \cdot 10^{-109} \cdot 10^{28}\, \bar{n}}{cm^2} \left(\frac{\text{GeV}}{\delta}\right) \exp\left[-\frac{(E - 2M_f/\bar{n})^2}{\delta^2}\right] \theta(2M_f - E). \tag{17}$$

A crude order-of-magnitude estimate of L from Eq. (17), assuming $\bar{n} = 10^3$ and $\delta \sim 1$ GeV, gives $L_{hom} \sim 10^{-78}\,\text{cm}^{-2}$. The observed flux, which can be extracted from Fig. 1 (for details, see Ref. [14]), is approximately a few times $10^{-55}\,\text{cm}^{-2}$. Thus, the observed flux exceeds the theoretical prediction by 23 orders of magnitude. The smallness of this result is explained by extremely week annihilation cross-section given in Eq. (6).

However, the annihilation can be significantly enhanced due to the resonance process of $f\bar{f}$-transition to the scalaron, as $2M_f$ is very close to M_R. Resonance effects in dark matter particle annihilation have been discussed in Refs. [15, 16]. Eq. (7) is valid for S-wave annihilation with an energy-independent cross-section. For an arbitrary dependence of the cross-section on the center-of-mass energy squared, $s = (p_f + p_{\bar{f}})^2$, the average value of $\sigma_{ann} v$ is calculated in Ref. [16]:

$$\langle \sigma_{ann} v \rangle = \frac{1}{8 M_f^4 T [K_2(M_f/T)]^2} \int_{4M_f^2}^{\infty} ds\, (s - 4M_f^2) \sigma_{ann}(s) \sqrt{s} K_1 \left(\frac{\sqrt{s}}{T}\right), \tag{18}$$

where T is the cosmic plasma temperature, and $K_{(1,2)}$ are the modified Bessel functions. Since $x = M_f/T \gg 1$ we can use the asymptotical limit of $K_n(x) \approx \sqrt{\pi/(2x)}\, e^{-x}$. Substituting this approximation, we obtain:

$$\langle \sigma_{ann} v \rangle = \frac{4}{\sqrt{\pi}} \sqrt{\frac{T}{M_f}} \int_0^{\infty} dz z e^{-z} \sigma_{ann}(z), \tag{19}$$

where the dimensionless variable z is defined as $s = 4M_f^2(1 + Tz/M_f)$.

In our case, the cross-section exhibits a resonance due to the intermediate scalaron state in f anti-f - annihilation, as the scalaron mass is very close to the sum of the masses of f and $\bar{f}$. According to Ref. [15], the resonance cross-section is given by:

$$\sigma_{ann}^{(res)} v = \frac{\alpha^2 s}{(M_R^2 - s)^2 + M_R^2 \Gamma_R^2}, \tag{20}$$

where $M_R = 3 \cdot 10^{13}$ GeV is the scalaron mass, and Γ_R is its decay width, equal to (see Eq. (3)) $\Gamma_R = M_f^2 M_R/(6 M_{Pl}^2)$ [10, 11].

Now, for the thermally averaged resonance cross-section derived from Eqs. (19) and (20), we obtain:

$$\langle \sigma_{res} v \rangle = \int_0^{\infty} dz z e^{-z} \frac{\alpha^2 s}{(M_R^2 - s)^2 + M_R^2 \Gamma_R^2} = \frac{\alpha^2}{M_R^2} \int_0^{\infty} \frac{dz z e^{-z}}{\gamma^2 + \eta^2 z^2}, \tag{21}$$

where $\gamma^2 = \Gamma_R^2/M_R^2 = 1/36\,(M_f/M_{Pl})^4 \approx 6.7 \cdot 10^{-26}$, and $\eta^2 = (T/M_f)^2 \approx 2.45 \cdot 10^{-52}$. Here, we used $T = T_{CMB} = 2.7K = 2.35 \cdot 10^{-4}$ eV and $M_f = 1.5 \cdot 10^{13}$ GeV.

Thus, the term $\eta^2 z^2$ can be neglected, leading to the conclusion that the resonance cross-section is 26 orders of magnitude higher than the previous estimate. Consequently, the contribution to the flux of cosmic rays may reach a sufficient level to explain the origin of ultra high energy cosmic rays with $E \gtrsim 10^{20}$ eV.

The effect is even stronger in the case of $f\bar{f}$-annihilation in denser regions of the Galaxy with the realistic distribution of dark matter.

Let us estimate the flux of cosmic rays originating from dark matter annihilation in the Galactic Center, where the local DM density is significantly higher than the average cosmological density [17]:

$$\rho_{GC} = 840 \text{ GeV/cm}^3. \tag{22}$$

This value exceeds the average DM density by 9 orders of magnitude. Such a strong magnification is related to the known fact that dark matter forms almost singular spikes in the galactic center that lead to multifold increase of dark matter density. Since the flux of cosmic rays from DM annihilation is proportional to the square of the DM particle density, smaller regions with higher local DM density can produce a significantly larger flux of cosmic rays compared to the average density regions.

In Eq. (15), the flux of cosmic rays L from DM annihilation in the entire galaxy is presented under the (unrealistic) assumption of a homogeneous distribution of dark matter. The obtained result should be rescaled as follows.

1. Multiply by the square of the ratio of the DM density in the Galactic Center to the average cosmological DM density since the annihilation rate is proportional to n_f^2, see Eq. (7).
2. Multiply by the volume of the high-density clump in the Galactic Center, $4\pi r_{cl}^3/3$, where r_{cl} is the radius of the clump.
3. Divide by the area of a sphere at the distance d_{gal} from the Galactic Center, $4\pi d_{gal}^2$.

Thus the following rescaling is to be done:

$$L_{GC} = L_{hom} \times \left(\frac{n_{GC}}{\bar{n}_{DM}}\right)^2 \frac{r_{cl}^3/(3\, d_{gal}^2)}{R_{max}} \approx 10^3\, L_{hom}, \tag{23}$$

where L_{hom} is determined by Eqs. (15), (16), (17). The factor $d\dot{n}_{pp}/dE$, entering these expressions, is given by Eq. (9) and $R_{max} = 10^{28}$ cm.

We assume that the size of this high density clump in the Galactic Center is approximately $r_{cl} = 10\text{pc} \approx 3 \cdot 10^{19}$ cm and its distance to Earth is $d_{gal} = 8$ kpc $= 2.4 \cdot 10^{22}$ cm. Thus, the flux could be increased by the factor 1.1×10^3.

To conclude this section, let us consider the flux of cosmic rays resulting from the annihilation of dark matter with a realistic distribution in the Galaxy.

We adopt the commonly accepted shape of the dark matter distribution [18]:

$$\rho(r) = \rho_0 \left[1 + \left(\frac{r}{r_c}\right)^2\right]^{-1} \equiv \rho_0 q(r), \tag{24}$$

where ρ_0 denotes the finite central density and r_c is the core radius. For the sake of estimation, we assume $r_c = 1$ kpc and calculate ρ_0 under the condition that at the position of the Earth at $r = l_\oplus = 8$ kpc the density of dark matter is approximately $\rho(l_\oplus) \approx 0.4\,\text{GeV/cm}^3$ [19]. Hence, we find:

$$\rho_0 = 65\rho(l_\oplus) = 26\,\text{GeV/cm}^3. \tag{25}$$

This value exceeds the average cosmological dark matter density, $\rho_{DM} = 1$ keV/cm^3 by a factor of 2.6×10^7.

Let us consider the annihilation of DM particles at a point specified by the radius vector $\vec{r}$, expressed in spherical coordinates (r, θ, ϕ), directed from the Galactic Center. The distance of this point to Earth is given by:

$$d_\oplus = \sqrt{(\vec{l_\oplus} + \vec{r})^2} = \sqrt{r^2 + l_\oplus^2 - 2r\, l_\oplus \cos\theta}. \tag{26}$$

As done above, we recalculate the flux of cosmic rays by rescaling Eq. (23) using the ratio of the dark matter density, given by (24) and (25), to the DM density in the Galactic Center. Additionally, we include the integral over the DM distribution up to R_{max}. Thus, for a realistic DM distribution in the Galaxy, we obtain:

$$L_{real} = L_{GC} \left(\frac{26\text{GeV}}{840\text{GeV}} \right)^2 \frac{3d_{gal}^2}{r_{cl}^3} J, \tag{27}$$

where J is the integral over DM distribution:

$$J = \int \frac{d^3 r q(r)}{d_\oplus^2} = 2\pi \int \frac{dr r^2 q(r) d\cos\theta}{r^2 + l_\oplus^2 - 2r l_\oplus \cos\theta} = 2\pi \int \frac{dr r q(r)}{l_\oplus} \ln \frac{l_\oplus + r}{l_\oplus - r}. \tag{28}$$

After a change of variables, $r = x l_\oplus$, the integral is reduced to the following expression and is evaluated numerically:

$$J = 2\pi\, l_\oplus \int_0^1 dx x \left(1 + 64x^2\right)^{-1} \ln \frac{1+x}{1-x} = 0.2\, l_\oplus. \tag{29}$$

Thus, we obtain $L_{real} = 3 \cdot 10^5 L_{GC}$. This value is significantly larger than the flux originating from the dense Galactic Center and requires much weaker amplification through resonance annihilation (Eq. (20)).

3. Decay of superheavy dark matter particles through virtual black hole in multidemensional gravity

In this section we consider another possibility for creation of ultra high energy cosmic rays: through the decays of superheavy dark matter particles produced by oscillating curvature. This problem is discussed in detail in the works [20, 21], here we briefly focus on main points.

Dark matter particles are usually assumed to be absolutely stable. However, in 1976, Ya. B. Zeldovich proposed a mechanism whereby the decay of any presumably stable particles could occur through the creation of virtual black holes [22, 23]. This effect, in particular, leads to non-conservation of the baryonic number and to the proton decay. The rate of proton decay, as calculated in the framework of canonical gravity with an energy scale equal to M_{Pl}, is extremely small. The corresponding lifetime of the proton far exceeds the age of the universe ($t_U \approx 1.5 \cdot 10^{10}$ years). However, the smaller scale of gravity and the huge mass of dark matter particles can both lead to a strong amplification of the Zeldovich effect.

Analogous effect of symmetry breaking due to impact of virtual black holes was studied later in Ref. [24].

In the presented work we particularly interested in superheavy dark matter particles with masses around $M_X \sim 10^{12}$ GeV. These particles may decay through the formation of virtual black holes with lifetimes several orders of magnitude longer than the universe age. The decay of such particles could make a significant contribution to the generation of ultra high energy cosmic rays.

We consider the model proposed in Refs. [25, 26], where the observable universe, containing the Standard Model particles, is confined to a 4-dimensional brane embedded in (4+d)-dimensional bulk. In this framework, gravity propagates throughout the bulk, while all other interactions remain restricted to the brane. In such scenarios, the Planck mass, M_{Pl}, becomes an effective long-distance 4-dimensional parameter, and its relationship with the fundamental gravity scale, M_*, is given by:

$$M_{Pl}^2 \sim M_*^{2+d} R_*^d, \tag{30}$$

where R_* is the size of the extra dimensions. The size R_* can be expressed as:

$$R_* \sim \frac{1}{M_*} \left(\frac{M_{Pl}}{M_*} \right)^{2/d}. \tag{31}$$

For the purposes of our application we choose $M_* \approx 3 \cdot 10^{17}$ GeV, leading to $R_* \sim 10^{(4/d)}/M_* > 1/M_*$.

The width of proton decay via a virtual black hole into a positively charged lepton and a quark-antiquark pair, in the framework of the multidimensional gravity model, was calculated in Ref. [27] and is given by the following expression:

$$\Gamma(p \to l^+ \bar{q} q) = \frac{m_p \, \alpha^2}{2^{12} \, \pi^{13}} \left(\ln \frac{M_{Pl}^2}{m_q^2} \right)^2 \left(\frac{\Lambda}{M_{Pl}} \right)^6 \left(\frac{m_p}{M_{Pl}} \right)^{4+\frac{10}{d+1}} \int_0^{1/2} dx x^2 (1-2x)^{1+\frac{5}{d+1}}. \tag{32}$$

Here, $m_p \approx 1$ GeV is the proton mass, $m_q \sim 300$ MeV is the constituent quark mass, $\Lambda \sim 300$ MeV is the QCD scale parameter, $\alpha = 1/137$ is the fine structure constant, and d denotes the number of "small' extra dimensions. The QCD coupling constant α_s is assumed to be equal to unity.

We applied the above result to the process $X \to L^+ \bar{q}_* q_*$, assuming that the heavy dark matter X-particle, with mass $M_X \sim 10^{12}$ GeV, consists of three heavy quarks, q_*, with comparable masses. The parameter Λ_* is left as a free variable. Substituting M_* in place of M_{Pl}, the life-time of X-particles can be evaluated using Eq. (32). In this evaluation, we make the following substitutions:

- $\alpha_* = 1/50$ instead of $\alpha = 1/137$,
- $M_X = 10^{12}$ GeV instead of m_p,
- the mass of the constituent quark $m_{q_*} = 10^{12}$ GeV,
- $d = 7$ for the number of extra dimensions.

Thus, the life-time of the X-particle can be expressed as:

$$\tau_X = \frac{1}{\Gamma_X} \approx 6.6 \times 10^{-25} \text{s} \cdot \frac{2^{10} \pi^{13}}{\alpha_*^2} \left(\frac{\text{GeV}}{M_X} \right) \left(\frac{M_*}{\Lambda_*} \right)^6 \left(\frac{M_*}{M_X} \right)^{4+\frac{10}{d+1}} \left(\ln \frac{M_*}{m_{q_*}} \right)^{-2} I(d)^{-1}, \tag{33}$$

where we took $1/\text{GeV} = 6.6 \times 10^{-25}$s and

$$I(d) = \int_0^{1/2} dx x^2 (1-2x)^{1+\frac{5}{d+1}}, \quad I(7) \approx 0.0057. \tag{34}$$

Now, all parameters, except for Λ_*, are fixed: $M_* = 3 \times 10^{17}$ GeV, $M_X = 10^{12}$ GeV, $m_{q_*} \sim M_X$. The life-time of X-particles can be estimated as:

$$\tau_X \approx 7 \times 10^{12} \text{ years} \left(10^{15}\, \text{GeV}/\Lambda_*\right)^6 \quad vs \quad t_U \approx 1.5 \times 10^{10} \text{ years}. \tag{35}$$

A slight variation of Λ_* near 10^{15} GeV allows to fix the life-time of the dark matter X-particles in the interesting range. These particles would be stable enough to behave as cosmological dark matter, while their decay could contribute significantly to the production of cosmic rays at ultra high energies.

4. Conclusions

- In R^2-modified gravity the viable canditates for dark matter particles could be very heavy, up to $M \sim 10^{13}$ GeV.
- The annihilation and decay of such superheavy particles are promising sources of extremely high energy cosmic rays, which are difficult to explain using canonical astrophysical mechanisms.
- The contribution to the flux of cosmic rays originated from different cosmological environment (e.g. DM clumps in the Galactic Center) might be sufficient to explain the origin of UHECR with $E \gtrsim 10^{20}$ eV.
- The flux of UHECR could be significantly enhanced in the case of resonance annihilation of superheavy DM particles with masses close to a half of the scalaron mass.
- DM particles are assumed to be stable with respect to conventional particle interactions. However, they could decay through the formation of virtual black holes. In the framework of high-dimensional gravity, the lifetime of such quasi-stable particles may exceed the age of the universe by several orders of magnitude.
- The mechanisms discussed may provide an explanation for the origin of UHECR observed by the Pierre Auger Observatory and the Telescope Array detectors.

Acknowledgement

This work was supported by the RSF Grant 22-12-00103.

References

[1] M. Kachelriess, "Extragalactic cosmic rays," PoS **ICRC2021** (2022), 018 [arXiv:2201.04535 [astro-ph.HE]].

[2] G. Sigl, "Topological defect models of ultrahigh-energy cosmic rays," Contribution to: International School of Cosmic Ray Astrophysics: 10th Course: Toward the Millennium in Astrophysics: Problems and Prospects, 31-38 [arXiv:astro-ph/9611190 [astro-ph]].

[3] D. V. Semikoz [Pierre Auger], "Constraints on top-down models for the origin of UHECRs from the Pierre Auger Observatory data," Contribution to: ICRC 2007, 433-436 [arXiv:0706.2960 [astro-ph]].

[4] V. Berezinsky, M. Kachelriess and A. Vilenkin, "Ultrahigh-energy cosmic rays without GZK cutoff," Phys. Rev. Lett. **79** (1997), 4302-4305 doi:10.1103/PhysRevLett.79.4302 [arXiv:astro-ph/9708217 [astro-ph]].

[5] V. A. Kuzmin and V. A. Rubakov, "Ultrahigh-energy cosmic rays: A Window to postinflationary reheating epoch of the universe?," Phys. Atom. Nucl. **61** (1998), 1028 [arXiv:astro-ph/9709187 [astro-ph]].

[6] M. Birkel and S. Sarkar, "Extremely high-energy cosmic rays from relic particle decays," Astropart. Phys. **9** (1998), 297-309 [arXiv:hep-ph/9804285 [hep-ph]].

[7] P. A. Zyla *et al.* [Particle Data Group], "Review of Particle Physics," PTEP **2020** (2020) no.8, 083C01.

[8] A. A. Starobinsky, "A New Type of Isotropic Cosmological Models Without Singularity," Phys. Lett. B **91** (1980), 99-102.

[9] T. Faulkner, M. Tegmark, E. F. Bunn and Y. Mao, "Constraining f(R) Gravity as a Scalar Tensor Theory," Phys. Rev. D **76** (2007), 063505 [arXiv:astro-ph/0612569 [astro-ph]].

[10] E. V. Arbuzova, A. D. Dolgov and A. S. Rudenko, "Calculations of Scalaron Decay Probabilities," Phys. Atom. Nucl. **86** (2023) no.3, 266-276 [arXiv:2112.11288 [hep-ph]].

[11] E. V. Arbuzova, A. D. Dolgov and R. S. Singh, "Dark matter in $R + R^2$ cosmology," JCAP **04** (2019), 014 [arXiv:1811.05399 [astro-ph.CO]].

[12] E. V. Arbuzova, A. D. Dolgov and R. S. Singh, "Superheavy dark matter in $R + R^2$ cosmology with conformal anomaly," Eur. Phys. J. C **80** (2020) no.11, 1047 [arXiv:2002.01931 [hep-ph]].

[13] E. Arbuzova, A. Dolgov and R. Singh, "R^2-Cosmology and New Windows for Superheavy Dark Matter," Symmetry **13** (2021) no.5, 877.

[14] E. V. Arbuzova, A. D. Dolgov and A. A. Nikitenko, "Cosmic rays from annihilation of heavy dark matter particles," Nucl. Phys. B **1010** (2025), 116754 [arXiv:2405.12560 [hep-ph]].

[15] K. Griest and D. Seckel, "Three exceptions in the calculation of relic abundances," Phys. Rev. D **43** (1991), 3191-3203.

[16] P. Gondolo and G. Gelmini, "Cosmic abundances of stable particles: Improved analysis," Nucl. Phys. B **360** (1991), 145-179.

[17] Y. Sofue, "Rotation Curve of the Milky Way and the Dark Matter Density," Galaxies **8** (2020) no.2, 37 [arXiv:2004.11688 [astro-ph.GA]].

[18] J. E. Gunn and J. R. Gott, III, "On the Infall of Matter into Clusters of Galaxies and Some Effects on Their Evolution," Astrophys. J. **176** (1972), 1-19.

[19] P. Salucci, F. Nesti, G. Gentile and C. F. Martins, "The dark matter density at the Sun's location," Astron. Astrophys. **523** (2010), A83 [arXiv:1003.3101 [astro-ph.GA]].

[20] E. V. Arbuzova, A. D. Dolgov and A. A. Nikitenko, "Cosmic Rays from Heavy Particle Decays," Phys. Atom. Nucl. **87** (2024) no.1, 49-55 [arXiv:2305.03313 [hep-ph]].

[21] E. Arbuzova, "Superheavy SUSY-kind dark matter and high energy cosmic rays," PoS **MULTIF2023** (2024), 014 [arXiv:2401.13717 [hep-ph]].

[22] Y. B. Zeldovich, "A New Type of Radioactive Decay: Gravitational Annihilation of Baryons," Phys. Lett. A **59** (1976), 254.

[23] Y. B. Zeldovich, "A Novel Type of Radioactive Decay: Gravitational Baryon Annihilation," Zh. Eksp. Teor. Fiz. **72** (1977), 18-21.

[24] G. S. Bisnovatyi-Kogan, "T symmetry violation as a result of virtual gravitational interaction," Nuovo Cim. B **107** (1992), 357-359

[25] N. Arkani-Hamed, S. Dimopoulos and G. R. Dvali, "The Hierarchy problem and new dimensions at a millimeter," Phys. Lett. B **429** (1998), 263-272 [arXiv:hep-ph/9803315 [hep-ph]].

[26] I. Antoniadis, N. Arkani-Hamed, S. Dimopoulos and G. R. Dvali, "New dimensions at a millimeter to a Fermi and superstrings at a TeV," Phys. Lett. B **436** (1998), 257-263 [arXiv:hep-ph/9804398 [hep-ph]].

[27] C. Bambi, A. D. Dolgov and K. Freese, "A Black Hole Conjecture and Rare Decays in Theories with Low Scale Gravity," Nucl. Phys. B **763** (2007), 91-114 [arXiv:hep-ph/0606321 [hep-ph]].

DISCUSSION

INGYIN ZAW: Do these models reproduce the sky distribution of UHECR's at $E > 10^{20}$ eV? If they come from the Galactic Center, they should point back to it, even if they are only a few.

ELENA ARBUZOVA: Indeed, the arrival direction of the ultrahigh energy cosmic rays, if they originate from the Galactic Center, should indicate to the source. There are only one or maybe two events of such extremely high energy. One event may happen, even if its probability is negligible.

PoS(FRAPWS2024)026

According to the data the most energetic particle originated from the empty space in the sky without any visible source. This fact is in favour of our model of UHECR creation by heavy dark matter particle decays. On the other hand it may also come from ultra heavy particle annihilation in the Galaxy or from galactic dark matter halo.