Superheavy dark matter particles and ultra high energy cosmic rays

Elena Arbuzova

Dubna State University & Novosibirsk State University

based on joint works with A.D. Dolgov, A.A. Nikitenko

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Measurements of CR by Pier Auger Observatory and Telescope Array

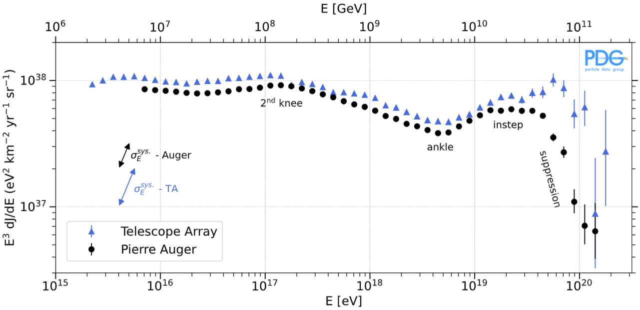

Figure 30.7: Measurements of the all-particle CR flux from Telescope Array (TA) [138] (blue triangles) and the Pierre Auger Observatory [139] (black circles). The direction and magnitude of the systematic uncertainty on the flux due to the energy scale (σ_E^{sys}) for TA and Auger is indicated by the corresponding arrows. For a comprehensive compilation of measurements see [140].

R. L. Workman *et al.* [Particle Data Group], "Review of Particle Physics," PTEP **2022** (2022), 083C01.

The problem of the origin of the ultra high energy cosmic rays (UHECR)

Registered events with enegies $\gtrsim 10^{20}$ eV: Extremely High Energy Cosmic Rays (EHECR).

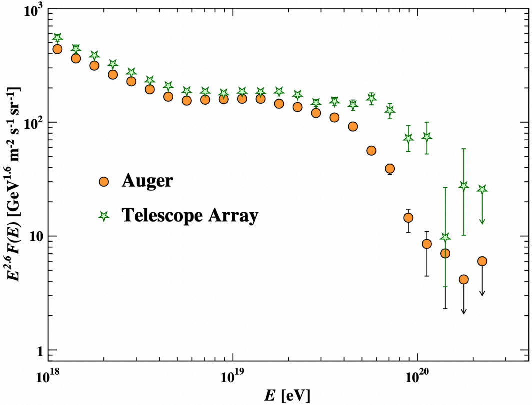

Figure: UHECR fluxes measured by Pier Auger Observatory and Telescope Array (Fig. 30.10, PDG, 2020)

Origin of UHECR – ???

No single opinion on the origin of UHECR

- Traditional approach: astrophysical sources such as active galactic nuclei, Seyfert galaxies, or possibly hypernovae.
- Alternative approaches: cosmic ray emission by topological defects, superheavy particle decays in SUSY due to instanton and wormholes effects, Binary Neutron Star Mergers

Two distinct ranges in energy of UHECR:

- Cosmic rays with $E \lesssim 10^{20}$ eV may be created by stellar processes by acceleration of stellar material in catastrophic processes.
- Cosmic rays with higher energies, $E \gtrsim 10^{20}$ eV, called EHECR, cannot be explained by stellar processes.

We suggest new possible sources of EHECR at energies $E \gtrsim 10^{20}$eV:

- Annihilation of superheavy dark matter particles.
- Decays of superheavy dark matter particles via virtual black hole.

Heavy DM particles are created in the model of the Starobinsky inflation:

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

R^2-term:

- leads to excitation of the scalar degree of freedom: scalaron with mass M_R.
- Amplitude of the observed density perturbations demands: $M_R = 3 \cdot 10^{13}$GeV.

The width of the scalaron decay into a pair of fermions with mass m_f:

(EA, A.D. Dolgov, A.S. Rudenko, 2112.11288 [hep-ph])

$$\Gamma_{m_f} = \frac{m_f^2 M_R}{6M_{Pl}^2}, \quad m_f \ll M_R$$

Scalaron decay into extremely heavy DM

We are interested in the case when the scalaron decays create particles with mass about 10^{20} eV, that is the energy of UHECR.

The width of the scalaron decay into superheavy fermions with mass $M_F \sim M_R/2$:

$$\Gamma_f = \frac{M_f^2 M_R}{6M_{Pl}^2}\sqrt{1 - \frac{4M_f^2}{M_R^2}}$$

- The phase space factor $(1 - 4M_F^2/M_R^2)^{1/2}$ makes it possible to arrange the density of presumably DM particles F to be equal to the observed density of DM: $\varrho_{DM} \approx 1$ keV/cm^3.

Part I. Annihilation of superheavy DM particles

- EA, A.D. Dolgov, A.A. Nikitenko, *"Cosmic rays from annihilation of heavy dark matter particles"*, e-Print: 2405.12560 [hep-ph]

Annihilation of superheavy dark matter particles

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

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

- v is the centre-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 $M_f = 1.5 \cdot 10^{13}$ GeV we estimate $\sigma_{ann} v \sim 2 \cdot 10^{-56} \text{cm}^2$.

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

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

The annihilation of heavy f-particles leads to a continuous contribution to the rate of cosmic ray production per unit time and unit volume equal to:

$$\dot{\varrho}_f = 2 M_f \dot{n}_f.$$

Energy distribution of the CR particles produced by $f\bar{f}$-ann

We postulate the differential energy spectrum of the number density flux:

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

- μ is a normalisation factor with dimension of mass, δ is the width of distr.
- $\bar{n}$ is the average number of particles created by $f\bar{f}$ - annihilation, $\bar{n} \sim 10^3$

The contribution from the heavy particle annihilation into cosmic ray flux:

$$\frac{d\dot{\varrho}_{PP}(E)}{dE} = E\,\frac{d\dot{n}_{PP}(E)}{dE}$$

The total flux of the energy density of the produced particles:

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

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

Total energy rate of CR created by $f\bar{f}$ -annihilation

Taking $n_f = \varrho_{DM}/2M_f$ and $M_f = 1.5 \cdot 10^{13}$ GeV we find for the total energy rate of cosmic rays created by $f\bar{f}$ -annihilation:

$$\dot{\varrho}_f^{(ann)} = 1.48 \cdot 10^{-54}\,\text{GeV}^{-1}\text{cm}^{-6}$$

The normalisation factor μ^3 can be calculated from the condition of equality of $\dot{\varrho}_f^{(ann)}$ and $\dot{\varrho}_{PP}$:

$$\dot{\varrho}_f^{(ann)} = \dot{\varrho}_{PP} \implies \mu^3 = \frac{1.48 \cdot 10^{-54}\,\bar{n}}{2\sqrt{\pi}\,\mathrm{GeV\,cm}^6 M_f \delta} = \frac{2.2 \cdot 10^{-109}\,\bar{n}}{\mathrm{cm}^3}\left(\frac{\mathrm{GeV}}{\delta}\right)$$

NB. We assume, that all dark matter consists of f-fermions.

Flux of cosmic rays from homogeneous dark matter

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

Flux created by source S from the spherical layer with radius R and width ΔR:

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

Integrating over the homogeneity scale we find the total flux:

$$L_{hom} = S_{hom} R_{max}, \quad S_{hom} = \frac{d\dot{n}_{PP}}{dE}, \quad R_{max} \approx 10^{28} cm$$

The contribution to the flux of high energy CR, emerging from the $f\bar{f}$ ann.:

$$L_{hom} = \frac{2.23 \cdot 10^{-81} \bar{n}}{cm^2} \left(\frac{\mathrm{GeV}}{\delta}\right) \exp\left[-\frac{(E - 2M_f/\bar{n})^2}{\delta^2}\right] \theta(2M_f - E)$$

A crude order of magnitude estimate assuming $\bar{n} = 10^3$ and $\delta \sim 1$ GeV would be:

$$L_{hom} \sim 10^{-78}\, cm^{-2} \quad vs \quad L_{obs} \sim 10^{-55}\, cm^{-2} (PDG)$$

The resononance effect in DM particle annihilation

The annihilation can be strongly enhanced due to resonance process of $f\bar{f}$-transition to scalaron, since the $2M_f$ is very close to M_R.

- 1. P. Gondolo, G. Gelmini, Nucl. Phys.B 360 (1991) 145
- 2. K. Griest, D. Seckel, Phys. Rev. D 43 (1991) 3191

The thermally averaged cross-section [1]:

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

- T is the cosmic plasma temperature, $s = (p_f + p_{\bar{f}})^2$ is the center of mass energy squared, and $K_{(1,2)}$ are the modified Bessel functions.

The resonance cross-section has the form [2]:

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

- $M_R = 3 \cdot 10^{13}$ GeV is the scalaron mass and $\Gamma_R = \frac{M_f^2 M_R}{6 M_{Pl}^2}$ is its decay width.

Thermally averaged resonance cross-section:

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

- dimensionless variable z is defined according to $s = 4M_f^2(1 + Tz/M_f)$.

For $M_f = 1.5 \cdot 10^{13}$ GeV and $T = T_{CMB} = 2.7K = 2.35 \cdot 10^{-4}$ eV:

$$\gamma^2 = \frac{\Gamma_R^2}{M_R^2} = \frac{1}{36} \left(\frac{M_f}{M_{Pl}} \right)^4 \approx 6.7 \cdot 10^{-26} \quad \text{vs} \quad \eta^2 = \left(\frac{T}{M_f} \right)^2 \approx 2.45 \cdot 10^{-52}$$

- We can neglect the term $\eta^2 z^2$ and conclude that the annihilation cross-section is 26 orders of magnitude higher than the estimate made above.
- The contribution to the flux of the cosmic rays might be at the sufficient level to explain the origin of UHECR with $E \gtrsim 10^{20}$ eV.

The effect is even stronger in the case of annihilation of $f\bar{f}$ in denser regions of the Galaxy (galactic center) with realistic distribution of DM.

Flux of UHECR from DM annihilation in the galactic center (GC)

Local density of DM in GC is much larger than the average cosmological density:

- Y. Sofue, arXiv:2004.11688 [astro-ph.GA]

$$\varrho_{GC} = 840\ \text{GeV/cm}^3 \gg \varrho_{obs} = 1\text{keV/cm}^3$$

Since the flux of the cosmic rays from DM annihilation is proportional to the square of the DM particle density, smaller objects with the number density larger than the average one can create a larger flux of the cosmic rays.

The result for L_{hom} should be rescaled as follows:

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

- $r_{cl} = 10$ pc $\approx 3 \cdot 10^{19}$ cm and $4\pi r_{cl}^3/3$ is volume of high density cluster in GC
- $4\pi d_{gal}^2$ is the area of the sphere at the distance d_{gal} from GC, $d_{gal} = 8$ kpc $= 2.4 \cdot 10^{22}$ cm, $R_{max} = 10^{28}$ cm.

Realistic Dark Matter distribution in the Galaxy

The commonly accepted shape of dark matter distribution (Gunn, 1972):

$$\varrho(r) = \varrho_0 \left[1 + \left(\frac{r}{r_c}\right)^2\right]^{-1} \equiv \varrho_0 q(r),$$

- ϱ_0 denotes the finite central density and r_c the core radius.

We assume that $r_c = 1$ kpc and calculate ϱ_0 from the condition that at the position of the Earth at $r = l_\oplus = 8$ kpc the density of DM is:

- P. Salucci et al., arXiv:1003.3101 [astro-ph.GA]

$$\varrho(l_\oplus = 8\,\text{kpc}) \approx 0.4\,\mathrm{GeV/cm^3} \implies \varrho_0 = 65\varrho(l_\oplus) = 26\,\mathrm{GeV/cm^3}$$

We consider the annihilation of DM particles at the point determined by the radius-vector $\vec{r}$ with the spherical coordinates r, θ, ϕ directed from GC.

The distance of this point to the Earth is:

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

CR flux from annihilation of DM with realistic distribution in Galaxy

We recalculate the flux of cosmic rays rescaling L_{GC} and obtain:

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

where J is the integral over DM distribution:

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

After change of variables, $r = x l_\oplus$, the integral is reduced to the expression below and is taken numericallly:

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

Thus we obtain $L_{real} = 3 \cdot 10^5 L_{GC}$. This is noticeably larger than the flux from the dense GC and allows for much weaker amplification by the resonance annihilation.

Part II. Decays of superheavy DM particles through virtual BH in multidemensional gravity

- EA, A.D. Dolgov, A.A. Nikitenko, "*Cosmic rays from heavy particle decays*", e-Print: 2305.03313 [hep-ph], Phys.Atom.Nucl. 87 (2024) 1, 49-55.

Decays through virtual Black Holes

- Usually dark matter particles are supposed to be absolutely stable.
- Zeldovich mechanism (1976): decay of any presumably stable particles is possible through creation of virtual black holes.
- The rate of the proton decay calculated in the canonical gravity, with the energy scale equal to M_{Pl}, is extremely tiny and the corresponding life-time is by far longer than the universe age.

However, the smaller scale of gravity and huge mass of DM particles both lead to a strong amplification of the Zeldovich effect.

Superheavy DM particles with $M_X \sim 10^{12}$ GeV may decay through the virtual BH with life-time several orders of magnitude longer than the universe age.

Decays of such particles could make essential contribution to the UHECR.

Multidimensional Modification of Gravity

Model: the observable universe with the SM particles is confined to a 4-dim brane embedded in a $(4+d)$-dim bulk, while gravity propagates throughout the bulk.

- N. Arkani-Hamed, S. Dimopoulos, G. Dvali, Phys. Lett. B **429**, 263 (1998); I.Antoniadis, N.Arkani-Hamed, S.Dimopoulos, G.Dvali, Phys.Lett.B**436**,257(1998).

The Planck mass M_{Pl} becomes a long-distance 4-dimensional parameter and the relation with the effective gravity scale at small distances, M_*, is given by:

$$M_{Pl}^2 \sim M_*^{2+d} R_*^d, \quad R_* \sim \frac{1}{M_*}\left(\frac{M_{Pl}}{M_*}\right)^{2/d},$$

- R_* is the size of the extra dimensions.

We choose $M_* \approx 3 \times 10^{17}$ GeV, so $R_* \sim 10^{(4/d)}/M_* > 1/M_*$.

Heavy proton type dark matter: $X \to L^+ \bar{q}_* q_*$

The width of the proton decay $p \to l^+ \bar{q} q$ via virtual BH:

- C. Bambi, A. D. Dolgov and K. Freese, Nucl. Phys. B **763** (2007), 91-114

$$\Gamma_p = \frac{m_p\, \alpha^2}{2^{12}\, \pi^{13}} \left(\ln \frac{M_{Pl}^2}{m_q^2} \right)^2 \left(\frac{\Lambda}{M_{Pl}} \right)^6 \left(\frac{m_p}{M_{Pl}} \right)^{4+\frac{10}{d+1}} \int_0^{1/2} dx x^2 (1-2x)^{1+\frac{5}{d+1}}$$

Decay $X \to L^+ \bar{q}_* q_*$: $m_p \Longrightarrow M_X \sim 10^{12}\, GeV$, $m_{q_*} \sim M_X$, $M_{Pl} \Longrightarrow M_*$.

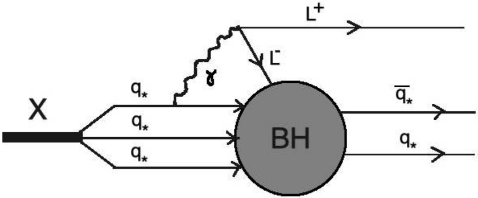

Figure: Diagram illustrated X-particle decay into $L^+ \bar{q}_* q_*$ through virtual BH.

NB. We assume, that BH has vacuum quantum numbers to avoid naked singularity.

Superheavy DM particle decay

The life-time of X-particles:

$$\tau_X \approx 10^{-24}\mathrm{s} \cdot \frac{2^{11}\pi^{13}}{3\alpha_*^2}\left(\frac{\mathrm{GeV}}{\mathrm{M_X}}\right)\left(\frac{\mathrm{M_*}}{\Lambda_*}\right)^6\left(\frac{\mathrm{M_*}}{\mathrm{M_X}}\right)^{4+10/(d+1)}\left(\ln\frac{\mathrm{M_*}}{\mathrm{m_{q_*}}}\right)^{-2}\mathrm{I(d)}^{-1},$$

where we took $1/\mathrm{GeV} = (2/3)\times 10^{-24}$ s and

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

Now all the parameters, except for Λ_*, are fixed:

- $M_* = 3\times 10^{17}$ GeV, $M_X = 10^{12}$ GeV, $m_{q_*} \sim M_X$, and $\alpha_* = 1/50$

The life-time of X-particles can be estimated as:

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

A slight variation of Λ_* near 10^{15} GeV allows to fix the life-time of DM particles in the interesting range. They would be stable enough to behave as the cosmological DM and their decay could make considerable contribution into cosmic rays at ultra high energies.

Conclusions

- In R^2-modified gravity the viable canditates for DM particles could be extremely heavy, up to $M \sim 10^{13}$ GeV.
- Annihilation and decay of such superheavy particles are promising sources of extremely high energy cosmic rays, which is difficult to explain by the canonical astrophysical mechanisms.
- The contribution to the flux of cosmic rays originated from different cosmological environment (e.g. DM clumps in the galactic centre) might be at the sufficient level to explain the origin of UHECR with $E \gtrsim 10^{20}$ eV.
- The flux of UHECR would be strongly enchanced in the case of the resonance annihilation of superheavy DM particles.
- DM particles are supposed to be stable with respect to the conventional particle interactions, but they could decay though the virtual BH formation. In the model of high dimensional gravity the life-time of such quasi-stable particles may exceed the universe age by several orders of magnitude.
- The considered mechanisms might explain the origin of cosmic rays observed by Pierre Auger and Telescope Array detectors.

THE END

THANK YOU FOR ATTENTION