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GALACTIC ANISOTROPY AS SIGNATURE OF "TOP-DOWN" MECHANISMS OF ULTRA-HIGH ENERGY COSMIC RAYS

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We show that "top-down" mechanisms of Ultra-High Energy Cosmic Rays which involve heavy relic particle-like objects predict Galactic anisotropy of highest energy cosmic rays at the level of minimum $\sim 20\%$. This anisotropy is large enough to be either observed or ruled out in the next generation of experiments.

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The origin and nature of Ultra-High Energy Cosmic Rays (UHE CR) with energies above 10^{19} eV [1] is one of the actively debated issues in modern astrophysics. At such a high energy the mean free path of protons, nuclei and photons is much shorter than the size of the Universe due to their interaction with cosmic microwave and radio background [2, 3]. Protons with $E > E_{\rm GZK} \sim 5 \cdot 10^{19}$ eV can only come from distances less than $R_{\rm GZK} \sim 50$ Mpc; the corresponding region for nuclei and photons is even smaller. The energy spectrum of cosmic rays is thus expected to have a rapid falloff at energies $E \sim \sim E_{\rm GZK}$ (the so-called Greisen – Zatsepin – Kuzmin cutoff).

The observation of few events with energies exceeding 10^{20} eV seems to indicate that noticeable fraction of UHE CR comes from relatively nearby ($R < R_{\rm GZK}$) sources. The latter is not easy to reconcile with conventional astrophysical mechanisms [4] as at these energies and distances the cosmic rays are not substantially deflected by magnetic fields and point in the direction of their source [5]. Corresponding astrophysical sources have not yet been identified. This prompts to consider particle physics mechanisms of UHE CR production, which are usually referred to as "top-down" mechanisms. Several such mechanisms involving topological defects [6] and decays of primordial heavy particles [7, 8, 9, 10] have been proposed. In this Letter we show that large class of the top-down mechanisms predict significant excess of highest energy events in the direction towards the center of our Galaxy. Thus, these mechanisms can be tested experimentally by studying

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the asymmetry in the angular distribution of UHE CR. The predicted asymmetry is large enough to be either observed or excluded by future experiments [11].

Our consideration concerns mechanisms in which production of UHE CR involves heavy relic particle-like objects which behave as part of cold dark matter (CDM). We call such mechanisms CDM-related. The crucial feature of these mechanisms is that the distribution of sources of UHE CR in the Universe between galaxies and intergalactic space is proportional to that of CDM (cf. ref.[12]) and does not depend on their nature. In particular, the sources are mainly concentrated in galactic halos, so that their average densities in the Universe ($\bar{n}$) and in galactic halo ($\bar{n}_h$) are related by

$$\frac{\bar{n}}{\bar{n}_h} \simeq \frac{\Omega_{\mathrm{CDM}}\, \rho_{crit}}{\bar{\rho}_{halo}} \sim 10^{-5}. \tag{1}$$

On the contrary, the distribution $n(x)$ of the sources in the galactic halo depends on their interaction with each other and with other matter and does not necessarily follow that of CDM[1]. For the decay-type mechanisms $n(x)$ is simply the density of decaying particles. For mechanisms based on collisions (see e.g. [13]) $n(x) \propto \tilde{n}^2(x)$, where $\tilde{n}(x)$ is the density of colliding particles. Note that in the latter case the distribution $n(x)$ is typically more concentrated around the galactic center.

The observed flux of UHE CR can be divided into Galactic and extragalactic parts,

$$j = j_{ext} + j_h,$$

where

$$j_h = C \int_{halo} \frac{d^3x}{x^2} n(x), \tag{2}$$

is the contribution of our Galaxy and

$$j_{ext} = C\, 4\pi R_{ext} \bar{n}$$

has extragalactic origin. Here $R_{ext} = R_{Universe} \sim 4$ Gpc for energies below E_{GZK} and $R_{ext} \sim 50$ Mpc for energies above E_{GZK}. The constant C is the same in both equations. Following ref.[9] we note that eq.(1) allows to estimate the relative magnitude of these two contributions,

$$\frac{j_{ext}}{j_h} = \alpha \frac{R_{ext}}{R_h} \frac{\bar{n}}{\bar{n}_h} \sim \alpha \frac{R_{ext}}{R_h} \cdot 10^{-5}, \tag{3}$$

where $R_h \sim 100$ kpc is the size of the Galactic halo and α is the constant of purely geometrical origin,

$$\alpha = \frac{3 \int_{r<R_h} d^3x\, n(x)}{R_h^2 \int_{r<R_h} \frac{d^3x}{x^2} n(x)}. \tag{4}$$

Here $r(x,\theta) = (x^2 + r_0^2 - 2xr_0 \cos\theta)^{1/2}$ is the distance between current point and the Galactic center while $r_0 = 8.5$ kpc is the distance to the Galactic center.

Numerical value of α is close to 1 for uniform distribution $n(x) =$ const and can be small for distributions concentrated around the galactic center. Although $n(x)$ does not have to coincide with CDM distribution in the halo, we consider as two examples the isothermal halo model [14]

$$n(r) \propto \frac{1}{(r_c^2 + r^2)} \tag{5}$$

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[1] We thank V.A.Kuzmin for drawing our attention to this point.

and more realistic distribution of ref.[15],

$$n(r) \propto \frac{1}{\sqrt{(r_c^2 + r^2)}(R_h + r)^2}, \tag{6}$$

which we have arbitrarily regularized at $r = 0$ by introducing the core size r_c. The value of α is $\alpha \simeq 0.15$ and $\alpha \simeq 0.5$ for distributions (5) and (6), respectively, with no strong dependence on r_c in the range $r_c = 2 - 10$ kpc.

From eq.(3) we find

$$\begin{aligned} \frac{j_{ext}}{j_h} &\sim \alpha && \text{for } E < E_{\rm GZK}, \\ \frac{j_{ext}}{j_h} &\sim 10^{-2} \times \alpha && \text{for } E > E_{\rm GZK}. \end{aligned} \tag{7}$$

Therefore, at $E < E_{\rm GZK}$ the Galactic and extragalactic contributions can be comparable (although the Galactic one is probably somewhat larger), while at $E > E_{\rm GZK}$ the extragalactic part is suppressed by a factor $\sim 10^{-2}$. In either case a substantial fraction of the observed UHE CR should come from the halo of our Galaxy. In this respect our conclusions agree with that of ref.[9].

The Galactic part of the total UHE CR flux, j_h, is anisotropic due to our position at 8.5 kpc from the center of the Galaxy. The anisotropy can be obtained from eq.(2),

$$j_h(\theta) \propto \int dx\, n(r(x, \theta)).$$

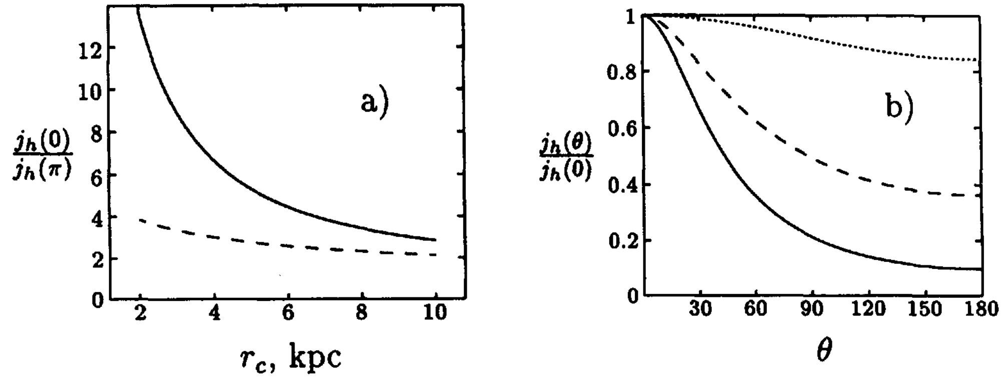
Figure shows the anisotropy $j_h(0)/j_h(\pi)$ as a function of the core radius for the trial distributions (5) and (6). For $n(x) = \text{const}$ the anisotropy is minimum and constitutes about 20%. Figure shows corresponding angular dependencies of $j_h(\theta)$ at $r_c = 5$ kpc. As can be seen from the picture, the anisotropy of the galactic contribution is at least $\sim 20\%$ and can be much larger if $n(x)$ is concentrated around the galactic center. Also, it should be noted that the anisotropy depends exclusively on $n(x)$ and does not depend on energy since cosmic rays with energy $E \sim E_{\rm GZK}$ are deflected by the Galactic magnetic field by only $\sim 3^\circ$ [5].

In turn, the extragalactic contribution $j_{\rm ext}$ consists of the isotropic part coming from distances $R \gg 50$ Mpc, which is comparable in magnitude to j_h and is present only at $E < E_{GZK}$, and the contribution from our "neighborhood" $R \lesssim 50$ Mpc. The latter should have peaks in the direction of nearby galaxies and clusters. The contribution of such a peak, δj_{ext}, equals

$$\frac{\delta j_{ext}}{j_h} = \alpha \frac{R_h^2}{3R^2} \frac{M}{M_G},$$

where R is the distance to the astronomical object, M is its mass, and M_G is the mass of our Galaxy including halo. For instance, contributions from Andromeda Nebula and Virgo Cluster are comparable and close to $10^{-2} \times \alpha$, in agreement with eq.(7) and ref.[9].

Since at energies above the GZK cutoff the extragalactic contribution is negligible, non-observation of the anisotropy at the level of $\sim 20\%$ would rule out the CDM related mechanisms of UHE CR. The observation of the Galactic anisotropy would allow to reconstruct the density profile $n(x)$ and, possibly, the distribution of CDM in the Galactic halo.



The anisotropy $j_h(0)/j_h(\pi)$ as a function of the core size r_c for the density profiles (5) (solid line) and (6) (dashed line). b) The corresponding angular distributions at $r_c = 5$ kpc. The dotted line shows the angular distribution for $n(x) = \text{const}$ (i.e., when the anisotropy is minimum)

At energies below the GZK cutoff, the anisotropy is smaller due to the relative enhancement of the isotropic extragalactic part. Since anisotropy does not depend on energy and can be measured at $E > E_{\rm GZK}$, it is possible, in principle, to determine the magnitude of the extragalactic contribution. Provided the CDM related mechanisms are dominant at $E \lesssim E_{\rm GZK}$ and the coefficient α is known, the ratio $j_h/j_{\rm ext}$ could give, in view of eqs.(1) and (3), an important information about the distribution of matter in the Universe.

Current data is not enough to draw definite conclusions about the angular distribution of highest energy cosmic rays both because of very limited statistics and the absence of data in the South hemisphere where the Galactic center is situated. However, since the anisotropy predicted by the CDM related mechanisms is large, it will be either observed or excluded already in the next generation of experiments [11]. Among these the Pierre Auger Project has the best potential due to large number of expected events (600–1000 events with $E > 10^{20}$ eV in 10 years) and the ability to see both hemispheres.

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