Superheavy dark matter as UHECR source versus the SUGAR data

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Abstract

Decay or annihilation products of superheavy dark matter (SHDM) could be responsible for the end of the Ultra-High Energy Cosmic Ray (UHECR) spectrum. In this case, the south array of the Pierre Auger Observatory should observe in the future a significant anisotropy of UHECR arrival directions towards the galactic center. Here we use the already existing data of the SUGAR array to test this possibility. If decaying SHDM is distributed according a Navarro-Frenk-White (NFW) dark matter profile with core radius \( R_c = 15 \) kpc and is responsible only for UHECRs above \( \sim 6 \times 10^{19} \) eV, i.e. the AGASA excess, then the arrival directions measured by the SUGAR array have a probability of \( \sim 10\% \) to be consistent with this model. By contrast, the model of annihilating SHDM is disfavoured at least at 99\% CL by the SUGAR data, if the smooth component of the DM dominates the signal.

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1 Introduction

Protons accelerated by uniformly distributed extragalactic astrophysical sources would be a perfect minimal explanation of the UHECR data above \( 10^{19} \) eV. However, protons with energy \( E > 4 \times 10^{19} \) eV loose quickly energy due to pion production on cosmic microwave background photons. Thus the proton spectrum should show the so-called Greisen-Zatsepin-Kuzmin (GZK) cutoff [1], which is not observed by the AGASA experiment [2]. Moreover, if the small-scale clusters in the arrival directions of UHECR measured by AGASA [3] are due to point-like sources, one can estimate their number [5]. This number is so small that the nearest source should be located at the distance \( R_{\text{min}} \sim 100 \) Mpc [6]. This means that the GZK cutoff is exponentially sharp at
$E \approx 6 \times 10^{19}$ eV and even the data of the HiRes experiment \cite{7} are inconsistent with the expected proton spectrum \cite{8}. This inconsistency becomes even stronger if BL Lacs, which show a statistically significant correlations with the arrival directions of UHECR with energy $E \sim 4 - 6 \times 10^{19}$ eV \cite{8}, are sources of UHECR.

A possible solution to this problem would be the existence of superheavy dark matter (SHDM) \cite{9, 10}. Superheavy particles with mass $M_X \sim 10^{13 - 14}$ GeV can be naturally produced during inflation and would be today the dominant component of dark matter \cite{11}. Such particles will concentrate in galactic halos and the secondaries from their decay could be responsible for the highest energy cosmic rays. It has also been suggested that not decays but annihilations of SHDM particles produce the observed UHECRs \cite{117}.

By construction, this model has two clean signatures: the dominance of photons at the highest energies \cite{9} and an anisotropy of the arrival directions with an increased flux from the Galactic center \cite{112, 113}. Unfortunately, both signatures are not very clean for the present experiments. Indeed, at 95% C.L., $\sim 30\%$ of the UHECR above $E > 10^{19}$ eV can be photons \cite{114}, which means that still most of UHECRs with $E > 4 \times 10^{19}$ eV can be photons without any contradiction to the experimental data. Since experiments in the northern hemisphere do not see the Galactic center, they are not very sensitive to a possible anisotropy of arrival directions of UHECR from SHDM. In contrast, the Galactic center was visible for the old Australian SUGAR experiment.

The anisotropy of the arrival directions using data from the full sky was discussed in Refs. \cite{15, 16}. Reference \cite{15} compared the flux from the Galactic center to the one from the anti-center and found them to be comparable. Similarly, the full-sky harmonic analysis including AGASA and SUGAR data from Ref. \cite{16} found no significant anisotropy. In this work, we use a two-component energy spectrum of UHECRs consisting of protons from uniformly distributed, astrophysical sources and the fragmentation products of SHDM calculated in SUSY-QCD. We compare their expected arrival direction distribution to the data of the SUGAR experiment using a Kolmogorov-Smirnov test. Contrary to the harmonic analysis, this test allows to quantify directly the (dis-) agreement of the measured distribution of arrival direction with the expected one in the SHDM model. We consider both decays and annihilations of SHDM.

The paper is organized as follows: In Section II we discuss the status of the SUGAR data. The contribution of SHDM to the UHECR spectrum is discussed in Section III. In Section IV we perform an harmonic analysis of the arrival directions measured by the SUGAR experiment. Then we use a Kolmogorov-Smirnov test in one and two dimensions to check the consistency of the SUGAR data with the probability distribution of arrival directions expected for SHDM in Section V. Finally we conclude in Section VI.

## 2 Assessment of the SUGAR data

In order to use the SUGAR energy spectrum correctly we compare their data given in Ref. \cite{20} to the energy spectrum measured by the AGASA \cite{2} and HiRes experiments \cite{7} in Fig. 1. Rescaling the SUGAR energies calculated with the Hillas prescription by 15% downwards, $E_{\text{Hillas}} \rightarrow E_{\text{Hillas}}/1.15$, makes their data consistent with the ones from AGASA.
Figure 1: UHECR spectrum measured by the AGASA, HiRes and SUGAR experiments. We scale the SUGAR spectrum down by $E/1.15$ and the HiRes spectrum up by $1.25 \times E$ using the AGASA spectrum as reference. The overall normalization of the spectra has only a weak influence on our results.

The same is true for the HiRes spectrum if the energy is rescaled up-wards by 25%. We have chosen arbitrary the AGASA spectrum as reference, but changing the overall normalization of the spectra affects our results only weakly. As seen from Fig. 1 the SUGAR spectrum has the ankle at the correct place around $E \approx 10^{19}$ eV and is consistent with the AGASA spectrum in the whole energy range. In particular, the SUGAR spectrum also does not show the GZK cutoff at the highest energies.

The rescaling of the SUGAR data downwards by 15% should be compared to the recent reevaluation of the energy conversion formula used in the Haverah Park experiment [22]. In this reference, the relation between $\rho(600)$ and the primary energy has been recalculated using QGSJET [24] and compared to the original relation suggested by Hillas. The new calibration results in $\sim 30\%$ lower primary energies.

The SUGAR experiment was a very sparse array of detectors and its energy determination of each single event was therefore rather unprecise. Thus, we shall use as a statistical test later on a method which relies only on the total flux measured by the SUGAR array, but uses not the energy of each single event. Since after the rescaling of the energies measured by SUGAR, $E_{\text{Hillas}} \rightarrow E_{\text{Hillas}}/1.15$, its measured flux is consistent with newer experiments like AGASA and HiRes, we conclude that on average the energy determination in the SUGAR experiment was reliable.

\[1\text{The aperture of HiRes is energy dependent; the rescaling we perform should be seen therefore just as a crude approximation.}\]
The energy conversion formula used in SUGAR to connect the measured muon number \( N_\mu \) with the primary energy assumes that the primary is a hadron. For photon primaries, predicted to be dominant in the SHDM model, the muon content of the shower is smaller by a factor 5 – 10 \cite{23}. Thus the energies of photon events is expected to be underestimated by the SUGAR experiment. The SUGAR spectrum shown in Fig. 1 would be unchanged at energies \( E \lesssim 5 \times 10^{19} \) eV, i.e at energies where all three experiments agree after rescaling.

The angular acceptance \( \eta(\delta) \) as function of declination \( \delta \) averaged over time of an experiment at geographical latitude \( b \) (\( b = -30.5^\circ \) for SUGAR) observing showers with maximal zenith angle \( \theta_{\text{max}} \) is

\[
\eta(\delta) \propto \int_0^{\alpha_{\text{max}}} d\alpha \cos(\theta) \propto [\cos(b) \cos(\delta) \sin(\alpha_{\text{max}}) + \alpha_{\text{max}} \sin(b) \sin(\delta)] \quad (1)
\]

where

\[
\xi = \frac{\cos(\theta_{\text{max}}) - \sin(b) \sin(\delta)}{\cos(b) \cos(\delta)} \quad (2)
\]

and

\[
\alpha_{\text{max}} = \begin{cases} \arccos(\xi) & \text{for } -1 \leq \xi \leq 1, \\ \pi & \text{for } \xi < -1, \\ 0 & \text{for } \xi > 1. \end{cases} \quad (3)
\]

We have checked that the zenith angle distribution of the SUGAR events agrees with the theoretical predicted one, \( dN_{\text{th}} \propto d\theta \sin(\theta) \cos(\theta) \), above \( E \gtrsim 4 \times 10^{19} \) eV. At lower energies, the acceptance of the experiment becomes energy dependent and deviations from \( dN_{\text{th}} \) start to grow.

### 3 Superheavy dark matter contribution to UHECR spectrum

We fix the contribution of SHDM to the total UHECR flux following the assumptions of Ref. \cite{18}: we assume that no galactic astrophysical sources contribute to the cosmic ray flux above \( 10^{19} \) eV and that the extragalactic cosmic ray flux can be characterized by an injection spectra of protons with a single power law, \( j_{\text{ex}}(E) \propto E^{-\alpha} \). For the choice of \( \alpha = 2.7 \), this energy spectra modified by redshift, \( e^+ e^- \) and pion production fits very well the measured spectra below \( E < 6 - 8 \times 10^{18} \) eV \cite{18}. The only difference with \cite{18} is that we take into account that total number of sources is small \cite{6}, if the small scale clusters measured by the AGASA experiment are due to point-like sources. The AGASA data favor as minimal distance to the nearest source \( D_{\min} \sim 100 \) Mpc \cite{6}. Therefore, the contribution of protons from extragalactic sources has a sharp cutoff. For the calculations of the proton spectrum we used the code \cite{28}. We use then the SUSY QCD fragmentation functions \( D(x, M_X) \) of superheavy particles with mass \( M_X \) calculated in Ref. \cite{19} to model the flux \( j_{\text{DM}}(E) \propto D_\gamma(x, M_X) \). The total UHECR flux is thus

\[
j(E) = (1 - \epsilon)j_{\text{ex}}(E) + \epsilon j_{\text{DM}}(E) \quad (4)
\]
We fix the constant $\epsilon$ determining the relative contribution of SHDM to the UHECR flux by a fit of $j(E)$ to the AGASA data [2]. In Fig. 2 we show our fits for the case of a harder $1/E^{2.3}$ (left) and a softer $1/E^{2.7}$ (right) injection spectrum of extragalactic protons. In the first case, the contribution of SHDM to the UHECR spectrum below the GZK cutoff is minimal and starts to dominate only at highest energies $E > 6 \times 10^{19}$ eV. For this choice of injection spectrum, the contribution of galactic sources dominate for $E < 10^{19}$ eV. In the second case, SHDM gives a larger contribution at lower energies $E < 6 \times 10^{19}$ than before, and again starts to dominate at $E > 6 \times 10^{19}$ eV. Note, that most UHECRs above $E > 6 \times 10^{19}$ eV should be photons in this model, but this does not contradict the rather weak existing bound of 30% of photons at $E > 10^{19}$ eV [14].

In the following, we shall use conservatively the case of the harder $1/E^{2.3}$ injection spectrum if not otherwise stated. Then the contribution of SHDM to the UHECR spectrum is fixed by Eq. (4).

4 Harmonic analysis

In order to compare SUGAR data with an uniform distribution typical for extragalactic sources we have performed an one-dimensional harmonic analysis. As usual we sum

$$a_k = \frac{2}{n} \sum_{a=1}^{n} \cos(k \phi) \quad \text{and} \quad b_k = \frac{2}{n} \sum_{a=1}^{n} \sin(k \phi)$$

over the $n$ data points.

The amplitude $r_k$ and and phase $\phi_k$ of the $k.$th harmonic are given by

$$r_k = \sqrt{a_k^2 + b_k^2} \quad \text{and} \quad \phi_k = \arctan(b_k/a_k)$$
Table 1: Direction $\phi$ to the signal in right ascension and chance probability of the $k$.th harmonics to arise from an isotropic distribution; for different cuts in energy $E$ and zenith angle $\theta < 55^\circ$.

with chance probability

$$p_{ch} = \exp \left( -nr_k^2/4 \right).$$

The direction to the signal is $\phi = k\phi_k$.

Results of a harmonic analysis in right ascension $\alpha$ depending on $E_{\text{min}}$ and $\theta_{\text{max}}$ are given in Table 1. The results for all harmonics show generally good agreement with an isotropic distribution for any cutoff energy we have used. Only the third harmonics shows some anisotropy, in particular at the highest energies, $E > 8 \times 10^{19}$ eV; however its phase does not points towards the galactic center (lying at $\alpha = 266^\circ$). Generally, all harmonics point instead towards $\alpha \sim 130^\circ$. Reference [25] derived the probability distribution (pdf) that a data set with phase $\phi_1$ and amplitude $r_1$ is drawn from an arbitrary pdf. However, we are not aware of a generalization to higher harmonics and, in particular, of a method to combine the information content of several harmonics. In the next section, we use therefore a Kolmogorov-Smirnov test to quantify the (dis-) agreement between the expected distribution of arrival direction and the SUGAR data.

5 Kolmogorov-Smirnov tests

The pdf to detect an event with energy $E$ and arrival direction $\alpha, \delta$ is a combination of the isotropic extragalactic and the SHDM flux,

$$p(E, \alpha, \delta) \propto \eta(\delta) \left[ j_{\text{ex}}(E) + j_{DM}(E) \int_{0}^{s_{\text{max}}} ds n_{DM}(r(\alpha, \delta)) \right]$$

where $s_{\text{max}} = R_E \cos \theta + \sqrt{R_h^2 - R_E^2 \sin^2 \theta}$ is given by the extension $R_h = 100$ kpc of the DM halo and $\theta$ is the angle relative to the direction to the GC. As explained, the relative size of the two contributions is fixed by the fit to Eq. (4).

For the two-dimensional test, we have integrated Eq. (8) over energy,

$$P_{2d}(\alpha, \delta) = \int_{E_{\text{min}}}^{E_{\text{max}}} dE \ p(E, \alpha, \delta),$$

where $E_{\text{min}}$ and $E_{\text{max}}$ are the energy cuts used in the analysis.
where $E_{\text{min}}$ and $E_{\text{max}}$ are the minimal and maximal energy considered in the UHECR spectrum. We have used $E_{\text{max}} = 10^{21-22}$ eV, but the results do depend on very weakly on the exact value. By contrast, the value of $E_{\text{min}}$ has a strong influence on the results obtained.

For the one-dimensional test, we have integrated Eq. (9) over the declination,

$$P_{\text{CR}}(\alpha) = \int_{-\pi/2}^{\pi/2} d\delta \cos \delta P_{2d}(\alpha, \delta).$$

(10)

In the standard one-dimensional Kolmogorov-Smirnov (KS) test, the maximal difference $D$ between the cumulative probability distribution function $P(x) = \int dx' p(x')$ and the cumulative distribution function of the data,

$$S(x) = \frac{1}{n} \sum_i \theta(x_i - x),$$

is used as estimator for the belief that the data are drawn from the distribution $p$. A variant of this test which is equally sensitive on differences for all $x$ and is especially well suited for data on $S^1$ uses instead of $D$ the symmetric estimator

$$V = D_+ + D_- = \max[S(x) - P(x)] + \max[P(x) - S(x)].$$

(12)

The significance of a certain value of $V$ is calculated with the formula given in [26]. Since the exposure of a ground-array experiment is uniform in right ascension $\alpha$, we use $\alpha$ as variable in the one-dimensional KS test. More exactly, we use as pdf Eq. (8) integrated over $dE$ and $d\delta \cos \delta$.

Figure 3: Left: Consistency level of the SUGAR data with SHDM distributed according a NFW profile as function of the core radius $R_c$; SHDM is assumed to be the source of all UHECRs above $E_{\text{min}} = 8 \times 10^{19}$ eV. Right: Comparison of $S(\alpha)$ and $P(\alpha)$ for $R_s = 15$ kpc, $E_{\text{min}} = 8 \times 10^{19}$ eV and $\theta_{\text{max}} = 45^\circ$.

As simplest test, we assume that all SUGAR events above $E_{\text{min}}$ are produced by SHDM. Thus we compare $S(\alpha)$ with $P(\alpha) = \int_0^\alpha d\alpha' P_{\text{CR}}(\alpha')$. The result is shown for
$E > 8 \times 10^{19} \text{ eV}$ in Fig. 3a for two different values of the maximal zenith angle, $\theta_{\text{max}} = 45^\circ$ and $\theta_{\text{max}} = 55^\circ$. While for $\theta_{\text{max}} = 45^\circ$ SHDM is disfavoured at the two sigma level for realistic values of the core radius, $R_c \sim 20 \text{ kpc}$, the SUGAR data have for the choice of $\theta_{\text{max}} = 55^\circ$ a rather large probability $p$ to be consistent with the SHDM hypothesis, $p \sim 20\%$. In Fig. 3b, we compare the two cumulative distributions $S(\alpha)$ and $P(\alpha)$ for $R_c = 15 \text{ kpc}$, $E_{\text{min}} = 8 \times 10^{19} \text{ eV}$ and $\theta_{\text{max}} = 45^\circ$. Inspecting $S(\alpha)$ makes it clear that the data in this case are not uniformly distributed but clustered around $\alpha \sim 130^\circ$ and $\alpha \sim 350^\circ$. Since none of these two directions coincide with the position of the GC, this data set disfavours the SHDM hypothesis more strongly than one would expect for uniformly distributed events from extragalactic sources. However, one should use a rather low value of $E_{\text{min}}$ to minimize the uncertainties in the SUGAR energy determination and we will therefore not rely on these results.

We consider therefore next as more realistic test the case that both SHDM and extragalactic sources contribute to the UHECR spectrum. Then the dependence of $p$ on $E_{\text{min}}$ should be diminished. More exactly, one would expect in the case that the SHDM hypothesis is disfavoured by the data that decreasing $E_{\text{min}}$ first decreases $p$. This decrease of $p$ should continue down until $E \sim (3 - 4) \times 10^{19} \text{ eV}$, i.e. until a point where the signal-to-background ratio becomes considerably smaller than one. Decreasing $E_{\text{min}}$ even further should result in an increase of $p$ because now practically all new events are from extragalactic sources.

![Figure 4: Left: Dependence of the probability on the energy cutoff in the SUGAR data for decaying SHDM. Right: Two-dimensional KS test give results similar to one-dimensional test.](image)

In Fig. 4a, we show the dependence of the probability on the energy cutoff for $R_c = 15 \text{ kpc}$ and $\theta_{\text{max}} = 55^\circ$. The two thick solid lines show $p$ for a combination of SHDM and uniform sources according Eq. (4); the upper one corresponds to an injection spectrum $1/E^{2.3}$, the lower one to an injection spectrum $1/E^{2.7}$. The behaviour of $p$ suggest that the minimum for $E_{\text{min}} \sim 7 \times 10^{19} \text{ eV}$ is a fluctuation similar to the maximum around $E_{\text{min}} \sim 5 \times 10^{19} \text{ eV}$. In the range $E_{\text{min}} \sim (3 - 4) \times 10^{19} \text{ eV}$, the fluctuations adding an additional event are relatively small. Therefore, we consider the probability in this range as more reliable indicator for the consistency of SHDM with the SUGAR arrival directions;
we conclude that the SUGAR data have the probability \( p = 5 - 20\% \) to be consistent with the SHDM depending on the injection spectrum of the extragalactic protons.

The thin solid line shows how consistent the SUGAR data are with an isotropic distribution. This distribution has also a minimum around \( E_{\text{min}} \sim 7 \times 10^{19} \text{eV} \) where the events cluster around two arrival directions. After including more low-energy data, the SUGAR arrival directions are consistent with an isotropic distribution. Finally, the dashed line shows the consistency of the SUGAR data with the assumption that all UHECR events above \( E_{\text{min}} \) are from SHDM. It is clear that only values of \( E_{\text{min}} \) above \( E_{\text{min}} \sim 4 \times 10^{19} \text{eV} \) are compatible with the SUGAR data. Similar, the spectral shape of the flux in the SHDM model allows a dominance of SHDM in the UHECR spectrum only above \( E > 6 \times 10^{19} \text{eV} \) \[19\]. In Fig. 4b we compare results from one- and two-dimensional KS tests (of \( \alpha \) and \( \delta \)) as function of the energy cutoff and find that they give rather similar results.

![Figure 5: Dependence of the probability on the energy cutoff in the SUGAR data for annihilations of SHDM. Left: for core radius \( R_c = 15 \text{kpc} \) and different \( \epsilon \) determining the SHDM contribution. Right: for several core radii \( R_c \); assumes that all events above \( E \) are from SHDM.](image)

Finally, we consider the model where not decays but annihilations of SHDM particles produce the observed UHECRs \[17\]. In the original version of this model it was suggested that the flux of the clumpy component dominates over the one from the smooth SHDM profile by 3 orders of magnitude. On the other side, it was shown in a recent paper \[30\] that the contribution of the clumpy component can be just a factor few larger than the one of the smooth component. Moreover, the newest numerical calculations show that the contribution of clumps is even subdominant and that it is very unlikely that a nearby clump will outshine the Galactic center \[31\]. Because of the arguments above, we assume that the clumpy part of the SHDM gives a subdominant contribution to the UHECR flux. In the opposite case our results for the SHDM model with annihilations will be less significant, depending on the relative contribution of the two components.

Since the flux is now \( \propto n_{\text{DM}}^2 \), the anisotropy in this model is much stronger than for decaying SHDM. This can be clearly seen in Fig. 5b, where we show the dependence of the probability of annihilating SHDM on the core radius \( R_c \) assuming that all events
above $E$ are from SHDM. Even for core radii as large as 30 kpc, annihilating SHDM is disfavoured by two sigma. Figure 5a shows similar to Fig. 4a the dependence of the probability on the energy cutoff for $R_c = 15$ kpc and $\theta_{\text{max}} = 55^\circ$. The two thick solid lines show $p$ for a combination of SHDM and uniform sources according Eq. (4); the upper one corresponds to an injection spectrum $1/E^{2.3}$, the lower one to an injection spectrum $1/E^{2.7}$. Depending on the injection spectrum of extragalactic protons, annihilations of SHDM are disfavoured by the SUGAR data between 3 and $4\sigma$.

6 Conclusions

In this paper we have tested the consistency of the SHDM model with the SUGAR data. In order to use the SUGAR data, we have compared its energy spectrum to the one of AGASA and found that they are compatible after rescaling down the SUGAR energies by 15%. We have assumed that the energy spectrum in the region $10^{19} \text{ eV} < E < 6 \times 10^{19}$, i.e. between ankle and GZK cutoff, is dominated by protons coming from uniformly distributed extragalactic sources. After fitting the relative contributions of SHDM decay products and extragalactic protons to the AGASA data, we have performed Kolmogorov-Smirnov tests of the SUGAR data. As result we have found that SUGAR data are able to disfavour strongly extreme case like annihilations of SHDM without clumps ($5\sigma$) or decaying SHDM (99% CL) assuming their contribution to the UHECR flux dominates down to $E = 4 \times 10^{19}$ eV. The phenomenologically most interesting case, decaying SHDM dominating the UHECR spectrum only above $E > 6 \times 10^{19}$ eV, is consistent with the SUGAR data with 5–20% probability. Thus the SUGAR data do not disfavour strongly this model but they neither support it. A statistically significant test of this model can be done by the Pierre Auger Observatory.

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Note added: After completing this work we have learnt about a preprint of H. B. Kim and P. Tinyakov [32] discussing also the consequences of the SUGAR data for the SHDM hypothesis. These authors come to similar conclusion as ours. We thank H. B. Kim and P. Tinyakov for sending us the preprint before publication.

References

[1] K. Greisen, Phys. Rev. Lett. 16, 748 (1966). G. T. Zatsepin and V. A. Kuzmin, JETP Lett. 4, 78 (1966) [Pisma Zh. Eksp. Teor. Fiz. 4, 114 (1966)].
[2] M. Takeda et al., Phys. Rev. Lett. 81, 1163 (1998), astro-ph/9807193; N. Hayashida et al., Astrophys. J. 522, 225 (1999) arXiv:astro-ph/0008102. See also http://www-akeno.icrr.u-tokyo.ac.jp/AGASA/.

[3] M. Takeda et al., Astrophys. J. 522 225, [arXiv:astro-ph/9902239]; Y. Uchihori, M. Nagano, M. Takeda, M. Teshima, J. Lloyd-Evans and A. A. Watson, Astropart. Phys. 13, 151 (2000) arXiv:astro-ph/9908193.

[4] P. G. Tinyakov and I. I. Tkachev, JETP Lett. 74, 1 (2001) [Pisma Zh. Eksp. Teor. Fiz. 74, 3 (2001)] arXiv:astro-ph/0102101.

[5] S. L. Dubovsky, P. G. Tinyakov and I. I. Tkachev, Phys. Rev. Lett. 85, 1154 (2000) arXiv:astro-ph/0001317.

[6] M. Kachelrieß, D. V. Semikoz and M. A. Tortola, hep-ph/0302161 to appear in Phys. Rev. D.

[7] D. Kieda et al., Proc. of the 26th ICRC, Salt Lake, 1999, see also http://www.physics.utah.edu/Resrch.html T. Abu-Zayyad et al. [High Resolution Fly’s Eye Collaboration], astro-ph/0208243.

[8] P. G. Tinyakov and I. I. Tkachev, JETP Lett. 74, 445 (2001) [Pisma Zh.Eksp.Teor.Fiz. 74, 499 (2001)] astro-ph/0102476; see also P. Tinyakov and I. Tkachev, astro-ph/0301336.

[9] V. Berezinsky, M. Kachelrieß and A. Vilenkin, Phys. Rev. Lett. 79, 4302 (1997) astro-ph/9708217.

[10] V. A. Kuzmin and V. A. Rubakov, Phys. Atom. Nucl. 61, 1028 (1998) [Yad. Fiz. 61, 1122 (1998)] astro-ph/9709187.

[11] V. Kuzmin and I. Tkachev, Phys. Rev. D 59, 123006 (1999) hep-ph/9809547; D. J. Chung, E. W. Kolb and A. Riotto, Phys. Rev. D 60, 063504 (1999) hep-ph/9809453.

[12] S. L. Dubovsky and P. G. Tinyakov, JETP Lett. 68, 107 (1998) hep-ph/9802382.

[13] V. Berezinsky, P. Blasi and A. Vilenkin, Phys. Rev. D 58, 103515 (1998).

[14] M. Ave, J. A. Hinton, R. A. Vazquez, A. A. Watson and E. Zas, Phys. Rev. Lett. 85, 2244 (2000) astro-ph/0007386; K. Shinozaki et al. [AGASA Collaboration], Astrophys. J. 571, 117 (2002).

[15] A. Benson, A. W. Wolfendale and A. Smialkowski, Astropart. Phys. 10, 313 (1999).

[16] L. A. Anchordoqui, C. Hojvat, T. P. McCauley, T. C. Paul, S. Reucroft, J. D. Swain and A. Widom, astro-ph/0305158.

[17] P. Blasi, R. Dick and E. W. Kolb, Astropart. Phys. 18, 57 (2002) astro-ph/0105232.
[18] V. Berezinsky, A. Z. Gazizov and S. I. Grigorieva, astro-ph/0210095.

[19] V. Berezinsky and M. Kachelrieß, Phys. Rev. D 63, 034007 (2001) hep-ph/0009053; R. Aloisio, V. Berezinsky and M. Kachelrieß, in preparation.

[20] M. M. Winn, J. Ulrichs, L. S. Peak, C. B. Mccusker and L. Horton, J. Phys. G 12, 653 (1986); see also the complete catalogue of SUGAR data in “Catalogue of highest energy cosmic rays No. 2”, ed. WDC-C2 for Cosmic Rays (1986).

[21] M. M. Winn, J. Ulrichs, L. S. Peak, C. B. Mccusker and L. Horton, J. Phys. G 12, 675 (1986).

[22] M. Ave, J. Knapp, J. Lloyd-Evans, M. Marchesini and A. A. Watson, Astropart. Phys. 19, 47 (2003) astro-ph/0112253.

[23] A. V. Plyasheshnikov and F. A. Aharonian, J. Phys. G 28, 267 (2002) astro-ph/0107592.

[24] N.N. Kalmykov, S.S. Ostapchenko and A.I. Pavlov, Nucl. Phys. (Proc. Suppl.) 52B, 17 (1997); N.N. Kalmykov and S.S. Ostapchenko, Preprint INP MSU 98-36/537, Moscow 1998; N.N. Kalmykov, S.S. Ostapchenko and A.I. Pavlov, Izv. RAN Ser. Fiz. 58, 21 (1994) (English translation in Bull.Russ.Acad.Sci (USA), Phys.Ser. v.58 1966 (1994).)

[25] J. Linsley, Phys. Rev. Lett. 34, 1530 (1975).

[26] W. H. Press, S. A. Teukolsky, W. T. Vetterling and B. P. Flannery, Numerical Recipes in Fortran, Cambridge University Press (1986, Cambridge).

[27] J. F. Navarro, C. S. Frenk and S. D. White, Astrophys. J. 462, 563 (1996) astro-ph/9508025.

[28] O. E. Kalashev, V. A. Kuzmin and D. V. Semikoz, astro-ph/9911035 Mod. Phys. Lett. A 16, 2505 (2001) astro-ph/0006349.

[29] A. Klypin, H. Zhao and R. S. Somerville, astro-ph/0110390.

[30] V. Berezinsky, V. Dokuchaev and Y. Eroshenko, astro-ph/0301551.

[31] F. Stoehr, S. D.M. White, V. Springel, G. Tormen and N. Yoshida, astro-ph/0307026.

[32] H. B. Kim and P. Tinyakov, astro-ph/0306413.