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Cosmic rays from dark matter halos?

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Abstract. The origin of CR of the highest energies is still the subject of argument and the 'top-down' mechanism is still a possibility. Here we examine the idea that dark matter particles are responsible, either through their decay or through their interactions.

1 Introduction

It is a common belief that cosmic rays of extremely high energies are of extra Galactic (EG) origin. Supreme arguments for this emerge from the analysis of the ultra high energy cosmic ray (UHECR) anisotropy. The recent review of the world data given by Wibig and Wolfendale (1999) strongly suggests that at about 10^{19}eV the EG cosmic ray flux predominates the Galactic component and just above 3×10^{19}eV almost no cosmic ray particles come from the Galaxy.

In principle there are two mechanisms of creation for particles with such big energies. The first, so-called "bottom up", refers to particle acceleration by some means from low energies. As one among many other examples the acceleration on shocks caused by galaxy-galaxy collisions discussed by Al-Dargazelli *et al.* (1996) can be mentioned here. The second way which is of concern in this work is the "top down" process. It can be realized in decays of very massive (of mass, say, $10^{22}eV$) particles (known as X-particles in Kuzmin and Tkachev (1999), cryptons in (Birkel and Sarkar, 1998) or other names as exotic as, e.g., Wimpzillas (Ziaeepour, 1999), (Kolb *et al.*, 1998)). All yield very energetic nucleons ($\approx$ 10^{20}eV). This attractive idea implies, if X-particles were created in the very early universe (e.g., (Kuzmin and Tkachev, 1999), (Chung *et al.*, 1998), see also (Berezinski *et al.*, 1997)), that these particles congregate (with, possibly, other dark matter particles) in galactic halos. Thus, following this idea, UHECR are created relatively close on the cosmological scale this makes the idea very attractive, eliminating the puzzling question of observational non-existence of famous Greisen-Zatzepin-Kuzmin cut-off. On the other hand, due to our not exactly central position in the Galaxy, there is, in principle, a possibility of its experimental verification.

It should be mentioned here another, quite exciting and recent hypothesis of UHECR origin as a result of the strong interaction of energetic massive neutrinos from distant sources with neutrinos gathered in the Galaxy dark matter (DM) halo. Just around the energies of our present interest the interaction energy (in respective center of mass system) corresponds to the mass of the Z_0 boson (Fargion *et al.*, 2000). The eventual anisotropy for such a model is exactly the same as for the X-particle halo UHECR generation.

2 Experimental results on the CR anisotropy

The experimental situation concerning studies of the directions of arrival of giant extensive air showers (GEAS) with energies estimated to be higher than 10^{19}eV is such that there are about 1000 events available for detailed analysis which among about half are registered by the SUGAR experiment located in the southern hemisphere; the northern experiments are Volcano Range, Haverah Park and Yakutsk. To this list,

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when the energy limit is shifted to 4×10^{19}eV, the AGASA experiment should be added, making the world data set of about 200 events (with 79 from Sydney array). Due to the currently increased interest of the UHECR domain caused by the construction and planning of new giant experiments with very high collection power some analysis of these data were performed recently (Berezinski and Mikhailov, 1998), (Benson *et al.*, 1999) and (Medina Tanco and Watson, 1999). Unfortunately, the conclusions of these works are not very consistent. In the present paper we would like to present results of our anisotropy studies dedicated specially to examining the DM halo production models.

3 Predicted anisotropies

To find the DM halo CR excess or, at least to put some limit on the fraction of UHECR coming from the halo, theoretical predictions concerning such excess are needed. The uncertainties of DM distribution are known, see, e.g., (Benson *et al.*, 1999) and (Calcaneo-Roldan and Moore, 2000) for recent reviews. The numerical modelling of the gravitational formation of structures identified with galactic halos gives some insight on the shape as well as on the matter density distribution within such clusters. Models of the Galaxy halo used in our studies are adjusted to the rotation curve which is the one datum which can be used here. It was shown in (Calcaneo-Roldan and Moore, 2000) that, surprisingly, simulations favour not the spherical halo shape but rather the prolate spheroid with the longer axis along the angular velocity direction. For completeness we examined also the oblate spheroid halo shape. The density distribution of the halo DM suggested by different authors differs little from the occupied halo model proposed by Benson *et al.* (1999).

Combining the UHECR produced according to the assumed DM density with some fraction of uniformly arriving GEAS and taking into account the acceptance of all considered experiments a map of expectations can be produced. By a comparison with what is observed the determination of the degree of belief for the particular model can be made. The straightforward way to do so, is to perform the Fourier analysis in right ascension (r.a.) of registered GEAS and use the amplitude (and phase) of the first harmonic as an anisotropy indicator. Such a method, however, has, for our particular purposes, a significant disadvantage. It is obvious that the DM halo CR production model does not lead to the cosine (in r.a.) dependence of GEAS directions.The use of the first harmonic alone implies meaningful reduction of information contained in the data. In particular it is not allowed to combine the southern and northern hemisphere experiment events. In Fig.1 an example of such procedure is shown. EAS of energies higher than 4×10^{19}eV from northern hemisphere experiments were used here. Dashed curves represent 1σ contours for each experiment separately, while the thick solid line and the cross show results for all data taken together. Vertical (almost) lines labeled 1-1-1, 1-1-2, and 2-2-1 show DM model predictions for spherical, prolate and oblate spheroid halos, respectively. The upper end of each line represents the case of 100% of UHECR created in the halo, while the lower end – 10%. Values for fractions in between are distributed almost uniformly along the lines. The density distribution of the form proposed by Calcaneo-Roldan and Moore (2000) was used.

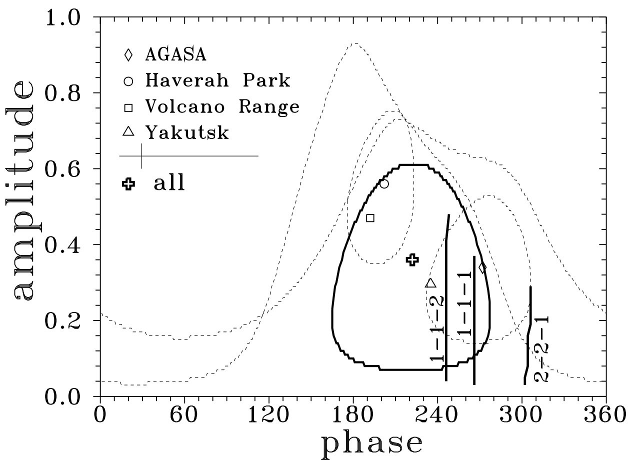

Fig. 1. Amplitude and phase of anisotropy for energies above 4×10^{19}eV seen in the northern hemisphere data and predicted by examined DM models.

4 Conclusions

4.1 First harmonic method

The conclusion which can be derived from the comparison of “observed and expected” is such that there is no significant contradictions for any DM halo production models (even the oblate spheroid predictions are quite close to 1σ statistical “error box”). This result is not far from the one given in (Medina Tanco and Watson, 1999). According to limitations of the harmonic analysis mentioned above such conclusions could be, however, induced by the method of analysis itself, not to real lack of information in the data.

4.2 The bin-by-bin method

In our view, a superior method is to examine the whole sky on a bin-by-bin basis. In Fig.2 some examples of such analyses are given. For a given halo shape and different fractions of UHECR created in the halo the χ^2 value can be calculated. By comparing such values with respective critical values on 1-, 2-, and 3σ levels some limits on the UHECR production in the halo can be given.

Energies of GEAS used for Fig.2 are the same as for Fig.1. As is clearly seen the bin-by-bin analysis leads to significant limits on DM halo production mechanisms. Another interesting conclusion is that although some minima of the curves in Fig.2 can be found, their interpretation as a “best fitted” value of the fraction of UHECR produced in the DM halo

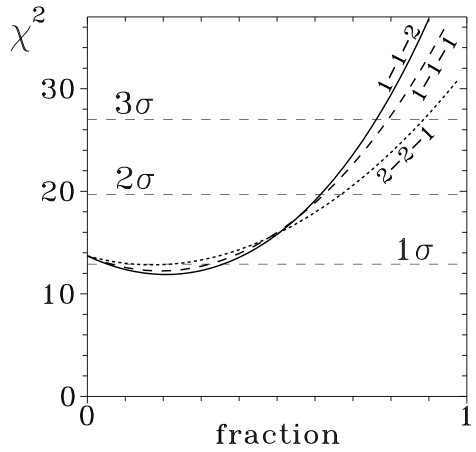

Fig. 2. The χ^2 of the comparison between all sky UHECR direction map and predictions of DM halo models as a function of fraction of CR produced in the halo.

model is not certain (from the statistical point of view).

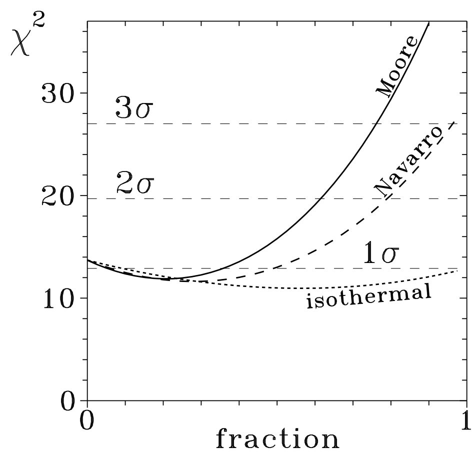

Fig. 3. The χ^2 values as in Fig.2 for the prolate halo shape and different DM distributions.

To see the effect of using different DM distributions within halos, similar calculations have been made using functions proposed by Navarro *et al.* (1996) and for a modified isothermal distribution (Calcaneo-Roldan and Moore, 2000) and the respective χ^2 lines are given in Fig.3. It is seen that the Navarro fuction is slightly less restrictive than the one preffered in the present work. The isothermal distribution allows for much more abundant CR production in the halo due to the artifical depletion of the central density assumed.

Similar analyses have been performed for EAS of energies higher than 10^{19}eV. In the Table the summary of results for the prolate halo shape and the Moore density distribution are given.

There is a class of UHECR production models assuming UHECR creation in processes of very heavy DM particle annihilation. They lead to the production power proportonal to the square of the DM density which gives a much stronger gradient for the source distribution. Thus the limits for the possible fraction of UHECR produced this way are (Wibig and Wolfendale, 1999) more restrictive, thereby making these hypothesis surely unlikely.

Table 1. Limits for UHECR production in DM halo models

Energy	halo shalpe	1σ	2σ	3σ
$> 10^{19}$eV	1-1-1	0.18	0.25	0.31
	1-1-2	0.18	0.24	0.30
	2-2-1	0.22	0.30	0.37
$> 4 \times 10^{19}$eV	1-1-1	0.32	0.62	0.79
	1-1-2	0.36	0.62	0.76
	2-2-1	0.22	0.67	0.89

4.3 Overall conclusion

Concluding we can say that for the examined UHECR creation in DM halo models the existing data on directions of observed giant EAS give limits for the fraction of cosmic rays which can originate in the halo of order of 25% for $E > 10^{19}$eV and 62% for $E > 4 \times 10^{19}$eV at the 95% confidence level.

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