

## Small scale anisotropies of UHECRs from super-heavy halo dark matter

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**Abstract.** The decay of very heavy metastable relics of the Early Universe can produce ultra-high energy cosmic rays (UHECRs) in the halo of our own Galaxy. In this model, no Greisen-Zatsepin-Kuzmin cutoff is expected because of the short propagation distances. We show here that, as a consequence of the hierarchical build up of the halo, this scenario predicts the existence of small scale anisotropies in the arrival directions of UHECRs, in addition to a large scale anisotropy, known from previous studies. We also suggest some other observable consequences of this scenario which will be testable with upcoming experiments, as Auger, EUSO and OWL.

### 1 Introduction

The production of heavy particles ( $m_X \sim 10^{12} - 10^{14}$  GeV) in the early universe has been studied by several authors (see for instance Chung et al. (1998); Berezhinsky et al. (1997); Kuzmin (1997); Kuzmin and Tkachev (1999)). If these particles have a sufficiently long lifetime they can play a role as dark matter candidates and possibly generate ultra-high energy cosmic rays, as widely discussed by Berezhinsky et al. (1997); Birkel and Sarkar (1998); Berezhinsky et al. (1998); Blasi (1999). For this to work, these particles must be quastable, which implies lifetimes larger than the present age of the Universe. Though problematic, this feature can be accomplished, as discussed by Berezhinsky et al. (1997) among others.

This model provides specific predictions for the spectrum, composition and anisotropy of the arrival directions of UHECRs, and these findings can be compared with present and upcoming data. We will concentrate here on the expected small scale anisotropies, after providing a short summary of the previous studies on the topic.

The decay of the heavy relics is expected to result mainly in the generation of hadronic jets initiated by quark and anti-

quarks. The content of the jets is strongly dominated by pions (95%), with a small contamination in the form of protons and neutrons (and their antiparticles). The decay products of the pions are dominated by gamma rays (that represent the bulk of ultra-high energy particles in this model), neutrinos and electron-positron pairs.

Some features of the hadronization process are sufficiently well understood to allow the following predictions: *i*) a flat energy spectrum of UHECRs; *ii*) composition dominated by gamma rays rather than by protons (see however Birkel and Sarkar (1998)). Moreover, as in all top-down models, heavy elements are expected to be completely absent. Unfortunately present data on the composition is extremely poor and it is impossible to rule out or confirm the presence of gamma rays in the UHECR events (however recent evidence against a gamma ray dominated composition seems to arise from the analysis carried out by Ave et al. (2000)).

Dubovsky and Tynyakov (1998) and Berezhinsky et al. (1998) first addressed the issue of the anisotropy, recently discussed in detail by Evans, Ferrer and Sarkar (2001). The anisotropy results from the asymmetric position of the Earth in the Galaxy, so that the flux of UHECRs coming from the direction of the galactic center should be appreciably larger than the flux from the anticenter direction. Berezhinsky and Mikhailov (1999) and Medina Tanco and Watson (1999) considered this issue more quantitatively, taking into account the exposure of the present experiments. All authors concur that the present data is consistent with the predictions of the relic model for practically all reasonable values of the model parameters.

Recently an interesting pattern has arisen from the analysis of the events with energy larger than  $4 \times 10^{19}$  eV: Takeda (1999) presented a sample with this energy cut, comprising 47 events, whose overall distribution in space does not show appreciable deviation from isotropy. However, 3 doublets and one triplet could be identified within an angular scale of  $2.5^\circ$ , comparable with the angular resolution of the experiment. A complete analysis, including the whole set of UHECR events above  $4 \times 10^{19}$  eV from the existing exper-

iments was performed by Uchihori et al. (2000). This extended sample comprises 92 events and shows 12 doublets and two triplets (each triplet is also counted as three doublets) within an angle of  $3^\circ$ . The chance probability of having more than this number of doublets was estimated to be  $\sim 1.5\%$ . Although it is probably too soon to rule out the possibility that these multiplets are just a random fluctuation, it is instructive to think about the possibility that their presence contains some physical information about the sources of UHECRs. Most of the top-down models for UHECRs (e.g. strings, necklaces, vortons, etc.) cannot naturally explain the multiplets.

In the following we will discuss how the multiplets can be interpreted in the context of the super-heavy dark matter (SHDM) model.

## 2 The halo dark matter

There is mounting evidence that there is plenty of dark matter in the universe. The formation of the large scale structures is relatively well understood in terms of hierarchical clustering, where larger objects are formed by the continuous merging of smaller ones.

High resolution N-body simulations, e.g., Ghigna et al. (1999), suggest that the density of dark matter particles in galaxy size halos is cuspy in the center, with the density profile scaling as  $\sim r^{-\gamma}$  with  $\gamma \sim 1 - 1.5$  on distances  $r$  which are much smaller than a core radius, of the order of several kpc in size; outside the core, the slope of the profile steepens, scaling as  $\propto r^{-3}$  at large distances.

The smooth component of the dark matter can be modeled in the form suggested by numerical simulations (Navarro et al. (1996)):

$$n_H(r) = n^0 \frac{(r/r_c)^{-1}}{\left[1 + \frac{r}{r_c}\right]^2} \quad (1)$$

where  $r_c$  is the core size and  $n^0$  is a normalization parameter. These two parameters can be set by requiring that the halo contains a given total mass ( $M_H$ ) and that the velocity dispersion at some distance from the center is known (in the case of the Galaxy, the velocity dispersion is  $\sim 200$  km/s in the vicinity of our solar system.). The parametrization of the dark matter density profile is not unique, and there is some discussion in the literature in this respect. Alternative fits to the simulated dark matter halos and a discussion of whether or not simulated halos appear to be consistent with observations are provided by Ghigna et al. (1999).

In addition to the smooth dark matter distribution, represented by eq. (1), N-body simulations also show that there is a clumped component which contains  $\sim 10 - 20\%$  of the total mass. The clumps form galactic halos by merging, mainly at about  $z \sim 3$  although the process is continuous. Much of the mass initially in a small clump which falls onto and orbits within the larger halo after that time gets tidally stripped from it. The amount of mass which is lost from any

given clump increases as the distance of closest approach to the galactic halo center decreases; the mass is stripped away, from the outside in, as the clump falls towards the center. We will call the size of a clump, after its outsides have been stripped away, the tidal radius of the clump. Dynamical friction makes the clumps gradually spiral in towards the halo center.

The spatial distribution of the clumps in the halo is not the same as that of the dark matter. We found that a good fit to the joint distribution in clump mass and position in the simulations of Ghigna et al. (1999) is

$$n_{cl}(r, m) = n_{cl}^0 \left(\frac{m}{M_H}\right)^{-\alpha} \left[1 + \left(\frac{r}{r_c^{cl}}\right)^2\right]^{-3/2}, \quad (2)$$

where  $n_{cl}^0$  is a normalization constant,  $r_c^{cl}$  is the core of the clumps distribution, and  $\alpha$  describes the relative numbers of massive to less massive clumps. The simulations suggest that  $\alpha \sim 1.9$  (Ghigna et al. (1999)). The constraints on the core size are weaker—we will study the range where  $r_c^{cl}$  is between 3 and 30 percent of  $R_H$ . In (Ghigna et al. (1999)), a halo with  $M_H \approx 2 \times 10^{12} M_\odot$  contains about 500 clumps with mass larger than  $\sim 10^8 M_\odot$ . This sets the normalization constant in eq. (2).

Clumps in the parent NFW halo are truncated at their tidal radii. The tidal radius of a clump depends on the clump mass, the density profile within the clump, and on how closely to the halo center it may have been. We assume that clumps of all mass are isothermal spheres (even though they are not truly isothermal, Ghigna et al. (1999) suggest this is reasonably accurate):  $\rho_{cl}(r_{cl}) \propto 1/r_{cl}^2$ , where  $r_{cl}$  is the radial coordinate measured from the center of the clump. The tidal radius of a clump ( $R_{cl}$ ) at a distance  $r$  from the center of the parent halo is determined by requiring that the density in the clump at distance  $R_{cl}$  from its center equals the local density of the NFW halo at the distance  $r$ . This means that

$$R_{cl} = \left(\frac{m}{4\pi n^0 x_c}\right)^{1/3} x^{1/3} \left[1 + \frac{x}{x_c}\right]^{2/3}, \quad (3)$$

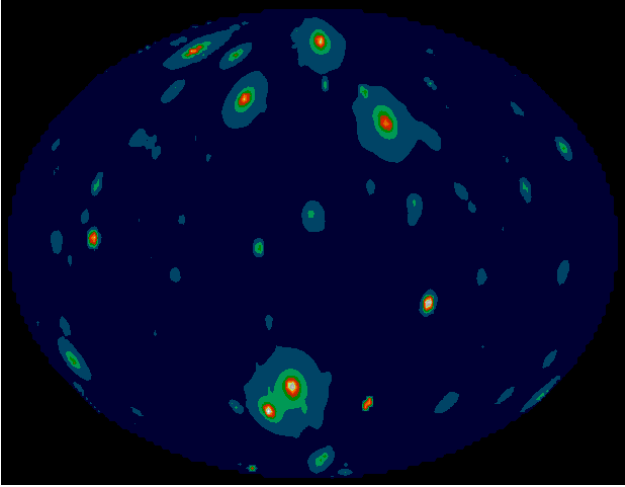
where  $x_c = r_c/R_H$ ,  $x = r/R_H$  and  $R_H$  is the virial radius of the halo, of order 300 kpc. The average overdensity within  $R_H$  is about 200 (Ghigna et al. (1999)).

## 3 Small scale anisotropies in UHECRs

As shown by Berezhinsky et al. (1998) and Medina Tanco and Watson (1999), the total (energy integrated) flux of UHECRs per unit solid angle from a smooth distribution of dark matter particles in the halo is:

$$\frac{d\Phi}{d\Omega} \propto \int_0^{R_{max}} dR n_H(r(R)), \quad (4)$$

where  $R$  is the distance from the detector, and  $r$  is the distance from the galactic center (so  $R$  and  $r$  are related by trigonometrical relations accounting for the off-center position of the Earth in the Galaxy). The upper limit,  $R_{max}$ , depends on the line of sight.



**Fig. 1.** Small scale anisotropies in the direction of arrival of UHECRs from the decay of super-heavy relics.

The existence of a clumped component changes the flux in eq. (4) only in that  $n_H$  should be replaced with the total dark matter density, the sum of the smooth and the clumped components.

Berezinsky (2000) was the first to point out that overdense regions would generate an excess in the UHECR flux, that would eventually result in multiplets of events.

To see how important the clumped contribution is, we used two different ways of simulating the observed number of events. The first approach consisted of calculating the flux per unit solid angle [eq. (4)] along different lines of sight directly, taking into account the smooth plus clumped contributions to the total density profile [eqs. 1 and 2]. Once a smooth flux map distribution had been obtained, the UHECR events were generated from this distribution. In the second approach, the events were generated in two steps. First, a random subset of the dark matter distribution, which is supposed to represent the subset of particles which decayed, was generated. The second step was to draw particles from this distribution, and then weigh by the probability that the event would actually have been detected—so a chosen particle generates an event with probability  $\propto 1/r^2$ , where  $r$  is the distance between the particle and the detector. In both codes, the detector was assumed to be at the position of the Earth in the Galaxy, and a cut on the directions of arrival was introduced to account for the exposure of the AGASA experiment (taken here as an example).

Fig. 1 shows as an example one of the generated flux maps: the map represents the ratio of the total flux including the contribution from clumps, to the flux obtained by using a smooth NFW profile. The various free parameters were  $r_c = 8$  kpc,  $r_c^{cl} = 10$  kpc, and the mass distribution was truncated at a clump mass of 1% of the mass of the NFW halo. This sort of plot emphasizes the clump contribution.

To calculate the small scale anisotropies, we generated  $10^4$  mock samples, each of 92 observed events, and counted the

number of doublets and triplets for angular scales of 3, 4, and 5 degrees. Our codes can also be used to check the corresponding numbers for the case of isotropic arrival directions (as in Uchihori et al. (2000)). Two sets of values of the cores for the NFW and the clumped component were adopted, one in which  $r_c = 8$  kpc and  $r_c^{cl} = 10$  kpc (case 1) and the other with  $r_c = r_c^{cl} = 20$  kpc (case 2). The observed numbers of doublets within 3, 4, and 5 degrees for an isotropic distribution of arrival directions are given in Uchihori et al. (2000) and are 12, 14 and 20 respectively. The number of doublets that we obtain in case 1 are 8, 14, and 21 within 3, 4, and 5 degrees respectively. The probability that the number of doublets equals or exceeds that observed is 12%, 47% and 57% respectively. This should be compared with the 1.5%, 13.4% and 15.9% quoted by Uchihori et al. (2000) for an isotropic distribution of arrival directions.

We repeated the same calculation for the case 2. The corresponding averages and probabilities of exceeding the observed number of doublets within 3, 4 and 5 degree scales are 6.6, 12, and 18, and 4.5%, 29% and 36% respectively.

In both cases 1 and 2, the number of doublets on angular scales of 4 and 5 degrees is consistent with the observed values; presumably the discrepancy at 3 degrees is random chance.

We have also studied the occurrence of triplets. There is some ambiguity as to how a triplet is best defined; we have chosen to define triplets as configurations in which all three pairs would have been classified as doublets. (This means, for example, that a co-linear configuration of two doublets is not necessarily a triplet.) With this definition, the average number of triplets in case one is 0.5, 1.5 and 3, with the probability of having more than the observed triplets (2, 2, 3 respectively) equal to 4%, 16% and 35%. For case 2, the correspondent numbers are 0.4, 1, and 2.5 triplets and 2%, 8% and 20% for the probabilities to have more triplets than observed.

What is responsible for the multiplet-events in the SHDM model? If we study the case in which all the halo mass is in the smooth NFW component, then the number of doublets typically drops by one or two. This suggests that the anisotropy due to our position in an NFW halo can result in a number of multiplets of events which is considerably larger than if the arrivals were from an isotropic background. The number of multiplets from the clumped component is mainly affected by the presence of large nearby clumps, whose number depends on the high mass cutoff imposed in the mass function of clumps. A maximum mass of 1% of the halo mass implies a total mass in the clumps of  $\sim 10 - 15\%$  of  $M_H$ , consistent with the results of the simulations by Ghigna et al. (1999). Larger cutoffs imply larger mass fractions, which are harder to reconcile with the N-body simulations.

The study of the composition, together with an improved measure of the spectrum of UHECRs, should nail down the nature of the “real” sources of UHECRs and confirm or rule out the SHDM model.

## 4 Conclusions

In this paper we focused on the small scale anisotropies expected in the model of super-heavy relics as the sources of UHECRs. In general, top-down models for the production of particles having energy in excess of  $10^{20}$  eV do not generate small scale anisotropies, with the possible exception of chance occurrences, that however can be isolated by a sufficiently large statistics of events. We demonstrated here that the model of super-heavy relics in the halo of our galaxy is an exception. This result is due to two main factors: 1) the inhomogeneous distribution of the smooth component of dark matter in the halo, and 2) the presence of a clumped component, predicted by N-body simulations as a consequence of hierarchical structure formation.

We find that with the current statistics, the number of multiplets (doublets and triplets) of events above  $4 \times 10^{19}$  eV predicted by the model agrees with the observed one. These multiplets are mainly due to the smooth component, and in this sense they are a chance occurrence determined by the inhomogeneous dark matter distribution. The presence of the clumps makes the occurrence of multiplets slightly more probable.

With an increased statistics of observed events, a quantity that would better describe the clustering of events on any scale is the correlation function, rather than the number of doublets and triplets, as described by Blasi and Sheth (2000). This increased statistics will eventually become available with upcoming detectors as the Pierre Auger Observatory (Cronin (1999)) or future experiments as EUSO/Airwatch (<http://ifcai.pa.cnr.it/ifcai/euso.html>) and OWL (<http://owl.gsfc.nasa.gov>).

The large enhancement in the number of events will also allow for a crucial discrimination between the model of super-heavy relics in the halo and other models, in terms of composition and spectra. In fact the super-heavy relic model predicts a gamma ray dominated composition of the highest energy events and a very flat spectrum, as determined by the hadronization process.

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