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Super heavy dark matter and UHECR anisotropy at low energy

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Abstract

Super heavy quasi-stable particles are naturally produced in the early universe and could represent a substantial fraction of the dark matter: the so-called super heavy dark matter (SHDM). The decay of SHDM represents also a possible source of ultra high energy cosmic rays (UHECR), with a reliably calculated spectrum of the particles produced in the decay ($\propto E^{-1.9}$). The SHDM model for the production of UHECR can explain quantitatively only the excess of UHE events observed by AGASA. In the case of an observed spectrum not showing the AGASA excess the SHDM model can provide only a *subdominant* contribution to the UHECR flux. We discuss here the basic features of SHDM for the production of a *subdominant* UHECR flux, we refer our study to the possible signatures of the model at the Auger observatory discussing in particular the expected chemical composition and anisotropy.

Keywords: Super heavy dark matter; Ultra high energy cosmic rays; Anisotropy

1. Introduction

Ultra high energy cosmic rays (UHECR) are the most energetic particles known in nature with energies exceeding 10^{20} eV, the observation of particles with such high energies raises many interesting questions about their origin and composition that involve both astrophysics and particle physics.

Soon after the discovery of the cosmic microwave background (CMB) radiation it was shown that the flux of UHE protons should be characterized by a sharp steepening at energy $\sim 5 \times 10^{19}$ eV, due to the photo–pion production process on the CMB radiation field [1]. This effect is the well known Greisen–Zatsepin–Kuzmin (GZK) cut-off. After a few decades of observations the detection of the GZK steepening of the CR flux is one of the major open problems in CR physics with experimental data still not conclusive. The AGASA experiment [2] observed 11 events with energy $E > 10^{20}$ eV in contrast with the expected depletion due to the GZK effect; on the other hand the HiRes experiment [3] observed an UHECR flux in agreement with the GZK cut-off [4]. The discrepancy between these two experimental results has been widely discussed and recently it has been shown that the GZK feature cannot be accurately determined with the small sample of events collected by AGASA and HiRes and that the discrepancy between the two experiments has a low statistical significance (at a 2σ level) [5]. Moreover, AGASA and HiRes are based on different experimental techniques: a ground array the former and a fluorescence detector the latter. Taking this difference into account, the differing results of AGASA and HiRes can be interpreted assuming the presence of a 30% systematic error in the relative energy determination. As shown by [6,5], correcting for these systematics the observations of AGASA and HiRes are brought into agreement at energies $E < 10^{20}$ eV and the discrepancy at the highest energies is softened. Recently, the Pierre Auger observatory [7], under completion in Argentina, published its first observations of the UHECR flux combining the ground based and fluorescence detection techniques. This preliminary result seems to confirm the presence of the GZK steepening [8].

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The presence of an excess of very high energy events, as claimed by AGASA, inspired the introduction of several exotic models for the production of UHECR. These models, collectively called top–down, reproduce the excess of AGASA and give also an explanation for the lack of any clear astrophysical counterpart to the highest energy events observed. Indeed, at energies $E > 5 \times 10^{19}$ eV the proton attenuation length is only about 20–30 Mpc and an astrophysical source at this distance should have been seen at least in different frequency ranges. This evidence could imply that particles with energy $E \sim 10^{20}$ eV have a different (top–down) origin respect to those at lower energies. Many different ideas have been proposed among top–down models: strongly interacting neutrinos [9] and new light hadrons [10] as unabsorbed signal carriers, Z-bursts [11], Lorentz-invariance violation [12], topological defects (TD) (see [13,14] for a review), and superheavy dark matter (SHDM) (see [15] for a review).

The two models based on SHDM and TD have common features: in both cases UHECR are produced in the decay (SHDM) or annihilation (TD) of super heavy particles, with a typical mass $M_X > 10^{13}$ GeV, that we will call collectively X-particles. As already discussed in [16], TD are distributed over cosmological distances therefore give only a marginal contribution to the UHECR flux. We will not discuss this case here, concentrating our attention on the SHDM hypothesis. The possible existence of super heavy relic particles is an interesting conclusion of modern cosmology, being first suggested in connection with UHECR production [17,18] and later developed as a suitable candidate for dark matter (DM).

Two main problems should be addressed in the discussion of SHDM models: how particles with very high mass ($M_X > 10^{13}$ GeV) can be quasi-stable, with a lifetime much longer than the age of the universe t_0, and how their abundance can be dominant in the universe today. The stability of SHDM can be achieved assuming the existence of a discrete gauge symmetry that protects the particle from decaying, in they same way as neutralino stability through R-parity in super symmetry (SUSY). This discrete symmetry can be weakly broken, assuring a lifetime $\tau_X > t_0$, through wormhole [17] or instanton [18] effects, an example of a particle with a lifetime exceeding the age of the universe can be found in [19]. The abundance of SHDM can easily be dominant in the universe today, with a SHDM density $\Omega_{\rm SHDM} \sim \Omega_{\rm DM}$. This effect can be obtained by gravitational production that resembles the production of density fluctuations during inflation [20].

The top–down hypothesis and, in particular, the UHECR production through SHDM decay can account only for the highest energy part of the observed spectrum, as in the case of AGASA excess at energies $E > 5 \times 10^{19}$ eV [16]. However, UHECR observations cannot exclude SHDM as explanation of the DM problem, assuming that SHDM is gravitationally produced than the X particle mass and density are unambiguously fixed, the only free parameter left to fit UHECR observations is the life-time τ_X. The observation of the AGASA excess fixes this value as $\tau_X \simeq 10^{20}$ y [16,21]. From the HiRes, Yakutsk and Auger data, that are compatible with the GZK steepening, follows only a lower bound on the value of τ_X. Within this lower bound it is still possible to test the SHDM hypothesis being connected with a *subdominant* contribution to the observed UHECR flux. In the present paper we will discuss such a possibility referring in particular to the observations of chemical composition and anisotropy of the Auger observatory.

The UHECR production through the decay of SHDM shows three basic signatures that can be used to test the model:

- SHDM particles, as any DM candidate, are clustered by gravitational interaction and accumulated in the halo of our galaxy with a typical over-density of $\delta \sim 2 \times 10^5$ [17]. Hence the UHECR spectrum from SHDM can overcome the constrain of the GZK steepening [17].
- In the decay of X-particles pions are extensively produced [21], therefore UHE neutrinos and photons are the dominant component of the primary flux [21].
- The non-central position of the Sun in the galactic halo results in an anisotropic flux of UHECR observed on earth [21,22].

The photons (and neutrinos) dominated flux expected from SHDM is one of the most striking predictions of the model. Recently, the expected SHDM photon flux at energies $E > 10^{19}$ eV was compared with the photon fraction in the AGASA events [21]: this fraction was determined by different groups with different results, being around 50% in [23] and higher 67% in [24]. Another important analysis on the photon content in UHECR events was recently published by the Auger collaboration [25]. From this analysis, performed at the highest ($E \gtrsim 10^{19}$ eV) energies, follows a stringent limit on the photon fraction that is around 2% at 10^{19}eV and below 40% at 10^{20} eV [25]. As recently discussed in [26], these limits do not exclude, but disfavor, the SHDM hypothesis for the explanation of the observed UHECR spectrum, in the next section we will come back to the expected photon fraction in SHDM models.

The second most important signature of UHECR production by SHDM is the peculiar anisotropy expected. This anisotropy in the flux is guaranteed by our position respect to the galactic center (GC). In particular, the distance between the Sun and the outer boundary of the galaxy is larger in the GC direction respect to the anti-center direction. In order to evaluate the expected anisotropy it is necessary to assume a particular distribution of SHDM in the galaxy: in this respect numerical simulations of the galactic DM distribution show an increase of the DM density towards the GC as $\propto r^{-1}$ [27] or $\propto r^{-1.5}$ [28], this further enhancing the expected anisotropy.

Already several authors have considered anisotropy computations, with reliable predictions of the expected sig-