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Constraints on top-down models for the origin of UHECRs from the Pierre Auger Observatory data

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Abstract: Taking into account the Pierre Auger Observatory limits on the photon fraction among the highest energy cosmic rays, we show that the models based on the decay of super-heavy dark matter in the halo of our Galaxy are essentially excluded from being the sources of UHECRs unless their contribution becomes significant only above ~ 100 EeV. Some top-down models based on topological defects are however compatible with the current data and may be best constrained in future by the high-energy neutrino flux limit.

Introduction

Ultra-high-energy cosmic rays (UHECRs) raise a number of observational as well as theoretical problems. While accelerating particles up to energies above 10^{20} eV appears challenging in even the most efficient astrophysical accelerators, a large variety of so-called *top-down models* have been proposed in which UHECRs are not accelerated from ambient, low-energy particles, but produced directly at ultra-high energy from the decay of putative supermassive particles with masses in excess of $\sim 10^{21}$ eV. Two main classes of such models can be considered, with distinct generic properties. The first one involves the decay or annihilation of topological defects (TDs) produced through a phase transition in the early universe [1]. Such events would occur roughly homogeneously throughout the universe, and generate supermassive particles that would in turn decay into quarks and leptons and lead to secondary UHECR protons and photons with an energy spectrum and relative abundances characteristic of the underlying hadronization process. These UHECRs would then propagate through the universe in much the same way as if accelerated by astrophysical sources, interacting with the CMB photons to produce e^+e^- pairs and pions (in the case of protons) – the so-called *GZK effect* [2].

In the second class of top-down models, the supermassive particles responsible for the observed UHECRs are produced directly in the early Universe [3] and have a lifetime larger then the age of the Universe. An important motivation for such a scenario is that these particles could make up the inferred dark matter in the universe, which also provides a natural link between cosmology and UHECRs, allowing one to relate their expected flux to the properties of these super-heavy dark matter (SHDM) particles. A key feature of SHDM scenarios is that the main contribution to the highest energy cosmic rays observed at Earth would be provided by supermassive particles concentrated in the halo of our Galaxy, so that propagation effects (including the GZK suppression of the spectrum) would be supressed by the two orders of magnitude [3]. These models have thus been extensively studied in the context of the report by the AGASA experiment of an excess of UHECR events above 10^{20} eV [4]. However, neither the spectrum reported by the HiRes experiment (suggesting the presence of the expected GZK suppression [5]) nor the Auger spectrum by themselves can rule out SHDM models.

A detailed review of the various top-down models can be found in ref. [6]. A review of previous UHE photonlimits can be found in ref. [7] and a summary of neutrinolimits in ref. [8]. In this paper, we analyse the constraints set on both TD and SHDM models by the data of the Pierre Auger Observatory, normalising the UHECR flux to the Auger spectrum [9] and using the derived photon limit [10] and neutrino flux limit [11].

Super-heavy dark matter scenarios (SHDM)

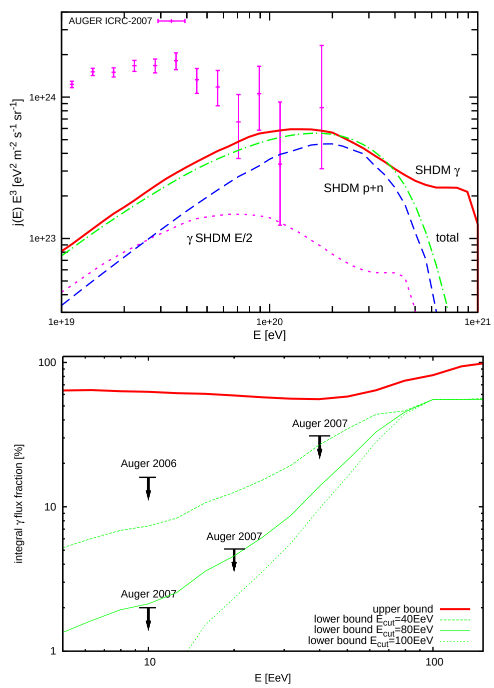

Figure 1: Top: Example of SHDM decay products fit to the Pierre Auger Observatory spectrum. Solid line shows the photon flux from SHDM, the dashed line is the SHDM nucleon flux, the dotted line is photon flux reconstructed as protons (in approximation $E = E_\gamma/2$) and the dot-dashed line is the total reconstructed spectrum from SHDM. Bottom: Corresponding photon fraction in percentage of the total UHECR spectrum integrated above energy E. Photon fraction located in the range between red and green lines with assumption that SHDM is responsible for the observed UHECR flux above 40 EeV, 80 EeV and 100 EeV. “Auger 2006” and “Auger 2007” upper limits are from [12] and [10], respectively.

As recalled above, most SHDM models predict UHECR fluxes dominated by the contribution of the Milky Way halo, so that propagation effects on both the spectrum and the composition are insignificant for the commonly used radio background models [13]. UHECRs should thus be observed as produced, with a relatively hard spectrum up to a fraction of the initial mass of the SHDM progenitors and a dominant photon component (here we use the recent results of [14]). The latter prediction can be tested with Auger, thanks to the photon/hadron discrimination power of both the surface detector and the fluorescence detector [12, 10]. In Fig. 1a, we show a fit of the highest energy part of UHECR spectrum by SHDM decay products, assumed to account for the measured flux above $8\,10^{19}$ eV. In addition to the primary photon flux, we show the “apparent flux” as would be reconstructed by the Auger analysis procedure assuming proton primaries, through which a photon of energy E_γ would be typically misinterpreted as a proton of energy $E_\mathrm{p} = E_\gamma/2$. This “apparent” photon component, added to the nucleon flux, makes up the total inferred UHECR spectrum.

To explore the parameter space of SHDM models, we fit the last few bins of the spectrum (above $4\,10^{19}$ eV, $8\,10^{19}$ eV, or 10^{20} eV) using different values for the mass and normalization amplitude, according to the procedure described in [15].

In Fig. 1b, we show the corresponding photon fraction for two extreme cases of SHDM scenarios, giving the largest (upper curve) or lowest possible photon fraction (three lower curves). The latter are derived under the assumption that SHDM particles provide the dominant contribution to the UHECRs above the three indicated energies, respectively. The superimposed experimental limits show that SHDM top-down scenarios are ruled out by the Auger photon limit, except if they only contribute significantly to the cosmic-ray flux above 10^{20} eV. Therefore, SHDM models can only have a subdominant contribution to essentially all the UHECRs observed so far.

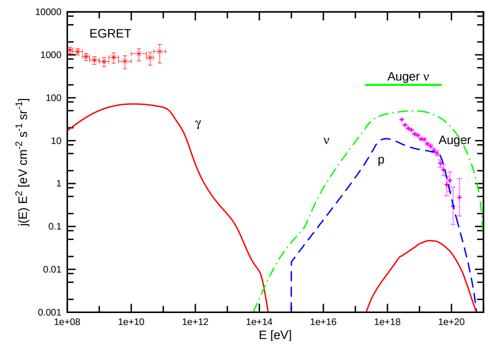

Figure 3: Photon (solid red line), neutrino (dashed-dotted green line), and proton (dashed blue line) fluxes from a TD model with cascade photons down to GeV. Also shown are Pierre Auger observatory UHECR spectrum [9] and neutrino limits [11] and the EGRET [16] limit on the diffuse gamma-ray background.

Scenarios involving Topological Defects (TDs)

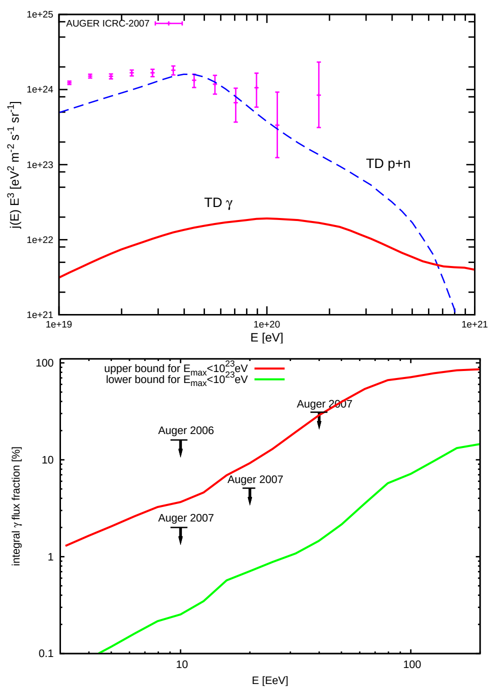

Figure 2: Top: Example of a fit of the Auger spectrum with nucleons (dahsed line) and photons (solid line) arising from TDs down to 40 EeV. Bottom: Photon fractions among UHECR, as in Fig. 1, for super-heavy particle masses, $M_{\rm SH} = 2E_{\rm max} < 2 \times 10^{23}$ eV.

The injection spectrum and composition of UHECRs produced by the decay or annihilation of TDs are similar to those of the SHDM case. However, since TDs are expected to be evenly distributed throughout the universe, propagation effects are important and photons are strongly suppressed by their interactions with the extragalactic photon backgrounds. Their energy loss length is much smaller than that of protons up to above 10^{20} eV, so that the predicted photon-to-proton ratio *at Earth* remains limited (much lower than the ratio at the source). In Fig. 2a, we show a fit of the highest energy part of the spectrum within a typical TD model, where the proton component dominates up to the highest detected energies. In Fig. 2b, the expected range of photon-to-proton ratios is shown for a variety of TD models (see, e.g., [1]), with different values of the maximum energies at the source. As can be seen, the current experimental limits only constrain the most photon-rich cases, and a wide range of models remain compatible with the data. Note that the model predictions arevery sensitive to the actual spectrum they are trying to account for. In particular, the results are different if one fits the AGASA data or the HiRes data with SHDM and TD models [17]. In the case of the Pierre Auger Observatory it is more difficult to constrain contribution of those models due to presence of the supression in the spectrum at highest energies [9].

In Fig. 3, we plot the overall proton, photon and neutrino spectra associated with the propagation of UHECRs from a typical TD model, down to 100 MeV. This involves the secondary neutrinos produced by charged pion decay and the gamma-rays from the electromagnetic cascade induced by the UHE photons in the extragalactic medium. Such TD models are not constrained by the EGRET [16] limit on the diffuse gamma-ray background. The neutrino upper limit set by Auger at high energy is also shown. Larger statistics expected in the future may lead to the strongest constraints on these models from the Auger data, or possibly the detection of their neutrino counterparts. Top-down photons should also be detected eventually in this case.

Discussion

We have analysed the implications to top-down UHECR source scenarios of three complementary experimental results of the Pierre Auger Observatory presented in this conference: the energy spectrum, the photon fraction limit and the neutrino flux limit. We found that super-heavy dark matter models are strongly constrained by the absence of identified photon candidates in the Auger data. In particular, they cannot provide the dominant contribution to the overall UHECR flux at any energy below $\sim 10^{20}$ eV, which strongly restricts their motivation. On the other hand, models involving topological defects generally predict photon fractions after propagation that are compatible with the current data, while their neutrino counterpart may be more strongly constrained by future neutrino flux limits obtained with the Pierre Auger Observatory.

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