Hunting for superheavy dark matter with the highest-energy cosmic rays

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In 15 years of data taking, the Pierre Auger Observatory has observed no events beyond $10^{11.3}$ GeV. This null result translates into an upper bound on the flux of ultrahigh-energy cosmic rays, implying $J(>10^{11.3} \text{ GeV}) < 3.6 \times 10^{-5} \text{ km}^{-2} \text{ sr}^{-1} \text{ yr}^{-1}$, at the 90% C.L. We interpret this bound as a constraint on extreme-energy photons originating in the decay super-heavy dark matter (SHDM) particles clustered in the Galactic halo. Armed with this constraint, we derive the strongest lower limit on the lifetime of hadronically decaying SHDM particles with masses in the range $10^{14} \lesssim M_X/\text{GeV} \lesssim 10^{16}$. We also explore the capability of NASA's future Probe of Extreme Multi-Messenger Astrophysics mission to search for SHDM signals.

I. INTRODUCTION

For the time being, a sovereign objective of the particle physics program is to ascertain the connection between dark matter (DM) and the Standard Model (SM). Existing data constrain the majority of DM to be nonbaryonic, cold or warm, and stable or long lived [1]. There are many ways to accommodate these constraints, and so feasible DM candidates with a very large range of masses and interaction strengths have been proposed [2].

For many decades, the favored models characterized the DM as a relic density of weakly interacting massive particles (WIMPs) [3–6].[1] However, LHC experiments have run extensive physics searches for WIMP signals which have returned only null results [11,12]. In addition, a broad WIMP search program has been developed with direct and indirect detection methods, which so far have given unsatisfactory answers [13–24]. Despite the fact that a complete exploration of the WIMP parameter space remains the highest priority of the DM community, there is now a strong motivation to explore alternatives to the WIMP paradigm.

Among the well-motivated ideas for what DM could be, the WIMPzilla hypothesis postulates that DM is made of gravitationally produced (nonthermal relic) superweakly interacting supermassive X-particles [25–33]. As a matter of fact, the gravitational production of super-heavy dark matter (SHDM) at the end of inflation may be taken as the only experimentally verified DM production mechanism because the observed cosmic microwave background (CMB) fluctuations have precisely the same origin. At the end of inflation, a fraction of fluctuations is not stretched beyond the horizon but remains as X-particles because the inflation slows down. The weakness of the gravitational interaction naturally explains the tiny initial abundance of WIMPzillas. Indeed, for such an abundance to be cosmologically relevant today, the X-particles must be supermassive.

On an entirely separate though somewhat related note, the surprising absence of any signals of new physics at the LHC experiments [34] seems to indicate that nature does not care too much about our notion of naturalness. Indeed, the required fine-tuning of SM fundamental parameters to accommodate the 15 orders of magnitude between the electroweak and the Planck scales may soon become a reality. Of course, the only reason one may try to incorporate such a shocking idea is that the existence of life may actually be contingent on this wicked conspiracy [35]. Namely, the weak and QCD scales come about just very close to one another, so that a plethora of atoms can exist to exchange energy over extremely long timescales, assembling the building blocks for life and durable habitats where it can thrive [36–39].[2] An additional, though not so severe,

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[1]For a precise calculation of the WIMP relic abundance, see [7,8]; partial wave unitarity dictates an upper bound on the WIMP mass ≤ 110 TeV [9,10].

[2]Investigations in string theory have applied a statistical approach to the enormous "landscape" of vacua present in the theory [37]. Remarkably, this huge number of metastable vacua, $\mathcal{O}(10^{500})$, can also accommodate the more severe fine-tuning required to characterize the SM with a small cosmological constant [40,41].

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anthropic argument applies to the abundance of DM, which cannot be too much larger or smaller than what is observed [42–45]. This is because DM plays a critical role in structure formation. Note that, since DM is only subject to the force of gravity, the gravitational Jeans instability which allows compact structures to form is not opposed by any force, such as radiation pressure. As a result, DM begins to collapse into a complex network of DM halos well before baryonic matter, which is impeded by pressure forces. Without DM, the epoch of galaxy formation would occur substantially later in the universe than is observed, and consequently the galaxies needed for our existence would not have formed in time. However, it is only the DM abundance and not any other details of the dark sector which is critical for life to exist. Therefore, it is quite reasonable to expect that the DM sector would not be as finely tuned as the visible SM sector. In other words, even if we are prepared to advocate the anthropic argument to accommodate the unnatural-ness of the weak scale, we would expect the DM particle spectrum to be as natural as possible, i.e., near the Planck scale that is the natural ultraviolet cutoff scale. For the most part, the WIMPzilla could then be a natural DM candidate and perhaps as well motivated as the WIMP paradigm.

Furthermore, precision CMB measurements enable a direct experimental test of the WIMPzilla hypothesis. This is because the production of SHDM during inflation gives rise to isocurvature perturbations that become sources of gravitational potential energy contributing to the tensor power spectrum of the CMB [46]. This implies a detectable primordial tensor-to-scalar ratio r in the CMB power spectrum. The combined (Planck satellite [47] together with BICEP2 and the Keck array [48]) 95% C.L. upper bound, $r < 0.07$, already constrains the X-particle mass to be $M_X \lesssim 10^{17}$ GeV in the limit of instantaneous reheating [49]. For slightly less efficient reheating, this upper limit strengthens to $M_X \lesssim 10^{16}$ GeV.

Note also that, while the WIMPzilla must be stable over cosmological timescales, instanton decays induced by operators involving both the hidden sector and the SM sector may give rise to observable signals in the spectrum of ultrahigh-energy cosmic rays (UHECRs) [50,51]. More concretely, the spectrum from WIMPzilla decay is expected to be dominated by photons and neutrinos because of a more effective production of pions than nucleons in the QCD cascades. Since the photons would not be attenuated owing to their proximity, they become the prime signal because it is easier to detect photons than neutrinos. In this article, we use the most recent UHECR data to derive the strongest lower limit on the lifetime of hadronically decaying WIMPzillas. We also investigate the prospects for next generation UHECR experiments to search for SHDM signals.

II. NEW LIMIT ON THE LIFETIME OF SHDM

The Pierre Auger Observatory has collected an exposure $\mathcal{E} = 67\,000$ km^2 sr yr without observation of any events with energy $E_0 > 10^{11.3}$ GeV [52]. This null result sets a generic upper limit on the integrated flux of UHECRs; namely,

$$J(>E_0) = \int_{E_0}^{\infty} J(E)dE < 2.44/\mathcal{E}$$
$$< 3.6 \times 10^{-5} \text{ km}^{-2} \text{ sr}^{-1} \text{ yr}^{-1}, \quad (1)$$

at the 90% C.L.; the limit is a factor of 1.266 less restrictive at the 95% C.L. [53]. When interpreted as a bound on extreme-energy photons and compared with existing bounds [54,55], this limit is more restrictive by about an order of magnitude, but at a slighter higher energy. Consequently, the all-particle limit of (1) could provide a better weapon to constrain WIMPzilla decay.

To estimate the photon flux from WIMPzilla decay, we need to evaluate two separate contributions: the astrophysical factor and the particle physics factor:

(1) The astrophysical factor is determined by the distribution of DM particles in the Galaxy. The DM density of X-particles is a function of the distance r from the Galactic Center and is usually described by a smooth profile function

$$\rho_{\text{DM}}(r) = \frac{\rho_s}{[1 - \beta + (r/r_s)^\alpha](1 + r/r_s)^{3-\alpha}}, \quad (2)$$

where ρ_s and r_s are respectively the scale density and scale radius. The traditional benchmark choice, motivated by N-body simulations, is the Navarro-Frenk-White (NFW) profile, in which $\alpha = 1$, $\beta = 1$, and $r_s = 24.42$ kpc [56]. The latest numerical simulations, however, seem to favor the Einasto profile,

$$\rho_{\text{DM}}(r) = \rho_s \exp\left\{-\frac{2}{0.17}\left[\left(\frac{r}{r_s}\right)^{0.17} - 1\right]\right\}, \quad (3)$$

which does not converge to a power law at the Galactic Center and becomes more chubby than NFW at kiloparsec scales, and where $r_s = 28.44$ kpc [57,58]. On the other hand, the cored profile put forward by Burkert, for which $\beta = 0$, $\alpha = 2$, and $r_s = 12.67$, is motivated by observations of galactic rotation curves [59]. Profiles steeper than the NFW have also been considered, e.g., the one by Moore and collaborators taking $\alpha = 1.16$, $\beta = 1$, and $r_s = 30.28$ kpc [60]. Herein, we take $\rho_X = \rho_{\text{DM}}$ and normalize to the local (solar) DM density, $\rho_X(r_\odot) = \rho_\odot^{\text{DM}} = 0.3$ GeV/cm^3, where $r_\odot = 8.33$ kpc is the distance between the Earth and the Galactic Center [61]. This leads to $\rho_s/(\text{GeV cm}^{-3}) = 0.184, 0.033,$
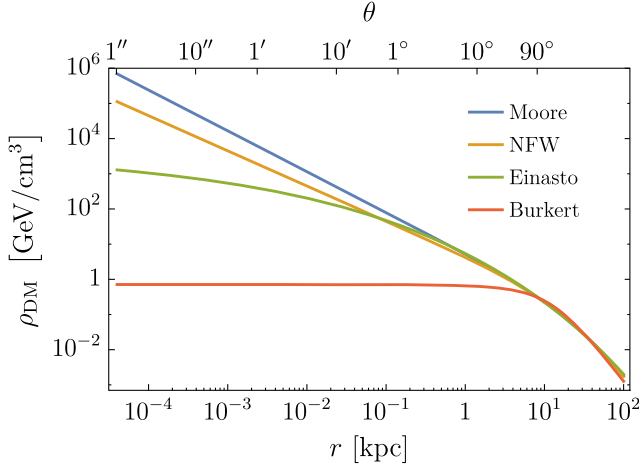
FIG. 1.   DM halo mass profiles. The upper horizontal axis shows the variation of the angle between the line of sight and the axis defined by Earth and the Galactic Center.

0.712, 0.105 for the profiles proposed by NFW, Einasto, Burket, and Moore, respectively [62]. A comparison of these profiles is given in Fig. 1. The ensuing discussion will be framed in the context of NFW, and we will comment on the other profiles after presenting our results.

(2) The particle physics factor is built in the fragmentation function of the SM particles produced by the X-decay. There is general agreement among the various computational schemes (relying on either analytic approximations [63] or else Monte Carlo simulations [64–67]) proposed to describe the secondary spectra of SM particles produced via X-decay. Herein, we obtain the final state stable particle spectra by solving the Dokshitzer-Gribov-Lipatov-Altarelli-Parisi equations numerically [68–71]. For an illustration, in Fig. 2, we show the resulting photon, proton, and neutrino ($\nu + \bar{\nu}$) spectra from $X \to q\bar{q}$ decay. From the observational perspective, the salient

features of the final state particles (photons, nucleons, and neutrinos) can be summarized as follows:

(a) the spectrum is flat ($dN/dE \propto E^{-1.9}$) and independent of the particle type,

(b) the photon/nucleon ratio is $2 \lesssim \gamma/N \lesssim 3$, and the neutrino/nucleon ratio is $3 \lesssim \nu/N \lesssim 4$, both of these ratios being quite independent of the energy.

The expected energy distribution on Earth follows the initial decay spectrum, whereas the angular distribution incorporates the (uncertain) distribution of dark matter in the Galactic halo via the line-of-sight integral [72–75]. The photon flux observed on Earth can be written as

$$J(E, \theta) = \frac{1}{4\pi} \frac{1}{\tau_X M_X} \frac{dN}{dE} \left\{ 2 \int_{r_\odot \sin\theta}^{r_\odot} dr\, r \frac{\rho_X(r)}{\sqrt{r^2 - r_\odot^2 \sin^2\theta}} \right.$$
$$\left. + \int_{r_\odot}^{R_H} dr\, r \frac{\rho_X(r)}{\sqrt{r^2 - r_\odot^2 \sin^2\theta}} \right\}, \tag{4}$$

where θ is the angle between the line of sight and the axis defined by Earth and the Galactic Center [76]. Here, τ_X is the WIMPzilla lifetime, and $R_H = 260$ kpc is the radius of the Galactic halo.

Following Ref. [77], we normalize the flux integrating over the whole sky ($0 < \theta < \pi$) and averaging over the directional exposure at the declination of the Pierre Auger Observatory [78]. For $M_X = 1.7 \times 10^{16}$ GeV and $\tau_X = 8.3 \times 10^{21}$ yr, the integral flux of photons at the location of the Pierre Auger Observatory is $J(>E_0) = 1.6 \times 10^{-4}$ km^{-2} yr^{-1} sr^{-1} [79]. This is a factor of 1.75 times smaller than the integral flux of photons derived in Ref. [80] for the same value of M_X and τ_X, using $\alpha = 3/2$, $\beta = 1$, and $r_s = 45$ Mpc as obtained in Ref. [81]. Now, we compare the integral flux with the upper limit derived in (1) to constrain the $\tau_X - M_X$ parameter space. Our results are encapsulated in Fig. 3. The growth of the final state stable particle spectra with decreasing x determines the functional form of the constraint on τ_X. For masses in the range, $10^{14} \lesssim M_X/\text{GeV} \lesssim 10^{16}$, the lower limit (95% C.L.) on the lifetime of SHDM particles derived in this work is a factor $\gtrsim 2$ more restrictive than previous bounds [77]; see also Refs. [82–84]. For $M_X \lesssim 10^{14}$ GeV, constraints on the diffuse photon flux below E_0 [54,55] provide the most restrictive bound on τ_X [85]. A point worth noting at this juncture is that the limit on τ_X is completely independent of the X-production mechanism, and consequently it applies to all SHDM models, e.g., Refs. [49,86].

There are a few caveats to our calculation. On the one hand, it is important to emphasize that the limit derived in Fig. 3 is calculated under the assumption that the photon-to-baryon relative exposure of the Auger surface detector array is equal to 1. This overly simplified assumption may overestimate the actual photon exposure [87,88]. We defer
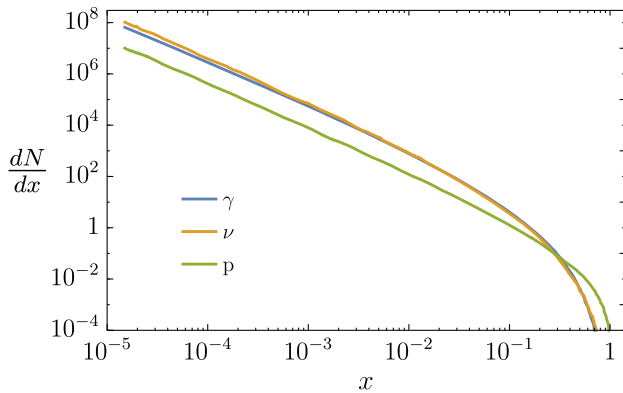

FIG. 2.   Spectra of photons, protons, and neutrinos ($\nu + \bar{\nu}$) from X-particle decay as a function of the dimensionless variable $x = 2E/M_X$. We have taken $M_X = 10^{16}$ GeV.
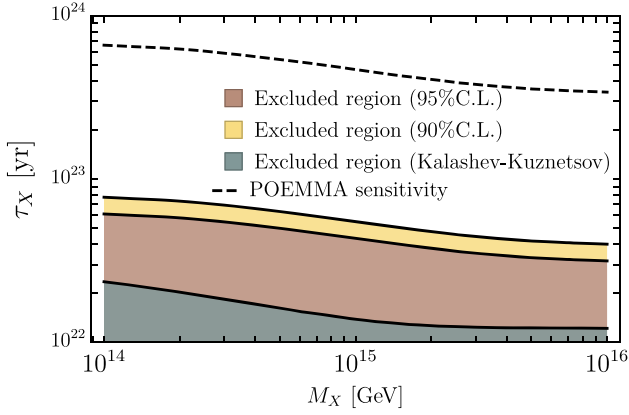
FIG. 3. Lower limit on the lifetime of SHDM particles together with the stereoscopic τ_X sensitivity (defined by the observation of one photon event above $10^{11.3}$ GeV in five years of data collection) of Probe of Extreme Multi-Messenger Astrophysics (POEMMA). The previous limit on τ_X derived in Ref. [77] is also shown for comparison.

a detailed description of the photon directional exposure to the Auger Collaboration. On the other hand, it is important to note that the contribution from the nucleon flux to the all-particle intensity would tend to compensate any possible reduction in the photon exposure. Indeed, we can derive a lower limit on τ_X using only the nucleon flux expected from the X-decay. A rough estimate of such a limit can be obtained through a rescaling of the results shown in Fig. 3 by the γ/N ratio. An additional compensation can be picked up by using also the Telescope Array (TA) observations. TA has accumulated an exposure of approximately $8,300$ km^2 sr yr without observation of events above $10^{11.3}$ GeV [89]. After removing the band of declination common to both experiments, this becomes an approximately 10% effect.

III. POEMMA DISCOVERY REACH

In line with our stated plan, we now estimate the sensitivity of next generation UHECR experiments to detect signals of WIMPzillas. At present, the most advanced concept in pursuit of this objective is POEMMA [90]. POEMMA will comprise two satellites flying in loose formation at 525 km altitudes, with stereoscopic UHECR observation mode and monocular Earth-limb viewing mode. In stereo fluorescence mode, the two detectors view a common immense atmospheric volume corresponding to approximately 10^{13} tons of atmosphere. The stereo mode yields roughly an order of magnitude increase in yearly UHECR exposure compared to that obtainable by ground observatory arrays and 2 orders of magnitude compared to ground fluorescence observations. In the limb-viewing mode, POEMMA reaches nearly 10^{10} gton. The stereoscopic sensitivity of POEMMA to probe the lifetime of SHDM is shown in Fig. 3. Detection of an

extreme-energy photon would be a momentous discovery. If this were the case, POEMMA could be switched into limb mode to rapidly increase statistics.

It is also noteworthy that cosmic-ray showers initiated by extreme-energy photons develop, on average, deeper in the atmosphere than air showers of the same primary energy initiated by protons [91]. This is portrayed through the observable X_{max}, which describes the atmospheric column depth at which the longitudinal development of a cosmic-ray shower reaches the maximum. Of particular interest here, for energies $E \gtrsim E_0$, the average X_{max} of photon and proton showers differs by more than 100 g/cm^2 [92]. Ergo, while the expected monocular performance of POEMMA to identify the UHECR primary ($\Delta X_{max} \sim 100$ g/cm^2) is not as accurate as that for the stereo mode ($\Delta X_{max} \lesssim 30$ g/cm^2), it is still sufficient to characterize the γ/N ratio.

We now comment on the impact of the adopted DM profile in our calculations. Because we are averaging over the entire field of view of the experiments, the selection of the DM profile carries only a very small effect. This is visible in Fig. 1, where we show that the differences between the DM halo profiles are evident for angles $\theta \lesssim 10°$. Indeed, the deviation from our results when considering the Burkert profile rather than the canonical NFW is about 10%. Because the Galactic Center is well within the field of view of Auger, the limit on τ_X is slightly relaxed when considering the Burkert profile. One the other hand, the POEMMA sensitivity that averages over the orbital period is increased.

IV. CONCLUSIONS

Thus far, the various ongoing efforts to produce or detect WIMPs have not given us any promising clues, and moreover, as of today, there have been no definitive hints for beyond SM physics at any accessible energy scale. This rather unexpected situation has motivated a new approach to understand the particle nature of DM. If the Universe is fine-tuned, then the natural mass range for the dark sector would be the Planck scale. Such SHDM can arise from string theory or other high-energy phenomena, and the observed DM abundance can be successfully produced during the inflationary epoch. We have studied the constraints on SHDM models given by recent UHECR observations. For masses in the range $10^{14} \lesssim M_X/\text{GeV} \lesssim 10^{16}$, we derived the strongest (95% C.L.) limit on the lifetime of hadronically decaying SHDM particles. We also explored the prospects for WIMPzilla discovery with future observations of UHECRs. We end with an observation: in five years of data collection, POEMMA (in the limb-viewing mode) will have the potential to accumulate an unprecedented exposure (approximately 10^6 km^2 sr yr) and become the ultimate WIMPzilla hunter.

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