Hunting WIMPzilla 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 \(10^{11.3} \text{ GeV}\). This null result translates into an upper bound on the flux of ultrahigh-energy cosmic rays implying \(f(>10^{13} \text{ GeV}) < 3.6 \times 10^{-5} \text{ km}^{-2} \text{sr}^{-1} \text{yr}^{-1}\), 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, \(10^{12} \leq M_X/\text{GeV} \leq 10^{16}\). We also explore the capability of future NASA’s POEMMA 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 non-baryonic, 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). More concretely, the WIMP paradigm assumes that the DM component of the universe is composed of a non-relativistic stable particle species \(\chi\) whose abundance is set by their annihilations in the early universe [3,5]. As such, at very high temperatures \(T \gg m_\chi\) the DM particles are thought to be in thermal equilibrium with the SM plasma. When the temperature drops below \(m_\chi\), the \(\chi\) particle abundance begins to decrease exponentially and \(\chi\chi \rightarrow ff\) annihilation processes become inefficient, where (in the simplest models) \(f\) denotes any particle of the SM. Eventually, for \(T_\text{fo} \sim m_\chi/20\), the DM comoving density freezes out. The WIMP relic abundance (that is the fraction of the critical density contributed by \(\chi\) today) is inversely proportional to the thermally-averaged velocity-weighted cross section for WIMP annihilation (to all channels) calculated at freeze-out: \(\Omega_\chi \propto h^2/(\sigma v)_{\text{fo}}\), where we adopted the convention of writing the Hubble constant at the present day as \(H_0 = 100 h \text{ km s}^{-1} \text{ Mpc}^{-1}\). The proportionality constant, which is driven by the dynamics of thermal freeze-out, is found to be \(3 \times 10^{-27} \text{ cm}^3 \text{s}^{-1}\) [6]. For a pair of non-relativistic WIMPs annihilating with relative velocity \(v\), partial wave unitarity dictates an upper bound: \(\Omega_{\text{DM}} \gtrsim 1.7 \times 10^{-6} \sqrt{m_\chi / T_{\text{fo}}} (m_\chi/\text{TeV})^2 h^{-2}\) [7], which implies \(m_\chi \lesssim 110 \text{ TeV}\) [8]. Curiously, a stable particle species with a weak-scale mass and interaction strength is predicted to freeze-out of thermal equilibrium with a relic abundance that is comparable to the measured cosmological density of dark matter: \(\Omega_{\text{DM}} \approx 0.1186(20) h^{-2}\) [9]. This can be seen taking a weak cross section derived from dimensional analysis: 
\[
\sigma \sim g_\chi^4 / (4\pi m_\chi)^2 \sim 10^{-8} \text{ GeV}^{-2}, \quad \text{with} \quad m_\chi \sim 1/ \sqrt{g_\chi}, \quad g_\chi \sim 0.65, \quad \text{and} \quad v \sim c/3 \quad \text{for} \quad T_{\text{fo}} \sim m_\chi/20 \quad [10].
\]
This remarkable coincidence is usually referred to as the “WIMP miracle.”

The WIMP paradigm has several appealing features. For instance, because of its thermal nature the mechanism of freeze-out is insensitive to any initial condition, or UV physics of the underlying quantum field theory. In addition, WIMPs are often found within frameworks that address the electroweak hierarchy problem (including, but not limited to, weak-scale supersymmetry [11]). WIMPs annihilate through \(\chi\chi \rightarrow ff\) interactions. This suggests that WIMPs can be detected through: \(\chi f \rightarrow \chi f\) scattering (direct detection), \(\chi\chi \rightarrow ff\) annihilations (indirect detection), and \(ff \rightarrow \chi\chi\) production at colliders. However, LHC experiments have run extensive physics searches for WIMP signals which have returned only null results [12, 13]. In addition, a broad WIMP search program has been developed with direct and indirect detection methods, which so far have given unsatisfactory answers [14, 25]. Despite the fact 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 (non-thermal relic) superweakly-interacting supermassive X-particles [25, 34]. As a matter of fact, the gravitational production of superheavy 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 are not stretched beyond the horizon but remain 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 [33] seems to indicate that nature does not too much care 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 [37,40]. An additional, though not so severe, anthropic argument applies to the abundance of DM, which cannot be too much larger or smaller than what is observed [38,39]. 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 fine tune as the visible SM sector. In other words, even if we are prepared to advocate the anthropic argument to accommodate the unnaturalness 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 detectable primordial tensor-to-scalar ratio $r$ in the CMB power spectrum. The combined Planck satellite [48] together with BICEP2 and the Keck array [49] 95% C.L. upper bound, $r < 0.07$, already constrains the $X$-particle mass to be $M_X \leq 10^{17}$ GeV [50].

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) [51,52]. 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 $E = 67,000 \text{ km}^2 \text{sr} \text{yr}$ without observation of any events with energy $E_0 > 10^{11.3}$ GeV [53]. This null result sets a generic upper limit on the integrated flux of UHECRs; namely,

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

at the 90% C.L.; the limit is a factor of 1.266 less restrictive at the 95% C.L. [54]. When interpreted as a bound on extreme-energy photons and compared with existing bounds [55,56], this limit is more restrictive by about an order of magnitude, but at a slightly 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.

- 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

$$\rho_X(r) = \frac{\rho_s}{(r/r_s)^\alpha(1 + r/r_s)^{3-\alpha}},$$

where $\rho_s$ and $r_s$ are respectively the scale density and scale radius, and where for the canonical Navarro-Frenk-White profile $\alpha = 1$ [57]. We take $r_s = 24.42$ kpc and normalize $\rho_X$ to the local (sol) DM density, $\rho_X(r_0) = \rho_{\Omega}^{DM} = 0.3 \text{ GeV/cm}^3$, where $r_0 = 8.33$ kpc is the distance between the Earth and the Galactic Center. This leads to $\rho_s = 0.184 \text{ GeV/cm}^3$ [58].

- The particle physics factor is built-in the fragmentation function of the SM particles produced by
the $X$-decay. There is a general agreement among
the various computational schemes (relying on ei-
ther analytic approximations [59] or else Monte
Carlo simulations [60–63]) proposed to describe
the secondary spectra of SM particles produced
via $X$-decay. From the observational perspective,
the salient features of the final state particles (pho-
tons, nucleons, and neutrinos) can be summarized
as follows: (i) the spectrum is flat ($dN/dE \propto E^{-1.9}$)
and independent of the particle type, (ii) the pho-
ton/nucleon ratio is $2 \leq \gamma/N \leq 3$ and the neu-
trino/nucleon ratio is $3 \leq \nu/N \leq 4$; 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 [64–67].

The photon flux observed on Earth can be written as

\begin{equation}
J(E, \theta) = \frac{1}{4\pi} \frac{1}{\tau_X} \frac{dN}{dE} \left( 2 \int_{r_0, \sin \theta}^{r_H} dr r \frac{\rho_X(r)}{\sqrt{r^2 - r_0^2 \sin^2 \theta}} \right), \quad (3)
\end{equation}

where $\theta$ is the angle between the line of sight and the
axis defined by Earth and the Galactic center [68]. Here,
$\tau_X$ is the WIMPzilla lifetime and $R_H = 260$ kpc is the
radius of the Galactic halo.

Following [69], we normalize the flux integrating over
the whole sky ($0 < \theta < \pi$) and averaging over the
directional exposure at the declination of the Auger Observa-
tory [70]. 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 Auger Observa-
tory is $J(> E_0) = 1.6 \times 10^{-4}$ km$^{-2}$ yr$^{-1}$ sr$^{-1}$ [71].
This is a factor of 1.75 times smaller than the integral flux
of photons derived in [72] for the same value of $M_X$ and
$\tau_X$, using $a = 3/2$ [73] and $r_S = 45$ Mpc as obtained in [74].

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. 1. 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 $\geq 2$ more restrictive than previous bounds [69];
see also [75–78]. A point worth noting at this juncture is
that the limit on $\tau_X$ is completely independent of the
$X$-production mechanism, and consequently it applies
to all SHDM models, e.g. [50, 79].

There are a few caveats to our calculation. On the one hand,
it is important to emphasize that the limit derived in Fig. 1
is calculated under the assumption that the photon-to-baryon
relative exposure of the Auger surface detector array is equal to one.
This overly simplified assumption may overestimate the actual photon exposure
[80, 81]. We defer a detailed description of the photon directional exposure to the Auger Collaboration.

On the other hand, it is important to note that the contribu-
tion 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 $\tau_X$ using only the nucleon flux expected from the $X$-
decay. A rough estimate of such a limit can be obtained
through a re-scaling of the results shown in Fig. 1 by the
$\gamma/N$ ratio. An additional compensation can be picked
up by using also the Telescope Array (TA) observations.
TA has accumulated an exposure $\sim 8,300$ km$^2$ sr yr
without observation of events above $10^{11.3}$ GeV [82]. After
removing the band of declination common to both experi-
ments this becomes a $\sim 10\%$ 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 the
Probe of ExtremeMulti-Messenger Astrophysics (PO-
EMMA) [83]. POEMMA will comprise two satellites
flying in loose formation at 525 km altitudes, with stereo-

FIG. 1: Lower limit on the lifetime of SHDM particles together
with the stereoscopic $\tau_X$ sensitivity (defined by the observation
of one photon event above $10^{11.3}$ GeV in 5 yr of data collection)
of POEMMA. The previous limit on $\tau_X$ derived in [69] is also
shown for comparison.
scopic 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 two orders of magnitude compared to ground fluorescence observations. In the limb-viewing mode, POEMMA reaches nearly $10^{10}$ gigatons. The stereoscopic sensitivity of POEMMA to probe the lifetime of SHDM is shown in Fig. 4. Detection of a extreme-energy photon would be 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 [84]. This is portrayed through the observable $X_{\text{max}}$, which describes the atmospheric column depth at which the longitudinal development of a cosmic-ray shower reaches maximum. Of particular interest here, for energies $E \gtrsim E_0$, the average $X_{\text{max}}$ of photon and proton showers differs by more than 100 g/cm$^2$ [85]. Ergo, while the expected monocular performance of POEMMA to identify the UHECR primary ($AX_{\text{max}} \sim 100$ g/cm$^2$) is not as accurate as that for the stereo mode ($AX_{\text{max}} \lesssim 30$ g/cm$^2$), it is still sufficient to characterize the $\gamma/N$ ratio.

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 5 yr of data collection POEMMA (in the limb-viewing mode) will have the potential to accumulate an unprecedented exposure ($\sim 10^8$ km$^2$sr yr) and become the ultimate WIMPzilla hunter.

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