DOI: 10.21468/SciPostPhysProc.13.013

SciPost Phys. Proc. 13, 013 (2023)

Limits to gauge coupling in the dark sector of super-heavy dark matter particles from the Pierre Auger Observatory data

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21st International Symposium on Very High Energy Cosmic Ray Interactions (ISVHECRI 2022)
Online, 23-28 May 2022
doi:10.21468/SciPostPhysProc.13

Abstract

Assuming that the energy density of super-heavy particles matches that of dark matter observed today, tight constraints on the couplings governing the decay process are presented as a function of the particle mass. These constraints are obtained from the lack of signatures that would be suggestive of decaying super-heavy X particles in the data of the Pierre Auger Observatory. In particular, instanton-induced decay processes allow us to derive a bound on the reduced coupling constant of gauge interactions in the dark sector: $\alpha_X \lesssim 0.09$, for $10^9 \lesssim M_X/\text{GeV} < 10^{19}$. Cosmological aspects for super-heavy dark matter production during the reheating epoch are discussed.

Received 27-09-2022
Accepted 28-08-2023
Published 28-09-2023
doi:10.21468/SciPostPhysProc.13.013

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1 Introduction

In most particle physics models, a tiny coupling, be it through the weak interaction or through a new feeble one, is introduced to enable standard model (SM) and dark matter (DM) sectors to communicate. The concordance model currently used in cosmology does not require necessarily, however, such a coupling so that the only portal between sectors could be of gravitational nature. Recent studies have indeed shown that the abundance of DM particles created gravitationally prior to the radiation-dominated era can match the relic abundance of DM inferred today for viable parameters governing the thermal history and geometry of the universe [1,2]. For the scenario to be viable, DM particles should be heavy, or even super heavy (mass ranging from TeV to the GUT scale).

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Independent of these considerations from cosmology, there are also good motivations coming from LHC results for considering super-heavy DM (SHDM) particles coming from LHC results. The estimation of the instability scale Λ_I of the SM that characterizes the scale at which the Higgs potential develops an instability at large field values is suggestive that new physics could manifest only at a very high energy scale, such as the GUT scale ($M_{GUT} \sim 10^{16}$ GeV). For the current values of the Higgs and top masses and the strong coupling constant, the range of Λ_I turns out to be high, namely 10^{10} to 10^{12} GeV [3–5]. While the change of sign of the Higgs quartic coupling λ at that scale could trigger a vacuum instability due to the Higgs potential suddenly becoming unbounded from below, the running of λ for energies above Λ_I turns out to be slow [3]. This peculiar behaviour leaves the possibility of extrapolating the SM to even higher energies than Λ_I, up to the Planck scale $M_P \sim 10^{19}$ GeV, with no need to introduce new physics to stabilize the SM. In this case, the mass spectrum of the dark sector could reflect the high energy scale of the new physics.

All in all, SHDM models in which the DM sector has no interaction with the SM one but gravitational are viable. The only gravitational coupling leaves few possible observational signatures. The large values of the Hubble expansion rate at the end of inflation H_{inf} needed to match the relic abundance $\Omega_{CDM}h$ imply tensor modes in the cosmological microwave background anisotropies that could be observed in the future [1] – but the observation of such modes would not necessarily imply that DM is from this scenario. On the other hand, even if the absence of direct interactions guarantees the stability of the X particles in the perturbative domain, DM particles protected from decay by a symmetry can eventually disintegrate due to non-perturbative effects in non-abelian gauge theories and produce ultra-high energy cosmic rays (UHECRs) such as (anti-)protons/neutrons, photons and (anti-)neutrinos. The aim of this study is to search for such signatures in the data from the Pierre Auger Observatory and to derive constraints on the various particle-physics and cosmological parameters governing the viability of this scenario for DM. Interested readers are refereed to [6, 7] for details.

2 Limits on ultra-high energy photon flux from the Pierre Auger observatory data

A compelling evidence for the observation of the decay of SHDM particles would be the detection of a flux of astrophysical photons with energies in excess of $\simeq 10^8$ GeV, in particular from regions of denser DM density such as the center of our Galaxy. The identification of photon primaries relies on the ability to distinguish the showers generated by photons from those initiated by the overwhelming background of protons and heavier nuclei. Since the radiation length in the atmosphere is more than two orders of magnitude smaller than the mean free path for photo-nuclear interactions, the transfer of energy to the hadron/muon channel is reduced in photon showers with respect to the bulk of hadron-induced air showers, resulting in a lower number of secondary muons. Additionally, as the development of photon showers is delayed by the typically small multiplicity of electromagnetic interactions, they reach the maximum development of the shower, X_{max}, deeper in the atmosphere with respect to showers initiated by hadrons.

Both the ground signal and X_{max} can be measured at the Pierre Auger Observatory [8], where a hybrid detection technique is employed for the observation of extensive air showers by combining fluorescence detectors with ground arrays of particle detectors. The combination of the various instruments allows showers to be measured in the energy range above 10^8 GeV.

Three different analyses, differing in the detector used, have been developed to cover the wide energy range probed at the Observatory [9–11]. No photons with energies above 2×10^8 GeV have been unambiguously identified so far, leading to the 95% C.L. flux upper

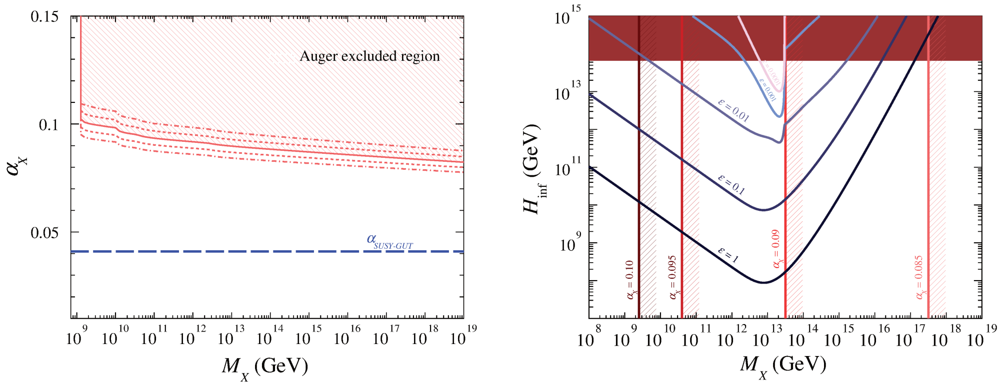

Figure 1: Left: Upper limits at 95% C.L. on the coupling constant α_X of a hidden gauge interaction as a function of the mass M_X of a dark matter particle X decaying into a dozen of $q\bar{q}$ pairs. For reference, the unification of the three SM gauge couplings is shown as the blue dashed line in the framework of supersymmetric GUT [20]. Right: Constraints in the $(H_{\rm inf}, M_X)$ plane. The red region is excluded by the non-observation of tensor modes in the cosmic microwave background [1, 21]. The regions of viable $(H_{\rm inf}, M_X)$ values needed to set the right abundance of DM are delineated by the blue lines for different values of reheating efficiency ϵ [22]. Additional constraints from the non-observation of instanton-induced decay of SHDM particles allow for excluding the mass ranges in the red-shaded regions, for the specified value of the dark-sector gauge coupling.

limits. The limit above $10^{11.2}$ GeV, stemming from the non-detection so far of any UHECR [12], including photons, is also constraining [13, 14].

3 Limits to gauge coupling in the dark sector

Stability of SHDM particles is calling for a new quantum number conserved in the dark sector so as to protect the particles from decaying. Nevertheless, even stable particles in the perturbative domain will in general eventually decay due to non-perturbative effects (instantons) in non-abelian gauge theories [15–17]. Instanton-induced decay can thus make observable a dark sector that would otherwise be totally hidden by the conservation of a quantum number [18]. Assuming quarks and leptons carry this quantum number and so contribute to anomaly relationships with contributions from the dark sector, they will be secondary products in the decays of SHDM together with the lightest hidden fermion. The lifetime of the decaying particle follows from Ref. [19],

$$\tau_X \simeq M_X^{-1} \exp(4\pi/\alpha_X), \tag{1}$$

with α_X the reduced coupling constant of the hidden gauge interaction.

Quite independently of the hidden gauge interaction, the exact content in instanton-induced decays of quarks and leptons, which will eventually produce hadrons decaying into photons and neutrinos, obeys selection rules that involve very large multiplicities. The differential decay width finally reads as the energy spectrum of the final particles, $dN_i(E, M_X)/dE$, normalized to the lifetime τ_X. The computational scheme used here follows from [23].

Due to their attenuation over intergalactic distances, only UHE photons emitted in the Milky Way can survive on their way to Earth. The emission rate per unit volume and unit energy q_γ from any point labelled by its Galactic coordinates is shaped by the density of SHDM

$n_{\rm DM}$,

$$q_\gamma(E,\mathbf{x}_\odot+s\mathbf{n})=\frac{1}{\tau_X}\frac{\mathrm{d}N_\gamma}{\mathrm{d}E}n_{\rm DM}(\mathbf{x}_\odot+s\mathbf{n})\,, \tag{2}$$

where $\mathbf{x}_\odot$ is the position of the Solar system in the Galaxy, and $\mathbf{n}\equiv\mathbf{n}(\ell,b)$ is a unit vector on the sphere pointing to the Galactic longitude ℓ and latitude b. Hereafter, the density is more conveniently expressed in terms of energy density $\rho_{\rm DM}=M_X n_{\rm DM}$. The energy density is normalized to $\rho_\odot=0.3\,\mathrm{GeV\,cm^{-3}}$. The directional flux (per steradian) of UHE photons produced by the decay of SHDM particles, $J_{\mathrm{DM},\gamma}(E,\mathbf{n})$, is then obtained by integrating the position-dependent emission rate q_γ along the path of the photons in the direction $\mathbf{n}$,

$$J_{\mathrm{DM},\gamma}(E,\mathbf{n})=\frac{1}{4\pi}\int_0^\infty \mathrm{d}s\; q_\gamma(E,\mathbf{x}_\odot+s\mathbf{n})\,, \tag{3}$$

where the 4π normalization factor accounts for the isotropy of the decay processes.

Assuming that the relic abundance of DM is saturated by SHDM, constraints can be inferred in the plane (τ_X,M_X) by requiring the flux calculated by averaging Eq. (3) over all directions to be less than the limits, $J_\gamma^{95\%}(\geq E)\leq\int_E^\infty \mathrm{d}E'\langle J_{\mathrm{DM},\gamma}(E',\mathbf{n})\rangle$. For a specific upper limit at one energy threshold, a scan of the value of the mass M_X is carried out so as to infer a lower limit of the τ_X parameter, which is subsequently transformed into an upper limit on α_X by means of Eq. (1). This defines a curve. By repeating the procedure for each upper limit on $J_\gamma^{95\%}(\geq E)$, a set of curves is obtained, reflecting the sensitivity of a specific energy threshold to some range of mass. The union of the excluded regions finally provides the constraints in the plane (α_X,M_X) as shown in the left panel of Fig. 1. The dotted and dashed-dotted lines illustrate systematic uncertainties stemming from "unknown unknowns" in the exact particle-physics model for the dark sector that could give rise to additional factor in front of the exponential in Eq. (1).

4 Link with cosmological aspects and conclusion

Gravitational interaction alone may have been sufficient to produce the right amount of SHDM particles at the end of the inflation era for a wide range of high masses, up to $M_{\rm GUT}$, accounting for the production by annihilation of SM particles [1] or of inflaton particles (ϕ hereafter) [2] through the exchange of a graviton. In this scenario, the relic abundance of SHDM particles can be estimated from the quite involved reheating dynamics [24, 25]. The energy density of the universe is then in the form of unstable inflaton particles, SM radiation and stable massive particles, the time evolution of which is governed by a set of coupled Boltzmann equations [24]. However, because the energy density of the massive particles is always subdominant, the evolution of the inflationary and radiation energy densities largely decouple from the time evolution of the X-particle density n_X. In addition, because SHDM particles interact through gravitation only, they never come to thermal equilibrium. In this case, the collision term in the Boltzmann equation can be approximated as a source term only,

$$\frac{\mathrm{d}n_X(t)}{\mathrm{d}t}+3H(t)n_X(t)\simeq\sum_i \overline{n}_i^2(t)\gamma_i\,. \tag{4}$$

Here, the sum in the right hand side stands for the contributions from the SM [1] and inflationary [2] sectors. In both sectors, the production rates γ_i for fermionic DM are considered in the following. Introducing the dimensionless abundance $Y_X=n_Xa^3/T_{\rm reh}^3$ to absorb the expansion of the universe, with $T_{\rm reh}$ the reheating temperature, and using $aH(a)\mathrm{d}t=\mathrm{d}a$ from the definition of the Hubble parameter (with a the scale factor), Eq. (4) becomes

$$\frac{\mathrm{d}Y_X(a)}{\mathrm{d}a} \simeq \frac{a^2}{T_{\mathrm{reh}}^3 H(a)} \sum_i \overline{n}_i^2(a)\gamma_i\,, \tag{5}$$

which, using the dynamics of the expansion rate during reheating, yields the present-day dimensionless abundance $Y_{X,0}$ assuming $Y_{X,\mathrm{inf}} = 0$. The present-day relic abundance, Ω_{CDM}, can then be related to M_X, H_{inf}, and $\epsilon = T_{\mathrm{reh}}/(0.25\sqrt{M_{\mathrm{P}}H_{\mathrm{inf}}})$ through [1]

$$\Omega_{\mathrm{CDM}}h^2 = 9.2\times 10^{24}\frac{\epsilon^4 M_X}{M_{\mathrm{P}}} Y_{X,0}\,. \tag{6}$$

As a result, one interesting viable possibility in the (H_{inf}, M_X) parameter space is that X particles with masses as large as the GUT energy scale could be sufficiently abundant to match the DM relic density, provided that the inflationary energy scale is high ($H_{\mathrm{inf}} \sim 10^{13}$ GeV) and the reheating efficiency is high (so that reheating is quasi-instantaneous). This rules out values of the dark-sector gauge coupling greater than $\simeq$0.085, as observed in the right panel of Fig. 1. The mass values could however be smaller if the reheating temperature is not that high. In general, for high efficiencies ϵ (corresponding to short duration of the reheating era), the SM+SM $\rightarrow$ SHDM+SHDM reaction allows for a wide range of M_X values to fulfill Eq. (6). For efficiencies below $\simeq 0.01$, the $\phi + \phi \rightarrow$ SHDM + SHDM reaction allows for solutions in a narrower range of the (H_{inf}, M_X) plane close to $M_X = 10^{13}$ GeV, with in particular $M_X \leq M_\phi$ as a result of the kinematic suppression in the corresponding rate γ_i [2].

It is likely that the examples of constraints inferred on models of dark sectors and physics in the reheating epoch in the framework of inflationary cosmologies only scratch the surface of the power of limits on UHE photon fluxes to constrain physics otherwise beyond the reach of laboratory experiments. Other studies are underway.

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