Limits to gauge coupling in the dark sector set by the non-observation of instanton-induced decay of Super-Heavy Dark Matter in the Pierre Auger Observatory data

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We investigate instanton-induced decay processes of super-heavy dark matter particles X produced during the inflationary epoch. Using data collected at the Pierre Auger Observatory we derive a bound on the reduced coupling constant of gauge interactions in the dark sector: $\alpha_X^{\rm eff} \lesssim 0.09$, for $10^{10} < M_X/{\rm GeV} < 10^{16}$. We show that this upper limit on $\alpha_X^{\rm eff}$ is complementary to that obtained from the non-observation of tensor modes in the cosmic microwave background.

Should a flux of astrophysical photons with energies in excess of $\simeq 10^8$ GeV be detected, it could be compelling evidence for the decay of super-heavy relics dating from the early universe [1, 2]. Possible mechanisms taking place during or at the end of the inflationary era in Big Bang cosmology have been shown to be capable of producing such particles [3–14]. The abundance of the stable super-heavy particles could then evolve to match the relic abundance of dark matter (DM) inferred today, for viable parameters governing the thermal history and the geometry of the universe, such as the reheating temperature or the Hubble expansion rate at the end of inflation. Stability for super-heavy particles is more easily achieved for a dark sector totally decoupled from the standard model (SM), except gravitationally, and the absence of such DM-SM couplings is consistent with the extensive observational evidence for the existence of DM based on gravitational effects alone. However, even 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 (UHE) photons. In this Letter, we show that the absence of such photons in the data of the Pierre Auger Observatory provides constraints on the coupling constant of a hidden sector pertaining to super-heavy dark matter (SHDM), possibly unified with SM interactions at a high scale. The constraints are illustrated in Fig. 1 in terms of the effective reduced coupling constant of a hidden gauge interaction and the mass of the SHDM candidate. Our results show that the coupling should be less than $\simeq 0.09$ for a wide range of masses. After explaining how these constraints are obtained, we briefly discuss their relevance for delineating viable regions of cosmological parameters, in a manner complementary to the constraints provided by the non-detection so far of tensor modes in the cosmological microwave background anisotropies [15, 16].

Contemporary motivations for SHDM. Among the multiple hypotheses proposed to describe DM, particles in the mass range 10^2–10^4 GeV undergoing weak interactions have been the prime target for experimental searches. Consistent with the technical naturalness to have new physics at the TeV scale [18], the thermal production of such weakly-interactive massive particles (WIMPs) leads, after their freeze-out from the thermal plasma, to a relic abundance matching that observed [19–21]. However, WIMPs have escaped any detection so far [22–24]. Although the exploration of the complete WIMP parameter space remains of great importance, a broader search program must also be actively pursued.

As an alternative to WIMPs, there are good motives for SHDM if new physics manifests only at a very high energy scale, possibly the Planck scale M_{Pl} or the GUT scale. Such a possibility has emerged from the absence of vacuum instability up to a scale $\Lambda_{\mathrm{I}} = 10^{10}-10^{12}$ GeV, the estimation of which at the two-loop level was made possible by the precise measurements of the Higgs mass and

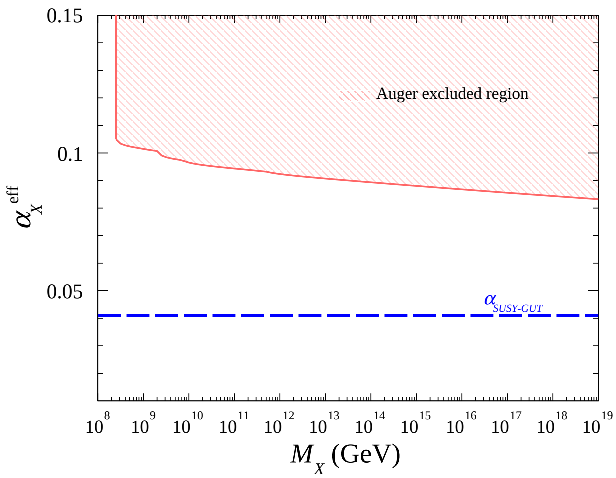

Figure 1: Upper limits at 95% C.L. on the effective coupling constant α_X^{eff} of a hidden gauge interaction as a function of the mass M_X of a dark matter particle X decaying into $q\bar{q}$. For reference, the unification of the three SM gauge couplings is shown as the blue dashed line in the framework of supersymmetric GUT [17].

of the top Yukawa coupling [25–27]. Moreover, the particular slow running of the Callan-Symanzik β_λ function relative to the self-Higgs coupling makes it even possible to extrapolate the SM up to M_{Pl} without encountering any instabilities [25]. Renouncing naturalness to solve the problem of the mass hierarchy, nothing forbids therefore that new degrees of freedom appear only in the range between Λ_{I} and M_{Pl}.

Nor do observational considerations preclude SHDM. Structure formation constrains the mass density of DM, but leaves a *carte blanche* for the mass spectrum of the DM particles. Moreover while some have argued that the properties of nuclei and atoms would not allow complex chemistry if the electroweak scale were too far from the confinement scale of QCD [28], there is no such anthropic requirement for the mass scale of DM. Actually, dark sectors would be as technically natural as possible if the DM mass scale is very high. All in all, consideration of super-heavy Dark Matter is well motivated.

Decay mechanisms of SHDM particles. Some SHDM models postulate the existence of super-weak couplings between the dark and SM sectors. The lifetime τ_X of the particles is then governed by the strength of the couplings g_X and by the dimension n of the operator standing for the SM fields in the effective interaction [29]. This results in lifetimes that are in general far too short for DM to be stable enough, unless a practically untenable fine tuning between g_X and n holds [3, 29]. Stability of SHDM particles is thus preferentially calling for a new quantum number conserved in the dark sector so as to protect the particles from decaying. Nevertheless, as we have already pointed out in the study motivation, even stable particles in the perturbative domain will in general eventually decay due to non-perturbative effects in non-abelian gauge theories. Such effects, known as instantons [30–32], provide a signal for the occurrence of quantum tunneling between distinct classes of vacua, forcing the fermion fields to evolve during the transitions and leading to the generation of particles depending on the associated anomalous symmetries [33].

Instanton-induced decay can thus make observable a dark sector that would otherwise be totally hidden by the conservation of a quantum number [34]. 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 [33]

$$\tau_X = \hbar M_X^{-1} \exp\left(4\pi/\alpha_X\right), \qquad (1)$$

with $\hbar$ the reduced Planck constant and α_X the reduced coupling constant of the hidden gauge interaction. This expression holds in the massless case. However, it remains valid in the massive case for a spontaneously broken gauge symmetry, substituting the coupling constant with an effective one $\alpha_X^{\rm eff} = \alpha_X/(1+\kappa\rho^2\mu^2/4)$, where ρ is the instanton size, μ the mass of the hidden-Higgs field responsible for the mass generation in the dark sector, and κ its quartic self coupling [35, 36]. Equation (1) provides us with a relationship connecting the lifetime τ_X, which is shown below to be constrained by the absence of UHE photons, to the coupling constant $\alpha_X^{\rm eff}$.

Production of ultra-high energy photons. The exact content of quarks and leptons in instanton-induced decays obeys selection rules that involve very large multiplicities. In such a regime, the differential decay width into particle species i is governed, quite independently of the hidden gauge interaction, by the known probability that a process initiated by parton a results in a specific hadron h, and by the differential decay width of SHDM into parton a. Starting from measurements at the electroweak scale, the fragmentation functions are evolved up to the energy scale fixed by M_X using the DGLAP equation to account for the splitting function that describes the emission of parton k by parton j [37]. The differential decay width finally reads as the energy spectrum of the final particles, $\mathrm{d}N_i(E,M_X)/\mathrm{d}E$, normalized to the lifetime τ_X. Among the various computational schemes [37–41], there is a general agreement for spectra of the form $E^{-1.9}$.

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 $n_{\rm DM}$:

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

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 $\rho_{\rm DM} = M_X n_{\rm DM}$. There are uncertainties in the determination of this profile. We assume the traditional NFW profile [42] and propagate a systematic uncertainty of 10% this assumption generates in the determination of τ_X [43]. The energy density is normalized to $\rho_\odot = 0.3$ GeV cm^{-3}. The directional flux (per steradian) of UHE photons produced by the decay of SHDM particles, $J_{\rm DM,\gamma}(E, \mathbf{n})$, is then obtained by integrating the position-dependent emission rate q_γ along the path of the photons in the direction $\mathbf{n}$:

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

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

Constraints on dark-sector coupling constant from instanton-induced decays. Of particular interest would be the detection of UHE photons from regions of denser DM density such as the center of our Galaxy. Due to the steepness of the expected flux, this search can presently only be done through large ground-based detectors that exploit the phenomenon of extensive air showers. 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, in photon showers the transfer of energy to the hadron/muon channel is reduced 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, $X_{\rm max}$, deeper in the atmosphere with respect to showers initiated by hadrons.

Both the ground signal and $X_{\rm max}$ can be measured at the Pierre Auger Observatory [44], where a hybrid detection technique is employed for the observation of extensive air showers by combining a fluorescence detector (FD) with a ground array of particle detectors (surface detector, SD) separated by 1,500 m. The FD provides direct observation of the longitudinal shower profile, which allows for the measurement of the energy and the $X_{\rm max}$ of a shower, while the SD samples the secondary particles at ground level. Although showers are observed at a fixed slice in depth with the SD, the longitudinal development is embedded in the signals detected. The FD and SD are complemented with the low-energy enhancements of the Observatory, namely three additional fluorescence telescopes with an elevated field of view, overlooking a denser SD array, in which the stations are separated by 750 m. The combination of these instruments allows showers to be measured in the energy range above 10^8 GeV.

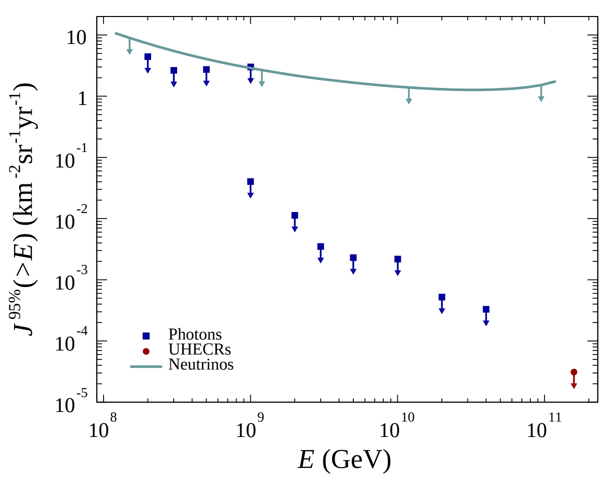

Figure 2: Flux upper limits of UHE photons, neutrinos and cosmic rays as a function of energy thresholds.

Three different analyses, differing in the detector used, have been developed to cover the wide energy range probed at the Observatory [45, 46]. No photons with energies above $2{\times}10^8$ GeV have been unambiguously identified so far, leading to the 95% C.L. flux upper limits displayed in Fig. 2. The limit above $10^{11.2}$ GeV, stemming from the non-detection so far of any UHECR [47], including photons, is also constraining [41, 48]. For comparison purposes, neutrino limits obtained at the Observatory [49] are also displayed as the continuous line. Indeed, neutrinos constitute another emblematic signature of SHDM decays. Except at the lowest energies, these limits are seen to be superseded by photon ones in the search of SHDM by-product decays dominated by those from the Galaxy.

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^{eff} 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 $(\alpha_X^{\mathrm{eff}}, M_X)$. In this manner the shaded red area is obtained in Fig. 1.

Connection to cosmological scenarios. We now briefly mention how the results shown in Fig. 1 can be connected to scenarios of inflationary cosmologies. In addition to the instanton-mediated decays, DM and SM particles can interact gravitationally. We shall see below that this mechanism alone may be sufficient to produce the right amount of SHDM particles. While the observation of UHE photons could open a window to explore high-energy gauge interactions and possibly GUTs effective in the early universe, the constraints inferred on α_X^{eff} allow us to probe the gravitational production of SHDM. Further details will be given in a future publication.

Following [9], super-heavy particles are assumed to be produced by annihilation of SM particles through the exchange of a graviton after the period of inflation has ended. In this context, SM particles are created by the decay of coherent oscillations of the inflaton field during the reheating era. They subsequently thermalize prior to the radiation-dominated era and can gravitationally populate the SHDM sector via freeze-in [50–52] with the right abundance to explain the relic abundance observed today. The decoupling of the dark sector is maximal here, as it is not even coupled to the inflationary sector.

In this scenario, SHDM production occurs dominantly during the reheating period, the dynamics of which is quite involved [53]. As the SM particles thermalize, the plasma temperature rises rapidly to a maximum before subsequently decreasing as $T(a) \propto a^{-3/8}$, with a being the cosmological scale factor. This scaling continues until the age of the universe is equal to the lifetime of the inflaton, signaling the beginning of the radiation-dominated era at the temperature $T_{\mathrm{reh}} \simeq 0.25\epsilon(M_{\mathrm{Pl}}H_{\mathrm{inf}})^{1/2}$. The parameter ϵ here is the reheating efficiency that measures the duration of the reheating period [9]. During this period, the Hubble rate $H(a)$ scales as the square root of the energy density of the inflaton, which itself scales as a^{-3}. Consequently, $H(a)$ evolves as $a^{-3/2}$, namely $H(a) = H_{\mathrm{inf}}(a/a_{\mathrm{inf}})^{-3/2}$ with a_{inf} being the scale factor at the end of inflation. After reheating, both the temperature and the Hubble rate follow the standard evolution in a radiation-dominated era, namely $T(a) \propto a^{-1}$ and $H(a) = H_{\mathrm{inf}}\epsilon^2(a/a_{\mathrm{reh}})^{-2}$. The scale factor at the end of reheating is $a_{\mathrm{reh}} = \epsilon^{-4/3}a_{\mathrm{inf}}$, guaranteeing the continuity of $H(a)$.

Based on these dynamics, the present-day relic abundance of DM, Ω_X, can be related to M_X, H_{inf}, and ϵ through [9]

$$\Omega_X h^2 = \frac{9.2{\times}10^{24}\epsilon^4 M_X}{M_{\mathrm{P}}T_{\mathrm{reh}}^3}\int_{a_{\mathrm{inf}}}^{\infty} \mathrm{d}a \; \frac{a^2}{H(a)}\langle\sigma v\rangle(n_X^{\mathrm{eq}}(a))^2, \tag{4}$$

where h is the dimensionless expansion rate, $\langle\sigma v\rangle$ the cross-section-times-velocity for freeze-in based on gravi-

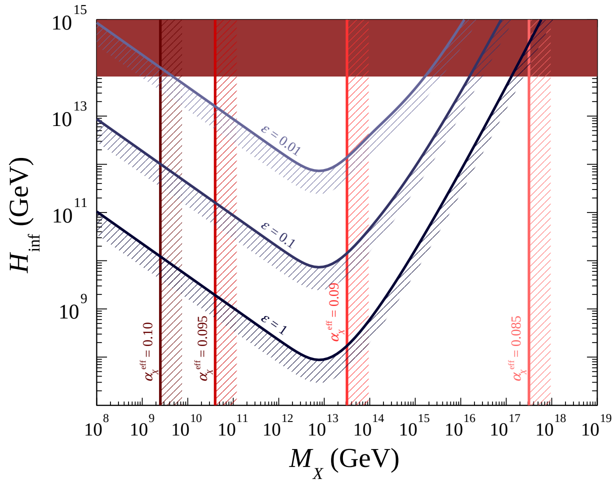

Figure 3: Constraints in the $(H_{\rm inf}, M_X)$ plane. The red region is excluded by the non-observation of tensor modes in the cosmic microwave background [9, 16]. The regions of viable $(H_{\rm inf}, M_X)$ values needed to set the right abundance of DM are delineated by the blue lines for different values of reheating efficiency ϵ [54] (the shaded areas represent the beginning of the exclusion regions). 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.

ton exchange for fermions [54], and $n_X^{\rm eq}$ the number density of SHDM once frozen [53]. For high M_X values, Eq. (4) can be satisfied provided that the reheating efficiency is large enough (corresponding to a short duration of the reheating era) and that the energy scale of the inflation ($H_{\rm inf}$ being the proxy) is high enough [9]. The viable $(H_{\rm inf}, M_X)$ parameter space is delineated by the blue curves corresponding to different values of ϵ in Fig. 3, where the excluded shaded regions extend to the whole parameter space below the curves. Arbitrarily large values of $H_{\rm inf}$ are however not permitted because of the 95% c.l. limits on the tensor-to-scalar ratio in the cosmic microwave background anisotropies, which, once converted into limits on the energy scale of inflation when the pivot scale exits the Hubble radius [9, 16], yield $H_{\rm inf} \leq 4.9{\times}10^{-6} M_{\rm Pl}$. The other possible signature could be the detection of UHE photons produced by the instanton-induced decay of the SHDM particles – so that no coupling between the sectors is required. The excluded mass ranges obtained from the non-observation of instanton-induced decay of SHDM particles are shown as the red shaded regions for different values of dark-sector gauge coupling. While the range of M_X extends from (well) below 10^8 GeV to $\simeq 10^{17}$ GeV in the case of instantaneous reheating ($\epsilon = 1$) and $\alpha_X^{\rm eff} \leq 0.085$, the parameter space is observed to shrink for longer reheating duration and larger dark-sector gauge coupling. With the current sensitivity, there are no longer pairs of values $(H_{\rm inf}, M_X)$ satisfying Eq. (4) for $(\epsilon \geq 0.01, \alpha_X^{\rm eff} \geq 0.10)$. With increased sensitivity to the tensor-to-scalar ratio on the one hand and to UHE photons thanks to the planned UHECR observatories in the next decade [55, 56] on the other hand, the parameter space will continue to shrink towards the low-mass range and/or small gauge coupling values.

Finally, it is important to assess the possible impacts of Big Bang cosmology on other aspects apart from SHDM production. In particular, the astronomically-long lifetime of the vacuum of the SM might be challenged in the cosmological context due to thermal fluctuations allowing the decay when the temperature was high enough, or due to large fluctuations of free fields generated by the dynamics on a curved background because of the presence of a non-minimal coupling ξ between the Higgs field and the curvature of space-time. Requiring the electroweak vacuum not to decay yields constraints between the non-minimal coupling ξ and the Hubble rate $H_{\rm inf}$ in viable regions [57]. Propagation of the stability bounds derived in the $(\xi, H_{\rm inf})$ plane into the $(\xi, J_\gamma(\geq E))$ plane can be achieved and will be reported elsewhere.

In summary, we have illustrated here the power of upper limits on the flux of UHE photons obtained at the Pierre Auger Observatory to place constraints on Grand Unified models and physics in the reheating epoch. It is likely that these examples only scratch the surface of the power of limits on UHE photon fluxes to constrain physics otherwise beyond the reach of laboratory experiments.

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[1] P. Bhattacharjee and G. Sigl, Phys. Rept. **327**, 109 (2000), arXiv:astro-ph/9811011 .
[2] L. A. Anchordoqui, Phys. Rept. **801**, 1 (2019), arXiv:1807.09645 [astro-ph.HE] .
[3] J. R. Ellis, G. Gelmini, J. L. Lopez, D. V. Nanopoulos, and S. Sarkar, Nucl. Phys. B **373**, 399 (1992).
[4] V. Berezinsky, M. Kachelrieß, and A. Vilenkin, Phys. Rev. Lett. **79**, 4302 (1997).
[5] D. J. H. Chung, E. W. Kolb, and A. Riotto, Phys. Rev. D **59**, 023501 (1998), arXiv:hep-ph/9802238 .
[6] V. Kuzmin and I. Tkachev, Phys. Rev. D **59**, 123006 (1999), arXiv:hep-ph/9809547 .
[7] D. J. H. Chung, E. W. Kolb, A. Riotto, and I. I. Tkachev, Phys. Rev. D **62**, 043508 (2000), arXiv:hep-ph/9910437 .
[8] M. A. Fedderke, E. W. Kolb, and M. Wyman, Phys. Rev. D **91**, 063505 (2015), arXiv:1409.1584 [astro-ph.CO] .
[9] M. Garny, M. Sandora, and M. S. Sloth, Phys. Rev. Lett. **116**, 101302 (2016), arXiv:1511.03278 [hep-ph] .
[10] J. Ellis, M. A. G. Garcia, D. V. Nanopoulos, K. A. Olive, and M. Peloso, JCAP **03**, 008 (2016), arXiv:1512.05701 [astro-ph.CO] .
[11] E. W. Kolb and A. J. Long, Phys. Rev. D **96**, 103540 (2017), arXiv:1708.04293 [astro-ph.CO] .
[12] E. Dudas, Y. Mambrini, and K. Olive, Phys. Rev. Lett. **119**, 051801 (2017), arXiv:1704.03008 [hep-ph] .
[13] K. Kaneta, Y. Mambrini, and K. A. Olive, Phys. Rev. D **99**, 063508 (2019), arXiv:1901.04449 [hep-ph] .
[14] Y. Mambrini and K. A. Olive, Phys. Rev. D **103**, 115009 (2021), arXiv:2102.06214 [hep-ph] .
[15] P. A. R. Ade et al. (BICEP2, Planck), Phys. Rev. Lett. **114**, 101301 (2015), arXiv:1502.00612 [astro-ph.CO] .
[16] P. A. R. Ade et al. (Planck), Astron. Astrophys. **594**, A20 (2016), arXiv:1502.02114 [astro-ph.CO] .
[17] P. A. Zyla et al. (Particle Data Group), PTEP **2020** (2020), 10.1093/ptep/ptaa104, 083C01, https://academic.oup.com/ptep/article-pdf/2020/8/083C01/34673722/ptaa104.pdf .
[18] G. 't Hooft, NATO Sci. Ser. B **59**, 135 (1980).
[19] P. Hut, Phys. Lett. B **69**, 85 (1977).
[20] B. W. Lee and S. Weinberg, Phys. Rev. Lett. **39**, 165 (1977).
[21] M. I. Vysotsky, A. D. Dolgov, and Y. B. Zeldovich, JETP Lett. **26**, 188 (1977).
[22] T. Marrodán Undagoitia and L. Rauch, J. Phys. G **43**, 013001 (2016), arXiv:1509.08767 [physics.ins-det] .
[23] S. Rappoccio, Rev. Phys. **4**, 100027 (2019), arXiv:1810.10579 [hep-ex] .
[24] J. M. Gaskins, Contemp. Phys. **57**, 496 (2016), arXiv:1604.00014 [astro-ph.HE] .
[25] D. Buttazzo, G. Degrassi, P. P. Giardino, G. F. Giudice, F. Sala, A. Salvio, and A. Strumia, JHEP **12**, 089 (2013), arXiv:1307.3536 [hep-ph] .
[26] S. Alekhin, A. Djouadi, and S. Moch, Phys. Lett. B **716**, 214 (2012), arXiv:1207.0980 [hep-ph] .
[27] A. V. Bednyakov, B. A. Kniehl, A. F. Pikelner, and O. L. Veretin, Phys. Rev. Lett. **115**, 201802 (2015), arXiv:1507.08833 [hep-ph] .
[28] T. Damour and J. F. Donoghue, Phys. Rev. D **78**, 014014

(2008), arXiv:0712.2968 [hep-ph] .
[29] H. J. de Vega and N. G. Sanchez, Phys. Rev. D **67**, 125019 (2003).
[30] A. A. Belavin, A. M. Polyakov, A. S. Schwartz, and Y. S. Tyupkin, Phys. Lett. B **59**, 85 (1975).
[31] S. R. Coleman, Subnucl. Ser. **15**, 805 (1979).
[32] A. I. Vainshtein, V. I. Zakharov, V. A. Novikov, and M. A. Shifman, Sov. Phys. Usp. **25**, 195 (1982).
[33] G. 't Hooft, Phys. Rev. Lett. **37**, 8 (1976).
[34] V. A. Kuzmin and V. A. Rubakov, Phys. Atom. Nucl. **61**, 1028 (1998), arXiv:astro-ph/9709187 .
[35] I. Affleck, Nucl. Phys. B **191**, 429 (1981).
[36] M. Nielsen and N. K. Nielsen, Phys. Rev. D **61**, 105020 (2000), arXiv:hep-th/9912006 .
[37] R. Aloisio, V. Berezinsky, and M. Kachelriess, Phys. Rev. D **69**, 094023 (2004), arXiv:hep-ph/0307279 .
[38] S. Sarkar and R. Toldra, Nucl. Phys. B **621**, 495 (2002), arXiv:hep-ph/0108098 .
[39] C. Barbot and M. Drees, Astropart. Phys. **20**, 5 (2003), arXiv:hep-ph/0211406 .
[40] M. Kachelriess, O. E. Kalashev, and M. Y. Kuznetsov, Phys. Rev. D **98**, 083016 (2018), arXiv:1805.04500 [astro-ph.HE] .
[41] E. Alcantara, L. A. Anchordoqui, and J. F. Soriano, Phys. Rev. D **99**, 103016 (2019), arXiv:1903.05429 [hep-ph] .
[42] J. F. Navarro, C. S. Frenk, and S. D. M. White, Astrophys. J. **462**, 563 (1996), arXiv:astro-ph/9508025 .
[43] C. Guépin, R. Aloisio, L. A. Anchordoqui, A. Cummings, J. F. Krizmanic, A. V. Olinto, M. H. Reno, and T. M. Venters, Phys. Rev. D **104**, 083002 (2021), arXiv:2106.04446 [hep-ph] .
[44] A. Aab et al. (Pierre Auger), Nucl. Instrum. Meth. A **798**, 172 (2015), arXiv:1502.01323 [astro-ph.IM] .
[45] J. Rautenberg (Pierre Auger), Proc. 36th International Cosmic Ray Conference (Madison, USA) **PoS (ICRC2019)**, 398 (2019), arXiv:1909.09073 [astro-ph.HE] .
[46] P. Savina (Pierre Auger), Proc. 37th International Cosmic Ray Conference (Berlin, Germany) **PoS (ICRC2021)**, 373 (2021).
[47] A. Aab et al. (Pierre Auger), Phys. Rev. D **102**, 062005 (2020), arXiv:2008.06486 [astro-ph.HE] .
[48] L. A. Anchordoqui et al., Astropart. Phys. **132**, 102614 (2021), arXiv:2105.12895 [hep-ph] .
[49] A. Aab et al. (Pierre Auger), JCAP **10**, 022 (2019), arXiv:1906.07422 [astro-ph.HE] .
[50] J. McDonald, Phys. Rev. Lett. **88**, 091304 (2002), arXiv:hep-ph/0106249 .
[51] L. J. Hall, K. Jedamzik, J. March-Russell, and S. M. West, JHEP **03**, 080 (2010), arXiv:0911.1120 [hep-ph] .
[52] N. Bernal, M. Heikinheimo, T. Tenkanen, K. Tuominen, and V. Vaskonen, Int. J. Mod. Phys. A **32**, 1730023 (2017), arXiv:1706.07442 [hep-ph] .
[53] G. F. Giudice, E. W. Kolb, and A. Riotto, Phys. Rev. D **64**, 023508 (2001), arXiv:hep-ph/0005123 .
[54] M. Garny, A. Palessandro, M. Sandora, and M. S. Sloth, JCAP **02**, 027 (2018), arXiv:1709.09688 [hep-ph] .
[55] A. V. Olinto et al. (POEMMA), JCAP **06**, 007 (2021), arXiv:2012.07945 [astro-ph.IM] .
[56] J. R. Hörandel (GCOS), PoS **395**, 027 (2021), arXiv:2203.01127 [astro-ph.HE] .
[57] T. Markkanen, S. Nurmi, A. Rajantie, and S. Stopyra, JHEP **06**, 040 (2018), arXiv:1804.02020 [hep-ph] .