Bounds from multi-messenger astronomy on the Super Heavy Dark Matter

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The purely gravitational evidence supporting the need for dark matter (DM) particles is compelling and based on Galactic to cosmological scale observations. Thus far, the promising weakly interacting massive particles scenarios have eluded detection, motivating alternative models for DM. We consider the scenarios involving the superheavy dark matter (SHDM) that potentially can be emitted by primordial black holes (PBHs) and can decay or annihilate into ultrahigh-energy (UHE) neutrinos and photons. The observation of a population of photons with energies $E \geq 10^{11}$ GeV would imply the existence of completely new physical phenomena, or shed some light on DM models. Only the ultra-high energy cosmic ray observatories have the capabilities to detect such UHE decay products via the measurements of UHE photon induced extensive air showers. Using the upper bound on the flux of UHE cosmic rays beyond $10^{11.3}$ GeV implying $J(>10^{11.3} \text{ GeV}) < 3.6 \times 10^{-5}$ km$^{-2}$sr$^{-1}$y$^{-1}$, at the 90% C.L. reported by the Pierre Auger Observatory, we obtain global limits on the lifetime of the DM particles with masses $10^{11} \leq M_X \leq 10^{17}$ GeV. The constraints derived here are new and cover a region of the parameter space not yet explored. We compare our results with the projected constraints from future POEMMA and JEM-EUSO experiments, in order to quantify the improvement that will be obtained by these missions.

Moreover, assuming that an epoch of early PBHs domination introduces a unique spectral break, $f_*$, in the gravitational wave spectrum, the frequency of which is related to the SHDM mass, we map potential probes and limits of the DM particles masses on the $f_* - M_X$ parameter space.

I. INTRODUCTION: SOURCES OF CONSTRAINTS ON X-PARTICLES

The current cosmological understanding of structure formation, without taking the hazardous jump away from standard General Relativity gravity implies postulating the existence of Dark Matter (DM). Such existence, that entails specific gravitational consequences on structures that have been well established [1, 2], although cosmologically dominant, continues to fail to produce constituent particles events in direct detection attempts, whether through nuclear recoil tanks or in accelerators [3–13], or in indirect surveys seeking detection through annihilation events of weakly interacting massive particle (WIMP) [14].

So far, many fundamental characteristics of DM particles remain quite unconstrained, including their mass or their self-annihilation time. Solutions to problems of the particle physics Standard Model (SM) have given birth to a wealth of DM models. Although most of them keep DM in a separate noninteracting sector, none of the models have won over the favors of the field because of their compelling theoretical appeal.

For many decades, the favored models characterized DM as a relic density of WIMPs [15–18] (for a precise calculation of the WIMP relic abundance, see [19, 20]; partial wave unitarity dictates an upper bound on the WIMP mass $\leq 110$ TeV). However, the extensive experimental program set up for WIMP detection in the direct and indirect detection experiments [21–33] as well as in the LHC has given negative or inconclusive results so far [34–36]. Despite these facts, a complete exploration of the WIMP parameter space remains the highest priority of the DM community, and WIMP discovery is still a viable option in next-generation experiments.

Because the assumption of relatively low-mass DM seems quite natural, it is rarely questioned. However, the null results from DM searches began closing the favored parameter space for the WIMP models and at the same time started to open a door to alternatives to the WIMP paradigm.

More recently, dark sector interactions have been given more serious consideration, which viability has been scrutinized in Comelli et al. [37]. Observational effects on galaxy clusters dynamics of such interactions have gathered credibility [38–46]. However, most of the current constraints tend to favour stable or long-lived, cold
or warm, non-baryonic DM [47]. They consequently prompted the exploration of improved interacting models that respect those constraints, opening fairly large mass and interaction strength ranges for acceptable DM candidates [48].

Alternative views on DM have emerged a while ago. The most radical of them suggests that DM interacts only gravitationally, explaining the negative experimental results. For example, cold DM could be a manifestation of the gravitational sector itself consisting of massive gravitons of bi-metric gravity [49, 50] — the only known self-consistent, ghost-free extension of General Relativity with massive spin-2 fields [51].

Among the well-motivated and less radical ideas for what DM could be, the WIMPzilla hypothesis postulates that DM is made of gravitationally produced (non-thermal relic) super weakly-interacting super massive so-called X-particles — the Super-Heavy Dark Matter (SHDM) [52–58]. The hypothesis of DM consisting of heavy long-lived particles has attracted significant attention in the context of inflationary cosmology [59–62]. There are several scenarios of effective DM particles production at various stages of early Universe evolution. SHDM can be created gravitationally at the end of inflation [52–54, 61], during preheating [63, 64] and reheating [59, 65, 66], and from the collisions of vacuum bubbles at phase transitions [55, 64], or from emission [67] of the primordial black holes (PBHs) [see 57, for a review].

Of course, SHDM particles have been considered before to a certain extent. In particular, there is an extensive literature regarding observational constraints on unusually heavy DM candidates [for example, see 68–71, and references therein].

The earliest observational hint of SHDM existence was provided in the AGASA experiment by detection of super–GZK cosmic rays [72, with GZK standing for Greisen, Zatsepin, and Kuzmin]. This GZK cut–off was later supported in results from next-generation cosmic ray experiments [73, 74]. The IceCube PeV neutrinos detection [77, 78] have lead to various DM decay propositions of interpretations [79–84]. However, recent analyses of the respective gamma-ray signal [85, 86] have deprecated most of them, although the photon production suppression feature of a few of those DM models keep them conceivable [82, 87, 88]. The search for signatures of Planckian-interacting massive particles in the data of the Pierre Auger Observatory and derive constraints were reported in [75, 76]. The ultrahigh-energy cosmic rays (UHECRs) flux appears, from experimental data, to be dominated, above its “ankle”, by an astrophysical, extragalactic component [80], most possibly sourced from starburst galaxies [90]. Supposing the systematic uncertainties of current high-energy hadronic interaction models remain sufficiently small, we can expect the acceleration of heavier nuclei, in addition to protons, as sources of this flux.

Nevertheless, experimental data still allow for a minority component of different origin which, beyond the suppression, could still dominate the flux [71, 91].

The possibility that the by-products of the decay of unstable SHDM particles can contribute to the UHECR flux has been studied extensively in the past [see for instance 92–97]. In these models, DM is composed of supermassive particles produced gravitationally during inflation [52–54, 57]. These particles would be clustered in the halo of the galaxies, such as ours.

The discovery of gravitational waves (GWs) by LIGO and Virgo collaboration of black holes [98–102] and neutron stars [103, 104] has opened up a new cosmic frontier for the SHDM search by examination of the stochastic GW background (SGWB) [105–108] in the multi-frequency range [67].

Two main problems should be addressed in the discussion of SHDM models: how particles with very high mass ($M_X > 10^{13}$ GeV) can be quasi-stable, with a lifetime much longer than the age of the Universe $t_0$, and how their abundance can be dominant in the Universe today. The stability of SHDM can be achieved assuming the existence of a discrete gauge symmetry that protects the particle from decaying, in the same way as neutralino stability through R-parity in Super Symmetry. This discrete symmetry can be weakly broken, assuring a lifetime $\tau_X > t_0$, through wormhole [60] or instanton [59] effects. An example of a particle with a lifetime exceeding the age of the Universe can be found in [109]. Instanton decays induced by operators involving both the hidden sector and the SM sector may give rise to observable signals in the spectrum of UHECRs [59, 60]. Another possible way to stabilize such particles may be a modification of the standard cosmological expansion law in such a way that the density of these heavy relics would be significantly reduced [110].

Therefore, technically the SHDM models have two main parameters: mass $M_X$ and lifetime, $\tau_X$, in which a minority component of the UHECRs originates from the decay of these unstable particles. Stable X-particles are not so interesting from the experimental point of view since their annihilation cross-section is bounded by unitarity: $\sigma_{\text{ann}}^{\text{X}} \sim 1/M_X^4$, which makes its indirect detection impossible for today’s experiments [111]. The spectrum from SHDM decay is expected to be dominated by gamma rays [112–114] and neutrinos [79, 115] because of 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. However, such gamma-ray production can be substantially different for different decay channels [71].

While it is very challenging to probe such superheavy DM via the traditional direct, indirect, or collider experiments, this paper aims to show the current bounds on such X particles, with a mass larger than the weak scale by several (perhaps many) orders of magnitude, from the perspective of the recent cosmic ray and GWs observations. In this paper, we examine particles’ mass range from $10^{15}$ GeV to $10^{17}$ GeV together with the most recent
UHECR and GWs data to derive the strongest lower limit on the lifetime of decaying superheavy WIMPs (WIMP-Pzillas) and their mass. In Sec. II we estimated the photon flux from SHDM decays. For this, we evaluated two separate contributions: the astrophysical factor and the particle physics factor. We used current high-energy gamma-ray measurements [116] to examine bounds that one may put on the parameter space of decaying SHDM. In addition, from the relation of the GW spectrum break, $f_s$, with the SHDM mass, following Ref. [67], we mapped potential probes and limits of the SHDM particles masses on the $f_s-M_X$ parameter space in Sec. III. Result discussion is given in Sec. IV and we conclude in Sec. V.

II. BOUNDS ON SHDM FROM THE GAMMA-RAY FLUX

Given the mass of the SHDM particles, the decay time corresponding to the scenario for the largest SHDM cosmic ray flux, compatible with the upper limits to the photon fraction obtained by the Pierre Auger Observer (Auger), can be estimated from the predicted integral gamma-ray flux [112], which may be observed on Earth by an observatory with uniform exposure, as

$$J(E) = \frac{N(E > E_{\text{min}})}{4\pi M_X \tau_X} \left[ \frac{\int_V \rho_{DM}(r) \omega(\delta, \alpha, \theta_{\text{max}}) \ dV}{2\pi} \right].$$

This expression can be easily adopted in case we start to look at cosmic rays using the Moon’s regoloth [117]. Here $N(E > E_{\text{min}})$ is an integral number of photons with energies higher than $E_{\text{min}}$ produced in the decay of X-particle; $\theta$ is the angle between the line of sight and the axis defined by Earth and the Galactic center [118]; $\tau_X$ is the SHDM lifetime, $10^{11} - 10^{22}$ years; $M_X$ is the SHDM particle mass, $10^{15} - 10^{17}$ GeV; $\rho_{DM}(r) \equiv \rho_X(r)$ is the density of DM in the Galaxy as function of distance, $r$, from the Galactic Center, in GeV cm$^{-3}$. Integration in the numerator ranges over all the volume of the halo ($R_H = 260$ kpc) and in the denominator over all the sky (the averaging over right ascension is included in the definition of the directional exposure, $\omega(\hat{\mathbf{n}})$).

The directional exposure, $\omega(\hat{\mathbf{n}})$, provides the effective time-integrated collecting area for a flux from each direction of the sky $\hat{\mathbf{n}}(\alpha, \delta)$, characterized by the right ascension $\alpha$ and the declination $\delta$. For an experiment at latitude $\lambda$, which is fully efficient for particles arriving with zenith angle $< \theta_{\text{max}}$ and that experiences stable operation, $\omega(\hat{\mathbf{n}})$ actually becomes independent of $\alpha$ when integrating the local-angle-detection efficiency over full periods of sidereal revolution of the Earth. Full efficiency means that the acceptance depends on $\theta$ only through the reduction in the perpendicular area given by $\cos(\theta)$.

The $\omega$ dependence on declination, $\delta$, geographical latitude of the given experiment $\lambda$ and the maximal zenith angle $\theta_{\text{max}}$ accessible for fully efficient observation in the experiment, relies on geometrical acceptance terms and is given by [119, 120]

$$\omega(S, \Delta t, \delta, \lambda, \theta) = \frac{S \Delta t \cos(\lambda) \cos(\delta) \sin(a_m(\theta, \delta, \lambda))}{2\pi} + \frac{S \Delta t}{2\pi} a_m(\theta, \delta, \lambda) \sin(\lambda) \sin(\delta),$$

where $S$ is the effective surface of the given experiment (detector array); $\Delta t$ is the total exposure time of the given experiment (or time of data collection). The location of the Pierre Auger Observatory, $35.1^\circ - 35.5^\circ S, 69.6^\circ W$ at 875 g/cm$^2$ atmospheric depth [112], corresponds to the Pampa Amarilla plain, in the Mendoza Province of Argentina, close to the Malargüe town. Initiating data collection in January 2004 and completing its baseline design construction by 2008, by 2021, the Auger collected exposure had exceeded $7.68 \times 10^6$ km$^{-2}$ sr yr, exceeding the sum over all of the other cosmic ray experiments available [122]. Therefore, for the Auger with $S = 1.037 \times 10^4$ km$^2$, $\Delta t = 7.41$ years from Ref. [122], $\lambda = -35.2^\circ$ and $-15^\circ \leq \delta \leq 25^\circ$.

The parameter $a_m$ of the observatory is given by

$$a_m(\theta, \delta, \lambda) = \begin{cases} 0 & \text{for } \xi > 1 \\ \pi & \text{for } \xi < -1 \\ \arccos(\xi) & \text{otherwise}, \end{cases}$$

with

$$\xi(\theta, \delta, \lambda) = \frac{\cos(\theta_{\text{max}}) - \sin(\lambda) \sin(\delta)}{\cos(\lambda) \cos(\delta)}.$$ (3)

The DM galactic distribution, or DM density profile $\rho_{DM}$, is a function of the Galactic longitude, $l$, and latitude $b$, which in turn is related to the line-of-sight, $s$, coordinate:

$$r(s, b, l) = \sqrt{s^2 + r_\odot^2 - 2sr_\odot \cos(b) \cos(l)},$$ (4)

where $r_\odot = 8.5$ kpc denotes the distance between the Earth and the Galactic Center. The local DM density is an important ancillary parameter when constraining DM signatures. However due to the lack of a robust estimate of $\rho_X$, the distribution of DM is assumed to follow a density profile inspired by numerical simulations, typically an analytic fit such as the well-known Navarro-Frenk-White (NFW) [123] or Einasto [124, 125] profiles, with two or more free parameters whose best-fit values are then determined from dynamical constraints.

In this work we adopt both reference profiles: the NFW profile

$$\rho_X^{\text{NFW}}(r) = \rho_s \left( \frac{r}{r_s} \left( 1 + \frac{r}{r_s} \right)^2 \right)^{-1}$$ (5)

with $r_s = 28.44$ kpc [123]; the Einasto profile

$$\rho_X^{\text{Einasto}}(r) = \rho_s e^{-\frac{3}{2} \left( \frac{r}{r_s} \right)^{1/\gamma}},$$ (6)
in contrast with the somewhat steeper NFW profile, with 
$r_s = 30.28 \text{ kpc}, \alpha = 0.17 \ [124, 126]$ and $\rho_s = 0.105 \text{ GeV} \ cm^{-3} \ [91]$. Most recent systematic efforts to estimate a proper DM profile were summarized in Ref.[127].

With all this in hand, and defining the element of Galaxy volume in Eq. (1) as

\[ dV = r^2 \sin(\varphi) dr d\varphi d\theta = r^2 \sin \left( \frac{\pi}{2} - \delta \right) dr d\delta d\theta \]  

one can rewrite the flux expression (1), as following

\[ J(E) = \frac{1}{4\pi} \frac{1}{M_X \tau_X} \frac{dN}{dE} \left\{ \int_{0}^{50 \text{kpc}} \frac{\rho_X(r)}{r^2} dr \int_{-\frac{\pi}{2}}^{\frac{\pi}{2}} \sin \left( \frac{\pi}{2} - \delta \right) d\delta \int_{0}^{2\pi} \frac{\omega(\delta, a_0, \theta_{\max})}{1} d\theta \right\}. \]  

(8)

Using the radius of the Galactic halo $R_H = 260 \text{ kpc}$, the integral in Eq. (8) can be splitted in two integrals as was shown in Refs. [91, 128].

Therefore, the expected energy distribution on Earth follows the initial decay spectrum, whereas the angular distribution incorporates the (uncertain) distribution of DM in the Galactic halo via the line-of-sight integral [93, 96, 129, 130].

The energy spectrum, $dN/dE$, of the expected gamma rays depends on the exact SHDM decay mechanism and is model dependent. Trying to avoid this issue, in our computation we used the following flat spectrum similar to [91],

\[ \frac{dN(E)}{dE} \propto \cos(\delta) \omega(S, \Delta t, \delta, \lambda, \theta) \left[ M_X^{0.9} \log \left( \frac{2E}{M_X} \right) \right]^{-1.9}, \]  

(10)

validated for $X \rightarrow q\bar{q}$ decay, it is independent of the particle type, assuming the photon/nucleon ratio is $2 \leq \gamma/N \leq 3$ and the neutrino/nucleon ratio is $3 \leq \nu/N \leq 4$. In comparison with the other spectra available in the literature [136–139], the spectrum from [91] is much flatter. This allows one to have fixed photon/nucleon and neutrino/nucleon ratios along the whole energy range.

The consideration of the bosonic decay channels such as $WW/ZZ/\gamma\gamma$, or leptonic $ee/\mu\mu/\tau\tau$ would require a different stable particle spectra in Eq. (9).

The Auger is composed of two types of instruments: a) fluorescence telescopes, that measure light from atmospheric nitrogen excitation by air shower particles, b) ground particle detectors, that sample air shower fronts arriving at the Earth’s surface. Its maximum zenith angle falls at $\theta_{\max} = 90^\circ$, with the downward-going (DG) channel constrained to $60^\circ \leq \theta \leq 90^\circ$ while the Earth-skimming (ES) channel extends to $60^\circ \leq \theta \leq 95^\circ$ [see 140]. Therefore, in order to make a direct comparison with current limits on the diffuse UHE gamma-ray flux, from Eq. (9), following [112], we compute the angle-averaged integral $\gamma$-flux over the whole sky ($0 < \theta < \pi$), averaging over the directional exposure at the declination of the Auger Observatory, where the declination limits are $−15^\circ \leq \delta \leq 25^\circ$ [120].

The SHDM flux contributions from the extragalactic and galactic haloes need to be resolved as they can be important due to the fact that the gamma rays and protons originating in that extragalactic halo come from a narrow region of the sky. Therefore, in that region the contribution of the extragalactic halo can be more important than the one corresponding to our galaxy, specially in regions far from the galactic center where the galactic contribution decreases considerably [128].

The fluxes obtained for the various DM mass and DM density profiles are listed in Table. I.

III. BOUNDS ON SHDM FROM THE GRAVITATIONAL WAVES OBSERVATIONS

Today the scientific community started to synthesize the various astronomical messengers, namely photons, neutrinos, cosmic rays, and gravitational waves. While photons, neutrinos, and cosmic rays still have a vital role to play in multi-messenger astronomy, GWs observation
with pan-spectral electromagnetic radiation has enriched our understanding of violent astronomical events [103].

The details of the SHDM production mechanism can leave their footprint on the primordial GW amplitude as well as the spectral features. However, such a scenario is only present if DM mass would be generated by spontaneous symmetry breaking of an Abelian symmetry, which is not the general case.

An early Universe cosmological phase transition induced by this spontaneous symmetry breaking [141] may result into emergence of a cosmic string network [142, 143] – line-like topological defects. Cosmic strings restore that broken Abelian symmetry at the core of these topological defects with vortex types of behavior [144]. Their network loses energy through the shrinking of its closed loops following their emission of GWs [145, 146]. The resulting primordial GW signal contains key signatures of ultraviolet physics that would otherwise remain far beyond the reach of regular ground detection. This is why such signal is a main focus of current and future investigations of the stochastic GW background (SGWB) [105–108]. In addition, observation of such a signal [135, 147, 148] can be a complementary probe to the range of SHDM mass if one assumes that such DM particles are produced by emission of the PBHs.

The shape of the GW spectrum from a cosmic string network is expected to follow a convex cored power law which slope varies with amplitude and frequency, as well as it parameterized by the product $G\mu$ between the string tension $\mu$ and Newton’s gravitation constant $G$.

The standard form of the spectral GWs energy density can be expressed today as the power-law:

$$\Omega_{GW}(f) = \frac{2\pi^2}{3H_0^2} A^2 f_{yr}^2 \left( \frac{f}{f_{yr}} \right)^{5-\gamma_N},$$

where $f_{yr} = 1yr^{-1}$, $A$ is the characteristic GW strain amplitude, $\gamma_N$ is the spectral index of the pulsar timing-residual cross-power spectrum and $H_0 = 67.7 \text{ km/}(\text{Mpc sec})$ is the present Hubble constant.

Following the recipe defined in [67] one can approximately determine the frequency at which the GW spectrum, $\Omega_{GW}(f) h^2$, changes slope from a plateau described by $f^0$ to $f^{-1/3}$ with the help of the following expression

$$f_* = 2.1 \times 10^{-8} \sqrt{\frac{50}{\zeta_{eq}\alpha \Gamma G\mu} \left( \frac{M_X}{T_0} \right)^{3/2} T_0^{-2} t_0^{-1}},$$

where $\Gamma = 50$ is the constant rate of GW radiation, $\alpha = 0.1$ characterises the cosmic string loop size at the time of

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**FIG. 1.** Map of the possible probes of $M_X$ and hence of the PBH evaporation temperature projecting the turning-point frequencies $f_\star$, Eq. (12), for the various SHDM particle masses. Here, each diagonal line corresponds to the $G\mu$ value in the range $10^{-19}$ to $10^{-7}$ running from top to bottom. Below $G\mu = 10^{-7}$ lies the CMB limit for the cosmic string tension [131]. The relevant sensitivity curves of current or future GW detectors, such as the Einstein Telescope (ET), Cosmic Explorer (CE), LISA[132], BBO [133] are reproduced from [67] using Eq. (12). The light yellow region is the allowed parameter space assuming the PBH emission to SHDM scenario from [67]. The dark and light green bands denote the predicted turning-point frequencies computed assuming the $1\sigma$ and $2\sigma$ prediction on $G\mu$ parameter taken from [134] obtained from the fits to the NANOGrav data [135] for the examined SHDM particle masses.
FIG. 2. The red graded area represents solutions of Eq. (14) with respect to the characteristic GW strain amplitude, $A$, at $f = f_*(M_X)$, projected onto the $\gamma_N - A$ plane. Three benchmark points for $A$ and $\gamma_N$ parameters, which were listed in Ref. [134], are shown as markers (o, *, ⋄). The dark and light contours denote the 1σ and 2σ posteriors in the NANOGrav analysis that allow to describe the observed stochastic process. Here, we use the contours taken from Ref. [135]. The black dashed vertical line indicates the theoretical prediction for a population of supermassive black hole binaries (SMBHBs), $\gamma_N = 13/3$. Points on the vertical line denote a 95% upper limit on the dimensionless strain amplitude $A = 3 \times 10^{-15}$ and $A = 1.34 \times 10^{-15}$ at a reference frequency of 1 yr$^{-1}$ and a spectral index of 13/3 obtained from the European Pulsar Timing Array (EPTA) data and from the NANOGrav report respectively [147, 148].

formation, $z_{eq} = 3387$ is the red-shift at the usual matter-radiation equality, occurring at the time $t_{eq}$, $T_0 = 2.725$ K is the photon temperature today, and $t_0 = 13.81$ Gyr is the age of the Universe.

With Eq. (12) we computed the turning-point frequencies, $f_*$, for the range of masses $M_X = 10^{12} - 10^{17}$ GeV assuming the dimensionless combination [67, 149] between the corresponding cosmic string tension and SHDM particle mass,

$$G\mu \sim GM_X^2.$$  \hspace{1cm} (13)

The obtained frequencies lie within the range from 2.16 to 0.021 Hz, for masses ranging from $10^{12}$ to $10^{17}$ GeV respectively. With such an assumption, furthermore admitting that the $G\mu$ value for $M_X = 10^{16}$ GeV is below the Cosmic Microwave Background (CMB) limit on $G\mu$ [134] (see black data-points on Fig. 1) while taking the resulted 1σ value of $G\mu$ [134] from the fits to the NANOGrav signal [135], which is $[4.9 \times 10^{-11}]$, we determined $f_*$ in the range of 1.76(1.17) to 27.94(18.63) Hz. This result is shown with the green band on Fig. 1 with the different probes of the $M_X$ and hence the PBH evaporation temperature. Assuming that PBHs evaporation causes a break in the GW spectrum at the turning point frequency [67], $f_*(M_X)$, from Eqs. (11) and (12) one may solve the following equality

$$2.1 \times 10^{-8} \sqrt{\frac{50}{z_{eq}\alpha T_0}} GM_X^2 \left(\frac{M_X}{T_0}\right)^{\frac{2}{7}} T_0 T_0^{-\alpha} A T_0^{\frac{2}{7}} f_0 \left(\frac{f_*(M_X)}{f_0}\right)^{\frac{2}{7}} = \frac{2\pi^2}{3\hbar^2} f_0^2 \left(\frac{f_*(M_X)}{f_0}\right)^{\frac{2}{7}} - \gamma_N,$$  \hspace{1cm} (14)

with respect to the characteristic GW strain amplitude, $A$ by scanning over $\gamma_N$ in the range of 3.5 to 5.5 with the step size of 0.005, $G\mu$ in the range of $10^{-12}$ to $10^{-7}$ with the step size of $10^{-15}$, and $\alpha$ in the range of 10$^{-6}$ to 0.2 with the step size of 0.025. The obtained solutions are compared with the NANOGrav observation in Fig. 2, where the red cone represents the domain of solutions for the mass range of $M_X = 10^9 - 10^{19}$ GeV. The results for the benchmark values of $G\mu$ and $\alpha$ parameters, which are listed in [134], are shown with the solid and dashed blue lines to guide the eye.

IV. RESULTS AND DISCUSSION

The integral fluxes of photons at the location of the Auger Observatory for the different masses of the DM particle candidates are shown in Table I.

In Fig. 3 we compare the result of this work with the current lifetime limits placed by Auger, the KASCADE-Grande observations [91]. We add the existing gamma-
FIG. 3. Comparison of the upper constraints obtained in the literature with the 95% C.L. exclusion plot for mass $M_X$ and lifetime $\tau_X$ of DM particles. The constraints that were obtained with the data of Pierre Auger full-sky analysis [150] assuming NFW DM profile (solid green lines), or with assumption that the DM profile is given by the Einasto model (dashed blue lines), constraints obtained using the DM flux estimation from Mikhail Kuznetsov given in the Ref. [91], are shown with the gray bold solid line. The lower limit on the lifetime of SHDM particles together with the stereoscopic constraints obtained from the possible observation of one photon event above $10^{15}$ GeV in 5 yr of data collection) of POEMMA (dashed dark gray line) was taken from [91]. The Alcantara 95% C.L. excluded region (dash-dotted dark magenta line) and the Kalashed-Kuznetsov excluded region (solid magenta line), all those curves are taken from [91]. The regions accessible to the JEM-EUSO experiment, each region corresponding to a different choice of the power law index in the inflation potential, $\beta = 2; 4/3; 1$, are plotted from left to right [95]. The gamma-ray limits placed by Chianese et al. [71] (orange solid line), the limits placed by Kachelriess et al. [115] (red dotted line) are also shown. For illustration purposes, the 95% CL upper limit on mass obtained from the possible value of the Hubble rate at the end of inflation for a reheating efficiency of 1% (10%) is shown as the vertical dashed (dotted) line [151]. The constraints derived from diffuse $\gamma$-ray and neutrino limits from the Auger (solid bold dark red line), from the KASKADE-Grande (solid bold red line). We also show for comparison the constraints obtained assuming Burkert DM profile (black short dashed line) using the data of Pierre Auger partial-sky analysis [150].
We estimate that the value of the GWs spectral break, which can be computed from the SHDM particle mass, could represent the smoking gun in the indirect searches for the SHDM with a certain mass. It is exciting that the GWs spectral break, \( f_s \), for the range of the examined SHDM masses would be precisely within the sensitivity ranges of mid-band detectors such as BBO and LISA, see Fig. 1.

In Fig. 2 we map the extracted characteristic GW strain amplitude, \( A \), by scanning the spectral index of the pulsar timing-minor cross-power spectrum, \( \gamma_N \), using Eq. (14) on the recent finding of a stochastic common-spectrum process by NANOGrav. No matter what prior assumption we made on the initial values of SHDM mass, \( G_\mu \), \( \alpha \) all obtained solutions intersect at the same value of the spectral index, \( \gamma_N \approx 4 \). The slope of the lines in Fig. 2 is driven by the choice of \( M_X \) and \( G_\mu \). For \( G_\mu \) we took the obtained 1\( \sigma \) and 2\( \sigma \) \( G_\mu \) from the fits to NANOGrav data [134].

V. SUMMARY AND CONCLUSION

The abundance of SHDM can easily be dominant in the Universe today, with an SHDM density \( \Omega_{\text{shdm}} \approx \Omega_{\text{dm}} \). This effect can be obtained by gravitational production that resembles the production of density fluctuations during inflation. The gravitational production of particles during inflation [58, 62] is the only experimentally verified DM production mechanism as the observed CMB fluctuations have exactly the same origin. 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 [152]. This implies a detectable primordial tensor-to-scalar ratio \( r \) in the CMB power spectrum. At the end of inflation, a fraction of fluctuations are not stretched beyond the horizon but remain as particles because the inflation slows down. The weakness of gravitational interaction naturally explains the tiny initial abundance of WIMPZillas [55]. Indeed, for such an abundance to be cosmologically relevant today, the X-particles must be supermassive. The combined [Ade et al. 153, Planck satellite, together with Ade et al. 154, BICEP2 and the Keck array] 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 [151]. For slightly less efficient reheating, this upper limit strengthens to \( M_X \lesssim 10^{16} \) GeV.

There are several sources of constraints for the SHDM parameters. In the energy range of interest the mass, \( M_X \), and lifetime, \( \tau_X \), are constrained by cosmic ray observations. The mass is subjected to cosmological constraints [52, 54, 55, 57, 152, 155] and GWs observations [67]. The lifetime of the DM particles can be effectively constrained with the observed fluxes of various high-energy particles or with the upper limit on these fluxes. The upper limits to the gamma-ray flux obtained

| \( M_X \), [GeV] | \( \tau_X \), [years] | \( J(> E_0) \) | \( \tau_X \), [years] | \( J(> E_0) \) |
|----------------|----------------|----------------|----------------|----------------|
| \( 10^{15} \)  | \( 10^{21} \)   | \( 6.803 \times 10^{-5} \) | \( 10^{22} \)   | \( 6.803 \times 10^{-6} \) |
| \( 10^{16} \)  | \( 10^{21} \)   | \( 7.406 \times 10^{-5} \) | \( 10^{22} \)   | \( 7.406 \times 10^{-6} \) |
| \( 10^{17} \)  | \( 10^{21} \)   | \( 8.571 \times 10^{-5} \) | \( 10^{22} \)   | \( 8.571 \times 10^{-6} \) |
| \( 10^{18} \)  | \( 10^{21} \)   | \( 1.028 \times 10^{-4} \) | \( 10^{24} \)   | \( 1.028 \times 10^{-4} \) |
| \( 10^{19} \)  | \( 10^{21} \)   | \( 3.250 \times 10^{-4} \) | \( 10^{24} \)   | \( 3.250 \times 10^{-4} \) |
| \( 10^{20} \)  | \( 10^{21} \)   | \( 1.028 \times 10^{-2} \) | \( 10^{22} \)   | \( 1.028 \times 10^{-3} \) |
| \( 10^{21} \)  | \( 10^{21} \)   | \( 5.867 \times 10^{-4} \) | \( 10^{24} \)   | \( 5.867 \times 10^{-4} \) |
| \( 10^{22} \)  | \( 10^{21} \)   | \( 1.855 \times 10^{-3} \) | \( 10^{22} \)   | \( 1.855 \times 10^{-4} \) |
| \( 10^{23} \)  | \( 10^{21} \)   | \( 5.867 \times 10^{-4} \) | \( 10^{22} \)   | \( 5.867 \times 10^{-4} \) |

TABLE I. Integral fluxes for the DM particle candidates with mass, \( M_X \). DM fluxes computed with the help of Eq. (9) assuming the Einasto and NFW DM density profiles. In addition, we show results obtained with the energy spectra from [136, 137].
by Auger [112] and the non detection of events above $10^{11.3}$ GeV by Auger impose tight constraints [91] to the flux corresponding to this hypothetical SHDM component, see dark red bold line on Fig. 3. The strongest limits for DM masses smaller than $\sim 10^9$ GeV are obtained from KASCADE-Grande [71], see red bold line on Fig. 3. In [156] the constraints, see thin magenta solid line on Fig. 3, have been put using the shape of charged cosmic-ray spectra. However, with the modern cosmic-ray data this method is not as effective in constraining cosmic-ray spectra.

Taking into account all currently available constraints in the literature on the SHDM, one may conclude that if the DM flux is around $10^{-5} \text{km}^{-2} \text{sr}^{-1} \text{y}^{-1}$ for masses in the range $10^{15} - 10^{17}$ GeV independently on the decay channel such SHDM hypothesis can be excluded. However, if there is some mechanism that may increase that flux by at least one order of magnitude, then there remains a window of opportunities to find these particles on the future POEMMA, JEM-EUSO and ZAP experiments.

Since the examined DM mass range significantly exceeds the sensitivity regions of the traditional DM detection experiment, in view of the recent proposals [67, 149] to search for the SHDM via GWs astronomy we put bounds on the possible DM signal probes with such detection technique.

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[1] M. Betoule et al. (SDSS), “Improved cosmological constraints from a joint analysis of the SDSS-II and SNLS supernova samples,” Astron. Astrophys. 568, A22 (2014), arXiv:1401.4064 [astro-ph.CO].

[2] P. A. R. Ade et al. (Planck), “Planck 2013 results. XVI. Cosmological parameters,” Astron. Astrophys. 571, A16 (2014), arXiv:1303.5076 [astro-ph.CO].

[3] Serguei Chatrchyan et al. (CMS), “Search for Dark Matter and Large Extra Dimensions in Monojet Events in pp Collisions at $\sqrt{s} = 7$ TeV,” JHEP 09, 094 (2012), arXiv:1206.5663 [hep-ex].

[4] Georges Aad et al. (ATLAS), “Search for dark matter candidates and large extra dimensions in events with a jet and missing transverse momentum with the ATLAS detector,” JHEP 04, 075 (2013), arXiv:1210.4491 [hep-ex].

[5] R. Agnese et al. (SuperCDMS), “Search for Low-Mass Weakly Interacting Massive Particles with SuperCDMS,” Phys. Rev. Lett. 112, 241302 (2014), arXiv:1402.7137 [hep-ex].

[6] G. Angloher et al., “Results from 730 kg days of the CRESST-II Dark Matter Search,” Eur. Phys. J. C 72, 1971 (2012), arXiv:1109.0702 [astro-ph.CO].

[7] M. Felizardo et al., “Final Analysis and Results of the Phase II SIMPLE Dark Matter Search,” Phys. Rev. Lett. 108, 201302 (2012), arXiv:1106.3014 [astro-ph.CO].

[8] Michael Klasen, Martin Pohl, and Günter Sigl, “Indirect and direct search for dark matter,” Prog. Part. Nucl. Phys. 85, 1–32 (2015), arXiv:1507.03800 [hep-ph].

[9] D. S. Akerib et al. (LUX), “First results from the LUX dark matter experiment at the Sanford Underground Research Facility,” Phys. Rev. Lett. 112, 091303 (2014), arXiv:1310.8214 [astro-ph.CO].

[10] Z. Ahmed et al. (CDMS-II), “Results from a Low-Energy Analysis of the CDMS II Germanium Data,” Phys. Rev. Lett. 106, 131302 (2011), arXiv:1011.2482 [astro-ph.CO].

[11] R. Bernabei et al. (DAMA, LIBRA), “New results from DAMA/LIBRA,” Eur. Phys. J. C 67, 39–49 (2010), arXiv:1002.1028 [astro-ph.GA].

[12] C. E. Aalseth et al. (CoGeNT), “Results from a Search for Light-Mass Dark Matter with a P-type Point Contact Germanium Detector,” Phys. Rev. Lett. 106, 131301 (2011), arXiv:1002.4703 [astro-ph.CO].

[13] E. Aprile et al. (XENON100), “Dark Matter Results from 225 Live Days of XENON100 Data,” Phys. Rev. Lett. 109, 181301 (2012), arXiv:1207.5988 [astro-ph.CO].

[14] Jan Conrad, “Indirect Detection of WIMP Dark Matter: a compact review,” in Interplay between Particle and Astroparticle physics (2014) arXiv:1411.1925 [hep-ph].

[15] Benjamin W. Lee and Steven Weinberg, “Cosmological Lower Bound on Heavy Neutrino Masses,” Phys. Rev. Lett. 39, 165–168 (1977).

[16] M. I. Vysotsky, A. D. Dolgov, and Ya. B. Zeldovich.
“Cosmological Restriction on Neutral Lepton Masses,” JETP Lett. 26, 188–190 (1977).

17. H. Goldberg, “Constraint on the Photino Mass from Cosmology,” Phys. Rev. Lett. 50, 1419 (1983), [Erratum: Phys.Rev.Lett. 103, 099905 (2009)].

18. Gary Steigman and Michael S. Turner, “Cosmological Constraints on the Properties of Weakly Interacting Massive Particles,” Nucl. Phys. B 253, 375–386 (1985).

19. Paolo Gondolo and Graciela Gelmini, “Cosmic abundances of stable particles: Improved analysis,” Nucl. Phys. B 360, 145–179 (1991).

20. Gary Steigman, Basudeb Dasgupta, and John F. Beacom, “Precise Relic WIMP Abundance and its Impact on Searches for Dark Matter Annihilation,” Phys. Rev. D 86, 023506 (2012), arXiv:1204.3622 [hep-ph].

21. M. Ackermann et al. (Fermi-LAT), “Constraints on the Galactic Halo Dark Matter from Fermi-LAT Diffuse Measurements,” Astrophys. J. 761, 91 (2012), arXiv:1205.6474 [astro-ph.CO].

22. Teresa Marrodán Undagoitia and Ludwig Rauch, “Dark matter direct-detection experiments,” J. Phys. G 43, 013001 (2016), arXiv:1509.08767 [physics.ins-det].

23. D. S. Akerib et al. (LUX), “Results from a search for dark matter in the complete LUX exposure,” Phys. Rev. Lett. 118, 021303 (2017), arXiv:1608.07648 [astro-ph.CO].

24. A. Albert et al., “Results from the search for dark matter in the Milky Way with 9 years of data of the ANTARES neutrino telescope,” Phys. Lett. B 769, 249–254 (2017), [Erratum: Phys.Lett.B 796, 253–255 (2019)], arXiv:1612.04595 [astro-ph.HE].

25. M. L. Ahnen et al. (MAGIC, Fermi-LAT), “Limits to Dark Matter Annihilation Cross-Section from a Combined Analysis of MAGIC and Fermi-LAT Observations of Dwarf Satellite Galaxies,” JCAP 02, 039 (2016), arXiv:1601.06590 [astro-ph.CO].

26. E. Aprile et al. (XENON), “First Dark Matter Search Results from the XENON1T Experiment,” Phys. Rev. Lett. 119, 181301 (2017), arXiv:1705.06655 [astro-ph.CO].

27. C. Amole et al. (PICO), “Dark Matter Search Results from the PICO-60 C2F5Br Bubble Chamber,” Phys. Rev. Lett. 118, 251301 (2017), arXiv:1702.07666 [astro-ph.CO].

28. M. G. Aartsen et al. (IceCube), “Search for Neutrinos from Dark Matter Self-Annihiliations in the center of the Milky Way with 3 years of IceCube/DeepCore,” Eur. Phys. J. C 77, 627 (2017), arXiv:1705.08103 [hep-ex].

29. Xiangyi Cui et al. (PandaX-II), “Dark Matter Results From 54-Ton-Day Exposure of PandaX-II Experiment,” Phys. Rev. Lett. 119, 181302 (2017), arXiv:1708.06917 [astro-ph.CO].

30. A. Albert et al. (HAWC), “Dark Matter Limits From Dwarf Spheroidal Galaxies with The HAWC Gamma-Ray Observatory,” Astrophys. J. 853, 154 (2018), arXiv:1706.01277 [astro-ph.HE].

31. A. U. Abeysekara et al. (HAWC), “A Search for Dark Matter in the Galactic Halo with HAWC,” JCAP 02, 049 (2018), arXiv:1710.10288 [astro-ph.HE].

32. H. Abdallah et al. (HESS), “Search for γ-Ray Line Signals from Dark Matter Annihilations in the Inner Galactic Halo from 10 Years of Observations with H.E.S.S.,” Phys. Rev. Lett. 120, 201101 (2018), arXiv:1805.05741 [astro-ph.HE].

33. Fernando Monteiro, Gadi Afek, Daniel Carney, Gordon Krnjaic, Jiaxiang Wang, and David C. Moore, “Search for composite dark matter with optimally levitated sensors,” Phys. Rev. Lett. 125, 181102 (2020), arXiv:2007.12067 [hep-ex].

34. Oliver Buchmueller, Caterina Doglioni, and Lian Tao Wang, “Search for dark matter at colliders,” Nature Phys. 13, 217–223 (2017), arXiv:1912.12739 [hep-ex].

35. Björn Penning, “The pursuit of dark matter at colliders—an overview,” J. Phys. G 45, 063001 (2018), arXiv:1712.01391 [hep-ex].

36. Salvatore Rappoccio, “The experimental status of direct searches for exotic physics beyond the standard model at the Large Hadron Collider,” Rev. Phys. 4, 100027 (2019), arXiv:1810.10579 [hep-ex].

37. D. Comelli, M. Pietroni, and A. Riotto, “Dark energy and dark matter,” Phys. Lett. B 571, 115–120 (2003), arXiv:hep-ph/0302080.

38. Orfeu Bertolami, F. Gil Pedro, and M. Le Delliou, “Dark Energy-Dark Matter Interaction and the Violation of the Equivalence Principle from the Abell Cluster A586,” Phys. Lett. B 654, 165–169 (2007), arXiv:astro-ph/0703462.

39. O. Bertolami, F. Gil Pedro, and M. Le Delliou, “The Abell Cluster A586 and the Equivalence Principle,” Gen. Rel. Grav. 41, 2839–2846 (2009), arXiv:0705.3118 [astro-ph].

40. Morgan Le Delliou, Orfeu Bertolami, and Francisco Gil Pedro, “Dark Energy-Dark Matter Interaction from the Abell Cluster A586 and violation of the Equivalence Principle,” AIP Conf. Proc. 957, 421–424 (2007), arXiv:0709.2505 [astro-ph].

41. E. Abdalla, L. Raul W. Abramo, L. Sodre, Jr., and B. Wang, “Signature of the interaction between dark energy and dark matter in galaxy clusters,” Phys. Lett. B 673, 107–110 (2009), arXiv:0710.1198 [astro-ph].

42. Orfeu Bertolami, Francisco Gil Pedro, and Morgan Le Delliou, “Dark Energy-Dark Matter Interaction from the Abell Cluster A586,” EAS Publ. Ser. 30, 161–167 (2008), arXiv:0801.0201 [astro-ph].

43. Elcio Abdalla, L. Raul Abramo, and Jose C. C. de Souza, “Signature of the interaction between dark energy and dark matter in observations,” Phys. Rev. D 82, 023508 (2010), arXiv:0910.5236 [gr-qc].

44. Orfeu Bertolami, Francisco Gil Pedro, and Morgan Le Delliou, “Testing the interaction of dark energy to dark matter through the analysis of virial relaxation of clusters Abell Clusters A586 and A1689 using realistic density profiles,” Gen. Rel. Grav. 44, 1073–1088 (2012), arXiv:1105.3033 [astro-ph.CO].

45. Morgan Le Delliou, Rafael J. F. Marcondes, Gastao B. Lima Neto, and Elcio Abdalla, “Non-virialized clusters for detection of dark energy–dark matter interaction,” Mon. Not. Roy. Astron. Soc. 453, 2–13 (2015), arXiv:1411.5863 [astro-ph.CO].

46. Morgan Le Delliou, Rafael J. F. Marcondes, and Gastão B. Lima Neto, “New observational constraints on interacting dark energy using galaxy clusters virial equilibrium states,” Mon. Not. Roy. Astron. Soc. 490, 1944–1952 (2019), arXiv:1811.10712 [astro-ph.CO].

47. G. Bertone, D. Hooper, and J. Silk, “Particle dark matter: Evidence, candidates and constraints,” Phys. Rept. 405, 279–390 (2005), arXiv:hep-ph/0404175.

48. Jonathan L. Feng, “Dark Matter Candidates from Par-
particle Physics and Methods of Detection,” Ann. Rev. Astron. Astrophys. 48, 495–545 (2010), arXiv:1003.0904 [astro-ph.CO].
[49] Eugeny Babichev, Luca Marzola, Martti Raidal, Anghnis Schmidt-May, Federico Urban, Hardi Veermäe, and Mikael von Strauss, “Bigravitational origin of dark matter,” Phys. Rev. D 94, 084055 (2016), arXiv:1604.08564 [hep-ph].
[50] Katsuki Aoki and Shinji Mukohyama, “Massive gravitons as dark matter and gravitational waves,” Phys. Rev. D 94, 024001 (2016), arXiv:1604.06704 [hep-th].
[51] S. F. Hassan and Rachel A. Rosen, “Bimetric Gravity from Ghost-free Massive Gravity,” JHEP 02, 126 (2012), arXiv:1109.3515 [hep-th].
[52] Daniel J. H. Chung, Edward W. Kolb, and Antonio Riotto, “Superheavy dark matter,” Phys. Rev. D 59, 023501 (1998), arXiv:hep-ph/9802238.
[53] Vadim Kuzmin and Igor Tkachev, “Ultrahigh-energy cosmic rays, superheavy long living particles, and matter creation after inflation,” JETP Lett. 68, 271–275 (1998), arXiv:hep-ph/9802304.
[54] Vadim Kuzmin and Igor Tkachev, “Matter creation via vacuum fluctuations in the early Universe and observed ultrahigh-energy cosmic ray events,” Phys. Rev. D 59, 123006 (1999), arXiv:hep-ph/9909547.
[55] Edward W. Kolb, Daniel J. H. Chung, and Antonio Riotto, “WIMPzillas!” AIP Conf. Proc. 484, 91–105 (1999), arXiv:hep-ph/9810361.
[56] Daniel J. H. Chung, Edward W. Kolb, Antonio Riotto, and Igor I. Tkachev, “Probing Planckian physics: Resonant production of particles during inflation and features in the primordial power spectrum,” Phys. Rev. D 62, 043508 (2000), arXiv:hep-ph/9910437.
[57] Vadim A. Kuzmin and Igor I. Tkachev, “Ultrahigh-energy cosmic rays and inflation relics,” Phys. Rept. 320, 199–221 (1999), arXiv:hep-ph/9903542.
[58] Daniel J. H. Chung, Patrick Crotty, Edward W. Kolb, and Antonio Riotto, “On the Gravitational Production of Superheavy Dark Matter,” Phys. Rev. D 64, 043503 (2001), arXiv:hep-ph/0104100.
[59] V. A. Kuzmin and V. A. Rubakov, “Ultrahigh-energy cosmic rays: A Window to postinflationary reheating epoch of the Universe?” Phys. Atom. Nucl. 61, 1028 (1998), arXiv:astro-ph/9709187.
[60] V. Berezinsky, M. Kachelriess, and A. Vilenkin, “Ultrahigh-energy cosmic rays without GZK cutoff,” Phys. Rev. Lett. 79, 4302–4305 (1997), arXiv:astro-ph/9708217.
[61] Edward W. Kolb, A. A. Starobinsky, and I. I. Tkachev, “Trans-Planckian wimpzillas,” JCAP 07, 005 (2007), arXiv:hep-th/0702143.
[62] Kristjan Kannike, Antonio Racioppi, and Martti Raidal, “Super-heavy dark matter – Towards predictive scenarios from inflation,” Nucl. Phys. B 918, 162–177 (2017), arXiv:1605.09378 [hep-ph].
[63] Brian R. Greene, Tomislav Prokopec, and Thomas G. Roos, “Inflaton decay and heavy particle production with negative coupling,” Phys. Rev. D 56, 6484–6507 (1997), arXiv:hep-ph/9705357.
[64] Daniel J. H. Chung, Edward W. Kolb, and Antonio Riotto, “Nonthermal supermassive dark matter,” Phys. Rev. Lett. 81, 4048–4051 (1998), arXiv:hep-ph/9805473.
[65] Daniel J. H. Chung, Edward W. Kolb, and Antonio Riotto, “Production of massive particles during reheating,” Phys. Rev. D 60, 063504 (1999), arXiv:hep-ph/9809453.
[66] D. S. Gorbunov and A. G. Panin, “Scalaron the mighty: producing dark matter and baryon asymmetry at reheating,” Phys. Lett. B 700, 157–162 (2011), arXiv:1009.2448 [hep-ph].
[67] Rome Samanta and Federico R. Urban, “Testing super heavy dark matter from primordial black holes with gravitational waves,” Journal of Cosmology and Astroparticle Physics 2022, 017 (2022), arXiv:2112.04836 [hep-ph].
[68] A. De Rujula, S. L. Glashow, and U. Sarid, “CHARGED DARK MATTER,” Nucl. Phys. B 333, 173–194 (1990).
[69] John R. Ellis, G. B. Gelmini, Jorge L. Lopez, Dimitri V. Nanopoulos, and Subir Sarkar, “Astrophysical constraints on massive unstable neutral relic particles,” Nucl. Phys. B 373, 399–437 (1992).
[70] Subir Sarkar, “Big Bang nucleosynthesis and physics beyond the Standard Model,” Rept. Prog. Phys. 59, 1493–1610 (1996), arXiv:hep-ph/9602260.
[71] Marco Cianese, Damiano F. G. Fiorillo, Rasmi Haifaj, Gennaro Miele, and Cinetta Saviano, “Constraints on heavy decaying dark matter with current gamma-ray measurements,” JCAP 11, 035 (2021), arXiv:2108.01678 [hep-ph].
[72] M. Takeda et al., “Energy determination in the Akeno Giant Air Shower Array experiment,” Astropart. Phys. 19, 447–462 (2003), arXiv:astro-ph/0209422.
[73] T. Abu-Zayyad, R. Aida, M. Allen, R. Anderson, R. Azuma, E. Barciowski, J. W. Belz, D. R. Bergman, S. A. Blake, R. Cady, and et al., “The cosmic-ray energy spectrum observed with the surface detector of the Telescope Array experiment,” The Astrophysical Journal 768, L1 (2013).
[74] J. Abraham et al. (Pierre Auger), “Observation of the suppression of the flux of cosmic rays above 4×10^{19} eV,” Phys. Rev. Lett. 101, 061101 (2008), arXiv:0806.4302 [astro-ph].
[75] P. Abreu et al. (Pierre Auger), “Cosmological implications of photon-flux upper limits at ultrahigh energies in scenarios of Planckian-interacting massive particles for dark matter,” Phys. Rev. D 107, 042002 (2023), arXiv:2208.02353 [astro-ph.HE].
[76] P. Abreu et al. (Pierre Auger), “Limits to Gauge Coupling in the Dark Sector Set by the Nonobservation of Instanton-Induced Decay of Super-Heavy Dark Matter in the Pierre Auger Observatory Data,” Phys. Rev. Lett. 130, 061101 (2023), arXiv:2203.08854 [astro-ph.HE].
[77] M. G. Aartsen et al. (IceCube), “Evidence for High-Energy Extraterrestrial Neutinos at the IceCube Detector,” Science 342, 1248256 (2013), arXiv:1311.5238 [astro-ph.HE].
[78] M. G. Aartsen et al. (IceCube), “Observation of High-Energy Astrophysical Neutrinos in Three Years of IceCube Data,” Phys. Rev. Lett. 113, 101101 (2014), arXiv:1405.5303 [astro-ph.HE].
[79] Kohta Murase, Ranjan Laha, Shin’ichiro Ando, and Markus Ahlers, “Testing the Dark Matter Scenario for PeV Neutrinos Observed in IceCube,” Phys. Rev. Lett. 115, 071301 (2015), arXiv:1503.04663 [hep-ph].
[80] Atri Bhattacharya, Mary Hall Reno, and Ina Sarce-
vic, “Reconciling neutrino flux from heavy dark matter decay and recent events at IceCube,” JHEP 06, 110 (2014), arXiv:1403.1862 [hep-ph].
[81] Arman Esmaili and Pasquale Dario Serpico, “Are IceCube neutrinos unveiling PeV-scale decaying dark matter?” JCAP 11, 054 (2013), arXiv:1308.1105 [hep-ph].
[82] P. S. Bhupal Dev, D. Kazanas, R. N. Mohapatra, V. L. Teplitz, and Yongchao Zhang, “Heavy right-handed neutrino dark matter and PeV neutrinos at IceCube,” JCAP 08, 034 (2016), arXiv:1606.04517 [hep-ph].
[83] Arman Esmaili, Sin Kyu Kang, and Pasquale Dario Serpico, “IceCube events and decaying dark matter: hints and constraints,” JCAP 12, 054 (2014), arXiv:1410.5979 [hep-ph].
[84] Carsten Rott, Kazunori Kohri, and Seong Chan Park, “Superheavy dark matter and IceCube neutrino signals: Bounds on decaying dark matter,” Phys. Rev. D 92, 023529 (2015), arXiv:1408.4575 [hep-ph].
[85] M. Yu. Kuznetsov, “Hadronically decaying heavy dark matter and high-energy neutrino limits,” JETP Lett. 105, 561–567 (2017), arXiv:1611.08884 [astro-ph.HE].
[86] Timothy Cohen, Kohta Murase, Nicholas L. Rodd, Benjamin R. Safdi, and Yotam Soreq, “γ-ray Constraints on Decaying Dark Matter and Implications for IceCube,” Phys. Rev. Lett. 119, 021102 (2017), arXiv:1612.05638 [hep-ph].
[87] Brian Feldstein, Alexander Kusenko, Shigeki Matsumoto, and Tsutomu T. Yanagida, “Neutrinos at IceCube from Heavy Decaying Dark Matter,” Phys. Rev. D 88, 015004 (2013), arXiv:1303.7320 [hep-ph].
[88] Nagisa Hiroshima, Ryuichiro Kitano, Kazunori Kohri, and Kohta Murase, “High-energy neutrinos from multibody decaying dark matter,” Phys. Rev. D 97, 023006 (2018), arXiv:1705.04419 [hep-ph].
[89] Alexander Aab et al. (Pierre Auger), “Observation of a Large-scale Anisotropy in the Arrival Directions of Cosmic Rays above 8 × 10^{18} eV,” Science 357, 1266–1270 (2017), arXiv:1709.07321 [astro-ph.HE].
[90] Alexander Aab et al. (Pierre Auger), “An Indication of anisotropy in arrival directions of ultra-high-energy cosmic rays through comparison to the flux pattern of extragalactic gamma-ray sources,” Astrophys. J. Lett. 853, L29 (2018), arXiv:1801.06160 [astro-ph.HE].
[91] Esteban Alcantara, Luis A. Anchordoqui, and Jorge F. Soriano, “Hunting for superheavy dark matter with the highest-energy cosmic rays,” Phys. Rev. D 99, 103016 (2019), arXiv:1903.05429 [hep-ph].
[92] Gustavo A. Medina-Tanco and A. A. Watson, “Dark matter halos and the anisotropy of ultrahigh-energy cosmic rays,” Astropart. Phys. 12, 25–34 (1999), arXiv:astro-ph/9903182.
[93] R. Aloisio and F. Tortorici, “Super Heavy Dark Matter and UHECR Anisotropy at Low Energy,” Astropart. Phys. 29, 307–316 (2008), arXiv:0706.3196 [astro-ph].
[94] Oleg E. Kalashev, B. A. Khrenov, P. Klimov, S. Sharakin, and Sergey V. Troitsky, “Global anisotropy of arrival directions of ultrahigh-energy cosmic rays: capabilities of space-based detectors,” JCAP 03, 003 (2008), arXiv:0710.1382 [astro-ph].
[95] R. Aloisio, S. Matarrese, and A. V. Olinto, “Super Heavy Dark Matter in light of BICEP2, Plack and Ultra High Energy Cosmic Rays Observations,” JCAP 08, 024 (2015), arXiv:1504.0319 [astro-ph.HE].
[96] O. E. Kalashev and M. Yu Kuznetsov, “Heavy decaying dark matter and large-scale anisotropy of high-energy cosmic rays,” JETP Lett. 106, 73–80 (2017), arXiv:1704.05300 [astro-ph.HE].
[97] Luca Marzola and Federico R. Urban, “Ultra High Energy Cosmic Rays \& Super-heavy Dark Matter,” Astropart. Phys. 93, 56–69 (2017), arXiv:1611.07180 [astro-ph.HE].
[98] B. P. Abbott et al. (LIGO Scientific, Virgo), “Observation of Gravitational Waves from a Binary Black Hole Merger,” Phys. Rev. Lett. 116, 061102 (2016), arXiv:1602.03837 [gr-qc].
[99] B. P. Abbott et al. (LIGO Scientific, Virgo), “GW170104: Observation of a 50-Solar-Mass Binary Black Hole Coalescence at Redshift 0.2,” Phys. Rev. Lett. 119, 221101 (2017), arXiv:1709.09660 [gr-qc].
[100] Benjamin P. Abbott et al. (LIGO Scientific, VIRGO), “GW170814: A Three-Detector Observation of Gravitational Waves from a Binary Black Hole Coalescence,” Phys. Rev. Lett. 119, 141101 (2017), arXiv:1709.05885 [gr-qc].
[101] B. P. Abbott et al. (LIGO Scientific, Virgo), “GW170817: Observation of Gravitational Waves from a Binary Neutron Star Inspirial,” Phys. Rev. Lett. 119, 161101 (2017), arXiv:1711.05578 [astro-ph.HE].
[102] B. P. Abbott et al. (LIGO Scientific, Virgo), “GW170814: Gravitational Waves from the Coalescence of a 23 Solar Mass Black Hole with a 2.6 Solar Mass Compact Object,” Astrophys. J. Lett. 896, L44 (2020), arXiv:2006.12611 [astro-ph.HE].
[103] Michele Maggiore, “Gravitational wave experiments and early universe cosmology,” Phys. Rept. 331, 283–367 (2000), arXiv:gr-qc/9909001.
[104] Joseph D. Romano and Neil J. Cornish, “Detection methods for stochastic gravitational-wave backgrounds: a unified treatment,” Living Rev. Rel. 20, 2 (2017), arXiv:1608.06889 [gr-qc].
[105] Chiara Caprini and Daniel G. Figguroa, “Cosmological Backgrounds of Gravitational Waves,” Class. Quant. Grav. 35, 163001 (2018), arXiv:1801.04268 [astro-ph.CO].
[106] Nelson Christensen, “Stochastic Gravitational Wave Backgrounds,” Rept. Prog. Phys. 82, 016903 (2019), arXiv:1811.08797 [gr-qc].
[107] John R. Ellis, Jorge L. Lopez, and Dimitri V. Nanopoulos, “Confinement of fractional charges yields integer charged relics in string models,” Phys. Lett. B 247, 257–264 (1990).
[108] E. V. Arbusova, “Superheavy dark matter in R^2-cosmology,” Int. J. Mod. Phys. D 30, 2140002 (2021), arXiv:2011.11423 [hep-ph].
[109] Dmitry S Gorbunov and Valery A Rubakov, Introduction to the Theory of the Early Universe: Cosmological perturbations and inflationary theory (World Scientific Publishing Company, 2011)
[112] O. K. Kalashev and M. Yu. Kuznetsov, “Constraining heavy decaying dark matter with the high energy gamma-ray limits,” Phys. Rev. D 94, 063535 (2016), arXiv:1606.07354 [astro-ph.HE].

[113] Kohta Murase and John F. Beacom, “Constraining Very Heavy Dark Matter Using Diffuse Backgrounds of Neutrinos and Cascaded Gamma Rays,” JCAP 10, 043 (2012), arXiv:1206.2595 [hep-ph].

[114] Arman Esmaili and Pasquale Dario Serpico, “Gamma-ray bounds from EAS detectors and heavy decaying dark matter constraints,” JCAP 10, 014 (2015), arXiv:1505.06486 [hep-ph].

[115] M. Kachelriess, O. E. Kalashev, and M. Yu. Kuznetsov, “Heavy decaying dark matter and IceCube high energy neutrinos,” Phys. Rev. D 98, 083016 (2018), arXiv:1805.04500 [astro-ph.HE].

[116] Darko Veberic, ed., The Pierre Auger Observatory: Contributions to the 35th International Cosmic Ray Conference (ICRC 2017) (2017) arXiv:1708.06592 [astro-ph.HE].

[117] Andres Romero-Wolf (ZAP), “The Zettavolt Askaryan Polarimeter (ZAP) mission concept: radio detection of ultra-high energy cosmic rays in low lunar orbit,” PoS ICRC2021, 403 (2021).

[118] Roberto Aloisio, V. Berezinsky, and M. Kachelriess, “On the status of superheavy dark matter,” Phys. Rev. D 74, 023516 (2006), arXiv:astro-ph/0604311.

[119] P. Sommers, “Cosmic ray anisotropy analysis with a full-sky observatory,” Astropart. Phys. 14, 271–286 (2000), arXiv:astro-ph/0004016.

[120] Alexander Aab et al. (Telescope Array, Pierre Auger), “Searches for Large-Scale Anisotropy in the Arrival Directions of Cosmic Rays Detected above Energy of 10^{19} eV at the Pierre Auger Observatory and the Telescope Array,” Astrophys. J. 794, 172 (2014), arXiv:1409.3128 [astro-ph.HE].

[121] J. Abraham et al., “Properties and performance of the prototype instrument for the pierre auger observatory,” Nuclear Instruments and Methods in Physics Research Section A: Accelerators, Spectrometers, Detectors and Associated Equipment 523, 50–95 (2004).

[122] Lino Miramonti, “Latest results and future prospects of the pierre auger observatory,” Journal of Physics: Conference Series 1766, 012002 (2021).

[123] Julio F. Navarro, Carlos S. Frenk, and Simon D. M. White, “The Structure of cold dark matter halos,” Astrophys. J. 462, 563-575 (1996), arXiv:astro-ph/9508025.

[124] J. Einasto, “On the Construction of a Composite Model for the Galaxy and on the Determination of the System of Galactic Parameters,” Trudy Astrofizicheskogo Instituta Alma-Ata 5, 87–100 (1965).

[125] Alister W. Graham, David Merritt, Ben Moore, Juerg Diemand, and Balsa Terzic, “Empirical models for Dark Matter Halos. I. Nonparametric Construction of Density Profiles and Comparison with Parametric Models,” Astron. J. 132, 2685–2700 (2006), arXiv:astro-ph/0509417.

[126] Julio F. Navarro, Aaron Ludlow, Volker Springel, Jie Wang, Mark Vogelsberger, Simon D. M. White, Adrian Jenkins, Carlos S. Frenk, and Amina Helmi, “The Diversity and Similarity of Cold Dark Matter Halos,” Mon. Not. Roy. Astron. Soc. 402, 21 (2010), arXiv:0810.1522 [astro-ph].

[127] Pablo F. de Salas and Axel Widmark, “Dark matter local density determination: recent observations and future prospects,” Rept. Prog. Phys. 84, 104901 (2021), arXiv:2012.11477 [astro-ph.GA].

[128] A. D. Supanitsky and G. Medina-Tanco, “Ultra high energy cosmic rays from super-heavy dark matter in the context of large exposure observatories,” JCAP 11, 036 (2019), arXiv:1909.09191 [astro-ph.HE].

[129] S. L. Dubovsky and P. G. Tinyakov, “Galactic anisotropy as signature of CDM ultrahigh-energy cosmic rays,” JETP Lett. 68, 107–111 (1998), arXiv:hep-ph/9802382.

[130] N. Wyn Evans, Francesc Ferrer, and Subir Sarkar, “The Anisotropy of the ultrahigh-energy cosmic rays,” Astropart. Phys. 17, 319–340 (2002), arXiv:astro-ph/0103085.

[131] M. Torki, H. Haji-azadeh, M. Farhang, A. Vafaeei Sadr, and S. M. S. Movahed, “Planck limits on cosmic string tension using machine learning,” Mon. Not. Roy. Astron. Soc. 509, 2169–2179 (2021), arXiv:2106.00059 [astro-ph.CO].

[132] Pau Amaro-Seoane et al. (LISA), “Laser Interferometer Space Antenna (LISA),” Class. Quant. Grav. 1766, 012002 (2021).

[133] Vincent Corbin and Neil J. Cornish, “Detecting the cosmic gravitational wave background with the big bang observer,” Class. Quant. Grav. 23, 2435–2446 (2006), arXiv:gr-qc/0512030.

[134] Simone Blasi, Vedran Brdar, and Kai Schmitz, “Has NANOGrav found first evidence for cosmic strings?” Phys. Rev. Lett. 126, 041305 (2021), arXiv:2009.06607 [astro-ph.CO].

[135] Zaven Arzoumanian et al. (NANOGrav), “The NANOGrav 12.5 yr Data Set: Search for an Isotropic Stochastic Gravitational-wave Background,” Astrophys. J. Lett. 905, L34 (2020), arXiv:2009.04496 [astro-ph.HE].

[136] Lars Bergstrom, Piero Ullio, and James H. Buckley, “Observability of gamma-rays from dark matter neutralino annihilations in the Milky Way halo,” Astropart. Phys. 9, 137–162 (1998), arXiv:astro-ph/9712318.

[137] Argyro Tasitsiomi and A. V. Olinto, “The Detectability of neutralino clumps via atmospheric Cherenkov telescopes,” Phys. Rev. D 66, 083006 (2002), arXiv:astro-ph/0206040.

[138] Torsten Bringmann, Lars Bergstrom, and Joskin Edsjö, “New Gamma-Ray Contributions to Supersymmetric Dark Matter Annihilation,” JHEP 01, 049 (2008), arXiv:0710.3169 [hep-ph].

[139] Francesca Calore, Valentina De Romeri, Mattia Di Mauro, Fiorenza Donato, and Federico Marinacci, “Realistic estimation for the detectability of dark matter sub-halos with Fermi-LAT,” Phys. Rev. D 96, 063009 (2017), arXiv:1611.03503 [astro-ph.HE].

[140] Francisco Pedreira (Pierre Auger), “Bounds on diffuse and point source fluxes of ultra-high energy neutrinos with the Pierre Auger Observatory,” PoS ICRC2019, 979 (2021).

[141] Aamap Mazumdar and Graham White, “Review of cosmic phase transitions: their significance and experimental signatures,” Rept. Prog. Phys. 82, 076901 (2019), arXiv:1811.01948 [hep-ph].

[142] T W B Kibble, “Topology of cosmic domains and
strings," Journal of Physics A: Mathematical and General 9, 1387–1398 (1976).

[143] Rachel Jeanerot, Jonathan Rocher, and Mairi Sakellariadou, “How generic is cosmic string formation in SUSY GUTs,” Phys. Rev. D 68, 103514 (2003), arXiv:hep-ph/0308134.

[144] H.B. Nielsen and P. Olesen, “Vortex-line models for dual strings,” Nuclear Physics B 61, 45–61 (1973).

[145] Tanmay Vachaspati and Alexander Vilenkin, “Gravitational radiation from cosmic strings,” Phys. Rev. D 31, 3052–3058 (1985).

[146] Pierre Auclair et al., “Probing the gravitational wave background from cosmic strings with LISA,” JCAP 04, 034 (2020), arXiv:1909.00819 [astro-ph.CO].

[147] L. Lentati et al., “European Pulsar Timing Array limits on an isotropic stochastic gravitational-wave background,” Monthly Notices of the Royal Astronomical Society 453, 2576–2598 (2015), arXiv:1504.03692 [astro-ph.CO].

[148] Z. Arzoumanian et al. (NANOGrav), “The NANOGrav 11-year Data Set: Pulsar-timing Constraints On The Stochastic Gravitational-wave Background,” Astrophys. J. 859, 47 (2018), arXiv:1801.02617 [astro-ph.HE].

[149] Ligong Bian, Xuewen Liu, and Ke-Pan Xie, “Probing superheavy dark matter with gravitational waves,” JHEP 11, 175 (2021), arXiv:2107.13112 [hep-ph].

[150] Teresa Bister, “Anisotropies in the arrival directions of ultra-high-energy cosmic rays measured at the pierre auger observatory,” Physica Scripta 96, 074003 (2021).

[151] Mathias Garny, McCullen Sandora, and Martin S. Sloth, “Planckian Interacting Massive Particles as Dark Matter,” Phys. Rev. Lett. 116, 101302 (2016), arXiv:1511.03278 [hep-ph].

[152] Daniel J. H. Chung, Edward W. Kolb, Antonio Riotto, and Leonardo Senatore, “Isocurvature constraints on gravitationally produced superheavy dark matter,” Phys. Rev. D 72, 023511 (2005), arXiv:astro-ph/0411468.

[153] P. A. R. Ade et al. (Planck), “Planck 2015 results. XX. Constraints on inflation,” Astron. Astrophys. 594, A20 (2016), arXiv:1502.02114 [astro-ph.CO].

[154] P. A. R. Ade et al. (BICEP2, Keck Array), “Improved Constraints on Cosmology and Foregrounds from BICEP2 and Keck Array Cosmic Microwave Background Data with Inclusion of 95 GHz Band,” Phys. Rev. Lett. 116, 031302 (2016), arXiv:1510.09217 [astro-ph.CO].

[155] D. S. Gorbunov and A. G. Panin, “Free scalar dark matter candidates in R”2-inflation: the light, the heavy and the superheavy,” Phys. Lett. B 718, 15–20 (2012), arXiv:1201.3539 [astro-ph.CO].

[156] Oleg E. Kalashev, G. I. Rubtsov, and Sergey V. Troitsky, “Sensitivity of cosmic-ray experiments to ultrahigh-energy photons: reconstruction of the spectrum and limits on the superheavy dark matter,” Phys. Rev. D 80, 103006 (2009), arXiv:0812.1020 [astro-ph].