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Snowmass2021 cosmic frontier white paper: Ultraheavy particle dark matter

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Abstract

We outline the unique opportunities and challenges in the search for "ultraheavy" dark matter candidates with masses between roughly 10 TeV and the Planck scale $m_{\rm pl} \approx 10^{16}$ TeV. This mass range presents a wide and relatively unexplored dark matter parameter space, with a rich space of possible models and cosmic histories. We emphasize that both current detectors and new, targeted search techniques, via both direct and indirect detection, are poised to contribute to searches for ultraheavy particle dark matter in the coming decade. We highlight the need for new developments in this space, including new analyses of current and imminent direct and indirect experiments targeting ultraheavy dark matter and development of new, ultra-sensitive detector technologies like next-generation liquid noble detectors, neutrino experiments, and specialized quantum sensing techniques.

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Contents

1 Introduction

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For decades, the search for dark matter (DM) has focused on two mass regions: ultralight axions (or axion-like particles) with mass $m_\chi \lesssim 1$ eV, and particles with mass around the electroweak scale $m_\chi \approx 100$ GeV with weak scale couplings (WIMP). Unfortunately, in spite of heroic experimental efforts, ultralight or weak-scale DM particles have not been found. This has motivated theorists to propose new cosmological mechanisms for the production of DM, and for experimentalists to study new ways to search in unexplored ranges of mass and interaction strength.

This community white paper focuses on one such less-explored region of parameter space: "ultraheavy" dark matter (UHDM). Here by ultraheavy we will mean particles that have a mass too large to be produced at any current colliders, $m_\chi \gtrsim 10$ TeV, while also having mass below roughly the Planck mass $m_\chi \lesssim m_{\rm pl} \approx 10^{19}$ GeV. The lower bound also roughly corresponds to the traditional relic production threshold $m_\chi \gtrsim 100$ TeV set by unitarity bounds on the production cross-section (see Sec. 2 for an extended discussion). The upper bound comes from considering the expected number density of DM: under standard halo density assumptions, Planck-scale dark matter would produce a flux of order 1 event/m^2/yr [see Eq. (1)]. Thus dark matter much beyond the Planck mass would be very difficult to detect directly in a terrestrial experiment. The UHDM parameter space constitutes a vast and relatively unexplored frontier, and our aim in this whitepaper is to outline the unique challenges and opportunities it presents.

We begin with an overview of the cosmological history and theory of such DM candidates. In this mass regime, new production mechanisms beyond the usual cold thermal relic picture must come into play. In addition to fundamental particles, a diverse set of DM candidates becomes viable, including composite objects, solitons, and relics of decaying black holes.

We then move on to a discussion of detection prospects, aiming to motivate further work with new and existing detection techniques. In the direct DM detection program, we emphasize that current and next-generation detectors built to search for usual DM candidates are also well-placed to search for certain UHDM candidates. We also highlight some ideas for future experiments aiming specifically for heavier DM detection. Finally, we emphasize the possibility of indirect detection of UHDM unstable to decays to visible signatures with a variety of current and upcoming observatories.

2 Cosmic history and models

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While much is known about the synthesis of Standard Model states, starting with Big Bang Nucleosynthesis (BBN) onward to the present era of galaxies and accelerated cosmic expansion, very little is known about the state of the Universe prior to BBN, when the Universe had a temperature of around a few MeV. The synthesis of DM particles is usually presumed to occur before BBN, and the synthesis of UHDM particles in particular is highly dependent on the unknown physics of the early Universe. In this section, we highlight a variety of cosmological scenarios and models of UHDM leading to the observed DM abundance.

The emergence of a concordance Λ Cold Dark Matter (ΛCDM) cosmology points to evidence that Standard Model particles were once thermalized in the early Universe [1]. Currently, we can empirically infer the thermal history of the Universe back up to the BBN scale, when ultra-relativistic species (*radiation*) dominated the cosmic expansion. However, one explanation for the flat, homogeneous and isotropic state of the present Universe is that it has undergone a phase of exponential expansion, i.e. inflation. The inflaton field driving inflation generates the radiation content, and therefore the cosmic entropy, via out-of-equilibrium decay [2]. This so-called *reheating* period dilutes any cosmic relic, which leads one to expect that DM was produced after inflation.

It is an open question whether the Universe was always radiation-dominated from the end of inflationary reheating or reheating after some other antecedent period up to the epoch of BBN. For example, one simple possibility is that an exotic BSM field fell out of equilibrium with a reheated SM bath, and grew to dominate the cosmic expansion after becoming non-relativistic, leading to a period of *early matter domination* (EMD) prior to BBN. In this case, the Universe would usually have undergone a *late reheating* period associated with the decay of this new field, injecting considerable entropy into the cosmic bath and diluting the abundance of all decoupled particles. As a consequence, many DM models predicated on a purely radiation-dominated Universe will entail heavier dark sector states, to compensate for late time dilution.

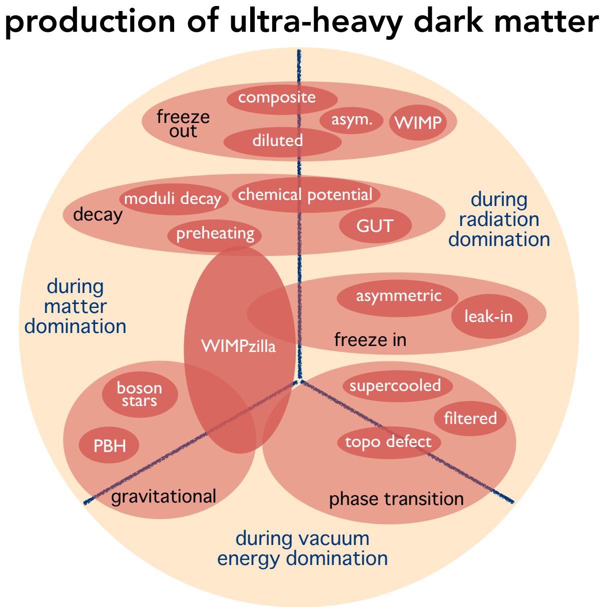

Figure 1: A non-exhaustive representation of cosmological production mechanisms of ultraheavy dark matter and corresponding models.

On the other hand, EMD also provides an intriguingly simple DM production scenario: The BSM field could decay directly to a heavy, out-of-equilibrium DM state. This process alone could set the relic abundance of DM.

The abundance can be determined, as described below, via several mechanisms that may have occurred during eras of radiation, matter, or vacuum energy domination. In what follows, we describe each of these production mechanisms. These are summarized in Figure 1.

Freeze-out: In this classic mechanism, DM particles begin in thermal equilibrium with the SM bath, with equal rates of DM production and annihilation. When DM particles become non-relativistic, their production is Boltzmann-suppressed, and they fall out of equilibrium as cosmic expansion becomes faster than annihilation.

Partial-wave unitarity sets an upper limit on perturbative DM annihilation cross sections. When DM is produced via freeze-out in a radiation-dominated Universe, an upper limit on s-wave $2 \to 2$ annihilation cross sections leads to a lower limit on the DM abundance, in turn translating to an upper limit of about 100 TeV on the DM mass [3]. However, if an EMD occurred after freeze-out, smaller annihilation cross sections would be needed to overcome the dilution and lead to the correct amount of DM. In this case, frozen-out DM with masses beyond $\mathcal{O}(100\text{ TeV})$ become allowed [4–6]. In models in which DM is much heavier than mediators, Sommerfeld enhancement of cross sections and the formation of bound states alters unitarity bounds [7–11]. DM might also be part of a hidden thermal bath, with a temperature different from the SM [12]. The lightest particles of the hidden sector can dominate the cosmic expansion after freeze-out, leading to an EMD era. In this case, *diluted* DM particles as heavy as 10^{10} GeV become viable [13–16]. The unitarity bound can also be circumvented in scenarios with additional degrees of freedom in the dark sector. In particular, in the presence of an additional species ζ with $m_\zeta < m_\chi < 3m_\zeta$, the DM χ remains stable, but the process $\chi\zeta^\dagger \to \chi\chi$ attenuates the relic density and allows m_χ to be as large as 10^9 GeV [17]. If the dark sector consists of many nearly-degenerate species that scatter with the SM through dark-flavor–changing interactions, m_χ can be as large as 10^{14} GeV without violating the unitarity bound [18].

Freeze-in: In the freeze-in mechanism, the DM population is initially negligible, and is produced via out-of-equilibrium decays and/or annihilation of species in the SM bath [19–21]. The production rates are always slower than the cosmic expansion and become negligible before backreaction becomes important. The end of the freeze-in production depends on DM-SM interactions. Typically, renormalizable couplings lead to an *infrared* freeze-in, in which DM production stops when it becomes too heavy to be produced and the final relic density depends only on the DM coupling strengths and mass.[1] On the other hand, non-renormalizable couplings typically lead to production rates with a high temperature-dependence. In this case, freeze-in can terminate during the post-inflationary reheating and is said to be *ultraviolet*, with a final relic density depending on the reheat temperature. DM candidates produced via ultraviolet freeze-in (UVFI) only need to be lighter than the maximal temperature of the SM bath, which can be as high as 10^{15} GeV [23–25]. In fact, the earliest proposals of UVFI detailed the production of UHDM candidates [26–28].

Out-of-equilibrium decay: DM can be directly produced from the decay of heavy fields which are not part of a thermal bath. This is the case of inflaton [29–31] and moduli [32–34] fields. Even when DM is heavier than the inflaton field and cannot be produced via decay during the inflationary reheating, nonperturbative quantum effects at the onset of inflaton oscillation (*preheating*) can still produce UHDM [35–37], with mass at the GUT scale [38]. Preheating could also produce ***dark monopole*** states that constitute DM [39]. It is also worth mentioning that the highly energetic decay products of heavy fields might also produce UHDM particles before the thermalization process is complete [40].

Phase transitions: UHDM can be produced at various stages of a first order phase transition, and can also be accompanied by gravitational wave signals. Production of UHDM with masses much higher than the energy scale of the phase transition can occur when particles present in the plasma cross ultrarelativistic bubble walls [41], or when such ultrarelativistic bubble walls collide [42]. UHDM can also obtain the correct relic density when the phase transition occurs in a confining sector and is supercooled, resulting in an appropriate dilution of the DM abundance [11, 43]. Bubble walls can filter dark matter particles out of the plasma and thereby control their relic abundance [44, 45] or collect them into composite objects [46, 47]. A first order electroweak phase transition could produce DM in the form of ***electroweak-symmetric solitons*** [48].

Gravitational particle production: All of the observational evidence for DM in our Universe arises from its gravitational interactions with ordinary states. Many DM models assume additional non-gravitational interactions, but explain DM production via gravity in the early Universe.

The phenomenon of inflationary gravitational particle production [49, 50], which occurs for quantum field theories in curved spacetime [51,52], can explain DM production, e.g. ***WIMPzillas*** [27, 53–55]. Typically, although though there are important exceptions, production is most efficient when the DM mass is comparable to the inflationary Hubble scale, $m_\chi \sim H_{\rm inf}$, and since cosmological observations constrain $H_{\rm inf} \lesssim 10^{14}$ GeV, such models usually involve superheavy elementary particles. Notable recent work has explored models of higher-spin DM [56–61], models of superheavy DM with $m_\chi > H_{\rm inf}$ [62–64], improved analytical techniques [65–67], and cosmological signatures such as isocurvature [68–70].

Primordial (extremal) black holes: Primordial black holes (PBHs) are a well-known DM candidate, and heavy PBHs are best regarded as compact objects for phenomenological purposes. However, very light PBHs have much more in common with elementary particles than with astrophysical compact objects. In particular, a wide class of models accommodate non-evaporating black hole remnants at the Planck scale or below. Such objects are effectively

[1] One can engineer complicated models of IR freeze-in with significantly heavy DM candidates, viz., the clockwork scenarios [22].

ultraheavy particles, and have long been considered a viable DM candidate [71,72]. This scenario provides a natural formation mechanism for a secluded dark sector: any sufficiently light population of PBHs quickly evaporates, leaving remnants that may only interact gravitationally. Without any BSM fields, magnetic black hole solutions with a "hairy" cloud of electroweak gauge and Higgs fields exist [73–76]. Depending on the UV completion for quantum gravity, the ***Planck-scale relics*** of the black-hole-like endpoints of gravitational collapse may be regarded as a general DM candidate, e.g. [77]. These remnants could carry $U(1)$ charges which could lead to unique observational signatures [78,79].

3 Direct detection

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Searches for ultraheavy dark matter are also possible with direct detection experiments, including currently existing detectors designed to look for much lighter DM candidates. In this section, we aim to motivate the basic detection problems and methods to perform searches both with existing and purpose-built future experiments.

As the mass of each DM constituent increases, the number density and corresponding flux of particles decreases. Assuming the standard DM mass density of $\rho \approx 0.3$ GeV/cm^3 and mean velocity of $\overline{v} \approx 220$ km/s, the expected flux of DM particles of individual mass m_χ passing through a detector is

$$\Phi = n\overline{v} \approx \frac{0.85}{\mathrm{m}^2\ \mathrm{yr}} \times \left(\frac{m_{\mathrm{pl}}}{m_\chi}\right). \tag{1}$$

Even a background-free detector is limited by needing at least a handful of dark matter particles to pass though during its lifetime. In a typical single-scatter search, the sensitivity of an experiment scales with the fiducial mass of the detector. However, ultraheavy dark matter may scatter several times as it crosses the detector for large enough cross sections, in which case the area of the detector becomes the most relevant factor [80].

The detailed sensitivity of a DM experiment to UHDM depends on how the UHDM couples to the Standard Model constituents in the detector. As examples of the basic ideas, here we will focus on two key cases. The first is UHDM coupled to nuclei through a weak, short-range interaction; essentially a much heavier version of the WIMP. The second is UHDM coupled to the Standard Model for a long-range force, which in the ultimate limit could simply be the gravitational coupling.

Consider first a search for UHDM with a weak contact interaction with nuclei. Fig. 2 shows current limits and projections on the ultraheavy parameter space under two models with different relationships between the DM-nucleus ($\sigma_{T\chi}$) and DM-nucleon ($\sigma_{n\chi}$) cross sections, respectively. In Model I (left) DM is opaque to the nucleus and no scaling from nucleon to nucleus is assumed, while in Model II (right) the typical A^4 scaling arising from contact interactions with the Born approximation is assumed. For more details on these models see Refs. [81, 100]. We note that when the DM-nucleus cross section approaches the geometric cross section of the nucleus, the Born approximation is no longer valid, and this A^4 scaling breaks down. The breakdown leads to a cross section that saturates at this geometric limit for a repulsive interaction, and one which displays resonant behavior for an attractive interaction. However, it may be possible to preserve the A^4 scaling for models of composite DM or light mediators.

It is important to note that for a large enough scattering cross section, dark matter can scatter so often in the overburden and lose enough energy that it becomes undetectable when

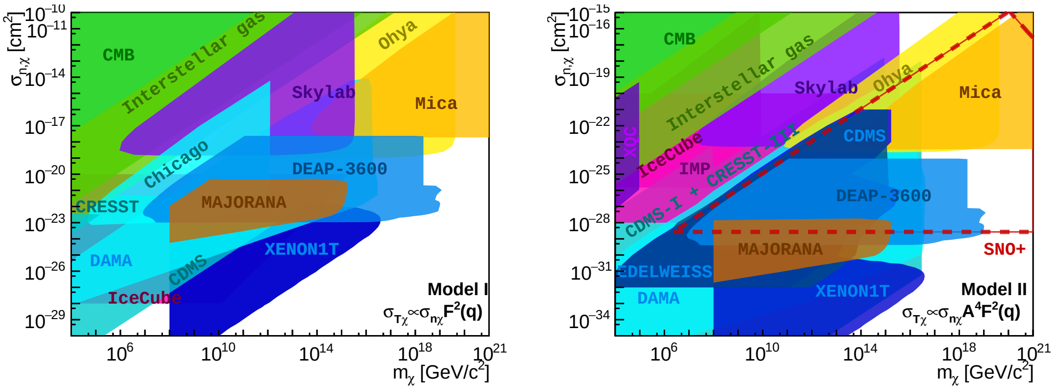

Figure 2: Current and projected experimental regions of ultraheavy parameter space excluded by cosmological/astrophysical constraints (green), direct detection dark matter detectors (blue), neutrino experiments (red/orange), space-based experiments (purple), and terrestrial track-based observations (yellow). Both models considered here assume different relations for the cross section scaling from a single nucleon to a nucleus with mass number A. In the left plot, we assume no scaling with A; in the right plot, we assume the cross section scales like A^4 (e.g., with two powers coming from nuclear coherence, and two from kinematic factors). Limits are shown from DEAP-3600 [81], DAMA [82,83], interstellar gas clouds [84,85], a recast of CRESST and CDMS-I [86], a recast of CDMS and EDELWEISS [87,88], a detector in U. Chicago [89], a XENON1T single-scatter analysis [90], tracks in the Skylab and Ohya plastic etch detectors [83], in ancient mica [91], the MAJORANA demonstrator [90], IceCube with 22 strings [92], XQC [93], CMB measurements [94,95], and IMP [96]. Also shown is the future reach of the liquid scintillator detector SNO+ as estimated in [97,98]. Not shown are recent limits from XENON1T [99] that overlap with other limits displayed; however this search constrains new parameter space in spin-dependent scattering.

it reaches an experiment, depending on the detector's energy threshold [80,97]. For relatively light DM, this attenuation is most accurately modeled using Monte Carlo simulations, which can track the trajectories of individual particles in 3-dimensional space as they scatter with nuclei in the overburden (see e.g. Ref. [101]). However, when the DM is much heavier than a nucleus, it follows a nearly straight trajectory, and requires a large number of collisions to be appreciably slowed. This means that attenuation of UHDM can be modeled as a continuous energy-loss process along a straight trajectory, which is computationally much faster than the full Monte Carlo approach [86, 102]. The resulting "ceiling", the maximum cross section to which an experiment is sensitive, is approximately proportional to the DM mass for UHDM, as can be seen in many of the exclusion regions in Fig. 2.

Since the energy deposited by each interaction is independent of the DM mass (because $m_\chi \gg m_N$), the total amount of energy deposited in the detector by a passing DM particle scales linearly with the cross section. This means that the total signal can span many orders of magnitude in deposited energy, and the signal shape can vary from one to many continuous hits inside the detector. As such, it is necessary for analyses to maintain sensitivity over a large range. The broad range of possible signal manifestations highlights the need for many different detector technologies capable of sampling various regions of this model space. Other challenges that may arise in these DM searches include computational difficulties related to performing a full optical simulation with a very large number of scatters, designing DAQ schema and low-level analyses that adequately differentiate between bright, long-duration pulses produced by ultraheavy DM and instrumental noise, and, at the lower end of the multi-scatter regime, adequately discriminate against pile-up or multi-scatter backgrounds.

Since the UHDM is very heavy, it is not appreciably deflected during each scattering event, and so the signal here is essentially a track of sub-threshold events. For a detector using a time projection chamber (TPC) which is able to determine both the time and location of the energy depositions, this is a striking signal. Not only is this type of search almost background-free, but it constitutes a direct measurement of the dark matter velocity vector [98]. With the observation of a sufficient number of such tracks, one could obtain a direct measurement of the dark matter velocity distribution. Note that this would be very different from the more commonly considered case of directional dark matter direct detection, in which one attempts to measure the energy and direction of the recoiling nucleus, and from this infer the velocity of the incoming dark matter particle. Instead, for multiply-interacting dark matter, one would directly measure the dark matter particle's velocity vector.

This track-like signature will also appear for models of UHDM coupled to the Standard Model through long-range forces, our second case study. If the force has sufficiently long range (i.e. is mediated by a sufficiently light boson), the DM will act coherently across an entire many-body target. One can then consider detecting it by using large, even macroscopic, targets [103–109]. A proof of concept demonstration was given in Ref. [108], which used a microgram-scale mechanical accelerometer to search for heavy, composite DM coupled to nuclei through a light gauged B-L vector boson. Any new long-range force coupling to nuclei is up against strong limits from existing experiments, but current generation sensors can already go beyond these limits in certain cases [110, 111]. Ultimately, with sufficiently heavy DM, it has been suggested [103–105] that one could use the only coupling DM is guaranteed to have—gravity—to perform searches this way. This would require a large array of devices, operating in a deeply quantum regime, as pursued by the Windchime collaboration [112]. Such an array would be sensitive to a wide variety of UHDM candidates [109]. In addition, well-characterized geologically old rock samples can also serve as UHDM detectors leveraging the long track-like signature as a background discrimination tool. Samples that have been stable for more than $\sim 10^9$ years provide sensitivity to even heavier UHDM candidates due to their long exposure time [113].

We also note that if an $O(1)$ fraction of DM is composed of charged PBH remnants, as proposed by Ref. [79], such objects can be detected terrestrially by several means. In particular, these objects exhibit unique signatures in large-volume LAr detectors, and are robustly detectable given an appropriate triggering mechanism. (See also Ref. [114].) Paleo-detectors [115] are also expected to be sensitive to charged remnants due to their long exposure times. Additionally, some UHDM candidates around the Planck mass, such as electroweak-symmetric solitons, could be discovered by nuclear capture signals [116]. For a wide range of UHDM models with a geometric interaction with the target nuclei, the O(1 GeV) photon energy from the radiative capture process may also be detectable at the IceCube detectors, similar to the search for non-relativistic magnetic monopoles [117]. Moreover, certain models of composite DM that cause nuclei and leptons to be accelerated in their binding potential, result in high energy bremsstrahlung photons [118] and low energy Migdal effect electrons [119], detectable at large-volume and DD experiments. Finally, scenarios with baryon charged multiply-interacting particles coupled to low mass mediators could also be detected with liquid scintillators [120].

In conclusion, the multi-scatter frontier opens up new parameter space to be explored by direct detection and neutrino experiments. It has already been demonstrated that dedicated analyses of existing data can be very fruitful in exploring new parameter space [81, 82, 90]. As the total integrated DM fluxes of future DM experiments are expected to increase by orders of magnitudes over their run-time, the maximum DM mass reachable in a direct search experiment (e.g. DARWIN/G3, Argo, or eventually possibly ktonne-scale detectors [121]) will be able to reach beyond the Planck mass $\simeq 10^{19}\,\mathrm{GeV}/c^2$ [80]. Moreover, a variety of new detector technologies, including mechanical sensors, can be brought to bear on this frontier. These are exciting prospects for the search of ultraheavy DM and these efforts will hopefully continue to expand as larger detectors come online in the following years.

4 Indirect detection

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If dark matter is not perfectly stable, then it can decay and produce Standard Model states that stream through the Universe to our detectors. Similarly, it could be that the primary signature of DM appears through its annihilation into SM states.[2] Searching for DM through these final states is known as *indirect detection*, and should the DM fall in the ultraheavy mass window, the physics of these searches is considerably enriched. Ultraheavy DM models in this category may be generically produced in the early Universe by a number of mechanisms discussed above, including freeze-out, freeze-in, gravitational production, and involving phase transitions.

For dark matter with mass well above the electroweak scale, the decays will inevitably produce a rich array of final states, including photons, neutrinos, and charged cosmic rays. This is true even if the DM decays only into neutrinos, as the neutrinos can shower electroweak bosons at such masses [124, 125]. Accordingly, such searches are inherently *multimessenger*, and benefit broadly from improvements in high energy astronomy. This point is highlighted in Fig. 3, where a partial set of present limits on the lifetime for DM$\rightarrow b\bar{b}$ are shown as an example. The results in green show limits obtained from low energy γ-rays collected by the *Fermi*-LAT telescope [126]. In Table 1, we provide a list of current and future observatories and their sensitivities to the relevant standard model final states.

Note that while *Fermi* is optimized to search for $\mathcal{O}$(GeV) photons, it can be sensitive to much heavier DM, as the high energy photons, electrons, and positrons produced in the decay will interact with cosmic background radiation, generating a cascade process converting energy down to lower scales [130–134]. The lower bound on the lifetime of heavy DM becomes essentially mass independent for DM masses above a few PeV if any appreciable portion of the mass energy is deposited into electromagnetic channels, since leptons and photons at these energies rapidly produce electromagnetic cascades extending down to GeV energies which may become visible in the isotropic gamma-ray sky [134]. If the direct decay products can be observed, however, the constraints are generally stronger as seen from the other constraints in Fig. 3. The IceCube collaboration has set strong constraints on the prompt neutrinos produced by $\mathcal{O}$(PeV) DM [123, 127], and the results are shown in cyan in the plot. Finally, in red we show constraints from instruments searching for high energy cosmic rays, such as KASCADE, Pierre Auger Observatory, and Telescope Array [128, 135]. Many other instruments can search for the signature of heavy DM decay, including extensive air shower observatories such as HAWC [136] or Tibet AS$_\gamma$ [137, 138].

All indirect searches for heavy DM are underpinned by a detailed theoretical understanding of the production and propagation of the high energy particles involved. As mentioned above, the propagation effects are central in determining what spectrum of states arrives at the detector. When considering photon final states, a careful accounting of the inverse-Compton scattering (ICS) contribution is also required [139]. Furthermore, the full development of electromagnetic cascades, from a cycle of ICS and pair-production, must be taken into account in order to predict diffuse and isotropic signals [131–134, 140]. Before the propagation

[2] See for example [122, 123]. For simplicity, we will mostly focus on decay in what follows.

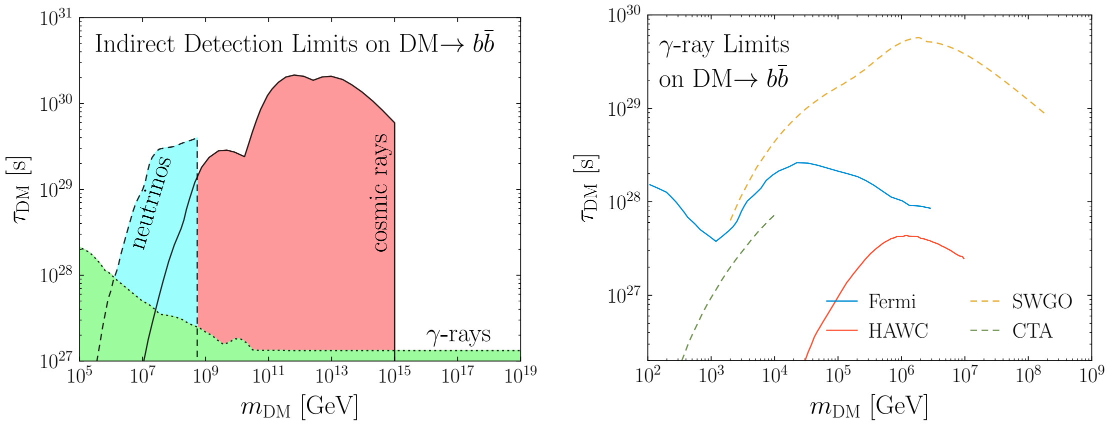

Figure 3: (Left) A subset of current indirect detection constraints on the DM lifetime for decays to $b\bar{b}$. The results are chosen to highlight the complementarity between different search strategies for this single DM hypothesis, and in particular we show limits obtained using γ-ray [126], neutrino [127], and cosmic-ray [128] studies. See the text for additional details. (Right) An example of the near term improvements that will be achieved in γ-ray searches for heavy DM. For this specific channel (DM→ $b\bar{b}$), it is clear that SWGO will considerably improve our reach, however, we note that for other channels leading results will be obtained by CTA. (We note that the results in this figure up to 2 TeV originally appeared in Ref. [129].)

can be considered, however, a detailed understanding of the prompt spectra emerging from the initial decays is required. For the range of DM masses considered in this white paper, the center-of-mass energies involved in the decay can reach the Planck scale, well above energies involved in colliders such as the LHC. Nevertheless, a common approach adopted in the literature is to adapt simulation software optimized for the LHC, such as `Pythia` [141–143]. More recently, results have become available which perform dedicated calculations relevant to heavy DM decays. See in particular Ref. [125], where it is shown the spectra can depart significantly from `Pythia`. In the future, further work will be required to ensure that accurate predictions of how heavy DM should appear in our telescopes are available.

The current generation of ground-based imaging gamma-ray instruments (VERITAS, HESS and MAGIC) provide sensitivity to DM annihilation and decay up to and above 100 TeV [152, 153]. As mentioned previously for *Fermi*-LAT, while the energy sensitivity range of the current-generation instruments extends to ∼100 TeV, it is possible to probe DM masses well beyond this range, as the detected final-state photons from the DM decay or annihilation are expected at lower energies. The future CTA observatory, with sensitivity to gamma rays up to ∼300 TeV, will probe heavy DM with a factor of ∼10 better sensitivity than the current-generation instruments [154]. The future SWGO observatory, with energy reach up to >1 PeV, will be able to probe DM masses more than 100x better than the current HAWC constraints, as shown in Fig. 3 [129].

Neutrino observatories are also highly sensitive to decaying UHDM. Stringent bounds on heavy decaying DM have been achieved with IceCube excluding lifetimes of up to 10^{28} s depending on the decay mode [127, 155]. Bounds are extremely competitive to indirect searches with γ-rays [152] and are the world's strongest for DM masses above 10 TeV. These searches continue to explore BSM scenarios with DM masses beyond the reach of LHC and have a high discovery potential. Neutrino signals from heavy decaying DM have been discussed extensively [130, 156–161]. At present the observed astrophysical neutrino flux is not well enough measured to determine if it contains hints of heavy decaying DM [131, 157, 158, 162–168]. A

Table 1: A non-exhaustive list of current and future indirect detection experiments sensitive to ultraheavy dark matter. See Refs. [135, 144–151].

Experiment	Final state	Threshold/sensitivity	Field of view	Location
Current experiments				
Fermi	Photons	10 MeV — 10^3 GeV	Wide	Space
HESS	Photons	30 GeV - 100 TeV	Targeted	Namibia
VERITAS	Photons	85 GeV - > 30 TeV	Targeted	USA
MAGIC	Photons	30 GeV - 100 TeV	Targeted	Spain
HAWC	Photons	300 GeV - >100 TeV	Wide	Mexico
LHAASO (partial)	Photons	10 TeV - 10 PeV	Wide	China
KASCADE	Photons	100 TeV - 10 PeV	Wide	Germany
KASCADE-Grande	Photons	10 - 100 PeV	Wide	Italy
Pierre Auger Observatory	Photons	1 - 10 EeV	Wide	Argentina
Telescope Array	Photons	1 - 100 EeV	Wide	USA
IceCube	Neutrinos	100 TeV - 100 EeV	Wide	Antarctica
ANITA	Neutrinos	EeV - ZeV	Wide	Antarctica
Pierre Auger Observatory	Neutrinos	0.1 - 100 EeV	Wide	Argentina
Future experiments				
CTA	Photons	20 GeV - 300 TeV	Targeted	Chile & Spain
SWGO	Photons	100 GeV - 1 PeV	Wide	South America
IceCube-Gen2	Neutrinos	10 TeV - 100 EeV	Wide	Antarctica
LHAASO (full)	Photons	100 GeV - 10 PeV	Wide	China
KM3NeT	Neutrinos	100 GeV - 10 PeV	Wide	Mediterranean Sea
POEMMA	Neutrinos	20 PeV - 100 EeV	Wide	Space

significant increase in event statistics will be required to better constrain DM models or discover any signal. IceCube-Gen2 will be particularly important to obtain better sensitivity to heavy DM.

Mass-dependent limits may also be set on the DM annihilation cross sections in combination with scattering cross sections if we consider DM annihilations inside celestial bodies after they are captured. Annihilation products that may be detected are those that can escape the celestial body, such as neutrinos or long-lived mediators that can decay to visible states. Particularly strong constraints can come from DM capture in the Sun, by virtue of its large mass and proximity. Leading constraints on DM annihilations to neutrinos in the Sun come from Super-Kamiokande [169], IceCube [170], and ANTARES [171]. While these publications display limits for DM mass $\leq$ 10 TeV, these may be extended to higher masses in a straightforward manner, with a lower bound on the mass set only by the minimum detectable flux.

For heavy annihilating DM, more energetic neutrinos are produced, which leads to strong attenuation and a highly suppressed neutrino flux in the Sun. In this case, long-lived or boosted mediator production of neutrinos can greatly increase the detectability, as shown in Ref. [172]. For long-lived or boosted mediator production of gamma rays, it was pointed out in Ref. [172] that HAWC is an optimal observatory to search for heavy DM. HAWC has consequently set leading limits, displaying results for up to DM masses of 10^6 TeV [173]. In the future, SWGO and LHAASO may have even better sensitivity to TeV-scale solar gamma rays from DM [172, 174]. **We strongly urge these collaborations to display the full extent of their limits along the DM mass axis.** The importance of populations of celestial bodies as the dominant source of DM annihilations, and as a probe of heavier-than-10-TeV DM with gamma rays, has also been investigated [175]. Similar DM gamma-ray searches using *Fermi*-LAT data of Jupiter have been performed [176]; although the results are only displayed up to 10 GeV DM mass, this search would also be able to provide sensitivity to much heavier DM.

A complementary method to probe heavy DM, down to smaller-than-electroweak scattering cross sections, is to observe the brightening of cold, isolated neutron stars (NS) via the transfer of DM kinetic energy during capture [177]. This may be done using upcoming infrared telescopes such as JWST, TMT and ELT [177] or telescopes operating at lower wavelengths if DM clusters into subhalos [178]; the possible presence of DM annihilations, a model-dependent issue, may boost the NS luminosity and help reduce telescope integration times. Various key particle and astrophysics implications of this probe have been investigated [179–200]. Assuming the presence of DM annihilation, this celestial body heating may also be detected using the Earth [201, 202] and exoplanets and brown dwarfs [203], which may be observable using JWST, Rubin, or the Roman telescopes in the next few years [203]. The observation of Population III stars is another probe of UHDM interactions with baryons [204, 205]. See also Refs. [206, 207]. Accumulation of asymmetric dark matter in compact astrophysical objects can also lead to low-mass black hole formation. Such black holes can be discovered by gravitational wave observatories, and this can in turn probe new parts of the parameter space [208–210].

Finally, cosmological observations could also constrain ultraheavy DM. CMB anisotropies would carry imprints of DM scattering with SM matter, which may be exploited to probe a wide range of DM masses [94, 95, 211, 212]. Moreover, ultraheavy DM produced gravitationally is accompanied by primordial non-Gaussianities that may be enhanced and observed in the CMB power spectrum [213, 214].

5 Summary

Ultraheavy dark matter presents an exciting and relatively unexplored regime of possible dark matter candidates. A rich variety of production mechanisms and DM models are viable in this parameter space. Existing direct and indirect detection programs already exhibit significant sensitivity to a number of potential candidates. In the future, we encourage these experiments to display the constraints on the entire range of DM mass sensitivity up to the ultraheavy scales considered here. We have presented a few example searches in order to encourage other experimental collaborations to consider analyses of these heavy DM candidates. Moreover, a number of technologies in current development are quickly coming online and will continue to explore swathes of open parameter space. We look forward to continuing rapid developments in this exciting frontier in the search for dark matter.

References

[1] Y. Akrami et al., *Planck 2018 results. X. Constraints on inflation*, Astron. Astrophys. **641**, A10 (2020), doi:10.1051/0004-6361/201833887.

[2] R. J. Scherrer and M. S. Turner, *Decaying particles do not "heat up" the Universe*, Phys. Rev. D **31**, 681 (1985), doi:10.1103/PhysRevD.31.681.

[3] K. Griest and M. Kamionkowski, *Unitarity limits on the mass and radius of dark-matter particles*, Phys. Rev. Lett. **64**, 615 (1990), doi:10.1103/PhysRevLett.64.615.

[4] J. Bramante and J. Unwin, *Superheavy thermal dark matter and primordial asymmetries*, J. High Energy Phys. **02**, 119 (2017), doi:10.1007/JHEP02(2017)119.

[5] M. Cirelli, Y. Gouttenoire, K. Petraki and F. Sala, *Homeopathic dark matter, or how diluted heavy substances produce high energy cosmic rays*, J. Cosmol. Astropart. Phys. **02**, 014 (2019), doi:10.1088/1475-7516/2019/02/014.

[6] D. Bhatia and S. Mukhopadhyay, *Unitarity limits on thermal dark matter in (non-)standard cosmologies*, J. High Energy Phys. **03**, 133 (2021), doi:10.1007/JHEP03(2021)133.

[7] J. Hisano, S. Matsumot, M. Nagai, O. Saito and M. Senami, *Non-perturbative effect on thermal relic abundance of dark matter*, Phys. Lett. B **646**, 34 (2007), doi:10.1016/j.physletb.2007.01.012.

[8] B. von Harling and K. Petraki, *Bound-state formation for thermal relic dark matter and unitarity*, J. Cosmol. Astropart. Phys. **12**, 033 (2014), doi:10.1088/1475-7516/2014/12/033.

[9] I. Baldes and K. Petraki, *Asymmetric thermal-relic dark matter: Sommerfeld-enhanced freeze-out, annihilation signals and unitarity bounds*, J. Cosmol. Astropart. Phys. **09**, 028 (2017), doi:10.1088/1475-7516/2017/09/028.

[10] J. Smirnov and J. F. Beacom, *Tev-scale thermal WIMPs: Unitarity and its consequences*, Phys. Rev. D **100**, 043029 (2019), doi:10.1103/PhysRevD.100.043029.

[11] I. Baldes, Y. Gouttenoire, F. Sala and G. Servant, *Supercool composite dark matter beyond 100 TeV*, J. High Energy Phys. **07**, 084 (2022), doi:10.1007/JHEP07(2022)084.

[12] X. Chu, T. Hambye and M. H. G. Tytgat, *The four basic ways of creating dark matter through a portal*, J. Cosmol. Astropart. Phys. **05**, 034 (2012), doi:10.1088/1475-7516/2012/05/034.

[13] A. Berlin, D. Hooper and G. Krnjaic, *Thermal dark matter from a highly decoupled sector*, Phys. Rev. D **94**, 095019 (2016), doi:10.1103/PhysRevD.94.095019.

[14] A. Berlin, D. Hooper and G. Krnjaic, *PeV-scale dark matter as a thermal relic of a decoupled sector*, Phys. Lett. B **760**, 106 (2016), doi:10.1016/j.physletb.2016.06.037.

[15] L. Heurtier and F. Huang, *Inflaton portal to a highly decoupled EeV dark matter particle*, Phys. Rev. D **100**, 043507 (2019), doi:10.1103/PhysRevD.100.043507.

[16] H. Davoudiasl and G. Mohlabeng, *Getting a THUMP from a WIMP*, J. High Energy Phys. **04**, 177 (2020), doi:10.1007/JHEP04(2020)177.

[17] E. D. Kramer, E. Kuflik, N. Levi, N. J. Outmezguine and J. T. Ruderman, *Heavy thermal dark matter from a new collision mechanism*, Phys. Rev. Lett. **126**, 081802 (2021), doi:10.1103/PhysRevLett.126.081802.

[18] H. Kim and E. Kuflik, *Superheavy thermal dark matter*, Phys. Rev. Lett. **123**, 191801 (2019), doi:10.1103/PhysRevLett.123.191801.

[19] J. McDonald, *Thermally generated gauge singlet scalars as self-interacting dark matter*, Phys. Rev. Lett. **88**, 091304 (2002), doi:10.1103/PhysRevLett.88.091304.

[20] L. J. Hall, K. Jedamzik, J. March-Russell and S. M. West, *Freeze-in production of FIMP dark matter*, J. High Energy Phys. **03**, 080 (2010), doi:10.1007/JHEP03(2010)080.

[21] N. Bernal, M. Heikinheimo, T. Tenkanen, K. Tuominen and V. Vaskonen, *The dawn of FIMP dark matter: A review of models and constraints*, Int. J. Mod. Phys. A **32**, 1730023 (2017), doi:10.1142/S0217751X1730023X.

[22] A. Goudelis, K. A. Mohan and D. Sengupta, *Clockworking FIMPs*, J. High Energy Phys. **10**, 014 (2018), doi:10.1007/JHEP10(2018)014.

[23] D. Chowdhury, E. Dudas, M. Dutra and Y. Mambrini, *Moduli portal dark matter*, Phys. Rev. D **99**, 095028 (2019), doi:10.1103/PhysRevD.99.095028.

[24] G. Bhattacharyya, M. Dutra, Y. Mambrini and M. Pierre, *Freezing-in dark matter through a heavy invisible* Z', Phys. Rev. D **98**, 035038 (2018), doi:10.1103/PhysRevD.98.035038.

[25] N. Bernal, M. Dutra, Y. Mambrini, K. Olive, M. Peloso and M. Pierre, *Spin-2 portal dark matter*, Phys. Rev. D **97**, 115020 (2018), doi:10.1103/PhysRevD.97.115020.

[26] D. J. H. Chung, E. W. Kolb and A. Riotto, *Production of massive particles during reheating*, Phys. Rev. D **60**, 063504 (1999), doi:10.1103/PhysRevD.60.063504.

[27] D. J. H. Chung, E. W. Kolb and A. Riotto, *Nonthermal supermassive dark matter*, Phys. Rev. Lett. **81**, 4048 (1998), doi:10.1103/PhysRevLett.81.4048.

[28] G. F. Giudice, E. W. Kolb and A. Riotto, *Largest temperature of the radiation era and its cosmological implications*, Phys. Rev. D **64**, 023508 (2001), doi:10.1103/PhysRevD.64.023508.

[29] F. Takahashi, *Gravitino dark matter from inflaton decay*, Phys. Lett. B **660**, 100 (2008), doi:10.1016/j.physletb.2007.12.048.

[30] A. Farzinnia and S. Kouwn, *Classically scale invariant inflation, supermassive WIMPs, and adimensional gravity*, Phys. Rev. D **93**, 063528 (2016), doi:10.1103/PhysRevD.93.063528.

[31] P. S. Bhupal Dev, A. Mazumdar and S. Qutub, *Constraining non-thermal and thermal properties of dark matter*, Front. Physics **2**, 26 (2014), doi:10.3389/fphy.2014.00026.

[32] T. Moroi and L. Randall, *Wino cold dark matter from anomaly mediated SUSY breaking*, Nucl. Phys. B **570**, 455 (2000), doi:10.1016/S0550-3213(99)00748-8.

[33] B. S. Acharya, K. Bobkov, G. Kane, J. Shao, S. Watson and P. Kumar, *Non-thermal dark matter and the moduli problem in string frameworks*, J. High Energy Phys. **06**, 064 (2008), doi:10.1088/1126-6708/2008/06/064.

[34] B. S. Acharya, G. Kane, S. Watson and P. Kumar, *Nonthermal "WIMP miracle"*, Phys. Rev. D **80**, 083529 (2009), doi:10.1103/PhysRevD.80.083529.

[35] L. Kofman, A. Linde and A. A. Starobinsky, *Reheating after inflation*, Phys. Rev. Lett. **73**, 3195 (1994), doi:10.1103/PhysRevLett.73.3195.

[36] L. Kofman, A. Linde and A. A. Starobinsky, *Towards the theory of reheating after inflation*, Phys. Rev. D **56**, 3258 (1997), doi:10.1103/PhysRevD.56.3258.

[37] E. W. Kolb, D. J. H. Chung and A. Riotto, *WIMPzillas!*, AIP Conf. Proc. **484**, 91 (1999), doi:10.1063/1.59655.

[38] S. Khlebnikov and I. Tkachev, *Resonant decay of cosmological Bose condensates*, Phys. Rev. Lett. **79**, 1607 (1997), doi:10.1103/PhysRevLett.79.1607.

[39] Y. Bai, M. Korwar and N. Orlofsky, *Electroweak-symmetric dark monopoles from preheating*, J. High Energy Phys. **07**, 167 (2020), doi:10.1007/JHEP07(2020)167.

[40] M. Drees and B. Najjari, *Energy spectrum of thermalizing high energy decay products in the early Universe*, J. Cosmol. Astropart. Phys. **10**, 009 (2021), doi:10.1088/1475-7516/2021/10/009.

[41] A. Azatov, M. Vanvlasselaer and W. Yin, *Dark matter production from relativistic bubble walls*, J. High Energy Phys. **03**, 288 (2021), doi:10.1007/JHEP03(2021)288.

[42] A. Falkowski and J. M. No, *Non-thermal dark matter production from the electroweak phase transition: Multi-TeV WIMPs and "baby-zillas"*, J. High Energy Phys. **02**, 034 (2013), doi:10.1007/JHEP02(2013)034.

[43] T. Hambye, A. Strumia and D. Teresi, *Super-cool dark matter*, J. High Energy Phys. **08**, 188 (2018), doi:10.1007/JHEP08(2018)188.

[44] M. J. Baker, J. Kopp and A. J. Long, *Filtered dark matter at a first order phase transition*, Phys. Rev. Lett. **125**, 151102 (2020), doi:10.1103/PhysRevLett.125.151102.

[45] D. Chway, T. H. Jung and C. S. Shin, *Dark matter filtering-out effect during a first-order phase transition*, Phys. Rev. D **101**, 095019 (2020), doi:10.1103/PhysRevD.101.095019.

[46] Y. Bai, A. J. Long and S. Lu, *Dark quark nuggets*, Phys. Rev. D **99**, 055047 (2019), doi:10.1103/PhysRevD.99.055047.

[47] J.-P. Hong, S. Jung and K.-P. Xie, *Fermi-ball dark matter from a first-order phase transition*, Phys. Rev. D **102**, 075028 (2020), doi:10.1103/PhysRevD.102.075028.

[48] E. Pontón, Y. Bai and B. Jain, *Electroweak symmetric dark matter balls*, J. High Energy Phys. **09**, 011 (2019), doi:10.1007/s13130-019-11194-5.

[49] L. Parker, *Quantized fields and particle creation in expanding universes. I*, Phys. Rev. **183**, 1057 (1969), doi:10.1103/PhysRev.183.1057.

[50] L. H. Ford, *Gravitational particle creation and inflation*, Phys. Rev. D **35**, 2955 (1987), doi:10.1103/PhysRevD.35.2955.

[51] N. D. Birrell and P. C. Davies, *Quantum fields in curved space*, Cambridge University Press, Cambridge, UK, ISBN 9780511622632 (1982), doi:10.1017/CBO9780511622632.

[52] L. Parker and D. Toms, *Quantum field theory in curved spacetime*, Cambridge University Press, Cambridge, UK, ISBN 9780521877879 (2009), doi:10.1017/CBO9780511813924.

[53] D. J. H. Chung, E. W. Kolb and A. Riotto, *Superheavy dark matter*, Phys. Rev. D **59**, 023501 (1998), doi:10.1103/PhysRevD.59.023501.

[54] V. Kuzmin and I. Tkachev, *Matter creation via vacuum fluctuations in the early Universe and observed ultrahigh energy cosmic ray events*, Phys. Rev. D **59**, 123006 (1999), doi:10.1103/PhysRevD.59.123006.

[55] D. J. H. Chung, P. Crotty, E. W. Kolb and A. Riotto, *Gravitational production of superheavy dark matter*, Phys. Rev. D **64**, 043503 (2001), doi:10.1103/PhysRevD.64.043503.

[56] P. W. Graham, J. Mardon and S. Rajendran, *Vector dark matter from inflationary fluctuations*, Phys. Rev. D **93**, 103520 (2016), doi:10.1103/PhysRevD.93.103520.

[57] F. Hasegawa, K. Mukaida, K. Nakayama, T. Terada and Y. Yamada, *Gravitino problem in minimal supergravity inflation*, Phys. Lett. B **767**, 392 (2017), doi:10.1016/j.physletb.2017.02.030.

[58] E. W. Kolb and A. J. Long, *Completely dark photons from gravitational particle production during the inflationary era*, J. High Energy Phys. **03**, 283 (2021), doi:10.1007/JHEP03(2021)283.

[59] E. W. Kolb, A. J. Long and E. McDonough, *Catastrophic production of slow gravitinos*, Phys. Rev. D **104**, 075015 (2021), doi:10.1103/PhysRevD.104.075015.

[60] E. Dudas, M. A. G. Garcia, Y. Mambrini, K. A. Olive, M. Peloso and S. Verner, *Slow and safe gravitinos*, Phys. Rev. D **103**, 123519 (2021), doi:10.1103/PhysRevD.103.123519.

[61] I. Antoniadis, K. Benakli and W. Ke, *Salvage of too slow gravitinos*, J. High Energy Phys. **11**, 063 (2021), doi:10.1007/JHEP11(2021)063.

[62] M. Fairbairn, K. Kainulainen, T. Markkanen and S. Nurmi, *Despicable dark relics: Generated by gravity with unconstrained masses*, J. Cosmol. Astropart. Phys. **04**, 005 (2019), doi:10.1088/1475-7516/2019/04/005.

[63] Y. Ema, K. Nakayama and Y. Tang, *Production of purely gravitational dark matter*, J. High Energy Phys. **09**, 135 (2018), doi:10.1007/JHEP09(2018)135.

[64] Y. Ema, K. Nakayama and Y. Tang, *Production of purely gravitational dark matter: The case of fermion and vector boson*, J. High Energy Phys. **07**, 060 (2019), doi:10.1007/JHEP07(2019)060.

[65] D. J. H. Chung, E. W. Kolb and A. J. Long, *Gravitational production of super-Hubble-mass particles: An analytic approach*, J. High Energy Phys. **01**, 189 (2019), doi:10.1007/JHEP01(2019)189.

[66] E. E. Basso and D. J. H. Chung, *Computation of gravitational particle production using adiabatic invariants*, J. High Energy Phys. **11**, 146 (2021), doi:10.1007/JHEP11(2021)146.

[67] S. Hashiba and Y. Yamada, *Stokes phenomenon and gravitational particle production — How to evaluate it in practice*, J. Cosmol. Astropart. Phys. **05**, 022 (2021), doi:10.1088/1475-7516/2021/05/022.

[68] D. J. H. Chung, E. W. Kolb, A. Riotto and L. Senatore, *Isocurvature constraints on gravitationally produced superheavy dark matter*, Phys. Rev. D **72**, 023511 (2005), doi:10.1103/PhysRevD.72.023511.

[69] T. Markkanen, A. Rajantie and T. Tenkanen, *Spectator dark matter*, Phys. Rev. D **98**, 123532 (2018), doi:10.1103/PhysRevD.98.123532.

[70] S. Ling and A. J. Long, *Superheavy scalar dark matter from gravitational particle production in α-attractor models of inflation*, Phys. Rev. D **103**, 103532 (2021), doi:10.1103/PhysRevD.103.103532.

[71] J. H. MacGibbon, *Can Planck-mass relics of evaporating black holes close the Universe?*, Nature **329**, 308 (1987), doi:10.1038/329308a0.

[72] P. Chen and R. J. Adler, *Black hole remnants and dark matter*, Nucl. Phys. B Proc. Suppl. **124**, 103 (2003), doi:10.1016/S0920-5632(03)02088-7.

[73] K. Lee, V. P. Nair and E. J. Weinberg, *A classical instability of Reissner-Nordström solutions and the fate of magnetically charged black holes*, Phys. Rev. Lett. **68**, 1100 (1992), doi:10.1103/PhysRevLett.68.1100.

[74] K. Lee, V. P. Nair and E. J. Weinberg, *Black holes in magnetic monopoles*, Phys. Rev. D **45**, 2751 (1992), doi:10.1103/PhysRevD.45.2751.

[75] J. Maldacena, *Comments on magnetic black holes*, J. High Energy Phys. **04**, 079 (2021), doi:10.1007/JHEP04(2021)079.

[76] Y. Bai and M. Korwar, *Hairy magnetic and dyonic black holes in the Standard Model*, J. High Energy Phys. **04**, 119 (2021), doi:10.1007/JHEP04(2021)119.

[77] U. Aydemir, B. Holdom and J. Ren, *Not quite black holes as dark matter*, Phys. Rev. D **102**, 024058 (2020), doi:10.1103/PhysRevD.102.024058.

[78] Y. Bai and N. Orlofsky, *Primordial extremal black holes as dark matter*, Phys. Rev. D **101**, 055006 (2020), doi:10.1103/PhysRevD.101.055006.

[79] B. V. Lehmann, C. Johnson, S. Profumo and T. Schwemberger, *Direct detection of primordial black hole relics as dark matter*, J. Cosmol. Astropart. Phys. **10**, 046 (2019), doi:10.1088/1475-7516/2019/10/046.

[80] J. Bramante, B. Broerman, R. F. Lang and N. Raj, *Saturated overburden scattering and the multiscatter frontier: Discovering dark matter at the Planck mass and beyond*, Phys. Rev. D **98**, 083516 (2018), doi:10.1103/PhysRevD.98.083516.

[81] P. Adhikari et al., *First direct detection constraints on Planck-scale mass dark matter with multiple-scatter signatures using the DEAP-3600 detector*, Phys. Rev. Lett. **128**, 011801 (2022), doi:10.1103/PhysRevLett.128.011801.

[82] R. Bernabei et al., *Extended limits on neutral strongly interacting massive particles and nuclearites from NaI(Tl) scintillators*, Phys. Rev. Lett. **83**, 4918 (1999), doi:10.1103/PhysRevLett.83.4918.

[83] A. Bhoonah, J. Bramante, B. Courtman and N. Song, *Etched plastic searches for dark matter*, Phys. Rev. D **103**, 103001 (2021), doi:10.1103/PhysRevD.103.103001.

[84] A. Bhoonah, J. Bramante, F. Elahi and S. Schon, *Galactic center gas clouds and novel bounds on ultralight dark photon, vector portal, strongly interacting, composite, and super-heavy dark matter*, Phys. Rev. D **100**, 023001 (2019), doi:10.1103/PhysRevD.100.023001.

[85] A. Bhoonah, J. Bramante, S. Schon and N. Song, *Detecting composite dark matter with long-range and contact interactions in gas clouds*, Phys. Rev. D **103**, 123026 (2021), doi:10.1103/PhysRevD.103.123026.

[86] B. J. Kavanagh, *Earth scattering of superheavy dark matter: Updated constraints from detectors old and new*, Phys. Rev. D **97**, 123013 (2018), doi:10.1103/PhysRevD.97.123013.

[87] I. F. M. Albuquerque and L. Baudis, *Direct detection constraints on superheavy dark matter*, Phys. Rev. Lett. **90**, 221301 (2003), doi:10.1103/PhysRevLett.90.221301.

[88] I. F. M. Albuquerque and L. Baudis, *Erratum: Direct detection constraints on superheavy dark matter [Phys. Rev. Lett. **90** , 221301 (2003)]*, Phys. Rev. Lett. **91**, 229903 (2003), doi:10.1103/PhysRevLett.91.229903.

[89] C. V. Cappiello, J. I. Collar and J. F. Beacom, *New experimental constraints in a new landscape for composite dark matter*, Phys. Rev. D **103**, 023019 (2021), doi:10.1103/PhysRevD.103.023019.

[90] M. Clark, A. Depoian, B. Elshimy, A. Kopec, R. F. Lang and J. Qin, *Direct detection limits on heavy dark matter*, Phys. Rev. D **102**, 123026 (2020), doi:10.1103/PhysRevD.102.123026.

[91] J. F. Acevedo, J. Bramante and A. Goodman, *Old rocks, new limits: Excavated ancient mica searches for dark matter*, (arXiv preprint) doi:10.48550/arXiv.2105.06473.

[92] I. F. M. Albuquerque and C. P. de los Heros, *Closing the window on strongly interacting dark matter with IceCube*, Phys. Rev. D **81**, 063510 (2010), doi:10.1103/PhysRevD.81.063510.

[93] A. L. Erickcek, P. J. Steinhardt, D. McCammon and P. C. McGuire, *Constraints on the interactions between dark matter and baryons from the x-ray quantum calorimetry experiment*, Phys. Rev. D **76**, 042007 (2007), doi:10.1103/PhysRevD.76.042007.

[94] C. Dvorkin, K. Blum and M. Kamionkowski, *Constraining dark matter-baryon scattering with linear cosmology*, Phys. Rev. D **89**, 023519 (2014), doi:10.1103/PhysRevD.89.023519.

[95] V. Gluscevic and K. K. Boddy, *Constraints on scattering of keV-TeV dark matter with protons in the early Universe*, Phys. Rev. Lett. **121**, 081301 (2018), doi:10.1103/PhysRevLett.121.081301.

[96] *IMP-8 project information*, https://spdf.gsfc.nasa.gov/pub/data/imp/imp8/documents/archived_website/project.html.

[97] J. Bramante, B. Broerman, J. Kumar, R. F. Lang, M. Pospelov and N. Raj, *Foraging for dark matter in large volume liquid scintillator neutrino detectors with multiscatter events*, Phys. Rev. D **99**, 083010 (2019), doi:10.1103/PhysRevD.99.083010.

[98] J. Bramante, J. Kumar and N. Raj, *Dark matter astrometry at underground detectors with multiscatter events*, Phys. Rev. D **100**, 123016 (2019), doi:10.1103/PhysRevD.100.123016.

[99] E. Aprile et al., *Searching for heavy dark matter near the Planck mass with XENON1T*, Phys. Rev. Lett. **130**, 261002 (2023), doi:10.1103/PhysRevLett.130.261002.

[100] M. C. Digman, C. V. Cappiello, J. F. Beacom, C. M. Hirata and A. H. G. Peter, *Not as big as a barn: Upper bounds on dark matter-nucleus cross sections*, Phys. Rev. D **100**, 063013 (2019), doi:10.1103/PhysRevD.100.063013.

[101] T. Emken and C. Kouvaris, *DaMaSCUS: the impact of underground scatterings on direct detection of light dark matter*, J. Cosmol. Astropart. Phys. **10**, 031 (2017), doi:10.1088/1475-7516/2017/10/031.

[102] G. D. Starkman, A. Gould, R. Esmailzadeh and S. Dimopoulos, *Opening the window on strongly interacting dark matter*, Phys. Rev. D **41**, 3594 (1990), doi:10.1103/PhysRevD.41.3594.

[103] E. D. Hall, R. X. Adhikari, V. V. Frolov, H. Müller and M. Pospelov, *Laser interferometers as dark matter detectors*, Phys. Rev. D **98**, 083019 (2018), doi:10.1103/PhysRevD.98.083019.

[104] A. Kawasaki, *Search for kilogram-scale dark matter with precision displacement sensors*, Phys. Rev. D **99**, 023005 (2019), doi:10.1103/PhysRevD.99.023005.

[105] D. Carney, S. Ghosh, G. Krnjaic and J. M. Taylor, *Proposal for gravitational direct detection of dark matter*, Phys. Rev. D **102**, 072003 (2020), doi:10.1103/PhysRevD.102.072003.

[106] D. Carney et al., *Mechanical quantum sensing in the search for dark matter*, Quantum Sci. Technol. **6**, 024002 (2021), doi:10.1088/2058-9565/abcfcd.

[107] D. C. Moore and A. A. Geraci, *Searching for new physics using optically levitated sensors*, Quantum Sci. Technol. **6**, 014008 (2021), doi:10.1088/2058-9565/abcf8a.

[108] F. Monteiro, G. Afek, D. Carney, G. Krnjaic, J. Wang and D. C. Moore, *Search for composite dark matter with optically levitated sensors*, Phys. Rev. Lett. **125**, 181102 (2020), doi:10.1103/PhysRevLett.125.181102.

[109] C. Blanco, B. Elshimy, R. F. Lang and R. Orlando, *Models of ultraheavy dark matter visible to macroscopic mechanical sensing arrays*, Phys. Rev. D **105**, 115031 (2022), doi:10.1103/PhysRevD.105.115031.

[110] P. W. Graham, D. E. Kaplan, J. Mardon, S. Rajendran and W. A. Terrano, *Dark matter direct detection with accelerometers*, Phys. Revi. D **93**, 075029 (2016), doi:10.1103/PhysRevD.93.075029.

[111] S. Knapen, T. Lin and K. M. Zurek, *Light dark matter: Models and constraints*, Phys. Rev. D **96**, 115021 (2017), doi:10.1103/PhysRevD.96.115021.

[112] A. Attanasio et al., *Snowmass 2021 white paper: The windchime project*, (arXiv preprint) doi:10.48550/arXiv.2203.07242.

[113] R. Ebadi et al., *Ultraheavy dark matter search with electron microscopy of geological quartz*, Phys. Rev. D **104**, 015041 (2021), doi:10.1103/PhysRevD.104.015041.

[114] I. Lazanu, S. Lazanu and M. Pârvu, *About detecting very low mass black holes in LAr detectors*, J. Cosmol. Astropart. Phys. **10**, 046 (2020), doi:10.1088/1475-7516/2020/10/046.

[115] S. Baum, A. K. Drukier, K. Freese, M. Górski and P. Stengel, *Searching for dark matter with paleo-detectors*, Phys. Lett. B **803**, 135325 (2020), doi:10.1016/j.physletb.2020.135325.

[116] Y. Bai and J. Berger, *Nucleus capture by macroscopic dark matter*, J. High Energy Phys. **05**, 160 (2020), doi:10.1007/JHEP05(2020)160.

[117] M. G. Aartsen et al., *Search for non-relativistic magnetic monopoles with IceCube*, Eur. Phys. J. C **74**, 2938 (2014), doi:10.1140/epjc/s10052-014-2938-8.

[118] J. F. Acevedo, J. Bramante and A. Goodman, *Nuclear fusion inside dark matter*, Phys. Rev. D **103**, 123022 (2021), doi:10.1103/PhysRevD.103.123022.

[119] J. F. Acevedo, J. Bramante and A. Goodman, *Accelerating composite dark matter discovery with nuclear recoils and the Migdal effect*, Phys. Rev. D **105**, 023012 (2022), doi:10.1103/PhysRevD.105.023012.

[120] H. Davoudiasl and G. Mohlabeng, *GeV-scale messengers of Planck-scale dark matter*, Phys. Rev. D **98**, 115035 (2018), doi:10.1103/PhysRevD.98.115035.

[121] A. Avasthi et al., *Kiloton-scale xenon detectors for neutrinoless double beta decay and other new physics searches*, Phys. Rev. D **104**, 112007 (2021), doi:10.1103/PhysRevD.104.112007.

[122] C. A. Argüelles, A. Diaz, A. Kheirandish, A. Olivares-Del-Campo, I. Safa and A. C. Vincent, *Dark matter annihilation to neutrinos*, Rev. Mod. Phys. **93**, 035007 (2021), doi:10.1103/RevModPhys.93.035007.

[123] C. Guépin, R. Aloisio, A. Cummings, L. A. Anchordoqui, J. F. Krizmanic, A. V. Olinto, M. H. Reno and T. M. Venters, *Indirect dark matter searches at ultrahigh energy neutrino detectors*, Phys. Rev. D **104**, 083002 (2021), doi:10.1103/PhysRevD.104.083002.

[124] P. Ciafaloni, D. Comelli, A. Riotto, F. Sala, A. Strumia and A. Urbano, *Weak corrections are relevant for dark matter indirect detection*, J. Cosmol. Astropart. Phys. **03**, 019 (2011), doi:10.1088/1475-7516/2011/03/019.

[125] C. W. Bauer, N. L. Rodd and B. R. Webber, *Dark matter spectra from the electroweak to the Planck scale*, J. High Energy Phys. **06**, 121 (2021), doi:10.1007/JHEP06(2021)121.

[126] T. Cohen, K. Murase, N. L. Rodd, B. R. Safdi and Y. Soreq, *γ-ray constraints on decaying dark matter and implications for IceCube*, Phys. Rev. Lett. **119**, 021102 (2017), doi:10.1103/PhysRevLett.119.021102.

[127] M. G. Aartsen et al., *Search for neutrinos from decaying dark matter with IceCube*, Eur. Phys. J. C **78**, 831 (2018), doi:10.1140/epjc/s10052-018-6273-3.

[128] M. Chianese, D. F. G. Fiorillo, R. Hajjar, G. Miele and N. Saviano, *Constraints on heavy decaying dark matter with current gamma-ray measurements*, J. Cosmol. Astropart. Phys. **11**, 035 (2021), doi:10.1088/1475-7516/2021/11/035.

[129] A. Viana, H. Schoorlemmer, A. Albert, V. de Souza, J. P. Harding and J. Hinton, *Searching for dark matter in the galactic halo with a wide field of view TeV gamma-ray observatory in the southern hemisphere*, J. Cosmol. Astropart. Phys. **12**, 061 (2019), doi:10.1088/1475-7516/2019/12/061.

[130] K. Murase and J. F. Beacom, *Constraining very heavy dark matter using diffuse backgrounds of neutrinos and cascaded gamma rays*, J. Cosmol. Astropart. Phys. **10**, 043 (2012), doi:10.1088/1475-7516/2012/10/043.

[131] K. Murase, R. Laha, S. Ando and M. Ahlers, *Testing the dark matter scenario for PeV neutrinos observed in IceCube*, Phys. Rev. Lett. **115**, 071301 (2015), doi:10.1103/PhysRevLett.115.071301.

[132] R. Alves Batista et al., *CRPropa 3 — A public astrophysical simulation framework for propagating extraterrestrial ultra-high energy particles*, J. Cosmol. Astropart. Phys. **05**, 038 (2016), doi:10.1088/1475-7516/2016/05/038.

[133] C. Heiter, D. Kuempel, D. Walz and M. Erdmann, *Production and propagation of ultra-high energy photons using CRPropa 3*, Astropart. Phys. **102**, 39 (2018), doi:10.1016/j.astropartphys.2018.05.003.

[134] C. Blanco and D. Hooper, *Constraints on decaying dark matter from the isotropic gamma-ray background*, J. Cosmol. Astropart. Phys. **03**, 019 (2019), doi:10.1088/1475-7516/2019/03/019.

[135] K. Ishiwata, O. Macias, S. Ando and M. Arimoto, *Probing heavy dark matter decays with multi-messenger astrophysical data*, J. Cosmol. Astropart. Phys. **01**, 003 (2020), doi:10.1088/1475-7516/2020/01/003.

[136] A. U. Abeysekara et al., *A search for dark matter in the galactic halo with HAWC*, J. Cosmol. Astropart. Phys. **02**, 049 (2018), doi:10.1088/1475-7516/2018/02/049.

[137] A. Esmaili and P. D. Serpico, *First implications of Tibet AS_γ data for heavy dark matter*, Phys. Rev. D **104**, L021301 (2021), doi:10.1103/PhysRevD.104.L021301.

[138] T. N. Maity, A. K. Saha, A. Dubey and R. Laha, *Search for dark matter using sub-PeV γ-rays observed by Tibet AS_γ*, Phys. Rev. D **105**, L041301 (2022), doi:10.1103/PhysRevD.105.L041301.

[139] A. Esmaili and P. D. Serpico, *Gamma-ray bounds from EAS detectors and heavy decaying dark matter constraints*, J. Cosmol. Astropart. Phys. **10**, 014 (2015), doi:10.1088/1475-7516/2015/10/014.

[140] C. Blanco, *γ-cascade: A simple program to compute cosmological gamma-ray propagation*, J. Cosmol. Astropart. Phys. **01**, 013 (2019), doi:10.1088/1475-7516/2019/01/013.

[141] T. Sjöstrand, S. Mrenna and P. Skands, *PYTHIA 6.4 physics and manual*, J. High Energy Phys. **05**, 026 (2006), doi:10.1088/1126-6708/2006/05/026.

[142] T. Sjöstrand, S. Mrenna and P. Skands, *A brief introduction to PYTHIA 8.1*, Comput. Phys. Commun. **178**, 852 (2008), doi:10.1016/j.cpc.2008.01.036.

[143] T. Sjöstrand et al., *An introduction to PYTHIA 8.2*, Comput. Phys. Commun. **191**, 159 (2015), doi:10.1016/j.cpc.2015.01.024.

[144] W. D. Apel et al., *KASCADE-grande limits on the isotropic diffuse gamma-ray flux between 100 TeV and 1 EeV*, Astrophys. J. **848**, 1 (2017), doi:10.3847/1538-4357/aa8bb7.

[145] A. Aab et al., *The Pierre Auger observatory: Contributions to the 34th international cosmic ray conference (ICRC 2015)*, (arXiv preprint) doi:10.48550/arXiv.1509.03732.

[146] A. Aab et al., *Search for photons with energies above 10^{18} eV using the hybrid detector of the Pierre Auger observatory*, J. Cosmol. Astropart. Phys. **04**, 009 (2017), doi:10.1088/1475-7516/2017/04/009.

[147] R. U. Abbasi et al., *Constraints on the diffuse photon flux with energies above 1018 eV using the surface detector of the telescope array experiment*, Astropart. Phys. **110**, 8 (2019), doi:10.1016/j.astropartphys.2019.03.003.

[148] M. G. Aartsen et al., *Constraints on ultrahigh-energy cosmic-ray sources from a search for neutrinos above 10 PeV with IceCube*, Phys. Rev. Lett. **117**, 241101 (2016), doi:10.1103/PhysRevLett.117.241101.

[149] C. Kopper, *Observation of astrophysical neutrinos in six years of IceCube data*, Proc. Sci. **301**, 981 (2017), doi:10.22323/1.301.0981.

[150] P. W. Gorham et al., *Constraints on the ultrahigh-energy cosmic neutrino flux from the fourth flight of ANITA*, Phys. Rev. D **99**, 122001 (2019), doi:10.1103/PhysRevD.99.122001.

[151] A. Aab et al., *The Pierre Auger observatory: Contributions to the 35th international cosmic ray conference (ICRC 2017)*, (arXiv preprint) doi:10.48550/arXiv.1708.06592.

[152] J. Rico, *Gamma-ray dark matter searches in Milky Way satellites — A comparative review of data analysis methods and current results*, Galaxies **8**, 25 (2020), doi:10.3390/galaxies8010025.

[153] V. A. Acciari et al., *Constraining dark matter lifetime with a deep gamma-ray survey of the Perseus galaxy cluster with MAGIC*, Phys. Dark Universe **22**, 38 (2018), doi:10.1016/j.dark.2018.08.002.

[154] A. Acharyya et al., *Sensitivity of the Cherenkov telescope array to a dark matter signal from the galactic centre*, J. Cosmol. Astropart. Phys. **01**, 057 (2021), doi:10.1088/1475-7516/2021/01/057.

[155] C. A. Argüelles and H. Dujmovic, *Searches for connections between dark matter and neutrinos with the IceCube high-energy starting event sample*, Proc. Sci. **358**, 839 (2019), doi:10.22323/1.358.0839.

[156] A. Esmaili, A. Ibarra and O. L. G Peres, *Probing the stability of superheavy dark matter particles with high-energy neutrinos*, J. Cosmol. Astropart. Phys. **11**, 034 (2012), doi:10.1088/1475-7516/2012/11/034.

[157] C. Rott, K. Kohri and S. C. Park, *Superheavy dark matter and IceCube neutrino signals: Bounds on decaying dark matter*, Phys. Rev. D **92**, 023529 (2015), doi:10.1103/PhysRevD.92.023529.

[158] C. El Aisati, M. Gustafsson and T. Hambye, *New search for monochromatic neutrinos from dark matter decay*, Phys. Rev. D **92**, 123515 (2015), doi:10.1103/PhysRevD.92.123515.

[159] S. B. Roland, B. Shakya and J. D. Wells, *PeV neutrinos and a 3.5 keV x-ray line from a PeV-scale supersymmetric neutrino sector*, Phys. Rev. D **92**, 095018 (2015), doi:10.1103/PhysRevD.92.095018.

[160] H. H. Patel, S. Profumo and B. Shakya, *Loop dominated signals from neutrino portal dark matter*, Phys. Rev. D **101**, 095001 (2020), doi:10.1103/PhysRevD.101.095001.

[161] N. Hiroshima, R. Kitano, K. Kohri and K. Murase, *High-energy neutrinos from multibody decaying dark matter*, Phys. Rev. D **97**, 023006 (2018), doi:10.1103/PhysRevD.97.023006.

[162] B. Feldstein, A. Kusenko, S. Matsumoto and T. T. Yanagida, *Neutrinos at IceCube from heavy decaying dark matter*, Phys. Rev. D **88**, 015004 (2013), doi:10.1103/PhysRevD.88.015004.

[163] A. Esmaili and P. D. Serpico, *Are IceCube neutrinos unveiling PeV-scale decaying dark matter?*, J. Cosmol. Astropart. Phys. **11**, 054 (2013), doi:10.1088/1475-7516/2013/11/054.

[164] L. A. Anchordoqui, V. Barger, H. Goldberg, X. Huang, D. Marfatia, L. H. M. da Silva and T. J. Weiler, *IceCube neutrinos, decaying dark matter, and the Hubble constant*, Phys. Rev. D **92**, 061301 (2015), doi:10.1103/PhysRevD.92.061301.

[165] M. Chianese, G. Miele and S. Morisi, *Interpreting IceCube 6-year HESE data as an evidence for hundred TeV decaying dark matter*, Phys. Lett. B **773**, 591 (2017), doi:10.1016/j.physletb.2017.09.016.

[166] A. Bhattacharya, M. H. Reno and I. Sarcevic, *Reconciling neutrino flux from heavy dark matter decay and recent events at IceCube*, J. High Energy Phys. **06**, 110 (2014), doi:10.1007/JHEP06(2014)110.

[167] M. Ahlers, Y. Bai, V. Barger and R. Lu, *Galactic neutrinos in the TeV to PeV range*, Phys. Rev. D **93**, 013009 (2016), doi:10.1103/PhysRevD.93.013009.

[168] A. Bhattacharya, A. Esmaili, S. Palomares-Ruiz and I. Sarcevic, *Update on decaying and annihilating heavy dark matter with the 6-year IceCube HESE data*, J. Cosmol. Astropart. Phys. **05**, 051 (2019), doi:10.1088/1475-7516/2019/05/051.

[169] K. Choi et al., *Search for neutrinos from annihilation of captured low-mass dark matter particles in the sun by Super-Kamiokande*, Phys. Rev. Lett. **114**, 141301 (2015), doi:10.1103/PhysRevLett.114.141301.

[170] M. G. Aartsen et al., *Search for annihilating dark matter in the sun with 3 years of IceCube data*, Eur. Phys. J. C **77**, 146 (2017), doi:10.1140/epjc/s10052-017-4689-9.

[171] S. Adrián-Martínez et al., *Limits on dark matter annihilation in the sun using the ANTARES neutrino telescope*, Phys. Lett. B **759**, 69 (2016), doi:10.1016/j.physletb.2016.05.019.

[172] R. K. Leane, K. C. Y. Ng and J. F. Beacom, *Powerful solar signatures of long-lived dark mediators*, Phys. Rev. D **95**, 123016 (2017), doi:10.1103/PhysRevD.95.123016.

[173] A. Albert et al., *Constraints on spin-dependent dark matter scattering with long-lived mediators from TeV observations of the Sun with HAWC*, Phys. Rev. D **98**, 123012 (2018), doi:10.1103/PhysRevD.98.123012.

[174] M. U. Nisa, J. F. Beacom, S. Y. BenZvi, R. K. Leane, T. Linden, K. C. Y. Ng, A. H. G. Peter and B. Zhou, *The sun at GeV–TeV energies: A new laboratory for astroparticle physics*, (arXiv preprint) doi:10.48550/arXiv.1903.06349.

[175] R. K. Leane, T. Linden, P. Mukhopadhyay and N. Toro, *Celestial-body focused dark matter annihilation throughout the Galaxy*, Phys. Rev. D **103**, 075030 (2021), doi:10.1103/PhysRevD.103.075030.

[176] R. K. Leane and T. Linden, *First analysis of jupiter in gamma rays and a new search for dark matter*, Phys. Rev. Lett. **131**, 071001 (2023), doi:10.1103/PhysRevLett.131.071001.

[177] M. Baryakhtar, J. Bramante, S. W. Li, T. Linden and N. Raj, *Dark kinetic heating of neutron stars and an infrared window on WIMPs, SIMPs, and pure Higgsinos*, Phys. Rev. Lett. **119**, 131801 (2017), doi:10.1103/PhysRevLett.119.131801.

[178] J. Bramante, B. J. Kavanagh and N. Raj, *Scattering searches for dark matter in subhalos: Neutron stars, cosmic rays, and old rocks*, Phys. Rev. Lett. **128**, 231801 (2022), doi:10.1103/PhysRevLett.128.231801.

[179] J. Bramante, A. Delgado and A. Martin, *Multiscatter stellar capture of dark matter*, Phys. Rev. D **96**, 063002 (2017), doi:10.1103/PhysRevD.96.063002.

[180] N. Raj, P. Tanedo and H.-B. Yu, *Neutron stars at the dark matter direct detection frontier*, Phys. Rev. D **97**, 043006 (2018), doi:10.1103/PhysRevD.97.043006.

[181] J. F. Acevedo, J. Bramante, R. K. Leane and N. Raj, *Warming nuclear pasta with dark matter: Kinetic and annihilation heating of neutron star crusts*, J. Cosmol. Astropart. Phys. **03**, 038 (2020), doi:10.1088/1475-7516/2020/03/038.

[182] C.-S. Chen and Y.-H. Lin, *Reheating neutron stars with the annihilation of self-interacting dark matter*, J. High Energy Phys. **08**, 069 (2018), doi:10.1007/JHEP08(2018)069.

[183] N. F. Bell, G. Busoni and S. Robles, *Heating up neutron stars with inelastic dark matter*, J. Cosmol. Astropart. Phys. **1809**, 018 (2018), doi:10.1088/1475-7516/2018/09/018.

[184] R. Garani, Y. Genolini and T. Hambye, *New analysis of neutron star constraints on asymmetric dark matter*, J. Cosmol. Astropart. Phys. **05**, 035 (2019), doi:10.1088/1475-7516/2019/05/035.

[185] D. A. Camargo, F. S. Queiroz and R. Sturani, *Detecting dark matter with neutron star spectroscopy*, J. Cosmol. Astropart. Phys. **09**, 051 (2019), doi:10.1088/1475-7516/2019/09/051.

[186] K. Hamaguchi, N. Nagata and K. Yanagi, *Dark matter heating vs. rotochemical heating in old neutron stars*, Phys. Lett. B **795**, 484 (2019), doi:10.1016/j.physletb.2019.06.060.

[187] W.-Y. Keung, D. Marfatia and P.-Y. Tseng, *Heating neutron stars with GeV dark matter*, J. High Energy Phys. **07**, 181 (2020), doi:10.1007/JHEP07(2020)181.

[188] N. F. Bell, G. Busoni, S. Robles and M. Virgato, *Improved treatment of dark matter capture in neutron stars*, J. Cosmol. Astropart. Phys. **09**, 028 (2020), doi:10.1088/1475-7516/2020/09/028.

[189] B. Dasgupta, A. Gupta and A. Ray, *Dark matter capture in celestial objects: Light mediators, self-interactions, and complementarity with direct detection*, J. Cosmol. Astropart. Phys. **10**, 023 (2020), doi:10.1088/1475-7516/2020/10/023.

[190] R. Garani, A. Gupta and N. Raj, *Observing the thermalization of dark matter in neutron stars*, Phys. Rev. D **103**, 043019 (2021), doi:10.1103/PhysRevD.103.043019.

[191] T. N. Maity and F. S. Queiroz, *Detecting bosonic dark matter with neutron stars*, Phys. Rev. D **104**, 083019 (2021), doi:10.1103/PhysRevD.104.083019.

[192] N. F. Bell, G. Busoni, T. F. Motta, S. Robles, A. W. Thomas and M. Virgato, *Nucleon structure and strong interactions in dark matter capture in neutron stars*, Phys. Rev. Lett. **127**, 111803 (2021), doi:10.1103/PhysRevLett.127.111803.

[193] Y.-P. Zeng, X. Xiao and W. Wang, *Constraints on pseudo-Nambu-Goldstone dark matter from direct detection experiment and neutron star reheating temperature*, Phys. Lett. B **824**, 136822 (2022), doi:10.1016/j.physletb.2021.136822.

[194] F. Anzuini, N. F. Bell, G. Busoni, T. F. Motta, S. Robles, A. W. Thomas and M. Virgato, *Improved treatment of dark matter capture in neutron stars III: Nucleon and exotic targets*, J. Cosmol. Astropart. Phys. **11**, 056 (2021), doi:10.1088/1475-7516/2021/11/056.

[195] N. F. Bell, G. Busoni and S. Robles, *Capture of leptophilic dark matter in neutron stars*, J. Cosmol. Astropart. Phys. **06**, 054 (2019), doi:10.1088/1475-7516/2019/06/054.

[196] R. Garani and J. Heeck, *Dark matter interactions with muons in neutron stars*, Phys. Rev. D **100**, 035039 (2019), doi:10.1103/PhysRevD.100.035039.

[197] A. Joglekar, N. Raj, P. Tanedo and H.-B. Yu, *Relativistic capture of dark matter by electrons in neutron stars*, Phys. Lett. B **809**, 135767 (2020), doi:10.1016/j.physletb.2020.135767.

[198] A. Joglekar, N. Raj, P. Tanedo and H.-B. Yu, *Dark kinetic heating of neutron stars from contact interactions with relativistic targets*, Phys. Rev. D **102**, 123002 (2020), doi:10.1103/PhysRevD.102.123002.

[199] N. F. Bell, G. Busoni, S. Robles and M. Virgato, *Improved treatment of dark matter capture in neutron stars II: Leptonic targets*, J. Cosmol. Astropart. Phys. **03**, 086 (2021), doi:10.1088/1475-7516/2021/03/086.

[200] J. Coffey, D. McKeen, D. E. Morrissey and N. Raj, *Neutron star observations of pseudoscalar-mediated dark matter*, Phys. Rev. D **106**, 115019 (2022), doi:10.1103/PhysRevD.106.115019.

[201] G. D. Mack, J. F. Beacom and G. Bertone, *Towards closing the window on strongly interacting dark matter: Far-reaching constraints from Earth's heat flow*, Phys. Rev. D **76**, 043523 (2007), doi:10.1103/PhysRevD.76.043523.

[202] J. Bramante, A. Buchanan, A. Goodman and E. Lodhi, *Terrestrial and martian heat flow limits on dark matter*, Phys. Rev. D **101**, 043001 (2020), doi:10.1103/PhysRevD.101.043001.

[203] R. K. Leane and J. Smirnov, *Exoplanets as sub-GeV dark matter detectors*, Phys. Rev. Lett. **126**, 161101 (2021), doi:10.1103/PhysRevLett.126.161101.

[204] C. Ilie, C. Levy, J. Pilawa and S. Zhang, *Probing below the neutrino floor with the first generation of stars*, (arXiv preprint) doi:10.48550/arXiv.2009.11478.

[205] C. Ilie and C. Levy, *Multicomponent multiscatter capture of dark matter*, Phys. Rev. D **104**, 083033 (2021), doi:10.1103/PhysRevD.104.083033.

[206] T. Aramaki et al., *Snowmass2021 cosmic frontier: The landscape of cosmic-ray and high-energy photon probes of particle dark matter*, (arXiv preprint) doi:10.48550/arXiv.2203.06894.

[207] M. Baryakhtar et al., *Dark matter in extreme astrophysical environments*, (arXiv preprint) doi:10.48550/arXiv.2203.07984.

[208] B. Dasgupta, R. Laha and A. Ray, *Low mass black holes from dark core collapse*, Phys. Rev. Lett. **126**, 141105 (2021), doi:10.1103/PhysRevLett.126.141105.

[209] H. Steigerwald, V. Marra and S. Profumo, *Revisiting constraints on asymmetric dark matter from collapse in white dwarf stars*, Phys. Rev. D **105**, 083507 (2022), doi:10.1103/PhysRevD.105.083507.

[210] S. Bhattacharya, B. Dasgupta, R. Laha and A. Ray, *Can LIGO detect nonannihilating dark matter?*, Phys. Rev. Lett. **131**, 091401 (2023), doi:10.1103/PhysRevLett.131.091401.

[211] M. A. Buen-Abad, R. Essig, D. McKeen and Y.-M. Zhong, *Cosmological constraints on dark matter interactions with ordinary matter*, Phys. Rep. **961**, 1 (2022), doi:10.1016/j.physrep.2022.02.006.

[212] D. V. Nguyen, D. Sarnaaik, K. K. Boddy, E. O. Nadler and V. Gluscevic, *Observational constraints on dark matter scattering with electrons*, Phys. Rev. D **104**, 103521 (2021), doi:10.1103/PhysRevD.104.103521.

[213] L. Li, T. Nakama, C. M. Sou, Y. Wang and S. Zhou, *Gravitational production of superheavy dark matter and associated cosmological signatures*, J. High Energy Phys. **07**, 067 (2019), doi:10.1007/JHEP07(2019)067.

[214] L. Li, S. Lu, Y. Wang and S. Zhou, *Cosmological signatures of superheavy dark matter*, J. High Energy Phys. **07**, 231 (2020), doi:10.1007/JHEP07(2020)231.