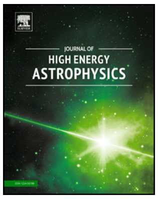
Journal of High Energy Astrophysics 35 (2022) 112–138

Contents lists available at ScienceDirect

Journal of High Energy Astrophysics

www.elsevier.com/locate/jheap



Snowmass2021 theory frontier white paper: Astrophysical and cosmological probes of dark matter

Kimberly K. Boddy[a,1], Mariangela Lisanti[b,c,1], Samuel D. McDermott[d,1], Nicholas L. Rodd[e,*,1], Christoph Weniger[f,1], Yacine Ali-Haïmoud[s], Malte Buschmann[b], Ilias Cholis[g], Djuna Croon[h], Adrienne L. Erickcek[i], Vera Gluscevic[q], Rebecca K. Leane[j,k], Siddharth Mishra-Sharma[l,m,n], Julian B. Muñoz[o], Ethan O. Nadler[p,q], Priyamvada Natarajan[t,u], Adrian Price-Whelan[c], Simona Vegetti[r], Samuel J. Witte[f]

[a] *Department of Physics, The University of Texas at Austin, Austin, TX 78712, USA*
[b] *Department of Physics, Princeton University, Princeton, NJ 08544, USA*
[c] *Center for Computational Astrophysics, Flatiron Institute, New York, NY 10010, USA*
[d] *Fermi National Accelerator Laboratory, Batavia, IL, 60510, USA*
[e] *Theoretical Physics Department, CERN, 1 Esplanade des Particules, CH-1211 Geneva 23, Switzerland*
[f] *GRAPPA Institute, Institute for Theoretical Physics Amsterdam and Delta Institute for Theoretical Physics, University of Amsterdam, 1098 XH Amsterdam, the Netherlands*
[g] *Department of Physics, Oakland University, Rochester, MI, 48309, USA*
[h] *Institute for Particle Physics Phenomenology, Department of Physics, Durham University, Durham DH1 3LE, UK*
[i] *Department of Physics and Astronomy, University of North Carolina at Chapel Hill, Chapel Hill, NC 27599, USA*
[j] *SLAC National Accelerator Laboratory, Stanford University, Stanford, CA 94039, USA*
[k] *Kavli Institute for Particle Astrophysics and Cosmology, Stanford University, Stanford, CA 94039, USA*
[l] *The NSF AI Institute for Artificial Intelligence and Fundamental Interactions, USA*
[m] *Center for Theoretical Physics, Massachusetts Institute of Technology, Cambridge, MA 02139, USA*
[n] *Department of Physics, Harvard University, Cambridge, MA 02138, USA*
[o] *Center for Astrophysics | Harvard & Smithsonian, 60 Garden St, Cambridge, MA, 02138, USA*
[p] *Carnegie Observatories, Pasadena, CA 91101, USA*
[q] *Department of Physics & Astronomy, University of Southern California, Los Angeles, CA, 90007, USA*
[r] *Max Planck Institute for Astrophysics, 85748 Garching bei München, Germany*
[s] *Center for Cosmology and Particle Physics, Department of Physics, New York University, New York, NY 10003, USA*
[t] *Department of Astronomy, Yale University, New Haven, CT 06520, USA*
[u] *Department of Physics, Yale University, New Haven, CT 06520, USA*

ARTICLE INFO

Article history:
Received 20 June 2022
Accepted 20 June 2022

ABSTRACT

While astrophysical and cosmological probes provide a remarkably precise and consistent picture of the quantity and general properties of dark matter, its fundamental nature remains one of the most significant open questions in physics. Obtaining a more comprehensive understanding of dark matter within the next decade will require overcoming a number of theoretical challenges: the groundwork for these strides is being laid now, yet much remains to be done. Chief among the upcoming challenges is establishing the theoretical foundation needed to harness the full potential of new observables in the astrophysical and cosmological domains, spanning the early Universe to the inner portions of galaxies and the stars therein. Identifying the nature of dark matter will also entail repurposing and implementing a wide range of theoretical techniques from outside the typical toolkit of astrophysics, ranging from effective field theory to the dramatically evolving world of machine learning and artificial-intelligence-based statistical inference. Through this work, the theory frontier will be at the heart of dark matter discoveries in the upcoming decade.

1. Introduction

Astrophysical and cosmological observations have historically played a critical role in the study of dark matter, underpin-

---

[*] Corresponding author.
E-mail address: nrodd@cern.ch (N.L. Rodd).
[1] Editors.

https://doi.org/10.1016/j.jheap.2022.06.005

ning our confidence that there is a missing mass component of the Universe. The evidence that observational measurements provide for dark matter is collected across many length scales. The earliest hints for dark matter arose from its gravitational effects on galaxies, explaining the observed flatness of rotation curves (Rubin and Ford, 1970; Roberts and Whitehurst, 1975; Rubin et al., 1980; Bosma, 1981). Gravitational lensing has also detected dark matter surrounding galaxy clusters (Clowe et al., 2006). On yet larger scales, the cosmic web of large-scale surveys (Springel et al., 2006), as well as the fluctuations of the cosmic microwave background (CMB) (Planck Collaboration et al., 2020a), have both been integral in the development of the cold dark matter (CDM) paradigm, where 85% of the Universe's matter budget is dark.

A complete theory of particle dark matter[2] will ultimately describe how it interacts with visible matter, as well as whether it interacts with other dark states in its own separate sector. Moreover, any such theory will be successful on both the largest scales of the Universe as well as the smallest (i.e., sub-galactic) scales. Over the next decade, astrophysical and cosmological probes will provide powerful tests of fundamental questions about dark matter, playing a unique and complementary role to the terrestrial dark matter experimental program. This review will focus on five specific theory questions where concrete advancements are anticipated during this time period:

- *Is the Cold Dark Matter paradigm correct?*
  In the CDM paradigm, dark matter is collision-less and non-relativistic during structure formation. A natural consequence of this is the prediction of an abundance of low-mass dark matter halos down to $\sim 10^{-6}\ M_\odot$ (Diemand et al., 2005). Observations that provide information on the matter power spectrum at small scales and various redshifts, therefore, will play a pivotal role in confirming the CDM hypothesis. Evidence of small-scale power suppression could, for example, suggest that dark matter is warmer (i.e., not non-relativistic) during structure formation (e.g. Lovell et al., 2014), is not collisionless (e.g. Boddy et al., 2016), is wave-like rather than particle-like (e.g. Hu et al., 2000), or underwent non-trivial phase transitions in the early Universe (e.g. Arvanitaki et al., 2020). As we will discuss, upcoming astrophysical surveys have the potential to start probing halo masses to much lower values and/or higher redshifts than previously accessible, opening the opportunity of definitively testing the CDM hypothesis.
- *Is dark matter production in the early Universe thermal?*
  The observed relic abundance of dark matter can be explained through a thermal freeze-out mechanism (see (e.g. Lisanti, 2017; Lin, 2019) for recent reviews). In this picture, dark matter is kept in thermal equilibrium with the photon bath at high temperatures through weak annihilation processes. Once dark matter becomes non-relativistic, dark matter is still allowed to annihilate, but the reverse process is kinematically forbidden. The continued annihilation of dark matter causes its comoving number density to be Boltzmann suppressed, until it freezes out due to Hubble expansion overcoming the annihilation rate. This process sets the present-day dark matter abundance. Importantly, the predicted abundance is sensitive to the detailed dark matter physics, including its particle mass as well as its specific interactions with the Standard Model. Weakly Interacting Massive Particles (WIMPs) provide a classic example of the freeze-out paradigm. In this case, a $\mathcal{O}$(GeV–TeV) mass particle that is weakly interacting yields the correct relic abundance. As we will demonstrate, upcoming astrophysical surveys will have the opportunity to definitively test key aspects of the WIMP hypothesis by searching for the rare dark matter annihilation and decay products that arise from the same interactions that set its abundance in the early Universe. A combination of improved instruments and the so-far non-observation of WIMPs has also led to the exploration of probing dark matter candidates that are lighter or heavier than the canonical WIMP window, and which often have a non-thermal origin in the early Universe. This broadening of the possible dark matter candidates that one can search for in indirect detection will continue to be driven by the theory community.
- *Is dark matter fundamentally wave-like or particle-like?*
  Model-independent arguments that rely on the phase-space packing of dark matter in galaxies have been used to set generic bounds on its minimum allowed mass. In particular, a fermionic dark matter candidate can have a minimum mass of $\sim$ keV (Horiuchi et al., 2014), while a bosonic candidate can have a minimum mass of $\sim 10^{-23}$ eV (Hu et al., 2000). Moreover, when the dark matter mass is much less than $\sim$ eV, its number density in a galaxy is so large that it can effectively be treated as a classical field. Oftentimes referred to as "axions" or "axion-like particles" (ALPs), these ultra-light bosonic states can have distinctive signatures due to their wave-like nature. The QCD axion (Peccei and Quinn, 1977a,b; Weinberg, 1978; Wilczek, 1978), originally introduced to address the strong CP problem, is a particularly well-motivated dark matter candidate for which there are clear mechanisms for how to generate the correct abundance today (Preskill et al., 1983; Abbott and Sikivie, 1983; Dine and Fischler, 1983; Di Luzio et al., 2020). In this framework, the axion mass and coupling are fundamentally related to each other through the symmetry-breaking scale of the theory. As we show, upcoming searches for astrophysical axions will have the sensitivity reach to probe highly-motivated mass ranges for the QCD axion.
- *Is there a dark sector containing other new particles and/or forces?*
  In a generic and well-motivated theory framework, dark matter can exist in a "dark sector" that communicates with the Standard Model through specific portal interactions. Within the dark sector, there can be multiple new states, as well as new forces that mediate interactions between the dark particles. Recent theory work has demonstrated classes of dark sector models that yield the correct dark matter abundance (see (e.g. Battaglieri et al., 2017) for a review), oftentimes for lower dark matter masses than expected for WIMPs. Dark sector models can lead to a rich phenomenology for both astrophysical and terrestrial dark matter searches, as we will discuss. Two properties of the dark sector where upcoming astrophysical surveys will be able to make decisive statements are the presence of self interactions between dark matter particles (Spergel and Steinhardt, 2000) and new light degrees of freedom.
- *How will the development of numerical methods progress dark matter searches?*
  Given the sheer volume and complexity of data expected from astrophysical surveys in the upcoming decade, the development of effective observational and data analysis strategies is imperative. Novel machine learning and statistical tools will play an important role in maximizing the utility of these datasets. In particular, scalable inference techniques and deep learning methods have the potential to open new dark matter discovery potential across several frontiers. Another critical numerical component to harness the anticipated flood of

---

[2] In this white paper, we focus on the general class of *particle* dark matter candidates and refer the reader to other Snowmass contributions for a description of primordial black holes (PBHs) as a dark matter candidate.

astrophysical data in the next decade is the further development of cosmological and zoom-in simulations needed to interpret the survey results. We will comment on how such simulations are essential for understanding the implications of particular dark matter models on small-scale structure formation.

This list is not intended to be comprehensive, but rather to provide well-motivated examples of areas where fundamental advancements are expected with upcoming astrophysical and cosmological probes. We have divided this white paper into two separate discussions reflecting what we can learn about dark matter from its interactions with visible matter in astrophysical systems (Sec. 2) as well as its early-Universe behavior and its role in the formation of structure (Sec. 3). Each section briefly reviews some of the most promising observational probes for tackling the specific theory questions delineated above. Sec. 4 is dedicated to the exciting advancements expected in applications of statistics and machine learning to astrophysical studies of dark matter. We conclude in Sec. 5.

Complementarity with additional White Papers: We note that there are a number of white papers which contain results complementary to the discussion we provide here. A non-exhaustive list includes *Cosmological Simulations for Dark Matter Physics* (Banerjee et al., 2022), *Data-Driven Cosmology* (Amin et al., 2022), *Dark Matter Physics from Halo Measurements* (Bechtol et al., 2022), *Ultra-heavy Particle Dark Matter* (Carney et al., 2022), *Puzzling Excesses and How to Resolve Them* (Leane et al., 2022), and *Detection of Early-Universe Gravitational Wave Signatures and Fundamental Physics* (Caldwell et al., 2022). We encourage interested readers to look to these related white papers for further details of how the search for dark matter will proceed in the coming decade.

2. Dark matter interactions with visible matter

Historically, a strong motivation for the existence of an interaction between dark and visible matter arises from the simple and compelling cosmologies described by the WIMP miracle or freeze-in production of sterile neutrinos. These scenarios have also long motivated indirect detection searches: the same interactions that generate dark matter could also be occurring today and allow it to decay or annihilate into detectable signatures arising from astrophysical sources. However, in the past decade, a substantial portion—although certainly not all—of the well-motivated parameter space for these models has been excluded (see (e.g. Leane et al., 2018; Foster et al., 2021)). Astrophysical searches for dark matter have broadened in perspective as the theoretical community has realized that the potential mass and interactions dark matter could have are much, much broader. In this section, we will highlight this paradigm shift, demonstrating that while conventional searches continue, ideas to probe significantly heavier and lighter dark matter are appearing and will continue to be developed in the coming years.

2.1. X-ray and γ-ray dark matter signatures

If the dark matter of our Universe can decay or annihilate, then one of the most promising channels for determining its particle nature is the detection of high-energy photons. In the past decade, considerable progress has been made in photon-based indirect detection for dark matter with masses $\mathcal{O}$(keV–TeV), which we will predominantly focus on in this section. This improvement has not been solely driven by the experimental observatories: often theoretical insights have led to dramatic leaps forward in our ability to probe dark matter. This bidirectional approach to progress must continue in the coming years.

The fundamental ingredient for indirect searches is observational datasets. A partial summary of the present and future landscape is provided in Fig. 1. At the highest energies, significant progress will be achieved beyond the existing reach of H.E.S.S. (de Naurois and Rolland, 2009), HAWC (Abeysekara et al., 2017), and similar observatories, through a combination of CTA (CTA Consortium Collaboration et al., 2018), SWGO (Abreu et al., 2019), and LHAASO (Bai et al., 2019a) (the last of which is already in operation, see (e.g. LHAASO Collaboration et al., 2021)). The combined dark matter discovery potential of these telescopes is significant. CTA has the possibility to discover the higgsino (Rinchiuso et al., 2021), one of the most well-motivated WIMP candidates. However, its ability to do so will depend on whether or not the broad program to understand electroweak effects for TeV scale dark matter can determine its annihilation spectrum and cross section with sufficient accuracy (Bauer et al., 2015; Ovanesyan et al., 2015; Baumgart et al., 2015; Baumgart and Vaidya, 2016; Ovanesyan et al., 2017; Baumgart et al., 2018; Beneke et al., 2018; Baumgart et al., 2019; Beneke et al., 2019, 2020). Observations at these energies further open the path to probing dark matter with masses above the unitarity limit, $m_\chi \gtrsim 100$ TeV (Griest and Kamionkowski, 1990). The space of models, cosmologies, and production mechanisms for such ultra-heavy dark matter is being actively developed, see (e.g. Carney et al., 2022). Discovering these models requires a detailed understanding of the spectrum of particles that emerge from their annihilation or decay, and how those states propagate to Earth. In recent years, public codes have been developed for the propagation of high-energy states (Murase and Beacom, 2012; Murase et al., 2015; Alves Batista et al., 2016; Heiter et al., 2018; Blanco, 2019). For the spectra, the most widely used approach exploits an analogy with colliders so that `Pythia` (Sjostrand et al., 2006, 2008; Sjöstrand et al., 2015) can be used for the calculation, as in `PPPC4DMID` (Ciafaloni et al., 2011; Cirelli et al., 2011). This analogy breaks down at higher energies—indeed, existing LHAASO projections simply end at $m_\chi = 100$ TeV due to an absence of theoretical calculations available above that scale (He et al., 2020). The first steps towards reliable spectra at higher masses have recently been taken in Bauer et al. (2021), although there remains significant work. The importance of these developments for γ-ray searches has been considered in Ishiwata et al. (2020); Chianese et al. (2021a); Esmaili and Serpico (2021); Maity et al. (2021).

In the $\mathcal{O}$(keV–GeV) band, observations must be made from space as the interaction of photons with the atmosphere does not produce a sufficiently detectable signature on the Earth's surface. This sets a fundamental limitation: a 1 m^2 instrument operating for a decade has an exposure of $\sim 10^{12.5}\,\text{cm}^2\,\text{s}$. At keV and GeV energies, this is roughly the sensitivity already achieved by XMM-Newton (Turner et al., 2001; Struder et al., 2001) and Fermi (Fermi-LAT Collaboration et al., 2009, 2021), with smaller exposures achieved for the intervening energies with NuSTAR (NuSTAR Collaboration et al., 2013; Madsen et al., 2015), INTEGRAL (Sizun et al., 2004), and COMPTEL (den Herder et al., 1992). In the longer term, instruments such as Athena (Barcons et al., 2015), AMEGO (AMEGO Team Collaboration and Kierans, 2020), and e-ASTROGAM (e-ASTROGAM Collaboration et al., 2018) can improve our sensitivity, but at many energies, the best anticipated datasets are already on disk. Progress will therefore be critically reliant on new insights for how to exploit the data. This is happening on many fronts, including identifying new objects in which to search for dark matter signals, such as newly discovered Milky Way dwarfs (DES Collaboration et al., 2015a,b; Koposov et al., 2015; Fermi-LAT, DES Collaboration et al., 2017; DES Collaboration et al., 2020; Ando et al., 2019), galaxy catalogs (Lisanti et al., 2018a,b), or dark substructure (Kuhlen et al., 2008; Buckley and Hooper,

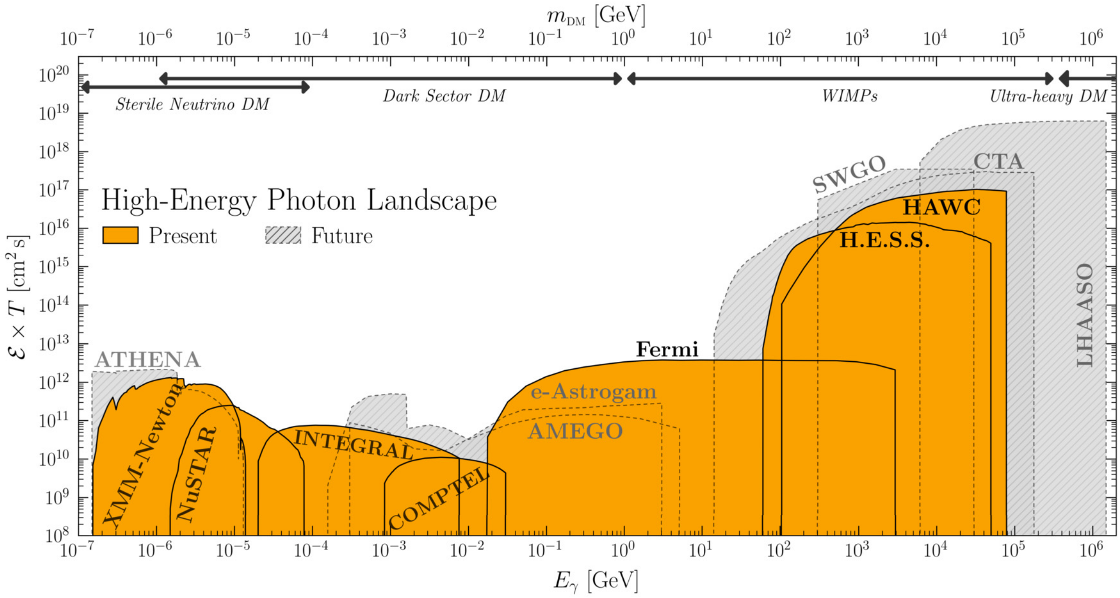


Fig. 1. The exposure of existing and upcoming X-ray and γ-ray instruments which can search for the decay or annihilation of dark matter. Significant progress in the coming years is expected at $\mathcal{O}$(TeV–PeV) energies, a full exploitation of which will require theoretical developments in the models and spectra of heavy dark matter. Such work will also complement instruments searching for even higher energy photons, such as PAO (The Pierre Auger Observatory, 2015; Pierre Auger Collaboration et al., 2017). At $\mathcal{O}$(keV–GeV) energies, the expected observational progress is far more modest at the level of exposure. Exposure—the product of effective area, $\mathcal{E}$, and observation time, T—partially controls how many photons an instrument will detect on average for a given dark matter flux. We caution that this is just one metric by which instruments can be compared: for certain dark matter searches, the field of view or energy resolution can be critical, and then the improvements made at lower energies will be more substantial. Regardless, improved analysis strategies will be crucial to further enhance the dark matter reach for this lower band. At the top of the figure, we highlight the approximate mass range of several canonical particle dark matter (DM) scenarios; one can roughly associate this mass range with the corresponding energy range of probes, although this connection is only approximate.

2010; Belikov et al., 2012; Fermi-LAT Collaboration et al., 2012; Zechlin and Horns, 2012; Berlin and Hooper, 2014; Bertoni et al., 2015; Schoonenberg et al., 2016; Bertoni et al., 2016; Mirabal et al., 2016; Hooper and Witte, 2017; Calore et al., 2017; Hütten et al., 2019; H.E.S.S. Collaboration et al., 2021; Calore et al., 2019; Coronado-Blázquez et al., 2019; Coronado-Blázquez and Sánchez-Conde, 2019; Facchinetti et al., 2020; Di Mauro et al., 2020; Somalwar et al., 2021), as well as the development of techniques such as cross correlation with different datasets (Xia et al., 2011; Ando, 2014; Ando et al., 2014; Xia et al., 2015; Regis et al., 2015; Cuoco et al., 2015; Ando and Ishiwata, 2016; Shirasaki et al., 2020), improvements in our modeling of diffuse backgrounds (Macias et al., 2018, 2019; Buschmann et al., 2020; Siegert et al., 2022), the extension to axion searches as we describe in Sec. 2.4, and the exploitation of the dark matter brightness of the ambient Milky Way (Foster et al., 2021; Cohen et al., 2017; Chang et al., 2018a; Dessert et al., 2020a). To expand on a single example, in Dessert et al. (2020a) it was demonstrated that the roughly twenty years of X-ray images collected by XMM-Newton, when combined with the insight that all of these observations occur through a column density of the Milky Way, allowed for a search for dark matter decay that was more than an order of magnitude stronger than previous analyses. The results were strong enough to considerably disfavor the longstanding 3.5 keV line dark matter anomaly (Bulbul et al., 2014; Boyarsky et al., 2014) (although see also (Boyarsky et al., 2020; Dessert et al., 2020b)). More generally, there remains several unexplained dark matter anomalies in this energy window whose resolution will depend on further insights from the theory community; for an extended discussion, we refer to Leane et al. (2022).

An additional strategy that has been developed recently considers dark matter that scatters and becomes captured within celestial bodies. The dark matter can then annihilate, generating a signal that depends on the mediator between the dark and visible sectors. If the mediator is short-lived (or insufficiently boosted), the annihilation products will remain within the celestial object, raising its temperature. Instead, a long-lived (or sufficiently boosted) mediator leads to annihilation products outside the body, which can then be searched for by telescopes. The strongest constraints on long-lived or boosted mediator models are due to γ-ray searches, as the γ-ray backgrounds for celestial objects are very low. An excellent candidate is the Sun, and solar γ-ray searches have been performed using both Fermi (Abdo et al., 2011; Ng et al., 2016; Linden et al., 2018, 2020) and HAWC (HAWC Collaboration et al., 2018a), yielding strong constraints on GeV-TeV dark matter (Leane et al., 2017; HAWC Collaboration et al., 2018b; Nisa et al., 2019). Optimizing for both proximity and size, the next best celestial body is Jupiter, and Fermi observations have been used to constrain sub-GeV dark matter (Leane and Linden, 2021). More broadly, analogous emission from the full population of brown dwarfs and neutron stars can constrain sub-GeV to TeV dark matter (Leane et al., 2021) (see also (Bose et al., 2021)). These searches are inherently multimessenger: solar dark matter searches for neutrinos have been performed with Super-Kamiokande (Super-Kamiokande Collaboration et al., 2015), IceCube (IceCube Collaboration et al., 2017), and ANTARES (ANTARES Collaboration et al., 2016). Above $\mathcal{O}(100)$ GeV, the neutrinos will be attenuated as they exit the Sun, and a long-lived mediator again improves detectability (Leane et al., 2017; Bell and Petraki, 2011). The scenario involving short-lived mediators can be studied with optical and infrared telescopes, including Hubble, JWST, and Roman observations of neutron stars (Goldman and Nussinov, 1989; Bertone and Fairbairn, 2008; Baryakhtar et al., 2017a; Acevedo et al., 2020; Bell et al., 2020), white dwarfs (Bertone and Fairbairn, 2008; Bell et al., 2021), population III stars (Freese et al., 2009; Taoso et al., 2008; Ilie et al., 2020a,b), and brown dwarfs and exoplanets (Leane and Smirnov, 2021).

2.2. Indirect searches with astrophysical neutrinos

While searches for dark matter in the electromagnetic spectrum may be more extensively developed, there is no fundamental reason that the first discovery could not happen through a different channel. If that channel is neutrinos, then the coming decade will be particularly exciting.

Already the possibility of dark matter decaying or annihilating to neutrinos can be probed from MeV to PeV masses through a combination of instruments ranging from Borexino to IceCube. For a recent review, see Argüelles et al. (2021). The detection of $\mathcal{O}(\text{TeV} - \text{PeV})$ neutrinos at IceCube is particularly tantalizing. While the experimental collaboration has produced limits under the assumption that the observed flux does not originate from dark matter (IceCube Collaboration et al., 2018, 2020), a complete understanding of where these neutrinos originate is lacking. (Although in 2017, a ~ 300 TeV neutrino event was shown to be coincident with a flaring γ-ray blazar (IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S., INTEGRAL, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, Swift NuSTAR, VERITAS, VLA/17B-403 Collaboration et al., 2018), which would make this the third extraterrestrial source ever detected in neutrinos after the Sun and Supernova 1987A.) There has been considerable work by theorists to determine whether the IceCube flux could have a component with a dark matter origin, see (e.g. Murase et al., 2015; Esmaili and Serpico, 2013; Feldstein et al., 2013; Rott et al., 2015; Bhattacharya et al., 2014; El Aisati et al., 2015; Anchordoqui et al., 2015; Chianese et al., 2017, 2019; Bhattacharya et al., 2019), and the question remains open.

A fundamental aspect of high-energy neutrino searches, and of high-energy indirect detection more generally, is its multimessenger nature: generically, a signal of heavy dark matter annihilation or decay will appear in multiple channels. If PeV scale dark matter decays to neutrinos, there will be a significant probability for the hard neutrinos to emit a W or Z boson and thereby produce additional Standard Model final states, including photons. As a consequence, γ-ray datasets provide important context for dark matter interpretations of the IceCube dataset (see (e.g. Murase and Beacom, 2012; Cohen et al., 2017; Ahlers et al., 2016)).

This multimessenger strategy will continue to future instruments that will probe neutrinos at ever higher energies. Already, there are tools available that make a partial accounting of the underlying physics of the unbroken Standard Model (Bauer et al., 2021; Liu et al., 2020a), which build on the observation that electroweak effects are generically relevant for heavy dark matter (Ciafaloni et al., 2011; Cirelli et al., 2011). As discussed for the corresponding photon signals, work remains to fully understand these processes. The importance of such exploration is emphasized by the wide array of upcoming observatories such as ARIANNA, RNA-G, POEMMA, Grand, IceCube-Gen2, and KM3NET, which have the potential to probe dark matter with masses up to the GUT scale of 10^{15} GeV (Ishiwata et al., 2020; Esmaili et al., 2012; Ng et al., 2020; Guépin et al., 2021; Chianese et al., 2021b).

2.3. Dark matter signals from charged cosmic-rays

High-energy cosmic-rays have long been a probe of new physical phenomena in the Milky Way. This is particularly true for antimatter cosmic-rays, a field which PAMELA and AMS-02 have brought into a precision era, providing a challenge to our understanding of the antimatter sources and generating claims of a possible dark matter contribution.

In antiprotons, there are claims of an excess in the AMS-02 data peaking near 10 GeV (Cuoco et al., 2017a; Cui et al., 2017). The excess appears robust to systematic uncertainties on the production cross sections, cosmic-ray injection rates, and the effects of propagation through the interstellar medium and heliosphere (Cholis et al., 2019; Cuoco et al., 2019). The anomaly has a local significance of 3–5σ and is consistent with the possibility that it is generated by the same dark matter models which could be generating the Galactic center γ-ray excess (Cuoco et al., 2017a; Cholis et al., 2019; Cuoco et al., 2019, 2017b) (a compelling possibility given the astrophysical uncertainties for the two signals would be uncorrelated, although see Winkler, 2017). The results at present do not account for the full correlation matrix of the dataset, although attempts to estimate the covariance suggest that it can significantly reduce the significance of the excess (Boudaud et al., 2020; Heisig et al., 2020; Kahlhoefer et al., 2021). At present, the AMS-02 collaboration has not released their correlation matrix, which will be critical in establishing or repudiating the antiproton excess. Looking forward, the GAPS experiment will provide an alternative measurement of low-energy antiprotons (Aramaki et al., 2016) that will improve the modeling of the propagation of antinuclei in the interstellar medium and heliosphere (Cholis et al., 2020a). More broadly, the combination of high-precision measurements of multiple cosmic-ray species and the observation of cosmic-ray protons and electrons from different time periods will further reduce the astrophysical uncertainties.

For sufficiently massive dark matter, any flux of antiprotons is expected to be accompanied by heavier anti-nuclei cosmic-rays (Korsmeier et al., 2018; Lin et al., 2018; Cholis et al., 2020b). While dark matter can only provide at most a small excess over the astrophysical backgrounds in antiprotons, the backgrounds are highly suppressed for more massive anti-nuclei (Donato et al., 2000; Baer and Profumo, 2005; Ibarra and Wild, 2013; Fornengo et al., 2013; Dal and Raklev, 2014; Ding et al., 2019), making them a potential smoking gun signal of new physics. Tantalizingly, the AMS-02 collaboration has presented results of the detection of several antihelium events (Sam, 2018), where essentially no background events were expected. While tentative, if confirmed, this result could revolutionize cosmic-ray and high-energy physics. Heavier anti-nuclei are, however, plagued by a number of uncertainties, particularly as related to their productions (see (e.g. Donato et al., 2017; Winkler and Linden, 2021)). At present, these uncertainties imply their predicted fluxes can vary by orders of magnitude (Korsmeier et al., 2018; Cholis et al., 2020b). Future low-energy collider measurements will be instrumental in reducing those uncertainties (Donato et al., 2017), and the first such measurements have recently been provided (ALICE Collaboration et al., 2018; LHCb Collaboration et al., 2018).

Cosmic-ray positrons are another potential dark matter probe. Given that positrons quickly lose their energy as they propagate in the interstellar medium, the sources must be increasingly localized to produce higher energy cosmic-rays. The rising positron fraction measured by PAMELA (PAMELA Collaboration et al., 2009), Fermi (Ackermann et al., 2012), and AMS-02 (AMS Collaboration et al., 2013) has been widely discussed as a putative signal of dark matter annihilation or, alternatively, of nearby pulsars or supernova remnants (see (e.g. Bergstrom et al., 2008; Arkani-Hamed et al., 2009; Cholis et al., 2009; Fox and Poppitz, 2009; Kopp, 2013; Blasi, 2009; Mertsch and Sarkar, 2009; Cholis and Hooper, 2013; Ahlers et al., 2009; Mertsch and Sarkar, 2014; Cholis et al., 2017; Di Mauro et al., 2014)). Dark matter explanations are particularly challenged by *Planck* measurements of the CMB temperature and polarization power spectra (Planck Collaboration et al., 2016; Madhavacheril et al., 2014; Slatyer, 2016) and have become increasingly fine-tuned although not entirely ruled out (see (e.g. Dienes et al., 2013; Baek et al., 2014)). Regardless, AMS-02 measurements remain a highly sensitive probe of dark matter annihilation (AMS Collaboration et al., 2019); for instance, one can search for spec-

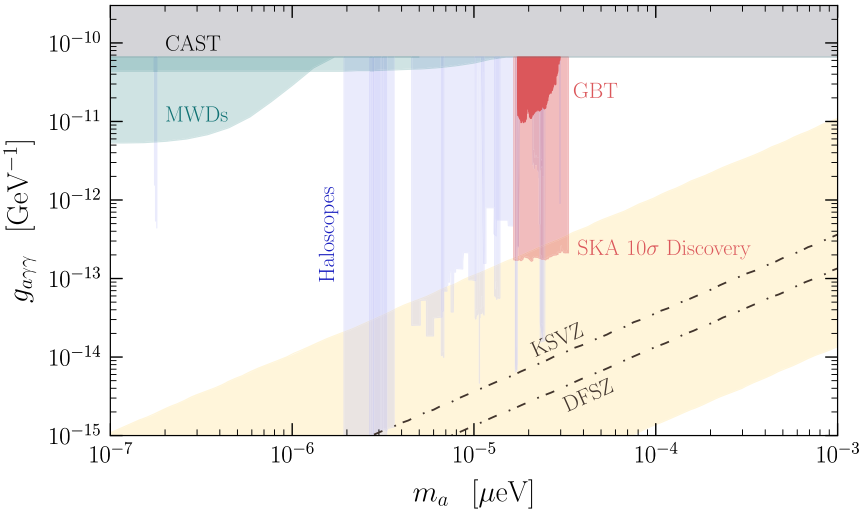


Fig. 2. Recent constraints derived on the axion-photon coupling using radio observations of the Galactic Center obtained with the Green Bank Telescope (Foster et al., 2022) (solid red, labeled "GBT"); shown for comparison is the 10σ discovery limit for SKA in the same frequency band (transparent red). These results are compared with the expected QCD axion parameter space (yellow), two benchmark QCD axion models (brown, dot-dashed), existing constraints from haloscopes (blue) (HAYSTAC Collaboration et al., 2018, 2021; ADMX Collaboration et al., 2020; Crisosto et al., 2020; ADMX Collaboration et al., 2021) and CAST (CAST Collaboration et al., 2017) (grey), and indirect searches using magnetic white dwarfs (MWDs) (Dessert et al., 2022a,b).

tral features associated with the dark matter mass (Bergstrom et al., 2013; John and Linden, 2021), although these must be interpreted carefully as astrophysical sources can also generate such features (Malyshev et al., 2009; Profumo, 2011). Existing and upcoming cosmic-ray and electromagnetic observations will be used to develop a deeper understanding of the properties of positron sources (Hooper et al., 2017; Linden et al., 2017; Mertsch, 2018; Cholis and Krommydas, 2022; Mukhopadhyay and Linden, 2021), which will further advance the program of probing dark matter with cosmic-rays.

2.4. Axion indirect detection

Recent years have seen significant development in indirect probes of axion dark matter. A common strategy is to exploit a putative axion-photon coupling. This coupling could be detected through the decay of axions to photons (which can be stimulated (Caputo et al., 2018, 2019; Battye et al., 2020; Ghosh et al., 2020; Arza and Todarello, 2022; Sun et al., 2021; Buen-Abad et al., 2021a; Arza and Todarello, 2021) or resonantly enhanced (Tkachev, 1987; Arza, 2019; Hertzberg and Schiappacasse, 2018; Sigl and Trivedi, 2019; Alonso-Álvarez et al., 2020; Arza et al., 2020; Ikeda et al., 2019; Blas and Witte, 2020a; Prabhu, 2020)), axion-photon mixing in an external magnetic field (Raffelt and Stodolsky, 1988) (which can notably also imprint an asymmetry on the polarization spectrum, see (e.g. Dessert et al., 2022a)), birefringence (Harari and Sikivie, 1992; Plascencia and Urbano, 2018; Fujita et al., 2019; Ivanov et al., 2019; McDonald and Ventura, 2020; Fedderke et al., 2019; Chen et al., 2020; Mcdonald and Ventura, 2020; Castillo et al., 2022), or the production of axions from non-orthogonal electric and magnetic fields (Prabhu, 2021). Axions could also couple to matter and thereby be produced abundantly in stars via bremsstrahlung emission (Raffelt, 2008). This process would produce anomalous cooling in these objects, which can then be used to constrain axion-nucleon and axion-electron interactions (Raffelt and Weiss, 1995; Corsico et al., 2001; Isern et al., 2008; Sedrakian, 2016; Hamaguchi et al., 2018; Buschmann et al., 2021); alternatively, these axions may convert back into photons in the magnetic fields outside of the star, generating anomalous high-energy emission (Dessert et al., 2022b). An example of recent progress is shown in Fig. 2.

Radio searches: The mixing of axions and photons is greatly enhanced in the magnetospheres of neutron stars, owing to the large ambient magnetic fields and the resonant amplification possible due to the ambient plasma (Battye et al., 2020; Foster et al., 2022; Pshirkov and Popov, 2009; Huang et al., 2018; Hook et al., 2018; Safdi et al., 2019; Leroy et al., 2020; Witte et al., 2021; Battye et al., 2021) (see also (Sen and Sivertsen, 2022)). The characteristic plasma mass near typical pulsars spans $\sim 0.1 - 100$ μeV (Goldreich and Julian, 1969), which roughly corresponds to the range of masses for which axions can simultaneously solve the strong CP problem and constitute dark matter (Irastorza and Redondo, 2018), and further to the frequency band of modern radio telescopes. The radio signal is expected to appear as a forest of spectral lines centered about the axion mass, with each line arising from a single neutron star in the Galactic population (Foster et al., 2022; Safdi et al., 2019). If dark matter is predominantly in miniclusters rather than smoothly distributed, the events will instead appear as transients spanning hours to weeks (Edwards et al., 2021a). Initial estimates indicate that near-future radio interferometers like the Square Kilometer Array may be capable of discovering the QCD axion (Hook et al., 2018; Edwards et al., 2021a). Searches using existing infrastructure (including the Effelsberg 100-m telescope, the Green Bank Telescope, and the Very Large Array) are already underway and have leading limits on the axion-photon coupling in the mass range $1 \lesssim m_a \lesssim 20\,\mathrm{GHz}$ (Foster et al., 2022, 2020; Battye et al., 2022) (see Fig. 2 for the most recent analysis).

Recently, there has been significant theoretical progress in our understanding of the radio signal, including a careful treatment of photon refraction, resonant cyclotron absorption, plasma-induced line broadening, anisotropic response of the medium in the photon production process, and general relativistic effects (Foster et al., 2022; Witte et al., 2021; Battye et al., 2021; Millar et al., 2021). Yet many open questions remain, including how axions and photons mix in a highly magnetized inhomogeneous plasma, how do charge distributions in active pulsars and magnetars impact the radio flux, what are the properties and distributions of neutron stars in dense dark matter environments, do we expect strong deviations from dipolar magnetic fields (and if so how does this impact the radio signal), how are axions distributed on astrophysical scales (i.e., do they reside in tidally disrupted axion miniclusters, and if so what are the properties of these objects in the Galactic Center), and how can we exploit the spatio-temporal properties of the radio signal to improve analyses. These are questions to be answered in the next decade, and the answers have the potential to establish radio searches as a powerful and robust probe of axion dark matter.

X-ray and γ-ray searches: High-energy photons emitted from astrophysical sources (including galaxies, blazars, supernovae, and quasars) may convert to axions in galactic- and cluster-scale magnetic fields (axions could also be produced in stellar cores (Dessert et al., 2020c)). The conversion probability depends on the magnetic field strength and configuration along the photon trajectory, as well as the plasma frequency. At sufficiently large photon energies, the photon-to-axion conversion probability becomes $\mathcal{O}(1)$ and is thus capable of generating large absorption features in the electromagnetic spectrum. The efficiency of this conversion process decreases at lower energies (at a fixed axion mass), generating small oscillatory features in the observed spectrum. Using this idea, constraints on the axion-photon coupling have been set using X-ray (Wouters and Brun, 2013; Marsh et al., 2017; Reynolds et al., 2019; Xiao et al., 2021; Reynés et al., 2021) and γ-ray (Fermi-LAT Collaboration et al., 2016; Meyer et al., 2017; Li et al., 2021a; Meyer and Petrushevska, 2020; Calore et al., 2021; H.E.S.S. Collaboration et al., 2013) telescopes for masses $m \lesssim 0.1$ µeV (excluding couplings $g_{a\gamma\gamma} \gtrsim 10^{-12}\,\text{GeV}^{-1}$ for $m_a \lesssim 10^{-11}$ eV), and they apply regardless of whether or not axions contribute to dark matter. Future progress will be aided by improved high-energy observations and by further understanding of galactic and cluster-scale magnetic fields.

2.5. Emission of dark sector states from compact objects

Standard Model particles in high-density environments, such as stars and supernovae, can emit new weakly-coupled states that might exist beyond the Standard Model. The particles emitted could either be dark matter themselves or, alternatively, part of a broader weakly-coupled "dark sector," which is potentially necessary to endow sub-GeV dark matter with the correct relic abundance. The emission process can result in either observable deviations from the Standard Model predictions on short timescales or long-term global changes to the evolution of the compact object, both of which can be constrained. The theory frontier has long played a crucial role in bridging the gap between astrophysical probes, complex multi-body Standard Model calculations, and inference on new particle properties.

The paradigmatic example of "short-term" constraints comes from the successful explosion of Supernova 1987A and the detection of neutrinos for the predicted ~ 10-second-long cooling phase (Kamiokande-II Collaboration et al., 1987; IMB Collaboration et al., 1988). The qualitative agreement of this observation with Standard Model-only numerical simulations (Burrows and Lattimer, 1986, 1987) has been used to constrain the properties of the QCD axion with ever-increasing fidelity and sophistication (Raffelt, 2008; Turner, 1988; Raffelt and Seckel, 1988; Burrows et al., 1989, 1990; Keil et al., 1997; Raffelt, 1996; Chang et al., 2018b). The theory frontier is still grappling with these calculations. Upcoming challenges will be centered on application of effective field theory techniques, which promise important changes in expected rates for Standard-Model-only processes (such as nuclear and neutrino matrix elements and scattering rates), as well as for beyond-the-Standard-Model rates.

A successful explosion of Supernova 1987A could also have been inhibited by a large dark sector (Chang et al., 2018b; Rrapaj and Reddy, 2016; Chang et al., 2017; Hardy and Lasenby, 2017). Broadly, Supernova 1987A provides the strongest bounds for any number of new particles in the $\mathcal{O}(1$–100 MeV) mass range, being cut off at high masses by Boltzmann suppression from thermal production in the core, which attains temperatures between 30–100 MeV (Burrows and Lattimer, 1986; Bollig et al., 2017). The power of these bounds at larger couplings is generally limited by the existence of a "trapping" limit. At couplings above the trapping limit, the new particles are more tightly coupled than the Standard Model neutrinos and thus are unable to drain the energy the neutrinos were observed to have taken away. Nevertheless, with the increasing fidelity of numerical simulations (Burrows and Vartanyan, 2021), the region beyond the trapping limit is a clear avenue for future theoretical and numerical investigations.

A second type of stellar constraint pertains most relevantly to particles that are substantially lighter and more weakly coupled than the MeV range in which supernova limits excel. In this mass range, dark matter must generally be non-thermal in order to avoid constraints on the number of new radiation degrees of freedom in the early Universe. Thus, such limits typically focus on bosonic particles such as the QCD axion, axion-like particles, Higgs-portal scalars, and the dark photon. A powerful approach is to require new particle emission to be subdominant to photon emission in stars (Hardy and Lasenby, 2017; Gondolo and Raffelt, 2009; An et al., 2013; Redondo and Raffelt, 2013; Viaux et al., 2013), analogous to the supernova bound wherein the new emission is limited by the neutrino emission. If this rule were to be violated, stellar lifetimes would be unacceptably short or other emission properties would change beyond measured values. A different method of constraining light particle emission from stars has been made possible recently by LIGO-Virgo Collaboration observations of gravitational waves and the corresponding mass census enabled by these observations, which are revealing the characteristics of Pop-III stellar progenitors for the first time (LIGO Scientific, Virgo Collaboration et al., 2021; LIGO Scientific, VIRGO, KAGRA Collaboration et al., 2021). One qualitative prediction of Standard Model-only astrophysics is the existence of a "black hole mass gap" formed from these objects at a characteristic mass scale slightly below 50 $M_\odot$ (Farmer et al., 2019; Mehta et al., 2022). New particle emission, gravitational trapping of dark matter, or dark matter coevolution all could change this mass scale (Croon et al., 2020a, 2021a; Sakstein et al., 2020; Ziegler and Freese, 2021; Baxter et al., 2021; Ellis, 2021). Theory frontier activities in the stellar domain promise to illuminate new, weakly-coupled particles that are not probed by other mechanisms (Dolan et al., 2021).

A different route by which dark matter could impact a "long-term" observable of compact objects is via the formation of a super-radiant cloud that extracts angular momentum from a central black hole (Dicke, 1954; Penrose and Floyd, 1971; Zel'Dovich, 1971; Misner, 1972; Starobinsky, 1973). For a sufficiently low-mass dark matter particle, this could lead to detectable changes in the observed black hole spin distribution (Ikeda et al., 2019; Cardoso et al., 2004; Arvanitaki et al., 2010; Bredberg et al., 2010; Cardoso and Pani, 2013; Herdeiro et al., 2013; East et al., 2014; Degollado and Herdeiro, 2014; Brito et al., 2014; Arvanitaki et al., 2015; Rosa, 2015; Cardoso et al., 2015; Wang and Herdeiro, 2016; Brito et al., 2015; Endlich and Penco, 2017; Rosa, 2017; Baryakhtar et al., 2017b; East and Pretorius, 2017; Cardoso et al., 2017; Rosa and Kephart, 2018; Frolov et al., 2018; Sen, 2018; Cardoso et al., 2018; Barack et al., 2019; Degollado et al., 2018; Ficarra et al., 2019; Baumann et al., 2019; Cardoso et al., 2020; Dima and Barausse, 2020; Brito et al., 2020; Stott, 2020; Blas and Witte, 2020b; Mehta et al., 2020; Baryakhtar et al., 2021; Ünal et al., 2021; Franzin et al., 2021; Caputo et al., 2021; Mehta et al., 2021; Cannizzaro et al., 2021; Jiang et al., 2021a; Karmakar and Maity, 2021; Khodadi and Pourkhodabakhshi, 2021). Future theoretical explorations will lead to a more comprehensive understanding of the impacts of backreaction of the superradiance on the conditions necessary to support the superradiant instability.

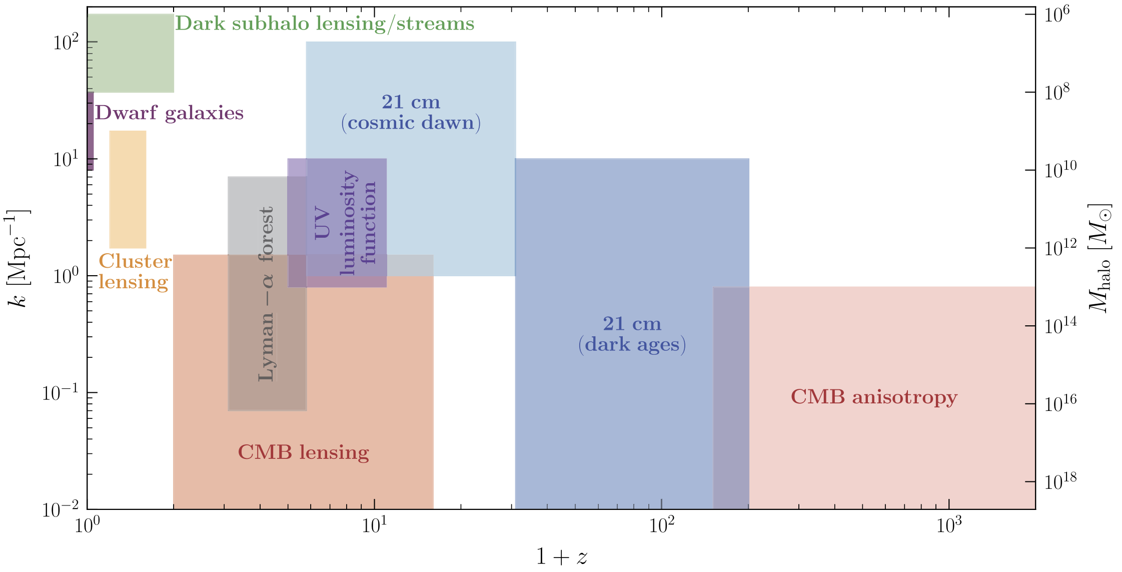


Fig. 3. Schematic representation of the coverage of current and future probes of dark matter physics across various ranges of redshift z (i.e., eras that observable photons or signals primarily originate from), wave number k, and the corresponding halo mass $M_{\rm halo}$. The ranges of individual probes are approximate. Note that some of the listed probes are well-established observationally, while some are still in nascent phases of observational development, but they all represent complementary probes of dark matter. We do not include probes that only affect background evolution and thus do not have an associated scale k to display in this figure. Similar figures can be found in (e.g. Buckley and Peter, 2018; Gluscevic et al., 2019; Sabti et al., 2021).

3. Dark matter origins and structure formation

Traditional methods of dark matter indirect detection are centered around the idea of detecting the Standard Model byproducts of dark matter interactions within astrophysical systems. New dark matter physics can also be indirectly observed through its impact in the early Universe and on the subsequent formation and evolution of collapsed structures of matter (see Fig. 3). Using such detection methods can cover regions of dark matter parameter space that are complementary to regions probed by traditional methods. Crucially, gravitational indirect detection is necessary to probe certain classes of dark matter theories that require the extreme conditions of the early Universe or dark sector theories that have rich phenomenology but do not couple to known physics except through gravity. In this section, we explore the theoretical progress made in this area, often going hand-in-hand with advancements in numerical simulations, and discuss the importance of continued theory efforts to take full advantage of the influx of cosmological and astrophysical data expected over the next decade.

3.1. Early-Universe evolution

The present-day abundance of dark matter may have been established after a period in which dark matter particles were in thermal and chemical equilibrium with some larger thermal reservoir, or it may have been established despite never attaining thermal equilibrium with its environment. The former case, which we refer to as "thermal" dark matter, whether that thermal equilibrium is attained with the Standard Model itself or with a secluded thermal bath, is commonly considered to be UV-insensitive: the initial conditions of the dark matter abundance will be erased by the thermal equilibrium condition. The latter case of "non-thermal" dark matter leads to a large number of observables that can potentially persist from the earliest moments of dark matter genesis.

One exception to the rule that thermal dark matter is insensitive to early-Universe microphysics could be if the dark sector underwent a first-order phase transition. This could generate a gravitational wave signal (e.g. Schwaller, 2015; Croon et al., 2018; Breitbach et al., 2019; Fairbairn et al., 2019; Bertone et al., 2020), which would remain thermally decoupled, even if dark matter particles were in thermal equilibrium. In fact, the occurrence of the first-order phase transition requires the dark sector to be at least self-formalized. The most widely studied example of this kind is a dark sector Higgs mechanism, resulting in a phase transition that can be first order if the sector contains a number of bosonic degrees of freedom (Croon et al., 2018). Dark sector confinement may also lead to the generation of a gravitational wave signal, if the global symmetry is large enough at the time of breaking (e.g. Bai et al., 2019b; Helmboldt et al., 2019; Croon et al., 2019; Reichert et al., 2022). Such scenarios have been studied in the context of axion models (Croon et al., 2019) and bound state formation such as dark quark nuggets (Bai et al., 2019b). Theoretical progress is necessary before the gravitational wave phenomenology of first-order phase transitions can be studied reliably: it has been demonstrated that even in perturbative models, two-loop thermal effects must be included to achieve better than $O(1)$ numerical accuracy (Kainulainen et al., 2019; Croon et al., 2021b; Gould and Tenkanen, 2021). Estimations of the gravitational wave spectrum in non-perturbative hidden sector models have used low- or high-energy effective field theories (see (Helmboldt et al., 2019) for a comparison), but their validity breaks down in the vicinity of the phase transition. Future theory frontier efforts will be critical in understanding this break down and extending the range of reliable predictions for models of new physics.

Non-thermal dark matter may produce gravitational wave signals, but more generally leads to a multitude of other tests of early-Universe physics. For instance, the evolution of the post-inflationary axion can result in an abundance of axion miniclusters (Kolb and Tkachev, 1994a; Zurek et al., 2007; Kolb and Tkachev, 1994b; Hardy, 2017; Davidson and Schwetz, 2016; Enander et al., 2017), which can potentially be discovered with dedicated search strategies (Kolb and Tkachev, 1996; Tkachev, 2015; Pshirkov, 2017; Fairbairn et al., 2018; Katz et al., 2018; Dai and Miralda-Escudé, 2020a; Croon et al., 2020b; Edwards et al., 2021b). Accurate predictions for the spectrum and abundance of such miniclusters require early-Universe simulations of the post-inflationary axion, which are inherently difficult to perform due to a separation of scales and large systematic uncertainties. Therefore, additional large-scale simulations and systematic tests are needed in the future to improve results.

Lastly, we note that the abundances of thermal and non-thermal dark matter are both affected by the evolution of the Universe between the end of inflation and the onset of Big Bang nucleosysthesis (BBN), and we cannot assume that the Universe was radiation dominated throughout this period (Kawasaki et al., 1999, 2000; Allahverdi et al., 2020). If dark matter chemically decouples while the Universe is not radiation dominated, the larger Hubble rate at a given temperature causes an earlier freeze-out and an enhanced relic abundance (Kamionkowski and Turner, 1990; Profumo and Ullio, 2003; Pallis, 2005; D'Eramo et al., 2017; Redmond and Erickcek, 2017). If the subsequent transition to radiation domination involves the creation of new Standard Matter particles, as occurs after an early matter-dominated era, then the relic abundance of dark matter is diluted (Kamionkowski and Turner, 1990; Giudice et al., 2001; Gelmini and Gondolo, 2006; Kane et al., 2016; Drees and Hajkarim, 2018). An early matter-dominated era also enhances dark matter density perturbations on scales that enter the horizon prior to the onset of the final radiation-dominated epoch (Erickcek and Sigurdson, 2011). Significant progress has been made in understanding the impact this has on the abundance of sub-Earth-mass microhalos (Erickcek and Sigurdson, 2011; Erickcek, 2015) and how the minimum halo mass depends on the properties of dark matter (Fan et al., 2014; Gelmini and Gondolo, 2008; Erickcek et al., 2016; Waldstein et al., 2017), as well as the properties of the particle responsible for the early matter-dominated era (Blanco et al., 2019; Erickcek et al., 2021, 2022; Barenboim et al., 2021). These microhalos provide a new observational probe of the early Universe; their impact on the dark matter annihilation rate can be constrained using the isotropic gamma-ray background (Erickcek et al., 2016; Blanco et al., 2019; Delos et al., 2019), and they can be detected gravitationally using pulsar timing arrays (Dror et al., 2019; Ramani et al., 2020; Lee et al., 2021; Delos and Linden, 2021) and observations of stellar microlensing events in galaxy clusters (Dai and Miralda-Escudé, 2020b; Blinov et al., 2021). Further study is needed to understand whether the CMB and the 21 cm background could further constrain dark matter annihilation in early-forming microhalos.

3.2. Early-Universe structure formation

The standard cosmological model of ΛCDM describes the large-scale structure of the Universe extremely well. The presence of CDM is crucial through its contribution to the overall energy density and through its density perturbations at early times. Comprising about 84% of the matter content in the Universe (Planck Collaboration et al., 2020b), the gravitational influence of dark matter is key in the formation of structure. Thus, cosmological observations provide important and unique insight into new dark matter physics that disturb the predictions of CDM.

Light degrees of freedom: A wide variety of dark matter models introduce new light degrees of freedom in the Universe at early times. In particular, dark sectors may contain light or massless force carriers, such as dark photons, that thermalize dark matter at a temperature that generally differs from the Standard Model bath. The introduction of new relativistic species alters the expansion rate of the Universe during radiation domination, in turn affecting CMB anisotropies (e.g. Brust et al., 2013) and predictions of the abundances of light elements created during BBN (e.g. Kawasaki et al., 2005; Iocco et al., 2009; Pospelov and Pradler, 2010). Standard contributions to the energy density of radiation during the BBN and CMB eras include photons and neutrinos, assuming their masses are not too large; however, neutrinos decouple from the photon bath at temperatures ~ 1 MeV, and their energy density contribution is encoded in the parameter $N_{\rm eff}$. For the three active neutrinos of the Standard Model, recent calculations yield $N_{\rm eff}^{\rm SM} = 3.044$ (de Salas and Pastor, 2016; Akita and Yamaguchi, 2020; Bennett et al., 2021; Froustey et al., 2020), and deviations $\Delta N_{\rm eff} \equiv N_{\rm eff} - N_{\rm eff}^{\rm SM}$ from this value could imply the existence of non-standard physics. Current CMB and BBN observations constrain $N_{\rm eff}$ to be close to its Standard Model value (e.g. Planck Collaboration et al., 2020b); therefore, in order to incorporate new massless species in a cosmological model, the dark sector temperature has to be lower than that of the photon bath to avoid contributing too much to the relativistic energy budget.

Thermal dark matter itself can contribute to the relativistic energy density during BBN if its mass is $\lesssim 20$ MeV. Additionally, if the dark matter relic abundance is set through a standard freeze-out process, dark matter may annihilate into neutrinos or visible particles, which in turn alter weak interaction rates that determine primordial abundances. Dark matter coupled to neutrinos or charged particles generates a positive or negative contribution, respectively, to $N_{\rm eff}$. Thus, cosmological observations can provide robust bounds on the mass of dark matter, for a given spin and annihilation channel (Boehm et al., 2013; Nollett and Steigman, 2015,?; Steigman and Nollett, 2014; Escudero, 2019; Giovanetti et al., 2021; An et al., 2022). In the future, CMB-S4 will obtain a sensitivity to new thermalized, light relics corresponding to $\Delta N_{\rm eff} < 0.06$ at 2σ (Abazajian et al., 2019). Dedicated theory work will be needed to understand the implications of CMB and BBN constraints across a variety of dark sector models.

CMB spectral distortions: Measurements of the CMB energy spectrum provide an opportunity to search for new physics that impacts the thermal history of the Universe. Deviations of the CMB spectrum from a perfect blackbody, referred to as spectral distortions, are sensitive to processes that inject energy into (or extract energy from) the photon-baryon plasma at redshifts $z \lesssim 2 \times 10^6$. Current measurements of the CMB spectrum show that it is extremely close to a blackbody with a present-day temperature $T_0 = 2.72548 \pm 0.00057$ K (Fixsen et al., 1996; Fixsen, 2009), with spectral distortions smaller than a few parts in 10^5 (Fixsen et al., 1996). Proposed experimental concepts could probe spectral distortions at least three orders of magnitude smaller (Kogut et al., 2011), thus opening new windows into exotic physics in the early Universe. Several known processes within the standard ΛCDM cosmological model generate spectral distortions (Chluba, 2016). In addition, spectral distortions may be generated through dark matter interactions with Standard Model particles.

Dark matter annihilating or decaying into photons or electrically charged particles would inject energy into the photon-baryon plasma, hence distorting the CMB energy spectrum (McDonald et al., 2000). CMB anisotropies are significantly more sensitive to s-wave annihilations than spectral distortions (McDonald et al., 2000); however, spectral distortions could be more sensitive to p-wave annihilations (Ali-Haïmoud, 2021), depending on the specifics of the dark matter model. In addition, spectral distortions can constrain decaying particles with lifetimes 10^6 sec $\lesssim \tau \lesssim 10^{12}$ sec, to which CMB anisotropies are insensitive. For such short lifetimes, the decaying particle could only comprise a small fraction of the total dark matter abundance (Bolliet et al., 2021).

Alternatively, dark matter particles may *extract* energy from the photon-baryon plasma if they scatter elastically with photons, electrons, or nuclei (Ali-Haïmoud, 2021; Ali-Haïmoud et al., 2015). Indeed, if dark matter is heavier than ~ 1 keV, it is non-relativistic by $z \sim 2 \times 10^6$ and therefore cools down adiabatically faster than the thermalized photon-baryon plasma. Elastic scattering would therefore lead to a systematic transfer of heat from the plasma to the dark matter fluid. This effect is increasingly large for light, thus more abundant, dark matter particles. While current spectral distortion limits only constrain elastically-scattering dark matter particles with masses $m_\chi \lesssim 100$ keV, proposed experiments could extend this sensitivity to $\sim$ GeV masses. Continued theoretical work is needed to ensure robust predictions (e.g. Ali-Haïmoud, 2019).

CMB anisotropies and dark matter annihilation/decay: Dark matter annihilation or decay via electromagnetic channels injects energy into the photon-baryon plasma, which increases the free-electron fraction x_e around and after cosmological recombination at $z \lesssim 1100$. The increase in x_e delays the last scattering epoch and affects the photon diffusion scale (and hence the damping of CMB anisotropies at small scales). Additionally, an increased x_e in the low-redshift tail of recombination suppresses CMB anisotropies on small scales and increases large-scale polarization fluctuations, an effect qualitatively similar to an increase in the reionization optical depth (Green et al., 2019).

Through these effects, CMB anisotropies are sensitive to very rare dark matter annihilation or decay processes (Slatyer, 2016; Chen and Kamionkowski, 2004), since as little energy as ~ 1 eV per baryon suffices to significantly alter the ionization history. In particular, even for dark matter produced in a standard freeze-out scenario, residual annihilation at $z \lesssim 1100$ may have a significant impact on CMB anisotropies, long after they no longer change the dark matter abundance. *Planck* data constrain the dark matter s-wave annihilation cross section to $\langle \sigma v \rangle \lesssim 3 \times 10^{-28} (m_\chi/\mathrm{GeV})$, ruling out a standard freeze-out production of dark matter for $m_\chi \lesssim 10$ GeV (Planck Collaboration et al., 2020a). *Planck* data also constrain the lifetime of decaying dark matter to $\tau \gtrsim 10^{24}$–10^{25} sec, depending on the decay channel (Slatyer and Wu, 2017; Poulin et al., 2017a), orders of magnitude larger than the age of the Universe. Near-future and planned CMB-anisotropy missions could achieve a factor of ~ 30 improvement in the sensitivity over current *Planck* limits on dark matter annihilation and decay (Cang et al., 2020).

More exotic dark matter candidates, such as PHBs, can be probed by CMB anisotropies through similar effects. PBHs can inject energy in the photon-baryon plasma through either Hawking radiation for masses $M \lesssim 10^{17}$ g (Poulin et al., 2017a) or accretion-powered radiation for masses $M \gtrsim M_\odot$ (Ricotti et al., 2008; Ali-Haïmoud and Kamionkowski, 2017; Poulin et al., 2017b). In contrast with the rather clean and well-understood physics involved in dark matter annihilation or decay (Slatyer, 2016; Liu et al., 2020b), the complex physics of accretion is highly uncertain and much theory work remains to be done to make existing limits more robust.

While the effects described above arise from changes to the *average* free-electron fraction, inhomogeneous energy injection from dark matter would also lead to spatial fluctuations in x_e (Dvorkin et al., 2013; Jensen and Ali-Haïmoud, 2021). These fluctuations would induce non-Gaussianities in CMB anisotropies, which could be a complementary avenue to probe energy injection from dark matter.

CMB anisotropies and dark matter scattering: Elastic scattering between dark matter and Standard Model particles in the early Universe can alter the evolution of perturbations, impacting CMB temperature, polarization, and lensing anisotropies. Scattering processes heat the dark matter fluid and induce a drag force from the exchange of momentum. The primary effect of the scattering is inhibiting the clustering capabilities of dark matter, thus washing out structure on a variety of observable scales. As a result, the CMB power spectra experience damping at large multipoles ℓ, corresponding to small angular scales on the sky, for models where dark matter decouples from baryons prior to matter-radiation equality (Chen et al., 2002; Dvorkin et al., 2014; Gluscevic and Boddy, 2018; Boddy and Gluscevic, 2018; Xu et al., 2018; Slatyer and Wu, 2018; Boddy et al., 2018). For models such as millicharged dark matter, scattering takes place at later times, and CMB anisotropy currently provides some of the best observational bounds on such models (e.g. Boddy and Gluscevic, 2018; Kovetz et al., 2018; Dvorkin et al., 2021). The theoretical developments and numerical implementation into Boltzmann codes, such as `CAMB` and `CLASS`, have enabled CMB searches of dark matter scattering with baryons (Chen et al., 2002; Dvorkin et al., 2014; Gluscevic and Boddy, 2018; Boddy and Gluscevic, 2018; Xu et al., 2018; Slatyer and Wu, 2018; Boddy et al., 2018), electrons (Nguyen et al., 2021; Buen-Abad et al., 2021b), photons (Boehm et al., 2002; Wilkinson et al., 2014a; Stadler and Bœhm, 2018), and neutrinos (Wilkinson et al., 2014b; Olivares-Del Campo et al., 2018). The strength of the interaction is a key parameter that controls the amount of power suppression in the CMB primary anisotropy, but including an energy or velocity dependence of the interaction influences the shape of the suppression, potentially allowing a way to distinguish between various scattering models. Even in the case of dark sectors, dark matter scattering with dark radiation (Cyr-Racine et al., 2016; Archidiacono et al., 2017, 2019) produces features in the CMB power spectra that can be differentiated from other models (Becker et al., 2021). Changing N_{eff} can have a similar effect of suppressing the CMB damping tail, but possible degeneracies can be broken using CMB lensing anisotropies (Li et al., 2018).

Upcoming ground-based instruments, such as the Simons Observatory (Simons Observatory Collaboration et al., 2019) and CMB-S4 (Abazajian et al., 2019), will measure the CMB with better precision at high ℓ and a much higher angular resolution than current experiments, allowing for greater sensitivity to dark matter interactions. In terms of theoretical development, most investigations have focused on thermal relic models, while future investigations of models where dark matter is produced non-thermally will also be of high interest in context of CMB probes. Furthermore, there is a notable synergy between the CMB primary anisotropy and other probes of the structure growth in the Universe, which can be further exploited in self-consistent analyses of CMB with other observables, for specific dark matter models.

21-cm line at high redshifts: The redshifted 21-cm line of neutral hydrogen presents a unique probe of the post-recombination Universe, prior to the birth of the first stars (cosmic dark ages, $z = 30$–100) and right after it (cosmic dawn, $z = 5$–30)—see (e.g. Furlanetto et al., 2006; Pritchard and Loeb, 2012) for reviews. The corresponding absorption signal imprinted on the CMB backlight during cosmic dawn (Hirata, 2006) captures the state of hydrogen gas and various microphysical processes that control it at this early epoch; mapping the absorption signal provides a (3D) view of the Universe at epochs that no other probes can reach. Many dark matter processes can affect the temperature of baryons during cosmic dawn, in turn affecting the 21-cm signal. The experiments targeting this era can use this connection to probe dark matter interactions with the visible sector.

A well-motivated model that can affect the 21-cm signal involves dark matter scattering with baryons through a light mediator (Slatyer and Wu, 2018; Kovetz et al., 2018; Tashiro et al., 2014; Muñoz et al., 2015; Muñoz and Loeb, 2018; Berlin et al., 2018; Barkana et al., 2018; Muñoz et al., 2018; Liu et al., 2019). For millicharged dark matter, current 21-cm measurements (e.g., from EDGES in the global signal (Bowman et al., 2018) or HERA for fluctuations (HERA Collaboration et al., 2022)) exclude millicharges as low as $q_\chi \sim 10^{-6} e$ (Muñoz and Loeb, 2018) (where e is the electron charge), even if less than a percent of dark matter is millicharged. Alternatively, models of dark photons that kinetically mix with Standard Model photons, with mixing parameter $\epsilon \sim 10^{-7}$ (Pospelov et al., 2018), can create a radio background that affects the 21-cm signal (Pospelov et al., 2018; Ewall-Wice et al., 2018; Fraser et al., 2018). Additionally, a classical WIMP, for instance, can heat gas through annihilations (Lopez-Honorez et al., 2016; Liu and Slatyer, 2018), and similar effects occur in case of decaying dark matter and dark-photon dark matter (Evoli et al., 2014; Kovetz et al., 2019); each in turn can affect the thermal properties of baryons during cosmic dawn. Even more exotic models, such as evaporating or accreting PBHs, can produce heating (Ali-Haïmoud et al., 2017; Clark et al., 2018).

The 21-cm signal during cosmic dawn is sensitive to structure formation because the first galaxies emit photons that produce Wouthuysen-Field coupling (Hirata, 2006), critical for the 21-cm absorption feature to arise. Those first galaxies were hosted in halos with masses $\sim 10^6\, M_\odot$ (Tegmark et al., 1997; Abel et al., 2002; Mirocha et al., 2015; Muñoz et al., 2021a), which correspond to fluctuations with wavenumbers as large as $k \approx 100$–$200\,\mathrm{Mpc}^{-1}$. As a consequence, altering the corresponding scales in the linear matter power spectrum affects the abundance of the first galaxies and the timing of the 21-cm signal (Muñoz et al., 2020). Small scales are often very sensitive to dark matter microphysics and can be used to probe warm dark matter and other beyond–CDM models.

While there are claims that the global (sky-averaged) signal has already been detected (Bowman et al., 2018), the tomographic signal is yet to be measured (HERA Collaboration et al., 2022) from interferometers such as HERA (DeBoer et al., 2017), LOFAR, MWA, or SKA (Mellema et al., 2013). However, it is expected that these observatories can yield constraints on the matter power spectrum up to $k = 100\,\mathrm{Mpc}^{-1}$ at the $\sim 10\%$ level (Muñoz et al., 2020), which can place powerful constraints on specific dark matter candidates such as ETHOS models (Muñoz et al., 2021b), warm dark matter (Sitwell et al., 2014), or fuzzy dark matter (Jones et al., 2021).

High-redshift galaxy luminosity function: The luminosity function (i.e., counting the number of galaxies versus their luminosity) provides a tracer of the abundance of dark matter halos at the redshifts of measurement. UV luminosity functions are constructed from the HST Ultra Deep Fields (HUDF), where the UV light from the most massive galaxies at $z = 4$–10 is detected by the visible/IR filters at the HST (Finkelstein et al., 2015; Bouwens et al., 2015). JWST observations will significantly contribute to constraining the population of early galaxies in the coming decade. There measurements can be used to determine the matter power spectrum during reionization up to $k = 10\,\mathrm{Mpc}^{-1}$ (Sabti et al., 2021, 2022; Yoshiura et al., 2020) and can provide probes of warm dark matter (Schultz et al., 2014; Dayal et al., 2015; Menci et al., 2017; Rudakovskyi et al., 2021), fuzzy dark matter (Bozek et al., 2015; Corasaniti et al., 2017), and ETHOS models (Lovell et al., 2018).

Lyman-α forest: The clustering of matter at intermediate redshifts traced by the redshifted forest of Lyman-α absorption lines is a sensitive probe of dark matter physics. Several authors have forward-modeled the Lyman-α forest to place lower limits on the thermal relic warm dark matter mass of $\mathcal{O}(3$–$5)$ keV (Viel et al., 2013; Baur et al., 2016; Iršič et al., 2017; Palanque-Delabrouille et al., 2020), where the details of the constraints depend on astrophysical assumptions about the temperature, density, and redshift evolution of baryons in the intergalactic medium (Garzilli et al., 2017, 2019). Other dark matter models such as those with dark matter–baryon interactions, ultra-light axions, and PBHs have also been constrained using similar methods (Kobayashi et al., 2017; Murgia et al., 2019; Rogers and Peiris, 2021a; Rogers et al., 2021), although there are dark matter-related modeling challenges in some cases (e.g. Zhang et al., 2018a). From a theoretical standpoint, the development of Lyman-α forest emulators (e.g. Rogers and Peiris, 2021b) has contributed to recent advances and will become increasingly important to enable robust, joint inference of cosmological, astrophysical, and dark matter physics in the coming decade. From an observational standpoint, dark matter analyses have generally been performed using ~ 10 s of high-resolution spectra (e.g., VLT, HIRES/KECK; (Viel et al., 2013)), ~ 100 s of intermediate-resolution spectra (e.g., XQ-100; (Iršič et al., 2017)), or ~ 1000 s of low-resolution spectra (e.g., SDSS/BOSS; (Palanque-Delabrouille et al., 2020)). Ongoing spectroscopic surveys including DESI will significantly enhance the number and redshift coverage of available high-resolution quasar spectra, potentially allowing for percent-level measurements of the Lyman-α flux power spectrum on small scales (Karaçaylı et al., 2020).

3.3. Present-day structure

Probes of small-scale structure at low redshifts have recently emerged as a key means to test a variety of dark matter properties, including its production mechanism, primordial temperature, self- and Standard Model-interactions, and minimum particle mass. These probes can broadly be categorized according to whether they rely on observations of the baryonic contents of low-mass halos or not. Here, we summarize the current status and future prospects for each of these probes, along with key theoretical considerations. In particular, we emphasize that connecting theoretically motivated predictions for dark matter's gravitational imprints to precise analytic and simulation-based predictions for small-scale structure distributions is a critical area for work over the next decade.

Massive galaxy clusters provide a unique opportunity to stringently test the CDM paradigm of structure formation. Combining strong and weak gravitational lensing detected in high-resolution images of massive clusters has revealed that the dark matter subhalos of cluster galaxies are less massive and less spatially extended compared to those hosting equivalent luminosity field galaxies, indicating that tidal stripping of dark matter is efficient in these dense, violent environments—see review by (Kneib and Natarajan, 2011) and, for a critical analysis of the range of lens modeling methodologies, see (Meneghetti et al., 2017) and (Niemiec et al., 2020) for recent developments. Comparison of the derived subhalo mass function from observed cluster lenses with CDM simulations has revealed that while the abundance and mass function of substructures was well reproduced, the radial distribution of subhalos was discrepant (Natarajan et al., 2017). Subhalos are more concentrated in the inner regions of observed clusters than predicted by CDM simulations.

A recent study of Galaxy-Galaxy Strong Lensing (GGSL) in clusters found that observed small-scale cluster substructures (on $\sim$ 5–10 kpc scales) are more efficient strong lenses than predicted by CDM simulations by more than an order of magnitude (Meneghetti et al., 2020). Further theoretical investigation will be needed to evaluate if this large discrepancy arises from hitherto undiagnosed systematic issues within simulations, or if in fact this serves as a hint for deviations from the CDM paradigm. Numerical effects arising from the resolution limits of simulations that lead to artificial subhalo disruption (van den Bosch et al., 2018) cannot account for the order of magnitude GGSL gap, as they are at most a 20% effect (Green et al., 2021). Importantly, baryonic feedback processes must be carefully investigated as a potential culprit for the discrepancy, as it is well understood that they alter the internal structure of cluster galaxies. This motivates a comparison of simulated galaxy clusters across several independent CDM simulations.

The GGSL discrepancy could potentially be revealing that dark matter might not be collisionless, especially in the extremely dense cluster environments. For elastic self-interactions that are velocity dependent (with large interaction cross sections), halos can undergo gravo-thermal collapse just as stellar systems. When this occurs, the inner halo develops a negative heat capacity due to outward transfer of energy (Balberg et al., 2002), resulting in a significant enhancement of the concentration of the inner density profile—precisely in the direction needed to address the GGSL discrepancy (Yang and Yu, 2021). The transformation produced by core-collapse motivates the investigation of this particular class of self-interacting models more deeply. Moreover, totally inelastic self-interactions can result in a collapse time-scale up to two orders of magnitude shorter than for the elastic case (Huo et al., 2020), for smaller interaction cross sections. Further theoretical study is needed to map out the space of self-interacting dark matter models that can potentially account for the GGSL discrepancy.

Dwarf galaxies are the smallest dark matter-dominated baryonic systems in the Universe and form in halos with $M_{\rm halo} \lesssim 10^{10}\ M_\odot$, down to the galaxy formation threshold of $M_{\rm halo} \sim 10^8\ M_\odot$ (Jethwa et al., 2018; Nadler et al., 2020). Thus, the smallest "ultra-faint" dwarf galaxies (Simon, 2019) are a particularly sensitive probe of low-mass halo abundances, which reflect dark matter's small-scale gravitational clustering. To date, ultra-faints have exclusively been detected within the virial radius of the Milky Way as satellite galaxies; recent wide-field photometric surveys, including the Sloan Digital Sky Survey, Pan-STARRS1, and the Dark Energy Survey, have increased the number of known Milky Way satellites to roughly 60 systems (see (Drlica-Wagner et al., 2020) for a recent census of the Milky Way satellite population). These observations have been used to constrain the warm dark matter particle mass at the level of 6.5 keV, the particle mass of fuzzy dark matter at the level of 2.9×10^{-21} eV, and the dark matter–proton interaction cross section at the level of 10^{-29} cm^2 (Nadler et al., 2021) (also see (Jethwa et al., 2018; Kim et al., 2018; Newton et al., 2021; Dekker et al., 2021; Nadler et al., 2019; Maamari et al., 2021)). Over the next decade, observational facilities, including the Vera C. Rubin Observatory and the Nancy Grace Roman Space Telescope, are expected to significantly improve upon current dwarf galaxy discovery power, both within and well beyond the virial radius of the Milky Way (e.g. Mutlu-Pakdil et al., 2021; Drlica-Wagner et al., 2019). With these upcoming improvements, continued theoretical developments are key to properly interpreting possible deviations of halo abundances from the CDM expectation.

In addition to their mass abundances, the individual properties and population statistics of dwarf galaxies are also sensitive to dark matter microphysics. For example, dark matter self-interactions can both suppress the inner densities of halos in a mass-dependent fashion (Vogelsberger et al., 2012; Zavala et al., 2013; Rocha et al., 2013; Peter et al., 2013; Kaplinghat et al., 2014) and eventually drive these systems towards gravothermal core collapse (Balberg et al., 2002; Koda and Shapiro, 2011; Elbert et al., 2015; Essig et al., 2019; Nishikawa et al., 2020; Kahlhoefer et al., 2019; Sameie et al., 2020; Turner et al., 2020; Zeng et al., 2021). These effects provide a mechanism for explaining the observed diversity of galactic rotation curves (Kamada et al., 2017; Creasey et al., 2017; Ren et al., 2019; Kaplinghat et al., 2020), although current observations are not yet sufficient to distinguish this scenario from feedback-affected CDM halos (Zentner et al., 2022). Conservative constraints based on the observed innermost densities of dwarf galaxies such as Draco (e.g. Read et al., 2018), coupled with constraints from galaxy clusters (e.g. Sagunski et al., 2021), demonstrate that self-interacting dark matter models with velocity-dependent interactions must undergo some degree of gravothermal collapse (Jiang et al., 2021b). This observation may provide a mechanism to explain observations suggesting that the most centrally-dense Milky Way dwarfs also have the smallest orbital pericenters (Kaplinghat et al., 2019). Improved theoretical modeling of dwarf properties and populations will be needed to harness the full potential of current and upcoming surveys that are amassing information on dwarf galaxies of Milky Way-like systems (Carlsten et al., 2020; Mao et al., 2021), as well as improved stellar kinematic data on the Milky Way's dwarfs from observatories like *Gaia* (Fritz et al., 2018).

Strong gravitational lensing allows us to detect low-mass halos within lens galaxies and along the line of sight via their effect on the observed multiple images of a background source. This process is purely gravitational and independent of whether these low-mass halos contain any baryons. It thus provides a unique approach to test dark matter models by probing the low-mass end of the halo and subhalo mass functions beyond the local Universe. The detection of low-mass halos with strongly lensed quasars is mainly based on so-called flux ratio anomalies—that is, changes induced to the relative flux of the multiple images (e.g. Mao and Schneider, 1998; Dalal and Kochanek, 2002; Nierenberg et al., 2017). In images of strongly lensed galaxies, a local change of the surface brightness distribution of the data, reflecting a change in the relative position of the images, is the tell-tale signature of the presence of low-mass halos (e.g. Koopmans, 2005; Vegetti and Koopmans, 2009; Vegetti et al., 2012; Hezaveh et al., 2016; Despali et al., 2018). This method is often referred to as the gravitational imaging technique.

Flux ratio anomalies and the gravitational imaging technique are complementary approaches that are subject to individual and shared sources of systematic errors (Hsueh et al., 2020; Enzi et al., 2021). The two techniques can also differ in their sensitivity to low-mass haloes. Depending on the size of the background source, flux ratio anomalies typically probe the halo and subhalo mass functions down to masses as low as $\sim 10^7\ M_\odot$ and potentially below. The number of available lens systems and the precision of the flux measurement then set the precision with which one can constrain the halo and subhalo mass functions (Gilman et al., 2019). For example, (Gilman et al., 2020) and (Hsueh et al., 2020) constrain the warm dark matter particle mass at 5.2 (5.5) keV at the 95% confidence level using eight (seven) quadruply imaged quasars.

The sensitivity to low-mass halos reached by the gravitational imaging technique is highly dependent on the angular resolution of the observations (Despali et al., 2022). At present, only a handful of systems for which Very Long Baseline Interferometry observations are available can probe the halo mass function down to $\sim 10^6\ M_\odot$ (McKean et al., 2015). From a sample of 20 HST-observed galaxy-galaxy lensed systems (sensitivity $\sim 10^{10} M_\odot$), (Enzi et al., 2021) infer a limit on the warm dark matter particle mass of 1.02 keV using both detections (Vegetti et al., 2010) and non-detections (Vegetti et al., 2014; Ritondale et al., 2019).

At present, the relatively low number of gravitational lens systems with high-enough data quality significantly limits the constraints on dark matter from both flux-ratio anomalies and the gravitational imaging technique. Luckily, ongoing and future surveys with instruments such as Euclid, the Vera Rubin, and SKA will increase the number of known gravitational lens systems by several orders of magnitudes (Oguri and Marshall, 2010; Collett, 2015; Weiner et al., 2020). This data, coupled with follow-up observations with, e.g., the ELT, TMT, and JWST, is projected to deliver tight constraints on the halo and subhalo mass function (Gilman et al., 2019; He et al., 2022).

Stellar streams are the tidally disrupted remnants of dwarf galaxies and globular clusters. Recently, the combination of astrometric, photometric, and spectroscopic observations has led to the discovery of a plethora of new streams orbiting the Milky Way (Shipp et al., 2018; Ibata et al., 2019; Li et al., 2021b) and intriguing structure in the density profiles of nearby streams like

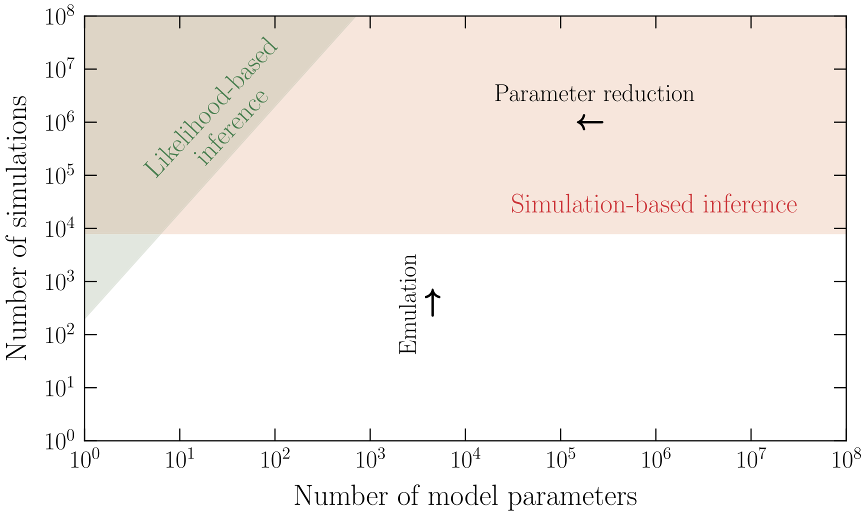


Fig. 4. Simplified comparison of likelihood-based and simulation-based algorithms in the space of number of required/affordable simulations vs. number of model parameters (including parameters of interests, uncertain parameters, and random states of the simulator). In general, the simulation requirements of likelihood-based techniques grow significantly with the number of model parameters. Instead, simulation-based inference techniques can—in principle—directly focus on estimating marginal posteriors for parameters of interest, independently of the total number of parameters. This reduces the need for parameter reduction techniques and enables the comparison of complex simulation results with complex data.

GD-1 (Price-Whelan and Bonaca, 2018) and ATLAS–Aliqa Uma (Li et al., 2021c). These substructured streams—and particularly the gaps in stream density profiles and other unexpected, off-stream features—have been modeled to place constraints on the properties of individual perturbers and candidate dark matter subhalos that may have gravitationally perturbed these streams (Bonaca et al., 2019), as well as the population statistics of subhalo perturbers in cold and warm dark matter contexts (Banik et al., 2021a,b). Deeper photometric measurements from upcoming facilities will continue to increase the population of known streams and reveal their fine-grained density structure, with potential sensitivity to subhalos as small as $\sim 10^6\ M_\odot$, regardless of their baryonic content (Drlica-Wagner et al., 2019; Banik et al., 2018).

4. Machine learning and statistics

Over the next decade, astrophysical data relevant for the study of the nature of dark matter will increase not only in volume, but also in complexity and detail. Upcoming gamma-ray and radio observatories like the Cherenkov Telescope Array (CTA) (CTA Consortium Collaboration et al., 2018) and the Square Kilometer Array (SKA) (Carilli and Rawlings, 2004; Braun et al., 2015) will produce petabytes of data (Alves Batista et al., 2016). Fully exploiting this data for scientific purposes will require increasingly detailed and complex physical models, which bring along higher computational costs for simulations, as well as a larger number of uncertain parameters, including those characterizing signal and background systematics. Established algorithms for parameter inference, like Markov Chain Monte Carlo (MCMC), nested sampling (Skilling, 2004; Handley et al., 2015), and Approximate Bayesian Computation (ABC) often requires a very large number of simulation runs, which often grow significantly as the number of model parameters increases; see Fig. 4 for an illustration. In many settings, it becomes impractical to compare physical models in their full complexity and detail with the data. As a result, analyses are often limited by the inference tools rather than statistics (Alves Batista et al., 2021; Trotta, 2017). Modern statistical algorithms based on deep learning and differentiable programming techniques can overcome the limitations of established techniques. Recent reviews can be found in Alves Batista et al. (2021); Algeri et al. (2018); Feigelson et al. (2021), and we will provide a brief overview of promising techniques and suggest necessary developments here.

Scalable inference techniques: Stochastic variational inference (SVI) (Hoffman et al., 2013; Zhang et al., 2018b) approaches inference of the posterior as an optimization problem, circumventing the need to sample from high-dimensional parameter spaces. The most commonly employed optimization target is here the evidence lower bound (ELBO) (Hoffman et al., 2013). It can be conveniently optimized using stochastic gradient descent (SGD), provided the physical simulator is fully differentiable with respect to all model parameters. This approach can scale to very high dimensional inference problems. Example applications are deblending starfields (Liu et al., 2021), disentangling the components of gamma-ray emission (Leike et al., 2020; Mishra-Sharma and Cranmer, 2020), and strong gravitational lensing (Coogan et al., 2020; Karchev et al., 2021). One challenge with SVI is that through the mode-seeking nature of the reverse KL divergence (Goodfellow, 2017), it tends to underestimate the posterior variance, potentially leading to over-confident posteriors. An important theoretical development front is the construction of differentiable forward models and simulators (e.g. Modi et al., 2021a,b), which is easily admitted using modern automatic differentiation tools (Bradbury et al., 2018; Paszke et al., 2019), or the use of differentiable surrogate models when this is not feasible (Himes et al., 2020; Shirobokov et al., 2020).

The use of differentiable models also allow for inference via gradient-assisted Monte Carlo methods like Hamiltonian Monte Carlo, which have higher sample efficiency and scale better with parameter dimension than traditional Monte Carlo techniques.

Methods based on deep learning: The likelihood function, which is a fundamental input to most established techniques including SVI, can be extremely difficult to compute, due to required marginalization over various unobserved instrumental and physical parameters (see Fig. 4 for an illustration). Simulation-based inference (SBI) methods (see (Cranmer et al., 2020; Lueckmann et al., 2021)) circumvent the evaluation of likelihoods by directly mapping observations and simulations onto summary statistics that are subsequently statistically interpreted. A classical SBI technique is ABC (Sisson et al., 2020). Various recently developed neural SBI methods use the training of deep neural networks both to generate informative summary statistics as well as performing estimation of posteriors, likelihoods (e.g. Papamakarios et al., 2021; Bond-Taylor et al., 2021), or likelihood-to-evidence ratios (e.g. Hermans et al., 2020a). This procedure can require orders of magnitude fewer simulations than established techniques (Alsing et al., 2019; Miller et al., 2020), see Fig. 4. Neural SBI has been used, for instance, for dark matter substructure inference (Coogan et al., 2020; Hermans et al., 2020b; Brehmer et al., 2019; Mishra-Sharma, 2022), dark matter indirect detection with gamma-ray data (Mishra-Sharma and Cranmer, 2021; List et al., 2020, 2021), and binary microlensing (Zhang et al., 2021). Fronts where still significant theoretical development is required are neural network architectures tailored to the structure of typical astrophysical data, which can significantly reduce simulation costs for simulation-based algorithms, and simulation-efficient training algorithms. This includes, for example, efforts to develop interpretable and/or explainable architectures for astrophysical data processing and the use of inference algorithms that produce statistically sound results for the purposes of scientific discovery and hypothesis testing (Hermans et al., 2021). These developments will also help foster community trust in results relying on deep learning methods, which have historically seen reluctance in adoption due to their reputation as black boxes.

In general, deep learning-based techniques enable more information to be extracted from data without requiring the use of simplified data representations and low-dimensional summary observables. Although this has the potential to significantly enhance the sensitivity of astrophysical dark matter searches, it can make typical methods more sensitive to how specific features in the data are modeled. This underscores the need for increased attention to accurately modeling the data.

Infrastructure and workforce: Realizing these goals will require development of both software and human resources. Given the potentially steep theoretical learning curve associated with the aforementioned statistical methods, the development of easy-to-use inference tools (e.g. Miller et al., 2020; Tejero-Cantero et al., 2020) adopting good documentation practices with end practitioners in mind is crucial.

Finally, given the necessity of cross-disciplinary expertise in developing these methods and tools, we recommend, through appropriate hiring practices and promotion options, viable career trajectories at the intersection of statistical methods and astrophysical data analysis for new physics. A concerted effort in this direction has demonstrated success in certain fields of cosmological (The LSSTC Data Science Fellowship Program, 2021) and collider (IRIS-HEP Fellows Program, 2021) data analysis. At the training stage, the existence of Ph.D. schools as well as curriculum-based learning of data analysis techniques is encouraged.

5. Conclusions

We are entering an era which holds the promise of resolving many of the most basic questions we have about dark matter. How was dark matter produced in the early Universe? Is dark matter a single missing piece or part of a broader dark sector? Is dark matter cold, warm, or better thought of as a wave? And above all else: what is dark matter?

A central source for optimism that the answer to these questions may be within our grasp is the upcoming advancements in instruments and observations. Yet, as we have outlined, the role of the theory community is not to simply wait for the experimental program to provide the answers to these questions, but instead to work with, extend, and optimize dark matter searches. Indeed, there is considerable work ahead for theorists to determine the behavior of dark matter and how this would manifest in our observations, and further in the development of techniques such as machine learning that could be required to confidently detect an eventual signal. While there are many challenges to overcome, as we have reviewed, there are clear paths for doing so. Viewed as a whole, there is every reason to be confident that in the coming years we will finally tease apart the mysteries of dark matter and move into a future where rather than wondering what dark matter is, we are instead asking how its particle nature modifies galaxies, cosmology, and possibly even opens a path towards understanding the broader world of physics that exists beyond the Standard Model.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

References

Rubin, V.C., Ford Jr., W.K., 1970. Rotation of the andromeda nebula from a spectroscopic survey of emission regions. Astrophys. J. 159, 379.

Roberts, M.S., Whitehurst, R.N., 1975. The rotation curve and geometry of M31 at large galactocentric distances. Astrophys. J. 201, 327.

Rubin, V.C., Thonnard, N., Ford Jr., W.K., 1980. Rotational properties of 21 SC galaxies with a large range of luminosities and radii, from NGC 4605 /R = 4kpc/ to UGC 2885 /R = 122 kpc/. Astrophys. J. 238, 471.

Bosma, A., 1981. 21-cm line studies of spiral galaxies. 2. The distribution and kinematics of neutral hydrogen in spiral galaxies of various morphological types. Astron. J. 86, 1825.

Clowe, D., Bradač, M., Gonzalez, A.H., Markevitch, M., Randall, S.W., Jones, C., Zaritsky, D., 2006. A direct empirical proof of the existence of dark matter. Astrophys. J. Lett. 648 (2), L109–L113. arXiv:astro-ph/0608407 [astro-ph].

Springel, V., Frenk, C.S., White, S.D.M., 2006. The large-scale structure of the Universe. Nature 440, 1137. arXiv:astro-ph/0604561.

Planck Collaboration, Aghanim, N., Akrami, Y., Ashdown, M., Aumont, J., Baccigalupi, C., Ballardini, M., Banday, A.J., Barreiro, R.B., Bartolo, N., Basak, S., Battye, R., Benabed, K., Bernard, J.P., Bersanelli, M., Bielewicz, P., Bock, J.J., Bond, J.R., Borrill, J., Bouchet, F.R., Boulanger, F., Bucher, M., Burigana, C., Butler, R.C., Calabrese, E., Cardoso, J.F., Carron, J., Challinor, A., Chiang, H.C., Chluba, J., Colombo, L.P.L., Combet, C., Contreras, D., Crill, B.P., Cuttaia, F., de Bernardis, P., de Zotti, G., Delabrouille, J., Delouis, J.M., Di Valentino, E., Diego, J.M., Doré, O., Douspis, M., Ducout, A., Dupac, X., Dusini, S., Efstathiou, G., Elsner, F., Enßlin, T.A., Eriksen, H.K., Fantaye, Y., Farhang, M., Fergusson, J., Fernandez-Cobos, R., Finelli, F., Forastieri, F., Frailis, M., Fraisse, A.A., Franceschi, E., Frolov, A., Galeotta, S., Galli, S., Ganga, K., Génova-Santos, R.T., Gerbino, M., Ghosh, T., González-Nuevo, J., Górski, K.M., Gratton, S., Gruppuso, A., Gudmundsson, J.E., Hamann, J., Handley, W., Hansen, F.K., Herranz, D., Hildebrandt, S.R., Hivon, E., Huang, Z., Jaffe, A.H., Jones, W.C., Karakci, A., Keihänen, E., Keskitalo, R., Kiiveri, K., Kim, J., Kisner, T.S., Knox, L., Krachmalnicoff, N., Kunz, M., Kurki-Suonio, H., Lagache, G., Lamarre, J.M., Lasenby, A., Lattanzi, M., Lawrence, C.R., Le Jeune, M., Lemos, P., Lesgourgues, J., Levrier, F., Lewis, A., Liguori, M., Lilje, P.B., Lilley, M., Lindholm, V., López-Caniego, M., Lubin, P.M., Ma, Y.Z., Macías-Pérez, J.F., Maggio, G., Maino, D., Mandolesi, N., Mangilli, A., Marcos-Caballero, A., Maris, M., Martin, P.G., Martinelli, M., Martínez-González, E., Matarrese, S., Mauri, N., McEwen, J.D., Meinhold, P.R., Melchiorri, A., Mennella, A., Migliaccio, M., Millea, M., Mitra, S., Miville-Deschênes, M.A., Molinari, D., Montier, L., Morgante, G., Moss, A., Natoli, P., Nørgaard-Nielsen, H.U., Pagano, L., Paoletti, D., Partridge, B., Patanchon, G., Peiris, H.V., Perrotta, F., Pettorino, V., Piacentini, F., Polastri, L., Polenta, G., Puget, J.L., Rachen, J.P., Reinecke, M., Remazeilles, M., Renzi, A., Rocha, G., Rosset, C., Roudier, G., Rubiño-Martín, J.A., Ruiz-Granados, B., Salvati, L., Sandri, M., Savelainen, M., Scott, D., Shellard, E.P.S., Sirignano, C., Sirri, G., Spencer, L.D., Sunyaev, R., Suur-Uski, A.S., Tauber, J.A., Tavagnacco, D., Tenti, M., Toffolatti, L., Tomasi, M., Trombetti, T., Valenziano, L., Valiviita, J., Van Tent, B., Vibert, L., Vielva, P., Villa, F., Vittorio, N., Wandelt, B.D., Wehus, I.K., White, M., White, S.D.M., Zacchei, A., Zonca, A., 2020a. Planck 2018 results. VI. Cosmological parameters. Astron. Astrophys. 641, A6. arXiv:1807.06209 [astro-ph.CO].

Diemand, J., Moore, B., Stadel, J., 2005. Earth-mass dark-matter haloes as the first structures in the early Universe. Nature 433, 389–391. arXiv:astro-ph/0501589.

Lovell, M.R., Frenk, C.S., Eke, V.R., Jenkins, A., Gao, L., Theuns, T., 2014. The properties of warm dark matter haloes. Mon. Not. R. Astron. Soc. 439, 300–317. arXiv:1308.1399 [astro-ph.CO].

Boddy, K.K., Kaplinghat, M., Kwa, A., Peter, A.H.G., 2016. Hidden sector hydrogen as dark matter: small-scale structure formation predictions and the importance of hyperfine interactions. Phys. Rev. D 94 (12), 123017. arXiv:1609.03592 [hep-ph].

Hu, W., Barkana, R., Gruzinov, A., 2000. Cold and fuzzy dark matter. Phys. Rev. Lett. 85, 1158–1161. arXiv:astro-ph/0003365.

Arvanitaki, A., Dimopoulos, S., Galanis, M., Lehner, L., Thompson, J.O., Van Tilburg, K., 2020. Large-misalignment mechanism for the formation of compact axion structures: signatures from the QCD axion to fuzzy dark matter. Phys. Rev. D 101 (8), 083014. arXiv:1909.11665 [astro-ph.CO].

Lisanti, M., 2017. Lectures on dark matter physics. In: Theoretical Advanced Study Institute in Elementary Particle Physics: New Frontiers in Fields and Strings, pp. 399–446. arXiv:1603.03797 [hep-ph].

Lin, T., 2019. Dark matter models and direct detection. PoS 333, 009. arXiv:1904.07915 [hep-ph].

Horiuchi, S., Humphrey, P.J., Onorbe, J., Abazajian, K.N., Kaplinghat, M., Garrison-Kimmel, S., 2014. Sterile neutrino dark matter bounds from galaxies of the Local Group. Phys. Rev. D 89 (2), 025017. arXiv:1311.0282 [astro-ph.CO].

Peccei, R.D., Quinn, H.R., 1977a. CP conservation in the presence of instantons. Phys. Rev. Lett. 38, 1440–1443.

Peccei, R.D., Quinn, H.R., 1977b. Constraints imposed by CP conservation in the presence of instantons. Phys. Rev. D 16, 1791–1797.

Weinberg, S., 1978. A new light boson? Phys. Rev. Lett. 40, 223–226.

Wilczek, F., 1978. Problem of strong P and T invariance in the presence of instantons. Phys. Rev. Lett. 40, 279–282.

Preskill, J., Wise, M.B., Wilczek, F., 1983. Cosmology of the invisible axion. Phys. Lett. B 120, 127–132.

Abbott, L.F., Sikivie, P., 1983. A cosmological bound on the invisible axion. Phys. Lett. B 120, 133–136.

Dine, M., Fischler, W., 1983. The not so harmless axion. Phys. Lett. B 120, 137–141.

Di Luzio, L., Giannotti, M., Nardi, E., Visinelli, L., 2020. The landscape of QCD axion models. Phys. Rep. 870, 1–117. arXiv:2003.01100 [hep-ph].

Battaglieri, M., et al., 2017. US cosmic visions: new ideas in dark matter 2017: community report. In: U.S. Cosmic Visions: New Ideas in Dark Matter, p. 7. arXiv:1707.04591 [hep-ph].

Spergel, D.N., Steinhardt, P.J., 2000. Observational evidence for selfinteracting cold dark matter. Phys. Rev. Lett. 84, 3760–3763. arXiv:astro-ph/9909386.

Banerjee, A., et al., 2022. Snowmass2021 cosmic frontier white paper: cosmological simulations for dark matter physics. arXiv:2203.07049 [astro-ph.CO].

Amin, M.A., et al., 2022. Snowmass2021 theory frontier white paper: data-driven cosmology. arXiv:2203.07946 [astro-ph.CO].

Bechtol, K., et al., 2022. Snowmass2021 cosmic frontier white paper: dark matter physics from halo measurements. arXiv:2203.07354 [hep-ph].

Carney, D., et al.. Snowmass2021 Cosmic Frontier White Paper: Ultraheavy Particle Dark Matter.

Leane, R.K., et al.. Snowmass2021 Cosmic Frontier White Paper: Puzzling Excesses in Dark Matter Searches and How to Resolve Them.

Caldwell, R., et al., 2022. Detection of early-Universe gravitational wave signatures and fundamental physics. arXiv:2203.07972 [gr-qc].

Leane, R.K., Slatyer, T.R., Beacom, J.F., Ng, K.C.Y., 2018. GeV-scale thermal WIMPs: not even slightly ruled out. Phys. Rev. D 98 (2), 023016. arXiv:1805.10305 [hep-ph].

Foster, J.W., Kongsore, M., Dessert, C., Park, Y., Rodd, N.L., Cranmer, K., Safdi, B.R., 2021. Deep search for decaying dark matter with XMM-Newton blank-sky observations. Phys. Rev. Lett. 127 (5), 051101. arXiv:2102.02207 [astro-ph.CO].

The Pierre Auger Observatory: Contributions to the 34th International Cosmic Ray Conference (ICRC 2015). arXiv:1509.03732 [astro-ph.HE].

Pierre Auger Collaboration, Aab, A., et al., 2017. Search for photons with energies above 10^{18} eV using the hybrid detector of the Pierre Auger observatory. J. Cosmol. Astropart. Phys. 04, 009. arXiv:1612.01517 [astro-ph.HE], Erratum: J. Cosmol. Astropart. Phys. 09, E02 (2020).

de Naurois, M., Rolland, L., 2009. A high performance likelihood reconstruction of gamma-rays for imaging atmospheric Cerenkov telescopes. Astropart. Phys. 32, 231. arXiv:0907.2610 [astro-ph.IM].

Abeysekara, A.U., et al., 2017. Observation of the crab nebula with the HAWC gamma-ray observatory. Astrophys. J. 843 (1), 39. arXiv:1701.01778 [astro-ph.HE].

CTA Consortium Collaboration, Acharya, B.S., et al., 2018. Science with the Cherenkov Telescope Array. WSP, vol. 11. arXiv:1709.07997 [astro-ph.IM].

Abreu, P., et al., 2019. The Southern Wide-Field Gamma-Ray Observatory (SWGO): a next-generation ground-based survey instrument for VHE gamma-ray astronomy. arXiv:1907.07737 [astro-ph.IM].

Bai, X., et al., 2019a. The Large High Altitude Air Shower Observatory (LHAASO) science white paper – 2021 edition. arXiv:1905.02773 [astro-ph.HE].

LHAASO Collaboration, Aharonian, F., et al., 2021. Extended very-high-energy gamma-ray emission surrounding PSR J0622+3749 observed by LHAASO-KM2A. Phys. Rev. Lett. 126 (24), 241103. arXiv:2106.09396 [astro-ph.HE].

Rinchiuso, L., Macias, O., Moulin, E., Rodd, N.L., Slatyer, T.R., 2021. Prospects for detecting heavy WIMP dark matter with the Cherenkov telescope array: the Wino and Higgsino. Phys. Rev. D 103 (2), 023011. arXiv:2008.00692 [astro-ph.HE].

Bauer, M., Cohen, T., Hill, R.J., Solon, M.P., 2015. Soft collinear effective theory for heavy WIMP annihilation. J. High Energy Phys. 01, 099. arXiv:1409.7392 [hep-ph].

Ovanesyan, G., Slatyer, T.R., Stewart, I.W., 2015. Heavy dark matter annihilation from effective field theory. Phys. Rev. Lett. 114 (21), 211302. arXiv:1409.8294 [hep-ph].

Baumgart, M., Rothstein, I.Z., Vaidya, V., 2015. Constraints on galactic wino densities from gamma ray lines. J. High Energy Phys. 04, 106. arXiv:1412.8698 [hep-ph].

Baumgart, M., Vaidya, V., 2016. Semi-inclusive wino and higgsino annihilation to LL'. J. High Energy Phys. 03, 213. arXiv:1510.02470 [hep-ph].

Ovanesyan, G., Rodd, N.L., Slatyer, T.R., Stewart, I.W., 2017. One-loop correction to heavy dark matter annihilation. Phys. Rev. D 95 (5), 055001. arXiv:1612.04814 [hep-ph], Erratum: Phys. Rev. D 100, 119901 (2019).

Baumgart, M., Cohen, T., Moult, I., Rodd, N.L., Slatyer, T.R., Solon, M.P., Stewart, I.W., Vaidya, V., 2018. Resummed photon spectra for WIMP annihilation. J. High Energy Phys. 03, 117. arXiv:1712.07656 [hep-ph].

Beneke, M., Broggio, A., Hasner, C., Vollmann, M., 2018. Energetic γ-rays from TeV scale dark matter annihilation resummed. Phys. Lett. B 786, 347–354. arXiv:1805.07367 [hep-ph], Erratum: Phys. Lett. B 810, 135831 (2020).

Baumgart, M., Cohen, T., Moulin, E., Moult, I., Rinchiuso, L., Rodd, N.L., Slatyer, T.R., Stewart, I.W., Vaidya, V., 2019. Precision photon spectra for wino annihilation. J. High Energy Phys. 01, 036. arXiv:1808.08956 [hep-ph].

Beneke, M., Broggio, A., Hasner, C., Urban, K., Vollmann, M., 2019. Resummed photon spectrum from dark matter annihilation for intermediate and narrow energy resolution. J. High Energy Phys. 08, 103. arXiv:1903.08702 [hep-ph], Erratum: J. High Energy Phys. 07, 145 (2020).

Beneke, M., Hasner, C., Urban, K., Vollmann, M., 2020. Precise yield of high-energy photons from Higgsino dark matter annihilation. J. High Energy Phys. 03, 030. arXiv:1912.02034 [hep-ph].

Griest, K., Kamionkowski, M., 1990. Unitarity limits on the mass and radius of dark matter particles. Phys. Rev. Lett. 64, 615.

Murase, K., Beacom, J.F., 2012. Constraining very heavy dark matter using diffuse backgrounds of neutrinos and cascaded gamma rays. J. Cosmol. Astropart. Phys. 10, 043. arXiv:1206.2595 [hep-ph].

Murase, K., Laha, R., Ando, S., Ahlers, M., 2015. Testing the dark matter scenario for PeV neutrinos observed in IceCube. Phys. Rev. Lett. 115 (7), 071301. arXiv:1503.04663 [hep-ph].

Alves Batista, R., Dundovic, A., Erdmann, M., Kampert, K.-H., Kuempel, D., Müller, G., Sigl, G., van Vliet, A., Walz, D., Winchen, T., 2016. CRPropa 3 - a public astrophysical simulation framework for propagating extraterrestrial ultra-high energy particles. J. Cosmol. Astropart. Phys. 05, 038. arXiv:1603.07142 [astro-ph.IM].

Heiter, C., Kuempel, D., Walz, D., Erdmann, M., 2018. Production and propagation of ultra-high energy photons using CRPropa 3. Astropart. Phys. 102, 39–50. arXiv:1710.11406 [astro-ph.IM].

Blanco, C., 2019. γ-cascade: a simple program to compute cosmological gamma-ray propagation. J. Cosmol. Astropart. Phys. 01, 013. arXiv:1804.00005 [astro-ph.HE].

Sjostrand, T., Mrenna, S., Skands, P.Z., 2006. PYTHIA 6.4 physics and manual. J. High Energy Phys. 05, 026. arXiv:hep-ph/0603175.

Sjostrand, T., Mrenna, S., Skands, P.Z., 2008. A brief introduction to PYTHIA 8.1. Comput. Phys. Commun. 178, 852–867. arXiv:0710.3820 [hep-ph].

Sjöstrand, T., Ask, S., Christiansen, J.R., Corke, R., Desai, N., Ilten, P., Mrenna, S., Prestel, S., Rasmussen, C.O., Skands, P.Z., 2015. An introduction to PYTHIA 8.2. Comput. Phys. Commun. 191, 159–177. arXiv:1410.3012 [hep-ph].

Ciafaloni, P., Comelli, D., Riotto, A., Sala, F., Strumia, A., Urbano, A., 2011. Weak corrections are relevant for dark matter indirect detection. J. Cosmol. Astropart. Phys. 03, 019. arXiv:1009.0224 [hep-ph].

Cirelli, M., Corcella, G., Hektor, A., Hutsi, G., Kadastik, M., Panci, P., Raidal, M., Sala, F., Strumia, A., 2011. PPPC 4 DM ID: a poor particle physicist cookbook for dark matter indirect detection. J. Cosmol. Astropart. Phys. 03, 051. arXiv:1012.4515 [hep-ph], Erratum: J. Cosmol. Astropart. Phys. 10, E01 (2012).

He, D.-Z., Bi, X.-J., Lin, S.-J., Yin, P.-F., Zhang, X., 2020. Expected LHAASO sensitivity to decaying dark matter signatures from dwarf galaxies gamma-ray emission. Chin. Phys. C 44 (8), 085001. arXiv:1910.05017 [astro-ph.HE].

Bauer, C.W., Rodd, N.L., Webber, B.R., 2021. Dark matter spectra from the electroweak to the Planck scale. J. High Energy Phys. 06, 121. arXiv:2007.15001 [hep-ph].

Ishiwata, K., Macias, O., Ando, S., Arimoto, M., 2020. Probing heavy dark matter decays with multi-messenger astrophysical data. J. Cosmol. Astropart. Phys. 01, 003. arXiv:1907.11671 [astro-ph.HE].

Chianese, M., Fiorillo, D.F.G., Hajjar, R., Miele, G., Saviano, N., 2021a. Constraints on heavy decaying dark matter with current gamma-ray measurements. J. Cosmol. Astropart. Phys. 11, 035. arXiv:2108.01678 [hep-ph].

Esmaili, A., Serpico, P.D., 2021. First implications of Tibet ASγ data for heavy dark matter. Phys. Rev. D 104 (2), L021301. arXiv:2105.01826 [hep-ph].

Maity, T.N., Saha, A.K., Dubey, A., Laha, R., 2021. Search for dark matter using sub-PeV γ-rays observed by Tibet ASγ. arXiv:2105.05680 [hep-ph].

Turner, M.J.L., et al., 2001. The European photon imaging camera on XMM-Newton: the MOS cameras. Astron. Astrophys. 365, L27–L35. arXiv:astro-ph/0011498.

Struder, L., et al., 2001. The European photon imaging camera on XMM-Newton: the PN-CCD camera. Astron. Astrophys. 365, L18–L26.

Fermi-LAT Collaboration, Atwood, W.B., et al., 2009. The large area telescope on the Fermi gamma-ray space telescope mission. Astrophys. J. 697, 1071–1102. arXiv:0902.1089 [astro-ph.IM].

Fermi-LAT Collaboration, Ajello, M., et al., 2021. Fermi large area telescope performance after 10 years of operation. Astrophys. J. Supp. 256 (1), 12. arXiv:2106.12203 [astro-ph.IM].

NuSTAR Collaboration, Harrison, F.A., et al., 2013. The nuclear spectroscopic telescope array (NuSTAR) high-energy X-ray mission. Astrophys. J. 770, 103. arXiv:1301.7307 [astro-ph.IM].

Madsen, K.K., et al., 2015. Calibration of the NuSTAR high energy focusing X-ray telescope. Astrophys. J. Suppl. 220 (1), 8. arXiv:1504.01672 [astro-ph.IM].

Sizun, P., et al., 2004. The integral/spi response and the crab observations. ESA SP 552, 815. arXiv:astro-ph/0406058.

den Herder, J.W., Aarts, H., Bennett, K., de Boer, H., Busetta, M., Collmar, W., Connors, A., Diehl, R., Hermsen, W., Ryan, J., Kippen, M., Kuiper, L., Lichti, G., Lockwood, J., Macri, J., McConnell, M., Morris, D., Much, R., Schoenfelder, V., Stacy, G., Steinle, H., Strong, A., Swanenburg, B., Taylor, B.G., Varendorff, M., de Vries, C., Winkler, C., 1992. COMPTEL: instrument description and performance. In: NASA Conference Publication. In: NASA Conference Publication, vol. 3137, pp. 85–94.

Barcons, X., Nandra, K., Barret, D., den Herder, J.-W., Fabian, A.C., Piro, L., G.W., M., 2015. Athena: the x-ray observatory to study the hot and energetic Universe. J. Phys. Conf. Ser. 610, 012008. https://doi.org/10.1088/1742-6596/610/1/012008.

AMEGO Team Collaboration, Kierans, C.A., 2020. AMEGO: exploring the extreme multimessenger Universe. Proc. SPIE Int. Soc. Opt. Eng. 11444, 1144431. arXiv:2101.03105 [astro-ph.IM].

e-ASTROGAM Collaboration, Tavani, M., et al., 2018. Science with e-ASTROGAM: a space mission for MeV-GeV gamma-ray astrophysics. J. High Energy Astrophys. 19, 1–106. arXiv:1711.01265 [astro-ph.HE].

DES Collaboration, Bechtol, K., et al., 2015a. Eight new Milky Way companions discovered in first-year dark energy survey data. Astrophys. J. 807 (1), 50. arXiv:1503.02584 [astro-ph.GA].

DES Collaboration, Drlica-Wagner, A., et al., 2015b. Eight ultra-faint galaxy candidates discovered in year two of the dark energy survey. Astrophys. J. 813 (2), 109. arXiv:1508.03622 [astro-ph.GA].

Koposov, S.E., Belokurov, V., Torrealba, G., Evans, N.W., 2015. Beasts of the southern wild: discovery of nine ultra faint satellites in the vicinity of the magellanic clouds. Astrophys. J. 805 (2), 130. arXiv:1503.02079 [astro-ph.GA].

Fermi-LAT, DES Collaboration, Albert, A., et al., 2017. Searching for dark matter annihilation in recently discovered Milky Way satellites with Fermi-LAT. Astrophys. J. 834 (2), 110. arXiv:1611.03184 [astro-ph.HE].

DES Collaboration, Drlica-Wagner, A., et al., 2020. Milky way satellite census. I. The observational selection function for Milky Way satellites in DES Y3 and pan-STARRS DR1. Astrophys. J. 893, 1. arXiv:1912.03302 [astro-ph.GA].

Ando, S., et al., 2019. Discovery prospects of dwarf spheroidal galaxies for indirect dark matter searches. J. Cosmol. Astropart. Phys. 10, 040. arXiv:1905.07128 [astro-ph.CO].

Lisanti, M., Mishra-Sharma, S., Rodd, N.L., Safdi, B.R., 2018a. Search for dark matter annihilation in galaxy groups. Phys. Rev. Lett. 120 (10), 101101. arXiv:1708.09385 [astro-ph.CO].

Lisanti, M., Mishra-Sharma, S., Rodd, N.L., Safdi, B.R., Wechsler, R.H., 2018b. Mapping extragalactic dark matter annihilation with galaxy surveys: a systematic study of stacked group searches. Phys. Rev. D 97 (6), 063005. arXiv:1709.00416 [astro-ph.CO].

Kuhlen, M., Diemand, J., Madau, P., 2008. The dark matter annihilation signal from galactic substructure: predictions for GLAST. Astrophys. J. 686, 262. arXiv:0805.4416 [astro-ph].

Buckley, M.R., Hooper, D., 2010. Dark matter subhalos in the Fermi first source catalog. Phys. Rev. D 82, 063501. arXiv:1004.1644 [hep-ph].

Belikov, A.V., Hooper, D., Buckley, M.R., 2012. Searching for dark matter subhalos in the Fermi-LAT second source catalog. Phys. Rev. D 86, 043504. arXiv:1111.2613 [hep-ph].

Fermi-LAT Collaboration, Ackermann, M., et al., 2012. Search for dark matter satellites using the FERMI-LAT. Astrophys. J. 747, 121. arXiv:1201.2691 [astro-ph.HE].

Zechlin, H.-S., Horns, D., 2012. Unidentified sources in the Fermi-LAT second source catalog: the case for DM subhalos. J. Cosmol. Astropart. Phys. 11, 050. arXiv:1210.3852 [astro-ph.HE], Erratum: J. Cosmol. Astropart. Phys. 02, E01 (2015).

Berlin, A., Hooper, D., 2014. Stringent constraints on the dark matter annihilation cross section from subhalo searches with the Fermi gamma-ray space telescope. Phys. Rev. D 89 (1), 016014. arXiv:1309.0525 [hep-ph].

Bertoni, B., Hooper, D., Linden, T., 2015. Examining the Fermi-LAT third source catalog in search of dark matter subhalos. J. Cosmol. Astropart. Phys. 12, 035. arXiv:1504.02087 [astro-ph.HE].

Schoonenberg, D., Gaskins, J., Bertone, G., Diemand, J., 2016. Dark matter subhalos and unidentified sources in the Fermi 3FGL source catalog. J. Cosmol. Astropart. Phys. 05, 028. arXiv:1601.06781 [astro-ph.HE].

Bertoni, B., Hooper, D., Linden, T., 2016. Is the gamma-ray source 3FGL J2212.5+0703 a dark matter subhalo? J. Cosmol. Astropart. Phys. 05, 049. arXiv:1602.07303 [astro-ph.HE].

Mirabal, N., Charles, E., Ferrara, E.C., Gonthier, P.L., Harding, A.K., Sánchez-Conde, M.A., Thompson, D.J., 2016. 3FGL demographics outside the galactic plane using supervised machine learning: pulsar and dark matter subhalo interpretations. Astrophys. J. 825 (1), 69. arXiv:1605.00711 [astro-ph.HE].

Hooper, D., Witte, S.J., 2017. Gamma rays from dark matter subhalos revisited: refining the predictions and constraints. J. Cosmol. Astropart. Phys. 04, 018. arXiv:1610.07587 [astro-ph.HE].

Calore, F., De Romeri, V., Di Mauro, M., Donato, F., Marinacci, F., 2017. Realistic estimation for the detectability of dark matter sub-halos with Fermi-LAT. Phys. Rev. D 96 (6), 063009. arXiv:1611.03503 [astro-ph.HE].

Hütten, M., Stref, M., Combet, C., Lavalle, J., Maurin, D., 2019. γ-ray and ν searches for dark matter subhalos in the Milky Way with a baryonic potential. Galaxies 7 (2), 60. arXiv:1904.10935 [astro-ph.HE].

H.E.S.S. Collaboration, Glawion, D., Malyshev, D., Moulin, E., Oakes, L., Rinchiuso, L., Viana, A., 2021. Unidentified Fermi objects in the view of H.E.S.S. - possible dark matter clumps. PoS ICRC2019, 518. arXiv:1909.01072 [astro-ph.HE].

Calore, F., Hütten, M., Stref, M., 2019. Gamma-ray sensitivity to dark matter subhalo modelling at high latitudes. Galaxies 7 (4), 90. arXiv:1910.13722 [astro-ph.HE].

Coronado-Blázquez, J., Sánchez-Conde, M.A., Di Mauro, M., Aguirre-Santaella, A., Ciucă, I., Domínguez, A., Kawata, D., Mirabal, N., 2019. Spectral and spatial analysis of the dark matter subhalo candidates among *Fermi* large area telescope unidentified sources. J. Cosmol. Astropart. Phys. 11, 045. arXiv:1910.14429 [astro-ph.HE].

Coronado-Blázquez, J., Sánchez-Conde, M.A., 2019. Constraints to dark matter annihilation from high-latitude HAWC unidentified sources. Galaxies 8 (1), 5. arXiv:2001.02536 [astro-ph.HE].

Facchinetti, G., Lavalle, J., Stref, M., 2020. Statistics for dark matter subhalo searches in gamma rays from a kinematically constrained population model. I: Fermi-LAT-like telescopes. arXiv:2007.10392 [astro-ph.HE].

Di Mauro, M., Stref, M., Calore, F., 2020. Investigating the detection of dark matter subhalos as extended sources with Fermi-LAT. Phys. Rev. D 102 (10), 103010. arXiv:2007.08535 [astro-ph.HE].

Somalwar, J.J., Chang, L.J., Mishra-Sharma, S., Lisanti, M., 2021. Harnessing the population statistics of subhalos to search for annihilating dark matter. Astrophys. J. 906 (1), 57. arXiv:2009.00021 [astro-ph.CO].

Xia, J.-Q., Cuoco, A., Branchini, E., Fornasa, M., Viel, M., 2011. A cross-correlation study of the Fermi-LAT γ-ray diffuse extragalactic signal. Mon. Not. R. Astron. Soc. 416, 2247–2264. arXiv:1103.4861 [astro-ph.CO].

Ando, S., 2014. Power spectrum tomography of dark matter annihilation with local galaxy distribution. J. Cosmol. Astropart. Phys. 10, 061. arXiv:1407.8502 [astro-ph.CO].

Ando, S., Benoit-Lévy, A., Komatsu, E., 2014. Mapping dark matter in the gamma-ray sky with galaxy catalogs. Phys. Rev. D 90 (2), 023514. arXiv:1312.4403 [astro-ph.CO].

Xia, J.-Q., Cuoco, A., Branchini, E., Viel, M., 2015. Tomography of the Fermi-lat γ-ray diffuse extragalactic signal via cross correlations with galaxy catalogs. Astrophys. J. Suppl. 217 (1), 15. arXiv:1503.05918 [astro-ph.CO].

Regis, M., Xia, J.-Q., Cuoco, A., Branchini, E., Fornengo, N., Viel, M., 2015. Particle dark matter searches outside the local group. Phys. Rev. Lett. 114 (24), 241301. arXiv:1503.05922 [astro-ph.CO].

Cuoco, A., Xia, J.-Q., Regis, M., Branchini, E., Fornengo, N., Viel, M., 2015. Dark matter searches in the gamma-ray extragalactic background via cross-correlations with galaxy catalogs. Astrophys. J. Suppl. 221 (2), 29. arXiv:1506.01030 [astro-ph.HE].

Ando, S., Ishiwata, K., 2016. Constraining particle dark matter using local galaxy distribution. J. Cosmol. Astropart. Phys. 06, 045. arXiv:1604.02263 [hep-ph].

Shirasaki, M., Macias, O., Ando, S., Horiuchi, S., Yoshida, N., 2020. Cross-correlation of the extragalactic gamma-ray background with the thermal Sunyaev-Zel'dovich effect in the cosmic microwave background. Phys. Rev. D 101 (10), 103022. arXiv:1911.11841 [astro-ph.CO].

Macias, O., Gordon, C., Crocker, R.M., Coleman, B., Paterson, D., Horiuchi, S., Pohl, M., 2018. Galactic bulge preferred over dark matter for the Galactic centre gamma-ray excess. Nat. Astron. 2 (5), 387–392. arXiv:1611.06644 [astro-ph.HE].

Macias, O., Horiuchi, S., Kaplinghat, M., Gordon, C., Crocker, R.M., Nataf, D.M., 2019. Strong evidence that the galactic bulge is shining in gamma rays. J. Cosmol. Astropart. Phys. 09, 042. arXiv:1901.03822 [astro-ph.HE].

Buschmann, M., Rodd, N.L., Safdi, B.R., Chang, L.J., Mishra-Sharma, S., Lisanti, M., Macias, O., 2020. Foreground mismodeling and the point source explanation of the Fermi Galactic center excess. Phys. Rev. D 102 (2), 023023. arXiv:2002.12373 [astro-ph.HE].

Siegert, T., Berteaud, J., Calore, F., Serpico, P.D., Weinberger, C., 2022. Diffuse Galactic emission spectrum between 0.5 and 8.0 MeV. arXiv:2202.04574 [astro-ph.HE].

Cohen, T., Murase, K., Rodd, N.L., Safdi, B.R., Soreq, Y., 2017. γ -ray constraints on decaying dark matter and implications for IceCube. Phys. Rev. Lett. 119 (2), 021102. arXiv:1612.05638 [hep-ph].

Chang, L.J., Lisanti, M., Mishra-Sharma, S., 2018a. Search for dark matter annihilation in the Milky Way halo. Phys. Rev. D 98 (12), 123004. arXiv:1804.04132 [astro-ph.CO].

Dessert, C., Rodd, N.L., Safdi, B.R., 2020a. The dark matter interpretation of the 3.5-keV line is inconsistent with blank-sky observations. Science 367 (6485), 1465–1467. arXiv:1812.06976 [astro-ph.CO].

Bulbul, E., Markevitch, M., Foster, A., Smith, R.K., Loewenstein, M., Randall, S.W., 2014. Detection of an unidentified emission line in the stacked X-ray spectrum of galaxy clusters. Astrophys. J. 789, 13. arXiv:1402.2301 [astro-ph.CO].

Boyarsky, A., Ruchayskiy, O., Iakubovskyi, D., Franse, J., 2014. Unidentified line in X-ray spectra of the andromeda galaxy and perseus galaxy cluster. Phys. Rev. Lett. 113, 251301. arXiv:1402.4119 [astro-ph.CO].

Boyarsky, A., Malyshev, D., Ruchayskiy, O., Savchenko, D., 2020. Technical comment on the paper of Dessert et al. "The dark matter interpretation of the 3.5 keV line is inconsistent with blank-sky observations". arXiv:2004.06601 [astro-ph.CO].

Dessert, C., Rodd, N.L., Safdi, B.R., 2020b. Response to a comment on Dessert et al. "The dark matter interpretation of the 3.5 keV line is inconsistent with blank-sky observations". Phys. Dark Universe 30, 100656. arXiv:2006.03974 [astro-ph.CO].

Abdo, A.A., Ackermann, M., Ajello, M., Baldini, L., Ballet, J., Barbiellini, G., Bastieri, D., Bechtol, K., Bellazzini, R., Berenji, B., Bonamente, E., Borgland, A.W., Bouvier, A., Bregeon, J., Brez, A., Brigida, M., Bruel, P., Buehler, R., Buson, S., Caliandro, G.A., Cameron, R.A., Caraveo, P.A., Casandjian, J.M., Cecchi, C., Charles, E., Chekhtman, A., Chiang, J., Ciprini, S., Claus, R., Cohen-Tanugi, J., Conrad, J., Cutini, S., de Angelis, A., de Palma, F., Dermer, C.D., Digel, S.W., do Couto e Silva, E., Drell, P.S., Dubois, R., Favuzzi, C., Fegan, S.J., Focke, W.B., Fortin, P., Frailis, M., Funk, S., Fusco, P., Gargano, F., Gasparrini, D., Gehrels, N., Germani, S., Giglietto, N., Giordano, F., Giroletti, M., Glanzman, T., Godfrey, G., Grenier, I.A., Grillo, L., Guiriec, S., Hadasch, D., Hays, E., Hughes, R.E., Iafrate, G., Jóhannesson, G., Johnson, A.S., Johnson, T.J., Kamae, T., Katagiri, H., Kataoka, J., Knödlseder, J., Kuss, M., Lande, J., Latronico, L., Lee, S.-H., Lionetto, A.M., Longo, F., Loparco, F., Lott, B., Lovellette, M.N., Lubrano, P., Makeev, A., Mazziotta, M.N., McEnery, J.E., Mehault, J., Michelson, P.F., Mitthumsiri, W., Mizuno, T., Moiseev, A.A., Monte, C., Monzani, M.E., Morselli, A., Moskalenko, I.V., Murgia, S., Nakamori, T., Naumann-Godo, M., Nolan, P.L., Norris, J.P., Nuss, E., Ohsugi, T., Okumura, A., Omodei, N., Orlando, E., Ormes, J.F., Ozaki, M., Paneque, D., Pelassa, V., Pesce-Rollins, M., Pierbattista, M., Piron, F., Porter, T.A., Rainò, S., Rando, R., Razzano, M., Reimer, A., Reimer, O., Reposeur, T., Ritz, S., Sadrozinski, H.F.-W., Schalk, T.L., Sgrò, C., Share, G.H., Siskind, E.J., Smith, P.D., Spandre, G., Spinelli, P., Strickman, M.S., Strong, A.W., Takahashi, H., Tanaka, T., Thayer, J.G., Thayer, J.B., Thompson, D.J., Tibaldo, L., Torres, D.F., Tosti, G., Tramacere, A., Troja, E., Uchiyama, Y., Usher, T.L., Vandenbroucke, J., Vasileiou, V., Vianello, G., Vilchez, N., Vitale, V., Vladimirov, A.E., Waite, A.P., Wang, P., Winer, B.L., Wood, K.S., Yang, Z., Ziegler, M., 2011. Fermilarge area telescope observations of two gamma-ray emission components from the quiescent sun. Astrophys. J. 734 (2), 116. https://doi.org/10.1088/0004-637X/734/2/116.

Ng, K.C.Y., Beacom, J.F., Peter, A.H.G., Rott, C., 2016. First observation of time variation in the solar-disk gamma-ray flux with Fermi. Phys. Rev. D 94 (2), 023004. arXiv:1508.06276 [astro-ph.HE].

Linden, T., Zhou, B., Beacom, J.F., Peter, A.H.G., Ng, K.C.Y., Tang, Q.-W., 2018. Evidence for a new component of high-energy solar gamma-ray production. Phys. Rev. Lett. 121 (13), 131103. arXiv:1803.05436 [astro-ph.HE].

Linden, T., Beacom, J.F., Peter, A.H.G., Buckman, B.J., Zhou, B., Zhu, G., 2020. First observations of solar disk gamma rays over a full solar cycle. arXiv:2012.04654 [astro-ph.HE].

HAWC Collaboration, Albert, A., et al., 2018a. First HAWC observations of the sun constrain steady TeV gamma-ray emission. Phys. Rev. D 98 (12), 123011. arXiv:1808.05620 [astro-ph.HE].

Leane, R.K., Ng, K.C.Y., Beacom, J.F., 2017. Powerful solar signatures of long-lived dark mediators. Phys. Rev. D 95 (12), 123016. arXiv:1703.04629 [astro-ph.HE].

HAWC Collaboration, Albert, A., et al., 2018b. Constraints on spin-dependent dark matter scattering with long-lived mediators from TeV observations of the Sun with HAWC. Phys. Rev. D 98, 123012. arXiv:1808.05624 [hep-ph].

Nisa, M.U., Beacom, J.F., BenZvi, S.Y., Leane, R.K., Linden, T., Ng, K.C.Y., Peter, A.H.G., Zhou, B., 2019. The Sun at GeV–TeV energies: a new laboratory for astroparticle physics. arXiv:1903.06349 [astro-ph.HE].

Leane, R.K., Linden, T., 2021. First analysis of Jupiter in gamma rays and a new search for dark matter. arXiv:2104.02068 [astro-ph.HE].

Leane, R.K., Linden, T., Mukhopadhyay, P., Toro, N., 2021. Celestial-body focused dark matter annihilation throughout the galaxy. Phys. Rev. D 103 (7), 075030. arXiv:2101.12213 [astro-ph.HE].

Bose, D., Maity, T.N., Ray, T.S., 2021. Neutrinos from captured dark matter annihilation in a galactic population of neutron stars. arXiv:2108.12420 [hep-ph].

Super-Kamiokande Collaboration, Choi, K., et al., 2015. Search for neutrinos from annihilation of captured low-mass dark matter particles in the Sun by super-Kamiokande. Phys. Rev. Lett. 114 (14), 141301. arXiv:1503.04858 [hep-ex].

IceCube Collaboration, Aartsen, M.G., et al., 2017. Search for annihilating dark matter in the Sun with 3 years of IceCube data. Eur. Phys. J. C 77 (3), 146. arXiv:1612.05949 [astro-ph.HE], Erratum: Eur. Phys. J. C 79, 214 (2019).

ANTARES Collaboration, Adrian-Martinez, S., et al., 2016. Limits on dark matter annihilation in the Sun using the ANTARES neutrino telescope. Phys. Lett. B 759, 69–74. arXiv:1603.02228 [astro-ph.HE].

Bell, N.F., Petraki, K., 2011. Enhanced neutrino signals from dark matter annihilation in the Sun via metastable mediators. J. Cosmol. Astropart. Phys. 04, 003. arXiv:1102.2958 [hep-ph].

Goldman, I., Nussinov, S., 1989. Weakly interacting massive particles and neutron stars. Phys. Rev. D 40, 3221–3230.

Bertone, G., Fairbairn, M., 2008. Compact stars as dark matter probes. Phys. Rev. D 77, 043515. arXiv:0709.1485 [astro-ph].

Baryakhtar, M., Bramante, J., Li, S.W., Linden, T., Raj, N., 2017a. Dark kinetic heating of neutron stars and an infrared window on WIMPs, SIMPs, and pure Higgsinos. Phys. Rev. Lett. 119 (13), 131801. arXiv:1704.01577 [hep-ph].

Acevedo, J.F., Bramante, J., Leane, R.K., Raj, N., 2020. Warming nuclear pasta with dark matter: kinetic and annihilation heating of neutron star crusts. J. Cosmol. Astropart. Phys. 03, 038. arXiv:1911.06334 [hep-ph].

Bell, N.F., Busoni, G., Motta, T.F., Robles, S., Thomas, A.W., Virgato, M., 2020. Nucleon structure and strong interactions in dark matter capture in neutron stars. arXiv:2012.08918 [hep-ph].

Bell, N.F., Busoni, G., Ramirez-Quezada, M.E., Robles, S., Virgato, M., 2021. Improved treatment of dark matter capture in white dwarfs. J. Cosmol. Astropart. Phys. 10, 083. arXiv:2104.14367 [hep-ph].

Freese, K., Gondolo, P., Sellwood, J.A., Spolyar, D., 2009. Dark matter densities during the formation of the first stars and in dark stars. Astrophys. J. 693, 1563–1569. arXiv:0805.3540 [astro-ph].

Taoso, M., Bertone, G., Meynet, G., Ekstrom, S., 2008. Dark matter annihilations in pop III stars. Phys. Rev. D 78, 123510. arXiv:0806.2681 [astro-ph].

Ilie, C., Levy, C., Pilawa, J., Zhang, S., 2020a. Probing below the neutrino floor with the first generation of stars. arXiv:2009.11478 [astro-ph.CO].

Ilie, C., Levy, C., Pilawa, J., Zhang, S., 2020b. Constraining dark matter properties with the first generation of stars. arXiv:2009.11474 [astro-ph.CO].

Leane, R.K., Smirnov, J., 2021. Exoplanets as sub-GeV dark matter detectors. Phys. Rev. Lett. 126 (16), 161101. arXiv:2010.00015 [hep-ph].

Argüelles, C.A., Diaz, A., Kheirandish, A., Olivares-Del-Campo, A., Safa, I., Vincent, A.C., 2021. Dark matter annihilation to neutrinos. Rev. Mod. Phys. 93 (3), 035007. arXiv:1912.09486 [hep-ph].

IceCube Collaboration, Aartsen, M.G., et al., 2018. Search for neutrinos from decaying dark matter with IceCube. Eur. Phys. J. C 78 (10), 831. arXiv:1804.03848 [astro-ph.HE].

IceCube Collaboration, Argüelles, C.A., Dujmovic, H., 2020. Searches for connections between dark matter and neutrinos with the IceCube high-energy starting event sample. PoS ICRC2019, 839. arXiv:1907.11193 [hep-ph].

IceCube, Fermi-LAT, MAGIC, AGILE, ASAS-SN, HAWC, H.E.S.S., INTEGRAL, Kanata, Kiso, Kapteyn, Liverpool Telescope, Subaru, Swift NuSTAR, VERITAS, VLA/17B-403 Collaboration, Aartsen, M.G., et al., 2018. Multimessenger observations of a flaring blazar coincident with high-energy neutrino IceCube-170922A. Science 361 (6398), eaat1378. arXiv:1807.08816 [astro-ph.HE].

Esmaili, A., Serpico, P.D., 2013. Are IceCube neutrinos unveiling PeV-scale decaying dark matter? J. Cosmol. Astropart. Phys. 11, 054. arXiv:1308.1105 [hep-ph].

Feldstein, B., Kusenko, A., Matsumoto, S., Yanagida, T.T., 2013. Neutrinos at IceCube from heavy decaying dark matter. Phys. Rev. D 88 (1), 015004. arXiv:1303.7320 [hep-ph].

Rott, C., Kohri, K., Park, S.C., 2015. Superheavy dark matter and IceCube neutrino signals: bounds on decaying dark matter. Phys. Rev. D 92 (2), 023529. arXiv:1408.4575 [hep-ph].

Bhattacharya, A., Reno, M.H., Sarcevic, I., 2014. Reconciling neutrino flux from heavy dark matter decay and recent events at IceCube. J. High Energy Phys. 06, 110. arXiv:1403.1862 [hep-ph].

El Aisati, C., Gustafsson, M., Hambye, T., 2015. New search for monochromatic neutrinos from dark matter decay. Phys. Rev. D 92 (12), 123515. arXiv:1506.02657 [hep-ph].

Anchordoqui, L.A., Barger, V., Goldberg, H., Huang, X., Marfatia, D., da Silva, L.H.M., Weiler, T.J., 2015. IceCube neutrinos, decaying dark matter, and the Hubble constant. Phys. Rev. D 92 (6), 061301. arXiv:1506.08788 [hep-ph], Erratum: Phys. Rev. D 94, 069901 (2016).

Chianese, M., Miele, G., Morisi, S., 2017. Interpreting IceCube 6-year HESE data as an evidence for hundred TeV decaying dark matter. Phys. Lett. B 773, 591–595. arXiv:1707.05241 [hep-ph].

Chianese, M., Fiorillo, D.F.G., Miele, G., Morisi, S., Pisanti, O., 2019. Decaying dark matter at IceCube and its signature on high energy gamma experiments. J. Cosmol. Astropart. Phys. 11, 046. arXiv:1907.11222 [hep-ph].

Bhattacharya, A., Esmaili, A., Palomares-Ruiz, S., Sarcevic, I., 2019. Update on decaying and annihilating heavy dark matter with the 6-year IceCube HESE data. J. Cosmol. Astropart. Phys. 05, 051. arXiv:1903.12623 [hep-ph].

Ahlers, M., Bai, Y., Barger, V., Lu, R., 2016. Galactic neutrinos in the TeV to PeV range. Phys. Rev. D 93 (1), 013009. arXiv:1505.03156 [hep-ph].

Liu, Q., Lazar, J., Argüelles, C.A., Kheirandish, A., 2020a. χaroν: a tool for neutrino flux generation from WIMPs. J. Cosmol. Astropart. Phys. 10, 043. arXiv:2007.15010 [hep-ph].

Esmaili, A., Ibarra, A., Peres, O.L.G., 2012. Probing the stability of superheavy dark matter particles with high-energy neutrinos. J. Cosmol. Astropart. Phys. 11, 034. arXiv:1205.5281 [hep-ph].

Ng, K.C.Y., et al., 2020. Sensitivities of KM3NeT on decaying dark matter. arXiv:2007.03692 [astro-ph.HE].

Guépin, C., Aloisio, R., Anchordoqui, L.A., Cummings, A., Krizmanic, J.F., Olinto, A.V., Reno, M.H., Venters, T.M., 2021. Indirect dark matter searches at ultra-high energy neutrino detectors. Phys. Rev. D 104 (8), 083002. arXiv:2106.04446 [hep-ph].

Chianese, M., Fiorillo, D.F.G., Hajjar, R., Miele, G., Morisi, S., Saviano, N., 2021b. Heavy decaying dark matter at future neutrino radio telescopes. J. Cosmol. Astropart. Phys. 05, 074. arXiv:2103.03254 [hep-ph].

Cuoco, A., Krämer, M., Korsmeier, M., 2017a. Novel dark matter constraints from antiprotons in light of AMS-02. Phys. Rev. Lett. 118 (19), 191102. arXiv:1610.03071 [astro-ph.HE].

Cui, M.-Y., Yuan, Q., Tsai, Y.-L.S., Fan, Y.-Z., 2017. Possible dark matter annihilation signal in the AMS-02 antiproton data. Phys. Rev. Lett. 118 (19), 191101. arXiv:1610.03840 [astro-ph.HE].

Cholis, I., Linden, T., Hooper, D., 2019. A robust excess in the cosmic-ray antiproton spectrum: implications for annihilating dark matter. Phys. Rev. D 99 (10), 103026. arXiv:1903.02549 [astro-ph.HE].

Cuoco, A., Heisig, J., Klamt, L., Korsmeier, M., Krämer, M., 2019. Scrutinizing the evidence for dark matter in cosmic-ray antiprotons. Phys. Rev. D 99 (10), 103014. arXiv:1903.01472 [astro-ph.HE].

Cuoco, A., Heisig, J., Korsmeier, M., Krämer, M., 2017b. Probing dark matter annihilation in the Galaxy with antiprotons and gamma rays. J. Cosmol. Astropart. Phys. 10, 053. arXiv:1704.08258 [astro-ph.HE].

Winkler, M.W., 2017. Cosmic ray antiprotons at high energies. J. Cosmol. Astropart. Phys. 02, 048. arXiv:1701.04866 [hep-ph].

Boudaud, M., Génolini, Y., Derome, L., Lavalle, J., Maurin, D., Salati, P., Serpico, P.D., 2020. AMS-02 antiprotons' consistency with a secondary astrophysical origin. Phys. Rev. Res. 2 (2), 023022. arXiv:1906.07119 [astro-ph.HE].

Heisig, J., Korsmeier, M., Winkler, M.W., 2020. Dark matter or correlated errors: systematics of the AMS-02 antiproton excess. Phys. Rev. Res. 2 (4), 043017. arXiv:2005.04237 [astro-ph.HE].

Kahlhoefer, F., Korsmeier, M., Krämer, M., Manconi, S., Nippel, K., 2021. Constraining dark matter annihilation with cosmic ray antiprotons using neural networks. J. Cosmol. Astropart. Phys. 12 (12), 037. arXiv:2107.12395 [astro-ph.HE].

Aramaki, T., et al., 2016. Review of the theoretical and experimental status of dark matter identification with cosmic-ray antideuterons. Phys. Rep. 618, 1–37. arXiv:1505.07785 [hep-ph].

Cholis, I., Hooper, D., Linden, T., 2020a. Constraining the charge-sign and rigidity-dependence of solar modulation. arXiv:2007.00669 [astro-ph.HE].

Korsmeier, M., Donato, F., Fornengo, N., 2018. Prospects to verify a possible dark matter hint in cosmic antiprotons with antideuterons and antihelium. Phys. Rev. D 97 (10), 103011. arXiv:1711.08465 [astro-ph.HE].

Lin, S.-J., Bi, X.-J., Yin, P.-F., 2018. Expectations of the cosmic antideuteron flux. arXiv:1801.00997 [astro-ph.HE].

Cholis, I., Linden, T., Hooper, D., 2020b. Antideuterons and antihelium nuclei from annihilating dark matter. Phys. Rev. D 102 (10), 103019. arXiv:2001.08749 [astro-ph.HE].

Donato, F., Fornengo, N., Salati, P., 2000. Anti-deuterons as a signature of supersymmetric dark matter. Phys. Rev. D 62, 043003. arXiv:hep-ph/9904481.

Baer, H., Profumo, S., 2005. Low energy antideuterons: shedding light on dark matter. J. Cosmol. Astropart. Phys. 12, 008. arXiv:astro-ph/0510722.

Ibarra, A., Wild, S., 2013. Prospects of antideuteron detection from dark matter annihilations or decays at AMS-02 and GAPS. J. Cosmol. Astropart. Phys. 02, 021. arXiv:1209.5539 [hep-ph].

Fornengo, N., Maccione, L., Vittino, A., 2013. Dark matter searches with cosmic antideuterons: status and perspectives. J. Cosmol. Astropart. Phys. 09, 031. arXiv:1306.4171 [hep-ph].

Dal, L.A., Raklev, A.R., 2014. Antideuteron limits on decaying dark matter with a tuned formation model. Phys. Rev. D 89 (10), 103504. arXiv:1402.6259 [hep-ph].

Ding, Y.-C., Li, N., Wei, C.-C., Wu, Y.-L., Zhou, Y.-F., 2019. Prospects of detecting dark matter through cosmic-ray antihelium with the antiproton constraints. J. Cosmol. Astropart. Phys. 06, 004. arXiv:1808.03612 [hep-ph].

Sam, T., 2018. Latest results from the AMS experiment on the international space station. In: Oral presentation CERN.

Donato, F., Korsmeier, M., Di Mauro, M., 2017. Prescriptions on antiproton cross section data for precise theoretical antiproton flux predictions. Phys. Rev. D 96 (4), 043007. arXiv:1704.03663 [astro-ph.HE].

Winkler, M.W., Linden, T., 2021. Dark matter annihilation can produce a detectable antihelium flux through $\bar{\Lambda}_b$ decays. Phys. Rev. Lett. 126 (10), 101101. arXiv:2006.16251 [hep-ph].

ALICE Collaboration, Acharya, S., et al., 2018. Production of deuterons, tritons, ^{3}He nuclei and their antinuclei in pp collisions at $\sqrt{s}$ = 0.9, 2.76 and 7 TeV. Phys. Rev. C 97 (2), 024615. arXiv:1709.08522 [nucl-ex].

LHCb Collaboration, Aaij, R., et al., 2018. Measurement of antiproton production in pHe collisions at $\sqrt{s_{NN}} = 110$ GeV. Phys. Rev. Lett. 121 (22), 222001. arXiv:1808.06127 [hep-ex].

PAMELA Collaboration, Adriani, O., et al., 2009. An anomalous positron abundance in cosmic rays with energies 1.5-100 GeV. Nature 458, 607–609. arXiv:0810.4995 [astro-ph].

Ackermann, M., Ajello, M., Allafort, A., Atwood, W.B., Baldini, L., Barbiellini, G., Bastieri, D., Bechtol, K., Bellazzini, R., Berenji, B., Blandford, R.D., Bloom, E.D., Bonamente, E., Borgland, A.W., Bouvier, A., Bregeon, J., Brigida, M., Bruel, P., Buehler, R., Buson, S., Caliandro, G.A., Cameron, R.A., Caraveo, P.A., Casandjian, J.M., Cecchi, C., Charles, E., Chekhtman, A., Cheung, C.C., Chiang, J., Ciprini, S., Claus, R., Cohen-Tanugi, J., Conrad, J., Cutini, S., de Angelis, A., de Palma, F., Dermer, C.D., Digel, S.W., Do Couto, E., Silva, E., Drell, P.S., Drlica-Wagner, A., Favuzzi, C., Fegan, S.J., Ferrara, E.C., Focke, W.B., Fortin, P., Fukazawa, Y., Funk, S., Fusco, P., Gargano, F., Gasparrini, D., Germani, S., Giglietto, N., Giommi, P., Giordano, F., Giroletti, M., Glanzman, T., Godfrey, G., Grenier, I.A., Grove, J.E., Guiriec, S., Gustafsson, M., Hadasch, D., Harding, A.K., Hayashida, M., Hughes, R.E., Jóhannesson, G., Johnson, A.S., Kamae, T., Katagiri, H., Kataoka, J., Knödlseder, J., Kuss, M., Lande, J., Latronico, L., Lemoine-Goumard, M., Llena Garde, M., Longo, F., Loparco, F., Lovellette, M.N., Lubrano, P., Madejski, G.M., Mazziotta, M.N., McEnery, J.E., Michelson, P.F., Mitthumsiri, W., Mizuno, T., Moiseev, A.A., Monte, C., Monzani, M.E., Morselli, A., Moskalenko, I.V., Murgia, S., Nakamori, T., Nolan, P.L., Norris, J.P., Nuss, E., Ohno, M., Ohsugi, T., Okumura, A., Omodei, N., Orlando, E., Ormes, J.F., Ozaki, M., Paneque, D., Parent, D., Pesce-Rollins, M., Pierbattista, M., Piron, F., Pivato, G., Porter, T.A., Rainò, S., Rando, R., Razzano, M., Razzaque, S., Reimer, A., Reimer, O., Reposeur, T., Ritz, S., Romani, R.W., Roth, M., Sadrozinski, H.F.W., Sbarra, C., Schalk, T.L., Sgrò, C., Siskind, E.J., Spandre, G., Spinelli, P., Strong, A.W., Takahashi, H., Takahashi, T., Tanaka, T., Thayer, J.G., Thayer, J.B., Tibaldo, L., Tinivella, M., Torres, D.F., Tosti, G., Troja, E., Uchiyama, Y., Usher, T.L., Vandenbroucke, J., Vasileiou, V., Vianello, G., Vitale, V., Waite, A.P., Winer, B.L., Wood, K.S., Wood, M., Yang, Z., Zimmer, S., 2012. Measurement of separate cosmic-ray electron and positron spectra with the Fermi large area telescope. Phys. Rev. Lett. 108 (1), 011103. arXiv:1109.0521 [astro-ph.HE].

AMS Collaboration, Aguilar, M., et al., 2013. First result from the alpha magnetic spectrometer on the international space station: precision measurement of the positron fraction in primary cosmic rays of 0.5–350 GeV. Phys. Rev. Lett. 110, 141102.

Bergstrom, L., Bringmann, T., Edsjo, J., 2008. New positron spectral features from supersymmetric dark matter - a way to explain the PAMELA data? Phys. Rev. D 78, 103520. arXiv:0808.3725 [astro-ph].

Arkani-Hamed, N., Finkbeiner, D.P., Slatyer, T.R., Weiner, N., 2009. A theory of dark matter. Phys. Rev. D 79, 015014. arXiv:0810.0713 [hep-ph].

Cholis, I., Dobler, G., Finkbeiner, D.P., Goodenough, L., Weiner, N., 2009. The case for a 700+ GeV WIMP: cosmic ray spectra from ATIC and PAMELA. Phys. Rev. D 80, 123518. arXiv:0811.3641 [astro-ph].

Fox, P.J., Poppitz, E., 2009. Leptophilic dark matter. Phys. Rev. D 79, 083528. arXiv:0811.0399 [hep-ph].

Kopp, J., 2013. Constraints on dark matter annihilation from AMS-02 results. Phys. Rev. D 88, 076013. arXiv:1304.1184 [hep-ph].

Blasi, P., 2009. The origin of the positron excess in cosmic rays. Phys. Rev. Lett. 103, 051104. arXiv:0903.2794 [astro-ph.HE].

Mertsch, P., Sarkar, S., 2009. Testing astrophysical models for the PAMELA positron excess with cosmic ray nuclei. Phys. Rev. Lett. 103, 081104. arXiv:0905.3152 [astro-ph.HE].

Cholis, I., Hooper, D., 2013. Dark matter and pulsar origins of the rising cosmic ray positron fraction in light of new data from AMS. Phys. Rev. D 88, 023013. arXiv:1304.1840 [astro-ph.HE].

Ahlers, M., Mertsch, P., Sarkar, S., 2009. On cosmic ray acceleration in supernova remnants and the FERMI/PAMELA data. Phys. Rev. D 80, 123017. arXiv:0909.4060 [astro-ph.HE].

Mertsch, P., Sarkar, S., 2014. AMS-02 data confront acceleration of cosmic ray secondaries in nearby sources. Phys. Rev. D 90, 061301. arXiv:1402.0855 [astro-ph.HE].

Cholis, I., Hooper, D., Linden, T., 2017. Possible evidence for the stochastic acceleration of secondary antiprotons by supernova remnants. Phys. Rev. D 95 (12), 123007. arXiv:1701.04406 [astro-ph.HE].

Di Mauro, M., Donato, F., Fornengo, N., Lineros, R., Vittino, A., 2014. Interpretation of AMS-02 electrons and positrons data. J. Cosmol. Astropart. Phys. 04, 006. arXiv:1402.0321 [astro-ph.HE].

Planck Collaboration, Ade, P.A.R., et al., 2016. Planck 2015 results. XIII. Cosmological parameters. Astron. Astrophys. 594, A13. arXiv:1502.01589 [astro-ph.CO].

Madhavacheril, M.S., Sehgal, N., Slatyer, T.R., 2014. Current dark matter annihilation constraints from CMB and low-redshift data. Phys. Rev. D 89, 103508. arXiv:1310.3815 [astro-ph.CO].

Slatyer, T.R., 2016. Indirect dark matter signatures in the cosmic dark ages. I. Generalizing the bound on s-wave dark matter annihilation from Planck results. Phys. Rev. D 93 (2), 023527. arXiv:1506.03811 [hep-ph].

Dienes, K.R., Kumar, J., Thomas, B., 2013. Dynamical dark matter and the positron excess in light of AMS results. Phys. Rev. D 88 (10), 103509. arXiv:1306.2959 [hep-ph].

Baek, S., Ko, P., Park, W.-I., Tang, Y., 2014. Indirect and direct signatures of Higgs portal decaying vector dark matter for positron excess in cosmic rays. J. Cosmol. Astropart. Phys. 06, 046. arXiv:1402.2115 [hep-ph].

AMS Collaboration, Aguilar, M., et al., 2019. Towards understanding the origin of cosmic-ray positrons. Phys. Rev. Lett. 122 (4), 041102.

Bergstrom, L., Bringmann, T., Cholis, I., Hooper, D., Weniger, C., 2013. New limits on dark matter annihilation from AMS cosmic ray positron data. Phys. Rev. Lett. 111, 171101. arXiv:1306.3983 [astro-ph.HE].

John, I., Linden, T., 2021. Cosmic-ray positrons strongly constrain leptophilic dark matter. J. Cosmol. Astropart. Phys. 12 (12), 007. arXiv:2107.10261 [astro-ph.HE].

Malyshev, D., Cholis, I., Gelfand, J., 2009. Pulsars versus dark matter interpretation of ATIC/PAMELA. Phys. Rev. D 80, 063005. arXiv:0903.1310 [astro-ph.HE].

Profumo, S., 2011. Dissecting cosmic-ray electron-positron data with Occam's Razor: the role of known pulsars. Cent. Eur. J. Phys. 10, 1–31. arXiv:0812.4457 [astro-ph].

Hooper, D., Cholis, I., Linden, T., Fang, K., 2017. HAWC observations strongly favor pulsar interpretations of the cosmic-ray positron excess. Phys. Rev. D 96 (10), 103013. arXiv:1702.08436 [astro-ph.HE].

Linden, T., Auchettl, K., Bramante, J., Cholis, I., Fang, K., Hooper, D., Karwal, T., Li, S.W., 2017. Using HAWC to discover invisible pulsars. Phys. Rev. D 96 (10), 103016. arXiv:1703.09704 [astro-ph.HE].

Mertsch, P., 2018. Stochastic cosmic ray sources and the TeV break in the all-electron spectrum. J. Cosmol. Astropart. Phys. 11, 045. arXiv:1809.05104 [astro-ph.HE].

Cholis, I., Krommydas, I., 2022. Utilizing cosmic-ray positron and electron observations to probe the averaged properties of Milky Way pulsars. Phys. Rev. D 105 (2), 023015. arXiv:2111.05864 [astro-ph.HE].

Mukhopadhyay, P., Linden, T., 2021. Self-generated cosmic-ray turbulence can explain the morphology of TeV Halos. arXiv:2111.01143 [astro-ph.HE].

Caputo, A., n. Garay, C.P., Witte, S.J., 2018. Looking for axion dark matter in dwarf spheroidals. Phys. Rev. D 98 (8), 083024. arXiv:1805.08780 [astro-ph.CO], Erratum: Phys. Rev. D 99, 089901 (2019).

Caputo, A., Regis, M., Taoso, M., Witte, S.J., 2019. Detecting the stimulated decay of axions at RadioFrequencies. J. Cosmol. Astropart. Phys. 03, 027. arXiv:1811.08436 [hep-ph].

Battye, R.A., Garbrecht, B., McDonald, J.I., Pace, F., Srinivasan, S., 2020. Dark matter axion detection in the radio/mm-waveband. Phys. Rev. D 102 (2), 023504. arXiv:1910.11907 [astro-ph.CO].

Ghosh, O., Salvado, J., Miralda-Escudé, J., 2020. Axion gegenschein: probing back-scattering of astrophysical radio sources induced by dark matter. arXiv:2008.02729 [astro-ph.CO].

Arza, A., Todarello, E., 2022. Axion dark matter echo: a detailed analysis. Phys. Rev. D 105 (2), 023023. arXiv:2108.00195 [hep-ph].

Sun, Y., Schutz, K., Nambrath, A., Leung, C., Masui, K., 2021. An axion dark matter-induced echo of supernova remnants. arXiv:2110.13920 [hep-ph].

Buen-Abad, M.A., Fan, J., Sun, C., 2021a. Axion echos from the supernova graveyard. arXiv:2110.13916 [hep-ph].

Arza, A., Todarello, E., 2021. The Echo method for axion dark matter detection. Symmetry 13 (11), 2150.

Tkachev, I.I., 1987. An axionic laser in the center of a galaxy? Phys. Lett. B 191, 41–45.

Arza, A., 2019. Photon enhancement in a homogeneous axion dark matter background. Eur. Phys. J. C 79 (3), 250. arXiv:1810.03722 [hep-ph].

Hertzberg, M.P., Schiappacasse, E.D., 2018. Dark matter axion clump resonance of photons. J. Cosmol. Astropart. Phys. 11, 004. arXiv:1805.00430 [hep-ph].

Sigl, G., Trivedi, P., 2019. Axion condensate dark matter constraints from resonant enhancement of background radiation. arXiv:1907.04849 [astro-ph.CO].

Alonso-Álvarez, G., Gupta, R.S., Jaeckel, J., Spannowsky, M., 2020. On the wondrous stability of ALP dark matter. J. Cosmol. Astropart. Phys. 03, 052. arXiv:1911.07885 [hep-ph].

Arza, A., Schwetz, T., Todarello, E., 2020. How to suppress exponential growth—on the parametric resonance of photons in an axion background. J. Cosmol. Astropart. Phys. 10, 013. arXiv:2004.01669 [hep-ph].

Ikeda, T., Brito, R., Cardoso, V., 2019. Blasts of light from axions. Phys. Rev. Lett. 122 (8), 081101. arXiv:1811.04950 [gr-qc].

Blas, D., Witte, S.J., 2020a. Imprints of axion superradiance in the CMB. Phys. Rev. D 102 (10), 103018. arXiv:2009.10074 [astro-ph.CO].

Prabhu, A., 2020. Optical lensing by axion stars: observational prospects with radio astrometry. arXiv:2006.10231 [astro-ph.CO].

Raffelt, G., Stodolsky, L., 1988. Mixing of the photon with low mass particles. Phys. Rev. D 37, 1237.

Dessert, C., Dunsky, D., Safdi, B.R., 2022a. Upper limit on the axion-photon coupling from magnetic white dwarf polarization. arXiv:2203.04319 [hep-ph].

Harari, D., Sikivie, P., 1992. Effects of a Nambu-Goldstone boson on the polarization of radio galaxies and the cosmic microwave background. Phys. Lett. B 289, 67–72.

Plascencia, A.D., Urbano, A., 2018. Black hole superradiance and polarization-dependent bending of light. J. Cosmol. Astropart. Phys. 04, 059. arXiv:1711.08298 [gr-qc].

Fujita, T., Tazaki, R., Toma, K., 2019. Hunting axion dark matter with protoplanetary disk polarimetry. Phys. Rev. Lett. 122 (19), 191101. arXiv:1811.03525 [astro-ph.CO].

Ivanov, M.M., Kovalev, Y.Y., Lister, M.L., Panin, A.G., Pushkarev, A.B., Savolainen, T., Troitsky, S.V., 2019. Constraining the photon coupling of ultra-light dark-matter axion-like particles by polarization variations of parsec-scale jets in active galaxies. J. Cosmol. Astropart. Phys. 02, 059. arXiv:1811.10997 [astro-ph.CO].

McDonald, J.I., Ventura, L.B., 2020. Optical properties of dynamical axion backgrounds. Phys. Rev. D 101 (12), 123503. arXiv:1911.10221 [hep-ph].

Fedderke, M.A., Graham, P.W., Rajendran, S., 2019. Axion dark matter detection with CMB polarization. Phys. Rev. D 100 (1), 015040. arXiv:1903.02666 [astro-ph.CO].

Chen, Y., Shu, J., Xue, X., Yuan, Q., Zhao, Y., 2020. Probing axions with event horizon telescope polarimetric measurements. Phys. Rev. Lett. 124 (6), 061102. arXiv:1905.02213 [hep-ph].

Mcdonald, J.I., Ventura, L.B., 2020. Bending of light in axion backgrounds. arXiv:2008.12923 [hep-ph].

Castillo, A., Martin-Camalich, J., Terol-Calvo, J., Blas, D., Caputo, A., Santos, R.T.G., Sberna, L., Peel, M., Rubiño Martín, J.A., 2022. Searching for dark-matter waves with PPTA and QUIJOTE pulsar polarimetry. arXiv:2201.03422 [astro-ph.CO].

Prabhu, A., 2021. Axion production in pulsar magnetosphere gaps. Phys. Rev. D 104 (5), 055038. arXiv:2104.14569 [hep-ph].

Raffelt, G.G., 2008. Astrophysical axion bounds. Lect. Notes Phys. 741, 51–71. arXiv:hep-ph/0611350.

Raffelt, G., Weiss, A., 1995. Red giant bound on the axion - electron coupling revisited. Phys. Rev. D 51, 1495–1498. arXiv:hep-ph/9410205.

Corsico, A.H., Benvenuto, O.G., Althaus, L.G., Isern, J., Garcia-Berro, E., 2001. The potential of the variable DA white dwarf G117 - B15A as a tool for fundamental physics. New Astron. 6, 197–213. arXiv:astro-ph/0104103.

Isern, J., Garcia-Berro, E., Torres, S., Catalan, S., 2008. Axions and the cooling of white dwarf stars. Astrophys. J. Lett. 682, L109. arXiv:0806.2807 [astro-ph].

Sedrakian, A., 2016. Axion cooling of neutron stars. Phys. Rev. D 93 (6), 065044. arXiv:1512.07828 [astro-ph.HE].

Hamaguchi, K., Nagata, N., Yanagi, K., Zheng, J., 2018. Limit on the axion decay constant from the cooling neutron star in Cassiopeia A. Phys. Rev. D 98 (10), 103015. arXiv:1806.07151 [hep-ph].

Buschmann, M., Dessert, C., Foster, J.W., Long, A.J., Safdi, B.R., 2021. Upper limit on the QCD axion mass from isolated neutron star cooling. arXiv:2111.09892 [hep-ph].

Dessert, C., Long, A.J., Safdi, B.R., 2022b. No evidence for axions from chandra observation of the magnetic white dwarf RE J0317-853. Phys. Rev. Lett. 128 (7), 071102. arXiv:2104.12772 [hep-ph].

Foster, J.W., Witte, S.J., Lawson, M., Linden, T., Gajjar, V., Weniger, C., Safdi, B.R., 2022. Extraterrestrial axion search with the breakthrough listen galactic center survey. arXiv:2202.08274 [astro-ph.CO].

HAYSTAC Collaboration, Zhong, L., et al., 2018. Results from phase 1 of the HAYSTAC microwave cavity axion experiment. Phys. Rev. D 97 (9), 092001. arXiv:1803.03690 [hep-ex].

HAYSTAC Collaboration, Backes, K.M., et al., 2021. A quantum-enhanced search for dark matter axions. Nature 590 (7845), 238–242. arXiv:2008.01853 [quant-ph].

ADMX Collaboration, Braine, T., et al., 2020. Extended search for the invisible axion with the axion dark matter experiment. Phys. Rev. Lett. 124 (10), 101303. arXiv:1910.08638 [hep-ex].

Crisosto, N., Sikivie, P., Sullivan, N.S., Tanner, D.B., Yang, J., Rybka, G., 2020. ADMX SLIC: results from a superconducting *LC* circuit investigating cold axions. Phys. Rev. Lett. 124 (24), 241101. arXiv:1911.05772 [astro-ph.CO].

ADMX Collaboration, Bartram, C., et al., 2021. Search for invisible axion dark matter in the 3.3–4.2 μeV mass range. Phys. Rev. Lett. 127 (26), 261803. arXiv:2110.06096 [hep-ex].

CAST Collaboration, Anastassopoulos, V., et al., 2017. New CAST limit on the axion-photon interaction. Nat. Phys. 13, 584–590. arXiv:1705.02290 [hep-ex].

Pshirkov, M.S., Popov, S.B., 2009. Conversion of dark matter axions to photons in magnetospheres of neutron stars. J. Exp. Theor. Phys. 108, 384–388. arXiv:0711.1264 [astro-ph].

Huang, F.P., Kadota, K., Sekiguchi, T., Tashiro, H., 2018. Radio telescope search for the resonant conversion of cold dark matter axions from the magnetized astrophysical sources. Phys. Rev. D 97 (12), 123001. arXiv:1803.08230 [hep-ph].

Hook, A., Kahn, Y., Safdi, B.R., Sun, Z., 2018. Radio signals from axion dark matter conversion in neutron star magnetospheres. Phys. Rev. Lett. 121 (24), 241102. arXiv:1804.03145 [hep-ph].

Safdi, B.R., Sun, Z., Chen, A.Y., 2019. Detecting axion dark matter with radio lines from neutron star populations. Phys. Rev. D 99 (12), 123021. arXiv:1811.01020 [astro-ph.CO].

Leroy, M., Chianese, M., Edwards, T.D.P., Weniger, C., 2020. Radio signal of axion-photon conversion in neutron stars: a ray tracing analysis. Phys. Rev. D 101 (12), 123003. arXiv:1912.08815 [hep-ph].

Witte, S.J., Noordhuis, D., Edwards, T.D.P., Weniger, C., 2021. Axion-photon conversion in neutron star magnetospheres: the role of the plasma in the Goldreich-Julian model. Phys. Rev. D 104 (10), 103030. arXiv:2104.07670 [hep-ph].

Battye, R.A., Garbrecht, B., McDonald, J.I., Srinivasan, S., 2021. Radio line properties of axion dark matter conversion in neutron stars. J. High Energy Phys. 09, 105. arXiv:2104.08290 [hep-ph].

Sen, S., Sivertsen, L., 2022. Electromagnetic radiation from axion condensates in a time dependent magnetic field. J. High Energy Phys. 05, 192. arXiv:2111.08728 [hep-ph].

Goldreich, P., Julian, W.H., 1969. Pulsar electrodynamics. Astrophys. J. 157, 869.

Irastorza, I.G., Redondo, J., 2018. New experimental approaches in the search for axion-like particles. Prog. Part. Nucl. Phys. 102, 89–159. arXiv:1801.08127 [hep-ph].

Edwards, T.D.P., Kavanagh, B.J., Visinelli, L., Weniger, C., 2021a. Transient radio signatures from neutron star encounters with QCD axion miniclusters. Phys. Rev. Lett. 127 (13), 131103. arXiv:2011.05378 [hep-ph].

Foster, J.W., Kahn, Y., Macias, O., Sun, Z., Eatough, R.P., Kondratiev, V.I., Peters, W.M., Weniger, C., Safdi, B.R., 2020. Green bank and effelsberg radio telescope searches for axion dark matter conversion in neutron star magnetospheres. Phys. Rev. Lett. 125 (17), 171301. arXiv:2004.00011 [astro-ph.CO].

Battye, R.A., Darling, J., McDonald, J.I., Srinivasan, S., 2022. Towards robust constraints on axion dark matter using PSR J1745-2900. Phys. Rev. D 105 (2), L021305. arXiv:2107.01225 [astro-ph.CO].

Millar, A.J., Baum, S., Lawson, M., Marsh, M.C.D., 2021. Axion-photon conversion in strongly magnetised plasmas. J. Cosmol. Astropart. Phys. 11, 013. arXiv:2107.07399 [hep-ph].

Dessert, C., Foster, J.W., Safdi, B.R., 2020c. X-ray searches for axions from super star clusters. Phys. Rev. Lett. 125 (26), 261102. arXiv:2008.03305 [hep-ph].

Wouters, D., Brun, P., 2013. Constraints on axion-like particles from X-ray observations of the hydra galaxy cluster. Astrophys. J. 772, 44. arXiv:1304.0989 [astro-ph.HE].

Marsh, M.C.D., Russell, H.R., Fabian, A.C., McNamara, B.P., Nulsen, P., Reynolds, C.S., 2017. A new bound on axion-like particles. J. Cosmol. Astropart. Phys. 12, 036. arXiv:1703.07354 [hep-ph].

Reynolds, C.S., Marsh, M.C.D., Russell, H.R., Fabian, A.C., Smith, R., Tombesi, F., Veilleux, S., 2019. Astrophysical limits on very light axion-like particles from Chandra grating spectroscopy of NGC 1275. arXiv:1907.05475 [hep-ph].

Xiao, M., Perez, K.M., Giannotti, M., Straniero, O., Mirizzi, A., Grefenstette, B.W., Roach, B.M., Nynka, M., 2021. Constraints on axionlike particles from a hard X-ray observation of Betelgeuse. Phys. Rev. Lett. 126 (3), 031101. arXiv:2009.09059 [astro-ph.HE].

Reynés, J.S., Matthews, J.H., Reynolds, C.S., Russell, H.R., Smith, R.N., Marsh, M.C.D., 2021. New constraints on light axion-like particles using chandra transmission grating spectroscopy of the powerful cluster-hosted quasar H1821+643. arXiv:2109.03261 [astro-ph.HE].

Fermi-LAT Collaboration, Ajello, M., et al., 2016. Search for spectral irregularities due to photon–axionlike-particle oscillations with the Fermi large area telescope. Phys. Rev. Lett. 116 (16), 161101. arXiv:1603.06978 [astro-ph.HE].

Meyer, M., Giannotti, M., Mirizzi, A., Conrad, J., Sánchez-Conde, M.A., 2017. Fermi large area telescope as a galactic supernovae axionscope. Phys. Rev. Lett. 118 (1), 011103. arXiv:1609.02350 [astro-ph.HE].

Li, H.-J., Guo, J.-G., Bi, X.-J., Lin, S.-J., Yin, P.-F., 2021a. Limits on axion-like particles from Mrk 421 with 4.5-year period observations by ARGO-YBJ and Fermi-LAT. Phys. Rev. D 103 (8), 083003. arXiv:2008.09464 [astro-ph.HE].

Meyer, M., Petrushevska, T., 2020. Search for axionlike-particle-induced prompt γ-ray emission from extragalactic core-collapse supernovae with the *Fermi* large area telescope. Phys. Rev. Lett. 124 (23), 231101. arXiv:2006.06722 [astro-ph.HE], Erratum: Phys. Rev. Lett. 125, 119901 (2020).

Calore, F., Carenza, P., Eckner, C., Fischer, T., Giannotti, M., Jaeckel, J., Kotake, K., Kuroda, T., Mirizzi, A., Sivo, F., 2021. 3D template-based *Fermi*-LAT constraints on axion-like particles. arXiv:2110.03679 [astro-ph.HE].

H.E.S.S. Collaboration, Abramowski, A., et al., 2013. Constraints on axionlike particles with H.E.S.S. from the irregularity of the PKS 2155-304 energy spectrum. Phys. Rev. D 88 (10), 102003. arXiv:1311.3148 [astro-ph.HE].

Kamiokande-II Collaboration, Hirata, K., et al., 1987. Observation of a neutrino burst from the supernova SN 1987a. Phys. Rev. Lett. 58, 1490–1493.

IMB Collaboration, Haines, T., et al., 1988. Neutrinos from SN1987A in the Imb Detector. Nucl. Instrum. Methods A 264, 28–31.

Burrows, A., Lattimer, J.M., 1986. The birth of neutron stars. Astrophys. J. 307, 178–196.

Burrows, A., Lattimer, J.M., 1987. Neutrinos from SN 1987A. Astrophys. J. Lett. 318, L63–L68.

Turner, M.S., 1988. Axions from SN 1987a. Phys. Rev. Lett. 60, 1797.

Raffelt, G., Seckel, D., 1988. Bounds on exotic particle interactions from SN 1987a. Phys. Rev. Lett. 60, 1793.

Burrows, A., Turner, M.S., Brinkmann, R.P., 1989. Axions and SN 1987a. Phys. Rev. D 39, 1020.

Burrows, A., Ressell, M.T., Turner, M.S., 1990. Axions and SN1987A: axion trapping. Phys. Rev. D 42, 3297–3309.

Keil, W., Janka, H.-T., Schramm, D.N., Sigl, G., Turner, M.S., Ellis, J.R., 1997. A fresh look at axions and SN-1987A. Phys. Rev. D 56, 2419–2432. arXiv:astro-ph/9612222.

Raffelt, G.G. Stars as Laboratories for Fundamental Physics: The Astrophysics of Neutrinos, Axions, and Other Weakly Interacting Particles.

Chang, J.H., Essig, R., McDermott, S.D., 2018b. Supernova 1987A constraints on sub-GeV dark sectors, millicharged particles, the QCD axion, and an axion-like particle. J. High Energy Phys. 09, 051. arXiv:1803.00993 [hep-ph].

Rrapaj, E., Reddy, S., 2016. Nucleon-nucleon bremsstrahlung of dark gauge bosons and revised supernova constraints. Phys. Rev. C 94 (4), 045805. arXiv:1511.09136 [nucl-th].

Chang, J.H., Essig, R., McDermott, S.D., 2017. Revisiting supernova 1987A constraints on dark photons. J. High Energy Phys. 01, 107. arXiv:1611.03864 [hep-ph].

Hardy, E., Lasenby, R., 2017. Stellar cooling bounds on new light particles: plasma mixing effects. J. High Energy Phys. 02, 033. arXiv:1611.05852 [hep-ph].

Bollig, R., Janka, H.T., Lohs, A., Martinez-Pinedo, G., Horowitz, C.J., Melson, T., 2017. Muon creation in supernova matter facilitates neutrino-driven explosions. Phys. Rev. Lett. 119 (24), 242702. arXiv:1706.04630 [astro-ph.HE].

Burrows, A., Vartanyan, D., 2021. Core-collapse supernova explosion theory. Nature 589 (7840), 29–39. arXiv:2009.14157 [astro-ph.SR].

Gondolo, P., Raffelt, G.G., 2009. Solar neutrino limit on axions and keV-mass bosons. Phys. Rev. D 79, 107301. arXiv:0807.2926 [astro-ph].

An, H., Pospelov, M., Pradler, J., 2013. New stellar constraints on dark photons. Phys. Lett. B 725, 190–195. arXiv:1302.3884 [hep-ph].

Redondo, J., Raffelt, G., 2013. Solar constraints on hidden photons re-visited. J. Cosmol. Astropart. Phys. 08, 034. arXiv:1305.2920 [hep-ph].

Viaux, N., Catelan, M., Stetson, P.B., Raffelt, G., Redondo, J., Valcarce, A.A.R., Weiss, A., 2013. Neutrino and axion bounds from the globular cluster M5 (NGC 5904). Phys. Rev. Lett. 111, 231301. arXiv:1311.1669 [astro-ph.SR].

LIGO Scientific, Virgo Collaboration, Abbott, R., et al., 2021. Population properties of compact objects from the second LIGO-Virgo gravitational-wave transient catalog. Astrophys. J. Lett. 913 (1), L7. arXiv:2010.14533 [astro-ph.HE].

LIGO Scientific, VIRGO, KAGRA Collaboration, Abbott, R., et al., 2021. The population of merging compact binaries inferred using gravitational waves through GWTC-3. arXiv:2111.03634 [astro-ph.HE].

Farmer, R., Renzo, M., de Mink, S.E., Marchant, P., Justham, S., 2019. Mind the gap: the location of the lower edge of the pair instability supernovae black hole mass gap. arXiv:1910.12874 [astro-ph.SR].

Mehta, A.K., Buonanno, A., Gair, J., Miller, M.C., Farag, E., deBoer, R.J., Wiescher, M., Timmes, F.X., 2022. Observing intermediate-mass black holes and the upper stellar-mass gap with LIGO and Virgo. Astrophys. J. 924 (1), 39. arXiv:2105.06366 [gr-qc].

Croon, D., McDermott, S.D., Sakstein, J., 2020a. New physics and the black hole mass gap. Phys. Rev. D 102 (11), 115024. arXiv:2007.07889 [gr-qc].

Croon, D., McDermott, S.D., Sakstein, J., 2021a. Missing in axion: where are XENON1T's big black holes? Phys. Dark Universe 32, 100801. arXiv:2007.00650 [hep-ph].

Sakstein, J., Croon, D., McDermott, S.D., Straight, M.C., Baxter, E.J., 2020. Beyond the standard model explanations of GW190521. Phys. Rev. Lett. 125 (26), 261105. arXiv:2009.01213 [gr-qc].

Ziegler, J., Freese, K., 2021. Filling the black hole mass gap: avoiding pair instability in massive stars through addition of nonnuclear energy. Phys. Rev. D 104 (4), 043015. arXiv:2010.00254 [astro-ph.HE].

Baxter, E.J., Croon, D., McDermott, S.D., Sakstein, J., 2021. Find the gap: black hole population analysis with an astrophysically motivated mass function. Astrophys. J. Lett. 916 (2), L16. arXiv:2104.02685 [astro-ph.CO].

Ellis, S.A.R., 2021. Premature black hole death of population III stars by dark matter. arXiv:2111.02414 [astro-ph.CO].

Dolan, M.J., Hiskens, F.J., Volkas, R.R., 2021. Constraining axion-like particles using the white dwarf initial-final mass relation. J. Cosmol. Astropart. Phys. 09, 010. arXiv:2102.00379 [hep-ph].

Dicke, R.H., 1954. Coherence in spontaneous radiation processes. Phys. Rev. 93, 99–110.

Penrose, R., Floyd, R.M., 1971. Extraction of rotational energy from a black hole. Nature 229, 177–179.

Zel'Dovich, Y.B., 1971. Generation of waves by a rotating body. Sov. JETPhys. Lett. 14, 180.

Misner, C.W., 1972. Interpretation of gravitational-wave observations. Phys. Rev. Lett. 28, 994–997.

Starobinsky, A.A., 1973. Amplification of waves reflected from a rotating "black hole". Sov. Phys. JETP 37 (1), 28–32.

Cardoso, V., Dias, O.J.C., Lemos, J.P.S., Yoshida, S., 2004. The Black hole bomb and superradiant instabilities. Phys. Rev. D 70, 044039. arXiv:hep-th/0404096, Erratum: Phys. Rev. D 70, 049903 (2004).

Arvanitaki, A., Dimopoulos, S., Dubovsky, S., Kaloper, N., March-Russell, J., 2010. String axiverse. Phys. Rev. D 81, 123530. arXiv:0905.4720 [hep-th].

Bredberg, I., Hartman, T., Song, W., Strominger, A., 2010. Black hole superradiance from Kerr/CFT. J. High Energy Phys. 04, 019. arXiv:0907.3477 [hep-th].

Cardoso, V., Pani, P., 2013. Tidal acceleration of black holes and superradiance. Class. Quantum Gravity 30, 045011. arXiv:1205.3184 [gr-qc].

Herdeiro, C.A.R., Degollado, J.C., Rúnarsson, H.F., 2013. Rapid growth of superradiant instabilities for charged black holes in a cavity. Phys. Rev. D 88, 063003. arXiv:1305.5513 [gr-qc].

East, W.E., Ramazanoğlu, F.M., Pretorius, F., 2014. Black hole superradiance in dynamical spacetime. Phys. Rev. D 89 (6), 061503. arXiv:1312.4529 [gr-qc].

Degollado, J.C., Herdeiro, C.A.R., 2014. Time evolution of superradiant instabilities for charged black holes in a cavity. Phys. Rev. D 89 (6), 063005. arXiv:1312.4579 [gr-qc].

Brito, R., Cardoso, V., Pani, P., 2014. Superradiant instability of black holes immersed in a magnetic field. Phys. Rev. D 89 (10), 104045. arXiv:1405.2098 [gr-qc].

Arvanitaki, A., Baryakhtar, M., Huang, X., 2015. Discovering the QCD axion with black holes and gravitational waves. Phys. Rev. D 91 (8), 084011. arXiv:1411.2263 [hep-ph].

Rosa, J.G., 2015. Testing black hole superradiance with pulsar companions. Phys. Lett. B 749, 226–230. arXiv:1501.07605 [gr-qc].

Cardoso, V., Brito, R., Rosa, J.L., 2015. Superradiance in stars. Phys. Rev. D 91 (12), 124026. arXiv:1505.05509 [gr-qc].

Wang, M., Herdeiro, C., 2016. Maxwell perturbations on Kerr–anti–de Sitter black holes: quasinormal modes, superradiant instabilities, and vector clouds. Phys. Rev. D 93 (6), 064066. arXiv:1512.02262 [gr-qc].

Brito, R., Cardoso, V., Pani, P., 2015. Superradiance: new frontiers in black hole physics. Lect. Notes Phys. 906, 1–237. arXiv:1501.06570 [gr-qc].

Endlich, S., Penco, R., 2017. A modern approach to superradiance. J. High Energy Phys. 05, 052. arXiv:1609.06723 [hep-th].

Rosa, J.G., 2017. Superradiance in the sky. Phys. Rev. D 95 (6), 064017. arXiv:1612.01826 [gr-qc].

Baryakhtar, M., Lasenby, R., Teo, M., 2017b. Black hole superradiance signatures of ultralight vectors. Phys. Rev. D 96 (3), 035019. arXiv:1704.05081 [hep-ph].

East, W.E., Pretorius, F., 2017. Superradiant instability and backreaction of massive vector fields around Kerr black holes. Phys. Rev. Lett. 119 (4), 041101. arXiv:1704.04791 [gr-qc].

Cardoso, V., Pani, P., Yu, T.-T., 2017. Superradiance in rotating stars and pulsar-timing constraints on dark photons. Phys. Rev. D 95 (12), 124056. arXiv:1704.06151 [gr-qc].

Rosa, J.a.G., Kephart, T.W., 2018. Stimulated axion decay in superradiant clouds around primordial black holes. Phys. Rev. Lett. 120 (23), 231102. arXiv:1709.06581 [gr-qc].

Frolov, V.P., Krtouš, P., Kubizňák, D., Santos, J.E., 2018. Massive vector fields in rotating black-hole spacetimes: separability and quasinormal modes. Phys. Rev. Lett. 120, 231103. arXiv:1804.00030 [hep-th].

Sen, S., 2018. Plasma effects on lasing of a uniform ultralight axion condensate. Phys. Rev. D 98 (10), 103012. arXiv:1805.06471 [hep-ph].

Cardoso, V., Dias, O.J.C., Hartnett, G.S., Middleton, M., Pani, P., Santos, J.E., 2018. Constraining the mass of dark photons and axion-like particles through black-hole superradiance. J. Cosmol. Astropart. Phys. 03, 043. arXiv:1801.01420 [gr-qc].

Barack, L., et al., 2019. Black holes, gravitational waves and fundamental physics: a roadmap. Class. Quantum Gravity 36 (14), 143001. arXiv:1806.05195 [gr-qc].

Degollado, J.C., Herdeiro, C.A.R., Radu, E., 2018. Effective stability against superradiance of Kerr black holes with synchronised hair. Phys. Lett. B 781, 651–655. arXiv:1802.07266 [gr-qc].

Ficarra, G., Pani, P., Witek, H., 2019. Impact of multiple modes on the black-hole superradiant instability. Phys. Rev. D 99 (10), 104019. arXiv:1812.02758 [gr-qc].

Baumann, D., Chia, H.S., Stout, J., ter Haar, L., 2019. The spectra of gravitational atoms. J. Cosmol. Astropart. Phys. 12, 006. arXiv:1908.10370 [gr-qc].

Cardoso, V., Duque, F., Ikeda, T., 2020. Tidal effects and disruption in superradiant clouds: a numerical investigation. Phys. Rev. D 101 (6), 064054. arXiv:2001.01729 [gr-qc].

Dima, A., Barausse, E., 2020. Numerical investigation of plasma-driven superradiant instabilities. Class. Quantum Gravity 37 (17), 175006. arXiv:2001.11484 [gr-qc].

Brito, R., Grillo, S., Pani, P., 2020. Black hole superradiant instability from ultralight spin-2 fields. Phys. Rev. Lett. 124 (21), 211101. arXiv:2002.04055 [gr-qc].

Stott, M.J., 2020. Ultralight bosonic field mass bounds from astrophysical black hole spin. arXiv:2009.07206 [hep-ph].

Blas, D., Witte, S.J., 2020b. Quenching mechanisms of photon superradiance. Phys. Rev. D 102 (12), 123018. arXiv:2009.10075 [hep-ph].

Mehta, V.M., Demirtas, M., Long, C., Marsh, D.J.E., Mcallister, L., Stott, M.J., 2020. Superradiance exclusions in the landscape of type IIB string theory. arXiv:2011.08693 [hep-th].

Baryakhtar, M., Galanis, M., Lasenby, R., Simon, O., 2021. Black hole superradiance of self-interacting scalar fields. Phys. Rev. D 103 (9), 095019. arXiv:2011.11646 [hep-ph].

Ünal, C., Pacucci, F., Loeb, A., 2021. Properties of ultralight bosons from heavy quasar spins via superradiance. J. Cosmol. Astropart. Phys. 05, 007. arXiv:2012.12790 [hep-ph].

Franzin, E., Liberati, S., Oi, M., 2021. Superradiance in Kerr-like black holes. Phys. Rev. D 103 (10), 104034. arXiv:2102.03152 [gr-qc].

Caputo, A., Witte, S.J., Blas, D., Pani, P., 2021. Electromagnetic signatures of dark photon superradiance. Phys. Rev. D 104 (4), 043006. arXiv:2102.11280 [hep-ph].

Mehta, V.M., Demirtas, M., Long, C., Marsh, D.J.E., McAllister, L., Stott, M.J., 2021. Superradiance in string theory. J. Cosmol. Astropart. Phys. 07, 033. arXiv:2103.06812 [hep-th].

Cannizzaro, E., Caputo, A., Sberna, L., Pani, P., 2021. Plasma-photon interaction in curved spacetime. II. Collisions, thermal corrections, and superradiant instabilities. Phys. Rev. D 104 (10), 104048. arXiv:2107.01174 [gr-qc].

Jiang, R., Lin, R.-H., Zhai, X.-H., 2021a. Superradiant instability of a Kerr-like black hole in Einstein-bumblebee gravity. Phys. Rev. D 104 (12), 124004. arXiv:2108.04702 [gr-qc].

Karmakar, R., Maity, D., 2021. Ringing black hole is superradiant: ultra-light scalar field. arXiv:2109.10940 [gr-qc].

Khodadi, M., Pourkhodabakhshi, R., 2021. Superradiance and stability of Kerr black hole enclosed by anisotropic fluid matter. Phys. Lett. B 823, 136775. arXiv:2111.03316 [gr-qc].

Buckley, M.R., Peter, A.H.G., 2018. Gravitational probes of dark matter physics. Phys. Rep. 761, 1–60. arXiv:1712.06615 [astro-ph.CO].

Gluscevic, V., et al., 2019. Cosmological probes of dark matter interactions: the next decade. arXiv:1903.05140 [astro-ph.CO].

Sabti, N., Muñoz, J.B., Blas, D., 2021. New roads to the small-scale Universe: measurements of the clustering of matter with the high-redshift UV galaxy luminosity function. arXiv:2110.13161 [astro-ph.CO].

Schwaller, P., 2015. Gravitational waves from a dark phase transition. Phys. Rev. Lett. 115 (18), 181101. arXiv:1504.07263 [hep-ph].

Croon, D., Sanz, V., White, G., 2018. Model discrimination in gravitational wave spectra from dark phase transitions. J. High Energy Phys. 08, 203. arXiv:1806.02332 [hep-ph].

Breitbach, M., Kopp, J., Madge, E., Opferkuch, T., Schwaller, P., 2019. Dark, cold, and noisy: constraining secluded hidden sectors with gravitational waves. J. Cosmol. Astropart. Phys. 07, 007. arXiv:1811.11175 [hep-ph].

Fairbairn, M., Hardy, E., Wickens, A., 2019. Hearing without seeing: gravitational waves from hot and cold hidden sectors. J. High Energy Phys. 07, 044. arXiv:1901.11038 [hep-ph].

Bertone, G., et al., 2020. Gravitational wave probes of dark matter: challenges and opportunities. SciPost Phys. Core 3, 007. arXiv:1907.10610 [astro-ph.CO].

Bai, Y., Long, A.J., Lu, S., 2019b. Dark quark nuggets. Phys. Rev. D 99 (5), 055047. arXiv:1810.04360 [hep-ph].

Helmboldt, A.J., Kubo, J., van der Woude, S., 2019. Observational prospects for gravitational waves from hidden or dark chiral phase transitions. Phys. Rev. D 100 (5), 055025. arXiv:1904.07891 [hep-ph].

Croon, D., Houtz, R., Sanz, V., 2019. Dynamical axions and gravitational waves. J. High Energy Phys. 07, 146. arXiv:1904.10967 [hep-ph].

Reichert, M., Sannino, F., Wang, Z.-W., Zhang, C., 2022. Dark confinement and chiral phase transitions: gravitational waves vs matter representations. J. High Energy Phys. 01, 003. arXiv:2109.11552 [hep-ph].

Kainulainen, K., Keus, V., Niemi, L., Rummukainen, K., Tenkanen, T.V.I., Vaskonen, V., 2019. On the validity of perturbative studies of the electroweak phase transition in the two Higgs doublet model. J. High Energy Phys. 06, 075. arXiv:1904.01329 [hep-ph].

Croon, D., Gould, O., Schicho, P., Tenkanen, T.V.I., White, G., 2021b. Theoretical uncertainties for cosmological first-order phase transitions. J. High Energy Phys. 04, 055. arXiv:2009.10080 [hep-ph].

Gould, O., Tenkanen, T.V.I., 2021. On the perturbative expansion at high temperature and implications for cosmological phase transitions. J. High Energy Phys. 06, 069. arXiv:2104.04399 [hep-ph].

Kolb, E.W., Tkachev, I.I., 1994a. Nonlinear axion dynamics and the formation of cosmological pseudosolitons. Phys. Rev. D 49, 5040–5051. https://link.aps.org/doi/10.1103/PhysRevD.49.5040.

Zurek, K.M., Hogan, C.J., Quinn, T.R., 2007. Astrophysical effects of scalar dark matter miniclusters. Phys. Rev. D 75, 043511. https://link.aps.org/doi/10.1103/PhysRevD.75.043511.

Kolb, E.W., Tkachev, I.I., 1994b. Large-amplitude isothermal fluctuations and high-density dark-matter clumps. Phys. Rev. D 50, 769–773. https://link.aps.org/doi/10.1103/PhysRevD.50.769.

Hardy, E., 2017. Miniclusters in the axiverse. J. High Energy Phys. 02, 046. arXiv:1609.00208 [hep-ph].

Davidson, S., Schwetz, T., 2016. Rotating drops of axion dark matter. Phys. Rev. D 93, 123509. https://link.aps.org/doi/10.1103/PhysRevD.93.123509.

Enander, J., Pargner, A., Schwetz, T., 2017. Axion minicluster power spectrum and mass function. J. Cosmol. Astropart. Phys. 2017 (12), 038. https://doi.org/10.1088/1475-7516/2017/12/038.

Kolb, E.W., Tkachev, I.I., 1996. Femtolensing and picolensing by axion miniclusters. Astrophys. J. 460 (1). https://doi.org/10.1086/309962.

Tkachev, I.I., 2015. Fast radio bursts and axion miniclusters. JETP Lett. 101 (1), 1–6. arXiv:1411.3900 [astro-ph.HE].

Pshirkov, M.S., 2017. May axion clusters be sources of fast radio bursts? Int. J. Mod. Phys. D 26 (07), 1750068. arXiv:1609.09658 [astro-ph.HE].

Fairbairn, M., Marsh, D.J.E., Quevillon, J., Rozier, S., 2018. Structure formation and microlensing with axion miniclusters. Phys. Rev. D 97, 083502. https://link.aps.org/doi/10.1103/PhysRevD.97.083502.

Katz, A., Kopp, J., Sibiryakov, S., Xue, W., 2018. Femtolensing by dark matter revisited. J. Cosmol. Astropart. Phys. 2018 (12), 005. https://doi.org/10.1088/1475-7516/2018/12/005.

Dai, L., Miralda-Escudé, J., 2020a. Gravitational lensing signatures of axion dark matter minihalos in highly magnified stars. Astron. J. 159 (2), 49. https://doi.org/10.3847/1538-3881/ab5e83.

Croon, D., McKeen, D., Raj, N., 2020b. Gravitational microlensing by dark matter in extended structures. Phys. Rev. D 101, 083013. https://link.aps.org/doi/10.1103/PhysRevD.101.083013.

Edwards, T.D.P., Kavanagh, B.J., Visinelli, L., Weniger, C., 2021b. Transient radio signatures from neutron star encounters with QCD axion miniclusters. Phys. Rev. Lett. 127, 131103. https://link.aps.org/doi/10.1103/PhysRevLett.127.131103.

Kawasaki, M., Kohri, K., Sugiyama, N., 1999. Cosmological constraints on late time entropy production. Phys. Rev. Lett. 82, 4168. arXiv:astro-ph/9811437.

Kawasaki, M., Kohri, K., Sugiyama, N., 2000. MeV scale reheating temperature and thermalization of neutrino background. Phys. Rev. D 62, 023506. arXiv:astro-ph/0002127.

Allahverdi, R., et al., 2020. The first three seconds: a review of possible expansion histories of the early Universe. arXiv:2006.16182 [astro-ph.CO].

Kamionkowski, M., Turner, M.S., 1990. Thermal relics: do we know their abundances? Phys. Rev. D 42, 3310–3320. https://link.aps.org/doi/10.1103/PhysRevD.42.3310.

Profumo, S., Ullio, P., 2003. SUSY dark matter and quintessence. J. Cosmol. Astropart. Phys. 11, 006. arXiv:hep-ph/0309220.

Pallis, C., 2005. Quintessential kination and cold dark matter abundance. J. Cosmol. Astropart. Phys. 10, 015. arXiv:hep-ph/0503080.

D'Eramo, F., Fernandez, N., Profumo, S., 2017. When the Universe expands too fast: relentless dark matter. J. Cosmol. Astropart. Phys. 05, 012. arXiv:1703.04793 [hep-ph].

Redmond, K., Erickcek, A.L., 2017. New constraints on dark matter production during kination. Phys. Rev. D 96 (4), 043511. arXiv:1704.01056 [hep-ph].

Giudice, G.F., Kolb, E.W., Riotto, A., 2001. Largest temperature of the radiation era and its cosmological implications. Phys. Rev. D 64 (2), 023508. arXiv:hep-ph/0005123 [hep-ph].

Gelmini, G., Gondolo, P., 2006. Neutralino with the right cold dark matter abundance in (almost) any supersymmetric model. Phys. Rev. D 74 (2), 023510. arXiv:hep-ph/0602230 [hep-ph].

Kane, G.L., Kumar, P., Nelson, B.D., Zheng, B., 2016. Dark matter production mechanisms with a nonthermal cosmological history: a classification. Phys. Rev. D 93 (6), 063527. arXiv:1502.05406 [hep-ph].

Drees, M., Hajkarim, F., 2018. Dark matter production in an early matter dominated era. J. Cosmol. Astropart. Phys. 02, 057. arXiv:1711.05007 [hep-ph].

Erickcek, A.L., Sigurdson, K., 2011. Reheating effects in the matter power spectrum and implications for substructure. Phys. Rev. D 84, 083503. arXiv:1106.0536 [astro-ph.CO].

Erickcek, A.L., 2015. The dark matter annihilation boost from low-temperature reheating. Phys. Rev. D 92 (10), 103505. arXiv:1504.03335 [astro-ph.CO].

Fan, J., Özsoy, O., Watson, S., 2014. Nonthermal histories and implications for structure formation. Phys. Rev. D 90 (4), 043536. arXiv:1405.7373 [hep-ph].

Gelmini, G.B., Gondolo, P., 2008. Ultra-cold weakly interacting massive particles: relics of non-standard pre-big-bang-nucleosynthesis cosmologies. J. Cosmol. Astropart. Phys. 10, 002. arXiv:0803.2349 [astro-ph].

Erickcek, A.L., Sinha, K., Watson, S., 2016. Bringing isolated dark matter out of isolation: late-time reheating and indirect detection. Phys. Rev. D 94 (6), 063502. arXiv:1510.04291 [hep-ph].

Waldstein, I.R., Erickcek, A.L., Ilie, C., 2017. Quasidecoupled state for dark matter in nonstandard thermal histories. Phys. Rev. D 95 (12), 123531. arXiv:1609.05927 [astro-ph.CO].

Blanco, C., Delos, M.S., Erickcek, A.L., Hooper, D., 2019. Annihilation signatures of hidden sector dark matter within early-forming microhalos. Phys. Rev. D 100 (10), 103010. arXiv:1906.00010 [astro-ph.CO].

Erickcek, A.L., Ralegankar, P., Shelton, J., 2021. Cannibal domination and the matter power spectrum. Phys. Rev. D 103 (10), 103508. arXiv:2008.04311 [astro-ph.CO].

Erickcek, A.L., Ralegankar, P., Shelton, J., 2022. Cannibalism's lingering imprint on the matter power spectrum. J. Cosmol. Astropart. Phys. 01 (01), 017. arXiv:2106.09041 [hep-ph].

Barenboim, G., Blinov, N., Stebbins, A., 2021. Smallest remnants of early matter domination. J. Cosmol. Astropart. Phys. 12 (12), 026. arXiv:2107.10293 [astro-ph.CO].

Delos, M.S., Linden, T., Erickcek, A.L., 2019. Breaking a dark degeneracy: the gamma-ray signature of early matter domination. Phys. Rev. D 100 (12), 123546. arXiv:1910.08553 [astro-ph.CO].

Dror, J.A., Ramani, H., Trickle, T., Zurek, K.M., 2019. Pulsar timing probes of primordial black holes and subhalos. Phys. Rev. D 100 (2), 023003. arXiv:1901.04490 [astro-ph.CO].

Ramani, H., Trickle, T., Zurek, K.M., 2020. Observability of dark matter substructure with pulsar timing correlations. J. Cosmol. Astropart. Phys. 12, 033. arXiv:2005.03030 [astro-ph.CO].

Lee, V.S.H., Mitridate, A., Trickle, T., Zurek, K.M., 2021. Probing small-scale power spectra with pulsar timing arrays. J. High Energy Phys. 06, 028. arXiv:2012.09857 [astro-ph.CO].

Delos, M.S., Linden, T., 2021. Dark matter microhalos in the solar neighborhood: pulsar timing signatures of early matter domination. arXiv:2109.03240 [astro-ph.CO].

Dai, L., Miralda-Escudé, J., 2020b. Gravitational lensing signatures of axion dark matter minihalos in highly magnified stars. Astron. J. 159 (2), 49. arXiv:1908.01773 [astro-ph.CO].

Blinov, N., Dolan, M.J., Draper, P., Shelton, J., 2021. Dark matter microhalos from simplified models. Phys. Rev. D 103 (10), 103514. arXiv:2102.05070 [astro-ph.CO].

Planck Collaboration, Aghanim, N., et al., 2020b. Planck 2018 results. VI. Cosmological parameters. Astron. Astrophys. 641, A6. arXiv:1807.06209 [astro-ph.CO].

Brust, C., Kaplan, D.E., Walters, M.T., 2013. New light species and the CMB. J. High Energy Phys. 12, 058. arXiv:1303.5379 [hep-ph].

Kawasaki, M., Kohri, K., Moroi, T., 2005. Big-bang nucleosynthesis and hadronic decay of long-lived massive particles. Phys. Rev. D 71, 083502. arXiv:astro-ph/0408426.

Iocco, F., Mangano, G., Miele, G., Pisanti, O., Serpico, P.D., 2009. Primordial nucleosynthesis: from precision cosmology to fundamental physics. Phys. Rep. 472, 1–76. arXiv:0809.0631 [astro-ph].

Pospelov, M., Pradler, J., 2010. Big Bang nucleosynthesis as a probe of new physics. Annu. Rev. Nucl. Part. Sci. 60, 539–568. arXiv:1011.1054 [hep-ph].

de Salas, P.F., Pastor, S., 2016. Relic neutrino decoupling with flavour oscillations revisited. J. Cosmol. Astropart. Phys. 07, 051. arXiv:1606.06986 [hep-ph].

Akita, K., Yamaguchi, M., 2020. A precision calculation of relic neutrino decoupling. J. Cosmol. Astropart. Phys. 08, 012. arXiv:2005.07047 [hep-ph].

Bennett, J.J., Buldgen, G., De Salas, P.F., Drewes, M., Gariazzo, S., Pastor, S., Wong, Y.Y.Y., 2021. Towards a precision calculation of $N_{\rm eff}$ in the standard model II: neutrino decoupling in the presence of flavour oscillations and finite-temperature QED. J. Cosmol. Astropart. Phys. 04, 073. arXiv:2012.02726 [hep-ph].

Froustey, J., Pitrou, C., Volpe, M.C., 2020. Neutrino decoupling including flavour oscillations and primordial nucleosynthesis. J. Cosmol. Astropart. Phys. 12, 015. arXiv:2008.01074 [hep-ph].

Boehm, C., Dolan, M.J., McCabe, C., 2013. A lower bound on the mass of cold thermal dark matter from Planck. J. Cosmol. Astropart. Phys. 08, 041. arXiv:1303.6270 [hep-ph].

Nollett, K.M., Steigman, G., 2015. BBN and the CMB constrain neutrino coupled light WIMPs. Phys. Rev. D 91 (8), 083505. arXiv:1411.6005 [astro-ph.CO].

Steigman, G., Nollett, K.M., 2014. Light WIMPs, equivalent neutrinos, BBN, and the CMB. Mem. Soc. Astron. Ital. 85, 175. arXiv:1401.5488 [astro-ph.CO].

Escudero, M., 2019. Neutrino decoupling beyond the standard model: CMB constraints on the dark matter mass with a fast and precise $N_{\rm eff}$ evaluation. J. Cosmol. Astropart. Phys. 02, 007. arXiv:1812.05605 [hep-ph].

Giovanetti, C., Lisanti, M., Liu, H., Ruderman, J.T., 2021. Joint CMB and BBN constraints on light dark sectors with dark radiation. arXiv:2109.03246 [hep-ph].

An, R., Gluscevic, V., Calabrese, E., Hill, J.C., 2022. What does cosmology tell us about the mass of thermal-relic dark matter? arXiv:2202.03515 [astro-ph.CO].

Abazajian, K., et al., 2019. CMB-S4 science case, reference design, and project plan. arXiv:1907.04473 [astro-ph.IM].

Fixsen, D.J., Cheng, E.S., Gales, J.M., Mather, J.C., Shafer, R.A., Wright, E.L., 1996. The cosmic microwave background spectrum from the full COBE FIRAS data set. Astrophys. J. 473, 576. arXiv:astro-ph/9605054.

Fixsen, D.J., 2009. The temperature of the cosmic microwave background. Astrophys. J. 707, 916–920. arXiv:0911.1955 [astro-ph.CO].

Kogut, A., Fixsen, D.J., Chuss, D.T., Dotson, J., Dwek, E., Halpern, M., Hinshaw, G.F., Meyer, S.M., Moseley, S.H., Seiffert, M.D., Spergel, D.N., Wollack, E.J., 2011. The Primordial Inflation Explorer (PIXIE): a nulling polarimeter for cosmic microwave background observations. J. Cosmol. Astropart. Phys. 2011 (7), 025. arXiv:1105.2044 [astro-ph.CO].

Chluba, J., 2016. Which spectral distortions do ΛCDM actually predict? Mon. Not. R. Astron. Soc. 460 (1), 227–239. arXiv:1603.02496 [astro-ph.CO].

McDonald, P., Scherrer, R.J., Walker, T.P., 2000. Cosmic microwave background constraint on residual annihilations of relic particles. Phys. Rev. D 63 (2), 023001. arXiv:astro-ph/0008134 [astro-ph].

Ali-Haïmoud, Y., 2021. Testing dark matter interactions with CMB spectral distortions. Phys. Rev. D 103 (4), 043541. arXiv:2101.04070 [astro-ph.CO].

Bolliet, B., Chluba, J., Battye, R., 2021. Spectral distortion constraints on photon injection from low-mass decaying particles. Mon. Not. R. Astron. Soc. 507 (3), 3148–3178. arXiv:2012.07292 [astro-ph.CO].

Ali-Haïmoud, Y., Chluba, J., Kamionkowski, M., 2015. Constraints on dark matter interactions with standard model particles from cosmic microwave background spectral distortions. Phys. Rev. Lett. 115 (7), 071304. arXiv:1506.04745 [astro-ph.CO].

Ali-Haïmoud, Y., 2019. Boltzmann-Fokker-Planck formalism for dark-matter–baryon scattering. Phys. Rev. D 99 (2), 023523. arXiv:1811.09903 [astro-ph.CO].

Green, D., Meerburg, P.D., Meyers, J., 2019. Aspects of dark matter annihilation in cosmology. J. Cosmol. Astropart. Phys. 2019 (4), 025. arXiv:1804.01055 [astro-ph.CO].

Chen, X., Kamionkowski, M., 2004. Particle decays during the cosmic dark ages. Phys. Rev. D 70 (4), 043502. arXiv:astro-ph/0310473 [astro-ph].

Slatyer, T.R., Wu, C.-L., 2017. General constraints on dark matter decay from the cosmic microwave background. Phys. Rev. D 95 (2), 023010. arXiv:1610.06933 [astro-ph.CO].

Poulin, V., Lesgourgues, J., Serpico, P.D., 2017a. Cosmological constraints on exotic injection of electromagnetic energy. J. Cosmol. Astropart. Phys. 2017 (3), 043. arXiv:1610.10051 [astro-ph.CO].

Cang, J., Gao, Y., Ma, Y.-Z., 2020. Probing dark matter with future CMB measurements. Phys. Rev. D 102 (10), 103005. arXiv:2002.03380 [astro-ph.CO].

Ricotti, M., Ostriker, J.P., Mack, K.J., 2008. Effect of primordial black holes on the cosmic microwave background and cosmological parameter estimates. Astrophys. J. 680 (2), 829–845. arXiv:0709.0524 [astro-ph].

Ali-Haïmoud, Y., Kamionkowski, M., 2017. Cosmic microwave background limits on accreting primordial black holes. Phys. Rev. D 95 (4), 043534. arXiv:1612.05644 [astro-ph.CO].

Poulin, V., Serpico, P.D., Calore, F., Clesse, S., Kohri, K., 2017b. CMB bounds on disk-accreting massive primordial black holes. Phys. Rev. D 96 (8), 083524. arXiv:1707.04206 [astro-ph.CO].

Liu, H., Ridgway, G.W., Slatyer, T.R., 2020b. Code package for calculating modified cosmic ionization and thermal histories with dark matter and other exotic energy injections. Phys. Rev. D 101 (2), 023530. arXiv:1904.09296 [astro-ph.CO].

Dvorkin, C., Blum, K., Zaldarriaga, M., 2013. Perturbed recombination from dark matter annihilation. Phys. Rev. D 87 (10), 103522. arXiv:1302.4753 [astro-ph.CO].

Jensen, T.W., Ali-Haïmoud, Y., 2021. Perturbed recombination from inhomogeneous photon injection and application to accreting primordial black holes. Phys. Rev. D 104 (6), 063534. arXiv:2106.10266 [astro-ph.CO].

Chen, X.-l., Hannestad, S., Scherrer, R.J., 2002. Cosmic microwave background and large scale structure limits on the interaction between dark matter and baryons. Phys. Rev. D 65, 123515. arXiv:astro-ph/0202496.

Dvorkin, C., Blum, K., Kamionkowski, M., 2014. Constraining dark matter-baryon scattering with linear cosmology. Phys. Rev. D 89 (2), 023519. arXiv:1311.2937 [astro-ph.CO].

Gluscevic, V., Boddy, K.K., 2018. Constraints on scattering of keV–TeV dark matter with protons in the early Universe. Phys. Rev. Lett. 121 (8), 081301. arXiv:1712.07133 [astro-ph.CO].

Boddy, K.K., Gluscevic, V., 2018. First cosmological constraint on the effective theory of dark matter-proton interactions. Phys. Rev. D 98 (8), 083510. arXiv:1801.08609 [astro-ph.CO].

Xu, W.L., Dvorkin, C., Chael, A., 2018. Probing sub-GeV dark matter-baryon scattering with cosmological observables. Phys. Rev. D 97 (10), 103530. arXiv:1802.06788 [astro-ph.CO].

Slatyer, T.R., Wu, C.-L., 2018. Early-Universe constraints on dark matter-baryon scattering and their implications for a global 21 cm signal. Phys. Rev. D 98 (2), 023013. arXiv:1803.09734 [astro-ph.CO].

Boddy, K.K., Gluscevic, V., Poulin, V., Kovetz, E.D., Kamionkowski, M., Barkana, R., 2018. Critical assessment of CMB limits on dark matter-baryon scattering: new treatment of the relative bulk velocity. Phys. Rev. D 98 (12), 123506. arXiv:1808.00001 [astro-ph.CO].

Kovetz, E.D., Poulin, V., Gluscevic, V., Boddy, K.K., Barkana, R., Kamionkowski, M., 2018. Tighter limits on dark matter explanations of the anomalous EDGES 21 cm signal. Phys. Rev. D 98 (10), 103529. arXiv:1807.11482 [astro-ph.CO].

Dvorkin, C., Lin, T., Schutz, K., 2021. Cosmology of sub-MeV dark matter freeze-in. Phys. Rev. Lett. 127 (11), 111301. arXiv:2011.08186 [astro-ph.CO].

Nguyen, D.V., Sarnaaik, D., Boddy, K.K., Nadler, E.O., Gluscevic, V., 2021. Observational constraints on dark matter scattering with electrons. Phys. Rev. D 104 (10), 103521. arXiv:2107.12380 [astro-ph.CO].

Buen-Abad, M.A., Essig, R., McKeen, D., Zhong, Y.-M., 2021b. Cosmological constraints on dark matter interactions with ordinary matter. arXiv:2107.12377 [astro-ph.CO].

Boehm, C., Riazuelo, A., Hansen, S.H., Schaeffer, R., 2002. Interacting dark matter disguised as warm dark matter. Phys. Rev. D 66, 083505. arXiv:astro-ph/0112522.

Wilkinson, R.J., Lesgourgues, J., Boehm, C., 2014a. Using the CMB angular power spectrum to study dark matter-photon interactions. J. Cosmol. Astropart. Phys. 04, 026. arXiv:1309.7588 [astro-ph.CO].

Stadler, J., Bœhm, C., 2018. Constraints on γ-CDM interactions matching the Planck data precision. J. Cosmol. Astropart. Phys. 10, 009. arXiv:1802.06589 [astro-ph.CO].

Wilkinson, R.J., Boehm, C., Lesgourgues, J., 2014b. Constraining dark matter-neutrino interactions using the CMB and large-scale structure. J. Cosmol. Astropart. Phys. 05, 011. arXiv:1401.7597 [astro-ph.CO].

Olivares-Del Campo, A., Bœhm, C., Palomares-Ruiz, S., Pascoli, S., 2018. Dark matter-neutrino interactions through the lens of their cosmological implications. Phys. Rev. D 97 (7), 075039. arXiv:1711.05283 [hep-ph].

Cyr-Racine, F.-Y., Sigurdson, K., Zavala, J., Bringmann, T., Vogelsberger, M., Pfrommer, C., 2016. ETHOS—an effective theory of structure formation: from dark particle physics to the matter distribution of the Universe. Phys. Rev. D 93 (12), 123527. arXiv:1512.05344 [astro-ph.CO].

Archidiacono, M., Bohr, S., Hannestad, S., Jørgensen, J.H., Lesgourgues, J., 2017. Linear scale bounds on dark matter–dark radiation interactions and connection with the small scale crisis of cold dark matter. J. Cosmol. Astropart. Phys. 11, 010. arXiv:1706.06870 [astro-ph.CO].

Archidiacono, M., Hooper, D.C., Murgia, R., Bohr, S., Lesgourgues, J., Viel, M., 2019. Constraining dark matter-dark radiation interactions with CMB, BAO, and Lyman-α. J. Cosmol. Astropart. Phys. 10, 055. arXiv:1907.01496 [astro-ph.CO].

Becker, N., Hooper, D.C., Kahlhoefer, F., Lesgourgues, J., Schöneberg, N., 2021. Cosmological constraints on multi-interacting dark matter. J. Cosmol. Astropart. Phys. 02, 019. arXiv:2010.04074 [astro-ph.CO].

Li, Z., Gluscevic, V., Boddy, K.K., Madhavacheril, M.S., 2018. Disentangling dark physics with cosmic microwave background experiments. Phys. Rev. D 98 (12), 123524. arXiv:1806.10165 [astro-ph.CO].

Simons Observatory Collaboration, Ade, P., et al., 2019. The Simons observatory: science goals and forecasts. J. Cosmol. Astropart. Phys. 02, 056. arXiv:1808.07445 [astro-ph.CO].

Furlanetto, S., Oh, S.P., Briggs, F., 2006. Cosmology at low frequencies: the 21 cm transition and the high-redshift Universe. Phys. Rep. 433, 181–301. arXiv:astro-ph/0608032.

Pritchard, J.R., Loeb, A., 2012. 21-cm cosmology. Rep. Prog. Phys. 75, 086901. arXiv:1109.6012 [astro-ph.CO].

Hirata, C.M., 2006. Wouthuysen-field coupling strength and application to high-redshift 21 cm radiation. Mon. Not. R. Astron. Soc. 367, 259–274. arXiv:astro-ph/0507102.

Tashiro, H., Kadota, K., Silk, J., 2014. Effects of dark matter-baryon scattering on redshifted 21 cm signals. Phys. Rev. D 90 (8), 083522. arXiv:1408.2571 [astro-ph.CO].

Muñoz, J.B., Kovetz, E.D., Ali-Haïmoud, Y., 2015. Heating of baryons due to scattering with dark matter during the dark ages. Phys. Rev. D 92 (8), 083528. arXiv:1509.00029 [astro-ph.CO].

Muñoz, J.B., Loeb, A., 2018. A small amount of mini-charged dark matter could cool the baryons in the early Universe. Nature 557 (7707), 684. arXiv:1802.10094 [astro-ph.CO].

Berlin, A., Hooper, D., Krnjaic, G., McDermott, S.D., 2018. Severely constraining dark matter interpretations of the 21-cm anomaly. Phys. Rev. Lett. 121 (1), 011102. arXiv:1803.02804 [hep-ph].

Barkana, R., Outmezguine, N.J., Redigolo, D., Volansky, T., 2018. Strong constraints on light dark matter interpretation of the EDGES signal. Phys. Rev. D 98 (10), 103005. arXiv:1803.03091 [hep-ph].

Muñoz, J.B., Dvorkin, C., Loeb, A., 2018. 21-cm fluctuations from charged dark matter. Phys. Rev. Lett. 121 (12), 121301. arXiv:1804.01092 [astro-ph.CO].

Liu, H., Outmezguine, N.J., Redigolo, D., Volansky, T., 2019. Reviving millicharged dark matter for 21-cm cosmology. Phys. Rev. D 100 (12), 123011. arXiv:1908.06986 [hep-ph].

Bowman, J.D., Rogers, A.E.E., Monsalve, R.A., Mozdzen, T.J., Mahesh, N., 2018. An absorption profile centred at 78 megahertz in the sky-averaged spectrum. Nature 555 (7694), 67–70. arXiv:1810.05912 [astro-ph.CO].

HERA Collaboration, Abdurashidova, Z., et al., 2022. HERA phase I limits on the cosmic 21 cm signal: constraints on astrophysics and cosmology during the epoch of reionization. Astrophys. J. 924 (2), 51. arXiv:2108.07282 [astro-ph.CO].

Pospelov, M., Pradler, J., Ruderman, J.T., Urbano, A., 2018. Room for new physics in the Rayleigh-jeans tail of the cosmic microwave background. Phys. Rev. Lett. 121 (3), 031103. arXiv:1803.07048 [hep-ph].

Ewall-Wice, A., Chang, T.C., Lazio, J., Dore, O., Seiffert, M., Monsalve, R.A., 2018. Modeling the radio background from the first black holes at cosmic dawn: implications for the 21 cm absorption amplitude. Astrophys. J. 868 (1), 63. arXiv:1803.01815 [astro-ph.CO].

Fraser, S., et al., 2018. The EDGES 21 cm anomaly and properties of dark matter. Phys. Lett. B 785, 159–164. arXiv:1803.03245 [hep-ph].

Lopez-Honorez, L., Mena, O., Moliné, A., Palomares-Ruiz, S., Vincent, A.C., 2016. The 21 cm signal and the interplay between dark matter annihilations and astrophysical processes. J. Cosmol. Astropart. Phys. 08, 004. arXiv:1603.06795 [astro-ph.CO].

Liu, H., Slatyer, T.R., 2018. Implications of a 21-cm signal for dark matter annihilation and decay. Phys. Rev. D 98 (2), 023501. arXiv:1803.09739 [astro-ph.CO].

Evoli, C., Mesinger, A., Ferrara, A., 2014. Unveiling the nature of dark matter with high redshift 21 cm line experiments. J. Cosmol. Astropart. Phys. 11, 024. arXiv:1408.1109 [astro-ph.HE].

Kovetz, E.D., Cholis, I., Kaplan, D.E., 2019. Bounds on ultralight hidden-photon dark matter from observation of the 21 cm signal at cosmic dawn. Phys. Rev. D 99 (12), 123511. arXiv:1809.01139 [astro-ph.CO].

Ali-Haïmoud, Y., Kovetz, E.D., Kamionkowski, M., 2017. Merger rate of primordial black-hole binaries. Phys. Rev. D 96 (12), 123523. arXiv:1709.06576 [astro-ph.CO].

Clark, S., Dutta, B., Gao, Y., Ma, Y.-Z., Strigari, L.E., 2018. 21 cm limits on decaying dark matter and primordial black holes. Phys. Rev. D 98 (4), 043006. arXiv:1803.09390 [astro-ph.HE].

Tegmark, M., Silk, J., Rees, M.J., Blanchard, A., Abel, T., Palla, F., 1997. How small were the first cosmological objects? Astrophys. J. 474, 1–12. arXiv:astro-ph/9603007.

Abel, T., Bryan, G.L., Norman, M.L., 2002. The formation of the first star in the Universe. Science 295, 93. arXiv:astro-ph/0112088.

Mirocha, J., Harker, G.J.A., Burns, J.O., 2015. Interpreting the global 21-cm signal from high redshifts. II. parameter estimation for models of galaxy formation. Astrophys. J. 813 (1), 11. arXiv:1509.07868 [astro-ph.CO].

Muñoz, J.B., Qin, Y., Mesinger, A., Murray, S.G., Greig, B., Mason, C., 2021a. The impact of the first galaxies on cosmic dawn and reionization. arXiv:2110.13919 [astro-ph.CO].

Muñoz, J.B., Dvorkin, C., Cyr-Racine, F.-Y., 2020. Probing the small-scale matter power spectrum with large-scale 21-cm data. Phys. Rev. D 101 (6), 063526. arXiv:1911.11144 [astro-ph.CO].

DeBoer, D.R., et al., 2017. Hydrogen Epoch of Reionization Array (HERA). Publ. Astron. Soc. Pac. 129 (974), 045001. arXiv:1606.07473 [astro-ph.IM].

Mellema, G., et al., 2013. Reionization and the cosmic dawn with the square kilometre array. Exp. Astron. 36, 235–318. arXiv:1210.0197 [astro-ph.CO].

Muñoz, J.B., Bohr, S., Cyr-Racine, F.-Y., Zavala, J., Vogelsberger, M., 2021b. ETHOS - an effective theory of structure formation: impact of dark acoustic oscillations on cosmic dawn. Phys. Rev. D 103 (4), 043512. arXiv:2011.05333 [astro-ph.CO].

Sitwell, M., Mesinger, A., Ma, Y.-Z., Sigurdson, K., 2014. The imprint of warm dark matter on the cosmological 21-cm signal. Mon. Not. R. Astron. Soc. 438 (3), 2664–2671. arXiv:1310.0029 [astro-ph.CO].

Jones, D., Palatnick, S., Chen, R., Beane, A., Lidz, A., 2021. Fuzzy dark matter and the 21 cm power spectrum. Astrophys. J. 913 (1), 7. arXiv:2101.07177 [astro-ph.CO].

Finkelstein, S.L., Ryan, J., Russell, E., Papovich, C., Dickinson, M., Song, M., Somerville, R.S., Ferguson, H.C., Salmon, B., Giavalisco, M., Koekemoer, A.M., Ashby, M.L.N., Behroozi, P., Castellano, M., Dunlop, J.S., Faber, S.M., Fazio, G.G., Fontana, A., Grogin, N.A., Hathi, N., Jaacks, J., Kocevski, D.D., Livermore, R., McLure, R.J., Merlin, E., Mobasher, B., Newman, J.A., Rafelski, M., Tilvi, V., Willner, S.P., 2015. The evolution of the galaxy rest-frame ultraviolet luminosity function over the first two billion years. Astrophys. J. 810 (1), 71. arXiv:1410.5439.

Bouwens, R.J., et al., 2015. UV luminosity functions at redshifts $z \sim 4$ to $z \sim 10$: 10000 galaxies from HST legacy fields. Astrophys. J. 803 (1), 34. arXiv:1403.4295 [astro-ph.CO].

Sabti, N., Muñoz, J.B., Blas, D., 2022. Galaxy luminosity function pipeline for cosmology and astrophysics. Phys. Rev. D 105 (4), 043518. arXiv:2110.13168 [astro-ph.CO].

Yoshiura, S., Oguri, M., Takahashi, K., Takahashi, T., 2020. Constraints on primordial power spectrum from galaxy luminosity functions. Phys. Rev. D 102 (8), 083515. arXiv:2007.14695 [astro-ph.CO].

Schultz, C., Oñorbe, J., Abazajian, K.N., Bullock, J.S., 2014. The high-z Universe confronts warm dark matter: galaxy counts, reionization and the nature of dark matter. Mon. Not. R. Astron. Soc. 442 (2), 1597–1609. arXiv:1401.3769 [astro-ph.CO].

Dayal, P., Mesinger, A., Pacucci, F., 2015. Early galaxy formation in warm dark matter cosmologies. Astrophys. J. 806 (1), 67. arXiv:1408.1102 [astro-ph.GA].

Menci, N., Merle, A., Totzauer, M., Schneider, A., Grazian, A., Castellano, M., Sanchez, N.G., 2017. Fundamental physics with the hubble frontier fields: constraining dark matter models with the abundance of extremely faint and distant galaxies. Astrophys. J. 836 (1), 61. arXiv:1701.01339 [astro-ph.CO].

Rudakovskyi, A., Mesinger, A., Savchenko, D., Gillet, N., 2021. Constraints on warm dark matter from UV luminosity functions of high-z galaxies with Bayesian model comparison. Mon. Not. R. Astron. Soc. 507 (2), 3046–3056. arXiv:2104.04481 [astro-ph.CO].

Bozek, B., Marsh, D.J.E., Silk, J., Wyse, R.F.G., 2015. Galaxy UV-luminosity function and reionization constraints on axion dark matter. Mon. Not. R. Astron. Soc. 450 (1), 209–222. arXiv:1409.3544 [astro-ph.CO].

Corasaniti, P.S., Agarwal, S., Marsh, D.J.E., Das, S., 2017. Constraints on dark matter scenarios from measurements of the galaxy luminosity function at high redshifts. Phys. Rev. D 95 (8), 083512. arXiv:1611.05892 [astro-ph.CO].

Lovell, M.R., Zavala, J., Vogelsberger, M., Shen, X., Cyr-Racine, F.-Y., Pfrommer, C., Sigurdson, K., Boylan-Kolchin, M., Pillepich, A., 2018. ETHOS – an effective theory of structure formation: predictions for the high-redshift Universe – abundance of galaxies and reionization. Mon. Not. R. Astron. Soc. 477 (3), 2886–2899. arXiv:1711.10497 [astro-ph.CO].

Viel, M., Becker, G.D., Bolton, J.S., Haehnelt, M.G., 2013. Warm dark matter as a solution to the small scale crisis: new constraints from high redshift Lyman-α forest data. Phys. Rev. D 88, 043502. arXiv:1306.2314 [astro-ph.CO].

Baur, J., Palanque-Delabrouille, N., Yèche, C., Magneville, C., Viel, M., 2016. Lyman-alpha forests cool warm dark matter. J. Cosmol. Astropart. Phys. 08, 012. arXiv:1512.01981 [astro-ph.CO].

Iršič, V., et al., 2017. New constraints on the free-streaming of warm dark matter from intermediate and small scale Lyman-α forest data. Phys. Rev. D 96 (2), 023522. arXiv:1702.01764 [astro-ph.CO].

Palanque-Delabrouille, N., Yèche, C., Schöneberg, N., Lesgourgues, J., Walther, M., Chabanier, S., Armengaud, E., 2020. Hints, neutrino bounds and WDM constraints from SDSS DR14 Lyman-α and Planck full-survey data. J. Cosmol. Astropart. Phys. 04, 038. arXiv:1911.09073 [astro-ph.CO].

Garzilli, A., Boyarsky, A., Ruchayskiy, O., 2017. Cutoff in the Lyman \alpha forest power spectrum: warm IGM or warm dark matter? Phys. Lett. B 773, 258–264. arXiv:1510.07006 [astro-ph.CO].

Garzilli, A., Ruchayskiy, O., Magalich, A., Boyarsky, A., 2019. How warm is too warm? Towards robust Lyman-α forest bounds on warm dark matter. arXiv:1912.09397 [astro-ph.CO].

Kobayashi, T., Murgia, R., De Simone, A., Iršič, V., Viel, M., 2017. Lyman-α constraints on ultralight scalar dark matter: implications for the early and late Universe. Phys. Rev. D 96 (12), 123514. arXiv:1708.00015 [astro-ph.CO].

Murgia, R., Scelfo, G., Viel, M., Raccanelli, A., 2019. Lyman-α forest constraints on primordial black holes as dark matter. Phys. Rev. Lett. 123 (7), 071102. arXiv:1903.10509 [astro-ph.CO].

Rogers, K.K., Peiris, H.V., 2021a. Strong bound on canonical ultralight axion dark matter from the Lyman-alpha forest. Phys. Rev. Lett. 126 (7), 071302. arXiv:2007.12705 [astro-ph.CO].

Rogers, K.K., Dvorkin, C., Peiris, H.V., 2021. New limits on light dark matter - proton cross section from the cosmic large-scale structure. arXiv:2111.10386 [astro-ph.CO].

Zhang, J., Kuo, J.-L., Liu, H., Tsai, Y.-L.S., Cheung, K., Chu, M.-C., 2018a. The importance of quantum pressure of fuzzy dark matter on Lyman-alpha forest. Astrophys. J. 863, 73. arXiv:1708.04389 [astro-ph.CO].

Rogers, K.K., Peiris, H.V., 2021b. General framework for cosmological dark matter bounds using N-body simulations. Phys. Rev. D 103 (4), 043526. arXiv:2007.13751 [astro-ph.CO].

Karaçaylı, N.G., Font-Ribera, A., Padmanabhan, N., 2020. Optimal 1D Ly α forest power spectrum estimation – I. DESI-lite spectra. Mon. Not. R. Astron. Soc. 497 (4), 4742–4752. arXiv:2008.06421 [astro-ph.CO].

Kneib, J.-P., Natarajan, P., 2011. Cluster lenses. Astron. Astrophys. Rev. 19, 47. arXiv:1202.0185 [astro-ph.CO].

Meneghetti, M., Natarajan, P., Coe, D., Contini, E., De Lucia, G., Giocoli, C., Acebron, A., Borgani, S., Bradac, M., Diego, J.M., Hoag, A., Ishigaki, M., Johnson, T.L., Jullo, E., Kawamata, R., Lam, D., Limousin, M., Liesenborgs, J., Oguri, M., Sebesta, K., Sharon, K., Williams, L.L.R., Zitrin, A., 2017. The frontier fields lens modelling comparison project. Mon. Not. R. Astron. Soc. 472 (3), 3177–3216. arXiv:1606.04548 [astro-ph.CO].

Niemiec, A., Jauzac, M., Jullo, E., Limousin, M., Sharon, K., Kneib, J.-P., Natarajan, P., Richard, J., 2020. hybrid-LENSTOOL: a self-consistent algorithm to model galaxy clusters with strong- and weak-lensing simultaneously. Mon. Not. R. Astron. Soc. 493 (3), 3331–3340. arXiv:2002.04635 [astro-ph.CO].

Natarajan, P., Chadayammuri, U., Jauzac, M., Richard, J., Kneib, J.-P., Ebeling, H., Jiang, F., van den Bosch, F., Limousin, M., Jullo, E., Atek, H., Pillepich, A., Popa, C., Marinacci, F., Hernquist, L., Meneghetti, M., Vogelsberger, M., 2017. Mapping substructure in the HST frontier fields cluster lenses and in cosmological simulations. Mon. Not. R. Astron. Soc. 468 (2), 1962–1980. arXiv:1702.04348 [astro-ph.GA].

Meneghetti, M., et al., 2020. An excess of small-scale gravitational lenses observed in galaxy clusters. Science 369 (o). 1347–1351. 6509. arXiv:2009.04471 [astro-ph.GA].

van den Bosch, F.C., Ogiya, G., Hahn, O., Burkert, A., 2018. Disruption of dark matter substructure: fact or fiction? Mon. Not. R. Astron. Soc. 474 (3), 3043–3066. arXiv:1711.05276 [astro-ph.GA].

Green, S.B., van den Bosch, F.C., Jiang, F., 2021. The tidal evolution of dark matter substructure - II. The impact of artificial disruption on subhalo mass functions and radial profiles. Mon. Not. R. Astron. Soc. 503 (3), 4075–4091. arXiv:2103.01227 [astro-ph.GA].

Balberg, S., Shapiro, S.L., Inagaki, S., 2002. Selfinteracting dark matter halos and the gravothermal catastrophe. Astrophys. J. 568, 475–487. arXiv:astro-ph/0110561.

Yang, D., Yu, H.-B., 2021. Self-interacting dark matter and small-scale gravitational lenses in galaxy clusters. Phys. Rev. D 104 (10), 103031. arXiv:2102.02375 [astro-ph.GA].

Huo, R., Yu, H.-B., Zhong, Y.-M., 2020. The structure of dissipative dark matter halos. J. Cosmol. Astropart. Phys. 2020 (06).

Jethwa, P., Erkal, D., Belokurov, V., 2018. The upper bound on the lowest mass halo. Mon. Not. R. Astron. Soc. 473 (2), 2060–2083. arXiv:1612.07834 [astro-ph.GA].

Nadler, E.O., Wechsler, R.H., Bechtol, K., Mao, Y.Y., Green, G., Drlica-Wagner, A., McNanna, M., Mau, S., Pace, A.B., Simon, J.D., Kravtsov, A., Dodelson, S., Li, T.S., Riley, A.H., Wang, M.Y., Abbott, T.M.C., Aguena, M., Allam, S., Annis, J., Avila, S., Bernstein, G.M., Bertin, E., Brooks, D., Burke, D.L., Rosell, A.C., Kind, M.C., Carretero, J., Costanzi, M., da Costa, L.N., De Vicente, J., Desai, S., Evrard, A.E., Flaugher, B., Fosalba, P., Frieman, J., García-Bellido, J., Gaztanaga, E., Gerdes, D.W., Gruen, D., Gschwend, J., Gutierrez, G., Hartley, W.G., Hinton, S.R., Honscheid, K., Krause, E., Kuehn, K., Kuropatkin, N., Lahav, O., Maia, M.A.G., Marshall, J.L., Menanteau, F., Miquel, R., Palmese, A., Paz-Chinchón, F., Plazas, A.A., Romer, A.K., Sanchez, E., Santiago, B., Scarpine, V., Serrano, S., Smith, M., Soares-Santos, M., Suchyta, E., Tarle, G., Thomas, D., Varga, T.N., Walker, A.R., DES Collaboration, 2020. Milky way satellite census. II. Galaxy-halo connection constraints including the impact of the large magellanic cloud. Astrophys. J. 893 (1), 48. arXiv:1912.03303 [astro-ph.GA].

Simon, J.D., 2019. The faintest dwarf galaxies. Annu. Rev. Astron. Astrophys. 57, 375–415. arXiv:1901.05465 [astro-ph.GA].

Drlica-Wagner, A., Bechtol, K., Mau, S., McNanna, M., Nadler, E.O., Pace, A.B., Li, T.S., Pieres, A., Rozo, E., Simon, J.D., Walker, A.R., Wechsler, R.H., Abbott, T.M.C., Allam, S., Annis, J., Bertin, E., Brooks, D., Burke, D.L., Carrasco Kind, M., Carretero, J., Costanzi, M., da Costa, L.N., De Vicente, J., Desai, S., Diehl, H.T., Doel, P., Eifler, T.F., Everett, S., Flaugher, B., Frieman, J., García-Bellido, J., Gaztanaga, E., Gruen, D., Gruendl, R.A., Gschwend, J., Gutierrez, G., Honscheid, K., James, D.J., Krause, E., Kuehn, K., Kuropatkin, N., Lahav, O., Maia, M.A.G., Marshall, J.L., Melchior, P., Menanteau, F., Miquel, R., Palmese, A., Plazas, A.A., Sanchez, E., Scarpine, V., Schubnell, M., Serrano, S., Sevilla-Noarbe, I., Smith, M., Suchyta, E., Tarle, G., DES Collaboration, 2020. Milky Way satellite census. I. The observational selection function for Milky Way satellites in DES Y3 and Pan-STARRS DR1. Astrophys. J. 893 (1), 47. arXiv:1912.03302 [astro-ph.GA].

Nadler, E.O., Drlica-Wagner, A., Bechtol, K., Mau, S., Wechsler, R.H., Gluscevic, V., Boddy, K., Pace, A.B., Li, T.S., McNanna, M., Riley, A.H., García-Bellido, J., Mao, Y.Y., Green, G., Burke, D.L., Peter, A., Jain, B., Abbott, T.M.C., Aguena, M., Allam, S., Annis, J., Avila, S., Brooks, D., Carrasco Kind, M., Carretero, J., Costanzi, M., da Costa, L.N., De Vicente, J., Desai, S., Diehl, H.T., Doel, P., Everett, S., Evrard, A.E., Flaugher, B., Frieman, J., Gerdes, D.W., Gruen, D., Gruendl, R.A., Gschwend, J., Gutierrez, G., Hinton, S.R., Honscheid, K., Huterer, D., James, D.J., Krause, E., Kuehn, K., Kuropatkin, N., Lahav, O., Maia, M.A.G., Marshall, J.L., Menanteau, F., Miquel, R., Palmese, A., Paz-Chinchón, F., Plazas, A.A., Romer, A.K., Sanchez, E., Scarpine, V., Serrano, S., Sevilla-Noarbe, I., Smith, M., Soares-Santos, M., Suchyta, E., Swanson, M.E.C., Tarle, G., Tucker, D.L., Walker, A.R., Wester, W., DES Collaboration, 2021. Constraints on dark matter properties from observations of Milky Way satellite galaxies. Phys. Rev. Lett. 126 (9), 091101. arXiv:2008.00022 [astro-ph.CO].

Kim, S.Y., Peter, A.H.G., Hargis, J.R., 2018. Missing satellites problem: completeness corrections to the number of satellite galaxies in the Milky Way are consistent with cold dark matter predictions. Phys. Rev. Lett. 121 (21), 211302. arXiv:1711.06267 [astro-ph.CO].

Newton, O., Leo, M., Cautun, M., Jenkins, A., Frenk, C.S., Lovell, M.R., Helly, J.C., Benson, A.J., Cole, S., 2021. Constraints on the properties of warm dark matter using the satellite galaxies of the Milky Way. J. Cosmol. Astropart. Phys. 2021 (8), 062. arXiv:2011.08865 [astro-ph.CO].

Dekker, A., Ando, S., Correa, C.A., Ng, K.C.Y., 2021. Warm dark matter constraints using Milky-Way satellite observations and subhalo evolution modeling, arXiv e-prints, arXiv:2111.13137 [astro-ph.CO].

Nadler, E.O., Gluscevic, V., Boddy, K.K., Wechsler, R.H., 2019. Constraints on dark matter microphysics from the Milky Way satellite population. Astrophys.

J. Lett. 878 (2), 32. arXiv:1904.10000 [astro-ph.CO], Erratum: Astrophys. J. Lett. 897, L46 (2020), Erratum: Astrophys. J. 897, L46 (2020).

Maamari, K., Gluscevic, V., Boddy, K.K., Nadler, E.O., Wechsler, R.H., 2021. Bounds on velocity-dependent dark matter-proton scattering from Milky Way satellite abundance. Astrophys. J. Lett. 907 (2), L46. arXiv:2010.02936 [astro-ph.CO].

Mutlu-Pakdil, B., Sand, D.J., Crnojević, D., Drlica-Wagner, A., Caldwell, N., Guhathakurta, P., Seth, A.C., Simon, J.D., Strader, J., Toloba, E., 2021. Resolved dwarf galaxy searches within 5 Mpc with the Vera Rubin observatory and Subaru hyper suprime-cam. Astrophys. J. 918 (2), 88. arXiv:2105.01658 [astro-ph.GA].

Drlica-Wagner, A., Mao, Y.-Y., Adhikari, S., Armstrong, R., Banerjee, A., Banik, N., Bechtol, K., Bird, S., Boddy, K.K., Bonaca, A., Bovy, J., Buckley, M.R., Bulbul, E., Chang, C., Chapline, G., Cohen-Tanugi, J., Cuoco, A., Cyr-Racine, F.-Y., Dawson, W.A., Díaz Rivero, A., Dvorkin, C., Erkal, D., Fassnacht, C.D., García-Bellido, J., Giannotti, M., Gluscevic, V., Golovich, N., Hendel, D., Hezaveh, Y.D., Horiuchi, S., Jee, M.J., Kaplinghat, M., Keeton, C.R., Koposov, S.E., Lam, C.Y., Li, T.S., Lu, J.R., Mandelbaum, R., McDermott, S.D., McNanna, M., Medford, M., Meyer, M., Marc, M., Murgia, S., Nadler, E.O., Necib, L., Nuss, E., Pace, A.B., Peter, A.H.G., Polin, D.A., Prescod-Weinstein, C., Read, J.I., Rosenfeld, R., Shipp, N., Simon, J.D., Slatyer, T.R., Straniero, O., Strigari, L.E., Tollerud, E., Tyson, J.A., Wang, M.-Y., Wechsler, R.H., Wittman, D., Yu, H.-B., Zaharijas, G., Ali-Haïmoud, Y., Annis, J., Birrer, S., Biswas, R., Blazek, J., Brooks, A.M., Buckley-Geer, E., Caputo, R., Charles, E., Digel, S., Dodelson, S., Flaugher, B., Frieman, J., Gawiser, E., Hearin, A.P., Hložek, R., Jain, B., Jeltema, T.E., Koushiappas, S.M., Lisanti, M., LoVerde, M., Mishra-Sharma, S., Newman, J.A., Nord, B., Nourbakhsh, E., Ritz, S., Robertson, B.E., Sánchez-Conde, M.A., Slosar, A., Tait, T.M.P., Verma, A., Vilalta, R., Walter, C.W., Yanny, B., Zentner, A.R., 2019. Probing the Fundamental Nature of Dark Matter with the Large Synoptic Survey Telescope, arXiv e-prints, arXiv:1902.01055 [astro-ph.CO].

Vogelsberger, M., Zavala, J., Loeb, A., 2012. Subhaloes in self-interacting galactic dark matter haloes. Mon. Not. R. Astron. Soc. 423 (4), 3740–3752. https://doi.org/10.1111/j.1365-2966.2012.21182.x.

Zavala, J., Vogelsberger, M., Walker, M.G., 2013. Constraining self-interacting dark matter with the Milky Way's dwarf spheroidals. Mon. Not. R. Astron. Soc. Lett. 431 (1), L20–L24. https://doi.org/10.1093/mnrasl/sls053.

Rocha, M., Peter, A.H.G., Bullock, J.S., Kaplinghat, M., Garrison-Kimmel, S., Oñorbe, J., Moustakas, L.A., 2013. Cosmological simulations with self-interacting dark matter – i. Constant-density cores and substructure. Mon. Not. R. Astron. Soc. 430 (1), 81–104. https://doi.org/10.1093/mnras/sts514.

Peter, A.H.G., Rocha, M., Bullock, J.S., Kaplinghat, M., 2013. Cosmological simulations with self-interacting dark matter – ii. Halo shapes versus observations. Mon. Not. R. Astron. Soc. 430 (1), 105–120. https://doi.org/10.1093/mnras/sts535.

Kaplinghat, M., Keeley, R.E., Linden, T., Yu, H.-B., 2014. Tying dark matter to baryons with self-interactions. Phys. Rev. Lett. 113, 021302. https://link.aps.org/doi/10.1103/PhysRevLett.113.021302.

Koda, J., Shapiro, P.R., 2011. Gravothermal collapse of isolated self-interacting dark matter haloes: N-body simulation versus the fluid model. Mon. Not. R. Astron. Soc. 415 (2), 1125–1137. arXiv:1101.3097 [astro-ph.CO].

Elbert, O.D., Bullock, J.S., Garrison-Kimmel, S., Rocha, M., Oñorbe, J., Peter, A.H.G., 2015. Core formation in dwarf haloes with self-interacting dark matter: no fine-tuning necessary. Mon. Not. R. Astron. Soc. 453 (1), 29–37. arXiv:1412.1477 [astro-ph.GA].

Essig, R., Mcdermott, S.D., Yu, H.-B., Zhong, Y.-M., 2019. Constraining dissipative dark matter self-interactions. Phys. Rev. Lett. 123 (12), 121102. arXiv:1809.01144 [hep-ph].

Nishikawa, H., Boddy, K.K., Kaplinghat, M., 2020. Accelerated core collapse in tidally stripped self-interacting dark matter halos. Phys. Rev. D 101 (6), 063009. arXiv:1901.00499 [astro-ph.GA].

Kahlhoefer, F., Kaplinghat, M., Slatyer, T.R., Wu, C.-L., 2019. Diversity in density profiles of self-interacting dark matter satellite halos. J. Cosmol. Astropart. Phys. 12, 010. arXiv:1904.10539 [astro-ph.GA].

Sameie, O., Yu, H.-B., Sales, L.V., Vogelsberger, M., Zavala, J., 2020. Self-interacting dark matter subhalos in the Milky Way's tides. Phys. Rev. Lett. 124 (14), 141102. arXiv:1904.07872 [astro-ph.GA].

Turner, H.C., Lovell, M.R., Zavala, J., Vogelsberger, M., 2020. The onset of gravothermal core collapse in velocity dependent self-interacting dark matter subhaloes. arXiv:2010.02924 [astro-ph.GA].

Zeng, Z.C., Peter, A.H.G., Du, X., Benson, A., Kim, S., Jiang, F., Cyr-Racine, F.-Y., Vogelsberger, M., 2021. Core-collapse, evaporation and tidal effects: the life story of a self-interacting dark matter subhalo. arXiv:2110.00259 [astro-ph.CO].

Kamada, A., Kaplinghat, M., Pace, A.B., Yu, H.-B., 2017. Self-interacting dark matter can explain diverse galactic rotation curves. Phys. Rev. Lett. 119 (11). https://doi.org/10.1103/PhysRevLett.119.111102.

Creasey, P., Sameie, O., Sales, L.V., Yu, H.-B., Vogelsberger, M., Zavala, J., 2017. Spreading out and staying sharp - creating diverse rotation curves via baryonic and self-interaction effects. Mon. Not. R. Astron. Soc. 468 (2), 2283–2295. arXiv:1612.03903 [astro-ph.GA].

Ren, T., Kwa, A., Kaplinghat, M., Yu, H.-B., 2019. Reconciling the diversity and uniformity of galactic rotation curves with self-interacting dark matter. Phys. Rev. X 9, 031020. https://doi.org/10.1103/PhysRevX.9.031020. arXiv:1808.05695 [astro-ph.GA].

Kaplinghat, M., Ren, T., Yu, H.-B., 2020. Dark matter cores and cusps in spiral galaxies and their explanations. J. Cosmol. Astropart. Phys. 2020 (06), 027. https://doi.org/10.1088/1475-7516/2020/06/027.

Zentner, A., Dandavate, S., Slone, O., Lisanti, M., 2022. A critical assessment of solutions to the galaxy diversity problem. arXiv:2202.00012 [astro-ph.GA].

Read, J.I., Walker, M.G., Steger, P., 2018. The case for a cold dark matter cusp in Draco. Mon. Not. R. Astron. Soc. 481 (1), 860–877. arXiv:1805.06934 [astro-ph.GA].

Sagunski, L., Gad-Nasr, S., Colquhoun, B., Robertson, A., Tulin, S., 2021. Velocity-dependent self-interacting dark matter from groups and clusters of galaxies. J. Cosmol. Astropart. Phys. 01, 024. arXiv:2006.12515 [astro-ph.CO].

Jiang, F., Kaplinghat, M., Lisanti, M., Slone, O., 2021b. Orbital evolution of satellite galaxies in self-interacting dark matter models. arXiv:2108.03243 [astro-ph.CO].

Kaplinghat, M., Valli, M., Yu, H.-B., 2019. Too big to fail in light of gaia. Mon. Not. R. Astron. Soc. 490 (1), 231–242. arXiv:1904.04939 [astro-ph.GA].

Carlsten, S.G., Greene, J.E., Peter, A.H.G., Greco, J.P., Beaton, R.L., 2020. Radial distributions of dwarf satellite systems in the local volume. Astrophys. J. 902 (2), 124. arXiv:2006.02444 [astro-ph.GA].

Mao, Y.-Y., Geha, M., Wechsler, R.H., Weiner, B., Tollerud, E.J., Nadler, E.O., Kallivayalil, N., 2021. The SAGA survey. II. Building a statistical sample of satellite systems around Milky Way-like galaxies. Astrophys. J. 907 (2), 85. arXiv:2008.12783 [astro-ph.GA].

Fritz, T.K., Battaglia, G., Pawlowski, M.S., Kallivayalil, N., van der Marel, R., Sohn, S.T., Brook, C., Besla, G., 2018. Gaia DR2 proper motions of dwarf galaxies within 420 kpc. Orbits, Milky Way mass, tidal influences, planar alignments, and group infall. Astron. Astrophys. 619. arXiv:1805.00908 [astro-ph.GA].

Mao, S., Schneider, P., 1998. Evidence for substructure in lens galaxies? Mon. Not. R. Astron. Soc. 295 (3), 587–594. arXiv:astro-ph/9707187 [astro-ph].

Dalal, N., Kochanek, C.S., 2002. Direct detection of cold dark matter substructure. Astrophys. J. 572 (1), 25–33. arXiv:astro-ph/0111456 [astro-ph].

Nierenberg, A.M., Treu, T., Brammer, G., Peter, A.H.G., Fassnacht, C.D., Keeton, C.R., Kochanek, C.S., Schmidt, K.B., Sluse, D., Wright, S.A., 2017. Probing dark matter substructure in the gravitational lens HE 0435-1223 with the WFC3 grism. Mon. Not. R. Astron. Soc. 471 (2), 2224–2236. arXiv:1701.05188 [astro-ph.CO].

Koopmans, L.V.E., 2005. Gravitational imaging of cold dark matter substructures. Mon. Not. R. Astron. Soc. 363 (4), 1136–1144. arXiv:astro-ph/0501324 [astro-ph].

Vegetti, S., Koopmans, L.V.E., 2009. Bayesian strong gravitational-lens modelling on adaptive grids: objective detection of mass substructure in Galaxies. Mon. Not. R. Astron. Soc. 392 (3), 945–963. arXiv:0805.0201 [astro-ph].

Vegetti, S., Lagattuta, D.J., McKean, J.P., Auger, M.W., Fassnacht, C.D., Koopmans, L.V.E., 2012. Gravitational detection of a low-mass dark satellite galaxy at cosmological distance. Nature 481 (7381), 341–343. arXiv:1201.3643 [astro-ph.CO].

Hezaveh, Y.D., Dalal, N., Marrone, D.P., Mao, Y.-Y., Morningstar, W., Wen, D., Blandford, R.D., Carlstrom, J.E., Fassnacht, C.D., Holder, G.P., Kemball, A., Marshall, P.J., Murray, N., Perreault Levasseur, L., Vieira, J.D., Wechsler, R.H., 2016. Detection of lensing substructure using ALMA observations of the dusty galaxy SDP.81. Astrophys. J. 823 (1), 37. arXiv:1601.01388 [astro-ph.CO].

Despali, G., Vegetti, S., White, S.D.M., Giocoli, C., van den Bosch, F.C., 2018. Modelling the line-of-sight contribution in substructure lensing. Mon. Not. R. Astron. Soc. 475 (4), 5424–5442. arXiv:1710.05029 [astro-ph.CO].

Hsueh, J.W., Enzi, W., Vegetti, S., Auger, M.W., Fassnacht, C.D., Despali, G., Koopmans, L.V.E., McKean, J.P., 2020. SHARP - VII. New constraints on the dark matter free-streaming properties and substructure abundance from gravitationally lensed quasars. Mon. Not. R. Astron. Soc. 492 (2), 3047–3059. arXiv:1905.04182 [astro-ph.CO].

Enzi, W., Murgia, R., Newton, O., Vegetti, S., Frenk, C., Viel, M., Cautun, M., Fassnacht, C.D., Auger, M., Despali, G., McKean, J., Koopmans, L.V.E., Lovell, M., 2021. Joint constraints on thermal relic dark matter from strong gravitational lensing, the Ly α forest, and Milky Way satellites. Mon. Not. R. Astron. Soc. 506 (4), 5848–5862. arXiv:2010.13802 [astro-ph.CO].

Gilman, D., Birrer, S., Treu, T., Nierenberg, A., Benson, A., 2019. Probing dark matter structure down to 10^7 solar masses: flux ratio statistics in gravitational lenses with line-of-sight haloes. Mon. Not. R. Astron. Soc. 487 (4), 5721–5738. arXiv:1901.11031 [astro-ph.CO].

Gilman, D., Birrer, S., Nierenberg, A., Treu, T., Du, X., Benson, A., 2020. Warm dark matter chills out: constraints on the halo mass function and the free-streaming length of dark matter with eight quadruple-image strong gravitational lenses. Mon. Not. R. Astron. Soc. 491 (4), 6077–6101. arXiv:1908.06983 [astro-ph.CO].

Despali, G., Vegetti, S., White, S.D.M., Powell, D.M., Stacey, H.R., Fassnacht, C.D., Rizzo, F., Enzi, W., 2022. Detecting low-mass haloes with strong gravitational lensing I: the effect of data quality and lensing configuration. Mon. Not. R. Astron. Soc. 510 (2), 2480–2494. arXiv:2111.08718 [astro-ph.GA].

McKean, J., Jackson, N., Vegetti, S., Rybak, M., Serjeant, S., Koopmans, L.V.E., Metcalf, R.B., Fassnacht, C., Marshall, P.J., Pandey-Pommier, M., 2015. Strong gravitational lensing with the SKA. In: Advancing Astrophysics with the Square Kilometre Array (AASKA14), p. 84. arXiv:1502.03362 [astro-ph.GA].

Vegetti, S., Koopmans, L.V.E., Bolton, A., Treu, T., Gavazzi, R., 2010. Detection of a dark substructure through gravitational imaging. Mon. Not. R. Astron. Soc. 408 (4), 1969–1981. arXiv:0910.0760 [astro-ph.CO].

Vegetti, S., Koopmans, L.V.E., Auger, M.W., Treu, T., Bolton, A.S., 2014. Inference of the cold dark matter substructure mass function at $z = 0.2$ using strong gravitational lenses. Mon. Not. R. Astron. Soc. 442 (3), 2017–2035. arXiv:1405.3666 [astro-ph.GA].

Ritondale, E., Vegetti, S., Despali, G., Auger, M.W., Koopmans, L.V.E., McKean, J.P., 2019. Low-mass halo perturbations in strong gravitational lenses at redshift $z \sim 0.5$ are consistent with CDM. Mon. Not. R. Astron. Soc. 485 (2), 2179–2193. arXiv:1811.03627 [astro-ph.CO].

Oguri, M., Marshall, P.J., 2010. Gravitationally lensed quasars and supernovae in future wide-field optical imaging surveys. Mon. Not. R. Astron. Soc. 405 (4), 2579–2593. arXiv:1001.2037 [astro-ph.CO].

Collett, T.E., 2015. The population of galaxy-galaxy strong lenses in forthcoming optical imaging surveys. Astrophys. J. 811 (1), 20. arXiv:1507.02657 [astro-ph.CO].

Weiner, C., Serjeant, S., Sedgwick, C., 2020. Predictions for strong-lens detections with the Nancy grace roman space telescope. Res. Notes Am. Astron. Soc. 4 (10), 190. arXiv:2010.15173 [astro-ph.GA].

He, M.Q., Robertson, A., Nightingale, J., Cole, S., Frenk, C.S., Massey, R., Amvrosiadis, A., Li, R., Cao, X., Etherington, A., 2022. A forward-modelling method to infer the dark matter particle mass from strong gravitational lenses. Mon. Not. R. Astron. Soc. arXiv:2010.13221 [astro-ph.CO].

Shipp, N., Drlica-Wagner, A., Balbinot, E., Ferguson, P., Erkal, D., Li, T.S., Bechtol, K., Belokurov, V., Buncher, B., Carollo, D., Carrasco Kind, M., Kuehn, K., Marshall, J.L., Pace, A.B., Rykoff, E.S., Sevilla-Noarbe, I., Sheldon, E., Strigari, L., Vivas, A.K., Yanny, B., Zenteno, A., Abbott, T.M.C., Abdalla, F.B., Allam, S., Avila, S., Bertin, E., Brooks, D., Burke, D.L., Carretero, J., Castander, F.J., Cawthon, R., Crocce, M., Cunha, C.E., D'Andrea, C.B., da Costa, L.N., Davis, C., De Vicente, J., Desai, S., Diehl, H.T., Doel, P., Evrard, A.E., Flaugher, B., Fosalba, P., Frieman, J., García-Bellido, J., Gaztanaga, E., Gerdes, D.W., Gruen, D., Gruendl, R.A., Gschwend, J., Gutierrez, G., Hartley, W., Honscheid, K., Hoyle, B., James, D.J., Johnson, M.D., Krause, E., Kuropatkin, N., Lahav, O., Lin, H., Maia, M.A.G., March, M., Martini, P., Menanteau, F., Miller, C.J., Miquel, R., Nichol, R.C., Plazas, A.A., Romer, A.K., Sako, M., Sanchez, E., Santiago, B., Scarpine, V., Schindler, R., Schubnell, M., Smith, M., Smith, R.C., Sobreira, F., Suchyta, E., Swanson, M.E.C., Tarle, G., Thomas, D., Tucker, D.L., Walker, A.R., Wechsler, R.H., DES Collaboration, 2018. Stellar streams discovered in the dark energy survey. Astrophys. J. 862 (2), 114. arXiv:1801.03097 [astro-ph.GA].

Ibata, R.A., Malhan, K., Martin, N.F., 2019. The streams of the gaping abyss: a population of entangled stellar streams surrounding the inner galaxy. Astrophys. J. 872 (2), 152. arXiv:1901.07566 [astro-ph.GA].

Li, T.S., Ji, A.P., Pace, A.B., Erkal, D., Koposov, S.E., Shipp, N., Da Costa, G.S., Cullinane, L.R., Kuehn, K., Lewis, G.F., Mackey, D., Simpson, J.D., Zucker, D.B., Ferguson, P.S., Martell, S.L., Bland-Hawthorn, J., Balbinot, E., Tavangar, K., Drlica-Wagner, A., De Silva, G.M., Simon, J.D., S5 Collaboration, 2021b. S^5: the orbital and chemical properties of one dozen stellar streams, arXiv e-prints, arXiv:2110.06950.

Price-Whelan, A.M., Bonaca, A., 2018. Off the beaten path: gaia reveals GD-1 stars outside of the main stream. Astrophys. J. 863 (2), L20. arXiv:1805.00425 [astro-ph.GA].

Li, T.S., Koposov, S.E., Erkal, D., Ji, A.P., Shipp, N., Pace, A.B., Hilmi, T., Kuehn, K., Lewis, G.F., Mackey, D., Simpson, J.D., Wan, Z., Zucker, D.B., Bland-Hawthorn, J., Cullinane, L.R., Da Costa, G.S., Drlica-Wagner, A., Hattori, K., Martell, S.L., Sharma, S., S5 Collaboration, 2021c. Broken into pieces: ATLAS and Aliqa Uma as one single stream. Astrophys. J. 911 (2), 149. arXiv:2006.10763 [astro-ph.GA].

Bonaca, A., Hogg, D.W., Price-Whelan, A.M., Conroy, C., 2019. The Spur and the gap in GD-1: dynamical evidence for a dark substructure in the Milky Way Halo. Astrophys. J. 880 (1), 38. arXiv:1811.03631 [astro-ph.GA].

Banik, N., Bovy, J., Bertone, G., Erkal, D., de Boer, T.J.L., 2021a. Evidence of a population of dark subhaloes from Gaia and Pan-STARRS observations of the GD-1 stream. Mon. Not. R. Astron. Soc. 502 (2), 2364–2380. arXiv:1911.02662 [astro-ph.GA].

Banik, N., Bovy, J., Bertone, G., Erkal, D., de Boer, T.J.L., 2021b. Novel constraints on the particle nature of dark matter from stellar streams. J. Cosmol. Astropart. Phys. 2021 (10), 043. arXiv:1911.02663 [astro-ph.GA].

Banik, N., Bertone, G., Bovy, J., Bozorgnia, N., 2018. Probing the nature of dark matter particles with stellar streams. J. Cosmol. Astropart. Phys. 2018 (7), 061. arXiv:1804.04384 [astro-ph.CO].

Carilli, C.L., Rawlings, S., 2004. Science with the square kilometer array: motivation, key science projects, standards and assumptions. New Astron. Rev. 48, 979. arXiv:astro-ph/0409274.

Braun, R., Bourke, T., Green, J.A., Keane, E., Wagg, J., 2015. Advancing astrophysics with the square kilometre array. PoS AASKA14, 174.

Skilling, J., 2004. Nested sampling. In: AIP Conference Proceedings. AIP.

Handley, W.J., Hobson, M.P., Lasenby, A.N., 2015. polychord: nested sampling for cosmology. Mon. Not. R. Astron. Soc. 450, L61–L65. arXiv:1502.01856 [astro-ph.CO].

Alves Batista, R., et al., 2021. EuCAPT white paper: opportunities and challenges for theoretical astroparticle physics in the next decade. arXiv:2110.10074 [astro-ph.HE].

Trotta, R., 2017. Bayesian methods in cosmology. arXiv:1701.01467 [astro-ph.CO].

Algeri, S., et al., 2018. Statistical challenges in the search for dark matter. arXiv:1807.09273 [hep-ph].

Feigelson, E.D., de Souza, R.S., Ishida, E.E.O., Babu, G. Jogesh, 2021. 21st century statistical and computational challenges in astrophysics. Annu. Rev. Stat. Appl. 8, 493–517. arXiv:2005.13025 [astro-ph.IM].

Hoffman, M.D., Blei, D.M., Wang, C., Paisley, J., 2013. Stochastic variational inference. J. Mach. Learn. Res. 14 (4), 1303–1347. http://jmlr.org/papers/v14/hoffman13a.html.

Zhang, C., Butepage, J., Kjellstrom, H., Mandt, S., 2018b. Advances in Variational Inference.

Liu, R., McAuliffe, J.D., Regier, J., 2021. Variational Inference for Deblending Crowded Starfields.

Leike, R.H., Glatzle, M., Enßlin, T.A., 2020. Resolving nearby dust clouds. Astron. Astrophys. 639, A138. https://doi.org/10.1051/0004-6361/202038169.

Mishra-Sharma, S., Cranmer, K., 2020. Semi-Parametric γ-ray Modeling with Gaussian Processes and Variational Inference.

Coogan, A., Karchev, K., Weniger, C., 2020. Targeted Likelihood-Free Inference of Dark Matter Substructure in Strongly-Lensed Galaxies.

Karchev, K., Coogan, A., Weniger, C., 2021. Strong-Lensing Source Reconstruction with Variationally Optimised Gaussian Processes.

Goodfellow, I.J., 2017. NIPS 2016 tutorial: generative adversarial networks. CoRR. arXiv:1701.00160 [abs].

Modi, C., Lanusse, F., Seljak, U., 2021a. FlowPM: distributed TensorFlow implementation of the FastPM cosmological N-body solver. Astron. Comput. 37, 100505. arXiv:2010.11847 [astro-ph.CO].

Modi, C., Lanusse, F., Seljak, U., Spergel, D.N., Perreault-Levasseur, L., 2021b. CosmicRIM: reconstructing early Universe by combining differentiable simulations with recurrent inference machines. arXiv:2104.12864 [astro-ph.CO].

Bradbury, J., Frostig, R., Hawkins, P., Johnson, M.J., Leary, C., Maclaurin, D., Necula, G., Paszke, A., VanderPlas, J., Wanderman-Milne, S., Zhang, Q., 2018. JAX: composable transformations of Python+NumPy programs. http://github.com/google/jax.

Paszke, A., Gross, S., Massa, F., Lerer, A., Bradbury, J., Chanan, G., Killeen, T., Lin, Z., Gimelshein, N., Antiga, L., Desmaison, A., Kopf, A., Yang, E., DeVito, Z., Raison, M., Tejani, A., Chilamkurthy, S., Steiner, B., Fang, L., Bai, J., Chintala, S., 2019. Pytorch: an imperative style, high-performance deep learning library. In: Wallach, H., Larochelle, H., Beygelzimer, A., d'Alché-Buc, F., Fox, E., Garnett, R. (Eds.), Advances in Neural Information Processing Systems 32. Curran Associates, Inc., pp. 8024–8035. http://papers.neurips.cc/paper/9015-pytorch-an-imperative-style-high-performance-deep-learning-library.pdf.

Himes, M.D., Harrington, J., Cobb, A.D., Baydin, A.G., Soboczenski, F., O'Beirne, M.D., Zorzan, S., Wright, D., Scheffer, Z., Domagal-Goldman, S., Arney, G., 2020. Accelerating Bayesian inference via neural networks: application to exoplanet retrievals. In: AAS/Division for Planetary Sciences Meeting Abstracts. In: AAS/Division for Planetary Sciences Meeting Abstracts, vol. 52, p. 207.07.

Shirobokov, S., Belavin, V., Kagan, M., Ustyuzhanin, A., Baydin, A.G., 2020. Black-box optimization with local generative surrogates. arXiv:2002.04632 [cs.LG].

Cranmer, K., Brehmer, J., Louppe, G., 2020. The frontier of simulation-based inference. Proc. Natl. Acad. Sci. 117 (48), 30055–30062. arXiv:1911.01429 [stat.ML].

Lueckmann, J.-M., Boelts, J., Greenberg, D.S., Gonçalves, P.J., Macke, J.H., 2021. Benchmarking simulation-based inference. arXiv:2101.04653 [cs, stat].

Sisson, S., Fan, Y., Beaumont, M., 2020. Handbook of Approximate Bayesian Computation, 1st ed. Chapman and Hall/CRC.

Papamakarios, G., Nalisnick, E., Rezende, D.J., Mohamed, S., Lakshminarayanan, B., 2021. Normalizing flows for probabilistic modeling and inference. arXiv:1912.02762 [cs, stat].

Bond-Taylor, S., Leach, A., Long, Y., Willcocks, C.G., 2021. Deep generative modelling: a comparative review of vaes, gans, normalizing flows, energy-based and autoregressive models. arXiv:2103.04922 [cs, stat].

Hermans, J., Begy, V., Louppe, G., 2020a. Likelihood-free MCMCa with amortized approximate ratio estimators. arXiv:1903.04057 [cs, stat].

Alsing, J., Charnock, T., Feeney, S., Wandelt, B., 2019. Fast likelihood-free cosmology with neural density estimators and active learning. Mon. Not. R. Astron. Soc. 488, 4440–4458. https://ui.adsabs.harvard.edu/abs/2019MNRAS.488.4440A.

Miller, B.K., Cole, A., Louppe, G., Weniger, C., 2020. Simulation-efficient marginal posterior estimation with swyft: stop wasting your precious time, arXiv:e-prints, arXiv:2011.13951. https://ui.adsabs.harvard.edu/abs/2020arXiv201113951M.

Hermans, J., Banik, N., Weniger, C., Bertone, G., Louppe, G., 2020b. Towards constraining warm dark matter with stellar streams through neural simulation-based inference. ArXiv:e-prints arXiv:2011.14923. https://ui.adsabs.Harvard.edu/abs/2020arXiv201114923H.

Brehmer, J., Mishra-Sharma, S., Hermans, J., Louppe, G., Cranmer, K., 2019. Mining for dark matter substructure: inferring subhalo population properties from strong lenses with machine learning. Astrophys. J. 886 (1), 49. arXiv:1909.02005 [astro-ph.CO].

Mishra-Sharma, S., 2022. Inferring dark matter substructure with astrometric lensing beyond the power spectrum. Mach. Learn. Sci. Tech. 3 (1), 01LT03. arXiv:2110.01620 [astro-ph.CO].

Mishra-Sharma, S., Cranmer, K., 2021. A neural simulation-based inference approach for characterizing the Galactic Center γ-ray excess. arXiv:2110.06931 [astro-ph.HE].

List, F., Rodd, N.L., Lewis, G.F., Bhat, I., 2020. The GCE in a new light: disentangling the γ-ray sky with Bayesian graph convolutional neural networks. Phys. Rev. Lett. 125, 241102. arXiv:2006.12504 [astro-ph.HE].

List, F., Rodd, N.L., Lewis, G.F., 2021. Extracting the Galactic Center excess' source-count distribution with neural nets. Phys. Rev. D 104 (12), 123022. arXiv:2107.09070 [astro-ph.HE].

Zhang, K., Bloom, J.S., Gaudi, B.S., Lanusse, F., Lam, C., Lu, J.R., 2021. Real-time likelihood-free inference of roman binary microlensing events with amortized neural posterior estimation. Astron. J. 161, 262. https://ui.adsabs.harvard.edu/abs/2021AJ....161..262Z.

Hermans, J., Delaunoy, A., Rozet, F., Wehenkel, A., Louppe, G., 2021. Averting A crisis in simulation-based inference, arXiv e-prints, arXiv:2110.06581 [stat.ML].

Tejero-Cantero, A., Boelts, J., Deistler, M., Lueckmann, J.-M., Durkan, C., Gonçalves, P.J., Greenberg, D.S., Macke, J.H., 2020. sbi: a toolkit for simulation-based inference. J. Open Sour. Softw. 5 (52), 2505. https://doi.org/10.21105/joss.02505.

The LSSTC Data Science Fellowship Program. https://www.lsstcorporation.org/fellowship_program/. (Accessed 13 February 2022). Online.

IRIS-HEP Fellows Program. https://iris-hep.org/fellows.html/. (Accessed 13 February 2022) Online.