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REVIEW

REVISED Overview of the ESCAPE Dark Matter Test Science Project for astronomers

[version 3; peer review: 2 approved, 1 approved with reservations, 1 not approved]

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Abstract

The search for dark matter has been ongoing for decades within both astrophysics and particle physics. Both fields have employed different approaches and conceived a variety of methods for constraining the properties of dark matter, but have done so in relative isolation of one another. From an astronomer's perspective, it can be challenging to interpret the results of dark matter particle physics experiments and how these results apply to astrophysical scales. Over the past few years, the ESCAPE Dark Matter Test Science Project has been developing tools to aid the particle physics community in constraining dark matter properties; however, ESCAPE itself also aims to foster collaborations between research disciplines. This is especially important in the search for dark matter, as while particle physics is concerned with detecting the particles themselves, all of the evidence for its existence lies solely within astrophysics and cosmology. Here, we present a short review of the progress made by the Dark Matter Test Science Project and their applications to existing experiments, with a view towards how this project can foster complementarity with astrophysical observations.

Keywords

dark matter, astroparticle physics, cosmology

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REVISED **Amendments from Version 2**

Following reviewer feedback, the publication has been updated with the following changes.
1. Section 1 has been expanded with more challenges of CDM and details of baryonic dark matter in the IGM.
2. Section 3 has a new subsection linking the astrophysical constraints to the particle physics experiments in Section 2.
3. Section 4.2 now has more clarity on GAMBIT usage.
4. Section 4.3 features an additional paragraph clarifying the vision of the VRE software and an idealised workflow.
5. Typos corrected and additional clarity added on the VRE, data lake, and the choice of listed experiments.

Any further responses from the reviewers can be found at the end of the article

1. Introduction

After the discovery of surprisingly large velocity dispersions for galaxies in the Coma cluster,[1] and following the discovery of discrepancies between spiral galaxy rotation curves and their observed stellar masses,[2] evidence has continued to mount for a missing mass component in the Universe. This dark matter has long been proposed as the explanation for various physical phenomena, and there have been various possibilities put forward as to its nature.[3,4] There are two main types of dark matter: baryonic and non-baryonic, where the former is thought to primarily exist as non-luminous gas in the intergalactic medium (IGM), or as massive compact halo objects (MACHOs), such as black holes and brown dwarfs, while the latter exists primarily in the form of new particles. The Universe consists of a much higher fraction of the latter – the matter density of non-baryonic matter is approximately five times that of all baryonic matter,[5] with the majority of baryons residing within filaments[6] and the diffuse IGM[150] rather than within galaxies themselves. Hence, for the rest of this review we primarily consider only the non-baryonic component. Cold dark matter (CDM) has proven to be the most enduring candidate: such non-relativistic particles have a shorter free-streaming length than warmer variants, causing them to quickly coalesce under gravity and allowing for the rapid formation of small-scale structures observed in the early Universe.[7–9]

Dark matter is thought to play a key role in the formation of structure on both galactic and cosmological scales, so to shine a light on its properties requires understanding the dark matter power spectrum and its evolution over cosmic time. Hence, multiple methods are employed to help constrain these properties.[10,11] On the largest scales, for example, the power spectrum of Cosmic Microwave Background (CMB) temperature fluctuations is accurately fitted by CDM, with the ratios of peaks providing measures of the relative densities of baryonic and non-baryonic matter in the Universe, among other cosmological parameter constraints. In fitting this power spectrum, results from the Planck Collaboration give an approximately 100σ detection of collisionless (i.e. non-baryonic) dark matter.[12–14] Meanwhile, x-ray emission from galaxy clusters indicates the presence of large quantities of hot gas that can only be explained should the clusters have a large dark matter component.[15] These dark matter haloes within which galaxies and galaxy clusters reside can also result in cosmic shear that, when modelled, provides constraints on the dark matter density (e.g. 16). Additionally, the alignment of galaxies along our line of sight can produce gravitational lenses, where the foreground galaxy acts as a 'lens' (albeit without focusing) around which the background galaxy is distorted and magnified; the modelled dark matter haloes of these lenses contain a central 'cuspy' slope (e.g. 17, 18) and potential substructures that can be used to constrain the properties of dark matter (e.g. 19, 20).

Despite the success of CDM, there still exists a number of astrophysical problems yet to be fully resolved, although alternative explanations have been proposed for many of these. For example, the detected excess of gamma rays from the Galactic Centre could be equally explained by self-annihilating dark matter or fast-rotating old pulsars,[151] and while the unidentified 3.5 keV x-ray line detected from galaxy clusters could come from the decay of sterile neutrinos (a candidate for warm dark matter), reanalyses suggest the signal may only be tentative (see e.g. 152). Similarly, a detected anomalous absorption of the redshifted 21 cm line from the early Universe[21] could be suggestive of interactions between baryonic dark matter and baryons,[22,23] however this detection has not been subsequently confirmed following a later non-detection,[24] with other works having sought alternative explanations (see e.g. 25 and references therein). More recently, a million-solar-mass object was discovered superposed on a gravitational arc,[153] with the object having a mass distribution seemingly compatible with SIDM models but not CDM, although the authors note that more numerical and theoretical work is needed. Other problems with CDM primarily arise from simulations of CDM haloes, often in CDM-only simulations. These include the "core-cusp" problem,[26,27] the "missing satellites" problem[28,29] and subsequent "too many satellites" problem,[30,31] and the "too big to fail" problem,[32,33] and much work has been done on improving the modelling of baryonic physics that may alleviate these issues. Likewise, the observed diversity of dwarf galaxy rotation curves - a challenge for CDM models - can be explained by recent simulations of active galactic nuclei (AGN) providing additional feedback and regulating stellar feedback.[154] As such, refinements to simulations and further observations from

new large-scale surveys like the *Euclid* survey[34,35] and the Vera C. Rubin Observatory's Legacy Survey of Space and Time (LSST[36]) are underway to consolidate the properties of dark matter on astrophysical scales.

Particle physics and astroparticle physics offer another, more local approach to understanding dark matter: numerous experiments in particle physics have been seeking to observe dark matter particles themselves, whether by producing dark matter itself, or by detecting it directly or indirectly through its interactions with ordinary matter. For more comprehensive reviews of dark matter candidates, the astrophysical evidence, and the range of particle physics experiments aiming to find them, see the following: 3, 4, 13, 37–44, along with the road map for the next decade of US research proposed in the latest Snowmass dark matter complementarity report.[45] For detailed reviews of the state of particle physics as a whole, see for example 46, and 47. Among the leading candidates for dark matter are weakly interacting massive particles (WIMPs): these theoretical CDM particles only interact through gravity and arise from extensions to the Standard Model.[48] However, given the above astrophysical problems with CDM and that no clear detections of WIMPs have yet been observed in particle physics experiments, other theoretical options are also being considered.[40] These theories include alternative CDM candidates such as axion-like particles[49] and primordial black holes (e.g. 50–52), non-CDM particles such as warm dark matter (WDM; e.g. 53) and self-interacting dark matter (SIDM; 54), as well as modifications to general relativity (e.g. 55).

1.1. Synergies in dark matter searches

Since the first evidence of its existence, the nature of dark matter has remained elusive, and while no dark matter particles have yet been observed, particle physics experiments and astrophysical evidence continue to ever tighten the constraints on its properties. With increasing search efforts for dark matter underway, efficient coordination and communication between dark matter-related communities is key. As a result, a number of dark matter discussion forums and collaborations have been established that bring together theorists and experimentalists[a].

The LHC Beyond the Standard Model (BSM) physics Working Group (LHC BSM WG) within the LHC Physics Centre at CERN (LPCC) aims to define guidelines for searches and recommendations for enhancing the reinterpretability of published LHC results. Within this domain, the LHC Dark Matter Working Group (LHC DM WG) focuses on particle physics models for LHC experiments that can highlight the complementarity between collider and non-collider experiments, while the LHC Long-lived Particles Working Group (LHC LLP WG) covers the physics of new long-lived particles and unconventional experimental signatures from dark matter and dark sector scenarios. Within the CERN Physics Beyond Colliders (PBC) Study Group,[56] the Feebly Interacting Particles Physics Centre (FPC) has been providing a forum for exchanges between the PBC experimental community and theorists, and developing the potential of the PBC experiments for the physics of feebly-interacting particles also by taking into account results from neighbouring fields like dark matter direct detection, astroparticle physics, and cosmology.

The European Consortium for Astroparticle Theory (EuCAPT[57]) aims to coordinate ideas, activities, resources and open environments for the European community of theoretical astroparticle physicists and cosmologists. The iDMEu project (the initiative for Dark Matter in Europe and Beyond[58]) aims to provide a common platform to facilitate both cross-community dark matter discussions and the collection of resources in an online meta-repository, supported by ECFA (the European Committee for Future Accelerators), NuPECC (the Nuclear Physics European Collaboration Committee) and APPEC (the Astroparticle Physics European Consortium).

1.2. Dark matter and open science

With ever-increasing data volumes of current and next-generation facilities, there is also a growing need for coordination and communication between research infrastructures, including across different domains of physics. Additionally, sustainability of these projects is required for scientific reuse, as concerns grow over the reproducibility of results in science: for example, a previous study showed that, across physics and engineering, 70% of researchers were unable to reproduce others' results, and 50% were unable to reproduce their own results.[59] As such, platforms are needed to host and publish data, analyses, and software to ensure accountability, accessibility, reinterpretability, and long-term reproducibility in accordance with open science principles.[60] For dark matter searches, we highlight the Dark Matter Data Centre (DMDC[61]) within the ORIGINS Data Science Laboratory (ODSL) as one such platform, including data sets, workflows, and interactive visualisations, with databases maintained on the Max Planck Computation & Data Facility GitLab[b].

[a] An overview of which can be found here: https://www.idmeu.org/dm-related-communities-centers-and-groups/
[b] https://www.origins-cluster.de/odsl/dark-matter-data-center

One of the European Union's Open Science enablers is the European Open Science Cloud (EOSC), which was created to provide a multidisciplinary environment for open research in Europe, where researchers can make use of tools and services to store and reuse the data and results of their and others' work according to FAIR (Findability, Accessibility, Interoperability and Reusability) principles. To support these open and FAIR practices of EOSC, the Open Science Clusters' Action for Research & Society (OSCARS) project has been established to bring together world-class European Research Infrastructures (RIs), connecting scientific communities and supporting collaborations, towards advances in open science – this review is supported by the OSCARS project. These RIs pertain to five Science Clusters: Humanities and Social Sciences; Life Sciences; Environmental Sciences; Photon and Neutron Science; and Astronomy, Nuclear and Particle Physics. In particular, the latter is covered by The European Science Cluster of Astronomy & Particle Physics ESFRI Research Infrastructures (ESCAPE), which includes next-generation RI facilities within the astronomy, astro-particle and particle physics communities. These RIs are especially concerned with challenges of data-driven research: ESCAPE developed federated storage, data services and infrastructure to accommodate this, including the ESCAPE Data Lake for exabyte-scale data storage and organisation, the Software Catalogue Open-source Scientific Software and Service Repository (OSSR)[c], and the Virtual Research Environment (VRE) analysis platform for developing and sharing end-to-end workflows[d] (see, e.g. 62, 63).

With funding from the EOSC-Future project,[64] ESCAPE developed the VRE and delivered the Dark Matter Test Science Project[e] (TSP[65]), connecting some of the RIs within ESCAPE that involve searches for dark matter. The Dark Matter TSP was established to demonstrate ESCAPE services and open science capabilities, enabling cross-talk between different experiments across astrophysics and particle physics, and delivering new scientific results in terms of dark matter searches.

To date, the focus within this TSP has been on particle physics experiments (see Section 2 for more details), with the TSP developing tools for the high energy particle physics and astroparticle physics communities to, for example, visualise the constraints on dark matter particle properties from various experiments. However, it is worth emphasising that all evidence for dark matter's existence is astrophysical in nature, yet there remains a disconnect between astronomers and the particle physics communities. The tools and workflows in the TSP do not as yet provide information interpretable for astronomy, nor are astrophysical constraints on dark matter integrated into these tools. This lack of shared tools and services prevents astronomers from understanding and utilising results and constraints from particle physics, and vice versa. As such, in this review we seek to address these concerns, primarily to help bridge this divide from an astronomy perspective. In this work, we provide an overview of the Dark Matter TSP, including the tools developed and the research utilising them in particle physics experiments. We do this from the point of view of astronomers, so that members of the astronomical community may understand and provide their own constraints on dark matter, and with the hope that they may use the ESCAPE tools themselves to provide up-to-date research/constraints on the nature of dark matter.

This paper is organised as follows. In Section 2, we provide an overview of the dark matter TSP, including the various particle physics experiments it supports and common tools available on the VRE. Section 3 presents explanations of example astrophysical observations of dark matter that could be incorporated into the TSP. Software tools available for astrophysical dark matter constraints, and for relating these to particle physics constraints, are presented in Section 4, followed by concluding remarks in Section 5.

2. The dark matter test science project

Through making use of ESCAPE tools and services hosted on the EOSC, the Dark Matter TSP seeks to store, distribute, and provide FAIR software and data access for dark matter research in order to highlight synergies between different research communities and allow them to collaborate to produce new results.[65] In particular, for now the project focuses on experimental data and software from the following direct detection, indirect detection, and particle collider experiments from within the ESCAPE partners, themselves invested in open science: the ATLAS general-purpose particle detector experiment; the DarkSide direct detection experiment; and the Cubic Kilometre Neutrino Telescope (KM3NeT), Fermi Large Area Telescope (Fermi LAT), and Cherenkov Telescope Array (CTA) indirect detection experiments. Theoretical and observational constraints are also to be used, with the aim of combining these data analyses in a coherent way, storing data and software on the ESCAPE Data Lake and OSSR respectively, and providing access to the data analysis pipeline through the ESCAPE VRE (where analyses for the above are already accessible[f]). These tools and services are provided for any dark matter experiments invested in open science, with the aim of incorporating more such experiments in future.

[c] https://zenodo.org/communities/escape2020/
[d] https://github.com/vre-hub *and* https://vre-hub.github.io/
[e] https://eoscfuture.eu/data/dark-matter/
[f] https://github.com/vre-hub/science-projects/tree/main

In this section we provide an overview of the above experiments, as well as how the dark matter TSP has contributed to each and to combining their results.

One of the goals of the Dark Matter TSP for comparing constraints and highlighting the complementarity of different experiments is to host the end-to-end workflows to produce the curves necessary for dark matter summary plots, which display individual experimental constraints from the outputs of each particle physics experiment workflow that can be interpreted in terms of the dark matter candidate properties.[64] These plots are commonly used in dark matter experiments and typically show constraints between dark matter candidate mass m_{DM} (GeV) and a cross-section σ (cm^2) describing the probability of a certain interaction during a collision between that candidate and a given particle, such as those sketched for the dark matter annihilation and WIMP-nucleon scattering cross-section in Figures 2 and 3 of 45. This interaction (scattering or annihilation) cross-section can be multiplied by the particle flux to give the interaction rate, i.e. the number of interactions per unit time. Depending on the model, different cross-sections can be represented, such as the spin-independent interaction cross-section σ_{SI} or the thermally averaged annihilation cross-section $\langle\sigma_{\mathrm{v}}\rangle(\mathrm{cm}^3\ \mathrm{s}^{-1})$. The latter is velocity-weighted, i.e. averaged over all dark matter velocities, and describes the average rate at which annihilation processes occur when multiplied by the dark matter number density.[42]

2.1. The ATLAS particle detector

Particle physics experiments seek to observe the presence of new particles directly from high-energy collisions between baryonic matter, and to detect the resulting particles either directly or from their decay products. Under the assumption that dark matter can couple (interact) with Standard Model particles in some way, at the Large Hadron Collider (LHC) at the European Organization for Nuclear Research (CERN), the general-purpose ATLAS experiment aims, among its other physics objectives, at producing invisible particles such as dark matter and inferring their existence from their decay into visible matter.

Each component of the ATLAS detector is specifically designed to record and identify different Standard Model particles. Quarks and gluons coming out of the LHC collisions give rise to a large number of hadrons which can be reconstructed into cone-shaped collider objects, called jets. The only Standard Model particle which does not interact with any of the detector components is the neutrino, since they are colour and charge neutral, and have faint weak interactions. In a collider hadron detector environment, only the plane transverse to the beam axis is of interest, and total transverse momentum of all particles has to be zero after collision, since the initial particles (protons) move along the beam axis. Missing transverse momentum (also termed missing transverse energy, or MET) is the transverse momentum carried away by non-detectable particles and thus 'missing' to cancel an observed net momentum in the direction transverse to the collider beam axis. The presence of neutrinos in a collision event causes an imbalance of transverse momentum and contributes to event MET. If, however, a collision only produces invisible particles (such as neutrinos or dark matter), it would also go undetected through the detector – this is a challenge when probing for dark matter models in a collider experiment. In the following, we discuss two searches using ATLAS, which have now been integrated into the ESCAPE tools, for dark matter candidates that should produce MET signatures.

2.1.1. ***Dilepton resonance search***

In simplified models of dark matter interactions with Standard Model (SM) particles,[66] the interactions between dark matter and SM particles are mediated by new massive particles. An example of such a mediator is the massive gauge boson labelled as a Z' boson (akin to the existing Z_0 boson in the Standard Model). These mediators can also decay back into a pair of SM particles, such as leptons or quarks, leading to a peak or 'resonance' in the invariant mass Standard Model continuum for these particles. One of the searches considered in the Dark Matter TSP is a dilepton resonance search, looking for these new mediator particles – since no new signal was found over the background in the data collected to date, constraints were set on the fiducial cross-section of the Z' particle,[67] which could be extrapolated to the full data set expected to be collected over the lifetime of the LHC.[68]

The Dark Matter TSP aimed to reinterpret this search using updated models of dark matter mediators, and to do so in a reproducible way using the tools developed by ESCAPE. Summary plots showing constraints on the fiducial cross-section of a new Z' particle as a function of mass were produced in the VRE and included in the US 'Snowmass process' reports,[69–72] the community vision for the next decade of particle physics research.

2.1.2. ***t-channel semi-visible jet search***

Several theories propose that dark matter manifests as part of a complex group of particles in a hidden sector,[73] akin to the Standard Model, governed by a new "dark force" – a framework known as dark Quantum Chromodynamics (dark QCD).

This force would explain interactions between the dark matter particles themselves, as well as between dark and Standard Model particles. These models target a non-WIMP scenario, giving rise to unusual and unexplored collider event-topologies. One such collider signature is termed as semi-visible jet, where parton evolution includes dark sector emissions, resulting in jets interspersed with dark matter particles. The total momentum of the dark matter is hence correlated with the momentum of the visible states, leading to the direction of MET being aligned close to a jet. If dark mesons exist, their evolution and hadronization procedure are currently little constrained. They could decay promptly and result in a very Standard Model QCD-like jet structure,[74] even though the original decaying particles are dark sector ones; they could behave as semi-visible jets[75,76]; or they could behave as completely detector-stable hadrons, in which case the final state is just the missing transverse momentum. Depending on the lifetime of the dark mesons, they could appear to "emerge" within the detector volume, termed as emerging jets.[77]

There have been initial searches for these models at the ATLAS experiment.[78–81] One of these ATLAS searches has probed the semi-visible jet signature in *t*-channel production mode, details of which can be found in work by 79. No new signal was found over the background of known particles for the collisions tested. Assuming a coupling strength of unity between the scalar mediator, a Standard Model quark and a dark quark, mediator mass limits were obtained. Additionally, upper limits on the coupling strengths were also derived. Owing to the broad range of possible collider signatures originating from these models, this search was designed in a generalised manner, using moderate kinematic selections. This enables the search to be reinterpreted in the context of a wider range of dark matter models which might have similar collider final-state signatures.

Separate to the Dark Matter TSP, the ATLAS Collaboration has since implemented the *t*-channel semi-visible jet search into ESCAPE services with the motive of analysis preservation in mind, and so the search is now fully available through the VRE. This analysis implementation hence prototyped and demonstrated the use of the VRE as a long-lasting service existing beyond the scope of the Dark Matter TSP.

2.2. DarkSide direct detection

Rather than directly producing dark matter, direct detection experiments aim to observe interactions of pre-existing dark matter particles with baryonic matter. As such interactions, if they exist, are extremely rare, large-scale experiments under carefully controlled conditions are needed to increase the likelihood of a detection. Under the assumption that dark matter consists of WIMP-like particles that can interact with baryonic matter to produce nuclear or electron recoil, the DarkSide experiment utilises a large chamber of liquid argon to search for both scintillation and ionisation that result from the elastic scattering of argon nuclei. Operating in the underground Gran Sasso National Laboratory (LNGS) in Italy, the latest iteration of the detector, DarkSide-50, contains almost 50 kg of liquid argon within its central dual-phase time projection chamber, using ultra-pure argon from underground sources to minimise the abundance of its radioactive isotope.[82,83]

From the data, the Dark Matter TSP has implemented reanalysis tools for high-mass searches on the ESCAPE VRE, producing DarkSide-50 exclusion curves for the WIMP-nucleon cross-section. They have also worked on implementing a low-mass analysis, as well as developing their tools to allow for different theoretical models to be inserted by users in order to produce different constraints on dark matter. Such tools may well be of use in the near future: the DarkSide collaboration is now also building a larger detector called DarkSide-20 k, containing tens of tonnes of liquid argon, to further extend the discovery potential of the direct detection program.[84,85]

2.3. Gamma ray & neutrino indirect detection

Another method of constraining dark matter is through various indirect detection methods, which infer the presence of dark matter from the visible-matter end products of its decay or annihilation, such as photons, electrons, and neutrinos. The dark matter TSP has focused on two main indirect detection methods, gamma rays and neutrinos, searching for an excess of these secondary particles above the expected background. Such methods are made challenging by complex astrophysical backgrounds that require sophisticated statistical and computational techniques to remove.

2.3.1. ***Fermi LAT***

The Fermi LAT is a space-based gamma ray detector that has been operating in the MeV to TeV range for more than a decade, scanning the entire sky every ∼192 minutes from the low-Earth orbit. One faint source of gamma rays could be from dark matter particle annihilation or decay that, while rare, would be most prevalent in denser dark matter regions, such as galaxy centres, galaxy clusters, and dwarf spheroidal galaxies.[86] The Fermi LAT's high angular and energy resolutions and its comparatively large effective area should allow it to detect such faint emissions,[87] whose energies scale directly with the dark matter particle mass.

One project prior to ESCAPE, MLFermiDwarfs, used real measurements to train machine learning models to predict the gamma ray background over the entire sky.[88,89] This aimed to remove foreground mismodelling in the data from Milky Way dwarf spheroidal galaxies, and to provide a more robust framework to derive constraints on the velocity-independent dark matter annihilation cross-section. For the Dark Matter TSP, the results and software tools used to produce them were reproduced and implemented on the VRE[g], along with data moved to the ESCAPE Data Lake, making them publicly accessible[90] and optimised to allow for customisation and quick checks of the viability of user-defined dark matter models. A similar process was also done for the analysis of gamma ray flux limits from dark matter capture rates in 13 nearby cold and old brown dwarfs by 91. Through scattering interactions, these objects are hypothesised to accumulate dark matter particles which can in turn annihilate into lighter mediator particles. If these particles are then long-lived enough to decay into photons once outside the brown dwarf, they can be detected. The results showed that the current sensitivity of Fermi is not high enough to enable bounds to be set on the dark matter-nucleon elastic scattering cross-section, requiring a factor of 9 improvement in the upper limits on the gamma-ray flux to be able to achieve bounds of $\sim 10 - 36\ \mathrm{cm}^2$ for dark matter masses below 10 GeV.[92] The software was again made open source[93] and fully available through the VRE[h] to allow others to extend the work to other astrophysical objects.

2.3.2. ***KM3NeT + CTA***

The KM3NeT neutrino telescope is a detector located deep underwater in the Mediterranean Sea, featuring the low-energy detector ORCA (Oscillation Research with Cosmics in the Abyss) and high-energy detector ARCA (Astroparticle Research with Cosmics in Abyss) which can be combined depending on the particle mass and decay channel of interest. Consisting of digital optical modules (DOMs; photomultiplier tubes arranged in glass spheres) positioned along vertical flexible strings, ORCA will feature 115 100 m-long strings at a depth of ∼2500 m, while ARCA will eventually have two sets of $115 \sim 700$ m-long strings each, collectively covering a $1\ \mathrm{km}^3$ volume anchored at a depth of 3500 m. Submerged in sea water that acts as a shield against atmospheric muons, the DOMs measure Cherenkov radiation produced by secondary particles from any interactions of neutrinos with the water. Such neutrinos may be produced from the decay or annihilation of dark matter from astrophysical sources, and may be accompanied by other signals: KM3NeT/ARCA is hence used for multimessenger astronomy, offering an accurate means of source detection in dense source regions (neutrinos only weakly interact so are negligibly deflected by matter on their path through space) that can be combined with electromagnetic or gravitational wave experiments that provide information about the energy spectrum and time window, respectively.

Here, the Dark Matter TSP has focused on the telescope's instrument response function (IRF), with regard to estimating rates expected for detection events and the background. For example, this can be used to show the relationship between energy resolution, effective area/volume and angular resolution of the detector, and can help circumvent the need for complex simulations. The tool developed for this was added to the VRE [i], as it may also be applicable to other experiments and the VRE enables remote execution of what is a computationally expensive task. As an example, similarities exist between gamma ray and neutrino astronomy which allowed the tool to be deployed[94] as part of a combination of data from KM3NeT with the high-energy ground-based gamma ray experiment CTA, and used to distinguish between different emission scenarios of gamma ray sources in the Milky Way.[95,96]

2.4. Common tools on the VRE

One of the main benefits of the EOSC and VRE is the ability to share common 'off the shelf' tools and algorithms that can be of benefit to various research projects and across research communities. For example, with increasing numbers of large-scale facilities and projects, the storage of vast amounts of data is becoming an ever-growing issue across communities, especially for particle physics and astronomy. Recognising this challenge, the Dark Matter TSP have developed and implemented on the VRE a prototype of a machine learning-based data compression tool called Baler[97,98] as an example of a reusable tool solving a common problem. Baler can be used to test the feasibility of compressing different types of scientific data using autoencoders, including training and testing a model, saving the resulting model and compressed data, and decompressing the model at a later date and plotting the performance.

Baler joins a number of other software packages available through the ESCAPE OSSR and VRE that are of use to astronomers[j]. For example, the platform includes Aladin Lite,[99] a browser-based astronomical HiPS visualiser;

[g]https://gitlab.in2p3.fr/escape2020/virtual-environment/mlfermilatdwarfs
[h]https://gitlab.in2p3.fr/escape2020/virtual-environment/brown-dwarfs-gamma
[i]https://gitlab.in2p3.fr/escape2020/virtual-environment/irf-from-km3net
[j]https://zenodo.org/communities/escape2020/

Gammapy,[100] a Python toolbox for gamma-ray astronomy; and a series of Jupyter Notebook tutorials on using astronomical databases and Virtual Observatory tools.[101]

In summary, the Dark Matter TSP has developed multiple open-source codes and workflows that run in the VRE, which are still being used for dark matter research, including producing up-to-date summary plots as new results come in from the various dark matter direct detection, indirect detection, and particle collider experiments.

3. Translating to astrophysical constraints

So what does all of this mean for astronomers? Having discussed some of the particle physics experiments and the constraints they place on dark matter properties, we now shift focus to examples of how these could relate to observable astrophysical constraints. While here we focus primarily on extragalactic tests for these examples, there exist a range of other probes on galactic and cosmological scales that could also be related to these constraints and incorporated into the VRE: for reviews, see e.g. 10 and 11, including Figure 1 and Figure 3 in the former that depict dark matter candidates in astronomically relevant parameter spaces.

3.1. Gravitational lensing

As mentioned in Section 1, the multiple distorted and magnified lensed images of a background galaxy ('source') around a foreground gravitational lens provide an observable way of measuring the distribution of matter and dark matter within the lens. For extended sources, whose images are both magnified and distorted into large arcs or Einstein rings, any substructure within the lens dark matter halo in turn produces perturbations in the lensed images that can be observed.[102] Meanwhile for unresolved sources like quasars, whose multiple lensed images are purely magnified in the form of an Einstein cross, lens substructure impacts the ratios of the fluxes of these images.[103] Work has also been done to combine both effects to increase the sensitivity to substructure.[104]

Different dark matter models are expected to produce differing numbers and properties of subhaloes: for example, compared to CDM, warm dark matter (WDM) particles have higher thermal velocities at early times and hence a larger free-streaming length that prevents small-scale structure from forming (e.g. 102, 105, 106), reducing the number of low-mass ($< 10^9$ $M_\odot$) subhaloes with a cut-off in the halo mass function that varies with the inverse of the particle mass (on the order of 10^8 $M_\odot$ for keV-scale particle masses[20]). Careful modelling of these subhaloes, using complex mass models within tools like lenstronomy[107,108] or PyAutoLens,[109] to reproduce the observed perturbations and flux ratios can therefore be used to place limits on dark matter free-streaming length and the particle masses of CDM (e.g. the 4.1 keV lower bound from 20) and WDM (e.g. the 2.0 keV lower bound from 110), with WDM models expected to produce fewer small-scale perturbations than CDM.[111] To date, only a few lenses have been studied in this way for low-mass haloes (e.g. 102, 112–114), however it is estimated that around 50–100 lenses with accurately measured substructure may be enough to set sufficient limits on WDM mass and potentially rule out CDM if no lower-mass haloes are detected.[115–117]

Another proposed family of models for dark matter is self-interacting dark matter (SIDM), for which such particles can have non-gravitational interactions that exchange energy and momentum, rather than remaining collisionless[54,118] Whether these interactions consist of elastic or inelastic scattering depends on the specific model, as does whether the interaction cross-section is constant or velocity dependent.[119–122] Such interactions between dark matter particles in the central halo and accreting subhaloes allow for ram-pressure stripping of the latter, with an efficiency that scales with the self-interacting cross-section.[111] This stripping suppresses the numbers of lower-mass subhaloes compared to CDM: for example, see the peak velocity function of model subhaloes in Figure 6 of 123, which shows the abundance of surviving SIDM subhaloes becoming increasingly suppressed compared to CDM simulations at lower peak velocities. As such, observations and simulations of gravitational lensing can be used to test these models, constraining the self-interaction cross-section at low velocities.

Within the high-density regions of haloes and subhaloes of SIDM, the self-interaction cross-sections also affect their central mass density profiles, with some experiencing core-collapse from the transfer of heat in these interactions and forming cuspy cores.[124–127] As such, observations of gravitational lenses can explore the potential diversity of these core distributions that would arise from SIDM.[128] For example 129, showed that flux ratios from quadruple-image strongly lensed quasars enable probing of self-interactions at velocities below 30 km s^{-1}, with 50 such objects having the potential to rule out CDM depending on the measured interaction cross-section amplitude at such low velocities. Such experiments need to use quasar emission at wavelengths in which the projected source-plane sizes are of the order milliarcseconds or larger, to minimise microlensing effects by stars within the foreground lens (e.g. 130). Meanwhile, simulations from 131 showed that the core-collapse of subhaloes exhibits unique observable features in lensing, with a SIDM cross-section of $\geq$200 cm^2 g^{-1} typically required for a significant fraction of subhalos to core-collapse. However, gravitational lens modelling suffers from a number of degeneracies that can, for example, lead to over- or

under-estimation of the number of low-mass subhaloes, a review of which is presented in 111. Nevertheless, in the coming decade these will no doubt be accounted for through the continued development of simulations paired with high-resolution imaging of orders of magnitude more lenses following wide-field surveys like LSST and *Euclid.*

3.2. Dwarf spheroidal galaxies

As mentioned in Section 2.3.1, dwarf spheroidal galaxies (dSphs) are considered to be promising targets for indirect dark matter detection using ground- and space-based γ-ray telescopes.[132,133] Measurements of stellar velocity dispersions in dSphs reveal very high measured mass-to-light ratios and therefore indicate high densities of dark matter are present. Moreover, dSphs contain relatively little gas and relatively few stars, which results in a low flux of background astrophysical γ-rays.[134] This makes distinguishing a faint dark-matter signal significantly less challenging than it would be in the direction of the Milky Way centre, for example.

High energy γ-rays are an expected product from the annihilation or decay of WIMP-like dark-matter particles. The γ-ray signal is expected to be characterised by continuum emission resulting from hadronization of decay products (including, e.g., $W^{\pm}$ bosons, quark-antiquark pairs or electron-positron pairs) and subsequent pion decay, or from direct decays yielding one or two γ-ray photons. While the latter process would produce a "smoking gun" line signal in the observed γ-ray spectrum, its flux is expected to be fainter than the continuum from hadronization by a factor $1/\alpha^2$ where α is the electromagnetic fine structure constant. This is because WIMP-like particles cannot couple directly to photons and so the Feynman diagram for the annihilation to photons must include a virtual charged particle loop.

For WIMP annihilation, the expression for the expected flux $d\Phi_\gamma/dE_\gamma$ of γ-rays produced with energy E_γ and arriving from within a solid angle $\Delta\Omega$ can be written as the product of two terms (e.g. 134, 135),

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\Delta\Omega)=\underbrace{\frac{1}{4\pi}\sigma_\gamma\frac{\langle\sigma_{\rm ann}v\rangle}{2m_{\rm DM}^2}\sum_f\frac{dN_\gamma^f}{dE_\gamma}B_f}_{\text{Particle Physics}}\times\underbrace{J(\Delta\Omega)}_{\text{Astrophysics}} \tag{1}$$

The first term in Equation (1) encapsulates parameters and quantities describing the particle physics of dark matter annihilation, including the velocity-averaged annihilation cross section $\langle\sigma_{\rm ann}v\rangle$, the WIMP mass m_{DM}, the expected spectrum dNγf/dEγ of γ-rays with energy E_γ produced by a specific annihilation channel f, and the branching ratio for that channel B_f, where the sum covers all possible annihilation channels.

The second term in Equation (1) is often referred to as the "J-factor" and describes an integral within a solid angle $\Delta\Omega$ along the observer's line of sight of the square of the dark matter density distribution. Typically, dSphs appear point-like at the spatial resolution of γ-ray telescopes, and so $\Delta\Omega$ is taken to be equal to the telescope's effective beam size.

By assuming that the annihilation cross-section is independent of the relative velocity between the annihilating dark matter particles (as is the case for s-wave annihilation[k]) and that density of the dSph's dark matter halo has a radially symmetric profile $\rho_{\rm DM}$, then the J-factor can be written as an integral along the line-of-sight (los) coordinate s and over the solid angle $\Delta\Omega$.

$$J(\Delta\Omega)=\int_{\Delta\Omega}d\Omega\int_{\rm los}\rho_{\rm DM}^2(s)\,ds \tag{2}$$

More generally, the annihilation cross-section may depend on the dark matter particles' relative velocities (e.g. for p-wave annihilation or for SIDM) and many dark matter models, including WDM, CDM and SIDM, predict that the dSph halo may have complex substructure.

In such cases, the J-factor depends on the detailed distribution of dark matter density along the line of sight. Unresolved dark matter substructures with higher density than the bulk dSph halo can significantly enhance (potentially by an order of magnitude) the J-factor when averaged over $\Delta\Omega$ since it must be the case that $\langle\rho^2\rangle \geq \langle\rho\rangle^2$.

[k]In quantum mechanics, a scattering quantum mechanics, a scattering process can be solved through a partial wave expansion, which decomposes the process into components and treats it as the scattering of constituent waves with defined angular momentum quantum numbers, l, such as *s- (l = 0)*, *p- (l = 1),* and *d*-waves *(l = 2)*. Hence, only the first few need taking into account for low-energy scattering processes.

Measurements of the locations and radial velocities of stars in dSphs can be used to constrain the form and normalisation of ρ_{DM} in Equation (2) (e.g. 136). However, making these measurements can be very challenging because dSphs are often very faint and contain very few stars. Consequently, estimates of the J-factor derived from astrophysical measurements are subject to significant systematic uncertainties, particularly when the stars belonging to a dSph are difficult to separate from foreground and background interlopers.

Ultimately, neither of the terms in Equation (1) is well constrained and unknown halo substructure parameters further complicate matters. To infer the physical properties of dark matter using indirect detection methods, one must typically make assumptions about the astrophysical parameters encapsulated in the J-factor (for example, whether the dark matter is clumpy or not), albeit that some of those assumptions can be constrained using observational data. Using these observationally constrained assumptions, one may compare the predicted γ-ray spectrum for various specific dark matter particle models and compare with that which is observed to determine the most likely model, given the available data.

3.3 Linking to particle physics

Ideally the integration of both astrophysical observations and particle physics experiments would provide more comprehensive constraints on dark matter properties, and while a full review of how these two fields would interact is beyond the scope of this work, a general summary relating the discussed areas are presented as follows – for more information on a given topic beyond that presented in this work, see the relevant sections of e.g. 44 and 155.

The dilepton resonance search in Section 2.1.1 assumes interactions exist between SM hadrons and dark matter particles, and that dark matter itself is a single particle - a fermion WIMP. Constraints on the fiducial cross-section of these interactions from this search are hence inherently connected to those from other experiments investigating WIMPs, such as the liquid argon-based DarkSide direct detection experiment (Section 2.2) for which any detection of dark matter-induced scintillation and ionisation would give evidence in favour of CDM. Such detections, or at least constraints on the cross-section from null detections, would also support work related to the theory of WIMPs, for example the release of secondary particles (gamma rays and neutrinos) from their decay within brown dwarfs and dSphs observed by the Fermi LAT detector, although Section 2.3.1 highlights that higher sensitivities are yet needed to derive sufficient constraints on the annihilation cross-section using this method. As discussed in Section 3.2, these cross-section constraints can also be improved for dSphs through astrophysical measurements of the positions and radial velocities of their stars in order to accurately model the distribution of dark matter substructure along the line of sight, for which the predicted γ-ray spectra of dark matter particle models can be compared to observations.

In addition to CDM and WIMPs, we have already discussed how particle physics is exploring more complex dark matter theories such as dark Quantum Chromodynamics (akin to a “dark” Standard Model) in Section 2.1.2. Such theories provide different mechanisms through which dark matter may self-interact and hence define SIDM cross-sections. While particle physics may focus on detecting the products of these interactions, astrophysics could instead provide constraints on SIDM cross-sections by searching for their large-scale effects on the dark matter subhaloes and central mass density profiles of strong gravitational lenses, comparing modelled lenses to simulations as discussed in Section 3.1. The observation of subhaloes in these systems and the flux ratios of lensed images can also place bounds on the free-streaming length and the particle masses of dark matter to further test the validity of CDM. As the collections of higher-resolution and more complex lensing configurations continue to increase, so can the precision by which these properties – and hence theories of CDM and SIDM – be constrained.

4. Tools for dark matter constraints

In addition to the online platforms and repositories mentioned in Section 1.2 and the software discussed in Section 2.4, various tools have been developed over the years to facilitate the above astrophysical dark matter constraints and relate these to particle physics constraints, a few examples of which are presented here. With sufficient interest, tools like these could be incorporated into the VRE to facilitate streamlined astrophysical dark matter searches.

4.1. pyHalo

Strong lens modelling can be used to constrain WDM and CDM halo properties such as the mass-concentration relation[137,138] when combined with software that can simulate full mass distributions with substructure, for instance the pyHalo Python package.[l,139] This code can also be used to constrain the self-interacting cross sections of SIDM, which is implemented by defining mass bins for subhaloes and field haloes and specifying the fraction of core-collapsed haloes in each bin (which have different density profiles to non-collapsed haloes). This is then passed to a lens modelling

[l]https://github.com/dangilman/pyHalo/

package, primarily lenstronomy[m],[107,108] to perform ray tracing to compute the effective gravitational distortion produced by all of the haloes and produce the resulting lensed images. Building on the work discussed in Section 3.1,[140] applied this method to study quadruply imaged quasars, from which their models disfavoured cross sections exceeding 100 $cm^2\ g^{-1}$ at relative velocities below 30 km s^{-1}, for which most haloes undergo core-collapse: they obtained the mass-binned core-collapse fractions based on a characteristic timescale of halo evolution that partially depends on the thermally-averaged cross section, halo mass, and redshift.[141,142]

4.2. GAMBIT

We have seen that there are many experiments and astrophysical observables for constraining dark matter properties, and the combination of multiple approaches will be necessary to provide concrete evidence for a given theory. The GAMBIT[n] (Global And Modular BSM Inference Tool[143]) software is a global fitting code for theories going Beyond the Standard Model (BSM), used to simultaneously analyse data from many sources. The code performs statistical global fits of such BSM models by combining theoretical predictions of observables with targeted searches across a wide range of experimental data from particle physics and astrophysics, computing observables and likelihoods alongside various statistical interpretations of results such as goodness-of-fit p-values and Bayes factors for model comparisons.

Along with a backend for dynamical interfacing with external tools used to compute physical quantities, GAMBIT also consists of several modules (or 'Bits') designed to provide native simulations for collider and astrophysics experiments, two of which we mention here: DarkBit[144] and CosmoBit.[145] The former module is designed for computing dark matter observables and likelihoods for multiple direct and indirect detection experiments, including interfacing with external packages to calculate relic densities,[146] and has been used to explore a range of dark matter candidates: see 147 for a review. Regarding the latter module, many BSM scenarios also have cosmological implications that are missed when fitting purely to particle physics experiments, and likewise many cosmological theories beyond ΛCDM can potentially produce new detectable signals in such experiments. As such, CosmoBit has been developed to combine cosmological and particle physics data simultaneously to better constrain theories, computing cosmological observables and likelihoods for Type Ia supernovae, large-scale structure, Big Bang Nucleosynthesis and the cosmic microwave background. It offers a flexible framework for beyond-ΛCDM theories to be tested, such as modifications to inflation, particle properties, and the effective number of relativistic degrees of freedom, and the code has already allowed for the first global analysis of the parameter space of axion-like particles, whose decay into photons would affect various astrophysical and cosmological observables.[148]

Much of the development of GAMBIT has been through assembling a comprehensive database of models and implementing efficient calculations for connecting them to experimental likelihoods. However, it should be noted that GAMBIT does not currently consider many scenarios of interest for the astrophysics community as such predictions are extremely expensive to calculate (e.g. via N-body simulations). For GAMBIT (or similar tools) to be fully applicable at astrophysical scales will require additional strategies such as employing neural network emulators or simulation-based inference techniques, although an in-depth discussion on this topic is beyond the scope of this review.

4.3. AxionLimits and the dark matter limit plotter

Of course, once a dark matter model has been tested, the resulting constraints need comparing to pre-existing limits, typically done visually by way of dark matter summary plots as mentioned in Section 2. With these graphs being so commonplace in particle physics, AxionLimits[o] hosts files and Python notebooks for creating summary plots for axions, axion-like particles, dark photons, and other ultralight bosons.[149] Additionally, the Dark Matter Limit Plotter[p] developed by the Super Cryogenic Dark Matter Search (SuperCDMS) at the SLAC National Accelerator Laboratory presents an interactive dashboard to generate customisable figures. Users can also apply for their results to be uploaded and included in the plotter for others to use, and as such it already contains many pre-existing limits from various experiments to which any new results can be compared.

Together, the tools discussed in this section, and others of interest to the astroparticle, particle physics and astrophysics communities, could allow the VRE analysis platform to uniquely provide a range of workflows for connecting these communities in deriving ever tighter constraints on dark matter in an open, FAIR manner, additionally making use of ESCAPE's federated storage and OSSR to overcome the challenges of this data-driven research. For example, an ideal future workflow on the VRE would have all necessary software integrated to allow researchers to compute any constraints

[m] https://github.com/lenstronomy/lenstronomy
[n] https://gambitbsm.org/
[o] https://github.com/cajohare/AxionLimits
[p] https://supercdms.slac.stanford.edu/science-results/dark-matter-limit-plotter

on or from astrophysical observations (e.g. via pyHalo) or particle physics predictions for a given dark matter model (such as though GAMBIT), then produce summary plots and custom figures, and be stored in such a way as to be user-friendly and reproducible.

5. Conclusions

There are currently several particle physics experiments and astrophysical observations that are being used to test a vast array of theoretical dark matter models. Acknowledging that many of the ESCAPE Research Infrastructures form part of this search, and with an ever-growing need to compare and combine the results from these approaches, the ESCAPE Dark Matter TSP was established to provide a platform to facilitate this in an open and FAIR way as part of EOSC. The project's analyses and tools are already aiding scientific communities in producing new constraints from particle detectors and direct and indirect detection experiments within particle physics, as well as ensuring reproducibility and providing a testing ground for future experiments' software and computing infrastructure.

In this review, we have provided an overview of the ESCAPE Dark Matter TSP, as well as some observational astronomical dark matter searches, and corresponding tools frequently used in the analyses of dark matter constraints. The review has been aimed primarily at astronomers rather than particle physicists, in order to provide an introduction to the dark matter searches currently incorporated in EOSC, which may share complementarity with observational astronomical dark matter searches. Additionally, to date the TSP has been limited to particle and astroparticle physics experiments but now seeks to expand its reach to incorporate astronomical dark matter searches into its services, for example to produce astronomically relevant and interpretable summary plots like those mentioned at the start of Section 3.

In providing this review, we encourage astronomers to make use of the ESCAPE services within the Dark Matter TSP to facilitate their own dark matter searches, enabling an open, collaborative pathway towards combining complementary constraints from astronomy and particle physics to maximise our understanding of dark matter over the coming decade.

Ethics and consent

Ethical approval and consent were not required.

Data and software availability

No data are associated with this article. The Virtual Research Environment (VRE) can be accessed here: https://vre-hub.github.io/, and links to the GitHub, GitLab, Zenodo and other webpages related to work mentioned in this review can be found in the Notes section.

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Open Peer Review

Current Peer Review Status: ✗ ✓ ? ✓

Version 3

Reviewer Report 27 April 2026

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✓ **Martine Lokken**
Institut de Física d'Altes Energies (IFAE), Barcelona, Spain

I am happy with the updates to the article and believe them to be sufficient to approve the indexing.

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Cosmology, astrophysics, large-scale structure

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Reviewer Report 16 April 2026

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✗ **Eugene Oks**
Auburn University, Auburn, AL, USA

According to Abdurashidova et al. (2022, *Astrophysical Journal* 924, 51), the latest observations from the Hydrogen Epoch of Reionization Array (HERA) do not disprove the results from EDGES (2018). Pearson et al. appear to have overlooked this and have continued attempts to question the observational results from EDGES (2018). Therefore, I do not recommend the paper for indexing.

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Astrophysics; Particle Physics

I confirm that I have read this submission and believe that I have an appropriate level of expertise to state that I do not consider it to be of an acceptable scientific standard, for reasons outlined above.

Version 2

Reviewer Report 06 January 2026

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Martine Lokken
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This article presents an introductory overview of the evidence for dark matter (DM), focusing on the current status of the cold dark matter model, and discusses several ongoing direct and indirect detection experiments in particle physics in the context of the ESCAPE DM Test Science Project. The authors then review several astrophysics efforts to further constrain the nature of DM, and present several available software tools for both fields on the Virtual Research Environment (VRE).

The DM Test Science Project and associated VRE are presented in a clear way that can be useful to astronomers, as is one of the goals of the article. The article is scientifically accurate, but the discussion of baryonic dark matter could be misleading. Additionally, as one of the stated goals of the article is to increase collaboration across fields, the review would benefit from more explicit linking between the astrophysics and particle physics experimental goals and scientific products. As it stands, the article (particularly sections 2 and 3) includes fairly disjoint overviews of particular ongoing DM experiments in the particle physics and astrophysics fields, but lacks clear discussion of connections between those experiments. This is the key point that I believe should be addressed before full acceptance of the article. There are also some issues with clarity; I provide further details in the following paragraphs.

The discussion of 'baryonic dark matter' is potentially misleading; as it stands, it implies that the 70% of unaccounted for baryons are in the form of MACHOs. I recommend clarifying that in fact most of these baryons are expected to exist in the intergalactic medium, which is difficult to observe. In fact, recent observations by fast radio burst dispersion measures have found baryon fractions consistent with the expected cosmic fraction (e.g., Yang et al 2022, arXiv: 2211.04058). Therefore, I recommend removing text that conflates the 'missing baryons' with dark matter. While I understand some of this text may have been added in response to a previous review, the

statements about baryonic dark matter should be qualified more carefully: e.g. when discussing the unaccounted-for baryons, one could state that "*even if* some of the unaccounted for baryonic matter belonged to an unexpected component like MACHOS, the implied ratio is *at least*..." I also note that the values given yield a ratio of 7.1, so the quoted value of 7.6 may be confusing to readers; I recommend quoting '7-8' or stating with higher precision the numbers leading to that calculation.

The organization of section 2.1 could be confusing to a non-particle-physics expert. The introduction of MET in 2.1 seems to set up further discussion of challenges with detection via MET in ATLAS in the following sections, but the subsequent section, 2.1.1, appears to discuss another detection method without mentioning MET again. Reorganization of the MET discussion, clearer sectioning, and/or the addition of linking sentences to connect and/or contrast subsequent paragraphs would help make this review more understandable to an astronomy audience.

Section 3 would be strengthened by providing more explicit links between the astrophysical dark matter searches discussed (subhalo lensing, gamma-ray production from DM annihilation) with the particle physics experiments discussed in Section 2. For example, many astronomers are aware of the astrophysical consequences of WDM or SIDM vs CDM, but are less likely to understand which of the indirect and direct detection experiments ongoing in the particle physics world are helping to constrain these models. I encourage the authors to state clear and explicit links between the experiments and models discussed in section 2 and those in section 3.

Lastly, I recommend adding summary text at the end of Section 4 summarizing why it would be worthwhile to incorporate astronomy software into the VRE, and clarifying the vision and purpose for a fully integrated and coherent dark matter research software environment. To demonstrate the vision, it could be useful to provide an example of an ideal future workflow: for example, after all software integration, will the future VRE allow a researcher to compute cosmology, large-scale structure, and particle physics predictions for a given DM model using, e.g., GAMBIT, and then subsequently compute and plot constraints, entirely within the VRE? Would this be a workflow that was not previously possible for the community?

I include below several minor grammatical notes to help improve readability:
Abstract: "complementary" --> "complementarity"

Introduction:
"Short" --> "shorter" [free-streaming length]
Incomplete sentence: "However, given the above astrophysical problems with CDM and that no clear detections of WIMPs have yet been observed in particle physics experiments, with other theoretical options also being considered"

1.2: Ris --> RIs

2.1: "and infer their existence" --> "and inferring their existence"

"invisible particles (such as neutrinos or dark matter) particles" --> remove one 'particles'

Perhaps the "Data and software availability" section could also link to the VRE, although I recognize it is linked in the footnotes already.

Is the topic of the review discussed comprehensively in the context of the current literature?
Partly

Are all factual statements correct and adequately supported by citations?
Partly

Is the review written in accessible language?
Yes

Are the conclusions drawn appropriate in the context of the current research literature?
Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Cosmology, astrophysics, large-scale structure

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Author Response 16 Mar 2026

James Pearson

We thank the reviewer for their insightful comments and suggested revisions. To address each point in order: 1. A subsection has been added to the end of Section 3 to address this, relating Sections 2 and 3 and pointing to two reviews providing more details on the subject. 2. After some thought, some of the text of the relevant paragraph was deemed unnecessary, so the text has been simplified with more of a focus on baryonic dark matter in the IGM rather than MACHOs. 3. For clarity, a linking sentence has been added before 2.1.1. 4. See point 1 above. 5. As suggested, a paragraph has been added clarifying the vision of the VRE software and an idealised workflow. 6. Grammatical notes: These have been updated in the text.

Competing Interests: No competing interests were disclosed.

Reviewer Report 31 December 2025

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I enjoyed reading this review and could not agree more with its overall goals. I am strongly in favour of making data sets and analysis routines publicly available and believe that the ESCAPE Dark Matter Test Science Project is making a valuable contribution in this regard that deserves to be highlighted and advertised. While I believe the manuscript should be published eventually, I have a number of suggestions for how the manuscript can be improved further:

- In its current state, the ESCAPE Dark Matter Test Science Project suffers from a lack of completeness, which limits its usefulness for the community. This is most obvious in the case of dark matter direct detection experiments, where most of the leading experiments (such as XENONnT, LZ and Panda-X) are missing. The article should comment on the reasons for this (which could be for example a lack of publicly available information, or a simple lack of personpower), why the DarkSide experiment was chosen specifically, and possible strategies to make the data base more complete.

- In my opinion, the main obstacle for a closer collaboration between particle physicists and astrophysicists is that in many cases astrophysics and particle physics do not probe the same properties of dark matter, making any connection model-dependent. For any astrophysical observation that only relies on the gravitational interactions of dark matter (which includes the free-streaming of warm dark matter), constraints from laboratory experiments are irrelevant. And even constraints on dark matter self-interactions cannot be connected to other particle physics observables in a model-independent way. Because of this, providing a database of constraints is not sufficient unless it is combined with a framework for calculating observables from fundamental models. This is where most conceptual work is required and where scientists are needed who understand both fields well enough to make these connections. From the article it does not become clear how ESCAPE aims to address this issue.

- Along the same lines, I have the impression that GAMBIT is somewhat misrepresented as a tool for statistical inference. Most of the effort in the development of GAMBIT actual go into the development of a database of models and the calculations needed to connect them to experimental likelihoods in an efficient way. However, GAMBIT currently does not consider many scenarios of interest for the astrophysics community, simply because the predictions are prohibitively expensive to calculate (e.g. N-body simulations needed to interpret gravitational lensing data). It would be interesting to discuss possible strategies to address this issue (e.g. neural network emulators, simulation-based inference techniques ...).

- The first referee report highlights yet another difficulty of collaboration between particle physicists and astrophysicists, which is that many of the latter are fundamentally opposed to the idea of new particles beyond the Standard Model. I therefore appreciate the effort of the authors to address also these parts of the community and to highlight the compelling case for non-baryonic dark matter. I think this part of the discussion could be sharpened further by reminding the reader that even if we didn't have the ability to detect neutrinos on Earth, we would still be

convinced of their existence through cosmological and astrophysical observations (e.g. the measurement of N_eff or the mechanism of supernova explosions).

- I find the recently added discussion of EDGES to be out of place. Of course it could be interesting to list various experimental/observational anomalies that could be related to the nature of dark matter (DAMA annual modulation, Galactic centre excess, keV x-ray/gamma-ray lines, diversity of dwarf galaxies...), many of which are more robust than the EDGES signal. But this is clearly not the goal of the article and would distract from its main message. Nevertheless, I do believe that 21cm intensity mapping is among the most interesting examples of the interplay between particle physics and cosmology and deserves to be mentioned in some form. Maybe the general concept can be discussed in a way that mentioned EDGES less prominently.

Is the topic of the review discussed comprehensively in the context of the current literature?
Partly

Are all factual statements correct and adequately supported by citations?
Yes

Is the review written in accessible language?
Yes

Are the conclusions drawn appropriate in the context of the current research literature?
Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Dark matter, particle physics

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard, however I have significant reservations, as outlined above.

Author Response 16 Mar 2026

James Pearson

We thank the reviewer for their insightful comments and suggested revisions. To address each point in order:

1. The text has been updated to clarify that the listed experiments are those currently within the ESCAPE partners who are themselves invested in open science, and the ESCAPE tools and services are provided for any dark matter experiments invested in open science, with the aim of incorporating more such experiments in future, which will depend on the willingness of such experiments to share their data and process them into an appropriate format.

2. The text has been updated to have a reduced focus on EDGES, instead expanding the paragraph with more challenges of CDM, such as those mentioned by the reviewer.

3. The ESCAPE tools have been created to facilitate other researchers (including the associated research infrastructures) to establish such a framework themselves (which is hence beyond the scope of this paper).

4. The text has been updated to include mention of this, although an in-depth discussion on this topic is beyond the scope of this review.

5. We appreciate the suggestion, however we feel that it would break the flow of the text and the reader may be confused by the sudden focus on neutrinos, so the text has not been updated to include this.

Competing Interests: No competing interests were disclosed.

Reviewer Report 29 December 2025

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Helena Garcia Escudero
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Report: Overview of the ESCAPE Dark Matter Test Science Project for Astronomers
Summary & Context
The article presents an overview of the ESCAPE Dark Matter Test Science Project (TSP), describing its goals, tools, and how it seeks to bridge the gap between the particle-physics and astronomy communities in the search for dark matter. The authors note that while dark matter detection efforts come from particle physics (direct detection, indirect detection, collider experiments), the evidence for dark matter's existence is fundamentally astrophysical or cosmological in nature.
The paper argues that a major challenge is that results from particle-physics experiments are often difficult for astronomers to interpret in the context of astrophysical observations, due to different conventions, data formats, and lack of unified tools.ESCAPE aims to address this by providing shared data infrastructure, software, and workflows — via a Virtual Research Environment (VRE), data lake, software catalog, and analysis pipelines — so that different experiments and communities can contribute, compare, and combine their constraints on dark matter in a consistent, reproducible, and interoperable way.
The review article is written with the goal of making this project and its tools accessible to astrophysicists, hopefully enabling them to use ESCAPE's outputs and integrate particle-

physics constraints with observational constraints.
Is the topic discussed comprehensively, in context of current literature?
Strengths:

- **The article does a good job explaining why a joint dark matter infrastructure is needed: the longstanding separation between particle-physics experiments and astronomical/cosmological observations. This is a well-known challenge in dark matter research.**

- **It outlines clearly the scope of the project: the types of experiments integrated (direct detection, indirect detection, collider experiments) — e.g. DarkSide, ATLAS, KM3NeT, Cherenkov Telescope Array — and describes the infrastructural tools (data lake, VRE, software catalogue) used to unify data/analysis.**
- **The authors also note current limitations: the existing TSP tools primarily support particle physics experiments; as of now, astrophysical constraints (e.g. from galaxy rotation curves, lensing, large-scale structure) are not yet integrated.**
- **They provide a roadmap / vision for how observational astronomers might contribute, and how the project could help integrate observational data with experimental constraints.**

Limitations / Missing Context:

- **Because the focus so far has been on particle-physics experiments, the review does not yet cover in detail how astrophysical data (e.g. gravitational lensing, galaxy dynamics, cosmological structure) would be represented within ESCAPE. The authors themselves note this gap.**
- **The article does not deeply discuss the limitations, systematic uncertainties, or model-dependence that plague both particle-physics and astrophysical searches. For example: how differences in dark matter halo modeling, astrophysical backgrounds, or assumptions about the dark matter particle (mass, interaction type) might affect the comparability of constraints. A more comprehensive literature review on these challenges would strengthen the discussion.**
- **There is limited discussion about how conflicting results across experiments (or null results) will be reconciled, especially given that many direct- and indirect-detection experiments have produced null results so far. The review might benefit from more context on the existing "state of exclusion limits," astrophysical vs. experimental tensions, and how ESCAPE aims to handle these.**

Conclusion on coverage: The topic is discussed well and thoughtfully within the project's scope. The review provides a clear introduction to the need for integration, outlines the infrastructure developed, and explains how TSP aims to help. However — since this is early-stage infrastructure — the review does not (yet) provide a fully comprehensive discussion of all relevant astrophysical constraints, theoretical uncertainties, or inter-experiment tensions. As a result, the coverage is appropriate for a project-oriented overview, but less so as a definitive review of dark matter constraints in the literature.
Are the factual statements correct and well cited?
Yes. The review draws on prior work and descriptions of the ESCAPE initiative, the experiments involved, and the challenges faced in dark matter searches. For instance:

- **The description of ESCAPE's aims (open science, data lake, VRE, bridging communities) is consistent with prior documentation.**
- **The identification of experiments (direct detection, indirect detection, collider) as part of the TSP scope matches the project's Indexed scope.**

- **The statement that the existing TSP tools "so far" focus on particle physics experiments and do not yet integrate astrophysical constraints is explicitly acknowledged.**

Where the authors note limitations or gaps (e.g. lack of astrophysical data integration), they do not overstate — which is scientifically honest.
Because this is a short review article (10 pages, no figures), the authors do not make sweeping claims beyond the status of the TSP and its goals; hence, the factual statements are modest and correctly supported.
Thus: factual correctness and citation support — yes.
Is the review written in accessible language?
Overall — yes, the review is reasonably accessible for its intended audience (astronomers / astrophysics researchers), while remaining scientifically appropriate. There are a few points for improvement.
Positives:

- **The writing is clear and directed toward an astronomical audience (not necessarily particle-physics experts), which was the explicit goal. The introduction frames the historical separation between astrophysical evidence and particle-physics experiments in understandable terms.**

- **Technical aspects (data infrastructure, VRE, examples of experiments) are described in conceptual terms, without unnecessary jargon, which makes the article approachable for astronomers or non-experts.**

- **The structure is logical: explanation of the problem, introduction of ESCAPE, description of tools and experiments, discussion of (future) use by astronomers.**

Areas for improvement:

- **Because the article necessarily involves several technical concepts (collider vs direct/indirect detection; data lakes; FAIR data; Virtual Research Environments), some readers without prior familiarity with computational infrastructure may find parts less accessible. Perhaps a brief "Glossary" or more contextualization for non-particle physicists could help.**

- **The article assumes some familiarity with common dark matter search methods. For example, it lists several experiments by name; someone entirely new to dark matter research might struggle to place their significance.**

Are the conclusions drawn appropriate in the context of current research literature?
Yes — the conclusions are modest, realistic, and well justified:

- **The authors conclude that the ESCAPE TSP provides a promising framework for cross-community collaboration by providing data and software infrastructure, which may help unify dark matter constraints from diverse experiments. This is supported by the description of the VRE, data lake, and the experimental scope.**

- **They also recognize current limitations: that astrophysical constraints and observational data are not yet integrated, and that further work is needed to expand tools to cover the astronomy side.**

- **The recommendation that astrophysicists engage with ESCAPE — using its tools,**

contributing observational constraints, and helping interpret experimental results in astrophysical context — is reasonable and aligns with the broader need for interdisciplinary cooperation in dark matter research.

Given the complexity and uncertainty inherent in dark matter searches, drawing bold claims (e.g. "we will find dark matter soon") would be inappropriate — but the authors avoid such overreach. Their conclusions remain grounded in what ESCAPE currently offers, and what it could enable in the future. That caution is appropriate.
Typos and Terminology

- **In the introduction, Standard Model is mentioned for the first time, but the abbreviation is not introduced at that point. The authors later use the acronym "SM," but it is not originally defined. I recommend introducing it upon first use, for example: "Standard Model (SM)" and replace SM consistently within the text.**

Overall Assessment and Recommendations
Overall, this review article is a valuable, timely, and well-crafted contribution. It addresses a real, persistent problem in dark matter research — the fragmentation between experimental and observational communities — and describes a concrete solution: shared infrastructure under ESCAPE. For astronomers or astrophysicists who have not closely followed the particle-physics side of dark matter searches, this paper serves as an excellent entry point. It also provides value for more knowledgeable experts by outlining the emerging ecosystem of shared data infrastructures, analysis tools, and cross-experiment pipelines, giving them a clear view of how their work can integrate with broader multi-messenger efforts and how upcoming open-science platforms may streamline collaborative, cross-disciplinary dark matter research.
For future improvements or next-phase work, I recommend:

- **Integrating observational astrophysics data (e.g. from galaxy dynamics, gravitational lensing, cosmological surveys) into the ESCAPE tools, so that astronomers can directly use those data to compare with experimental constraints.**

- **Providing tutorials, documentation, or user-friendly interfaces for the VRE / data to lower the barrier for astronomers unfamiliar with particle-physics workflows.**

- **Expanding the review to discuss limitations, model dependencies, and uncertainties in both experimental and observational dark matter constraints — which could help users critically interpret combined results.**

Offering case studies or example analyses that combine experimental (e.g. direct detection) constraints with astrophysical observations, to demonstrate how ESCAPE tools can be used in practice.

Is the topic of the review discussed comprehensively in the context of the current literature?
Yes

Are all factual statements correct and adequately supported by citations?
Yes

Is the review written in accessible language?
Yes

Are the conclusions drawn appropriate in the context of the current research literature?
Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Cosmology and astroparticle physics

I confirm that I have read this submission and believe that I have an appropriate level of expertise to confirm that it is of an acceptable scientific standard.

Author Response 16 Mar 2026

James Pearson

We thank the reviewer for their insightful comments and suggested revisions. To address each point in order: 1. Limitations / Missing Context:
a) Given the widely different astrophysical observations, the data may vary substantially and hence how the data would be represented in ESCAPE will require close collaboration with the specific astrophysical communities, which the leads of the Dark Matter Test Science Project encourage.
b & c) Such a comprehensive literature review over astrophysics and particle physics dark matter searches is beyond the scope of this paper - apt discussions of exclusion limits, tensions and limitations already feature in the more comprehensive reviews cited in the Introduction. Meanwhile, this paper aims to focus on the DM TSP project while providing some examples of such searches for integration with ESCAPE tools. Through discussion on the needs of each community, ESCAPE tools are aimed at facilitating researchers to handle such tensions etc., rather than the ESCAPE project handling them itself.

2. Accessibility:
a) The VRE & data lake has been expanded upon in the text. FAIR principles are commonly employed and fairly self-explanatory given the abbreviation and reference, and each particle experiment type is explained at the start of the relevant subsection.
b) The text has been updated to clarify that the listed experiments are those currently within the ESCAPE partners who are themselves invested in open science.

3. Typos: This has now been corrected.

4. Future improvements or next-phase work: We appreciate the detailed list of ideas for where to take the work next, though here we leave that to future work.

Competing Interests: No competing interests were disclosed.

Reviewer Report 19 December 2025

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Eugene Oks
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The paper has been improved, but it still has significant flaws, as follows.

First, the authors refer to Singh et al (2022) observation at SARAS 3 as not confirming the anomalous 21 cm absorption signal observed at the EDGES by Bowman et al (2018). However, Prof. Bowman (the Head of the EDGES team) in his private communication to me shared with me the following *concerns with the Singh et al paper*.

- 1. The limited amount of data which causes *low sensitivity and reduces options for testing for instrumental effects.*
- 2. The narrow bandwidth that makes the 21cm *parameter estimation weaker and less robust.*
- 3. The lack of assessment of *systematic errors* in their parameter estimation.

Prof. Bowman added: "These experiments are extremely challenging. As we noted in the 2018 paper, we made many tests of the instrument and analysis before reporting our evidence of a detection."

Further problems with Singh et al (2022) observation at SARAS 3 are the following.

- At the SARAS 3, there was some *unwanted contribution* from receiver noise and thermal emission from water beneath the antenna, the antenna being floated on a large body of water (on lakes in Southern India).
- The *noise level* at the SARAS 3 was 213 mK, which was several times higher than the noise level of 87 mK at the EDGES.
- *Radio Frequency Interference (RFI):* At the SARAS 3 observing sites in India, substantial RFI was encountered up to 55 MHz and the spectrum was also unusable above 85 MHz. In distinction, in Australia (where the EDGES is located), there are no licensed digital TV transmitters below 174 MHz, what allowed Bowman et al (2018) to perform observations in the broader range of 50 – 100 MHz.

For all of the above reasons, Singh et al (2022) observation at the SARAS 3 are **unreliable** compared to Bowman et al (2018) observation at the EDGES. Last but not least: according to Abdurashidova et al paper of 2022 (Astrophys. J. 924, 51), the latest observations at the Hydrogen Epoch Reionization Array (HERA) do **not disprove** the results from EDGES of 2018.

Second, the authors refer to alternative explanations of the anomalous 21 cm signal, citing Bevins et al (2022) paper and references therein. So, let us briefly analyze the alternative explanations.

1. A possible cooling of baryons by some exotic dark matter particles of the charge of the million times smaller than the electron charge, as hypothesized in paper by Muñoz & Loeb of 2018 (Nature 557, 684) and Liu et al paper of 2019 (Phys. Rev. D, 100, 123011). However, the *hypothetical* exotic dark matter particles of the charge of the million times smaller than the electron charge were never discovered experimentally. Besides, Liu et al (2019)

estimated that if there would be charged dark matter particles, they can only constitute ~ 10^{-8} of the total dark matter energy density.

2. Another alternative explanation requires an additional *hypothetical* radio background suggested by Feng & Holder (2018, Astrophys. J. 858, L17), Ewall-Wice et al (2018, Astrophys. J. 868, 63), Fialkov & Barkana (2019, MNRAS 486, 1763), and Reis, Fialkov & Barkana (2020, MNRAS 499, 5993). However, Sharma showed (already in 2018, MNRAS 481, L6) and Cang et al reconfirmed (in 2024, arXiv: 2411.08134.v1) that an additional radio background **cannot** explain the observed absorption signal.

Therefore, the most plausible explanation of the anomalous 21 cm signal is the one suggested by Barkana (2018, Nature, 555, 71) and reconfirmed by McGaugh (2018, Research Notes Amer. Astron. Soc. 2, 37): baryonic dark matter particles cooled down the primordial hydrogen gas by collisions. In paper published in Research in Astronomy and Astrophysics (2020, 20, 109) it was shown that if the unspecified (in the above papers by Barkana and by McGaugh) baryonic dark matter particles were the Second Flavor of Hydrogen Atoms (SFHA), then the anomalous 21 cm signal can be explained not only qualitatively, but also quantitatively.

Theoretically, the SFHA results from the second solution of the standard Dirac equation for hydrogen atoms – the solution that became legitimate for all S-states (i.e., the states of the zero angular momentum) after the allowance for the finite size of protons and for the actual experimental charge density distribution inside protons. Due to the selection rules of quantum mechanics, the SFHA by virtue of having only the S-states, cannot emit or absorb the electromagnetic radiation: the SFHA remains *dark*. Most significantly, the SFHA is not just a theoretical construct – the actual existence of the SFHA is evidenced by three different types of atomic experiments: these experiments revealed huge (up to several orders of magnitude) discrepancies with the corresponding previous theories and the SFHA-based explanations completely removed these huge discrepancies, while alternative explanations were never provided. Last but not least: the SFHA-based explanation completely resolved the long-standing puzzle of the neutron lifetime; so, the SFHA does exist – for details see, e.g., papers published in Int. J. Mod. Phys. D 2025, 34, 2550008, in Nuclear Phys. B 2025, 1014, 116879, in Symmetry 2025, 17, 517, as well as the review published in New Astronomy Reviews 2023, 96, 101673.

The most important: in distinction to all attempted alternative explanations of the anomalous 21 cm signal, the theory behind the SFHA *does not make any assumptions* and, being based on the standard Dirac equation, is *within the Standard Model.* Therefore, it is favored by the *Occam Razor principle* stating that when several theories compete, the one that makes the least assumptions is the most probable to correspond to reality. Thus, the *existing* SFHA is more favorable than all alternative, exotic explanations of the anomalous 21 cm signal.

Because of the above significant flaws in the revised paper, I still cannot recommend it for indexing.

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Astrophysics; Particle Physics

I confirm that I have read this submission and believe that I have an appropriate level of expertise to state that I do not consider it to be of an acceptable scientific standard, for reasons outlined above.

Author Response 16 Mar 2026

James Pearson

We thank the reviewer for their insightful comments and suggested revisions. While we appreciate the detailed response, we do not believe the paper should be significantly modified on the basis of unpublished private communications between third parties. In agreement with comments from other reviewers, we have expanded the discussion on problems with lambda-CDM and their alternate explanations and slightly reduced the focus specifically on the EDGES signal as EDGES (and indeed a fully in-depth review of dark matter candidates) is not the focus of this work – such comprehensive discussions of the EDGES signal and the limitations of all other works would be best left to another review.

Competing Interests: No competing interests were disclosed.

Version 1

Reviewer Report 13 November 2025

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Eugene Oks
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The paper provides a useful overview of the tools for the particle physics community involved in the experimental searches for dark matter. The authors encourage astronomers to utilize the ESCAPE services within Dark Matter Test Science Project.

However, the paper has significant flaws, as follows.

1. From astrophysical observations (Planck Collaboration) follows that in the Universe there are two types of Dark Matter (DM): baryonic DM and non-baryonic DM – baryonic DM is in the ratio 1 to 5 to non-baryonic DM (see, e.g., review by Arbey and Mahmoudy, Progr. Part. Nucl. Phys., 119 (2021) 103865). Therefore, the authors should clearly state in Introduction the existence of these two types of DM, both definitely existing, as shown by the astrophysical observations – otherwise the readers would be confused from the very beginning of the paper.

2. Out of the major astrophysical observations, causing to resort to DM, the authors mention only the flattening of the rotation curves of galaxies and gravitational microlensing. However, there is also the third type: the observation of the anomalous absorption in the redshifted 21 cm line from the early Universe (Bowman et al, Nature 555 (2018) 67) – the absorption signal was found to be 2 to 3 times stronger than predicted by the standard cosmology. This meant that the

primordial hydrogen gas was significantly cooler than expected from the standard cosmology. The consistent, noncontroversial explanation of this anomalous absorption required baryonic DM that cooled the hydrogen gas by collisions (Barkana, Nature 555 (2018) 71; McGaugh, Res. Notes Amer. Astron. Soc. 2 (2018) 37).

3. While referring to reviews on DM in peer-reviewed journals, the authors cite only relatively old reviews indexed between 2002 and 2020. However, there are more recent reviews on DM indexed in the peer-reviewed journal of the tremendous impact factor 24.8: New Astronomy Reviews 96 (2023) 101673; 93 (2021) 101632.

Thus, the paper requires a major revision.

Is the topic of the review discussed comprehensively in the context of the current literature?

Partly

Are all factual statements correct and adequately supported by citations?

Partly

Is the review written in accessible language?

Yes

Are the conclusions drawn appropriate in the context of the current research literature?

Yes

Competing Interests: No competing interests were disclosed.

Reviewer Expertise: Astrophysics; Particle Physics

I confirm that I have read this submission and believe that I have an appropriate level of expertise to state that I do not consider it to be of an acceptable scientific standard, for reasons outlined above.

Author Response 28 Nov 2025

James Pearson

We thank the reviewer for their insightful comments and suggested reviews. To address each point in order:

1. As a clarification, the suggested review generally refers to dark matter as being separate from baryonic matter, with the ratio of all baryonic matter to cold dark matter being around 1:5 according to the quoted Planck18 results. Through works by e.g. de Graaff et al. (2019), about 30 percent of the baryon budget can be accounted for, and so the rest could be regarded as 'baryonic dark matter', giving a ratio of baryonic-to-non-baryonic dark matter of roughly 1:7.6. Regardless, the first paragraph of the Introduction has been updated to clarify the existence of both baryonic and non-baryonic dark matter and the focus of this work on the latter.

2. Additional text has been added to the paper regarding the anomalous absorption of the

redshifted 21cm line in data from the Experiment to Detect the Global Epoch of Reionization Signature (EDGES; Bowman et al. 2018). We mention that this could be evidence for baryonic dark matter (Barkana 2018; McGaugh 2018), however we also highlight that this detection has not been confirmed, such as the non-detection by the Shaped Antenna measurement of the background RAdio Spectrum 3 experiment (SARAS 3; Singh et al. 2022), with other works having sought alternative explanations (see e.g. Bevins et al. 2022 and references therein). It is also worth noting that the CMB gives an approximately 100-sigma detection of collisionless (i.e. non-baryonic) dark matter (Planck Collaboration 2018; Arbey & Mahmoudi 2021; Turner 2025), providing concrete evidence of non-baryonic dark matter - this has also been added to the Introduction. Also as a clarification, while the lack of gravitational microlensing of MACHOS have ruled out some mass ranges for baryonic dark matter, gravitational microlensing itself does not provide any evidence for non-baryonic dark matter; rather, it is strong and weak gravitational lensing on cosmological scales that provides this evidence and hence what we focus on here.

3. We have included references to more recent reviews, including the suggested Oks (2021) paper, Arbey & Mahmoudi (2021), and a recent review by Cirelli et al. (2024).

Competing Interests: No competing interests were disclosed.