

OVERVIEW OF THE ESCAPE DARK MATTER TEST SCIENCE PROJECT FOR ASTRONOMERS

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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 complementary with astrophysical observations.

Subject headings: cosmology: dark matter, astroparticle physics

1. INTRODUCTION

After the discovery of surprisingly large velocity dispersions for galaxies in the Coma cluster (Zwicky 1933), and following the discovery of discrepancies between spiral galaxy rotation curves and their observed stellar masses (Rubin & Ford 1970), 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 while there have been various possibilities put forward as to its nature (Bertone et al. 2005; Peter 2012), cold dark matter (CDM) has proven to be the most enduring; such non-relativistic particles have a short 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 (Blumenthal et al. 1984; Frenk & White 2012; Conselice 2014).

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 (Buckley & Peter 2018; Mayer 2022). 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. 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 (Allen et al.

2002). 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. To et al. 2021). 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. Shajib et al. 2021; Sonnenfeld & Cautun 2021) and potential substructures that can be used to constrain the properties of dark matter (e.g. Amorisco et al. 2022; He et al. 2022). Despite the success of CDM, there still exists a number of astrophysical problems yet to be fully resolved, primarily arising from simulations of CDM haloes. These include the “core-cusp” problem (Flores & Primack 1994; Moore 1994), the “missing satellites” problem (Klypin et al. 1999; Moore et al. 1999) and subsequent “too many satellites” problem (Kelley et al. 2019; Kim & Peter 2021), and the “too big to fail” problem (Boylan-Kolchin et al. 2011, 2012). As such, refinements to simulations and further observations from new large-scale surveys like the *Euclid* survey (Laureijs et al. 2011; Euclid Collaboration et al. 2024) and the Vera C. Rubin Observatory’s Legacy Survey of Space and Time (LSST, Ivezić et al. 2019) 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: Sumner (2002); Bertone et al. (2005); Peter (2012); Bauer & Plehn (2017); Baudis (2018); Bertone & Tait (2018); Tao (2020); Balazs et al. (2024), along with the road map for the next decade of US research proposed in the latest Snowmass dark matter complementarity report (Boveia et al. 2025). For detailed reviews of the state of particle physics as a whole, see for example, Workman et al. (2022) and Navas et al. (2024). 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 (Roszkowski et al. 2018). 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 (Bertone & Tait 2018). These theories include alternative CDM candidates such as axion-like particles (Nagano et al. 2019) and primordial black holes (e.g. Jedamzik 2020; Green & Kavanagh 2021; Green 2024), non-CDM particles such as warm dark matter (WDM; e.g., Dayal & Giri 2024) and self-interacting dark matter (SIDM; Adhikari et al. 2022), as well as modifications to general relativity (e.g. Belgacem et al. 2019).

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 experimentalists¹.

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 (Beacham et al. 2020), 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.

¹ An overview of which can be found here: <https://www.idmeu.org/dm-related-communities-centers-and-groups/>

The European Consortium for Astroparticle Theory (EuCAPT; Alves Batista et al. 2021) 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; Cirelli et al. 2024) 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 (Baker 2016). 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 (European Commission 2025). For dark matter searches, we highlight the Dark Matter Data Centre (DMDC; Banerjee & Ferreiro Iachellini 2023) 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 GitLab².

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, astroparticle 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, the Soft-

² <https://www.origins-cluster.de/odsl/dark-matter-data-center>

ware Catalogue Open-source Scientific Software and Service Repository (OSSR)³, and the Virtual Research Environment (VRE) analysis platform⁴ (see, e.g., Gazzarrini et al. 2024; Bhattacharjee et al. 2023a).

With funding from the EOSC-Future project (Bird 2021), ESCAPE developed the VRE and delivered the Dark Matter Test Science Project⁵ (TSP, Cuoco et al. 2021), 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 (Cuoco et al. 2021). In particular, the project focuses on experimental data and software from the following direct detection,

indirect detection, and particle collider experiments: 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 accessible⁶). 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 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 (Bird 2021). 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 $\sigma(\text{cm}^2)$ 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 Boveia et al. (2025). 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 $\langle\sigma v\rangle(\text{cm}^3 \text{s}^{-1})$. 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 (Balazs et al. 2024).

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 infer 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

³ <https://zenodo.org/communities/escape2020/>

⁴ <https://github.com/vre-hub>, and <https://vre-hub.github.io/>

⁵ <https://eoscfuture.eu/data/dark-matter/>

⁶ <https://github.com/vre-hub/science-projects/tree/main>

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) particles, it would also go undetected through the detector. This is a challenge when probing for dark matter models in a collider experiment.

2.1.1. Dilepton resonance search

In simplified models of dark matter interactions with SM particles (Abercrombie et al. 2020), 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 (ATLAS Collaboration 2019), which could be extrapolated to the full data set expected to be collected over the lifetime of the LHC (ATLAS Collaboration 2018).

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 (Albert et al. 2022; Bose et al. 2022; Boveia et al. 2022a,b), 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 (Strassler & Zurek 2007), 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 (Park & Zhang 2019), even though the original decaying particles are dark sector ones; they could behave as semi-visible jets (Cohen et al. 2015, 2017); 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 (Schwaller et al. 2015).

There have been initial searches for these models at the ATLAS experiment (ATLAS Collaboration 2024a,b, 2025a,b). 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 ATLAS Collaboration (2024b). 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 50kg 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 (Agnes et al. 2015, 2016).

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-20k, containing tens of tonnes of liquid argon, to further extend the discovery potential of the direct detection program (Manthos 2023; DarkSide-20k Collaboration 2024).

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 (Bringmann & Weniger 2012). The *Fermi* LAT’s high angular and energy resolutions and its comparatively large effective area should allow it to detect such faint emissions (Charles et al. 2016), 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 (Calore et al. 2018; Alvarez et al. 2020). 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 VRE⁷, along with data moved to the ESCAPE Data Lake, making them publicly accessible (Calore et al. 2021) 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 Bhattacharjee et al. (2023b). 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 $\sim 10^{-36} \text{ cm}^2$ for dark matter masses below 10 GeV (Bhattacharjee et al. 2024b). The software was again made open source (Bhattacharjee et al. 2024a) and fully available through the VRE⁸ 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 100m-long strings at a depth of $\sim 2500\text{m}$, while ARCA will eventually have two sets of 115 $\sim 700\text{m}$ -long strings each, collectively covering a 1km^3 volume anchored at a depth of 3500m. 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 VRE⁹, 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 (Unbehaun et al. 2023) 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 (Smirnov & KM3NeT Collaboration 2024; Unbehaun et al. 2024).

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

⁷ <https://gitlab.in2p3.fr/escape2020/virtual-environment/mlf-ermilatdwarfs>

⁸ <https://gitlab.in2p3.fr/escape2020/virtual-environment/brown-dwarfs-gamma>

⁹ <https://gitlab.in2p3.fr/escape2020/virtual-environment/irf-from-km3net>

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 (Bengtsson et al. 2023; Ekman et al. 2024) 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 astronomers¹⁰. For example, the platform includes ALADIN LITE (Baumann et al. 2022), a browser-based astronomical HiPS visualiser; GAMMAPY (Donath et al. 2023), a Python toolbox for gamma-ray astronomy; and a series of Jupyter Notebook tutorials on using astronomical databases and Virtual Observatory tools (Marchand et al. 2025).

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. Buckley & Peter (2018) and Mayer (2022), including Figures 1 and 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 (Hezaveh et al. 2016). 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 (Keeley et al. 2023). Work has also been done to combine both effects to increase the sensitivity to substructure (Gilman et al. 2024).

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. Bode et al. 2001; Hezaveh et al. 2016; Asgari et al. 2023), 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; He et al. 2022). Careful modelling of these subhaloes, using complex mass models within tools like LENSTRONOMY (Birrer & Amara 2018; Birrer et al. 2021) or PYAUTOLENS (Nightingale et al. 2021), 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 He et al. 2022) and WDM (e.g. the 2.0 keV lower bound from Birrer et al. 2017), with WDM models expected to produce fewer small-scale perturbations than CDM (Vegetti et al. 2023). To date, only a few lenses have been studied in this way for low-mass haloes (e.g. Vegetti et al. 2010, 2012; Hezaveh et al. 2016; Hsueh et al. 2020), 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 (Li et al. 2016; Gilman et al. 2019; Simon et al. 2019).

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 (Spergel & Steinhardt 2000; Adhikari et al. 2022). 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 (Vogelsberger et al. 2012; Rocha et al. 2013; Robertson et al. 2018, 2021). 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 (Vegetti et al. 2023). 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 Nadler et al. (2020), 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 (Kaplinghat et al. 2014; Sameie et al. 2018; Despali et al. 2019; Zeng et al. 2022). As such, observations of gravitational lenses can explore the potential diversity of these core distributions that would arise from SIDM (Robertson et al. 2019). For example, Gilman et al. (2021) showed that flux ratios from quadruple-image strongly lensed quasars

¹⁰ <https://zenodo.org/communities/escape2020/>

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. [Nierenberg et al. 2024](#)). Meanwhile, simulations from [Zeng et al. \(2025\)](#) showed that the core-collapse of subhaloes exhibits unique observable features in lensing, with a SIDM cross-section of $\geq 200 \text{ cm}^2 \text{ g}^{-1}$ typically required for a significant fraction of subhaloes 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 [Vegetti et al. \(2023\)](#). 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 (dSph) are considered to be promising targets for indirect dark matter detection using ground- and space-based γ -ray telescopes ([Strigari 2018](#); [Acharyya et al. 2024](#)). 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 ([Armand & Herrmann 2022](#)). 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 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. [Bergström et al. 1998](#); [Armand & Herrmann 2022](#)),

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

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 $\langle\sigma_{\text{ann}} v\rangle$, the WIMP mass m_{DM} , the expected spectrum dN_γ^f/dE_γ 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 annihilation¹¹) and that density of the dSph’s dark-matter halo has a radially symmetric profile ρ_{DM} , then the J-factor can be written as an integral along the line-of-sight (los) coordinate s and over the solid angle $\Delta\Omega$.

$$J(\Delta\Omega) = \int_{\Delta\Omega} d\Omega \int_{\text{los}} \rho_{\text{DM}}^2(s) ds \quad (2)$$

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 $\langle\rho^2\rangle \geq \langle\rho\rangle^2$.

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. [Hayashi et al. 2020](#)). 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

¹¹ In 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.

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.

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 (Schneider et al. 2012; Gilman et al. 2020b) when combined with software that can simulate full mass distributions with substructure, for instance the PYHALO Python package¹² (Gilman et al. 2020a). 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 package, primarily LENSTRONOMY¹³ (Birrer & Amara 2018; Birrer et al. 2021), 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, Gilman et al. (2023) applied this method to study quadruply imaged quasars, from which their models disfavoured cross sections exceeding $100 \text{ cm}^2 \text{ g}^{-1}$ 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 (Yang et al. 2023a,b).

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 GAMBIT¹⁴ (Global And Modular BSM Inference Tool; Athron et al. 2017) 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 (Bringmann et al. 2017) and COSMOBIT (Renk et al. 2021). 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 (Cornell & GAMBIT Collaboration 2020), and has been used to explore a range of dark matter candidates: see Balazs (2025) 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 Λ CDM 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- Λ CDM 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 (Balázs et al. 2022).

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, AXIONLIMITS¹⁵ hosts files and Python notebooks for creating summary plots for axions, axion-like particles, dark photons, and other ultralight bosons (O’Hare 2020). Additionally, the DARK MATTER LIMIT PLOTTER¹⁶ 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.

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

¹² <https://github.com/dangilman/pyHalo/>

¹³ <https://github.com/lenstronomy/lenstronomy>

¹⁴ <https://gambitbsm.org/>

¹⁵ <https://github.com/cajohare/AxionLimits>

¹⁶ <https://supercdms.slac.stanford.edu/science-results/dark-matter-limit-plotter>

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.

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DATA AVAILABILITY

No new data were generated or analysed in support of this research.

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