Dark Matter Science Project

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Abstract. A Dark Matter Science Project is being developed in the context of the ESCAPE (European Science Cluster of Astronomy and Particle physics ESFRI research infrastructure) project as a collaboration between scientists in European Research Infrastructures and experiments seeking to explain the nature of dark matter (such as HL-LHC, KM3NeT, CTA, DarkSide). The goal of this ESCAPE Science Project is to highlight the synergies between different dark matter communities and experiments, by producing new scientific results as well as by making the necessary data and software tools fully available. As part of this Science Project, we use experimental data and software algorithms from selected direct detection, indirect detection, and particle collider experiments involved in ESCAPE as prototypes for end-to-end analysis pipelines on a Virtual Research Environment that is being prepared as one of the building blocks of the European Open Science Cloud (EOSC). This contribution focuses on the implementation of the workflows on the Virtual Research Environment using ESCAPE tools (such as the Data Lake and REANA), and on the prospects for data management, data analysis and computing in the EOSC-Future project.

1 Introduction

Galaxies in our universe appear to rotate with such speed that the gravity generated by their observable matter could not possibly hold them together. The same is true of cluster galaxies. This leads scientists to believe that something we have yet to detect is giving these galaxies extra mass, generating extra gravity they need to stay intact. This strange and unknown matter was called "dark matter" since it does not seem to interact with the electromagnetic field. The nature of dark matter, corresponding to 85% of the matter currently present in the universe, is still unknown [1]. The presence and distribution of dark matter is detected through its gravitational interactions by observatories and experiments, while the interactions of dark matter with ordinary matter particles can be observed indirectly and directly in astrophysics experiments [2, 3]. These interactions also allow for dark matter to be produced in collisions of ordinary matter and observed in experiments at colliders [4] and at particle accelerators [5], providing complementary information about dark matter interactions with ordinary matter. Data from this abundance of astrophysics and particle physics experiments, combined with theoretical models and interpretations, will shed new light on dark matter. Considering the

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presence of dark matter in astrophysical observations and the lack of evidence for dark matter particles in experiments, if dark matter has interactions with ordinary matter they must be feeble and produce very subtle signals. Connecting the results and potential discoveries from the various different experiments requires the involvement of all communities involved.

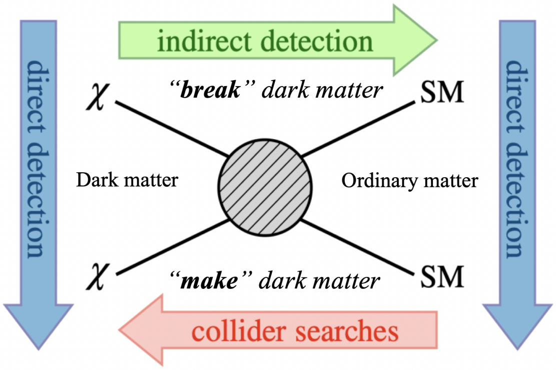


Figure 1. Overview of different dark matter detection methods. Dark matter particles are denoted by χ, while standard model (SM) particles are denoted by SM. Going from left-to-right you "break" dark matter, two dark matter particles interact and produce SM particles. Going top-to-bottom is "shaking" dark matter, where a dark matter particle interacts with a SM particle. Finally, going right-to-left you "make" dark matter by colliding SM particles to produce dark matter particles.

The ESCAPE Project [18] is an EU funded project with the aim of bringing together different research infrastructures. In this way the productivity of researchers could be improved while gaining new insights and innovations across disciplines. The dark matter science project (DM SP) provides scientific added value as well as the added value in the context of open science. The scientific added value for the DM SP is provided by new dark matter (DM) analyses coming from the complementary experiments involved as well as from theoretical and observational constraints, all interpreted within the same framework with an emphasis on interpretations showcasing their synergies. Experiments exploiting each of the dark matter detection methods, shown in Figure 1, are involved in this science project. The DM SP takes the digital objects from these new dark matter analyses and implements them within the ESCAPE infrastructure for open science and the European open science cloud (EOSC) through the virtual research environment (VRE) [19], a platform providing the services to develop and store our end-to-end analyses and workflows.

Within the DM SP we developed new analyses searching for dark matter particles and converted their data and software procedures to sustainable analysis pipelines as a prototype for direct detection, indirect detection, and collider experiments involved in ESCAPE, relying on the ESCAPE service infrastructure. The ESCAPE data infrastructure for open science was utilized in order to store, distribute, and provide data access to the dark matter scientific community, also making this data searchable while respecting experiment Open Data policies. This science project builds a prototype to include as much data and as many digital objects as possible while understanding the limitations that may arise when attempting to encapsulate many complex experiments onto one analysis platform. The final output of each workflow is an individual experimental curves to be interpreted in terms of dark matter particle properties, that can then be combined or compared within summary plots for certain dark matter models.

The pipelines will also be designed so that they can ultimately automatically (re)produce this kind of plots with new models.

2 The Virtual Research Environment

CERN developers have accumulated experience and expertise in engineering tools for handling, processing, and analyzing large data volumes. However, scientists outside of high-energy physics are more recently entering this domain, and therefore need to acquire the ability to efficiently track and process their data while meeting FAIR (Findable, Accessible, Interoperable, Reusable) data principles. Open data alone is not sufficient to foster the reuse and reproducibility in physics. To ensure the usability and longevity of results we must capture structured information about the analysis and workflow [6]. These workflows are complex, requiring the reduction of these very large data volumes. Around half or more of researchers cannot reproduce their own results [7]. The EU-funded H2020 projects aim to democratize data-intensive technologies, allowing scientists to gain expertise on new solutions and fostering the cross-fertilization across disciplines. Scientific collaborations are becoming more international and common infrastructures that allow reliable and efficient federated data management and data transfer services, federated distributed storage, data processing and orchestration, and software and analysis reproducibility are becoming increasingly popular.

The VRE tries to encompass all of the above, while placing special attention on the user experience by providing the scientist with an enhanced notebook interface. The VRE's configuration can be flexibly modified to access heterogeneous external resources such as storage and computing, managed by EU partner institutions.

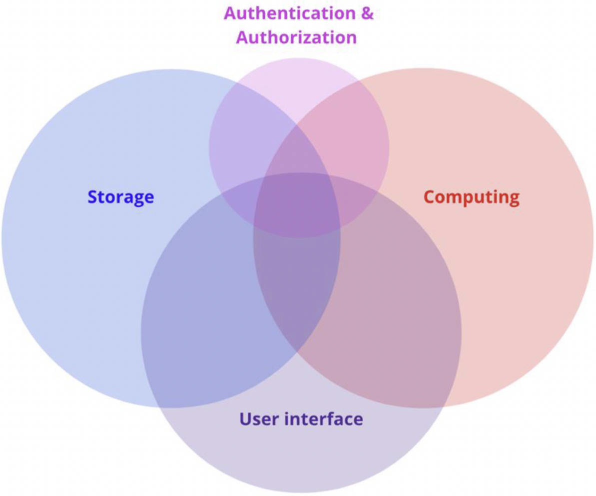


Figure 2. The VRE brings together storage and computing facilities, allowing a user to be authenticated and given access to their experiments data as well as a platform to perform analysis on this data.

The problem of imposing limits on the mass of DM is a fundamental question in physics: Direct Detection methods study the interaction of particles inside underground detectors, collider physics produces DM candidates by colliding protons, and Indirect Detection methods investigate annihilating DM by looking at its decay products, such as neutrinos. Figure 1 illustrates these different methods and shows how the VRE is a useful tool for fostering the collaboration of these different experiments, a requirement if we wish to set the best possible limits on candidate dark matter particles.

3 Dark Matter Experiments

As mentioned in Section 1, this science project is a collaborative effort with contributions from the three different dark matter detection methods: direct detection, indirect detection, and dark matter production at colliders. Cutting-edge dark matter experiments are increasingly unique; they are large, complex, and costly experiments with only one or a few of each type worldwide. It is absolutely imperative that we maximize the scientific outputs of each experiment. This requires not only creating but also storing new analyses, datasets, and results. In this way we will be able to combine multiple results studying the same question, as is the case across dark matter experiments. Storing the datasets, analysis software and computing environments, and results will facilitate these combinations as well as the reinterpretation of the results to study new questions, a point that is becoming increasingly important.

This interoperability is crucial for the exploration of dark matter. In the event that on experiment sees a hint of a dark matter signal compatible with dark matter, a different dark matter experiment using a different technique could be guided to confirm these hints. In this scenario a collider could be built or directed to target particles with the mass of this dark matter candidate and shed light on its interactions with ordinary matter. Such a scenario requires this interoperability as well as reproducible analyses with end-to-end workflows available for cross-checks.

For dark matter production at colliders the ATLAS experiment is involved, for the direct detection method the DarkSide experiment, and in the indirect detection method there are searches with gamma rays and KM3NeT.

3.1 Collider Physics - The ATLAS Experiment at the LHC

The ATLAS experiment [8] at the LHC is a multipurpose particle detector with a forward–backward symmetric cylindrical geometry and a near 4π coverage in solid angle. It consists of an inner tracking detector surrounded by a thin superconducting solenoid providing a 2 T axial magnetic field, electromagnetic and hadron calorimeters, and a muon spectrometer. The first-level trigger is implemented in hardware and uses a subset of the detector information to accept events at a rate below 100 kHz. This is followed by a software-based trigger that reduces the accepted event rate to 1 kHz on average depending on the data-taking conditions. An extensive software suite [9] is used in data simulation, in the reconstruction and analysis of real and simulated data, in detector operations, and in the trigger and data acquisition systems of the experiment.

The ATLAS experiment is a general purpose detector investigating a wide range of physics processes, making precision measurements of SM properties as well as searching for new physics which could include dark matter particles. At the LHC we are trying to produce dark matter particles, which could provide the opportunity to probe its interactions with ordinary matter and better understand its nature.

There are two projects that were implemented on the VRE from the ATLAS experiment, both related to the inclusive dilepton resonance search using data taken from 2015-2018 [10]. Searches in the dilepton (dielectron and dimuon) final state have a long and illustrious history with the discovery of the J/ψ meson in 1974, the Υ meson in 1977, and the Z-boson in 1983. These were key steps in the establishment of the SM of particle physics and the study of the same final state could help give us a clue as to where physics lies beyond the SM, including how it might interact with dark matter particles.

You can see the invariant mass distribution from the inclusive dilepton resonance search in Figure 3. The data is very well modeled by the SM background, so no new physics was observed in this analysis. Therefore, the analysis set limits on the fiducial cross-section so the result could be interpreted and reinterpreted to set limits on a multitude of different models. One reinterpretation in terms of dark matter mediators was performed using these limits on the VRE, an analysis that contributed to the Snowmass report. Assuming a non-zero coupling to leptons, a neutral mediator (Z') associated with a dark sector would produce an excess in the dilepton invariant mass distribution.

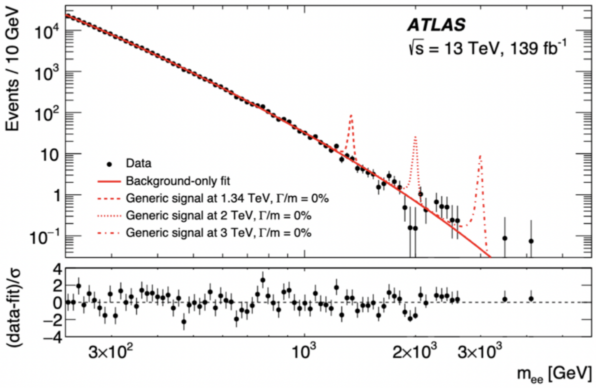


Figure 3. Invariant mass distribution in the dielectron final state from the inclusive dilepton resonance search. A fit to SM background predictions is shown by the solid red line while data is shown by the black dots. A few signal models stacked above the background are demonstrated by the dashed red line, where new physics in this channel would be expected to produce a resonance in the data.

New dark matter signal models were produced and stored on the data lake, where the VRE was used to analyze these models and reinterpret the dilepton result and set new limits. You can see how the limits are calculated by looking at Figure 4. A particular model is generated for a particular mass of the Z' and dark matter particles, where we apply the same fiducial selection as the resonance search and extract the fiducial cross-section. This is then repeated by varying the mass of the Z', in order to calculate the fiducial cross-section as a function of Z' mass (as in the upper left plot in Figure 4). Where this fiducial cross-section crosses the fiducial limit is the point at which we can say we expected to observe this model in the analysis, and therefore we set this limit in the $\chi - Z'$ mass-plane. This process is then repeated for different dark matter masses and can be summarized, as shown in the upper right plot in Figure 4). The lower plot shows the result in the Snowmass report, where different analyses with different final states also set limits on the same dark matter mediator. This analysis, contained in the VRE, contributed to the dilepton (purple) region of this summary.

This reinterpretation demonstrates the ability of the VRE to bring the data and software into a computing environment and perform a small two-step workflow, but most analyses will be far more complex. At ATLAS we have three-to-four stage workflows beginning with data on the order of many terabytes, consisting of different software packages and computing environments. It would not be possible to run such an analysis in this manner. For a larger and more complex analysis, we would need the ability to send the data from the data lake directly onto a remove computing cluster along with the software and some instructions for the computing environment. For this we utilize REANA[20], a reproducible research data analysis platform. Different stages of a workflow can be stored in git, containerized using

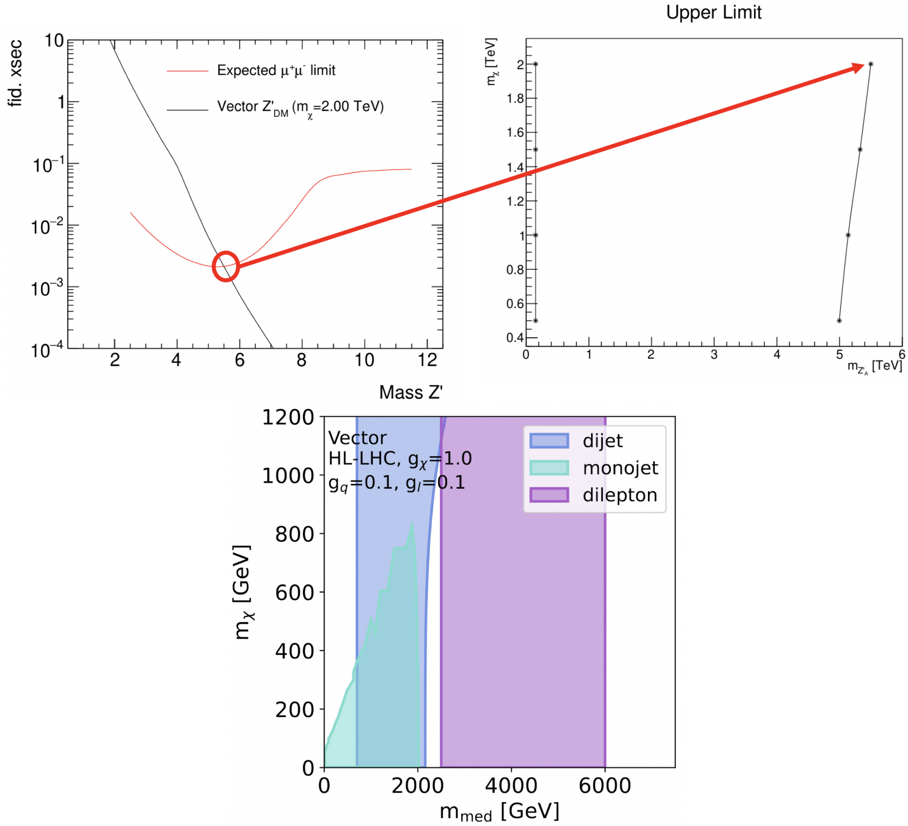
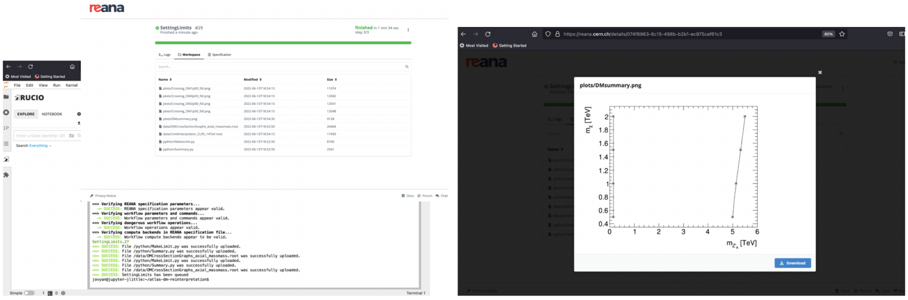


Figure 4. Reinterpretation of the inclusive dilepton analysis. Fiducial cross-section is compared with the fiducial limit and summarized. On the bottom you see the combination from the Snowmass report, where this summary was reported as the purple curve.

docker or singularity, and passed to a remote computing cluster. On top of this the different stages of the workflow can be daisy-chained, with the output of one stage being passed to the input of the next. In this way, we can store more complex analysis workflows in a way that facilitates their reuse.

The reinterpretation of the dilepton resonance search was used to test our ability to store and reuse a multi stage workflow. A job was sent to the remote cluster using REANA, where we set limits for different dark matter masses and pass these limits into a different job to summarize and produce our final summary plot. The outputs can be retreived by the VRE, as well as viewed and retreived using a web interface as shown in Figure 5.

The inclusive dilepton resonance search is an important analysis to be done, it is a generic final state with a long history and high potential for discovery. However, as you can see in Figure 3, there is a lot of background in the low-mass region (below around 1 TeV). There could be new physics hidden in this region, so a new analysis targeting dilepton resonances in the dilepton plus missing transverse energy (E_T^{miss}) was developed [11]. This analysis was developed with reinterpretation in mind, using benchmark models as a guide but keeping the analysis selections more general. We believe that by targeting dilepton plus E_T^{miss} final states we can be more sensitive in this low-mass region. This result was just made public, with



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plots/Crossing_DM0p50_fsll.png	2022-06-13T18:54:15	12082
plots/Crossing_DM2p00_fsll.png	2022-06-13T18:54:15	12051
plots/Crossing_DM1p50_fsll.png	2022-06-13T18:54:15	12048
plots/DMsummary.png	2022-06-13T18:54:35	9128
data/DMCrossSectionGraphs_axial_massmass.root	2022-06-13T18:52:50	26404
data/LimitInterpolator_CL95_14TeV.root	2022-06-13T18:54:15	17439
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Figure 5. REANA remote web interface from the VRE. Multistage workflows can be sent to a remote computing cluster, where the jobs can be monitored and results viewed from the web interface.

much of it being stored and available from the VRE already while the last pieces are being developed.

3.2 Direct Detection - DarkSide

The DarkSide collaboration seeks to directly detect dark matter using dual-phase liquid argon time projection chambers (TPCs) deployed at the Gran Sasso National Laboratory. DarkSide aims to detect dark matter that enters the detector, striking the nucleus of the gas and creating a recoil which induces scintillation and ionization. The scintillation and ionization are both measured through light signals, where they are used to search for high-mass dark matter particles. If the kinetic energy of the nucleus can be reconstructed, we can understand more about the dark matter that initiated the event.

These experiments look for events which are rare and difficult to distinguish from those induced by natural radioactivity, which contaminates detector materials and the surroundings. They are often very large and operated at underground facilities, which are naturally shielded from cosmic rays, and consist of kg to multi-tonne-size targets instrumented in order to be able to detect the recoil of ordinary particles after they are hit by dark matter.

The DarkSide collaboration began with DarkSide-50, an experiment with 50 kg of liquid argon from 2013-2018. DarkSide-20k, which is 400 times as large as DarkSide-50, is planned for 2026-2036. The DarkSide-50 TPC is a cylinder 36.5 cm in height and diameter, instrumented with 19 photomultiplier tubes per endcap. This TPC is also surrounded by an additional liquid scintillator detector filled with 30 t of liquid boron, which is chosen to maximize the probability of detecting possible interaction between neutrons and argon nuclei, a signal which would mimick the dark matter-nucleus interaction. All of this is also surrounded by a water-based Cherenkov detector used to reject cosmic muons.

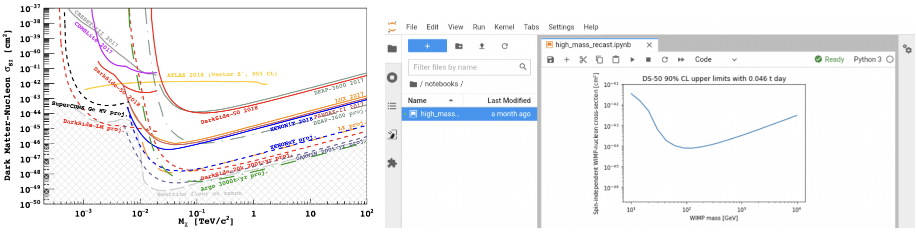


Figure 6. The limit curve from DarkSide was reproduced on the VRE, shown on the right.

On the VRE we have reproduced the dark matter limit curve, placing limits on dark matter cross-section as a function of its mass as shown in Figure 6. A reanalysis tool for a high-mass search has also been implemented and made available on the VRE platform, producing an exclusion curve on the dark matter nucleon cross-section. Different theoretical models can be inserted by the user to produce different limit results. Further work is ongoing to implement a reanalysis tool for the low mass search.

3.3 Indirect Detection

The indirect detection method is one of the popular ways to identify the invisible DM signals. DM can annihilate (or decay) to quark-anti-quark pairs and then they decay into the ordinary SM particles. With this detection method we probe the end product of the DM self-annihilation which could include photons, proton-antiproton, electrons, and neutrinos and then measure the particle spectra generated from them. The spectra would provide us with valuable information about the nature of DM particles. There are several dedicated (ongoing and planned) indirect detection experiments that are designed for solving the mystery of the DM.

3.3.1 Fermi-LAT

Gamma-rays, including both direct line photons and diffusion photons are one of the most popular methods for detecting DM indirectly. At high energy, the neutral pions decay to a pair of mono-energetic photons that can create the prompt line of gamma-rays. When DM directly annihilates to the gamma-rays, the energy of the photons is proportional to the mass of DM. Since the mass of DM is of the order of GeV, it would create very high energy gamma-rays and detection of any such gamma-ray line would give an obvious indication of the DM annihilation. Another source of the gamma-rays are the internal bremsstrahlung of charged particles produced in the annihilation process. Since 2008, the Fermi Large Area Telescope (LAT) has played a very important role to unveil the characteristics of DM candidates. Fermi-LAT is a gamma-ray space telescope which surveys the whole sky every 192 minutes and observes the gamma-rays in an energy range between 20 MeV and 500 GeV. Fermi-LAT is expected to perform as a brilliant gamma-ray space detector over the entire celestial sphere, with comparatively better sensitivity than other earlier gamma-ray missions. Fermi-LAT team has made significant improvements in angular resolution, effective area, field of view, energy resolution and time resolution of the detector.

Software analyzing the publicly accessible data from the Fermi Large Area Telescope has been made fully available on the VRE. Code is written entirely using python and well-known packages, such as scikit-learn. This package can be optimized from the command line, allowing the user to quickly insert a dark matter model and check its viability.

The first project using this workflow was to reproduce the results presented in Alvarez, A et al [12]. Data was moved into the data lake, with the software [13] and computing environment being made available. As shown in the left-hand side of Figure 7, this result is made available in the VRE with access to all of the tools for interpretation of different dark matter models.

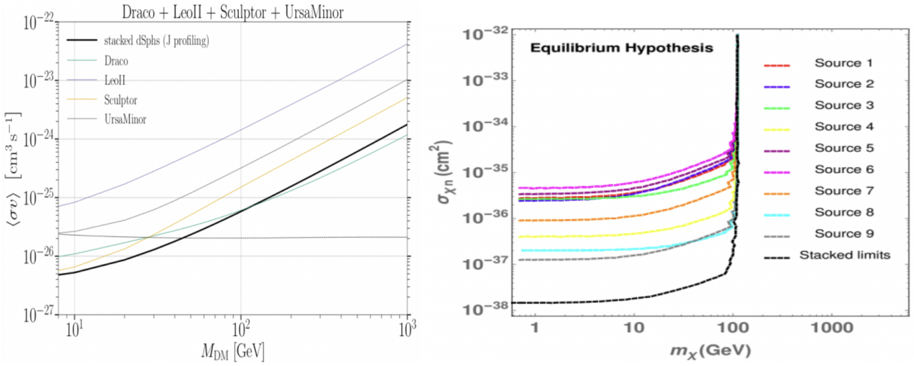
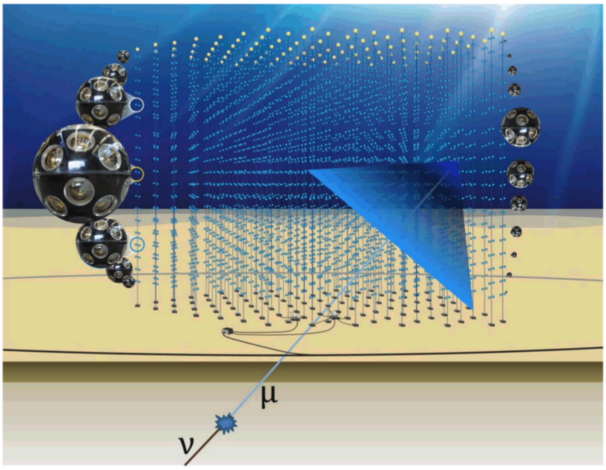


Figure 7. Results from the gamma-ray observations produced on the VRE. On the left, results from Alvarez, A et al [12] are shown. On the right, results from the gamma-ray flux from brown dwarfs [14] are shown.

A new analysis was also developed targeting gamma-ray flux limits from brown dwarfs [14]. This result was published this year with the data and workflow [15], similar to Alvarez above, being fully available within the VRE. One of the outputs from the VRE is shown on the right-hand side of Figure 7.

3.3.2 KM3NeT

The cubic kilometre neutrino telescope (KM3NeT) is another indirect detection experiment involved in the DM SP. The existence of high energy neutrinos was proven by the IceCube experiment. The new generation of neutrino telescopes will provide a more detailed analysis. KM3NeT is located in the Mediterranean Sea and is one of the most promising such experiments. Neutrinos are detected by measuring the Cherenkov light induced by charged secondary particles emerging from a neutrino interaction in the sea water, which serves as target material and Cherenkov radiator as well as a shield for downgoing atmospheric muons. The light is detected by photomultiplier tubes arranged in glass spheres, digital optical modules (DOM), that withstand the water pressure. Each optical module carries 31 3-inch PMTs optimizing the photo-cathode area, the directional sensitivity, the angular coverage per DOM, and the photon counting capability. The DOMs of the KM3NeT detector are arranged along flexible strings with a total height of about 700 m. KM3NeT will consist of two building blocks of 115 strings each, with 18 DOMs per string, vertically spaced by 36 m. Each block will have a roughly circular footprint with an average distance between strings of about 90



m. The two blocks together will cover an instrumented volume of about $1km^3$. They will be deployed and anchored in the Capo Passero site, at a depth of 3500 m, and will be connected to the shore station via a 100 km electro-optical cable to transfer power and data between shore and the detector.

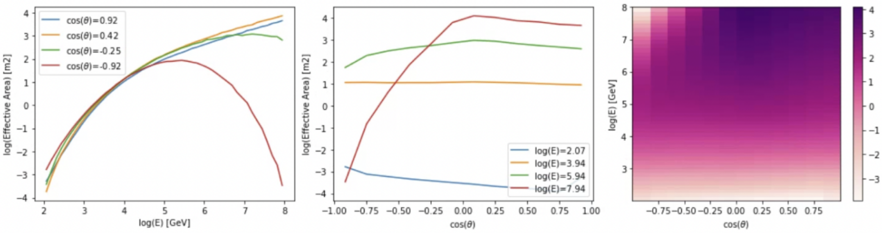


Figure 8. Instrument response function output of KM3NeT on the VRE, providing a quantitative estimation of event and background rates.

The instrument response function (IRF) of KM3NeT provides a quantitative estimation of the event and background rates within the detector. It contains the physical characteristics of the detector and allows the experiment to avoid extensive simulations each time they want to change the configuration of neutrino sources. The compatibility with gammapy will give an easy combination with other gamma experiments, such as CTA. The IRF is another great motivation for creating a common platform, it is a tool that could be very useful across many experiments. It was implemented successfully on the VRE, as shown in Figure 8, and successfully employed in a combination of KM3NeT and CTA data to distinguish between leptonic and hadronic emission scenarios of gamma-ray sources in the Milky Way.

3.4 Common Tools

The sharing of common tools on the VRE is one of the biggest and most obvious advantages of a common platform. There are a plethora of tools from each experiment that could be utilized by others. For example, storing large amounts of data is a challenge faced by most experiments today. One common tool that could be useful to any large experiment is Baler [16], a machine learning based data compression tool.

Baler was developed and implemented on the VRE. It compresses data by training an autoencoder on scientific data, as shown in Figure 9, storing the model and autoencoders latent space. The encoder is a neural network that maps each input to an abstract latent point, generally of lower dimensionality than the input. The decoder then extrapolates the latent space back to the same dimensions as the input to give the reconstructed output.

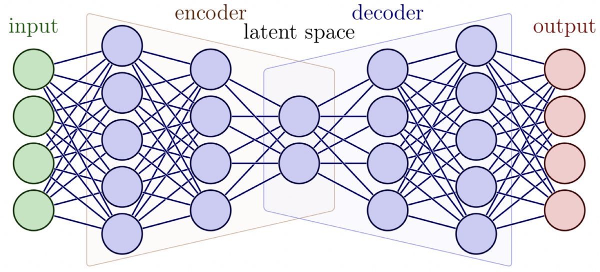


Figure 9. Illustration of an autoencoder, where data is compressed and decompressed by training an autoencoder.

Baler shows some promising results when compressing high-energy physics data. You can see such studies in Ekman, A. et al. [17], where an autoencoder model is trained on a single HEP dataset and its performance is quantified by looking at the relative difference between the original and the decompressed data. The input file size is taken from 116.9 MB down to around 73 MB while still retaining considerably good performance.

4 Conclusion

With the DM SP analyses and tools on the VRE, we are making progress in many areas. Experiments involved are producing new scientific results constraining dark matter hypotheses while providing other communities the tools and understanding needed to reproduce their analyses. Plots demonstrating the synergies between the different communities are highlighted to encourage the comparison and combination of these results to further constrain dark matter hypotheses. We are demonstrating interoperable workflows while using FAIR data principles as an example for the scientific community while building a working prototype for EOSC, providing a testing ground for software and computing that can be explored by future experiments.

The DM SP is now turning towards the next step. We have identified some of the main challenges in order to scale up and make more analyses available. Onboarding large analyses has proved challenging, namely moving larger datasets into the data lake currently requires a large effort. A process to streamline this would encourage more users to engage with the VRE and allow us to further stress-test the platform. We also need to guarantee restricted data access across users, allowing experiments to restrict access to their data until an embargo is lifted.

Acknowledgements

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