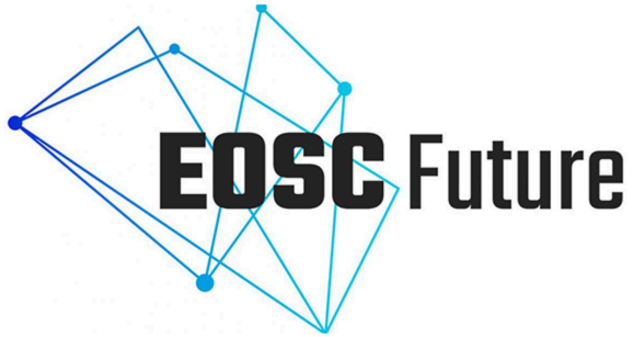


The Dark Matter Science Project

JARED LITTLE, ON BEHALF OF THE DARK MATTER SCIENCE PROJECT RESEARCHERS

ESCAPE – Open Science

Open Science Projects bring together different ESCAPE services.

- ESCAPE is an EU-funded project which aims to bring together different research infrastructures.
- Improve productivity of researchers.
- Gain new insights and innovation across disciplines.
- 31 partners including 10 ESFRI projects and landmarks.
  - CTA, EST, FAIR, HL-LHC, KM3NeT, SKA, LSST, VIRGO,ESO,JIVE
- 2 pan-European International Organizations: CERN, ESO
- 4 supporting European consortia: APPEC,ASTRONET,ECFA, and NuPECC

D. Large-scale data-intensive software and computing infrastructures are an essential ingredient to particle physics research programmes. The community faces major challenges in this area, notably with a view to the HL-LHC. As a result, the software and computing models used in particle physics research must evolve to meet the future needs of the field. ***The community must vigorously pursue common, coordinated R&D efforts in collaboration with other fields of science and industry, to develop software and computing infrastructures that exploit recent advances in information technology and data science. Further development of internal policies on open data and data preservation should be encouraged, and an adequate level of resources invested in their implementation.***


Astroparticle Physics European Consortium (APPEC)

APPEC Contribution to the
European Particle Physics Strategy

December 17, 2018

Editorial Board:
S. Katsanevas, A. Masiero, T. Montaruli, J. de Kleuver, A. Haungs

Contact Person:
T. Montaruli (APPEC Chair from Jan. 1, 2019)
Email: teresa.montaruli@unige.ch

Website : http://www.appec.org

APPEC

See following talk by **G. Lamanna**

https://indico.jlab.org/event/459/contributions/11808/

The EOSC Future project is co-funded by the European Union Horizon Programme call INFRAEOSC-03-2020 Grant Agreement Number 101017536

ESCAPE – Open Science Projects

Open Science Projects proposed to bring together different ESCAPE services.

- ESCAPE services will contribute to the European Open Science Cloud (EOSC) through the **EOSC-Future** project.
- **Two science projects** being developed.
  - Produce cutting-edge science results while exploring synergies between different research facilities.
- Demonstrate open science capabilities.
- Bringing together the services implemented within ESCAPE.

1. **Dark Matter Science Project**
2. **Extreme Universe Science Project**

ESCAPE - The European Science Cluster of Astronomy & Particle Physics ESFRI Research Infrastructures has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement no. 824064.

The EOSC Future project is co-funded by the European Union Horizon Programme call INFRAEOSC-03-2020 Grant Agreement Number 101017536

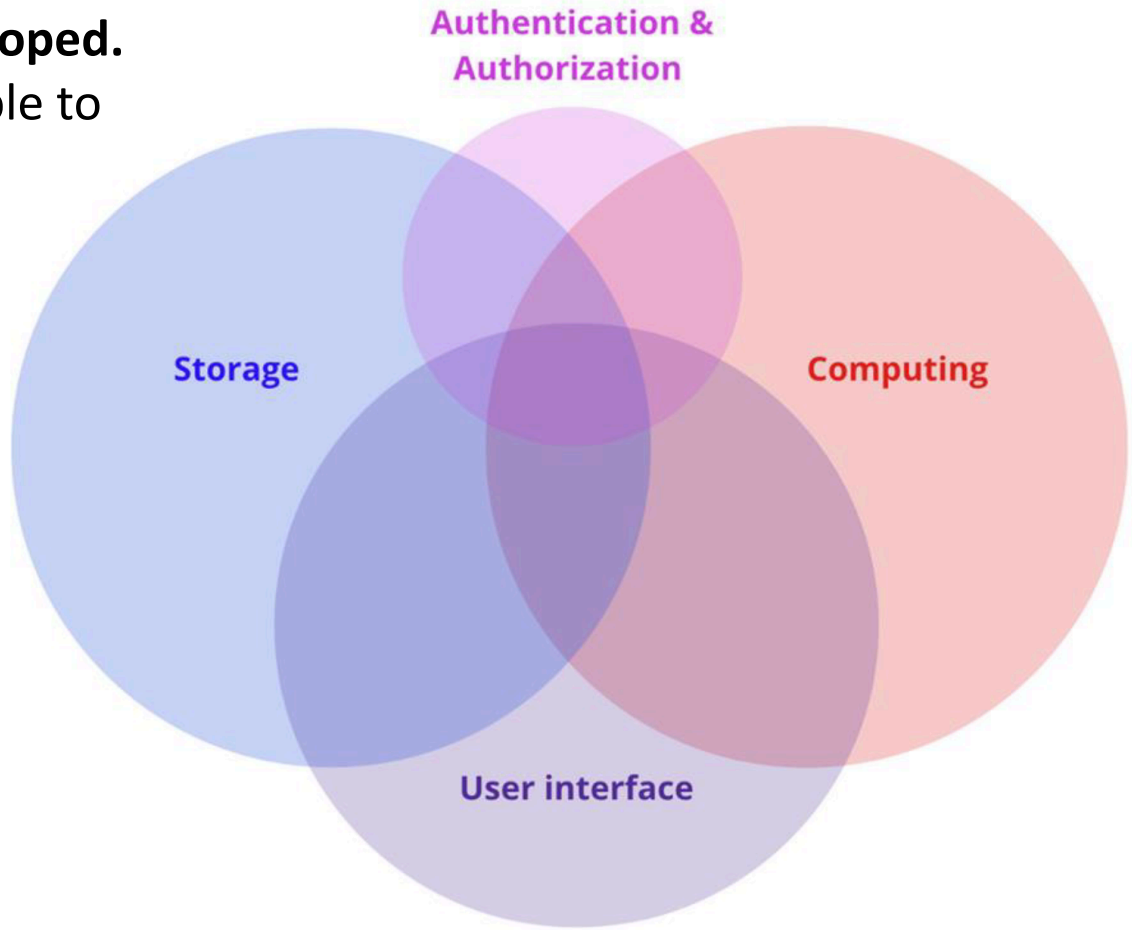
EOSC Future – Virtual Research Environment

The ESCAPE Virtual Research Environment (VRE) is being developed.

- Collaborative online platform where science projects are able to develop and share end-to-end workflows.
- Access all digital content needed, in compliance with FAIR principles.

The VRE is actively used by members of both science projects

- Analyze, preserve, run, share analyses.
- Education and outreach.

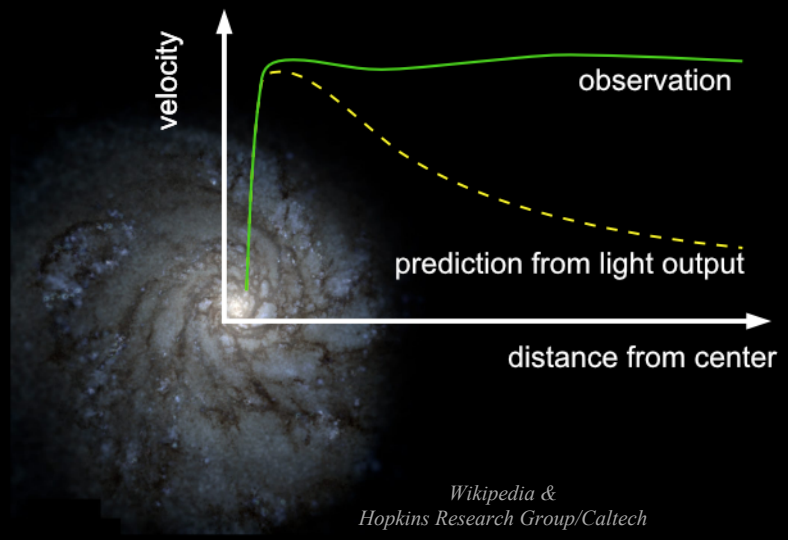


See talk by **E. Gazzarrini**

https://indico.jlab.org/event/459/contributions/11671/

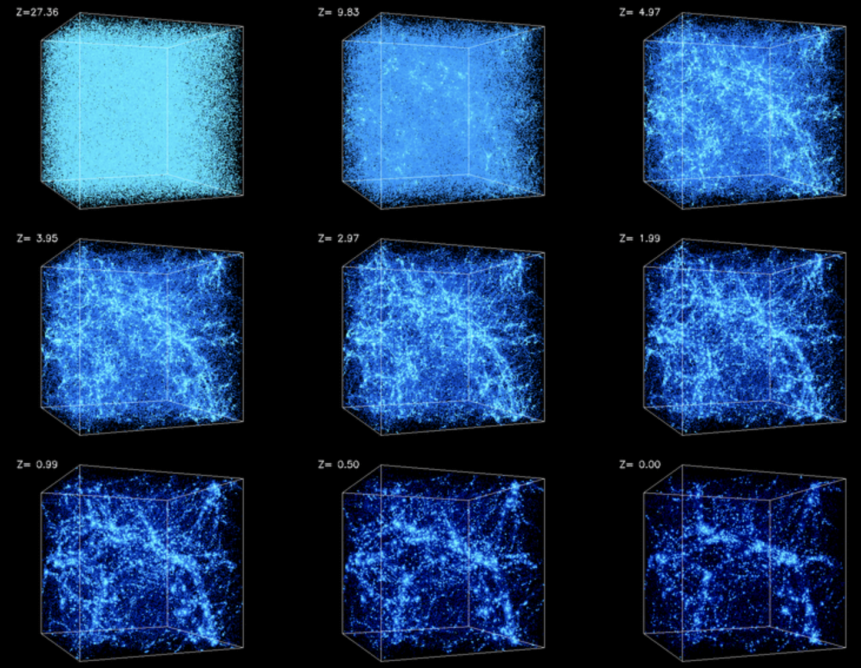
The EOSC Future project is co-funded by the European Union Horizon Programme call INFRAEOSC-03-2020 Grant Agreement Number 101017536

Big science question: Dark Matter



Wikipedia &
Hopkins Research Group/Caltech

Vera Rubin,
© Washington Times & Zuma

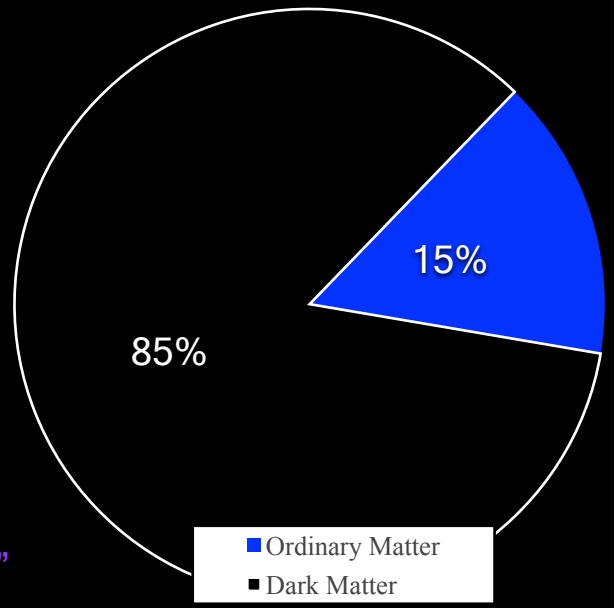


Simulations were performed at the National Center for Supercomputer Applications by A. Kravtsov and A. Klypin.

visible matter

NASA/CXC/M. Weiss

"invisible" matter



https://cordis.europa.eu/project/id/679305

Dark Matter Experiments

Cutting edge dark matter experiments are increasingly unique

- large, complex, costly experiments
- only one or a few experiments of each type worldwide

Maximizing each experiment's science outputs is imperative:

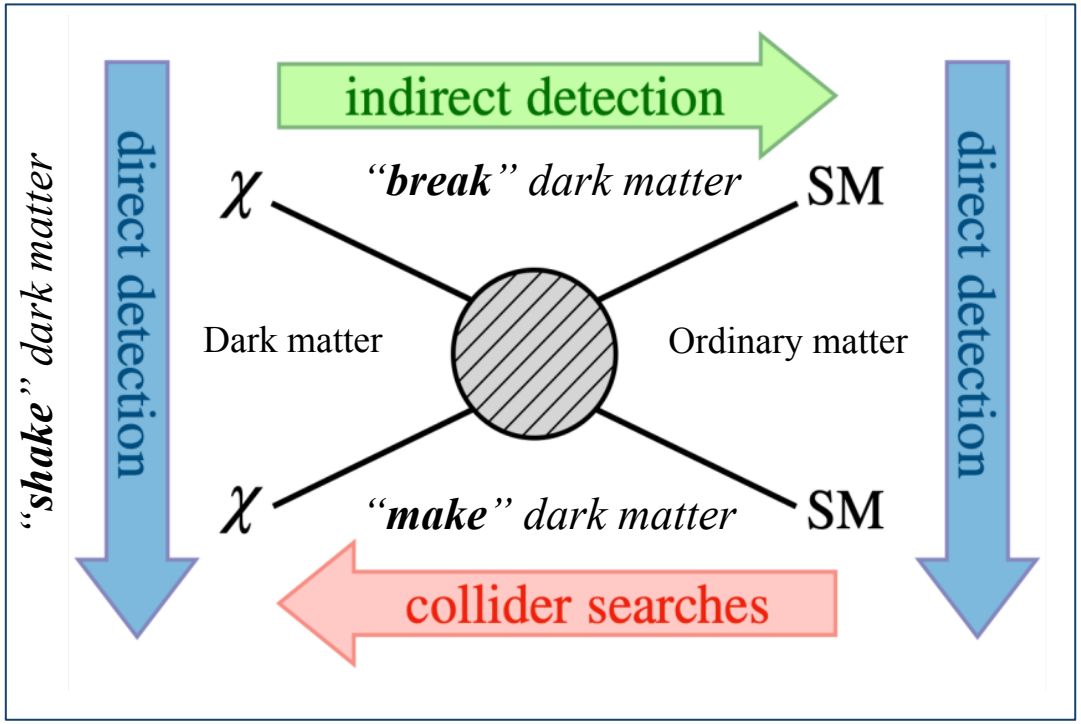
- **create** and store new analyses, datasets and results
- **combine** multiple results studying the same question
- **reinterpret** existing studies for new questions

The Dark Matter Science Project provides the community with tools to do all these tasks and allows access to data and software on the EOSC through ESCAPE infrastructure

The EOSC Future project is co-funded by the European Union Horizon Programme call INFRAEOSC-03-2020 Grant Agreement Number 101017536

Dark Matter: Complementary Approach

Focus: Looking for **W**eakly **I**nteracting **M**assive **P**articles (**WIMP**s)



A joint discovery of the nature of dark matter requires different experiments and inputs

Experiments have **different** data sizes, workflows, data, and result sharing policies

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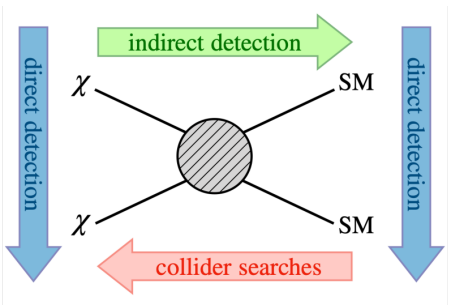
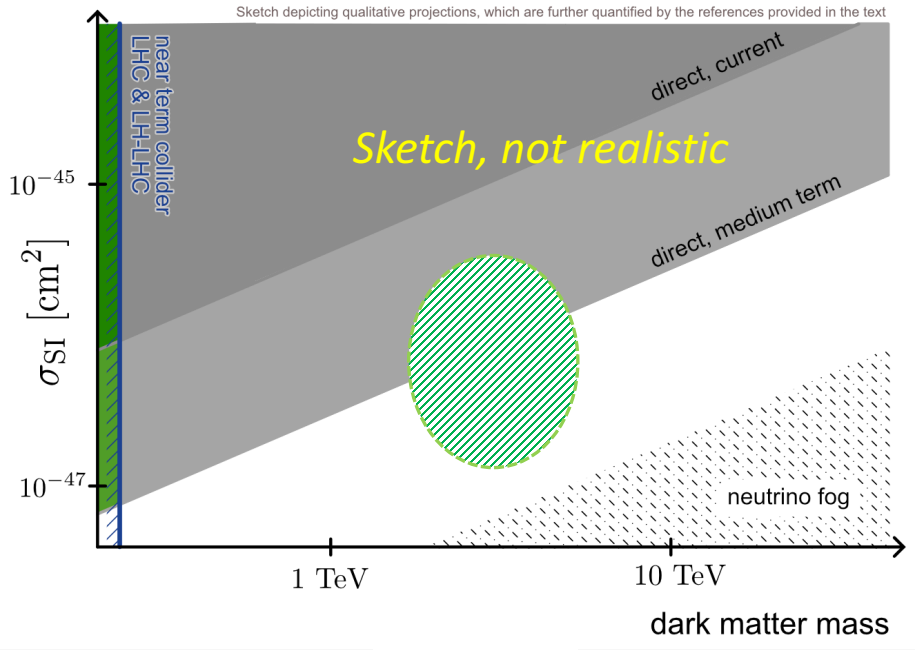
Example of a *discovery scenario*



Late 2020s **Direct detection** experiment sees a hint of a signal, with characteristics compatible with WIMP DM

Mid 2030s

2040s



Inspired by:
[Dark Matter Complementarity (Snowmass report), arXiv:2210.01770]
[T. Slatyer's "Paths to discovery" talk at Snowmass 2022]

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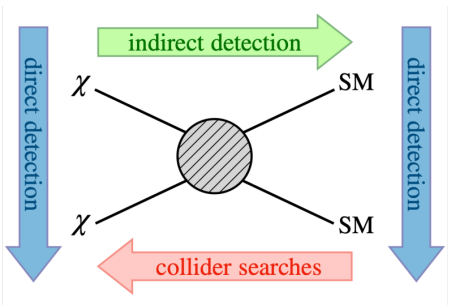

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Direct detection experiment (using another technique) confirms these hints

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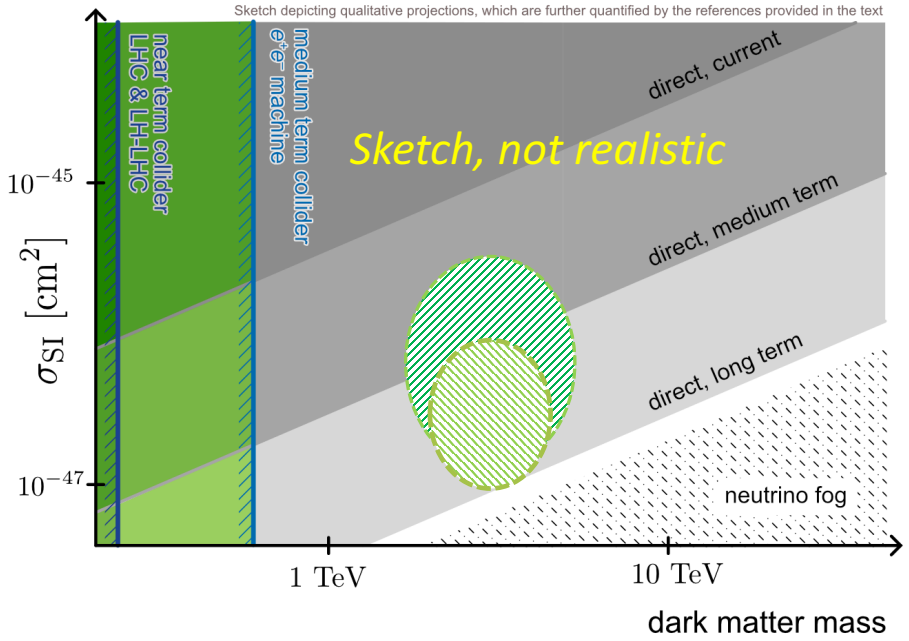

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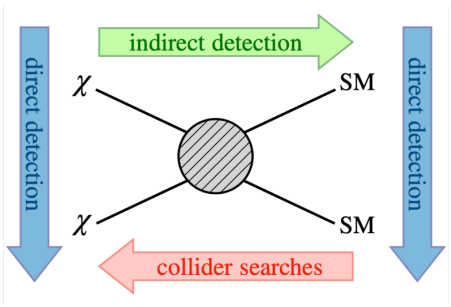

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Indirect detection experiment observes signals of DM annihilation

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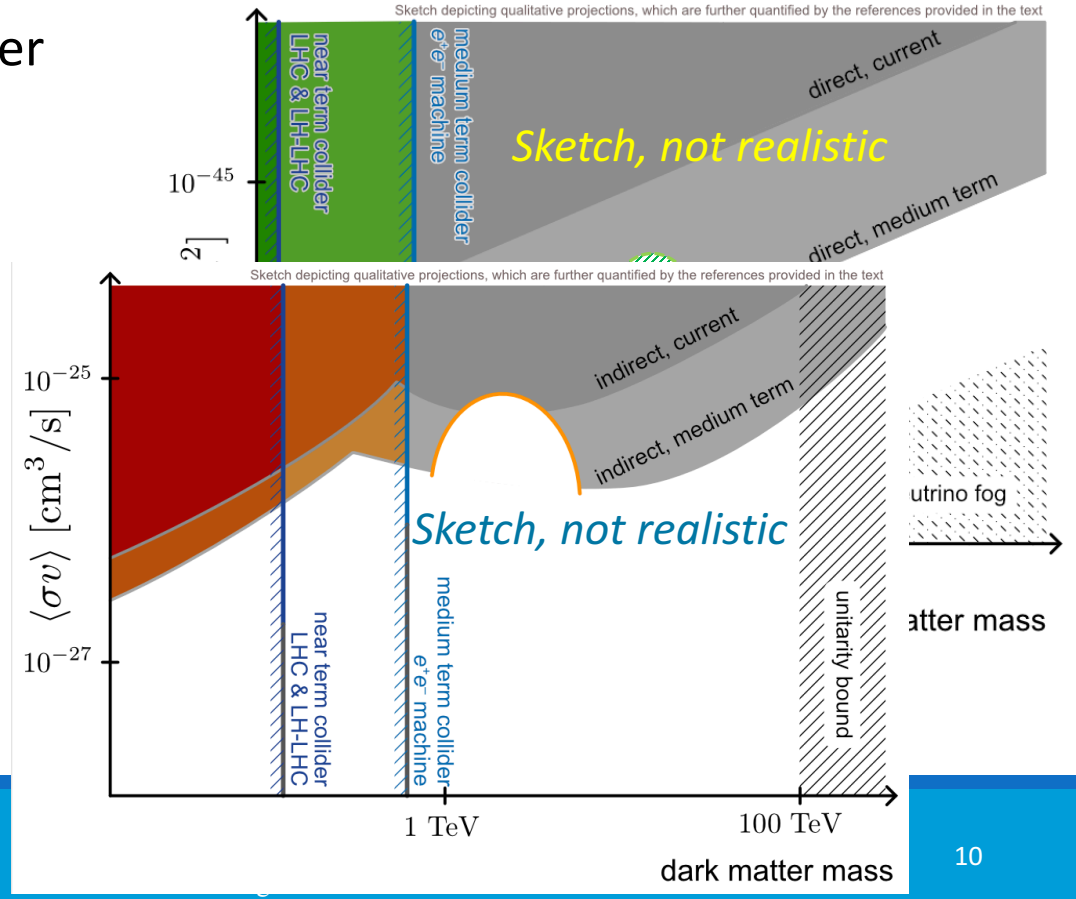

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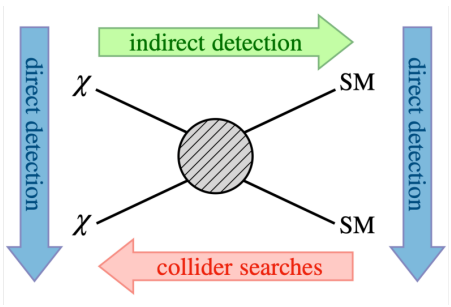

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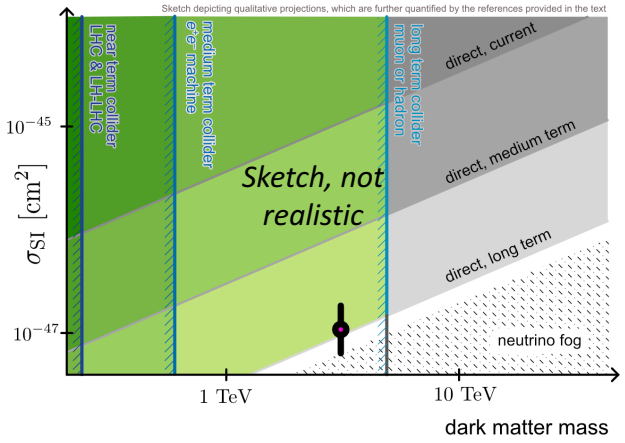
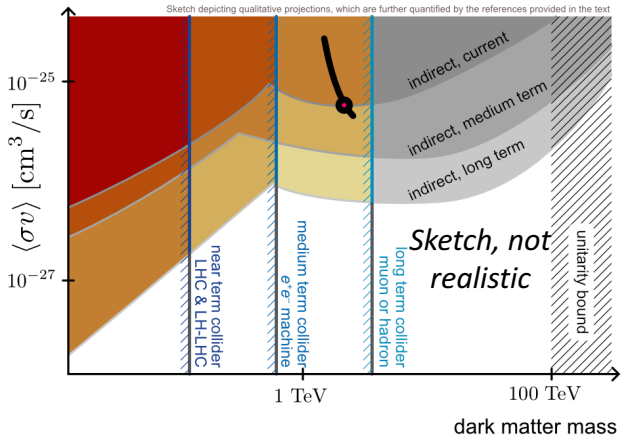
Future collider, built to target particles with the mass of the putative DM candidate, sheds light on interactions between DM and ordinary matter





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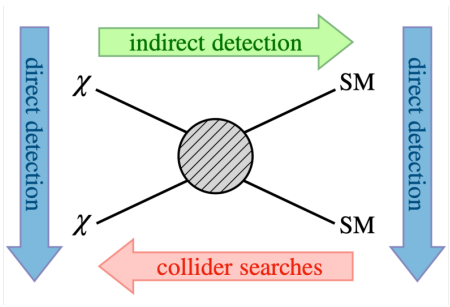

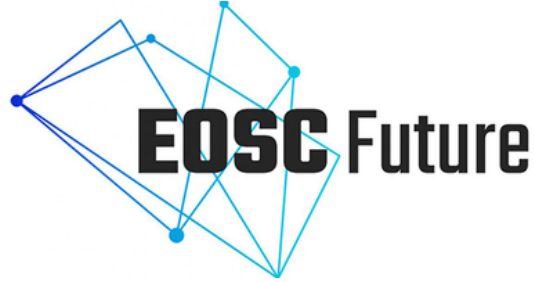

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Indirect detection experiment observes signals of DM annihilation

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Inspired by:
Dark Matter Complementarity (Snowmass report), arXiv:2210.01770
T. Slatyer's "Paths to discovery" talk at Snowmass 2022

Such a scenario requires **interoperable and reproducible analyses**

- **comparison** and **combination** of results from different experiments
- **end-to-end workflows** available for cross-checks

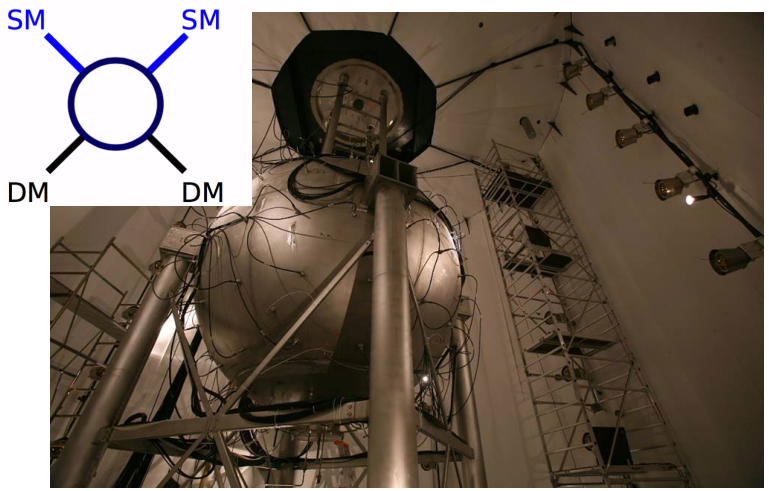
With the Dark Matter Science Project, we build a prototype that fulfills these requirements

The EOSC Future project is co-funded by the European Union Horizon Programme call INFRAEOSC-03-2020 Grant Agreement Number 101017536

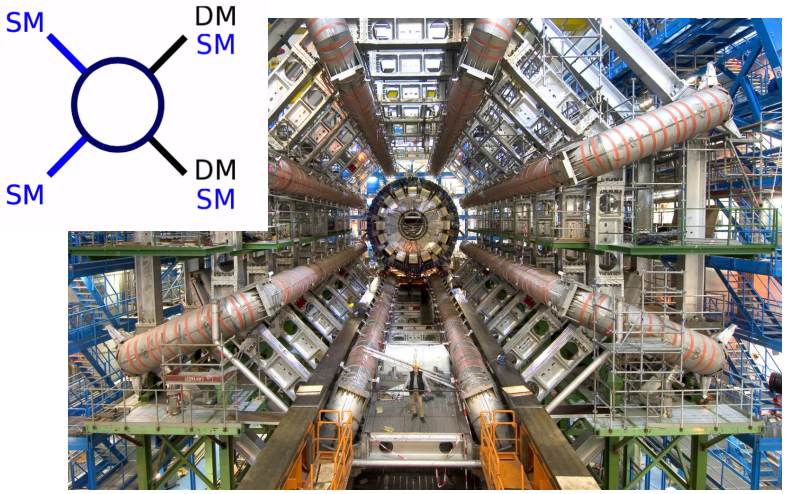
Experiments involved in the Dark Matter Science Project

EOSC Future

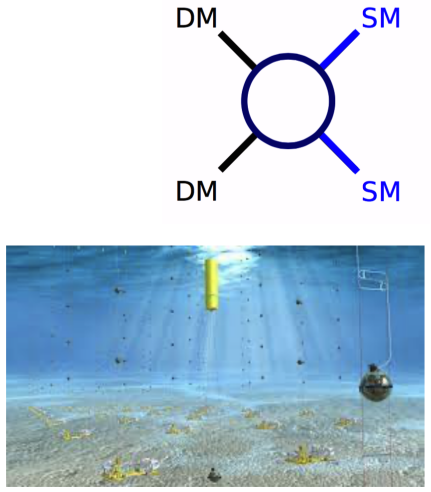
Direct detection: DarkSide



Colliders: ATLAS @ LHC



Indirect detection: FermiLAT, KM3NeT



…and their evolutions: ***DarkSide-20k / Argo, ATLAS @ HL-LHC, CTA***
Some of the ***analysis & ML tools*** *necessary for these evolutions are also part of this Science Project*

With the Dark Matter Science Project,
we understand the computing and analysis challenges of some of the future DM experiments

EUROPEAN OPEN SCIENCE CLOUD

ATLAS EXPERIMENT

The EOSC Future project is co-funded by the European Union Horizon Programme call INFRAEOSC-03-2020 Grant Agreement Number 101017536

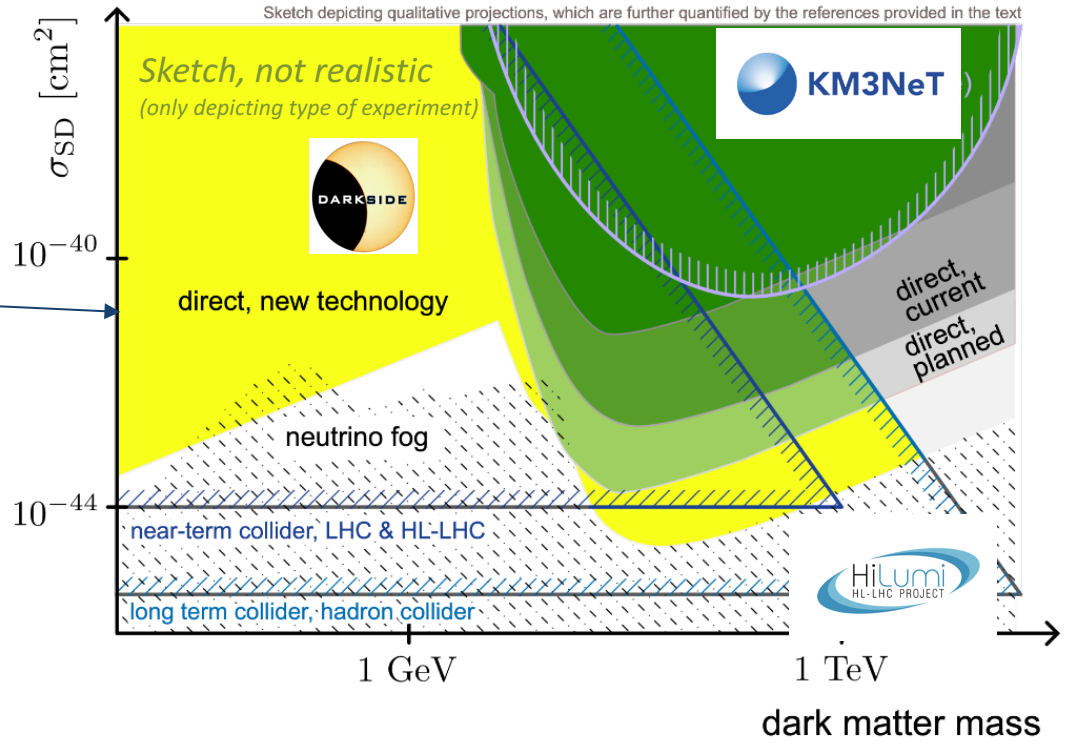
Science outputs of the DM TSP

Planned domain science outputs

- Individual results and publications
- Plots highlighting complementarity of different experimental efforts
- Combination of experimental results

Data and software objects + pipelines

- Data on the Data Lake, and software on the ESCAPE Software Catalogue
- Pipelines accessible via VRE



Example sketch (not using ESCAPE experiments yet) highlighting direct detection, neutrino experiment indirect detection and collider complementarity

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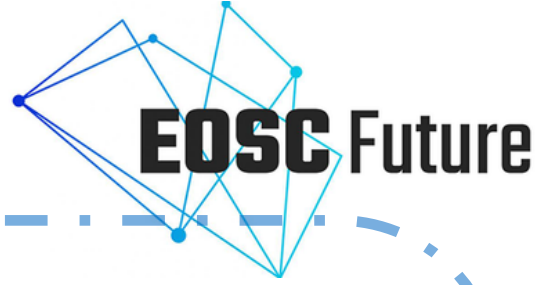
Analysis Workflows for the DM Science Project



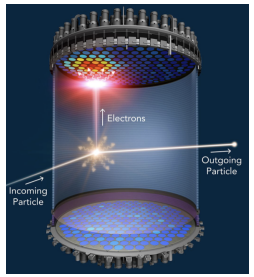
Technical solutions

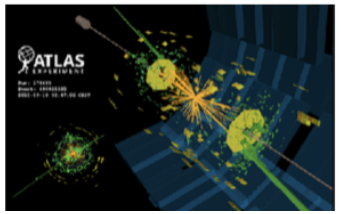
JupyterHub
(smaller workflows)

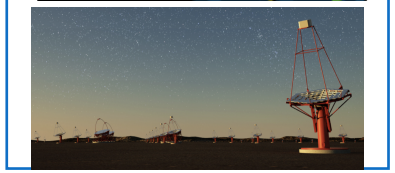
REANA
(larger workflows)

Generation & simulation

Expt. data







Credit: SLAC/LZ/ATLAS/CTA

Data **processing** (including reconstruction & calibration wherever possible)

Analysis of events/distributions (including background subtraction, background estimation, statistical analysis)

Interpretation of results

Combination of results with other searches/experiments

Comparison of results with other searches / experiments

ESCAPE tools, used in EOSC-Future

Virtual Research Environment

Data Lake

Software Catalogue

Data sharing and data processing

Data analysis, preservation and interpretation

The EOSC Future project is co-funded by the European Union Horizon Programme call INFRAEOSC-03-2020 Grant Agreement Number 101017536

Dark matter at particle colliders: searches in the ATLAS experiment

Jared Little
(LAPP)

Supervised by:
Tanya Hrn'ova and Stephane Jezequel (LAPP),
Caterina Doglioni
(University of Manchester and Lund University)

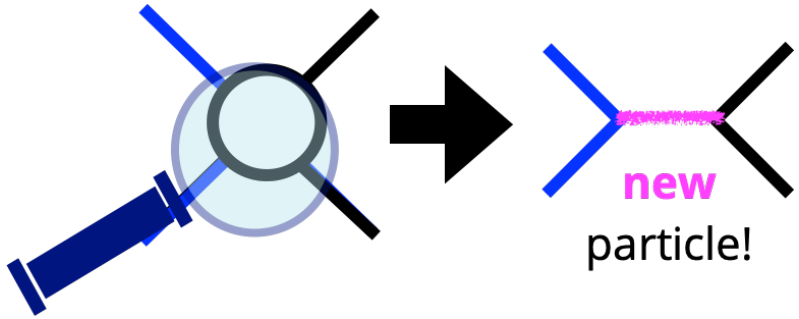
ESCAPE - The European Science Cluster of Astronomy & Particle Physics ESFRI Research Infrastructures has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement no. 824064.

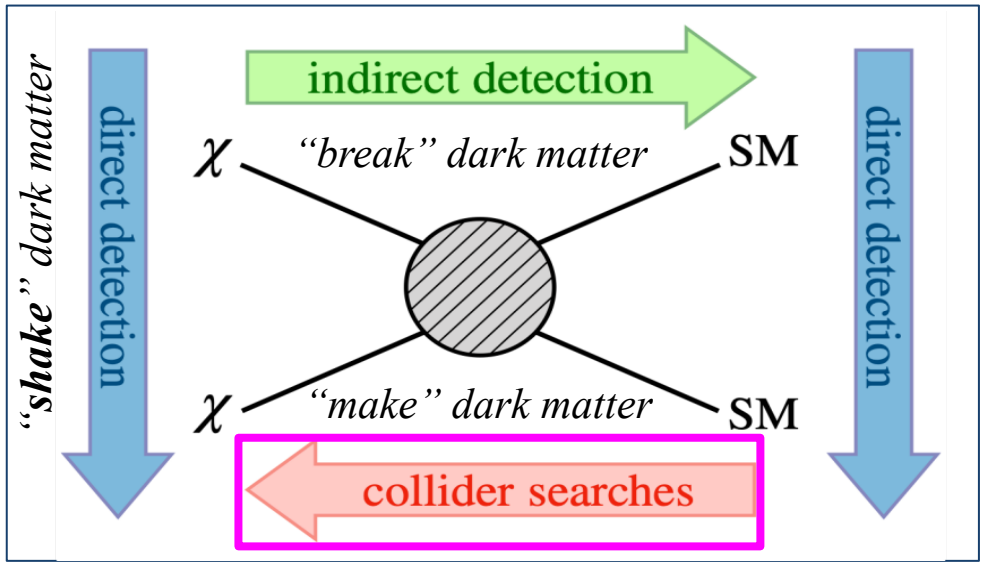
DM Science Project - ATLAS

The ATLAS Experiment, along with CMS, are two general purpose detectors located on the Large Hadron Collider.

Wide range of physics investigated:

- Higgs discovered in 2012.
- Precision measurements on Standard Model properties.
- Searches for new physics, including particles that make up dark matter.



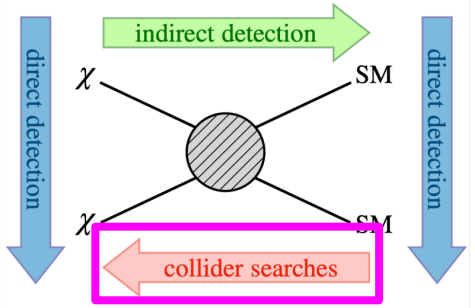


At the LHC, we are trying to "make" dark matter.

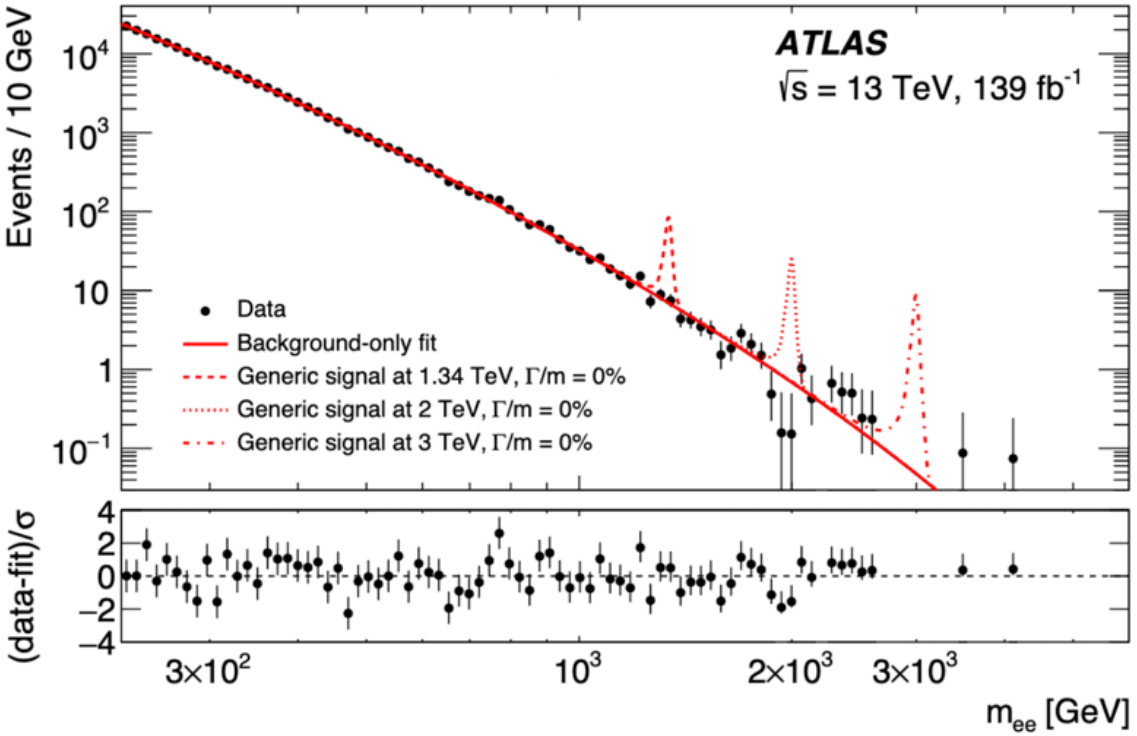
- By probing the interactions with ordinary matter, we can better understand the nature of DM.

The EOSC Future project is co-funded by the European Union Horizon Programme call INFRAEOSC-03-2020 Grant Agreement Number 101017536

Inclusive Dilepton Resonance Search



Looking for a bump (= new particle) over the background of known particles



DM mediator decays in two electrons
→ search in di-electron final state

- No signal → constraints on the fiducial cross-section of a new Z' particle.

Large backgrounds in the region below 1 TeV.

- Well-motivated dark matter models could have evaded detection!
- We can improve sensitivity to new physics by performing a more specific (*exclusive*) search

Two projects within this TSP:

1. Reinterpretation of inclusive resonance search in terms of dark matter mediators ✅
2. Exclusive Z'+MET analysis

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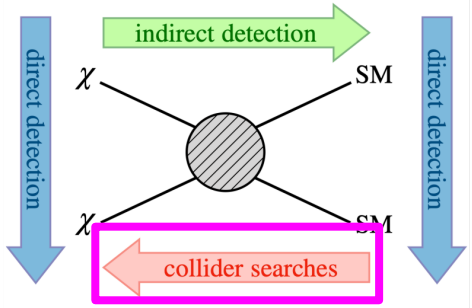
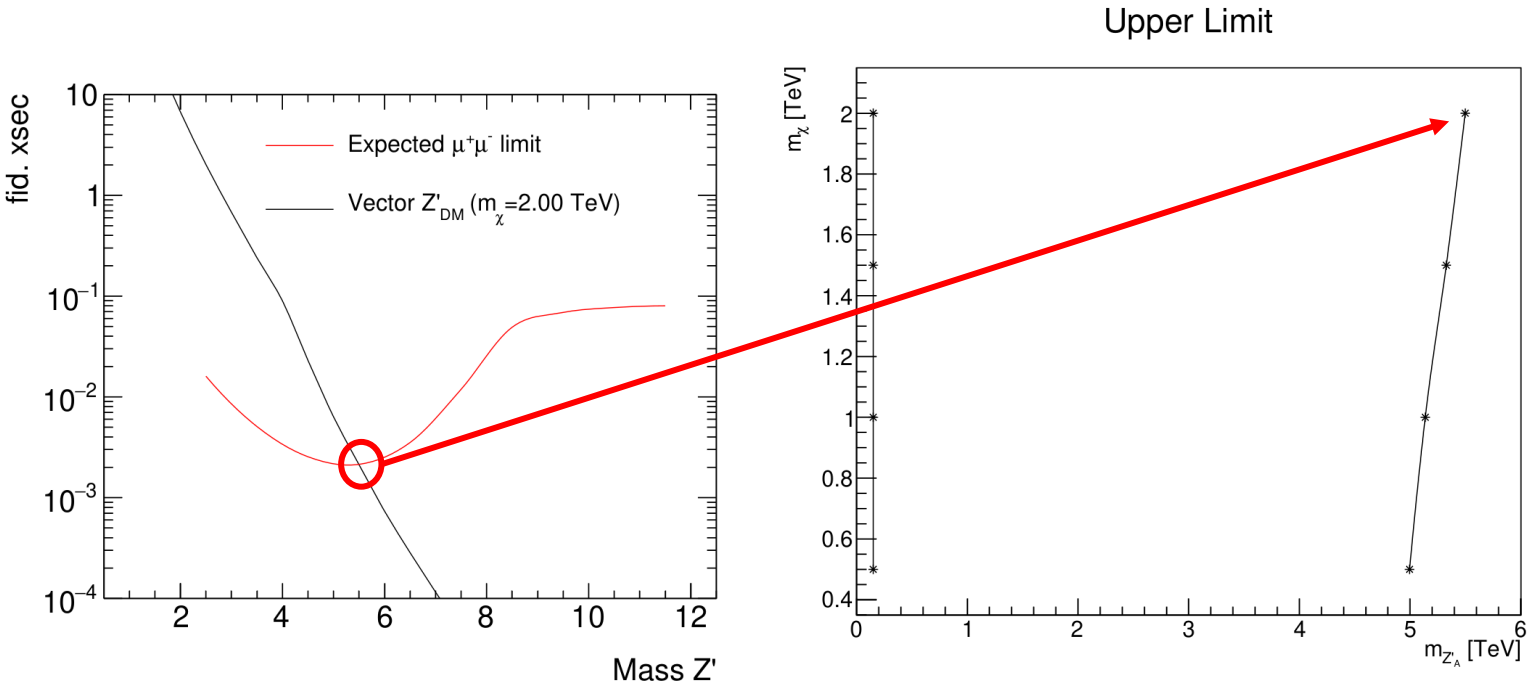
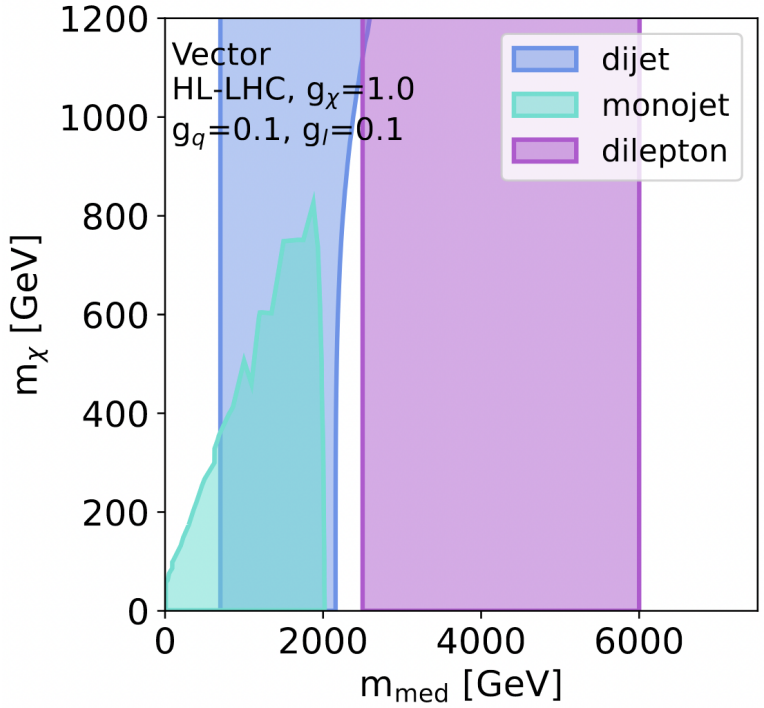
Reinterpretation of the Resonance Search



Use the dilepton resonance search to constrain dark matter mediators.

- Assuming a non-zero coupling to leptons, a neutral mediator associated with a dark sector would produce an excess in the dilepton invariant mass distribution.





Results included in this paper: https://arxiv.org/abs/2206.03456
(prepared within the US prioritization effort "Snowmass")

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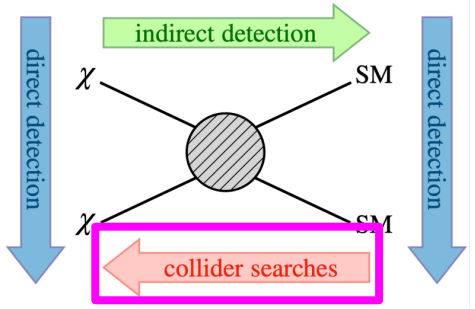
Reinterpretation of the Resonance Search

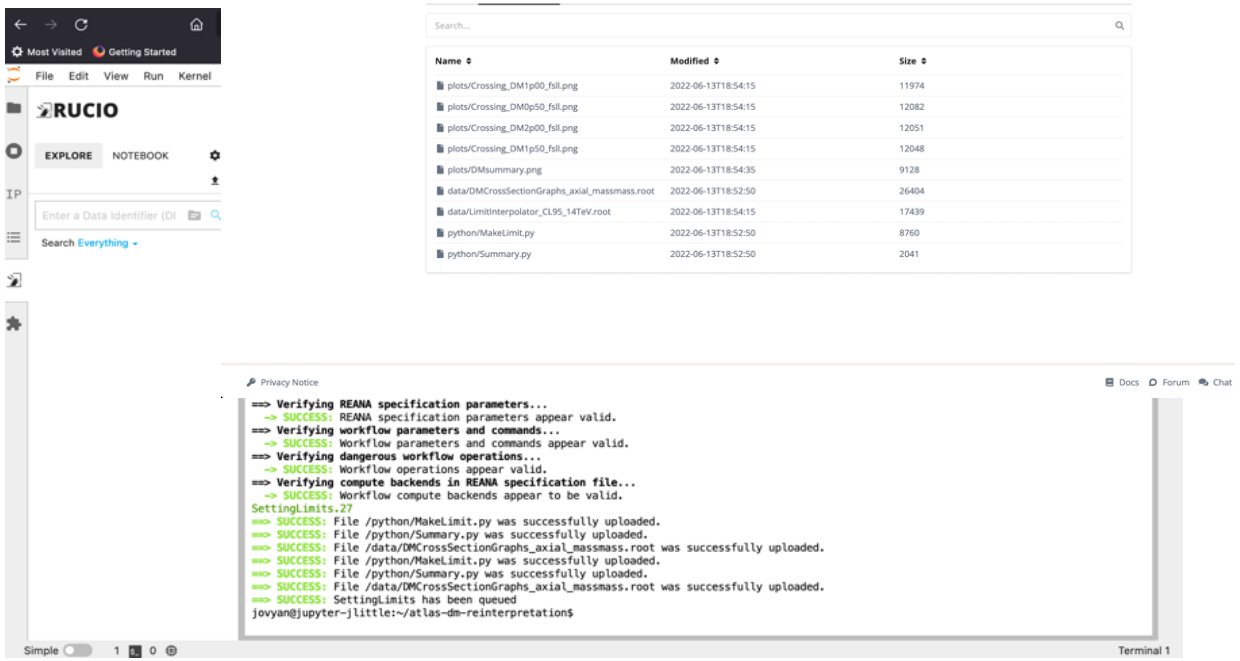


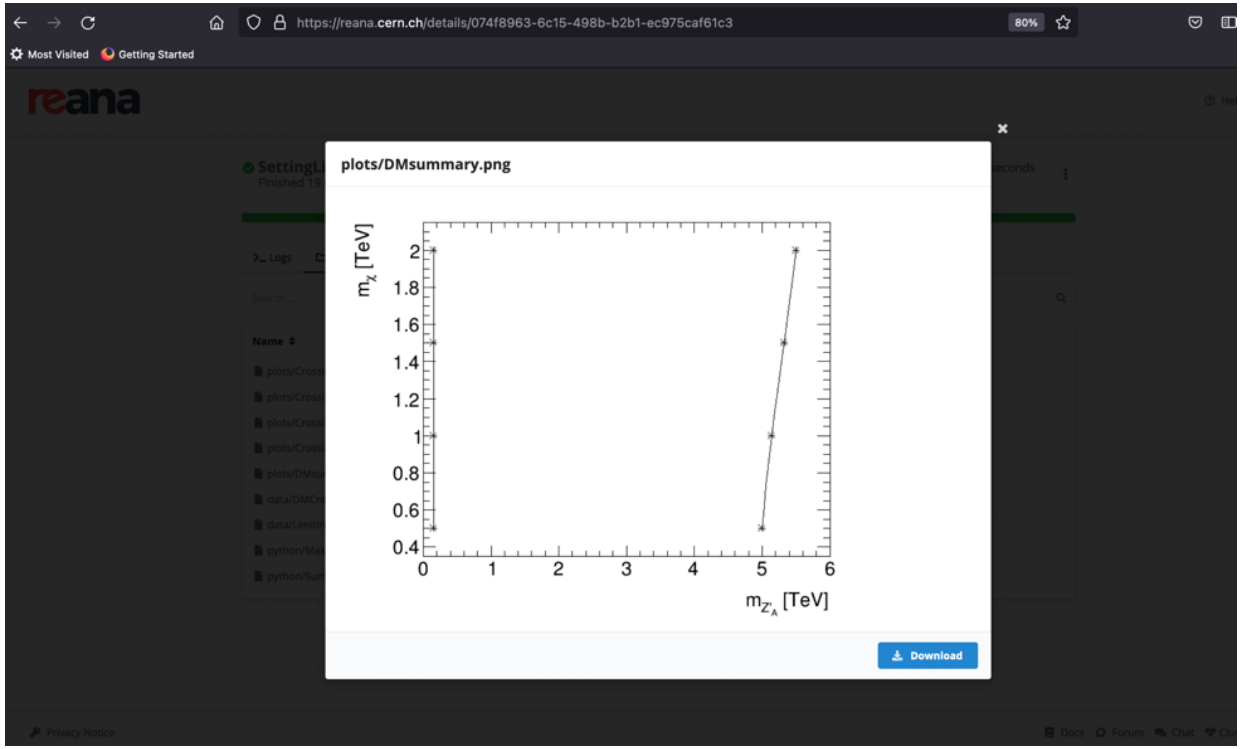
This reinterpretation was set up with **REANA**, sending the jobs to a remote computer from the **VRE**.

- Multiple stage workflows can be sent, passing the output to the following stage.

reana

Reproducible research data analysis platform





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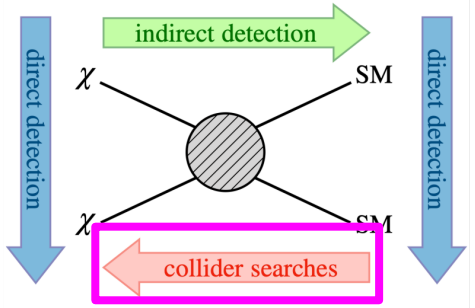
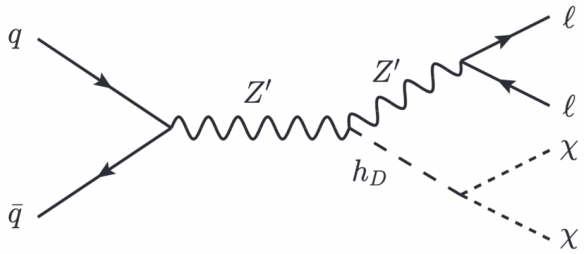
Exclusive Z'+MET Analysis



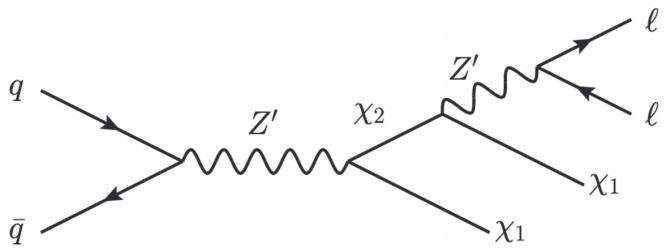
Search targeting dilepton resonances in the ll+MET final state.

- Searching for well-motivated models that could have escaped detection up to this point.
- Benchmark models help guide our analysis techniques, but we aim to stay as general as possible.
  - **Reproducible and reinterpretable results** are necessary for **collaboration.**
- By targeting dilepton events with MET in the final state, we will be more sensitive in the low-mass regions where the dilepton analysis was dominated by Standard Model events.
  - **Results expected soon.**

Dark Higgs



Light Vector



https://arxiv.org/pdf/1504.01386.pdf

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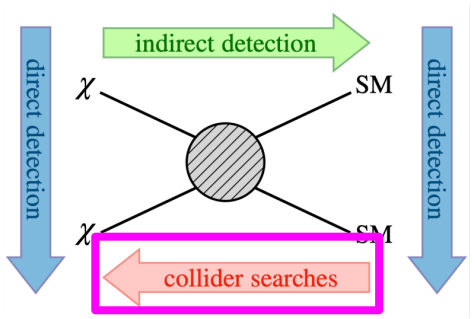
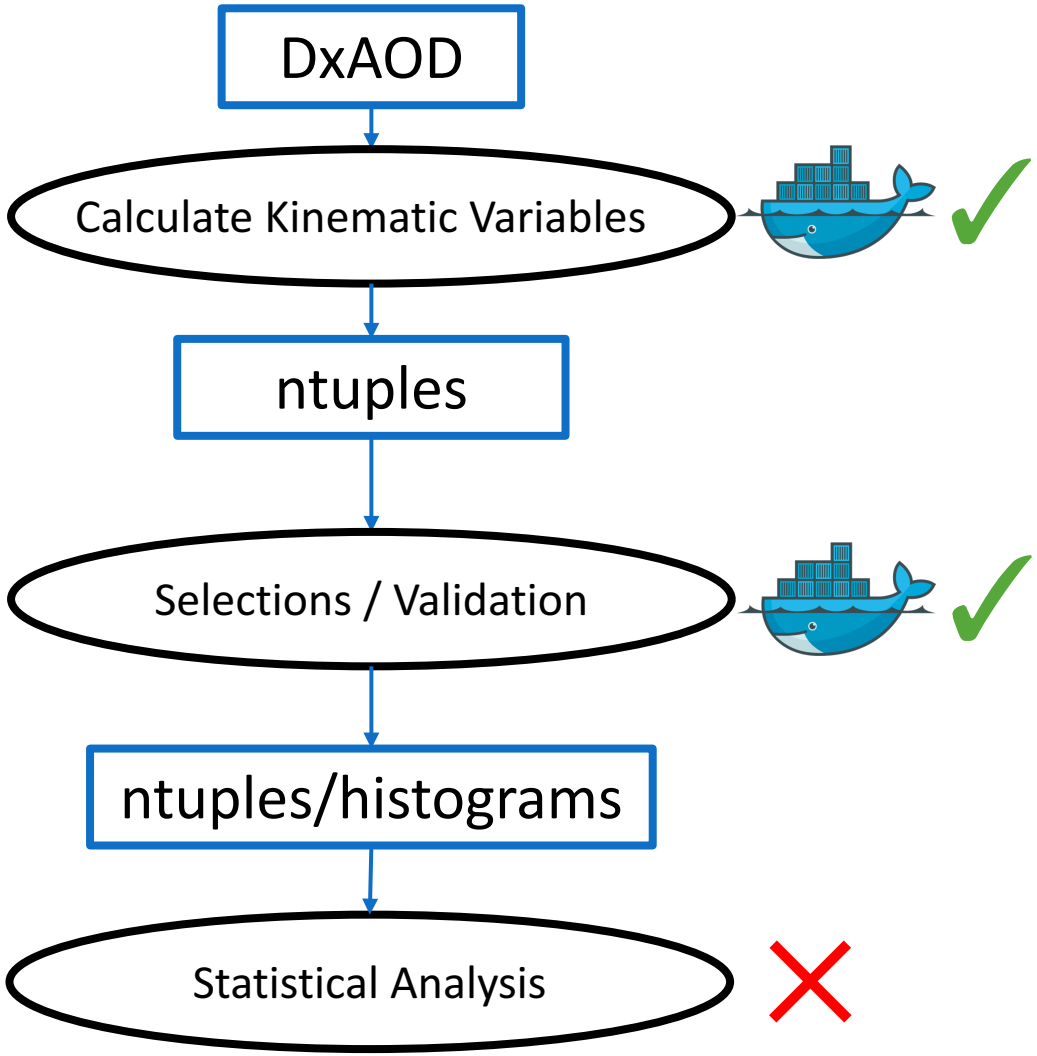
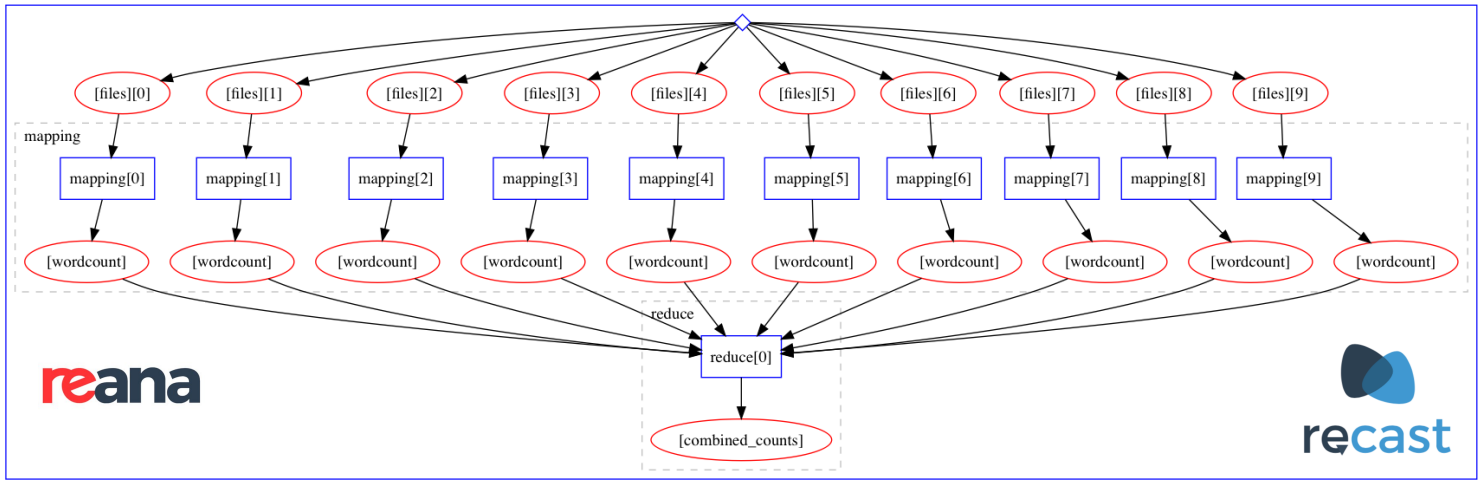
Exclusive Z'+MET Analysis





$\geq 10\ TB$



The EOSC Future project is co-funded by the European Union Horizon Programme call INFRAEOSC-03-2020 Grant Agreement Number 101017536

Dark matter direct detection: DarkSide plans and results

Maria Adriana Sabia (INFN/La Sapienza)
Paolo Salomone (INFN/La Sapienza)
Marco Rescigno (INFN)
Valerio Ippolito (INFN)

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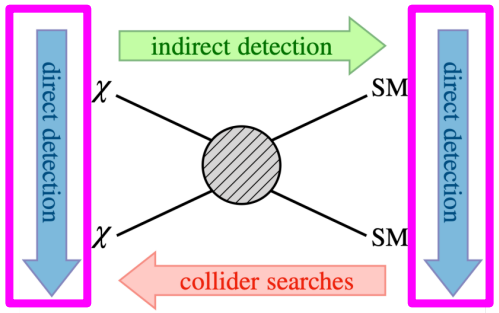
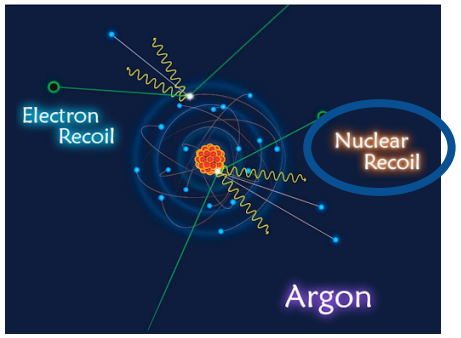
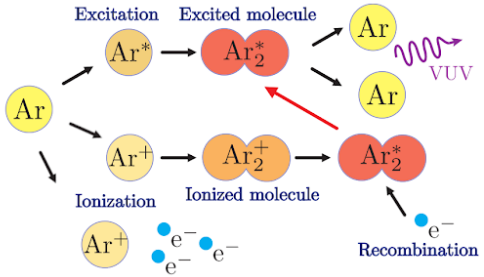
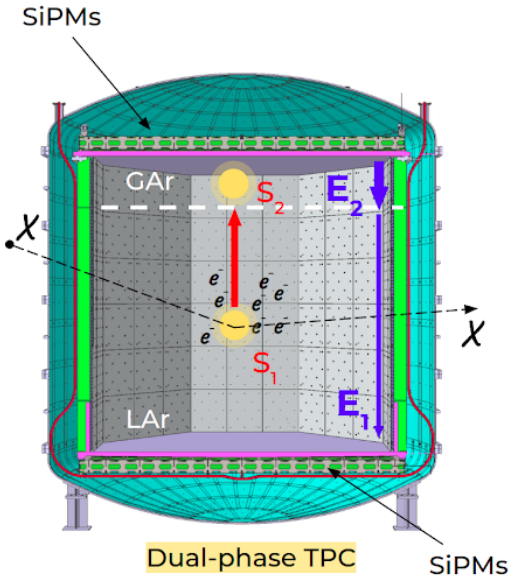
Direct Detection with a LAr TPC



- DM as WIMP-like particle produces a **nuclear** or an **electron recoil**.
- Elastic scattering with Argon Nuclei results in **Scintillation & Ionization**.

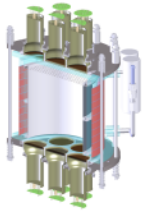






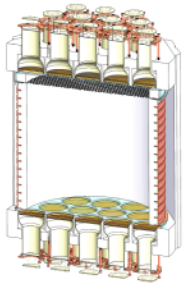
Evolution of the DarkSide Experiment

2012



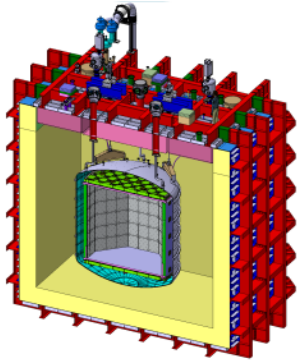
DarkSide-10

2013 - 2018



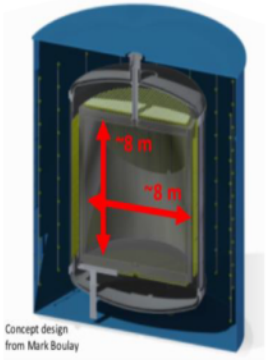
DarkSide-50
16 t d

2026 - 2036



DarkSide-20k
200 t yr

2030+



Argo
3000 t yr

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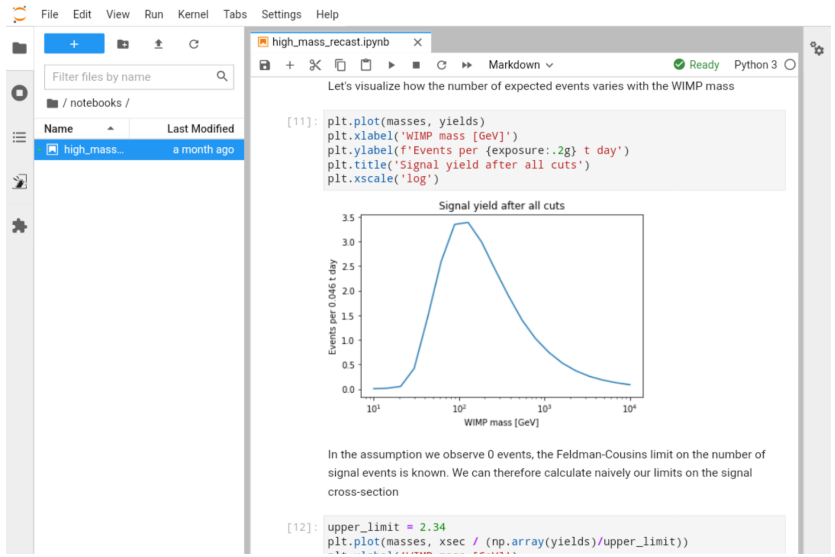
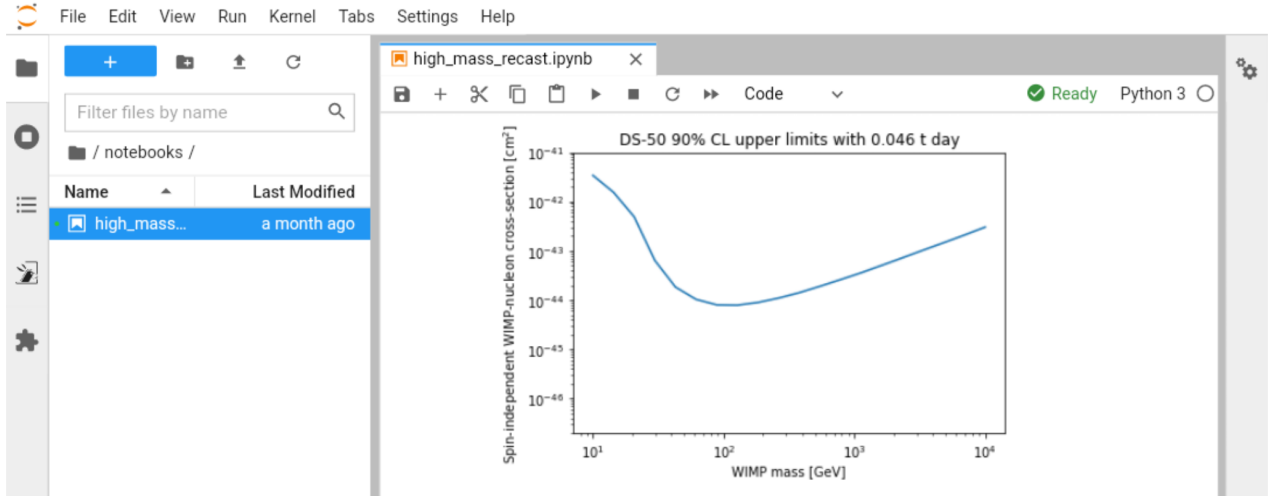
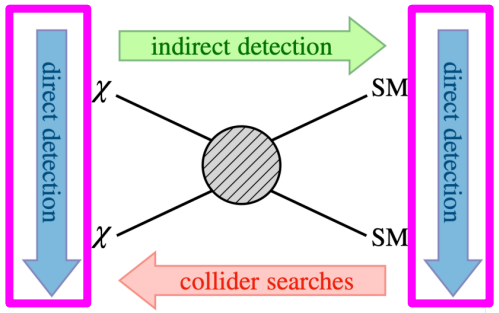
DarkSide Plans







Implemented a reanalysis tool for a high-mass search on the VRE platform.

- Output: **DarkSide50** exclusion curve for WIMP-nucleon cross section.

Further work is ongoing.

- Low mass analysis to be implemented.
- Different **theoretical models** (WIMP halo, argon response…) can be inserted by the user to produce different limit results.
- Working towards first open implementation.

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Indirect dark matter search with gamma rays and its association with VRE platform via open-science tools

Pooja Bhattacharjee, Christopher Eckner
Laboratoire d'Annecy De Physique Des Particules (L.A.P.P)

Supervised by:
Francesca Calore
Laboratoire d'Annecy-le-Vieux de Physique Théorique (L.A.P.Th)

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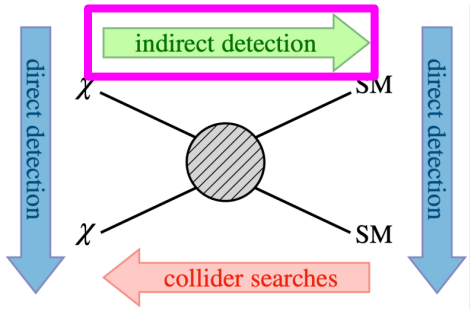
Fermi Large Area Telescope



Indirect Dark Matter Detection on the VRE.

- Gamma-ray data from the Fermi Large Area Telescope (Fermi-LAT).
- The data and main processing software (Fermi Science Tools) are publicly accessible, and now fully available in the VRE.
- Code is entirely written in python 3 using well-known packages like scikit-learn.
- Package can be optimized from the command line enabling a quick check of the viability of a user-defined Dark Matter model.

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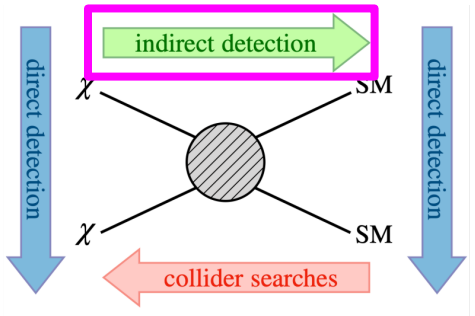
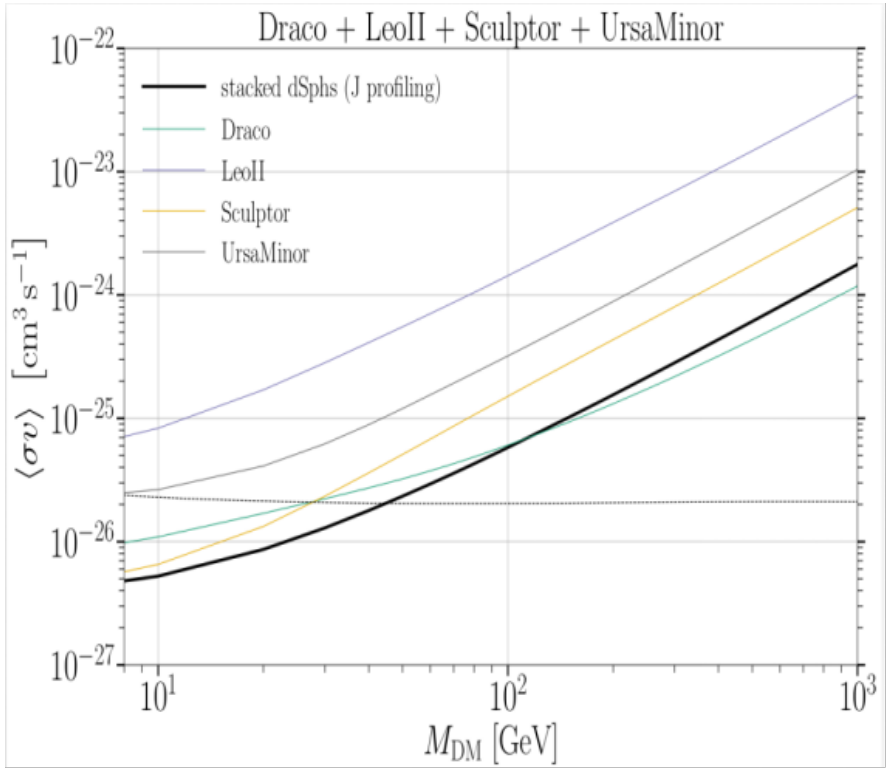
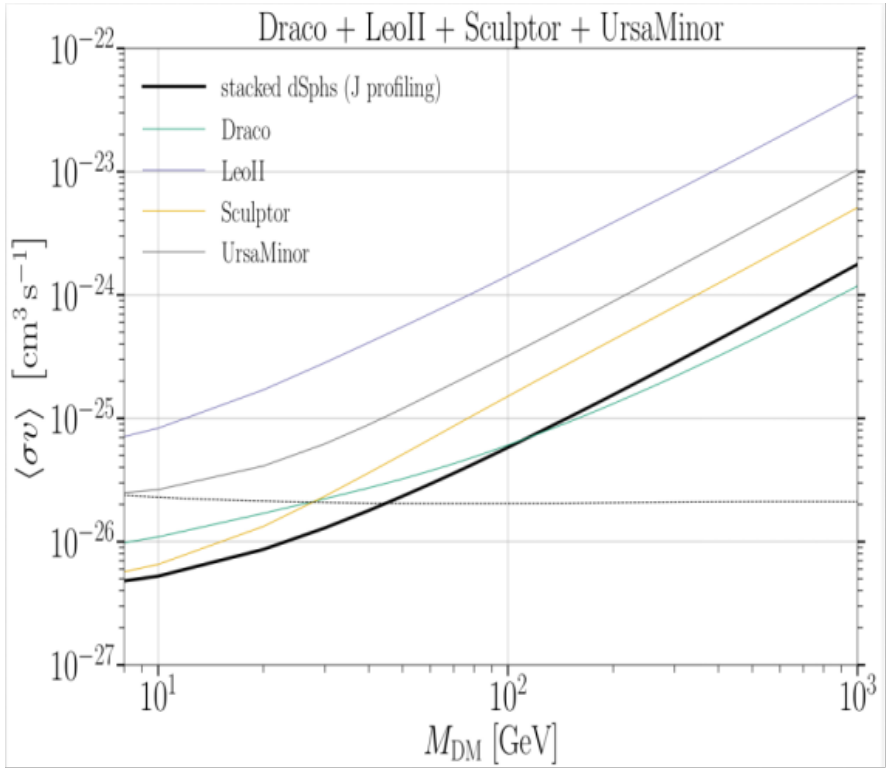
Fermi Dwarfs







- Based on the Fermi-LAT data set used for paper **A. Alvarez et al. JCAP09 (2020) 004.**
- MLFermiDwarfs code is accessible from https://gitlab.in2p3.fr/escape2020/virtualenvironment/mlfermilatdwarfs

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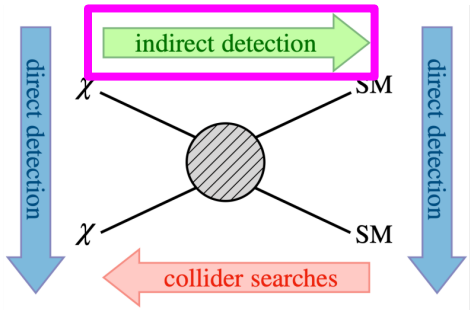
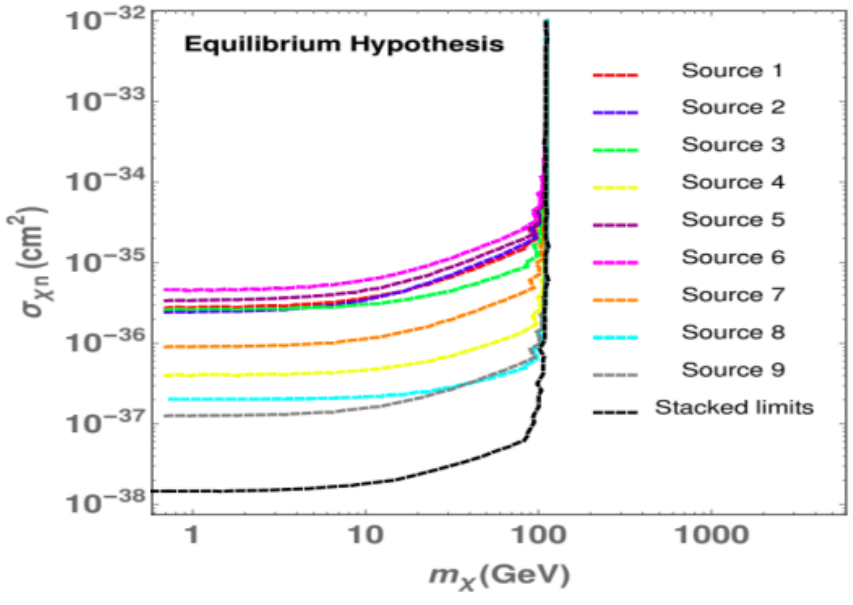
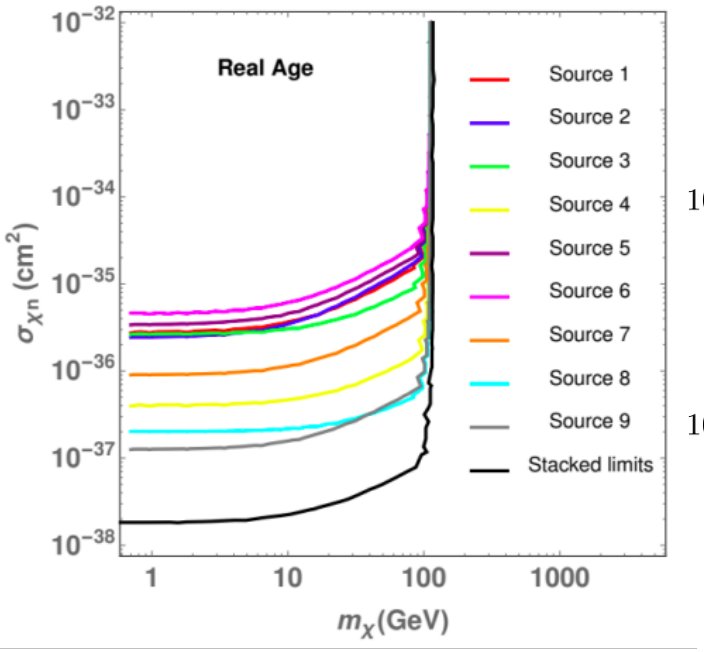
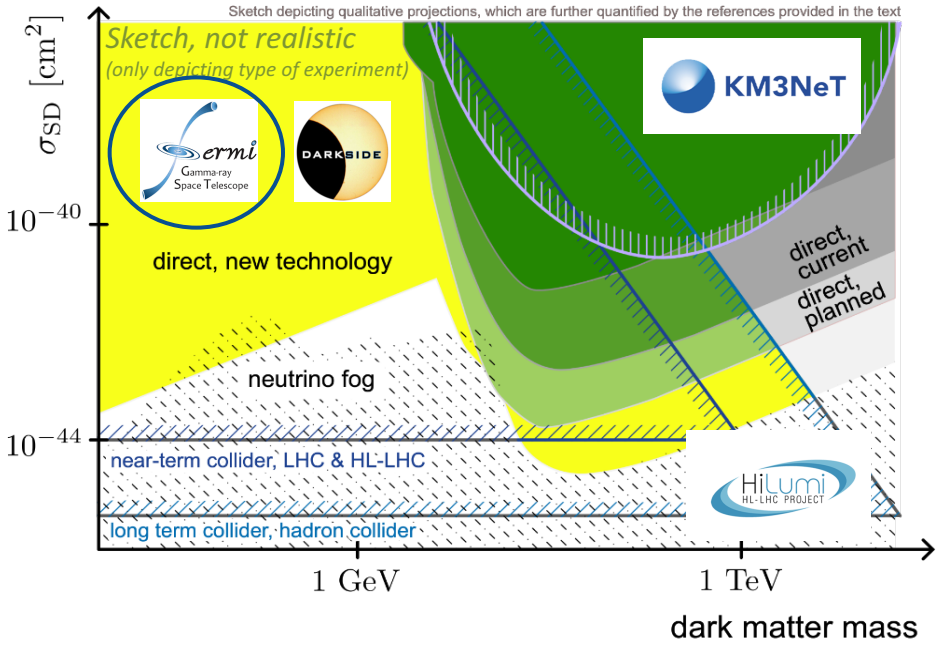
Brown Dwarf Analysis









- Based on the recent Published paper on **Bhattacharjee et.al, PRD,107, 043012, 2023.**
- Code is accessible from https://gitlab.in2p3.fr/escape2020/virtual-environment/brown-dwarfs-gamma

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Extreme Universe Science Project

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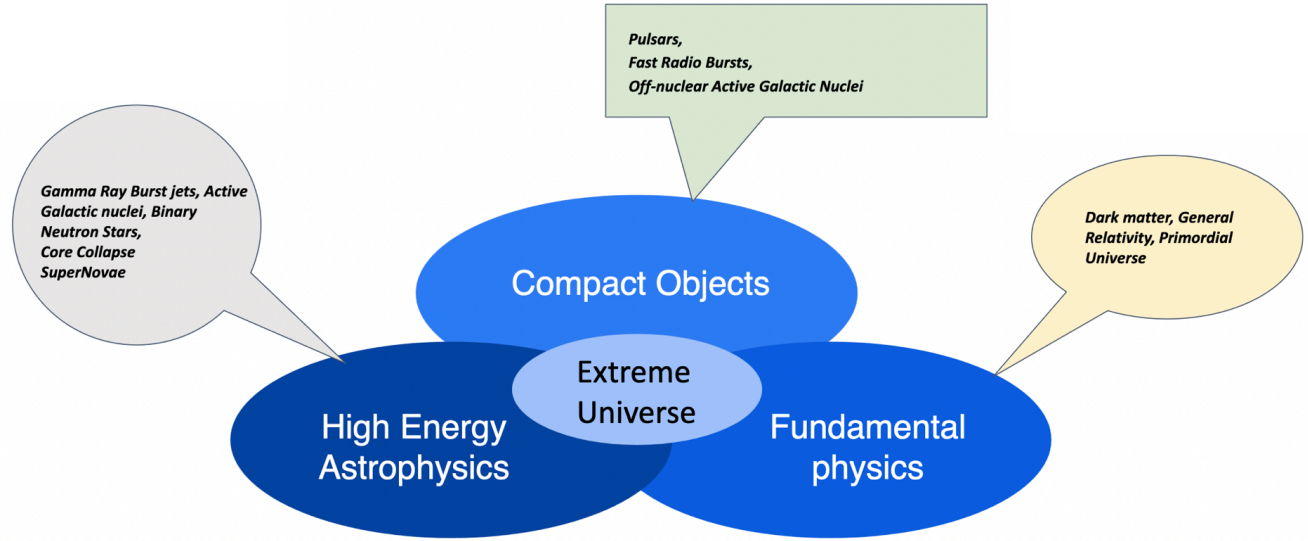
Extreme Universe

Gravitational wave discoveries and multi messenger astronomy opened windows to new perspectives for the study of events in the Extreme Universe.

- **Collaboration** among scientists of different disciplines is mandatory

EU Pilot Projects

- Broadband spectral energy distribution fitting of blazars
  - Estelle Pons, (LAPP)
- Wavefier: Multi-Messenger Astronomy
  - Alberti Iess (Scuola Normale Superiore)
- Searching for fast radio burst persistent radio source counterparts in dwarf galaxies using LOFAR
  - Danny Vohl (UvA/ASTRON)
- **KM3NeT Instrument Response Function** for point source analysis (shared with DM Science Project)
  - Mikhail Smirnov (Friedrich-Alexander University)
- Gravitational Wave detection follow-up observations within the ESCAPE Virtual Observatory.



The EOSC Future project is co-funded by the European Union Horizon Programme call INFRAEOSC-03-2020 Grant Agreement Number 101017536

Instrument Response Function of KM3NeT for point-source analysis

Mikhail Smirnov
(Friedrich-Alexander University FAU-ECAP)

Supervised by:
Kay Graf
Friedrich-Alexander University FAU-ECAP

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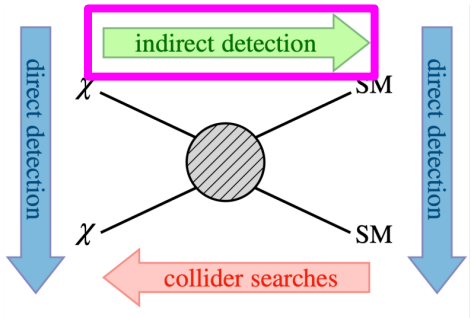
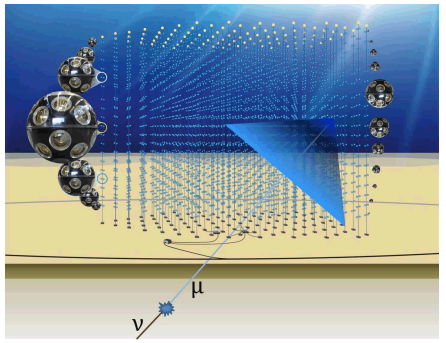
KM3NeT – IRF Concept



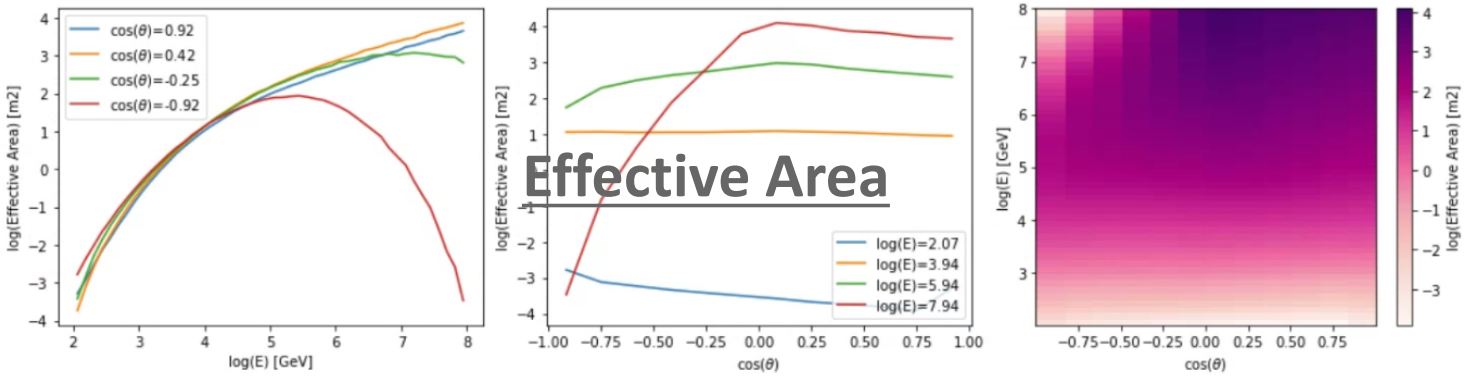
Instrument Response Function of neutrino telescope provides a quantitative estimation of the event and background rates.

- Contains physical characteristics of the detector.
- It allows to avoid extensive MC simulations each time for a new configuration of neutrino source.
- It supports different configurations of neutrino sources:
  - Point source with power law E^-a
  - Diffuse source
  - Extended source

```
pip install km3irf
from km3irf import utils
new_plot = utils.DrawAeff()
new_plot.peek()
```



- Compatibility with `gammapy` will give an easy combination with other gamma experiments like CTA.
- Active development of the `km3irf` python package.



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Common tools: Machine learning for big data compression

Axel Gallén, Alexander Ekman
(Lund University)

Supervised by:
Caterina Doglioni
University of Manchester and Lund University

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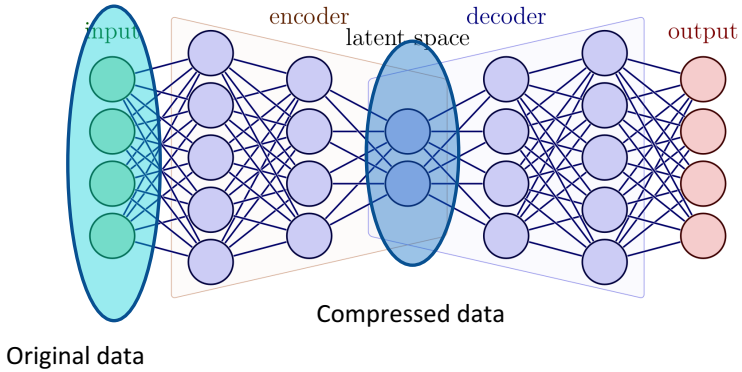
Baler: data compression using ML

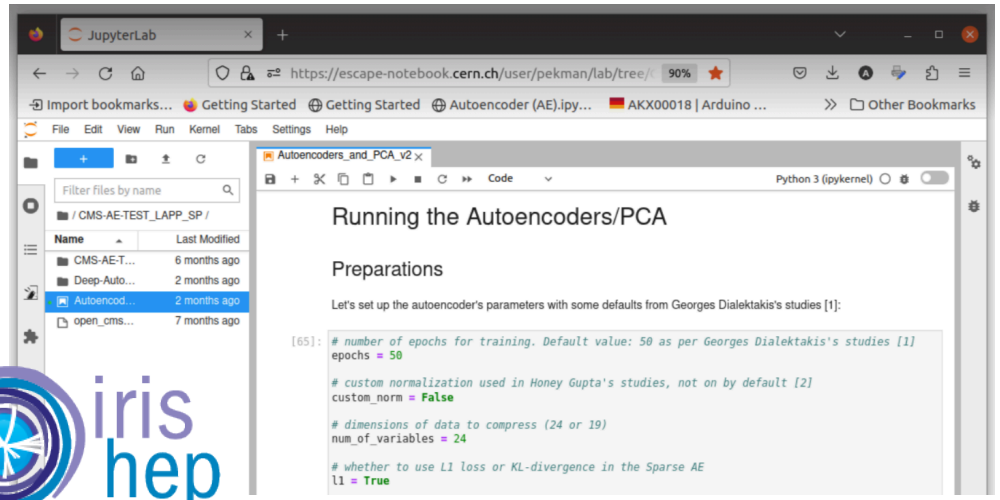
Idea behind the Baler compression tool:

- Train autoencoder on scientific (e.g. HEP) data
- Compress/decompress data by storing model + autoencoder's *latent space* (fewer dimensions)



Idea behind its inclusion in European Open Science Cloud / EOSC Software Catalogue:

- Provide "off the shelf" algorithms/tools that everyone can use



IRIS-HEP fellow Maxym Nauchyk

Status:

- Jupyter notebook containing Baler prototype available on Virtual Research Environment
- Many improvements since (Zenodo release), these will be ported on VRE as well

See talk by **A. Ekman and A. Gallen**

https://indico.jlab.org/event/459/contributions/11723/

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Summary

ESCAPE - The European Science Cluster of Astronomy & Particle Physics ESFRI Research Infrastructures has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement no. 824064.

Challenges and Consolidation

Upcoming challenges for the Dark Matter TSP:

- Onboard new analyses requiring:
  - very **large amounts of data**, o(TB) → turn to pledged resources
  - more **complex workflows** → stress-test VRE & EOSC cell, using REANA
- Guarantee **restricted data access** until embargos lifted → use EOSC core **authentication**
- Publish software and pipelines on **ESCAPE Software Catalogue**
- Future (subject to time/resources):
  - Use Gambit software for **combination** of results)
  - Expand use cases to **real-time analysis on constrained infrastructure**

Consolidation of the Science Projects (DM and Extreme Universe)

- Widening participation of **scientists** to **Open Science tools**
  - more support needed for combination of results, training, documentation
- Consolidation work on EOSC for **lasting infrastructure**
  - Integration of services with EOSC core
- **Strengthening cooperation and sharing experience** across Science Projects in EOSC-Future

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Conclusions

With the **DM Science Project's analyses** and **tools** on the **VRE**, we are making progress towards:

- production of **new scientific results** discovering or constraining dark matter hypotheses
  - providing other communities with the necessary understanding to reproduce the analysis
- **comparing and combining** results from different experiments
- demonstrating **FAIR data and interoperable workflows** as an example for the community
- building a **working prototype cell for the European Open Science Cloud**
  - providing a testing ground for software & computing that can be explored by future experiments

Thanks to the Dark Matter SP Team!

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