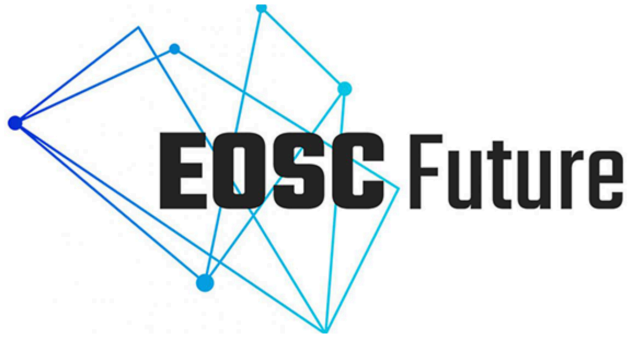


The Dark Matter Science Project

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

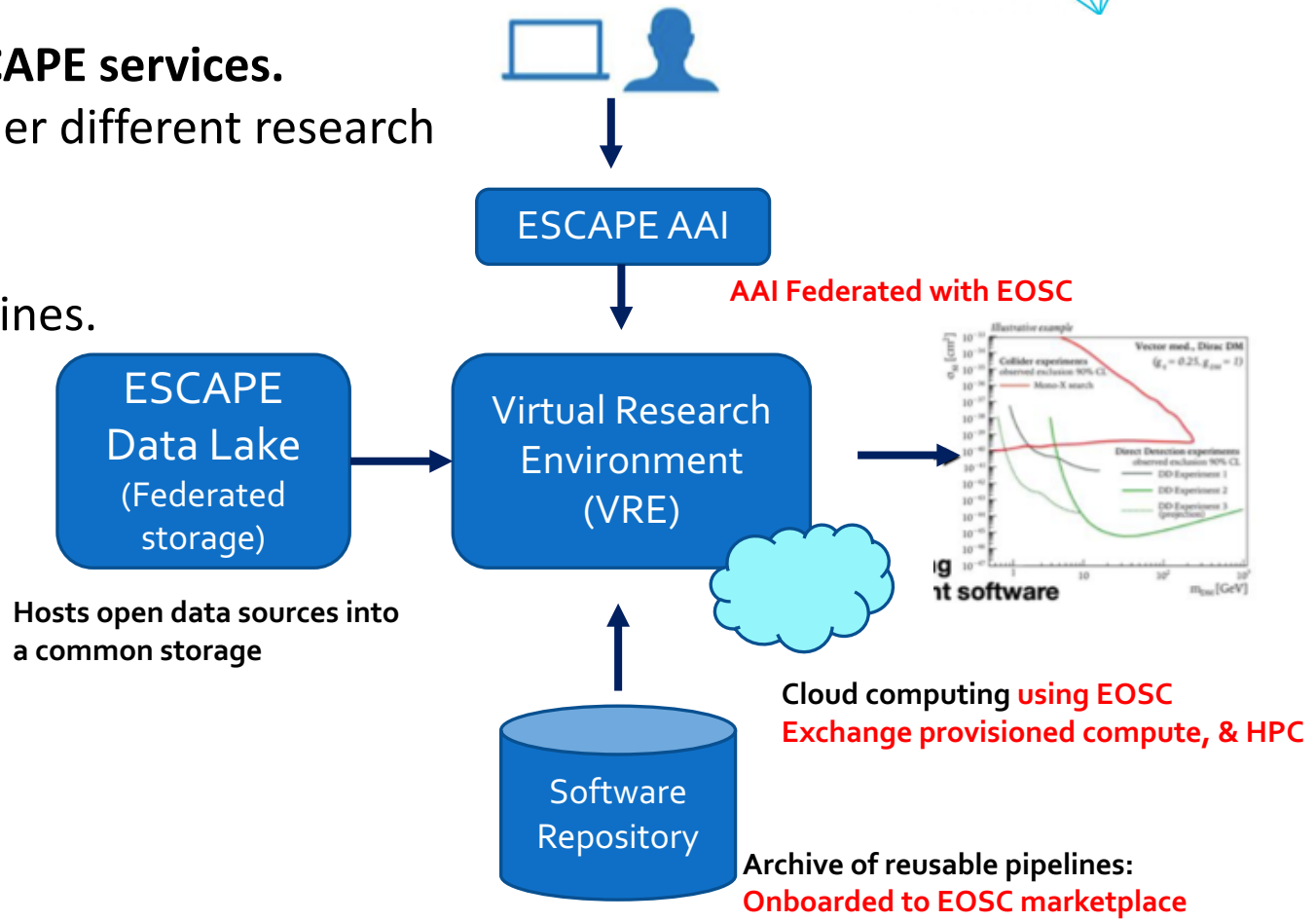
ESCAPE, Open Science Projects

Open Science Projects bring together different ESCAPE services.

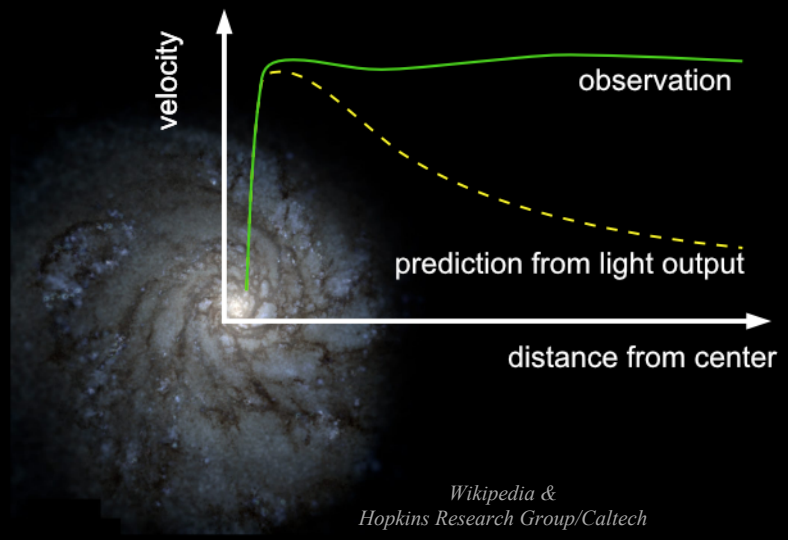
- ESCAPE is an EU-funded project to bring together different research infrastructures.
- Improve productivity of researchers.
- Gain new insights and innovation across disciplines.
- Two science projects being developed.

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

See following talk by **G. Lamanna**

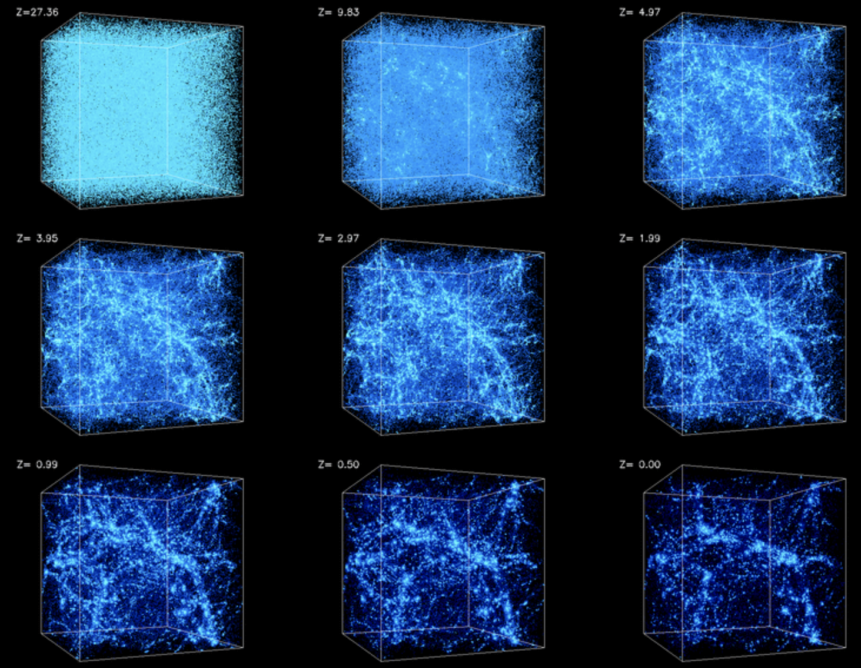


Big science question: Dark Matter



Wikipedia &
Hopkins Research Group/Caltech

Vera Rubin,
© Washington Times & Zuma

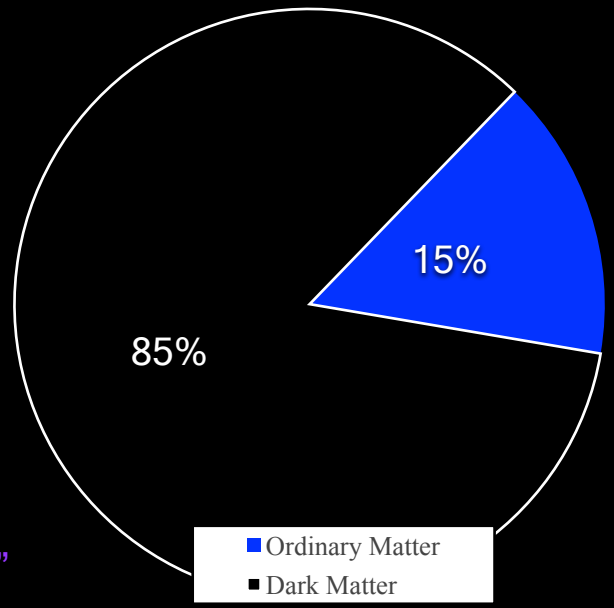


Simulations were performed at the National Center for Supercomputer Applications by A. Kravtsov and A. Klypin.

visible matter

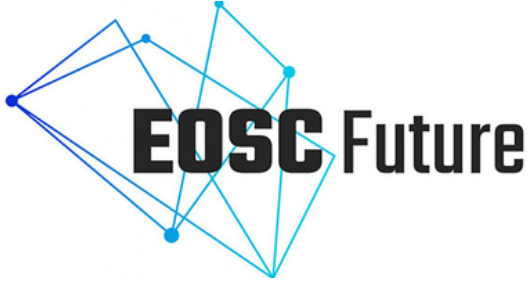
NASA/CXC/M. Weiss

"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:

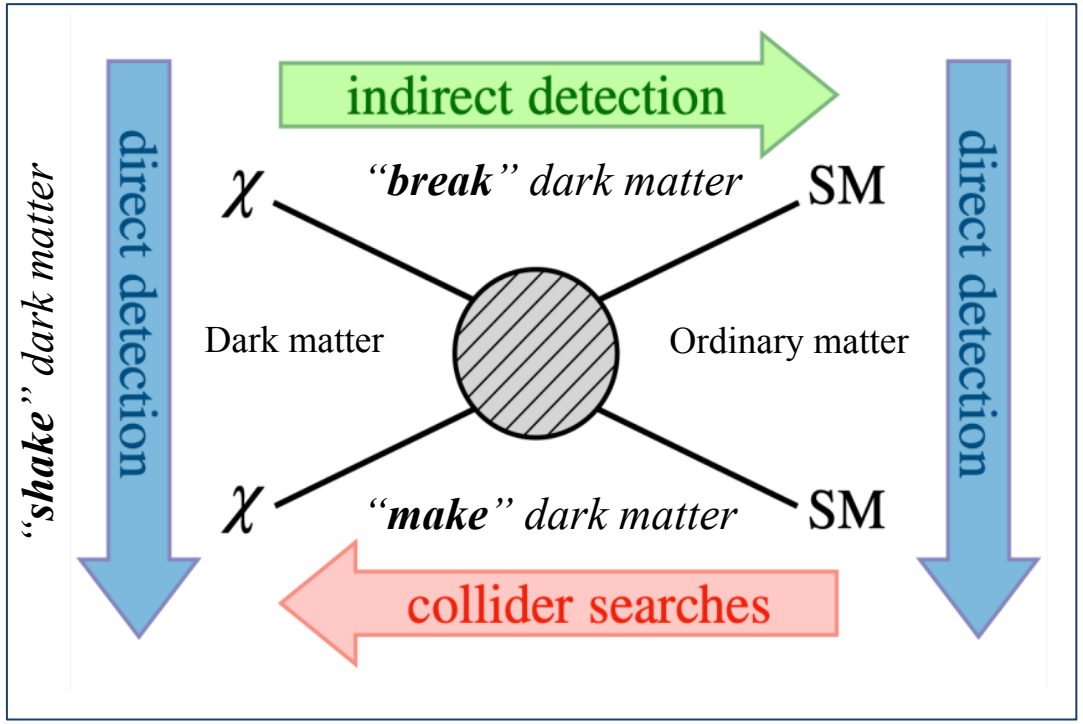
- **create** and store new analyses, datasets and results
- **combine** multiple results studying the same question
- **reinterpret** existing studies for new questions

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

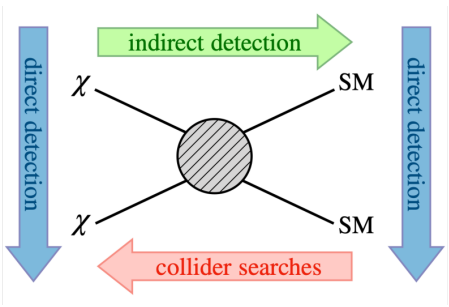
Dark Matter: Complementary Approach

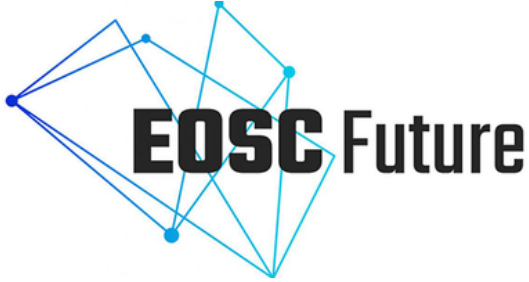
A joint discovery of the nature of dark matter requires different experiments and inputs

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



Example of a *discovery scenario*

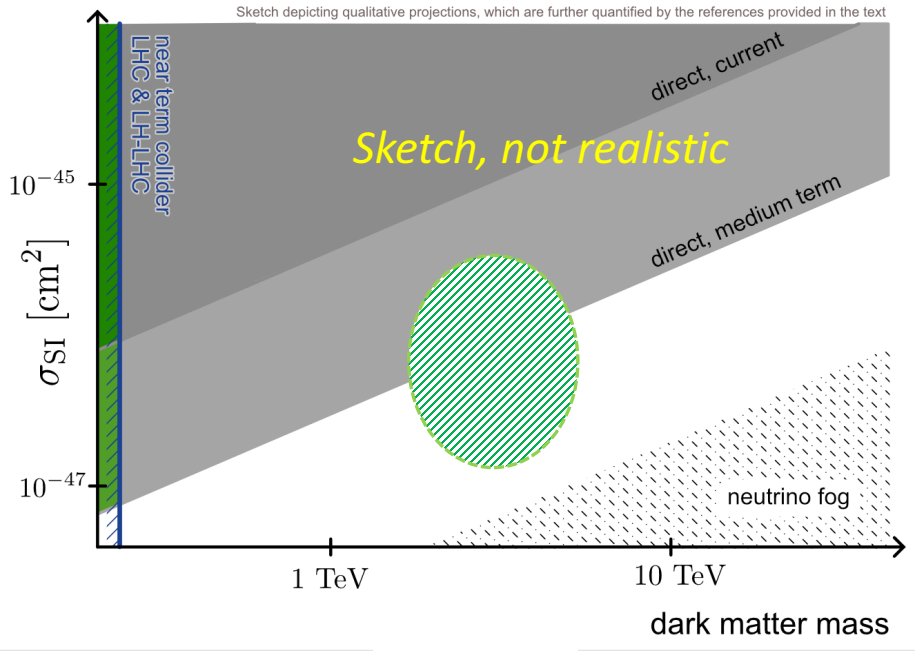




Late 2020s **Direct detection** experiment sees a hint of a signal, with characteristics compatible with WIMP DM

Mid 2030s

2040s



Inspired by:
[Dark Matter Complementarity (Snowmass report), arXiv:2210.01770]
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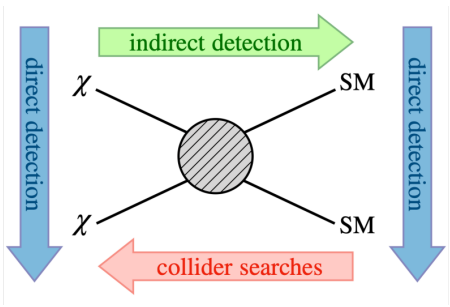

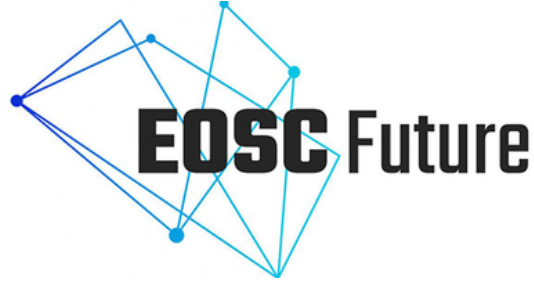

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Direct detection experiment (using another tech confirms these hints

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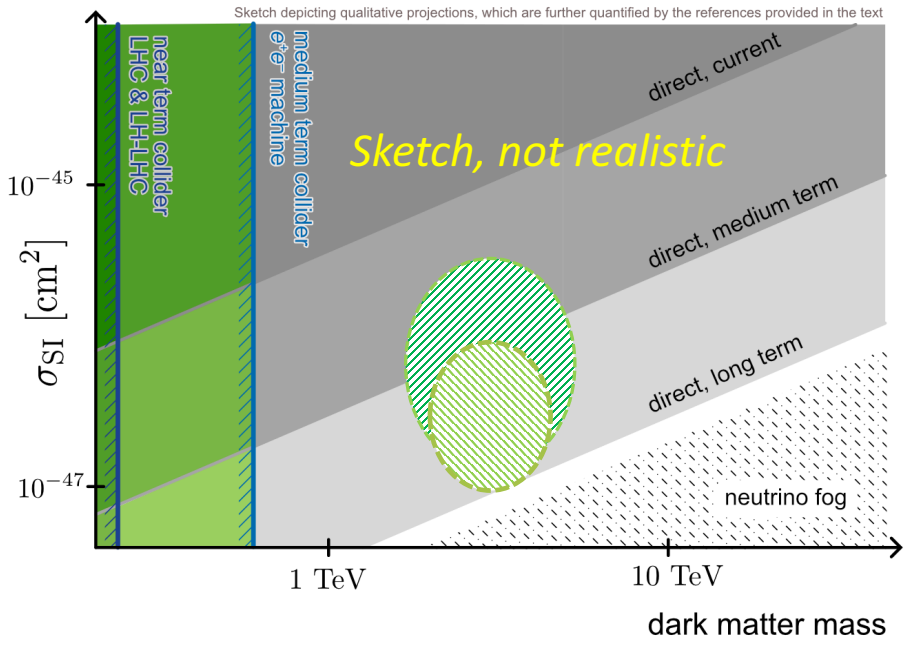

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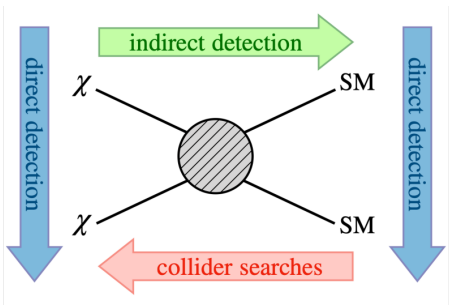

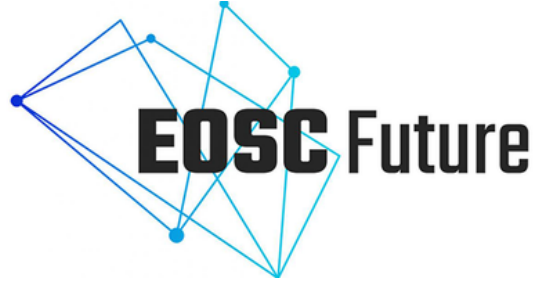

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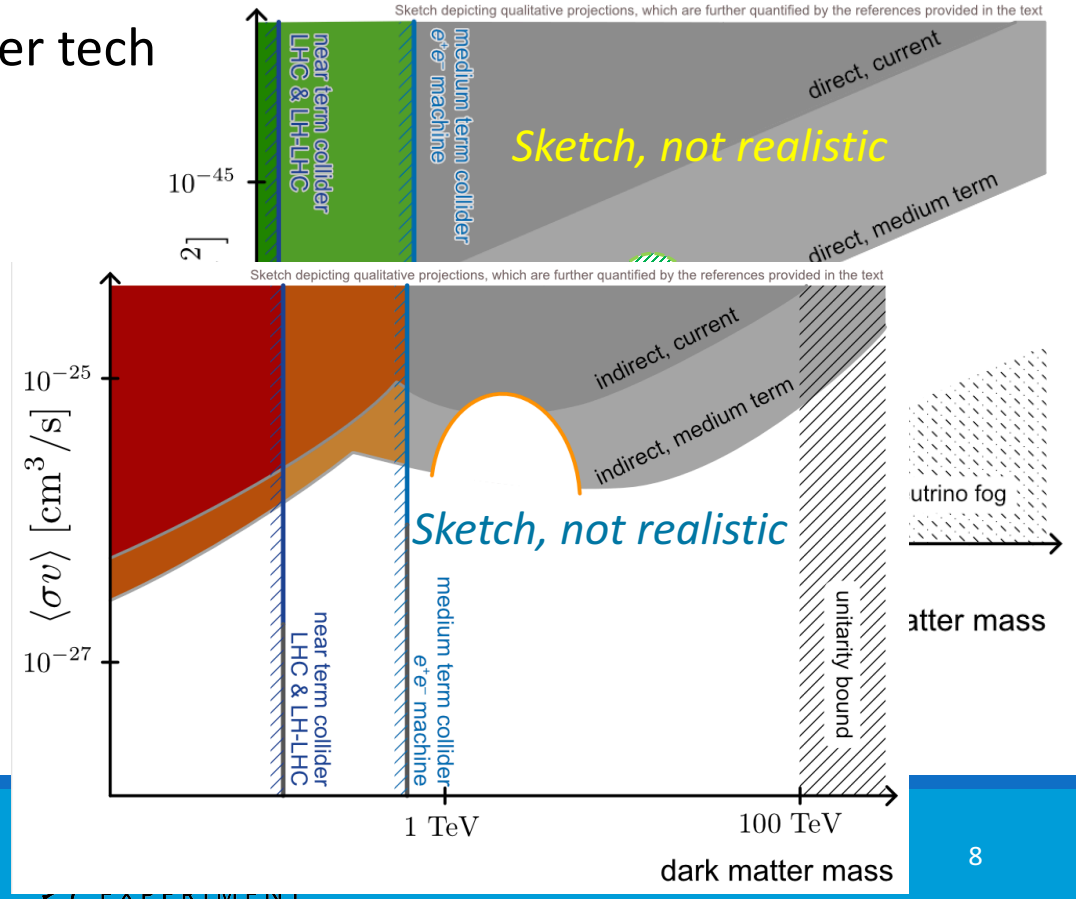

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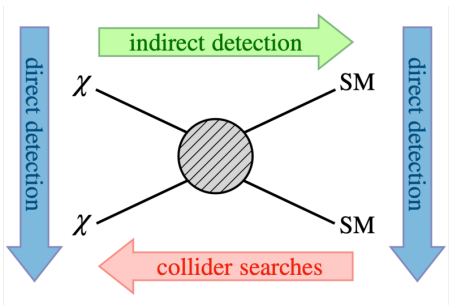

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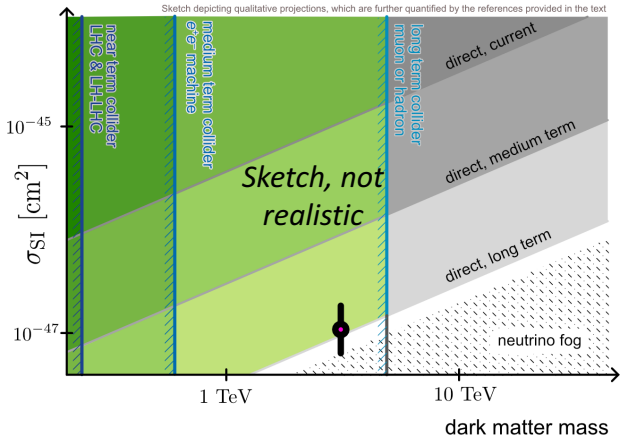
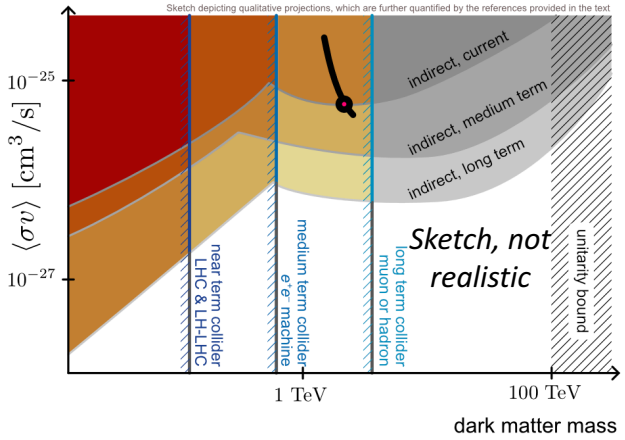
Future collider, built to target particles with the mass of the putative DM candidate, sheds light on interactions between DM and ordinary matter





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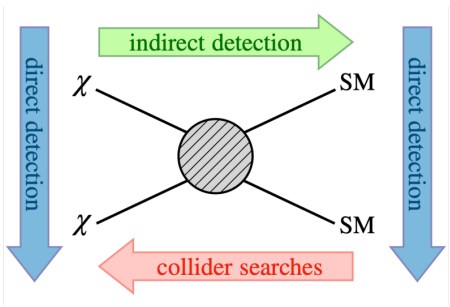

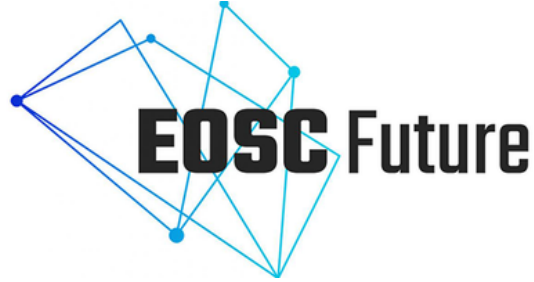

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Inspired by:
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Such a scenario requires **interoperable and reproducible analyses**

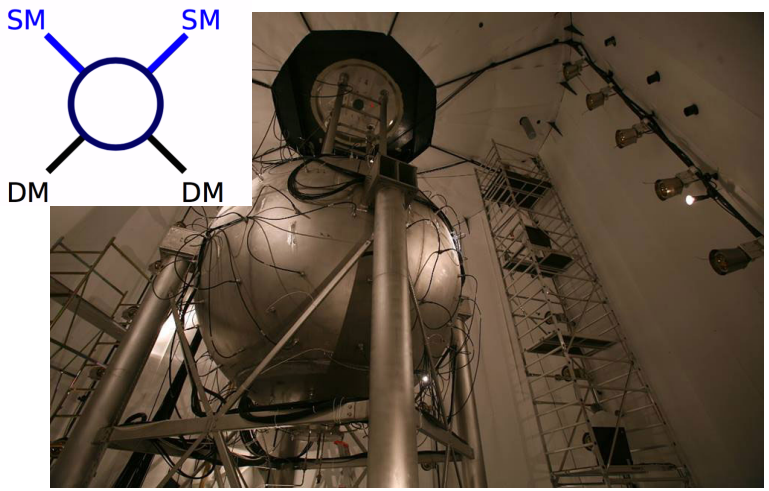
- **comparison** and **combination** of results from different experiments
- **end-to-end workflows** available for cross-checks

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

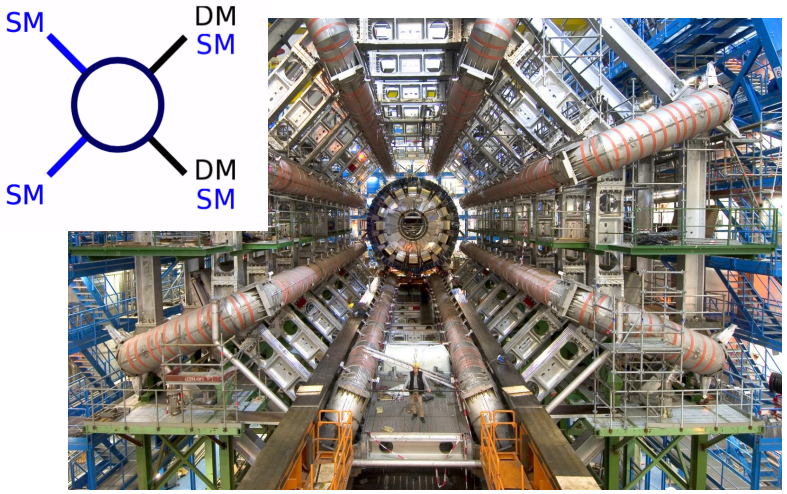
Experiments involved in the Dark Matter Science Project

EOSC Future

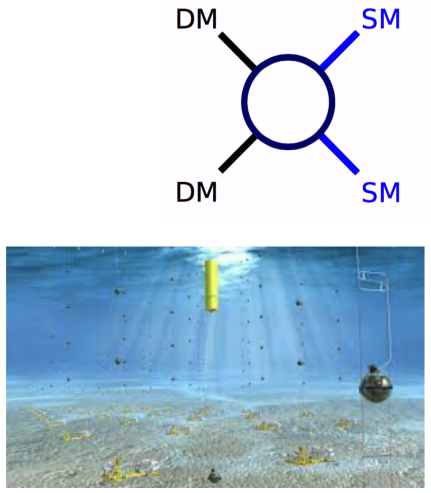
Direct detection: DarkSide



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

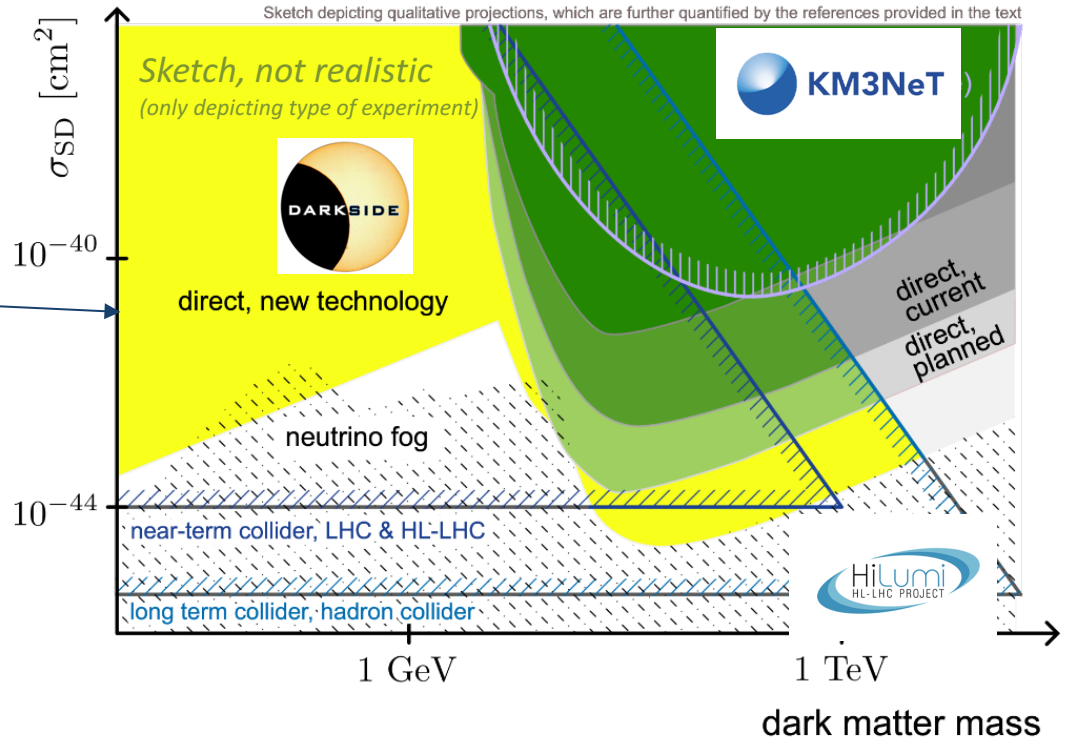
Science outputs of the DM TSP

Planned domain science outputs

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

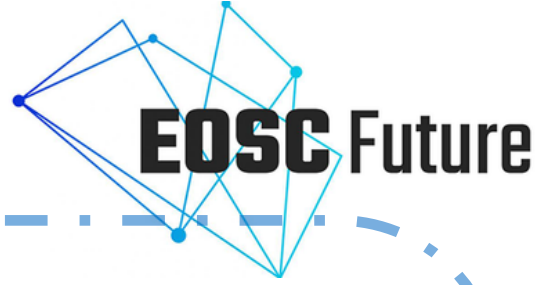
Data and software objects + pipelines

- 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

Analysis Workflows for the DM Science Project



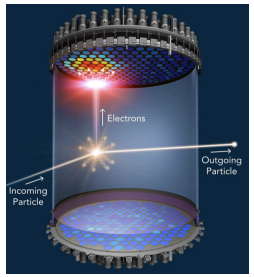
Technical solutions

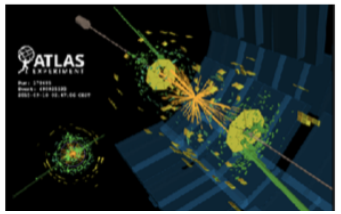
JupyterHub
(smaller workflows)

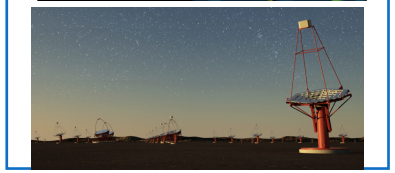
REANA
(larger workflows)

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

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)

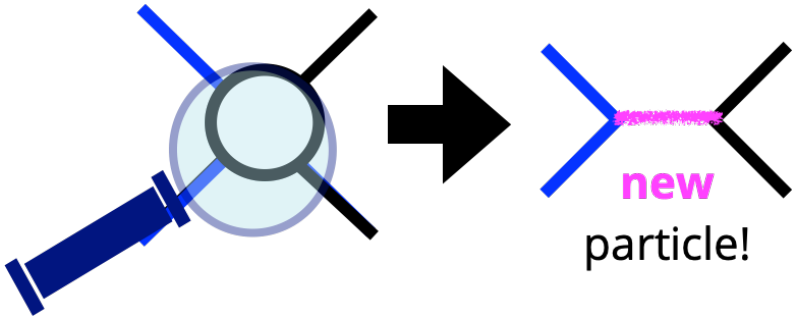
ESCAPE - The European Science Cluster of Astronomy & Particle Physics ESFRI Research Infrastructures has received funding from the European Union's Horizon 2020 research and innovation programme under Grant Agreement no. 824064.

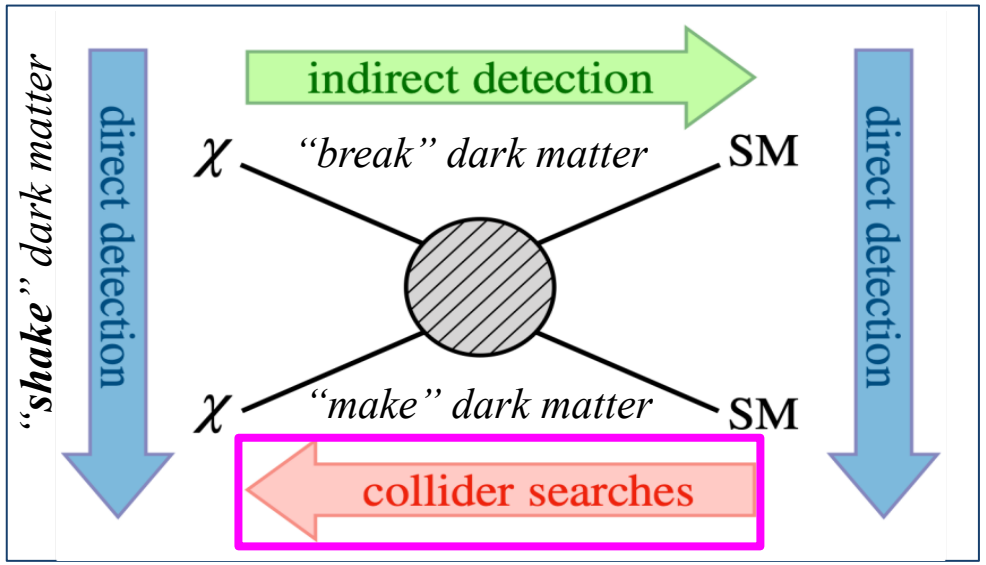
DM Science Project - ATLAS

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.

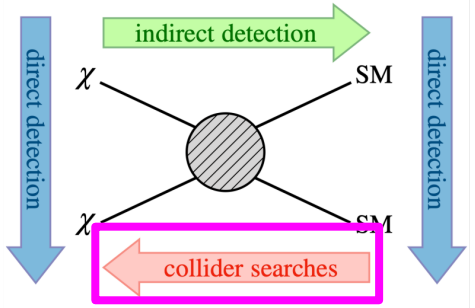




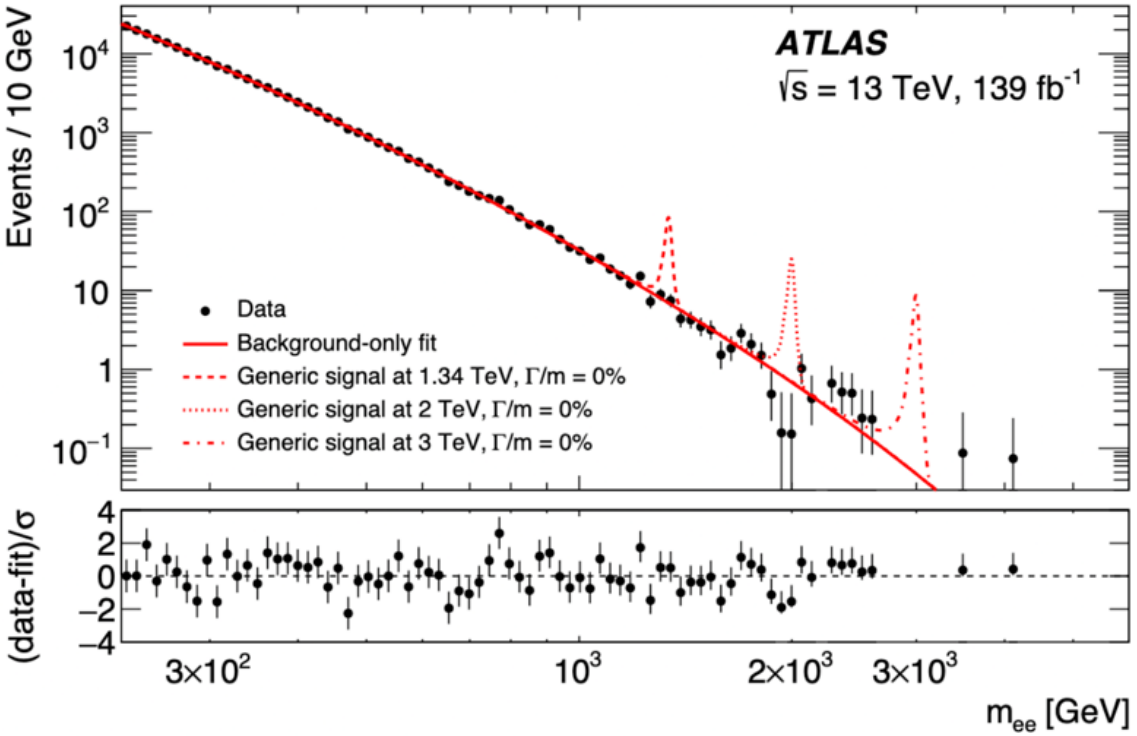
At the LHC, we are trying to "make" dark matter.

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

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.

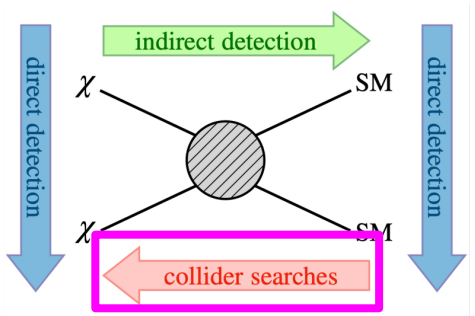
Large backgrounds in the region below 1 TeV.

- 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:

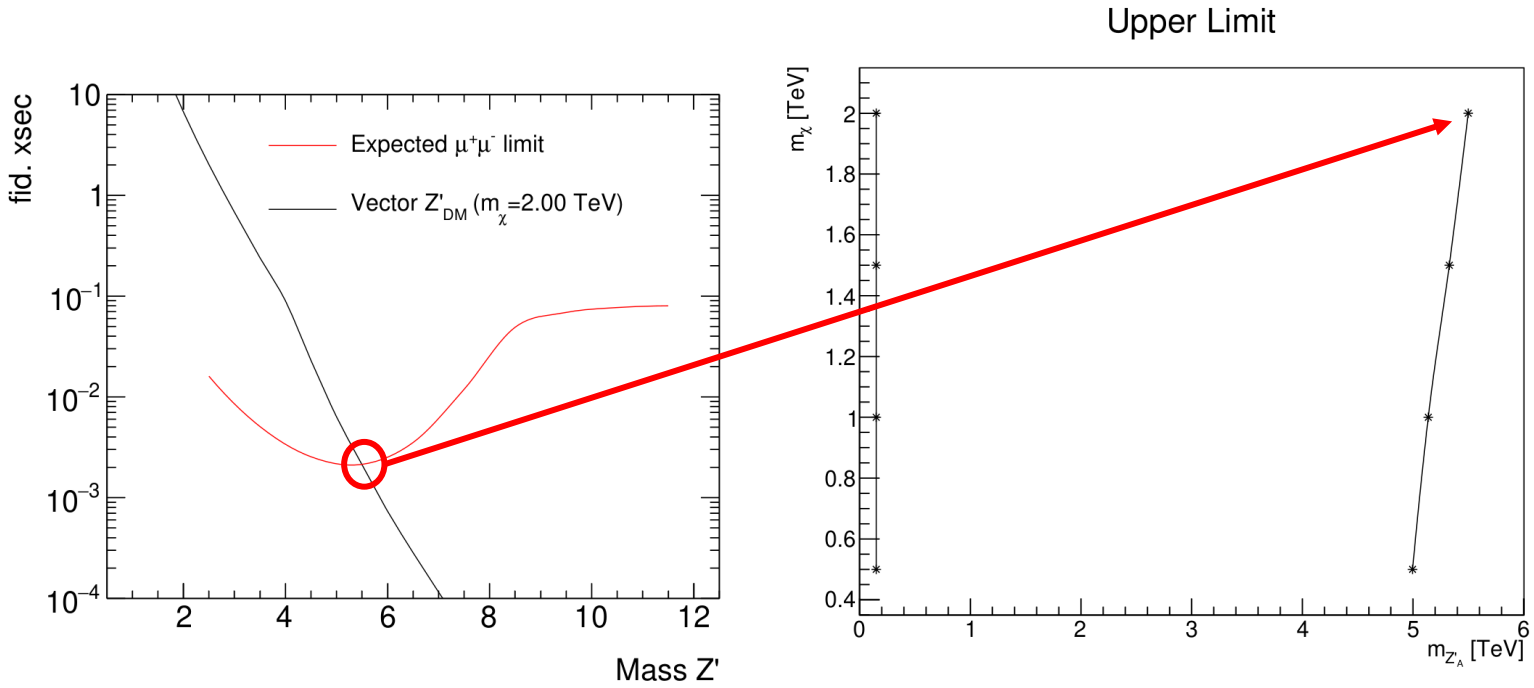
1. Reinterpretation of inclusive resonance search in terms of dark matter mediators ✅
2. Exclusive Z'+MET analysis
   - New results expected soon!

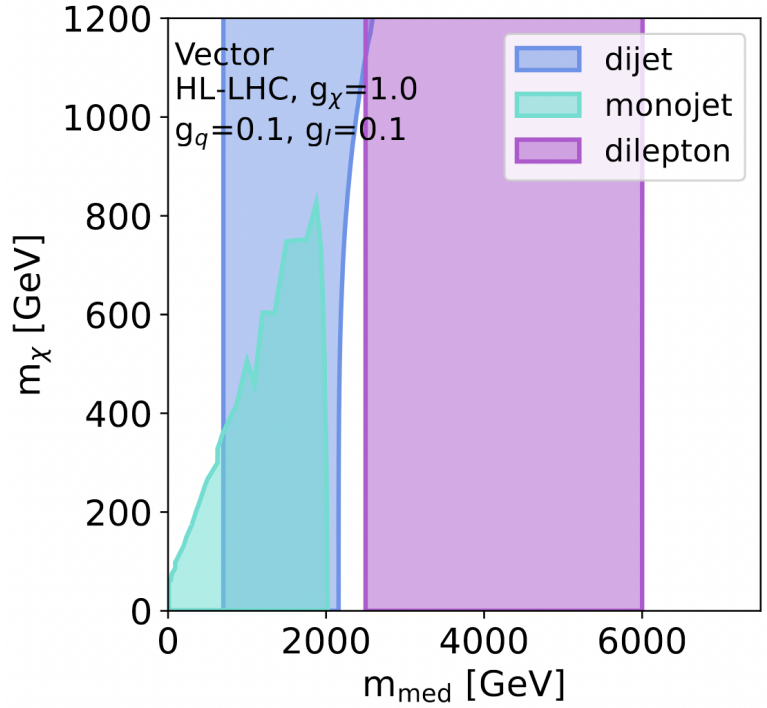
Reinterpretation of the Resonance Search



Use the dilepton resonance search to constrain dark matter mediators.

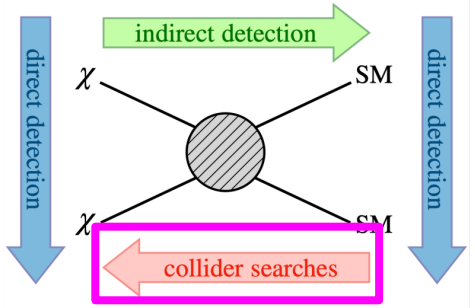
- Assuming a non-zero coupling to leptons, a neutral mediator associated with a dark sector would produce an excess in the dilepton invariant mass distribution.





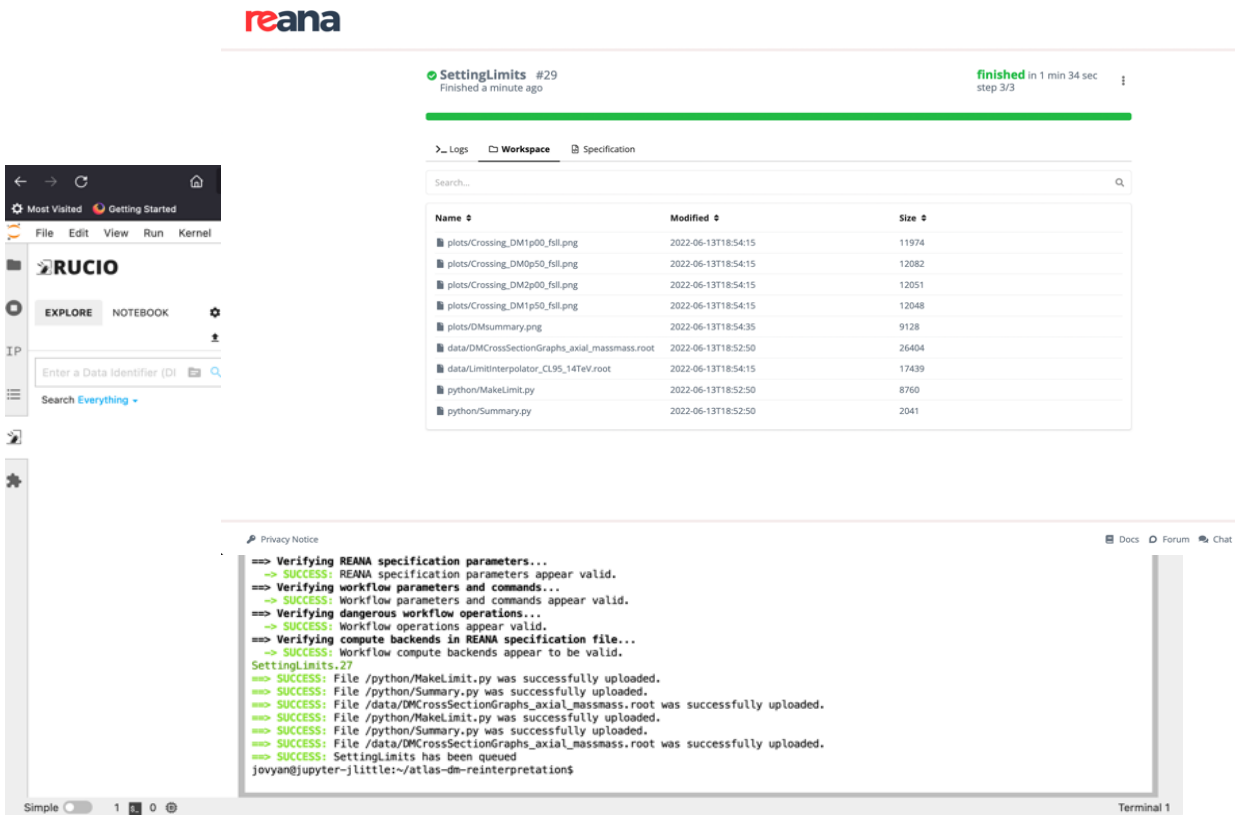
Results included in this paper: https://arxiv.org/abs/2206.03456
(prepared within the US prioritization effort “Snowmass”)

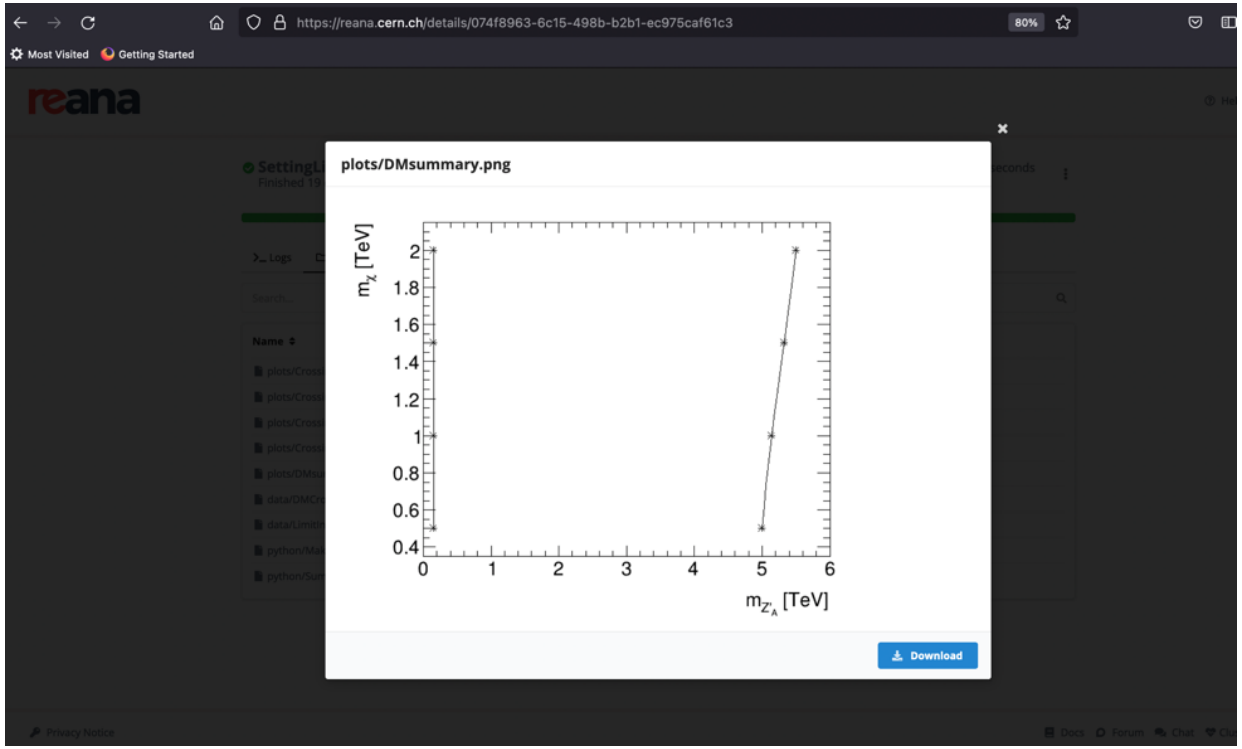
Reinterpretation of the Resonance Search



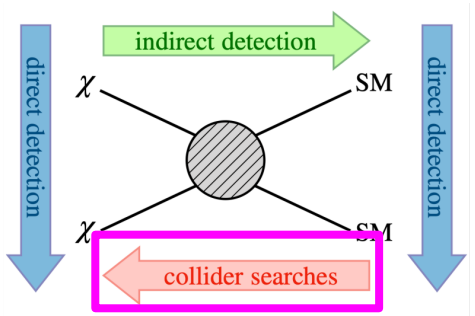
This reinterpretation was set up with REANA, sending the jobs to a remote computer.

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





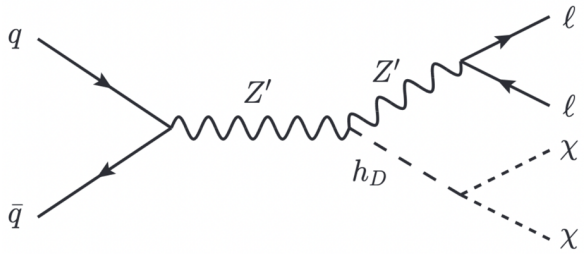
Exclusive Z'+MET Analysis



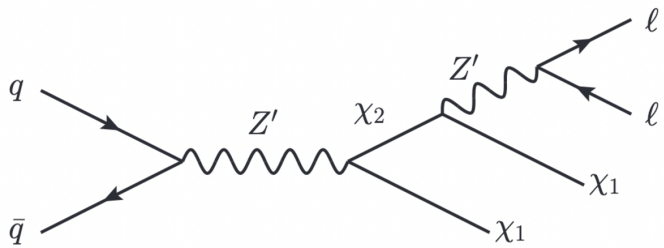
Search targeting dilepton resonances in the ll+MET final state.

- 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.

Dark Higgs



Light Vector



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

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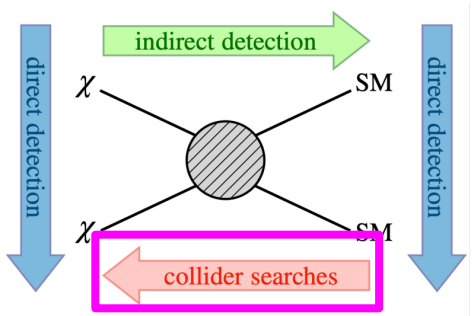
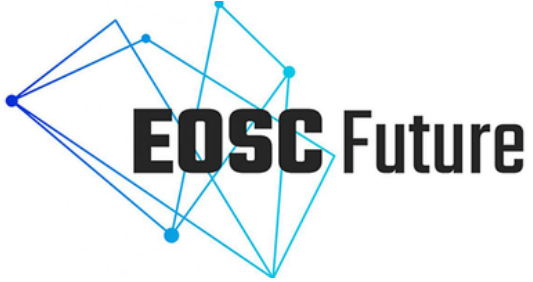
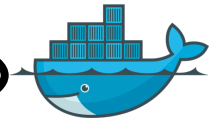




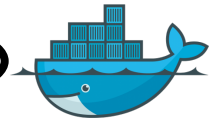
DxAOD

Calculate Kinematic Variables



ntuples

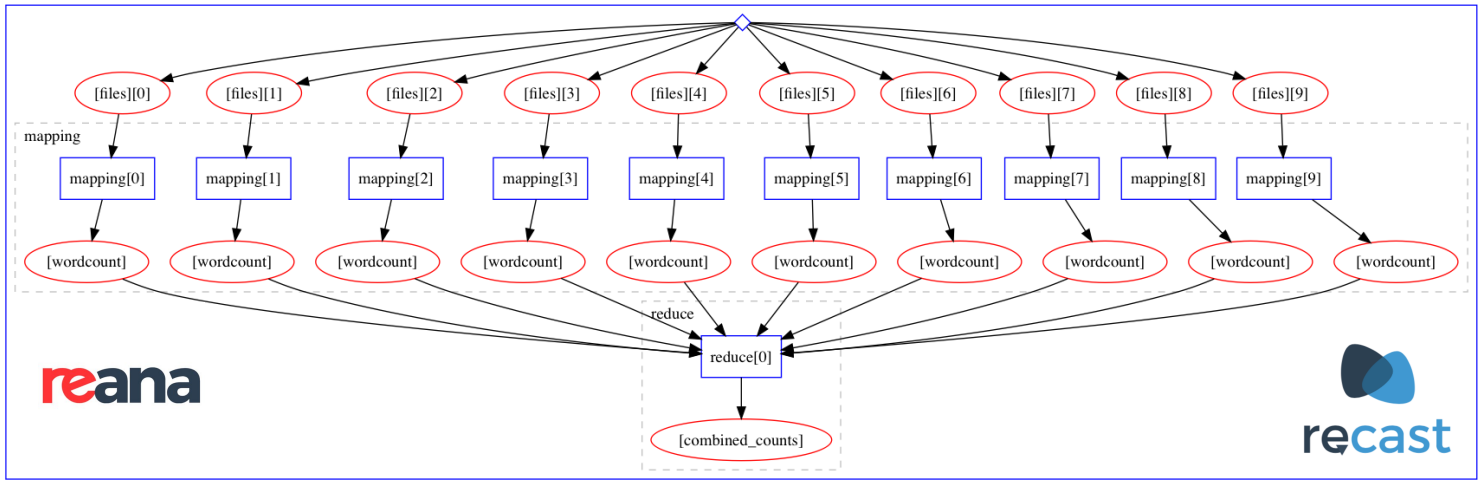
Selections / Validation



ntuples/histograms

Statistical Analysis

$\geq 10\ TB$



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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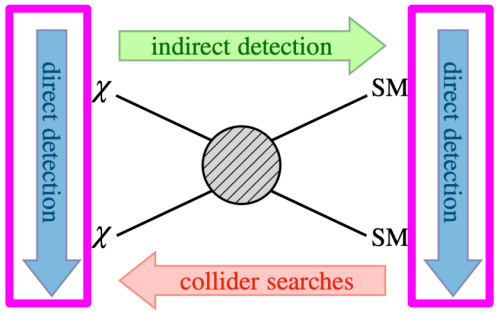
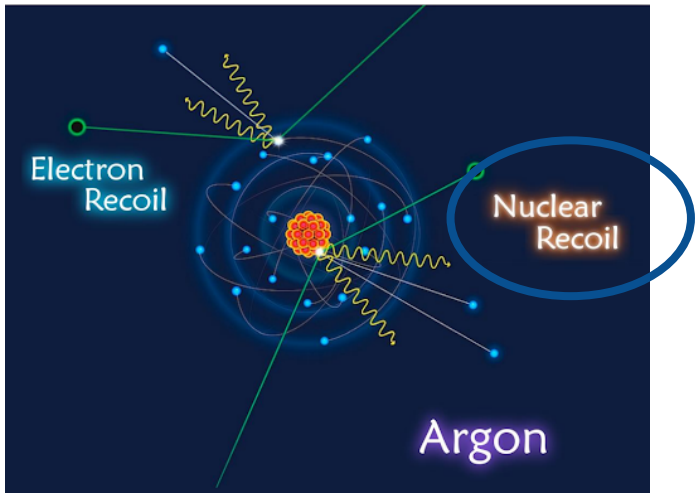
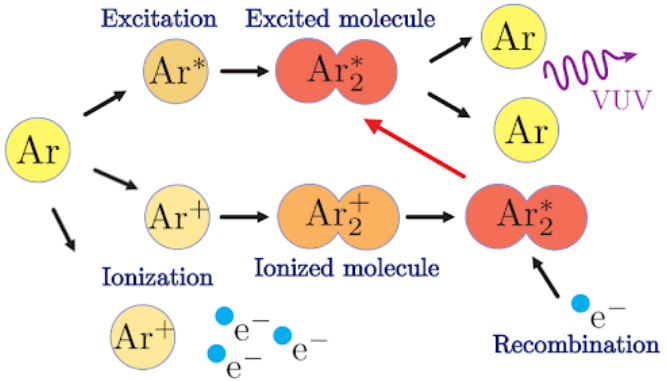
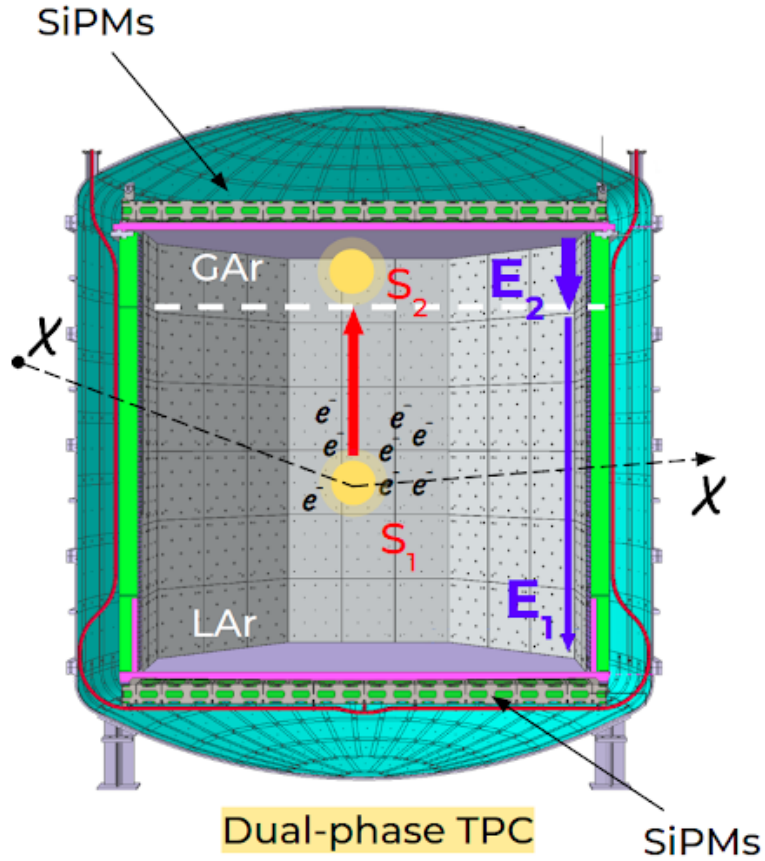
Direct Detection with a LAr TPC



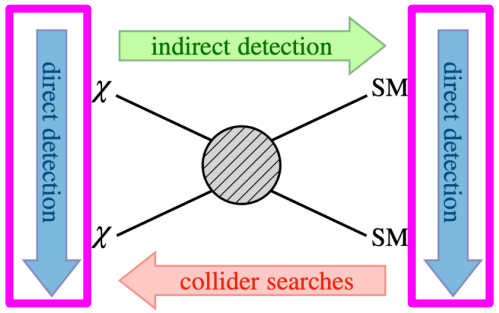
- DM as WIMP-like particle produces a **nuclear** or an **electron recoil**.
- Elastic scattering with Argon Nuclei results in **Scintillation & Ionization**.

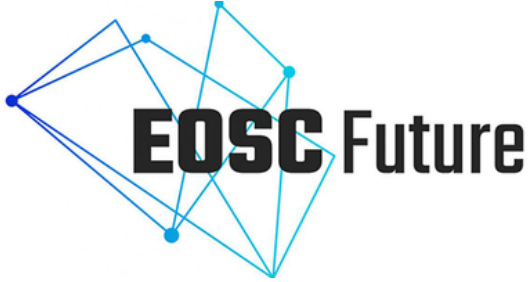




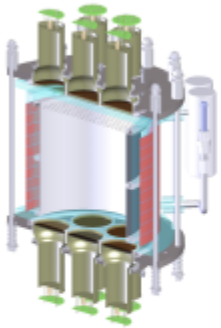


DarkSide Experimental Program



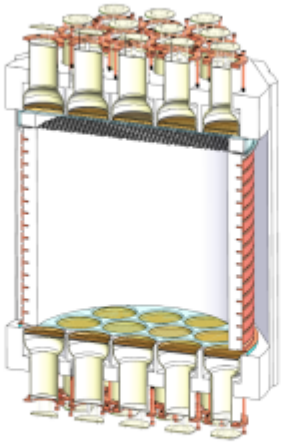


2012



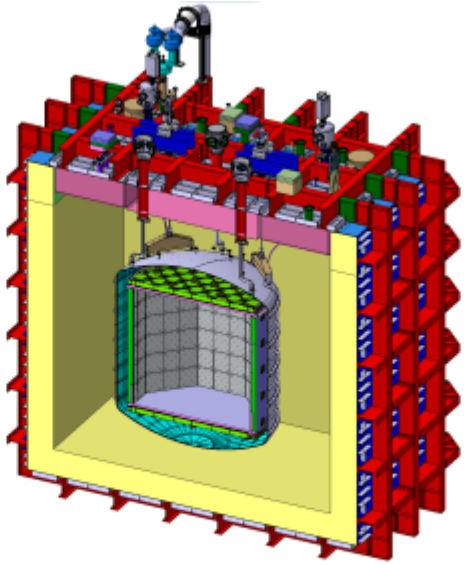
DarkSide-10

2013 - 2018



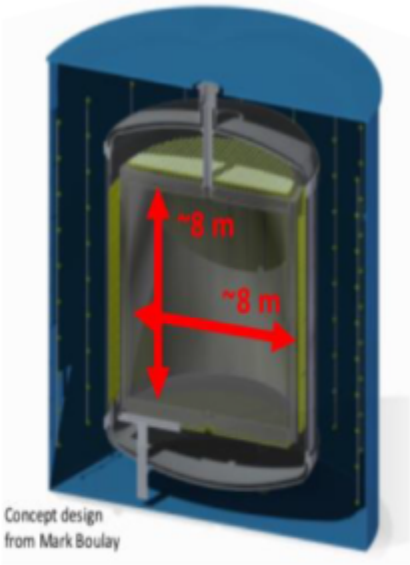
DarkSide-50
16 t d

2026 - 2036



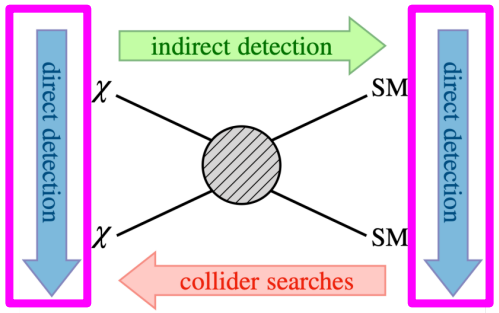
DarkSide-20k
200 t yr

2030+



Argo
3000 t yr

DarkSide Plans



- Implemented a reanalysis tool for a high-mass search on the **VRE platform**.
  - Output: **DarkSide50** exclusion curve for WIMP-nucleon cross section.
- 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.

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

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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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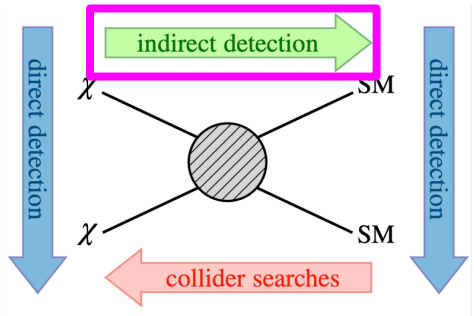
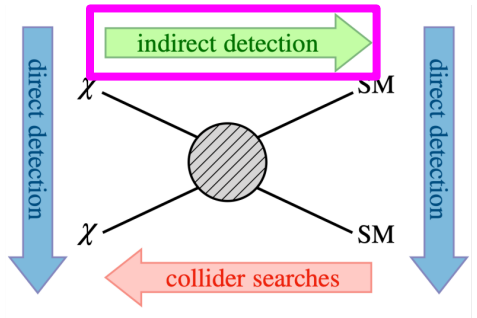
Code Structure: MLFermiDwarfs

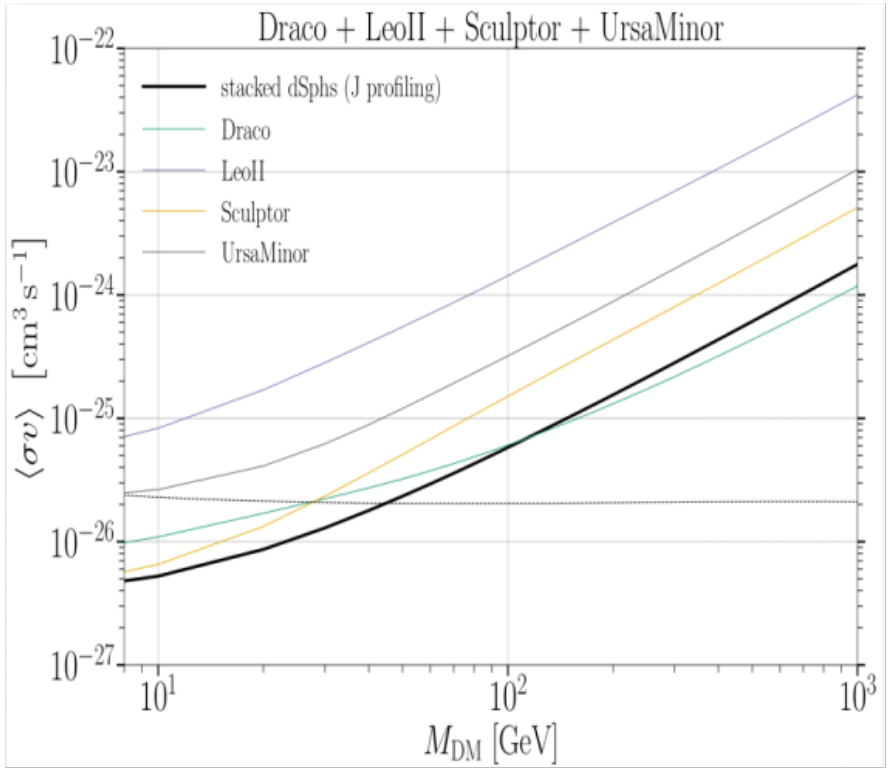


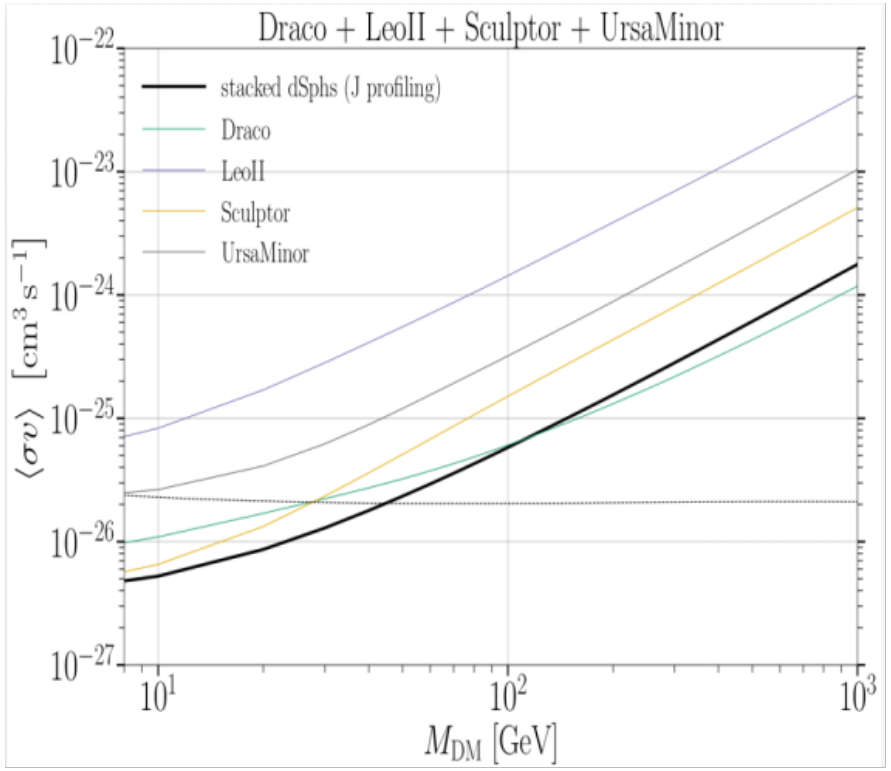
Insert figure

- 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.

MLFermiDwarfs

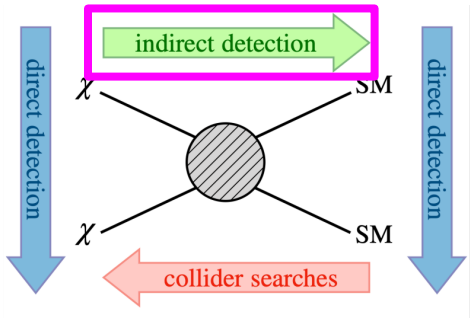


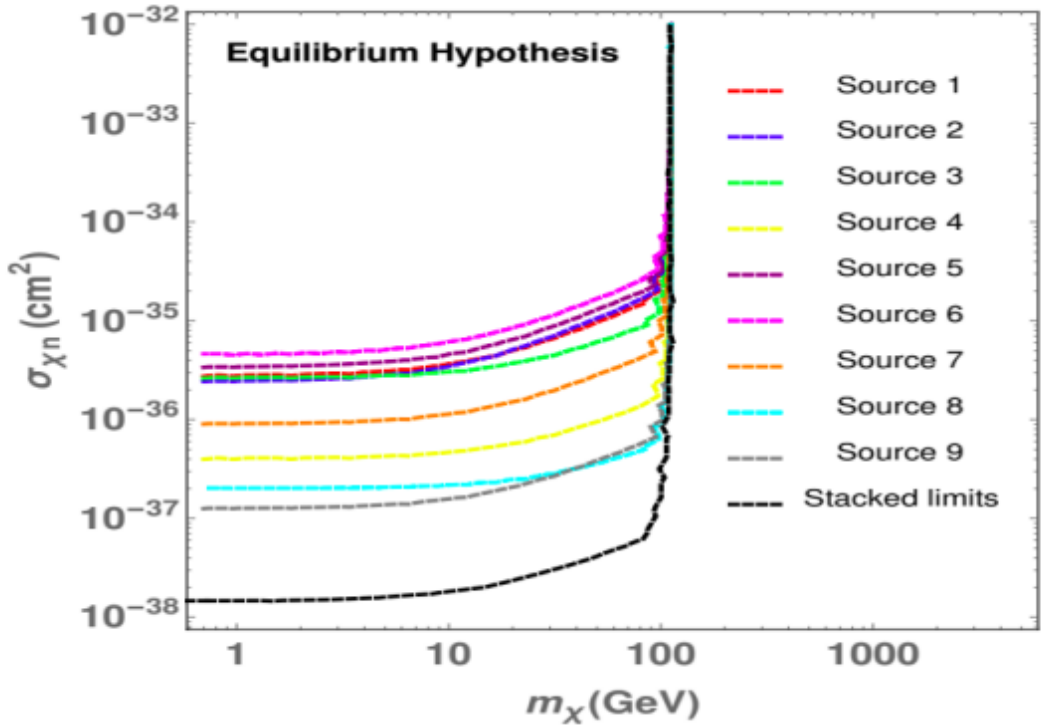


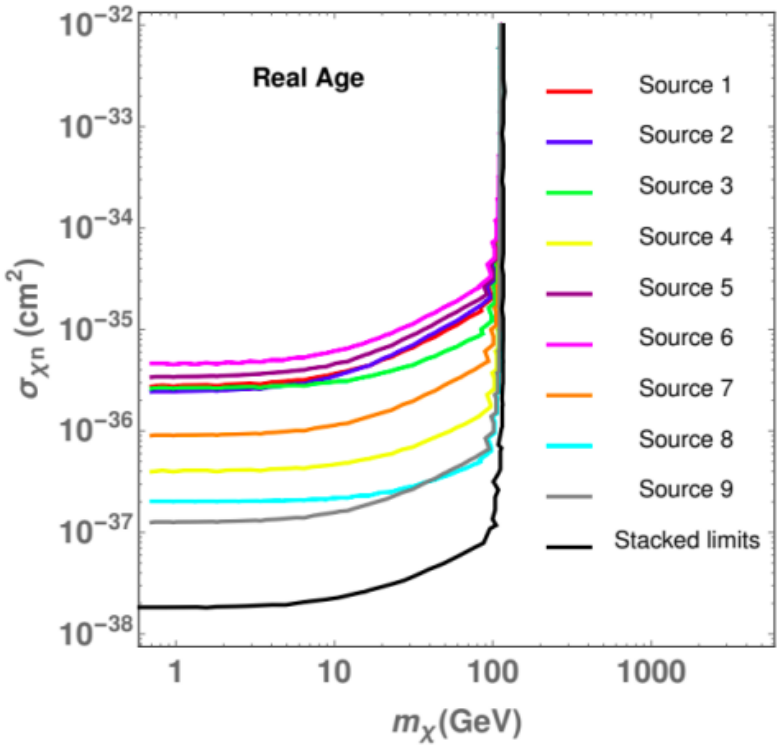


- Based on the Fermi-LAT data set used for paper **A. Alvarez et al. JCAP09 (2020) 004.**
- MLFermiDwarfs code is accessible from https://gitlab.in2p3.fr/escape2020/virtualenvironment/mlfermilatdwarfs

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

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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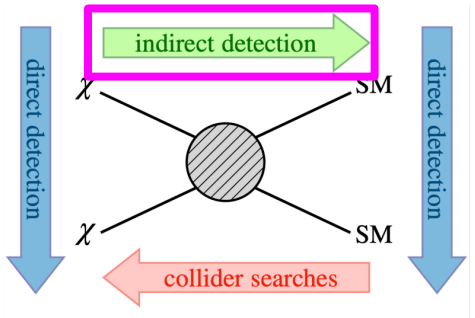
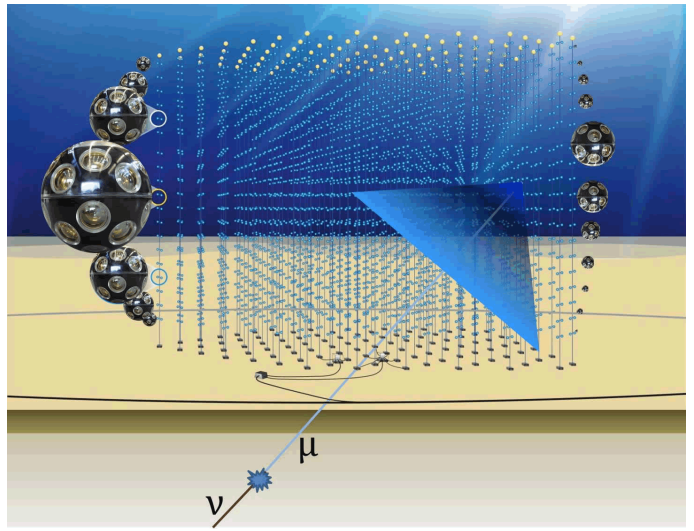
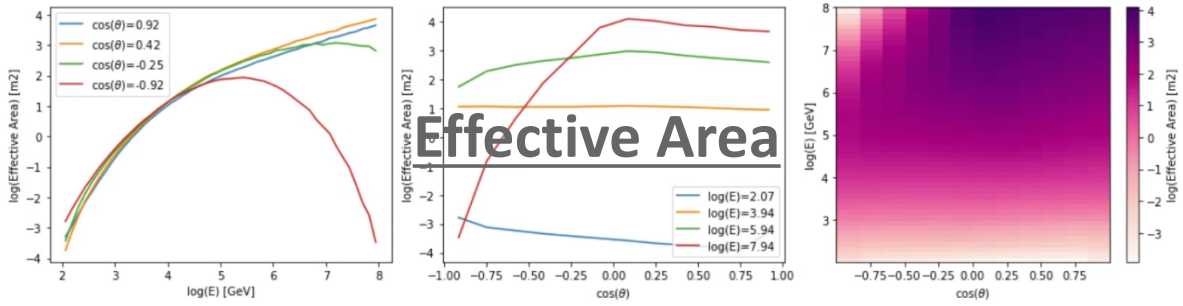
IRF Concept



- **I**nstrument **R**esponse **F**unction of neutrino telescope provides a quantitative estimation of the event rate and the background rate
- 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
- Compatibility with `gammapy` will give an easy combination with other gamma experiments like CTA
- Active development of the `km3irf` python package




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



Summary

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Challenges and Consolidation for Dark Matter SP

Upcoming challenges for DM 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 **OSSR**
- Use Gambit software for **combination** of results (subject to time/resources)
- Expand use cases to **real-time analysis on constrained infrastructure** (subject to time/resources)

Consolidation (common across DM and Extreme Universe Science Project)

- 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

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!

Backup

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Machine learning tools for big data compression

Axel Gallén, Alexander Ekman
(Lund University)

Supervised by:
Caterina Doglioni
University of Manchester and Lund University

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Insert if any

Link to talk at CHEP

Extreme Universe

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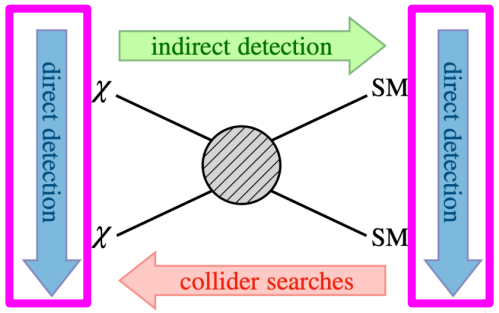
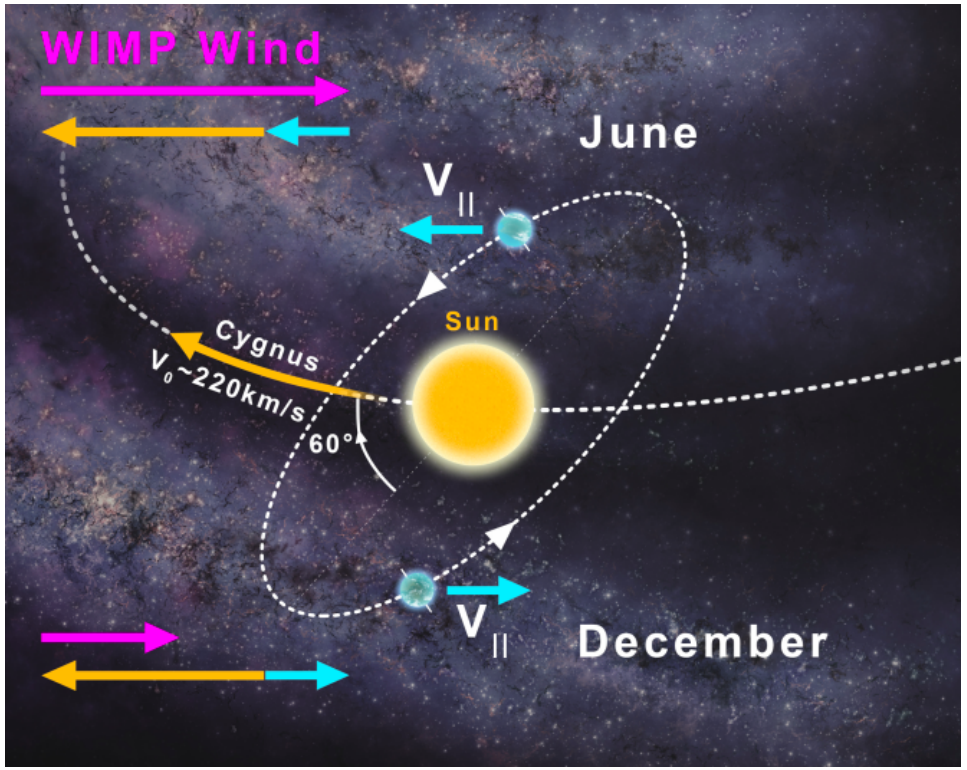
1-2 slides for EU SP?

Dark Matter Direct Detection



WIMP Rate and Cross Section limits



$$\frac{dR}{dE_r} = \frac{MT}{2m_W\mu_N^2} \times \sigma_{Wn} \times \frac{\mu_N^2}{\mu_p} A^2 \times F^2(E_r) \times \rho_0 \times \int_{v_{min}}^{v_{max}} \frac{f(\vec{v})}{v} d^3v$$

Particle physics | Nuclear physics | Astrophysics