# Indirect dark matter search with gamma rays via open-science tools


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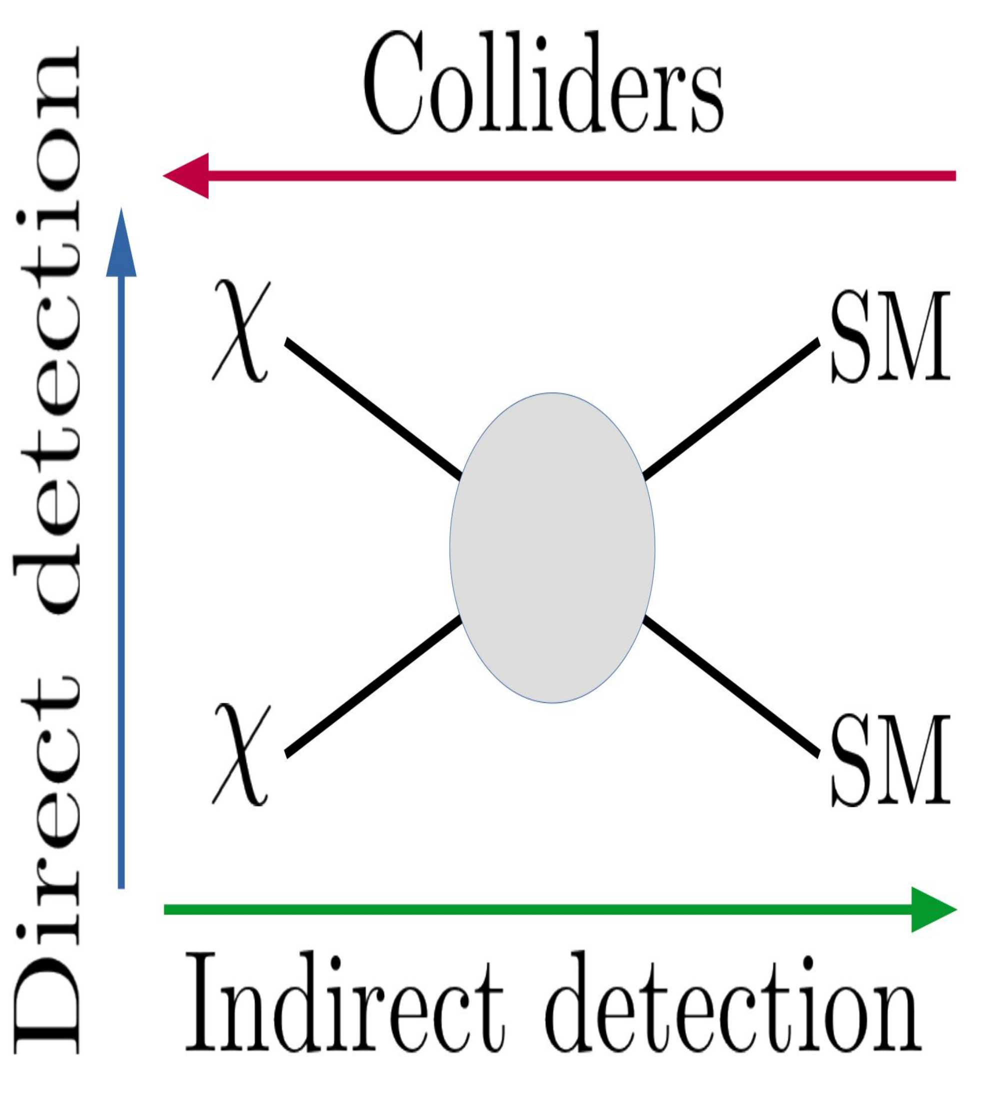
**EOSC Future is an EU-funded H2020 project that is implementing the European Open Science Cloud (EOSC).**

# Plan of the talk

- Brief Introduction on indirect detection of dark matter
- Dwarf Spheroidal Galaxies
- A public code to analyse Fermi-LAT data from dwarf spheroidal galaxies: MLFermiDwarfs
- Association with VRE platform and its Open Science Uptake
- Outlook
- Demo of our working platform

# Weak Scale Thermal Dark Matter (DM) Detection Methods

Three Complementary Methods:

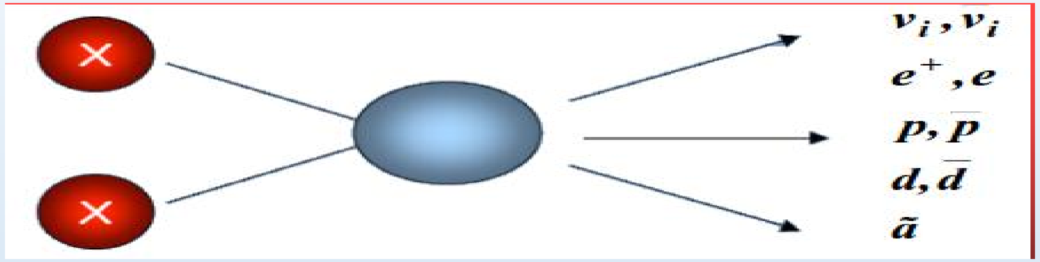



**Direct Detection: Elastic DM- nuclei scattering**
**e.g.: DAMA/LIBRA, CDMS, XENON...**

**Indirect Detection: Search for the products of DM Annihilation/Decay products**
**e.g.: Fermi-LAT, PAMELA, IceCube, HESS, HAWC, CTA...**

**Collider experiments: production of DM**
**e.g.: ATLAS, CMS, LHCb**

# Indirect Detection of DM

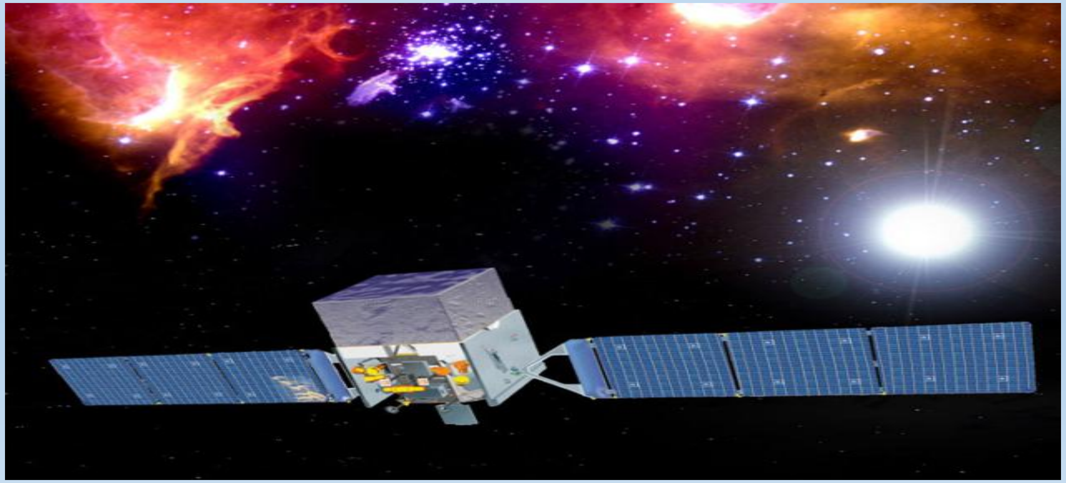


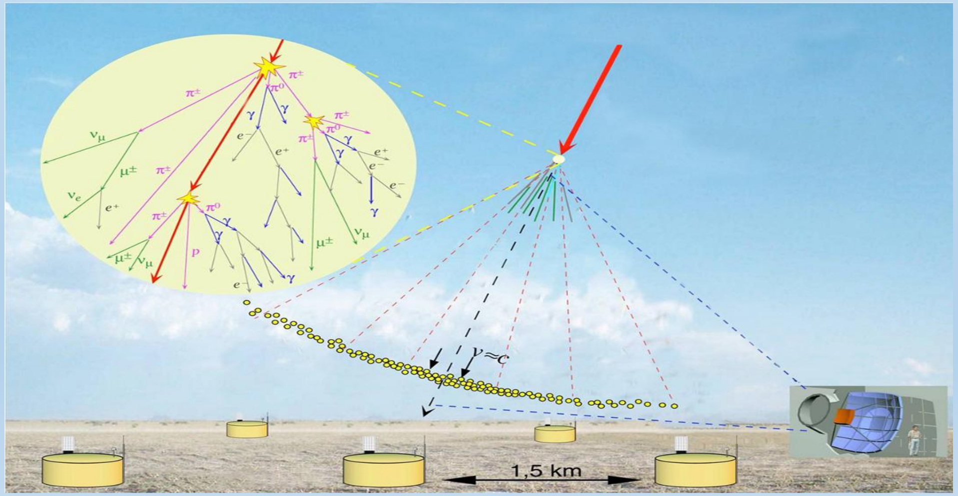

Annihilation of DM particles will produce gamma rays, antimatter, neutrinos

We can probe them

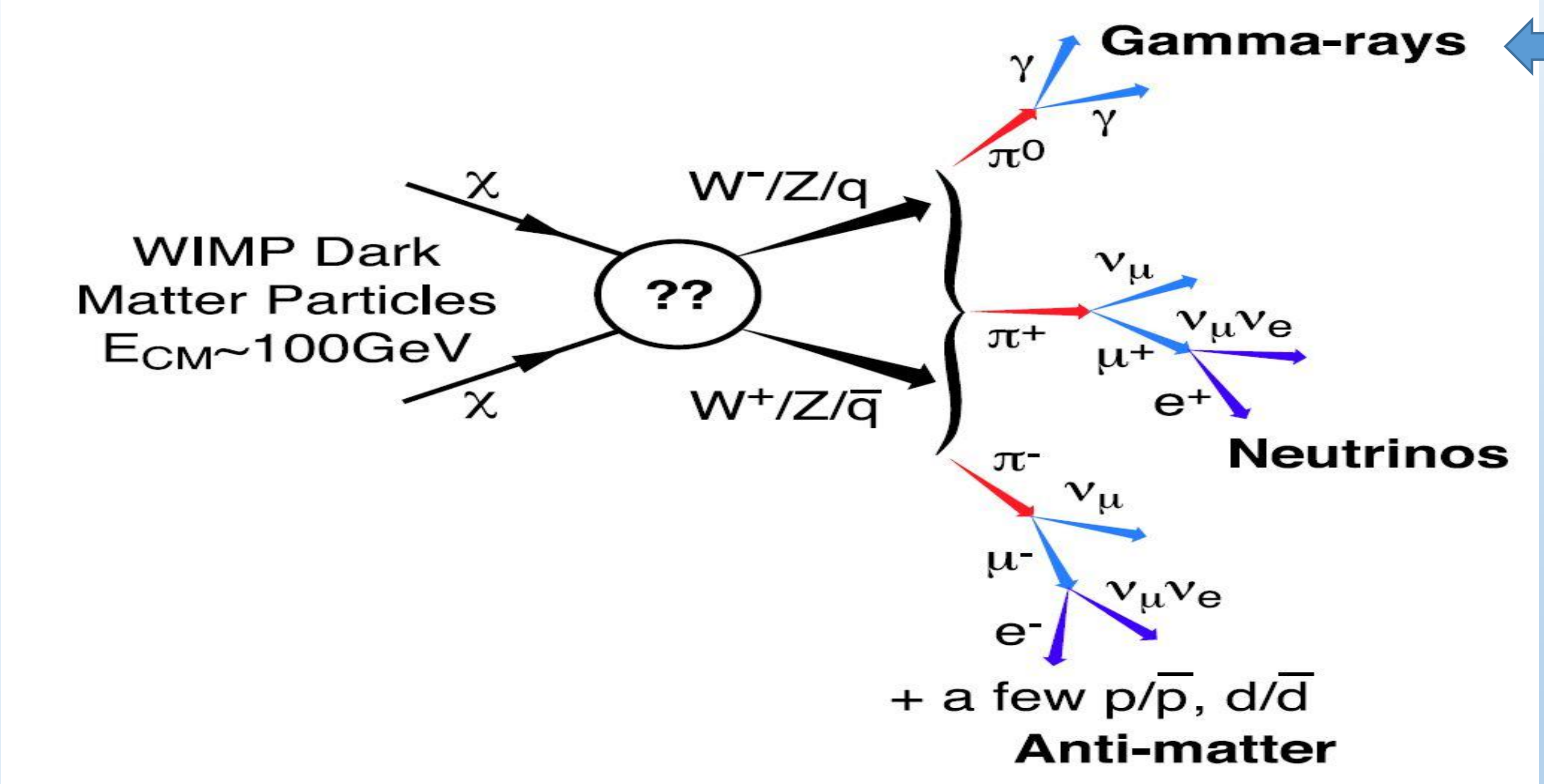
**Either with space-based detectors:**
**e.g.: Fermi-LAT, PAMELA, AMS**

**Or with ground-based Cherenkov telescopes:**
**e.g.: MAGIC, HESS, VERITAS, CTA**





# Formulation for detecting the dark matter signal through gamma-ray study



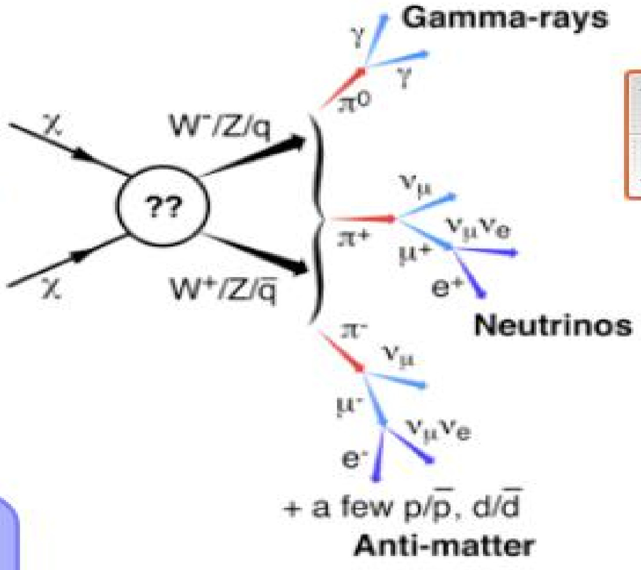

**Our Interest**

# Gamma-ray Flux from Dark Matter annihilation

Baltz et al, 2008

**Gamma-ray Flux**
(signal in data)

**Particle Physics**
(photons per annihilation)



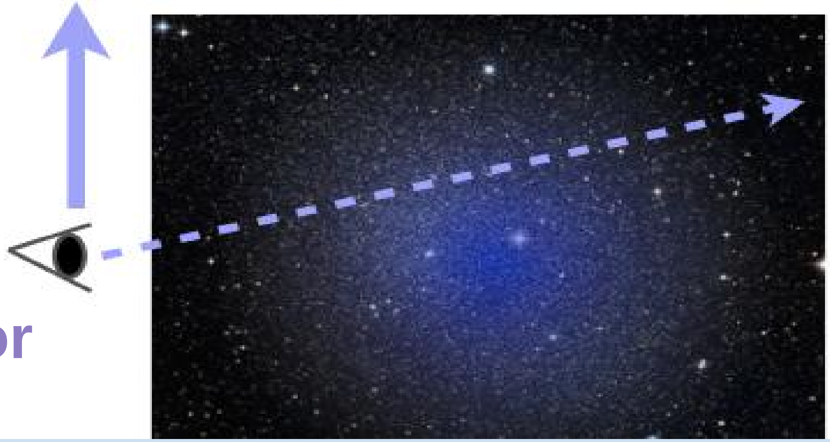

$$\frac{d\Phi_\gamma}{dE_\gamma}(E_\gamma,\phi,\theta) = \frac{1}{4\pi}\frac{<\sigma_{ann}v>}{2m^2_{WIMP}}\sum_f \frac{dN^f_\gamma}{dE_\gamma}B_f$$

$$\times$$

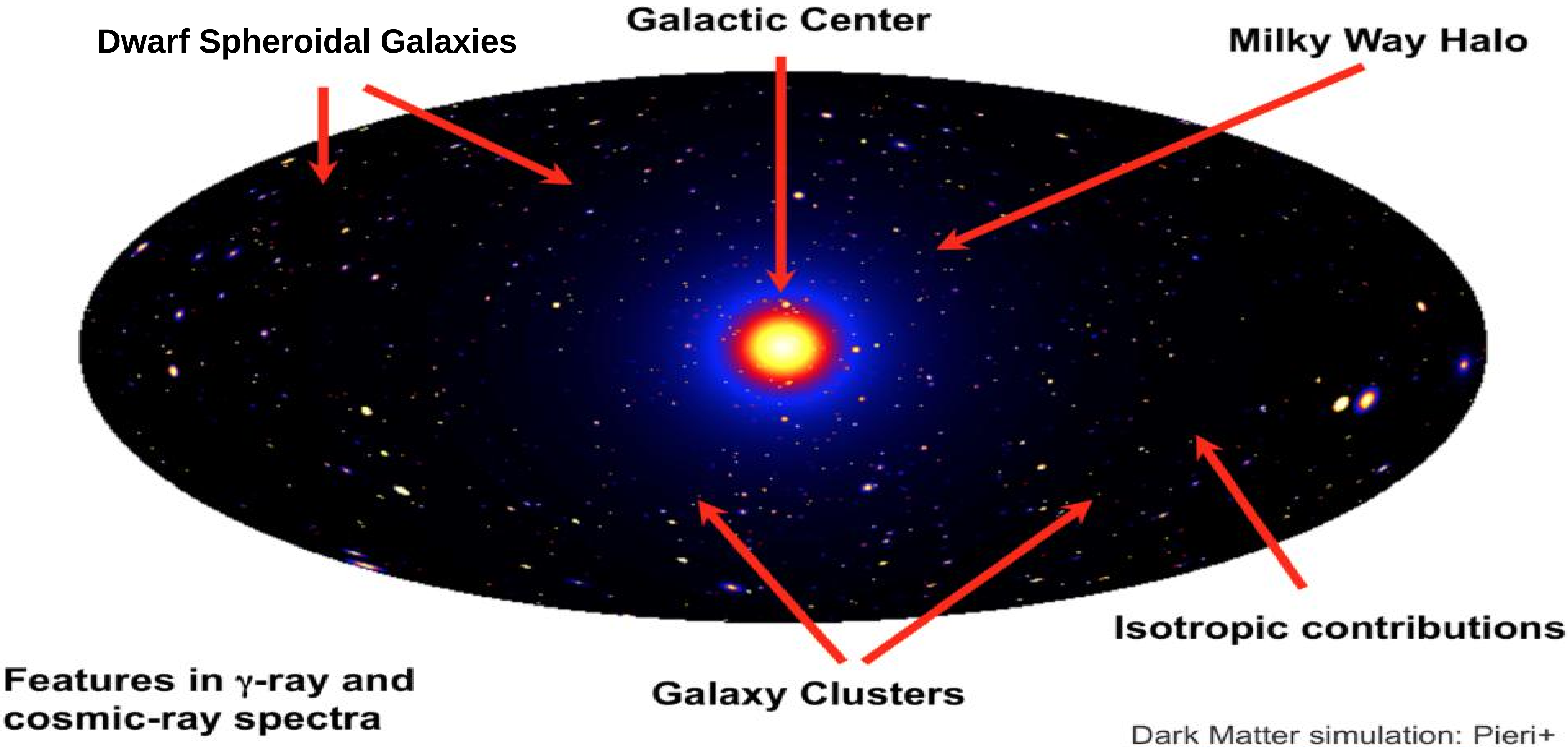
$$\int_{\Delta\Omega(\phi,\theta)} d\Omega' \int_{los} \rho^2(r(l,\phi'))dl(r,\phi')$$

**Dark Matter Distribution**
(line-of-sight integral)

**Astrophysical J-factor**



# Dark Matter Dominated Region




Dark Matter simulation: Pieri+
2011PhRvD..83b3518P

# Dwarf Spheroidal Galaxy (Dsph)

**DM dominated objects in the universe.**

**Mass to light ration ~ 100-1000** $M_{\odot}/L_{\odot}$

**Mostly the satellite galaxies of our Milky Way.**

**Relatively close (d~**25 - 150 **Kpc)**

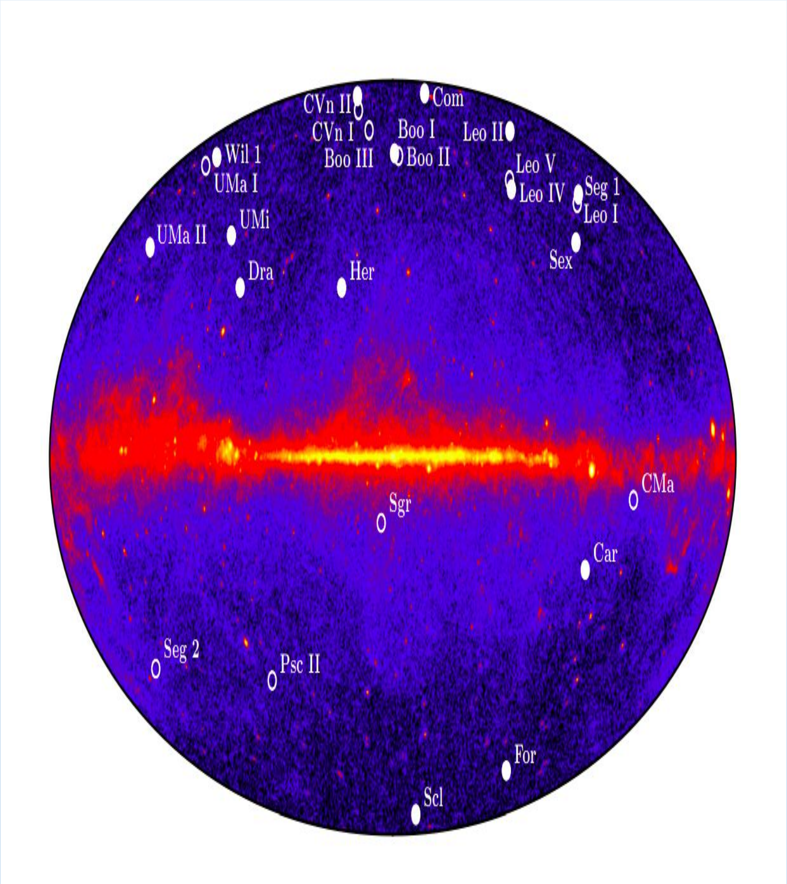
Lie at **High Galactic latitudes**–minimize astrophysical foregrounds

**Hardly show any sign of gas and dust!**

Appearing as **the metal-poor with high-velocity dispersion.**

**No sign of active star formation**

**No appreciable magnetic fields**




i.e. **no strong mechanism for astrophysical gamma-ray production**

# MLFermiDwarfs
# A data-driven framework for dark matter constraints from dwarf galaxies

Performance of the approach already demonstrated in two publications:

— F. Calore et al. JCAP10 (2018) 029

— A. Alvarez et al. JCAP09 (2020) 004

# Summary of papers F. Calore et al.,2018 and A. Alvarez et al.,2020

Reported **an updated analysis of the gamma-ray flux from the directions of classical Dsphs**.

The general idea of this approach is to **improve on the standard Fermi-LAT analysis of Dsphs.**

Proposed **a data-driven method by utilising the whole-sky data to estimate this astrophysical background**.

They estimate the **probability density by Kernel method**, i.e.

$$\hat{f}(x_0) = \frac{\sum_{i=1}^{N} K_\lambda(x_0, x_i) y_i}{\sum_{i=1}^{N} K_\lambda(x_0, x_i)}$$

# Likelihood analysis and limits on Dark Matter

**The generic form of the likelihood $\mathcal{L}$ at the dSph d in the energy bin e:**

$$\mathscr{L}_{d,e}(\lambda_{d,e}, \log_{10} J_d, \ln b_{d,e}) = \frac{\lambda_{d,e}^{c_{d,e}} e^{-\lambda_{d,e}}}{c_{d,e}!} \mathscr{N}(\log_{10} J_d) \mathscr{B}(\ln b_{d,e})$$

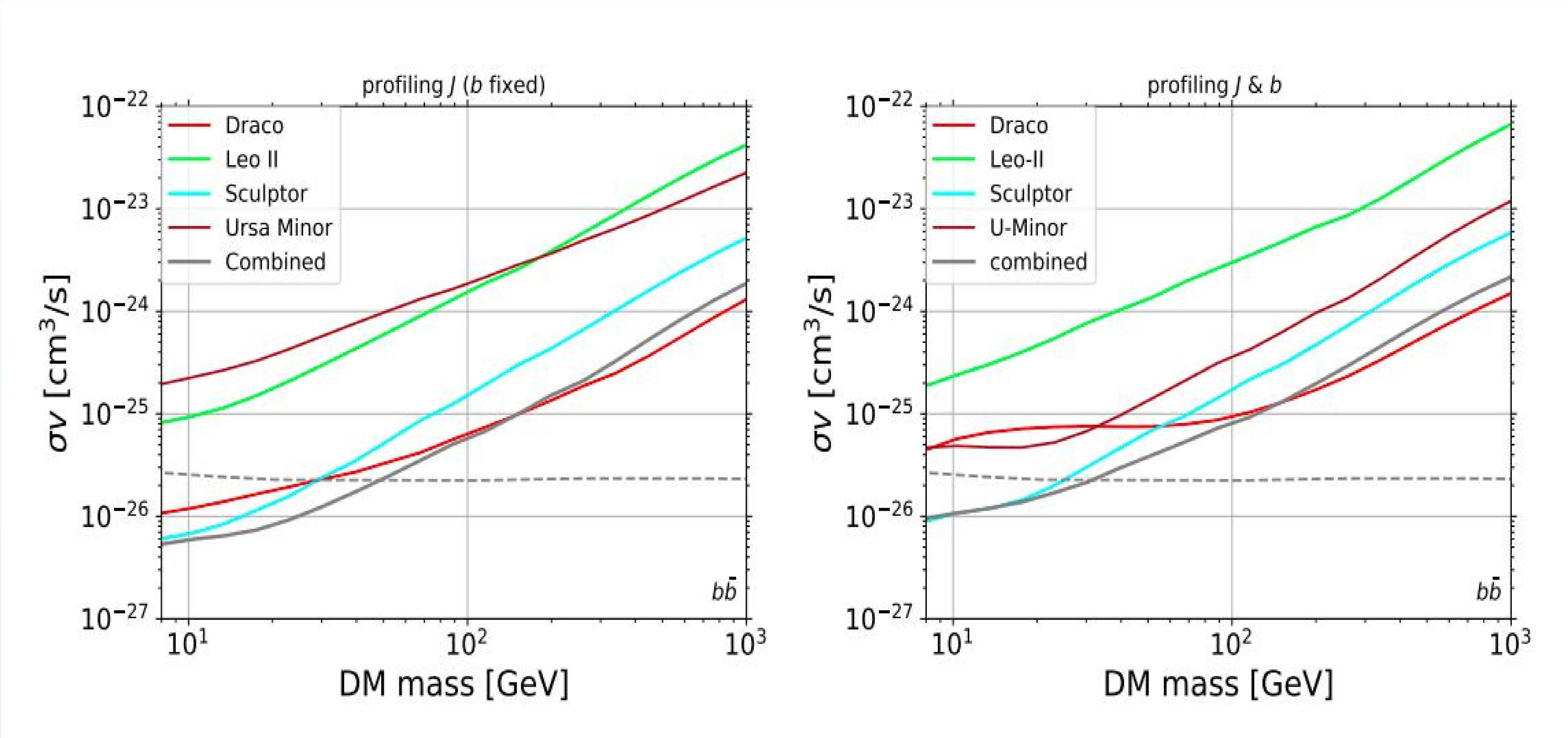
**$c_{d,e}$ = measured number of counts;**
**$\lambda_{d,e}$ = expected model counts including both signal and background**
**and $\mathcal{B}$ = distribution of the background counts.**

$$\lambda_{d,e} = \lambda_{d,e}(\langle \sigma v \rangle, m_{\mathrm{DM}}, \log_{10} J_d, \ln b_{d,e}) = 10^{\log_{10} J_d} \langle \sigma v \rangle \, f_{d,e}(m_{\mathrm{DM}}) + e^{\ln b_{d,e}}$$

**The expression for Gaussian distribution of $\log_{10} J_d$:**

$$\mathscr{N}(\log_{10} J_d) = \frac{1}{\sqrt{2\pi}\sigma_d^J} \exp\left[ -\left( \frac{\log_{10} J_d - \overline{\log_{10} J_d}}{\sqrt{2}\sigma_d^J} \right)^2 \right]$$

# Limits to DM parameter space




**Left: Bound from stacked dSphs when profiling only over J-factor distributions.**
**Right: Bound from stacked dSphs when profiling over both J-factor distributions and the background ones.**

# A public code to analyse Fermi-LAT data from Dsphs: "MLFermiDwarfs"

❖The scientific objective of this project is to **design a data-driven framework based on the indirect detection methodology of DM signals from dwarf spheroidal galaxies (Dsphs).**

❖ **Machine learning-based assessment that connects dark matter, gamma rays and Dsphs.**

❖ Estimates the **astrophysical gamma-ray background of a Milky Way Dsphs in the Fermi-LAT energy range that goes beyond the usual assumptions defined by the Fermi LAT collaboration.**

❖ As an output, we obtain **constraints on the (velocity-independent) dark matter pair-annihilation cross-section with a user-selected list of Dsphs.**

❖**A first release of the code MLFermiDwarfs was onboarded in the ESCAPE OSSC by C. Eckner.**

❖ **The MLFermiDwarfs code is now public** to the scientific community and is in **full agreement with the Open Science Uptake.**

❖ It can be accessed from : **https://gitlab.in2p3.fr/escape2020/virtual-environment/mlfermilatdwarfs**

# Code Structure

❖ **Domains and type :** Astroparticle Physics; Theory and Phenomenology

❖ **Data provenance:** Gamma-ray data detected by **Fermi Large Area Telescope (Fermi-LAT)**. The data and main processing software (Fermi Science Tools) are publicly accessible, and **now also fully imported into the data lake.**

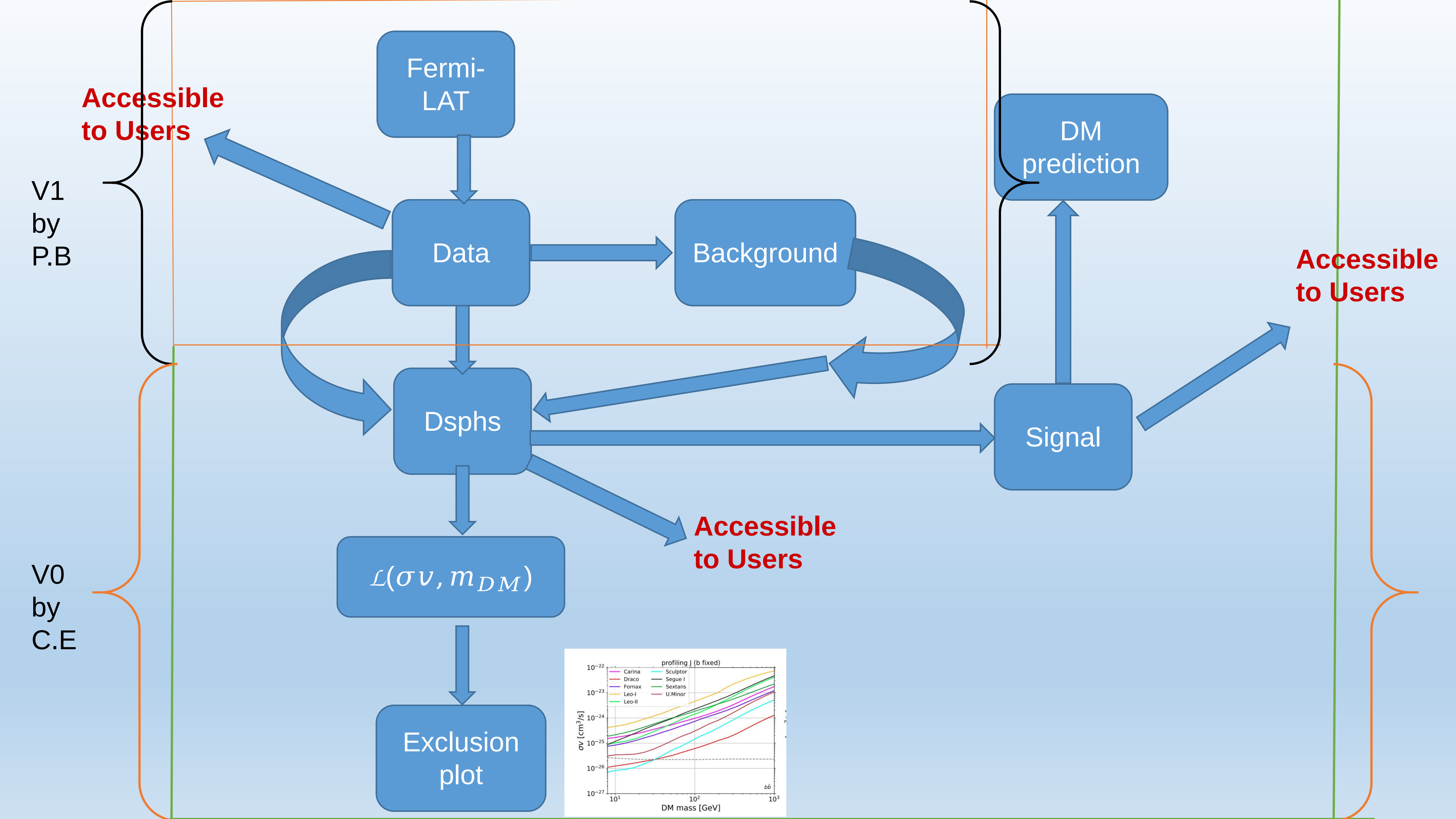
❖ P**rogramming language:** Code is entirely written in **python 3 and relatively well-known packages like scikit-learn.**

❖ **User access:** Package can be optimised from the command line enabling **a quick check of the viability of a user-defined DM model.**

❖ **Reproduction :** It is based on the Fermi-LAT data set used for paper **A. Alvarez et al. JCAP09 (2020) 004**

❖ **Modification:** In the latest version, we added a few changes:

—>It gives users the freedom to use their choice of Fermi-LAT data
—> User can access the background files.



V1
by
P.B
V0
by
C.E
Fermi-LAT
Data
Background
DM prediction
Dsphs
Signal
$\mathcal{L}(\sigma v, m_{DM})$
Exclusion plot
Accessible to Users
Accessible to Users
Accessible to Users
profiling J (b fixed)
Carina
Draco
Fornax
Leo-I
Leo-II
Sculptor
Segue I
Sextans
U.Minor
σv [cm³/s]
DM mass [GeV]

# What can we find on VRE platform and its Open Science Uptake

❖ **Software development on VRE gitlab:**
MLFermiDwarfs is accessible from **https://gitlab.in2p3.fr/escape2020/virtualenvironment/mlfermilatdwarfs.**

❖ **What is available on VRE?**
**source code, python setup script, tutorial jupyter notebook, default data to run the analysis and to reproduce the figures of A. Alvarez et al. JCAP09 (2020) 004**

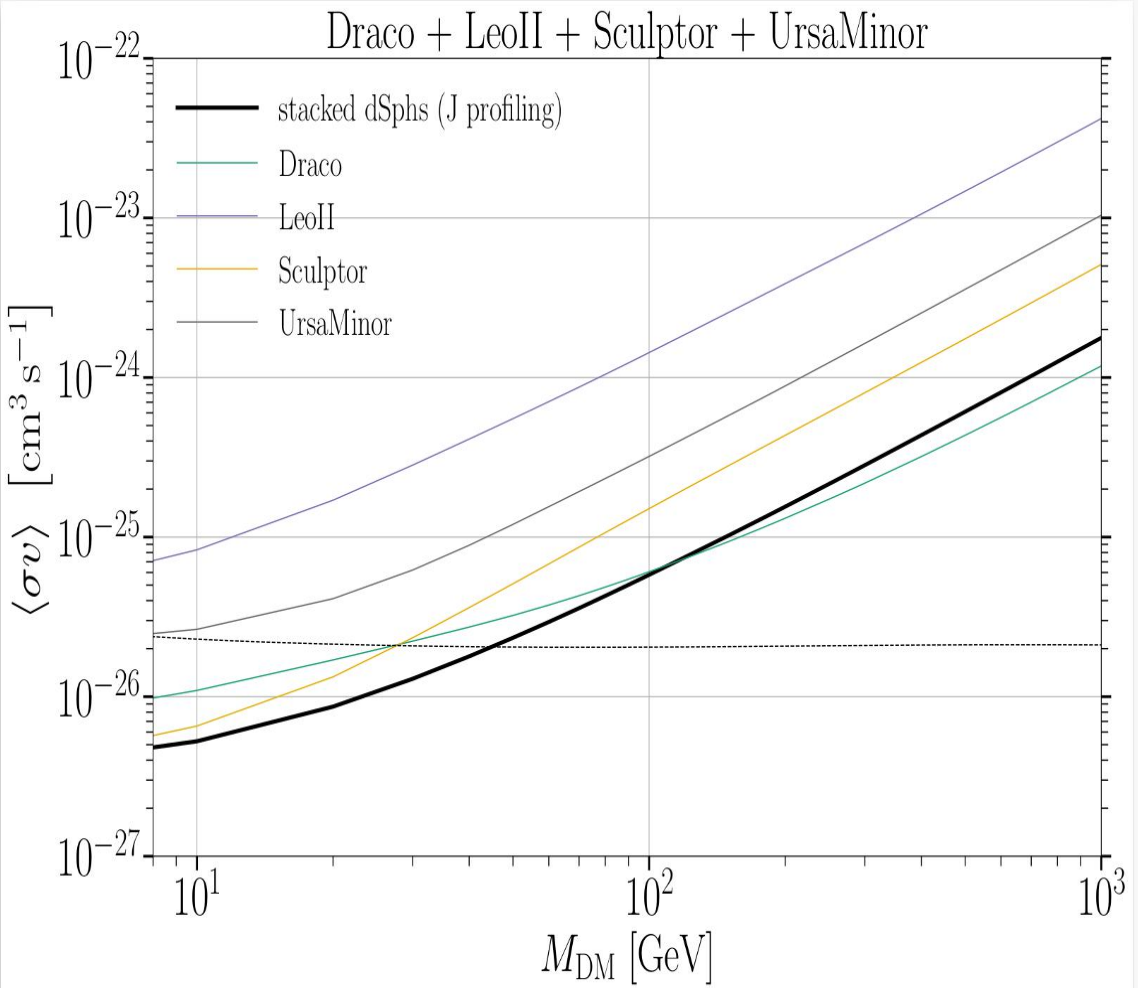
❖ **New changes are also available on VRE:**
**The modification done by P. Bhattacharjee now contains a complete-running workflow that connects the data lake to the final science results (constraints on annihilation cross section).**

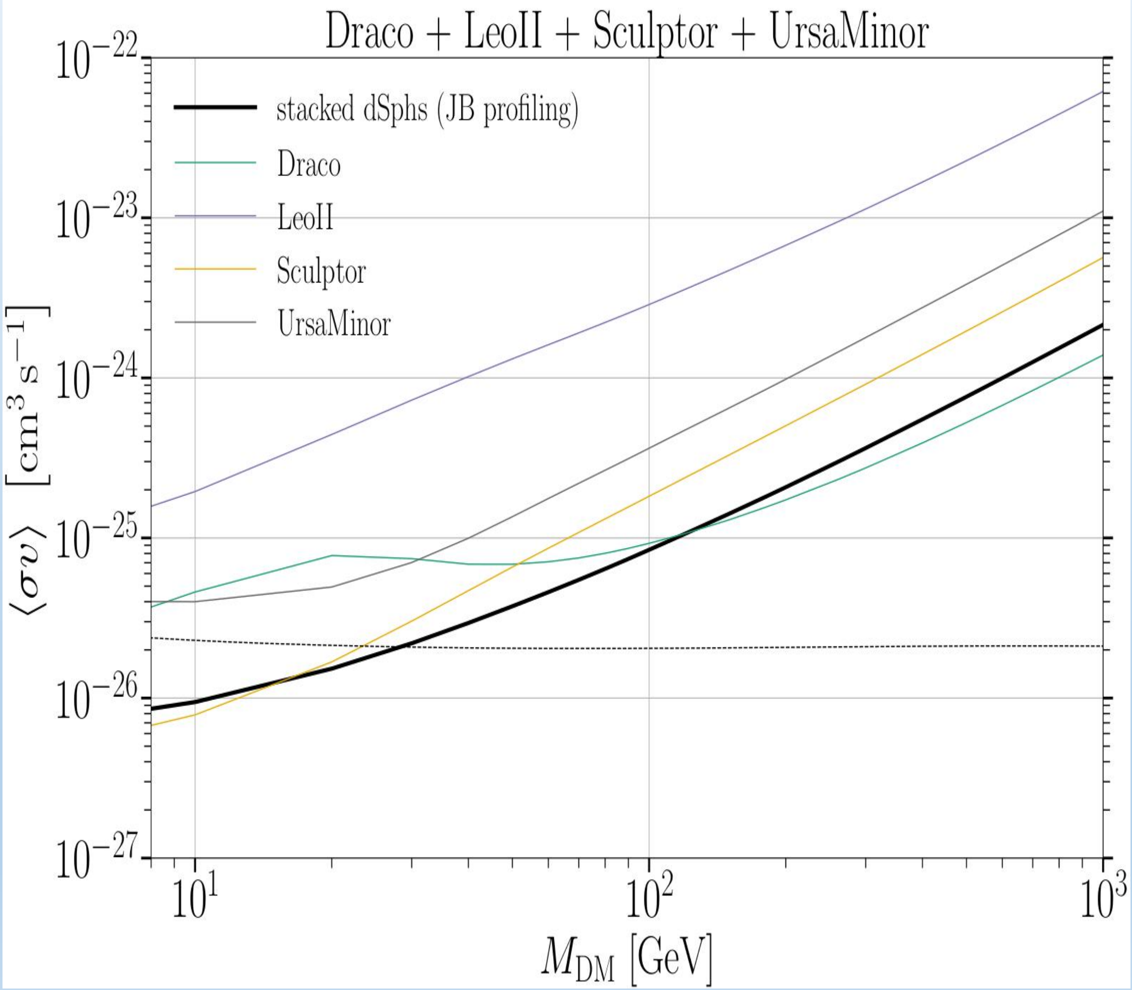
❖ **Date uploaded to RUCIO:**
**The Fermi-LAT's weekly photons and spacecraft files (Fermi-LAT's data is getting updated every week) are now uploaded to the RUCIO data lake.**

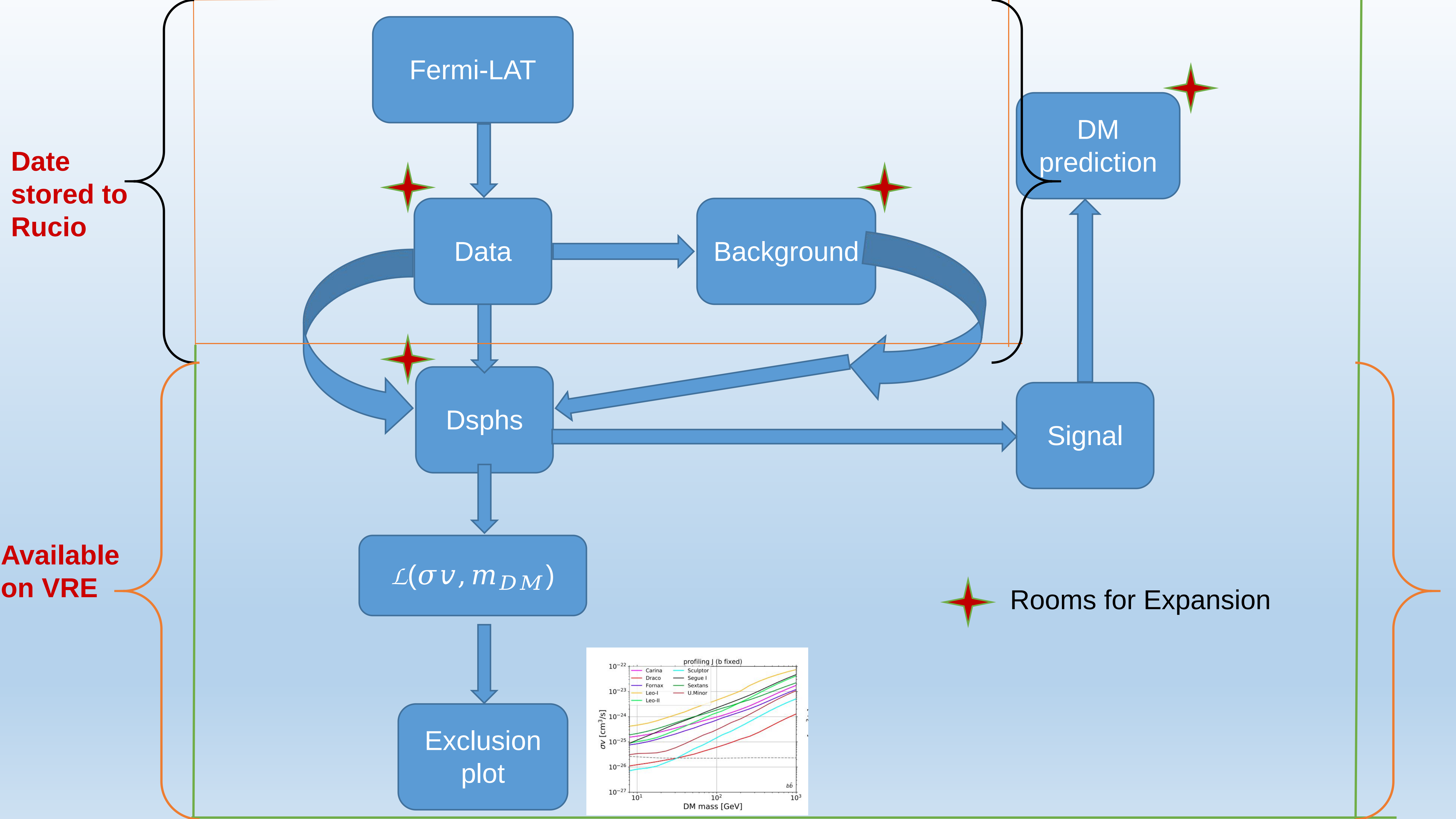
❖ **Complete running workflow:**
We developed a **complete-running workflow** connecting the **open VRE with the RUCIO data lake**.
After setting up the RUCIO scope, we can run MLFermiDwarfs code within the VRE, calling the Fermi-LAT from the data lake and obtaining our desired outputs (exclusion plots).

# Output from VRE

**We reproduce the results of A. Alvarez et al. JCAP09 (2020) 004**





Date stored to Rucio
Fermi-LAT
Data
Background
DM prediction
Dsphs
Signal
$\mathcal{L}(\sigma v, m_{DM})$
Exclusion plot
profiling J (b fixed)
Carina
Draco
Fornax
Leo-I
Leo-II
Sculptor
Segue I
Sextans
U.Minor
$\sigma v$ [cm$^3$/s]
DM mass [GeV]
$b\bar{b}$
Available on VRE
Rooms for Expansion

# Outlook of Open Science uptake

❖ **MLFermiDwarfs is an example of a fully public code within the ESCAPE services, available to the scientific community to derive DM constraints from dwarf galaxies with user-defined particle dark matter models.**

❖ **Our work is an example of <u>a complete-running workflow that connects the open VRE with the RUCIO data lake.</u>**

❖ **A series of original improvements to the code are foreseen:**

1) To choose a user-specified data set and background model optimisation.

2) To enlarge the spectrum of DM signal models by using different particle dark matter predictions, as well as the list of targets with assigned properties.

3) To extend the analysis to the CTA case, performing realistic sensitivity studies (with respect to the region of interest, the background, etc.) using already existing open source software of broad use within CTA such as Gammapy and Ctools.

# A demo of our working platform

- ❖ The README_analysis_rundown.ipynb jupyter notebook serves as an ideal starting point for this demo …

VRE - Tools | ESCAPE2020 / virtual-env

https://escape2020.pages.in2p3.fr/virtual-environment/home/research-tools.html

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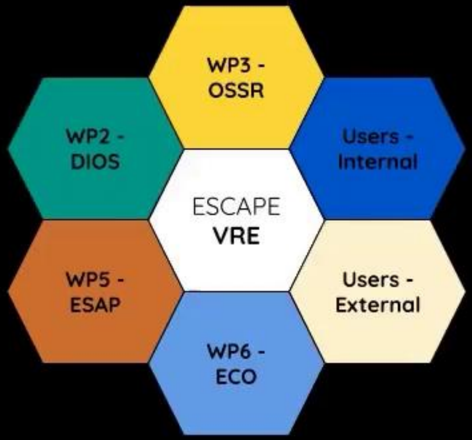
ESCAPE VRE

RESOURCES

# Let's work!

## The Virtual Researh Enviroment Toolbox




**Scroll down**, click any of the **boxes** in the matrix and **explore the resource**. You can use the elements in the vertical-left bar to **filter** among several categories This table will grow thanks to the aditions of new resources in ESCAPE.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