Studying dark matter with MadDM, status and updates

Daniele Massaro, CERN IT-FTI-PSE
On behalf of the MadDM developers team

Dark Tools 2025
Turin, Italy
18th June 2025

* Thanks to my friends and team-mates for all the material I borrowed for this talk and the precious help to put the new version of the code together: Chiara Arina, Andrew Cheek, Mattia Di Mauro, Jan Heisig, Gian Marco Lucchetti, Olivier Mattelaer.

NexTGen Next Generation Triggers

CERN

The team

From 6 institutions across 5 countries: UCLouvain (Belgium), SJTU (China), INFN Turin (Italy), RWTH Aachen U. (Germany), UniBo (Italy), CERN (Switzerland).

Challenge - guess who's who: Chiara, Andrew, Mattia, Jan, Gian Marco, Daniele, Olivier.

Motivations

Everyone wants to understand:

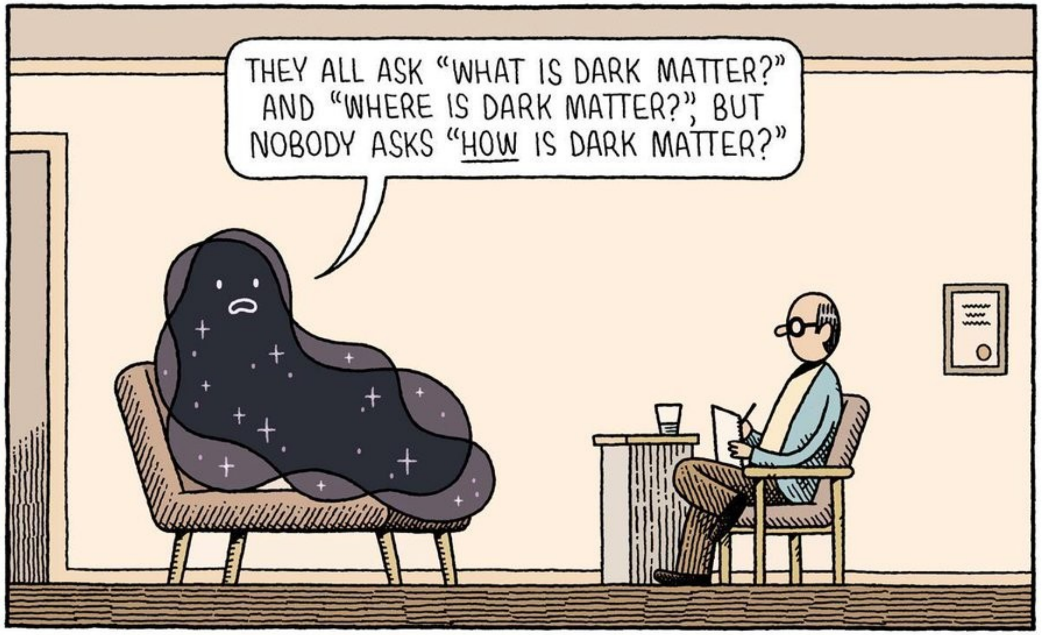
- **What** is dark matter?
- **Where** is dark matter?

Motivations

Everyone wants to understand:

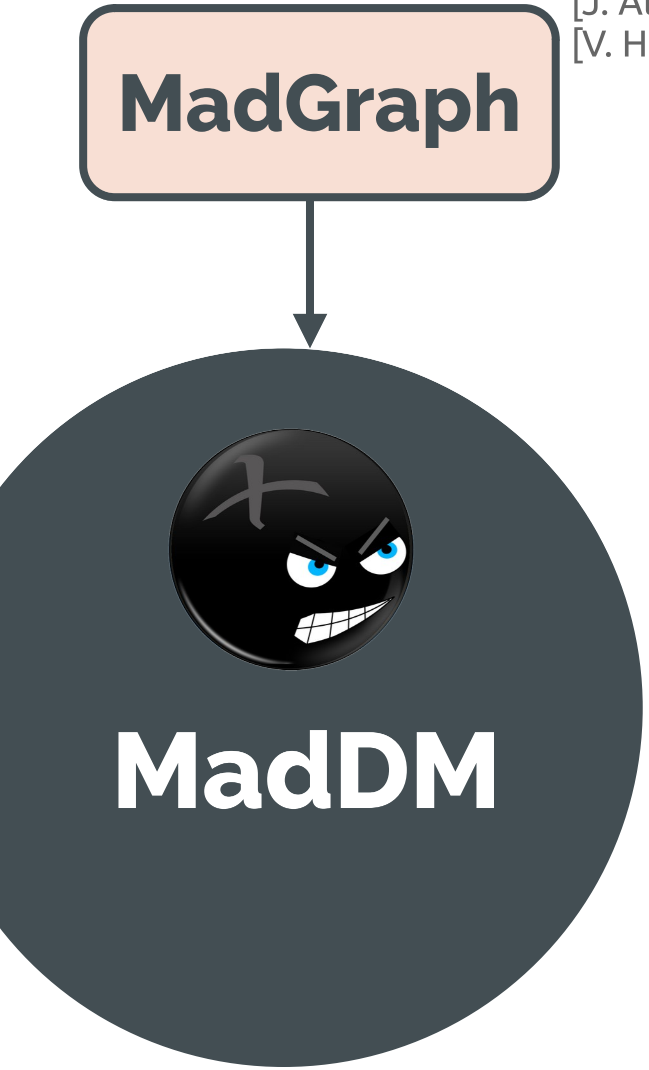
- **What** is dark matter?
- **Where** is dark matter?
- But we should ask more **how is dark matter?**

Software and simulation tools are **essential to understand** the implications of the numerous models trying to describe dark matter, and **make predictions**.



[https://knowyourmeme.com/photos/2099516-nobody-asks-how-is-x]

MadDM



[J. Alwall et al. JHEP 06 (2011) 128]
[V. Hirschi. JHEP 10 (2015) 146]

Automatic

MG5 plugin
User-friendly interface

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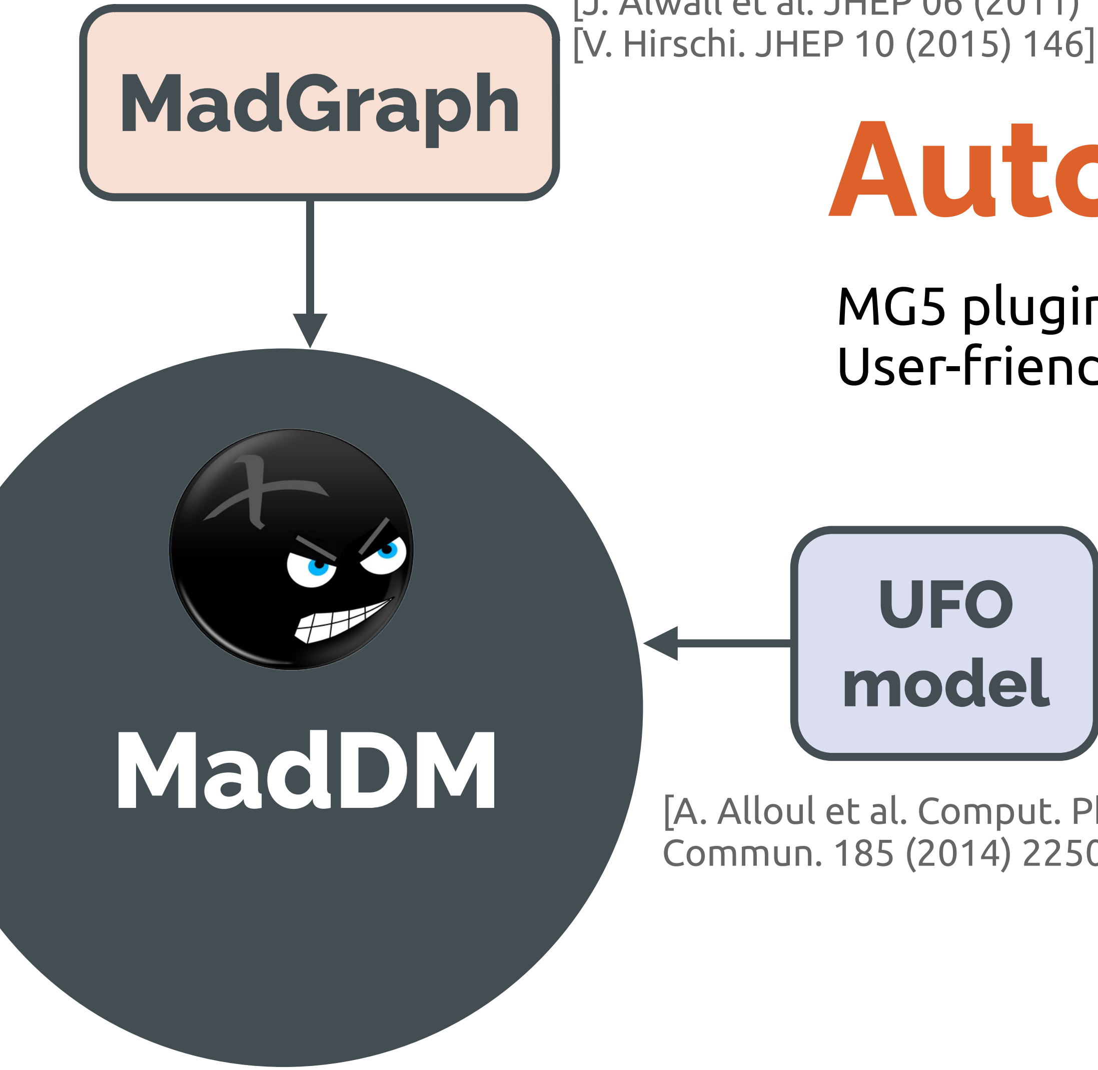
MG5_aMC>install maddm
```



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[A. Alloul et al. Comput. Phys. Commun. 185 (2014) 2250–2300]

Generic

Any UFO dark matter model

```
MadDM>import model IDM
MadDM>define darkmatter h0
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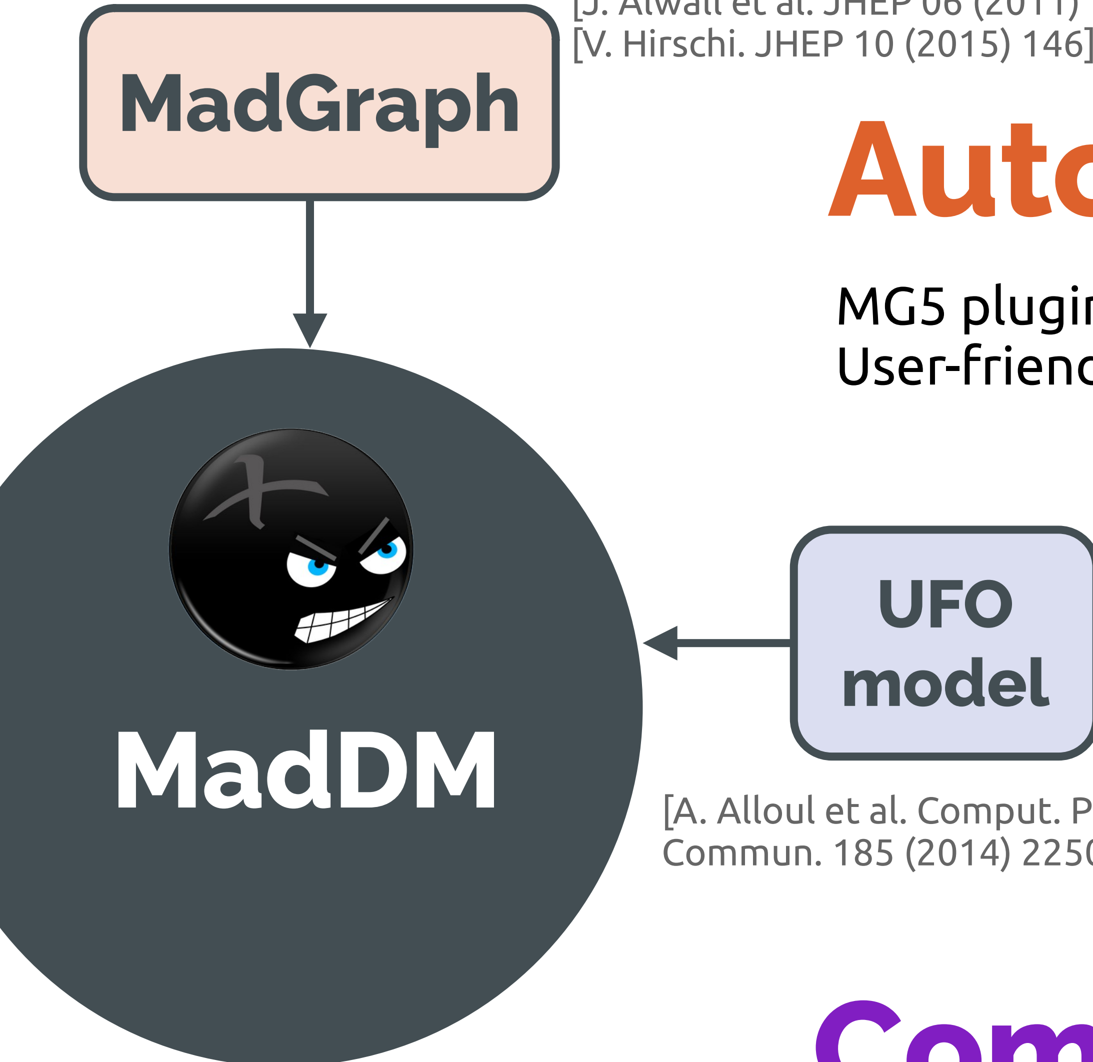

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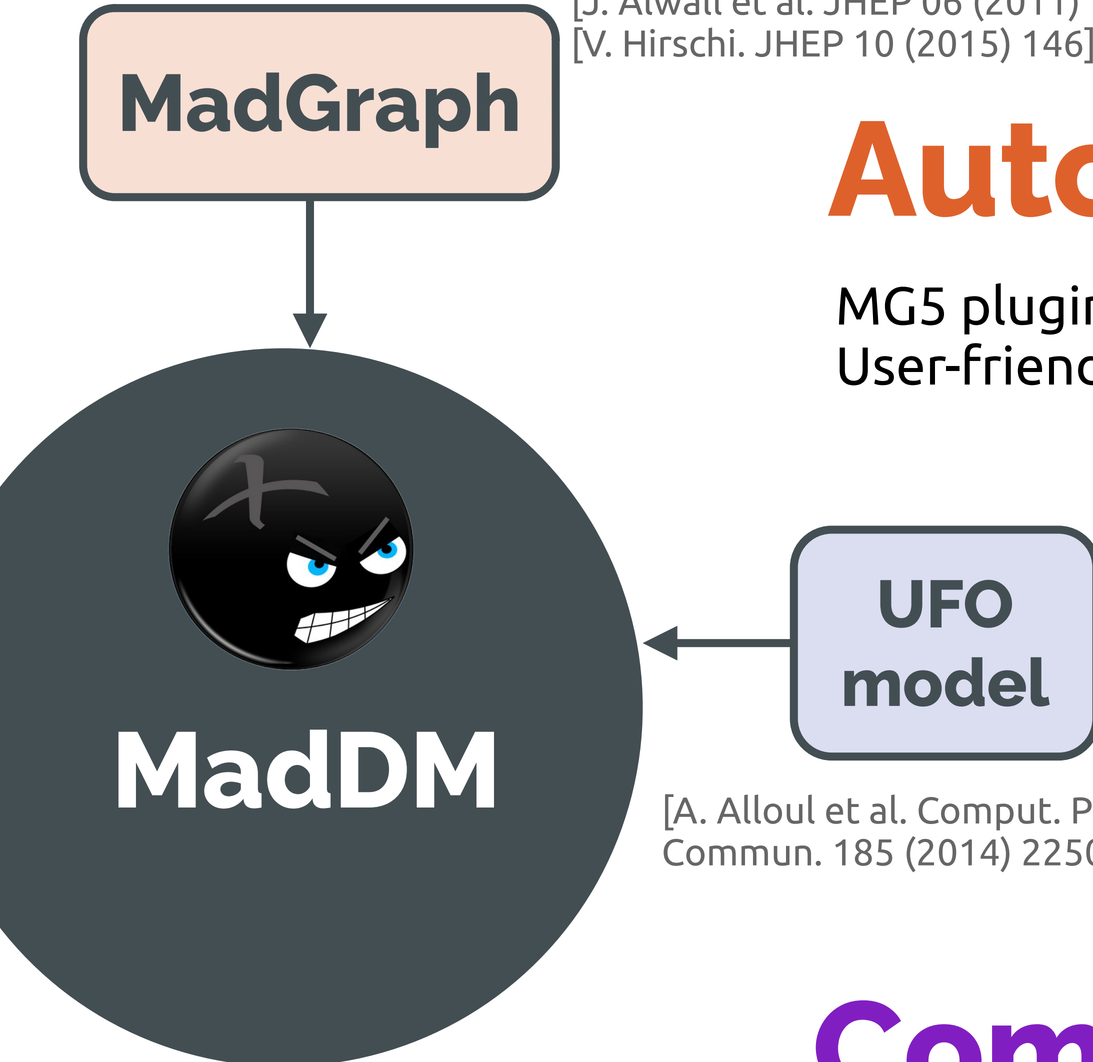
Comprehensive

Comparison with main experimental constraints



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Comprehensive

Comparison with main experimental constraints

Cool

Focused on WIMPs

MadDM computations

RELIC DENSITY

2 to 2 tree-level annihilations diagrams
freeze-out temperature

```
MadDM>generate relic_density
```

DIRECT DETECTION

Spin-dependent and independent nucleon-dm
+ electron-DM & RAPIDD integration in v.3.3
Comparison with current constraints

```
MadDM>generate direct_detection
```

MadDM computations

INDIRECT DETECTION

```
MadDM>generate indirect_detection
MadDM>generate indirect_spectral_features
```

Since MadDM v3.0

- Theoretical prediction for $\langle v \rangle$
- Generation of energy spectra (link to PPPC4DMID and Pythia 8) **+ updates in v3.3**
- Computation of fluxes
- Fermi-LAT likelihoods for dwarf spheroidal galaxies

[F. Ambrogi et al. Phys. Dark Univ. 24 (2019) 100249]

Since MadDM v3.2

- Loop-induced processes
- Gamma-line spectrum analysis
- Computation of astrophysical quantities
- New constraints implemented

[C. Arina, J. Heisig, F. Maltoni, DM and O. Mattelaer (July 2021). arXiv:2107.04598]

MadDM v3.3

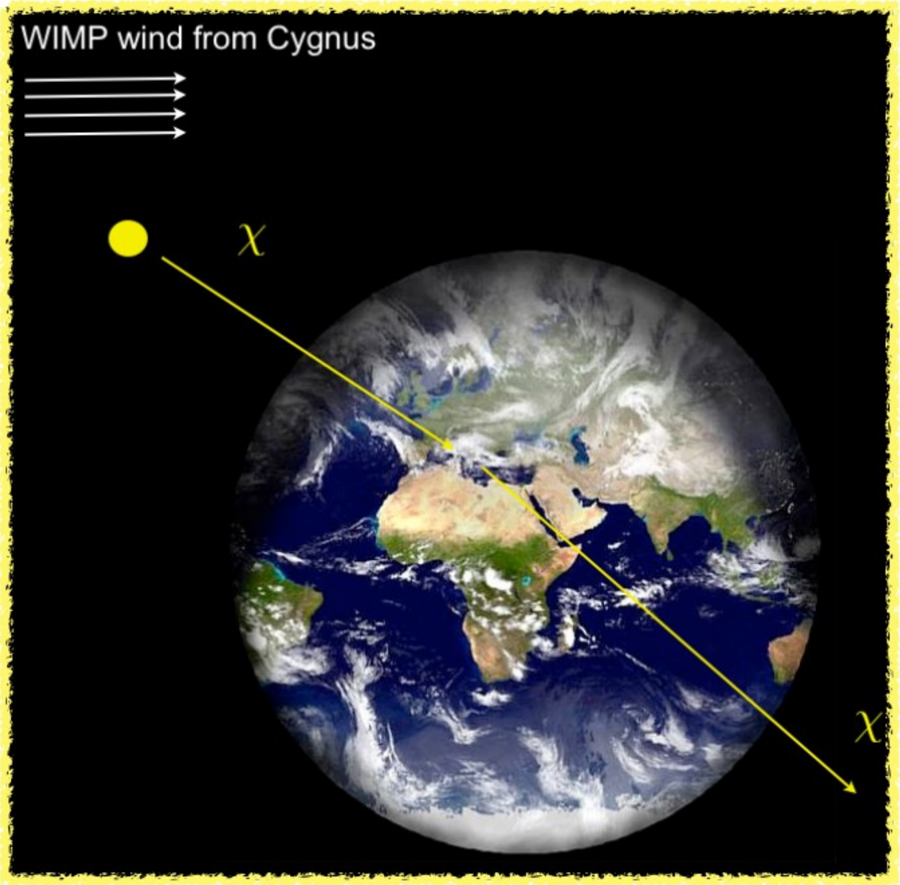
Code-wise

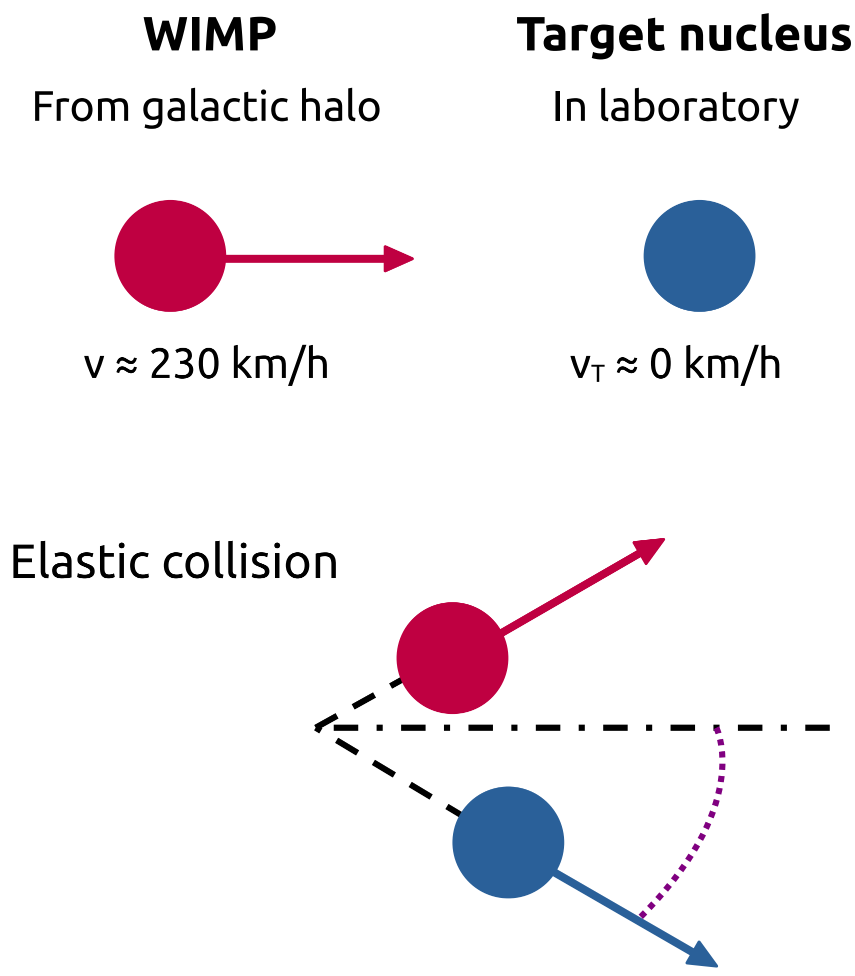
- Move from Launchpad to GitHub;
- Support for Python 3;
- Support for latest (v3.x) versions of MadGraph;

Physics-wise

- Direct detection:
  - Interface with RAPIDD code (in progress) for non-relativistic DM-nucleus scattering.
  - First tentative implementation of DM-electron scattering.
- Indirect detection:
  - Link to CosmiXs for computation electroweak-corrected DM annihilation spectra in multiple channels (→ Mattia's talk tomorrow).
  - Evaluation of the antinuclei spectra.
  - Improved Pythia tuning for the spectra: takes into account a tuning which is compatible with LEP data.
  - General updates of the main constraints.

Direct detection: DM-nucleus scattering

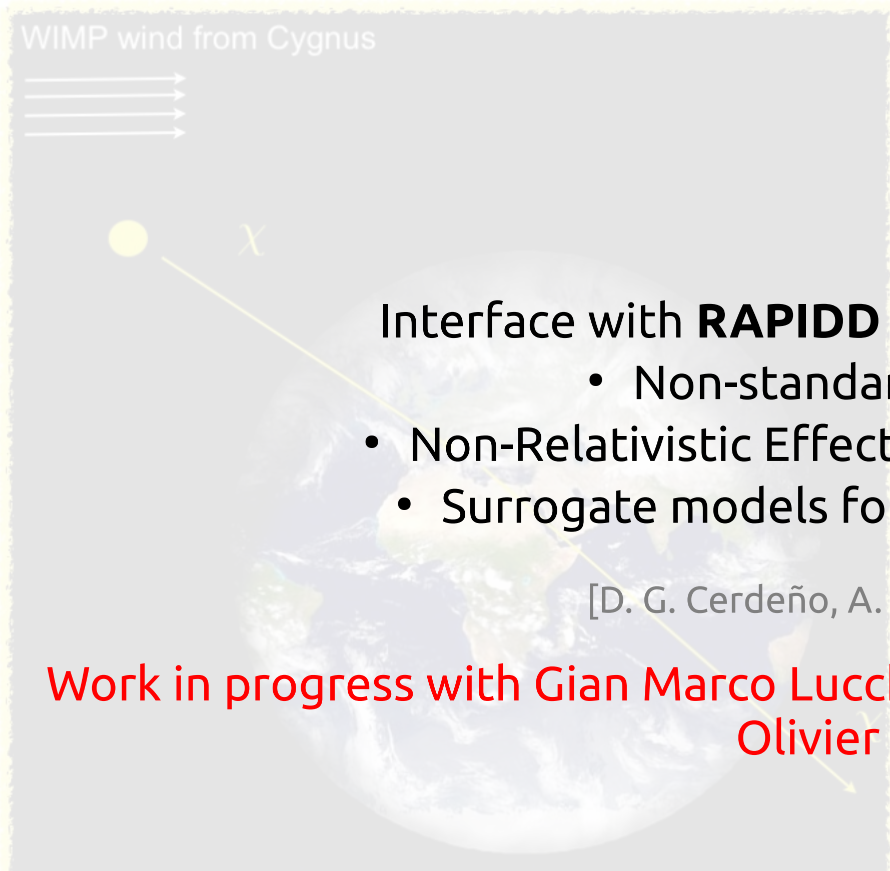


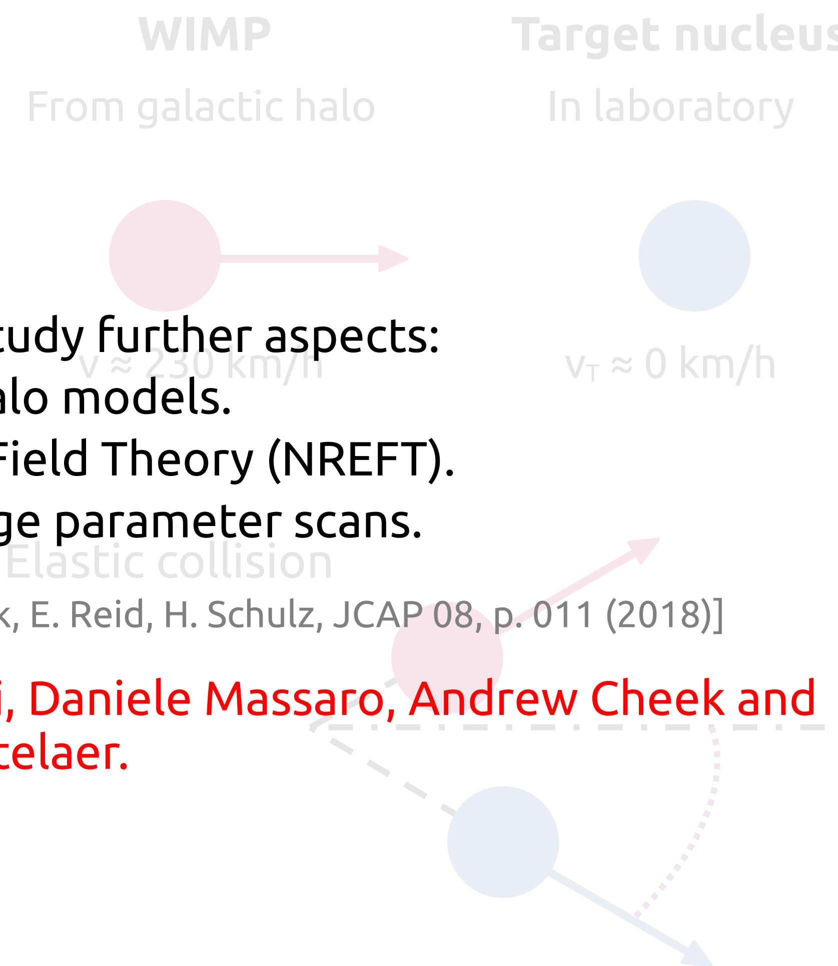


Momentum transfer ≈ MeV
(non-relativistic transfer)

$$E_R = \frac{\mu^2 v^2}{m_X}(1 - \cos\vartheta)$$

Direct detection: DM-nucleus scattering





Interface with **RAPIDD** to study further aspects:

- Non-standard halo models.
- Non-Relativistic Effective Field Theory (NREFT).
- Surrogate models for large parameter scans.

[D. G. Cerdeño, A. Cheek, E. Reid, H. Schulz, JCAP 08, p. 011 (2018)]

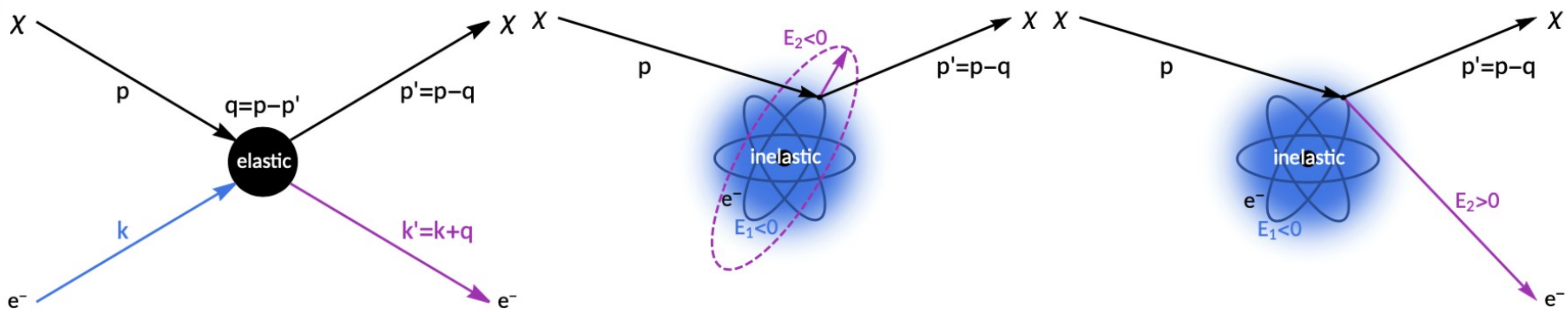
Work in progress with Gian Marco Lucchetti, Daniele Massaro, Andrew Cheek and Olivier Mattelaer.

Momentum transfer ≈ MeV
(non-relativistic transfer)

$$E_R = \frac{\mu^2 v^2}{m_X}(1-\cos\vartheta)$$

Dir[illegible]detection: DM-electron scattering

PRELIMINARY



- Electrons are much lighter than protons.
- Recoil energy ≈ eV for m_{DM} > O(MeV).

In MadDM:

- Matrix element → hard process is computed considering a free electron.
- MadDM linked to the code DarkART [R.Catena et al 2019] to describe electrons within atoms, atomic ionization form factors and dark matter response functions.

Work in progress with Gian Marco Lucchetti, Daniele Massaro, Andrew Cheek and Olivier Mattelaer.

Direct detection: DM-electron scattering

PRELIMINARY

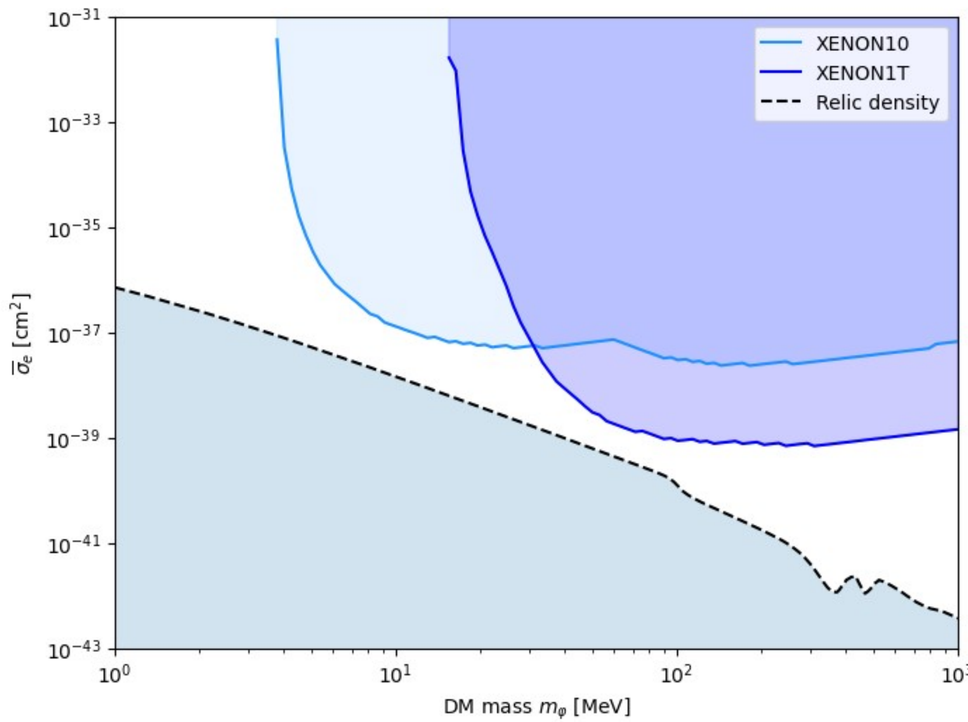
Dark photon model

$$\mathcal{L}_{\rm int} = (g_D \mathcal{J}'_\mu - \varepsilon e \mathcal{J}_\mu) A'^\mu + e \mathcal{J}_\mu A^\mu$$

$$\mathcal{J}^\mu = \sum_f \overline{\psi}_f \gamma^\mu \psi_f$$

$$\mathcal{J}'^\mu = i \varphi^\dagger \partial^\mu \varphi + \text{h.c.}$$

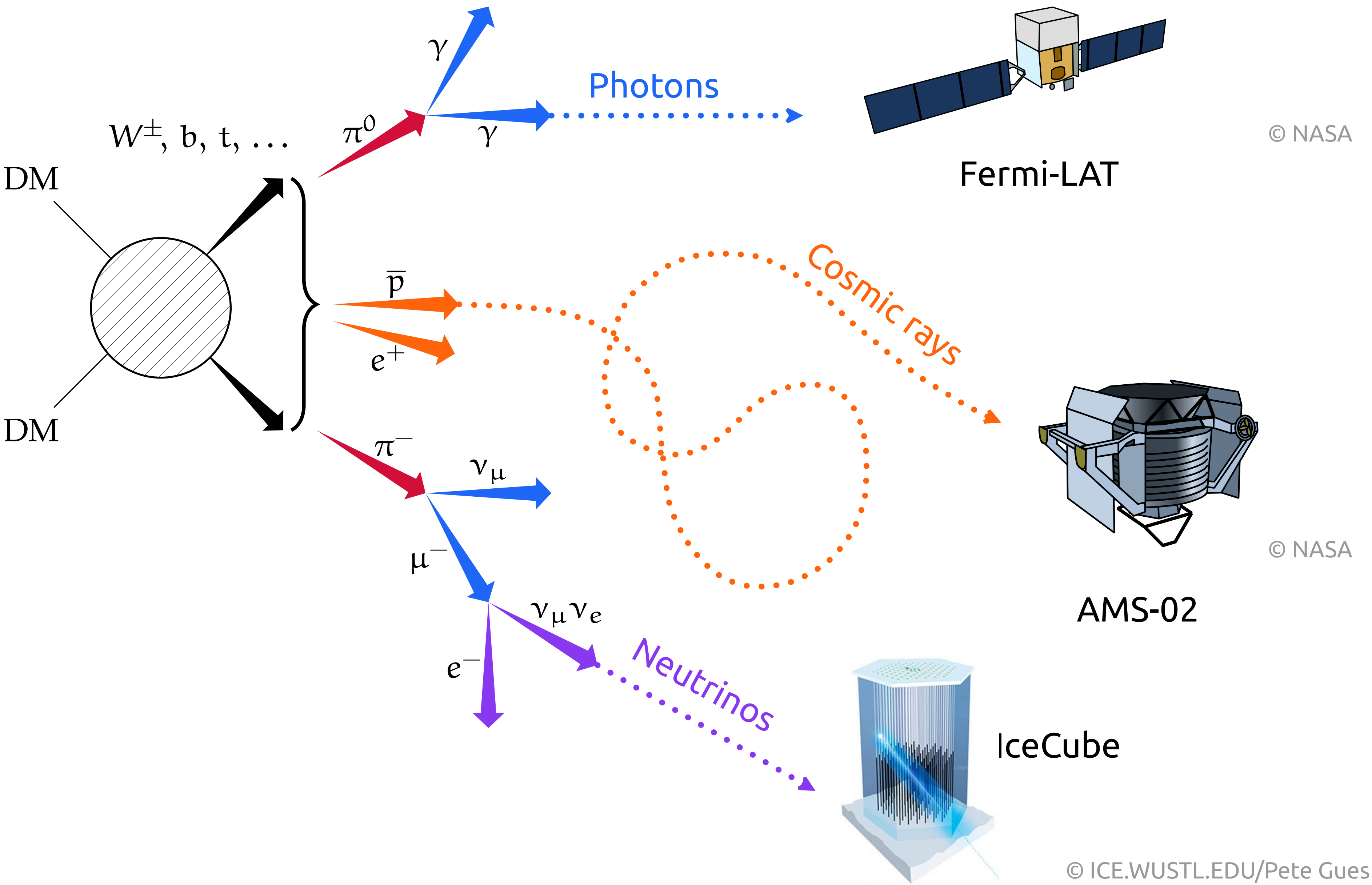
$$\overline{\sigma}_e = \frac{\mu_{f,e}^2}{\pi m_{A'}^4} (\varepsilon e g_D)^2$$



We included the XENON1T likelihood in MadDM.

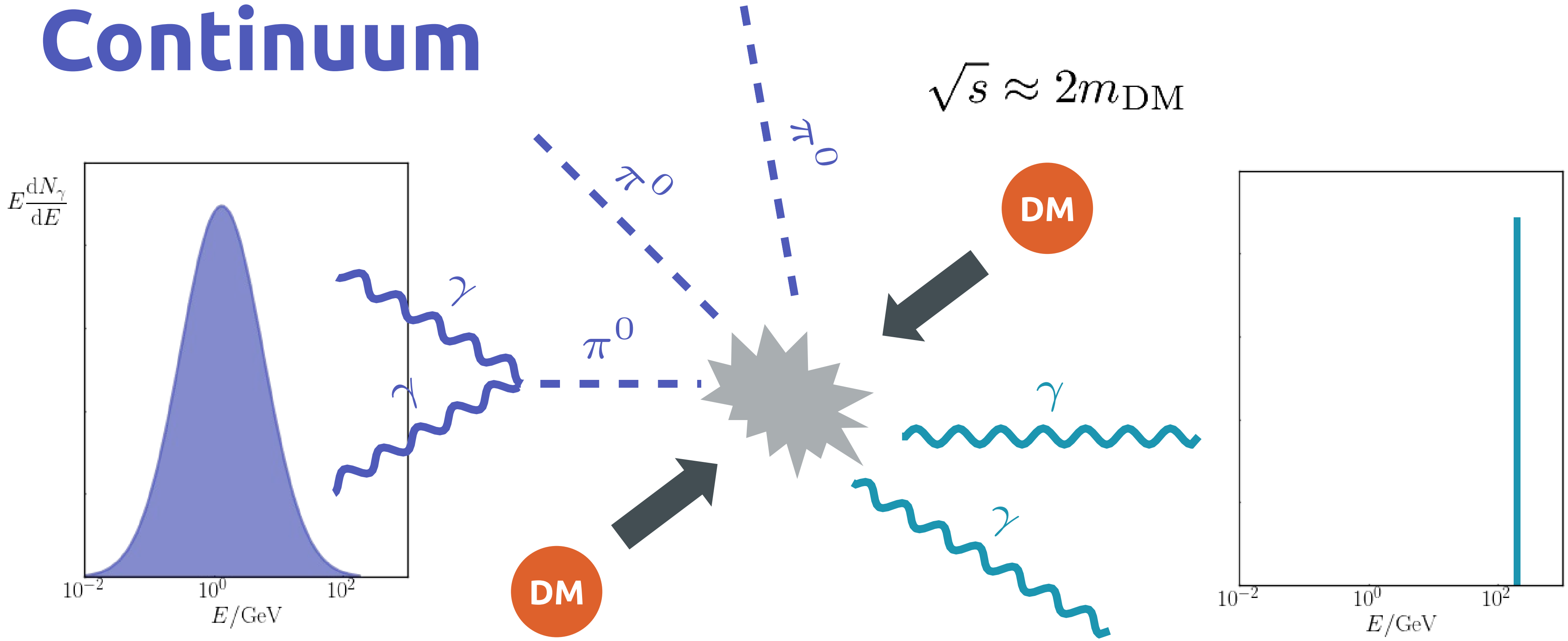
Next generation detectors could probe this model.

Indirect detection



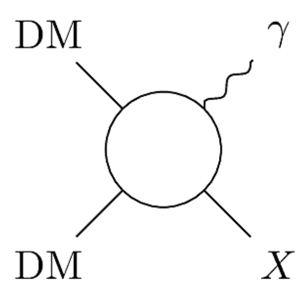
Indirect detection: photon lines

Continuum



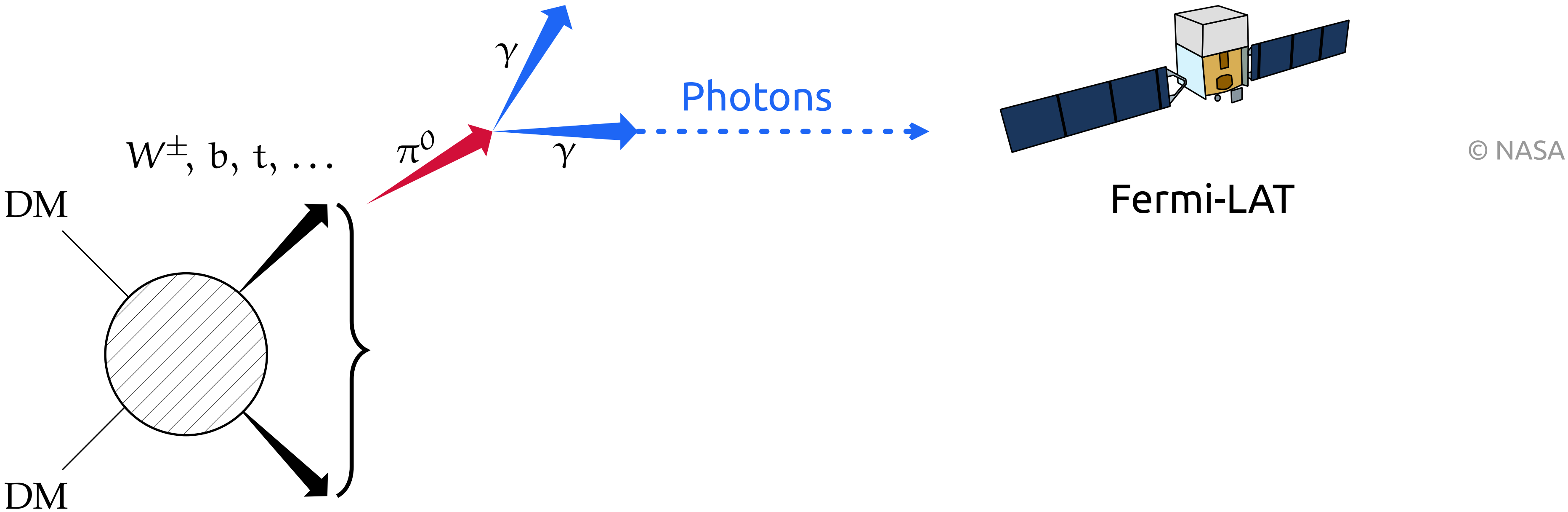
Loop-induced process

Line

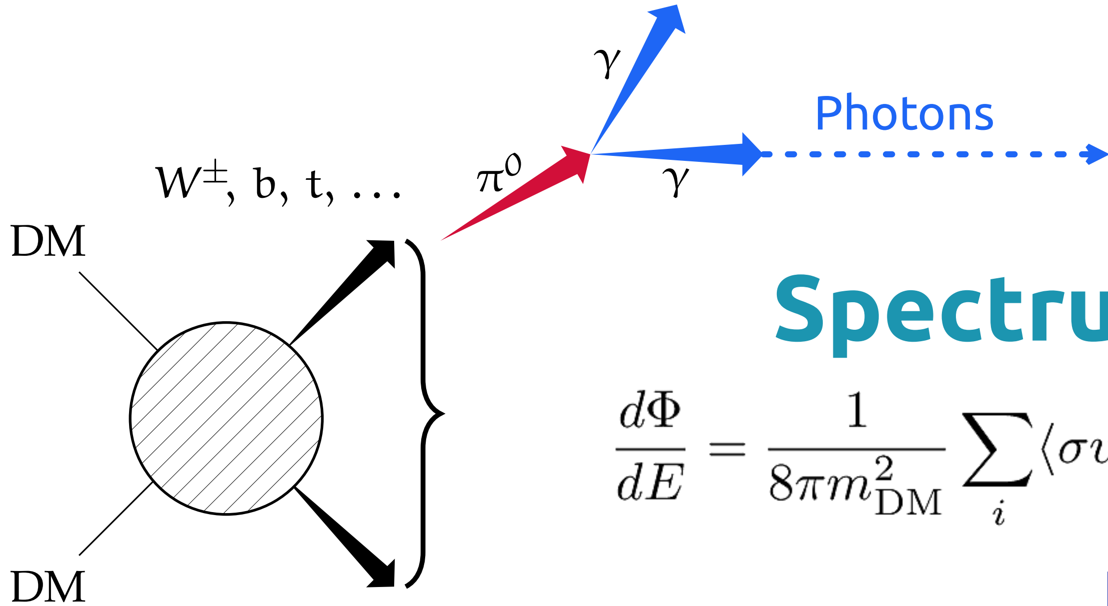


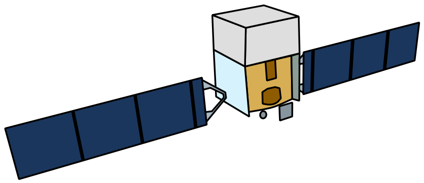
Smoking-gun signature
Hard to mimic with astrophysical background.

Continuum spectrum



Continuum spectrum





Fermi-LAT

Spectrum

$$\frac{d\Phi}{dE} = \frac{1}{8\pi m_{\rm DM}^2} \sum_i \langle \sigma v \rangle_i \frac{dN_\gamma^i}{dE} \int_{\rm ROI} \mathrm{d}\Omega \int_{\rm l.o.s.} \rho^2(\boldsymbol{r})\, \mathrm{d}l$$

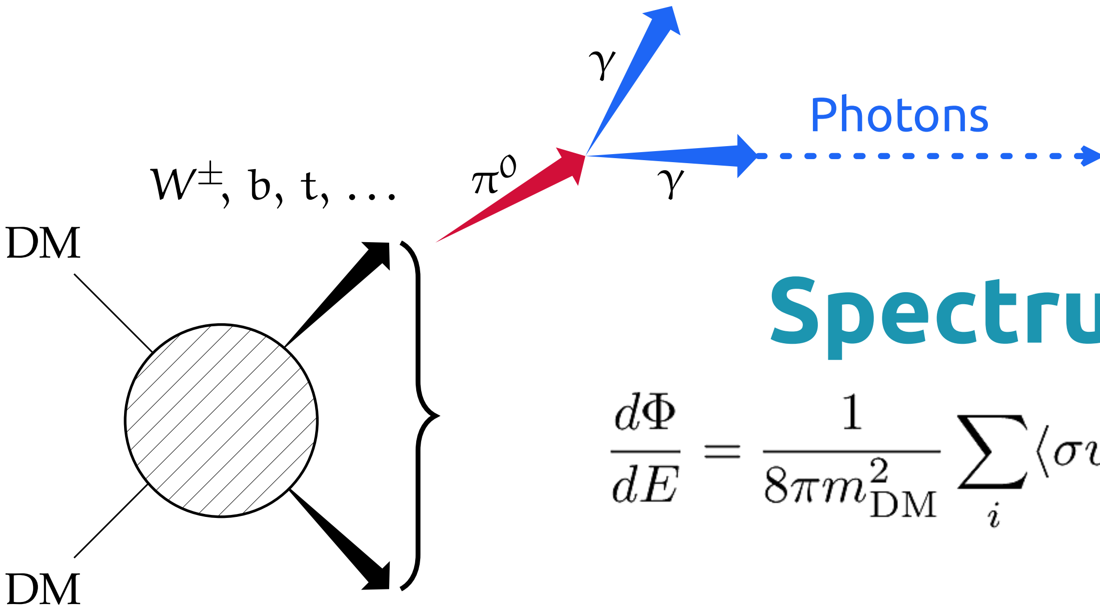
J-factor

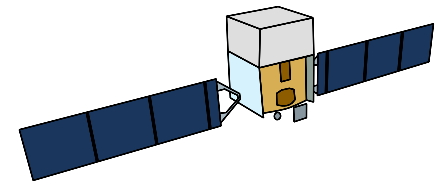
ROI + mask
over galactic plane

Density profile

NFW
Einasto
isothermal
Burkert

Continuum spectrum





© NASA

Fermi-LAT

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J-factor

ROI + mask
over galactic plane

Density profile

NFW
Einasto
isothermal
Burkert

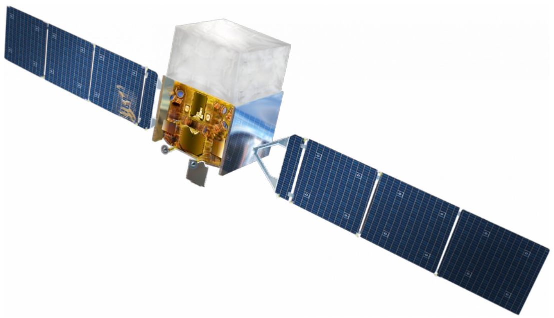
- Comparison with Fermi exclusion limits.
- Computation of Upper Limits with Fermi Likelihoods (40 likelihoods for dSph):
  - Utilize binned public likelihood (Fermi-LAT 2016).
  - Give **Likelihood**, **p-value** and **<σv>$_{UL}$** for given point.

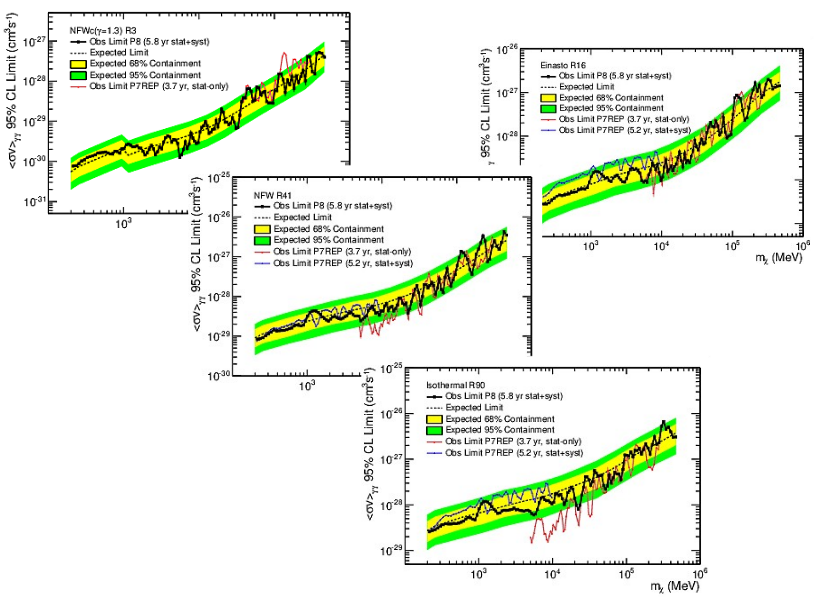
$$\mathrm{TS} = -2 \sum_{\mathrm{dSph}} \int \frac{\mathcal{L}(\hat{J}, \sigma v)}{\mathcal{L}(\hat{\hat{J}}, \widehat{\sigma v})}$$

Line spectrum

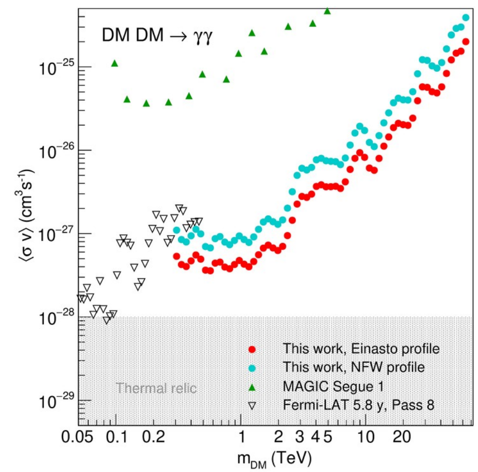
Fermi-LAT

Fermi-LAT © NASA





[M. Ackermann et al. Phys. Rev. D 91 (12) (2015) 122002]



H.E.S.S. © MPIK / Christian Föhr

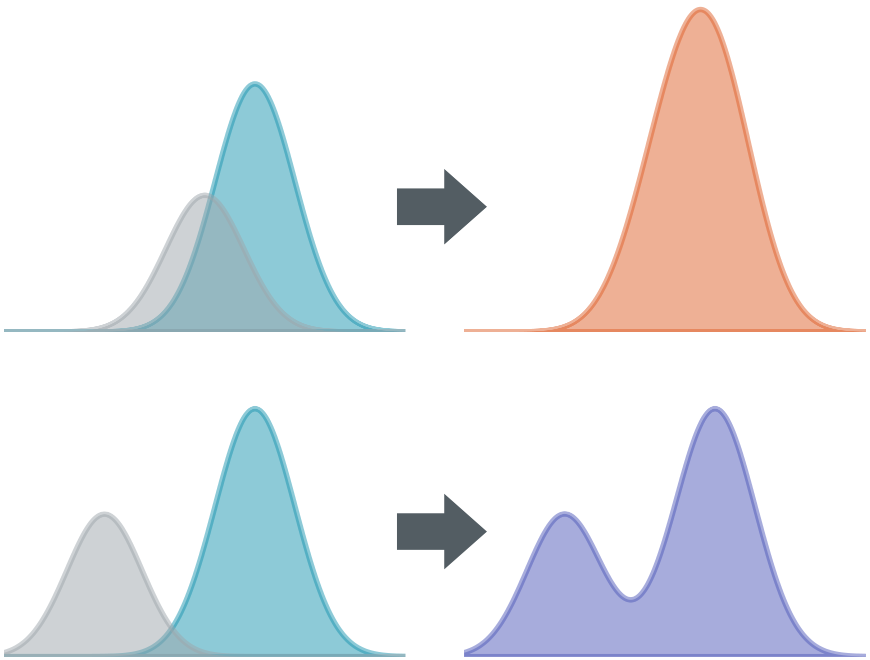
H.E.S.S.

[H. Abdallah et al. Phys. Rev. Lett. 120 (20) (2018) 201101]

Gamma line spectrum

Line on spectrum: **Gaussian peak:**

- $E_\gamma = m_{\rm DM}\left(1 - \frac{m_{\rm X}^2}{4m_{\rm DM}^2}\right)$
- Peak smeared by the energy resolution of experiment



Peak's analysis

- Close enough: merge them.
- Well-separated: study each one separately.
- Not well-separated: analysis is questionable.

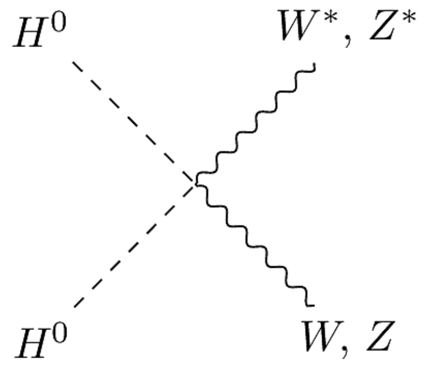
Inert Doublet Model (IDM)

$$V = \mu_1^2|H|^2 + \mu_2^2|\Phi|^2 + \lambda_1|H|^4 + \lambda_2|\Phi|^4 + \lambda_3|H|^2|\Phi|^2 + \lambda_4|H^\dagger\Phi|^2 + \frac{\lambda_5}{2}\left[(H^\dagger\Phi)^2 + \mathrm{h.c.}\right]$$

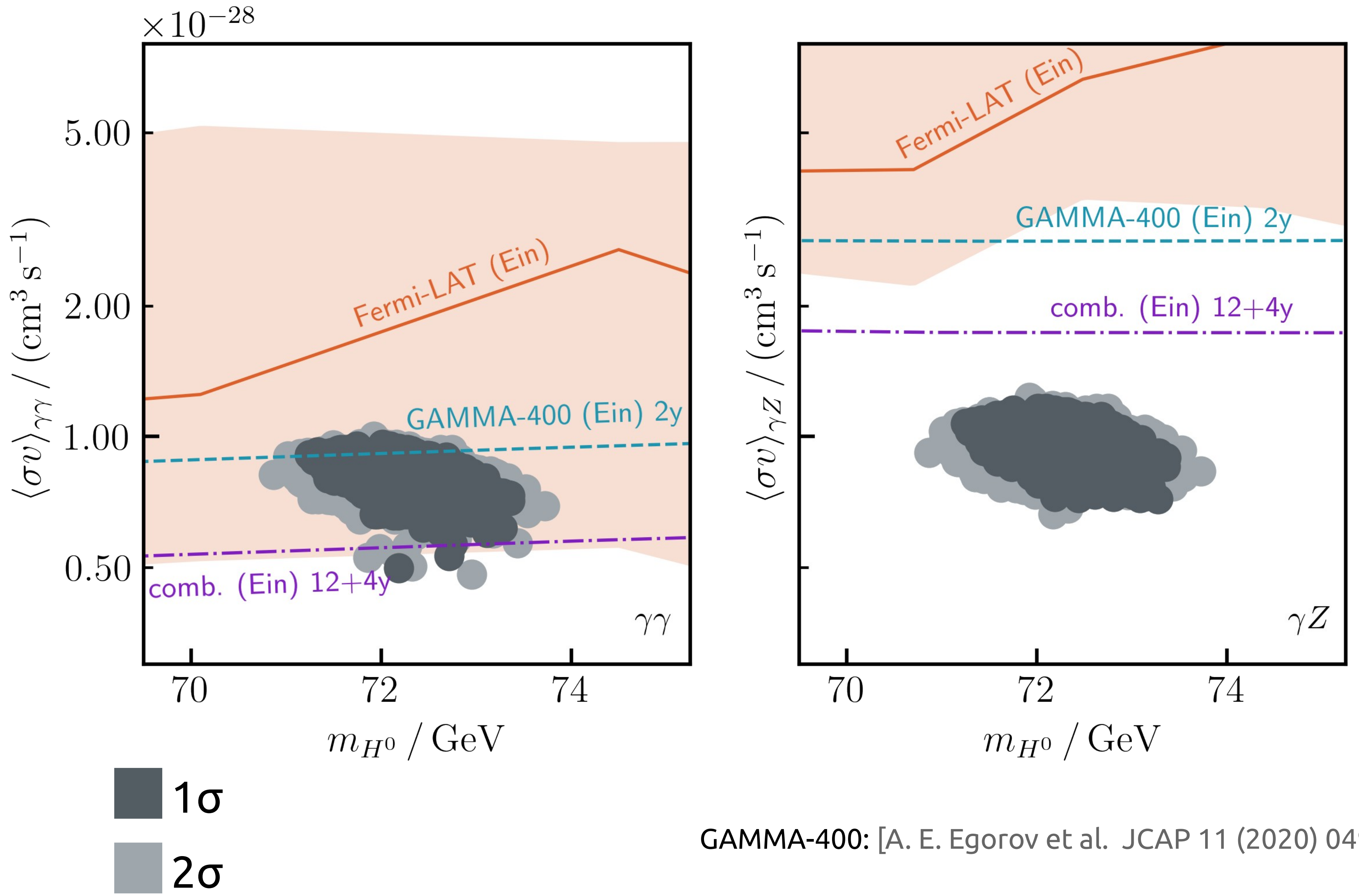
$$\Phi = \begin{pmatrix} H^\pm \\ \frac{1}{\sqrt{2}}(H^0 + iA^0) \end{pmatrix}$$

- Scalar dark matter candidate
- 5 free parameters $m_{H^0}, m_{A^0}, m_{H^\pm}, \lambda_L, \lambda_2$
- [J. Heisig et al. Eur. Phys. J. C 77 (9) (2017) 624]: performed a scan on the parameter space.

Low mass sweet spot: $m_{H^0} \approx 72\,\mathrm{GeV}$
Reproduce relic density, without tuned coupling.
Not challenged by other constraints.



Parameter space



GAMMA-400: [A. E. Egorov et al. JCAP 11 (2020) 049]

Indirect detection: CosmiXs

[C. Arina, M. Di Mauro, R. Ruiz de Astrui, A. Jueid, N. Fornengo and J. Heisig, JCAP 03, p. 035 (2024)]

- CosmiXs: set of tabulated spectra from DM annihilation and decay in
  - Antiprotons
  - Gammas
  - Neutrinos
  - Positrons
  - Anti-Deuterons

© CosmiXs developers

- Features of spectra generation:
  - Use Vincia (EW-corrected spectra) interfaced to MadDM (helicity is "passed" along the shower).
  - Trilinear gauge bosons diagrams.
  - EW corrections important for DM masses > 1 TeV.
  - Parameter tuning to fit Z resonance LEP data.

→ Mattia's talk tomorrow

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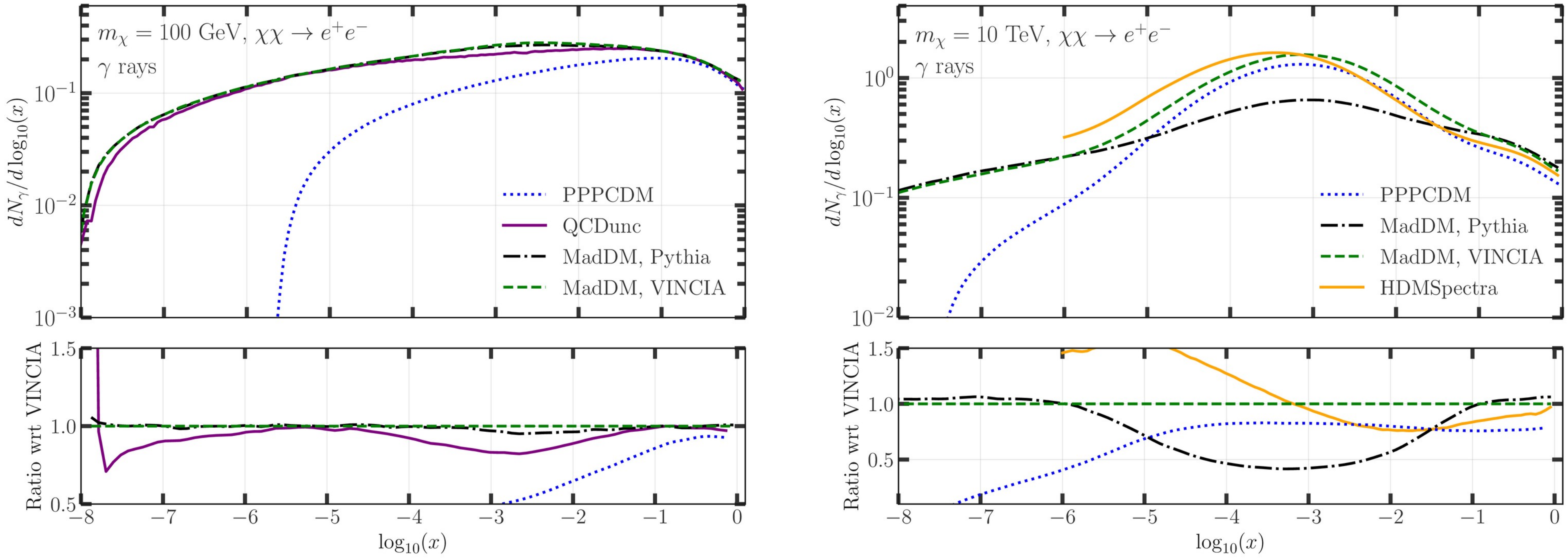


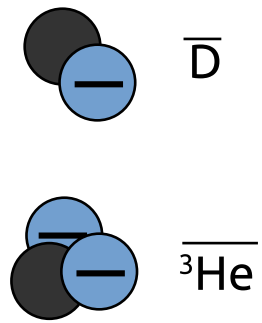
Comparison betwenn PPPC4DMID, a special tuning of Pythia with QCD uncertainties, Pythia, VINCIA, HDMSpectra.

[N. Fischer, S. Prestel, M. Ritzmann, and P. Skands. Eur. Phys. J. C 76 (2016), 11 589]
[C. W. Bauer, N. L. Rodd, and B. R. Webber. JHEP 06 (2021) 121]
[S. Amoroso, S. Caron, A. Jueid, R. Ruiz de Austri, and P. Skands. JCAP 05 (2019) 007]
[A. Jueid, J. Kip, R. R. de Austri, and P. Skands. JCAP 04 (2023) 068]
[A. Jueid, J. Kip, R. R. de Austri, and P. Skands. JHEP 02 (2024) 119]

Antideuterons and antihelion

[M. Di Mauro, R. Ruiz de Astrui, A. Jueid, N. Fornengo and F. Bellini, arXiv:2411.04815]

- Promising channels for ID: clear signatures.
- Unclear modelling of their production (coalescence models).
- Quantum-mechanical treatment: Wigner approach.

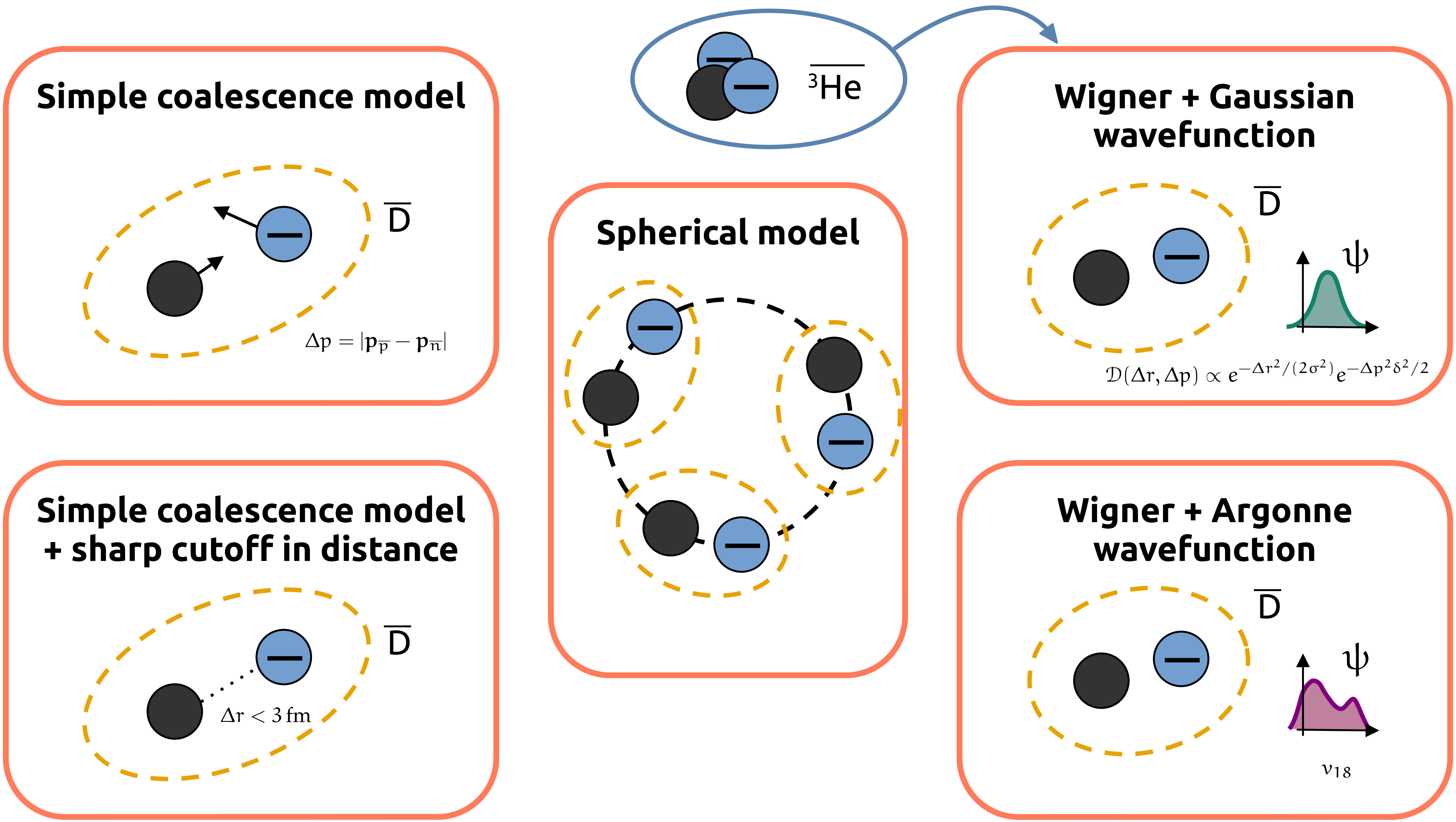


To obtain the spectra (implemented in CosmiXs)

- MC simulation:
  - **Generate** anti-neutrons and anti-protons from DM annihilation/decay.
  - **Search** for all the pairs anti-neutrons—anti-protons.
  - **Assess** whether you can form anti-deuteron.
    - Use Wigner-Argonne potential (see later).
- Use Pythia & VINCIA.
- Spectra tabulated from 5 GeV to 100 TeV.

Antideuterons and antihelion

[M. Di Mauro, R. Ruiz de Astrui, A. Jueid, N. Fornengo and F. Bellini, arXiv:2411.04815]



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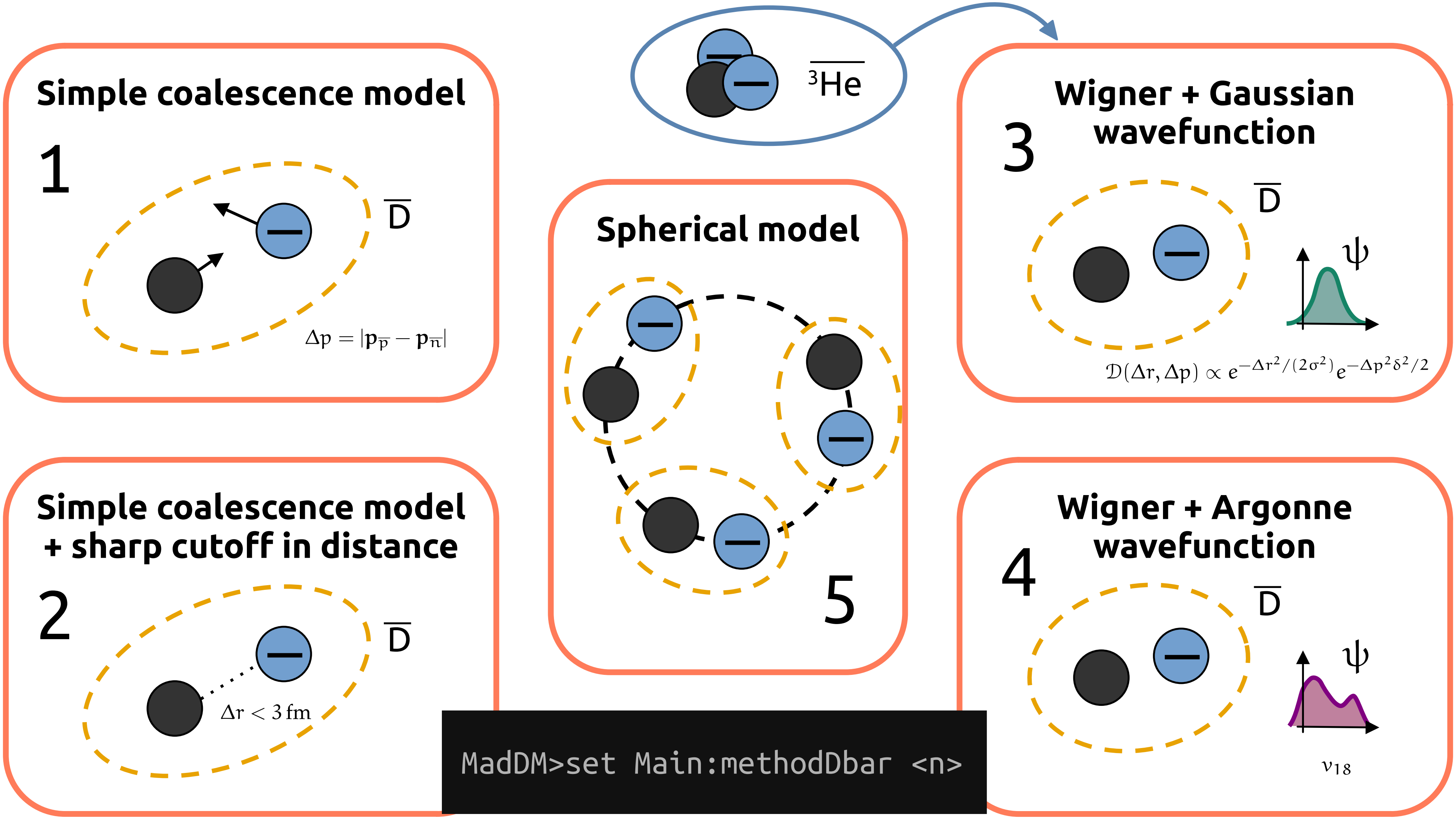

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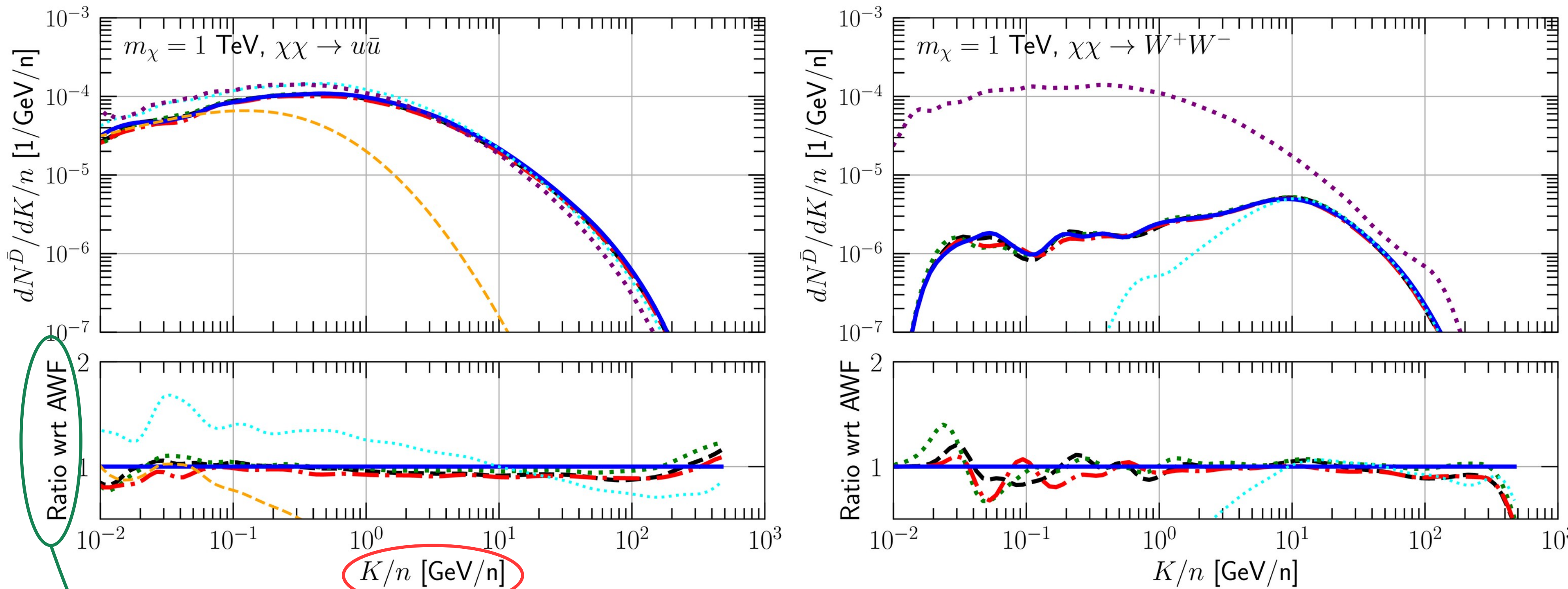
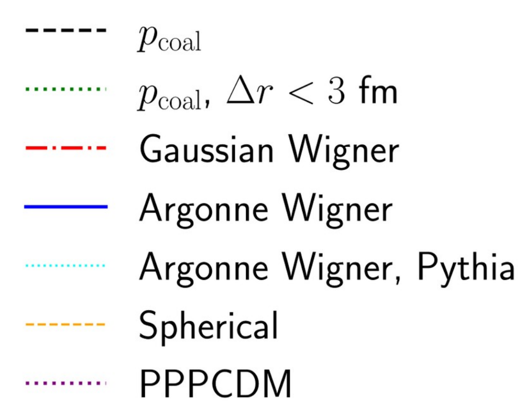


Kinetic energy per nucleon

Ratio of the spectra with respect to the Argonne-Wigner case



Indirect detection: J-factor

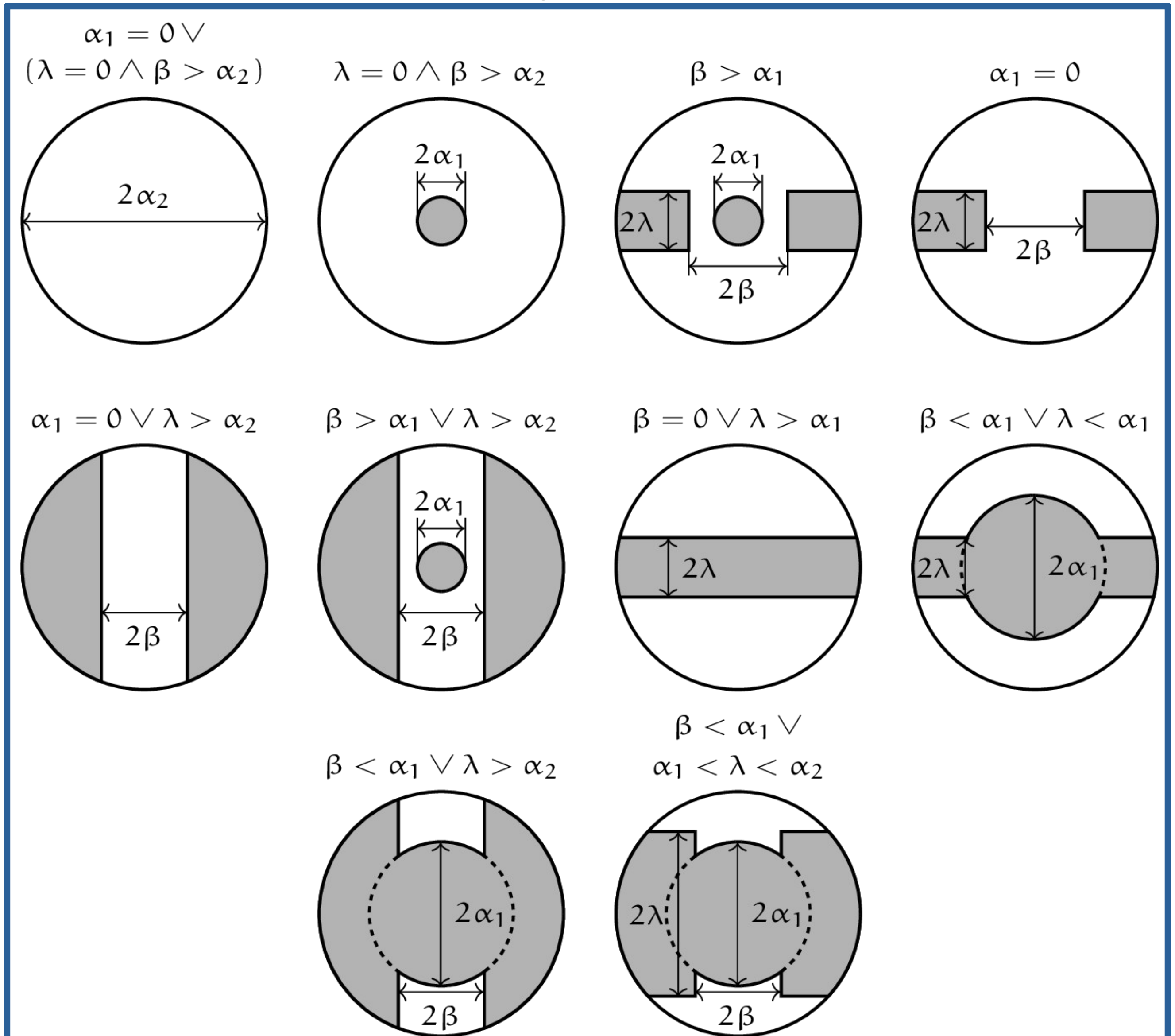
- MadDM is now shipped with a separate script `jfactor_gc.py`
- It can be used either standalone or through MadDM prompt.

```
MadDM>jfactor
```

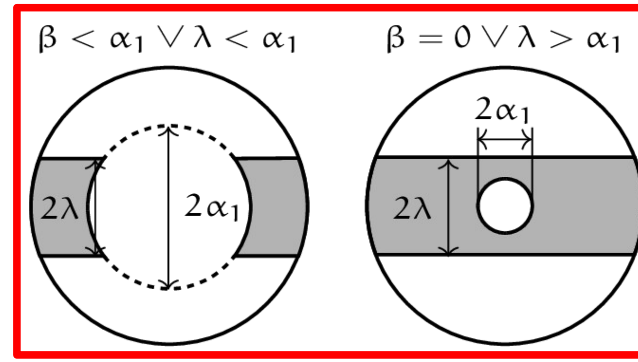
```
user@host(maddm) > ./jfactor_gc.py

usage: jfactor_gc.py [-h] [--mask-inner-amplitude alpha_1] [--mask-
         longitude beta] [--mask-latitude lambda] [--strategy
         {normal,inverted}] [--no-mask] [--r_max r_max] [--r_sun r_sun]
         [--rho_sun rho_sun] [--rho_s rho_s] [--r_s r_s] alpha_2
         {nfw,einasto,burkert,isothermal} ...

Compute the J-factor on the Galactic Center, given a dark matter profile
and the parameters of a possible mask over the galactic plane. The
normalization of the density profile is computed using rho_sun and
r_sun: rho_s = rho(r_sun), unless rho_s is explicitly provided via the
--rho_s option. The specified value in the latter case is used instead.
Returns the J-factor expressed in GeV^2 cm^{-5}.
```

Indirect detection: J-factor

Strategy: normal



Strategy: Inverted



The grey part is the mask on the galactic centre that is going to be excluded in the calculation.

New developments: MadDM on GPU

- This follows the recent deployment of a GPU version of MadGraph through the plugin CUDACPP.

[S. Hageboeck et al. EPJ Web Conf. 295 (2024), p. 11013]
[A. Valassi et al. ACAT 2022 (2023)]

- The matrix element computation (one of the most computing intensive tasks) has been offloaded to GPU (or vector CPUs)

  → **recorded speedups of nearly 800%** (process and hardware dependent).

- MadDM can naturally inherit this capabilities:
  - Speedups for various processes, in particular 2→3, or 2→4 which could be important for indirect detection.
  - Achieve **huge speedups for parameter scans** that can accommodate broader parameter spaces with the same computational time.
- Follow the (early stage) developments on the feature branches!

Summary

- MadDM is one of the tools for dark matter predictions:
  - High customisability
  - Modular structure
  - Ability to study wide range of signals
- New release v3.3 (now in beta, see branch rc/3.3):
  - **Python 3** compatible
  - Improvements for **direct detection**:
    - **NREFT w/ RAPIDD**
    - **DM-e** scattering
  - Interface with the most precise energy spectra up-to-date from **CosmiXs**:
    - Inclusion of cosmic-rays **anti-deuterons** spectra with only few % theoretical uncertainty.
- Future developments: GPU version, database with experimental likelihoods, provide significance for dSph limits.

See you at the tutorial session later!