MadDM v.3.0

Part 1 - Introduction

Federico Ambrogi

with C.Arina, M. Backovic, J. Heisig, F. Maltoni, L. Mantani,
O. Mattelaer, G. Mohlabeng

MC4BSM Workshop
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MadDM v.3.0 is out!

MadDM v.3.0: a Comprehensive Tool for Dark Matter Studies

Federico Ambrogi, Chiara Arina, Mihailo Backovic, Jan Heisig, Fabio Maltoni, Luca Mantani, Olivier Mattelaer, Gopolang Mohlabeng

(Submitted on 30 Mar 2018)

https://arxiv.org/abs/1804.00044

- MadDM is now a MadGraph5_aMC@NLo plugin
- Beta version available at https://launchpad.net/maddm or at the wiki below
- completely integrated in the MG5_aMC framework

—> after beta phase: ./bin/mg5_aMC

install madd

- Currently uses an unreleased version of MG5_aMC (no direct installation yet)

MadDM wiki page:

https://cp3.irmp.ucl.ac.be/projects/madgraph/wiki/MadDm

Introduction: what's new

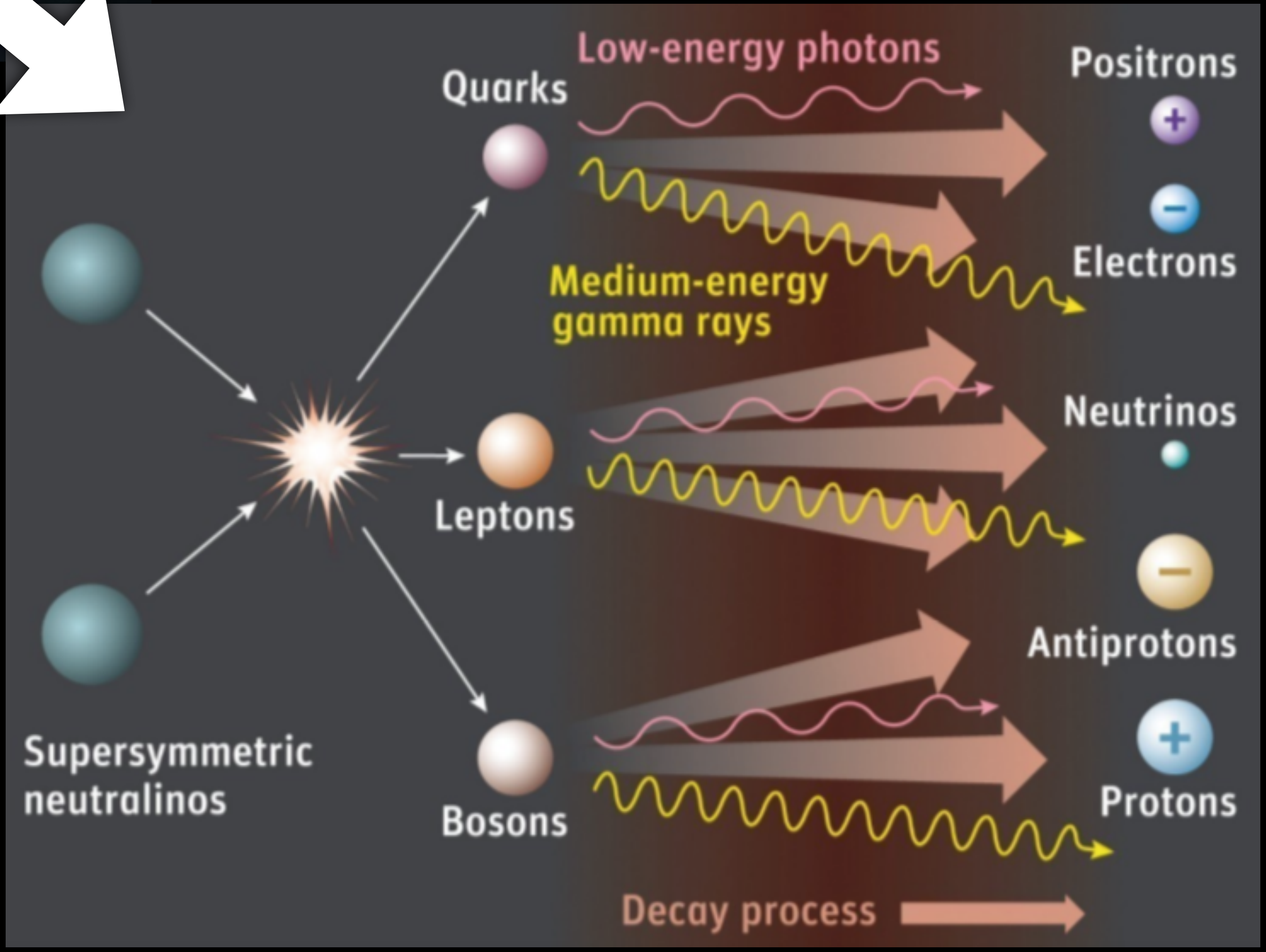
- MadDM v.1.0 : relic density
- MadDM v.2.0 : direct detection
- **MadDM v.3.0 : indirect detection**

Overview

- dedicated module for indirect detection theory predictions
- module for *experimental constraints*
- inherits the capabilities of MG5 to automatically compute and generate 'complicated' processes
- advanced functionalities for scanning from MG5 or **PyMultiNest**

Focus on the
Indirect detection module

DM annihilation in the halos
(external galaxies or in the Milky way)

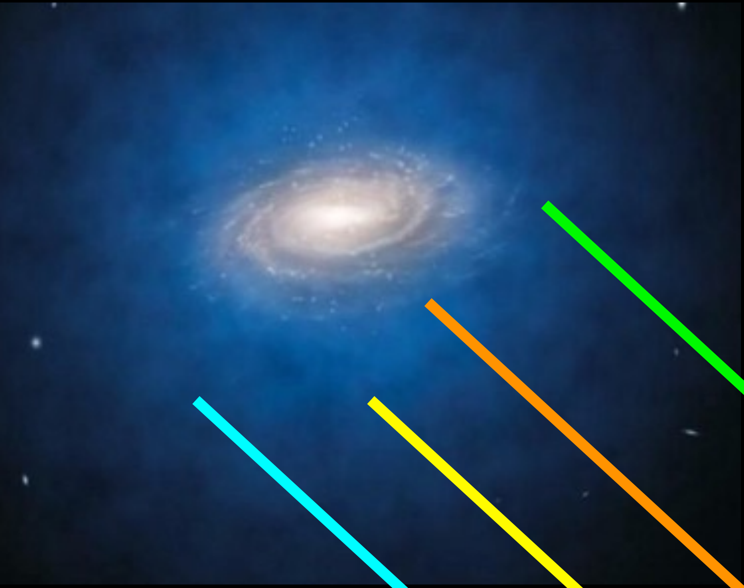


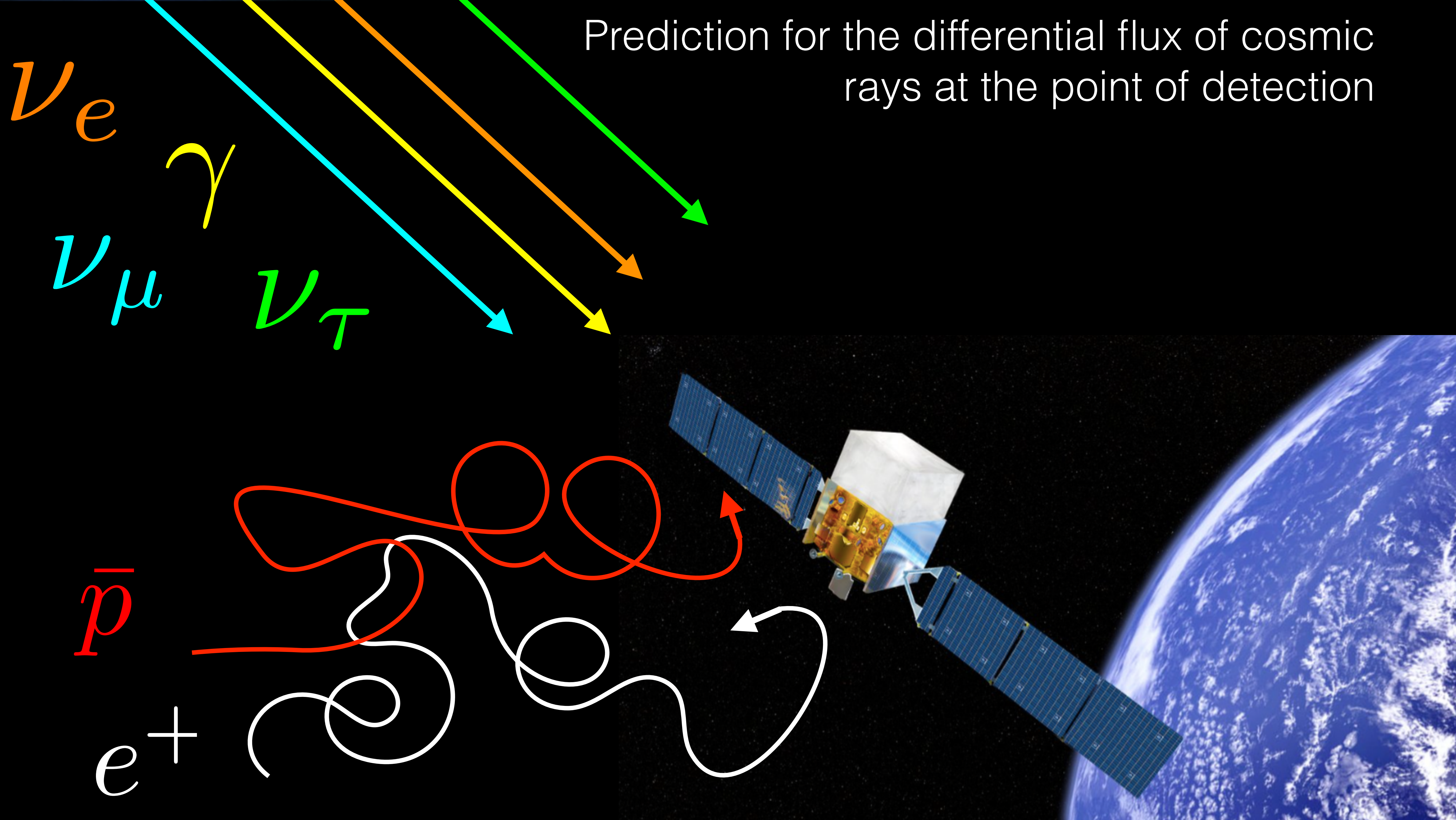
(Possible DM candidate)

DM annihilation in the halos (external galaxies or in the Milky way)

$$\frac{d\Phi}{dE_\gamma}(E_\gamma, \psi) = \frac{\langle \sigma v \rangle}{2m_\chi^2} \sum_i B_i \frac{dN_\gamma^i}{dE_\gamma} \frac{1}{4\pi} \int_\psi \frac{d\Omega}{\Delta\psi} \int_{\text{los}} \rho^2(\psi, l)\, dl$$

Prediction for the differential flux of cosmic rays at the point of detection





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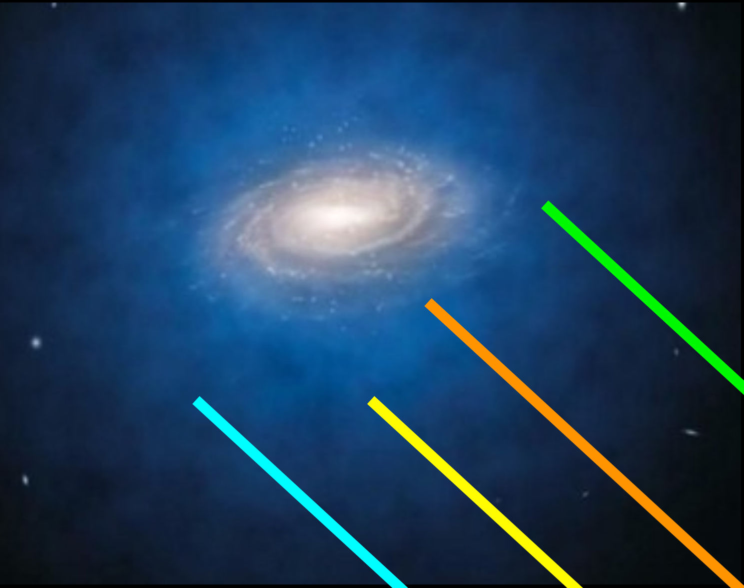

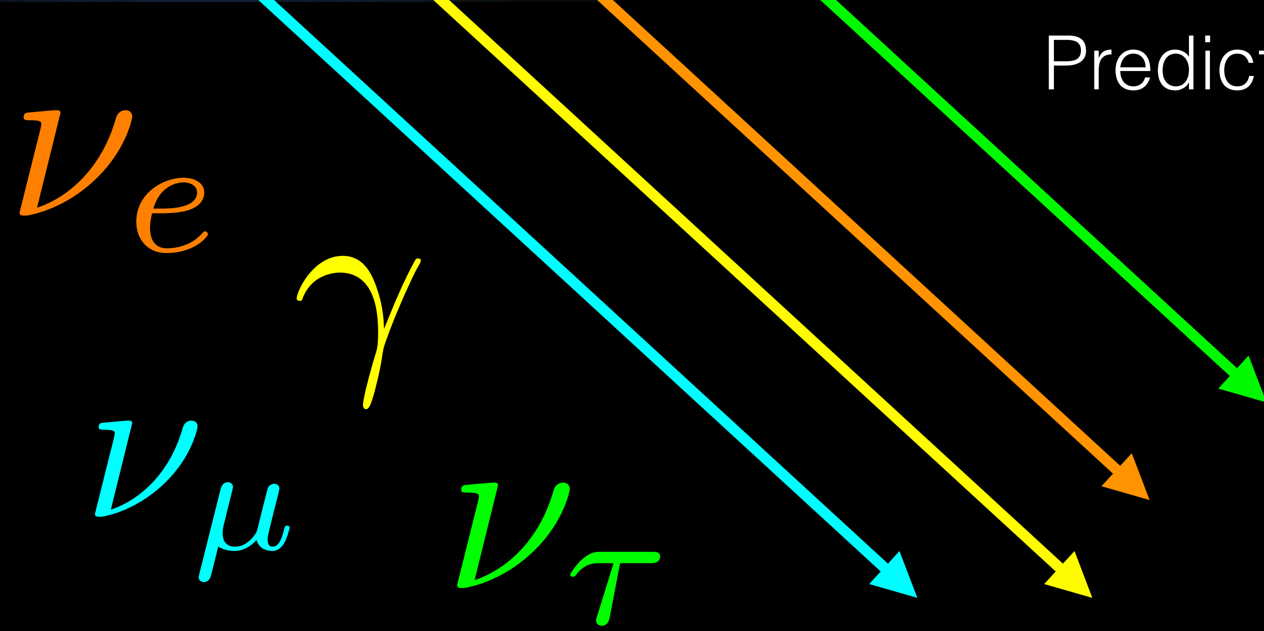

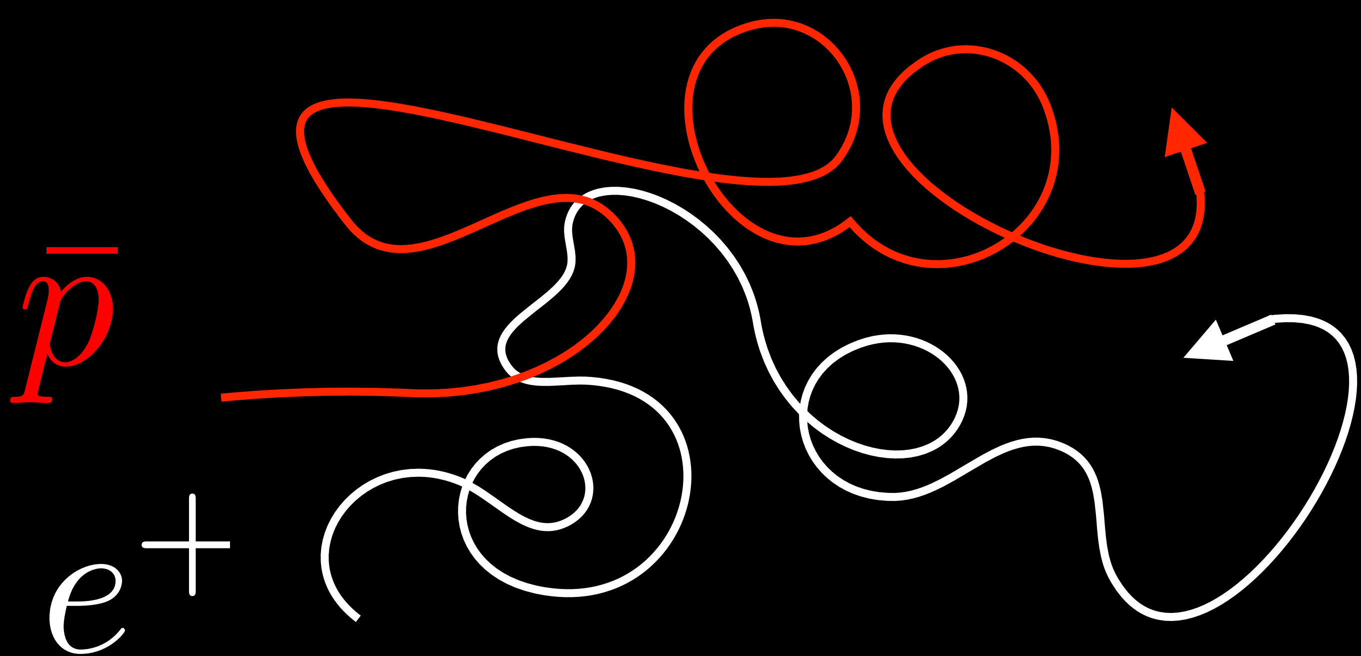

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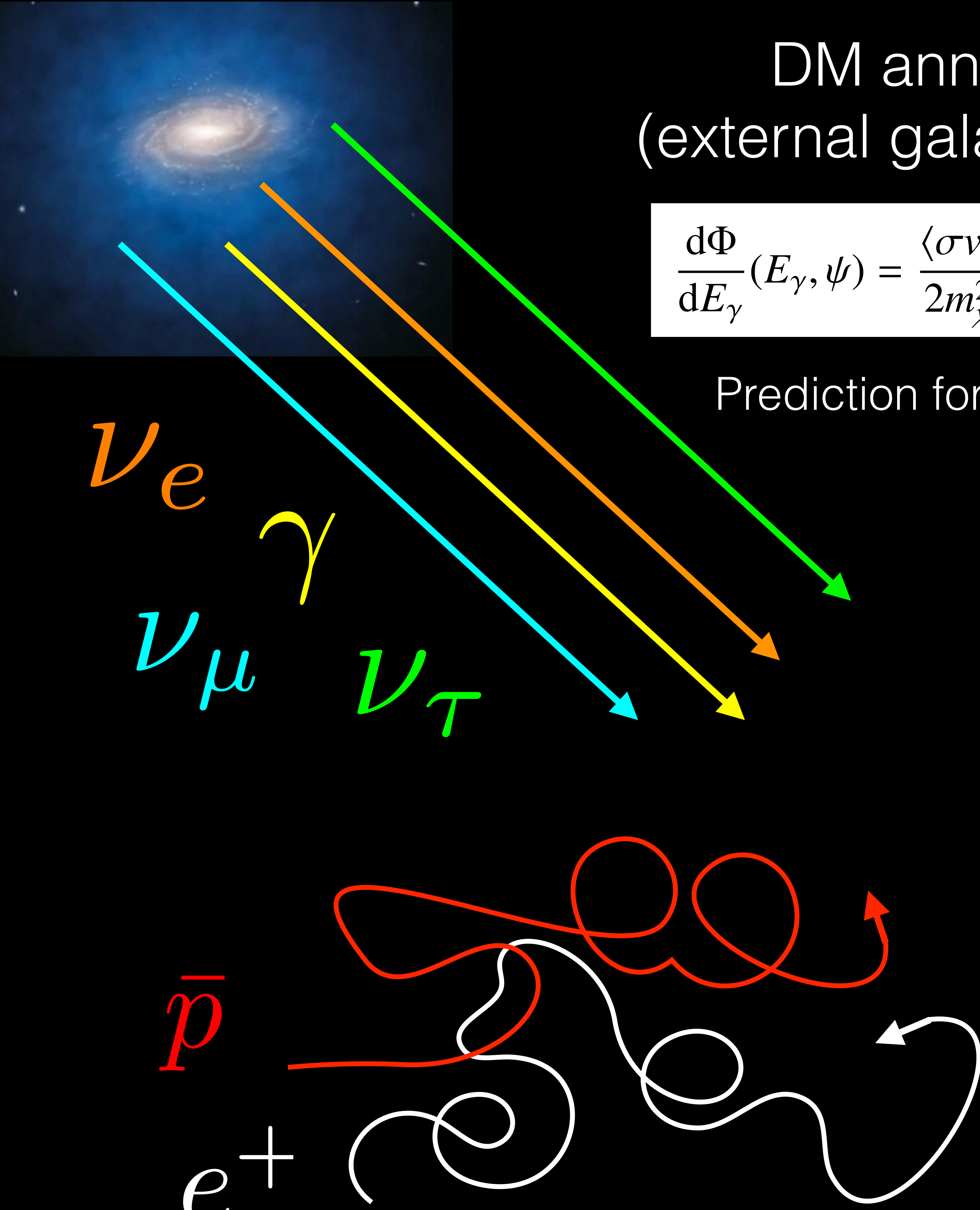
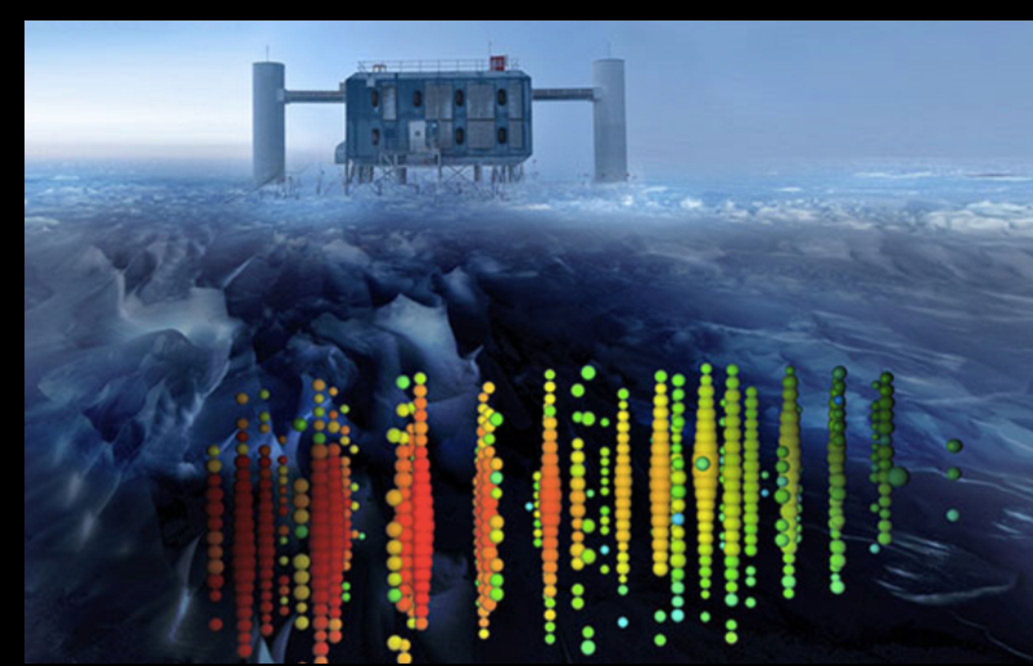


Fermi-LAT , AMS-02 , IceCube , …



Indirect Detection Module - keywords

The new indirect detection module allows to:

- compute velocity averaged DM annihilation cross section

Inclusive

Reshuffling

Madevent

- calculate spectra of cosmic rays (CR) and fluxes at detection

PPPC4DMID

Pythia8

- compare with experimental constraints

Experimental constraints module

- call the **DRAGON** software for galactic positrons/antiprotons propagation

DRAGON

Indirect Detection Module

Main observable for indirect detection: differential flux of cosmic rays at detection

sum taken over all the particle species

$$\frac{\mathrm{d}\Phi}{\mathrm{d}E_\gamma}(E_\gamma,\psi) = \frac{\langle\sigma v\rangle}{2m_\chi^2}\sum_i B_i \frac{\mathrm{d}N_\gamma^i}{\mathrm{d}E_\gamma}\frac{1}{4\pi}\int_\psi \frac{\mathrm{d}\Omega}{\Delta\psi}\int_{\mathrm{los}}\rho^2(\psi,l)\,\mathrm{d}l$$

[particles/(GeV sr cm^2 s)]

Indirect Detection Module

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$$\frac{d\Phi}{dE_\gamma}(E_\gamma,\psi) = \boxed{\frac{\langle\sigma v\rangle}{2m_\chi^2}} \sum_i B_i \boxed{\frac{dN_\gamma^i}{dE_\gamma}} \frac{1}{4\pi} \boxed{\int_\psi \frac{d\Omega}{\Delta\psi} \int_{\text{los}} \rho^2(\psi,l)\, dl}$$

[particles/(GeV sr cm^2 s)]

J-factor from astrophysical observation

MadDM calculates the velocity averaged annihilation cross section

MadDM produces the energy spectra of the cosmic rays

See the tutorial for more details

1. Computation of <σv> for DM annihilation

General expression for <σv>

$$\langle \sigma v \rangle = \int d^3\boldsymbol{v}_1 d^3\boldsymbol{v}_2 P_{\boldsymbol{r}}(\boldsymbol{v}_1) P_{\boldsymbol{r}}(\boldsymbol{v}_2)\, \sigma v_{\rm rel}$$

Inclusive

- Very fast, but considers only **DM DM -> 2-body** (SM or BSM) at LO
- Takes $P(v) = \delta_D(v_{rel})$, integrates over angles
- 10-20 % agreement wrt the other two more precise methods

MadEvent

- Amplitudes for all relevant subprocesses + full phase space integration
- Generic **DM DM -> n-body**
- Generates unweighted events to pass to Pythia8

Reshuffling

- MadEvent + events re-weighting with a Maxwell-Boltzmann distribution

$$\tilde{P}_{\boldsymbol{r},\rm rel}(v_{\rm rel}) = \sqrt{\frac{2}{\pi}}\frac{v_{\rm rel}^2}{v_0^3}\exp\left(-\frac{v_{\rm rel}^2}{2v_0^2}\right)$$

2. Energy spectra for Cosmic Rays (CR) - 1

CR Energy spectra and indirect detection limits are typically presented in terms of DM annihilation into SM channels

$$\chi\chi \quad \rightarrow \quad gg, q\bar{q}, c\bar{c}, b\bar{b}, t\bar{t}, e^+e^-, \mu^+\mu^-, \tau^+\tau^-$$

100% branching ratio

$$\nu_e\bar{\nu}_e, \nu_\mu\bar{\nu}_\mu, \nu_\tau\bar{\nu}_\tau, ZZ, W^+W^-, hh$$

decay, shower, hadronization with Pythia8

CR energy spectra at source

$$\boxed{\gamma, \nu_e, \nu_\mu, \nu_\tau, e^+, \bar{p}}$$

Two ways of extracting the spectra

PPPC4DMID Tables

- Requires the installation of the PPPC4DMID module
- Fast but precise if annihilation is dominated by SM

Pythia8 Spectra

- Includes decays of BSM final states

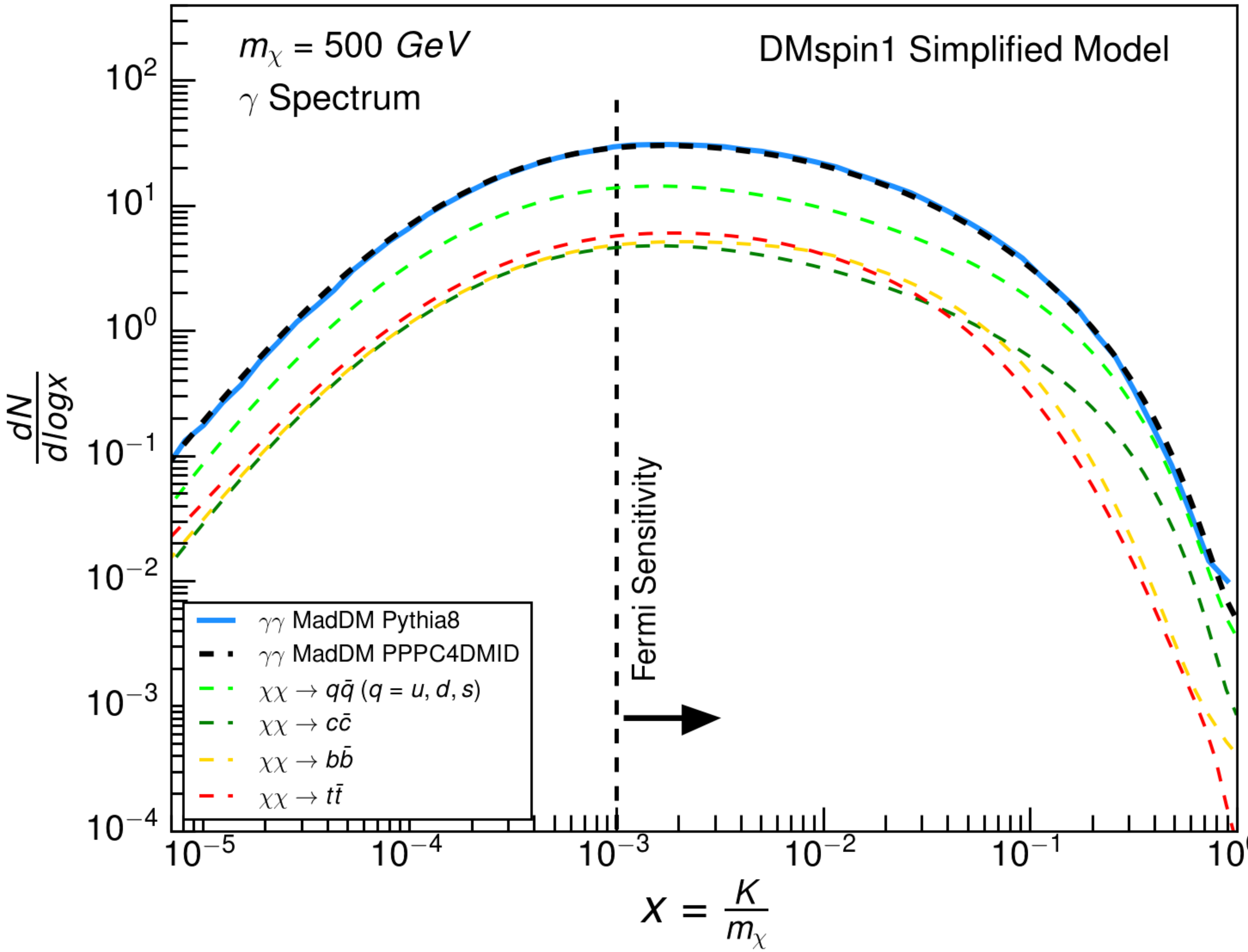
2. Energy spectra for Cosmic Rays (CR) - 2

PPPC4DMID = A Poor Particle Physicist Cookbook for Dark Matter Indirect Detection

http://www.marcocirelli.net/PPPC4DMID.html

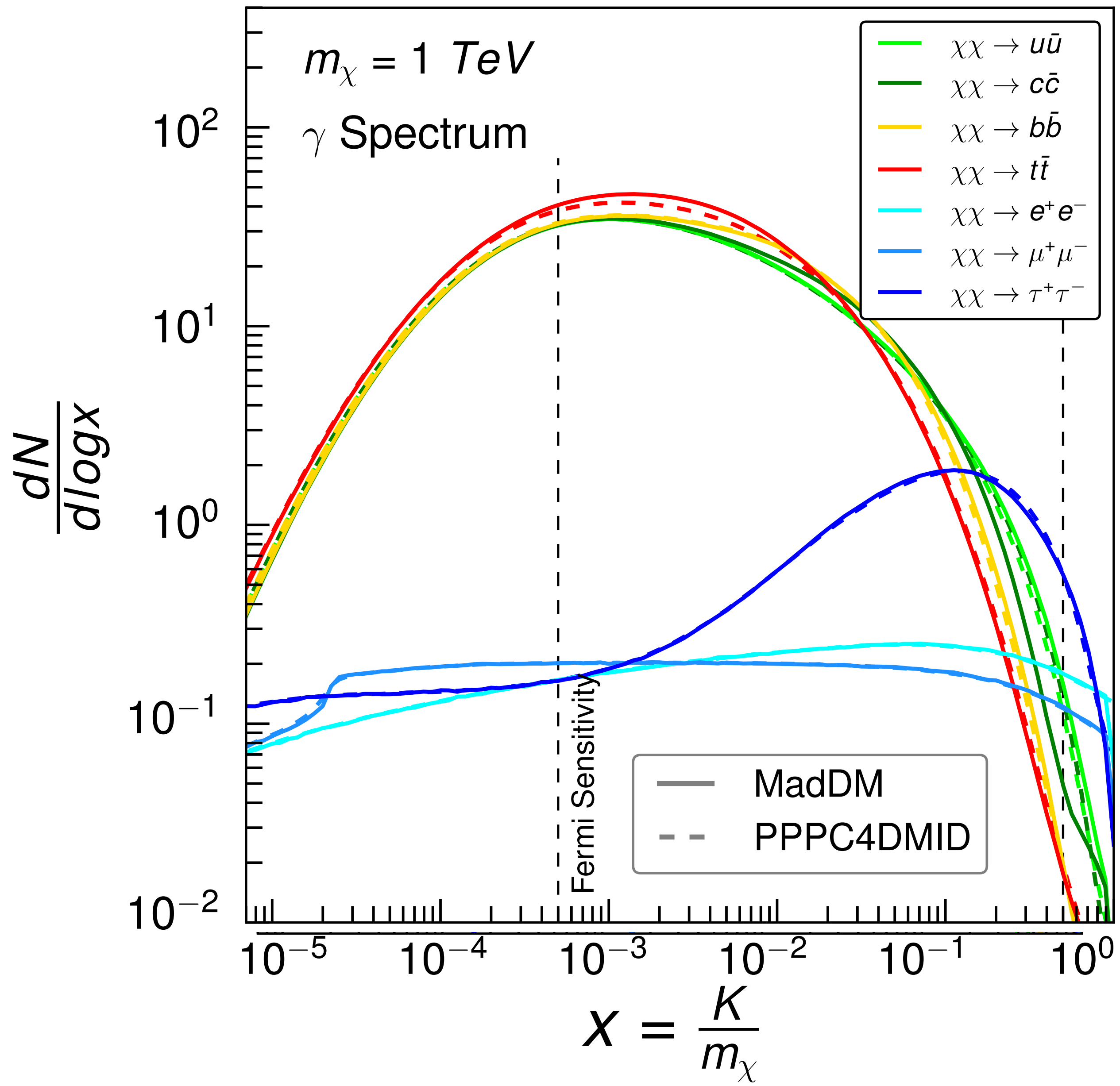
$$\chi\chi \quad \rightarrow \quad q\bar{q}, c\bar{c}, b\bar{b}, t\bar{t}$$

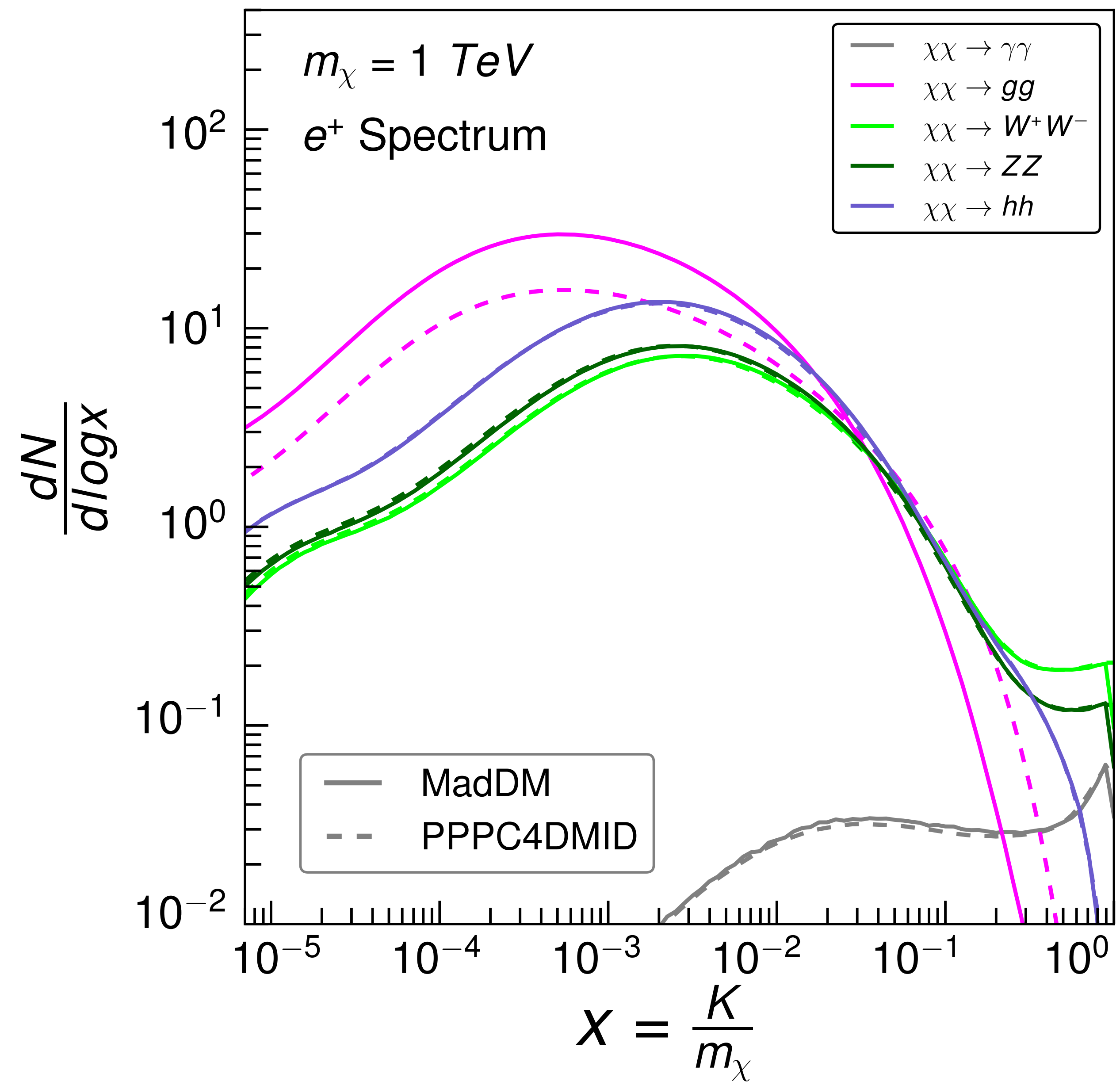
- MadDM includes the PPPD4DMID tabulated energy spectra for ***DM DM > SM SM***
- CR spectra added up according to their branching fraction



2. Energy spectra for Cosmic Rays - 3

$$\chi\chi \quad \to \quad gg, q\bar{q}, c\bar{c}, b\bar{b}, t\bar{t}, e^+e^-, \mu^+\mu^-, \tau^+\tau^-$$
$$\nu_e\bar{\nu}_e, \nu_\mu\bar{\nu}_\mu, \nu_\tau\bar{\nu}_\tau, ZZ, W^+W^-, hh$$



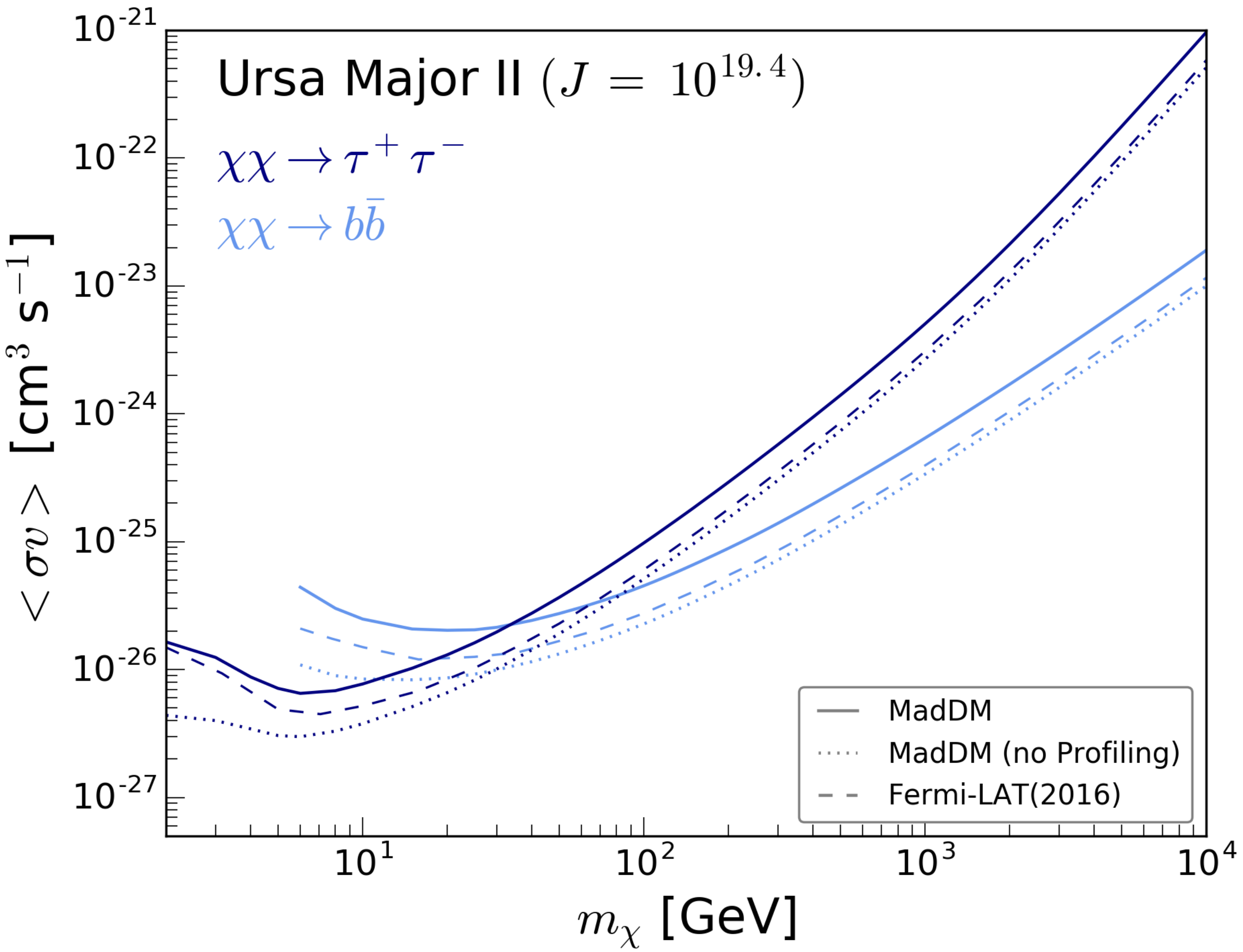


Fermi-LAT sensitive to γ in the energy range ~ [0.5 - 500 GeV]

- The Fermi collaboration gives limits on DM annihilation into two channels:

DM DM > $b\bar{b}$, $\tau^+\tau^-$

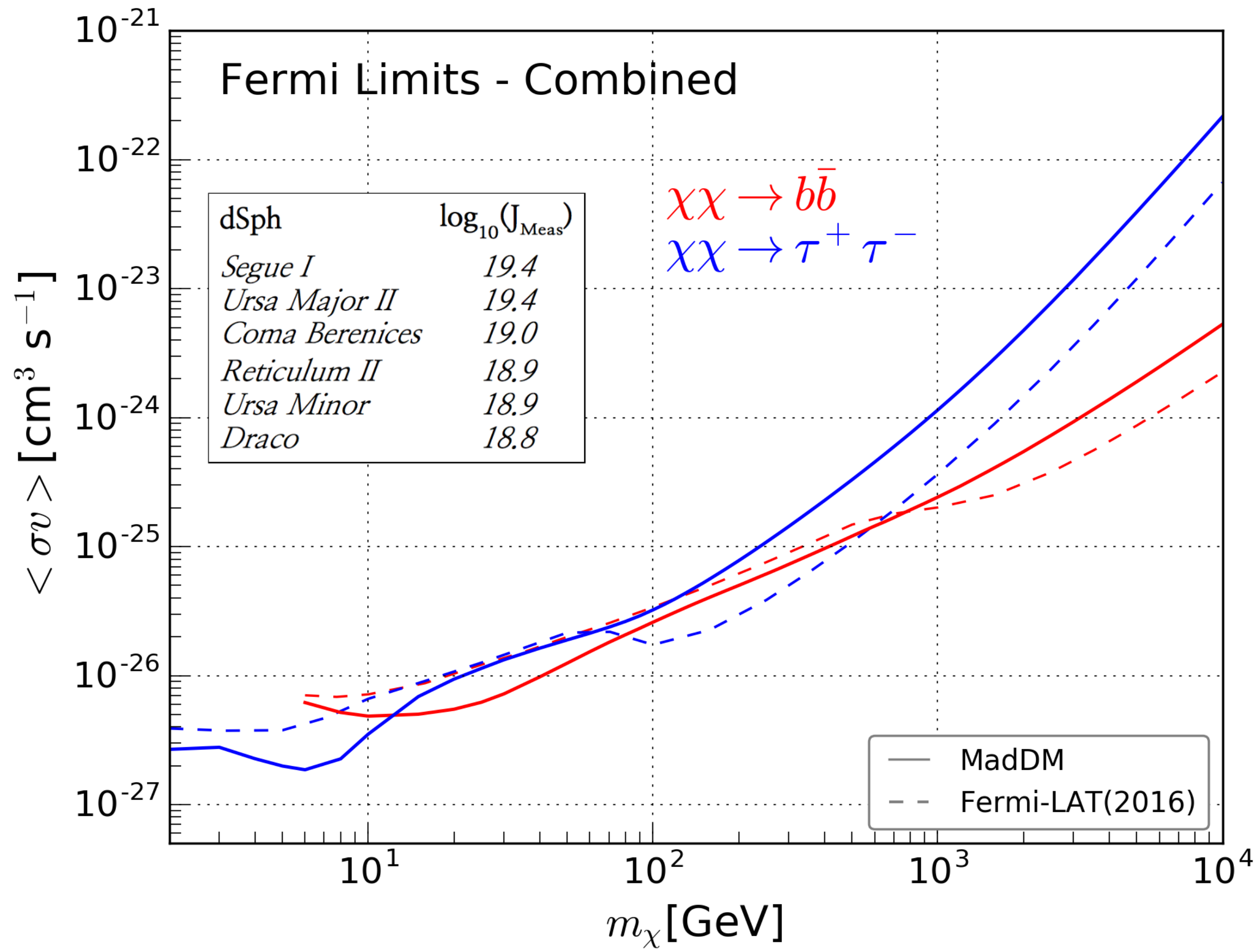
- They also made available the likelihood profiles for a set of dwarf spheroidal galaxies to derive the upper limits (UL) on <σv>



2. Fermi-LAT limits

- MadDM makes use of the likelihood profiles for the 6 dwarf spheroidal galaxies with the highest J-factors to extract the combined limits
- It is possible to calculate the limits for arbitrary

DM DM > SM SM



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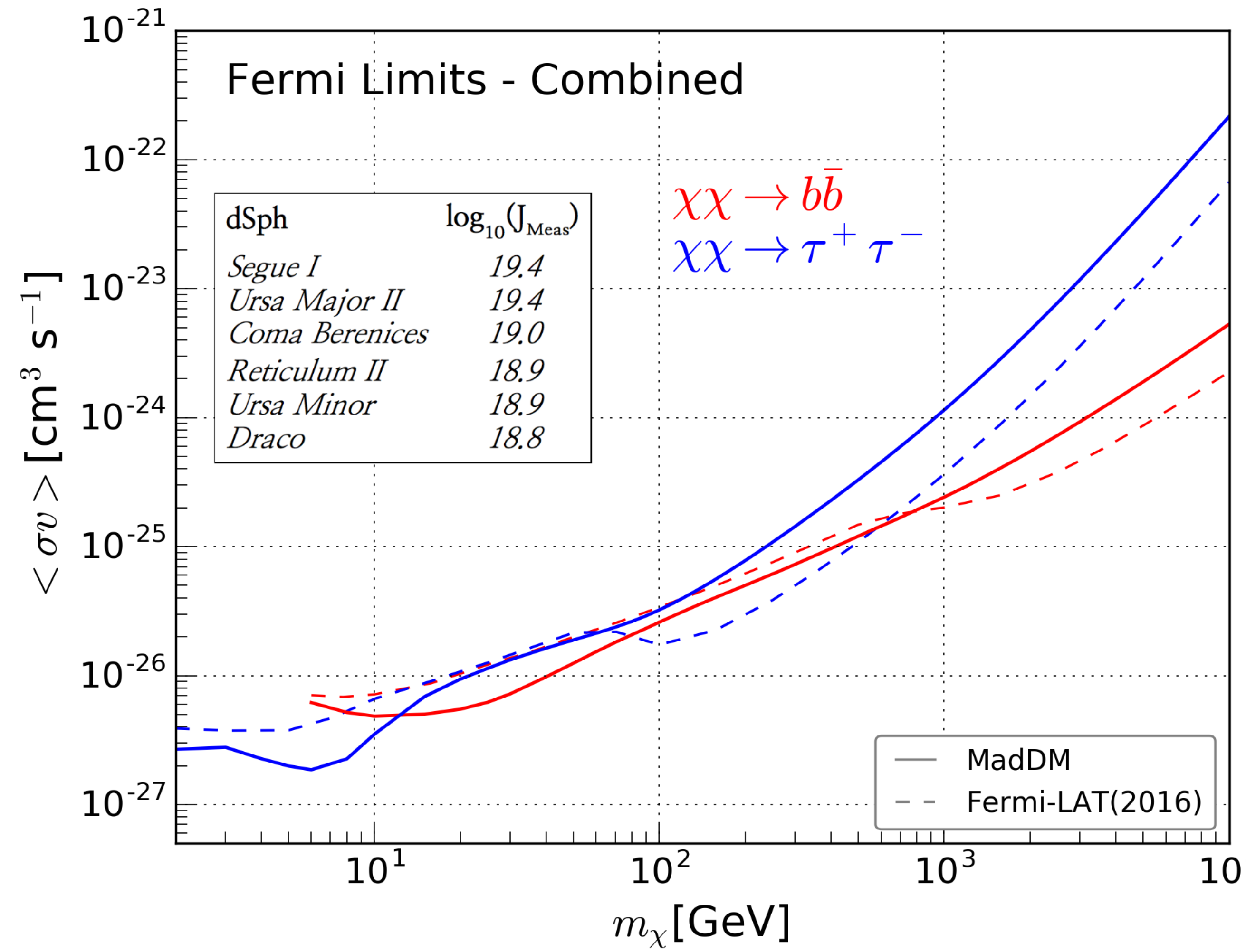

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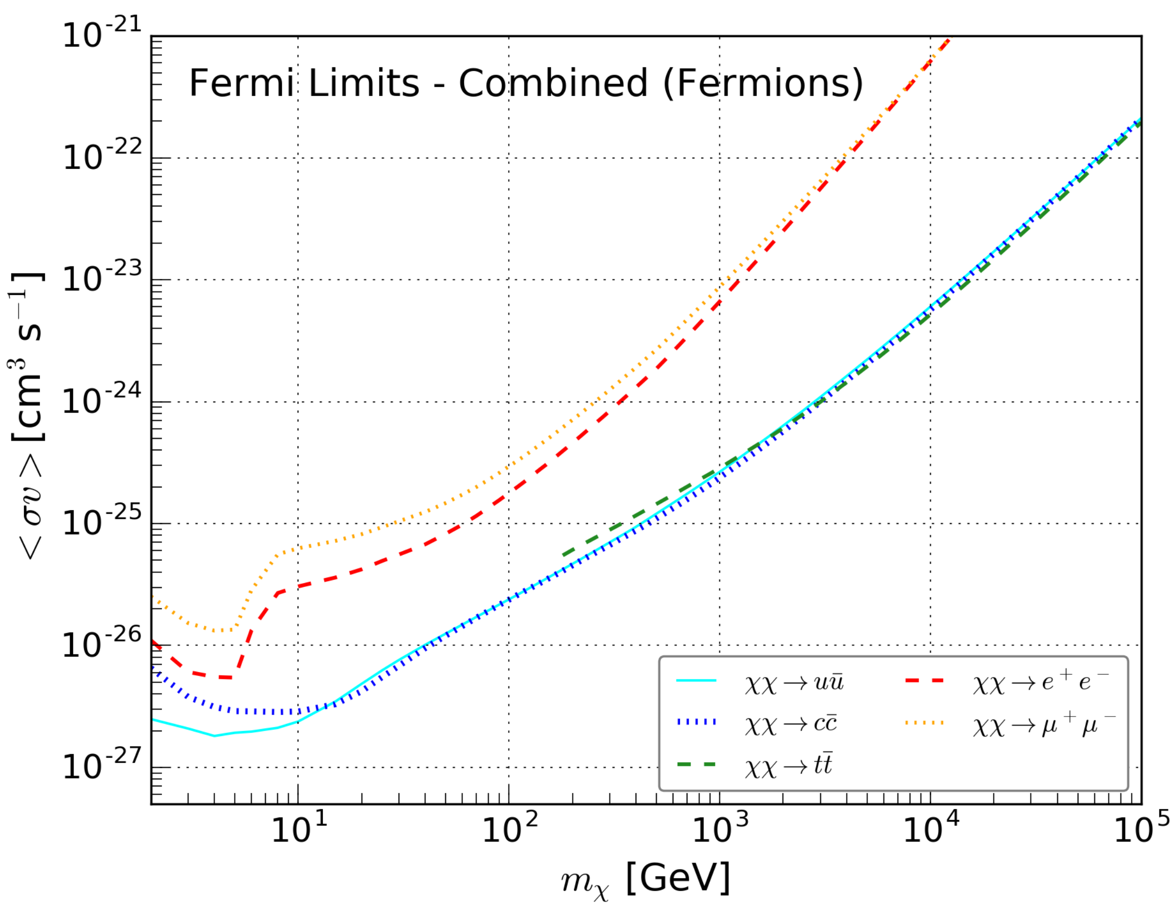

- Added the new limits in the Exp. constraints module

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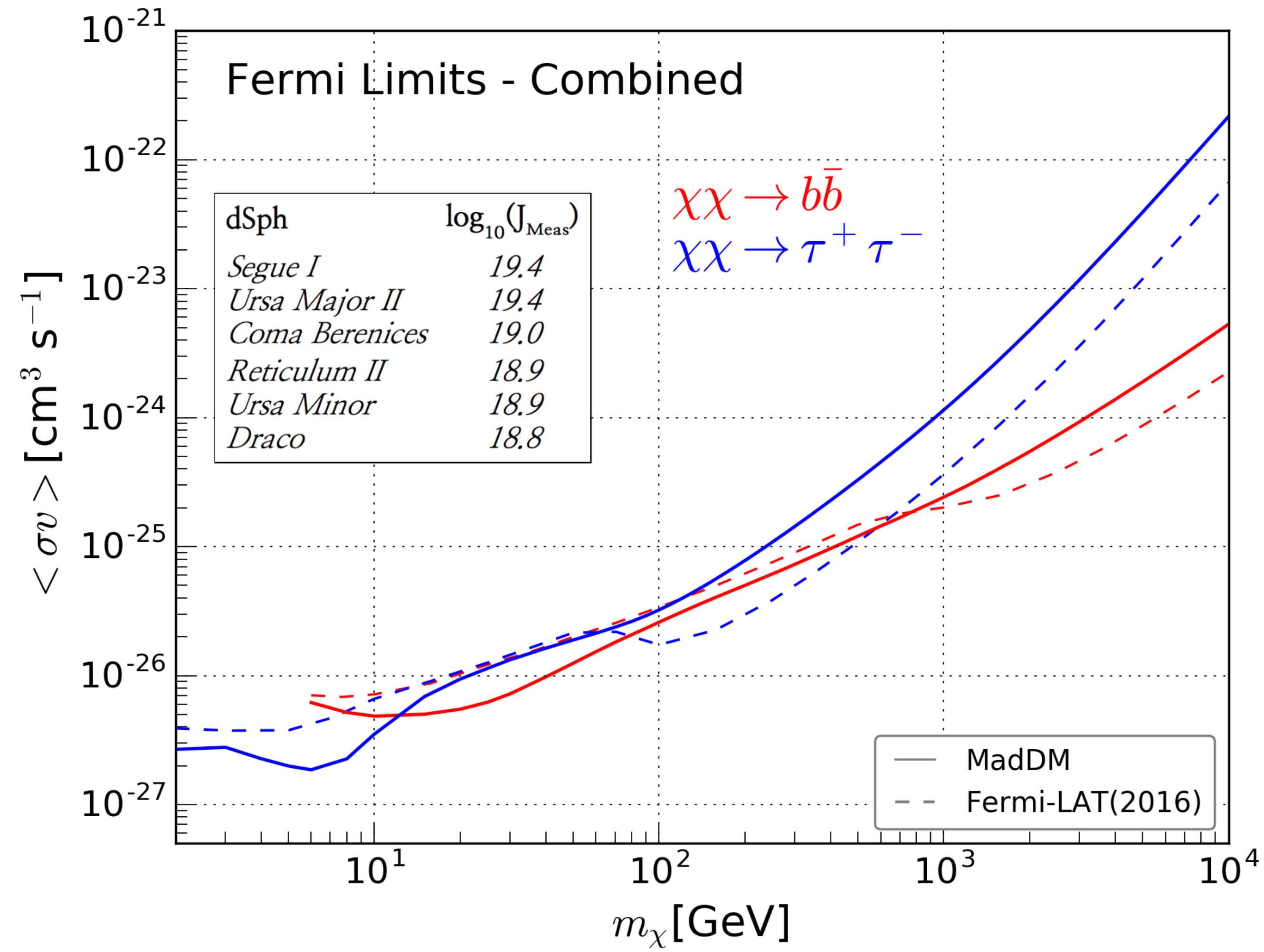
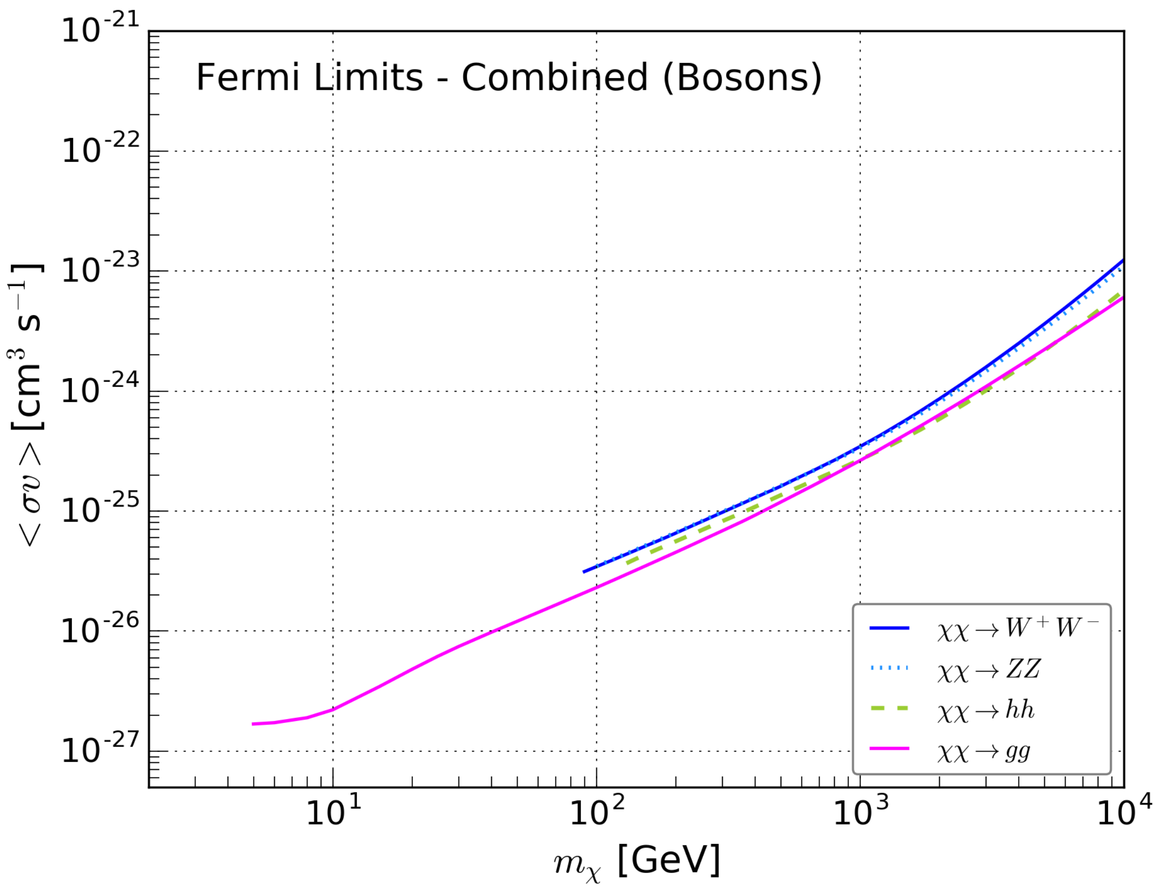




- We calculated the limits of any

  DM DM > SM SM
- Added the new limits in the Exp. constraints module

3. Experimental Constraints class

Relic Density : **Ωh^2 Planck**

Direct detection:

Spin independent	***XENONT1***
Spin dependent - neutrons	***LUX***
Spin dependent - protons	***PICO 60***

Indirect detection:

- Precomputed limits for DM DM > SM SM
- On the fly computation with the global gamma ray spectra

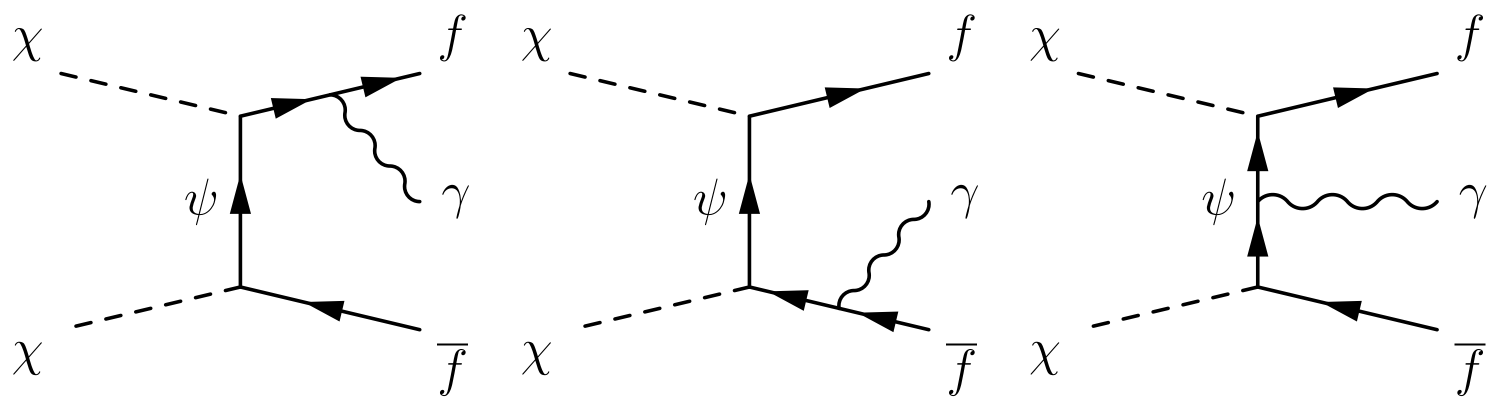
Fermi-LAT likelihood

The users can easily update and extend the experimental upper limits

Example: helicity suppression lift

Interesting process that can be easily implemented in MadDM

$$\mathcal{L} \supset y_R \chi_r \bar{\Psi}_R q_R + y_L \chi_r \bar{\Psi}_L Q_L + h.c.$$



DM DM > f f' γ *(2 -> 3)*
internal bremsstrahlung

- χ: real scalar DM coupling to Fermions
- Ψ: fermionic mediator
- DM DM > f f' is s-wave and p-wave suppressed
- DM DM > f f' γ gets enhanced (s-wave contribution)

$$\sigma v \propto v^4$$

see tutorial for an example

Example: helicity suppression lift

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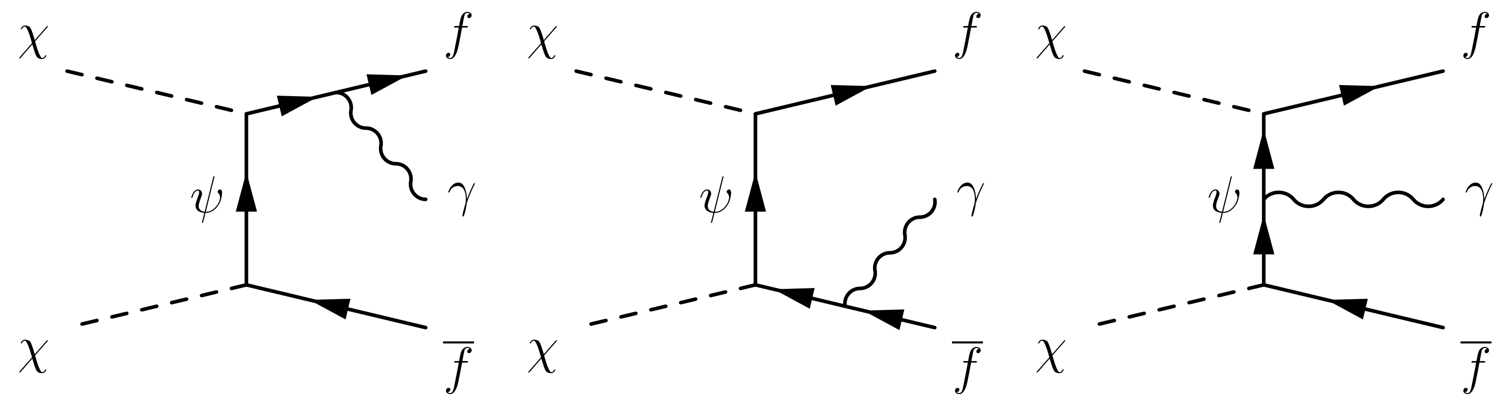
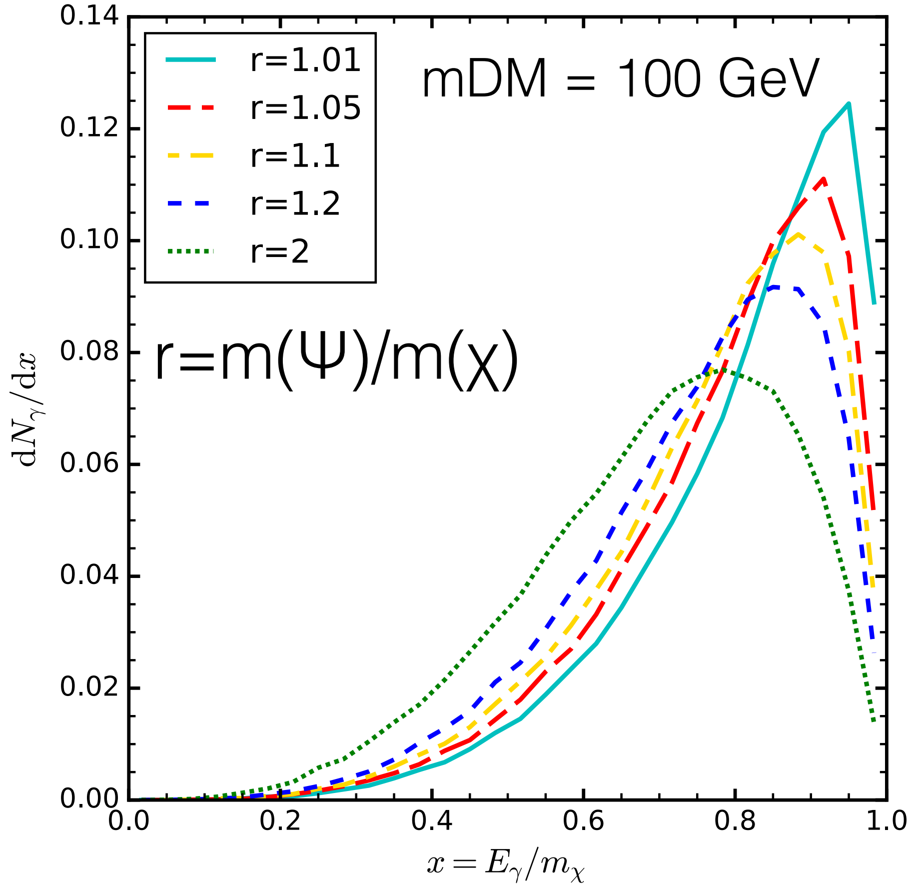
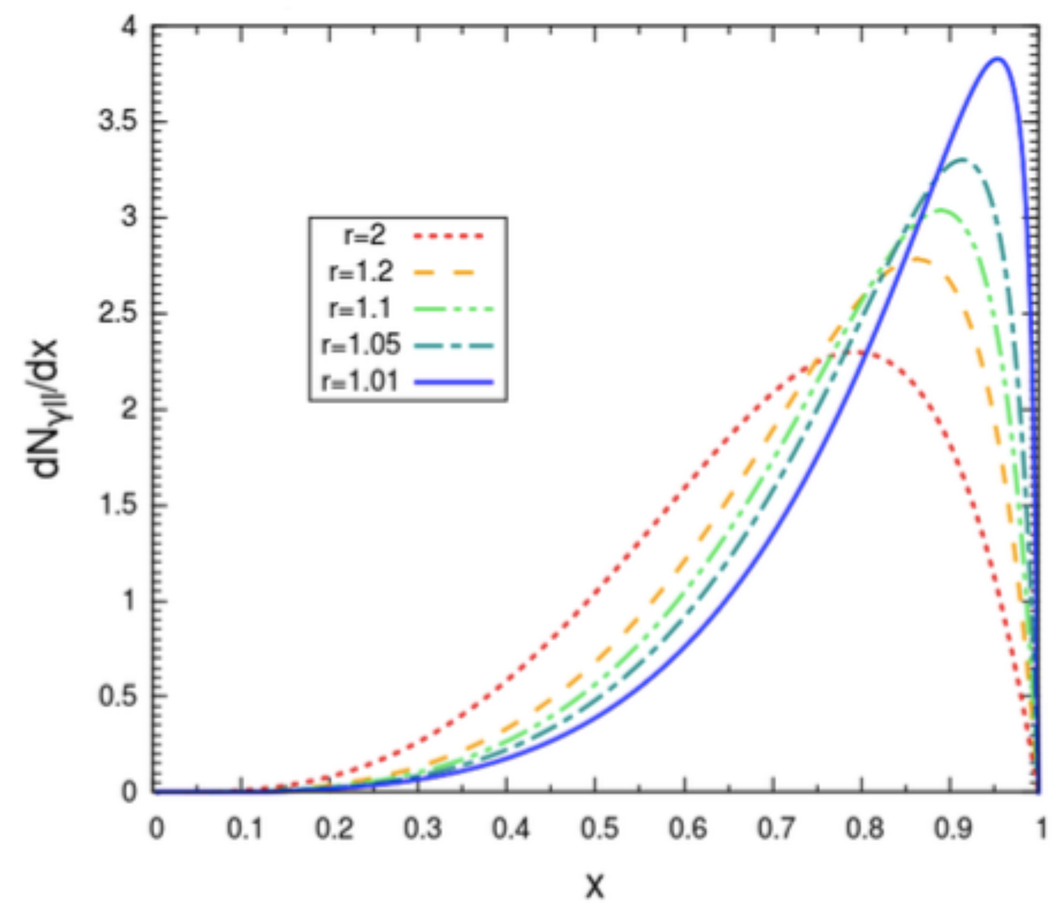


MadDM v.3.0



VS



https://arxiv.org/abs/1307.6480

4. Cosmic Rays Propagation - fluxes at detection

$$\frac{d\Phi}{dE_\gamma}(E_\gamma, \psi) = \frac{\langle \sigma v \rangle}{2m_\chi^2} \sum_i B_i \frac{dN_\gamma^i}{dE_\gamma} \frac{1}{4\pi} \int_\psi \frac{d\Omega}{\Delta\psi} \int_{\text{los}} \rho^2(\psi, l)\, dl$$

[particles/(GeV sr cm^2 s)]

- **Neutrinos oscillations (from far galaxies to Earth)**

- **PPPC4DMID Tables for e+**

  Halo profile: **NFW, Moore, Einasto, Isothermal**
  Galactic magnetic field model: **MF1, MF2, MF3**
  Propagation model: **MIN, MED, MAX**

- **DRAGON**

  Interface with the fully numerical code DRAGON for the propagation of positrons/antiprotons within the galaxy

Conclusions and Outlook

- MadDM v.3.0 is out (beta version)
- Currently in a stand-alone package, requires MG5_aMC new release
- Brand new functionalities for DM indirect detection
- Experimental limits class than can be loaded outside MadDM
- New dedicated module for parameter space scanning

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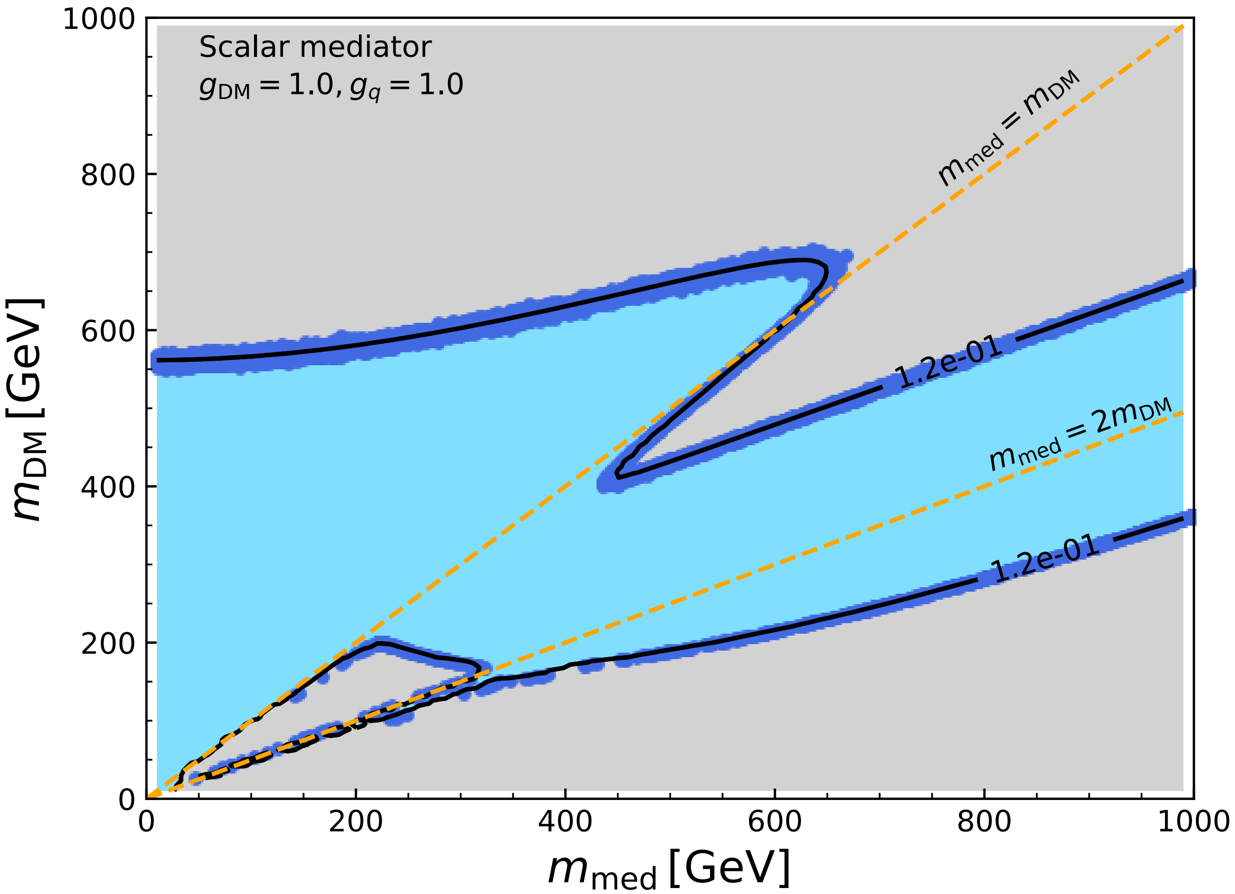
Thank you!

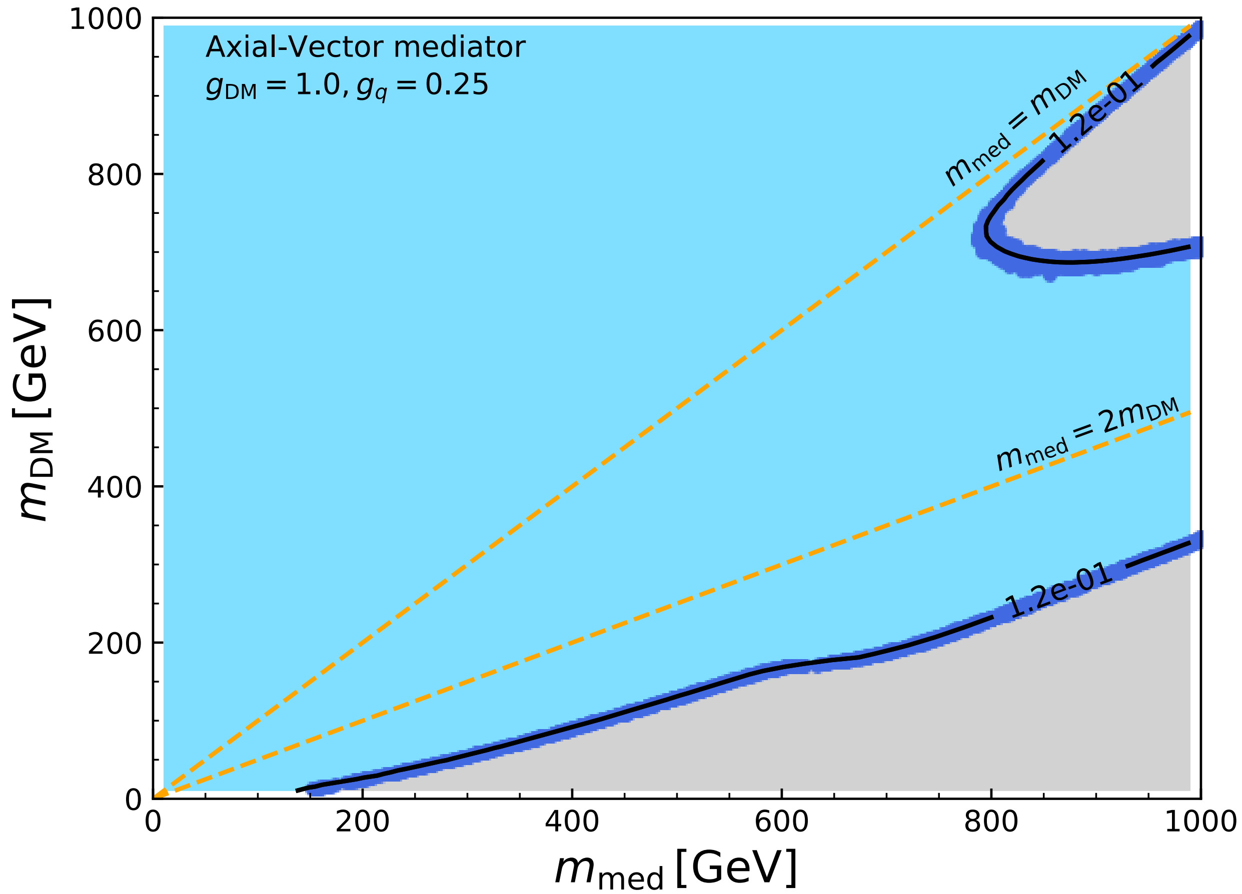
See also the tutorial presentation

Backup

Scanning the parameter space with PyMultiNest



Dirac DM candidate
s-channel scalar mediator



Dirac DM candidate
s-channel spin1 axial-vector

- Black solid lines obtained with the sequential scan
- Dark blue dots: points sampled by PyMultiNest requiring that the relic density matches Planck measured value

Example: helicity suppression lift

$$\sigma v_{f\bar{f}} = \frac{y_L^4}{4\pi m_\chi^2}\frac{m_f^2}{m_\chi^2}\frac{1}{(1+\mu)^2} - \frac{y_L^4}{6\pi m_\chi^2}\frac{m_f^2}{m_\chi^2}\frac{1+2\mu}{(1+\mu)^4}v^2 \quad + \frac{y_L^4}{60\pi m_\chi^2}\frac{1}{(1+\mu)^4}v^4 + \mathcal{O}\left(v^6\right)$$

s-wave , p-wave suppression

$$\sigma v_{f\bar{f}\gamma}^{\mathrm{VIB}} = \frac{Q^2 \alpha_{\mathrm{em}} y_L^4}{8\pi^2 m_\chi^2} \; + \; \ldots$$

cross section enhancement

Introduction: overview

MadDM capabilities

For a generic dark matter model with UFO files

<u>Relic density</u> (MadDM v.1.0)

- Coannihilation
- Multi-component dark matter

<u>Direct detection</u> (MadDM v.2.0)

- Theoretical elastic spin-independent and spin-dependent cross section dark matter off nucleons
- Directional event rate (double differential event rate)
- LUX likelihood

<u>Indirect detection</u> (MadDM v.3.0)

- Theoretical prediction for the velocity averaged cross section at present time
- Generation of energy spectra from dark matter annihilation
- Computation of fluxes at source and detection
- Fermi-LAT likelihood for dwarf spheroidal galaxies

<u>Model parameter space sampling</u> (MadDM v.3.0)

- Sequential grid scan
- PyMultiNest interface

<u>Experimental constraints module</u> (MadDM v.3.0)

Computation of <σv> - more

$$\langle \sigma v \rangle = \int d^3\boldsymbol{v}_1 d^3\boldsymbol{v}_2 P_{\boldsymbol{r}}(\boldsymbol{v}_1) P_{\boldsymbol{r}}(\boldsymbol{v}_2)\, \sigma v_{\rm rel} \xrightarrow{\text{rewrite}} \langle \sigma v \rangle = \int dv_{\rm rel}\, \tilde{P}_{\boldsymbol{r},{\rm rel}}(v_{\rm rel})\, \sigma v_{\rm rel}$$

$$\tilde{P}_{\boldsymbol{r},{\rm rel}}(v_{\rm rel}) = \sqrt{\frac{2}{\pi}} \frac{v_{\rm rel}^2}{v_0^3} \exp\left(-\frac{v_{\rm rel}^2}{2v_0^2}\right)$$

Maxwell-Boltzmann distribution

If σ is dominated by s-wave + p-wave terms: $v_{rel} = \sqrt{3} v_0$

Example: results

MadDM screen output

```
***** Relic Density
INFO: Relic Density         = 3.06e-03       ALLOWED
INFO: x_f                   = 2.60e+01
INFO: sigmav(xf)            = 3.96e-08
INFO: xsi                   = 2.56e-02
INFO:
***** Direct detection [cm^2]:
INFO: SigmaN_SI_p           Thermal = 9.76e-40      EXCLUDED       All DM = 3.82e-38       EXCLUDED         Xenon1ton ul       = 6.44e-46
INFO: SigmaN_SI_n           Thermal = 9.72e-40      EXCLUDED       All DM = 3.80e-38       EXCLUDED         Xenon1ton ul       = 6.44e-46
INFO: SigmaN_SD_p           Thermal = 1.01e-62      ALLOWED        All DM = 3.93e-61       ALLOWED          Pico60 ul          = 2.03e-40
INFO: SigmaN_SD_n           Thermal = 4.64e-62      ALLOWED        All DM = 1.81e-60       ALLOWED          Lux2017 ul         = 1.22e-40
INFO:
****** Indirect detection [cm^3/s]:
INFO: <sigma v> method: madevent
INFO: DM particle halo velocity: 2e-05/c
INFO: xxdxxdb_ccx           Thermal = 1.19e-28      ALLOWED        All DM = 1.83e-25       EXCLUDED         Fermi ul           = 1.19e-25
INFO: xxdxxdb_ddx           Thermal = 1.19e-28      ALLOWED        All DM = 1.83e-25       EXCLUDED         Fermi ul           = 1.20e-25
INFO: xxdxxdb_uux           Thermal = 1.19e-28      ALLOWED        All DM = 1.83e-25       EXCLUDED         Fermi ul           = 1.20e-25
INFO: xxdxxdb_bbx           Thermal = 1.19e-28      ALLOWED        All DM = 1.83e-25       EXCLUDED         Fermi ul           = 1.21e-25
INFO: xxdxxdb_ssx           Thermal = 1.19e-28      ALLOWED        All DM = 1.83e-25       EXCLUDED         Fermi ul           = 1.20e-25
INFO: xxdxxdb_ttx           Thermal = 1.19e-28      ALLOWED        All DM = 1.81e-25       EXCLUDED         Fermi ul           = 1.44e-25
INFO: xxdxxdb_y1y1          Thermal = 5.34e-28      NO LIMIT       All DM = 8.16e-25       NO LIMIT         Fermi ul           = -1.00e+00
INFO: Skipping zero cross section processes for: emep, mummup, xxcxxcb, vlvl, tamtap
INFO: Using generic Fermi limits for light quarks (u,d,s)
INFO: Total limits calculated with Fermi likelihood:
INFO: DM DM > all           Thermal = 1.25e-27      ALLOWED        All DM = 1.91e-24       EXCLUDED         Fermi ul           = 4.19e-25
```

[Run using Madevent + Pythia8]

Example: results

MadDM screen output

Theory Predictions

Exp. UL

```
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INFO: x_f                 = 2.60e+01
INFO: sigmav(xf)          = 3.96e-08
INFO: xsi                 = 2.56e-02
INFO:
***** Direct detection [cm^2]:
INFO: SigmaN_SI_p         Thermal = 9.76e-40    EXCLUDED     All DM = 3.82e-38    EXCLUDED     Xenon1ton ul     = 6.44e-46
INFO: SigmaN_SI_n         Thermal = 9.72e-40    EXCLUDED     All DM = 3.80e-38    EXCLUDED     Xenon1ton ul     = 6.44e-46
INFO: SigmaN_SD_p         Thermal = 1.01e-62    ALLOWED      All DM = 3.93e-61    ALLOWED      Pico60 ul        = 2.03e-40
INFO: SigmaN_SD_n         Thermal = 4.64e-62    ALLOWED      All DM = 1.81e-60    ALLOWED      Lux2017 ul       = 1.22e-40
INFO:
****** Indirect detection [cm^3/s]:
INFO: <sigma v> method: madevent
INFO: DM particle halo velocity: 2e-05/c
INFO: xxdxxdb_ccx         Thermal = 1.19e-28    ALLOWED      All DM = 1.83e-25    EXCLUDED     Fermi ul         = 1.19e-25
INFO: xxdxxdb_ddx         Thermal = 1.19e-28    ALLOWED      All DM = 1.83e-25    EXCLUDED     Fermi ul         = 1.20e-25
INFO: xxdxxdb_uux         Thermal = 1.19e-28    ALLOWED      All DM = 1.83e-25    EXCLUDED     Fermi ul         = 1.20e-25
INFO: xxdxxdb_bbx         Thermal = 1.19e-28    ALLOWED      All DM = 1.83e-25    EXCLUDED     Fermi ul         = 1.21e-25
INFO: xxdxxdb_ssx         Thermal = 1.19e-28    ALLOWED      All DM = 1.83e-25    EXCLUDED     Fermi ul         = 1.20e-25
INFO: xxdxxdb_ttx         Thermal = 1.19e-28    ALLOWED      All DM = 1.81e-25    EXCLUDED     Fermi ul         = 1.44e-25
INFO: xxdxxdb_y1y1        Thermal = 5.34e-28    NO LIMIT     All DM = 8.16e-25    NO LIMIT     Fermi ul         = -1.00e+00
INFO: Skipping zero cross section processes for: emep, mummup, xxcxxcb, vlvl, tamtap
INFO: Using generic Fermi limits for light quarks (u,d,s)
INFO: Total limits calculated with Fermi likelihood:
INFO: DM DM > all         Thermal = 1.25e-27    ALLOWED      All DM = 1.91e-24    UDED         Fermi ul         = 4.19e-25
```

Limits stored in the Exp. class module

Calculated 'on the fly' with Pyhtia8/PPPC4DMID spectrum

[Run using Madevent + Pythia8]