MadDM v.3.0

Federico Ambrogi
(MC short term student @ CP3 Louvain-La-Neuve)

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

MCNet Network Meeting
April 11th 2018 - CERN (Geneva)

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 / twiki page below
- completely integrated in the MG5 framework

—> *after beta phase*: ./bin/mg5_aMC

install madd

- Currently uses an un-released version of MG5 (no direct installation yet)

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**

See slide 8

- inherits the capabilities of MG5 to automatically compute and generate 'complicated' processes (e.g. ***DM DM > u u~ γ***)
- dedicated module for indirect detection theory predictions
- independent module for *experimental constrains*
- advanced functionalities for scanning from MG5 or **PyMultiNest**

Indirect Detection Module - keywords

Main improvements for physics studies, allowing to:

- compute DM annihilation cross section

Inclusive

Madevent

Reshuffling

- 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

./bin/maddm.py

```
=====================================================
|                    MadDM v3.0                     |
=====================================================

                Launchpad:  launchpad.net/maddm

                            arXiv:1308.4955
                            arXiv:1505.04190

Need to learn? -> type tutorial

=====================================================
|          A MadGraph5_aMC@NLO plugin.              |
=====================================================
*        VERSION 2.6.2.beta          2018-03-30       *
*        BZR maddm_dev2                     390       *

The following switches determine which programs are run:
/============== Description ==============|================== values ==================|========== other options ===========\
| 1. Compute the Relic Density            |          relic = ON                         |     OFF                            |
| 2. Compute direct(ional) detection      |         direct = directional                |     direct|OFF                     |
| 3. Compute indirect detection/flux      |       indirect = sigmav                     |     flux_source|flux_earth|OFF |
| 4. Run Multinest scan                   |       nestscan = OFF                        |     Please install module          |
\=====================================================================================================================================/
 You can also edit the various input card:
 * Enter the name/number to open the editor
 * Enter a path to a file to replace the card
 * Enter set NAME value to change any parameter to the requested value
 /=========================================================================\
 |  5. Edit the model parameters     [param]                               |
 |  6. Edit the MadDM options        [maddm]                               |
 \=========================================================================/
```

Focus on the Indirect detection module

1. Computation of <σv> for DM annihilation

General expression for <σv>

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

Inclusive

- Very fast, but consider 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

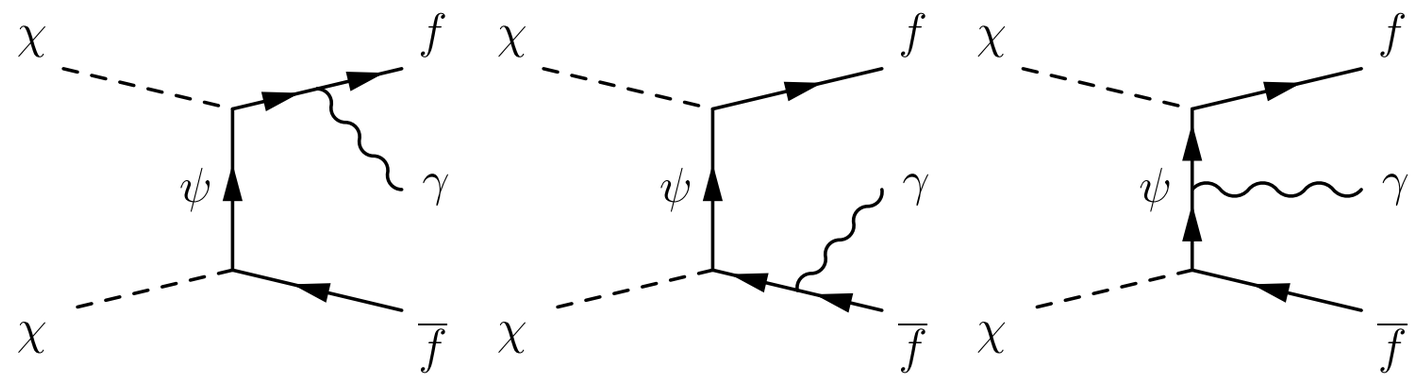
- MadEvent + events re-weighting with a Maxwell-Boltzmann distribution

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

Example: helicity suppression lift

Interesting DM model studied a few years ago to explain the (gone) gamma rays galactic excess ~ 130 GeV

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



DM DM > f f' γ *(2 -> 3)*

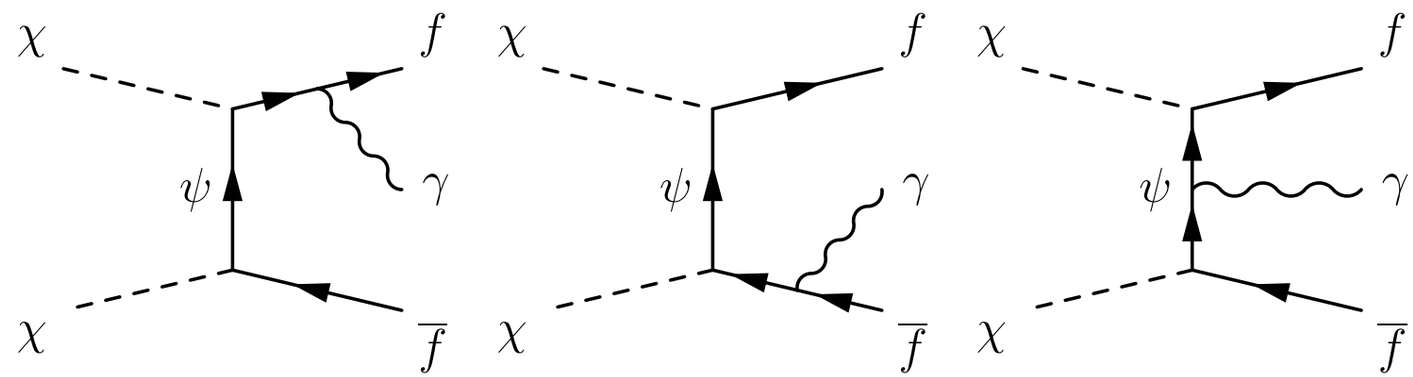
internal bremsstrahlung

- χ: fermionic DM coupling to Fermions
- Ψ: fermionic mediator, color triplet
- DM DM > f f' is s-wave and p-wave suppressed $\sigma v \propto v^4$
- DM DM > f f' γ gets enhanced (s-wave contribution)
- can be tuned to get <σv> and gamma lines to explain the excess

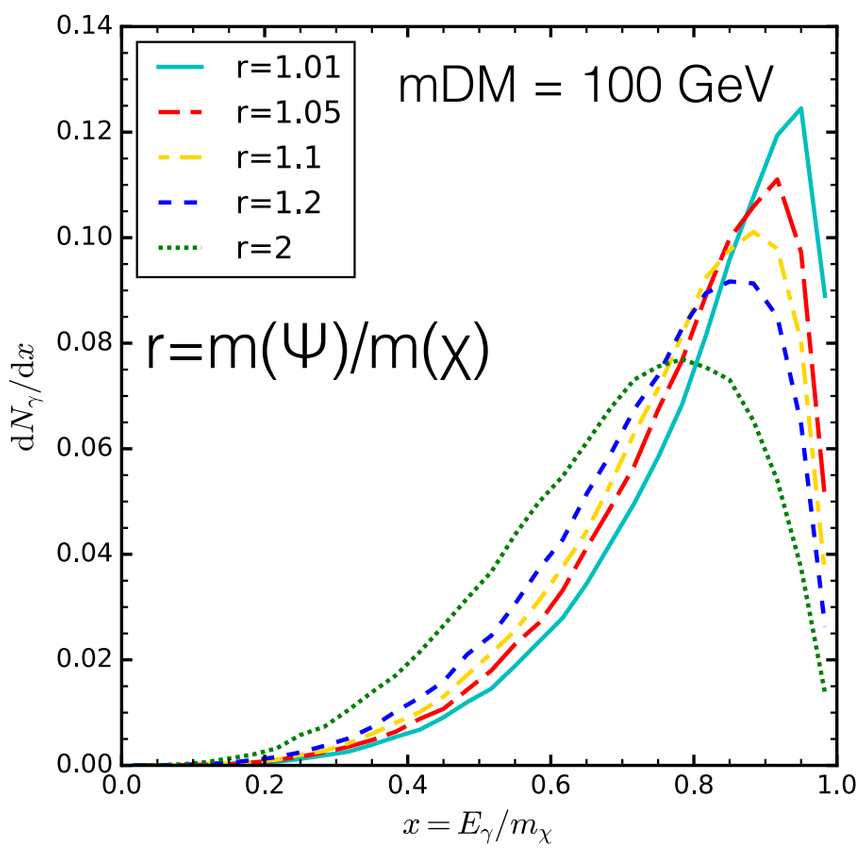
Example: helicity suppression lift

Interesting DM model studied a few years ago to explain the (gone) gamma rays galactic excess ~ 130 GeV

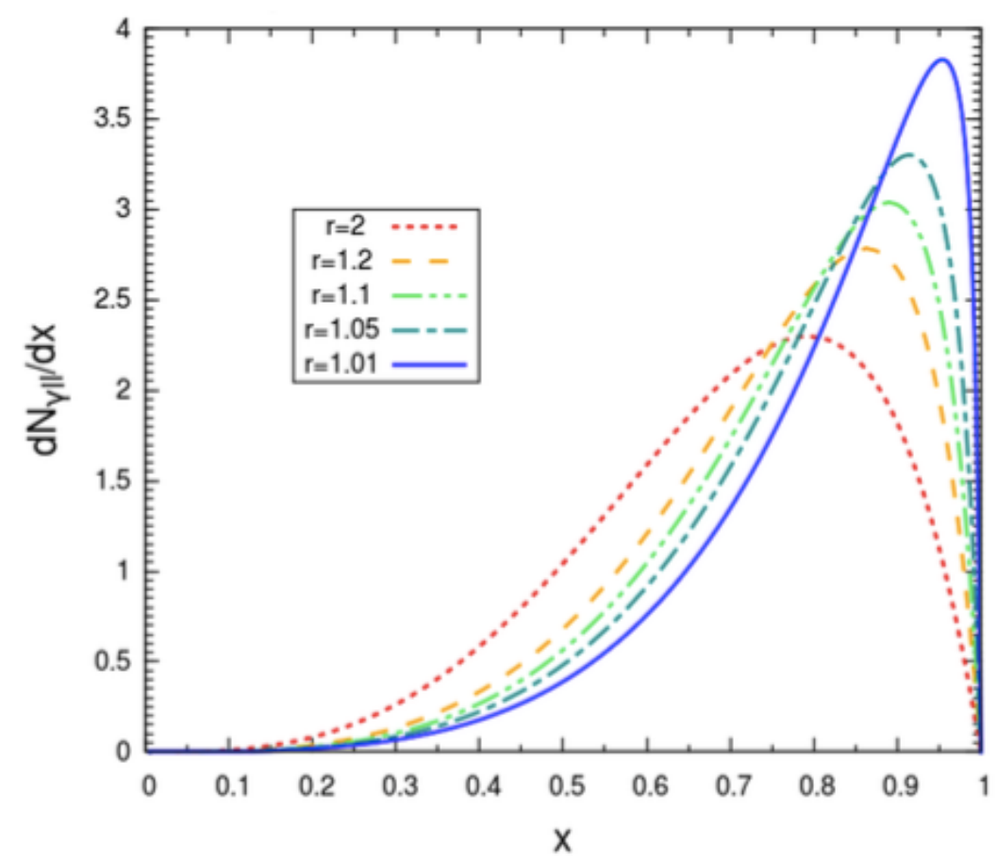
$$\mathcal{L} \supset y_R \chi_r \bar{\Psi}_R q_R + y_L \chi_r \bar{\Psi}_L Q_L + h.c.$$



MadDM v.3.0



VS



work by Fabio, Luca

https://arxiv.org/abs/1307.6480

2. Energy spectra for Cosmic Rays (CR)

CR Energy spectra and indirect detection limits from Fermi-LAT 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, hadronize… 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

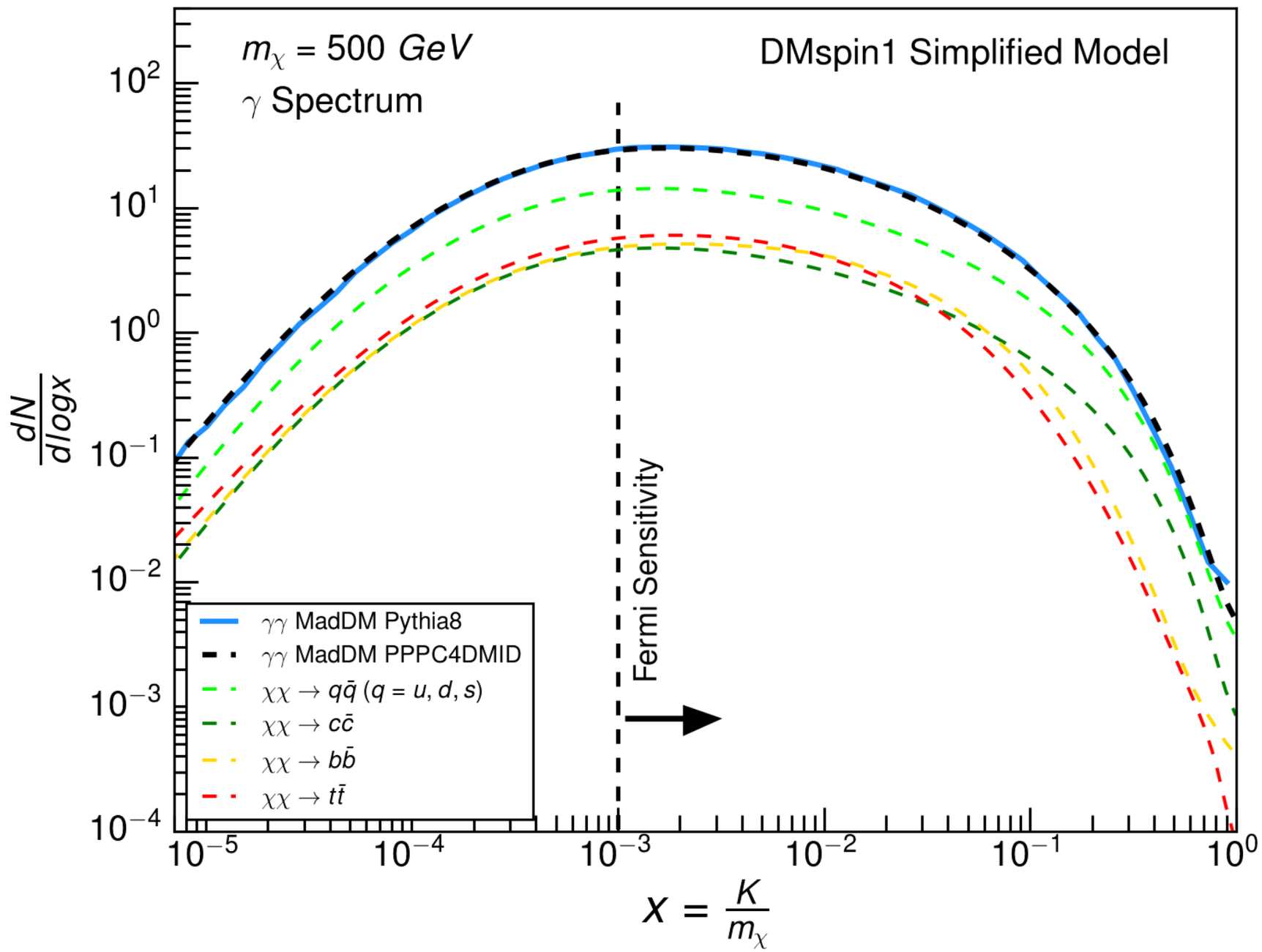
2. Energy spectra for Cosmic Rays - 2

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

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

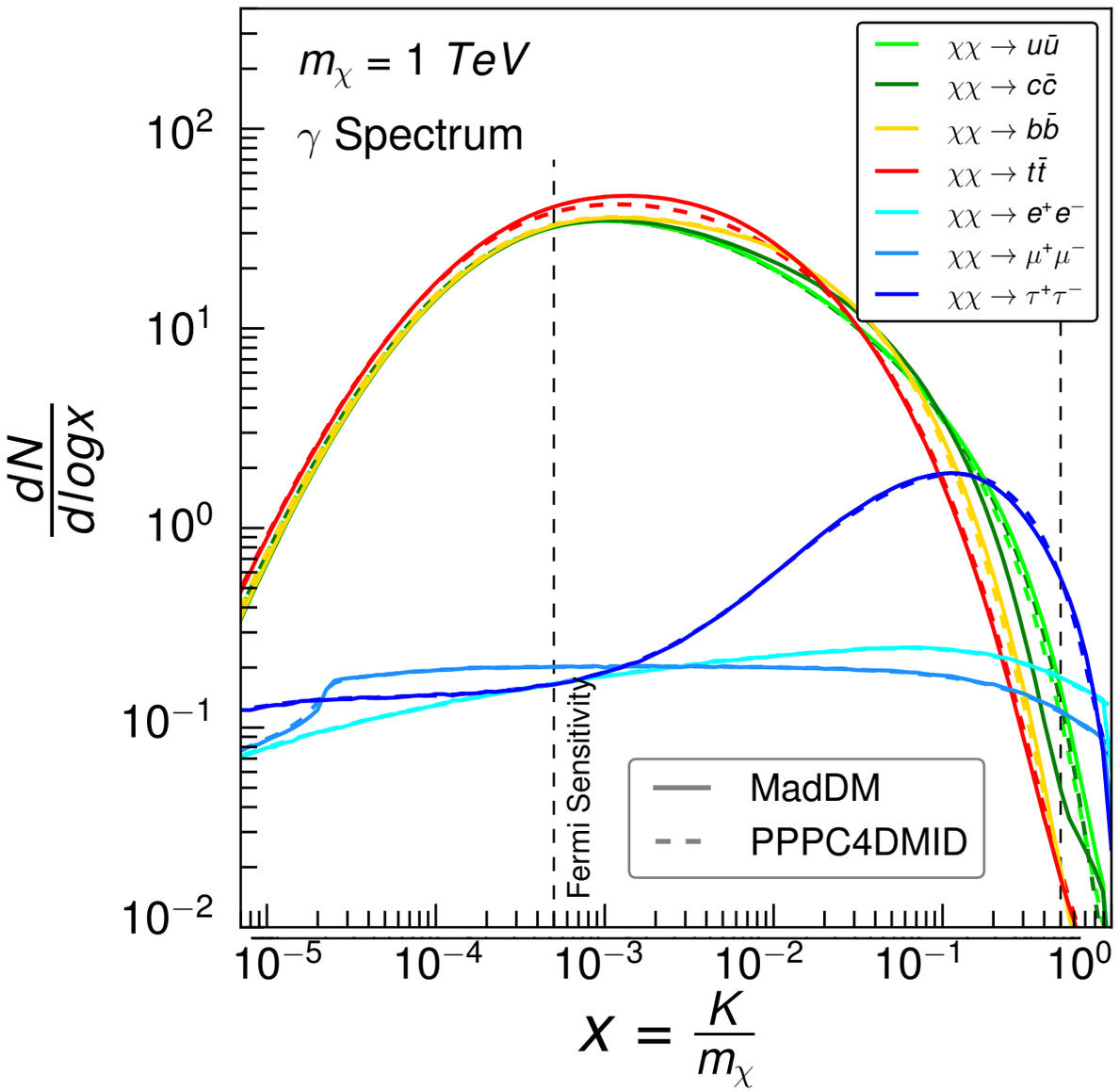
$$\chi\chi \quad \rightarrow \quad q\bar{q}, c\bar{c}, b\bar{b}, t\bar{t}$$

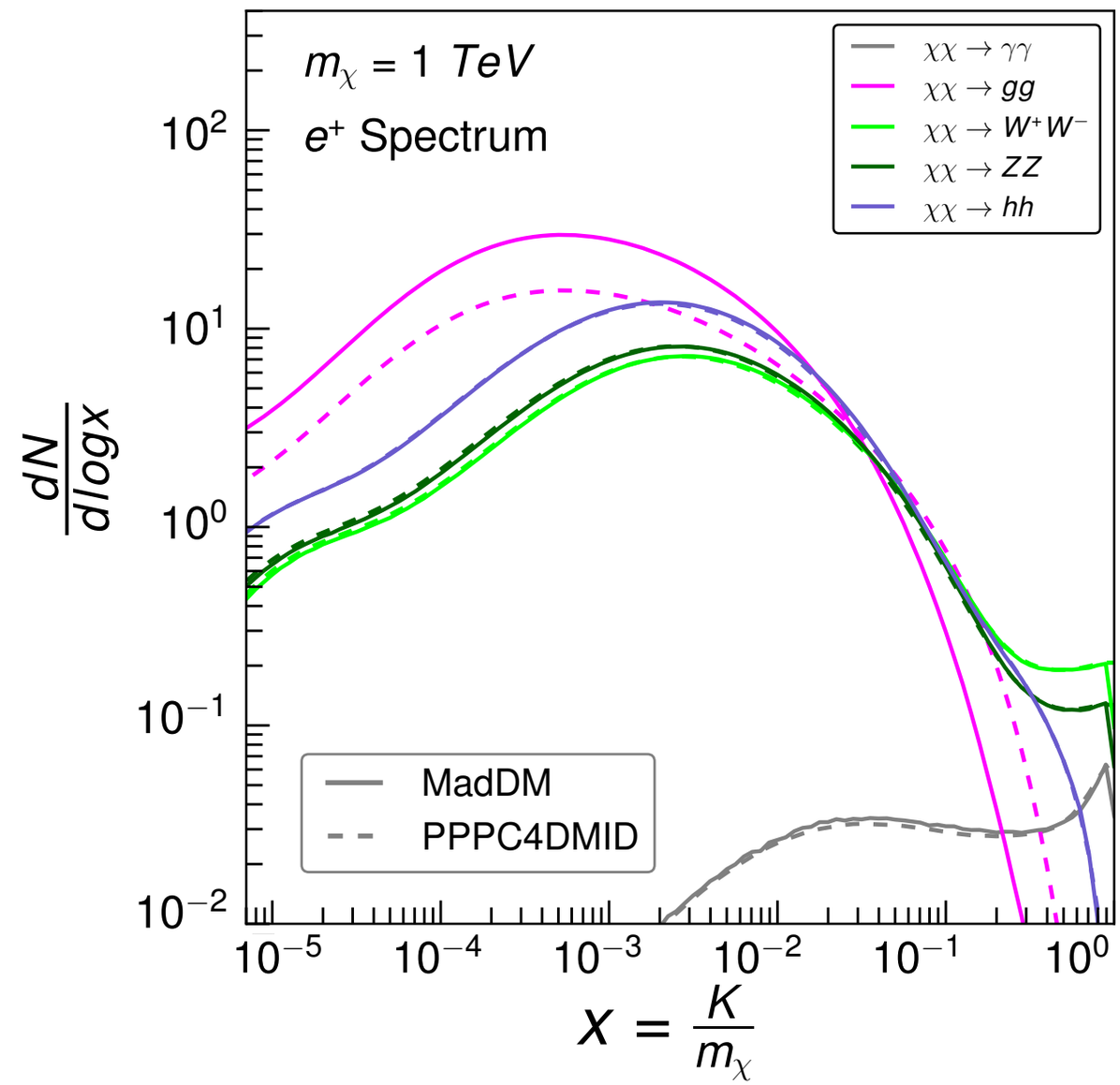
- MadDM includes the PPPD4DMID tabulated energy spectra for ***DM DM > SM SM***
- CR spectra added up according to their branching fraction



2. Energy spectra for Cosmic Rays - 3

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





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

2. Fermi-LAT limits

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

[particles/(GeV str cm^2 s]

2. Fermi-LAT limits

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

[particles/(GeV str cm^2 s]

MadDM

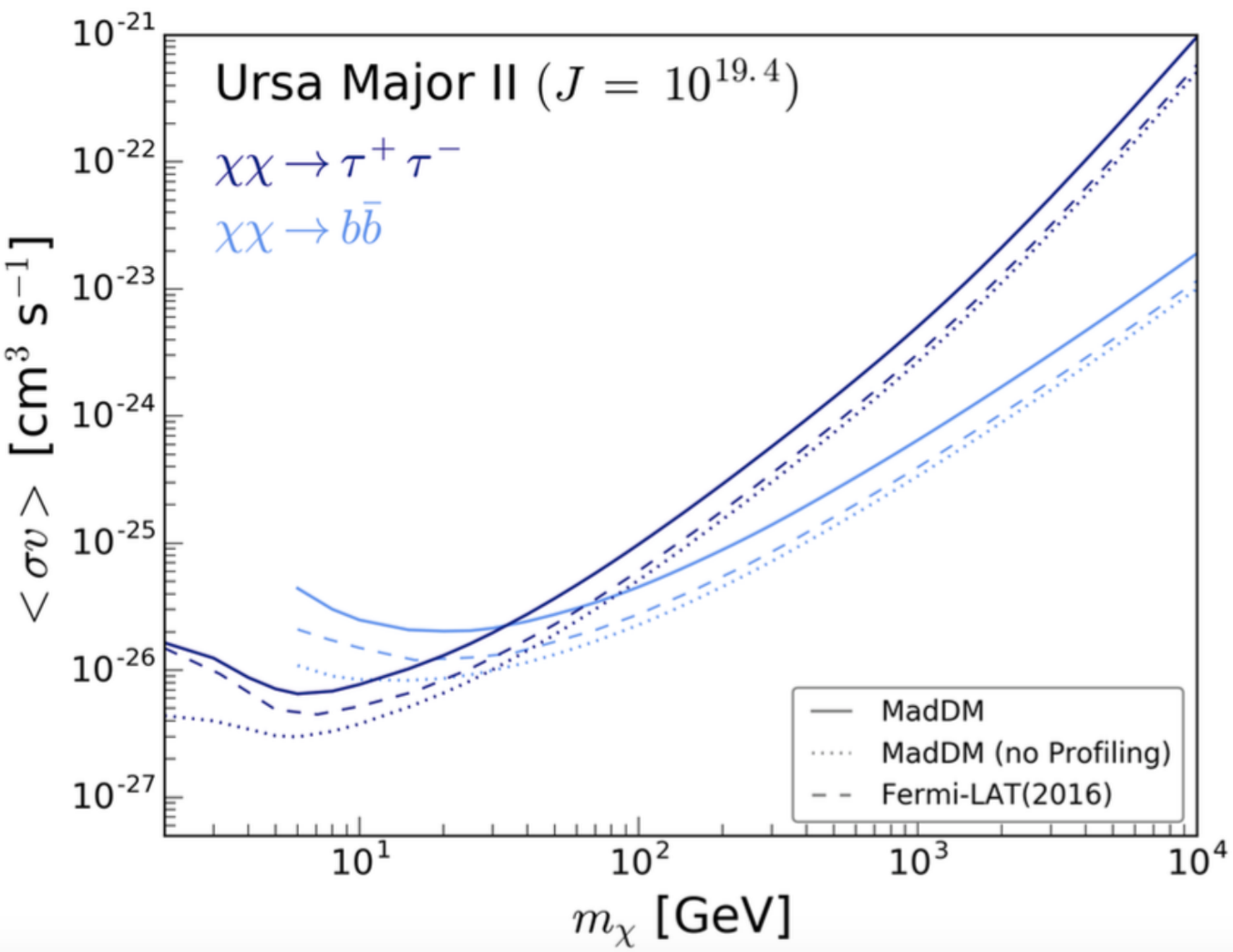
2. Fermi-LAT limits

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

[particles/(GeV str cm^2 s]

MadDM

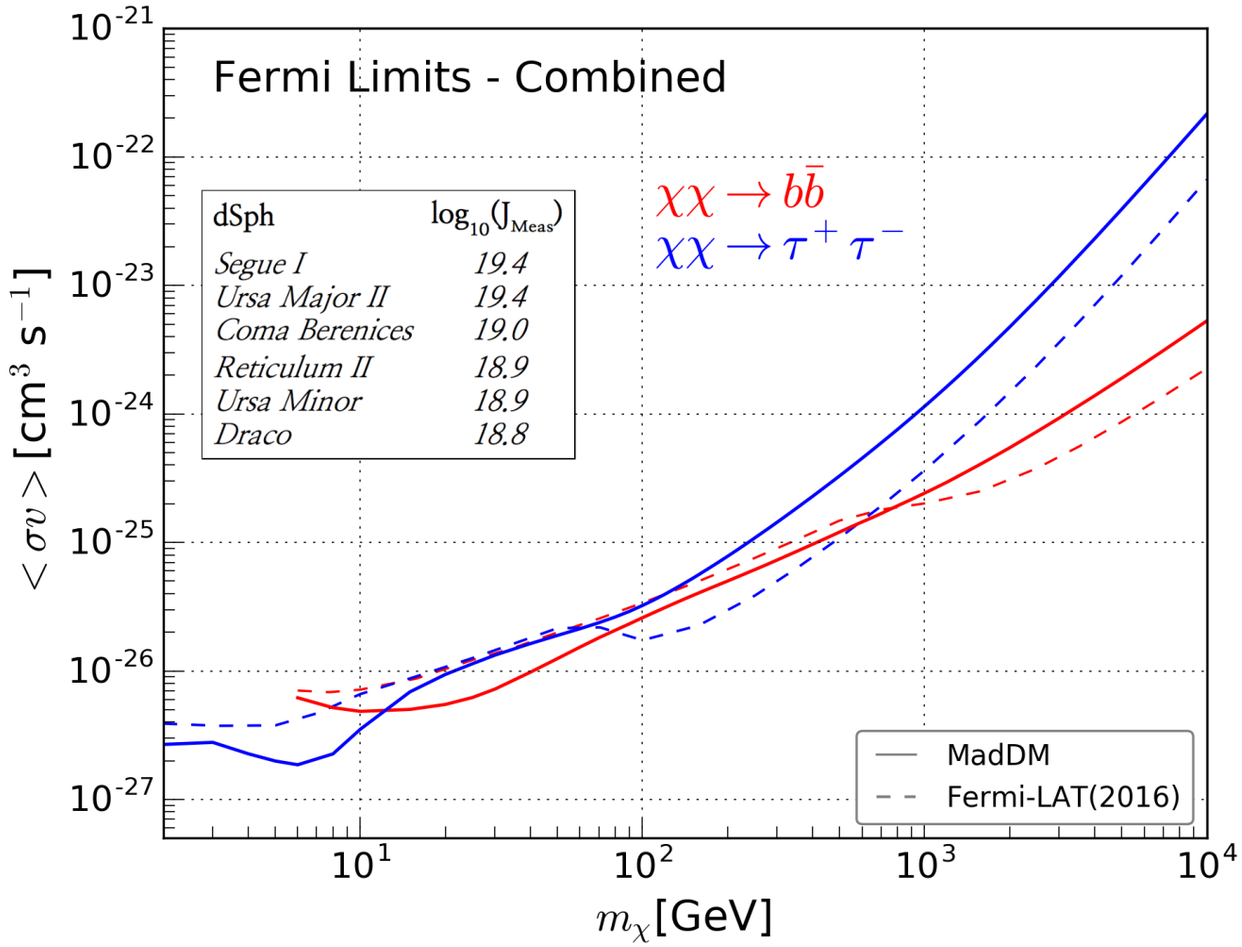
Astrophysical J-factor



- The Fermi collaboration made available the likelihood profiles to derive gamma-ray flux upper limits (UL)
- Possible to derive UL for arbitrary annihilation channels
- MadDM includes the likelihood profiles for the 6 dwarf galaxies with highest J-factor

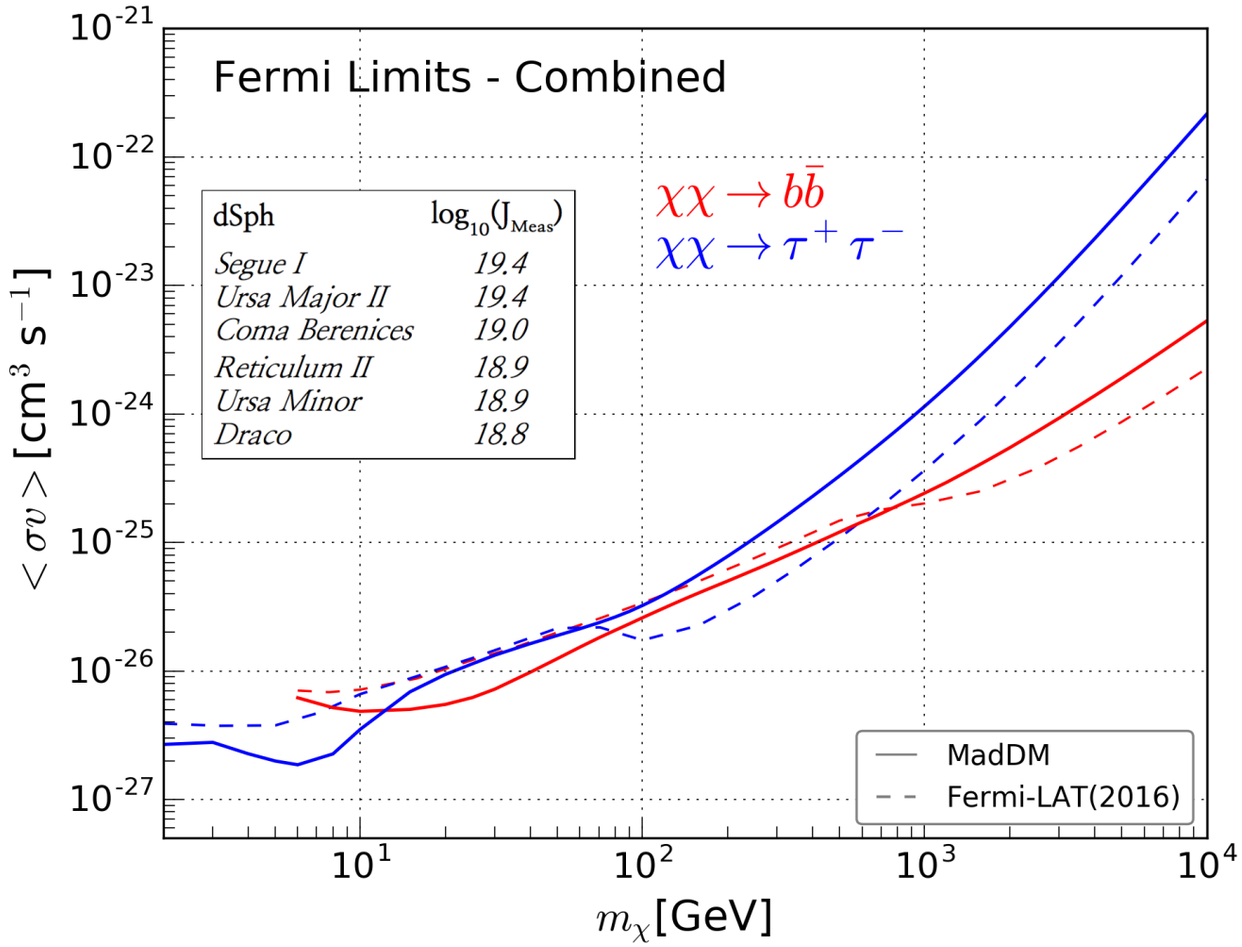
2. Fermi-LAT limits

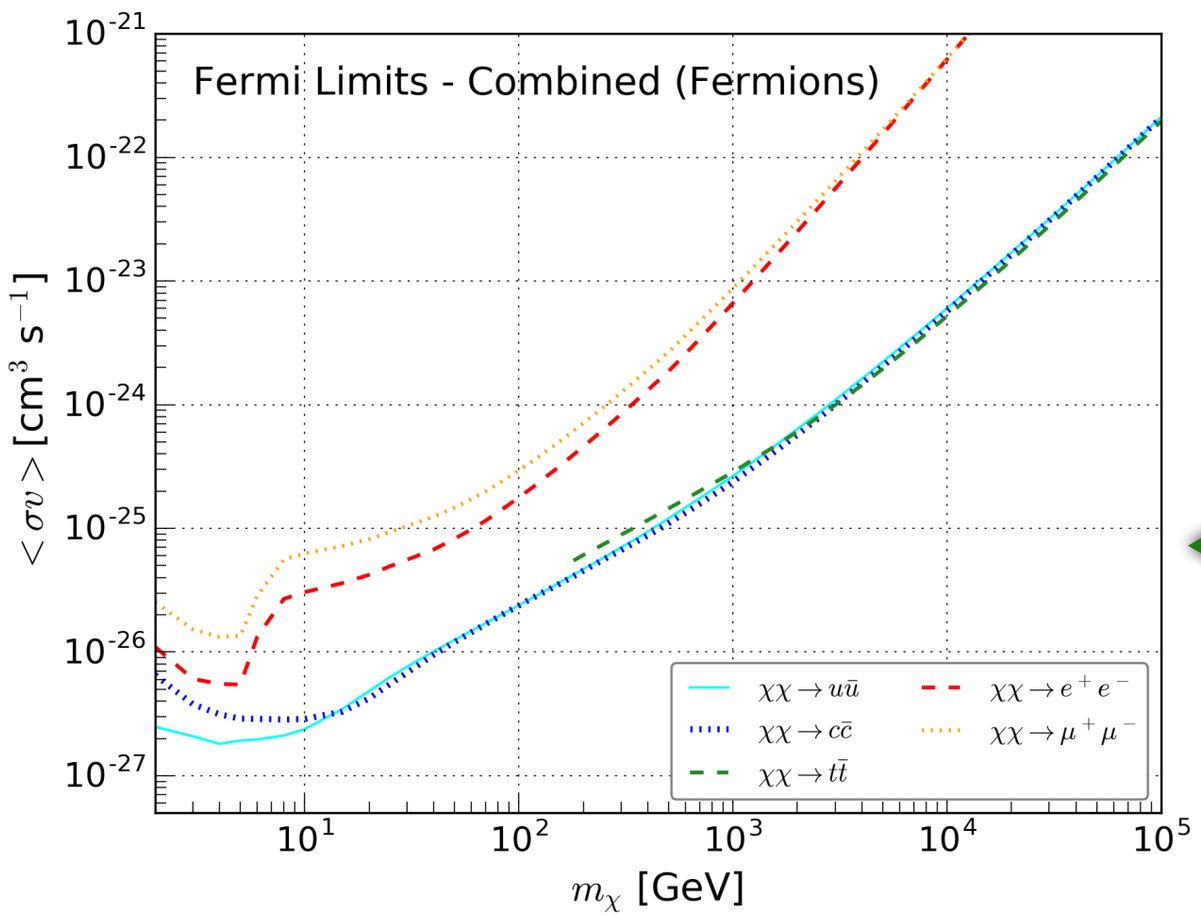
Fermi coll. only gives limits for the two simplified models
DM DM > b bar / tau+tau-



2. Fermi-LAT limits

Fermi coll. only gives limits for the two simplified models
DM DM > b bar / tau+tau-

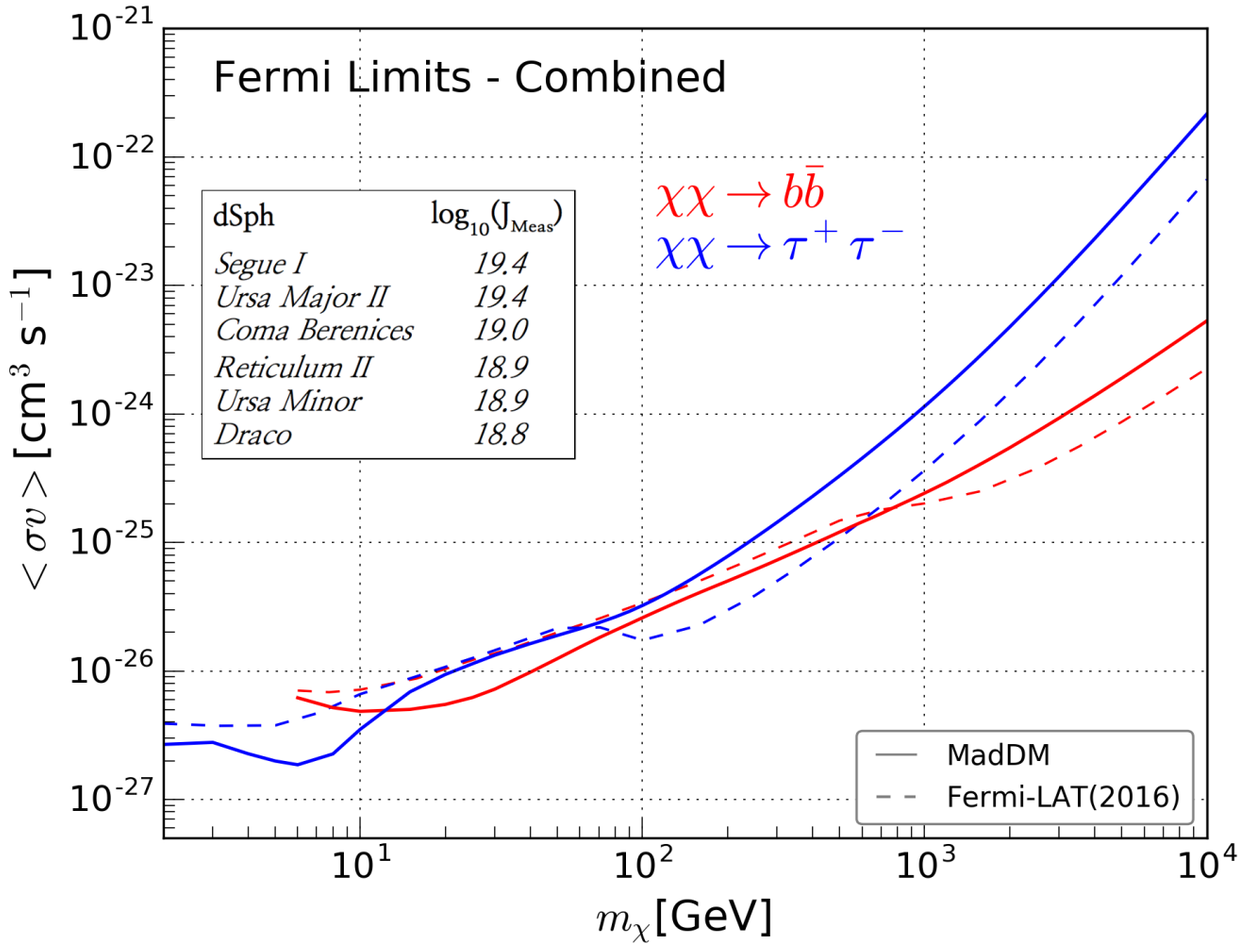


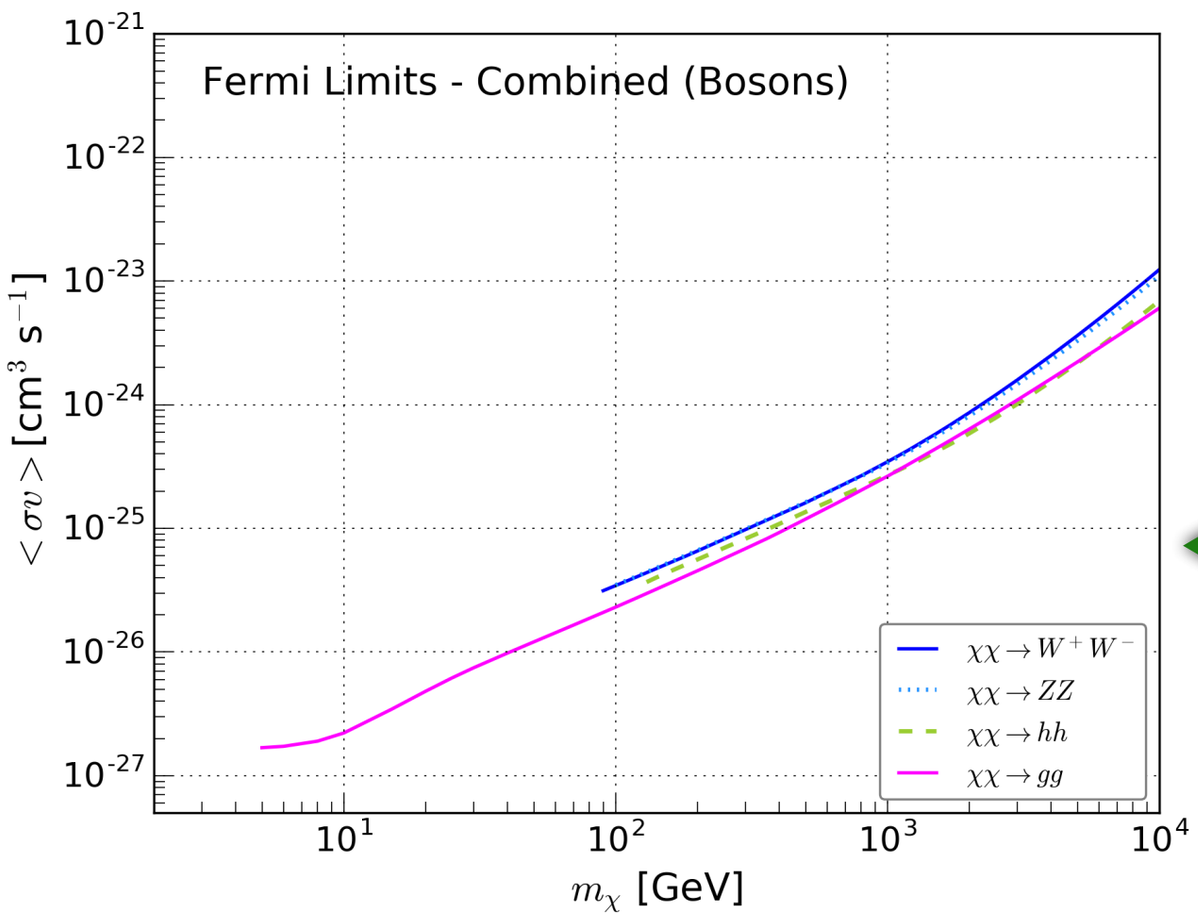


- We calculated the limits of any *DM DM > SM SM*
- Added the new limits in the Exp. constraints module

2. Fermi-LAT limits

Fermi coll. only gives limits for the two simplified models
DM DM > b bar / tau+tau-





- 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 : **Ω Planck**

Direct detection:

Spin independent	***Xenon 1 ton***
Spin dependent - nuetrons	***LUX***
Spin dependent - protons	***Pico 60***

Indirect detection:

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

Fermi-LAT likelihood

- Competely 'externalisable' module that can be loaded independently of MadDM
- The users can easily update/ add limits

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

```
***** Relic Density
INFO: Relic Density        = 3.06e-03        ALLO
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

```
***** Relic Density
INFO: Relic Density        = 3.06e-03        ALLO
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]

4. Cosmic Rays Propagation - fluxes at detection

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

[particles/(GeV str cm^2 s]

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

- **PPPC4DMID Tables for e+**

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

- **DRAGON**

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

Conclusions and Outlook

- MadDM v.3.0 is out (beta version)
- Waiting for feedbacks from the users for bug fixing
- Currently in a stand-alone package, requires MG5 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

Conclusions and Outlook

- MadDM v.3.0 is out (beta version)
- Waiting for feedbacks from the users for bug fixing
- Currently in a stand-alone package, requires MG5 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

Thank you!

Backup

DM Annihilation and Fermi Bounds

MadDM v.3.0:

1. calculates the thermally averaged annihilation cross section <σv>

2. generate/reads energy spectra for $\gamma, \nu_e, \nu_\mu, \nu_\tau, e^+, \bar{p}$

3. calculates experimental UL using Fermi-LAT likelihood

4. propagates/reads CR fluxes at Earth

Two different approaches

'Fast' Method

'Precision' Method

Each step is performed in a different way according to the user's need (speed, high precision, or a balance of the two?)

Example: helicity suppression lift

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

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

For a generic dark matter model with UFO files

MadDM capabilities

Relic density (MadDM v.1.0)

- Coannihilation
- Multi-component dark matter

Direct detection (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

Indirect detection (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

Model parameter space sampling (MadDM v.3.0)

- Sequential grid scan
- PyMultiNest interface

Experimental constraints module (MadDM v.3.0)

Computation of <σv> - more

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

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

Maxwell-Boltzmann distribution

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