

*MadDM v3: towards a comprehensive tool for Dark Matter studies**

Chiara Arina

IRN Terascale@Bruxelles

October 18th 2019

- * Based on F. Ambrogi, CA, M. Backovic, J. Heisig, F. Maltoni, L. Mantani, O. Mattelaer, G. Mohlabeng, arXiv:1804.00044, Phys. Dark Univ. (2019)



Wish list for WIMP-like dark matter analyses

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \mathcal{L}_{\text{BSM}}$$



Model Predictions

- relic density
- direct detection rates
- indirect detection signals
- collider signatures

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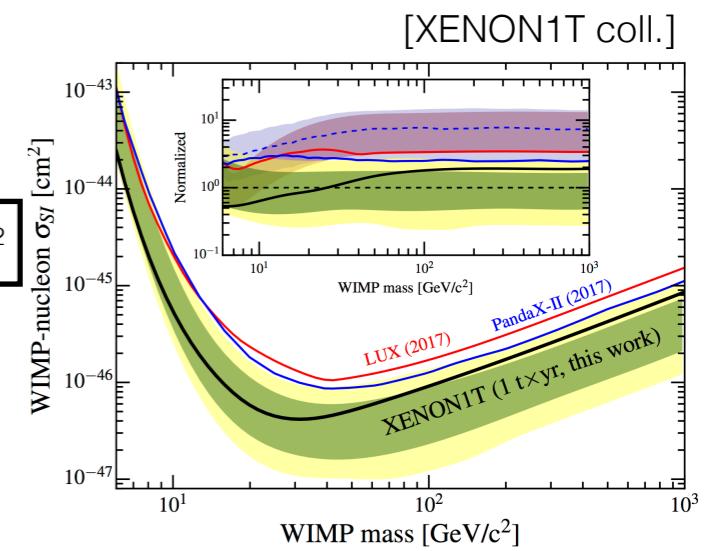
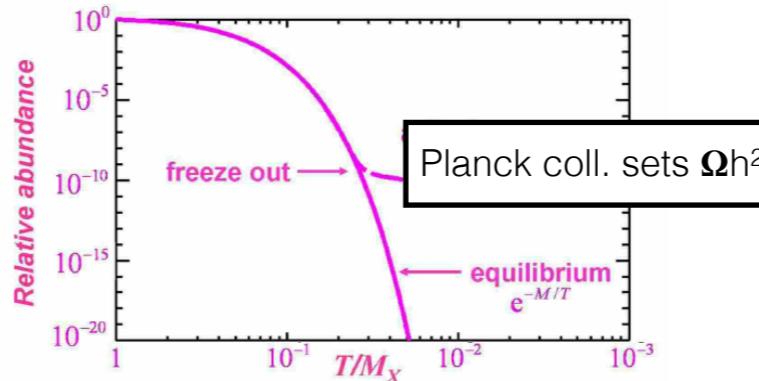
How to compute those
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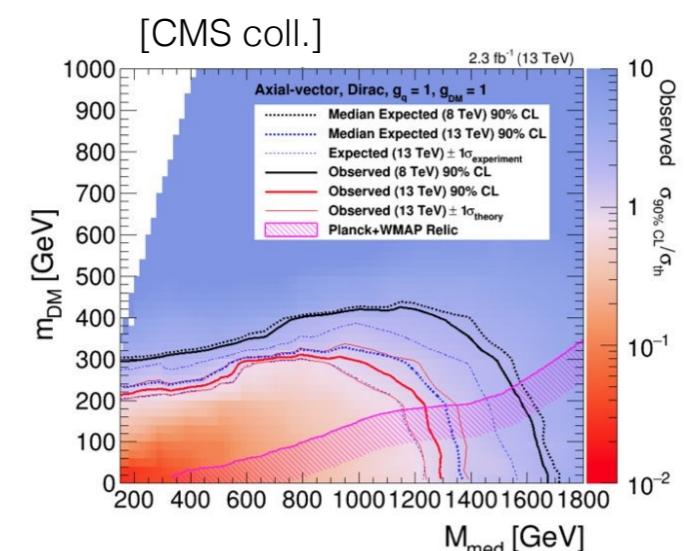
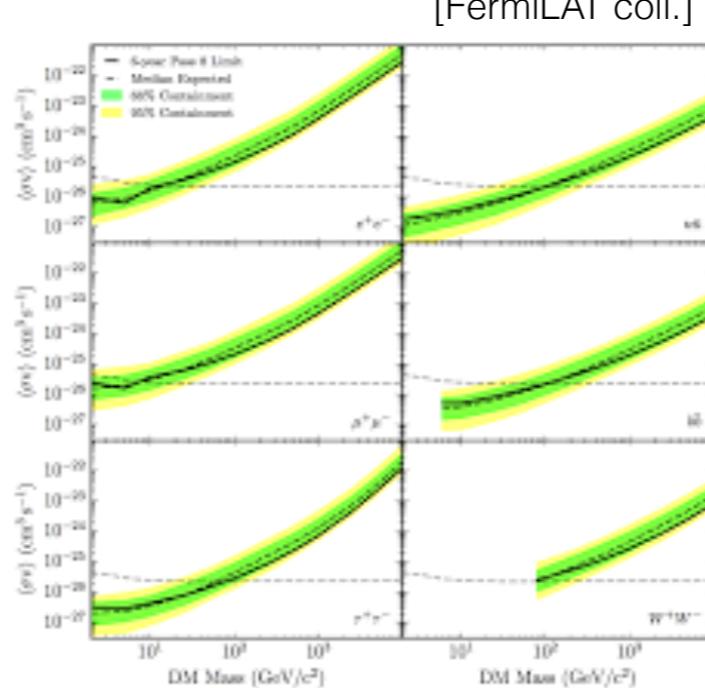
Experimental observations



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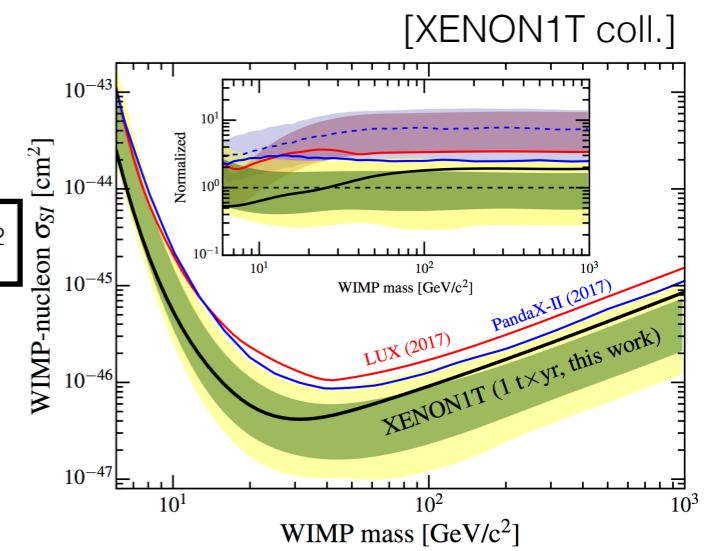
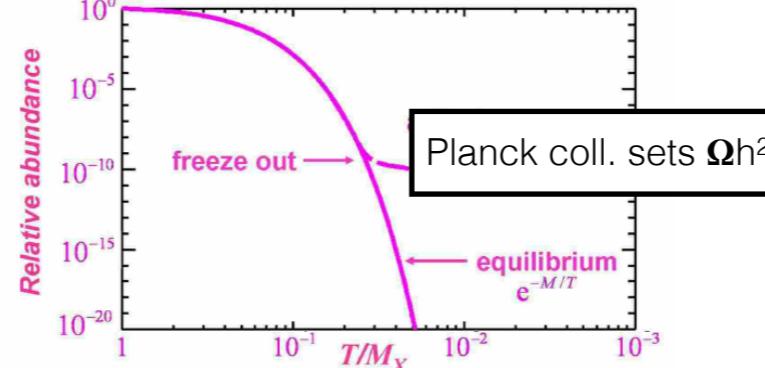


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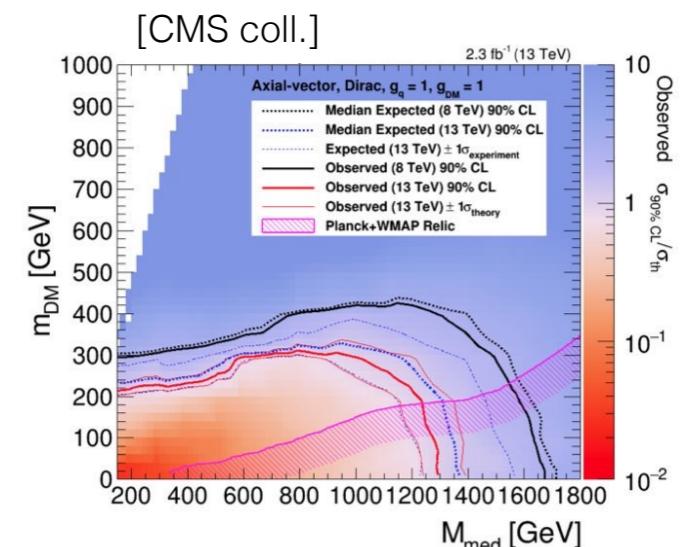
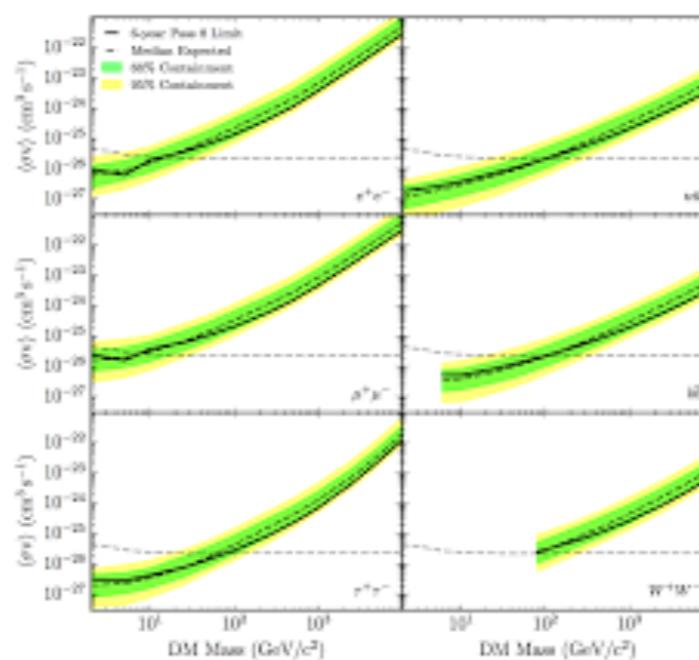
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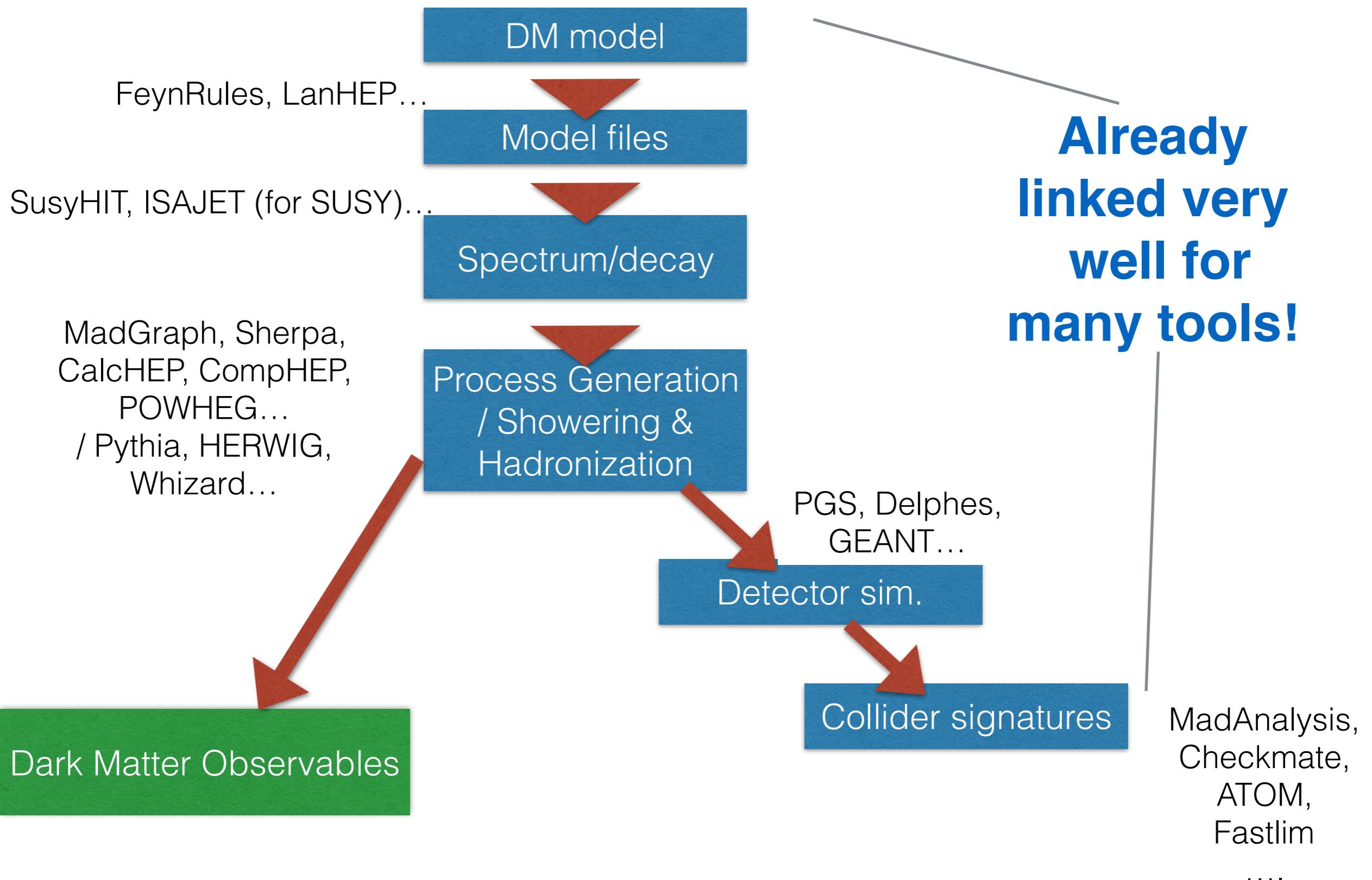
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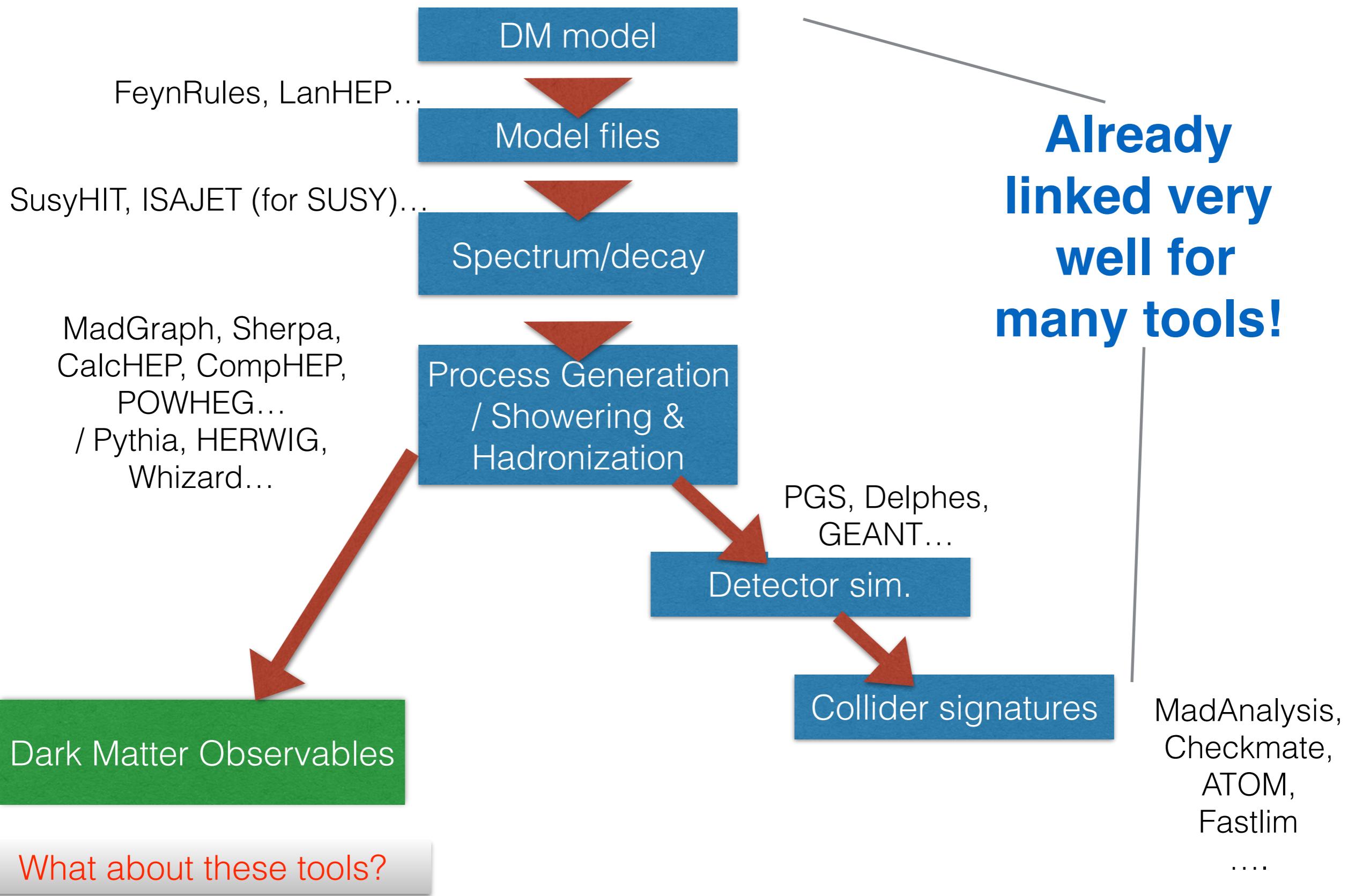


How to compare with experiments?

Tools in the LHC era



Tools in the LHC era



Dark Matter tools

micrOMEGAs
[Bélanger, Boudjema, Pukhov,
Semenov 2001]

SUSY related:

- DarkSUSY [Gondolo, Edsjo, Ullio, Bergstrom, Schelke, Baltz 2004]
- SuperBayes [Ruiz De Astrui, Trotta, ... 2010]
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Model independent
PPPC4DM [Cirelli et al. 2010]

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MadDM [2013]

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- DM **predictions** with different degree of completeness
- Some includes **experimental constraints**
- Can be hacked for generic BSM model but not always easy

Model independent
PPPC4DM [Cirelli et al. 2010]

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MadDM [2013]

What can MadDM do

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

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This talk

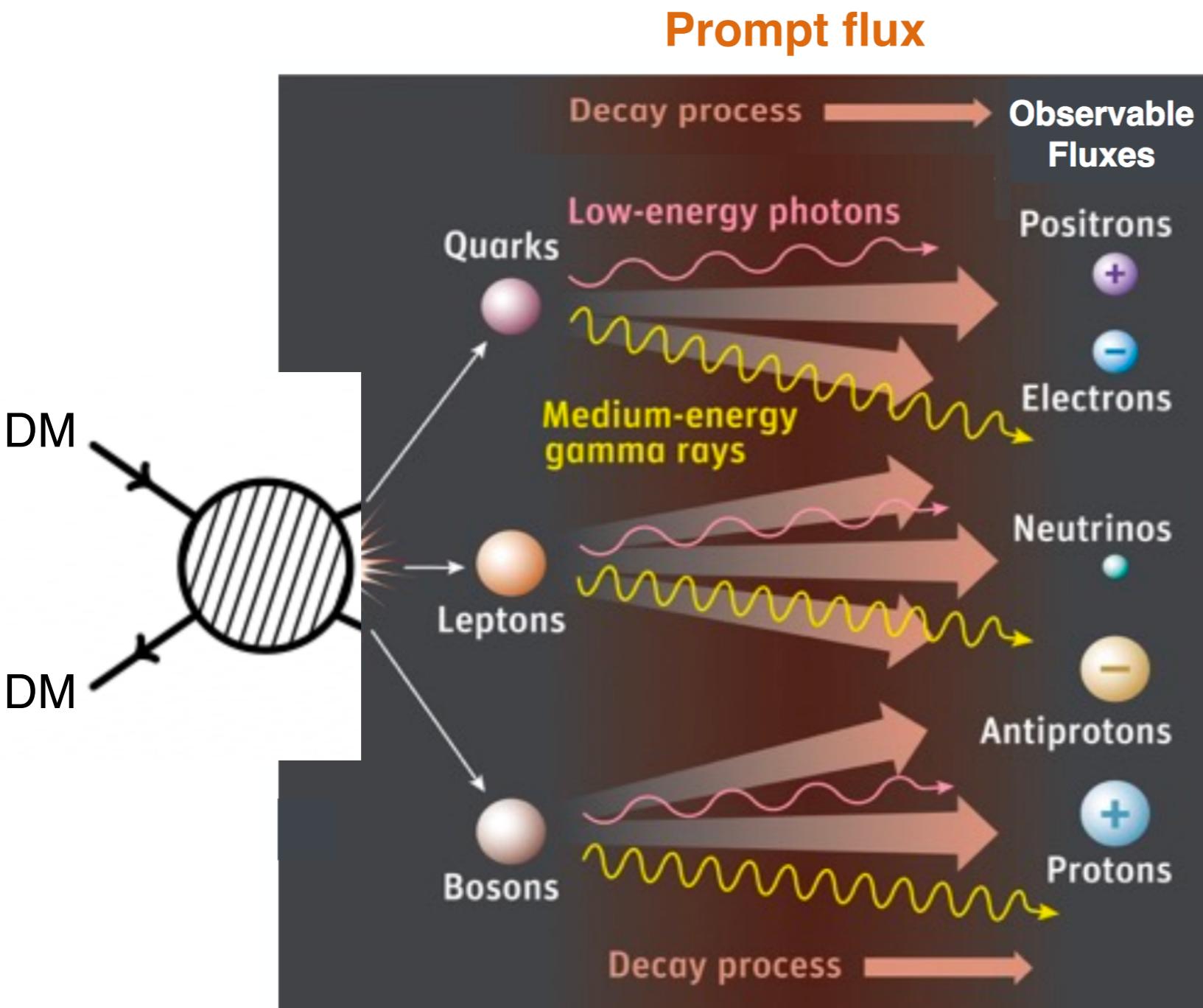
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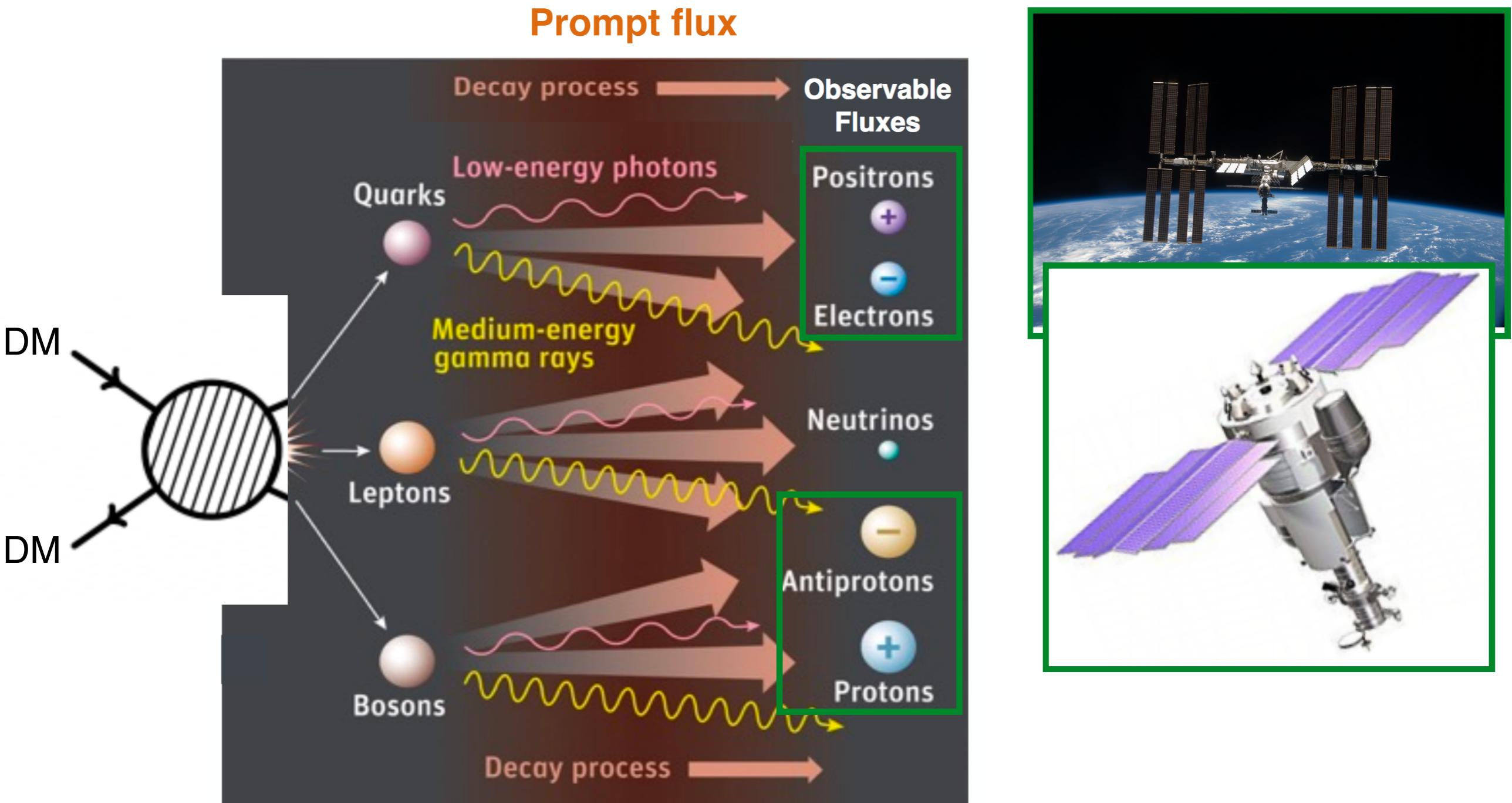
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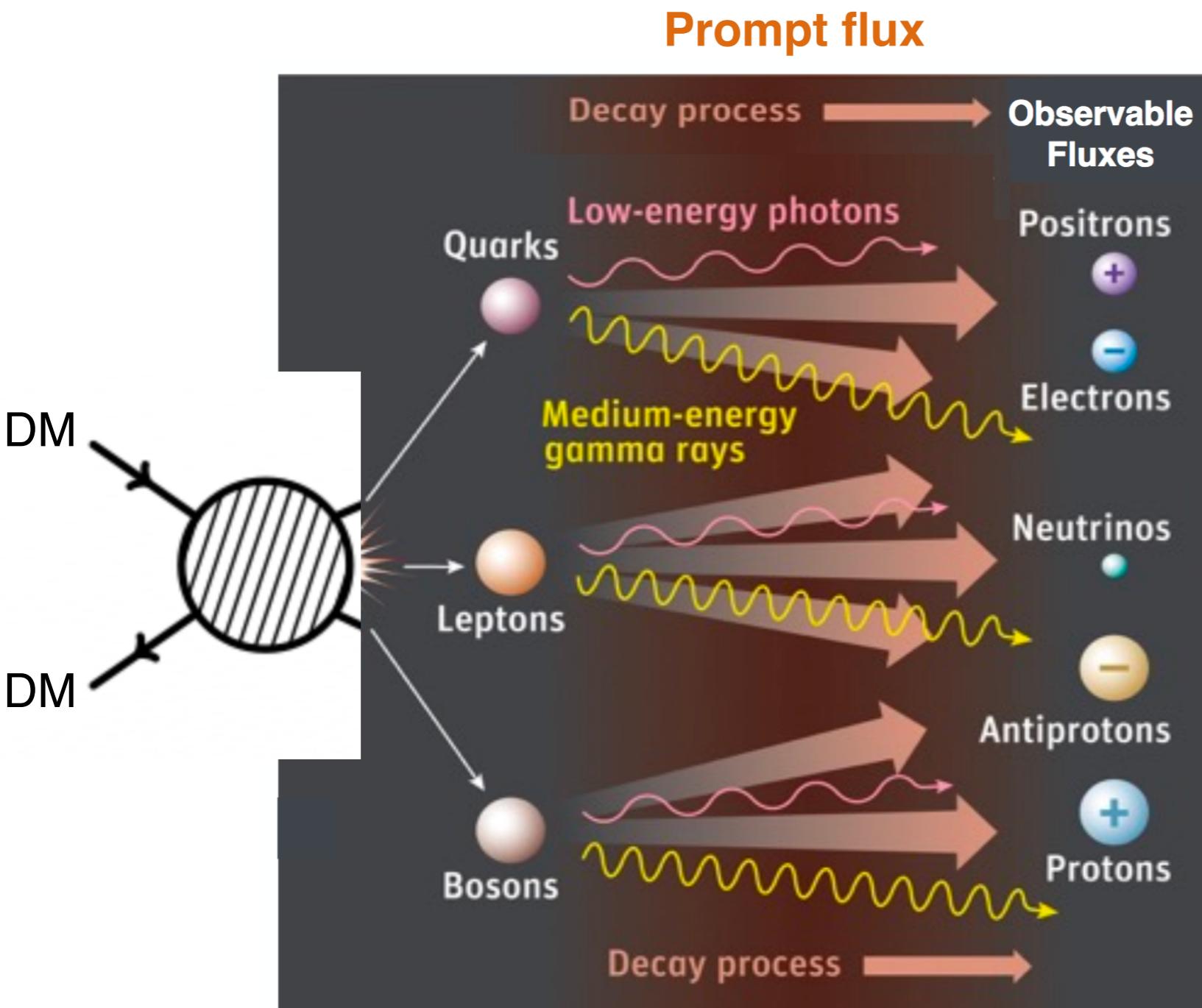
Dark Matter annihilation in galactic halos



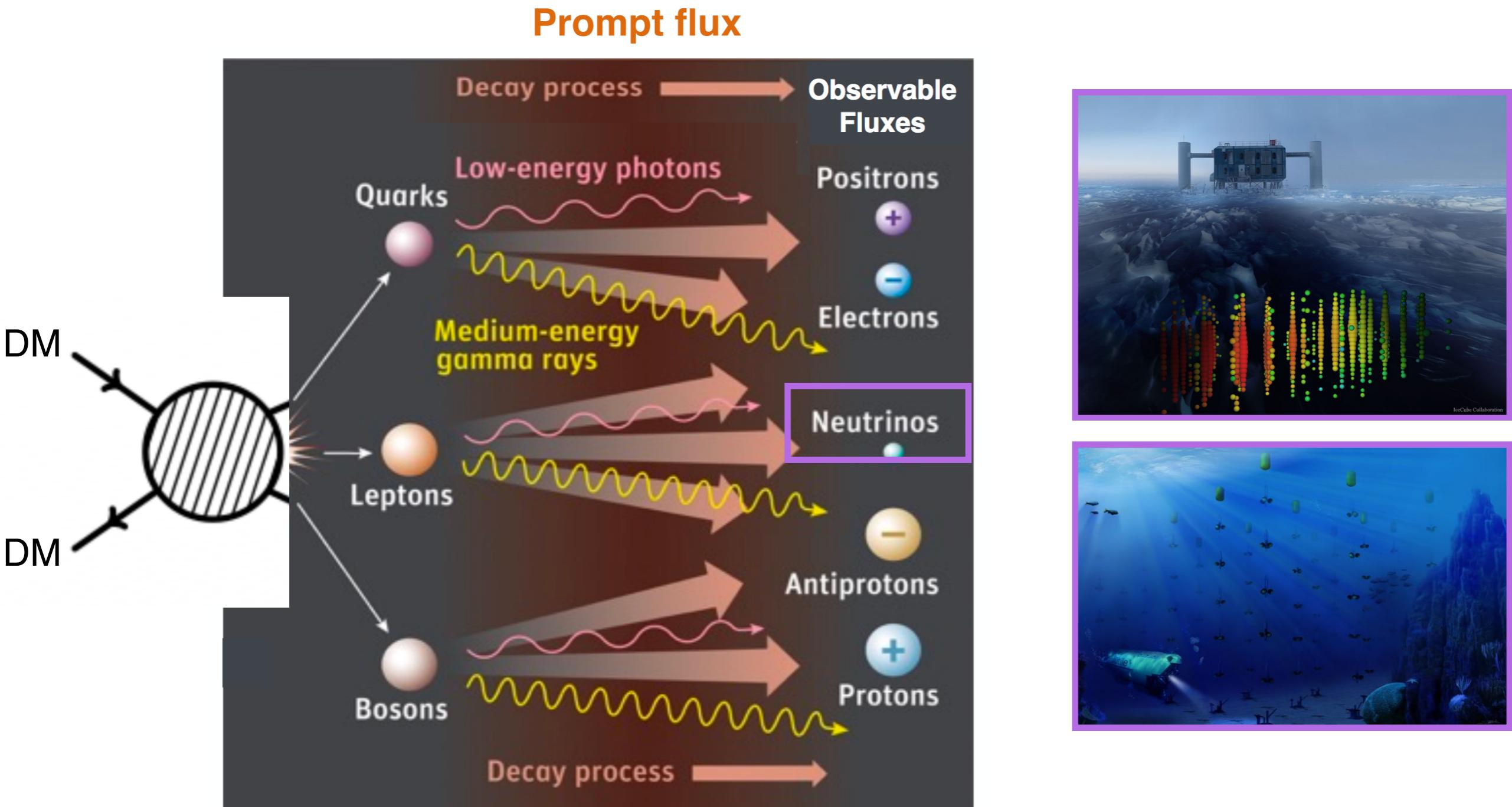
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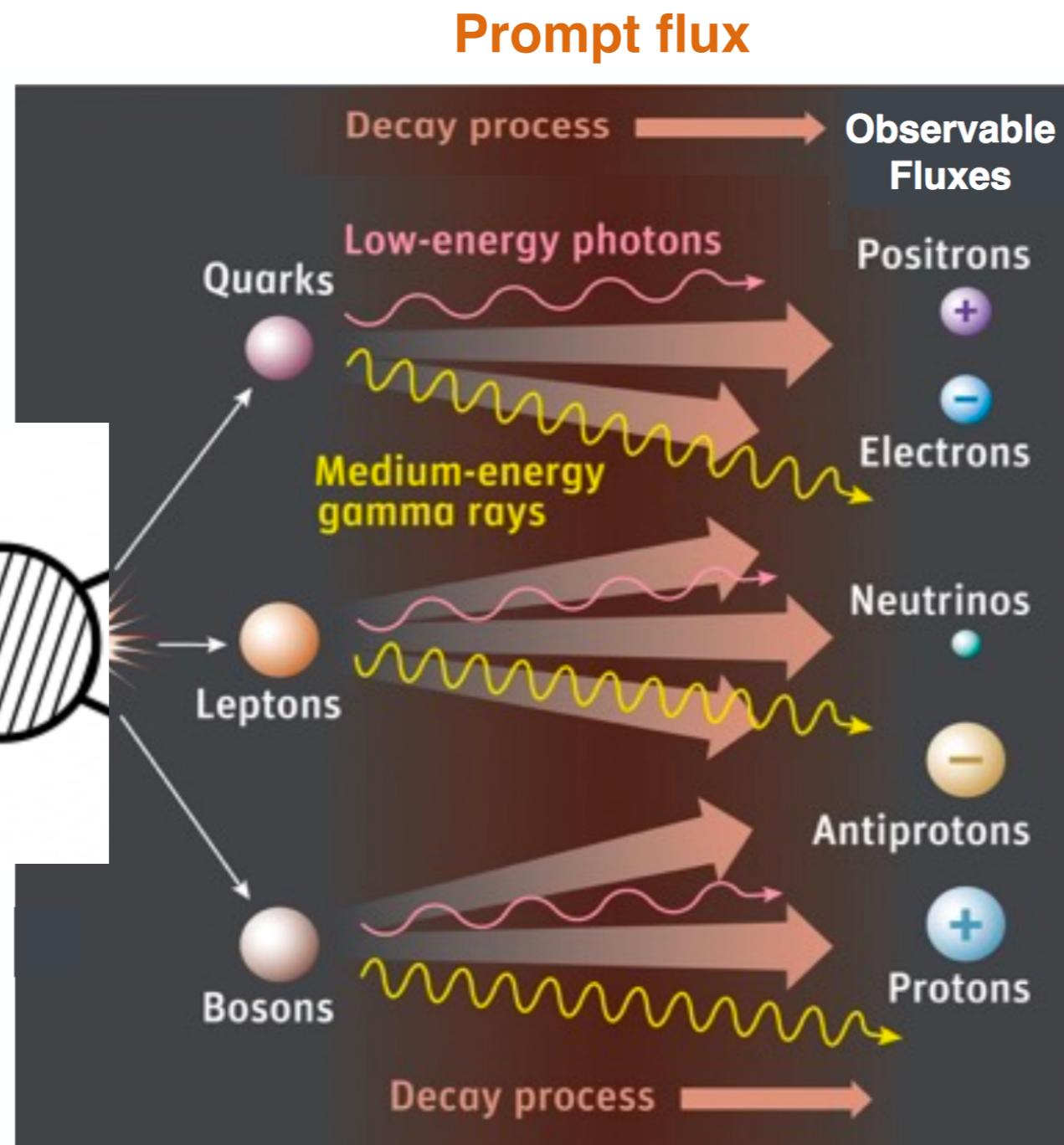
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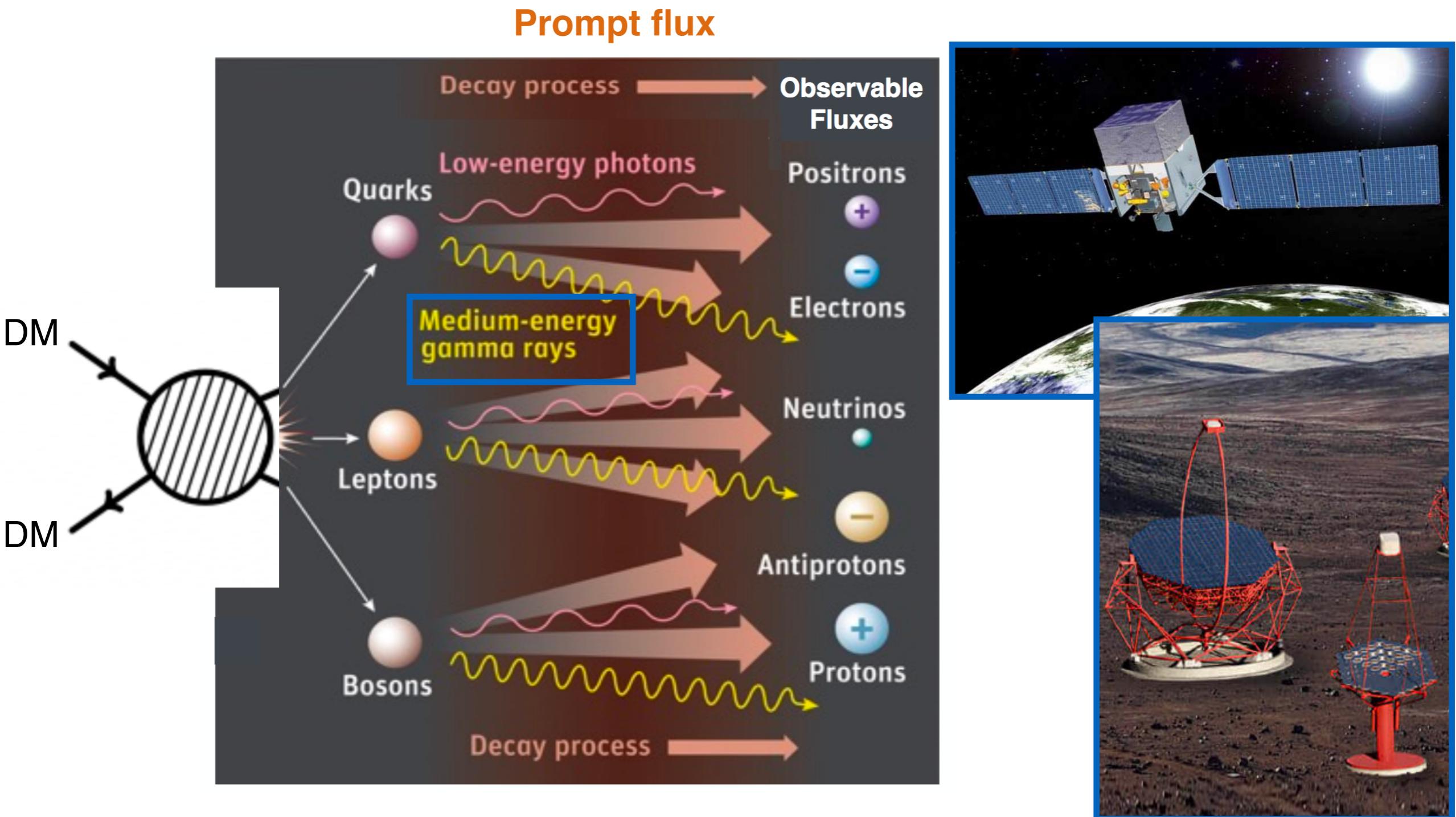
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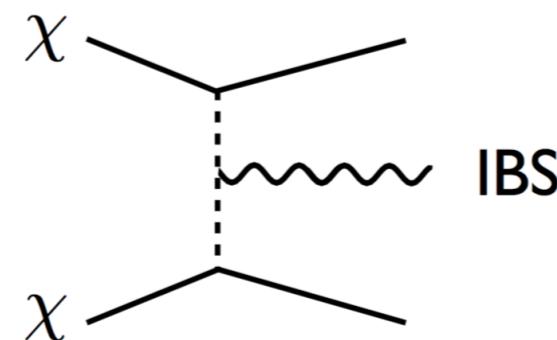
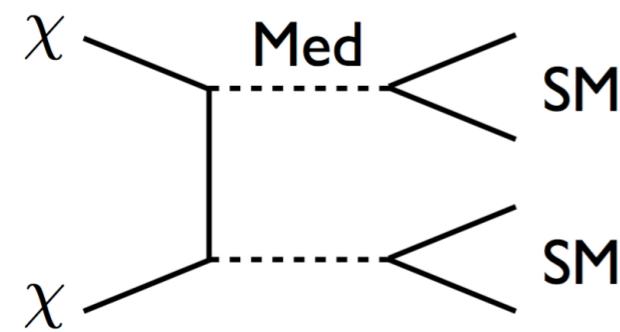


Predictions for annihilation $2 \rightarrow n$

- micrOMEGAs and DarkSUSY provide tabulated spectra for dark matter annihilation into SM particles

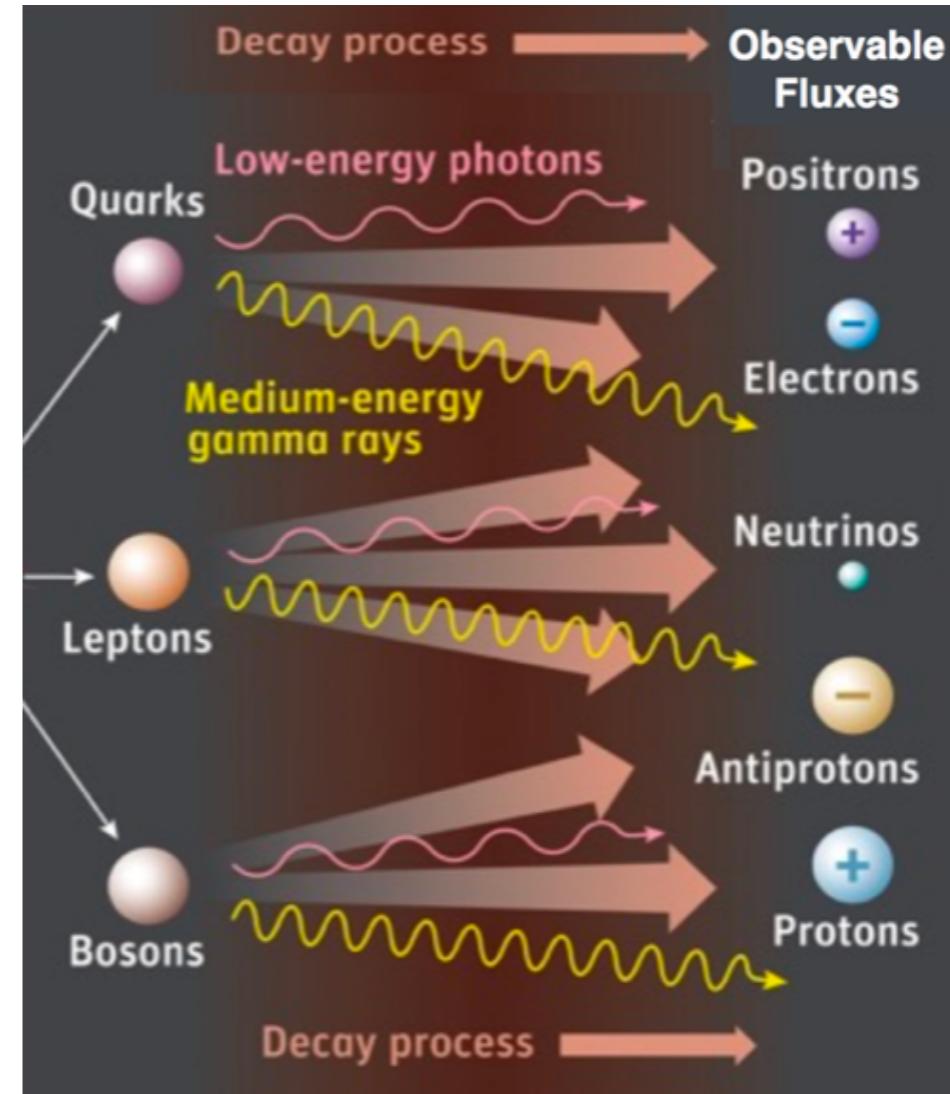
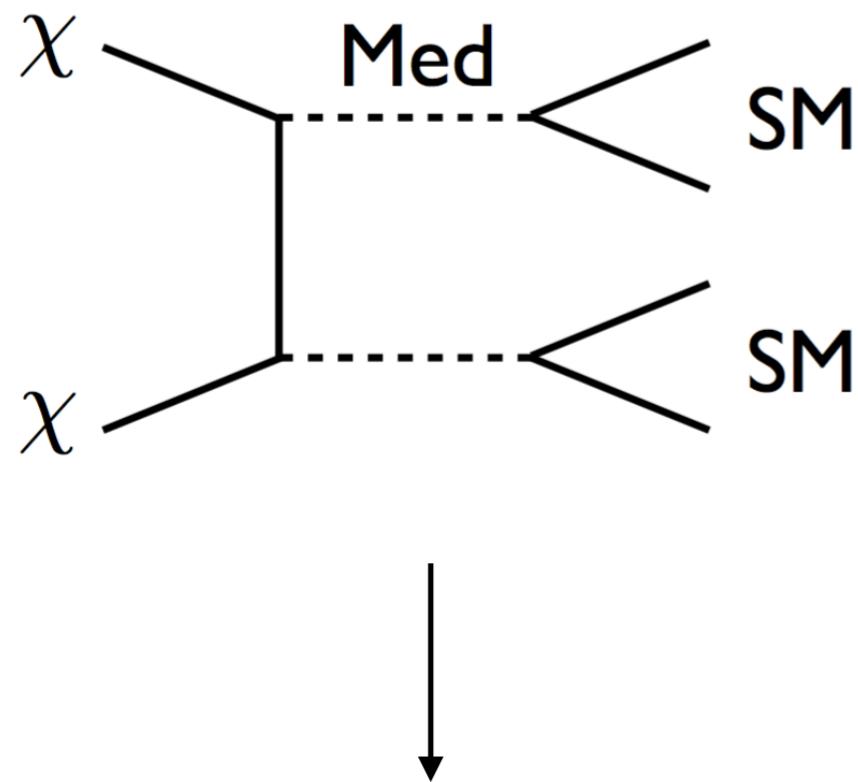
$$\chi\chi \rightarrow gg, q\bar{q}, c\bar{c}, b\bar{b}, t\bar{t}, e^+e^-, \mu^+\mu^-, \tau^+\tau^-, \nu_e\bar{\nu}_e, \nu_\mu\bar{\nu}_\mu, \nu_\tau\bar{\nu}_\tau, ZZ, W^+W^-, hh$$

- MadDM can compute the annihilation cross-section and the spectra for any tree level annihilation in an automated way



Predictions for annihilation $2 \rightarrow n$

MadDM does the following
(precision mode):

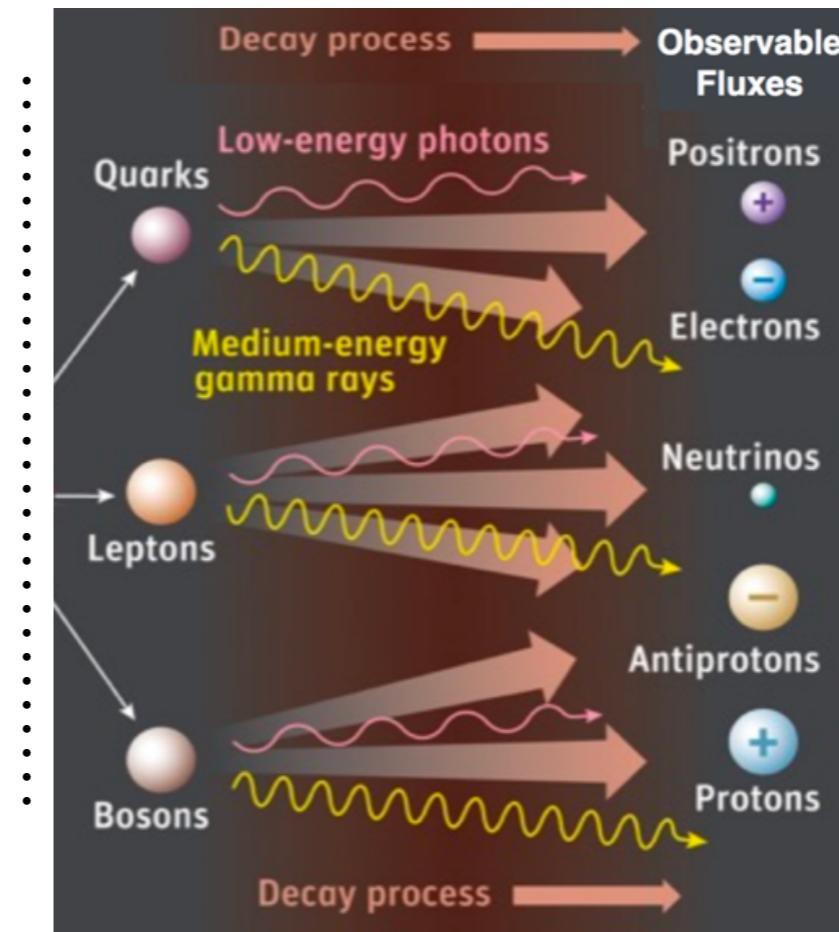
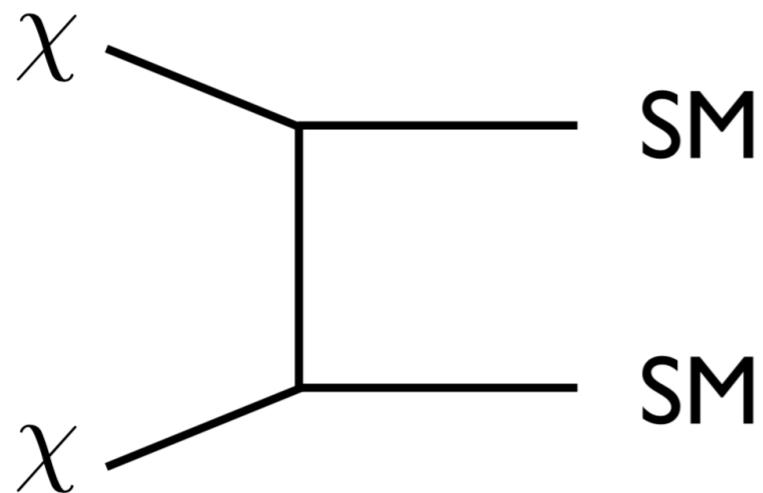


$\langle \sigma v(v_{\text{rel}}) \rangle$ MadEvent $\xrightarrow{\text{lhe}}$ Pythia 8 \longrightarrow Spectra for $\gamma, \bar{p}, e^+, \nu$

Fixed velocity
or
with Maxwell-Boltzmann distribution
Unique to MadDM

Particle Spectra at source for annihilation $2 \rightarrow SM\ SM$

MadDM does the following
(fast mode):



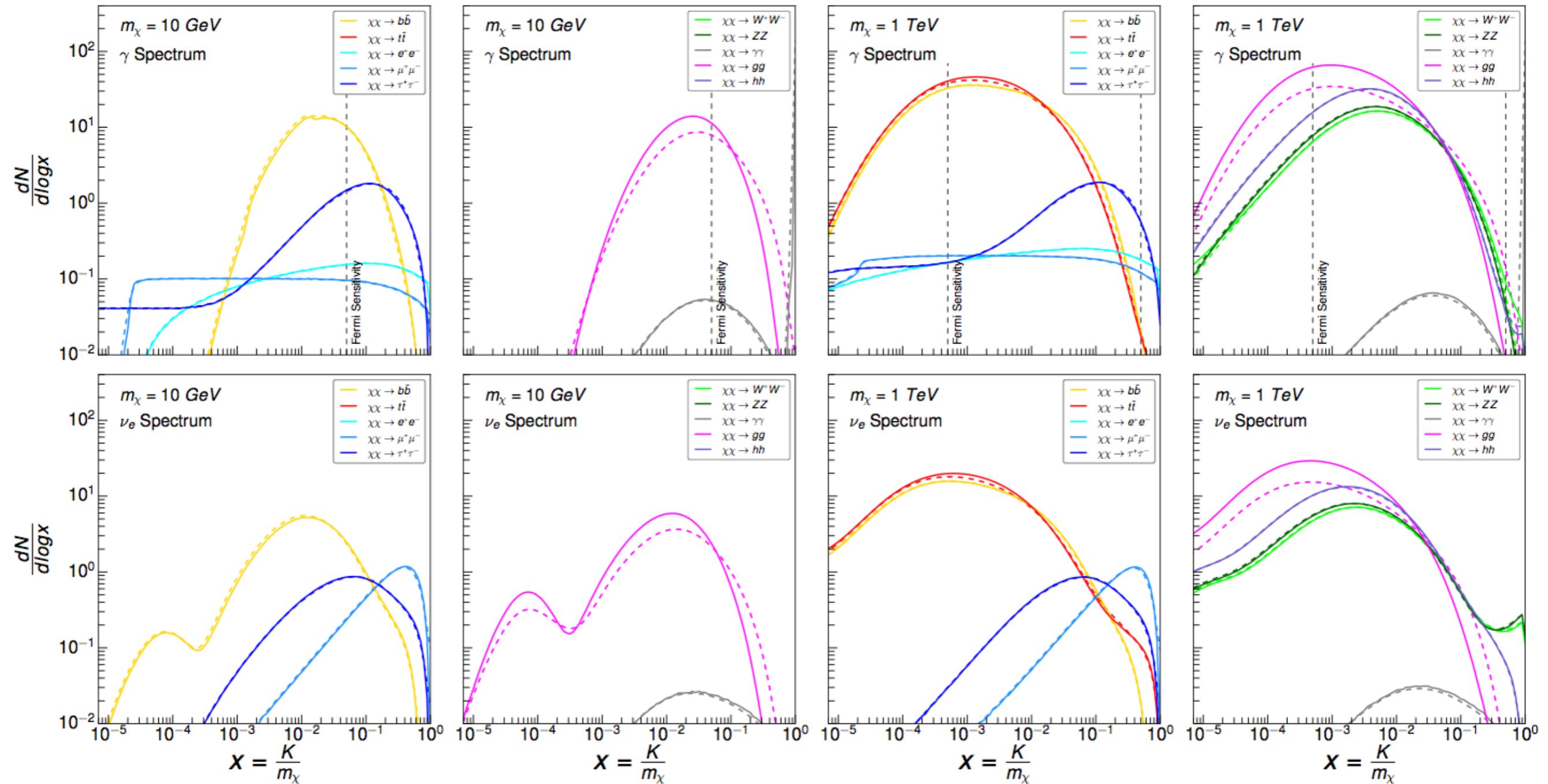
Uses pre-computed spectra* for $\gamma, \bar{p}, e^+, \nu$

Very fast mode but limited to 2 body SM final states

* We thank M. Cirelli for granting us the usage of PPPC4DM tables.

Energy spectra for $2 \rightarrow 2$ processes

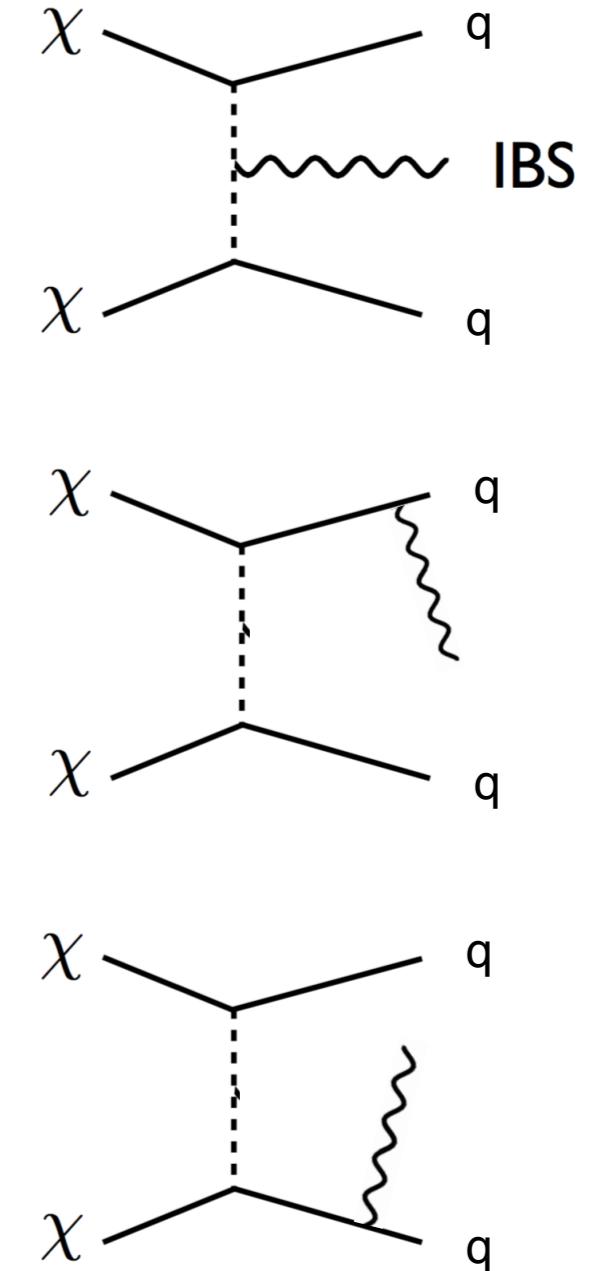
Energy spectra computed with Pythia 8, for any DM model



Validation of energy spectra against tabulated PPPC4DMID spectra [M.Cirelli et al. 2010]

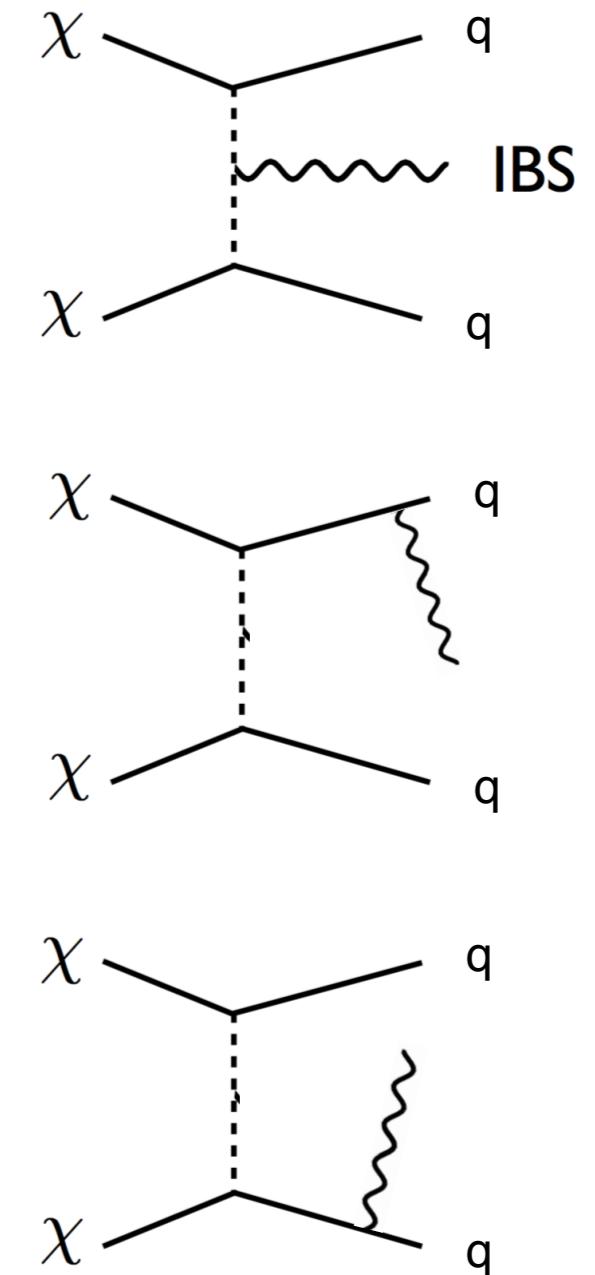
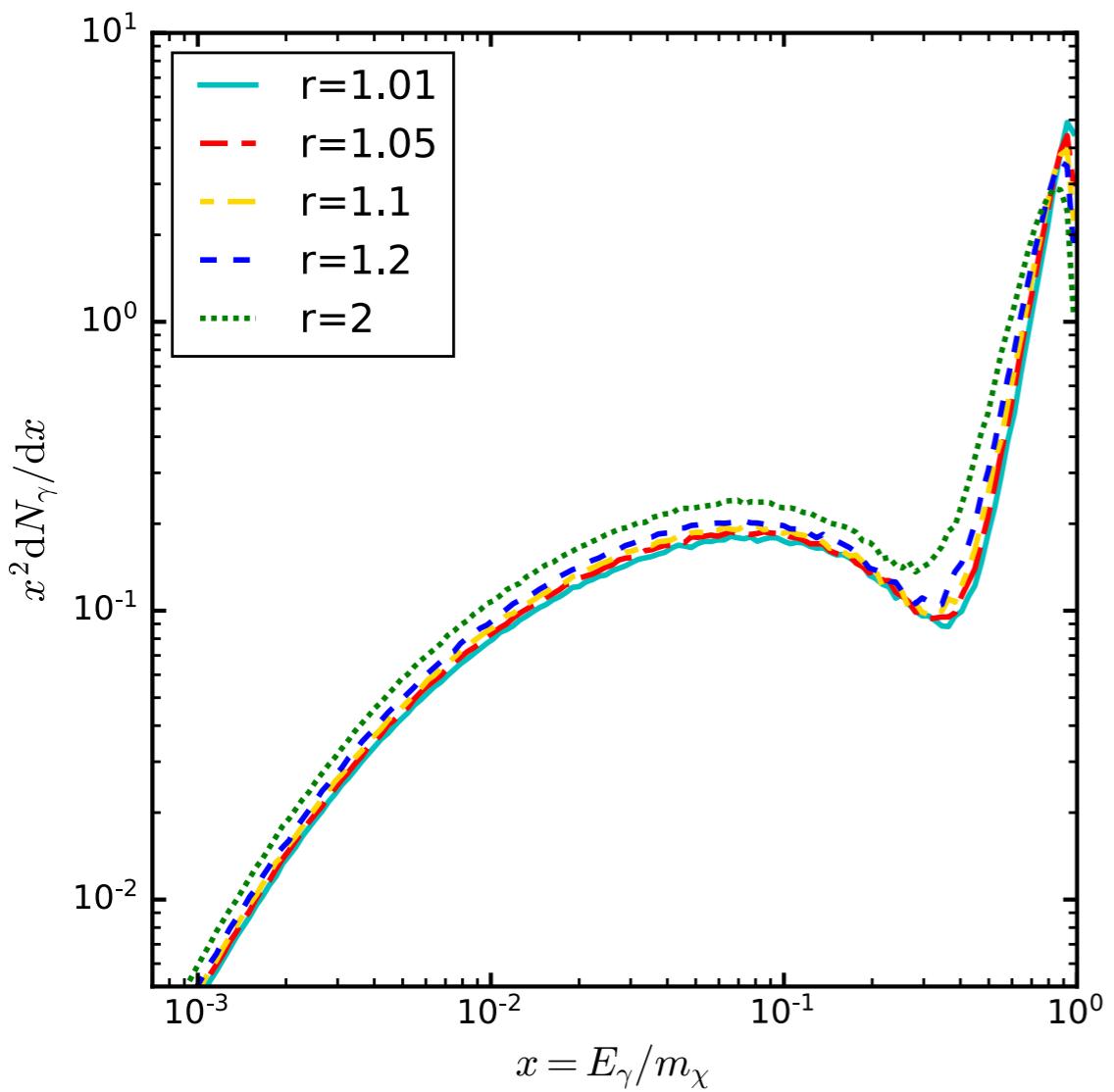
Automatized $2 \rightarrow 3$ processes

```
import model DMsimp_t_f3
define darkmatter xr
generate indirect detection u u~ a
output test_uuxa
launch test_uuxa
set sigmav_method madevent
set indirect_flux_source pythia8
set vave_indirect 1e-3
set nevents 100000
set Mxr 100
set MYur1 scan:[101,105,110,120,200]
set save_output all
```



Validation of energy spectra against tabulated PPPC4DMID spectra [F.Giacchino et al. 2013]

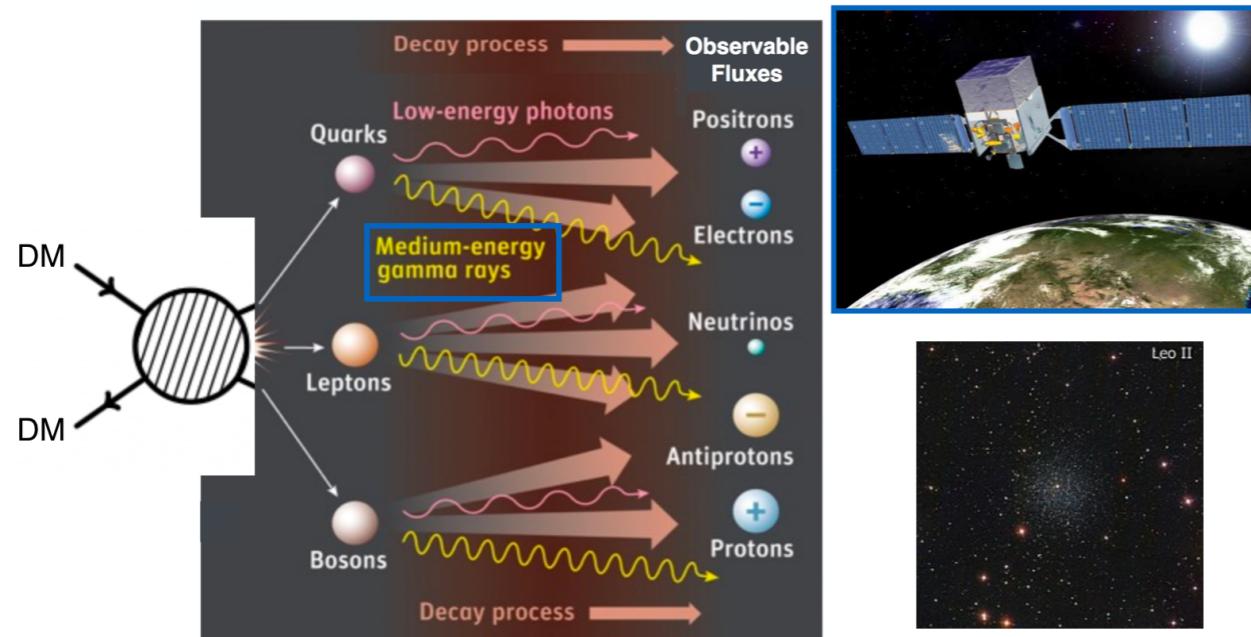
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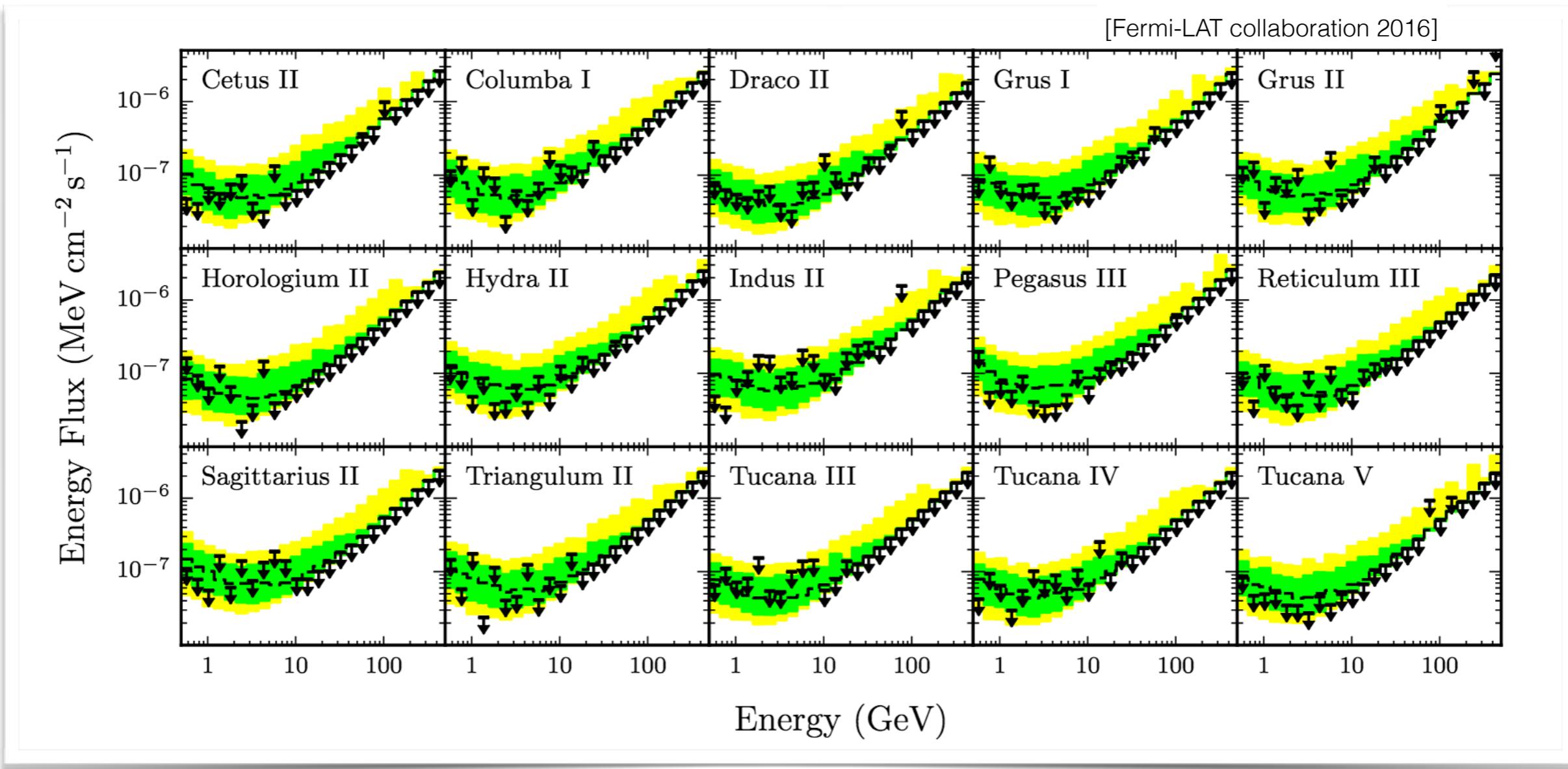
Implementation of the Fermi-LAT likelihood

- Dwarf spheroidal galaxies are among the most constraining targets for dark matter searches



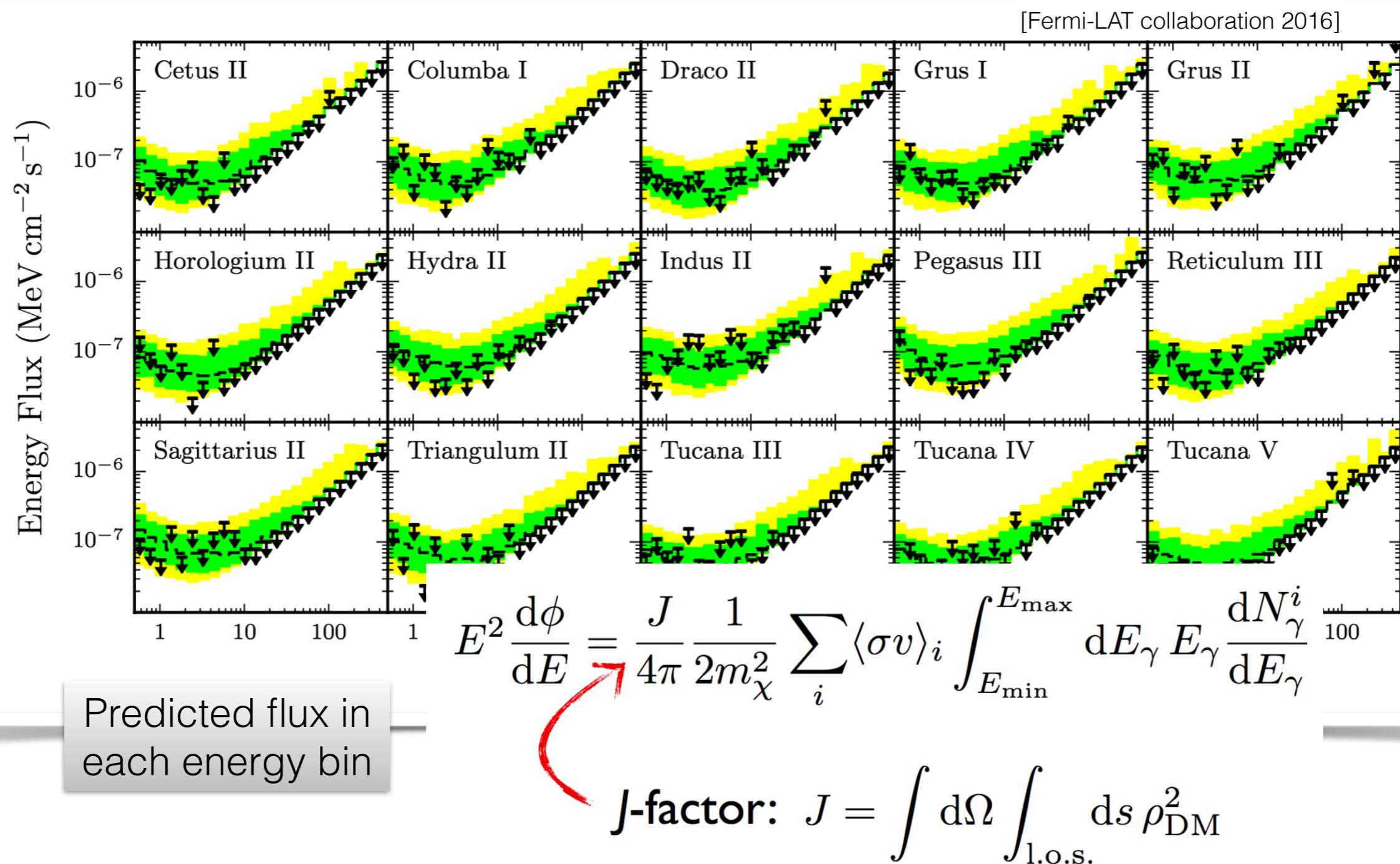
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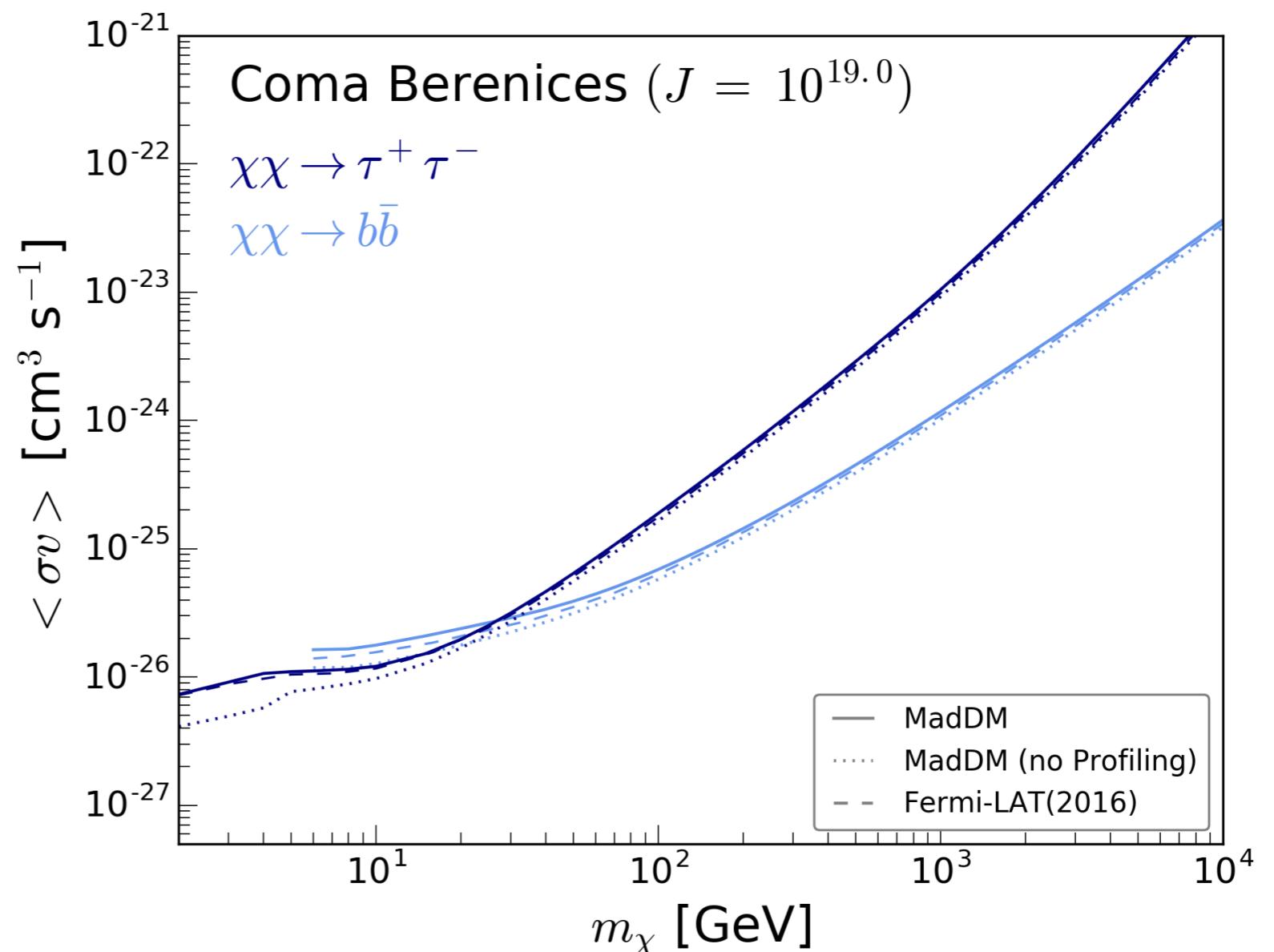
Implementation and Validation of the Fermi-LAT likelihood

- Used Public binned Likelihood functions for 45 dwarfs (https://www-glast.stanford.edu/pub_data/1203/)
- Upper limit at 95% CL for the annihilation cross-section computed by profiling over J factors

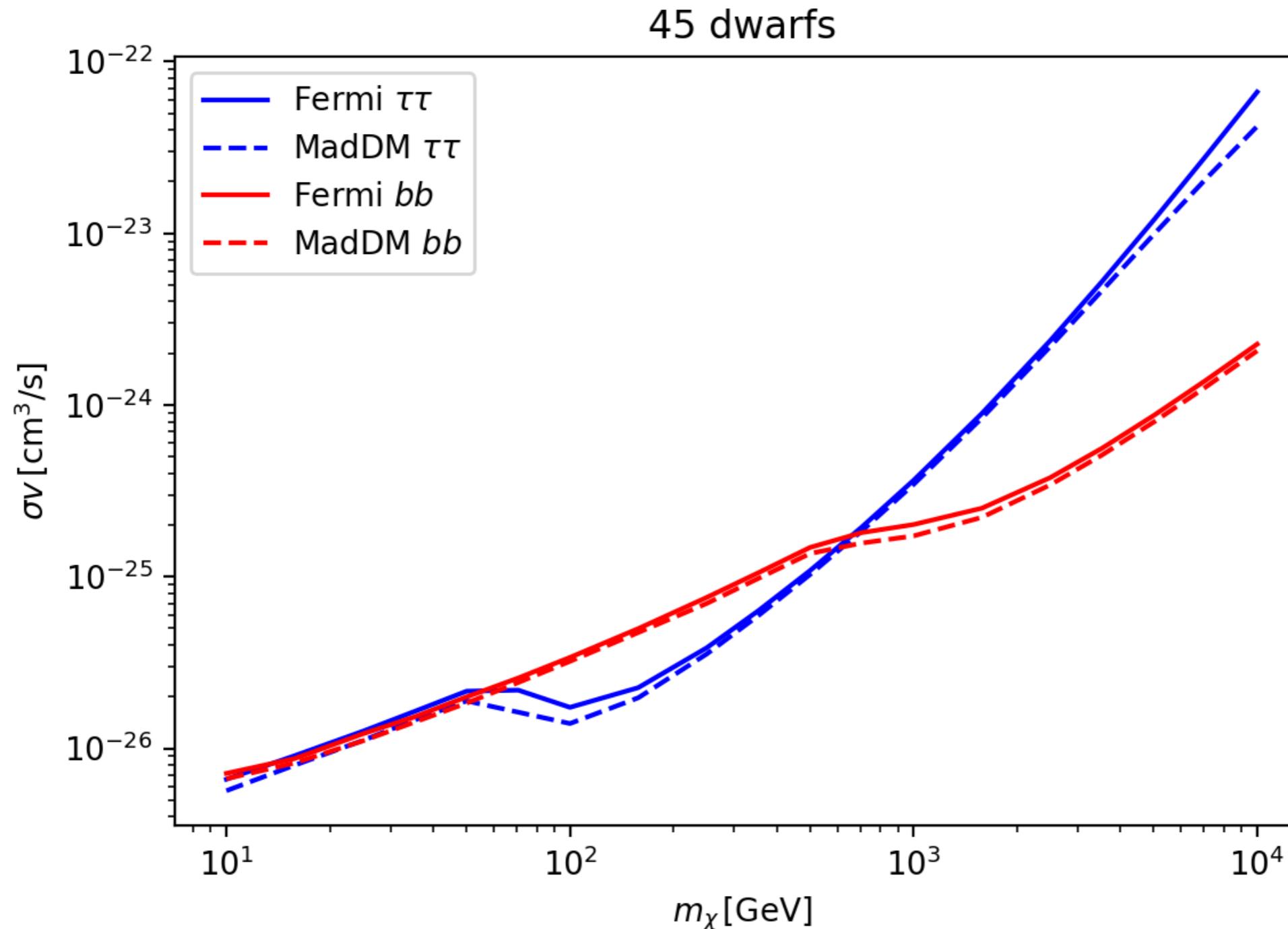
$$TS = -2 \sum_{\text{dwarfs}} \frac{\mathcal{L}(\hat{J}, \sigma v)}{\mathcal{L}(\hat{\bar{J}}, \hat{\sigma} v)}$$

MadDM output provides

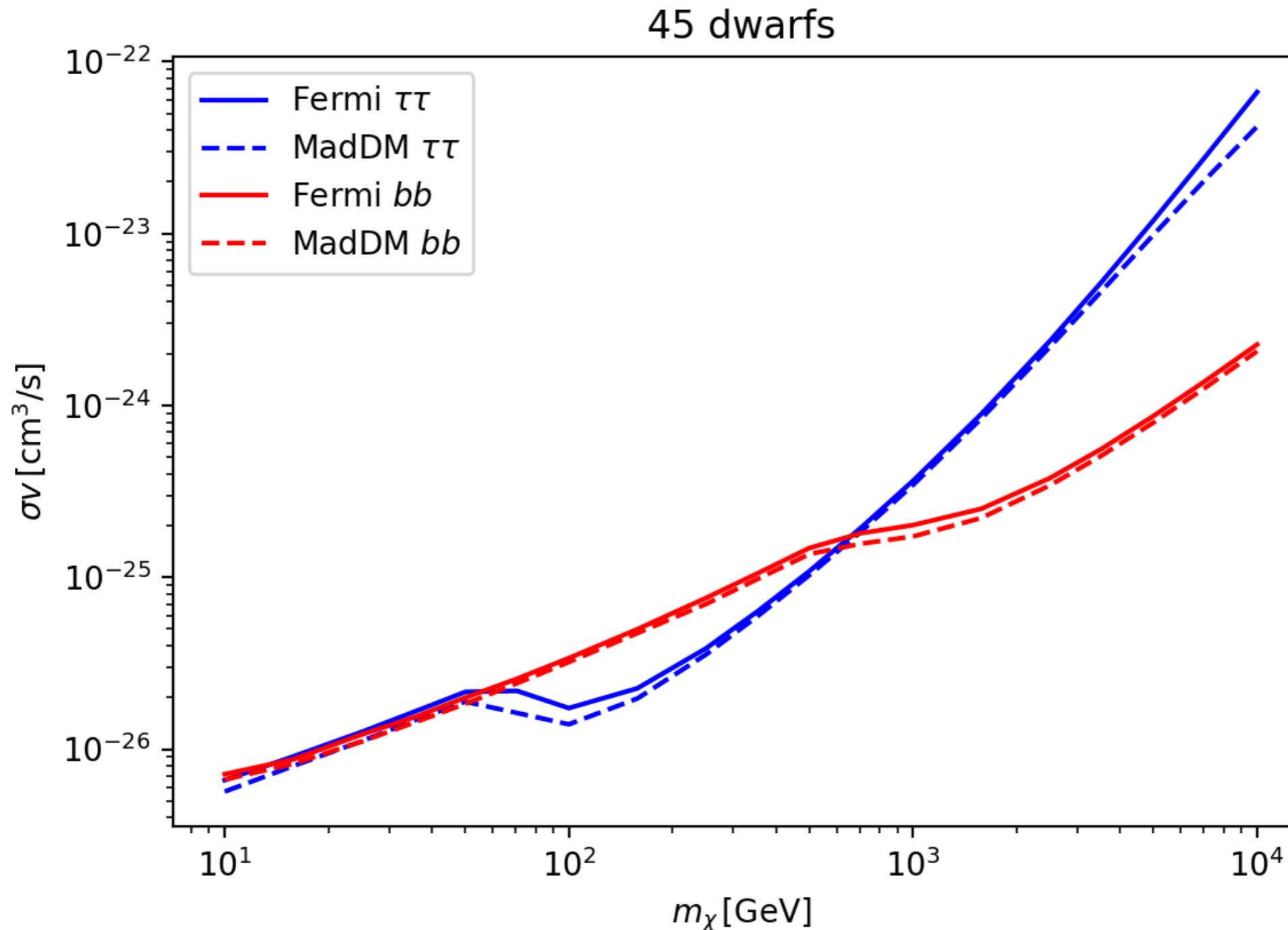
- likelihood
- p-value
- upper limit



Validation of the Fermi-LAT likelihood

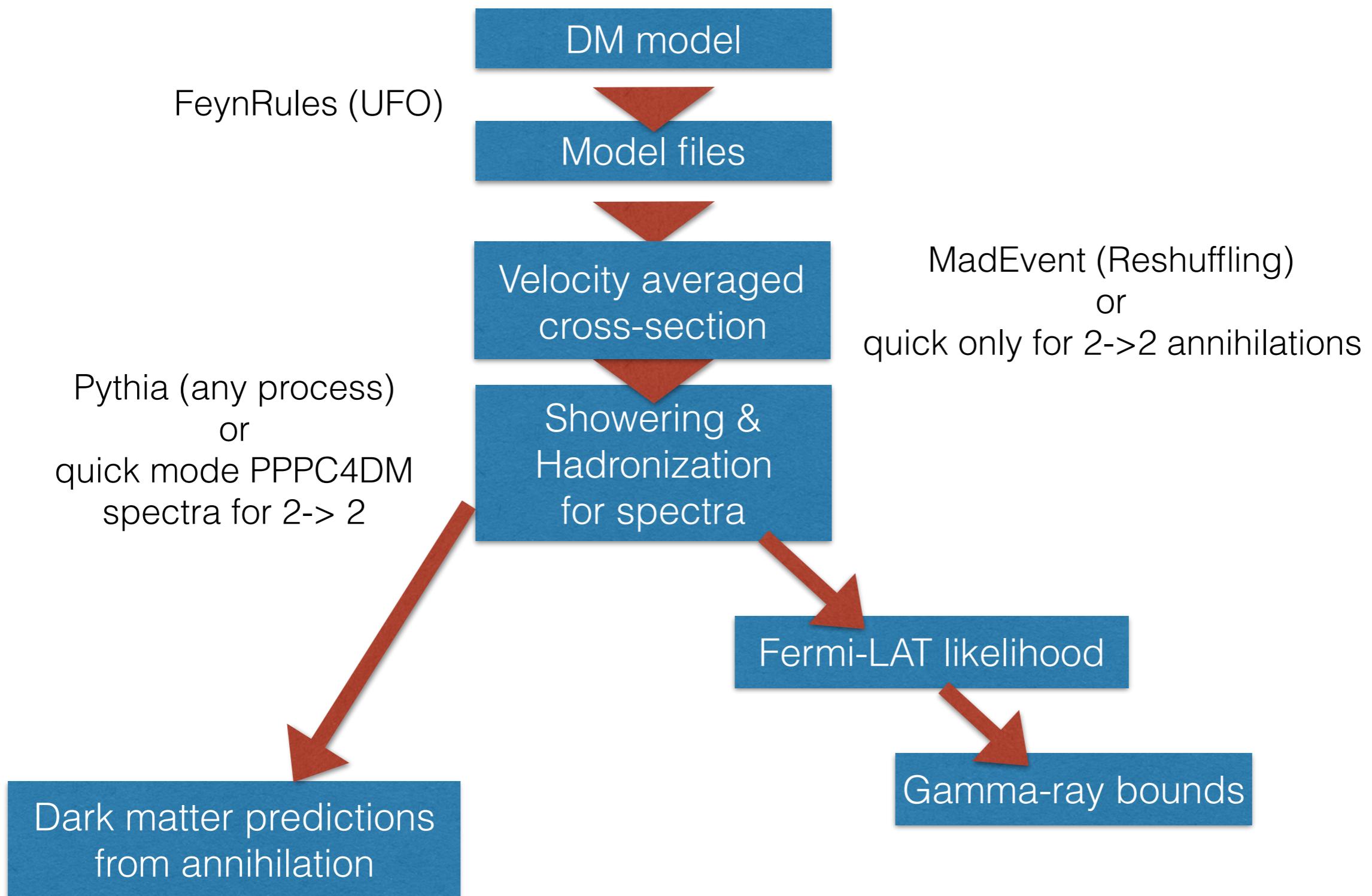


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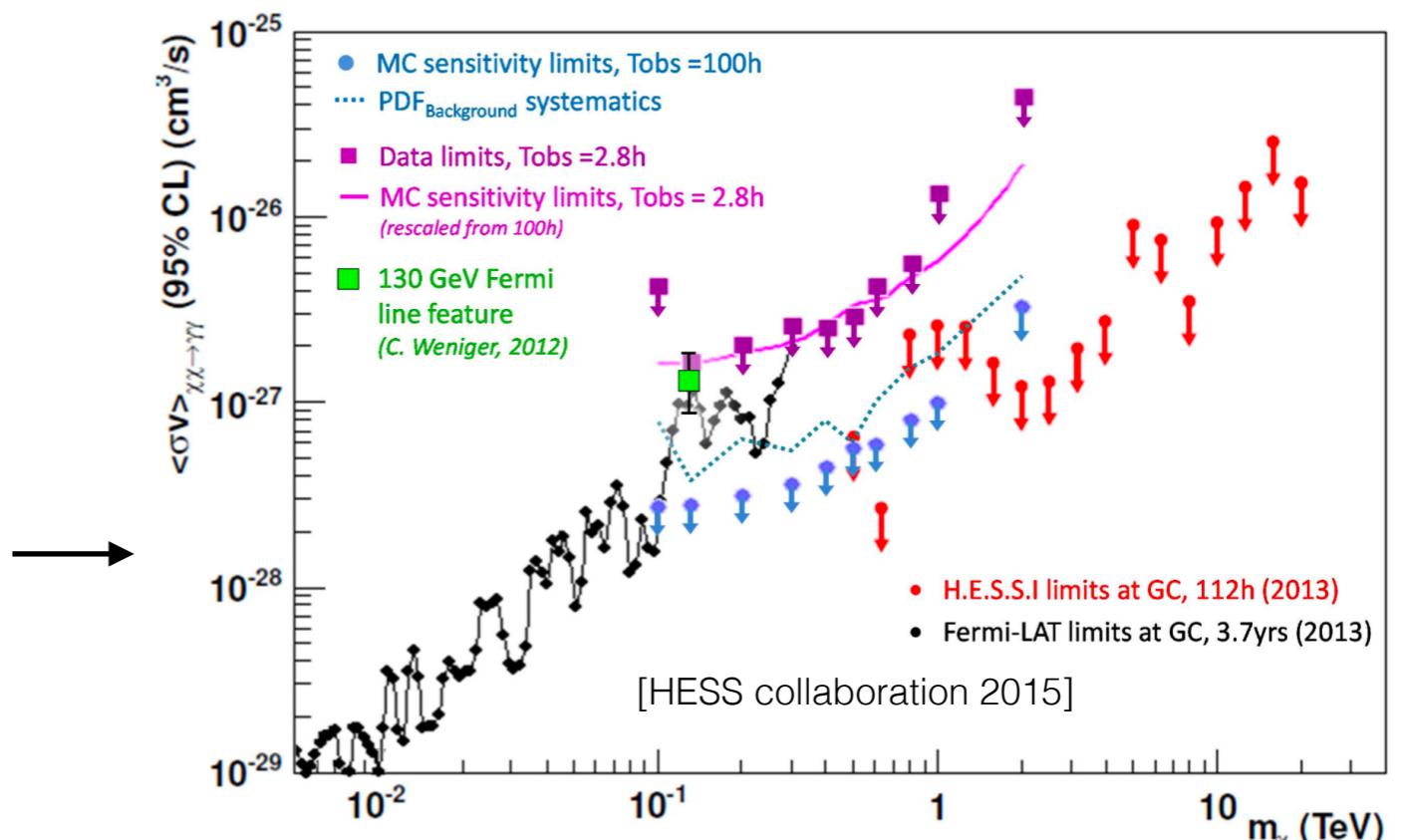
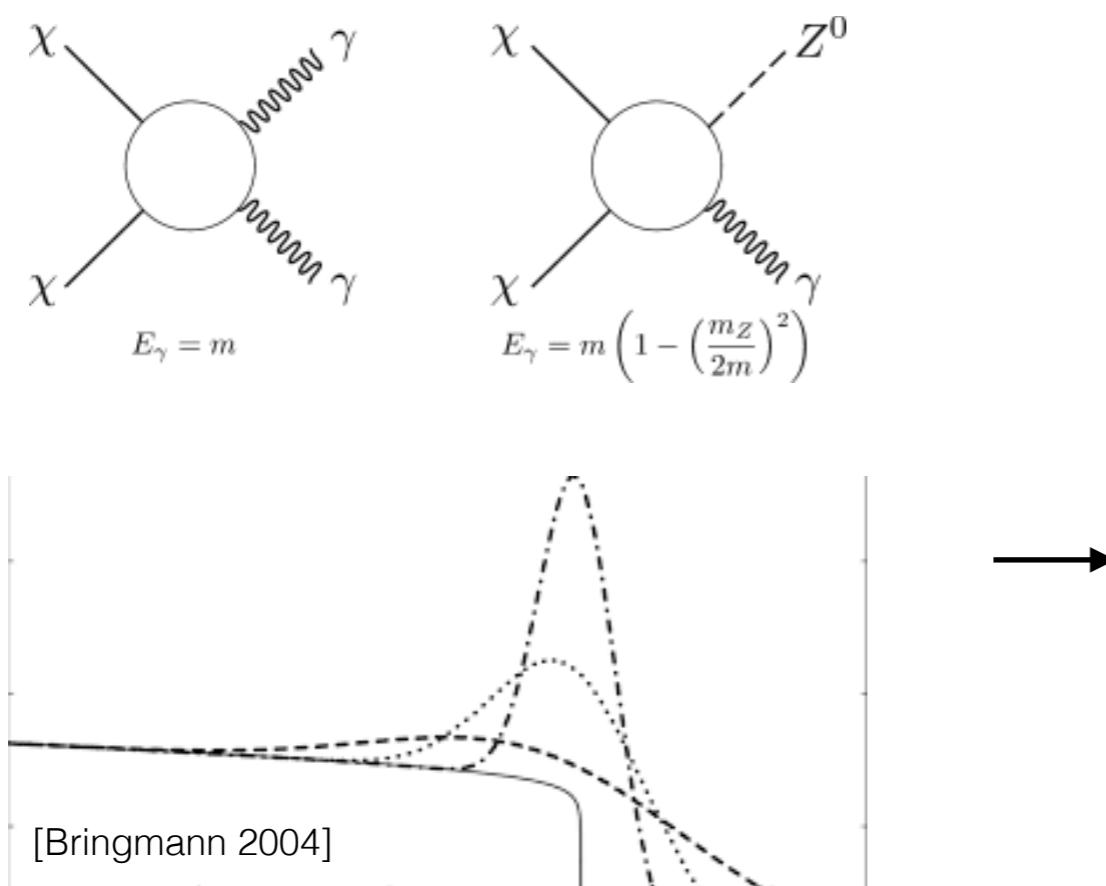
MadDM provides exclusion limits in all SM final states !

MadDM functioning for ID



Work in progress: loop induced processes

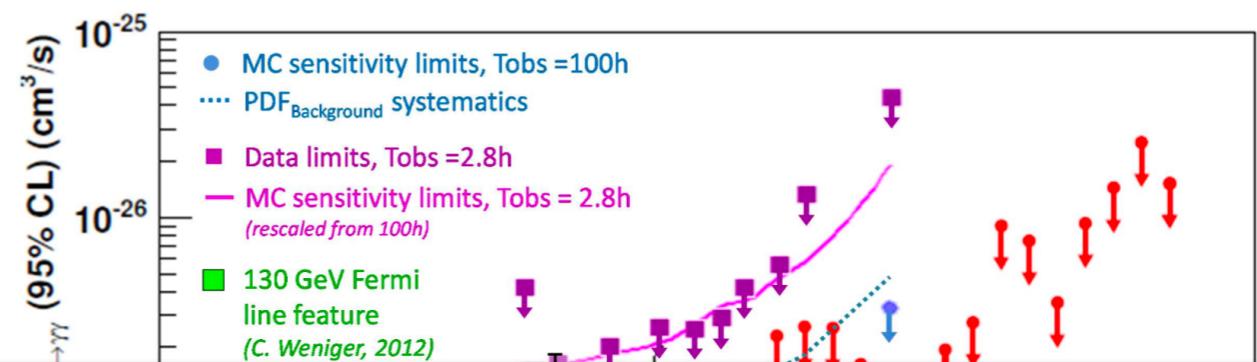
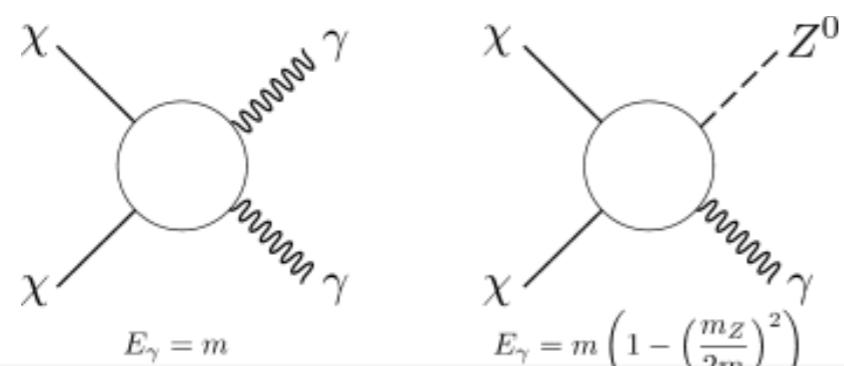
- MadDM can handle NLO processes (loop induced) with MadLoop (MG5_aMC@NLO)
- Loop induced processes relevant for DM phenomenology (very low background)



Different purpose than DM@NLO [Hermann et al. 2007] who deals with (SUSY)-QCD corrections for relic density

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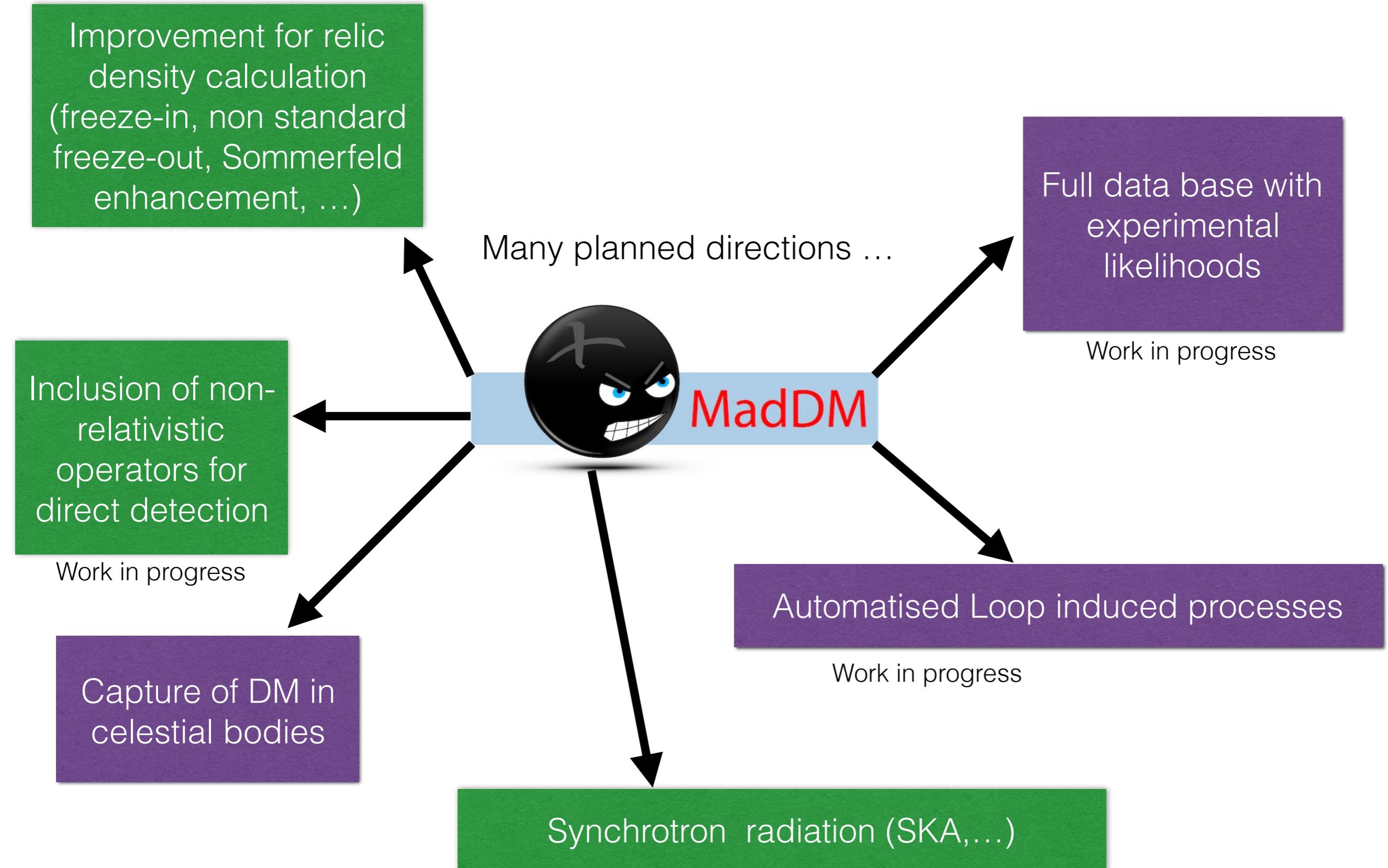
- Validation of AUTOMATIZED loop induced processes with D. Massaro, J. Heisig and O. Mattelaer
- Simple and simplified dark matter models give results for $\langle\sigma v\rangle_{\gamma\gamma}$ in excellent agreement with analytic available computations

[Bringmann 2004]

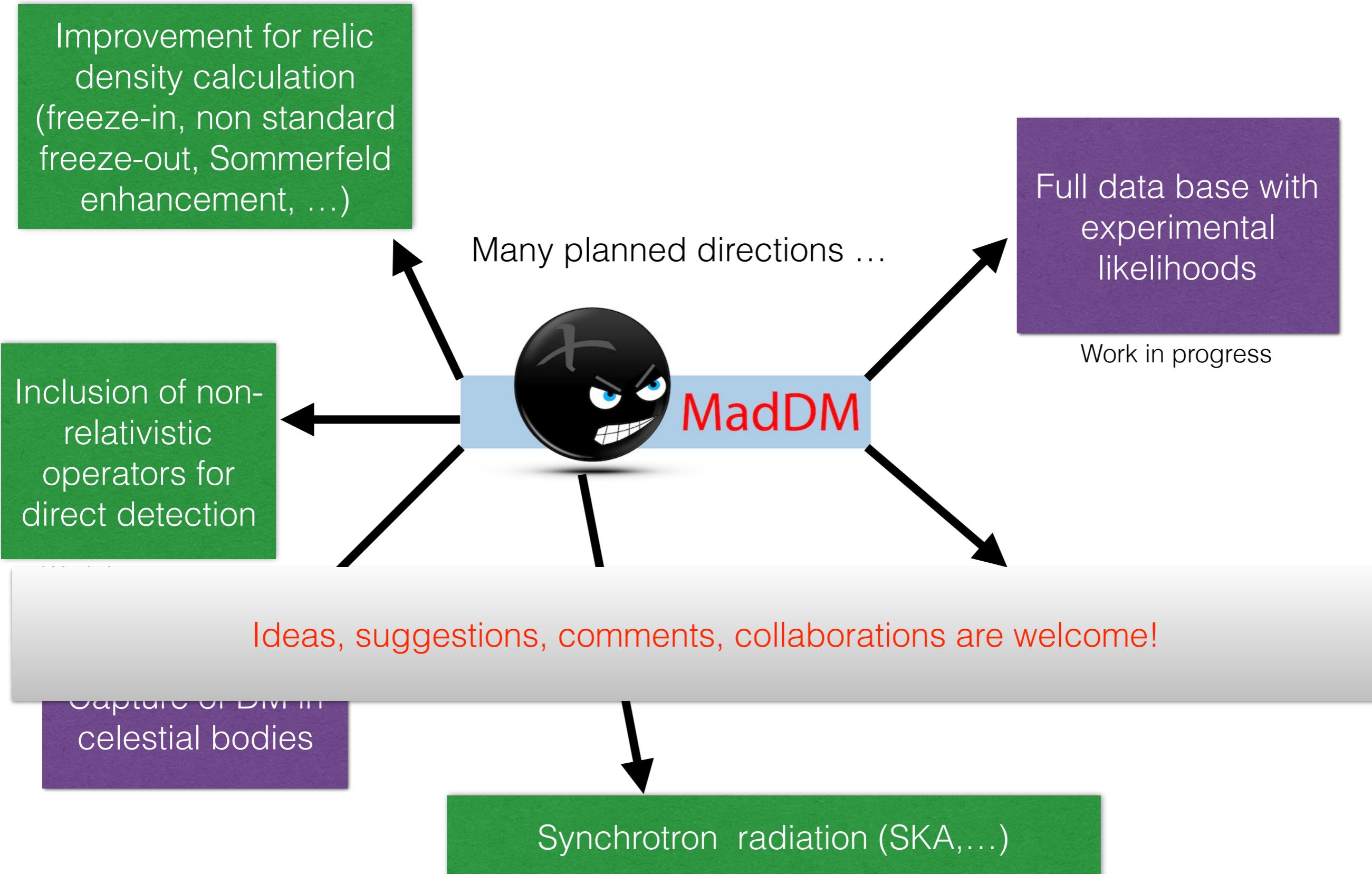


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Plans for the (more or less distant) future



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Back up slides

Automatized Indirect detection @ NLO with MadDM *

$$\mathcal{L} = \mathcal{L}_{\text{SM}} + \frac{1}{2}\partial_\mu S \partial^\mu S - \frac{1}{2}m_{S,0}^2 S^2 - \frac{1}{4}\lambda_S S^4 - \frac{1}{2}\lambda_{HS} S^2 H^\dagger H$$

Singlet Scalar model
Dark Matter = S

Write down the NLO UFO file (as for MG5_aMC@NLO) with feynrules, feynarts, NLOCT

* In collaboration with D. Massaro, J. Heisig, O. Mattelaer and F. Maltoni

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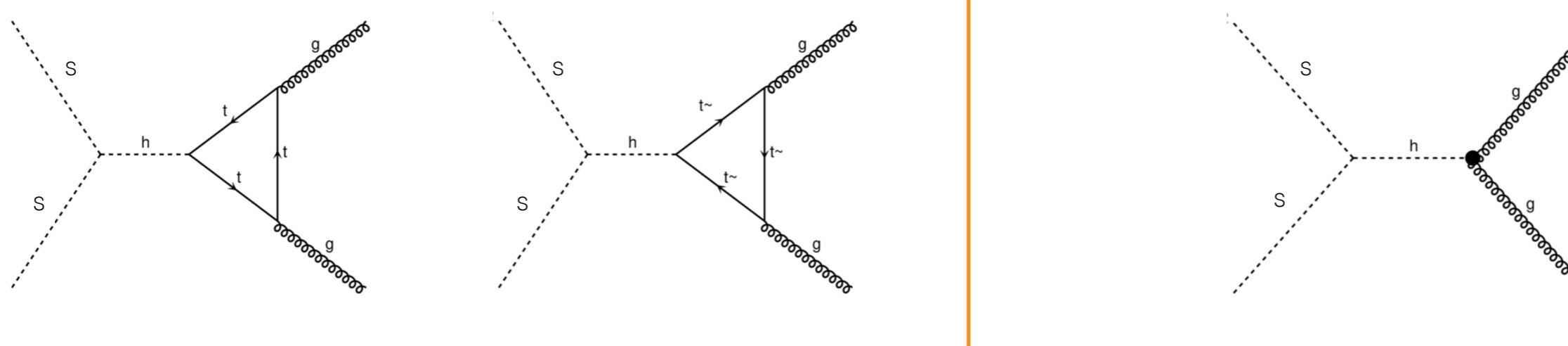
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Test first QCD loop

versus Higgs Effective Field Theory

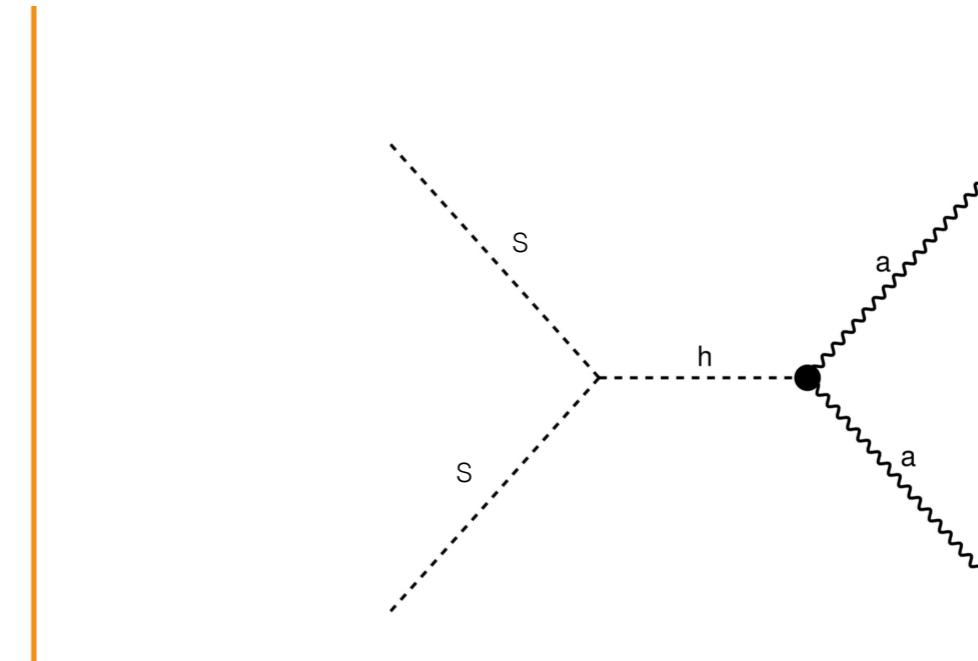
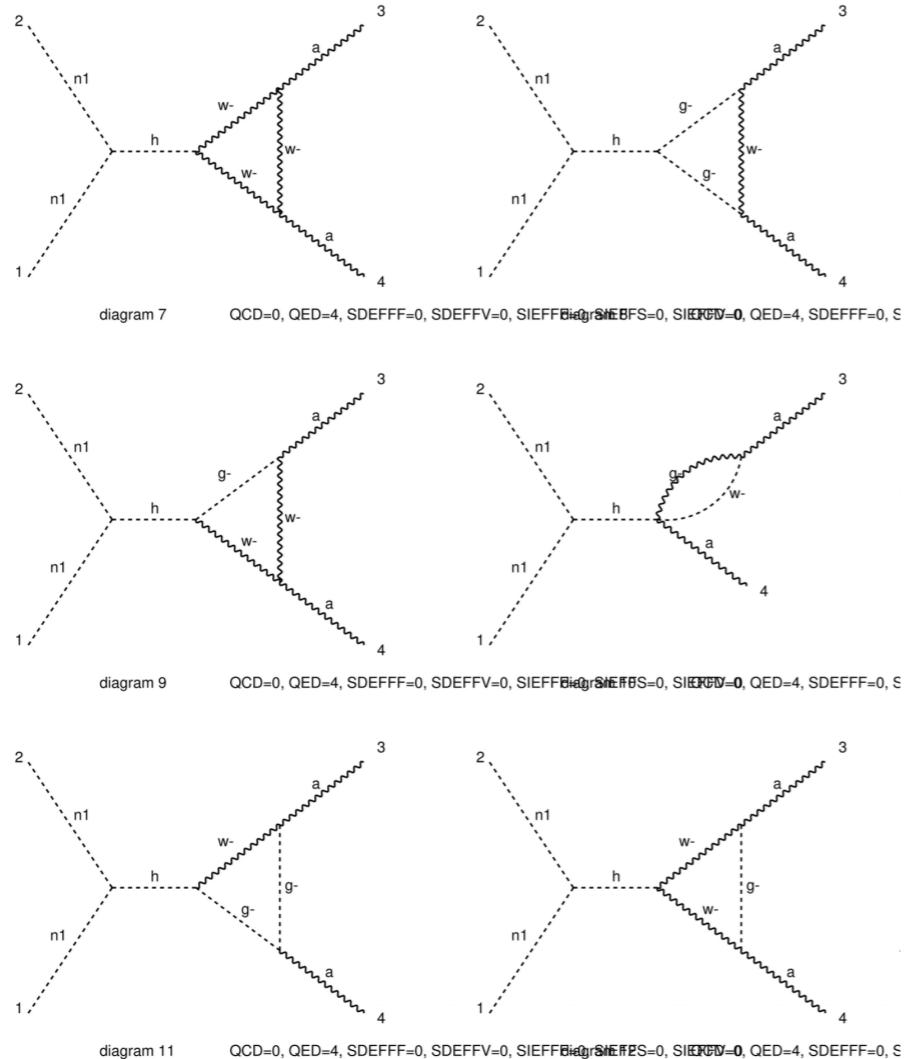


m_S [GeV]	Model	$\langle \sigma v_0 \rangle_{gg}$ [cm ³ /s]
50	Singlet DM (QCD only)	5.20×10^{-26}
	HEFT	5.20×10^{-26}
70	Singlet DM (QCD only)	1.92×10^{-25}
	HEFT	1.92×10^{-25}

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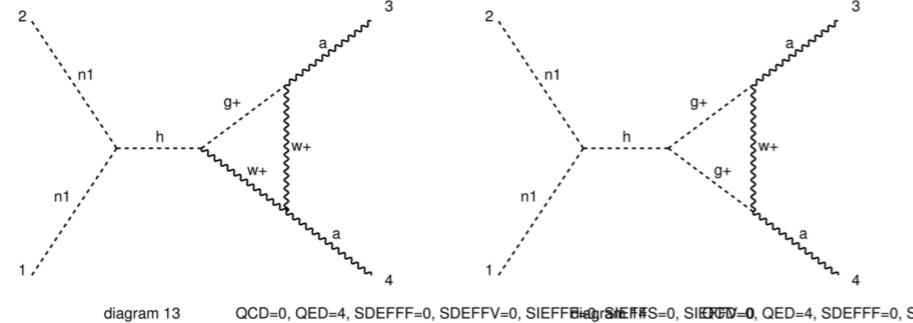
Test full NLO model including EW loops for annihilation into $\gamma \gamma$



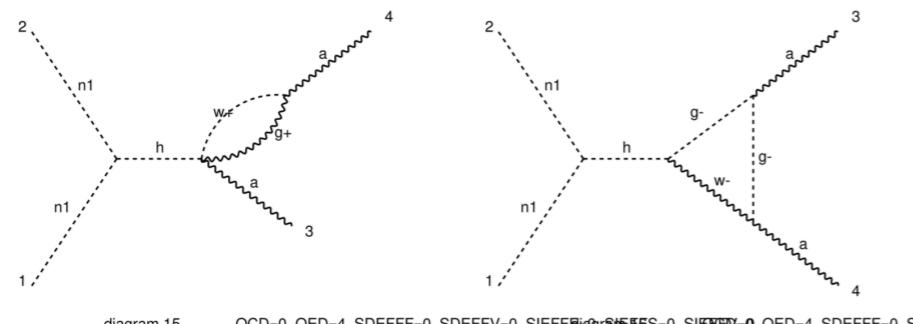
- Singlet Scalar model very simple and loops are SM like
- Models involving more BSM particles are being investigated (Inert Doublet Model, SUSY like, KK dark matter...)
- Works for any BSM model with NLO UFO file

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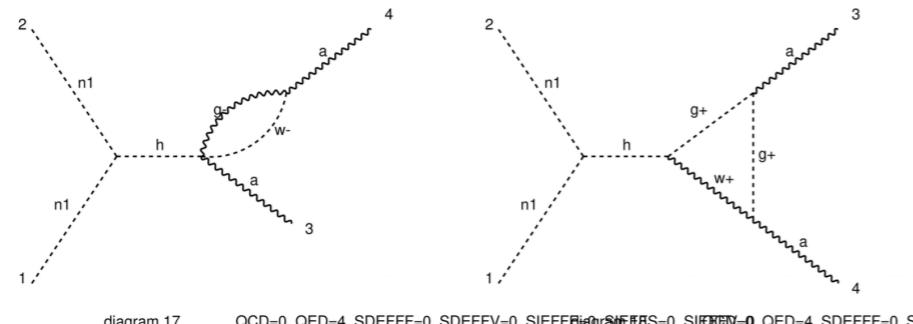
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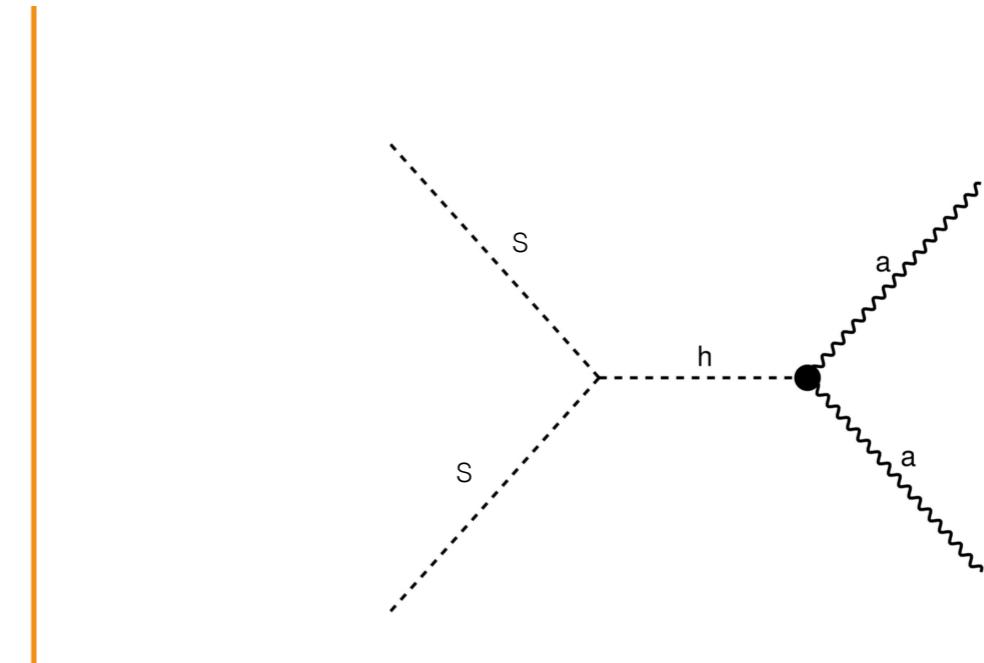
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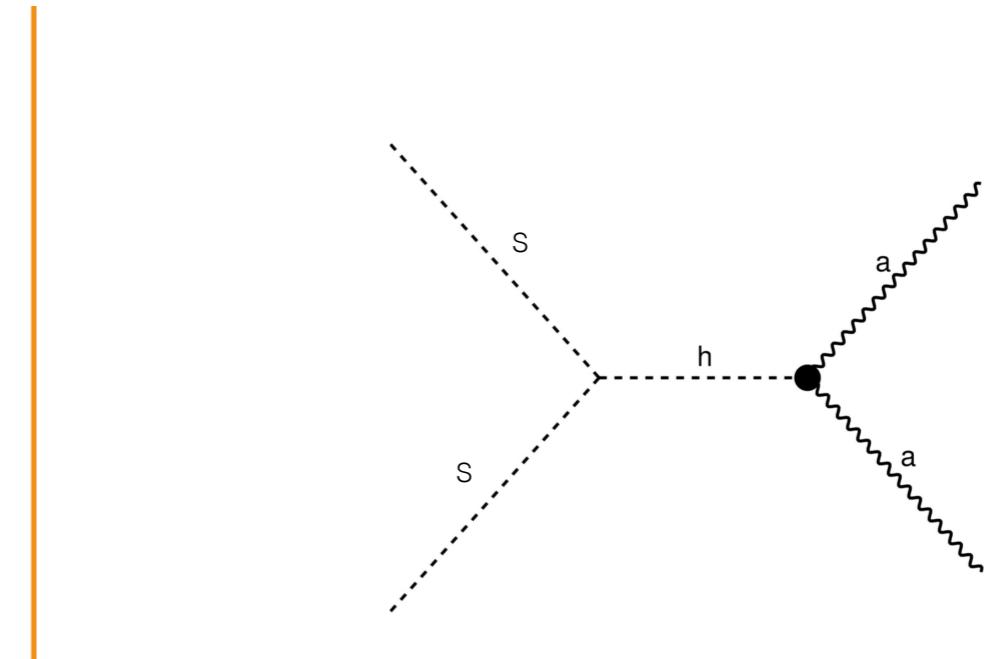
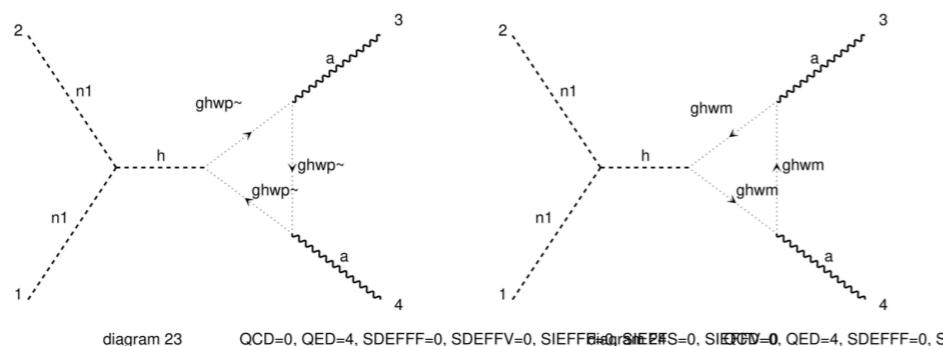
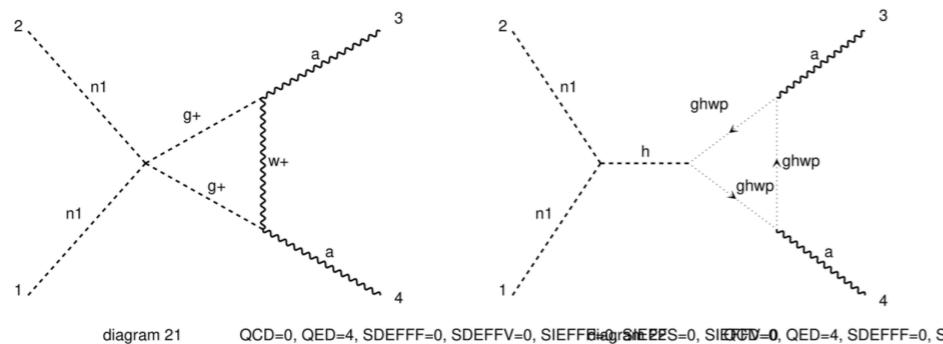
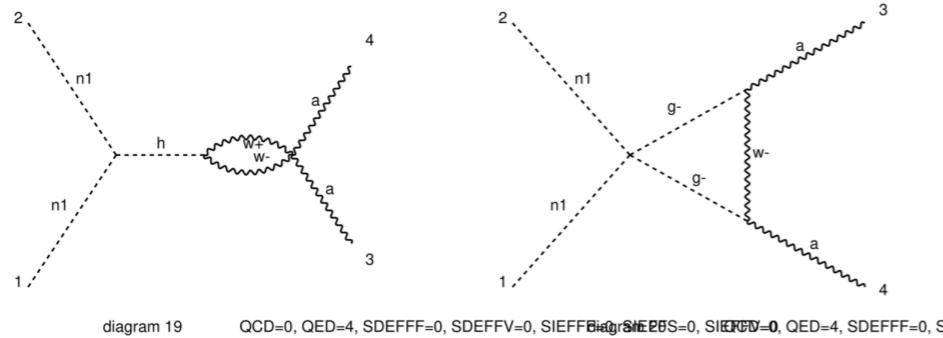
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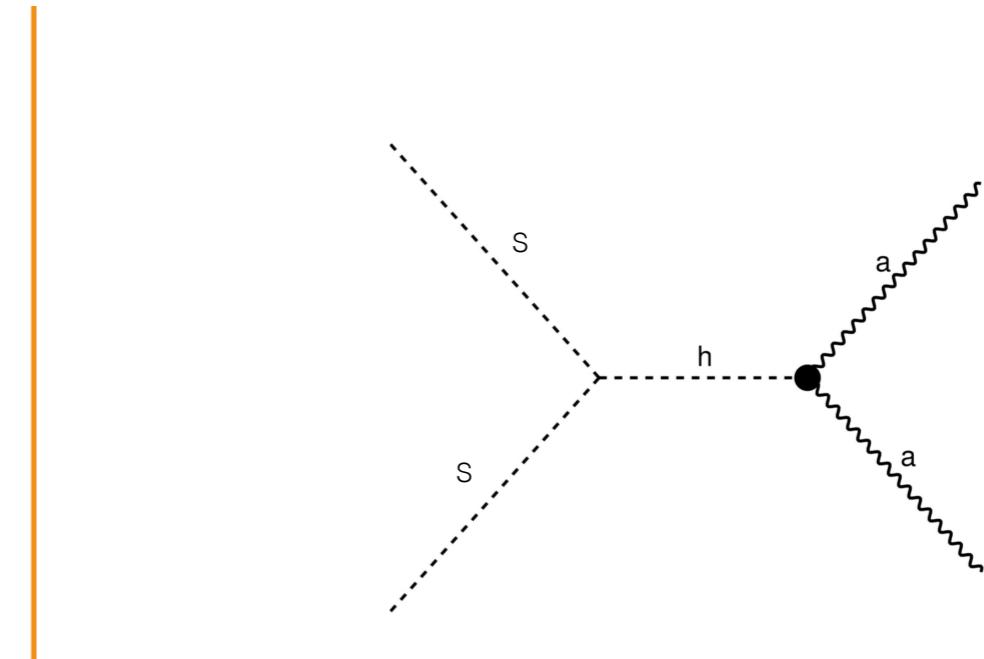
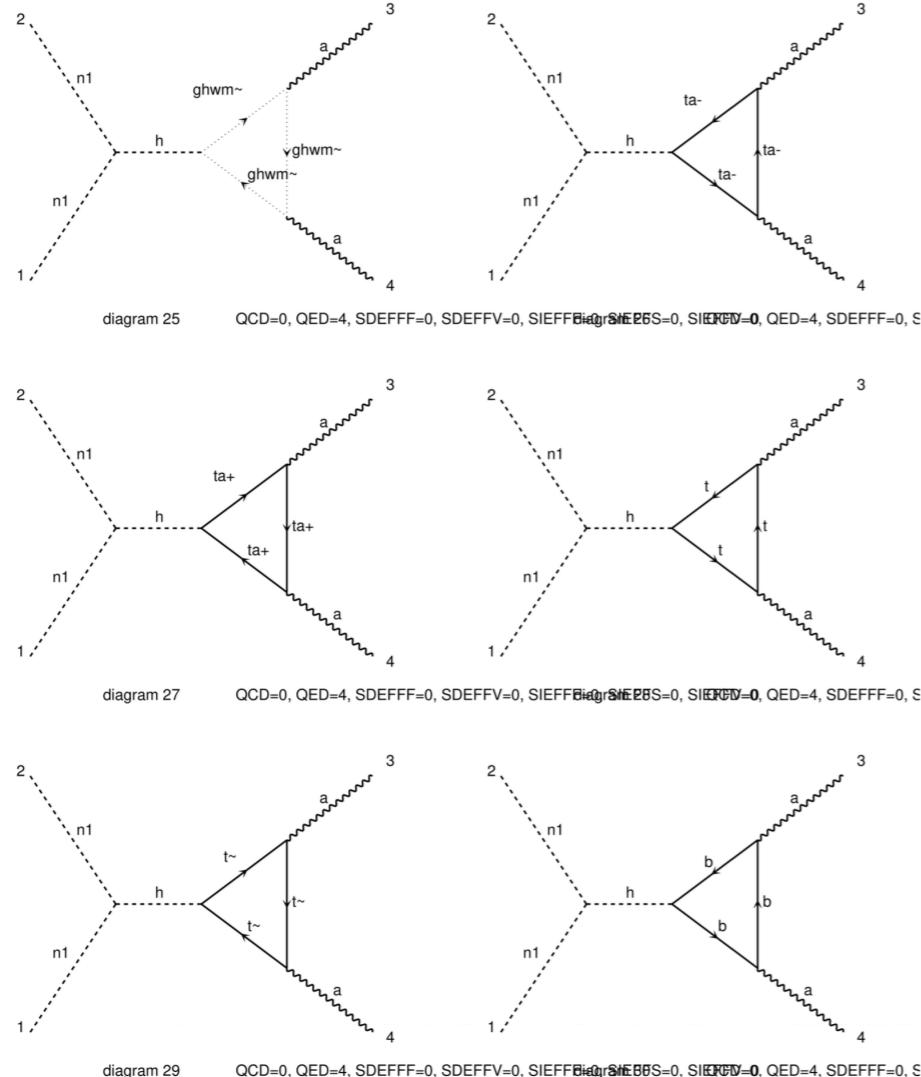
Test full NLO model including EW loops for annihilation into $\gamma \gamma$



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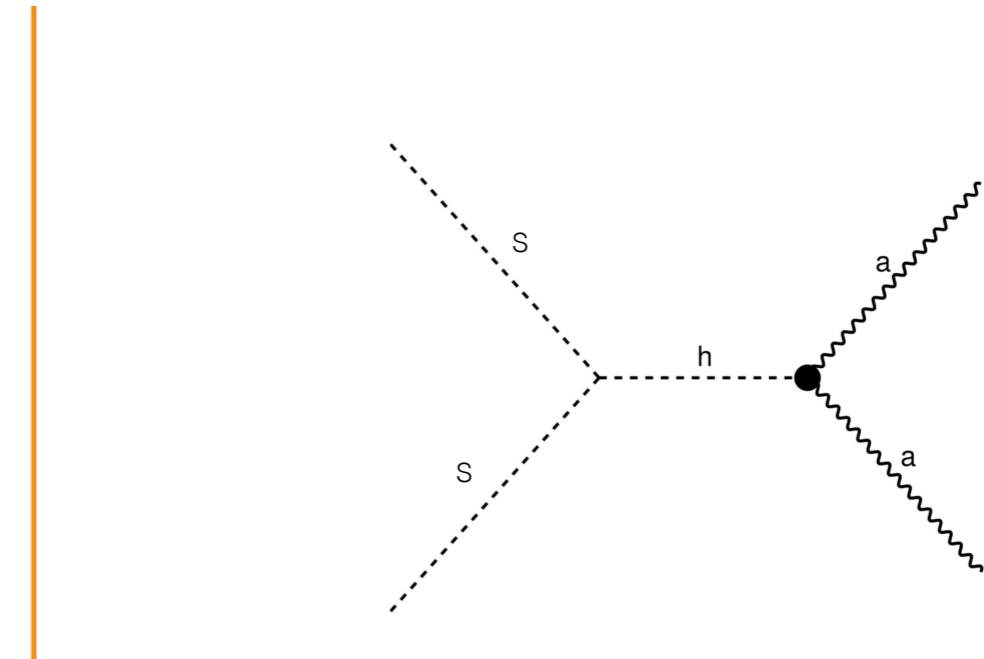
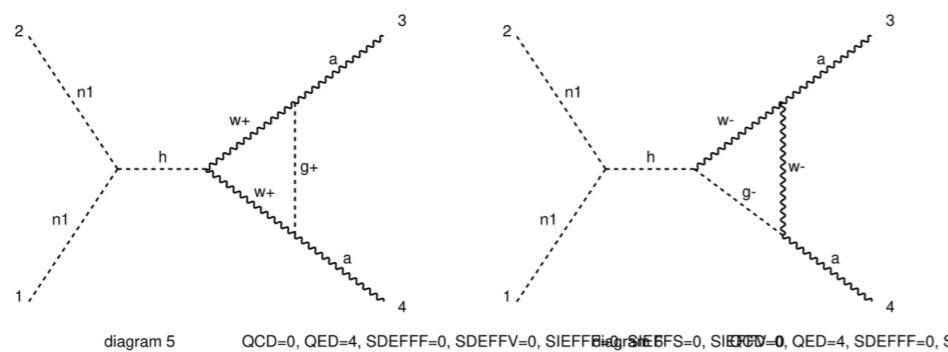
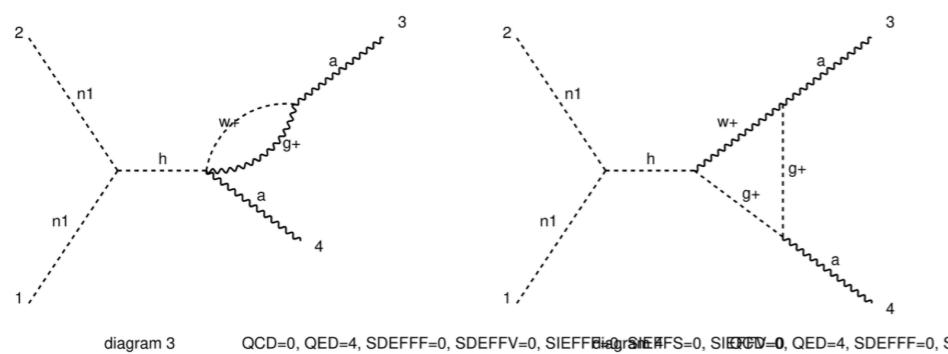
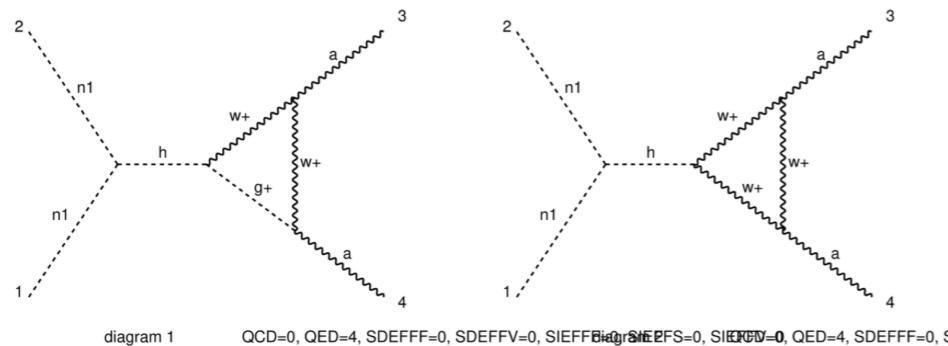
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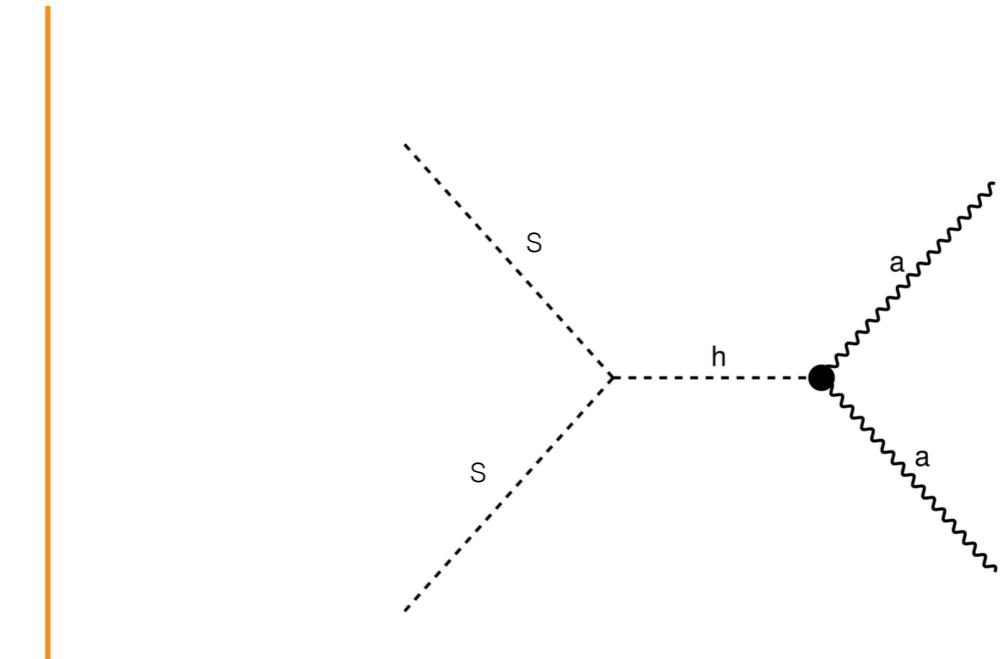
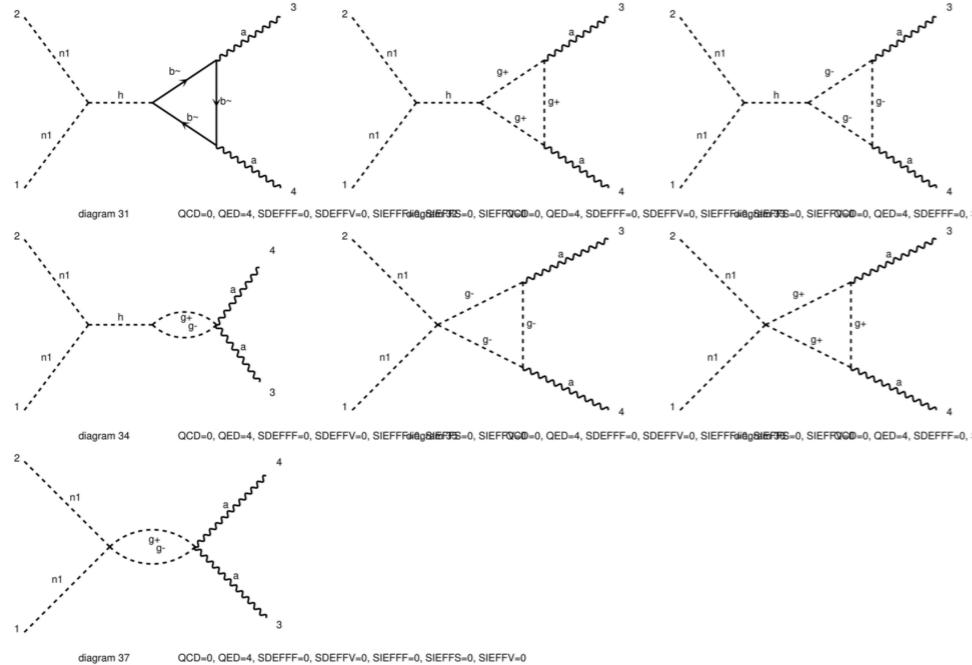
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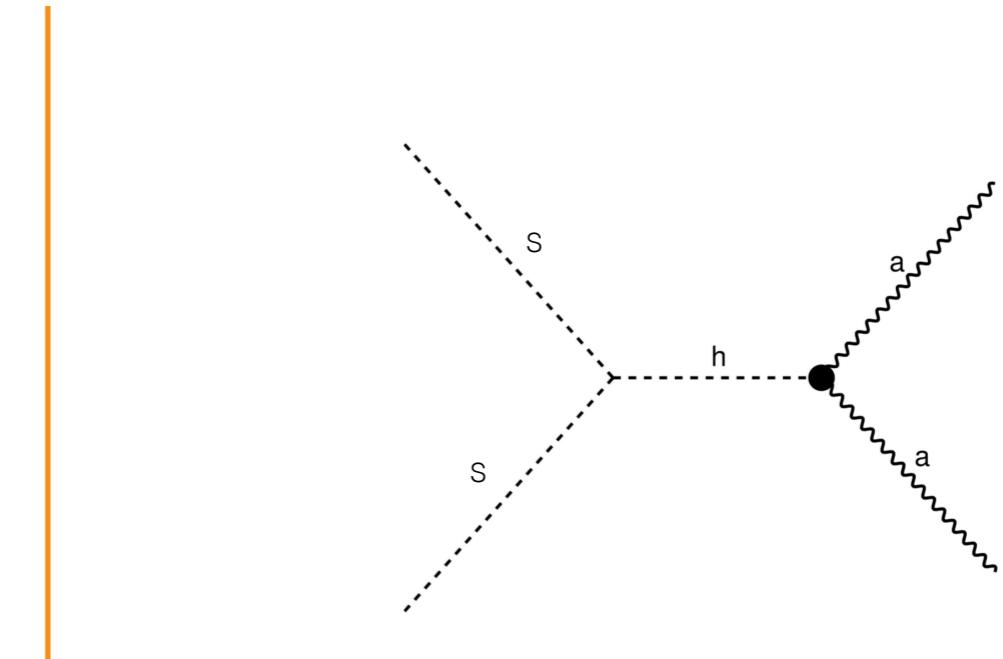
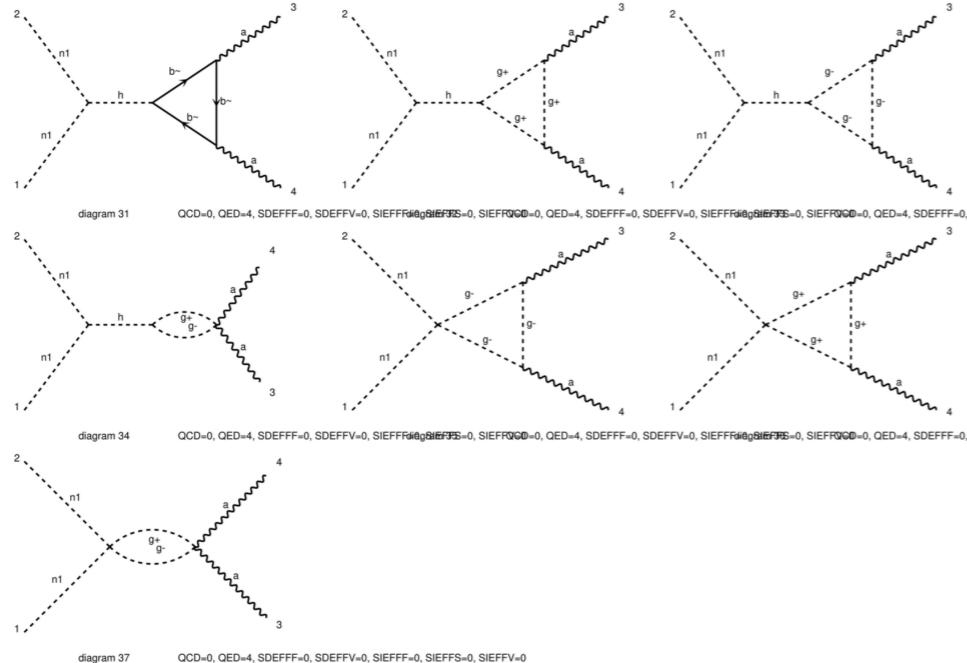
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Test full NLO model including EW loops for annihilation into $\gamma \gamma$



m_S [GeV]	Model	$\langle\sigma v_0\rangle_{\gamma\gamma}$ [cm 3 /s]
50	Singlet DM (full NLO, b and τ massless)	1.98×10^{-27}
	Singlet DM (full NLO)	2.02×10^{-27}
	HEFT	1.98×10^{-27}
70	Singlet DM (full NLO, b and τ massless)	1.14×10^{-26}
	Singlet DM (full NLO)	1.16×10^{-26}
	HEFT	1.12×10^{-26}

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MadDM v.3

<https://launchpad.net/maddm>

- Now a plugin of Madgraph (and also of MG5_aMC@NLO)



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install maddm



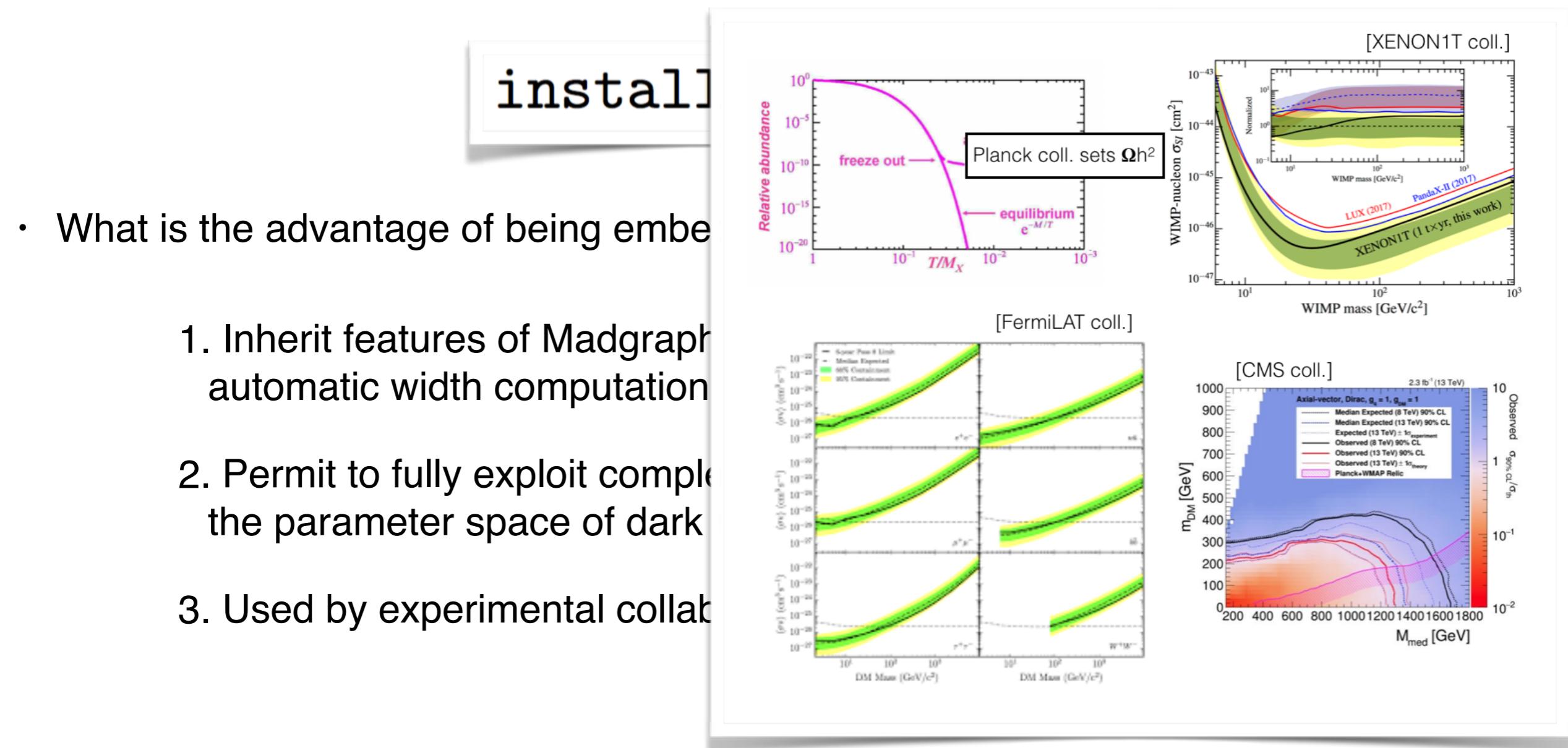
- Now a plugin of Madgraph (and also of MG5_aMC@NLO)

install maddm

- What is the advantage of being embedded in Madgraph?
 1. Inherit features of Madgraph (MadEvent, scan command, automatic width computation, ...)
 2. Permit to fully exploit complementarity of searches to corner the parameter space of dark matter models
 3. Used by experimental collaborations (ex. ATLAS)



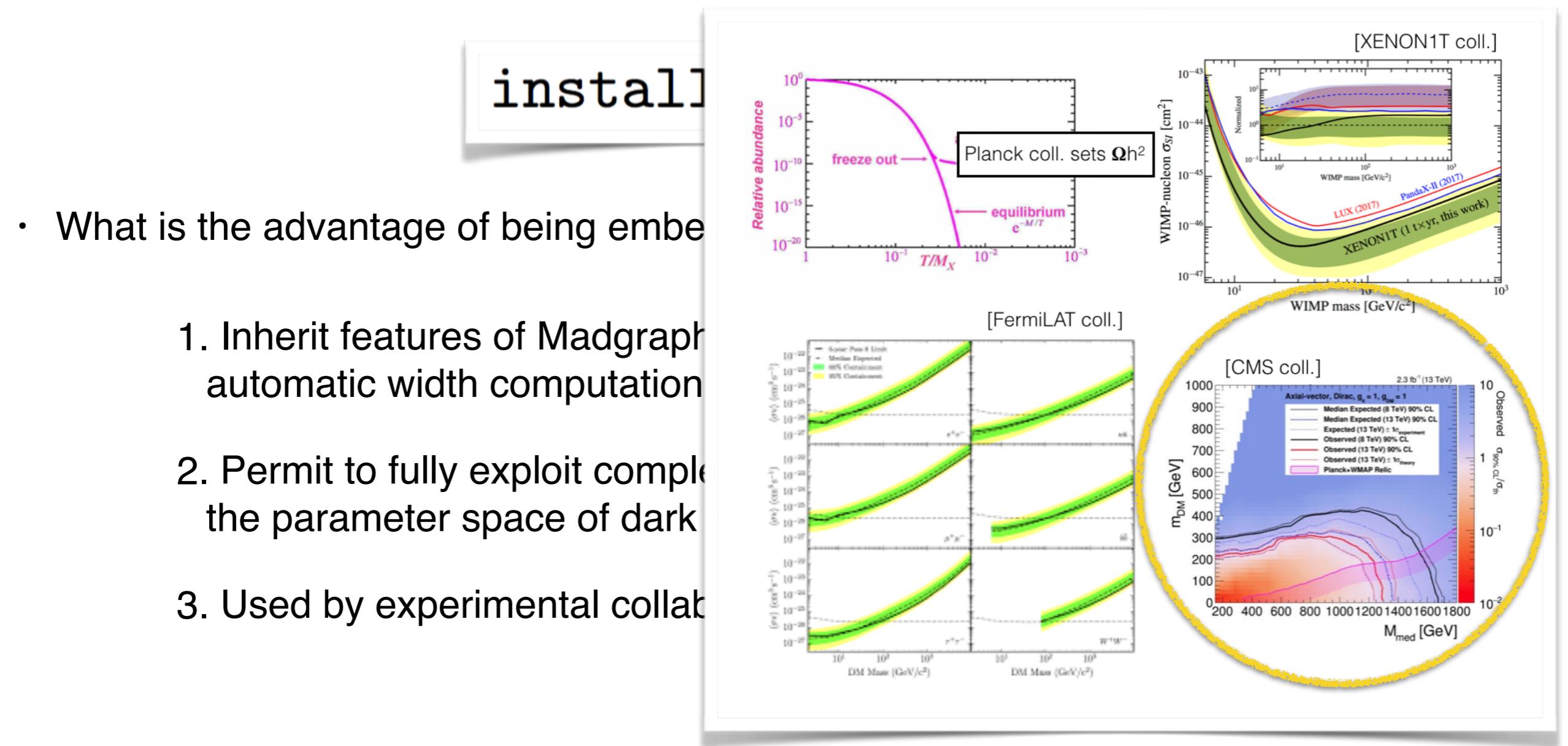
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Resume of Indirect detection capabilities

	Indirect detection module			Experimental constraints	Scans
Running mode	$\langle \sigma v \rangle$	Energy Spectra	Flux at Earth	Module available:	Module available:
Fast	$(\sigma \times v) _{v=v_{\text{rel}}}$ Allows <u>only</u> $\text{DM DM} \rightarrow 2 \text{ particles}$	Numerical tables Allows <u>only</u> $\text{DM DM} \rightarrow \text{SM SM}$	Prompt photons Neutrinos Positrons (fixed sets of propagation parameters)	Simplified framework based on the ExpConstraint class	Sequential grid scan PyMultiNest
Precise	Full integration over the DM velocity distribution Allows for <u>any</u> DM annihilation process $\text{DM DM} \rightarrow n \text{ particles}$	Pythia 8 computes on the fly the energy spectra Allows for <u>any</u> DM annihilation process $\text{DM DM} \rightarrow n \text{ particles}$	Prompt photons Neutrinos Positrons Anti-protons (free choice of propagation parameters)	Fermi-LAT likelihood for dSPhs + ExpConstraint class	Sequential grid scans PyMultinest



MadDM v.3

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Towards a tool for comprehensive dark matter studies*

Dark Matter Indirect Detection:

- Compute annihilation cross section in halos at present time
- Compute the energy spectrum of dark matter products for ANY process
- Compute the flux at the Earth position

* GAMBIT collaboration has the same spirit [2017]



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Automatic Multi-dimensional Parameter Sampling:

- Sequential grid method (good for 2D scans)
- Interface with PyMultiNest (similar to Markov Chain Monte Carlo); good and stable for a large number of parameters

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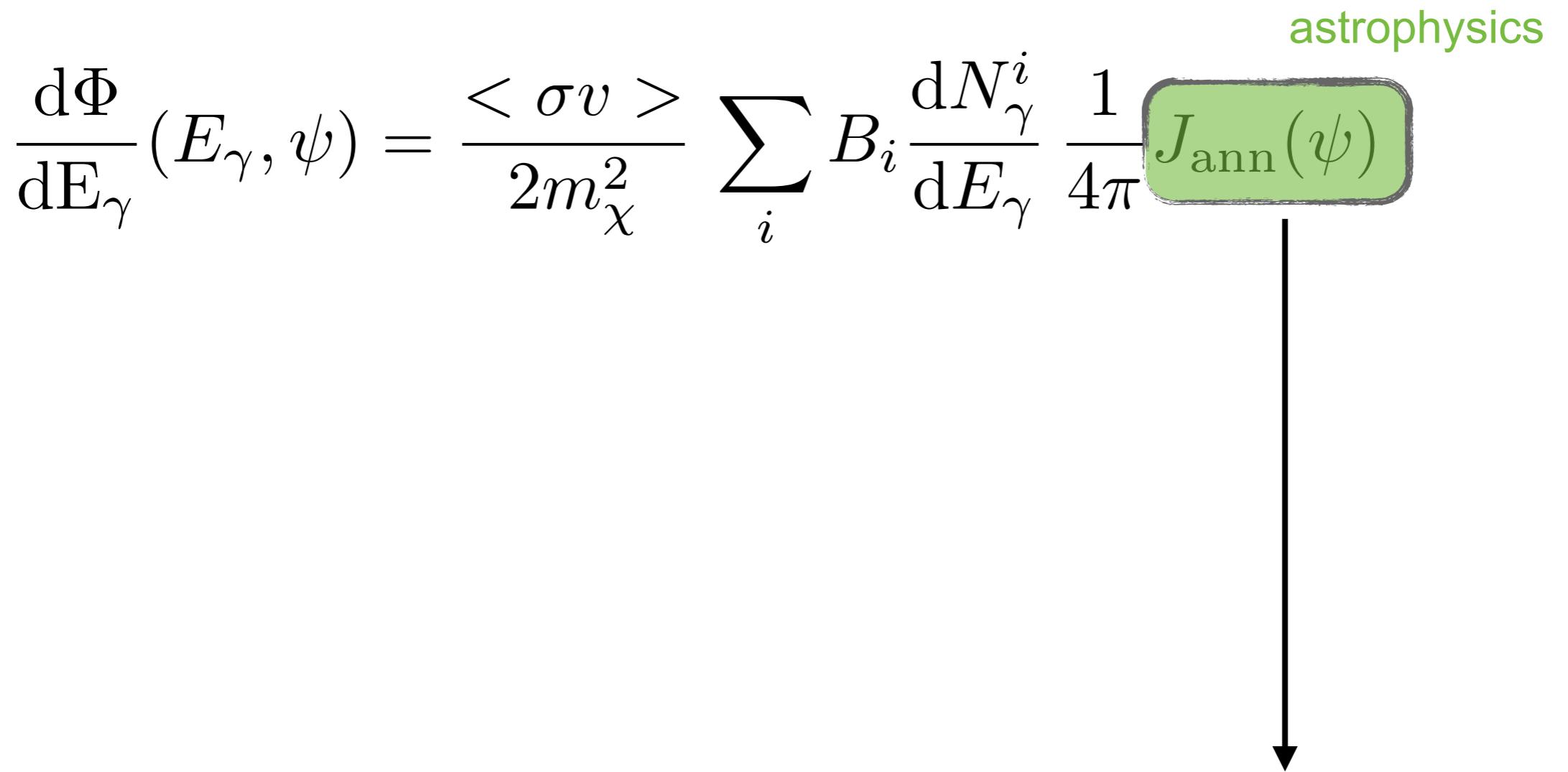
Example of differential energy spectrum

$$\frac{d\Phi}{dE_\gamma}(E_\gamma, \psi) = \frac{\langle \sigma v \rangle}{2m_\chi^2} \sum_i B_i \frac{dN_\gamma^i}{dE_\gamma} \frac{1}{4\pi} J_{\text{ann}}(\psi)$$

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astrophysics



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Depends on the DM density distribution and experiments:

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$$\langle \sigma v(v_{\text{rel}}) \rangle \propto \int d^3v_{\text{rel}} P_{\vec{r},\text{rel}}(\vec{v}_{\text{rel}}) \sigma(v_{\text{rel}})$$

- Typically $P(v_{\text{rel}})$ is neglected
- Integral computed with the reshuffling technique of MadGraph
- Unique to MadDM

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astrophysics

Energy spectrum: number of photons produced by DM annihilation into particles i

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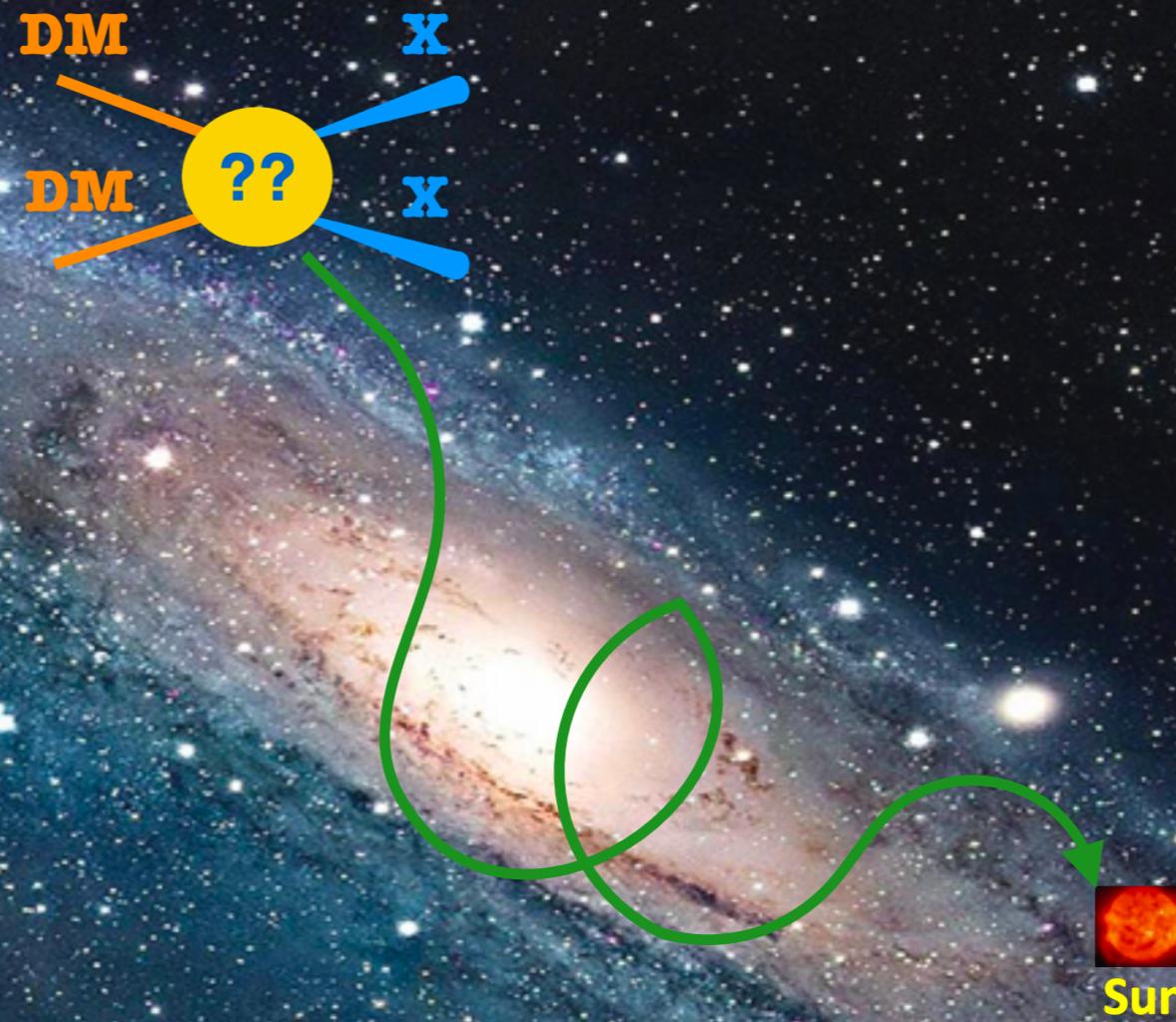
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Particle propagation from the source to Earth



Particle propagation from the source to Earth

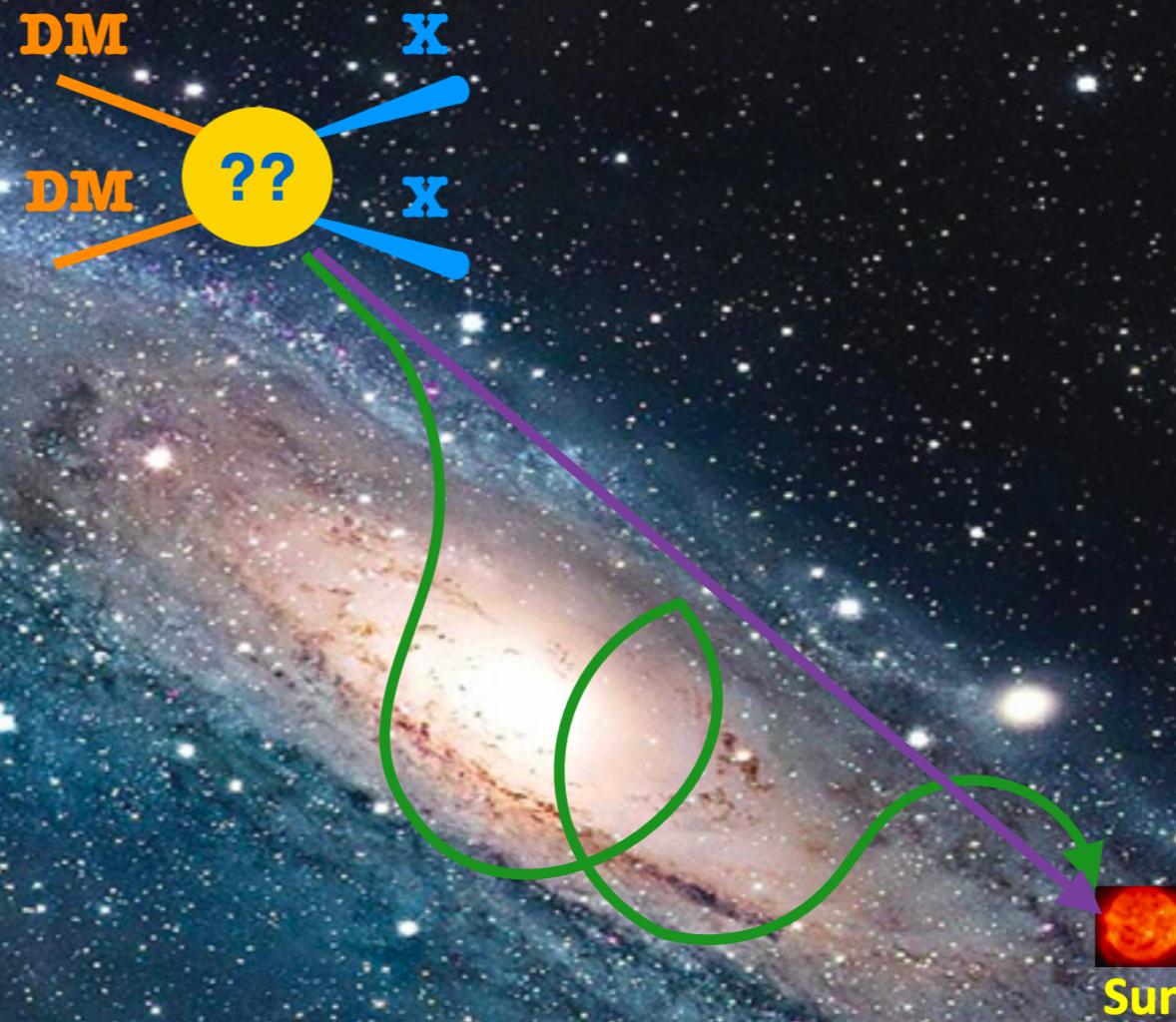


Positrons, anti-protons and anti-deuterons:

- A. Loose information on the direction due to propagation in the magnetic galactic field
- B. Spectral information

MadDM provides a user friendly interface to DRAGON [Evoli et al 2008]

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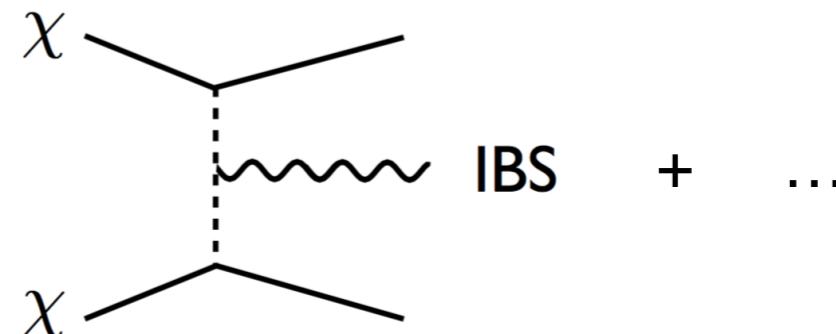
Photons and neutrinos:

- A. Spatial information
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MadDM v.3.0 provides the flux at Earth

Automatized $2 \rightarrow 3$ processes

- Final state radiation out of the box

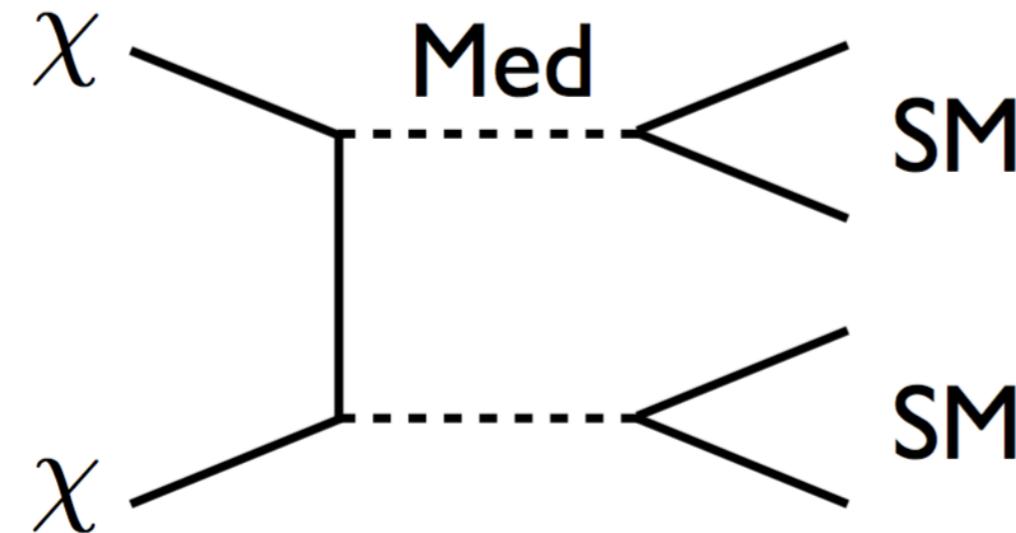


$$\mathcal{L} \supset y_R \chi_r \bar{\Psi}_R q_R + y_L \chi_r \bar{\Psi}_L Q_L + h.c.$$

- Dark matter annihilation into light fermions is d-wave suppressed
- Emission of a photon from final state uplift the suppression and the cross-section becomes s-wave

Secluded dark matter

[Batell, Pospelov, Ritz, Shang 2009]

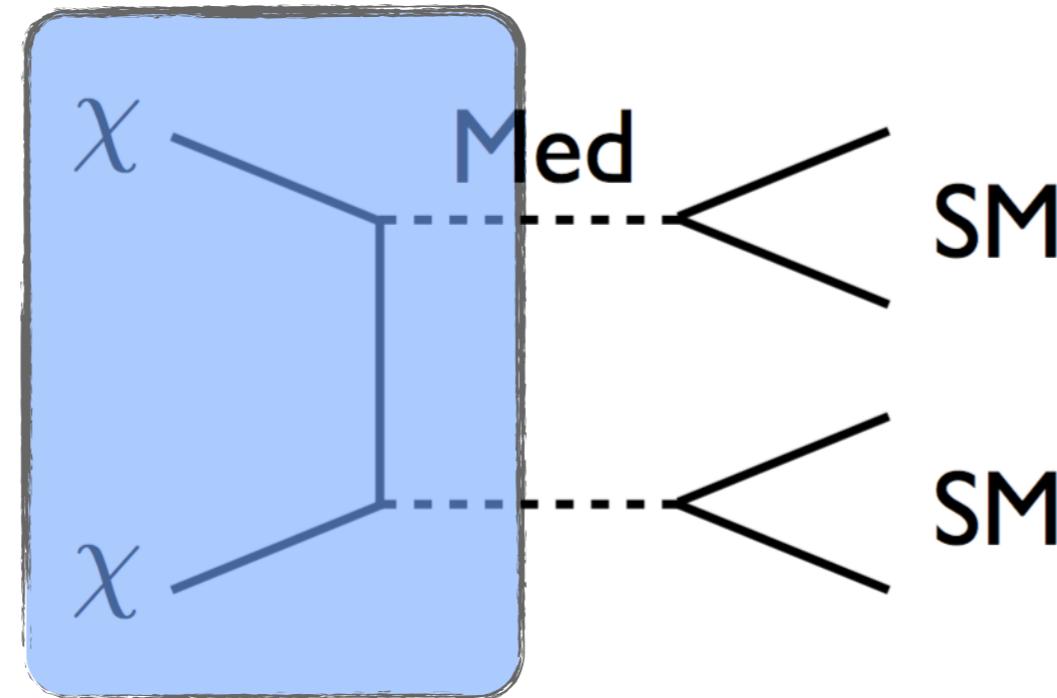


- Simplified model: $\mathcal{L} = g_q y_q \bar{q} [\cos \theta + i \sin \theta \gamma_5] q Y_0 + g_X \bar{X}_d [\cos \theta + i \sin \theta \gamma_5] X_d Y_0$
- Avoids direct detection and collider bounds
- Mixed pseudo-scalar mediator annihilates s-wave \rightarrow only probe*

* [CA, M.Baskovic, J.Heisig and M.Lucente arXiv:1703.08087, Phys.Rev.D 2017]

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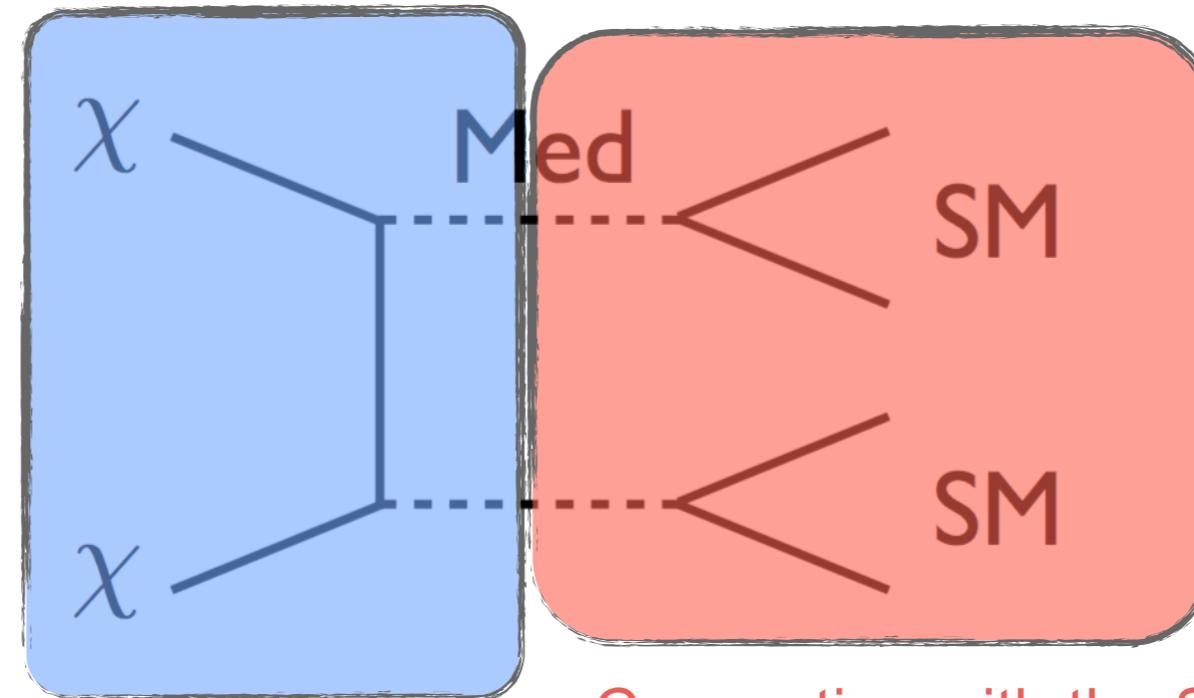
Annihilation into
mediator fixes
relic density

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Annihilation into
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Connection with the SM
independent of the relic
density, can be very small

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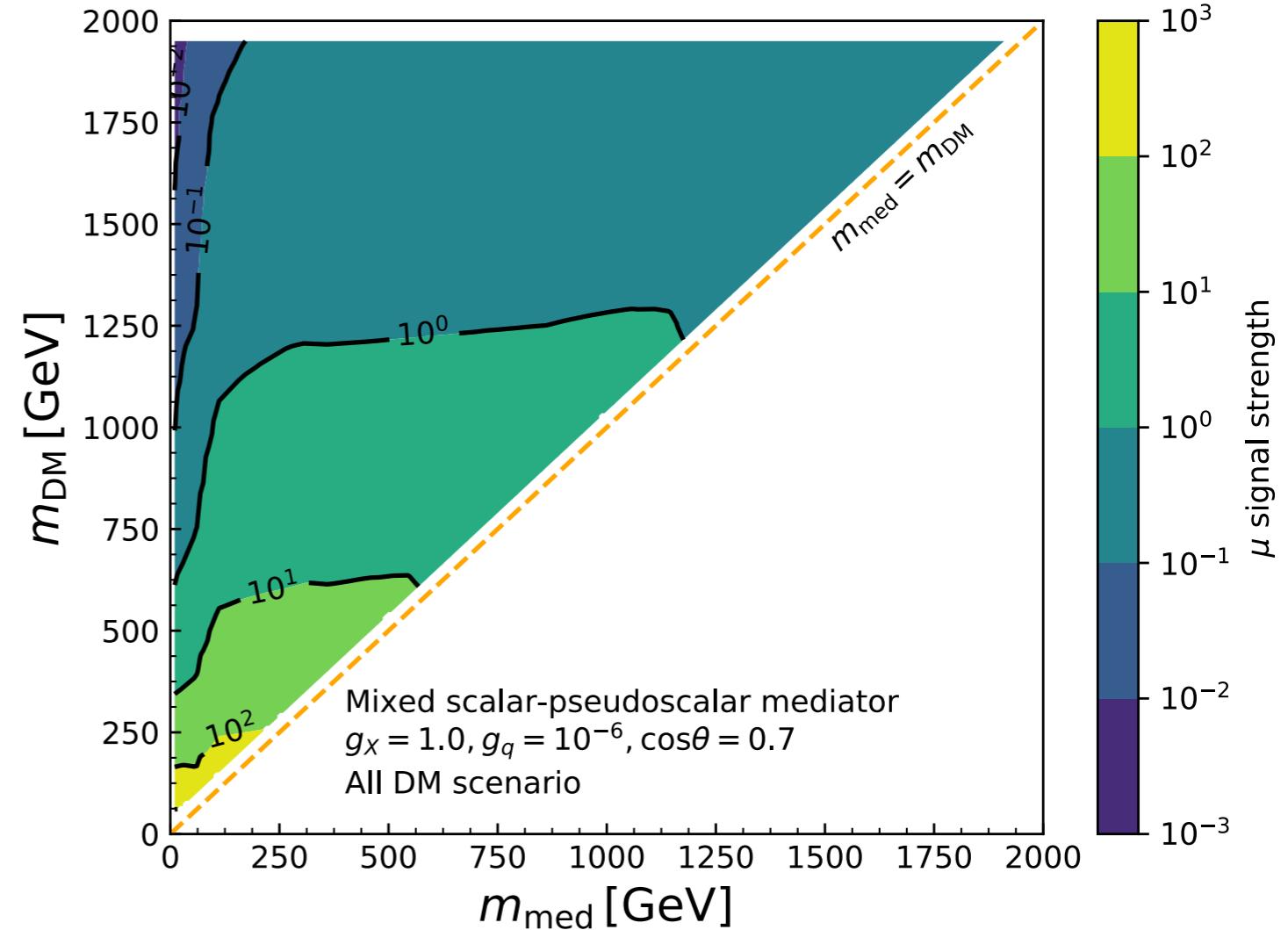
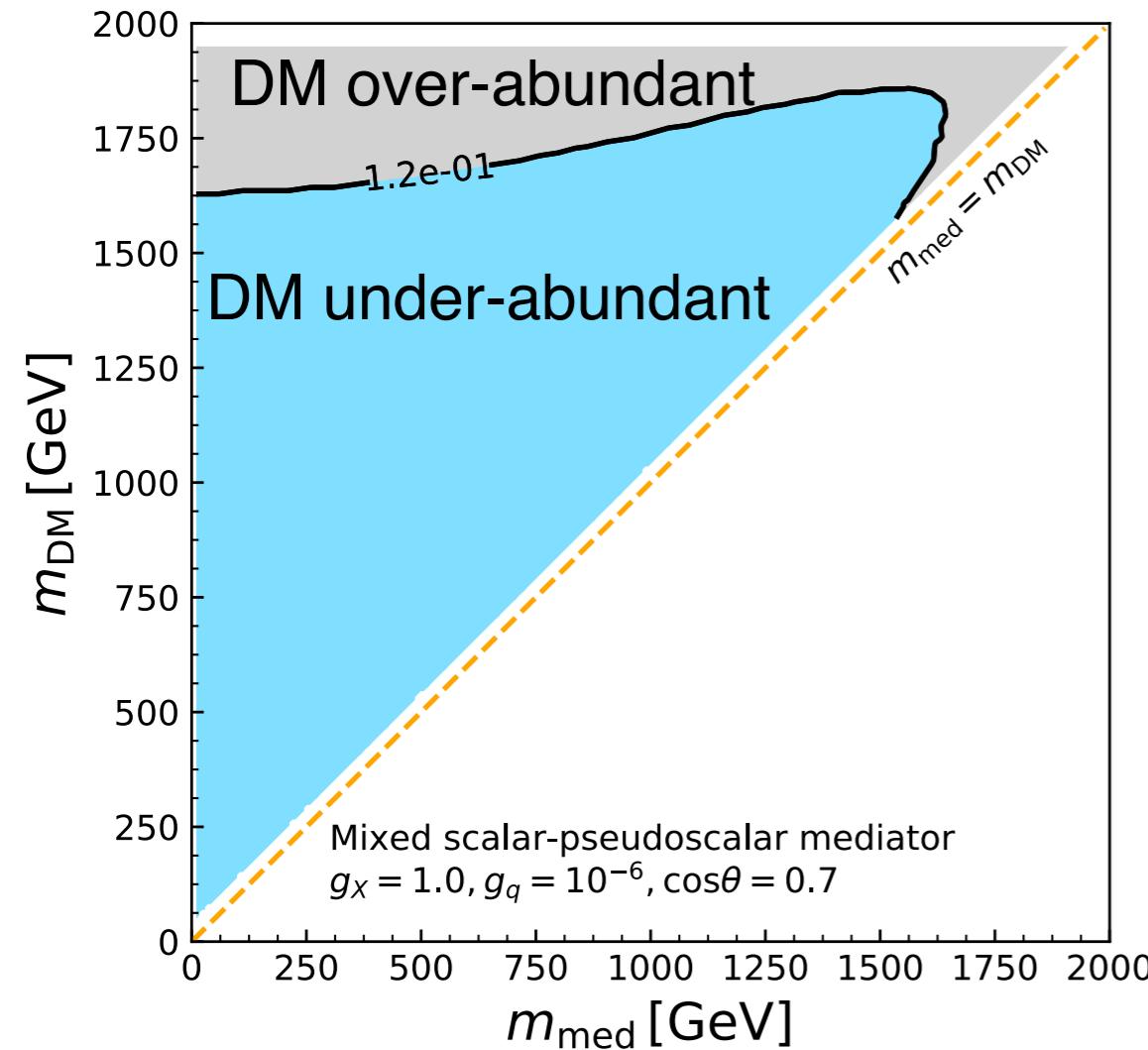
UFO files can be found at: <http://feynrules.irmp.ucl.ac.be/wiki/DMsimp>

```
import model DMsimp_s_spin0_mixed_MD
generate relic density
define q= u d s c b t
define qbar= u~ d~ s~ c~ b~ t~
add indirect detection y0 y0, y0 > q qbar
output secluded_dm_gammarays

launch secluded_dm_gammarays
set WY0 auto
set nevents 50000
set gq 1e-6
set theta 0.7
set MXd scan1:[10*x for x in range(1,200) for y in range(1,200) if x < y]
set MY0 scan1:[10*y for x in range(1,200) for y in range(1,200) if x < y]
set save_output all
```

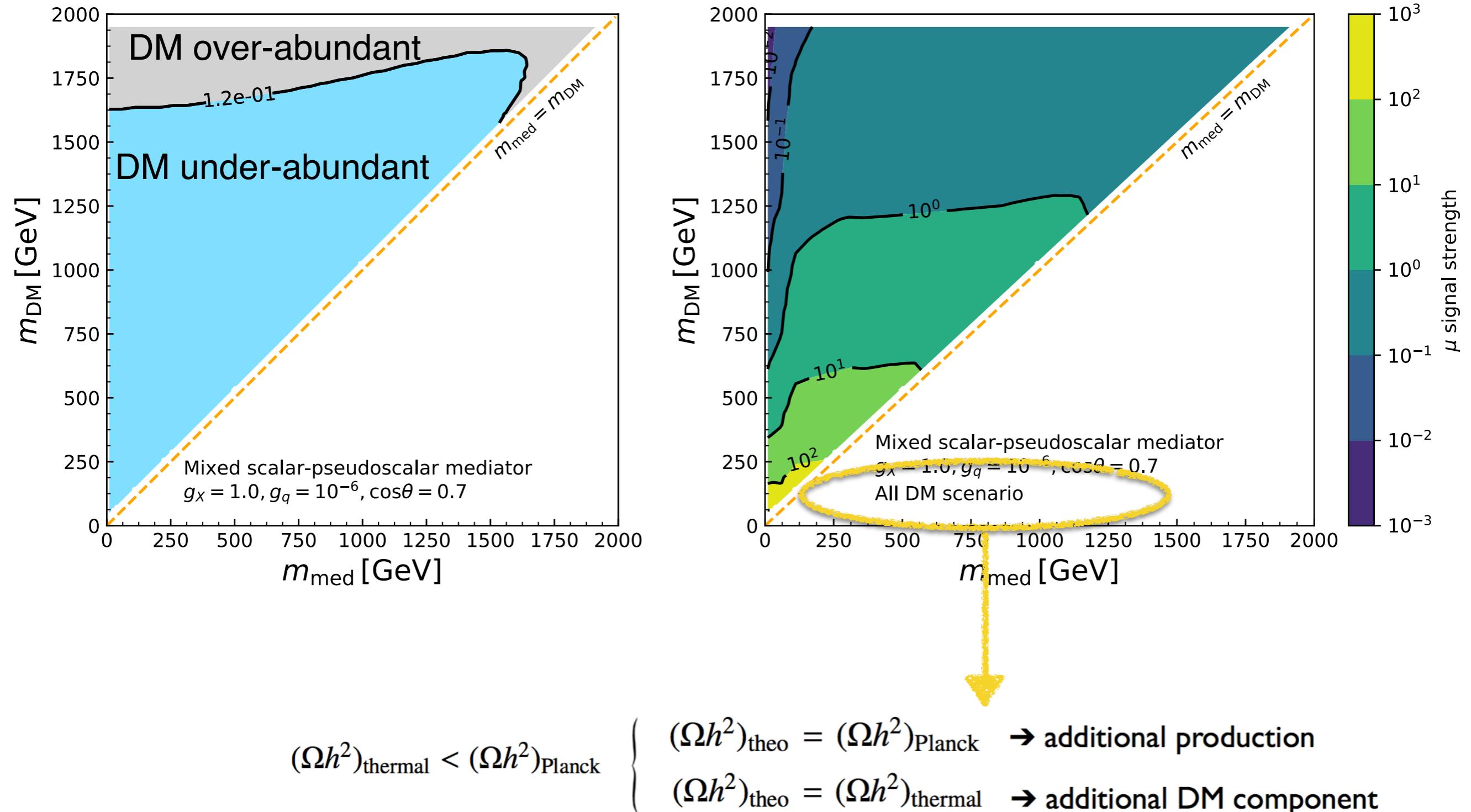
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Example of sampling procedure

$$\mathcal{L} = \bar{X}_d \left(g_{X_d}^S + i g_{X_d}^P \gamma_5 \right) X_d Y_0 + \sum_{i,j} \left[\bar{d}_i \frac{y_{ij}^d}{\sqrt{2}} \left(g_{d_{ij}}^S + i g_{d_{ij}}^P \gamma_5 \right) d_j + \bar{u}_i \frac{y_{ij}^u}{\sqrt{2}} \left(g_{u_{ij}}^S + i g_{u_{ij}}^P \gamma_5 \right) u_j \right] Y_0$$

- Grid scan (as in Madgraph)

```
import model DMsimp_s_spin0_MD
define darkmatter ~xd
generate relic_density
output sampling_s0_mxd_my0
launch sampling_s0_mxd_my0
set MXd scan:[10*x in range(0,100)]
set MY0 scan:[10*x in range(0,100)]
set gSXd 1
set gSu11 1
set gSu22 1
set gSu33 1
set gSd11 1
set gSd22 1
set gSd33 1
set WY0 AUTO
```

UFO files can be found at: <http://feynrules.irmp.ucl.ac.be/wiki/DMsimp>

Example of sampling procedure

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- Grid scan (as in Madgraph)
- Nested sampling PyMultinest

```
import model DMsimp_s_spin0_MD
define darkmatter ~xd
generate relic_density
output sampling_s0_mxd_my0

launch sampling_s0_mxd_my0
nestscan = ON
```

and edit `multinest_card.dat`

UFO files can be found at: <http://feynrules.irmp.ucl.ac.be/wiki/DMsimp>

Example of sampling procedure

