



# MadDM

Dark Matter Phenomenology  
in the MG5\_aMC@NLO framework

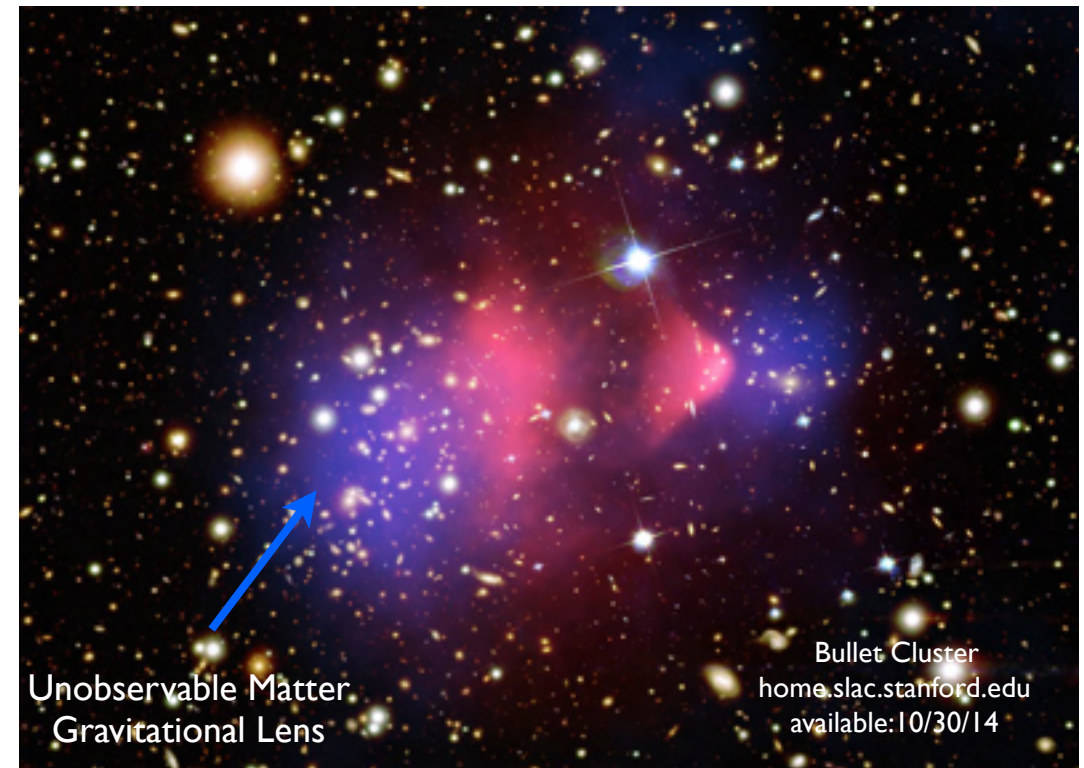
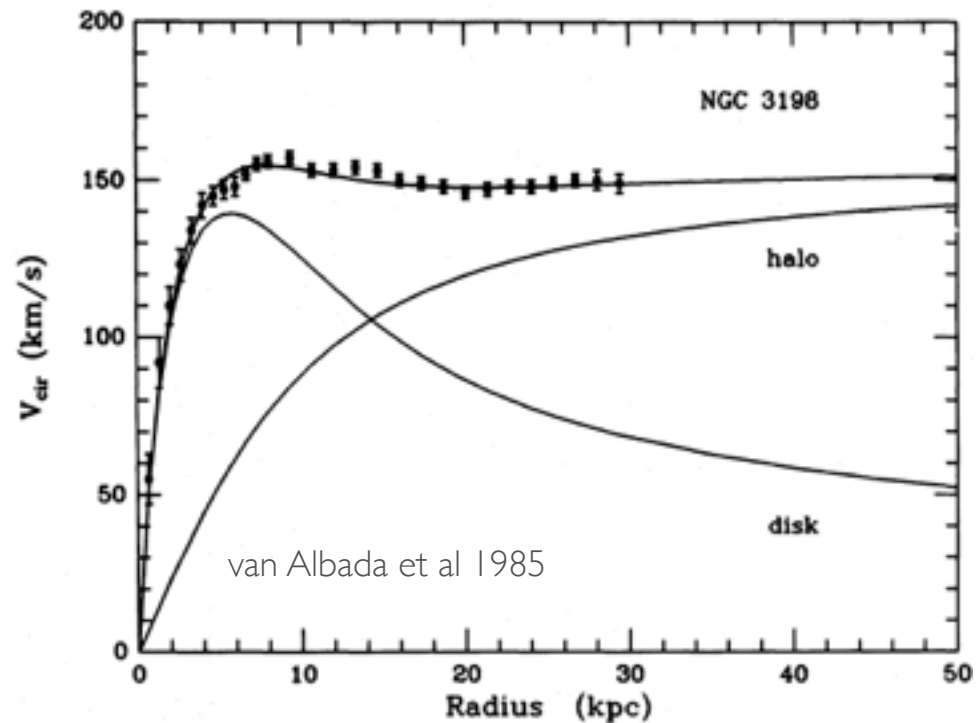
Gopolang (Gopi) Mohlabeng  
with

Mihailo Backovic, K.C. Kong, Antony Martini and Olivier Mattelaer

# Evidence for Dark Matter

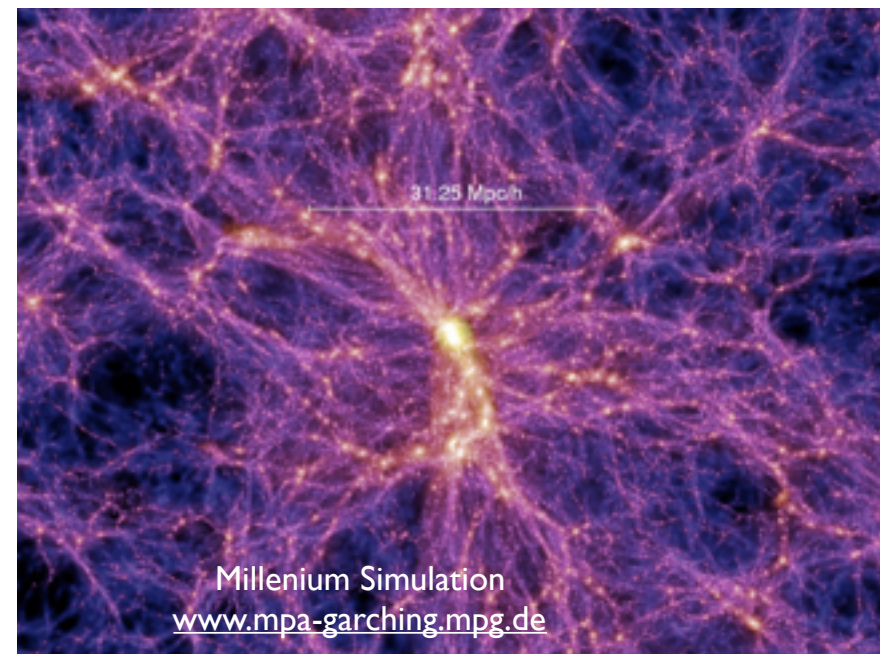
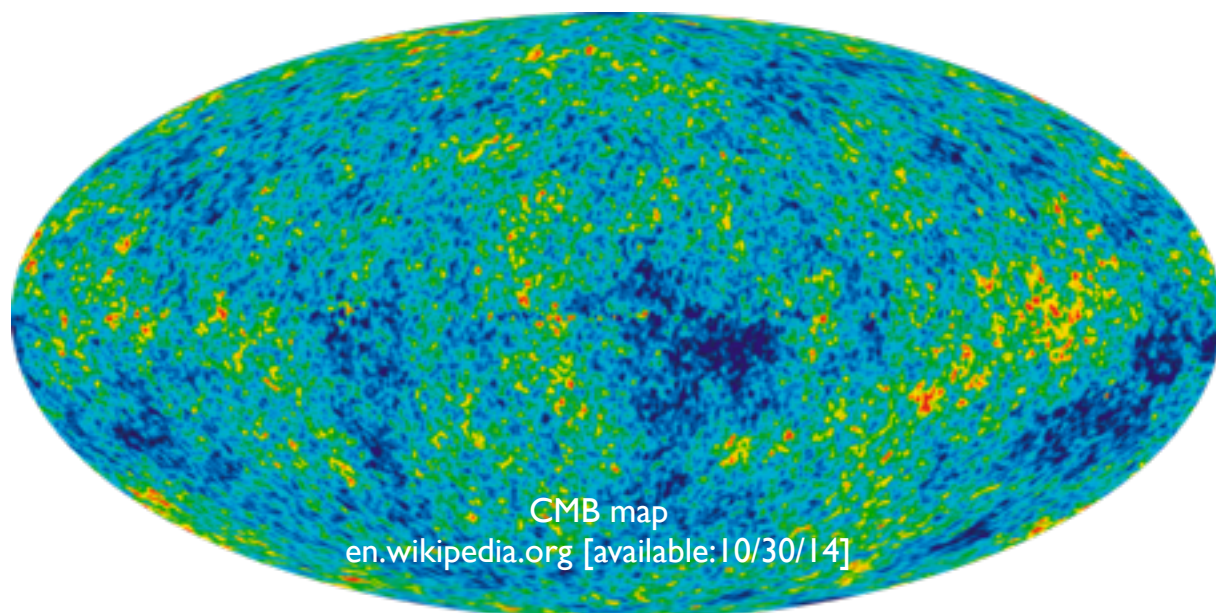
We have many hints DM exist, **but no direct evidence!**

## Rotational velocities of spiral galaxies



## Gravitational Lensing

## Velocity dispersions, CMB maps, N-body simulations



# The (Inconvenient) Truth about DM

If particle DM exists, **what do we know about it?**

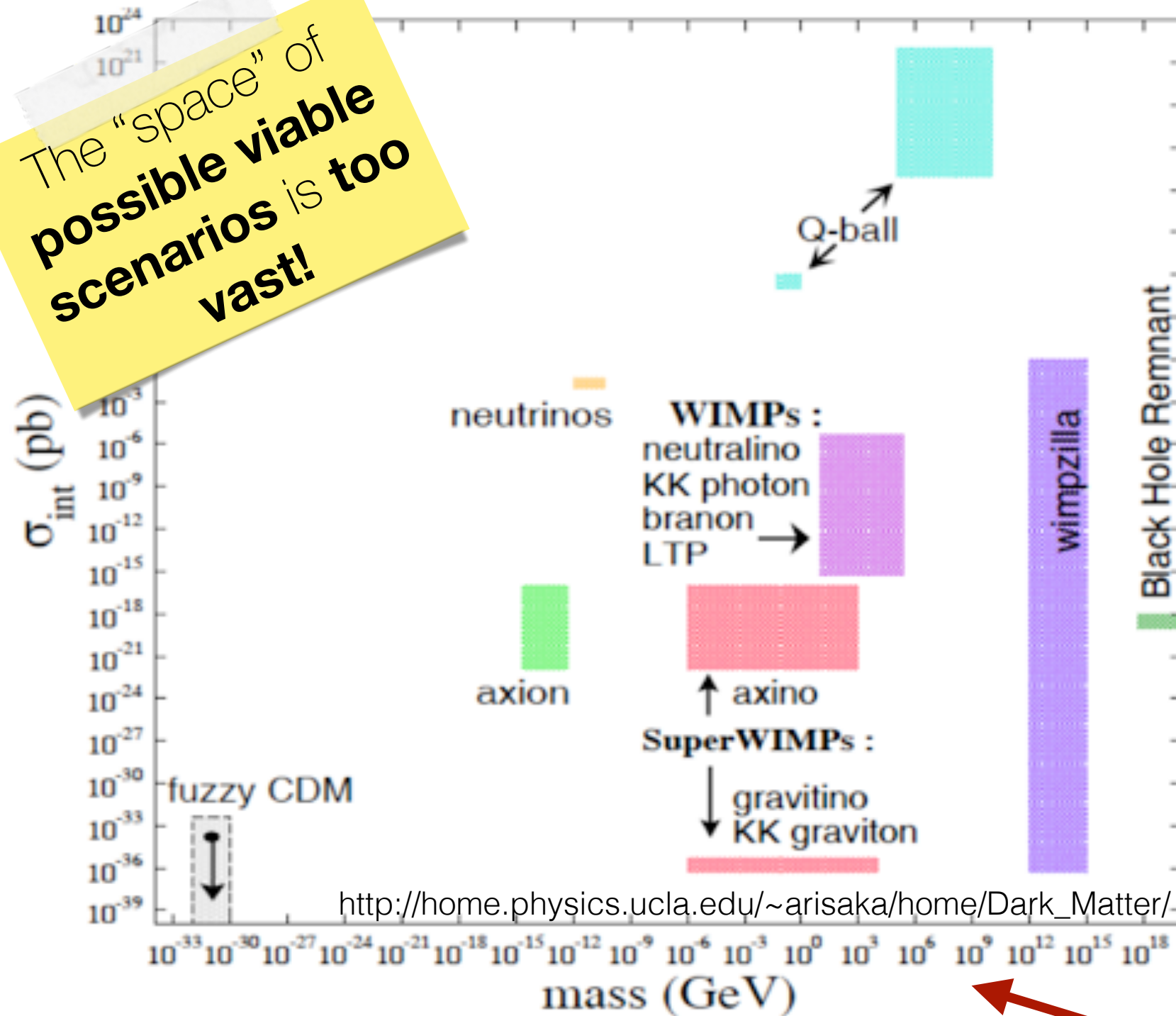
## Dark Matter:

1. Mass = ???
2. Spin = ???
3. Decays = ???
4. Interactions = **Gravity**, ???
5. Elementary = ???
6. ...



- We have no sense of where new physics is **hiding**

The "space" of possible viable scenarios is **too vast!**



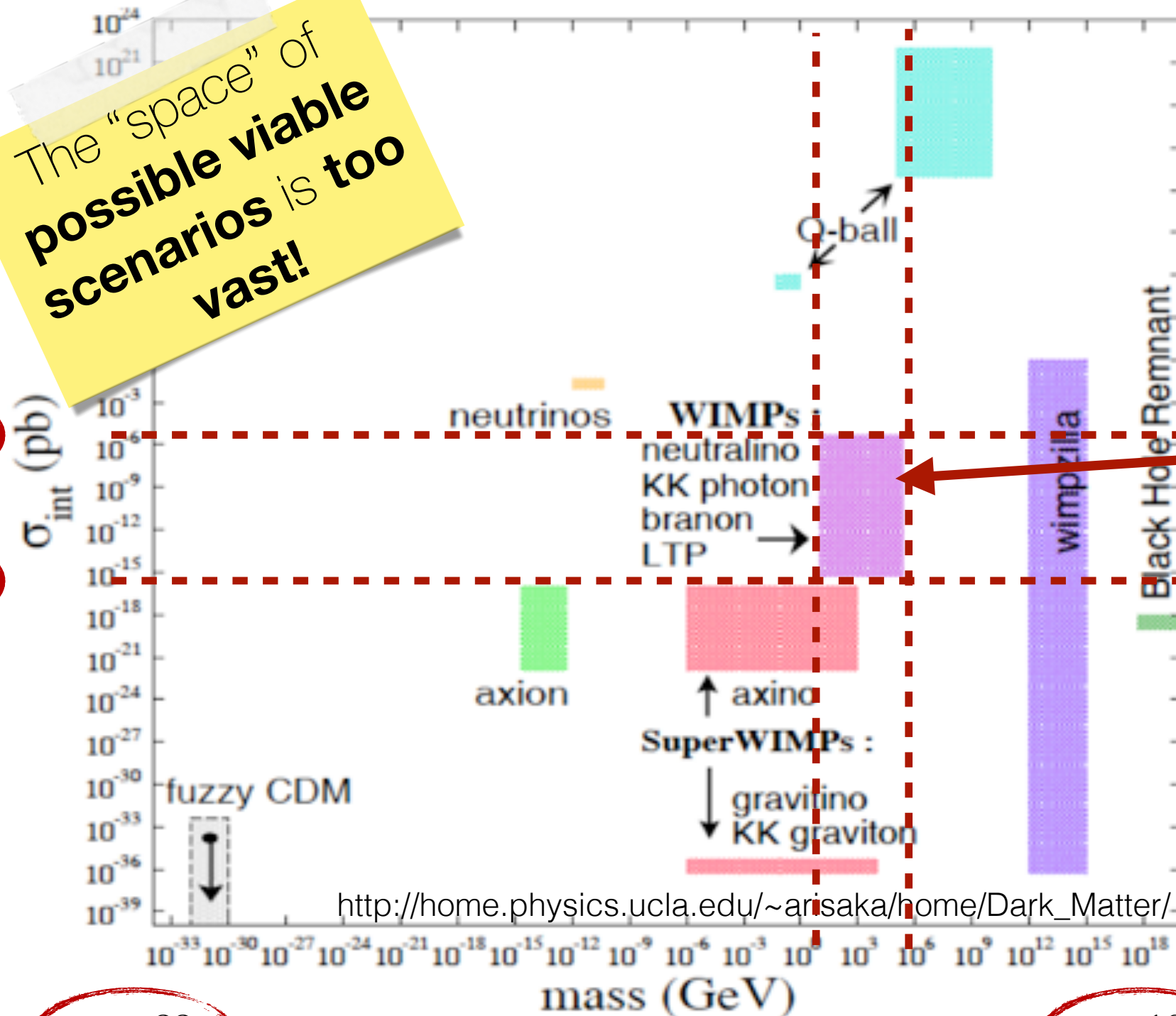
DM models alone span many orders of magnitude in energy scales

- We have no sense of where new physics is **hiding**

The "space" of possible viable scenarios is **too vast!**

$10^{-6}$

$10^{-25}$



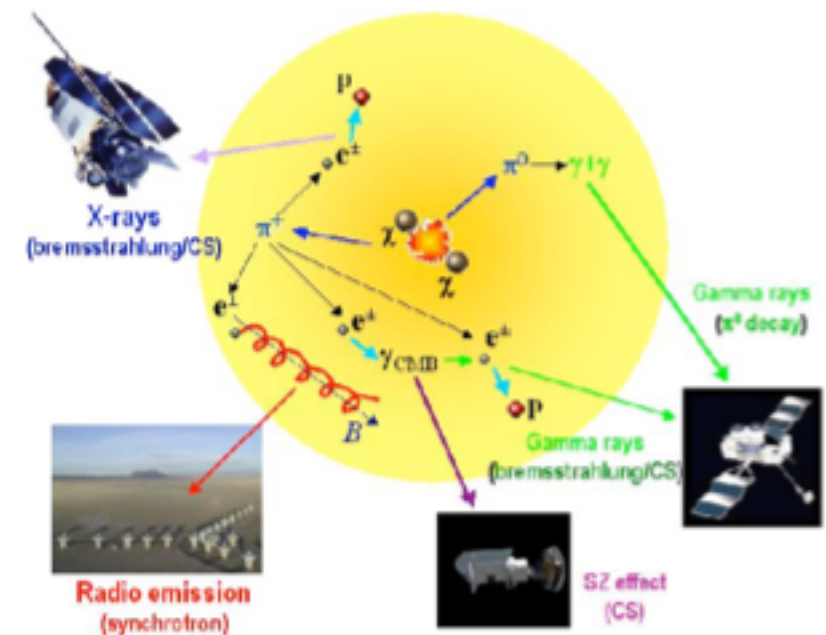
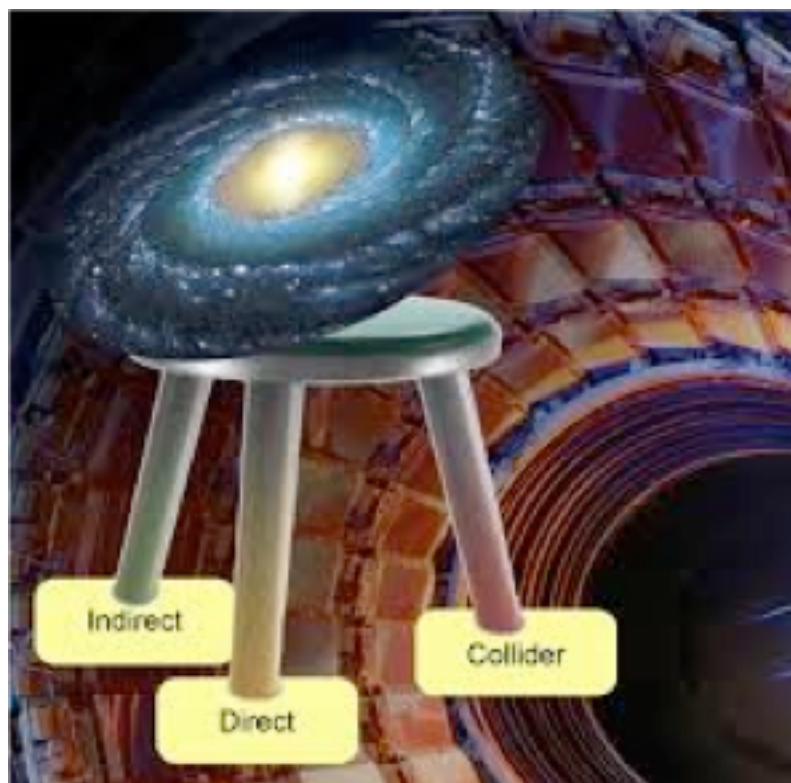
$10^{-33}$

$10^{18}$

Even if you only consider **WIMPs**, they span:  
**6 orders of magnitude in mass and 19 orders of magnitude in interaction cross section**

# DM Detection

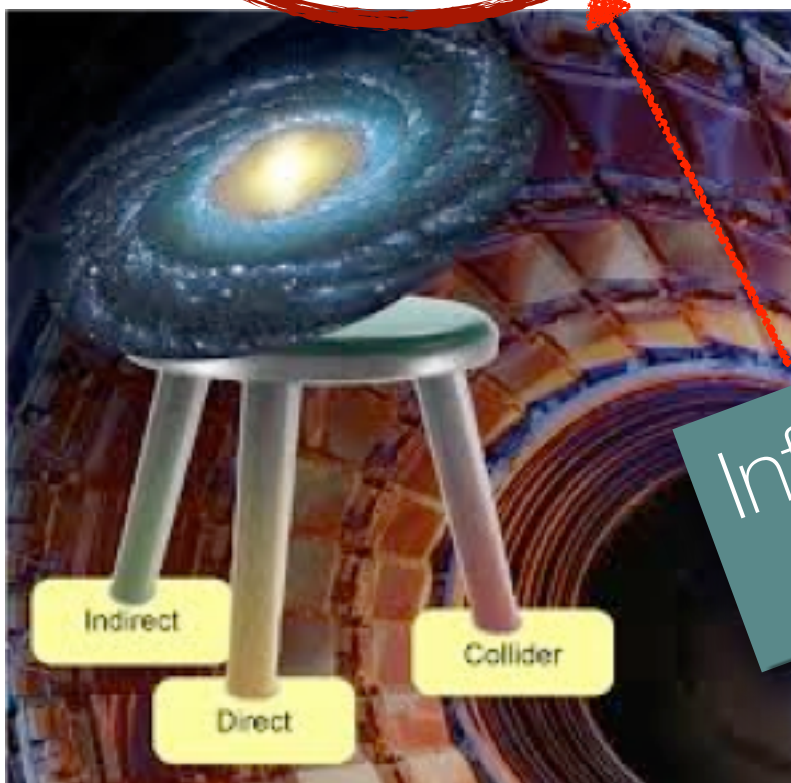
- Astrophysics and Cosmology:  $\longrightarrow \chi\chi \rightarrow \text{all}$
- Direct Detection:  $\longrightarrow p/n \chi \rightarrow p/n \chi$
- Indirect Detection:  $\longrightarrow \chi\chi \rightarrow e^+e^-, p\bar{p}, \gamma\gamma$
- Colliders:  $\longrightarrow pp \rightarrow \chi\chi + j, Z, \gamma\dots$



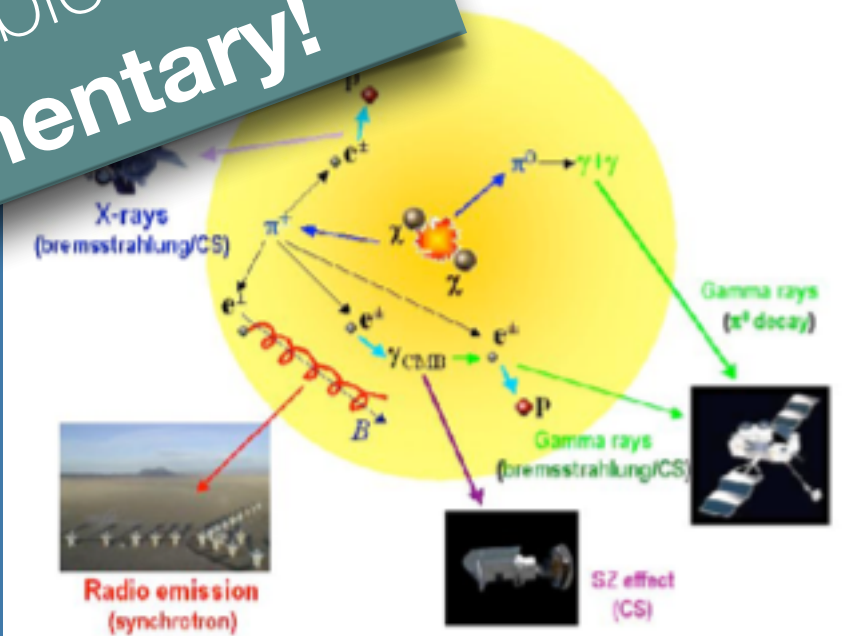


# DM Detection

- Astrophysics and Cosmology:  $\rightarrow \chi\chi \rightarrow \text{all}$
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- Indirect Detection:  $\rightarrow \chi\chi \rightarrow e^+e^-, p\bar{p}, \gamma\gamma$
- Colliders:  $\rightarrow pp \rightarrow \chi\chi + j, Z, \gamma\dots$



Information from all the possible search approaches is **complementary!**



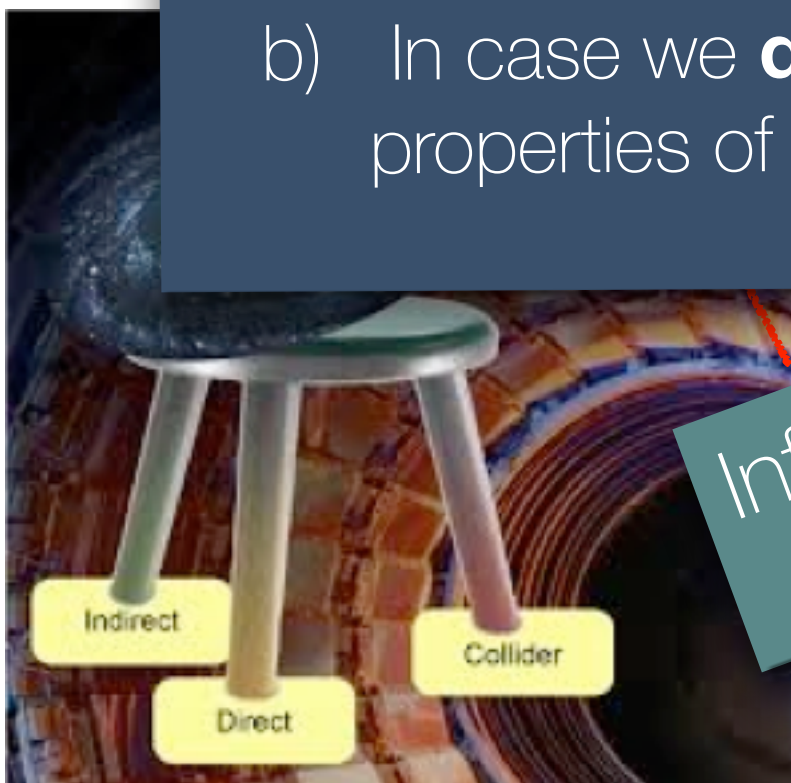
# DM Detection

- Astrophysics and Cosmology:  $\rightarrow \chi\chi \rightarrow \text{all}$

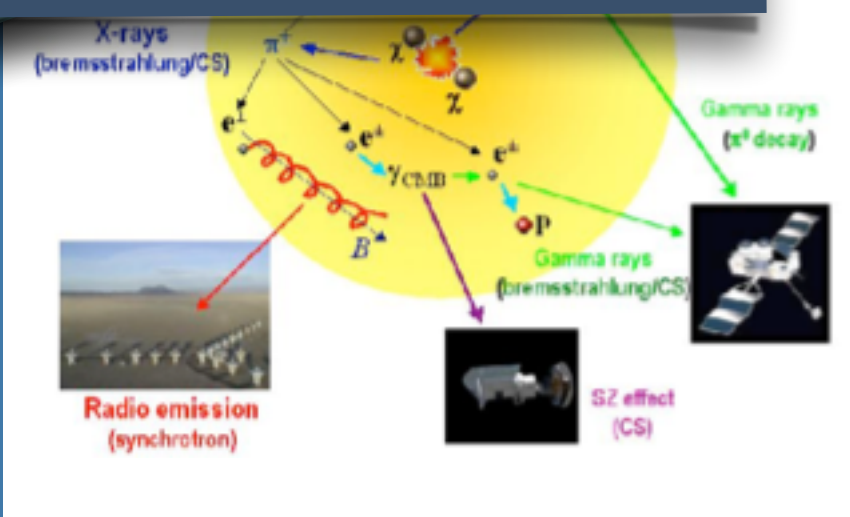
- Direct Detection:

**Complementarity is important** because:

- a) In case we **don't observe DM**, it allows us to efficiently “carve out” the remaining possible DM scenarios.
- b) In case we **do observe DM**, it allows us to determine the properties of DM more accurately.



Information from different approaches is **complementary**

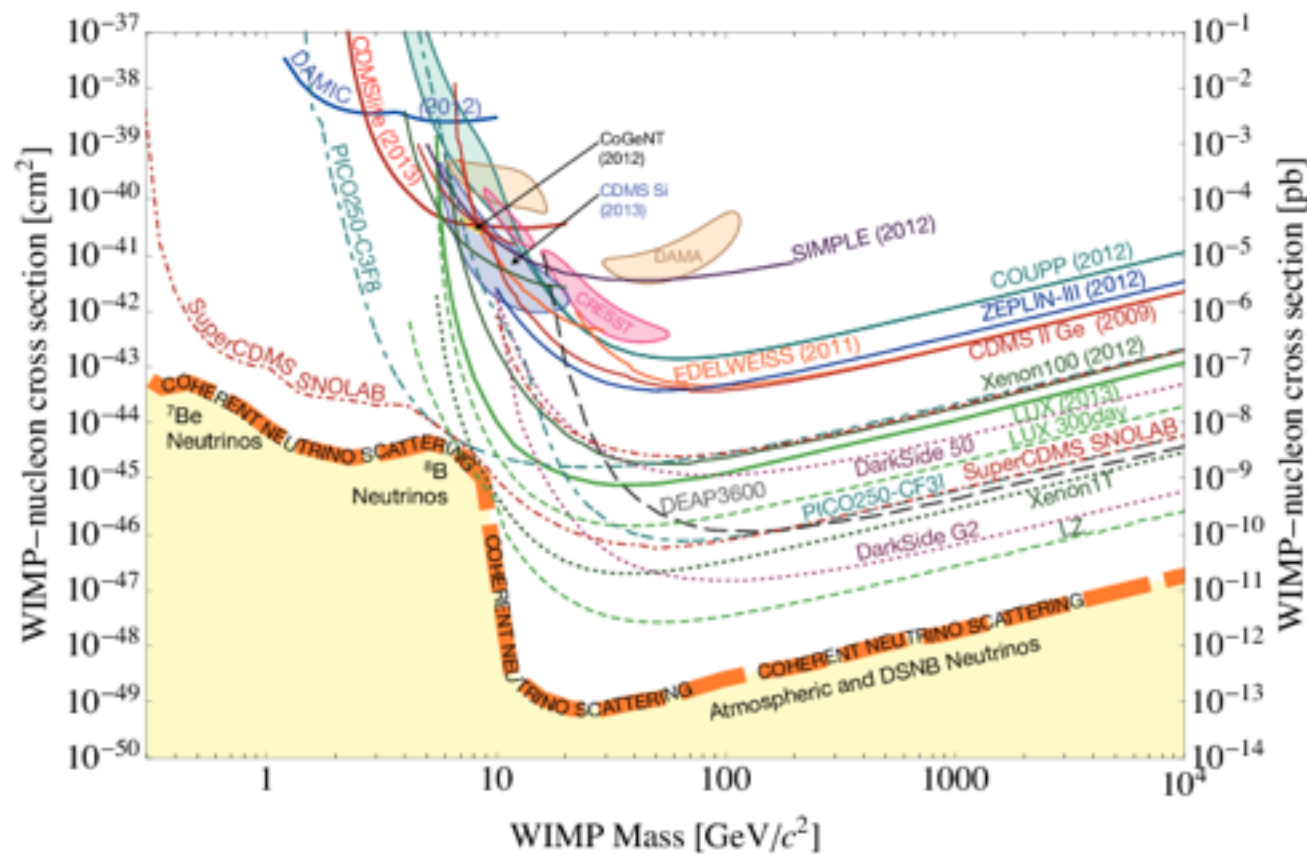




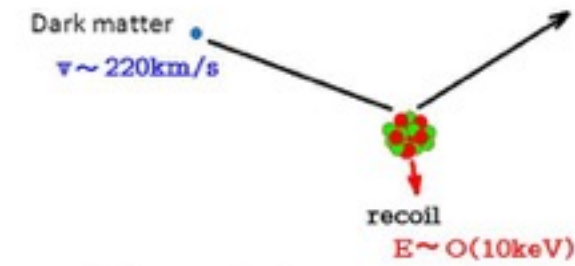
# Dark Matter Complementarity

- Direct detection experiments have placed constraints on DM scattering off nuclei.

Mostly sensitive to EW scale



Dark matter direct detection experiments



$$\mathcal{L} = \sum_{N=p,n} f_N \bar{\chi}^0 \chi^0 \bar{N} N + a_N \bar{\chi}^0 \sigma_a \chi^0 \bar{N} \sigma_a N$$

Spin-independent (SI) interaction                      Spin-dependent (SD) interaction

Elastic scattering cross section with nucleus ( $m_T$ : nucleus mass,  $n_{p/n}$ : # of proton and neutron)

$$\sigma = \frac{4}{\pi} \left( \frac{m_{\chi} m_T}{m_{\chi^0} + m_T} \right)^2 \left[ \frac{(n_p f_p + n_n f_n)^2}{\text{SI}} + 4 \frac{J+1}{J} \frac{(a_p \langle S_p \rangle + a_n \langle S_n \rangle)^2}{\text{SD}} \right]$$

The SI cross section is enhanced for large atomic number nucleus.

Based on arXiv: 1504.00915v1

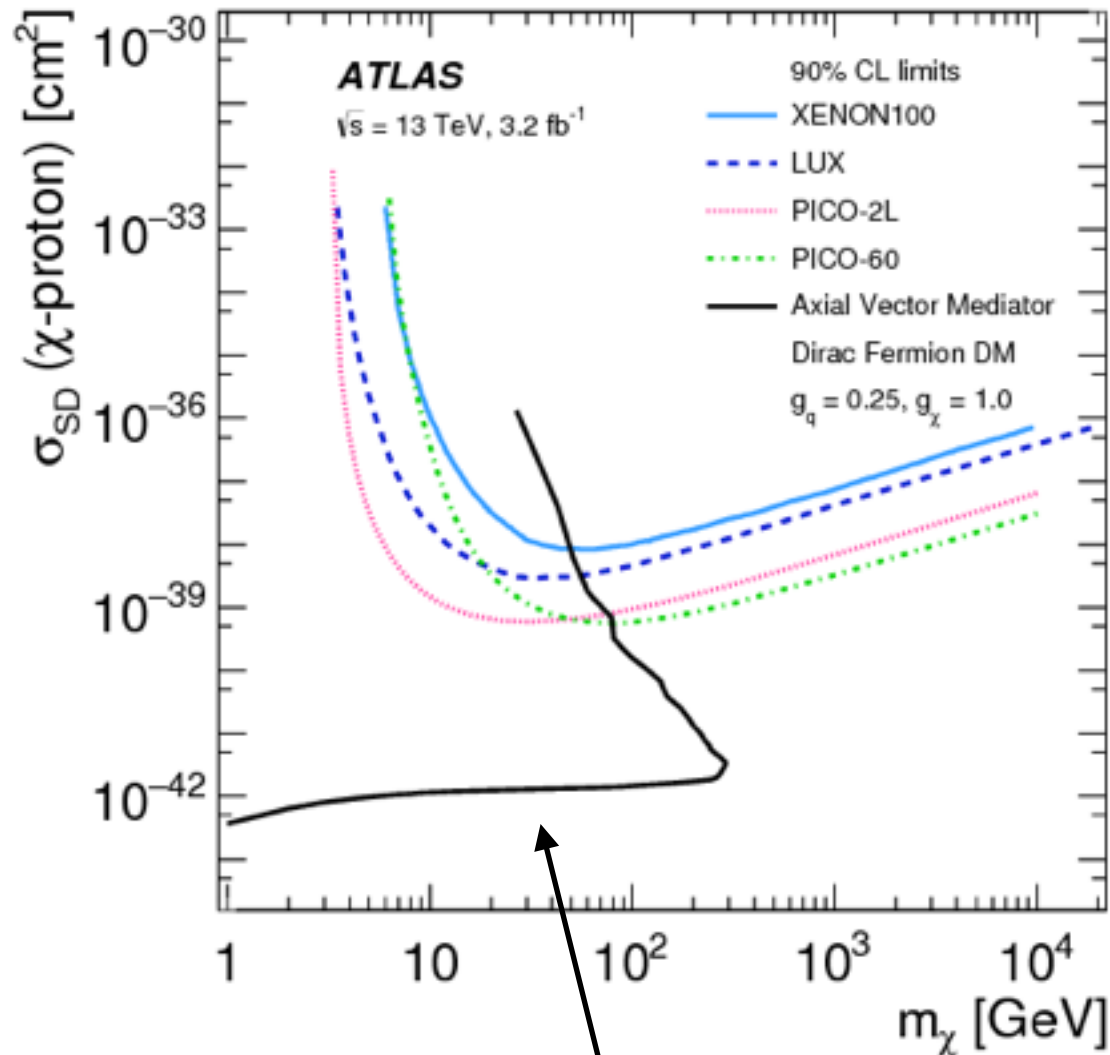
Phys.Dark Univ. 4 (2014) 92-97

- LHC experiments can probe different scales.

# Dark Matter Complementarity

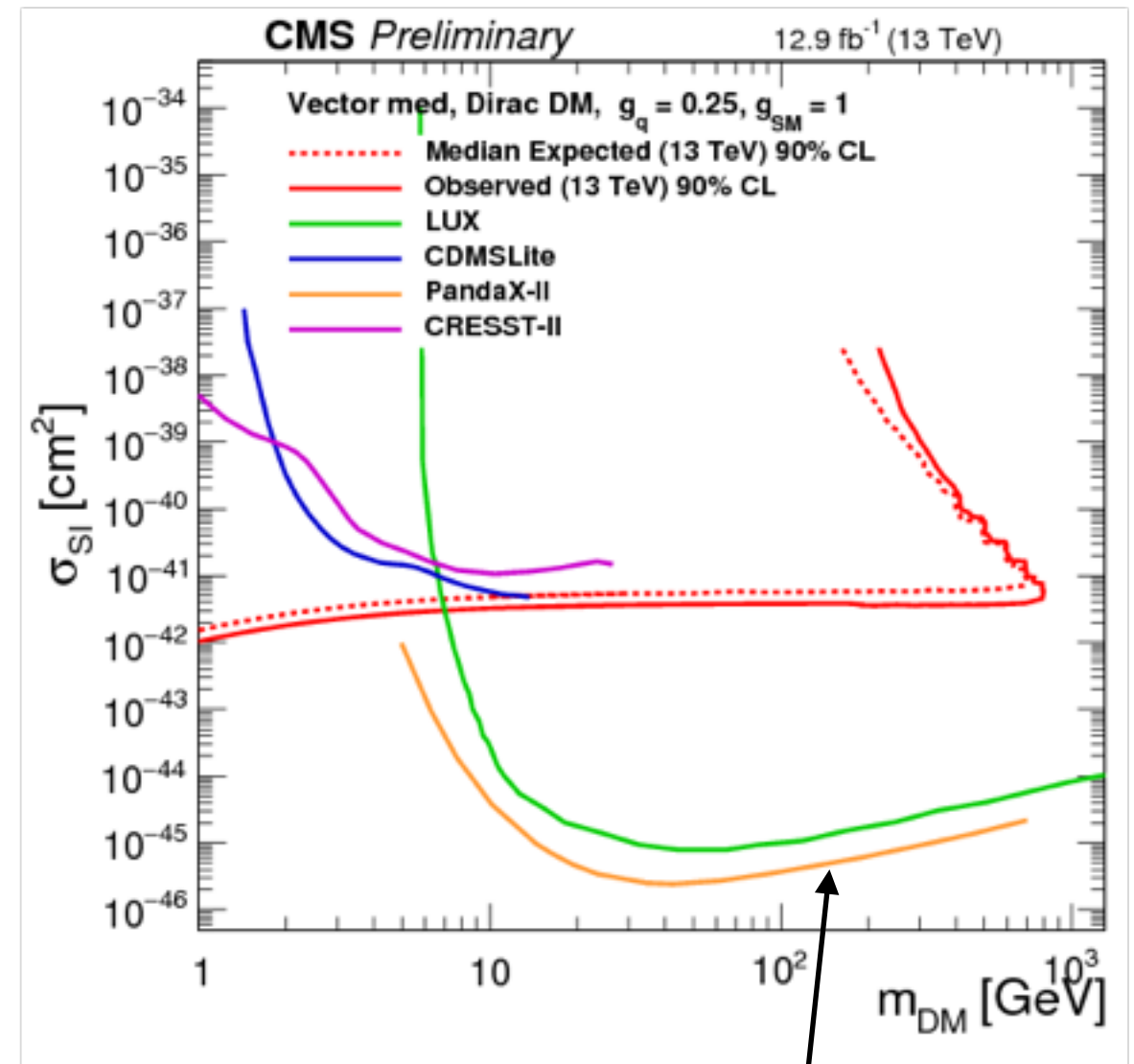
- Recently LHC Analysis provided complementary information to underground experiments.

ATLAS Collaboration: Phys.Rev.D.94.032005



**Colliders** can be more sensitive to low mass DM

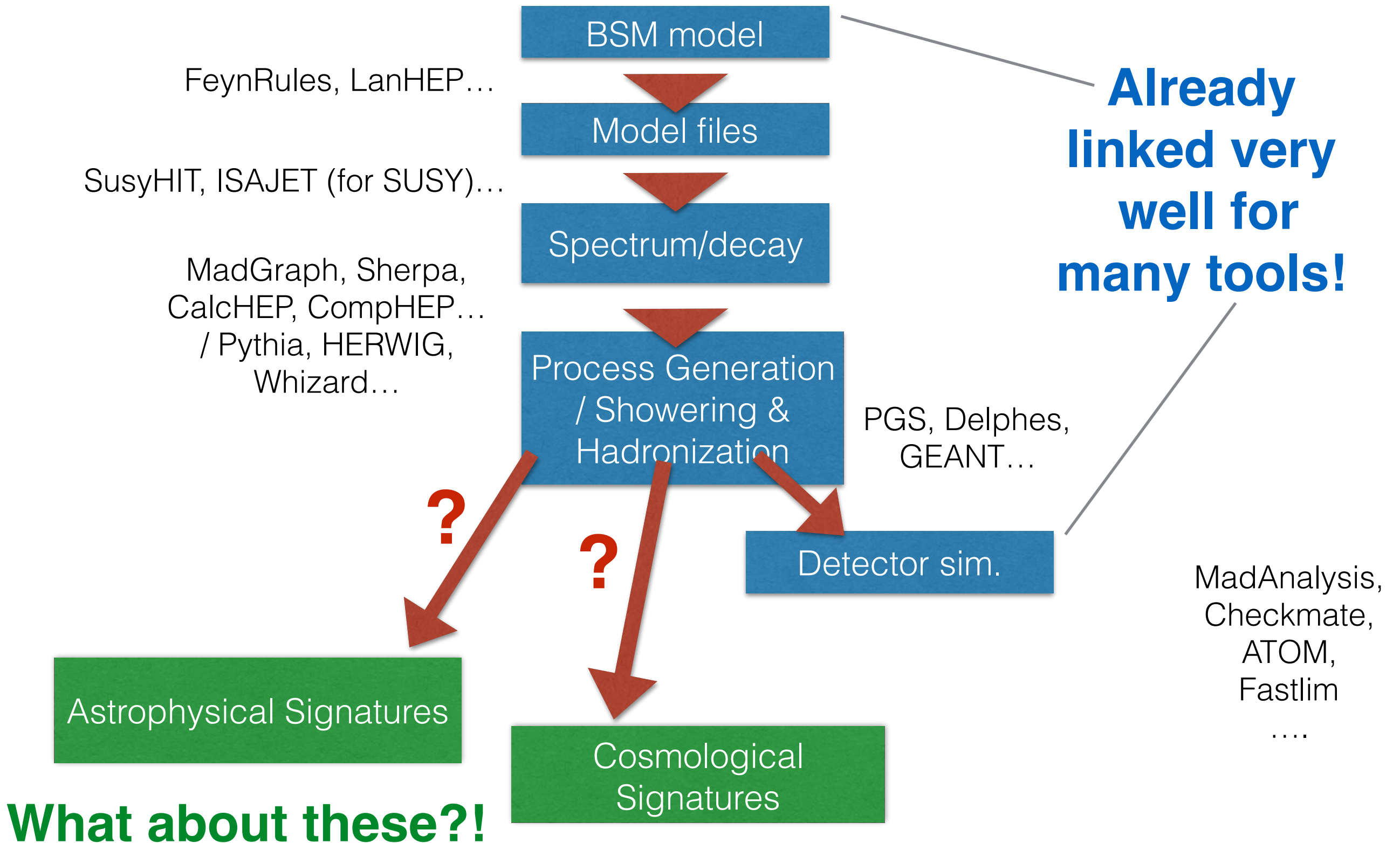
CMS collaboration 2017: CMS-PAS-EXO-16-037



**Direct detection** provides better limit in "high mass" regime

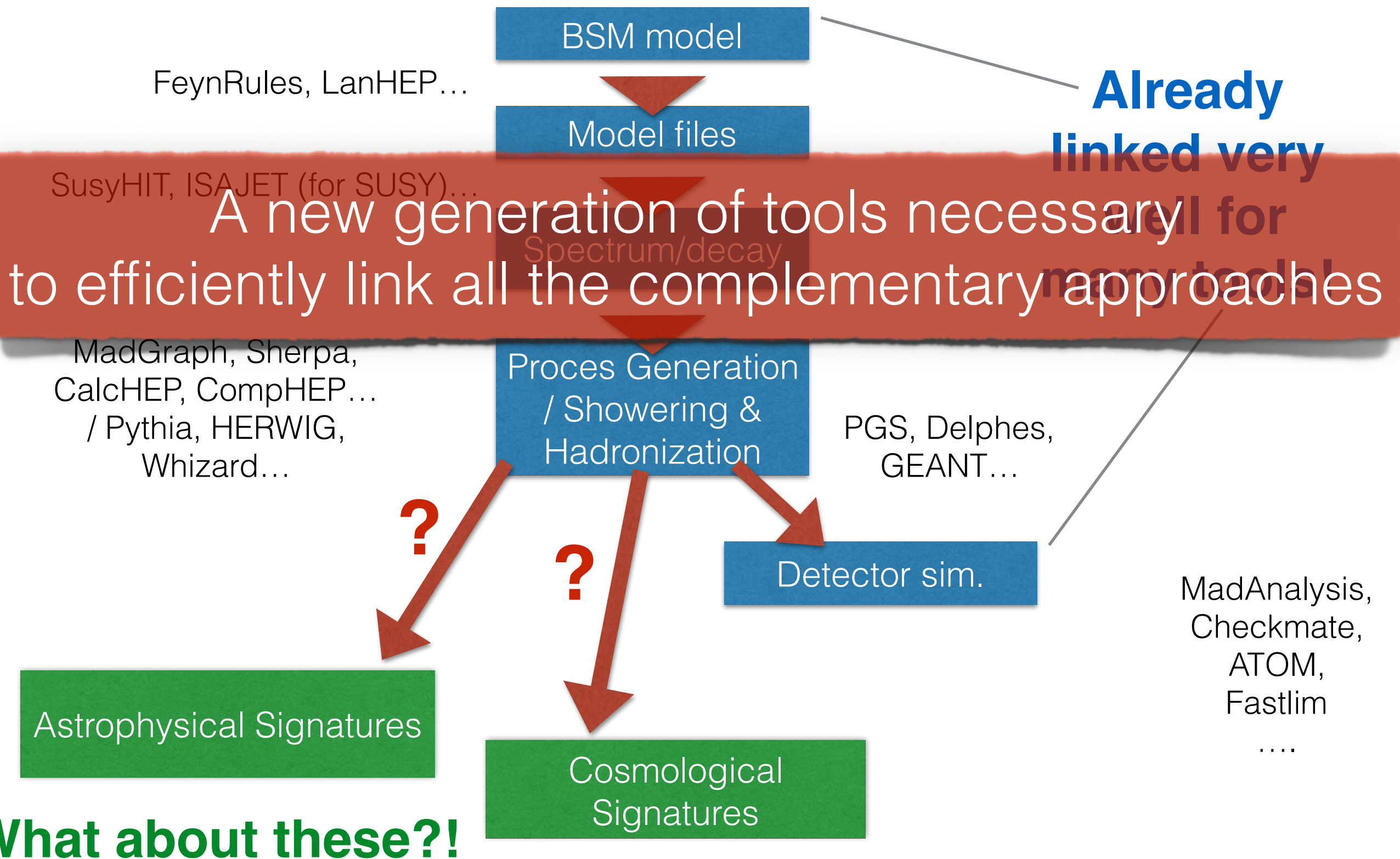
Complementarity studies require powerful simulation tools

# BSM tools in LHC era





# BSM tools in LHC era





**MadDM**

**MadDM** emerged as an effort to link:

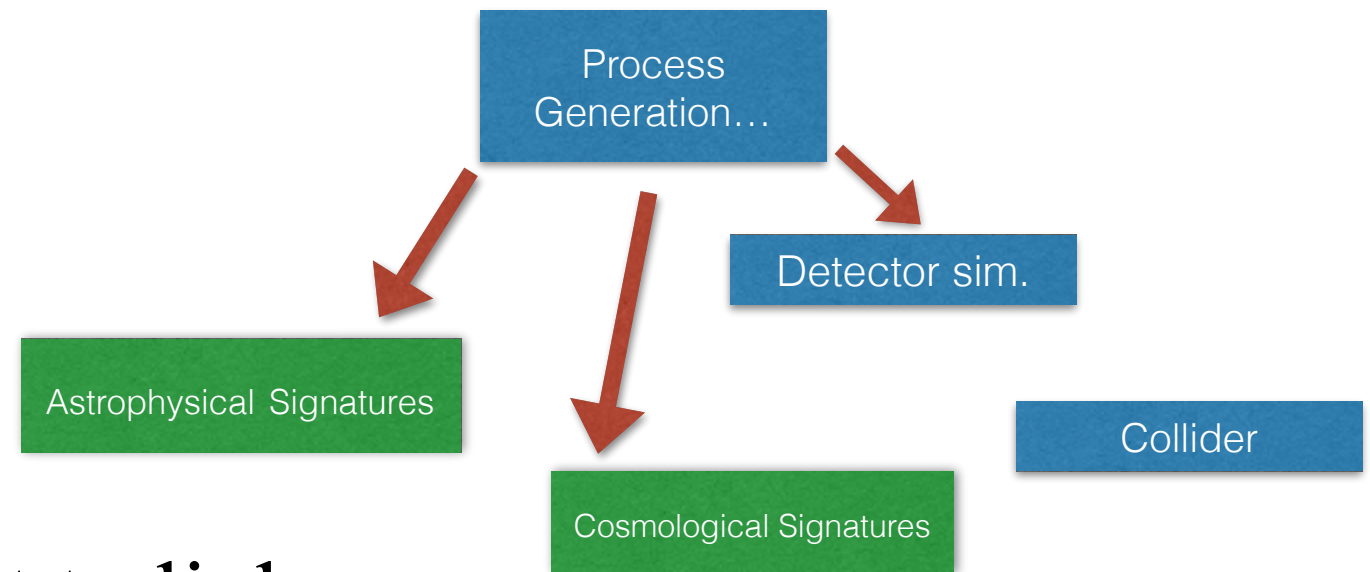
- **DM collider searches**, with
- **early cosmology** signatures (relic density) and
- **direct/indirect detection**.

**Goal** is to allow both **Experimentalists** and **Theorists** to calculate signatures of DM models at all interfaces with click of a button.

User friendly architecture of **MadGraph5\_aMC@NLO** provides ideal framework for MadDM development.



**MadDM**



**MadDM** emerged as an effort to link:

- **DM collider searches**, with
- **early cosmology signatures** (relic density) and
- **direct/indirect detection**.

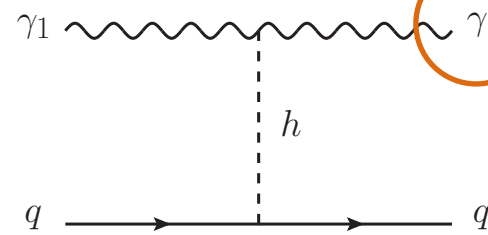
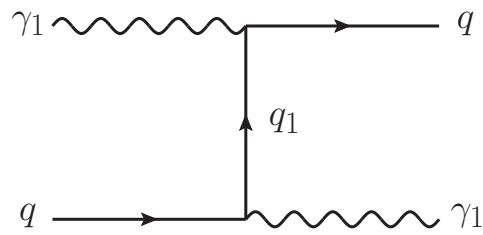
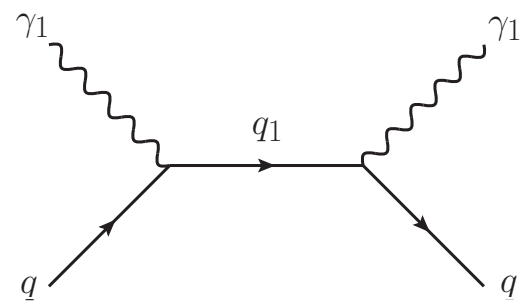
**Version 1.0** of MadDM focused on calculations of **DM relic density** (in a generic UFO model).

**Version 2.0** of MadDM extended the functionality to **DM direct and directional detection**.

**Version 3.0** **DM Indirect detection. (soon!)**



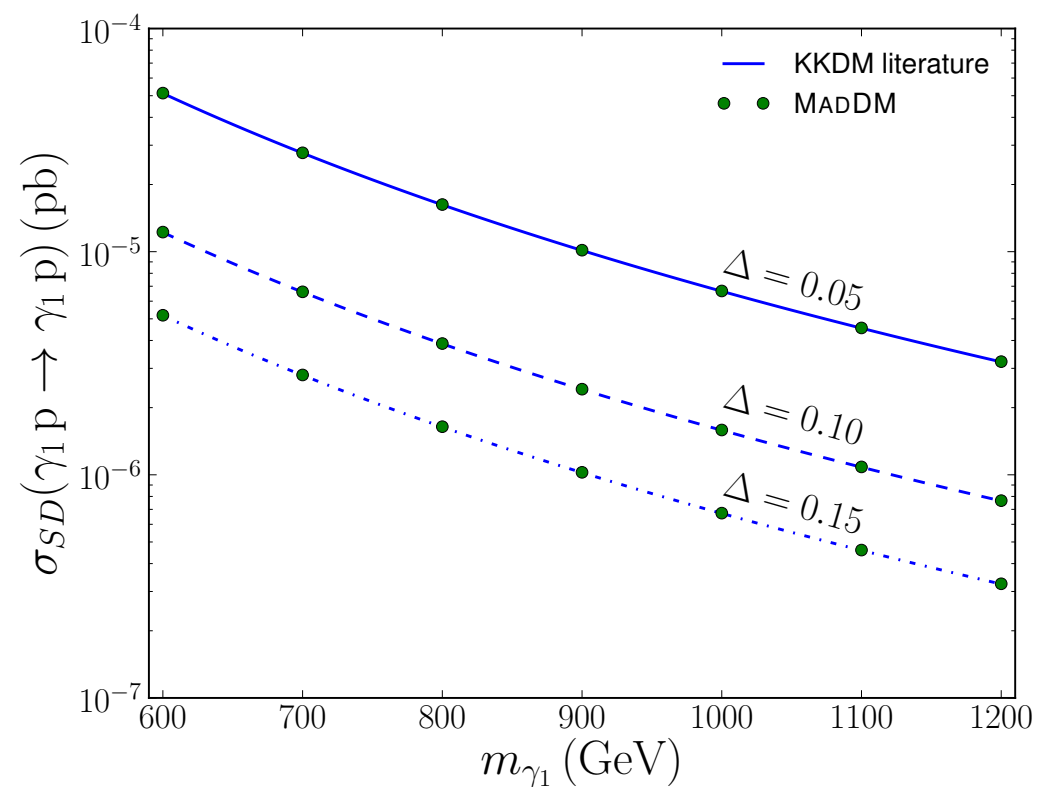
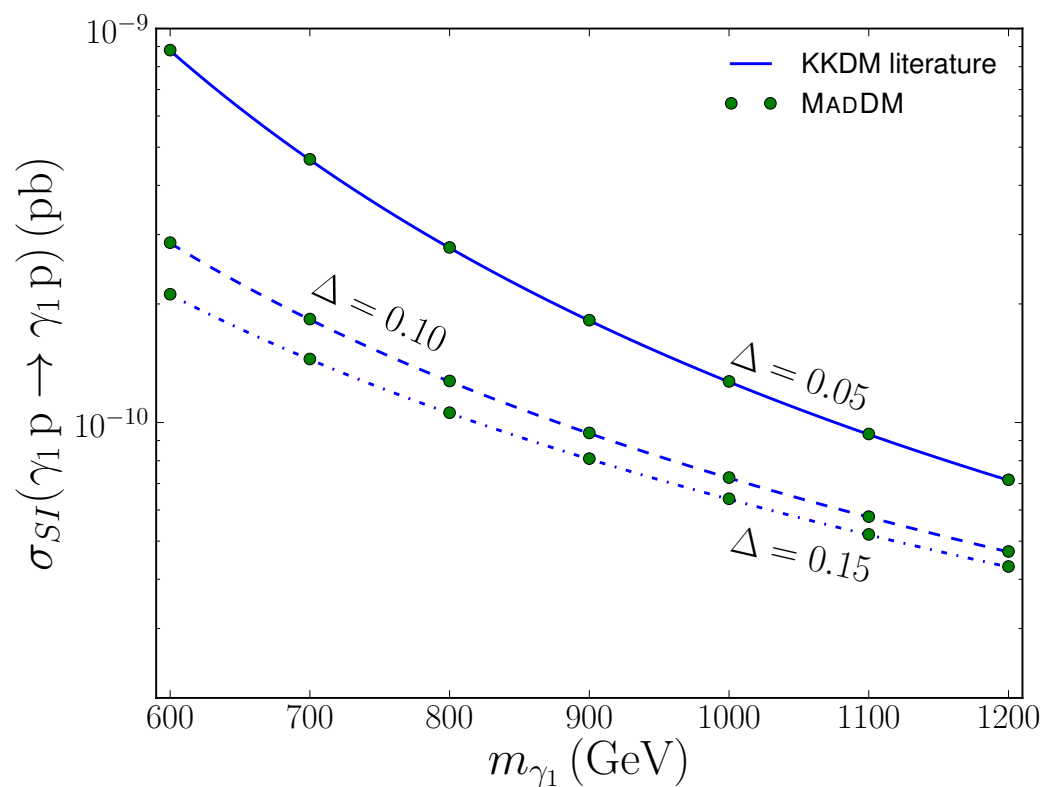
# Validations (mUED):



**KK photon**

$$\Delta = \frac{m_{q_1} - m_{\gamma_1}}{m_{\gamma_1}}$$

Arrenberg et al, arXiv:1307.6581

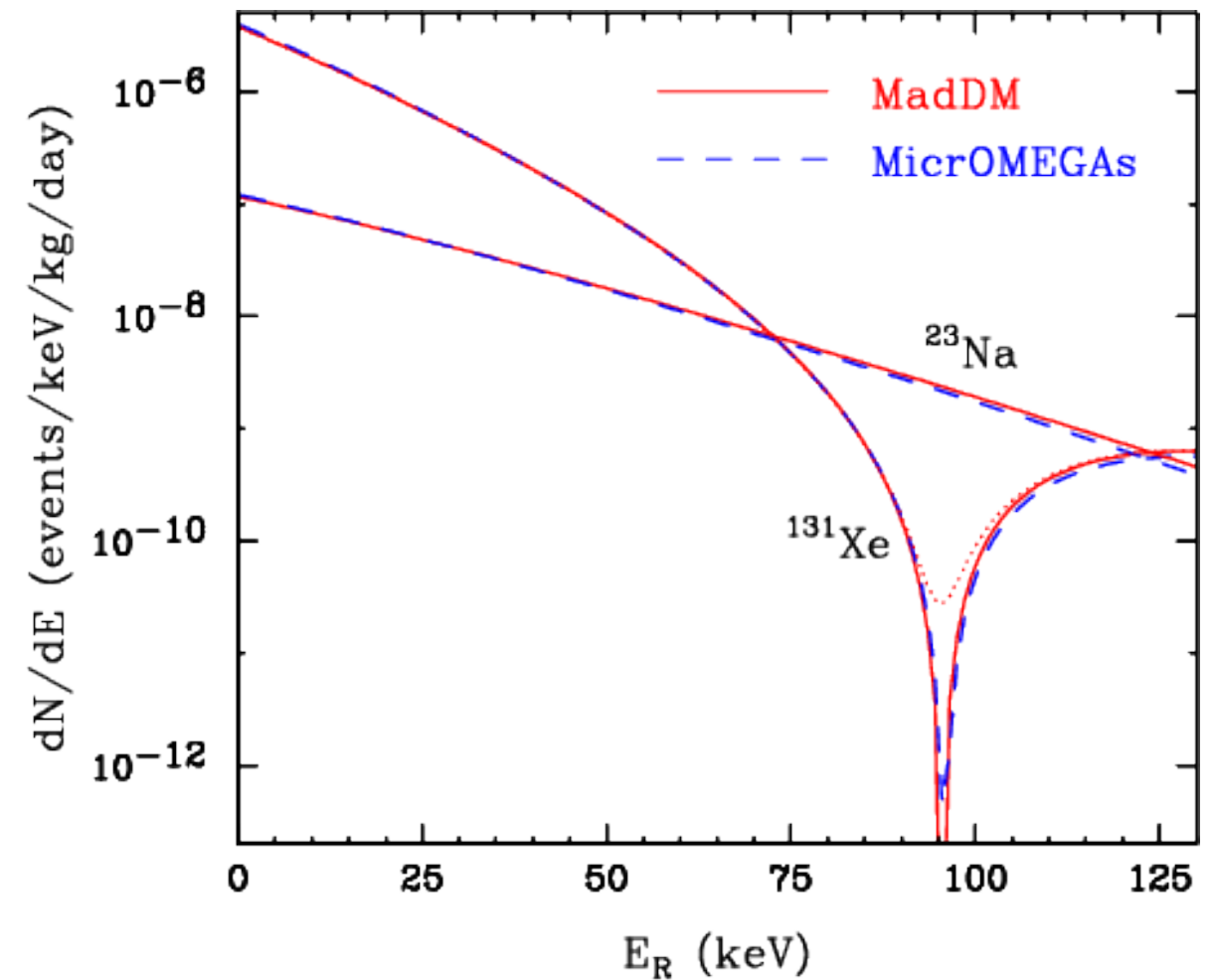
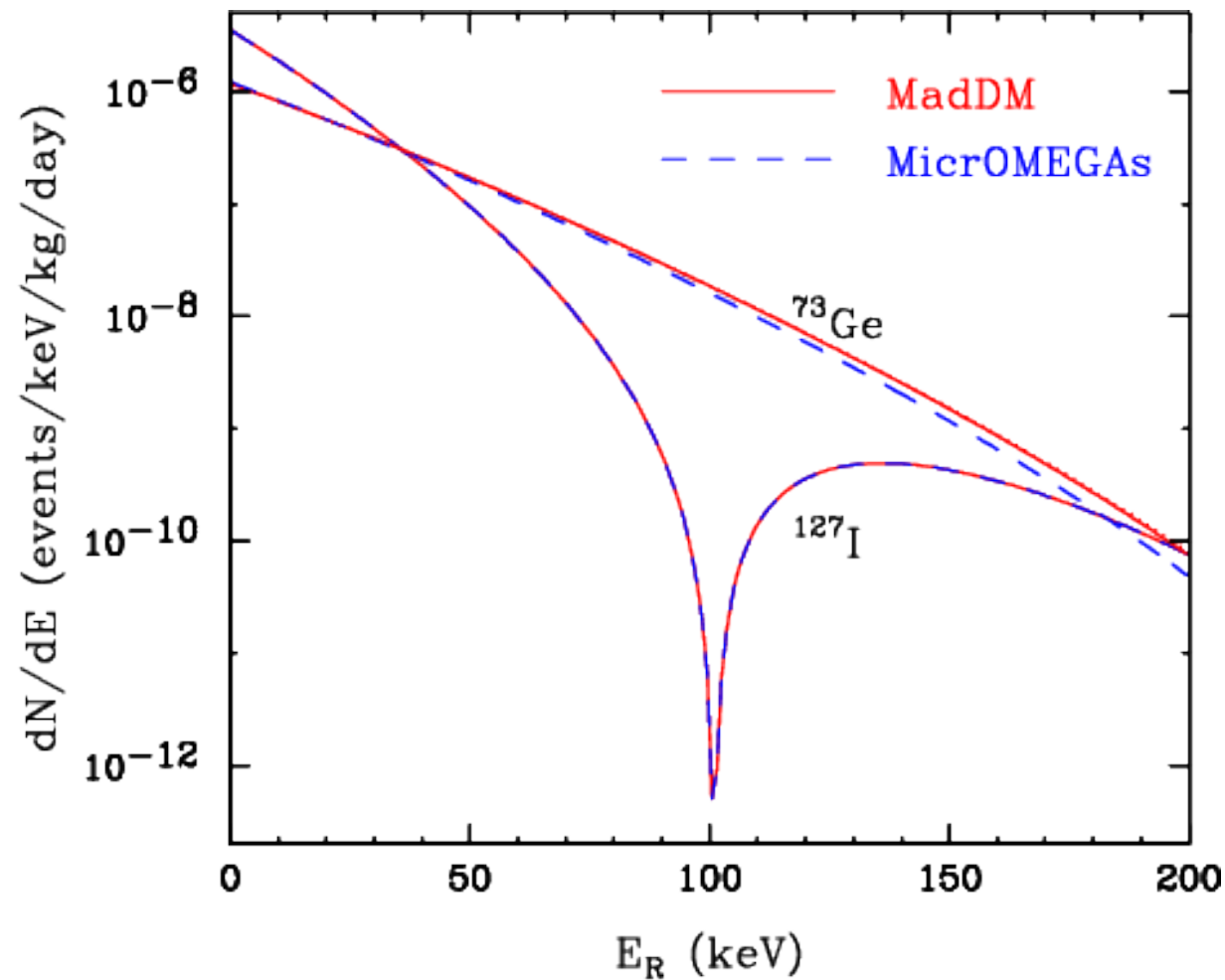


**Excellent agreement** between MadDM and literature!

We also validated the calculation of SI and SD cross sections in a wide range of simplified models.

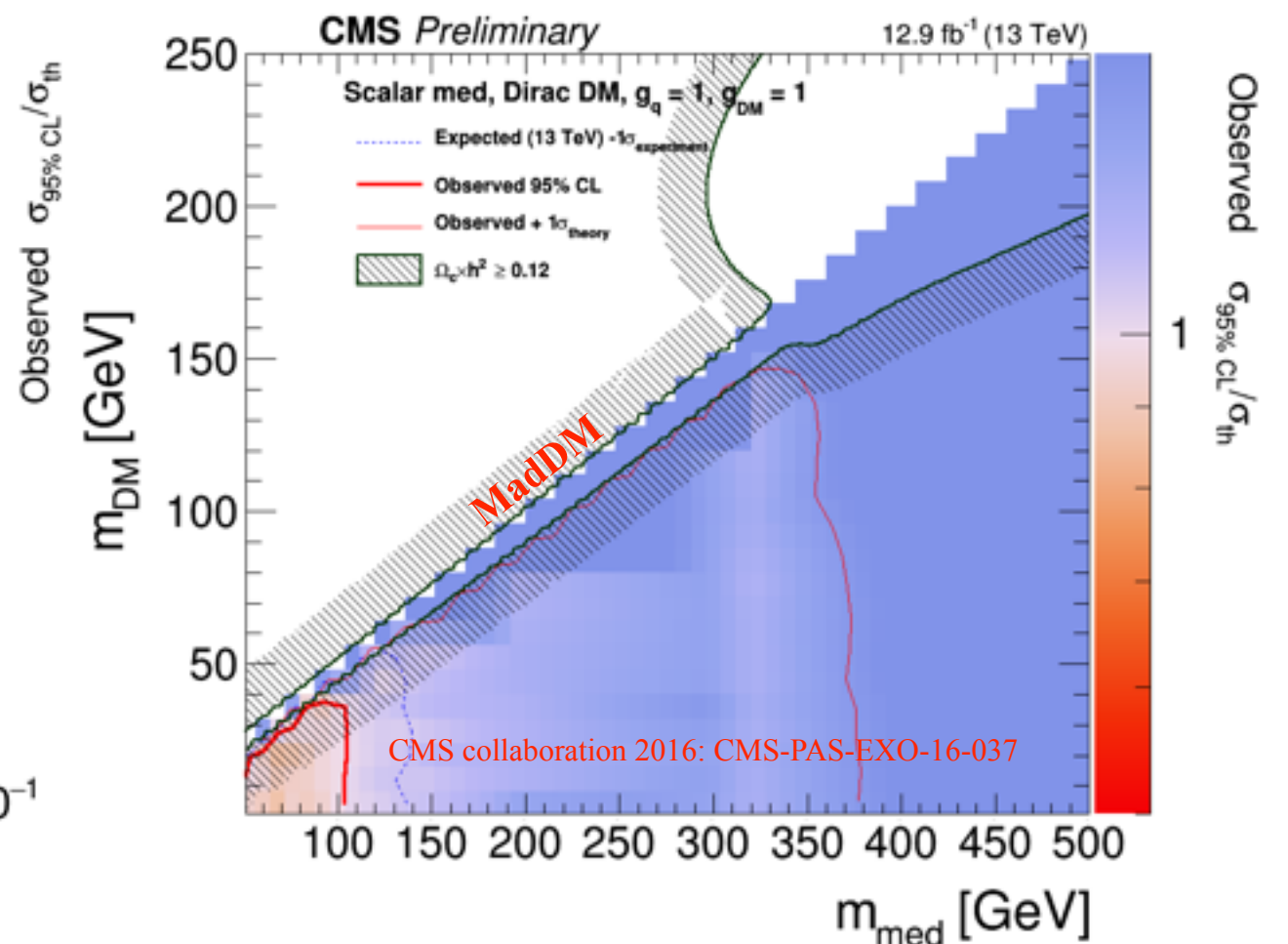
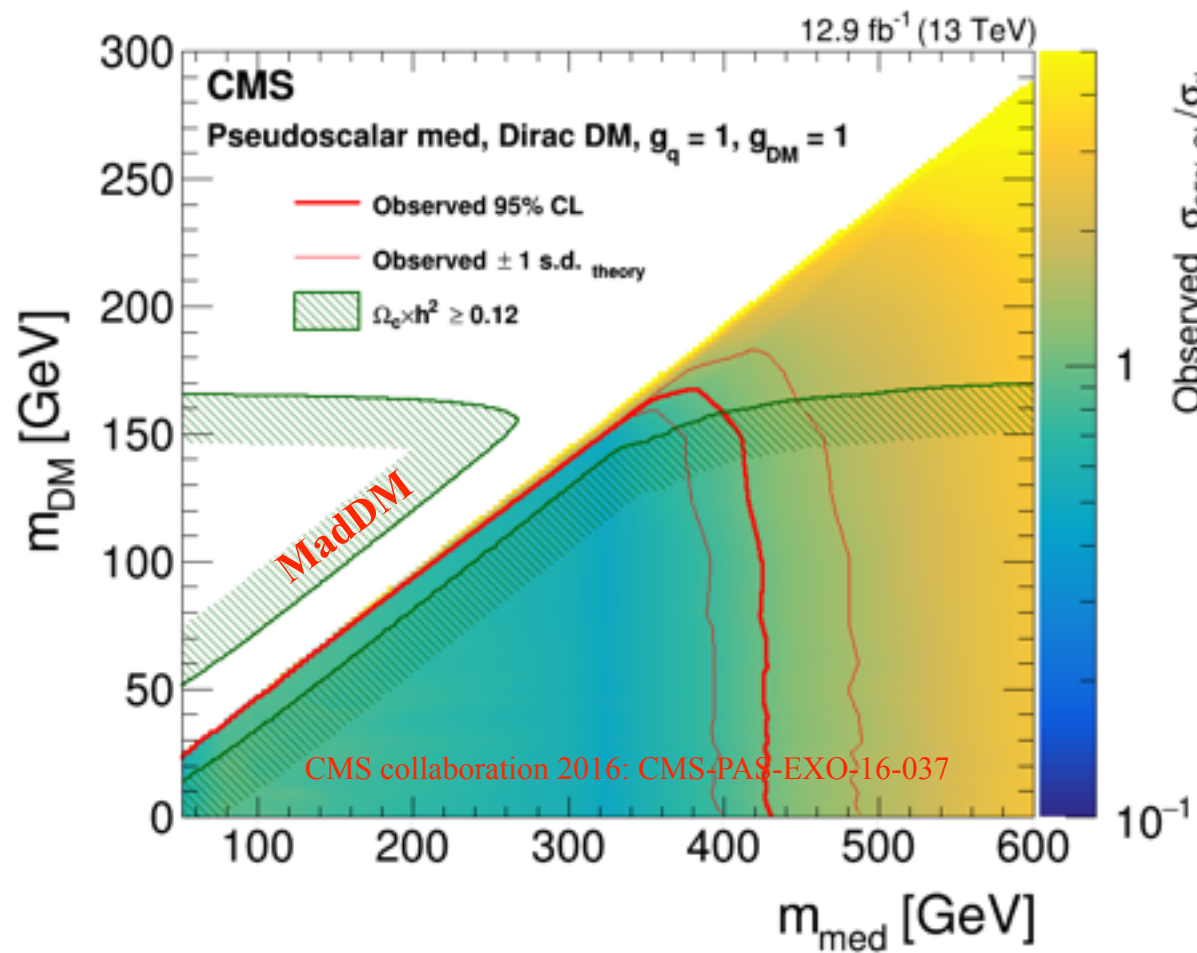
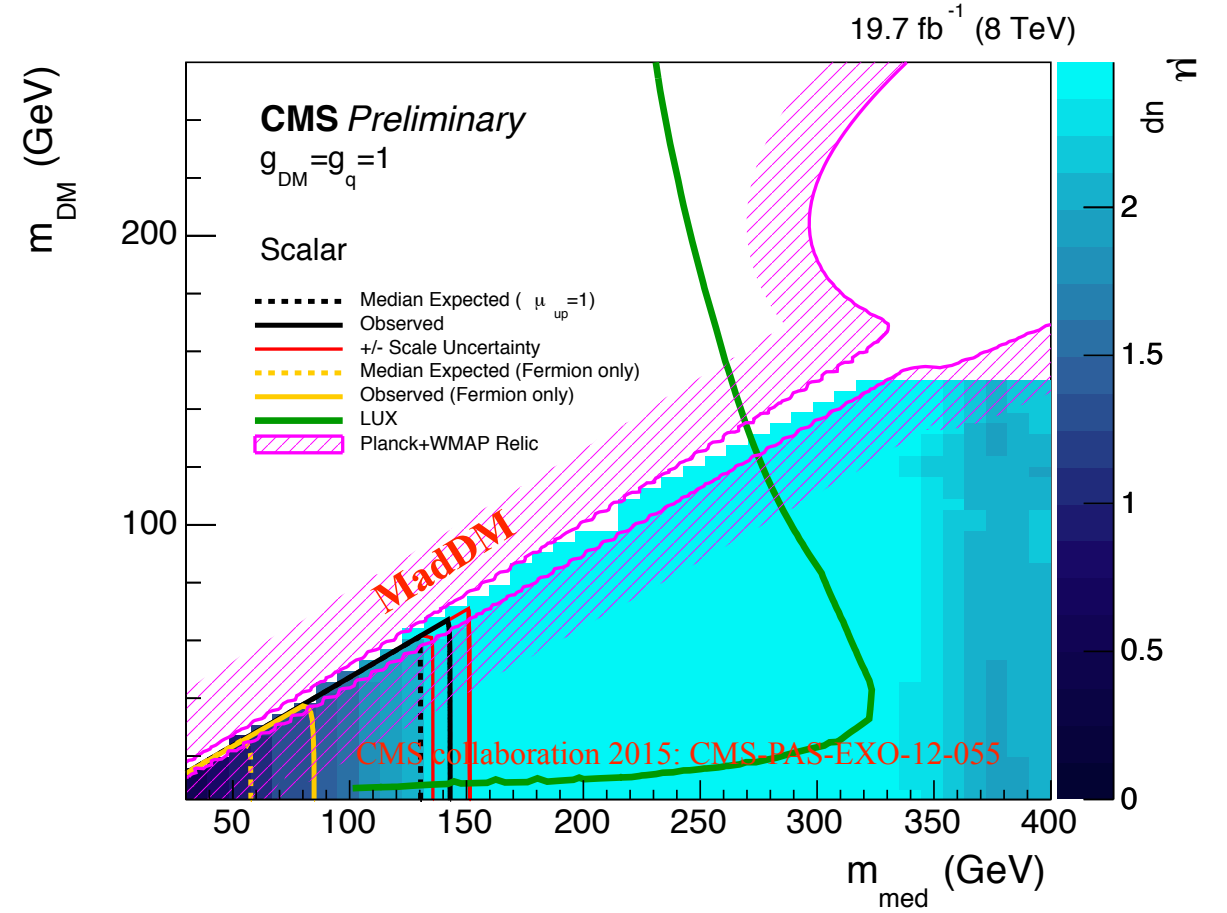
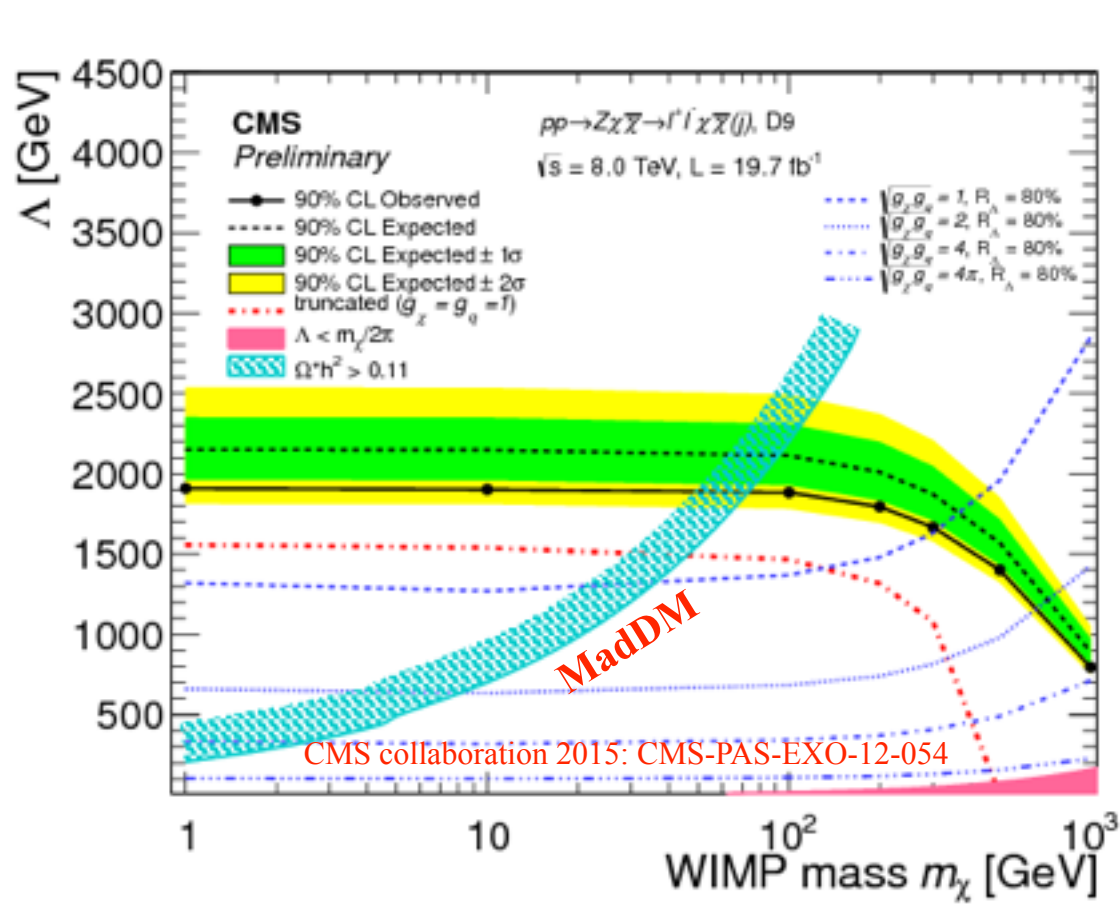
# Validations (Higgs portal, scalar DM)

We find good agreement in recoil rates with micrOMEGAs.



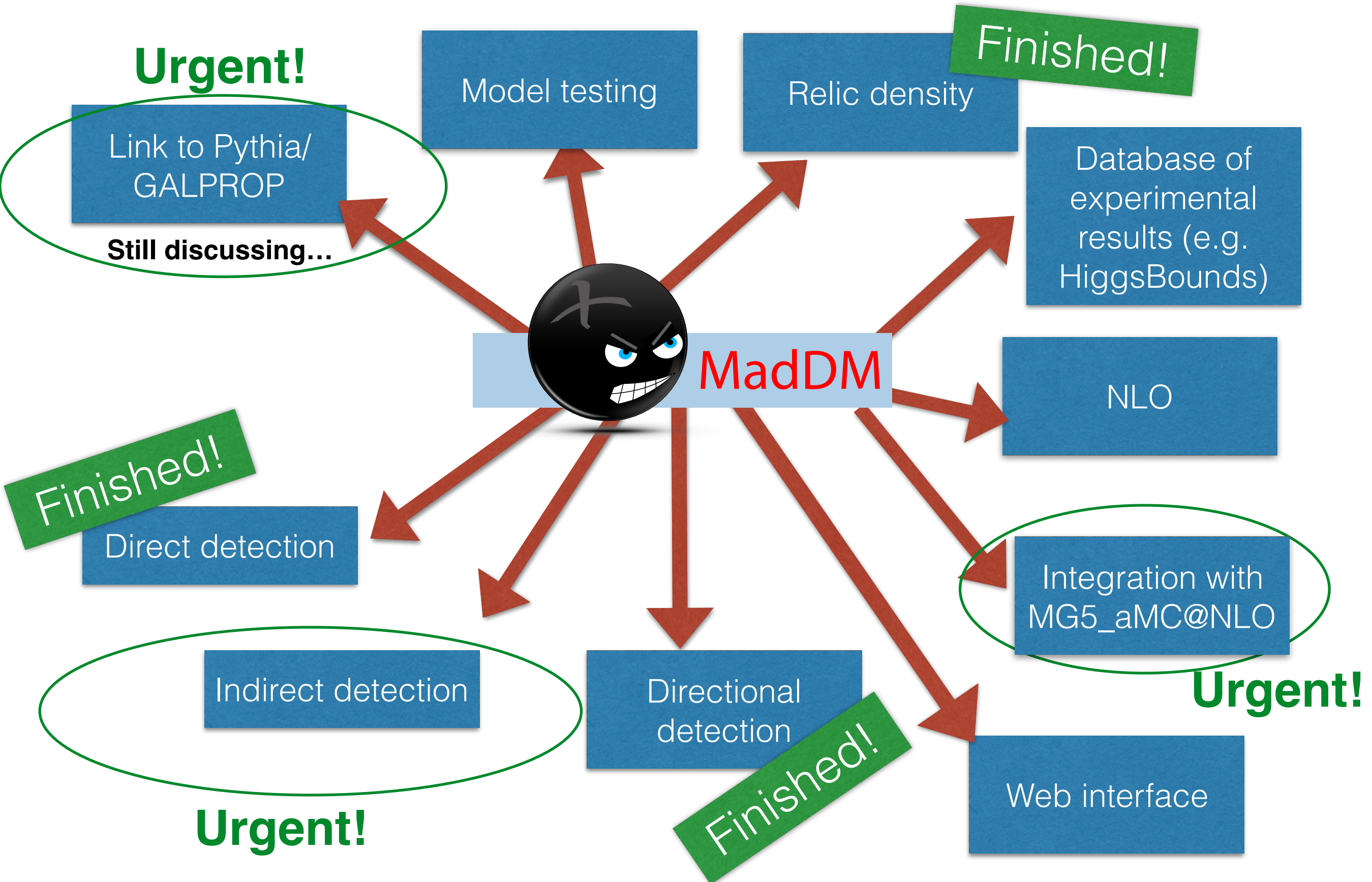
Assuming a 1pb DM-nucleon scattering cross section

- MadDM has already been used by the CMS experiment

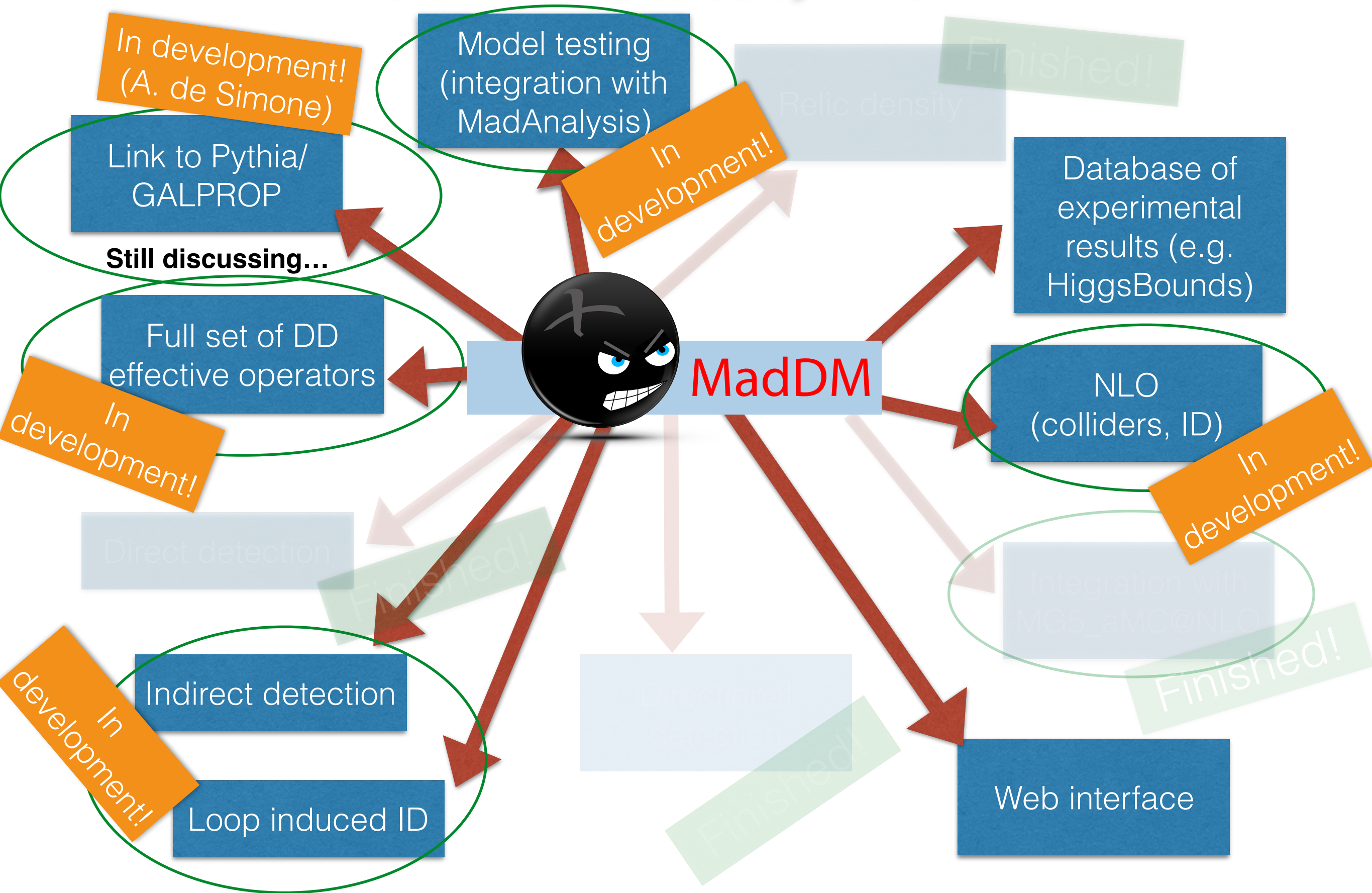




# MadDM Status, MC4BSM 2015



# MadDM Status, NOW





# Integration with MG5\_aMC@NLO

- MadDM is now a **MG5 plugin** (took a long time and required some structural changes both in MadDM and MG5\_aMC@NLO)

This means that you can install it using the MG5 interface

```
MG5_aMC> install maddm
```

It also means that MadDM now inherits the features of MG5

★ **Automatic resonance width computation**

```
DECAY 54 AUTO # WY0 (set up in param_card.dat)
```

★ **Integrated parameter scans**

```
54 scan:range(100, 1000, 100) # MY0 (set up in param_card.dat)
```

★ **Ability to do calculations at NLO / Loop induced!**

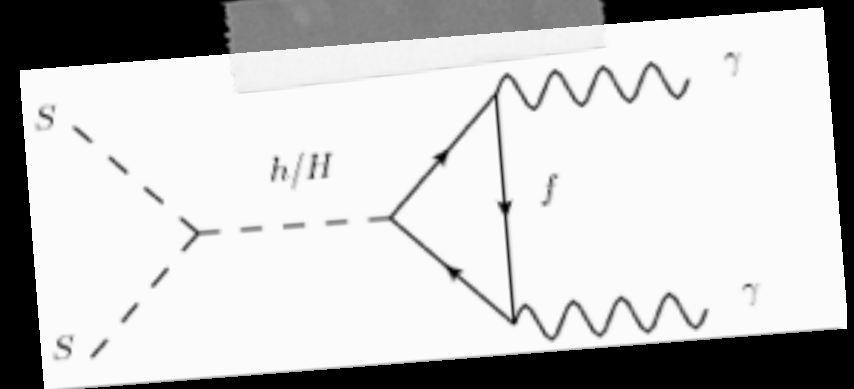


# MadDM Upgrades

- MadDM code now “knows” when/where **resonances** occur in amplitudes (Improves the speed of relic density computation)
- We implemented faster approximate methods for freeze out temperature determination.

We also **completely revamped the interface**

```
import model DMsimp_spin0_LO_UFO
define darkmatter xd
generate relic_density
generate direct_detection
generate indirect_detection b b~
add indirect_detection a a
...
output DMsimp
launch
```



← Will do loop induced annihilation!!  
← Collider signatures here soon!!

We still need to finish the astro-physical part for the ID (cosmic ray flux/propagation)!

# MadDM upgrades

The result of **launch** feels and looks like a MG5 run:

```
Here is the current status of requested run :
* Enter the name/number to (de-)activate the corresponding feature
  1. Compute the Relic Density      relic          = ON
  2. Compute Direct Detection       direct         = ON
  3. Compute Directional Detection directional = ON
  4. Compute Indirect Detection     indirect       = ON
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
  4. Edit the model parameters     [param]
  5. Edit the MadDM options        [maddm]
```

A standard output:

```
INFO: *** RESULTS ***
INFO: relic density      : 8.69e+04 Model excluded (relic not in range [0,0.12])
INFO: x_f                 : 5.00
INFO: sigmav(xf)          : 1.35e-15 GeV^-2 = 5.25e-07 pb
INFO: sigmaN_SI_p         : 2.74e-19 GeV^-2 = 1.07e-10 pb
INFO: sigmaN_SI_n         : 2.81e-19 GeV^-2 = 1.09e-10 pb
INFO: sigmaN_SD_p         : 4.17e-34 GeV^-2 = 1.62e-25 pb
INFO: sigmaN_SD_n         : 2.01e-33 GeV^-2 = 7.82e-25 pb
INFO: Nevents             : 1
INFO: smearing             : 0.00e+00
INFO: Indirect detection cross section at v = 1e-03: 2.33e-09+-4e-12
```



# MadDM v3.0

- 2->N annihilation, linking to MadEvent.
- Gamma-ray, positron fluxes, DM density profiles.
- Galactic propagation (link to Pythia/Galprop) & halo models
- Loop induced DM annihilations to **photons/electrons/neutrinos**.
- Loops for collider and direct detection studies.  
*eg. Higgs Portal models*
- Multicomponent DM: Semi annihilations, Assisted Freeze-out.
- Output in html form just as in current MG5.

Indirect  
detection

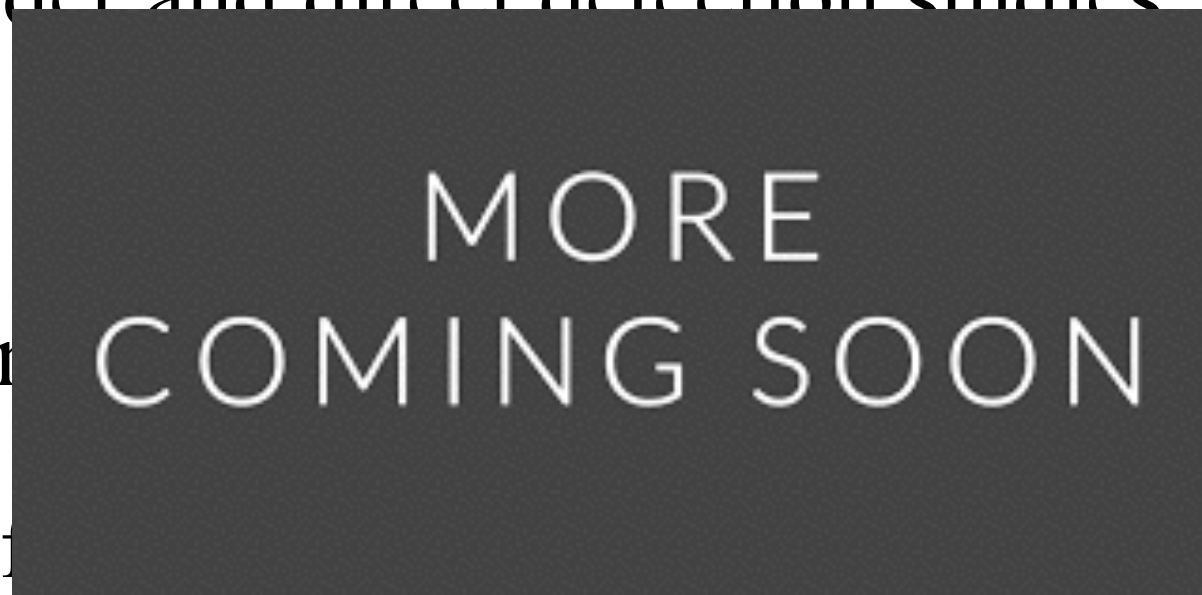
Link to  
MG5\_aMC  
@NLO





# MadDM v3.0

- 2->N annihilation
- Gamma-ray, positron
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- Loop induced D
- Loops for collis
- Multicomponen
- Output in html



Indirect detection

es.  
c halo models  
trons/neutrinos.

Link to  
MG5\_aMC  
@NLO

sted Freeze-out.

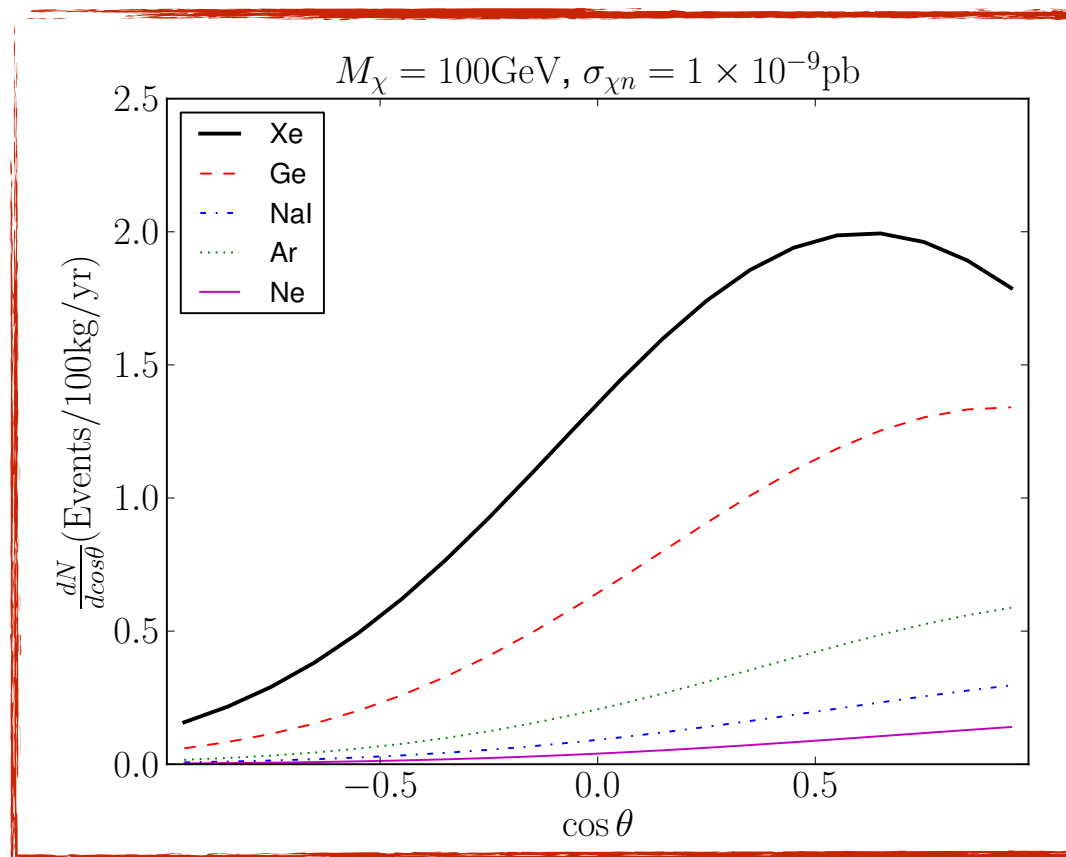
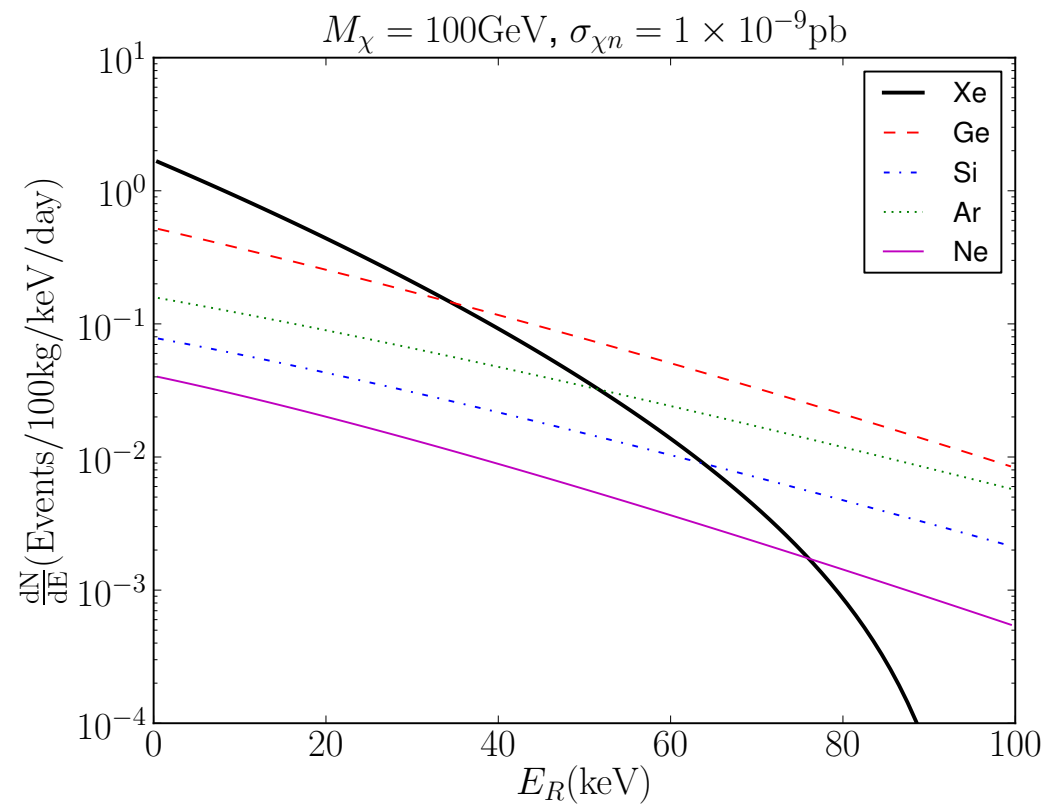
Thank you!



BACK UP



# Example recoil distributions



People typically calculate  $dR/dE$  because this is the quantity dir. detection experiments can measure...

...yet, there are **many reasons to consider**  $dR/dE d\cos(\theta)$

MadDM is the first public code to allow for calculations of angular recoil distributions!

# Simulation of Detector Effects

- Given the user defined energy and angular resolution, **MadDM can smear the recoil distributions**

- We assume a Gaussian smearing function  
**(this can be easily modified by the user):**

$$F(E, \theta) = \int F(E', \theta') \left( \frac{1}{\sigma_E \sqrt{2\pi}} e^{-\frac{(E-E')^2}{2\sigma_E^2}} \right) \left( \frac{1}{\sigma_\theta \sqrt{2\pi}} e^{-\frac{(\theta-\theta')^2}{2\sigma_\theta^2}} \right) dE' d\theta',$$

Unsmearred  
distribution

Energy smearing

angular smearing

As a validation we reproduced the LUX exclusion  
(**calculation fully automated in MadDM**)

