MadDM

past, present and future

Mihailo Backović (CP3-UCL)

The (Inconvenient) Truth about DM

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

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

Dark Matter:

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

DM could in principle only interact gravitationally…

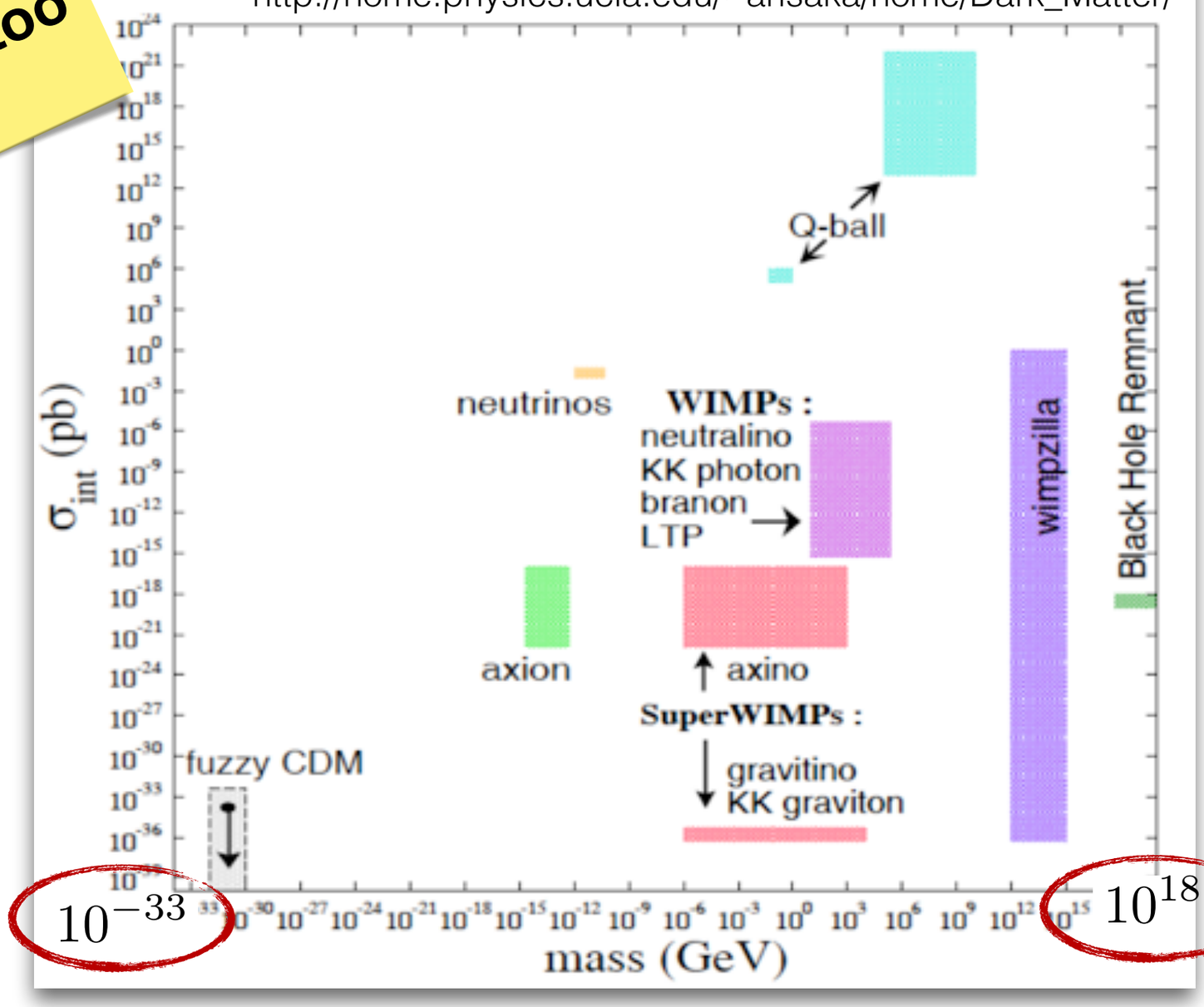
… **in which case, the rest of this talk is completely useless**

The (Inconvenient) Truth about DM

In fact, we have almost **no sense of energy scale** associated with DM!

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

http://home.physics.ucla.edu/~arisaka/home/Dark_Matter/



The (Inconvenient) Truth about DM

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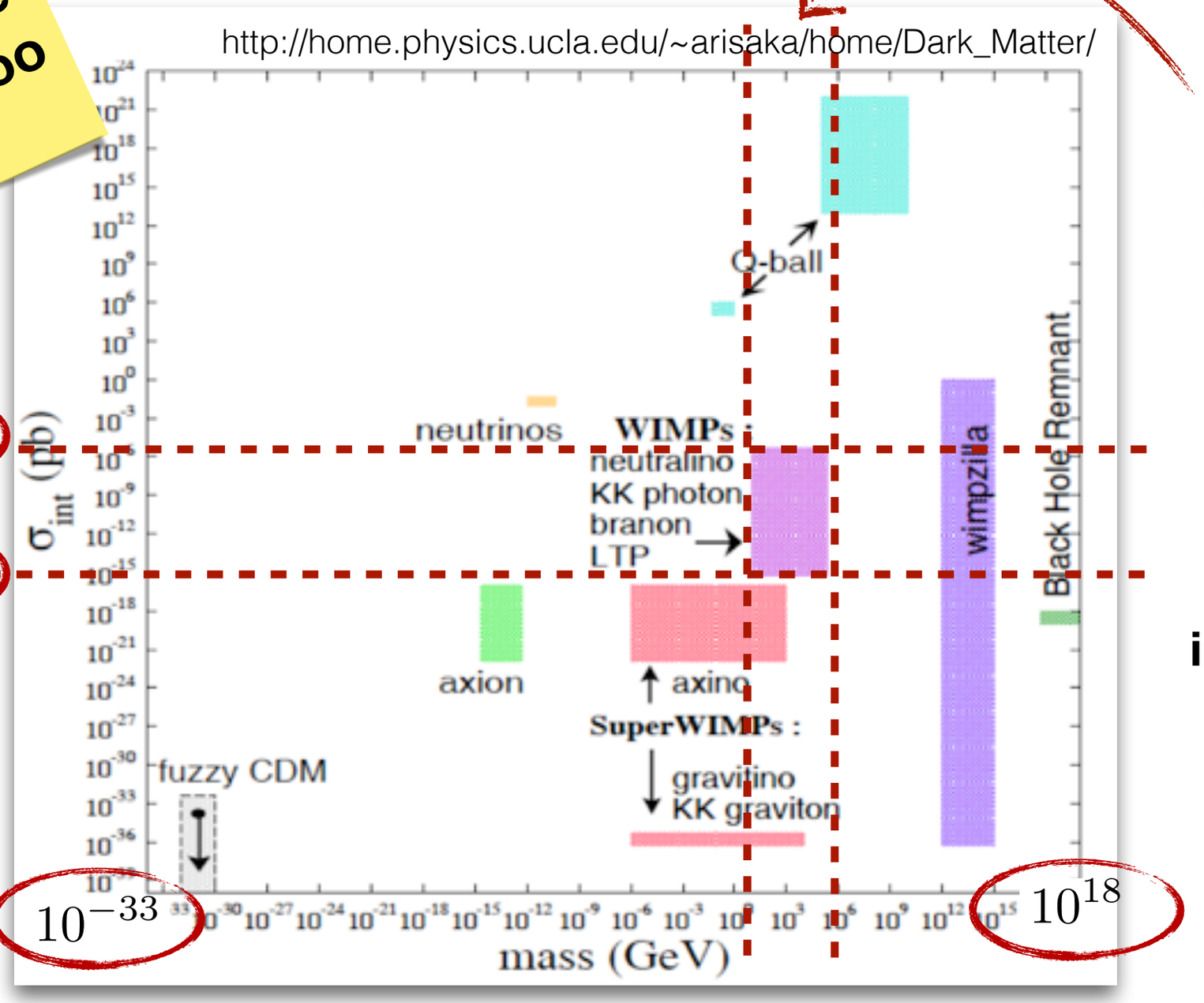

Even if you only consider **WIMPs**, they span:

6 orders of magnitude in mass and

19 orders of magnitude in interaction cross section

Dark Matter (DM) searches

DM searches at the interface of **collider physics, astrophysics and cosmology:**

	Experiments	Example process measured
Direct Detection	LUX, Xenon, LZ…	$p/n\ \chi \to p/n\ \chi$
Indirect Detection	AMS, FERMI/LAT …	$\chi\chi \to e^+e^-,\ p\bar{p},\ \gamma\gamma$
Colliders	LHC…	$pp \to \chi\chi + j, Z, \gamma ...$
Cosmology	WMAP, Planck …	$\chi\chi \to \mathrm{all}$

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Cosmology	WMAP, Planck .	

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

Dark Matter (DM) searches

DM studies at the interface of **collider physics**

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.

Colliders — LHC…

$$pp \to \chi\chi + j, Z, \gamma$$

Cosmology — WMAP, Planck ,

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

Comprehensive DM studies

Collider Signals
- w/ missing energy
- w/o missing energy

+

Cosmological Signals
- DM relic density
- Baryon asymmetry
- …

+

Astro-physical Signals
- cosmic ray fluxes
- direct detection
- …

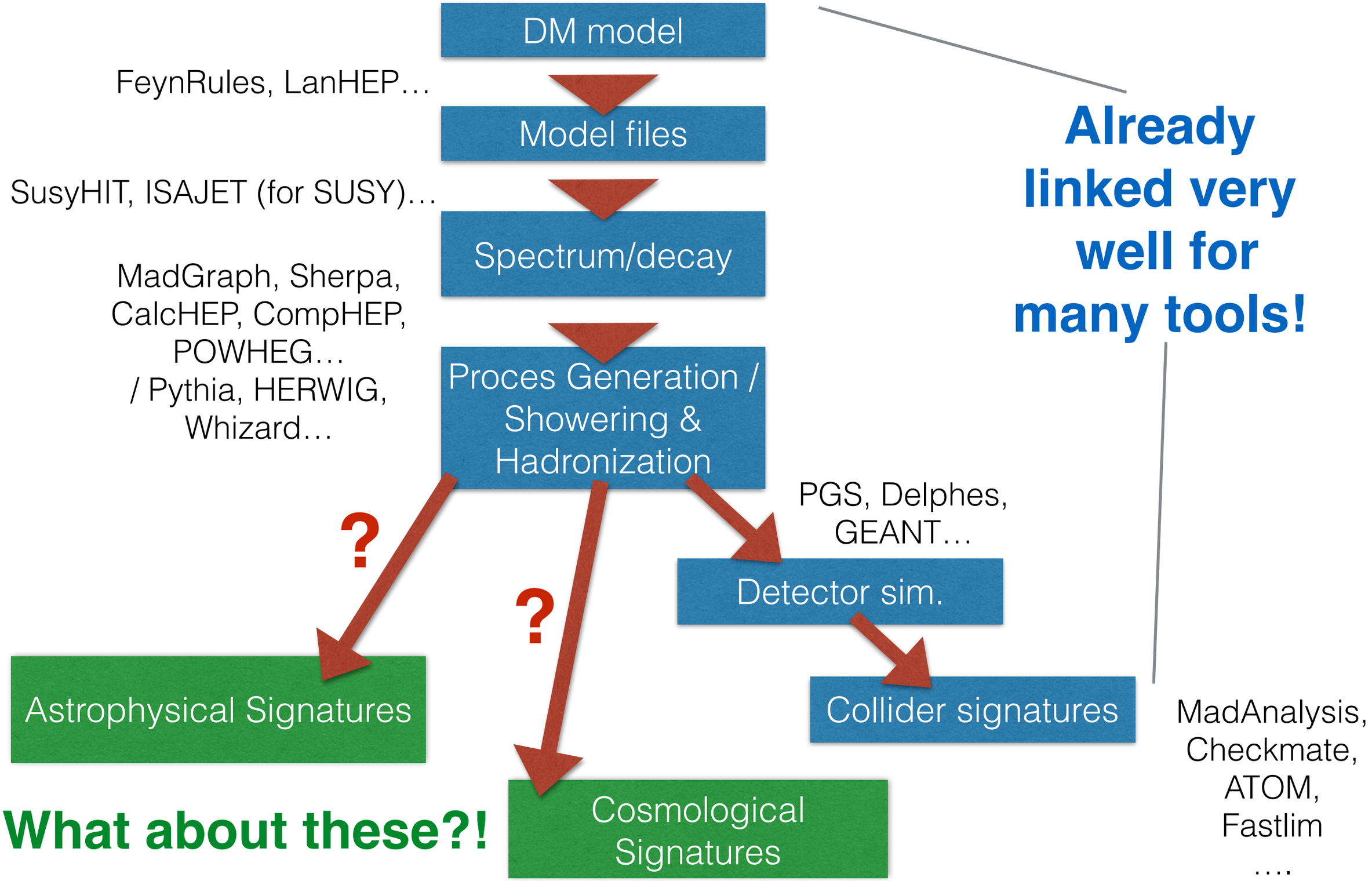
+

Complex Parameter Spaces
- Scans over N parameters

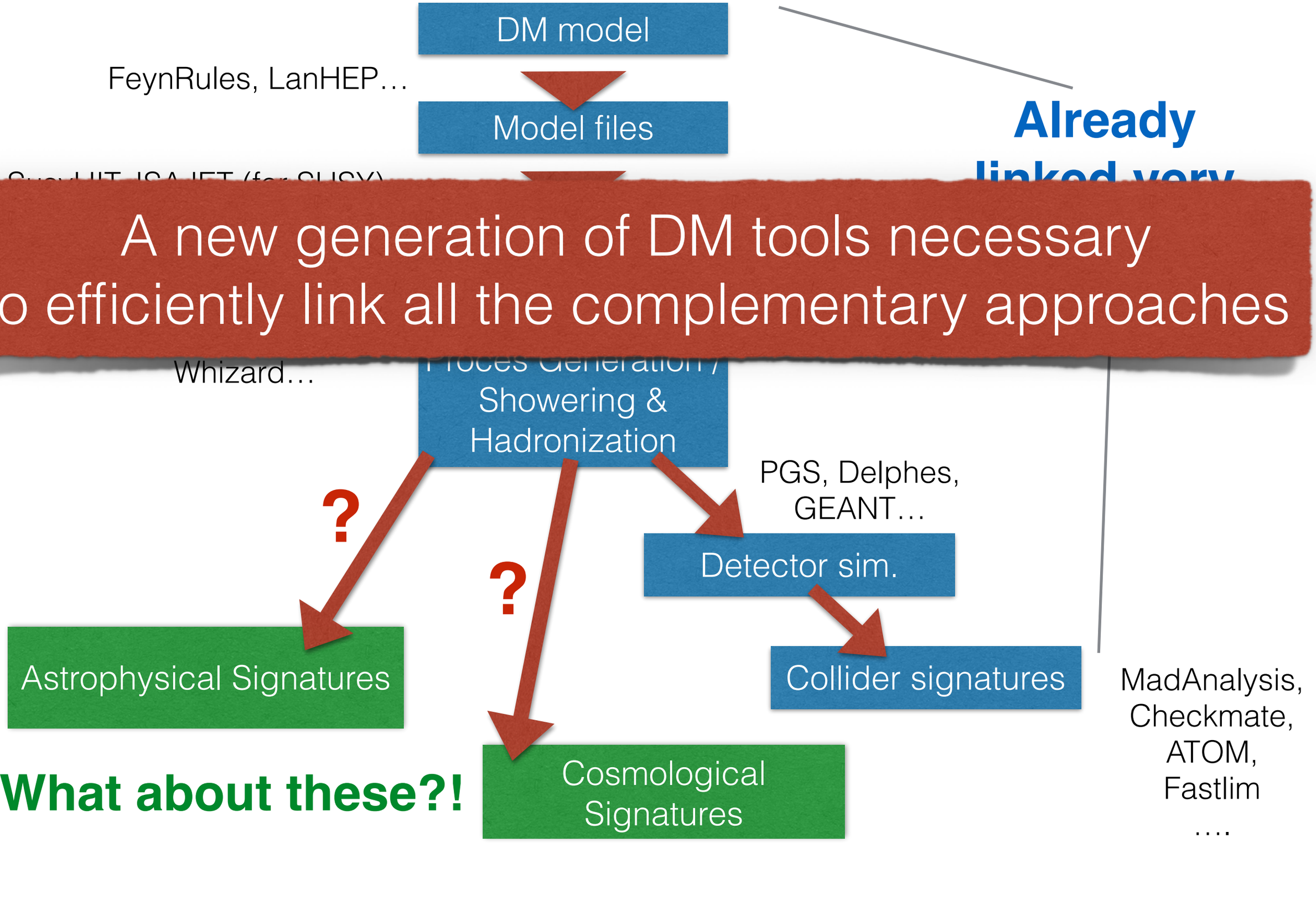
= Comprehensive DM study

MadDM aims to be a tool for **easy and efficient comprehensive DM studies**!

DM Tools in the LHC era



DM Tools in the LHC era



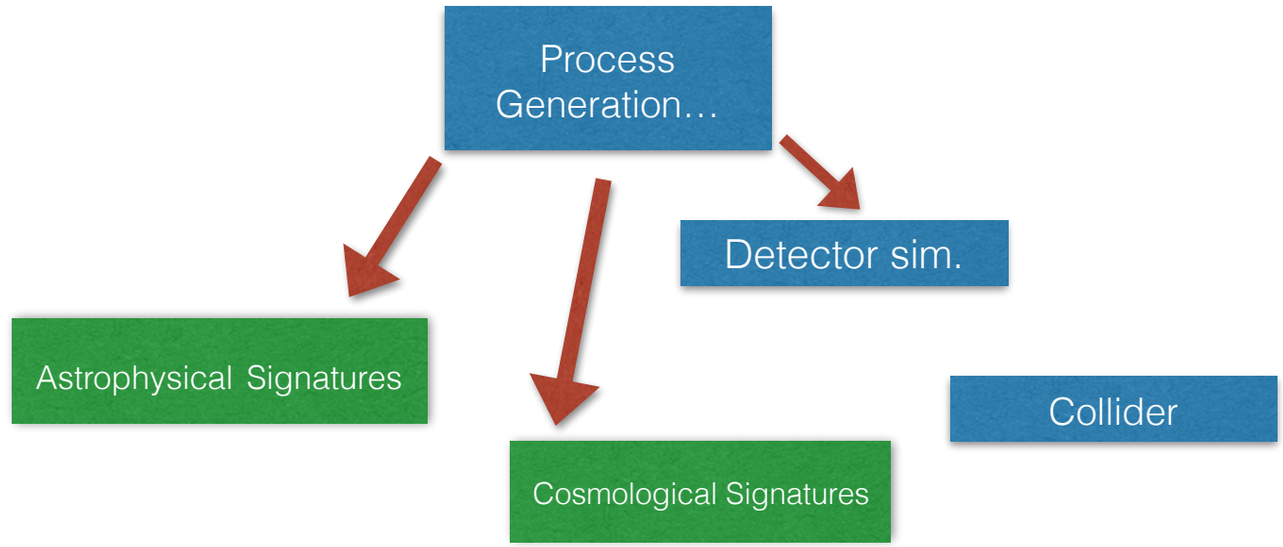
Already linked very

A new generation of DM tools necessary
to efficiently link all the complementary approaches

What about these?!

DM Tools in the LHC era

MadDM



MadDM emerged as an effort to link:

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

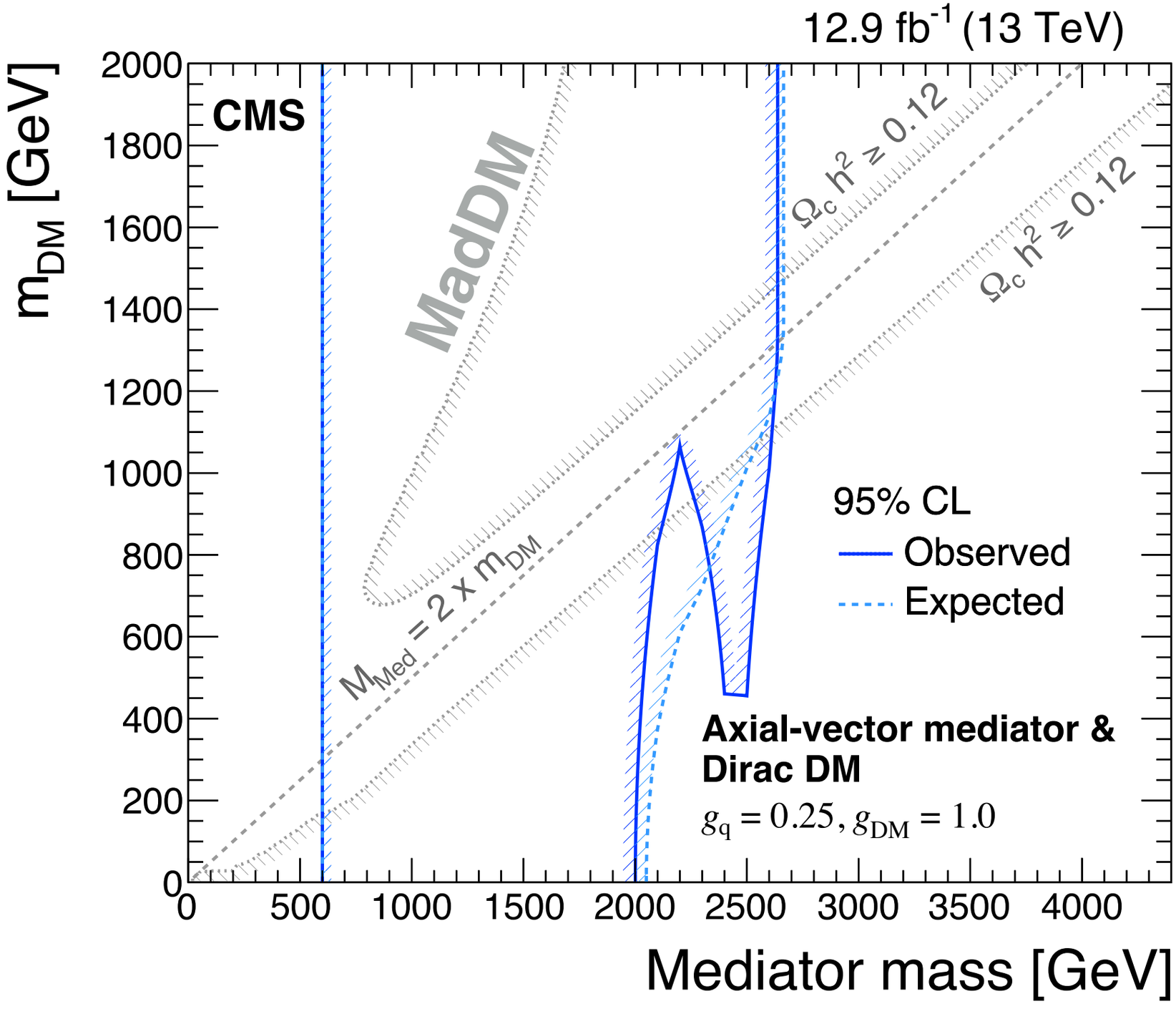
Version 1.0 of MadDM focused on calculations of **DM relic density** (in a generic UFO model).

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

Version 3.0 DM Indirect detection. (soon!)

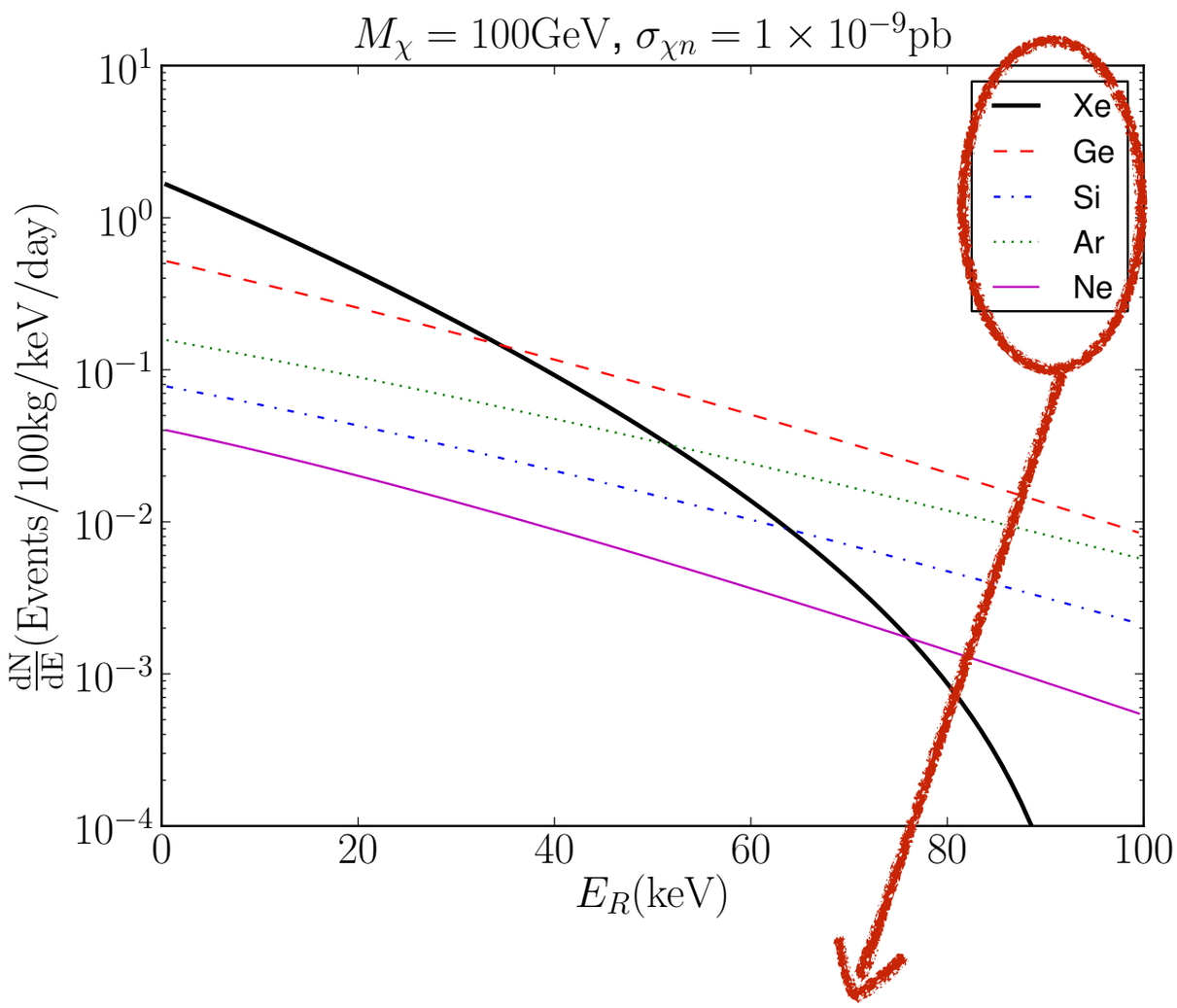
MadDM v.2.0 example calculations

Relic Density (simplified models)



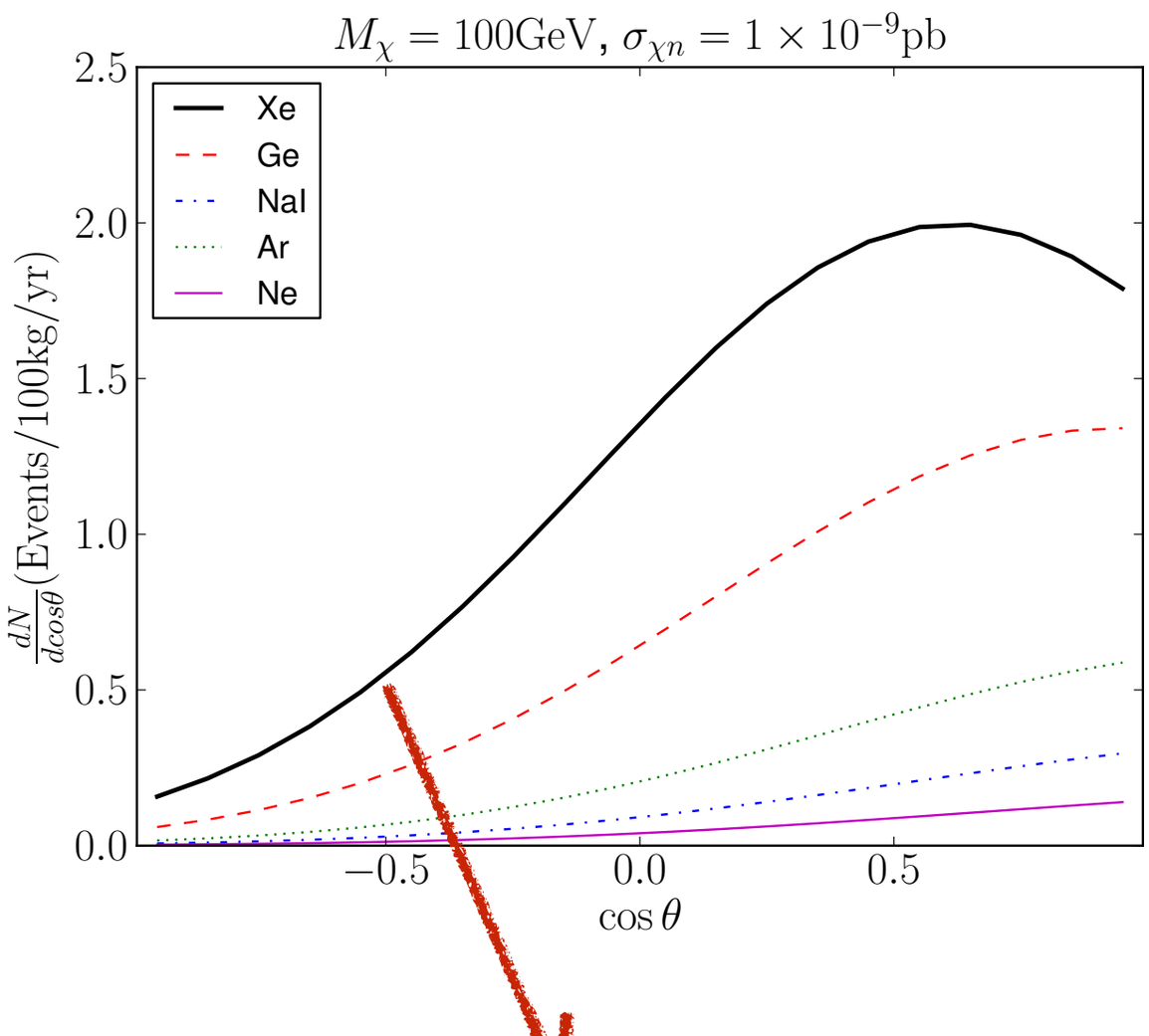
MadDM v.2.0 example calculations

Indirect Detection - Recoil rates



a wide range of target materials!

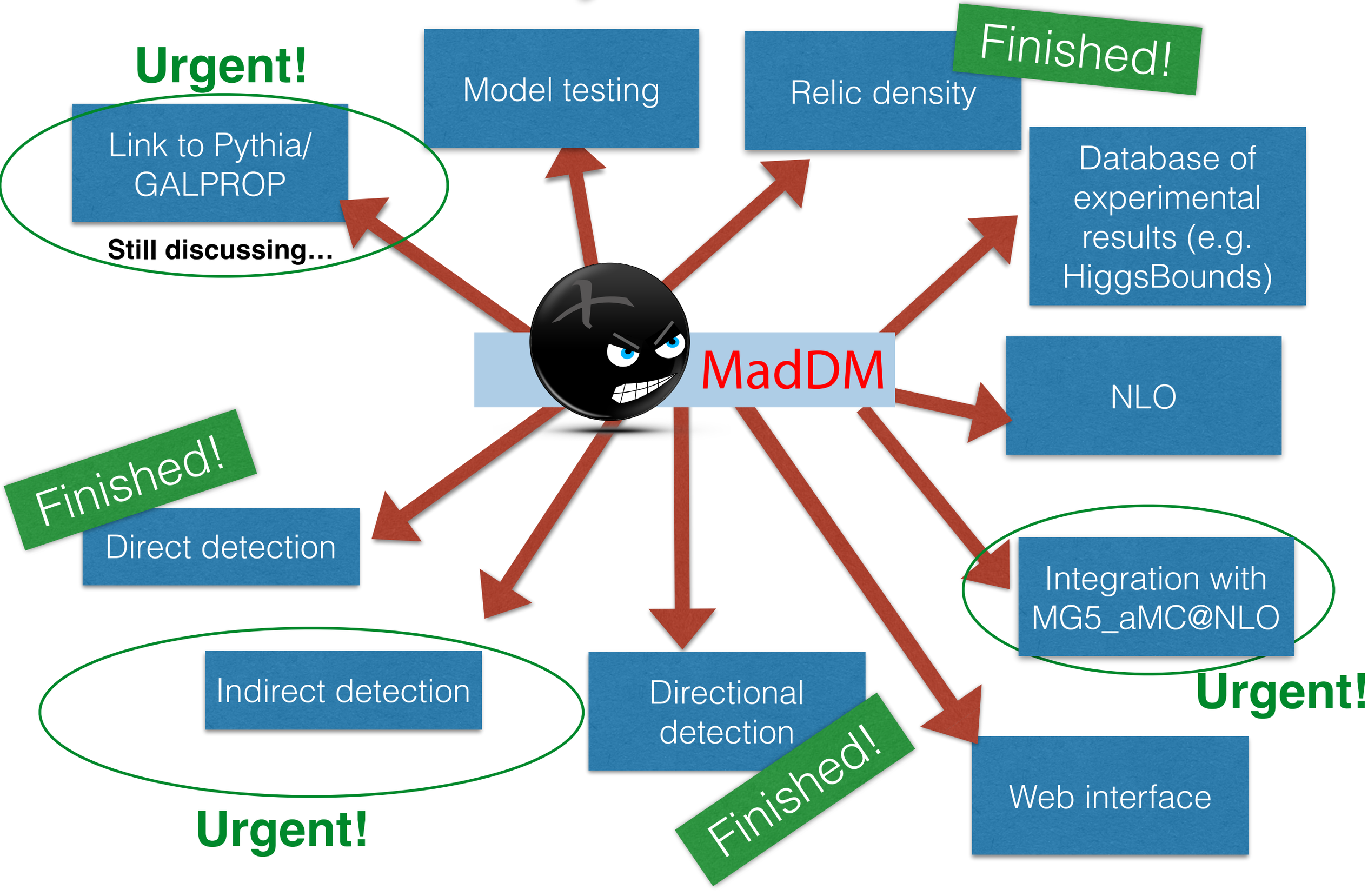
(**also composites: NaI and CF**)



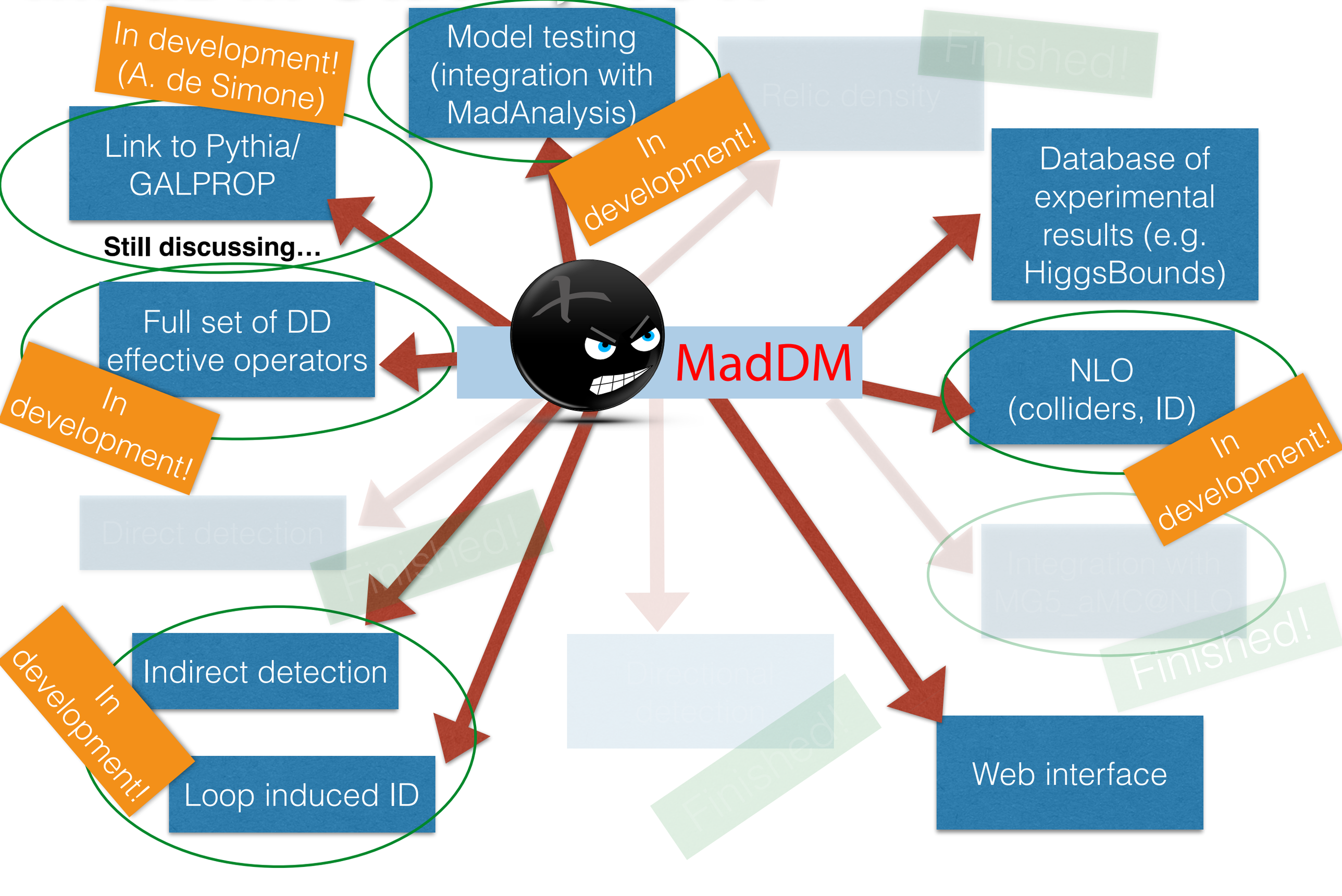
Nuclear recoil due to DM has preferred direction

(**due to DM "wind"**)

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)
```

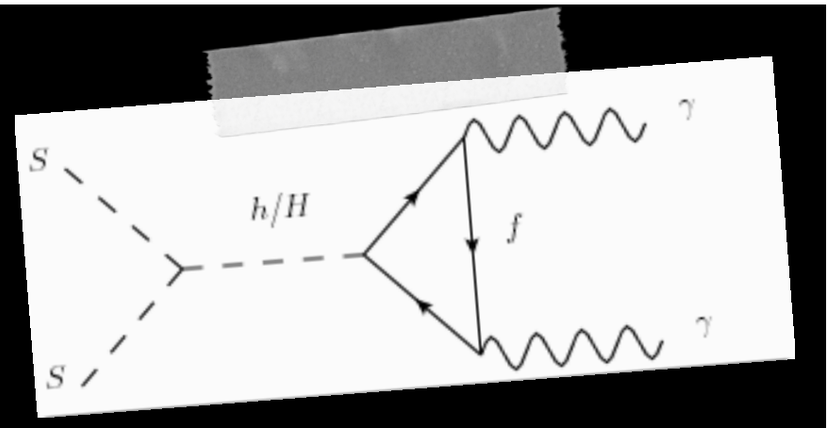
★Ability to do calculations at NLO / Loop induced!

MadDM upgrades

- MadDM code now “knows” when/where **resonances** occur in amplitudes (Improves the speed of relic density computation in models with)
- 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      <———— Will do loop induced annihilation!!
...                             <———— Collider signatures here soon!!
output DMsimp
launch
```



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
```

Example: Top-philic DM simplified model

1605.09242

$$\mathcal{L}^{Y_0}_{t,X} = -\left(g_t \frac{y_t}{\sqrt{2}} \bar{t}t + g_X \bar{X}X\right) Y_0$$

Four free parameters: g_t, g_X, m_X, m_Y

Arise from UV complete theories?

- Y_0 could be part of an SU(2) doublet

  ➔ 2HDM with a large degree of alignment $\cos(\beta - \alpha) \sim 0$

  [see e.g. Craig *et al.* '13; Carena *et al.* '13]

- Y_0 SM singlet

  ➔ Higgs-Portal model

  Additional phenomenological aspects

  [see e.g. Kim *et al.* '08; Baek *et al.* '11, '14; Lopez-Honorez *et al.* '12; Khoze *et al.* '15; Ko, *et al.* '16]

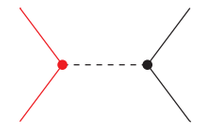
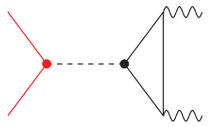
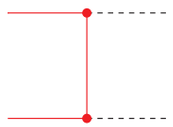
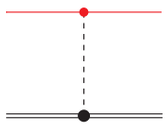
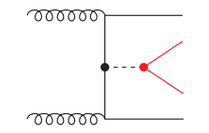
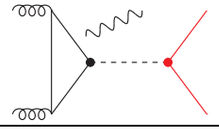
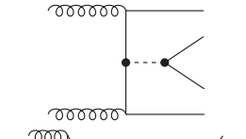
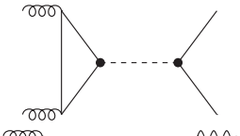
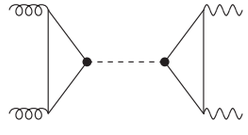
...

Credit for slide to Jan Heisig

Example: Top-philic DM simplified model

1605.09242

Plethora of signatures

Cosmology	relic		$m_X > m_t$	
			$m_X < m_t$	Planck, FermiLAT
Astrophysics	indirect		$m_X > m_Y$	
	direct		$m_X > 1$ GeV	LUX, CDMSLite
Colliders	$\not{E}_T$		$m_Y > 2m_X$	$+t\bar{t}$
			$m_Y > 2m_X$	$+j$, $+Z$, $+h$
	no $\not{E}_T$		$m_Y > 2m_t$	$4t$
			$m_Y > 2m_t$	$t\bar{t}$
			$m_Y < 2m_X, 2m_t$	jj, $\gamma\gamma$

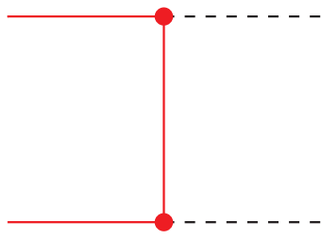
Credit for slide to Jan Heisig

Example: Top-philic DM simplified model

1605.09242

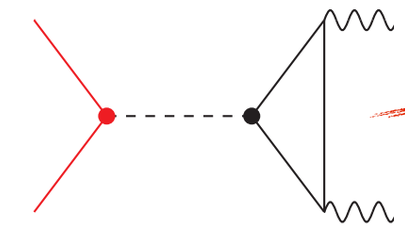
Relic density constraints

$m_X \gtrsim m_Y$:

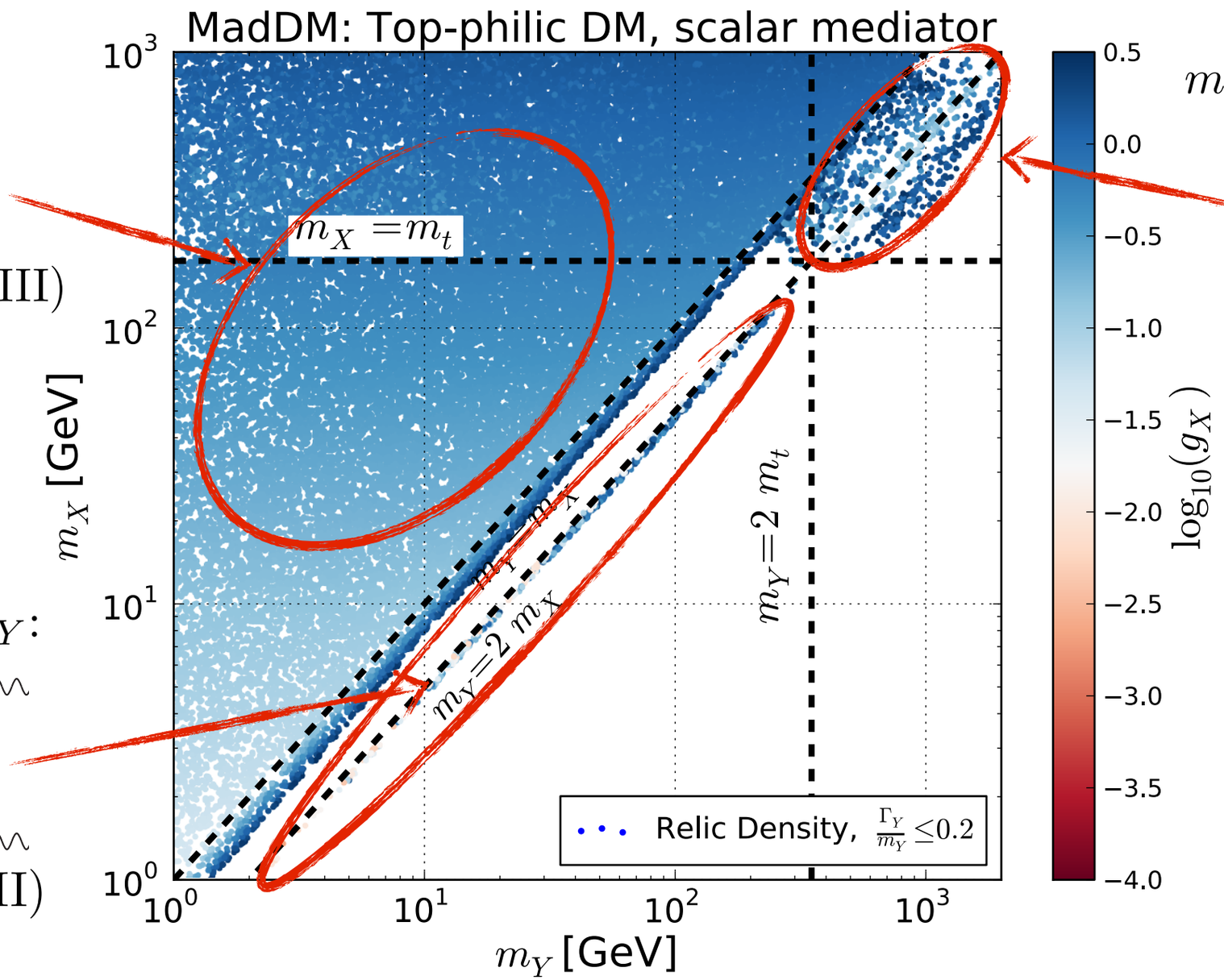


$X\bar{X} \to Y_0 Y_0$ (III)

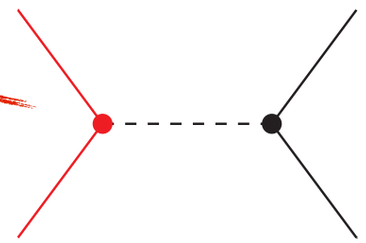
$m_X \lesssim m_t$, m_Y:



$X\bar{X} \to gg$ (II)



$m_Y \gtrsim m_X \gtrsim m_t$:



$X\bar{X} \to t\bar{t}$ (I)

[Computed with MadDM,]

Credit for slide to Jan Heisig

Example: Top-philic DM simplified model

Relic density constraints

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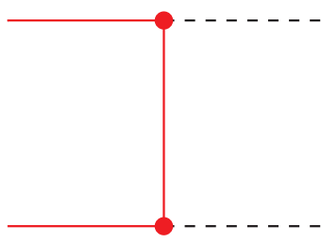
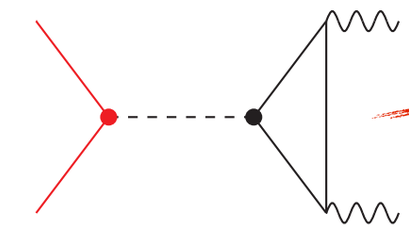
$m_X \gtrsim m_Y$:

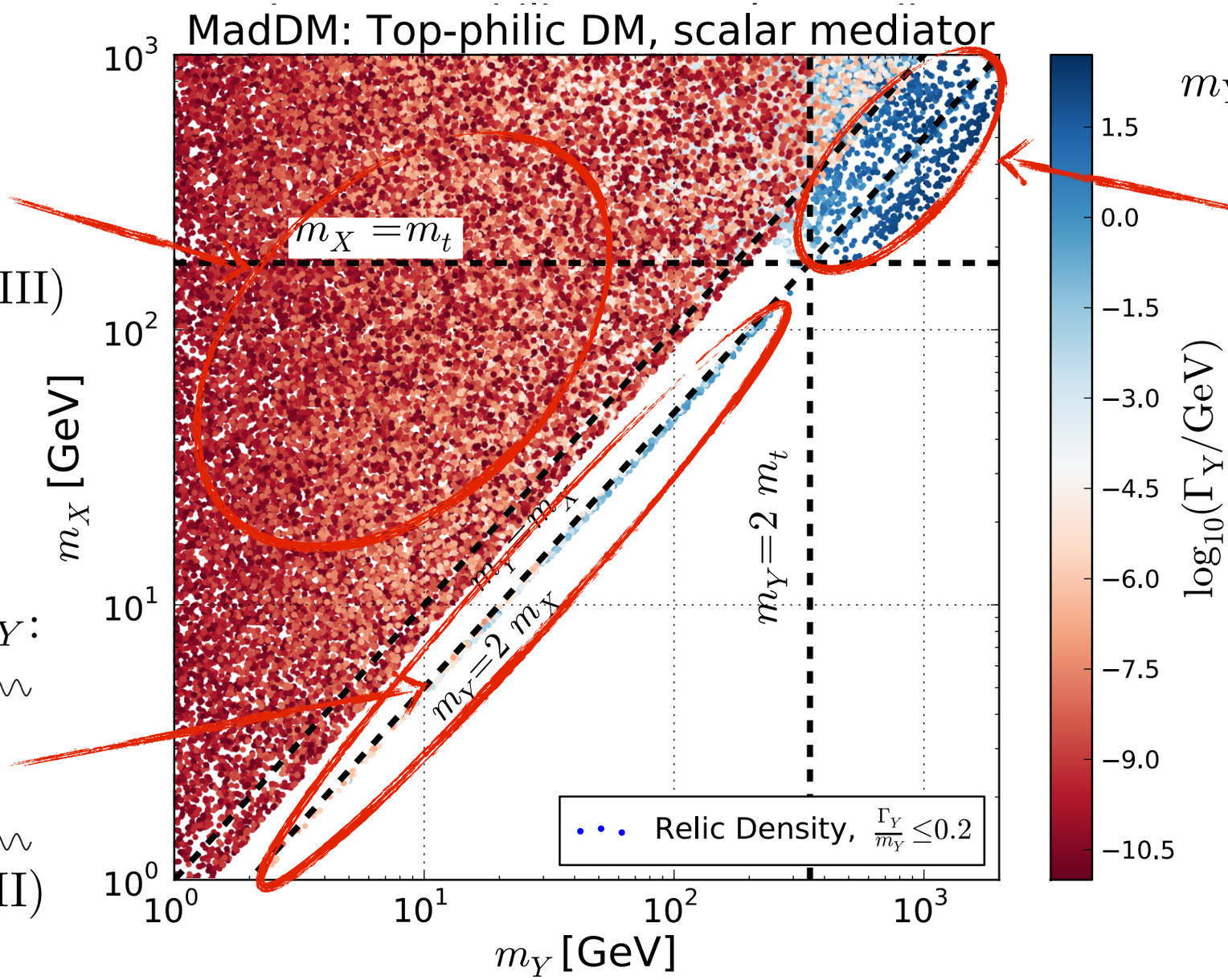


$X\bar{X} \to Y_0 Y_0$ (III)

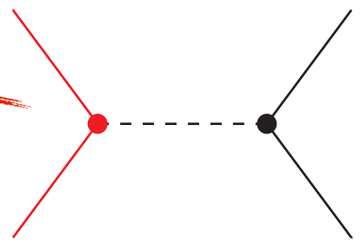
$m_X \lesssim m_t$, m_Y:



$X\bar{X} \to gg$ (II)



$m_Y \gtrsim m_X \gtrsim m_t$:



$X\bar{X} \to t\bar{t}$ (I)

[Computed with MadDM,]

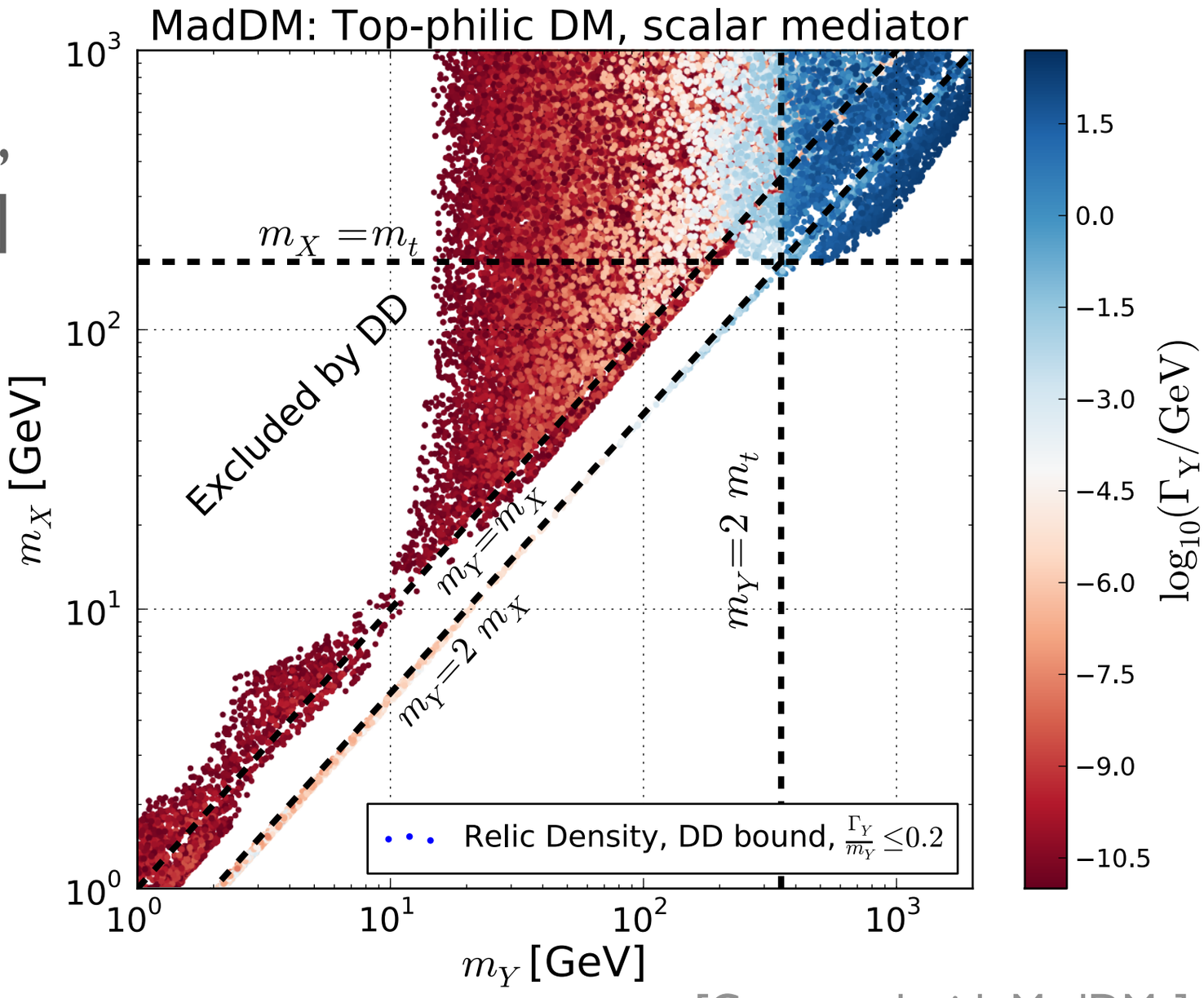
Credit for slide to Jan Heisig

Example: Top-philic DM simplified model

1605.09242

Direct detection bounds

[CDMSlite, LUX 2013]



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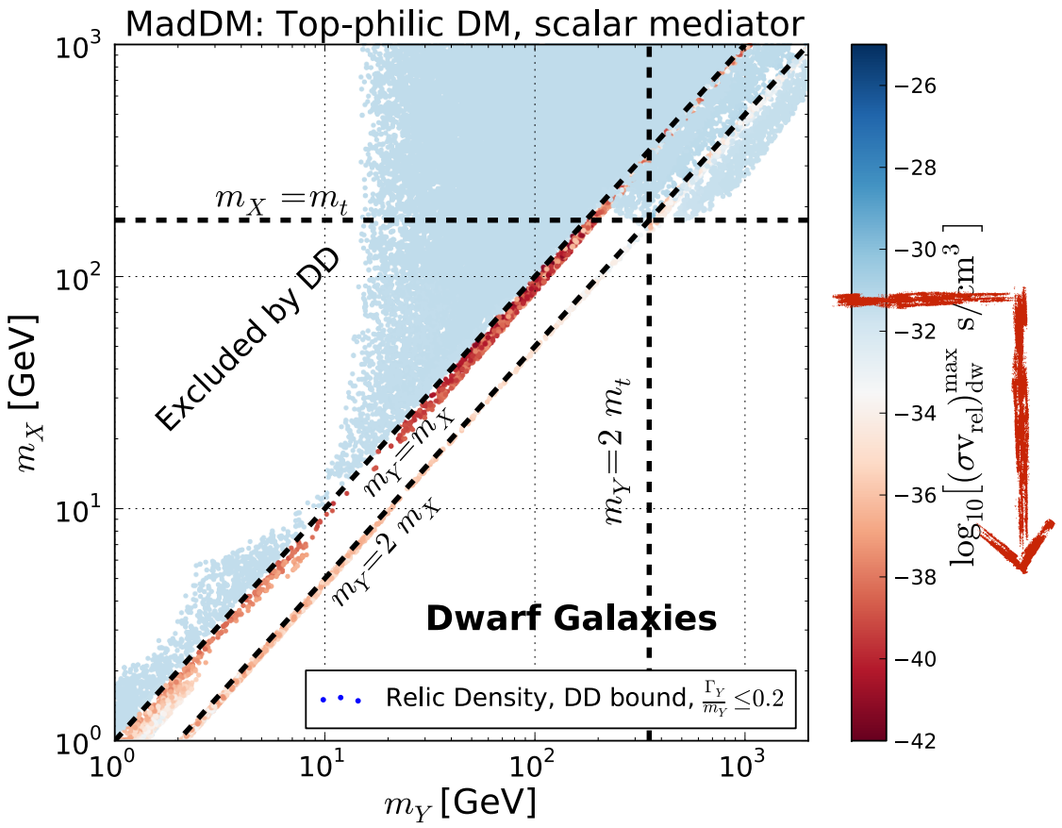
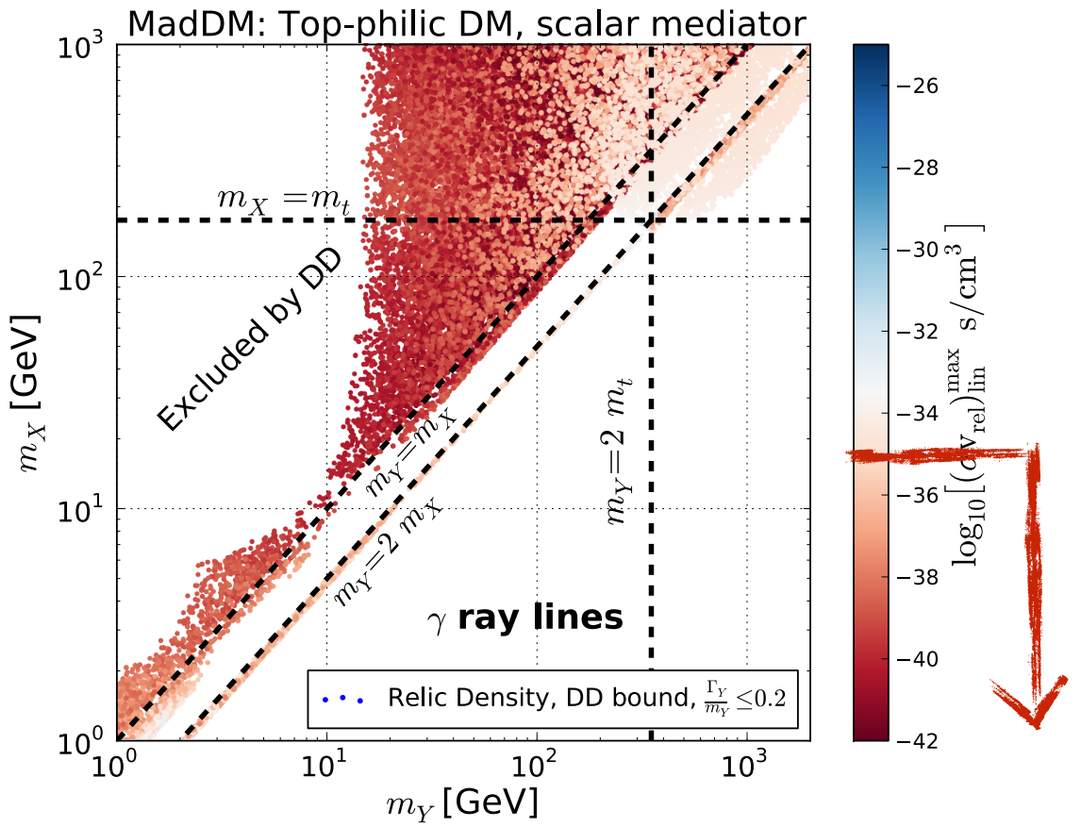
Example: Top-philic DM simplified model

Indirect detection bounds

1605.09242

[*Fermi*-LAT 2015]





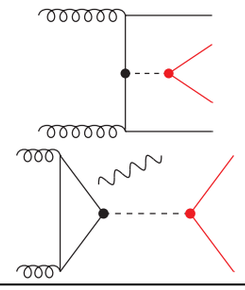
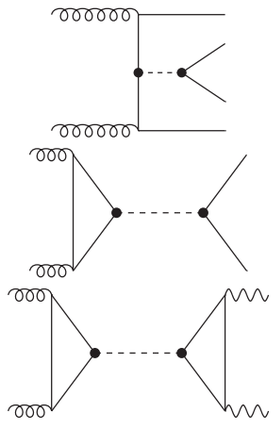
- *p*-wave suppression for all annihilation processes for scalar mediator
- For pseudo-scalar mediator only process XX > YY *p*-wave suppressed

Credit for slide to Jan Heisig

Example: Top-philic DM simplified model

1605.09242

Collider searches

Colliders	$\not{E}_T$		$m_Y > 2m_X$	$+t\bar{t}$
			$m_Y > 2m_X$	$+j,\ +Z,\ +h$
	no $\not{E}_T$		$m_Y > 2m_t$	$4t$
			$m_Y > 2m_t$	$t\bar{t}$
			$m_Y < 2m_X, 2m_t$	$jj,\ \gamma\gamma$

Final state	Imposed constraint	Reference	Comments
$\not{E}_T + t\bar{t}$	MadAnalysis5 PAD (new)	CMS [1504.03198]	Semileptonic top-antitop decay
$\not{E}_T + j$	MadAnalysis5 PAD (new)	CMS [1408.3583]	
$\not{E}_T + Z$	$\sigma(\not{E}_T > 150\ \text{GeV}) < 0.85\,\text{fb}$	CMS [1511.09375]	Leptonic Z-boson decay
$\not{E}_T + h$	$\sigma(\not{E}_T > 150\ \text{GeV}) < 3.6\,\text{fb}$	ATLAS [1510.06218]	$h \to b\bar{b}$ decay
jj	$\sigma(m_Y = 500\ \text{GeV}) < 10\,\text{pb}$	CMS [1604.08907]	Only when $m_Y > 500\,\text{GeV}$
$\gamma\gamma$	$\sigma(m_Y = 150\ \text{GeV}) < 30\,\text{fb}$	CMS [1506.02301]	Only when $m_Y > 150\,\text{GeV}$
$t\bar{t}$	$\sigma(m_Y = 400\ \text{GeV}) < 3\,\text{pb}$	ATLAS [1505.07018]	Only when $m_Y > 400\,\text{GeV}$
$t\bar{t}t\bar{t}$	$\sigma < 32\,\text{fb}$	CMS [1409.7339]	Upper limit on the SM cross section

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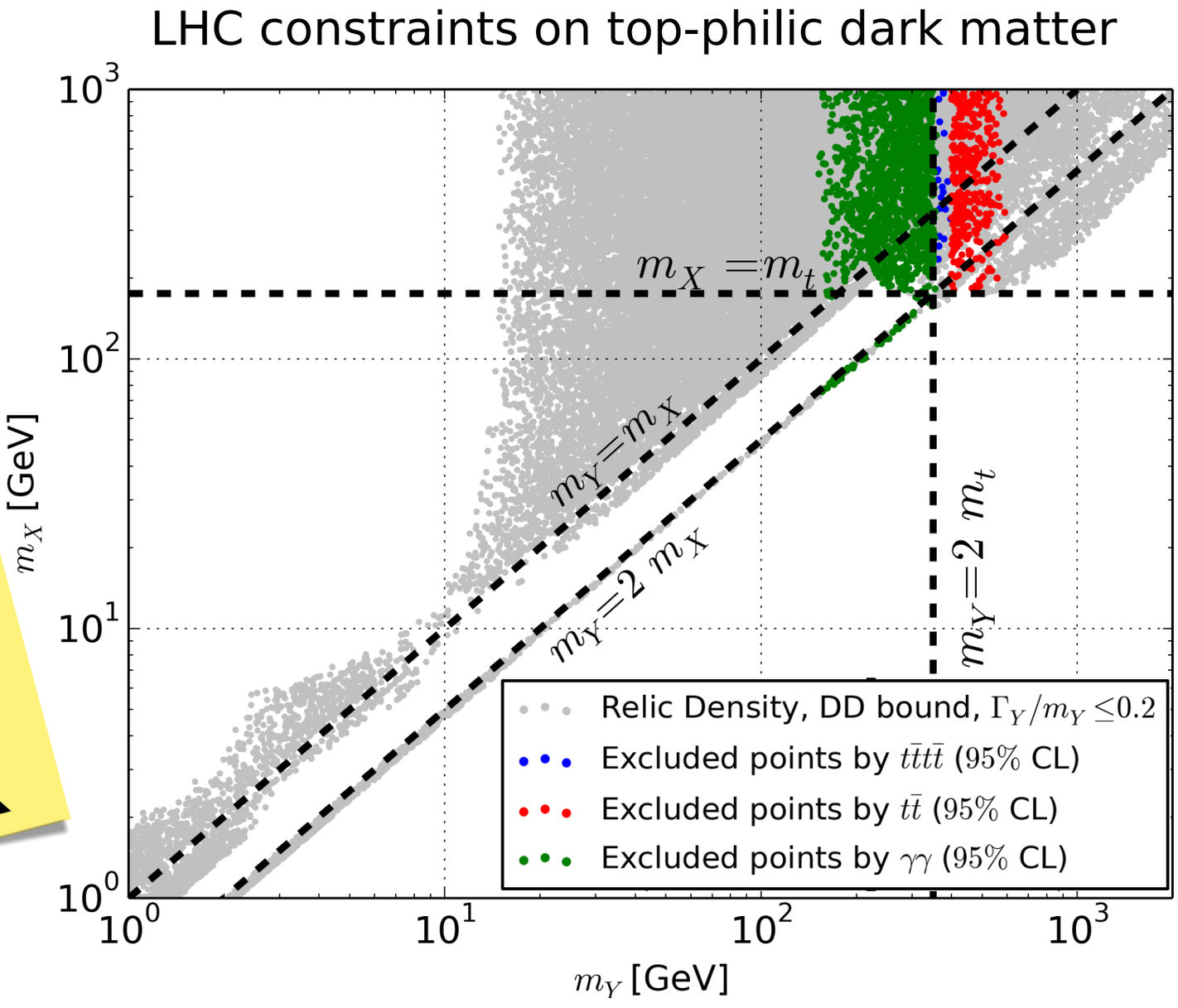
Example: Top-philic DM simplified model

1605.09242

Combined constraints



Only **mediator searches** provide useful constraints!

Need close to non-perturbative couplings to have **constraints from mono-X**

$$g_{t,X} = [10^{-4}, \pi]$$

Credit for slide to Jan Heisig

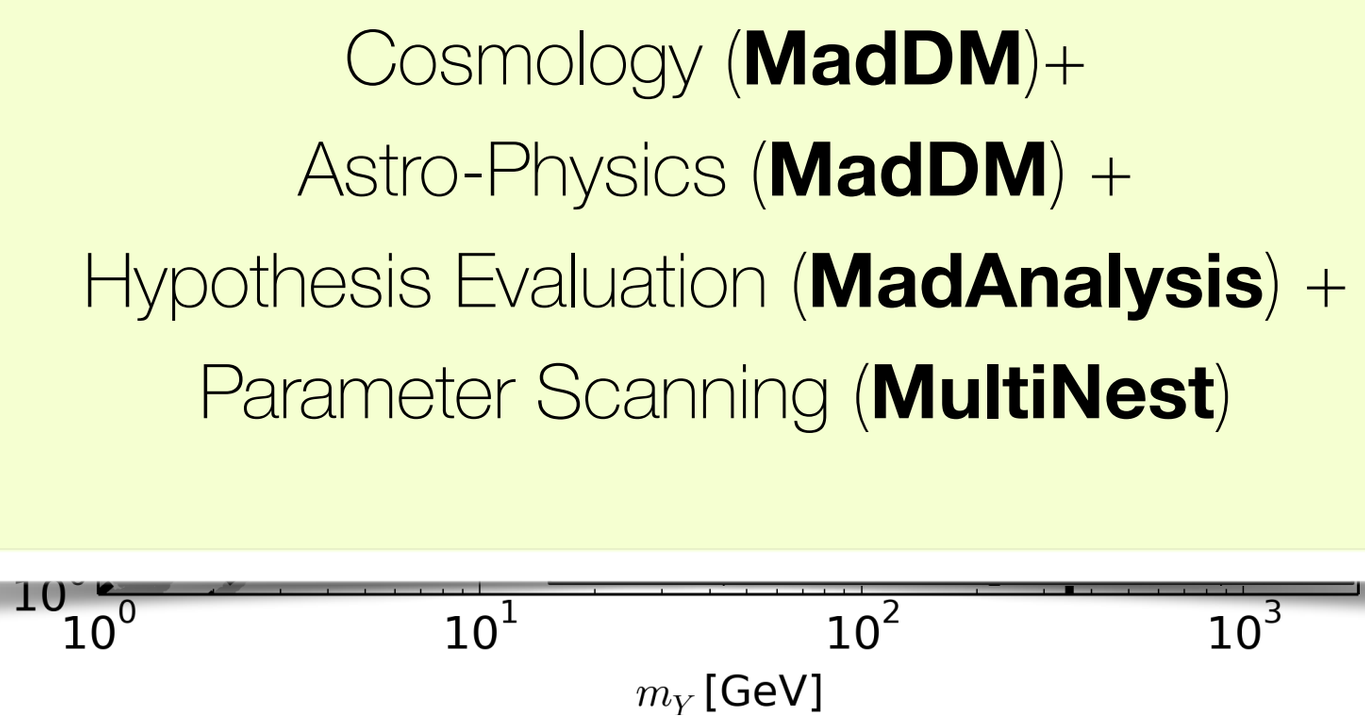
Example: Top-philic DM simplified model

1605.09242

Combined constraints

This study is a **proof of principle** that we can automate Comprehensive studies of DM.

Collider searches (NLO accuracy) (**MadGraph**) +
Cosmology (**MadDM**)+
Astro-Physics (**MadDM**) +
Hypothesis Evaluation (**MadAnalysis**) +
Parameter Scanning (**MultiNest**)



$g_{t,X} = [10^{-4}, \pi]$

Credit for slide to Jan Heisig


Thank you!