Comprehensive Dark Matter Searches

Mihailo Backović (CP3-UCL)

UCL Université catholique de Louvain

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. …

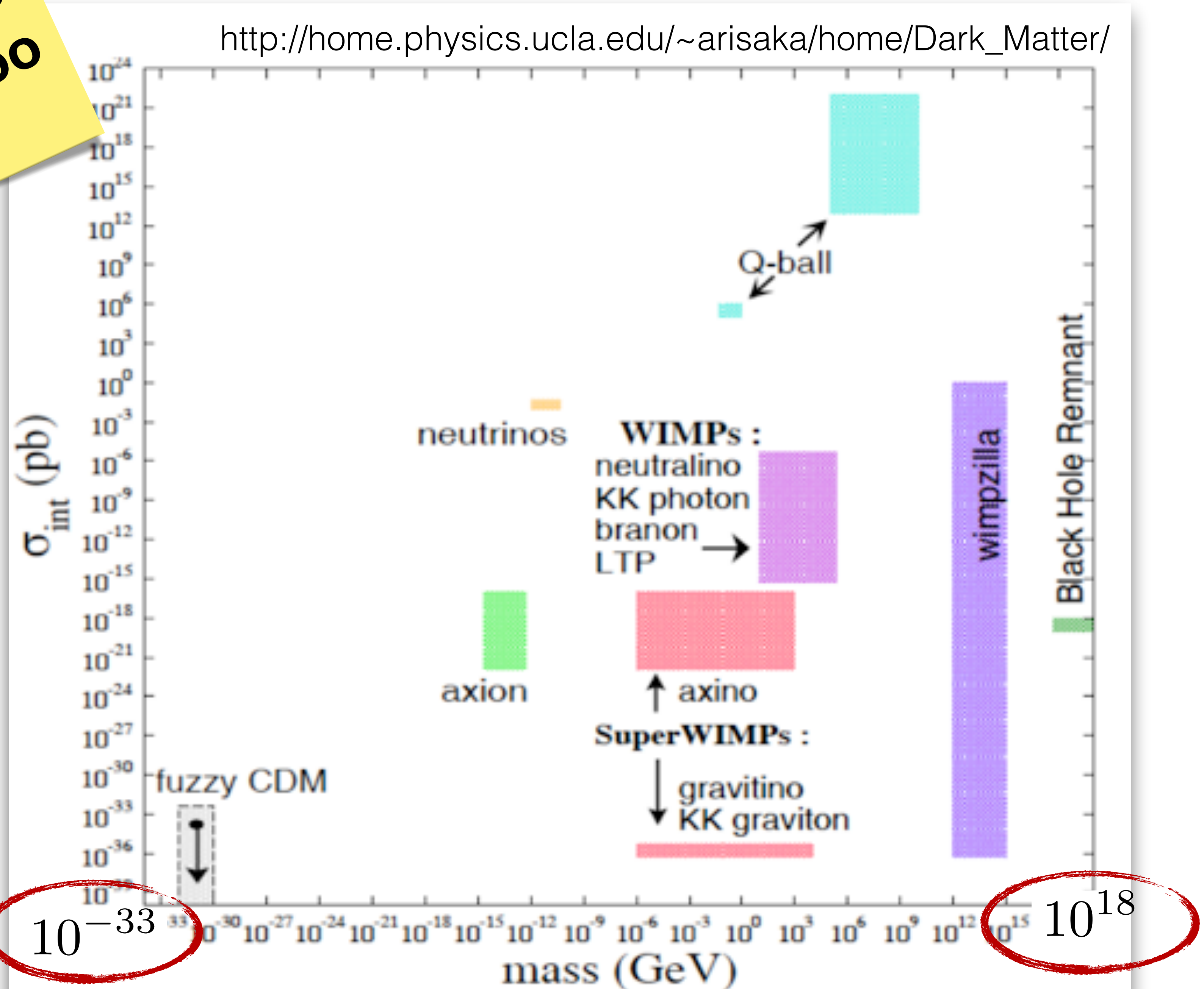
DM could in principle only interact gravitationally…

… **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!**



The (Inconvenient) Truth about DM

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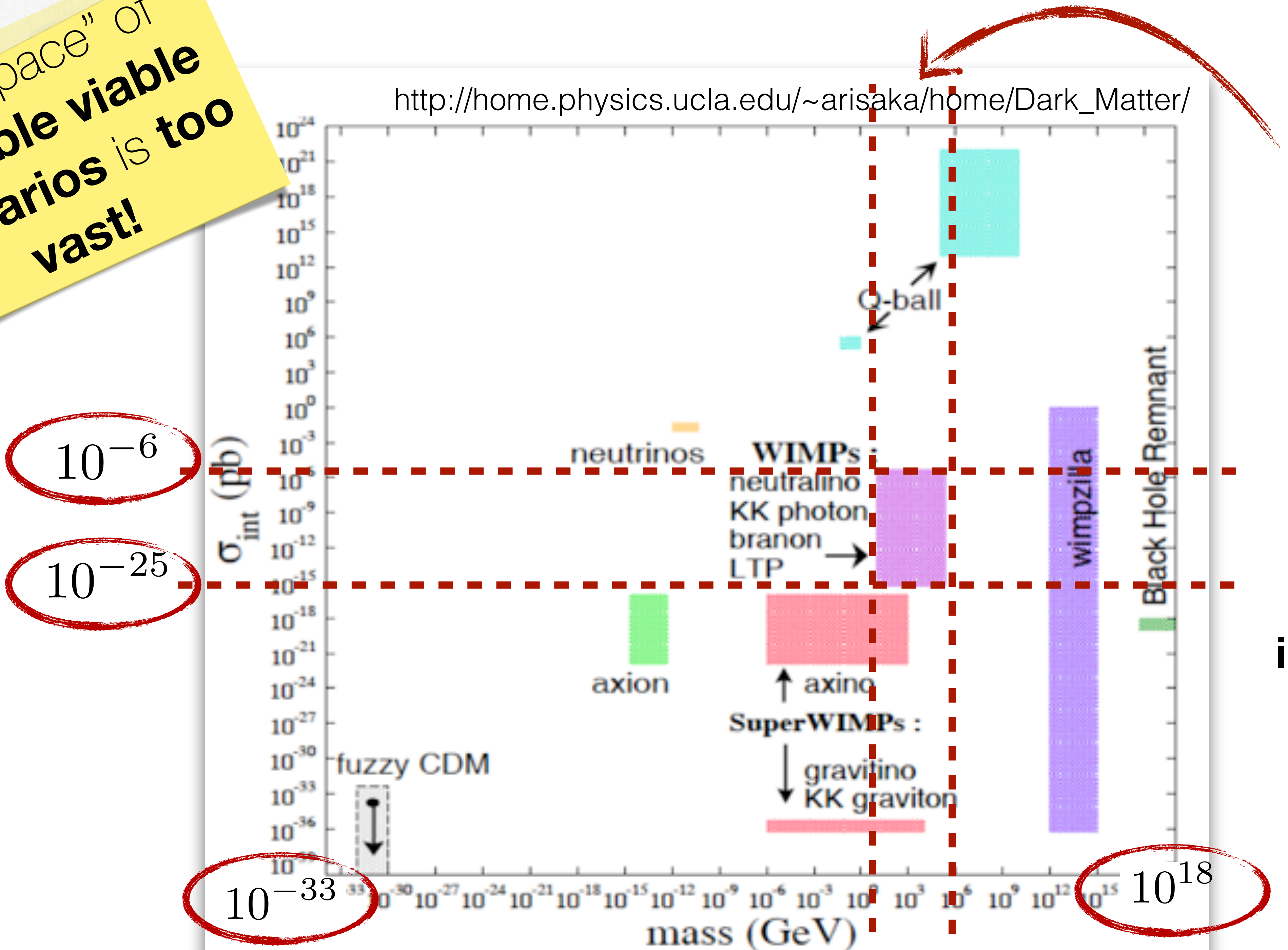


Even if you only consider **WIMPs**, they span:

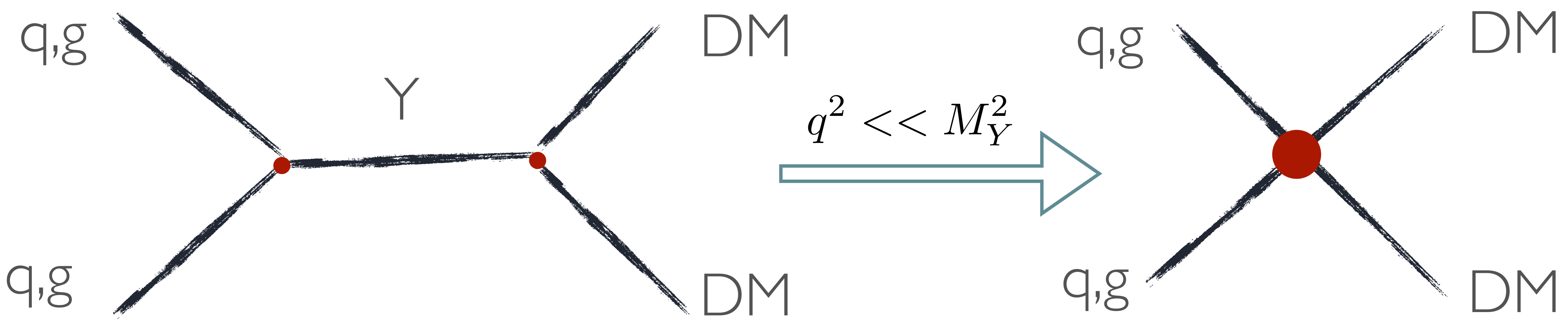
6 orders of magnitude in mass and

19 orders of magnitude in interaction cross section

DM Simplified Models

It is hence **imperative** to cover as much ground as possible:

One option is to study **simplified models:**



"Simplified models" **EFT**

- Probably the "best deal for your buck".
- Simplified models allow to cover many classes of UV complete theories.

DM Simplified Models

Simplified models "standardized":

arXiv:1507.00966v1 [hep-ex] 3 Jul 2015

Dark Matter Benchmark Models for Early LHC Run-2 Searches: Report of the ATLAS/CMS Dark Matter Forum

August 8, 2016

Daniel Abercrombie *MIT, USA*
Nural Akchurin *Texas Tech University, USA*
Ece Akilli *Université de Genève, DPNC, Switzerland*
Juan Alcaraz Maestre *Centro de Investigaciones Energéticas Medioambientales y Tecnológicas (CIEMAT), Spain*
Brandon Allen *MIT, USA*
Barbara Alvarez Gonzalez *CERN, Switzerland*
Jeremy Andrea *Institut Pluridisciplinaire Hubert Curien/Département Recherches Subatomiques, Université de Strasbourg/CNRS-IN2P3, France*
Alexandre Arbey *Université de Lyon and Centre de Recherche Astrophysique de Lyon, CNRS and Ecole Normale Supérieure de Lyon, France and CERN Theory Division, Switzerland*
Georges Azuelos *University of Montreal and TRIUMF, Canada*
Patrizia Azzi *INFN Padova, Italy*

LHC Dark Matter Working Group:

arXiv:1603.04156v1 [hep-ex] 14 Mar 2016

Recommendations on presenting LHC searches for missing transverse energy signals using simplified s-channel models of dark matter

Antonio Boveia,[1,*] Oliver Buchmueller,[2,*] Giorgio Busoni,[3] Francesco D'Eramo,[4] Albert De Roeck,[1,5] Andrea De Simone,[6] Caterina Doglioni,[7,*] Matthew J. Dolan,[3] Marie-Helene Genest,[8] Kristian Hahn,[9,*] Ulrich Haisch,[10,11,*] Philip C. Harris,[1] Jan Heisig,[12] Valerio Ippolito,[13] Felix Kahlhoefer,[14,*] Valentin V. Khoze,[15] Suchita Kulkarni,[16] Greg Landsberg,[17] Steven Lowette,[18] Sarah Malik,[2] Michelangelo Mangano,[11,*] Christopher McCabe,[19,*] Stephen Mrenna,[20] Priscilla Pani,[21] Tristan du Pree,[1] Antonio Riotto,[11] David Salek,[19,22] Kai Schmidt-Hoberg,[14] William Shepherd,[23] Tim M.P. Tait,[24,*] Lian-Tao Wang,[25] Steven Worm[26] and Kathryn Zurek[27]

Example (vector mediator):

Couplings to the dark sector:

$$\mathcal{L}_{X_D}^{Y_1} = \bar{X}_D \gamma_\mu (g^V_{X_D} + g^A_{X_D}\gamma_5) X_D \, Y_1^\mu$$

Couplings to the quarks:

$$\mathcal{L}_{\rm SM}^{Y_1} = \sum_{i,j} \Big[\bar{d}_i \gamma_\mu (g^V_{d_{ij}} + g^A_{d_{ij}}\gamma_5) d_j + \bar{u}_i \gamma_\mu (g^V_{u_{ij}} + g^A_{u_{ij}}\gamma_5) u_j \Big] Y_1^\mu$$

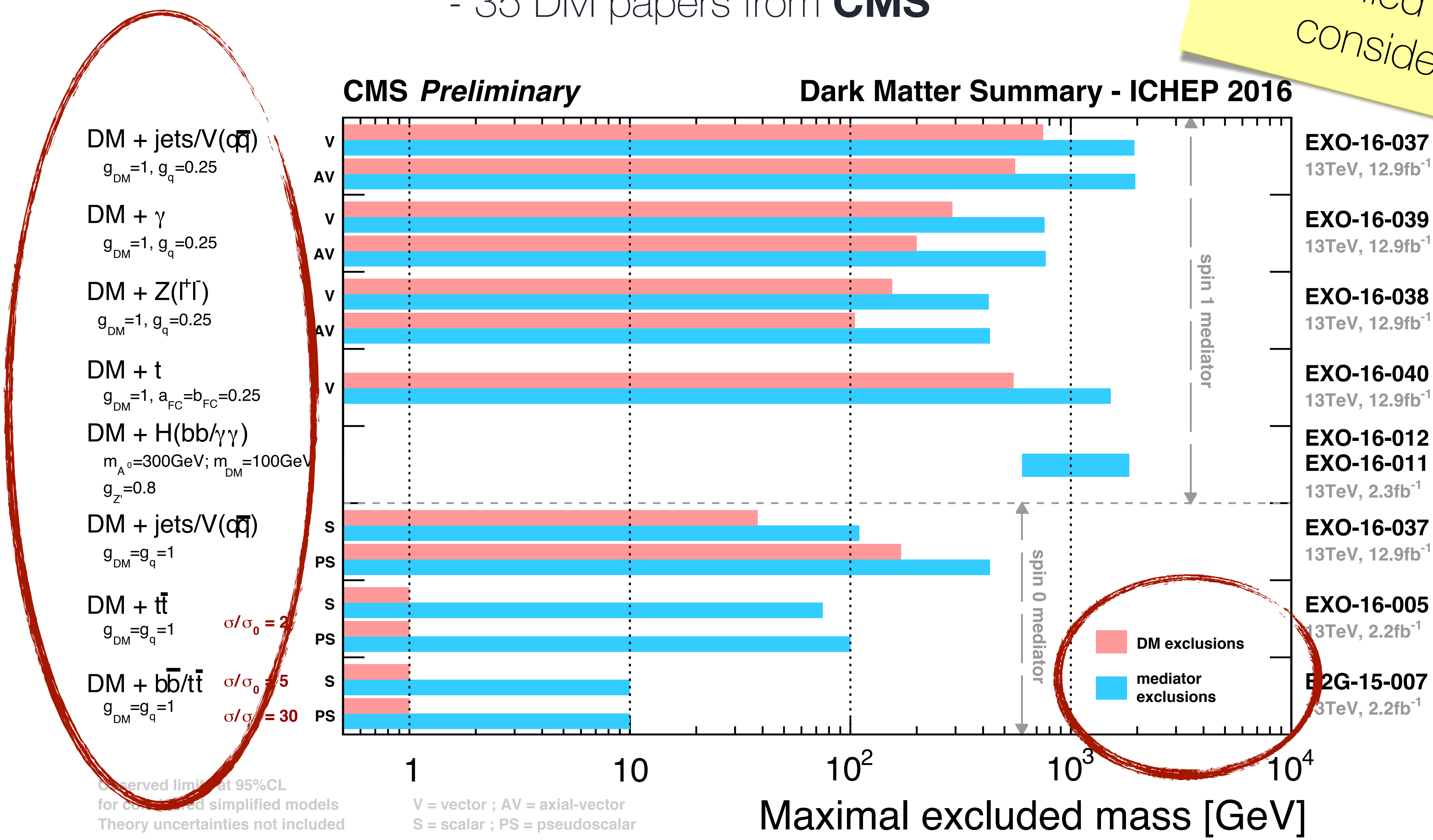
DM Simplified Models at LHC

Recently **much exp. effort** to study Simplified Models at colliders:

Since 2014: - 23 DM papers from **ATLAS**

- 35 DM papers from **CMS**

Many final states & simplified models considered!



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 …	$\chi\chi \to \text{all}$

Dark Matter (DM) searches

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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!**

DM Simplified Models at LHC

At this point, a theorist will ask two (or more) questions:

1. What kinds of **UV completions** (and related issues) can we study from simplified models?

Do I have to worry about anomalies?

Mixing with SM particles?

....

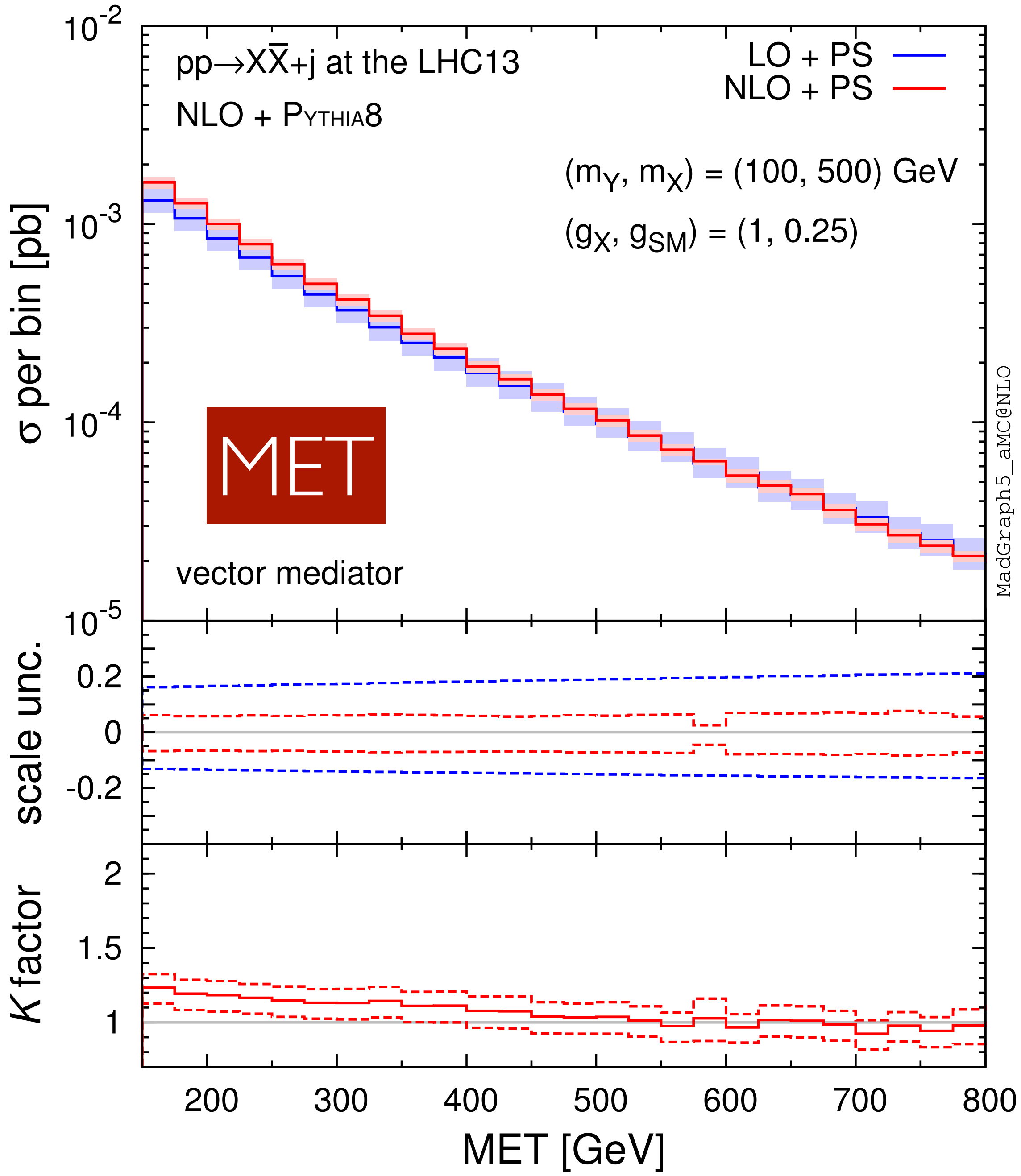
2. Can we **improve** the LHC searches for DM in any way?

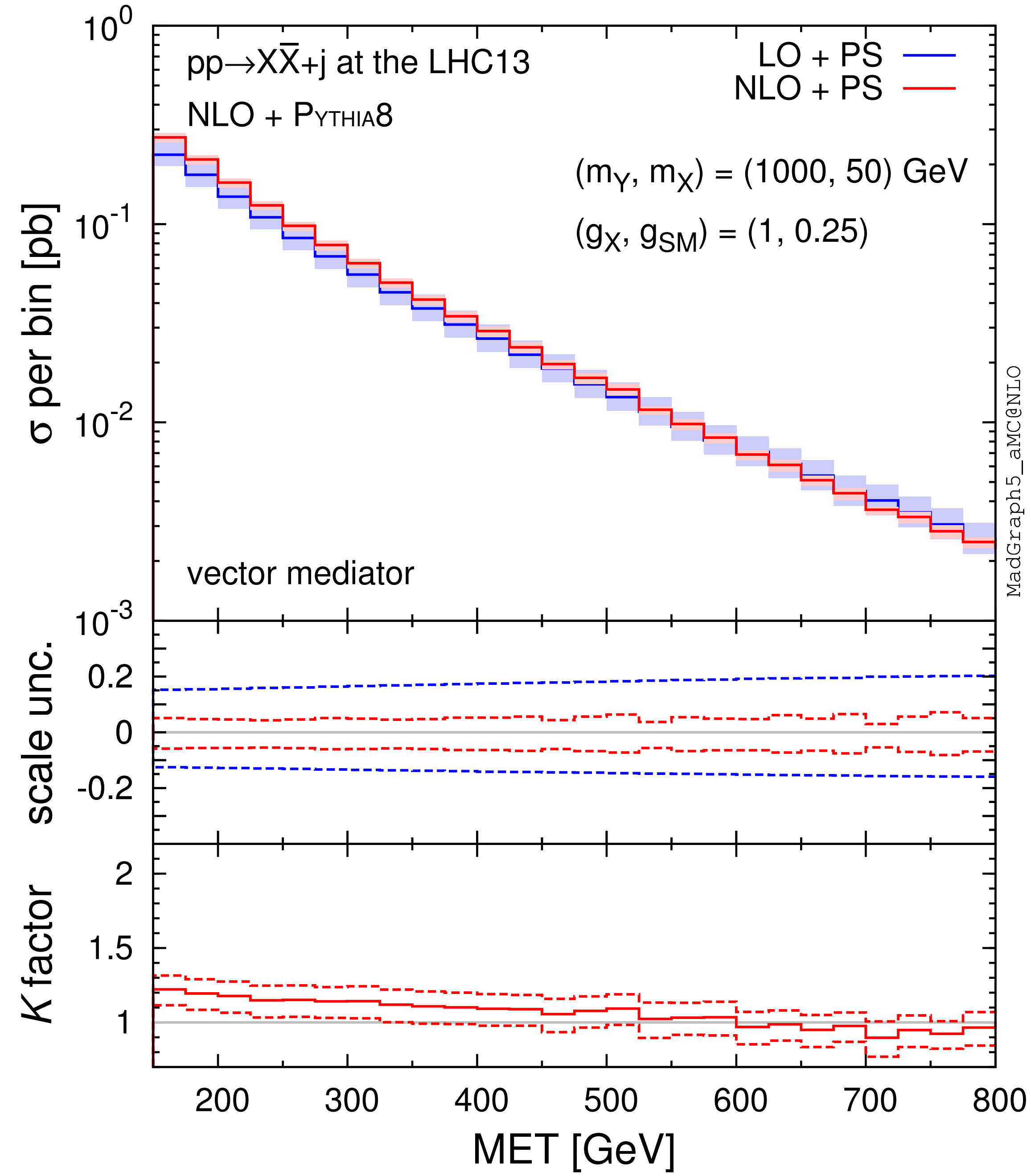
- *Effect of NLO corrections?*
- *Complementarity of LHC and other searches?*
- *How comprehensive are LHC DM searches?*
- *Can we further automate the computations?*

DM production at NLO (QCD)

Let's look at a few examples:

Simplified models with large mass scales don't have large NLO K-factors

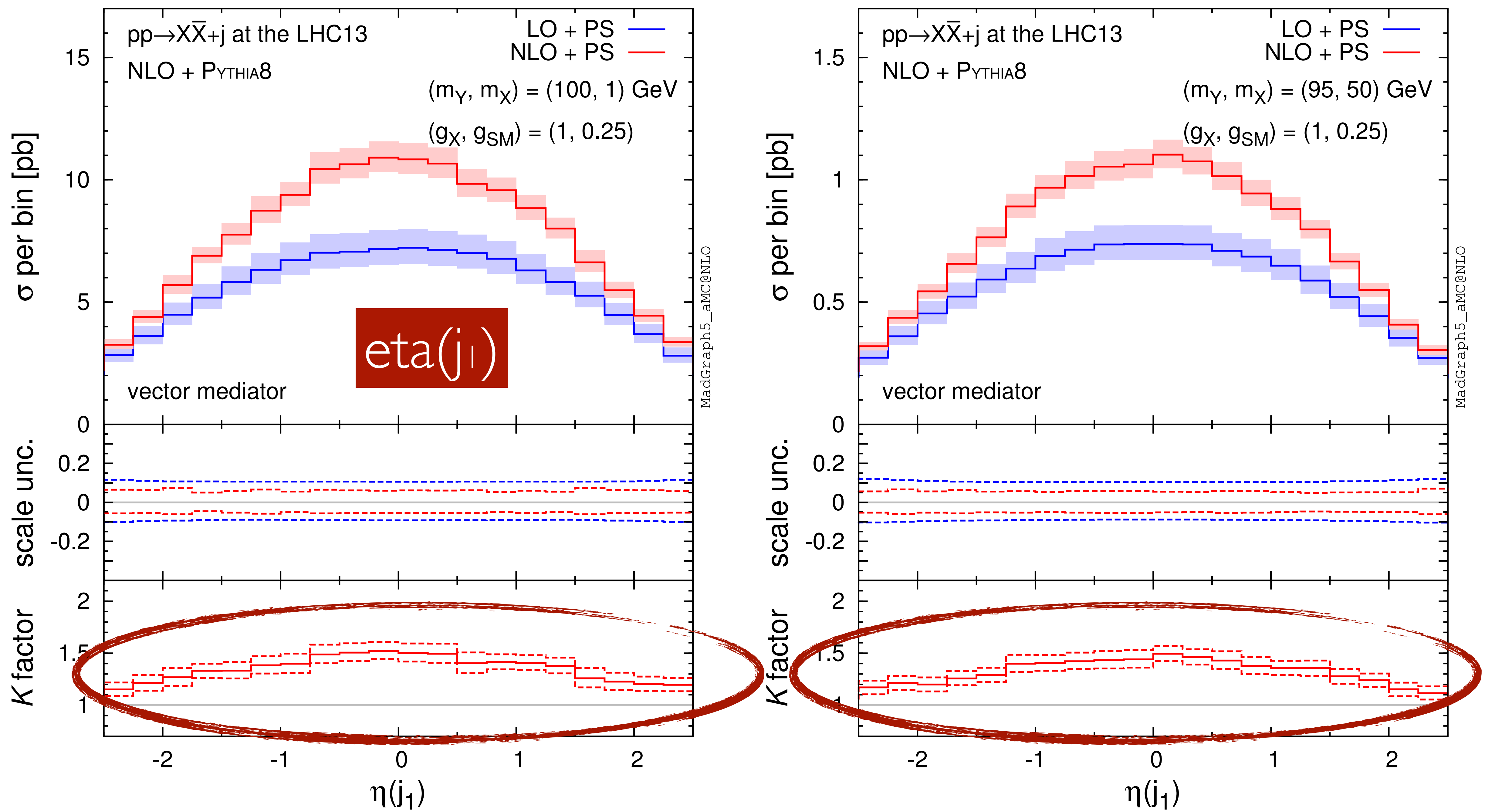




… but you get a **factor of 2 improvement in scale uncertainties!**

DM production at NLO (QCD)

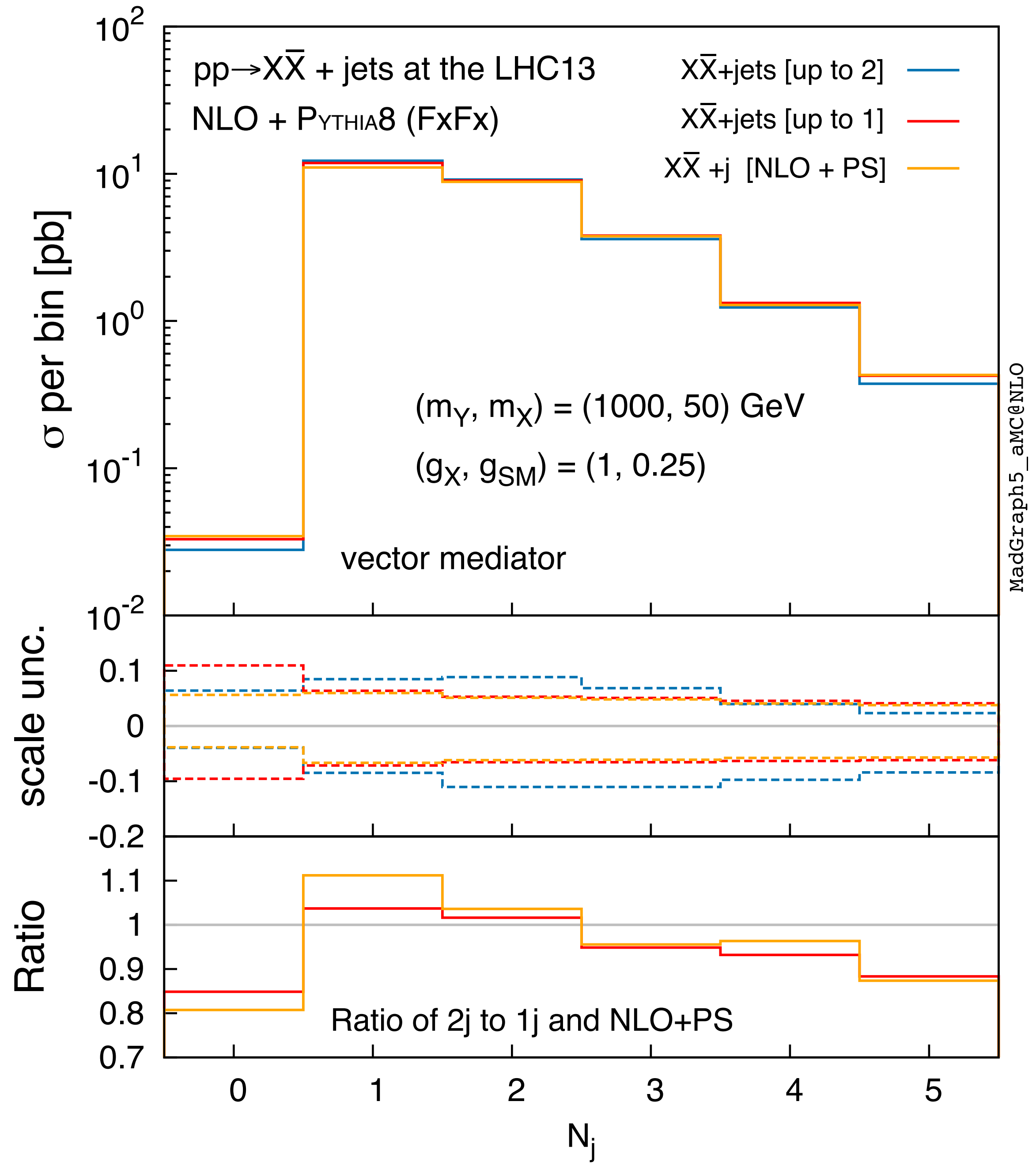
Also, **shapes of distributions** can be affected by NLO corrections

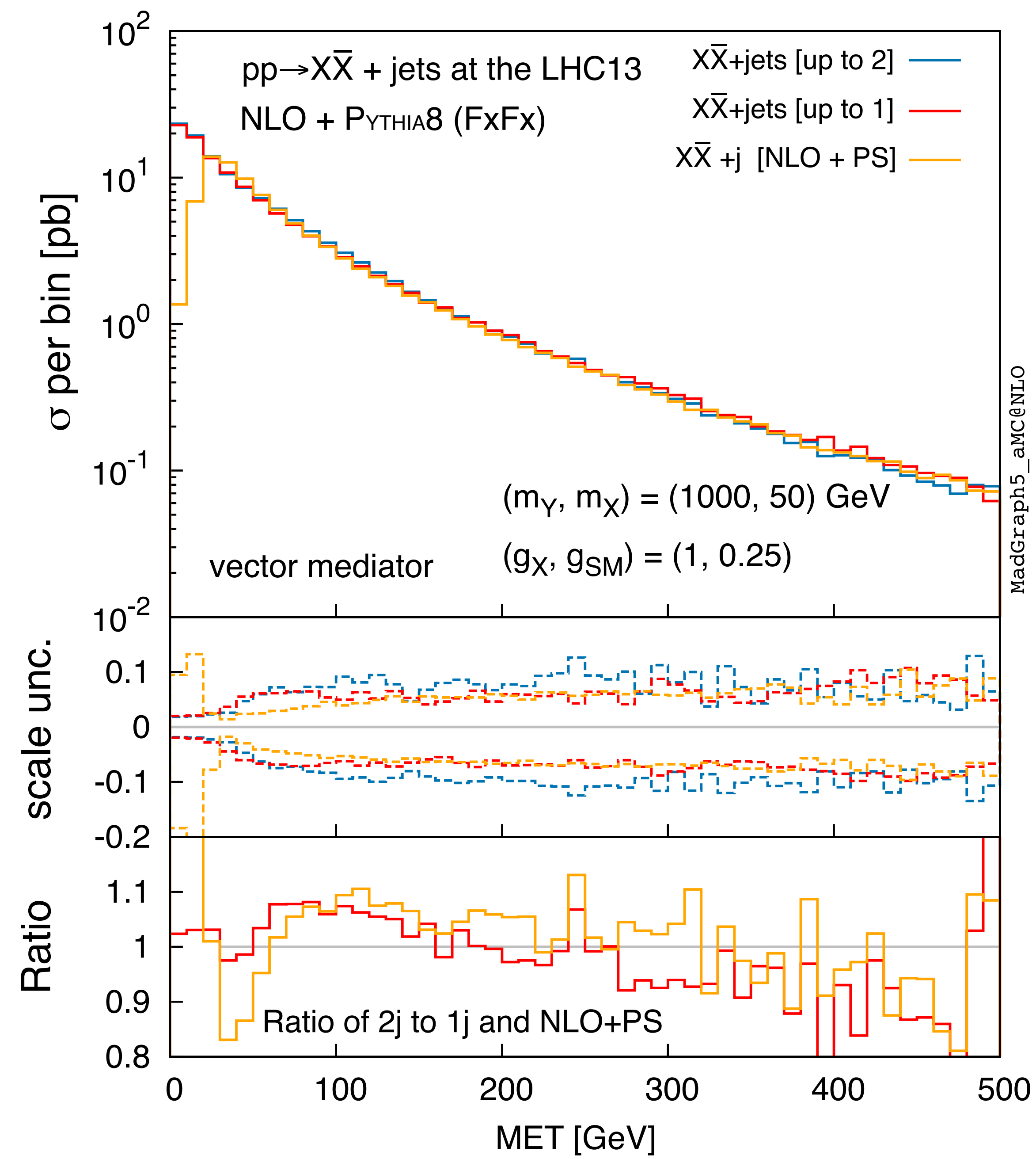


Simple overall K-factors **might not be enough** to capture the NLO effects!

DM production at NLO (QCD)

Effects of NLO merging (FxFx)





Merging effects are relatively small (~ 10%)

DM production at NLO

Tools for NLO (QCD) simp. models

- POWHEG + PS
  (Haisch, Re, Kahlhoefer)
- MCFM (Fox, Williams)

Works great…
but “brute force”
implementation.
Not very flexible.

- MG5_aMC@NLO
  - Flexible framework.
  - Easy links to **PS /merging**.
  - Easy links to **DM tools (MadDM)**

DM production at NLO

Tools for NLO (QCD) simp. models

- POWHEG + PS
  (Haisch, Re, Kahlhoefer)

  ...ce
  ...mentation.
  Not very flexible.

- MCFM (Fo...

It is a great thing that we have more than one tool!!!

- MG5_aMC@NLO
  - Flexible framework.
  - Easy links to **PS /merging**.
  - Easy links to **DM tools (MadDM)**

DM production at NLO

DM simplified models for **s-channel mediators** are **implemented** in the aMC@NLO framework at NLO (QCD) accuracy **(and publicly available)**

Publication	Mediator (s-ch.)	DM	Interactions
arXiv:1508.05327 (**MB**, Kramer, Maltoni, Martini, Mawatari, Pellen)	S, PS, V, PV	Dirac, Scalar, CScalar	q, t
arXiv:1508.00564 (Mattelaer, Vryonidou)	S, PS, V, PV	Dirac	b,t (**loop induced**)
arXiv:1509.05785 (Neubert,	S, PS, V, PV	Dirac, Cscalar	Z

With the FeynRules+NLOCT we can generate the NLO UFO models quickly!

More coming!

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

How difficult is it to do this in a generic DM scenario?

Example: Top-philic DM simplified model

1605.09242

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

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]

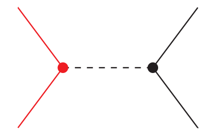
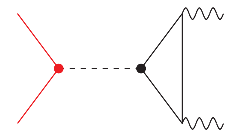
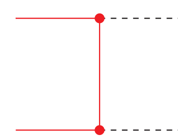
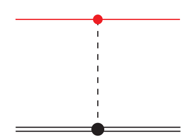
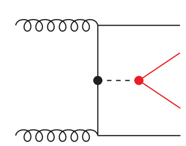
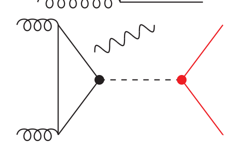
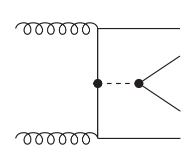
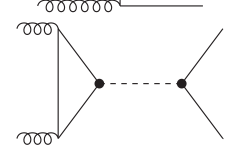
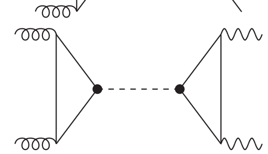
…

Credit for slide to Jan Heisig

Example: Top-philic DM simplified model

1605.09242

Plethora of signatures

Cosmology	relic		$m_X > m_t$	
	indirect		$m_X < m_t$	Planck, FermiLAT
Astrophysics			$m_X > m_Y$	
	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

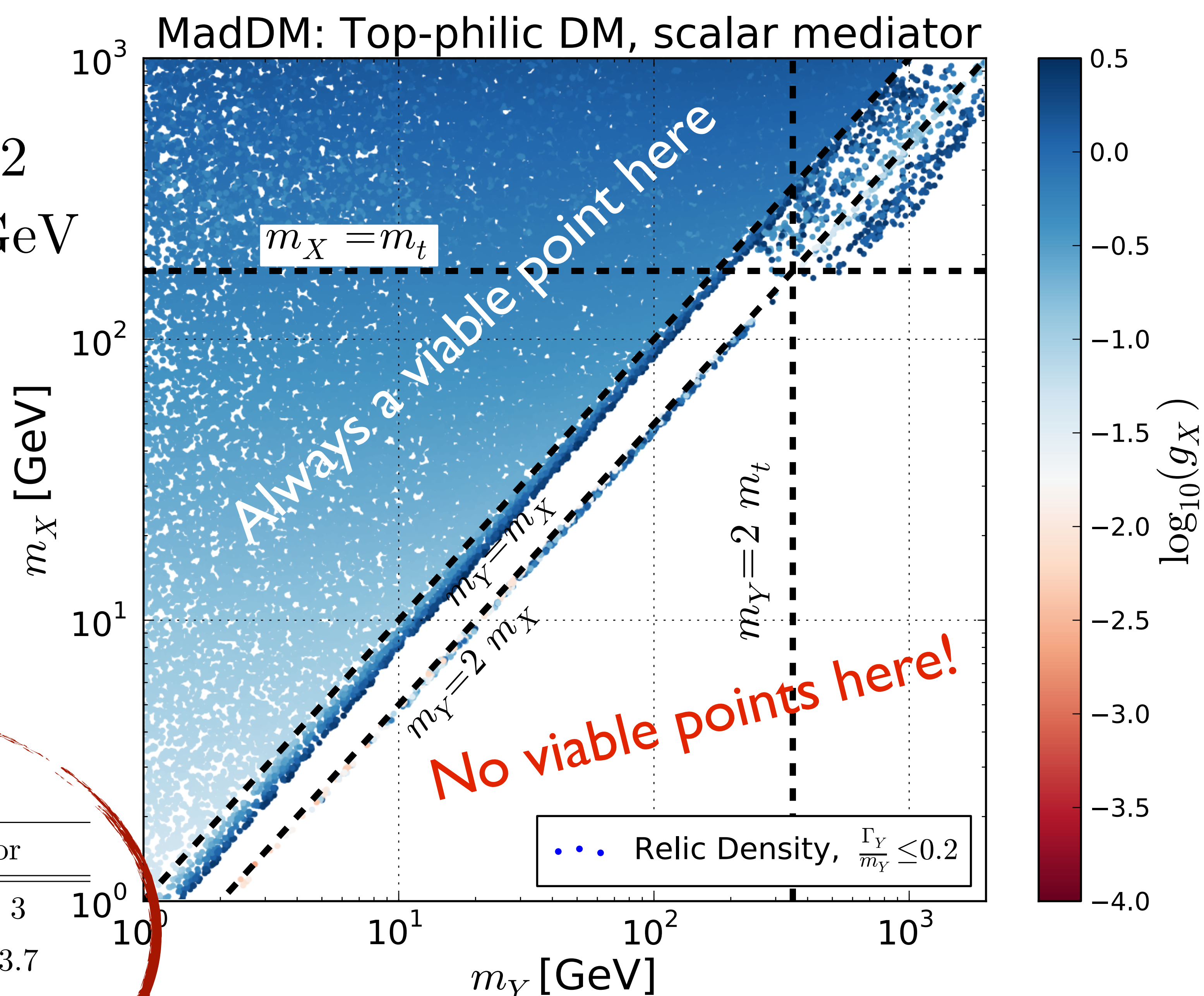
Example: Top-philic DM simplified model

1605.09242

Relic density constraints

$\Gamma_Y / m_Y < 0.2$

$\Gamma_Y > 10^{-11}$ GeV



[Computed with MadDM,]

Scan:

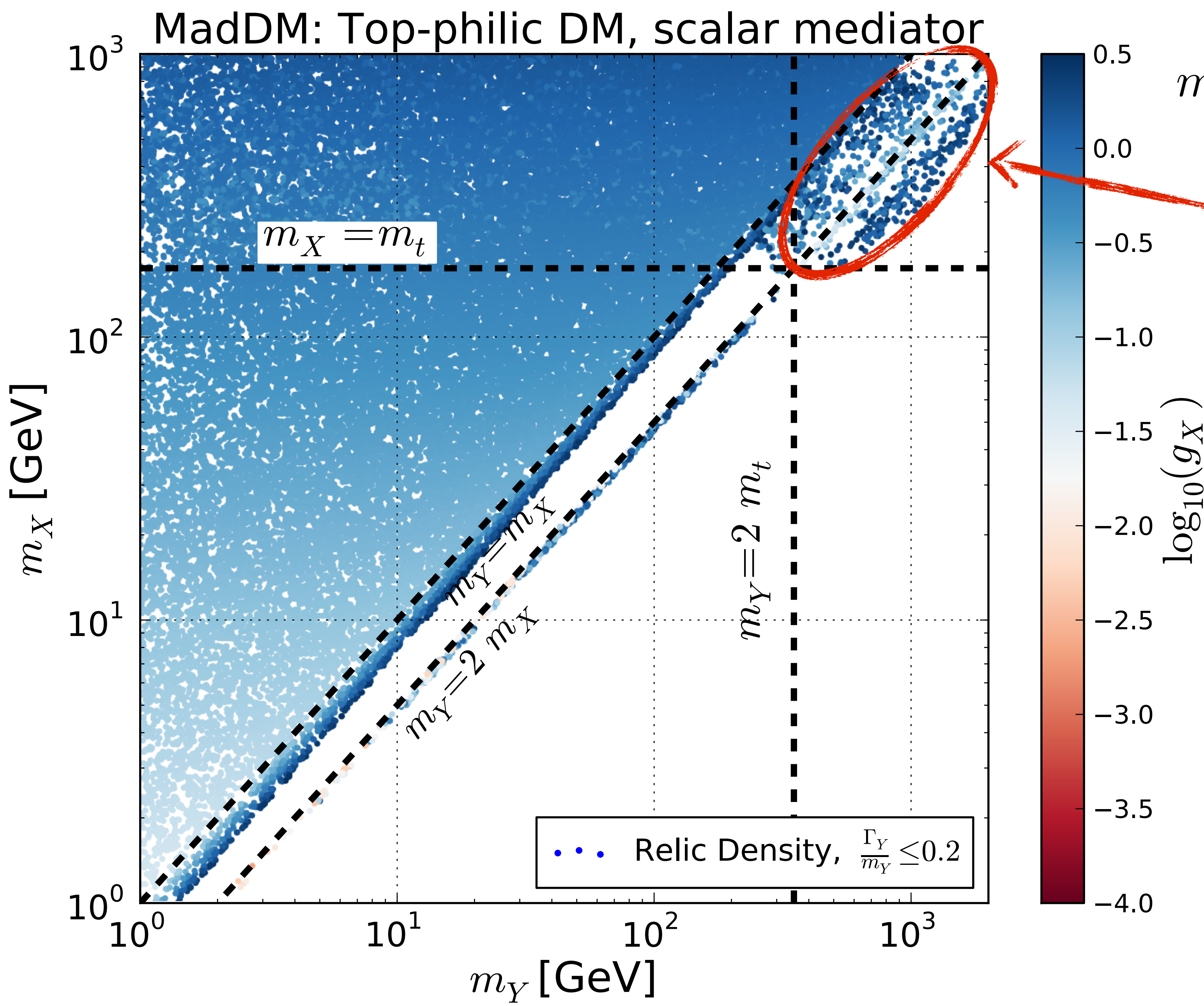
MultiNest parameter	Prior
$\log(m_X/\ \mathrm{GeV})$	$0 \to 3$
$\log(m_Y/\ \mathrm{GeV})$	$0 \to 3.7$
$\log(g_X)$	$-4 \to \log(\pi)$
$\log(g_t)$	$-4 \to \log(\pi)$

Credit for slide to Jan Heisig

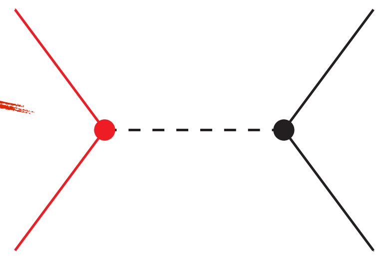
Example: Top-philic DM simplified model

1605.09242

Relic density constraints



$m_Y \gtrsim m_X \gtrsim m_t$:



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

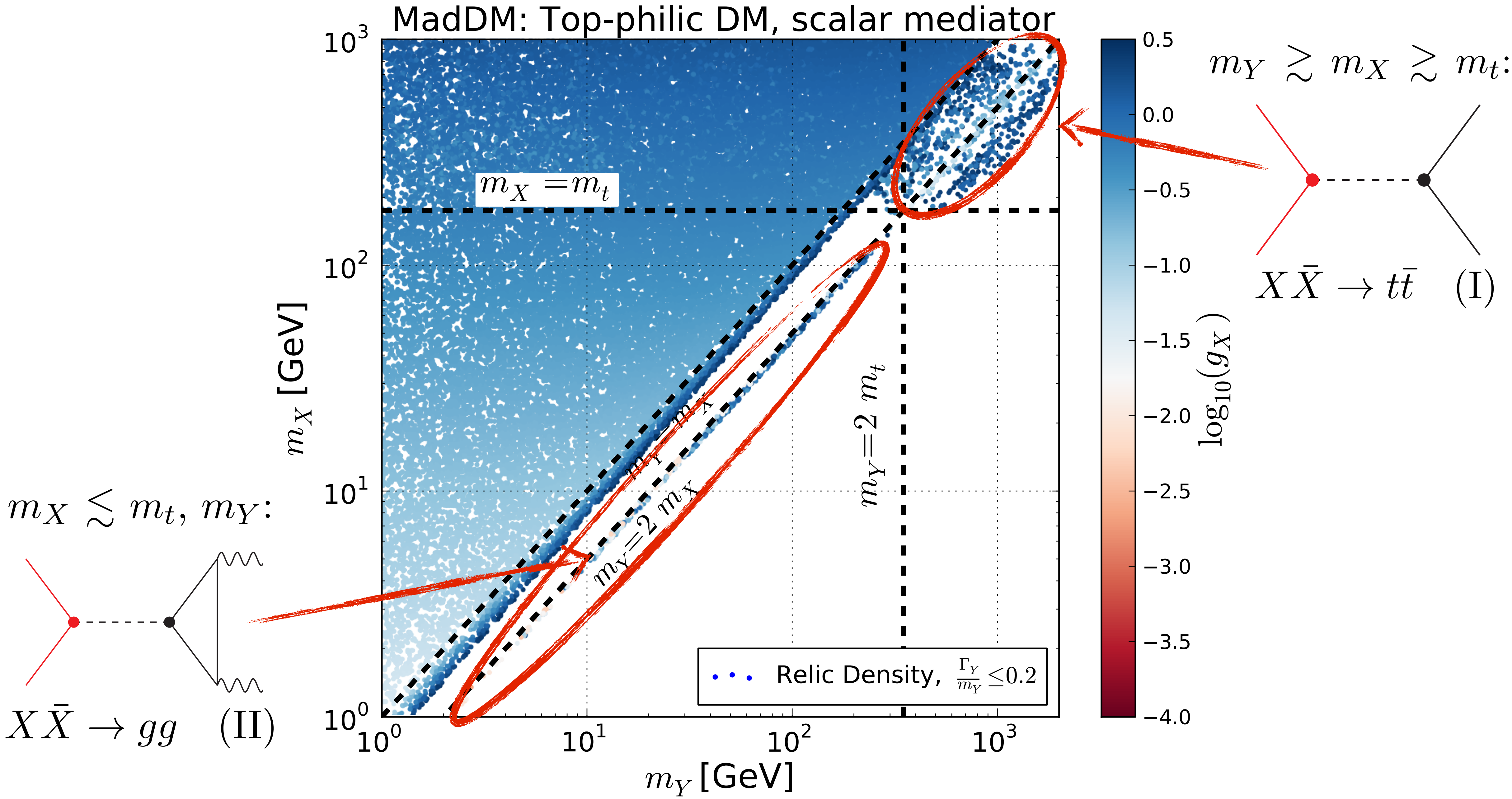
[Computed with MadDM,]

Credit for slide to Jan Heisig

Example: Top-philic DM simplified model

1605.09242

Relic density constraints



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Example: Top-philic DM simplified model

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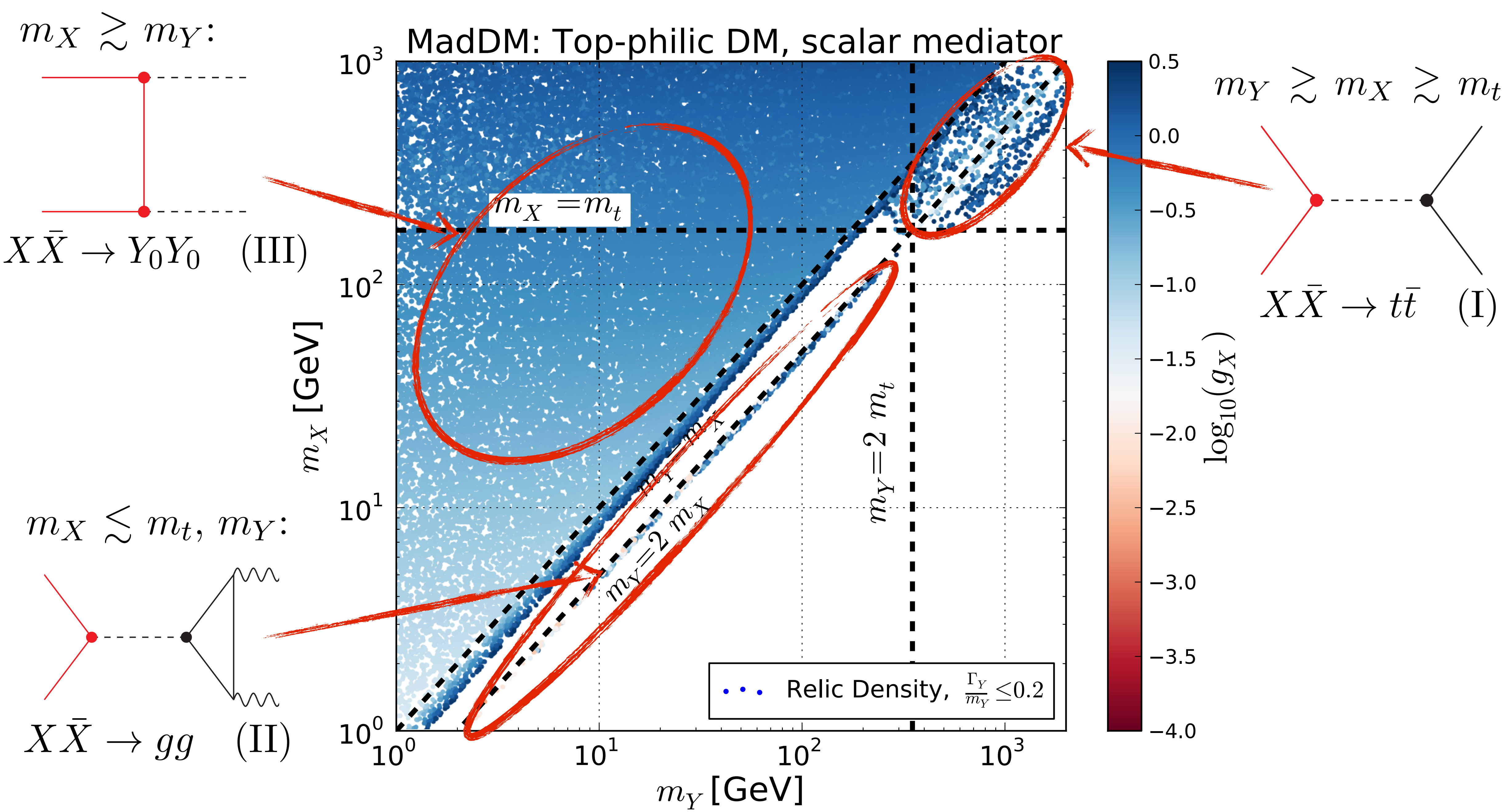
Relic density constraints



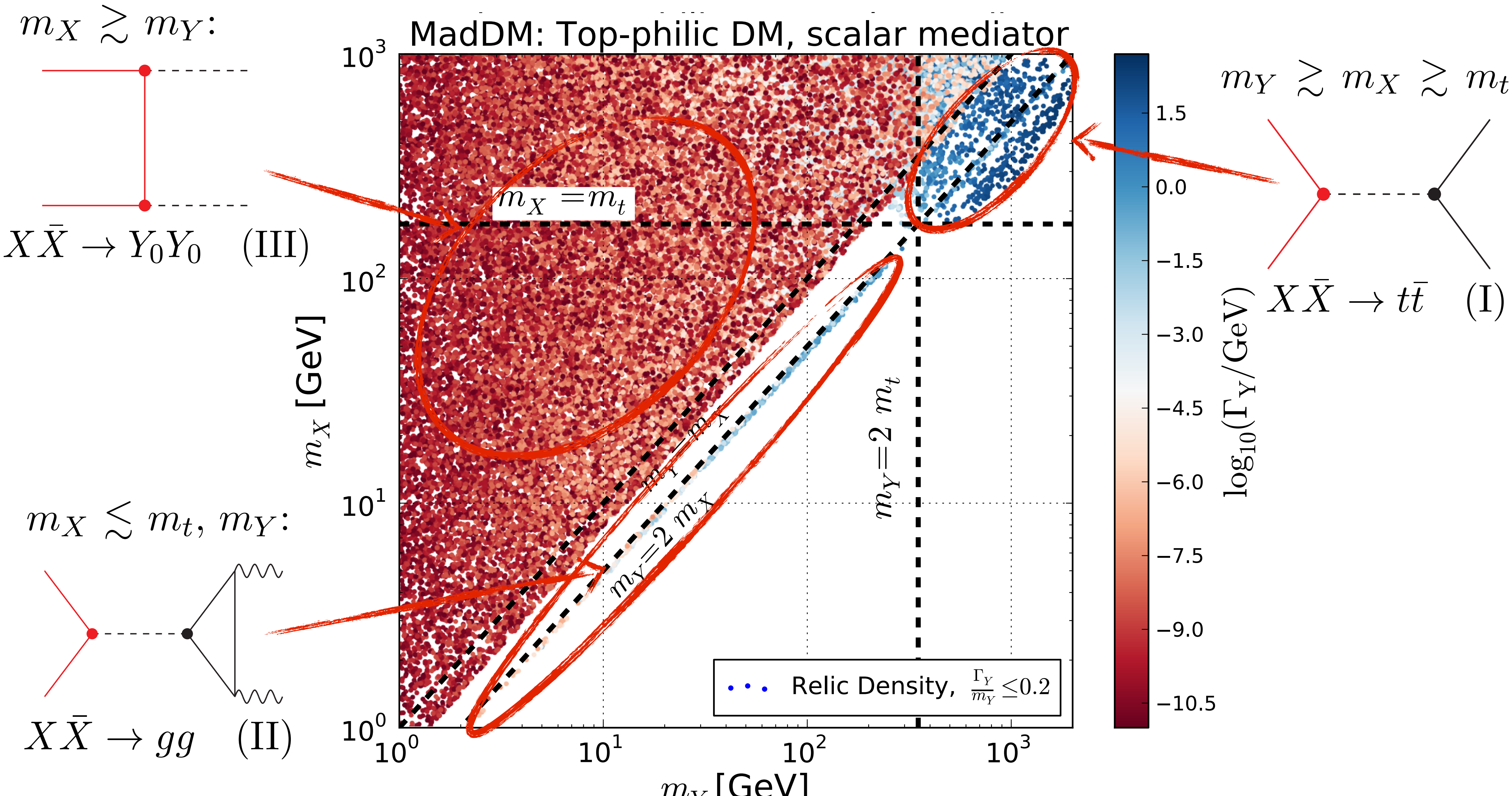
[Computed with MadDM,]

Credit for slide to Jan Heisig

Example: Top-philic DM simplified model

1605.09242

Relic density constraints



[Computed with MadDM,]

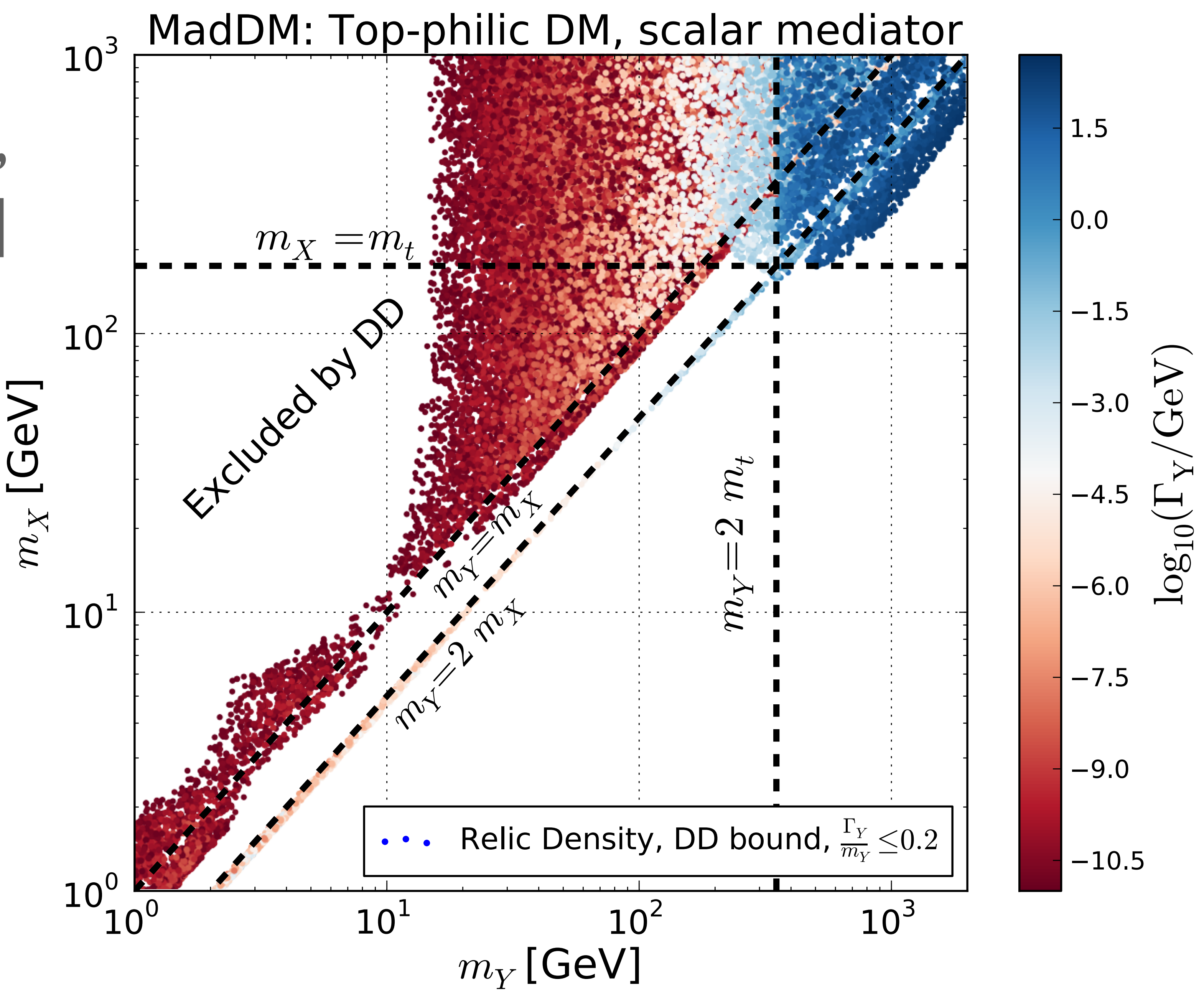
Credit for slide to Jan Heisig

Example: Top-philic DM simplified model

1605.09242

Direct detection bounds

[CDMSlite, LUX 2013]



[Computed with MadDM,]

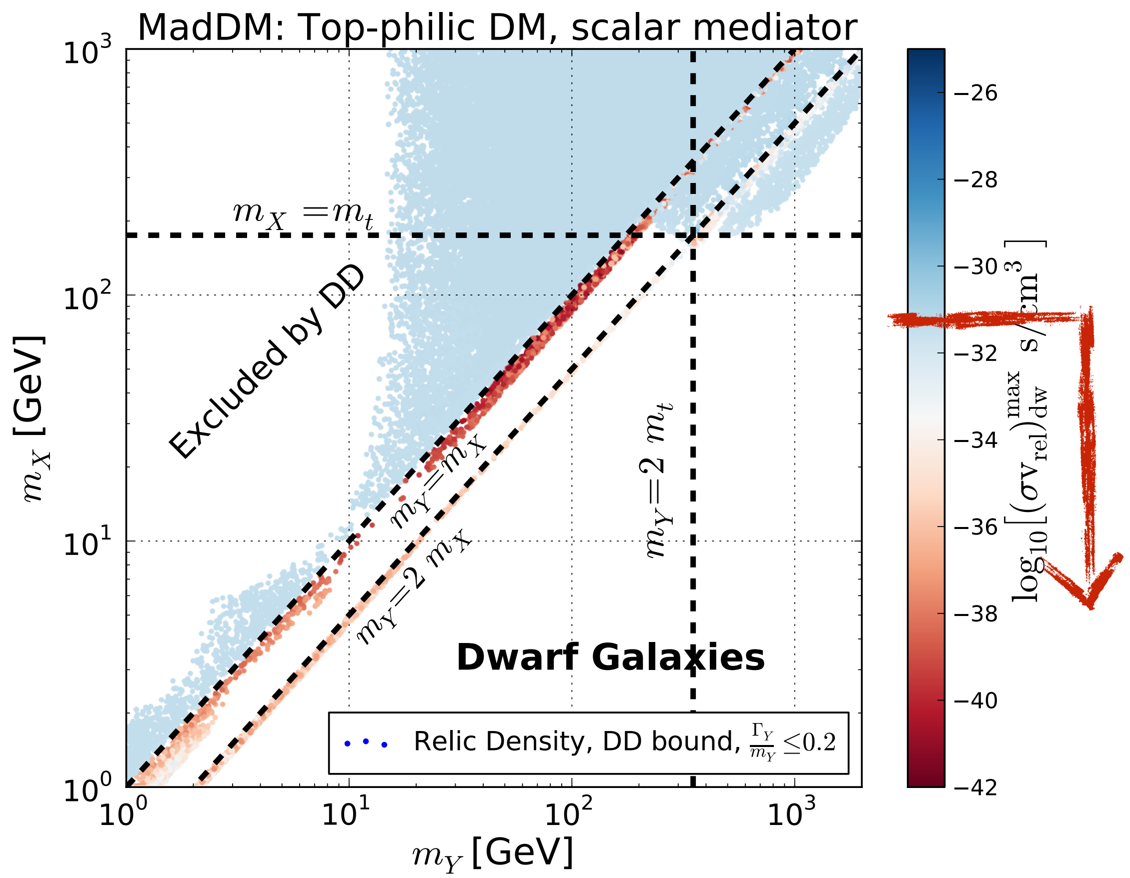
Credit for slide to Jan Heisig

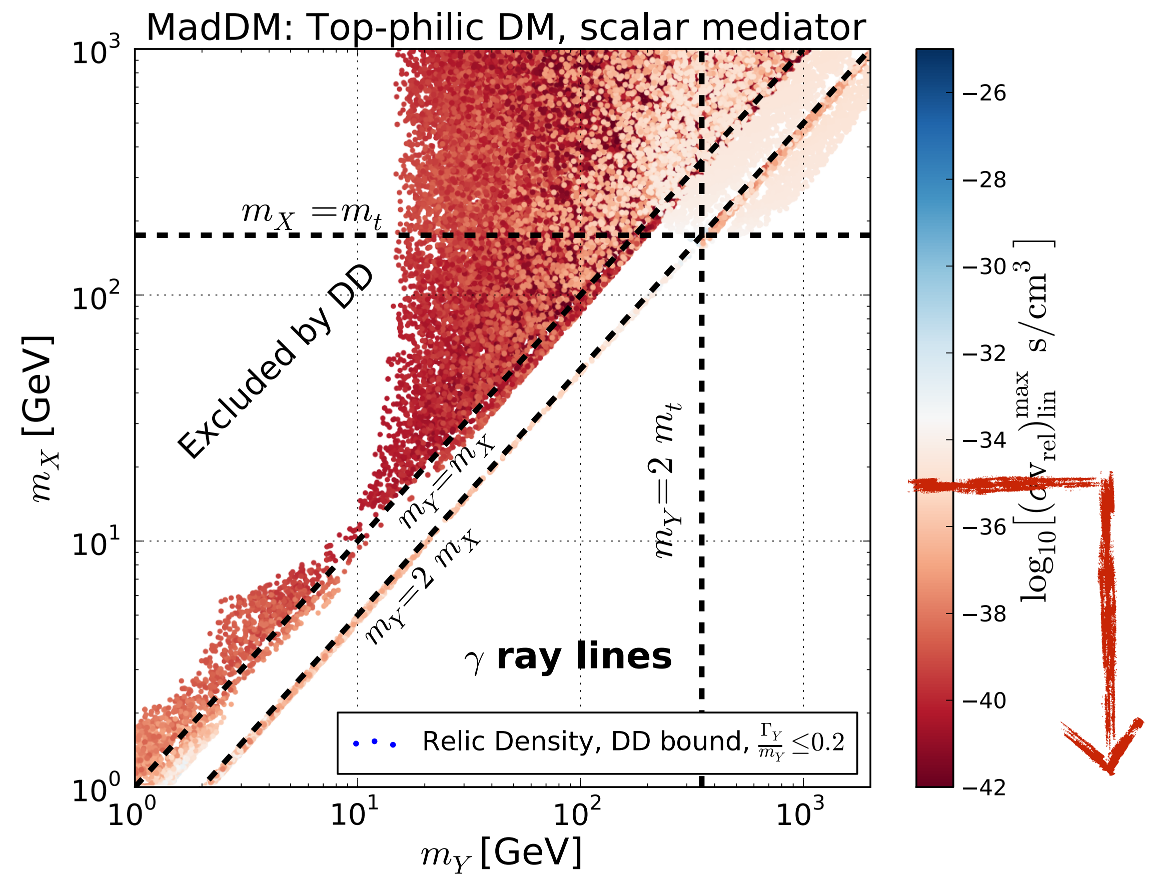
Example: Top-philic DM simplified model

1605.09242

Indirect detection bounds

[*Fermi*-LAT 2015]





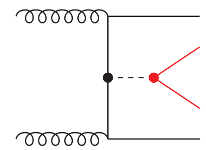
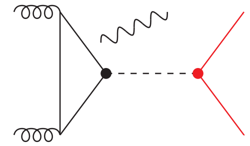
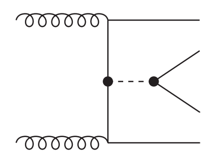
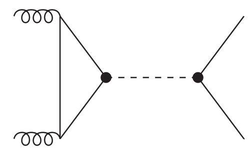
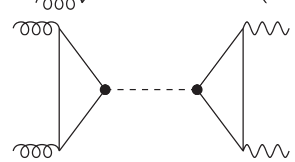
- *p*-wave suppression for all annihilation processes for scalar mediator
- For pseudo-scalar mediator only process XX > YY *p*-wave suppressed

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

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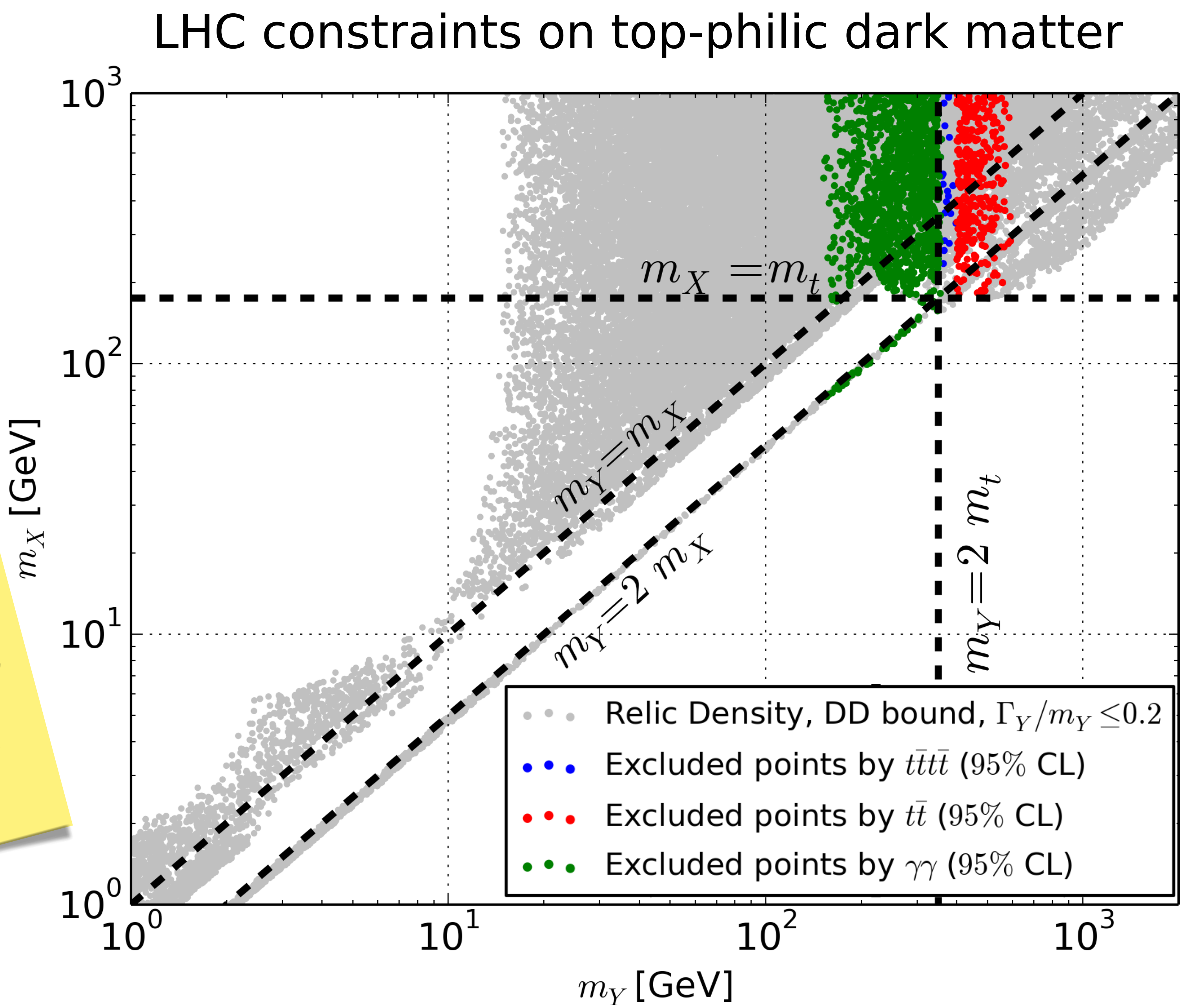
Combined constraints



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

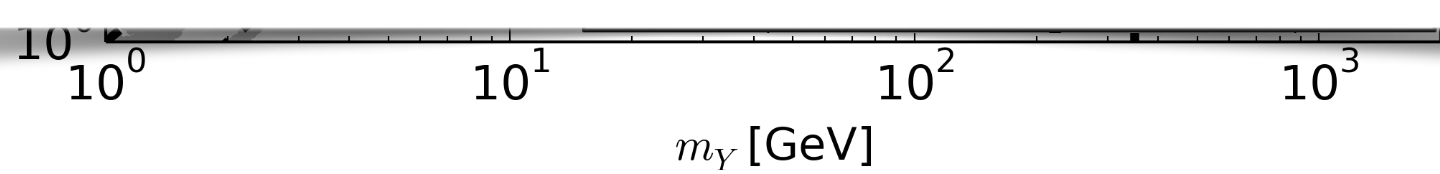
Example: Top-philic DM simplified model

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!